GAP - Reference Manual

Release 4.11.1, 2021-03-02

The GAP Group
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1.4 of this manual.

GAP has been developed over a long time and has many authors and contributors. More detailed
information can be found in Section 1.2 of this manual.
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Chapter 1

Preface

Welcome to GAP. This is one of the manuals documenting the core part of GAP, the others being the GAP Tutorial and HPC-GAP Reference Manual.

There is also a document CHANGES.md on the changes from earlier versions in the root directory. This preface serves not only to introduce “The GAP Reference Manual”, but also as an introduction to the whole system.

GAP stands for Groups, Algorithms and Programming. The name was chosen to reflect the original aim of the system, which is introduced in this reference manual. Since that choice, the system has become somewhat broader, and you will also find information about algorithms and programming for other algebraic structures, such as semigroups and algebras.

This manual, the GAP Reference Manual contains the official definitions of GAP functions. It should contain all the information needed to use GAP, and is not intended to be read cover-to-cover.

To get started a new user may first look at parts of the GAP Tutorial.

A lot of the functionality of the system and a number of contributed extensions are provided as “GAP packages” which are developed independently of the core part of GAP and can be loaded into a GAP session. Each package comes with a its own manual which is also available through the GAP help system.

This manual is divided into chapters, sections and subsections. Chapter 2 describes the help system, which provides access to all the manuals from a running GAP session. Chapter 3 gives technical advice for running GAP. Chapter 4 introduces the GAP language, and the next chapters deal with the environment provided by GAP for the user. These are followed by the main bulk of chapters which are devoted to the various mathematical structures that GAP can handle.

Subsequent sections of this preface explain the structure of the system and provide copyright and licensing information.

1.1 The GAP System

GAP is a free, open and extensible software package for computation in discrete abstract algebra. The terms “free” and “open” describe the conditions under which the system is distributed – in brief, it is free of charge (except possibly for the immediate costs of delivering it to you), you are free to pass it on within certain limits, and all of the workings of the system are open for you to examine and change. Details of these conditions can be found in Section (Reference: Copyright and License).

The system is “extensible” in that you can write your own programs in the GAP language, and use them in just the same way as the programs which form part of the system (the “library”). Indeed,
we actively support the contribution, refereeing and distribution of extensions to the system, in the form of “GAP packages”. Further details of this can be found in Chapter (Reference: Using and Developing GAP Packages), and on our website.

Development of GAP began at Lehrstuhl D für Mathematik, RWTH-Aachen, under the leadership of Joachim Neubüser in 1985. Version 2.4 was released in 1988 and version 3.1 in 1992. In 1997 coordination of GAP development, now very much an international effort, was transferred to St Andrews. A complete internal redesign and almost complete rewrite of the system was completed over the following years and version 4.1 was released in July 1999. A sign of the further internationalization of the project was the GAP 4.4 release in 2004, which has been coordinated from Colorado State University, Fort Collins.

More information on the motivation and development of GAP to date, can be found on our website in a section entitled “Some History of GAP”:

For those readers who have used an earlier version of GAP, an overview of the changes from GAP 4.4 and a brief summary of changes from earlier versions is given in CHANGES.md file in the main directory.

The system that you are getting now consists of a “core system” and a number of packages. The core system consists of four main parts.

1. A kernel, written in C, which provides the user with

   • automatic dynamic storage management, which the user needn’t bother about when programming;
   • a set of time-critical basic functions, e.g. “arithmetic”, operations for integers, finite fields, permutations and words, as well as natural operations for lists and records;
   • an interpreter for the GAP language, an untyped imperative programming language with functions as first class objects and some extra built-in data types such as permutations and finite field elements. The language supports a form of object-oriented programming, similar to that supported by languages like C++ and Java but with some important differences.
   • a small set of system functions allowing the GAP programmer to handle files and execute external programs in a uniform way, regardless of the particular operating system in use.
   • a set of programming tools for testing, debugging, and timing algorithms.
   • a “read-eval-view” style user interface.

2. A much larger library of GAP functions that implement algebraic and other algorithms. Since this is written entirely in the GAP language, the GAP language is both the main implementation language and the user language of the system. Therefore a user can, as easily as the original programmers, investigate and vary algorithms of the library and add new ones to it, first for their own use and eventually for the benefit of all GAP users.

3. A library of group theoretical data which contains various libraries of groups, including the library of small groups (containing all groups of order at most 2000, except those of order 1024) and others. Large libraries of ordinary and Brauer character tables and Tables of Marks are included as packages.

4. The documentation. This is available as on-line help, as printable files in PDF format and as HTML for viewing with a Web browser.
Also included with the core system are some test files and a few small utilities which we hope you will find useful.

**GAP packages** are self-contained extensions to the core system. A package contains **GAP** code and its own documentation and may also contain data files or external programs to which the **GAP** code provides an interface. These packages may be loaded into **GAP** using the LoadPackage (Reference: LoadPackage) command, and both the package and its documentation are then available just as if they were parts of the core system. Some packages may be loaded automatically, when **GAP** is started, if they are present. Some packages, because they depend on external programs, may only be available on the operating systems where those programs are available (usually UNIX). You should note that, while the packages included with this release are the most recent versions ready for release at this time, new packages and new versions may be released at any time and can be easily installed in your copy of **GAP**.

With **GAP** there are two packages (the library of ordinary and Brauer character tables, and the library of tables of marks) which contain functionality developed from parts of the **GAP** core system. These have been moved into packages for ease of maintenance and to allow new versions to be released independently of new releases of the core system. The library of small groups should also be regarded as a package, although it does not currently use the standard package mechanism. Other packages contain functionality which has never been part of the core system, and may extend it substantially, implementing specific algorithms to enhance its capabilities, providing data libraries, interfaces to other computer algebra systems and data sources such as the electronic version of the Atlas of Finite Group Representations; therefore, installation and usage of packages is recommended.

Further details about **GAP** packages can be found in chapter (Reference: Using and Developing **GAP** Packages), and on the **GAP** website here: [https://www.gap-system.org/Packages/packages.html](https://www.gap-system.org/Packages/packages.html).

### 1.2 Authors and Maintainers

**GAP** is the work of very many people, many of whom still maintain parts of the system. A complete list of authors, and an approximation to the current list of maintainers can be found on the **GAP** website at [https://www.gap-system.org/Contacts/People/authors.html](https://www.gap-system.org/Contacts/People/authors.html) and [https://www.gap-system.org/Contacts/People/modules.html](https://www.gap-system.org/Contacts/People/modules.html). All **GAP** packages have their own authors and maintainers. It should however be noted that some packages provide interfaces between **GAP** and an external program, a copy of which is included for convenience, and that, in these cases, we do not claim that the package authors or maintainers wrote, or maintain, this external program. Similarly, the system and some packages include large data libraries that may have been computed by many people. We try to make clear in each case what credit is attributable to whom.

We have, for some time, operated a refereeing system for contributed packages, both to ensure the quality of the software we distribute, and to provide recognition for the authors. We now consider this to be a refereeing system for modules, and we would note, in particular that, although it does not use the standard package interface, the library of small groups has been refereed and accepted on exactly the same basis as the accepted packages.

We also include with this distribution a number of packages which have not (yet) gone through our refereeing process. Some may be accepted in the future, in other cases the authors have chosen not to submit them. More information can be found on our website (see Section 1.5).
1.3 Acknowledgements

Very many people have worked on, and contributed to, GAP over the years since its inception. On our website you will find the prefaces to the previous releases, each of which acknowledges people who have made special contributions to that release. Even so, it is appropriate to mention here Joachim Neubüser whose vision of a free, open and extensible system for computational algebra inspired GAP in the first place, and Martin Schönert, who was the technical architect of GAP 3 and GAP 4.

1.4 Copyright and License

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You are permitted to modify and redistribute GAP, but you are not allowed to restrict further redistribution. That is to say proprietary modifications will not be allowed. We want all versions of GAP to remain free.

If you modify any part of GAP and redistribute it, you must supply a README document. This should specify what modifications you made in which files. We do not want to take credit or be blamed for your modifications.

Of course we are interested in all of your modifications. In particular we would like to see bug-fixes, improvements and new functions. So again we would appreciate it if you would inform us about all modifications you make.

In addition to the general copyright for GAP set forth above, the following terms apply to the versions of GAP for Windows.

The executable of GAP for Windows that we distribute was compiled with the gcc compiler supplied with Cygwin installation (https://cygwin.com/).

The GNU C compiler is
1.5 Further Information about GAP

Information about GAP is best obtained from the GAP website https://www.gap-system.org. There you will find, amongst other things:

- directions to the sites from which you can download the current GAP distribution, all accepted and deposited GAP packages, and a selection of other contributions.

- the GAP manual and an archive of the gap-forum mailing list, formatted for reading with a Web browser, and indexed for searching.

- information about GAP developers, and about the email addresses available for comment, discussion and support.

We would particularly ask you to note the following things:

- The GAP Forum – an email discussion forum for comments, discussions or questions about GAP. You must subscribe to the list before you can post to it, see the website for details. In particular we will announce new releases in this mailing list.

- The email address support@gap-system.org to which you are asked to send any questions or bug reports which do not seem likely to be of interest to the whole GAP Forum. Please give a (short, if possible) self-contained excerpt of a GAP session containing both input and output that illustrates your problem (including comments of why you think it is a bug) and state the type of the machine, operating system, (compiler used, if UNIX/Linux) and the version of GAP you are using (the first line after the GAP 4 banner starting GAP, Version 4...).

- We also ask you to send a brief message to support@gap-system.org when you install GAP.

- The correct form of citation of GAP, which we ask you use whenever you publish scientific results obtained using GAP.

It finally remains for us to wish you all pleasure and success in using GAP, and to invite your constructive comment and criticism.

The GAP Group, 2021-03-02
Chapter 2

The Help System

This chapter describes the GAP help system. The help system lets you read the documentation interactively.

2.1 Invoking the Help

The basic command to read GAP’s documentation from within a GAP session is as follows.

\[ ?[book:][?]topic \]

For an explanation and some examples see (Tutorial: Help).

Note that the first question mark must appear in the first position after the gap> prompt. The search strings book and topic are normalized in a certain way (see the end of this section for details) before the search starts. This makes the search case insensitive and there can be arbitrary white space after the first question mark.

When there are several manual sections that match the query a numbered list of topics is displayed. These matches can be accessed with \texttt{?number}.

There are some further specially handled commands which start with a question mark. They are explained in Section 2.2.

By default GAP shows the help sections as text in the terminal (window), page by page if the shown text does not fit on the screen. But there are several other choices to read (other formats of) the documents: via a viewer for pdf files or via a web browser. This is explained below in Section 2.3.

Details of the string normalization process

Here is a precise description how the search strings book and topic are normalized before a search starts: backslashes and double or single quotes are removed, parentheses and braces are substituted by blanks, non-ASCII characters are considered as ISO-latin1 characters and the accented letters are substituted by their non-accented counterpart. Finally white space is normalized.

2.2 Browsing through the Sections

Help books for GAP are organized in chapters, sections, and subsections. There are a few special commands starting with a question mark (in the first position after the gap> prompt) which allow browsing a book section or chapter wise.

\[ ?>> \]

\[ ?< \]
The two help commands ?< and ?> allow one to browse through a whole help book. ?< displays the section or subsection preceding the previously shown (sub)section, and ?> takes you to the section or subsection following the previously shown one.

?>>
?>>

?<< takes you back to the beginning of the current chapter. If you are already at the start of a chapter ?<< takes you to the beginning of the previous chapter. ?>> takes you to the beginning of the next chapter.

?-
?+

GAP remembers the last few sections that you have read. ?? takes you to the one that you have read before the current one, and displays it again. Further applications of ?? take you further back in this history. ?+ reverses this process, i.e., it takes you back to the section that you have read after the current one. It is important to note that ?? and ?+ do not alter the history like the other help commands.

?books

This command shows a list of the books which are currently known to the help system. For each book there is a short name which is used with the book part of the basic help query and there is a long name which hopefully tells you what this book is about.

A short name which ends in (not loaded) refers to a GAP package whose documentation is loaded but which needs a call of LoadPackage (76.2.1) before you can use the described functions.

? \[book: \] sections
\[book: \] chapters

These commands show tables of contents for all available, respectively the matching books. For some books these commands show the same, namely the whole table of contents.

? ?

These commands redisplay the last shown help section. In the form ?& the next preferred help viewer is used for the display (provided one has chosen several viewers), see SetHelpViewer (2.3.1) below.

### 2.3 Changing the Help Viewer

Books of the GAP help system or package manuals can be available in several formats. Currently the following formats occur (not all of them may be available for all books):

- **text** This is used for display in the terminal window in which GAP is running. Complicated mathematical expressions may not be easy to read in this format.

- **pdf** Adobe’s pdf format. Can be used for printing and onscreen reading on most current systems (with freely available software). Some manual books contain hyperlinks in this format.

- **HTML** The format of web pages. Can be used with any web browser. There may be hyperlink information available which allows a convenient browsing through the book via cross-references. This format has the problem that complicated formulae may be not be easy to read since there is no syntax for formulae in HTML. (Some older manual books use special symbol fonts for formulae.
and need a particular configuration of the web browser for correct display. Some manuals may use technology for quite sophisticated formula display.)

Depending on your operating system and available additional software you can use several of these formats with GAP’s help system. This is configured with the following command.

2.3.1 SetHelpViewer

\>$\text{SetHelpViewer}($viewer1$, \text{viewer}2$, \ldots$)$\quad$\text{(function)}$

This command takes an arbitrary number of arguments which must be strings describing a viewer. The recognized viewers are explained below. A call with no arguments shows the current setting.

The first given arguments are those with higher priority. So, if a help section is available in the format needed by viewer1, this viewer is used. If not, availability of the format for viewer2 is checked and so on. Recall that the command ?& displays the last seen section again but with the next possible viewer in your list, see 2.2.

The viewer "screen" is always silently appended since we assume that each help book is available in text format.

If you want to change the default setting you can use a call of SetUserPreference("HelpViewers", [ ... ] ); (the list in the second argument containing the viewers you want) in your gap.ini file (see 3.2).

"screen"

This is the default setting. The help is shown in text format using the Pager (2.4.1) command. Hint: Text versions of manuals are formatted assuming that your terminal displays at least 80 characters per line, if this is not the case some sections may look very bad. We suggest to use a terminal in UTF-8 encoding with a fixed width font (this is the default on most modern Linux/Windows/Mac systems anyway). Terminals in ISO-8859-X encoding will also work reasonably well (so far, since we do not yet use many special characters which such terminals could not display).

"firefox", "chrome", "mozilla", "netscape", "konqueror"

If a book is available in HTML format this is shown using the corresponding web browser. How well this works, for example by using a running instance of this browser, depends on your particular start script of this browser. (Note, that for some old books the browser must be configured to use symbol fonts.)

"browser"

(for MS Windows) If a book is available in HTML format, it will be opened using the Windows default application (typically, a web browser).

"links2", "w3m", "lynx"

If a book is available in HTML format this is shown using the text based "links2" (in graphics mode), w3m or lynx web browser, respectively, inside the terminal running GAP. (Formulae in some older books which use symbol fonts may be unreadable.)

"mac default browser", "browser", "safari", "firefox"

(for Mac OS X) If a book is available in HTML format this is shown in a web browser. The
options "safari" and "firefox" use the corresponding browsers. The other two options use the program default browser (which can be set in Safari’s preferences, in the “General” tab).

"xpdf"
(on X-windows systems) If a book is available in pdf format it is shown with the onscreen viewer program xpdf (which must be installed on your system). This is a nice program, once it is running it is reused by GAP for the next displays of help sections.

"acroread"
If a book is available in pdf format it is shown with the onscreen viewer program acroread (which must be available on your system). This program does not allow remote commands or startup with a given page. Therefore the page numbers you have to visit are just printed on the screen. When you are looking at several sections of the same book, this viewer assumes that the acroread window still exists. When you go to another book a new acroread window is launched.

"pdf viewer", "skim", "preview", "adobe reader"
(for Mac OS X) If a book is available in pdf format this is shown in a pdf viewer. The options "skim", "preview" and "adobe reader" use the corresponding viewers. The other two options use the pdf viewer which you have chosen to open pdf files from the Finder. Note that only "Skim" seems to be capable to open a pdf file on a given page. For the other help viewers, the page numbers where the information can be found will just be printed on the screen. None of the help viewers seems to be capable of opening a pdf at a given named destination (i.e., jump to precisely the place where the information can be found). The pdf viewer "Skim" is open source software, it can be downloaded from https://skim-app.sourceforge.io/.

"less" or "more"
This is the same as "screen" but additionally the user preferences "Pager" and "PagerOptions" are set, see the section 2.4 for more details.

Please, send ideas for further viewer commands to support@gap-system.org.

2.4 The Pager Command

GAP contains a builtin pager which shows a text string which does not fit on the screen page by page. Its functionality is very rudimentary and self-explaining. This is because (at least under UNIX) there are powerful external standard programs which do this job.

2.4.1 Pager

Pager(lines) (function)

This function can be used to display a text on screen using a pager, i.e., the text is shown page by page.

There is a default builtin pager in GAP which has very limited capabilities but should work on any system.

At least on a UNIX system one should use an external pager program like less or more. GAP assumes that this program has a command line option +nr which starts the display of the text with line number nr.
Which pager is used can be controlled by setting the user preference "Pager". The default value is "builtin" which means that the internal pager is used.

On UNIX systems you probably want to set the user preference "Pager" to the value "less" or "more", you can do this for example in your gap.ini file (see 3.2). In that case you can also tell GAP a list of standard options for the external pager, via the user preference "PagerOptions".

Example

```gap
SetUserPreference( "Pager", "less" );
SetUserPreference( "PagerOptions", ["-f","-r","-a","-i","-M","-j2"] );
```

The argument lines can have one of the following forms:

1. a string (i.e., lines are separated by newline characters)
2. a list of strings (without newline characters) which are interpreted as lines of the text to be shown
3. a record with component lines as in 1. or 2. and optional further components

In case 3. currently the following additional components are used:

- **formatted**
  can be false or true. If set to true the builtin pager tries to show the text exactly as it is given (avoiding GAP's automatic line breaking).

- **start**
  must be a positive integer. This is interpreted as the number of the first line shown by the pager (one may see the beginning of the text via back scrolling).

- **exitAtEnd**
  can be false or true. If set to true (the default), the builtin pager is terminated as soon as the end of the list is shown; otherwise entering the Q key is necessary in order to return from the pager.

The Pager command is used by GAP's help system for displaying help sections in text format. But, of course, it may be used for other purposes as well.

Example

```gap
gap> s6 := SymmetricGroup(6);;
gap> words := ["This", "is", "a", "very", "stupid", "example"];;
gap> l := List(s6, p-> Permuted(words, p));;
gap> Pager(List(l, a-> JoinStringsWithSeparator(a," ")));;
```
Chapter 3

Running GAP

This chapter contains information about the command line options for GAP (see 3.1), about some files in user specific GAP root directory (see 3.2) and about saving and loading a GAP workspace (see 3.3).

3.1 Command Line Options

When you start GAP from a command line or from a script you may specify a number of options on the command-line to change the default behaviour of GAP. All these options start with a hyphen -, followed by a single letter. Options must not be grouped, e.g., gap -gq is invalid, use gap -g -q instead. Some options require an argument, this must follow the option and must be separated by whitespace, e.g., gap -m 256m, it is not correct to say gap -m256m instead. Certain boolean options (-b, -q, -e, -r, -A, -D, -M, -T, -X, -Y) toggle the current value so that gap -b -b is equivalent to gap and to gap -b -q -b -q etc.

GAP for UNIX will distinguish between upper and lower case options.

As described in the GAP installation instructions (see the INSTALL file in the GAP root directory, or at https://www.gap-system.org/Download/INSTALL), usually you will not execute GAP directly. Instead you will call a (shell) script, with the name gap, which in turn executes GAP. This script sets some options which are necessary to make GAP work on your system. This means that the default settings mentioned below may not be what you experience when you execute GAP on your system.

During a GAP session, one can find the current values of command line options in the record GAPInfo.CommandLineOptions (see GAPInfo (3.5.1)), whose component names are the command line options (without the leading -).

-A  By default, some needed and suggested GAP packages (see 76) are loaded, if present, into the GAP session when it starts. This option disables (actually toggles) the loading of suggested packages, which can be useful for debugging or testing. The needed packages (and their needed packages, and so on) are loaded in any case.

-B architecture

Executable binary files that form part of GAP or of a GAP package are kept in a subdirectory of the bin directory within the GAP or package root directory. The subdirectory name is determined from the operating system, processor and compiler details when GAP (resp. the package)
is installed. Under rare circumstances, it may be necessary to override this name, and this can be done using the -B option.

-\texttt{b} tells \texttt{GAP} to suppress the banner. That means that \texttt{GAP} immediately prints the prompt. This is useful when, after a while, you get tired of the banner. This option can be repeated to enable the banner; each -\texttt{b} toggles the state of banner display.

-\texttt{D} The -D option tells \texttt{GAP} to print short messages when it is reading files or loading modules. This option may be repeated to toggle this behavior on and off. The message,

\begin{verbatim}
Example
#I READ_GAP_ROOT: loading 'lib/kernel.g' as GAP file
\end{verbatim}

tells you that \texttt{GAP} has started to read the library file \texttt{lib/kernel.g}.

\begin{verbatim}
Example
#I READ_GAP_ROOT: loading 'lib/kernel.g' statically
\end{verbatim}

tells you that \texttt{GAP} has used the compiled version of the library file \texttt{lib/kernel.g}. This compiled module was statically linked to the \texttt{GAP} kernel at the time the kernel was created.

\begin{verbatim}
Example
#I READ_GAP_ROOT: loading 'lib/kernel.g' dynamically
\end{verbatim}

tells you that \texttt{GAP} has loaded the compiled version of the library file \texttt{lib/kernel.g}. This compiled module was dynamically loaded to the \texttt{GAP} kernel at runtime from a corresponding .so file.

Obviously, this is a debugging option and most users will not need it.

-\texttt{E} If your \texttt{GAP} installation uses the \texttt{readline} library for command line editing (see 6.9), this may be disabled by using -E option. This option may be repeated to toggle this behavior on and off. If your \texttt{GAP} installation does not use the \texttt{readline} library (you can check by \texttt{IsBound(GAPInfo.UseReadline)}; if this is the case), this option will have no effect at all.

-\texttt{e} tells \texttt{GAP} not to quit when receiving a CTRL-D on an empty input line (see 6.4.1). This option should not be used when the input is a file or pipe. This option may be repeated to toggle this behavior on and off.

-\texttt{f} tells \texttt{GAP} to enable the line editing and history (see 6.8).

In general line editing will be enabled if the input is connected to a terminal. There are rare circumstances, for example when using a remote session with a corrupted telnet implementation, when this detection fails. Try using -\texttt{f} in this case to enable line editing. This option does not toggle; you must use -n to disable line editing.

-\texttt{g} tells \texttt{GAP} to print a message every time a full garbage collection is performed.

\begin{verbatim}
Example
#G FULL 44580/2479kb live 57304/4392kb dead 734/4096kb free
\end{verbatim}

For example, this tells you that there are 44580 live objects that survived a full garbage collection, that 57304 unused objects were reclaimed by it, and that 734 kilobytes from a total allocated memory of 4096 kilobytes are available afterwards.
If you give the option \texttt{-g} twice, \texttt{GAP} prints a information message every time a partial or full garbage collection is performed. The message, \begin{verbatim}
Example
#G PART 9405/961kb+live 7525/1324kb+dead 2541/4096kb free
\end{verbatim}
for example, tells you that 9405 objects survived the partial garbage collection and 7525 objects were reclaimed, and that 2541 kilobytes from a total allocated memory of 4096 kilobytes are available afterwards.

\texttt{-h} tells \texttt{GAP} to print a summary of all available options (\texttt{-h} is mnemonic for “help”). \texttt{GAP} exits after printing the summary, all other options are ignored.

\texttt{-K memory} is like the \texttt{-o} option. But while the latter actually allocates more memory if the system allows it and then prints a warning inside a break loop the \texttt{-K} options tells \texttt{GAP} not even to try to allocate more memory. Instead \texttt{GAP} just exits with an appropriate message. The default is that this feature is switched off. You have to set it explicitly when you want to enable it.

\texttt{-L filename} The option \texttt{-L} tells \texttt{GAP} to load a saved workspace. See section 3.3.

\texttt{-l path\_list} can be used to set or modify \texttt{GAP}'s list of root directories (see 9.2). The default if no \texttt{-l} option is given is the current directory \texttt{./}. This option can be used several times. Depending on the \texttt{-r} option a further user specific path is prepended to the list of root directories (the path in \texttt{GAPInfo.UserGapRoot}).

\texttt{path\_list} should be a list of directories separated by semicolons. No whitespace is permitted before or after a semicolon. If \texttt{path\_list} does not start or end with a semicolon, then \texttt{path\_list} replaces the existing list of root directories. If \texttt{path\_list} starts with a semicolon, then \texttt{path\_list} is appended to the existing list of root directories. If \texttt{path\_list} ends with a semicolon and does not start with one, then the new list of root directories is the concatenation of \texttt{path\_list} and the existing list of root directories. After \texttt{GAP} has completed its startup procedure and displays the prompt, the list of root directories can be seen in the variable \texttt{GAPInfo.RootPaths}, see \texttt{GAPInfo (3.5.1)}.

Usually this option is used inside a startup script to specify where \texttt{GAP} is installed on the system. The \texttt{-l} option can also be used by individual users to tell \texttt{GAP} about privately installed modifications of the library, additional \texttt{GAP} packages and so on. Section 9.2 explains how several root paths can be used to do this.

\texttt{GAP} will attempt to read the file \texttt{root\_dir/lib/init.g} during startup where \texttt{root\_dir} is one of the directories in its list of root directories. If \texttt{GAP} cannot find its \texttt{init.g} file it will print the following warning.

\begin{verbatim}
Example
gap: hmm, I cannot find 'lib/init.g' maybe use option '-l <gaproot>''?
\end{verbatim}

It is not possible to use \texttt{GAP} without the library files, so you must not ignore this warning. You should leave \texttt{GAP} and start it again, specifying the correct root path using the \texttt{-l} option.
-M tells GAP not to check for, nor to use, compiled versions of library files. This option may be repeated to toggle this behavior on and off.

-m memory
tells GAP to allocate memory bytes at startup time. If the last character of memory is k or K it is taken as kilobytes, if the last character is m or M memory is taken as megabytes and if it is g or G it is taken as gigabytes.

This amount of memory should be large enough so that computations do not require too many garbage collections. On the other hand, if GAP allocates more memory than is physically available, it will spend most of the time paging.

-n tells GAP to disable the line editing and history (see 6.8).

You may want to do this if the command line editing is incompatible with another program that is used to run GAP. For example if GAP is run from inside a GNU Emacs shell window, -n should be used since otherwise every input line will be echoed twice, once by Emacs and once by GAP. This option does not toggle; you must use -f to enable line editing.

-o memory
tells GAP to allocate at most memory bytes without asking. The option argument memory is specified as with the -m option.

If more than this amount is required during the GAP session, GAP prints an error message and enters a break loop. In that case you can enter return; which implicitly doubles the amount given with this option.

-q tells GAP to be quiet. This means that GAP displays neither the banner nor the prompt gap>.
This is useful if you want to run GAP as a filter with input and output redirection and want to avoid the banner and the prompts appearing in the output file. This option may be repeated to disable quiet mode; each -q toggles quiet mode.

-R The option -R tells GAP not to load a saved workspace previously specified via the -L option. This option does not toggle.

-r The option -r tells GAP to ignore any user specific configuration files. In particular, the user specific root directory GAPInfo.GapRoot is not added to the GAP root directories and so gap.ini and gaprc files that may be contained in that directory are not read, see 3.2. Multiple -r options toggle this behaviour.

-s memory
With this option GAP does not use sbrk to get memory from the operating system. Instead it uses mmap, malloc or some other command for the amount given with this option to allocate space for the GASMAN memory manager. Usually GAP does not really use all of this memory, the options -m, -o, -K still work as documented. This feature assumes that the operating system only assigns physical memory to the GAP process when it is accessed, so that specifying a large amount of memory with -s should not cause any performance problem. The advantage of using
this option is that GAP can work together with kernel modules which allocate a lot of memory with malloc.

The option argument *memory* is specified as with the `-m` option.

- **-T** suppresses the usual break loop behaviour of GAP. With this option GAP behaves as if the user quit immediately from every break loop, and also suppresses displaying any error backtrace. This is intended for automated testing of GAP. This option may be repeated to toggle this behavior on and off.

- **-x length**
  With this option you can tell GAP how long lines are. GAP uses this value to decide when to split long lines. After starting GAP you may use `SizeScreen (6.12.1)` to alter the line length.
  The default value is 80, unless another value can be obtained from the Operating System, which is the right value if you have a standard terminal application. If you have a larger monitor, or use a smaller font, or redirect the output to a printer, you may want to increase this value.

- **-y length**
  With this option you can tell GAP how many lines your screen has. GAP uses this value to decide after how many lines of on-line help it should wait. After starting GAP you may use `SizeScreen (6.12.1)` to alter the number of lines.
  The default value is 24, unless another value can be obtained from the Operating System, which is the right value if you have a standard terminal application. If you have a larger monitor, or use a smaller font, or redirect the output to a printer, you may want to increase this value.

*filename ... *

Further arguments are taken as filenames of files that are read by GAP during startup, after the system and private init files are read, but before the first prompt is printed. The files are read in the order in which they appear on the command line. GAP only accepts up to 14 filenames on the command line. If a file cannot be opened GAP will print an error message and will abort.

Additional options, `-C`, `-P`, `-W`, `-p` and `-z` are used internally by the `gac` script (see 76.3.11) and/or on specific operating systems.

### 3.2 The gap.ini and gaprc files

When you start GAP, it looks for files with the names `gap.ini` and `gaprc` in its root directories (see 9.2), and reads the first `gap.ini` and the first `gaprc` file it finds. These files are used for certain initializations, as follows.

The file `gap.ini` is read early in the startup process. Therefore, the parameters set in this file can influence the startup process, such as which packages are automatically loaded (see `LoadPackage (76.2.1)`) and whether library files containing obsolete variables are read (see Chapter 77). On the other hand, only calls to a restricted set of GAP functions are allowed in a `gap.ini` file. Usually, it should only contain calls of `SetUserPreference (3.2.3)`. This file can be generated (or updated when new releases introduce further user preferences) with the command `WriteGapIniFile (3.2.3)`. This file is read whenever GAP is started, with or without a workspace.

The file `gaprc` is read after the startup process, before the first input file given on the command line (see 3.1). So the contents of this file cannot influence the startup process, but all GAP library
functions can be called in this file. When GAP is started with a workspace then the file is read only if no gaprc file had been read before the workspace was created. (With this setup, it is on the one hand possible that administrators provide a GAP workspace for several users such that the user's gaprc file is read when GAP is started with the workspace, and on the other hand one can start GAP, read one's gaprc file, save a workspace, and then start from this workspace without reading one's gaprc file again.)

Note that by default, the user specific GAP root directory GAPInfo.UserGapRoot is the first GAP root directory. So you can put your gap.ini and gaprc files into this directory. This mechanism substitutes the much less flexible reading of a user's gaprc file in versions of GAP up to 4.4. For compatibility this gaprc file is still read if the directory GAPInfo.UserGapRoot does not exist, see 77.5 how to migrate your old setup.

3.2.1 The gap.ini file

The file gap.ini is read after the declaration part of the GAP library is read, before the declaration parts of the packages needed and suggested by GAP are read, and before the implementation parts of GAP and of the packages are read.

The file gap.ini is expected to consist of calls to the function SetUserPreference (3.2.3), see Section SetUserPreference (3.2.3).

Since the file gap.ini is read before the implementation part of GAP is read, not all GAP functions may be called in the file. Assignments of numbers, lists, and records are admissible as well as calls to basic functions such as Concatenation (21.20.1) and JoinStringsWithSeparator (27.7.20).

Note that the file gap.ini is read also when GAP is started with a workspace.

3.2.2 The gaprc file

If a file gaprc is found it is read after GAP's init.g, but before any of the files mentioned on the command line are read. You can use this file for your private customizations. (Many users may be happy with using just user preferences in the gap.ini file (see above) for private customization.) For example, if you have a file containing functions or data that you always need, you could read this from gaprc. Or if you find some of the names in the library too long, you could define abbreviations for those names in gaprc. The following sample gaprc file does both.

```
Example
Read( "/usr/you/dat/mygroups.grp" );
Ac := Action;
ActHom := ActionHomomorphism;
RepAc := RepresentativeAction;
```

Note that only one gaprc file is read when GAP is started. When a workspace is created in a GAP session after a gaprc file has been read then no more gaprc file will be read when GAP is started with this workspace.

Also note that the file must be called gaprc. If you use a Windows text editor, in particular if your default is not to show file suffixes, you might accidentally create a file gaprc.txt or gaprc.doc which GAP will not recognize.
3.2.3 Configuring User preferences

- SetUserPreference([package, ]name, value) (function)
- UserPreference([package, ]name) (function)
- ShowUserPreferences(package1, package2, ... ) (function)
- WriteGapIniFile([dir, ]ignorecurrent) (function)

Some aspects of the behaviour of GAP can be customized by the user via user preferences. Examples include the way help sections are displayed or the use of colors in the terminal.

User preferences are specified via a pair of strings, the first is the (case insensitive) name of a package (or "GAP" for the core GAP library) and the second is some arbitrary case sensitive string.

User preferences can be set to some value with SetUserPreference. The current value of a user preference can be found with UserPreference. In both cases, if no package name is given the default "GAP" is used. If a user preference is not known or not set then UserPreference returns fail.

The function ShowUserPreferences with no argument shows in a pager an overview of all known user preferences together with some explanation and the current value. If one or more strings package1, ... are given then only the user preferences for these packages are shown.

The easiest way to make use of user preferences is probably to use the function WriteGapIniFile, usually without argument. This function creates a file gap.ini in your user specific GAP root directory (GAPInfo.UserGapRoot). If such a file already exists the function will make a backup of it first. This newly created file contains descriptions of all known user preferences and also calls of SetUserPreference for those user preferences which currently do not have their default value. You can then edit that file to customize (further) the user preferences for future GAP sessions.

Should a later version of GAP or some packages introduce new user preferences then you can call WriteGapIniFile again since it will set the previously known user preferences to their current values.

Optionally, a different directory for the resulting gap.ini file can be specified as argument dir to WriteGapIniFile. Another optional argument is the boolean value true, if this is given, the settings of all user preferences in the current session are ignored.

Note that your gap.ini file is read by GAP very early during its startup process. A consequence is that the value argument in a call of SetUserPreference must be some very basic GAP object, usually a boolean, a number, a string or a list of those. A few user preferences support more complicated settings. For example, the user preference "UseColorPrompt" admits a record as its value whose components are available only after the GAPDoc package has been loaded, see ColorPrompt (3.6.1). If you want to specify such a complicated value, then move the corresponding call of SetUserPreference from your gap.ini file into your gaprc file (also in the directory GAPInfo.UserGapRoot). This file is read much later.

```
Example

gap> SetUserPreference( "Pager", "less" );
gap> SetUserPreference("PagerOptions",
> [ "-f", "-r", "-a", "-i", "-M", "-j2" ] );
gap> UserPreference("Pager");
"less"
```

The first two lines of this example will cause GAP to use the program less as a pager. This is highly recommended if less is available on your system. The last line displays the current setting.
3.2.4 DeclareUserPreference

This function can be used (also in packages) to introduce new user preferences. It declares a user preference, determines a default value and contains documentation of the user preference. After declaration a user preference will be shown with ShowUserPreferences (3.2.3) and WriteGapIniFile (3.2.3).

When this declaration is evaluated it is checked, if this user preference is already set in the current session. If not the value of the user preference is set to its default. (Do not use fail as default value since this indicated that a user preference is not set.)

The argument record of DeclareUserPreference must be a record with the following components.

name
a string or a list of strings, the latter meaning several preferences which belong together,

description
a list of strings describing the preference(s), one string for each paragraph; if several preferences are declared together then the description refers to all of them,

default
the default value that is used, or a function without arguments that computes this default value; if several preferences are declared together then the value of this component must be the list of default values for the individual preferences.

The following components of record are optional.

check
a function that takes a value as its argument and returns either true or false, depending on whether the given value is admissible for this preference; if several preferences are declared together then the number of arguments of the function must equal the length of the name list,

values
the list of admissible values, or a function without arguments that returns this list,

multi
true or false, depending on whether one may choose several values from the given list or just one; needed (and useful only) if the values component is present,

package
the name of the GAP package to which the preference is assigned; if the declaration happens inside a file that belongs to this package then the value of this component is computed, using GAPInfo.PackageCurrent; otherwise, the default value for package is "GAP",

omitFromGapIniFile
if the value is true then this user preference is ignored by WriteGapIniFile (3.2.3).

Example

```gap
gap> UserPreference( "MyFavouritePrime" );
fail
```
3.3 Saving and Loading a Workspace

GAP workspace files are binary files that contain the data of a GAP session. One can produce a workspace file with \texttt{SaveWorkspace (3.3.1)}, and load it into a new GAP session using the \texttt{-L} command line option, see Section 3.1.

One purpose of workspace files is of course the possibility to save a “snapshot” image of the current GAP workspace in a file.

The recommended way to start GAP is to load an existing workspace file, because this reduces the startup time of GAP drastically. So if you have installed GAP yourself then you should think about creating a workspace file immediately after you have started GAP, and then using this workspace file later on, whenever you start GAP. If your GAP installation is shared between several users, the system administrator should think about providing such a workspace file.

3.3.1 SaveWorkspace

\texttt{SaveWorkspace(filename)}

will save a “snapshot” image of the current GAP workspace in the file \texttt{filename}. This image then can be loaded by another copy of GAP which then will behave as at the point when \texttt{SaveWorkspace} was called.

\begin{verbatim}
gap> a:=1;
gap> SaveWorkspace("savefile");
gap> quit;
\end{verbatim}

\texttt{SaveWorkspace} can only be used at the main \texttt{gap>} prompt. It cannot be included in the body of a loop or function, or called from a break loop.

3.4 Testing for the System Architecture

3.4.1 ARCH_IS_UNIX

\texttt{ARCH\_IS\_UNIX ()}

tests whether GAP is running on a UNIX system (including Mac OS X).
3.4.2 ARCH_IS_MAC_OS_X

ARCH_IS_MAC_OS_X() (function)

tests whether GAP is running on Mac OS X. Note that on Mac OS X, also ARCH_IS_UNIX (3.4.1) will be true.

3.4.3 ARCH_IS_WINDOWS

ARCH_IS_WINDOWS() (function)

tests whether GAP is running on a Windows system.

3.5 Global Values that Control the GAP Session

3.5.1 GAPInfo

GAPInfo (global variable)

Several global values control the GAP session, such as the command line, the architecture, or the information about available and loaded packages. Many of these values are accessible as components of the global record GAPInfo. Typically, these components are set and read in low level GAP functions, so changing the values of existing components of GAPInfo “by hand” is not recommended.

Important components are documented via index entries, try the input ??GAPInfo for getting an overview of these components.

3.6 Coloring the Prompt and Input

GAP provides hooks for functions which are called when the prompt is to be printed and when an input line is finished.

An example of using this feature is the following function.

3.6.1 ColorPrompt

ColorPrompt(bool[, optrec]) (function)

With ColorPrompt(true); GAP changes its user interface: The prompts and the user input are displayed in different colors. Switch off the colored prompts with ColorPrompt(false);

Note that this will only work if your terminal emulation in which you run GAP understands the so-called ANSI color escape sequences –almost all terminal emulations on current UNIX/Linux (xterm, rxvt, konsole, ...) systems do so.

The colors shown depend on the terminal configuration and cannot be forced from an application. If your terminal follows the ANSI conventions you see the standard prompt in bold blue and the break loop prompt in bold red, as well as your input in red.

If it works for you and you like it, put a call of SetUserPreference("UseColorPrompt", true); in your gap.ini file. If you want a more complicated setting as explained below then put your SetUserPreference("UseColorPrompt", rec( ... ) ); call into your gaprc file.
The optional second argument \texttt{optrec} allows one to further customize the behaviour. It must be a record from which the following components are recognized:

\textbf{MarkupStdPrompt}  
\begin{itemize}  
\item a string or no argument function returning a string containing the escape sequence used for the main prompt \texttt{gap>}.  
\end{itemize}

\textbf{MarkupContPrompt}  
\begin{itemize}  
\item a string or no argument function returning a string containing the escape sequence used for the continuation prompt \texttt{>}.  
\end{itemize}

\textbf{MarkupBrkPrompt}  
\begin{itemize}  
\item a string or no argument function returning a string containing the escape sequence used for the break prompt \texttt{brk...>}.  
\end{itemize}

\textbf{MarkupInput}  
\begin{itemize}  
\item a string or no argument function returning a string containing the escape sequence used for user input.  
\end{itemize}

\textbf{TextPrompt}  
\begin{itemize}  
\item a no argument function returning the string with the text of the prompt, but without any escape sequences. The current standard prompt is returned by \texttt{CPROMPT()}. But note that changing the standard prompts makes the automatic removal of prompts from input lines impossible (see \texttt{6.2}).  
\end{itemize}

\textbf{PrePrompt}  
\begin{itemize}  
\item a function called before printing a prompt.  
\end{itemize}

Here is an example.

```gap
LoadPackage("GAPDoc");
timeSHOWMIN := 100;
ColorPrompt(true, rec(  
    # usually cyan bold, see ?TextAttr  
    MarkupStdPrompt := Concatenation(TextAttr.bold, TextAttr.6),  
    MarkupContPrompt := Concatenation(TextAttr.bold, TextAttr.6),  
    PrePrompt := function()  
        # show the 'time' automatically if at least timeSHOWMIN  
        if CPROMPT() = "gap> " and time >= timeSHOWMIN then  
            Print("Time of last command: ", time, " ms\n");  
        fi;  
    end) );
```
Chapter 4

The Programming Language

This chapter describes the GAP programming language. It should allow you, in principle, to predict the result of each and every input. In order to know what we are talking about, we first have to look more closely at the process of interpretation and the various representations of data involved.

4.1 Language Overview

First we have the input to GAP, given as a string of characters. How those characters enter GAP is operating system dependent, e.g., they might be entered at a terminal, pasted with a mouse into a window, or read from a file. The mechanism does not matter. This representation of expressions by characters is called the external representation of the expression. Every expression has at least one external representation that can be entered to get exactly this expression.

The input, i.e., the external representation, is transformed in a process called reading to an internal representation. At this point the input is analyzed and inputs that are not legal external representations, according to the rules given below, are rejected as errors. Those rules are usually called the syntax of a programming language.

The internal representation created by reading is called either an expression or a statement. Later we will distinguish between those two terms. However for now we will use them interchangeably. The exact form of the internal representation does not matter. It could be a string of characters equal to the external representation, in which case the reading would only need to check for errors. It could be a series of machine instructions for the processor on which GAP is running, in which case the reading would more appropriately be called compilation. It is in fact a tree-like structure.

After the input has been read it is again transformed in a process called evaluation or execution. Later we will distinguish between those two terms too, but for the moment we will use them interchangeably. The name hints at the nature of this process, it replaces an expression with the value of the expression. This works recursively, i.e., to evaluate an expression first the subexpressions are evaluated and then the value of the expression is computed from those values according to rules given below. Those rules are usually called the semantics of a programming language.

The result of the evaluation is, not surprisingly, called a value. Again the form in which such a value is represented internally does not matter. It is in fact a tree-like structure again.

The last process is called printing. It takes the value produced by the evaluation and creates an external representation, i.e., a string of characters again. What you do with this external representation is up to you. You can look at it, paste it with the mouse into another window, or write it to a file.
Let's look at an example to make this more clear. Suppose you type in the following string of 8 characters

```
1 + 2 * 3;
```

**GAP** takes this external representation and creates a tree-like internal representation, which we can picture as follows

```
+ / \ 
1 * / \ 
2 3
```

This expression is then evaluated. To do this **GAP** first evaluates the right subexpression 2*3. Again, to do this **GAP** first evaluates its subexpressions 2 and 3. However they are so simple that they are their own value, we say that they are self-evaluating. After this has been done, the rule for * tells us that the value is the product of the values of the two subexpressions, which in this case is clearly 6. Combining this with the value of the left operand of the +, which is self-evaluating, too, gives us the value of the whole expression 7. This is then printed, i.e., converted into the external representation consisting of the single character 7.

In this fashion we can predict the result of every input when we know the syntactic rules that govern the process of reading and the semantic rules that tell us for every expression how its value is computed in terms of the values of the subexpressions. The syntactic rules are given in sections 4.2, 4.3, 4.4, 4.5, and 4.6, the semantic rules are given in sections 4.7, 4.8, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.23, and the chapters describing the individual data types.

### 4.2 Lexical Structure

Most input of **GAP** consists of sequences of the following characters.

- Digits, uppercase and lowercase letters, SPACE, TAB, NEWLINE, RETURN and the special characters

```
" ' ( ) * + , - #
. / : ; < = > ~
[ \ ] ^ _ { } !
```

It is possible to use other characters in identifiers by escaping them with backslashes, but we do not recommend the use of this feature. Inside strings (see section 4.3 and chapter 27) and comments (see 4.4) the full character set supported by the computer is allowed.

### 4.3 Symbols

The process of reading, i.e., of assembling the input into expressions, has a subprocess, called *scanning*, that assembles the characters into symbols. A *symbol* is a sequence of characters that form a
lexical unit. The set of symbols consists of keywords, identifiers, strings, integers, and operator and delimiter symbols.

A **keyword** is a reserved word (see 4.5). An **identifier** is a sequence of letters, digits and underscores (or other characters escaped by backslashes) that contains at least one non-digit and is not a keyword (see 4.6). An integer is a sequence of digits (see 14), possibly prepended by - and + sign characters. A **string** is a sequence of arbitrary characters enclosed in double quotes (see 27).

Operator and delimiter symbols are

\[ + - * / ^ ~ ! = <> <= >= ![ ] { } ( ) : \]

Note also that during the process of scanning all whitespace is removed (see 4.4).

### 4.4 Whitespaces

The characters `SPACE`, `TAB`, `NEWLINE`, and `RETURN` are called **whitespace characters**. Whitespace is used as necessary to separate lexical symbols, such as integers, identifiers, or keywords. For example `Thorondor` is a single identifier, while `Th or ondor` is the keyword `or` between the two identifiers `Th` and `endor`. Whitespace may occur between any two symbols, but not within a symbol. Two or more adjacent whitespace characters are equivalent to a single whitespace. Apart from the role as separator of symbols, whitespace characters are otherwise insignificant. Whitespace characters may also occur inside a string, where they are significant. Whitespace characters should also be used freely for improved readability.

A **comment** starts with the character `#`, which is sometimes called sharp or hatch, and continues to the end of the line on which the comment character appears. The whole comment, including `#` and the `NEWLINE` character is treated as a single whitespace. Inside a string, the comment character `#` loses its role and is just an ordinary character.

For example, the following statement

```plaintext
if i<0 then a:=-i;else a:=i;fi;
```

is equivalent to

```plaintext
if i < 0 then  # if i is negative
    a := -i;    # take its additive inverse
else          # otherwise
    a := i;    # take itself
fi;
```

(which by the way shows that it is possible to write superfluous comments). However the first statement is *not* equivalent to

```plaintext
ifi<i then a:=-i;else a:=i;fi;
```

since the keyword `if` must be separated from the identifier `i` by a whitespace, and similarly `then` and `a`, and `else` and `a` must be separated.
4.5 Keywords

Keywords are reserved words that are used to denote special operations or are part of statements. They must not be used as identifiers. The list of keywords is contained in the GAPInfo.Keywords component of the GAPInfo record (see 3.5.1). We will show how to print it in a nice table, demonstrating at the same time some list manipulation techniques:

```
Example

gap> keys:=SortedList( GAPInfo.Keywords );; l:=Length( keys );;
gap> arr:= List( [ 0 .. Int( l/4 )-1 ], i-> keys{ 4*i + [ 1 .. 4 ] } );;
gap> if l mod 4 <> 0 then Add( arr, keys{[ 4*Int(l/4) + 1 .. l ]} ); fi;
gap> Length( keys ); PrintArray( arr );
35
[ [ Assert, Info, IsBound, QUIT ],
  [ TryNextMethod, Unbind, and, atomic ],
  [ break, continue, do, elif ],
  [ else, end, false, fi ],
  [ for, function, if, in ],
  [ local, mod, not, od ],
  [ or, quit, readonly, readwrite ],
  [ rec, repeat, return, then ],
  [ true, until, while ] ]
```

Note that (almost) all keywords are written in lowercase and that they are case sensitive. For example `else` is a keyword; `Else`, `eLsE`, `ELSE` and so forth are ordinary identifiers. Keywords must not contain whitespace, for example `elif` is not the same as `elif`.

Note: Several tokens from the list of keywords above may appear to be normal identifiers representing functions or literals of various kinds but are actually implemented as keywords for technical reasons. The only consequence of this is that those identifiers cannot be re-assigned, and do not actually have function objects bound to them, which could be assigned to other variables or passed to functions. These keywords are `true`, `false`, `Assert` (7.5.3), `IsBound` (4.8.1), `Unbind` (4.8.2), `Info` (7.4.6) and `TryNextMethod` (78.5.1).

Keywords `atomic`, `readonly`, `readwrite` are not used at the moment. They are reserved for the future version of GAP to prevent their accidental use as identifiers.

4.6 Identifiers

An identifier is used to refer to a variable (see 4.8). An identifier usually consists of letters, digits, underscores _, and “at”-characters @, and must contain at least one non-digit. An identifier is terminated by the first character not in this class. Note that the “at”-character @ is used to implement namespaces, see Section 4.10 for details.

Examples of valid identifiers are

```
a         foo       aLongIdentifier
hello     Hello    HELLO
x100      100x     _100
some_people_prefer_underscores_to_separate_words
WePreferMixedCaseToSeparateWords
abc@def
```
Note that case is significant, so the three identifiers in the second line are distinguished.

The backslash \ can be used to include other characters in identifiers; a backslash followed by a character is equivalent to the character, except that this escape sequence is considered to be an ordinary letter. For example

\(G\(2, 5\)

is an identifier, not a call to a function \(G\).

An identifier that starts with a backslash is never a keyword, so for example \(\ast\) and \(\mod\) are identifiers.

The length of identifiers is not limited, however only the first 1023 characters are significant. The escape sequence \(\text{NEWLINE}\) is ignored, making it possible to split long identifiers over multiple lines.

### 4.6.1 IsValidIdentifier

\[\text{IsValidIdentifier(str)}\]

returns true if the string \(str\) would form a valid identifier consisting of letters, digits and underscores; otherwise it returns false. It does not check whether \(str\) contains characters escaped by a backslash \(\backslash\).

Note that the “at”-character is used to implement namespaces for global variables in packages. See 4.10 for details.

### 4.7 Expressions

An expression is a construct that evaluates to a value. Syntactic constructs that are executed to produce a side effect and return no value are called statements (see 4.14). Expressions appear as right hand sides of assignments (see 4.15), as actual arguments in function calls (see 4.11), and in statements.

Note that an expression is not the same as a value. For example \(1 + 11\) is an expression, whose value is the integer 12. The external representation of this integer is the character sequence 12, i.e., this sequence is output if the integer is printed. This sequence is another expression whose value is the integer 12. The process of finding the value of an expression is done by the interpreter and is called the evaluation of the expression.

Variables, function calls, and integer, permutation, string, function, list, and record literals (see 4.8, 4.11, 14, 42, 27, 4.23, 21, 29), are the simplest cases of expressions.

Expressions, for example the simple expressions mentioned above, can be combined with the operators to form more complex expressions. Of course those expressions can then be combined further with the operators to form even more complex expressions. The operators fall into three classes. The comparisons are \(=\), \(<>,\), \(<=\), \(>\), \(>=\), and \(\text{in}\) (see 4.12 and 30.6). The arithmetic operators are \(+\), \(-\), \(*\), \(/\), \(\mod\), and \(^\) (see 4.13). The logical operators are \(\text{not}\), \(\text{and}\), and \(\text{or}\) (see 20.4).

The following example shows a very simple expression with value 4 and a more complex expression.

\[\text{gap> } 2 \times 2;\]

\[4\]

\[\text{gap> } 2 \times 2 + 9 = \text{Fibonacci}(7) \text{ and Fibonacci}(13) \text{ in Primes};\]

\[\text{true}\]
For the precedence of operators, see 4.12.

4.8 Variables

A variable is a location in a GAP program that points to a value. We say the variable is bound to this value. If a variable is evaluated it evaluates to this value.

Initially an ordinary variable is not bound to any value. The variable can be bound to a value by assigning this value to the variable (see 4.15). Because of this we sometimes say that a variable that is not bound to any value has no assigned value. Assignment is in fact the only way by which a variable, which is not an argument of a function, can be bound to a value. After a variable has been bound to a value an assignment can also be used to bind the variable to another value.

A special class of variables is the class of arguments of functions. They behave similarly to other variables, except they are bound to the value of the actual arguments upon a function call (see 4.11).

Each variable has a name that is also called its identifier. This is because in a given scope an identifier identifies a unique variable (see 4.6). A scope is a lexical part of a program text. There is the global scope that encloses the entire program text, and there are local scopes that range from the function keyword, denoting the beginning of a function definition, to the corresponding end keyword. A local scope introduces new variables, whose identifiers are given in the formal argument list and the local declaration of the function (see 4.23). Usage of an identifier in a program text refers to the variable in the innermost scope that has this identifier as its name. Because this mapping from identifiers to variables is done when the program is read, not when it is executed, GAP is said to have lexical scoping. The following example shows how one identifier refers to different variables at different points in the program text.

```
g := 0; # global variable g
x := function ( a, b, c )
   local y;
   g := c; # c refers to argument c of function x
   y := function ( y )
      local d, e, f;
      d := y; # y refers to argument y of function y
      e := b; # b refers to argument b of function x
      f := g; # g refers to global variable g
      return d + e + f;
   end;
   return y( a ); # y refers to local y of function x
end;
```

It is important to note that the concept of a variable in GAP is quite different from the concept of a variable in most compiled programming languages.

In those languages a variable denotes a block of memory. The value of the variable is stored in this block. So in those languages two variables can have the same value, but they can never have identical values, because they denote different blocks of memory. Note that some languages have the concept of a reference argument. It seems as if such an argument and the variable used in the actual function call have the same value, since changing the argument’s value also changes the value of the variable used in the actual function call. But this is not so; the reference argument is actually a pointer to the variable used in the actual function call, and it is the compiler that inserts enough magic to make the pointer
invisible. In order for this to work the compiler needs enough information to compute the amount of memory needed for each variable in a program, which is readily available in the declarations.

In GAP on the other hand each variable just points to a value, and different variables can share the same value.

### 4.8.1 IsBound (for a global variable)

\begin{verbatim}
$\mathtt{IsBound(ident)}$
\end{verbatim}

returns \texttt{true} if the variable \texttt{ident} points to a value, and \texttt{false} otherwise.

For records and lists \texttt{IsBound} can be used to check whether components or entries, respectively, are bound (see Chapters 29 and 21).

### 4.8.2 Unbind (unbind a variable)

\begin{verbatim}
$\mathtt{Unbind(ident)}$
\end{verbatim}

deletes the identifier \texttt{ident}. If there is no other variable pointing to the same value as \texttt{ident} was, this value will be removed by the next garbage collection. Therefore \texttt{Unbind} can be used to get rid of unwanted large objects.

For records and lists \texttt{Unbind} can be used to delete components or entries, respectively (see Chapters 29 and 21).

### 4.9 More About Global Variables

The vast majority of variables in GAP are defined at the outer level (the global scope). They are used to access functions and other objects created either in the GAP library or packages or in the user’s code.

Note that for packages there is a mechanism to implement package local namespaces on top of this global namespace. See Section 4.10 for details.

Certain special facilities are provided for manipulating global variables which are not available for other types of variable (such as local variables or function arguments).

First, such variables may be marked \textit{read-only} using \texttt{MakeReadOnlyGlobal} (4.9.2). In which case attempts to change them will fail. Most of the global variables defined in the GAP library are so marked. \textit{read-only} variables can be made read-write again by calling \texttt{MakeReadWriteGlobal} (4.9.3).

GAP also features \textit{constant} variables, which are created by calling \texttt{MakeConstantGlobal} (4.9.4). Constant variables can never be changed. In some cases, GAP can optimise code which uses \textit{constant} variables, as their value never changes. In this version GAP these optimisations can be observed by printing the function back out, but this behaviour may change in future.

```
gap> globali := 1 + 2;;
gap> globalb := true;;
gap> MakeConstantGlobal("globali");
gap> MakeConstantGlobal("globalb");
gap> f := function()
>   if globalb then
>     return globali + 1;
>   else
```
Second, a group of functions are supplied for accessing and altering the values assigned to global variables. Use of these functions differs from the use of assignment, Unbind (4.8.2) and IsBound (4.8.1) statements, in two ways. First, these functions always affect global variables, even if local variables of the same names exist. Second, the variable names are passed as strings, rather than being written directly into the statements.

Note that the functions NamesGVars (4.9.9), NamesSystemGVars (4.9.10), and NamesUserGVars (4.9.11), deal with the global namespace.

### 4.9.1 IsReadOnlyGlobal

- **IsReadOnlyGlobal(name)** (function)

  returns true if the global variable named by the string name is read-only and false otherwise (the default).

### 4.9.2 MakeReadOnlyGlobal

- **MakeReadOnlyGlobal(name)** (function)

  marks the global variable named by the string name as read-only.
  A warning is given if name has no value bound to it or if it is already read-only.

### 4.9.3 MakeReadWriteGlobal

- **MakeReadWriteGlobal(name)** (function)

  marks the global variable named by the string name as read-write.
  A warning is given if name is already read-write.

**Example**

```
gap> xx := 17;
17
gap> IsReadOnlyGlobal("xx");
false
gap> xx := 15;
15
gap> MakeReadOnlyGlobal("xx");
gap> xx := 16;
Variable: 'xx' is read only
not in any function
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
```
4.9.4 MakeConstantGlobal

MakeConstantGlobal (name) marks the global variable named by the string name as constant. A constant variable can never be changed or made read-write. Constant variables can only take an integer value, true or false. There is a limit on the size of allowed integers.

A warning is given if name is already constant.

4.9.5 ValueGlobal

returns the value currently bound to the global variable named by the string name. An error is raised if no value is currently bound.

4.9.6 IsBoundGlobal

returns true if a value currently bound to the global variable named by the string name and false otherwise.

4.9.7 UnbindGlobal

removes any value currently bound to the global variable named by the string name. Nothing is returned.

A warning is given if name was not bound. The global variable named by name must be writable, otherwise an error is raised.

4.9.8 BindGlobal

BindGlobal(name, val)  (function)
BindConstant(name, val)  (function)
BindGlobal and BindConstant set the global variable named by the string name to the value val, provided that variable is writable. BindGlobal makes the resulting variable read-only, while BindConstant makes it constant. If name already had a value, a warning message is printed.

This is intended to be the normal way to create and set “official” global variables (such as operations, filters and constants).

Caution should be exercised in using these functions, especially UnbindGlobal (4.9.7) as unexpected changes in global variables can be very confusing for the user.

Example

```gap
gap> xx := 16;
16
gap> IsReadOnlyGlobal("xx");
false
gap> ValueGlobal("xx");
16
gap> IsBoundGlobal("xx");
true
gap> BindGlobal("xx",17);
#W BIND_GLOBAL: variable ‘xx’ already has a value
gap> xx;
17
gap> IsReadOnlyGlobal("xx");
true
gap> MakeReadWriteGlobal("xx");
gap> Unbind(xx);
```

4.9.9 NamesGVars

▶ NamesGVars()

This function returns an immutable (see 12.6) sorted (see 21.19) list of all the global variable names known to the system. This includes names of variables which were bound but have now been unbound and some other names which have never been bound but have become known to the system by various routes.

4.9.10 NamesSystemGVars

▶ NamesSystemGVars()

This function returns an immutable sorted list of all the global variable names created by the GAP library when GAP was started.

4.9.11 NamesUserGVars

▶ NamesUserGVars()

This function returns an immutable sorted list of the global variable names created since the library was read, to which a value is currently bound.
4.10 Namespaces for GAP packages

As mentioned in Section 4.9 above all global variables share a common namespace. This can relatively easily lead to name clashes, in particular when many GAP packages are loaded at the same time. To give package code a way to have a package local namespace without breaking backward compatibility of the GAP language, the following simple rule has been devised:

If in package code a global variable that ends with an “at”-character @ is accessed in any way, the name of the package is appended before accessing it. Here, “package code” refers to everything which is read with ReadPackage (76.3.1). As the name of the package the entry PackageName in its PackageInfo.g file is taken. As for all identifiers, this name is case sensitive.

For example, if the following is done in the code of a package with name xYz:

```
gap> a@ := 12;
```

Then actually the global variable a@xYz is assigned. Further accesses to a@ within the package code will all be redirected to a@xYz. This includes all the functions described in Section 4.9 and indeed all the functions described Section 79.10 like for example DeclareCategory (13.3.5). Note that from code in the same package it is still possible to access the same global variable via a@xYz explicitly.

All other code outside the package as well as interactive user input that wants to refer to that variable a@xYz must do so explicitly by using a@xYz.

Since in earlier releases of GAP the “at”-character @ was not a legal character (without using backslashes), this small extension of the language does not break any old code.

4.11 Function Calls

4.11.1 Function Call With Arguments

```
function-var( [arg-expr[, arg-expr, ...]] )
```

The function call has the effect of calling the function `function-var`. The precise semantics are as follows.

First GAP evaluates the `function-var`. Usually `function-var` is a variable, and GAP does nothing more than taking the value of this variable. It is allowed though that `function-var` is a more complex expression, such as a reference to an element of a list (see Chapter 21) list-var[int-expr], or to a component of a record (see Chapter 29) record-var.ident. In any case GAP tests whether the value is a function. If it is not, GAP signals an error.

Next GAP checks that the number of actual arguments `arg-exprs` agrees with the number of formal arguments as given in the function definition. If they do not agree GAP signals an error. An exception is the case when the function has a variable length argument list, which is denoted by adding ... after the final argument. In this case there must be at least as many actual arguments as there are formal arguments before the final argument and can be any larger number (see 4.23 for examples).

Now GAP allocates for each formal argument and for each formal local (that is, the identifiers in the local declaration) a new variable. Remember that a variable is a location in a GAP program that points to a value. Thus for each formal argument and for each formal local such a location is allocated.

Next the arguments `arg-exprs` are evaluated, and the values are assigned to the newly created variables corresponding to the formal arguments. Of course the first value is assigned to the new variable corresponding to the first formal argument, the second value is assigned to the new variable...
corresponding to the second formal argument, and so on. However, GAP does not make any guarantee about the order in which the arguments are evaluated. They might be evaluated left to right, right to left, or in any other order, but each argument is evaluated once. An exception again occurs if the last formal argument has the name \textit{arg}. In this case the values of all the actual arguments not assigned to the other formal parameters are stored in a list and this list is assigned to the new variable corresponding to the formal argument \textit{arg}.

The new variables corresponding to the formal locals are initially not bound to any value. So trying to evaluate those variables before something has been assigned to them will signal an error.

Now the body of the function, which is a statement, is executed. If the identifier of one of the formal arguments or formal locals appears in the body of the function it refers to the new variable that was allocated for this formal argument or formal local, and evaluates to the value of this variable.

If during the execution of the body of the function a \texttt{return} statement with an expression (see 4.24) is executed, execution of the body is terminated and the value of the function call is the value of the expression of the \texttt{return}. If during the execution of the body a \texttt{return} statement without an expression is executed, execution of the body is terminated and the function call does not produce a value, in which case we call this call a procedure call (see 4.16). If the execution of the body completes without execution of a \texttt{return} statement, the function call again produces no value, and again we talk about a procedure call.

\begin{example}
\texttt{gap> Fibonacci( 11 );}
\end{example}

The above example shows a call to the function \texttt{Fibonacci} (16.3.1) with actual argument \texttt{11}, the following one shows a call to the operation \texttt{RightCosets} (39.7.2) where the second actual argument is another function call.

\begin{example}
\texttt{gap> RightCosets( G, Intersection( U, V ) );;}
\end{example}

\subsection*{4.11.2 Function Call With Options}

\begin{verbatim}
function-var( arg-expr [, arg-expr, ...][ : [ option-expr [,option-expr, ....]]])
\end{verbatim}

As well as passing arguments to a function, providing the mathematical input to its calculation, it is sometimes useful to supply “hints” suggesting to GAP how the desired result may be computed more quickly, or specifying a level of tolerance for random errors in a Monte Carlo algorithm.

Such hints may be supplied to a function-call \textit{and to all subsidiary functions called from that call} using the options mechanism. Options are separated from the actual arguments by a colon : and have much the same syntax as the components of a record expression. The one exception to this is that a component name may appear without a value, in which case the value \texttt{true} is silently inserted.

The following example shows a call to \texttt{Size} (30.4.6) passing the options \texttt{hard} (with the value \texttt{true}) and \texttt{tcselection} (with the string "external" as value).

\begin{example}
\texttt{gap> Size( fpgrp : hard, tcselection := "external" );}
\end{example}

Options supplied with function calls in this way are passed down using the global options stack described in chapter 8, so that the call above is exactly equivalent to
Example

```gap
gap> PushOptions( rec( hard := true, tcselection := "external") );
gap> Size( fpgrp );
gap> PopOptions( );
```

Note that any option may be passed with any function, whether or not it has any actual meaning for that function, or any function called by it. The system provides no safeguard against misspelled option names.

4.12 Comparisons

left-expr = right-expr  
left-expr <> right-expr

The operator = tests for equality of its two operands and evaluates to true if they are equal and to false otherwise. Likewise <> tests for inequality of its two operands. For each type of objects the definition of equality is given in the respective chapter. Objects in different families (see 13.1) are never equal, i.e., = evaluates in this case to false, and <> evaluates to true.

left-expr < right-expr  
left-expr > right-expr  
left-expr <= right-expr  
left-expr => right-expr

< denotes less than, <= less than or equal, > greater than, and => greater than or equal of its two operands. For each kind of objects the definition of the ordering is given in the respective chapter.

Note that < implements a total ordering of objects (which can be used for example to sort a list of elements). Therefore in general < will not be compatible with any inclusion relation (which can be tested using IsSubset (30.5.1)). (For example, it is possible to compare permutation groups with < in a total ordering of all permutation groups, but this ordering is not compatible with the relation of being a subgroup.)

Only for the following kinds of objects, an ordering via < of objects in different families (see 13.1) is supported. Rationals (see IsRat (17.2.1)) are smallest, next are cyclotomics (see IsCyclotomic (18.1.3)), followed by finite field elements (see IsFFE (59.1.1)); finite field elements in different characteristics are compared via their characteristics, next are permutations (see IsPerm (42.1.1)), followed by the boolean values true, false, and fail (see IsBool (20.1.1)), characters (such as {a}’, see IsChar (27.1.1)), and lists (see IsList (21.1.1)) are largest; note that two lists can be compared with < if and only if their elements are again objects that can be compared with <.

For other objects, GAP does not provide an ordering via <. The reason for this is that a total ordering of all GAP objects would be hard to maintain when new kinds of objects are introduced, and such a total ordering is hardly used in its full generality.

However, for objects in the filters listed above, the ordering via < has turned out to be useful. For example, one can form sorted lists containing integers and nested lists of integers, and then search in them using PositionSorted (see 21.16).

Of course it would in principle be possible to define an ordering via < also for certain other objects, by installing appropriate methods for the operation <. But this may lead to problems at least as soon as one loads GAP code in which the same is done, under the assumption that one is completely free to define an ordering via < for other objects than the ones for which the “official” GAP provides already an ordering via <.
Comparison operators, including the operator in (see 21.8), are not associative. Hence it is not allowed to write \( a = b \leftrightarrow c = d \), you must use \((a = b) \leftrightarrow (c = d)\) instead. The comparison operators have higher precedence than the logical operators (see 20.4), but lower precedence than the arithmetic operators (see 4.13). Thus, for instance, \( a \ast b = c \) and \( d \) is interpreted as \(((a \ast b) = c) \text{ and } d\).

The following example shows a comparison where the left operand is an expression.

```
Example

gap> 2 * 2 + 9 = Fibonacci(7);
true
```

For the underlying operations of the operators introduced above, see 31.11.

### 4.13 Arithmetic Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ <code>right-expr</code></td>
<td>Addition of two numbers</td>
</tr>
<tr>
<td>- <code>right-expr</code></td>
<td>Subtraction of two numbers</td>
</tr>
<tr>
<td><code>left-expr + right-expr</code></td>
<td>Addition of two numbers</td>
</tr>
<tr>
<td><code>left-expr - right-expr</code></td>
<td>Subtraction of two numbers</td>
</tr>
<tr>
<td><code>left-expr * right-expr</code></td>
<td>Multiplication of two numbers</td>
</tr>
<tr>
<td><code>left-expr / right-expr</code></td>
<td>Division of two numbers</td>
</tr>
<tr>
<td><code>left-expr mod right-expr</code></td>
<td>Modulo operation</td>
</tr>
<tr>
<td><code>left-expr ^ right-expr</code></td>
<td>Exponentiation</td>
</tr>
</tbody>
</table>

The arithmetic operators are +, -, *, /, mod, and ^. The meanings (semantics) of those operators generally depend on the types of the operands involved, and they are defined in the various chapters describing the types. However basically the meanings are as follows.

- \( a + b \) denotes the addition of additive elements \( a \) and \( b \).
- \( a - b \) denotes the addition of \( a \) and the additive inverse of \( b \).
- \( a \ast b \) denotes the multiplication of multiplicative elements \( a \) and \( b \).
- \( a / b \) denotes the multiplication of \( a \) with the multiplicative inverse of \( b \).
- \( a \mod b \), for integer or rational left operand \( a \) and for non-zero integer right operand \( b \), is defined as follows. If \( a \) and \( b \) are both integers, \( a \mod b \) is the integer \( r \) in the integer range \( 0 \ldots |b| - 1 \) satisfying \( a = r + b q \), for some integer \( q \) (where the operations occurring have their usual meaning over the integers, of course).

  If \( a \) is a rational number and \( b \) is a non-zero integer, and \( a = m / n \) where \( m \) and \( n \) are coprime integers with \( n \) positive, then \( a \mod b \) is the integer \( r \) in the integer range \( 0 \ldots |b| - 1 \) such that \( m \) is congruent to \( r n \) modulo \( b \), and \( r \) is called the “modular remainder” of \( a \) modulo \( b \). Also, \( 1 / n \mod b \) is called the “modular inverse” of \( n \) modulo \( b \). (A pair of integers is said to be coprime (or relatively prime) if their greatest common divisor is 1.)

  With the above definition, \( 4 / 6 \mod 32 \) equals \( 2 / 3 \mod 32 \) and hence exists (and is equal to 22), despite the fact that 6 has no inverse modulo 32.

  **Note:** For rational \( a \), \( a \mod b \) could have been defined to be the non-negative rational \( c \) less than \( |b| \) such that \( a - c \) is a multiple of \( b \). However this definition is seldom useful and **not** the one chosen for GAP.

+ and - can also be used as unary operations. The unary + is ignored. The unary - returns the additive inverse of its operand; over the integers it is equivalent to multiplication by \(-1\).
^ denotes powering of a multiplicative element if the right operand is an integer, and is also used to denote the action of a group element on a point of a set if the right operand is a group element.

The precedence of those operators is as follows. The powering operator ^ has the highest precedence, followed by the unary operators + and -, which are followed by the multiplicative operators *, /, and mod, and the additive binary operators + and - have the lowest precedence. That means the expression \(-2 \cdot -2 \cdot 3 + 1\) is interpreted as \((-2 \cdot (-2)) \cdot 3 + 1\). If in doubt use parentheses to clarify your intention.

The associativity of the arithmetic operators is as follows. ^ is not associative, i.e., it is invalid to write \(2 \cdot 3 \cdot 4\), use parentheses to clarify whether you mean \((2 \cdot 3) \cdot 4\) or \(2 \cdot (3 \cdot 4)\). The unary operators + and - are right associative, because they are written to the left of their operands. *, /, mod, +, and - are all left associative, i.e., \(1-2-3\) is interpreted as \((1-2)-3\) not as \(1-(2-3)\). Again, if in doubt use parentheses to clarify your intentions.

The arithmetic operators have higher precedence than the comparison operators (see 4.12 and 30.6) and the logical operators (see 20.4). Thus, for example, \(a \cdot b = c\) and \(d\) is interpreted, \(((a \cdot b) = c)\) and \(d\).

Example

```
gap> 2 \cdot 2 + 9;  # a very simple arithmetic expression
13
```

For other arithmetic operations, and for the underlying operations of the operators introduced above, see 31.12.

### 4.14 Statements

Assignments (see 4.15), Procedure calls (see 4.16), if statements (see 4.17), while (see 4.18), repeat (see 4.19) and for loops (see 4.20), and the return statement (see 4.24) are called statements. They can be entered interactively or be part of a function definition. Every statement must be terminated by a semicolon.

Statements, unlike expressions, have no value. They are executed only to produce an effect. For example an assignment has the effect of assigning a value to a variable, a for loop has the effect of executing a statement sequence for all elements in a list and so on. We will talk about evaluation of expressions but about execution of statements to emphasize this difference.

Using expressions as statements is treated as syntax error.

Example

```
gap> i := 7;;
gap> if i <> 0 then k = 16/i; fi;
Syntax error: := expected
if i <> 0 then k = 16/i; fi;
```

As you can see from the example this warning does in particular address those users who are used to languages where = instead of := denotes assignment.

Empty statements are permitted and have no effect.

A sequence of one or more statements is a statement sequence, and may occur everywhere instead of a single statement. Each construct is terminated by a keyword. The simplest statement sequence is a single semicolon, which can be used as an empty statement sequence. In fact an empty statement
sequence as in for i in [ 1 .. 2 ] do od is also permitted and is silently translated into the sequence containing just a semicolon.

4.15 Assignments

\texttt{var := expr;}

The assignment has the effect of assigning the value of the expressions \texttt{expr} to the variable \texttt{var}.

The variable \texttt{var} may be an ordinary variable (see 4.8), a list element selection \texttt{list-var[int-expr]} (see 21.4) or a record component selection \texttt{record-var.ident} (see 29.3). Since a list element or a record component may itself be a list or a record the left hand side of an assignment may be arbitrarily complex.

Note that variables do not have a type. Thus any value may be assigned to any variable. For example a variable with an integer value may be assigned a permutation or a list or anything else.

Example

\begin{verbatim}
gap> data:= rec( numbers:= [ 1, 2, 3 ] );
rec( numbers := [ 1, 2, 3 ] )
gap> data.string:= "string";; data;
rec( numbers := [ 1, 2, 3 ], string := "string" )
gap> data.numbers[2]:= 4;; data;
rec( numbers := [ 1, 4, 3 ], string := "string" )
\end{verbatim}

If the expression \texttt{expr} is a function call then this function must return a value. If the function does not return a value an error is signalled and you enter a break loop (see 6.4). As usual you can leave the break loop with \texttt{quit;}. If you enter \texttt{return return-expr;} the value of the expression \texttt{return-expr} is assigned to the variable, and execution continues after the assignment.

Example

\begin{verbatim}
gap> f1:= function( x ) Print( "value: ", x, "\n" ); end;;
gap> f2:= function( x ) return f1( x ); end;;
gap> f2( 4 );
value: 4
Function Calls: <func> must return a value at return f1( x );
called from <function>( <arguments> ) called from read-eval-loop
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or you can supply one by 'return <value>;' to continue
brk> return "hello";
"hello"
\end{verbatim}

In the above example, the function \texttt{f2} calls \texttt{f1} with argument 4, and since \texttt{f1} does not return a value (but only prints a line "value: ..."), the \texttt{return} statement of \texttt{f2} cannot be executed. The error message says that it is possible to return an appropriate value, and the returned string "hello" is used by \texttt{f2} instead of the missing return value of \texttt{f1}.

4.16 Procedure Calls

\texttt{procedure-var( [arg-expr [,arg-expr, ...]] )};
The *procedure call* has the effect of calling the procedure `procedure-var`. A procedure call is done exactly like a function call (see 4.11). The distinction between functions and procedures is only for the sake of the discussion. GAP does not distinguish between them. So we state the following conventions.

A *function* does return a value but does not produce a side effect. As a convention the name of a function is a noun, denoting what the function returns, e.g., "Length", "Concatenation" and "Order".

A *procedure* is a function that does not return a value but produces some effect. Procedures are called only for this effect. As a convention the name of a procedure is a verb, denoting what the procedure does, e.g., "Print", "Append" and "Sort".

Example

```gap
gap> Read( "myfile.g" ); # a call to the procedure Read
gap> l := [ 1, 2 ];;
gap> Append( l, [ 3, 4, 5 ] ); # a call to the procedure Append
```

There are a few exceptions of GAP functions that do both return a value and produce some effect. An example is Sortex (21.18.3) which sorts a list and returns the corresponding permutation of the entries.

### 4.17 If

```gap
if bool-expr1 then statements1 [ elif bool-expr2 then statements2 ] [ else statements3 ] fi;
```

The if statement allows one to execute statements depending on the value of some boolean expression. The execution is done as follows.

First the expression `bool-expr1` following the if is evaluated. If it evaluates to `true` the statement sequence `statements1` after the first `then` is executed, and the execution of the if statement is complete.

Otherwise the expressions `bool-expr2` following the `elif` are evaluated in turn. There may be any number of `elif` parts, possibly none at all. As soon as an expression evaluates to `true` the corresponding statement sequence `statements2` is executed and execution of the if statement is complete.

If the if expression and all, if any, `elif` expressions evaluate to `false` and there is an `else` part, which is optional, its statement sequence `statements3` is executed and execution of the if statement is complete. If there is no `else` part the if statement is complete without executing any statement sequence.

Since the if statement is terminated by the `fi` keyword there is no question where an `else` part belongs, i.e., GAP has no “dangling else”. In

```gap
if expr1 then if expr2 then stats1 else stats2 fi; fi;
```

the `else` part belongs to the second if statement, whereas in

```gap
if expr1 then if expr2 then stats1 fi; else stats2 fi;
```

the `else` part belongs to the first if statement.

Since an if statement is not an expression it is not possible to write
abs := if x > 0 then x; else -x; fi;

which would, even if legal syntax, be meaningless, since the if statement does not produce a value that could be assigned to abs.

If one of the expressions bool-expr1, bool-expr2 is evaluated and its value is neither true nor false an error is signalled and a break loop (see 6.4) is entered. As usual you can leave the break loop with quit;. If you enter return true;, execution of the if statement continues as if the expression whose evaluation failed had evaluated to true. Likewise, if you enter return false;, execution of the if statement continues as if the expression whose evaluation failed had evaluated to false.

Example
gap> i := 10;;
gap> if 0 < i then
>   s := 1;
> elif i < 0 then
>   s := -1;
> else
>   s := 0;
> fi;
gap> s; # the sign of i
1

4.18 While

while bool-expr do statements od;

The while loop executes the statement sequence statements while the condition bool-expr evaluates to true.

First bool-expr is evaluated. If it evaluates to false execution of the while loop terminates and the statement immediately following the while loop is executed next. Otherwise if it evaluates to true the statements are executed and the whole process begins again.

The difference between the while loop and the repeat until loop (see 4.19) is that the statements in the repeat until loop are executed at least once, while the statements in the while loop are not executed at all if bool-expr is false at the first iteration.

If bool-expr does not evaluate to true or false an error is signalled and a break loop (see 6.4) is entered. As usual you can leave the break loop with quit;. If you enter return false;, execution continues with the next statement immediately following the while loop. If you enter return true;, execution continues at statements, after which the next evaluation of bool-expr may cause another error.

The following example shows a while loop that sums up the squares $1^2, 2^2, \ldots$ until the sum exceeds 200.

Example
gap> i := 0;; s := 0;;
gap> while s <= 200 do
>   i := i + 1; s := s + i^2;
> od;
gap> s;
204

A while loop may be left prematurely using break, see 4.21.
4.19 Repeat

```
repeat statements until bool-expr;
```

The `repeat` loop executes the statement sequence `statements` until the condition `bool-expr` evaluates to `true`.

First `statements` are executed. Then `bool-expr` is evaluated. If it evaluates to `true` the `repeat` loop terminates and the statement immediately following the `repeat` loop is executed next. Otherwise if it evaluates to `false` the whole process begins again with the execution of the `statements`.

The difference between the `while` loop (see 4.18) and the `repeat until` loop is that the `statements` in the `repeat until` loop are executed at least once, while the `statements` in the `while` loop are not executed at all if `bool-expr` is `false` at the first iteration.

If `bool-expr` does not evaluate to `true` or `false` an error is signalled and a break loop (see 6.4) is entered. As usual you can leave the break loop with `quit;`. If you enter `return true;`, execution continues with the next statement immediately following the `repeat` loop. If you enter `return false;`, execution continues at `statements`, after which the next evaluation of `bool-expr` may cause another error.

The `repeat` loop in the following example has the same purpose as the `while` loop in the preceding example, namely to sum up the squares $1^2, 2^2, ...$ until the sum exceeds 200.

```
Example

gap> i := 0;; s := 0;;
gap> repeat
>    i := i + 1; s := s + i^2;
> until s > 200;
gap> s;
204
```

A `repeat` loop may be left prematurely using `break`, see 4.21.

4.20 For

```
for simple-var in list-expr do statements od;
```

The `for` loop executes the statement sequence `statements` for every element of the list `list-expr`.

The statement sequence `statements` is first executed with `simple-var` bound to the first element of the list `list-expr`, then with `simple-var` bound to the second element of `list-expr` and so on. `simple-var` must be a simple variable, it must not be a list element selection `list-var[int-expr]` or a record component selection `record-var.ident`.

The execution of the `for` loop over a list is exactly equivalent to the following `while` loop.

```
Example

loop_list := list;
loop_index := 1;
while loop_index <= Length(loop_list) do
    variable := loop_list[loop_index];
    statements
    loop_index := loop_index + 1;
od;
```
with the exception that "loop_list" and "loop_index" are different variables for each \texttt{for} loop, i.e., these variables of different \texttt{for} loops do not interfere with each other.

The list \texttt{list-expr} is very often a range (see \ref{sec:ranges}).

\begin{verbatim}
for variable in [from..to] do statements od;
\end{verbatim}

corresponds to the more common

\begin{verbatim}
for variable from from to to do statements od;
\end{verbatim}
in other programming languages.

\begin{example}
\begin{verbatim}
gap> s := 0;;
gap> for i in [1..100] do s := s + i; od;
gap> s;
5050
\end{verbatim}
\end{example}

Note in the following example how the modification of the \texttt{list} in the loop body causes the loop body also to be executed for the new values.

\begin{example}
\begin{verbatim}
gap> l := [ 1, 2, 3, 4, 5, 6 ];
gap> for i in l do
> Print( i, " ");
> if i mod 2 = 0 then Add( l, 3 * i / 2 ); fi;
> od; Print( "\n" );
1 2 3 4 5 6 3 6 9 9
gap> l;
[ 1, 2, 3, 4, 5, 6, 3, 6, 9, 9 ]
\end{verbatim}
\end{example}

Note in the following example that the modification of the \texttt{variable} that holds the list has no influence on the loop.

\begin{example}
\begin{verbatim}
gap> l := [ 1, 2, 3, 4, 5, 6 ];
gap> for i in l do
> Print( i, " ");
> l := [];
> od; Print( "\n" );
1 2 3 4 5 6
\end{verbatim}
\end{example}

\begin{verbatim}
for variable in iterator do statements od;
\end{verbatim}

It is also possible to have a \texttt{for}-loop run over an iterator (see \ref{sec:iterators}). In this case the \texttt{for}-loop is equivalent to

\begin{verbatim}
while not IsDoneIterator(iterator) do
  variable := NextIterator(iterator)
  statements
od;
\end{verbatim}
for variable in object do statements od;

Finally, if an object object which is not a list or an iterator appears in a for-loop, then GAP will attempt to evaluate the function call Iterator(object). If this is successful then the loop is taken to run over the iterator returned.

```gap
gap> g := Group((1,2,3,4,5),(1,2)(3,4)(5,6));
Group([ (1,2,3,4,5), (1,2)(3,4)(5,6) ])
gap> count := 0;; sumord := 0;;
gap> for x in g do
> count := count + 1; sumord := sumord + Order(x); od;
> count;
120
> sumord;
471
```

The effect of
for variable in domain do
should thus normally be the same as
for variable in AsList(domain) do
but may use much less storage, as the iterator may be more compact than a list of all the elements.
See 30.8 for details about iterators.

A for loop may be left prematurely using break, see 4.21. This combines especially well with a loop over an iterator, as a way of searching through a domain for an element with some useful property.

### 4.21 Break

`break;`

The statement `break;` causes an immediate exit from the innermost loop enclosing it.

```gap
gap> g := Group((1,2,3,4,5),(1,2)(3,4)(5,6));
Group([ (1,2,3,4,5), (1,2)(3,4)(5,6) ])
gap> for x in g do
> if Order(x) = 3 then
> break;
> fi; od;
gap> x;
(1,5,2)(3,4,6)
```

It is an error to use this statement other than inside a loop.

```gap
gap> break;
Syntax error: 'break' statement not enclosed in a loop
```

### 4.22 Continue

`continue;`
The statement `continue;` causes the rest of the current iteration of the innermost loop enclosing it to be skipped.

```
Example

gap> g := Group((1,2,3),(1,2));
Group([ (1,2,3), (1,2) ])
gap> for x in g do
> if Order(x) = 3 then
> continue;
> fi; Print(x,"\n"); od;
() (2,3) (1,3) (1,2)
```

It is an error to use this statement other than inside a loop.

```
Example

gap> continue;
Syntax error: 'continue' statement not enclosed in a loop
```

### 4.23 Function

```
function( [ arg-ident {, arg-ident} ] )
    [local loc-ident {, loc-ident} ; ]
    statements
end
```

A function is in fact a literal and not a statement. Such a function literal can be assigned to a variable or to a list element or a record component. Later this function can be called as described in 4.11.

The following is an example of a function definition. It is a function to compute values of the Fibonacci sequence (see Fibonacci (16.3.1)).

```
Example

gap> fib := function ( n )
>    local f1, f2, f3, i;
>    f1 := 1; f2 := 1;
>    for i in [3..n] do
>        f3 := f1 + f2;
>        f1 := f2;
>        f2 := f3;
>    od;
>    return f2;
> end;;
gap> List( [1..10], fib );
[ 1, 1, 2, 3, 5, 8, 13, 21, 34, 55 ]
```

Because for each of the formal arguments `arg-ident` and for each of the formal locals `loc-ident` a new variable is allocated when the function is called (see 4.11), it is possible that a function calls itself. This is usually called *recursion*. The following is a recursive function that computes values of the Fibonacci sequence.
Example

```gap
gap> fib := function ( n )
>     if n < 3 then
>         return 1;
>     else
>         return fib(n-1) + fib(n-2);
>     fi;
> end;;
gap> List( [1..10], fib );
[ 1, 1, 2, 3, 5, 8, 13, 21, 34, 55 ]
```

Note that the recursive version needs \(2 \times \text{fib}(n)-1\) steps to compute \(\text{fib}(n)\), while the iterative version of \(\text{fib}\) needs only \(n-2\) steps. Both are not optimal however, the library function \texttt{Fibonacci} (16.3.1) only needs about \(\log(n)\) steps.

As noted in Section 4.11, the case where a function’s last argument is followed by \(...\) is special. It provides a way of defining a function with a variable number of arguments. The values of the actual arguments are computed and the first ones are assigned to the new variables corresponding to the formal arguments before the last argument, if any. The values of all the remaining actual arguments are stored in a list and this list is assigned to the new variable corresponding to the final formal argument. There are two typical scenarios for wanting such a possibility: having optional arguments and having any number of arguments.

The following example shows one way that the function \texttt{Position} (21.16.1) might be encoded and demonstrates the “optional argument” scenario.

```gap
gap> position := function ( list, obj, arg... )
>     local pos;
>     if 0 = Length(arg) then
>         pos := 0;
>     else
>         pos := arg[1];
>     fi;
>     repeat
>         pos := pos + 1;
>         if pos > Length(list) then
>             return fail;
>         fi;
>         until list[pos] = obj;
>     return pos;
> end;
> function( list, obj, arg... ) ... end
gap> position([1, 4, 2], 4);
2
gap> position([1, 4, 2], 3);
fail
gap> position([1, 4, 2], 4, 2);
fail
```

The following example demonstrates the “any number of arguments” scenario.

```gap
gap> sum := function ( l... )
>     local total, x;
>     total := 0;
>     repeat
>         x := l[1];
>         total := total + x;
>         until l[1] = fail;
> return total;
> end;
> function( l... ) ... end
gap> sum([1, 2, 3, 4, 5]);
15
```

The user should compare the above with the GAP function \texttt{Sum (21.20.27)} which, for example, may take a list argument and optionally an initial element (which zero should the sum of an empty list return?).

GAP will also special case a function with a single argument with the name \texttt{arg} as function with a variable length list of arguments, as if the user had written \texttt{arg...}.

Note that if a function \texttt{f} is defined as above then \texttt{NumberArgumentsFunction (f)} returns minus the number of formal arguments (including the final argument) (see \texttt{NumberArgumentsFunction (5.1.2)}).

Using the ... notation on a function \texttt{f} with only a single named argument tells GAP that when it encounters \texttt{f} that it should form a list out of the arguments of \texttt{f}. What if one wishes to do the “opposite”: tell GAP that a list should be “unwrapped” and passed as several arguments to a function. The function \texttt{CallFuncList (5.2.1)} is provided for this purpose.

Also see Chapter 5.

\begin{verbatim}
{ arg-list } -> expr
This is a shorthand for
function ( arg-list ) return expr; end.
arg-list is a (possibly empty) argument list. Any arguments list which would be valid for a normal GAP function is also valid here (including variadic arguments).

The following gives a couple of examples of a typical use of such a function
\end{verbatim}
The \{ and \} may be omitted for functions with one argument:

```
gap> f();
2
```

Example

```
gap> Sum( List( [1..100], {x} -> x^2 ) );
338350
```

```
gap> Sum( List( [1..100], x -> x^2 ) );
338350
```

When the definition of a function \textit{fun1} is evaluated inside another function \textit{fun2}, GAP binds all the identifiers inside the function \textit{fun1} that are identifiers of an argument or a local of \textit{fun2} to the corresponding variable. This set of bindings is called the environment of the function \textit{fun1}. When \textit{fun1} is called, its body is executed in this environment. The following implementation of a simple stack uses this. Values can be pushed onto the stack and then later be popped off again. The interesting thing here is that the functions \textit{push} and \textit{pop} in the record returned by \texttt{Stack} access the local variable \texttt{stack} of \texttt{Stack}. When \texttt{Stack} is called, a new variable for the identifier \texttt{stack} is created. When the function definitions of \textit{push} and \textit{pop} are then evaluated (as part of the \texttt{return} statement) each reference to \texttt{stack} is bound to this new variable. Note also that the two stacks \texttt{A} and \texttt{B} do not interfere, because each call of \texttt{Stack} creates a new variable for \texttt{stack}.

Example

```
gap> Stack := function ()
>   local stack;
>   stack := [];
>   return rec(
>     push := function ( value )
>       Add( stack, value );
>     end,
>     pop := function ()
>       local value;
>       value := stack[Length(stack)];
>       Unbind( stack[Length(stack)] );
>       return value;
>     end
>  );
> end;
> A := Stack();;
> B := Stack();;
> A.push( 1 ); A.push( 2 ); A.push( 3 );
> B.push( 4 ); B.push( 5 ); B.push( 6 );
> A.pop(); A.pop(); A.pop();
1
2
3
>`
```
```
gap> B.pop(); B.pop(); B.pop();
6
5
4
```

This feature should be used rarely, since its implementation in \texttt{GAP} is not very efficient.
4.24 Return (With or without Value)

```plaintext
return;
```
In this form `return` terminates the call of the innermost function that is currently executing, and control returns to the calling function. An error is signalled if no function is currently executing. No value is returned by the function.

```plaintext
return expr;
```
In this form `return` terminates the call of the innermost function that is currently executing, and returns the value of the expression `expr`. Control returns to the calling function. An error is signalled if no function is currently executing.

Both statements can also be used in break loops (see 6.4). `return;` has the effect that the computation continues where it was interrupted by an error or the user hitting CTRL-C. `return expr;` can be used to continue execution after an error. What happens with the value `expr` depends on the particular error.

For examples of `return` statements, see the functions `fib` and `Stack` in Section 4.23.

4.25 Syntax Trees

This section describes the tools available to handle GAP syntax trees.

4.25.1 SyntaxTree

```plaintext
▷ SyntaxTree(f)
```
Takes a GAP function `f` and returns its syntax tree.
Chapter 5

Functions

The section 4.23 describes how to define a function. In this chapter we describe functions that give information about functions, and various utility functions used either when defining functions or calling functions.

5.1 Information about a function

5.1.1 NameFunction

\texttt{NameFunction(func)}

returns the name of a function. For operations, this is the name used in their declaration. For functions, this is the variable name they were first assigned to. (For some internal functions, this might be a name different from the name that is documented.) If no such name exists, the string "unknown" is returned.

\begin{verbatim}
gap> NameFunction(SylowSubgroup);
"SylowSubgroup"
gap> Blubberflutsch:=x->x;;
gap> HasNameFunction(Blubberflutsch);
true
gap> NameFunction(Blubberflutsch);
"Blubberflutsch"
gap> a:=Blubberflutsch;;
gap> NameFunction(a);
"Blubberflutsch"
gap> SetNameFunction(a, "f");
gap> NameFunction(a);
"f"
gap> HasNameFunction(x->x);
false
gap> NameFunction(x->x);
"unknown"
\end{verbatim}
5.1.2 NumberArgumentsFunction

NumberArgumentsFunction(func)

(operation)

returns the number of arguments the function func accepts. -1 is returned for all operations. For functions that use ... or arg to take a variable number of arguments, the number returned is -1 times the total number of parameters. For attributes, 1 is returned.

Example

gap> NumberArgumentsFunction(function(a,b,c,d,e,f,g,h,i,j,k)return 1;end);
11
gap> NumberArgumentsFunction(Size);
1
gap> NumberArgumentsFunction(IsCollsCollsElms);
3
gap> NumberArgumentsFunction(Sum);
-1

gap> NumberArgumentsFunction(function(a, x...) return 1; end);
-2

5.1.3 NamesLocalVariablesFunction

NamesLocalVariablesFunction(func)

(operation)

returns a mutable list of strings; the first entries are the names of the arguments of the function func, in the same order as they were entered in the definition of func, and the remaining ones are the local variables as given in the local statement in func. (The number of arguments can be computed with NumberArgumentsFunction (5.1.2).)

Example

gap> NamesLocalVariablesFunction(function( a, b ) local c; return 1; end);
[ "a", "b", "c" ]
gap> NamesLocalVariablesFunction(function( arg ) local a; return 1; end);
[ "arg", "a" ]
gap> NamesLocalVariablesFunction( Size );
fail

5.1.4 FilenameFunc

FilenameFunc(func)

(function)

For a function func, FilenameFunc returns either fail or the absolute path of the file from which func has been read. The return value fail occurs if func is a compiled function or an operation. For functions that have been entered interactively, the string "*stdin*" is returned, see Section 9.5.

Example

gap> FilenameFunc( LEN_LIST ); # a kernel function
fail
gap> FilenameFunc( Size ); # an operation
fail
gap> FilenameFunc( x -> x^2 ); # an interactively entered function
"*stdin*"
5.1.5 StartlineFunc

Let \textit{func} be a function. If \texttt{FilenameFunc} (5.1.4) returns \texttt{fail} for \textit{func} then also \texttt{StartlineFunc} returns \texttt{fail}. If \texttt{FilenameFunc} (5.1.4) returns a filename for \textit{func} then \texttt{StartlineFunc} returns the line number in this file where the definition of \textit{func} starts.

\texttt{EndlineFunc} behaves similarly and returns the line number in this file where the definition of \textit{func} ends.

```
gap> meth := ApplicableMethod( Size, [ Group( () ) ] );;
gap> FilenameFunc( meth );
"... some path .../grpperm.gi"
gap> StartlineFunc( meth );
487
gap> EndlineFunc( meth );
487
```

5.1.6 LocationFunc

Let \textit{func} be a function. Returns a string describing the location of \textit{func}, or an empty string if the information cannot be found. This uses the information provided by \texttt{FilenameFunc} (5.1.4) and \texttt{StartlineFunc} (5.1.5).

```
gap> LocationFunc( Intersection );
"... some path ... gap4r5/lib/grpperm.gi:2467"
# String is an attribute, so no information is stored
gap> LocationFunc( String );
"
```

5.1.7 PageSource

This shows the file containing the source code of the function or method \textit{func} in a pager (see \texttt{Pager} (2.4.1)). The display starts at a line shortly before the code of \textit{func}.

For operations \textit{func} the function shows the source code of the declaration of \textit{func}. Operations can have several declarations, use the optional second argument to specify which one should be shown (in the order the declarations were read); the default is to show the first.

For kernel functions the function tries to show the C source code.

If GAP cannot find a file containing the source code this will be indicated.
Usage examples:
met := ApplicableMethod(`^`, [(1,2),2743527]); PageSource(met);
PageSource(Combinations);
PageSource(SORT_LIST);
PageSource(Size, 2);
ct := CharacterTable(Group((1,2,3))); met := ApplicableMethod(Size,[ct]); PageSource(met);

5.2 Calling a function with a list argument that is interpreted as several arguments

5.2.1 CallFuncList

\[ \text{CallFuncList}(\text{func, args}) \]
\[ \text{CallFuncListWrap}(\text{func, args}) \]

returns the result, when calling function \text{func} with the arguments given in the list \text{args}, i.e. \text{args} is “unwrapped” so that \text{args} appears as several arguments to \text{func}.

\begin{verbatim}
gap> CallFuncList(+, [6, 7]);
13
\end{verbatim}

A more useful application of \text{CallFuncList} is for a function \text{g} that is called in the body of a function \text{f} with (a sublist of) the arguments of \text{f}, where \text{f} has been defined with a single formal argument \text{arg} (see 4.23), as in the following code fragment.

\begin{verbatim}
f := function ( arg )
  CallFuncList(g, arg);
  ...
end;
\end{verbatim}

In the body of \text{f} the several arguments passed to \text{f} become a list \text{arg}. If \text{g} were called instead via \text{g(arg...)} then \text{g} would see a single list argument, so that \text{g} would, in general, have to “unwrap” the passed list. The following (not particularly useful) example demonstrates both described possibilities for the call to \text{g}.

\begin{verbatim}
gap> PrintNumberFromDigits := function ( arg )
  >  CallFuncList( Print, arg );
  >  Print( "\n" );
  > end;
function( arg... ) ... end

 gap> PrintNumberFromDigits( 1, 9, 7, 3, 2 );
 19732
 gap> PrintDigits := function ( arg )
  >  Print( arg );
  > end;
\end{verbatim}
CallFuncListWrap differs only in that the result is a list. This returned list is empty if the called function returned no value, else it contains the returned value as its single member. This allows wrapping functions which may, or may not return a value.

Example

```gap
gap> CallFuncListWrap( x -> x, [1] );
[ 1 ]
gap> CallFuncListWrap( function(x) end, [1] );
[ ]
```

5.3 Wrapping a function, so the values produced are cached

5.3.1 MemoizePosIntFunction

```gap
MemoizePosIntFunction(function[, options])
```

MemoizePosIntFunction returns a function which behaves the same as `function`, except it caches the results for any inputs that are positive integers. Thus if the new function is called multiple times with the same input, then any call after the first will return the cached value, instead of recomputing it. By default, the cache can be flushed by calling `FlushCaches (79.10.3)`.

The returned function will by default only accept positive integers.

This function does not promise to never call `function` more than once for any input – values may be removed if the cache gets too large, or if `FlushCaches (79.10.3)` is called, or if multiple threads try to calculate the same value simultaneously.

The optional second argument is a record which provides a number of configuration options. The following options are supported.

`defaults` (default an empty list)

Used to initialise the cache, both initially and after each flush. If `defaults[i]` is bound, then this is used as default value for the input i.

`flush` (default true)

If this is true, the cache is emptied whenever `FlushCaches (79.10.3)` is called; if false, then the cache cannot be flushed.

`errorHandler` (defaults to `Error (6.6.1)`)  

A function to be called when an input which is not a positive integer is passed to the cache. The function can either raise an error, or else return a value which is then returned by the cache. Note that such a value does not get cached itself.

Example

```gap
f := MemoizePosIntFunction(
    function(i) Print("Check: ",i,"\n"); return i*i; end,
    rec(defaults := [,60], errorHandler := x -> "Bad")
);;
```
5.4 Functions that do nothing

The following functions return fixed results (or just their own argument). They can be useful in places when the syntax requires a function, but actually no functionality is required. So ReturnTrue (5.4.1) is often used as family predicate in InstallMethod (78.3.1).

5.4.1 ReturnTrue

\[ \texttt{ReturnTrue(...)} \]

This function takes any number of arguments, and always returns \texttt{true}.

\[
\begin{verbatim}
gap> f:=ReturnTrue;
function( arg... ) ... end
\gap> f();
true
\gap> f(42);
true
\end{verbatim}

5.4.2 ReturnFalse

\[ \texttt{ReturnFalse(...)} \]

This function takes any number of arguments, and always returns \texttt{false}.

\[
\begin{verbatim}
gap> f:=ReturnFalse;
function( arg... ) ... end
\gap> f();
false
\gap> f("any_string");
false
\end{verbatim}

5.4.3 ReturnFail

\[ \text{ReturnFail}(\ldots) \]

This function takes any number of arguments, and always returns fail.

\begin{verbatim}
gap> oops:=ReturnFail;
gap> oops(arg...) ... end
fail

gap> oops(-42);
fail
\end{verbatim}

5.4.4 ReturnNothing

\[ \text{ReturnNothing}(\ldots) \]

This function takes any number of arguments, and always returns nothing.

\begin{verbatim}
gap> n:=ReturnNothing;
gap> n(object...) ... end

gap> n();
gap> n(-42);
\end{verbatim}

5.4.5 ReturnFirst

\[ \text{ReturnFirst}(\ldots) \]

This function takes one or more arguments, and always returns the first argument. \text{IdFunc (5.4.6)} behaves similarly, but only accepts a single argument.

\begin{verbatim}
gap> f:=ReturnFirst;
gap> f(first, rest...) ... end

gap> f(1);
1

gap> f(2,3,4);
2

gap> f();
Error, Function: number of arguments must be at least 1 (not 0)
\end{verbatim}

5.4.6 IdFunc

\[ \text{IdFunc}(\text{obj}) \]

returns \text{obj}. \text{ReturnFirst (5.4.5)} is similar, but accepts one or more arguments, returning only the first.
```gap
Example
gap> id:=IdFunc;
  function( object ) ... end
gap> id(42);
  42
gap> f:=id(SymmetricGroup(3));
  Sym( [ 1 .. 3 ] )
gap> s:=One(AutomorphismGroup(SymmetricGroup(3)));
  IdentityMapping( Sym( [ 1 .. 3 ] ) )
gap> f=s;
  false
```

### 5.5 Function Types

Functions are GAP objects and thus have categories and a family.

#### 5.5.1 IsFunction

- `IsFunction(obj)` *(Category)*

  is the category of functions.

```gap
Example
gap> IsFunction(x->x^2);
  true
gap> IsFunction(Factorial);
  true
gap> f:=One(AutomorphismGroup(SymmetricGroup(3)));
  IdentityMapping( Sym( [ 1 .. 3 ] ) )
gap> IsFunction(f);
  false
```

#### 5.5.2 FunctionsFamily

- `FunctionsFamily` *(family)*

  is the family of all functions.

### 5.6 Naming Conventions

The way functions are named in GAP might help to memorize or even guess names of library functions.

If a variable name consists of several words then the first letter of each word is capitalized.

If the first part of the name of a function is a verb then the function may modify its argument(s) but does not return anything, for example `Append (21.4.5)` appends the list given as second argument to the list given as first argument. Otherwise the function returns an object without changing the arguments, for example `Concatenation (21.20.1)` returns the concatenation of the lists given as arguments.
If the name of a function contains the word “Of” then the return value is thought of as information deduced from the arguments. Usually such functions are attributes (see 13.5). Examples are GeneratorsOfGroup (39.2.4), which returns a list of generators for the group entered as argument, or DiagonalOfMat (24.12.1).

For the setter and tester functions of an attribute Attr the names SetAttr resp. HasAttr are available (see 13.5).

If the name of a function contains the word “By” then the return value is thought of as built in a certain way from the parts given as arguments. For example, creating a group as a factor group of a given group by a normal subgroup can be done by taking the image of NaturalHomomorphismByNormalSubgroup (39.18.1). Other examples of “By” functions are GroupHomomorphismByImages (40.1.1) and LaurentPolynomialByCoefficients (66.13.1).

Often such functions construct an algebraic structure given by its generators (for example, RingByGenerators (56.1.4)). In some cases, “By” may be replaced by “With” (like e.g. GroupWithGenerators (39.2.3)) or even both versions of the name may be used. The difference between StructByGenerators and StructWithGenerators is that the latter guarantees that the GeneratorsOfStruct value of the result is equal to the given set of generators (see 31.3).

If the name of a function has the form “AsSomething” then the return value is an object (usually a collection which has the same family of elements), which may, for example:

- know more about its own structure (and so support more operations) than its input (e.g. if the elements of the collection form a group, then this group can be constructed using AsGroup (39.2.5));
- discard its additional structure (e.g. AsList (30.3.8) applied to a group will return a list of its elements);
- contain all elements of the original object without duplicates (like e.g. AsSet (30.3.10) does if its argument is a list of elements from the same family);
- remain unchanged (like e.g. AsSemigroup (51.1.6) does if its argument is a group).

If Something and the argument of AsSomething are domains, some further rules apply as explained in Tutorial: Changing the Structure.

If the name of a function fun1 ends with “NC” then there is another function fun2 with the same name except that the “NC” is missing. “NC” stands for “no check”. When fun2 is called then it checks whether its arguments are valid, and if so then it calls fun1. The functions SubgroupNC (39.3.1) and Subgroup (39.3.1) are a typical example.

The idea is that the possibly time consuming check of the arguments can be omitted if one is sure that they are unnecessary. For example, if an algorithm produces generators of the derived subgroup of a group then it is guaranteed that they lie in the original group; Subgroup (39.3.1) would check this, and SubgroupNC (39.3.1) omits the check.

Needless to say, all these rules are not followed slavishly, for example there is one operation Zero (31.10.3) instead of two operations ZeroOfElement and ZeroOfAdditiveGroup.

5.7 Code annotations (pragmas)

GAP supports the use of code annotations (pragmas) in functions, i.e., adding comments to functions that are stored in the function object itself, unlike regular comments. Pragmas are single-line comments, starting with #%:
Pragmas can be used to mark parts of functions that should later be manipulated using 4.25. Please note that heavy use of pragmas in functions slows down the execution of your function in the same way as adding empty; statements to your code.

```gap
Example

```gap
function()
  # This is a pragma
  return;
end;;
```
```
Example

```gap
gap> function()
  # This is not a pragma
  return;
end
```
```
```
Chapter 6

Main Loop and Break Loop

This chapter is a first of a series of chapters that describe the interactive environment in which you use GAP.

6.1 Main Loop

The normal interaction with GAP happens in the so-called read-eval-print loop. This means that you type an input, GAP first reads it, evaluates it, and then shows the result. Note that the term print may be confusing since there is a GAP function called Print (6.3.4) (see 6.3) which is in fact not used in the read-eval-print loop, but traditions are hard to break. In the following, whenever we want to express that GAP places some characters on the standard output, we will say that GAP shows something.

The exact sequence in the read-eval-print loop is as follows.

To signal that it is ready to accept your input, GAP shows the prompt gap>. When you see this, you know that GAP is waiting for your input.

Note that every statement must be terminated by a semicolon. You must also enter RETURN (i.e., strike the RETURN key) before GAP starts to read and evaluate your input. (The RETURN key may actually be marked with the word ENTER and a returning arrow on your terminal.) Because GAP does not do anything until you enter RETURN, you can edit your input to fix typos and only when everything is correct enter RETURN and have GAP take a look at it (see 6.8). It is also possible to enter several statements as input on a single line. Of course each statement must be terminated by a semicolon.

It is absolutely acceptable to enter a single statement on several lines. When you have entered the beginning of a statement, but the statement is not yet complete, and you enter RETURN, GAP will show the partial prompt >. When you see this, you know that GAP is waiting for the rest of the statement. This happens also when you forget the semicolon ; that terminates every GAP statement. Note that when RETURN has been entered and the current statement is not yet complete, GAP will already evaluate those parts of the input that are complete, for example function calls that appear as arguments in another function call which needs several input lines. So it may happen that one has to wait some time for the partial prompt.

When you enter RETURN, GAP first checks your input to see if it is syntactically correct (see Chapter 4 for the definition of syntactically correct). If it is not, GAP prints an error message of the following form.
The first line tells you what is wrong about the input, in this case the \* operator takes two expressions as operands, so obviously the right one is missing. If the input came from a file (see \texttt{Read (9.7.1)}), this line will also contain the filename and the line number. The second line is a copy of the input. And the third line contains a caret pointing to the place in the previous line where \texttt{GAP} realized that something is wrong. This need not be the exact place where the error is, but it is usually quite close.

Sometimes, you will also see a partial prompt after you have entered an input that is syntactically incorrect. This is because \texttt{GAP} is so confused by your input, that it thinks that there is still something to follow. In this case you should enter \texttt{RETURN} repeatedly, ignoring further error messages, until you see the full prompt again. When you see the full prompt, you know that \texttt{GAP} forgave you and is now ready to accept your next –hopefully correct– input.

If your input is syntactically correct, \texttt{GAP} evaluates or executes it, i.e., performs the required computations (see Chapter 4 for the definition of the evaluation).

If you do not see a prompt, you know that \texttt{GAP} is still working on your last input. Of course, you can \texttt{type ahead}, i.e., already start entering new input, but it will not be accepted by \texttt{GAP} until \texttt{GAP} has completed the ongoing computation.

When \texttt{GAP} is ready it will usually show the result of the computation, i.e., the value computed. Note that not all statements produce a value, for example, if you enter a \texttt{for} loop, nothing will be printed, because the \texttt{for} loop does not produce a value that could be shown.

Also sometimes you do not want to see the result. For example if you have computed a value and now want to assign the result to a variable, you probably do not want to see the value again. You can terminate statements by \texttt{two semicolons} to suppress showing the result.

If you have entered several statements on a single line \texttt{GAP} will first read, evaluate, and show the first one, then read, evaluate, and show the second one, and so on. This means that the second statement will not even be checked for syntactical correctness until \texttt{GAP} has completed the first computation.

After the result has been shown \texttt{GAP} will display another prompt, and wait for your next input. And the whole process starts all over again. Note that if you have entered several statements on a single line, a new prompt will only be printed after \texttt{GAP} has read, evaluated, and shown the last statement.

In each statement that you enter, the result of the previous statement that produced a value is available in the variable \texttt{last}. The next to previous result is available in \texttt{last2} and the result produced before that is available in \texttt{last3}.

Also in each statement the time spent by the last statement, whether it produced a value or not, is available in the variable \texttt{time (7.6.4)}. This is an integer that holds the number of mil-
liseconds. Similarly the amount of memory allocated during that statement (in bytes) is stored in the variable `memory_allocated` (7.7.2). The variables `last`, `last2`, `last3`, `time` (7.6.4) and `memory_allocated` (7.7.2) are all write-protected.

### 6.2 Special Rules for Input Lines

The input for some GAP objects may not fit on one line, in particular big integers, long strings or long identifiers. In these cases you can still type or paste them in long single lines. For nicer display you can also specify the input on several lines. This is achieved by ending a line by a backslash or by a backslash and a carriage return character, then continue the input on the beginning of the next line. When reading this GAP will ignore such continuation backslashes, carriage return characters and newline characters. GAP also prints long strings and integers this way.

```gap
gap> n := 1234\> 567890;
1234567890
gap> "This is a very long string that does not fit on a line \ 
> and is therefore continued on the next line."
"This is a very long string that does not fit on a line and is therefo\ 
re continued on the next line."
```

There is a special rule about GAP prompts in input lines: In line editing mode (usual user input and GAP started without \-n) in lines starting with whitespace following `gap>`, `>`, or `brk>` this beginning part is removed. This rule is very convenient because it allows to cut and paste input from other GAP sessions or manual examples easily into your current session.

### 6.3 View and Print

GAP has three different operations to display or print objects: `Display` (6.3.6), `ViewObj` (6.3.5) and `PrintObj` (6.3.5), and these three have different purposes as follows. The first, `Display` (6.3.6), should print the object to the standard output in a human-readable relatively complete and verbose form. The second, `ViewObj` (6.3.5), should print the object to the standard output in a short and concise form, it is used in the main read-eval-print loop to display the resulting object of a computation. The third, `PrintObj` (6.3.5), should print the object to the standard output in a complete form which is GAP-readable if at all possible, such that reading the output into GAP produces an object which is equal to the original one.

All three operations have corresponding operations which do not print anything to standard output but return the output as a string. These are `DisplayString` (27.7.1), `ViewString` (27.7.3) and `PrintString` (27.7.5) (corresponding to `PrintObj` (6.3.5)). Additionally, there is `String` (27.7.6) which is very similar to `PrintString` (27.7.5) but does not insert control characters for line breaks.

For implementation convenience it is allowed that some of these operations have methods which delegate to some other of these operations. However, the rules for this are that a method may only delegate to another operation which appears further down in the following table:
This is to avoid circular delegations.

Note in particular that none of the methods of the string producing operations may delegate to the corresponding printing operations. Note also that the above mentioned purposes of the different operations suggest that delegations between different operations will be sub-optimal in most scenarios.

6.3.1 Default delegations in the library

The library contains the following low ranked default methods:

- A method for `DisplayString (27.7.1)` which returns the constant value of the global variable `DEFAULTDISPLAYSTRING (27.7.2)`.
- A method for `ViewString (27.7.3)` which returns the constant value of the global variable `DEFAULTVIEWSTRING (27.7.4)`.
- A method for `Display (6.3.6)` which first calls `DisplayString (27.7.1)` and prints the result, if it is a different object than `DEFAULTDISPLAYSTRING (27.7.2)`. Otherwise the method delegates to `PrintObj (6.3.5)`.
- A method for `ViewObj (6.3.5)` which first calls `ViewString (27.7.3)` and prints the result, if it is a different object than `DEFAULTVIEWSTRING (27.7.4)`. Otherwise the method delegates to `PrintObj (6.3.5)`.
- A method for `PrintObj (6.3.5)` which prints the result of `PrintString (27.7.5)`.
- A method for `PrintString (27.7.5)` which returns the result of `String (27.7.6)`.

6.3.2 Recommendations for the implementation

This subsection describes what methods for printing and viewing one should implement for new GAP objects.

One should at the very least install a `String (27.7.6)` method to allow printing. Using the standard delegations this enables a limited form of viewing, displaying and printing.

If, for larger objects, nicer line breaks are needed, one should install a separate `PrintString (27.7.5)` method which puts in positions for good line breaks using the control characters `< (ASCII 1)` and `> (ASCII 2)`.

If, for even larger objects, output performance and memory usage matters, one should install a separate `PrintObj (6.3.5)` method.

One should usually install a `ViewString (27.7.3)` method, unless the above `String (27.7.6)` method is good enough for `ViewObj (6.3.5)` purposes. Performance and memory should never matter here, so it is usually unnecessary to install a separate `ViewObj (6.3.5)` method.
If the type of object calls for it one should install a DisplayString (27.7.1) method. This is the case if a human readable verbose form is required.

If the performance and memory usage for Display (6.3.6) matters, one should install a separate Display (6.3.6) method.

Note that if only a String (27.7.6) method is installed, then ViewObj (6.3.5) works and ViewString (27.7.3) returns DEFAULTVIEWSTRING (27.7.4). Likewise, Display (6.3.6) works and DisplayString (27.7.1) returns DEFAULTDISPLAYSTRING (27.7.2). If you want to avoid this then install methods for these operations as well.

6.3.3 View

▷ View(obj1, obj2...)

(function)

View shows the objects obj1, obj2... etc. in a short form on the standard output by calling the ViewObj (6.3.5) operation on each of them. View is called in the read-eval-print loop, thus the output looks exactly like the representation of the objects shown by the main loop. Note that no space or newline is printed between the objects.

6.3.4 Print

▷ Print(obj1, obj2, ...)

(function)

Also Print shows the objects obj1, obj2... etc. on the standard output. The difference compared to View (6.3.3) is in general that the shown form is not required to be short, and that in many cases the form shown by Print is GAP readable.

Example

```
gap> z:= Z(2);
Z(2)^0
gap> v:= [ z, z, z, z, z, z, z ];
[ Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0 ]
gap> ConvertToVectorRep(v);; v;
<a GF2 vector of length 7>
gap> Print( v, "\n" );
[ Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0, Z(2)^0 ]
```

Another difference is that Print shows strings without the enclosing quotes, so Print can be used to produce formatted text on the standard output (see also chapter 27). Some characters preceded by a backslash, such as \n, are processed specially (see chapter 27.2). PrintTo (9.7.3) can be used to print to a file.

Example

```
gap> for i in [1..5] do
>     Print( i, " ", i^2, " ", i^3, "\n" );
>     od;
1 1 1
2 4 8
3 9 27
4 16 64
5 25 125
```

```gap> g:= SmallGroup(12,5);```
6.3.5 ViewObj

The functions View (6.3.3) and Print (6.3.4) actually call the operations ViewObj and PrintObj, respectively, for each argument. By installing special methods for these operations, it is possible to achieve special printing behavior for certain objects (see chapter 78). The only exceptions are strings (see Chapter 27), for which the default PrintObj and ViewObj methods as well as the function View (6.3.3) print also the enclosing doublequotes, whereas Print (6.3.4) strips the doublequotes.

The default method for ViewObj is to call PrintObj. So it is sufficient to have a PrintObj method for an object in order to View (6.3.3) it. If one wants to supply a “short form” for View (6.3.3), one can install additionally a method for ViewObj.

6.3.6 Display

Displays the object obj in a nice, formatted way which is easy to read (but might be difficult for machines to understand). The actual format used for this depends on the type of obj. Each method should print a newline character as last character.

Example

\begin{verbatim}
  gap> Display( [ [ 1, 2, 3 ], [ 4, 5, 6 ] ] * Z(5) );
  2 4 1
  3 . 2
\end{verbatim}

One can assign a string to an object that Print (6.3.4) will use instead of the default used by Print (6.3.4), viaSetName (12.8.1). Also, Name (12.8.2) returns the string previously assigned to the object for printing, via SetName (12.8.1). The following is an example in the context of domains.

Example

\begin{verbatim}
  gap> g:= Group( (1,2,3,4) );
  Group([ (1,2,3,4) ])
  gap> SetName( g, "C4" ); g;
  C4
  gap> Name( g );
  "C4"
\end{verbatim}

When setting up examples, in particular if for beginning users, it sometimes can be convenient to hide the structure behind a printing name. For many objects, such as groups, this can be done using SetName (12.8.1). If the objects however is represented internally, for example permutations representing group elements, this function is not applicable. Instead the function SetNameObject (6.3.7) can be used to interface with the display routines on a lower level.
6.3.7 SetNameObject

SetNameObject(o, s)

SetNameObject sets the string \( s \) as display name for object \( o \) in an interactive session. When applying View (6.3.3) to object \( o \), for example in the system’s main loop, \texttt{GAP} will print the string \( s \). Calling SetNameObject for the same object \( o \) with \( s \) set to \texttt{fail} deletes the special viewing setup. since use of this features potentially slows down the whole print process, this function should be used sparingly.

Example

\begin{verbatim}
gap> SetNameObject(3,"three");
gap> Filtered([1..10],IsPrimeInt);
[ 2, three, 5, 7 ]
gap> SetNameObject(3,fail);
gap> Filtered([1..10],IsPrimeInt);
[ 2, 3, 5, 7 ]
\end{verbatim}

6.4 Break Loops

When an error has occurred or when you interrupt \texttt{GAP} (usually by hitting \texttt{CTRL-C}) \texttt{GAP} enters a break loop, that is in most respects like the main read eval print loop (see 6.1). That is, you can enter statements, \texttt{GAP} reads them, evaluates them, and shows the result if any. However those evaluations happen within the context in which the error occurred. So you can look at the arguments and local variables of the functions that were active when the error happened and even change them. The prompt is changed from \texttt{gap> to brk> to indicate that you are in a break loop.}

Example

\begin{verbatim}
gap> 1/0;
Rational operations: <divisor> must not be zero not in any function Entering break read-eval-print loop ... you can 'quit;' to quit to outer loop, or you can replace <divisor> via 'return <divisor>;' to continue
\end{verbatim}

If errors occur within a break loop \texttt{GAP} enters another break loop at a deeper level. This is indicated by a number appended to \texttt{brk}:

\begin{verbatim}
brk> 1/0;
Rational operations: <divisor> must not be zero not in any function Entering break read-eval-print loop ... you can 'quit;' to quit to outer loop, or you can replace <divisor> via 'return <divisor>;' to continue
brk_02
\end{verbatim}

There are two ways to leave a break loop, see 6.4.1 and 6.4.2.
6.4.1 quit from a break loop

The first way to leave a break loop is to quit the break loop. To do this you enter quit; or type the eof (end of file) character, which is usually CTRL-D except when using the -e option (see Section 3.1). Note that GAP code between quit; and the end of the input line is ignored.

Example
brk_02> quit;
brk>

In this case control returns to the break loop one level above or to the main loop, respectively. So iterated break loops must be left iteratively. Note also that if you type quit; from a gap> prompt, GAP will exit (see 6.7).

Note: If you leave a break loop with quit without completing a command it is possible (though not very likely) that data structures will be corrupted or incomplete data have been stored in objects. Therefore no guarantee can be given that calculations afterwards will return correct results! If you have been using options quitting a break loop generally leaves the options stack with options you no longer want. The function ResetOptionsStack (8.1.3) removes all options on the options stack, and this is the sole intended purpose of this function.

6.4.2 return from a break loop

The other way to leave a break loop is to return from a break loop. To do this you type return; or return obj; If the break loop was entered because you interrupted GAP, then you can continue by typing return;. If the break loop was entered due to an error, you may have to modify the value of a variable before typing return; (see the example for IsDenseList (21.1.2)) or you may have to return an object obj (by typing: return obj;) to continue the computation; in any case, the message printed on entering the break loop will tell you which of these alternatives is possible. For example, if the break loop was entered because a variable had no assigned value, the value to be returned is often a value that this variable should have to continue the computation.

Example
brk> return 9; # we had tried to enter the divisor 9 but typed 0 ...
1/9
gap>

6.4.3 OnBreak

OnBreak()

By default, when a break loop is entered, GAP prints a trace of the innermost 5 commands currently being executed. This behaviour can be configured by changing the value of the global variable OnBreak. When a break loop is entered, the value of OnBreak is checked. If it is a function, then it is called with no arguments. By default, the value of OnBreak is Where (6.4.5).

Example
gap> OnBreak := function() Print("Hello\n"); end;
function( ) ... end
In cases where a break loop is entered during a function that was called with options (see Chapter 8), a `quit;' will also cause the options stack to be reset and an Info-ed warning stating this is emitted at InfoWarning (7.4.8) level 1 (see Chapter 7.4).

Note that for break loops entered by a call to Error (6.6.1), the lines after "Entering break read-eval-print loop ..." and before the `brk> prompt can also be customised, namely by re-defining OnBreakMessage (6.4.4).

Also, note that one can achieve the effect of changing OnBreak locally. As mentioned above, the default value of OnBreak is Where (6.4.5). Thus, a call to Error (6.6.1) generally gives a traceback up to five levels of calling functions. Conceivably, we might like to have a function like Error (6.6.1) that does not trace back without globally changing OnBreak. Such a function we might call ErrorNoTraceBack and here is how we might define it. (Note ErrorNoTraceBack is not a GAP function.)

```gap
gap> ErrorNoTraceBack := function(arg) # arg is special variable that GAP > # knows to treat as list of arg's > local SavedOnBreak, ENTBOnBreak; > SavedOnBreak := OnBreak; # save current value of OnBreak > > ENTBOnBreak := function() # our 'local' OnBreak > local s; > for s in arg do > Print(s); > od; > OnBreak := SavedOnBreak; # restore OnBreak afterwards > end; > > OnBreak := ENTBOnBreak; > Error(); > end; > function( arg... ) ... end
```

Here is a somewhat trivial demonstration of the use of ErrorNoTraceBack.

```gap
gap> ErrorNoTraceBack("Gidday!", " How's", " it", " going?\n"); Error, Gidday! How's it going? Entering break read-eval-print loop ... you can 'quit;' to quit to outer loop, or you can 'return;' to continue > brk> quit;
```

Now we call Error (6.6.1) with the same arguments to show the difference.
Example

gap> Error("Gidday!", " How’s", " it", " going?\n");
Error, Gidday! How’s it going?
Hello
Entering break read-eval-print loop ... you can 'quit;' to quit to outer loop, or you can 'return;' to continue
brk> quit;

Observe that the value of OnBreak before the ErrorNoTraceBack call was restored. However, we had changed OnBreak from its default value; to restore OnBreak to its default value, we should do the following.

gap> OnBreak := Where;;

6.4.4 OnBreakMessage

\[ OnBreakMessage() \]

When a break loop is entered by a call to Error (6.6.1) the message after the "Entering break read-eval-print loop ..." line is produced by the function OnBreakMessage, which just like OnBreak (6.4.3) is a user-configurable global variable that is a function with no arguments.

Example

gap> OnBreakMessage(); # By default, OnBreakMessage prints the following you can 'quit;' to quit to outer loop, or you can 'return;' to continue

Perhaps you are familiar with what’s possible in a break loop, and so don’t need to be reminded. In this case, you might wish to do the following (the first line just makes it easy to restore the default value later).

Example

gap> NormalOnBreakMessage := OnBreakMessage;; # save the default value
gap> OnBreakMessage := function() end; # do-nothing function
function( ) ... end
gap> OnBreakMessage();
gap> OnBreakMessage := NormalOnBreakMessage;; # reset

With OnBreak (6.4.3) still set away from its default value, calling Error (6.6.1) as we did above, now produces:

Example

gap> Error("!\n");
Error, !
Hello
Entering break read-eval-print loop ... brk> quit; # to get back to outer loop
However, suppose you are writing a function which detects an error condition and `OnBreakMessage` needs to be changed only locally, i.e., the instructions on how to recover from the break loop need to be specific to that function. The same idea used to define `ErrorNoTraceBack` (see `OnBreak` (6.4.3)) can be adapted to achieve this. The function `CosetTableFromGensAndRels` (47.6.5) is an example in the GAP code where the idea is actually used.

### 6.4.5 Where

\[ \text{Where}(nr) \quad \text{(function)} \]
\[ \text{WhereWithVars}(nr) \quad \text{(function)} \]

Shows the last `nr` commands on the execution stack during whose execution the error occurred. If not given, `nr` defaults to 5. (Assume, for the following example, that after the last example `OnBreak` (6.4.3) has been set back to its default value.) `WhereWithVars` acts the same as `Where` while also showing the arguments and local variables of each function.

**Example**

```
gap> StabChain(SymmetricGroup(100)); # After this we typed ^C
user interrupt at
bpt := S.orbit[1];
called from
SiftedPermutation( S, (g * rep) ^ -1 ) called from
StabChainStrong( S.stabilizer, [ sch ], options ); called from
StabChainStrong( S.stabilizer, [ sch ], options ); called from
StabChainStrong( S, GeneratorsOfGroup( G ), options ); called from
StabChainOp( G, rec( ) ) called from...

... Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you can 'return;' to continue
brk> Where(2);
called from
SiftedPermutation( S, (g * rep) ^ -1 ) called from
StabChainStrong( S.stabilizer, [ sch ], options ); called from
```

Note that the variables displayed even in the first line of the `Where` list (after the `called from` line) may be already one environment level higher and `DownEnv` (6.5.1) may be necessary to access them.

At the moment this backtrace does not work from within compiled code (this includes the method selection which by default is compiled into the kernel). If this creates problems for debugging, call GAP with the `-N` option (see 3.1) to avoid loading compiled code.

(Function calls to `Info` (7.4.6) and methods installed for binary operations are handled in a special way. In rare circumstances it is possible therefore that they do not show up in a `Where` log but the log refers to the last proper function call that happened before.)

The command line option `-T` to GAP disables the break loop. This is mainly intended for testing purposes and for special applications. If this option is given then errors simply cause GAP to return to the main loop.
6.5 Variable Access in a Break Loop

In a break loop access to variables of the current break level and higher levels is possible, but if the same variable name is used for different objects or if a function calls itself recursively, of course only the variable at the lowest level can be accessed.

6.5.1 DownEnv and UpEnv

\texttt{DownEnv}(\texttt{nr}) \quad \texttt{(function)}

\texttt{UpEnv}(\texttt{nr}) \quad \texttt{(function)}

\texttt{DownEnv} moves down \texttt{nr} steps in the environment and allows one to inspect variables on this level; if \texttt{nr} is negative it steps up in the environment again; \texttt{nr} defaults to 1 if not given. \texttt{UpEnv} acts similarly to \texttt{DownEnv} but in the reverse direction (the mnemonic rule to remember the difference between \texttt{DownEnv} and \texttt{UpEnv} is the order in which commands on the execution stack are displayed by \texttt{Where (6.4.5)}).

\begin{verbatim}
Example

 gap> OnBreak := function() Where(0); end;; # eliminate back-tracing on
 gap> # entry to break loop
 gap> test:= function( n )
>     if n > 3 then Error( "!\n" ); fi; test( n+1 ); end;;
 gap> test( 1 );
Error, !
Entering break read-eval-print loop ... you can 'quit;' to quit to outer loop, or you can 'return;' to continue
brk> Where();
called from
test( n + 1 ); called from
test( n + 1 ); called from
test( n + 1 ); called from
<function>( <arguments> ) called from read-eval-loop
brk> n;
4
brk> DownEnv();
brk> n;
3
brk> Where();
called from
test( n + 1 ); called from
test( n + 1 ); called from
<function>( <arguments> ) called from read-eval-loop
brk> DownEnv(2);
brk> n;
1
brk> Where();
called from
<function>( <arguments> ) called from read-eval-loop
brk> DownEnv(-2);
brk> n;
3
\end{verbatim}
Note that the change of the environment caused by `DownEnv` only affects variable access in the break loop. If you use `return` to continue a calculation, `GAP` automatically jumps to the right environment level again.

Note also that search for variables looks first in the chain of outer functions which enclosed the definition of a currently executing function, before it looks at the chain of calling functions which led to the current invocation of the function.

```
gap> foo := function()
>    local x; x := 1;
>    return function() local y; y := x*x; Error("!!\n"); end;
> end;
function( ) ... end
gap> bar := foo();
function( ) ... end
gap> fun := function() local x; x := 3; bar(); end;
function( ) ... end
gap> fun();
Error, !!
called from
bar( ); called from
<function>( <arguments> ) called from read-eval-loop
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you can 'return;' to continue
brk> x;
1
brk> DownEnv(1);
brk> x;
3
```

Here the `x` of `foo` which contained the definition of `bar` is found before that of `fun` which caused its execution. Using `DownEnv` we can access the `x` from `fun`.

### 6.6 Error and ErrorCount

#### 6.6.1 Error

Error signals an error from within a function. First the messages `messages` are printed, this is done exactly as if `Print` (6.3.4) (see 6.3) were called with these arguments. Then a break loop (see 6.4) is entered, unless the standard error output is not connected to a terminal. You can leave this break loop with `return;` to continue execution with the statement following the call to `Error`. `ErrorNoReturn` (6.6.2) operates identically to `Error`, except it does not allow using `return;` to continue execution.
6.6.2 ErrorNoReturn

\[\text{ErrorNoReturn(messages, ...)}\]

ErrorNoReturn signals an error from within a function. First the messages \text{messages} are printed, this is done exactly as if \text{Print (6.3.4)} (see 6.3) were called with these arguments. Then a break loop (see 6.4) is entered, unless the standard error output is not connected to a terminal. This break loop can only be exited with \text{quit;}. The function differs from \text{Error (6.6.1)} by not allowing execution to continue.

6.6.3 ErrorCount

\[\text{ErrorCount()}
\]

ErrorCount returns a count of the number of errors (including user interruptions) which have occurred in the GAP session so far. The count is incremented by each error, even if GAP was started with the \text{-T} option to disable the break loop.

6.7 Leaving GAP

The normal way to terminate a GAP session is to enter either \text{quit; (note the semicolon)} or an end-of-file character (usually \text{CTRL-D}) at the \text{gap}> prompt in the main read eval print loop.

6.7.1 QUIT

\[\text{QUIT (global variable)}\]

An emergency way to leave GAP is to enter \text{QUIT at any gap> or brk> or brk.nn> prompt.}

6.7.2 GAP_EXIT_CODE

\[\text{GAP_EXIT_CODE(ret)}\]

A \text{GAP_EXIT_CODE} sets the return value which will be used when GAP exits. This may be an integer, or a boolean (where true is interpreted as 0, and false is interpreted as 1.

6.7.3 QUIT_GAP

\[\text{QUIT_GAP([ret])}\]

A \text{QUIT_GAP} acts similarly to the keyword \text{quit}. It exits GAP cleanly, calling any function installed using \text{InstallAtExit}. The optional argument will be passed to \text{GAP_EXIT_CODE}.

6.7.4 FORCE_QUIT_GAP

\[\text{FORCE_QUIT_GAP([ret])}\]
A `FORCE_QUIT_GAP` is similar to `QUIT_GAP`, except it ignores any functions installed with `InstallAtExit`, or any other functions normally run at GAP exit, and exits GAP immediately. The optional argument will be passed to `GAP_EXIT_CODE`.

### 6.7.5 InstallAtExit

\[ \text{InstallAtExit(func)} \]  
\[ \text{QUITTING} \]  

Before actually terminating, GAP will call (with no arguments) all of the functions that have been installed using `InstallAtExit`. These typically perform tasks such as cleaning up temporary files created during the session, and closing open files. If an error occurs during the execution of one of these functions, that function is simply abandoned, no break loop is entered.

**Example**

```gap
gap> InstallAtExit(function() Print("bye\n"); end);
gap> quit;
bye
```

During execution of these functions, the global variable `QUITTING` will be set to `true` if GAP is exiting because the user typed `QUIT` and `false` otherwise. Since `QUIT` is considered as an emergency measure, different action may be appropriate.

### 6.7.6 SaveOnExitFile

\[ \text{SaveOnExitFile} \]  

If, when GAP is exiting due to a `quit` or end-of-file (i.e. not due to a `QUIT`) the variable `SaveOnExitFile` is bound to a string value, then the system will try to save the workspace to that file.

### 6.8 Line Editing

In most installations GAP will be compiled to use the Gnu readline library (see the line `Libs used: on GAP startup`). In that case skip to the next section 6.9. (The line editing commands described in the rest of this section were available in previous versions of GAP, they will work almost the same in the standard configuration of the Gnu readline library.)

GAP allows one you to edit the current input line with a number of editing commands. Those commands are accessible either as control keys or as escape keys. You enter a control key by pressing the CTRL key, and, while still holding the CTRL key down, hitting another key key. You enter an escape key by hitting ESC and then hitting another key key. Below we denote control keys by `CTRL-key` and escape keys by `ESC-key`. The case of `key` does not matter, i.e., `CTRL-A` and `CTRL-a` are equivalent.

Normally, line editing will be enabled if the input is connected to a terminal. Line editing can be enabled or disabled using the command line options `-e` and `-n` respectively (see 3.1), however this is a machine dependent feature of GAP.

Typing `CTRL-key` or `ESC-key` for characters not mentioned below always inserts `CTRL-key` resp. `ESC-key` at the current cursor position.
The first few commands allow you to move the cursor on the current line.

**CTRL-A**
move the cursor to the beginning of the line.

**ESC-B**
move the cursor to the beginning of the previous word.

**CTRL-B**
move the cursor backward one character.

**CTRL-F**
move the cursor forward one character.

**ESC-F**
move the cursor to the end of the next word.

**CTRL-E**
move the cursor to the end of the line.

The next commands delete or kill text. The last killed text can be reinserted, possibly at a different position, with the “yank” command **CTRL-Y**.

**CTRL-H or del**
delete the character left of the cursor.

**CTRL-D**
delete the character under the cursor.

**CTRL-K**
kills up to the end of the line.

**ESC-D**
kills forward to the end of the next word.

**ESC-de1**
kills backward to the beginning of the last word.

**CTRL-X**
kills entire input line, and discard all pending input.

**CTRL-Y**
insert (yank) a just killed text.

The next commands allow you to change the input.

**CTRL-T**
exchange (twiddle) current and previous character.

**ESC-U**
upcase next word.
**Esc-L**
lowercase next word.

**Esc-C**
capitalize next word.

The **TAB** character, which is in fact the control key **CTRL-I**, looks at the characters before the cursor, interprets them as the beginning of an identifier and tries to complete this identifier. If there is more than one possible completion, it completes to the longest common prefix of all those completions. If the characters to the left of the cursor are already the longest common prefix of all completions hitting **TAB** a second time will display all possible completions.

**TAB**  complete the identifier before the cursor.

The next commands allow you to fetch previous lines, e.g., to correct typos, etc.

**CTRL-L**
insert last input line before current character.

**CTRL-P**
redisplay the last input line, another **CTRL-P** will redisplay the line before that, etc. If the cursor is not in the first column only the lines starting with the string to the left of the cursor are taken.

**CTRL-N**
Like **CTRL-P** but goes the other way round through the history.

**Esc-<**
goes to the beginning of the history.

**Esc->**
goes to the end of the history.

**CTRL-O**
accepts this line and perform a **CTRL-N**.

Finally there are a few miscellaneous commands.

**CTRL-V**
enter next character literally, i.e., enter it even if it is one of the control keys.

**CTRL-U**
execute the next line editing command 4 times.

**Esc-num**
execute the next line editing command *num* times.

**Esc-CTRL-L**
redisplay input line.

The four arrow keys (cursor keys) can be used instead of **CTRL-B**, **CTRL-F**, **CTRL-P**, and **CTRL-N**, respectively.
6.9 Editing using the readline library

The descriptions in this section are valid only if your GAP installation uses the readline library for command line editing. You can check by IsBound(GAPInfo.UseReadline); if this is the case.

You can use all the features of readline, as for example explained in https://tiswww.case.edu/php/chet/readline/rluserman.html. Therefore the command line editing in GAP is similar to the bash shell and many other programs. On a Unix/Linux system you may also have a manpage, try man readline.

Compared to the command line editing which was used in GAP up to version 4.4 (or compared to not using the readline library) using readline has several advantages:

- Most keys still do the same as explained in 6.8 (in the default configuration).
- There are many additional commands, e.g. undoing (CTRL-_), keyboard macros (CTRL-X(, CTRL-X) and CTRL-XE), file name completion (hit ESC two or four times), showing matching parentheses, vi-style key bindings, deleting and yanking text, ...
- Lines which are longer than a physical terminal row can be edited more conveniently.
- Arbitrary unicode characters can be typed into string literals.
- The key bindings can be configured, either via your ~/.inputrc file or by GAP commands, see 6.9.1.
- The command line history can be saved to and read from a file, see 6.9.2.
- Adventurous users can even implement completely new command line editing functions on GAP level, see 6.9.4.

6.9.1 Readline customization

You can use your readline init file (by default ~/.inputrc on Unix/Linux) to customize key bindings. If you want settings be used only within GAP you can write them between lines containing $if GAP and $endif. For a detailed documentation of the available settings and functions see here.

```plaintext
$if GAP
  set blink-matching-paren on
  "\C-n": dump-functions
  "\ep": kill-region
$endif
```

Alternatively, from within GAP the command ReadlineInitLine(line); can be used, where line is a string containing a line as in the init file.

Note that after pressing CTRL-V the next special character is input verbatim. This is very useful to bind keys or key sequences. For example, binding the function key F3 to the command kill-whole-line by using the sequence CTRL-V F3 looks on many terminals like this: ReadlineInitLine("\"^[OR":kill-whole-line"); (You can get the line back later with CTRL-Y.)

The CTRL-G key can be used to type any unicode character by its code point. The number of the character can either be given as a count, or if the count is one the input characters before the cursor
are taken (as decimal number or as hex number which starts with 0x. For example, the double stroke character Z can be input by any of the three key sequences Esc 8484 Ctrl-G, 8484 Ctrl-G or 0x2124 Ctrl-G.

Some terminals bind the Ctrl-S and Ctrl-Q keys to stop and restart terminal output. Furthermore, sometimes Ctrl-\ quits a program. To disable this behaviour (and maybe use these keys for command line editing) you can use Exec("stty stop undef; stty start undef; stty quit undef"); in your GAP session or your gaprc file (see 3.2).

6.9.2 The command line history

GAP can save your input lines for later reuse. The keys Ctrl-P (or Up), Ctrl-N (or Down), Esc< and Esc> work as documented in 6.8, that is they scroll backward and forward in the history or go to its beginning or end. Also, Ctrl-O works as documented, it is useful for repeating a sequence of previous lines. (But Ctrl-L clears the screen as in other programs.)

The command line history can be used across several instances of GAP via the following two commands.

6.9.3 SaveCommandLineHistory

\[ \text{SaveCommandLineHistory([fname, ] [app])} \]
\[ \text{Returns: fail or number of saved lines} \]
\[ \text{ReadCommandLineHistory([fname, ] [app])} \]
\[ \text{Returns: fail or number of added lines} \]

The first command saves the lines in the command line history to the file given by the string fname. The default for fname is history in the user's GAP root path GAPInfo.UserGapRoot or "/.gap_hist" if this directory does not exist. If the optional argument app is true then the lines are appended to that file otherwise the file is overwritten.

The second command is the converse, it reads the lines from file fname. If the optional argument app is true the lines are prepended to the history, else it prepends them.

By default, the command line history stores up to 1000 input lines. command line history. This number may be restricted or enlarged via via SetUserPreference("HistoryMaxLines", num); which may be set to a non negative number num to store up to num input lines or to infinity to store arbitrarily many lines. An automatic storing and restoring of the command line history can be configured via SetUserPreference("SaveAndRestoreHistory", true);.

Note that these functions are only available if your GAP is configured to use the readline library.

6.9.4 Writing your own command line editing functions

It is possible to write new command line editing functions in GAP as follows.

The functions have one argument l which is a list with five entries of the form [count, key, line, cursorpos, markpos] where count and key are the last pressed key and its count (these are not so useful here because users probably do not want to overwrite the binding of a single key), then line is a string containing the line typed so far, cursorpos is the current position of the cursor (point), and markpos the current position of the mark.

The result of such a function must be a list which can have various forms:

\[ [\text{str}] \]

with a string \text{str}. In this case the text \text{str} is inserted at the cursor position.
[kill, begin, end]
where kill is true or false and begin and end are positions on the input line. This removes
the text from the lower position to before the higher position. If kill is true the text is killed,
i.e. put in the kill ring for later yanking.

[begin, end, str]
where begin and end are positions on the input line and str is a string. Then the text from
position begin to before end is substituted by str.

[1, lstr]
where lstr is a list of strings. Then these strings are displayed like a list of possible comple-
tions. The input line is not changed.

[2, chars]
where chars is a string. The characters from chars are used as the next characters from the
input. (At most 512 characters are possible.)

[100]
This rings the bell as configured in the terminal.

In the first three cases the result list can contain a position as a further entry, this becomes the new
cursor position. Or it can contain two positions as further entries, these become the new cursor position
and the new position of the mark.

Such a function can be installed as a macro for readline via InstallReadlineMacro(name,
fun); where name is a string used as name of the macro and fun is a function as above. This macro
can be called by a key sequence which is returned by InvocationReadlineMacro(name);

As an example we define a function which puts double quotes around the word under or before
the cursor position. The space character, the characters in "(,)", and the beginning and end of the
line are considered as word boundaries. The function is then installed as a macro and bound to the key
sequence Esc Q.

```
Example

    gap> EditAddQuotes := function(l)
    > local str, pos, i, j, new;
    > str := l[3];
    > pos := l[4];
    > i := pos;
    > while i > 1 and (not str[i-1] in ",,( )") do
    >   i := i-1;
    > od;
    > j := pos;
    > while IsBound(str[j]) and not str[j] in ",,) " do
    >   j := j+1;
    > od;
    > new := "\"
    > Append(new, str[i..j-1]));
    > Append(new, "\"");
    > return [i, j, new];
    > end;
    gap> InstallReadlineMacro("addquotes", EditAddQuotes);
    gap> invl := InvocationReadlineMacro("addquotes");
    gap> ReadlineInitLine(Concatenation("\"\eQ":"", invl, ",")):;
```
6.10 Editing Files

In most cases, it is preferable to create longer input (in particular GAP programs) separately in an editor, and to read in the result via Read (9.7.1). Note that Read (9.7.1) by default reads from the directory in which GAP was started (respectively under Windows the directory containing the GAP binary), so you might have to give an absolute path to the file.

If you cannot create several windows, the Edit (6.10.1) command may be used to leave GAP, start an editor, and read in the edited file automatically.

6.10.1 Edit

\[ \text{\texttt{Edit}}(\text{\texttt{filename}}) \]

Edit starts an editor with the file whose filename is given by the string \texttt{filename}, and reads the file back into GAP when you exit the editor again.

GAP will call your preferred editor if you call \texttt{SetUserPreference("Editor", \texttt{path})}; where \texttt{path} is the path to your editor, e.g., \texttt{/usr/bin/vim}. On Windows you can use edit.com.

Under Mac OS X, you should use \texttt{SetUserPreference("Editor", "open")}; this will open the file in the default editor. If you call \texttt{SetUserPreference("EditorOptions", \texttt{"-t"})}; the file will open in TextEdit, and \texttt{SetUserPreference("EditorOptions", \texttt{"-x", "<appl>"})}; will open the file using the application \texttt{<appl>},

This can for example be done in your \texttt{gap.ini} file, see Section 3.2.1.

6.11 Editor Support

In the \texttt{etc} subdirectory of the GAP installation we provide some setup files for the editors \texttt{vim} and \texttt{emacs/}xemacs.

\texttt{vim} is a powerful editor that understands the basic \texttt{vi} commands but provides much more functionality. You can find more information about it (and download it) from \texttt{https://www.vim.org}.

To get support for GAP syntax in \texttt{vim}, create in your home directory a directory \texttt{.vim} with subdirectories \texttt{.vim/syntax} and \texttt{.vim/indent} (If you are not using Unix, refer to the \texttt{vim} documentation on where to place syntax files). Then copy the file \texttt{etc/vim/gap.vim} to \texttt{.vim/syntax/gap.vim} and the file \texttt{etc/vim/gap_indent.vim} to \texttt{.vim/indent/gap.vim}.

Then edit the \texttt{.vimrc} file in your home directory. Add lines as in the following example:

```plaintext
if has("syntax")
    syntax on           " Default to no syntax highlighting
endif

" For GAP files
augroup gap
   " Remove all gap autocommands
   au!
   autocmd BufRead,BufNewFile *.g,*.gi,*.gd set filetype=gap comments=s:\##\ ,m:\##\ ,e:\##\ b:\#

   " I'm using the external program 'par' for formatting comment lines starting
   " with '## '. Include these lines only when you have par installed.
   autocmd BufRead,BufNewFile *.g,*.gi,*.gd set formatprg="par $6p4s0j"
```

This can for example be done in your \texttt{gap.ini} file, see Section 3.2.1.
6.12 Changing the Screen Size

6.12.1 SizeScreen

\[ \text{SizeScreen([sz])} \]

Called with no arguments, \texttt{SizeScreen} returns the size of the screen as a list with two entries. The first is the length of each line, the second is the number of lines. Called with one argument that is a list \texttt{sz}, \texttt{SizeScreen} sets the size of the screen; The first entry of \texttt{sz}, if bound, is the length of each line, and the second entry of \texttt{sz}, if bound, is the number of lines. The values for unbound entries of \texttt{sz} are left unaffected. The function returns the new values.

Note that those parameters can also be set with the command line options \texttt{-x} for the line length and \texttt{-y} for the number of lines (see Section 3.1).

To check/change whether line breaking occurs for files and streams see \texttt{PrintFormattingStatus (10.4.8)} and \texttt{SetPrintFormattingStatus (10.4.8)}.

The line length must be between 20 and 4096 characters (inclusive) and the number of lines must be at least 10. Values outside this range will be adjusted to the nearest endpoint of the range.

6.13 Teaching Mode

When using \texttt{GAP} in the context of (undergraduate) teaching it is often desirable to simplify some of the system output and functionality defaults (potentially at the cost of making the printing of objects more expensive). This can be achieved by turning on a teaching mode:

6.13.1 TeachingMode

\[ \text{TeachingMode([switch])} \]

When called with a boolean argument \texttt{switch}, this function will turn teaching mode respectively on or off.

Example

\begin{verbatim}
gap> a:=Z(11)^3;
Z(11)^3
gap> TeachingMode(true);
#I Teaching mode is turned ON
gap> a;
ZmodnZObj(8,11)
gap> TeachingMode(false);
#I Teaching mode is turned OFF
gap> a;
Z(11)^3
\end{verbatim}
At the moment, teaching mode changes the following things

**Prime Field Elements**
Elements of fields of prime order are printed as \( \mathbb{Z}/n\mathbb{Z}\)Obj (14.5.3) instead as power of a primitive root.

**Quadratic Irrationalities**
Elements of a quadratic extension of the rationals are printed using the square root \( \sqrt{\cdot} \) (18.4.2) instead of using roots of unity.

**Creation of some small groups**
The group creator functions CyclicGroup (50.1.2), AbelianGroup (50.1.3), ElementaryAbelianGroup (50.1.4), and DihedralGroup (50.1.6) create by default (if no other representation is specified) not a pc group, but a finitely presented group, which makes the generators easier to interpret.
Chapter 7

Debugging and Profiling Facilities

This chapter describes some functions that are useful mainly for debugging and profiling purposes.

Probably the most important debugging tool in GAP is the break loop (see Section 6.4) which can be entered by putting an Error (6.6.1) statement into your code or by hitting Control-C. In the break loop one can inspect variables, stack traces and issue commands as usual in an interactive GAP session. See also the DownEnv (6.5.1), UpEnv (6.5.1), Where (6.4.5) and WhereWithVars (6.4.5) functions.

Sections 7.2 and 7.3 show how to get information about the methods chosen by the method selection mechanism (see chapter 78).

The final sections describe functions for collecting statistics about computations (see Runtime (7.6.2), 7.8).

7.1 Recovery from NoMethodFound-Errors

When the method selection fails because there is no applicable method, an error as in the following example occurs and a break loop is entered:

```
Example

gap> IsNormal(2,2);
Error, no method found! For debugging hints type ?Recovery from NoMethodFound
Error, no 1st choice method found for 'IsNormal' on 2 arguments at GAPROOT/lib/methsel2.g:250 called from
<function "HANDLE_METHOD_NOT_FOUND">( <arguments> )
called from read-eval loop at *stdin*:1
type 'quit;' to quit to outer loop
brk>
```

This only says, that the method selection tried to find a method for IsNormal on two arguments and failed. In this situation it is crucial to find out, why this happened. Therefore there are a few functions which can display further information. Note that you can leave the break loop by the quit command (see 6.4.1) and that the information about the incident is no longer accessible afterwards.

7.1.1 ShowArguments

```
ShowArguments()  (function)
```
This function is only available within a break loop caused by a “No Method Found”-error. It prints as a list the arguments of the operation call for which no method was found.

### 7.1.2 ShowArgument

\[\texttt{ShowArgument(nr)}\]

This function is only available within a break loop caused by a “No Method Found”-error. It prints the \(nr\)-th arguments of the operation call for which no method was found. \texttt{ShowArgument} needs exactly one argument which is an integer between 0 and the number of arguments the operation was called with.

### 7.1.3 ShowDetails

\[\texttt{ShowDetails()}\]

This function is only available within a break loop caused by a “No Method Found”-error. It prints the details of this error: The operation, the number of arguments, a flag which indicates whether the operation is being traced, a flag which indicates whether the operation is a constructor method, and the number of methods that refused to apply by calling \texttt{TryNextMethod (78.5.1)}. The last number is called \texttt{Choice} and is printed as an ordinal. So if exactly \(k\) methods were found but called \texttt{TryNextMethod (78.5.1)} and there were no more methods it says \texttt{Choice: kth}.

### 7.1.4 ShowMethods

\[\texttt{ShowMethods([verbosity])}\]

This function is only available within a break loop caused by a “No Method Found”-error. It prints an overview about the installed methods for those arguments the operation was called with (using 7.2. The verbosity can be controlled by the optional integer parameter \texttt{verbosity}. The default is 2, which lists all applicable methods. With verbosity 1 \texttt{ShowMethods} only shows the number of installed methods and the methods matching, which can only be those that were already called but refused to work by calling \texttt{TryNextMethod (78.5.1)}. With verbosity 3 not only all installed methods but also the reasons why they do not match are displayed.

### 7.1.5 ShowOtherMethods

\[\texttt{ShowOtherMethods([verbosity])}\]

This function is only available within a break loop caused by a “No Method Found”-error. It prints an overview about the installed methods for a different number of arguments than the number of arguments the operation was called with (using 7.2. The verbosity can be controlled by the optional integer parameter \texttt{verbosity}. The default is 1 which lists only the number of applicable methods. With verbosity 2 \texttt{ShowOtherMethods} lists all installed methods and with verbosity 3 also the reasons, why they are not applicable. Calling \texttt{ShowOtherMethods} with verbosity 3 in this function will normally not make any sense, because the different numbers of arguments are simulated by supplying the corresponding number of ones, for which normally no reasonable methods will be installed.
7.2 Inspecting Applicable Methods

7.2.1 ApplicableMethod

\[\text{ApplicableMethod}(\text{opr}, \text{args [, printlevel [, nr]}])\] (function)

\[\text{ApplicableMethodTypes}(\text{opr}, \text{args [, printlevel [, nr]}])\] (function)

Called with two arguments, ApplicableMethod returns the method of highest rank that is applicable for the operation opr with the arguments in the list args. The default printlevel is 0. If no method is applicable then fail is returned.

If a positive integer is given as the fourth argument nr then ApplicableMethod returns the nr-th applicable method for the operation opr with the arguments in the list args, where the methods are ordered according to descending rank. If less than nr methods are applicable then fail is returned.

If the fourth argument nr is the string "all" then ApplicableMethod returns a list of all applicable methods for opr with arguments args, ordered according to descending rank.

Depending on the integer value printlevel, additional information is printed. Admissible values and their meaning are as follows.

0 no information,
1 information about the applicable method,
2 also information about the not applicable methods of higher rank,
3 also for each not applicable method the first reason why it is not applicable,
4 also for each not applicable method all reasons why it is not applicable.
6 also the function body of the selected method(s)

When a method returned by ApplicableMethod is called then it returns either the desired result or the string "TRY_NEXT_METHOD", which corresponds to a call to TryNextMethod (78.5.1) in the method and means that the method selection would call the next applicable method.

Note: The GAP kernel provides special treatment for the infix operations \(+, \-, \*, /, ^, \mod\) and \(\in\). For some kernel objects (notably cyclotomic numbers, finite field elements and row vectors thereof) it calls kernel methods circumventing the method selection mechanism. Therefore for these operations ApplicableMethod may return a method which is not the kernel method actually used.

The function ApplicableMethodTypes takes the types or filters of the arguments as argument (if only filters are given of course family predicates cannot be tested).

7.3 Tracing Methods

7.3.1 TraceMethods (for operations)

\[\text{TraceMethods}(\text{opr1, opr2, ...})\] (function)

\[\text{TraceMethods}(\text{oprs})\] (function)

After the call of TraceMethods, whenever a method of one of the operations opr1, opr2, ... is called, the information string used in the installation of the method is printed. The second form has the same effect for each operation from the list oprs of operations.
7.3.2 TraceAllMethods

\[ \text{TraceAllMethods()} \] (function)

Invokes TraceMethods for all operations.

7.3.3 UntraceMethods (for operations)

\[ \begin{align*} & \text{UntraceMethods}(\text{opr}_1, \text{opr}_2, \ldots) \quad \text{(function)} \\
& \text{UntraceMethods}(\text{oprs}) \quad \text{(function)} \\
\end{align*} \]

turns the tracing off for all operations \( \text{opr}_1, \text{opr}_2, \ldots \) or in the second form, for all operations in the list \( \text{oprs} \).

Example

\begin{verbatim}
gap> TraceMethods([Size]);
gap> g:= Group((1,2,3), (1,2));;
gap> Size( g );
#I Size: for a permutation group at /gap5/lib/grpperm.gi:487
#I Setter(Size): system setter
#I Size: system getter
#I Size: system getter
6
gap> UntraceMethods([Size]);
\end{verbatim}

7.3.4 UntraceAllMethods

\[ \text{UntraceAllMethods()} \] (function)

Equivalent to calling UntraceMethods for all operations.

7.3.5 TraceImmediateMethods

\[ \begin{align*} & \text{TraceImmediateMethods}([\text{flag}]) \quad \text{(function)} \\
& \text{UntraceImmediateMethods()} \quad \text{(function)} \\
\end{align*} \]

\text{TraceImmediateMethods} enables tracing for all immediate methods if \( \text{flag} \) is either \text{true}, or not present. \text{UntraceImmediateMethods}, or \text{TraceImmediateMethods} with \( \text{flag} \) equal \text{false} turns tracing off. (There is no facility to trace specific immediate methods.)

Example

\begin{verbatim}
gap> TraceImmediateMethods();
gap> g:= Group((1,2,3), (1,2));;
#I RunImmediateMethods
#I immediate: Size
#I immediate: IsCyclic
#I immediate: IsCommutative
#I immediate: IsTrivial
gap> Size( g );
#I immediate: IsPerfectGroup
#I immediate: IsNonTrivial
#I immediate: Size
\end{verbatim}
This example gives an explanation for the two calls of the “system getter” for \texttt{Size} (30.4.6). Namely, there are immediate methods that access the known size of the group. Note that the group \( g \) was known to be finitely generated already before the size was computed, the calls of the immediate method for \texttt{IsFinitelyGeneratedGroup} (39.15.17) after the call of \texttt{Size} (30.4.6) have other arguments than \( g \).

### 7.4 Info Functions

The \texttt{Info} (7.4.6) mechanism permits operations to display intermediate results or information about the progress of the algorithms. Information is always given according to one or more \textit{info classes}. Each of the info classes defined in the \texttt{GAP} library usually covers a certain range of algorithms, so for example \texttt{InfoLattice} covers all the cyclic extension algorithms for the computation of a subgroup lattice.

Note that not all info classes defined in the \texttt{GAP} library are currently documented. Many \texttt{GAP} packages define additional info classes, which are typically documented in the corresponding package documentation. The function \texttt{ShowUsedInfoClasses} (7.4.5) will show all info classes which \texttt{GAP} considers while executing code.

The amount of information to be displayed by each info class can be separately specified by the user. This is done by selecting a non-negative integer \textit{level} for the info class: no information will be displayed at level 0, and the higher the level, the more information that will be displayed. At creation, an info class has level 0. By default, all built-in \texttt{GAP} info classes have level 0, except for the following info classes, which have level 1:

- \texttt{InfoWarning} (7.4.8),
- \texttt{InfoPackageLoading} (76.2.5),
- \texttt{InfoDebug},
- \texttt{InfoPerformance},
- \texttt{InfoTempDirectories},
- \texttt{InfoPrimeInt}, and
- \texttt{InfoSLP}.
7.4.1 NewInfoClass

▷ NewInfoClass(name) (operation)

creates a new info class with name name.

7.4.2 DeclareInfoClass

▷ DeclareInfoClass(name) (function)

creates a new info class with name name and binds it to the global variable name. The variable must previously be writable, and is made readonly by this function.

7.4.3 SetInfoLevel

▷ SetInfoLevel(infoClass, level) (operation)

Sets the info level for infoClass to the non-negative integer level.

7.4.4 InfoLevel

▷ InfoLevel(infoClass) (operation)

returns the info level of infoClass.

7.4.5 ShowUsedInfoClasses

▷ ShowUsedInfoClasses(infoClass) (function)

Called with argument true, this makes GAP print the info class and level of any executed Info statement. Calling with the argument false stops this printing. Each level of each info class is only printed once. The history of printed info classes and levels is reset whenever true is passed.

Example

```gap
gap> ShowUsedInfoClasses(true);
gap> Intersection(Group((1,3,2,4,5,6)), Group((1,2,3,4,5,6))); #I Would print info with SetInfoLevel(InfoOptions,1)
#I Would print info with SetInfoLevel(InfoBckt,1)
#I Would print info with SetInfoLevel(InfoBckt,3)
#I Would print info with SetInfoLevel(InfoBckt,5)
Group(());
gap> Intersection(Group((1,3,2,4,5,6)), Group((1,2,3,4,5,6))); #I Would print info with SetInfoLevel(InfoOptions,1)
Group(());
```

7.4.6 Info

▷ Info(infoClass, level, info[, moreinfo, ...]) (function)
If the info level of `infoclass` is at least `level`, then the remaining arguments, `info`, and possibly `moreinfo` and so on, are evaluated. (Technically, `Info` is a keyword and not a function.)

By default, the results of these evaluations are viewed, preceded by the string "#I " and followed by a newline.

If the info level of `infoclass` is strictly less than `level`, then the third and subsequent arguments are not evaluated. (The latter can save substantial time when displaying difficult results.)

The behaviour can be customized with `SetInfoHandler` (7.4.7).

Example

```gap
gap> InfoExample:=NewInfoClass("InfoExample");;
gap> Info(InfoExample,1,"one");Info(InfoExample,2,"two");
gap> Info(InfoExample,1,"one");Info(InfoExample,2,"two");
  #I one
  gap> SetInfoLevel(InfoExample,2);
gap> Info(InfoExample,1,"one");Info(InfoExample,2,"two");
  #I one
  #I two
  gap> InfoLevel(InfoExample);
    2
  gap> Info(InfoExample,3,Length(Combinations([1..9999])));
Note that the last `Info` call is executed without problems, since the actual level 2 of `InfoExample` causes `Info` to ignore the last argument, which prevents `Length(Combinations([1..9999]))` from being evaluated; note that an evaluation would be impossible due to memory restrictions.

A set of info classes (called an `info selector`) may be passed to a single `Info` statement. As a shorthand, info classes and selectors may be combined with + rather than `Union` (30.5.3). In this case, the message is triggered if the level of any of the classes is high enough.

Example

```gap
gap> InfoExample:=NewInfoClass("InfoExample");;
gap> SetInfoLevel(InfoExample,0);
gap> Info(InfoExample + InfoWarning, 1, "hello");
  #I hello
  gap> Info(InfoExample + InfoWarning, 2, "hello");
  gap> SetInfoLevel(InfoExample,2);
gap> Info(InfoExample + InfoWarning, 2, "hello");
  #I hello
  gap> InfoLevel(InfoWarning);
    1
```

7.4.7 Customizing `Info` (7.4.6) statements

- `SetInfoHandler(infoclass, handler)`
  (function)
- `SetInfoOutput(infoclass, out)`
  (function)
- `UnbindInfoOutput(infoclass)`
  (function)
- `InfoOutput(infoclass)`
  (function)
- `SetDefaultInfoOutput(out)`
  (function)

Returns: nothing
This allows one to customize what happens in an `Info(infoclass, level, ...)` statement.
In the first function, `handler` must be a function with three arguments `infoclass`, `level`, `list`. Here `list` is the list containing the third argument and any subsequent optional arguments of the `Info` (7.4.6) call.

The default handler is the function `DefaultInfoHandler`. It prints "#I "., then the third and further arguments of the info statement, and finally a "\n".

If the first argument of an `Info` (7.4.6) statement is a sum of `Info` classes, the handler of the first summand is used.

The file or stream to which `Info` (7.4.6) statements for individual `Info` (7.4.6) classes print can be overridden with `SetInfoOutput`, retrieved with `InfoOutput` and reset to the default with `UnbindInfoOutput`. The initial default for all `Info` (7.4.6) classes is the string "*Print*" which means the current output file. The default can be changed with `SetDefaultInfoOutput`. The argument `out` can be a filename or an open stream, the special names "*Print*", "*errout*" and "*stdout*" are also recognized.

For example, `SetDefaultInfoOutput("*errout*")`; would send `Info` (7.4.6) output to standard error, which can be interesting if GAPs output is redirected.

### 7.4.8 InfoWarning

- **InfoWarning**

  is an info class to which general warnings are sent at level 1, which is its default level. More specialised warnings are shown via calls of `Info` (7.4.6) at `InfoWarning` level 2, e.g. information about the autoloading of GAP packages and the initial line matched when displaying an on-line help topic.

### 7.5 Assertions

Assertions are used to find errors in algorithms. They test whether intermediate results conform to required conditions and issue an error if not.

#### 7.5.1 SetAssertionLevel

- **SetAssertionLevel**

  assigns the global assertion level to `lev`. By default it is zero.

#### 7.5.2 AssertionLevel

- **AssertionLevel**

  returns the current assertion level.

#### 7.5.3 Assert

- **Assert**

  (function)
With two arguments, if the global assertion level is at least \( \text{lev} \), condition \( \text{cond} \) is tested and if it does not return \text{true} an error is raised. Thus \text{Assert(lev, cond)} is equivalent to the code

```gap
if AssertionLevel() >= lev and not <cond> then
  Error("Assertion failure");
fi;
```

With the \text{message} argument form of the \text{Assert} statement, if the global assertion level is at least \( \text{lev} \), condition \( \text{cond} \) is tested and if it does not return \text{true} then \text{message} is evaluated and printed.

Assertions are used at various places in the library. Thus turning assertions on can slow code execution significantly.

### 7.6 Timing

#### 7.6.1 Runtimes

\text{Runtimes} returns a record with components bound to integers or \text{fail}. Each integer is the cpu time (processor time) in milliseconds spent by \text{GAP} in a certain status:

- \text{user\_time}
  - cpu time spent with \text{GAP} functions (without child processes).
- \text{system\_time}
  - cpu time spent in system calls, e.g., file access (\text{fail} if not available).
- \text{user\_time\_children}
  - cpu time spent in child processes (\text{fail} if not available).
- \text{system\_time\_children}
  - cpu time spent in system calls by child processes (\text{fail} if not available).

Note that this function is not fully supported on all systems. Only the \text{user\_time} component is (and may on some systems include the system time).

The following example demonstrates tasks which contribute to the different time components:

```gap
gap> Runtimes(); # after startup
rec( user_time := 3980, system_time := 60, user_time_children := 0,
    system_time_children := 0 )
gap> Exec("cat /usr/bin/*|wc"); # child process with a lot of file access
         893799 7551659 200928302
gap> Runtimes();
rec( user_time := 3909, system_time := 60, user_time_children := 1590,
    system_time_children := 600 )
gap> a:=0;;for i in [1..100000000] do a:=a+1; od; # GAP user time
gap> Runtimes();
rec( user_time := 12980, system_time := 70, user_time_children := 1590,
    system_time_children := 600 )
gap> ?blabla # first call of help, a lot of file access
```
Help: no matching entry found

```gap
gap> Runtimes();
rec( user_time := 13500, system_time := 440, user_time_children := 1590,
    system_time_children := 600 )
```

### 7.6.2 Runtime

**Runtime()**

Runtime returns the time spent by GAP in milliseconds as an integer. It is the same as the value of the `user_time` component given by `Runtimes` (7.6.1), as explained above.

See `StringTime` (27.10.9) for a translation from milliseconds into hour/minute format.

### 7.6.3 NanosecondsSinceEpoch

**NanosecondsSinceEpoch()**

NanosecondsSinceEpoch returns the time in nanoseconds that has passed since some fixed, but unspecified time in the past. This function is appropriate for doing wallclock time measurements. The actual resolution depends on the system that GAP is run on. Information about the used timers can be obtained by calling `NanosecondsSinceEpochInfo`, which returns a record containing members `Method`, `Monotonic`, `Reliable` and `Resolution`.

`Method` is a string describing the method used to obtain timer values. This will usually contain the name of the syscall used.

`Monotonic` is a boolean. If it is true, then the values returned by `NanosecondsSinceEpoch` are guaranteed to be strictly monotonically increasing between two calls, if it is false then there is no such guarantee.

`Resolution` is an integer reflecting the resolution of the timer used in nanoseconds.

`Reliable` is a boolean. If it is true then the value `Resolution` is deemed reliable in the sense that it was obtained by querying the operating system, otherwise `Resolution` should be treated as an estimate.

### 7.6.4 time

**time**

In the read-eval-print loop, `time` stores the number of milliseconds the last command took (see also `memory_allocated` (7.7.2) for the number of bytes of memory it allocated).

### 7.6.5 Sleep

**Sleep(time)**

**MicroSleep(time)**

These functions make GAP stop execution for a given period of time. The time to stop is given to `Sleep` in seconds and `MicroSleep` in microseconds.
7.7 Tracking Memory Usage

7.7.1 TotalMemoryAllocated

\[ \text{T} \text{otalMemoryAllocated}() \] (function)

TotalMemoryAllocated returns the total amount of memory in bytes allocated by the GAP memory manager since GAP started.

7.7.2 memory_allocated

\[ \text{memory\_allocated} \] (global variable)

In the read-eval-print loop, memory_allocated (7.7.2) stores the number of bytes of memory allocated by the last completed statement (see also time (7.6.4) for the number of milliseconds it took).

7.8 Profiling

Profiling of code can be used to determine in which parts of a program how much time has been spent and how much memory has been allocated during runtime. GAP has two different methods of profiling. GAP can either profile by function, or line-by-line. Line by line profiling is currently only used for code coverage, while function profiling tracks memory and time usage.

7.8.1 Function Profiling

This section describes how to profiling at the function level. The idea is that

- first one switches on profiling for those GAP functions the performance of which one wants to check,
- then one runs some GAP computations,
- then one looks at the profile information collected during these computations,
- then one runs more computations (perhaps clearing all profile information before, see ClearProfile (7.8.10)),
- and finally one switches off profiling.

For switching on and off profiling, GAP supports entering a list of functions (see ProfileFunctions (7.8.5), UnprofileFunctions (7.8.6)) or a list of operations whose methods shall be (un)profiled (ProfileMethods (7.8.7), UnprofileMethods (7.8.8)), and DisplayProfile (7.8.9) can be used to show profile information about functions in a given list.

Besides these functions, ProfileGlobalFunctions (7.8.2), ProfileOperations (7.8.3), and ProfileOperationsAndMethods (7.8.4) can be used for switching on or off profiling for all global functions, operations, and operations together with all their methods, respectively, and for showing profile information about these functions.

Note that GAP will perform more slowly when profiling than when not.
7.8.2 ProfileGlobalFunctions

Called with argument true, ProfileGlobalFunctions starts profiling of all functions that have been declared via DeclareGlobalFunction (7.9.10.4). Old profile information for all these functions is cleared. A function call with the argument false stops profiling of all these functions. Recorded information is still kept, so you can display it even after turning the profiling off.

When ProfileGlobalFunctions is called without argument, profile information for all global functions is displayed, see DisplayProfile (7.8.9).

7.8.3 ProfileOperations

Called with argument true, ProfileOperations starts profiling of all operations. Old profile information for all operations is cleared. A function call with the argument false stops profiling of all operations. Recorded information is still kept, so you can display it even after turning the profiling off.

When ProfileOperations is called without argument, profile information for all operations is displayed (see DisplayProfile (7.8.9)).

7.8.4 ProfileOperationsAndMethods

Called with argument true, ProfileOperationsAndMethods starts profiling of all operations and their methods. Old profile information for these functions is cleared. A function call with the argument false stops profiling of all operations and their methods. Recorded information is still kept, so you can display it even after turning the profiling off.

When ProfileOperationsAndMethods is called without argument, profile information for all operations and their methods is displayed, see DisplayProfile (7.8.9).

7.8.5 ProfileFunctions

starts profiling for all function in the list funcs. You can use ProfileGlobalFunctions (7.8.2) to turn profiling on for all globally declared functions simultaneously.

7.8.6 UnprofileFunctions

stops profiling for all function in the list funcs. Recorded information is still kept, so you can display it even after turning the profiling off.
7.8.7 ProfileMethods

*ProfileMethods*(ops) (function)

starts profiling of the methods for all operations in the list *ops*.

7.8.8 UnprofileMethods

*UnprofileMethods*(ops) (function)

stops profiling of the methods for all operations in the list *ops*. Recorded information is still kept, so you can display it even after turning the profiling off.

7.8.9 DisplayProfile

*DisplayProfile*([functions, ] [mincount, mintime]) (function)

*GAPInfo.ProfileThreshold* (global variable)

Called without arguments, *DisplayProfile* displays the profile information for profiled operations, methods and functions. If an argument *functions* is given, only profile information for the functions in the list *functions* is shown. If two integer values *mincount, mintime* are given as arguments then the output is restricted to those functions that were called at least *mincount* times or for which the total time spent (see below) was at least *mintime* milliseconds. The defaults for *mincount* and *mintime* are the entries of the list stored in the global variable *GAPInfo.ProfileThreshold*.

The default value of *GAPInfo.ProfileThreshold* is [10000, 30].

Profile information is displayed in a list of lines for all functions (including operations and methods) which are profiled. For each function, “count” gives the number of times the function has been called. “self/ms” gives the time (in milliseconds) spent in the function itself, “chld/ms” the time (in milliseconds) spent in profiled functions called from within this function, “stor/kb” the amount of storage (in kilobytes) allocated by the function itself, “chld/kb” the amount of storage (in kilobytes) allocated by profiled functions called from within this function, and “package” the name of the GAP package to which the function belongs; the entry “GAP” in this column means that the function belongs to the GAP library, the entry “(oprt.)” means that the function is an operation (which may belong to several packages), and an empty entry means that *FilenameFunc* (5.1.4) cannot determine in which file the function is defined.

The list is sorted according to the total time spent in the functions, that is the sum of the values in the columns “self/ms” and “chld/ms”.

At the end of the list, two lines are printed that show the total time used and the total memory allocated by the profiled functions not shown in the list (label OTHER) and by all profiled functions (label TOTAL), respectively.

An interactive variant of *DisplayProfile* is the function *BrowseProfile* (*Browse: BrowseProfile*) that is provided by the GAP package *Browse*.

7.8.10 ClearProfile

*ClearProfile*() (function)

clears all stored profile information.
7.8.11 An Example of Function Profiling

Let us suppose we want to get information about the computation of the conjugacy classes of a certain permutation group. For that, first we create the group, then we start profiling for all global functions and for all operations and their methods, then we compute the conjugacy classes, and then we stop profiling.

```gap
gap> g := PrimitiveGroup( 24, 1 );;
gap> ProfileGlobalFunctions( true );
gap> ProfileOperationsAndMethods( true );
gap> ConjugacyClasses( g );;
gap> ProfileGlobalFunctions( false );
gap> ProfileOperationsAndMethods( false );
```

Now the profile information is available. We can list the information for all profiled functions with DisplayProfile (7.8.9).

```gap
gap> DisplayProfile();
```

<table>
<thead>
<tr>
<th>count</th>
<th>self/ms</th>
<th>chld/ms</th>
<th>stor/kb</th>
<th>chld/kb</th>
<th>package</th>
<th>function</th>
</tr>
</thead>
<tbody>
<tr>
<td>17647</td>
<td>0</td>
<td>0</td>
<td>275</td>
<td>0</td>
<td>GAP</td>
<td>BasePoint</td>
</tr>
<tr>
<td>10230</td>
<td>0</td>
<td>0</td>
<td>226</td>
<td>0</td>
<td>(oprt.)</td>
<td>ShallowCopy</td>
</tr>
<tr>
<td>10139</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PositionSortedOp: for*</td>
<td></td>
</tr>
<tr>
<td>10001</td>
<td>0</td>
<td>0</td>
<td>688</td>
<td>0</td>
<td>UniteSet: for two int*</td>
<td></td>
</tr>
<tr>
<td>10001</td>
<td>8</td>
<td>0</td>
<td>28</td>
<td>688</td>
<td>(oprt.)</td>
<td>UniteSet</td>
</tr>
<tr>
<td>14751</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>=: for two families: *</td>
<td></td>
</tr>
<tr>
<td>10830</td>
<td>8</td>
<td>4</td>
<td>182</td>
<td>276</td>
<td>GAP</td>
<td>Concatenation</td>
</tr>
<tr>
<td>2700</td>
<td>20</td>
<td>12</td>
<td>313</td>
<td>55</td>
<td>GAP</td>
<td>AddRefinement</td>
</tr>
<tr>
<td>2444</td>
<td>28</td>
<td>4</td>
<td>3924</td>
<td>317</td>
<td>GAP</td>
<td>ConjugateStabChain</td>
</tr>
<tr>
<td>4368</td>
<td>0</td>
<td>32</td>
<td>7</td>
<td>714</td>
<td>(oprt.)</td>
<td>Size</td>
</tr>
<tr>
<td>2174</td>
<td>32</td>
<td>4</td>
<td>1030</td>
<td>116</td>
<td>GAP</td>
<td>List</td>
</tr>
<tr>
<td>585</td>
<td>4</td>
<td>32</td>
<td>45</td>
<td>742</td>
<td>GAP</td>
<td>RRefine</td>
</tr>
<tr>
<td>1532</td>
<td>32</td>
<td>8</td>
<td>194</td>
<td>56</td>
<td>GAP</td>
<td>AddGeneratorsExtendSc*</td>
</tr>
<tr>
<td>1221</td>
<td>8</td>
<td>32</td>
<td>349</td>
<td>420</td>
<td>GAP</td>
<td>Partition</td>
</tr>
<tr>
<td>185309</td>
<td>28</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>(oprt.)</td>
<td>Length</td>
</tr>
<tr>
<td>336</td>
<td>4</td>
<td>40</td>
<td>95</td>
<td>817</td>
<td>GAP</td>
<td>ExtendSeriesPermGroup</td>
</tr>
<tr>
<td>4</td>
<td>28</td>
<td>20</td>
<td>488</td>
<td>454</td>
<td>(oprt.)</td>
<td>Sortex</td>
</tr>
<tr>
<td>2798</td>
<td>0</td>
<td>52</td>
<td>54</td>
<td>944</td>
<td>GAP</td>
<td>StabChainForcePoint</td>
</tr>
<tr>
<td>560</td>
<td>4</td>
<td>48</td>
<td>83</td>
<td>628</td>
<td>GAP</td>
<td>StabChainSwap</td>
</tr>
<tr>
<td>432</td>
<td>16</td>
<td>40</td>
<td>259</td>
<td>461</td>
<td>GAP</td>
<td>SubmagmaWithInversesNC</td>
</tr>
<tr>
<td>185553</td>
<td>48</td>
<td>8</td>
<td>915</td>
<td>94</td>
<td>(oprt.)</td>
<td>Add</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>64</td>
<td>0</td>
<td>2023</td>
<td>(oprt.)</td>
<td>CentralizerOp</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>64</td>
<td>0</td>
<td>2023</td>
<td>GAP</td>
<td>CentralizerOp: perm g*</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>64</td>
<td>0</td>
<td>2023</td>
<td>GAP</td>
<td>Centralizer: try to e*</td>
</tr>
<tr>
<td>152</td>
<td>4</td>
<td>64</td>
<td>0</td>
<td>2024</td>
<td>(oprt.)</td>
<td>Centralizer</td>
</tr>
<tr>
<td>1605</td>
<td>0</td>
<td>68</td>
<td>0</td>
<td>2032</td>
<td>(oprt.)</td>
<td>StabilizerOfExternalS*</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>68</td>
<td>0</td>
<td>2024</td>
<td>GAP</td>
<td>Meth(StabilizerOfExte*</td>
</tr>
<tr>
<td>382</td>
<td>0</td>
<td>96</td>
<td>69</td>
<td>1922</td>
<td>GAP</td>
<td>TryPcgsPermGroup</td>
</tr>
<tr>
<td>5130</td>
<td>4</td>
<td>96</td>
<td>309</td>
<td>3165</td>
<td>GAP</td>
<td>ForAll</td>
</tr>
<tr>
<td>7980</td>
<td>24</td>
<td>116</td>
<td>330</td>
<td>6434</td>
<td>GAP</td>
<td>ChangeStabChain</td>
</tr>
<tr>
<td>12076</td>
<td>12</td>
<td>136</td>
<td>351</td>
<td>6478</td>
<td>GAP</td>
<td>ProcessFixpoint</td>
</tr>
<tr>
<td>192</td>
<td>0</td>
<td>148</td>
<td>4</td>
<td>3029</td>
<td>GAP</td>
<td>StabChainMutable: cal*</td>
</tr>
<tr>
<td>2208</td>
<td>4</td>
<td>148</td>
<td>3</td>
<td>3083</td>
<td>(oprt.)</td>
<td>StabChainMutable</td>
</tr>
</tbody>
</table>
We can restrict the list to global functions with `ProfileGlobalFunctions(7.8.2)`.

```
gap> ProfileGlobalFunctions();
    count    self/ms  chld/ms  stor/kb  chld/kb  package function
    17647      0        0       275      0    GAP BasePoint
    10830      8        4       182      276    GAP Concatenation
    2700     20       12       313      55    GAP AddRefinement
    2444     28       4        394      317    GAP ConjugateStabChain
    2174     32       4       1030     116    GAP List
     586       4       32        45     742    GAP RRefine
    1532     32       8       194      56    GAP AddGeneratorsExtendSc*
    1221       8       32       349     420    GAP Partition
     336       4       40        95     817    GAP ExtendSeriesPermGroup
    2798       0      52        54     944    GAP StabChainForcePoint
     560       4       48        83     628    GAP StabChainSwap
    432      16      40        259     461    GAP SubmagmaWithInversesNC
     382       0      96        69    1922    GAP TryPcgsPermGroup
     510       4       96        309    3165    GAP ForAll
    7980     24      116        330    6434    GAP ChangeStabChain
    12076     12      136        351    6478    GAP ProcessFixpoint
     216      36      464        334    12546   GAP PartitionBacktrack
    1479     12      668        666    18474   GAP RepOpElmTuplesPermGro*
    126      0       728        13    19233   GAP ConjugacyClassesTry
     160      0       736        0    19671   GAP ConjugacyClassesByRan*
    13400   1164      0        0       0    GAP ConjugacyClasses: per*
     484      12052   0        0       0    GAP Position
  20488     23319   0        0       0    TOTAL
```

We can restrict the list to operations with `ProfileOperations(7.8.3)`.

```
gap> ProfileOperations();
    count    self/ms  chld/ms  stor/kb  chld/kb  package function
    10230      0        0       226      0    (oprt.) ShallowCopy
    10001      8        0       28       688    (oprt.) UniteSet
     4368      0       32        7      714    (oprt.) Size
   185309      28      12        0       0    (oprt.) Length
      4      28       20       488      454    (oprt.) Sortex
   1855553      48       8       915       94    (oprt.) Add
       26      0       64       2023    (oprt.) CentralizerOp
```
We can restrict the list to operations and their methods with `ProfileOperationsAndMethods(7.8.4)`.

```gap
gap> ProfileOperationsAndMethods();

<table>
<thead>
<tr>
<th>count</th>
<th>self/ms</th>
<th>chld/ms</th>
<th>stor/kb</th>
<th>chld/kb</th>
<th>package</th>
<th>function</th>
</tr>
</thead>
<tbody>
<tr>
<td>10230</td>
<td>0</td>
<td>0</td>
<td>226</td>
<td>0</td>
<td>(oprt.)</td>
<td>ShallowCopy</td>
</tr>
<tr>
<td>10139</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Position</td>
<td>SortedOp: for*</td>
</tr>
<tr>
<td>10001</td>
<td>0</td>
<td>688</td>
<td>0</td>
<td>0</td>
<td>UniteSet</td>
<td>for two int*</td>
</tr>
<tr>
<td>10001</td>
<td>8</td>
<td>28</td>
<td>688</td>
<td>0</td>
<td>(oprt.)</td>
<td>UniteSet</td>
</tr>
<tr>
<td>4368</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(oprt.)</td>
<td>Size</td>
</tr>
<tr>
<td>185309</td>
<td>28</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>(oprt.)</td>
<td>Length</td>
</tr>
<tr>
<td>185553</td>
<td>48</td>
<td>8</td>
<td>915</td>
<td>94</td>
<td>(oprt.)</td>
<td>Add</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>64</td>
<td>0</td>
<td>2023</td>
<td>(oprt.)</td>
<td>CentralizerOp</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>64</td>
<td>0</td>
<td>2023</td>
<td>GAP</td>
<td>CentralizerOp: perm g*</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>64</td>
<td>0</td>
<td>2023</td>
<td>GAP</td>
<td>Centralizer: try to e*</td>
</tr>
<tr>
<td>152</td>
<td>4</td>
<td>64</td>
<td>0</td>
<td>2024</td>
<td>(oprt.)</td>
<td>CentralizerOp</td>
</tr>
<tr>
<td>1605</td>
<td>0</td>
<td>68</td>
<td>0</td>
<td>2032</td>
<td>(oprt.)</td>
<td>StabilizerOfExternalS*</td>
</tr>
<tr>
<td>2208</td>
<td>4</td>
<td>148</td>
<td>3</td>
<td>3083</td>
<td>(oprt.)</td>
<td>StabChainMutable</td>
</tr>
<tr>
<td>217</td>
<td>0</td>
<td>160</td>
<td>0</td>
<td>3177</td>
<td>(oprt.)</td>
<td>StabChainOp</td>
</tr>
<tr>
<td>217</td>
<td>12</td>
<td>148</td>
<td>60</td>
<td>3117</td>
<td>GAP</td>
<td>StabChainOp: group an*</td>
</tr>
<tr>
<td>1453</td>
<td>12</td>
<td>684</td>
<td>56</td>
<td>18460</td>
<td>GAP</td>
<td>in: perm class rep</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>736</td>
<td>2</td>
<td>19678</td>
<td>(oprt.)</td>
<td>ConjugacyClasses</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>736</td>
<td>0</td>
<td>19675</td>
<td>GAP</td>
<td>ConjugacyClasses: perm*</td>
</tr>
<tr>
<td>13400</td>
<td>1164</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(oprt.)</td>
<td>Position</td>
</tr>
</tbody>
</table>

Finally, we can restrict the list to explicitly given functions with `DisplayProfile(7.8.9)` by entering the list of functions as an argument.

```gap
gap> DisplayProfile( [ StabChainOp, Centralizer ] );

<table>
<thead>
<tr>
<th>count</th>
<th>self/ms</th>
<th>chld/ms</th>
<th>stor/kb</th>
<th>chld/kb</th>
<th>package</th>
<th>function</th>
</tr>
</thead>
<tbody>
<tr>
<td>152</td>
<td>0</td>
<td>64</td>
<td>0</td>
<td>2024</td>
<td>(oprt.)</td>
<td>Centralizer</td>
</tr>
<tr>
<td>217</td>
<td>0</td>
<td>160</td>
<td>0</td>
<td>3177</td>
<td>(oprt.)</td>
<td>StabChainOp</td>
</tr>
</tbody>
</table>

OTHER

2048   23319  TOTAL
7.8.12 Line By Line Profiling

Line By Line profiling tracks which lines have been executed in a piece of GAP code. Built into GAP are the methods necessary to generate profiles, the resulting profiles can be displayed with the 'profiling' package.

7.8.13 Line by Line profiling example

There are two kinds of profiles GAP can build:

- Coverage: This records which lines of code are executed
- Timing: This records how much time is spent executing each line of code

A timing profile provides more information, but will take longer to generate and parse. A timing profile is generated using the functions ProfileLineByLine (7.8.14) and UnprofileLineByLine (7.8.16), as follows:

Example

```gap
gap> ProfileLineByLine("output.gz");
gap> Size(AlternatingGroup(10)); ; # Execute some GAP code you want to profile
gap> UnprofileLineByLine();
```

For code coverage, use instead the functions CoverageLineByLine (7.8.15) and UncoverageLineByLine (7.8.17). The profiler will only record lines which are read and executed while the profiler is running. If you want to perform code coverage or profile GAP's library, then you can use the GAP command line option '--cover filename.gz', which executes CoverageLineByLine (7.8.15) before GAP starts. Similarly the option '--prof filename.gz' executes ProfileLineByLine (7.8.14) before GAP starts. The profiler is designed for high performance, because of this, there are some limitations which users should be aware of:

- By default the profiler records the wall-clock time which has passed, rather than the CPU time taken (because it is lower overhead), so any time taken writing commands will be charged to the last GAP statement which was executed. Therefore it is better to write a function which starts profiling, executes your code, and then stops profiling.
- If you end the filename with "gz", the resulting file will automatically be compressed. This is highly recommended!
- The profiler can only track GAP code which occurs in a function – this is most obvious when looking at code coverage examples, which will appear to miss lines of code in files not in a function.
- If the current GAP is forked, using the IO_fork function in the IO package, a new profile output file will be created for the new child process, with the process ID of the child attached to the end of the filename.

Profiles are transformed into a human-readable form with 'profiling' package, for example with the 'OutputAnnotatedCodeCoverageFiles' function.
7.8.14 ProfileLineByLine

ProfileLineByLine begins GAP recording profiling data to the file `filename`. This file will get *very* large very quickly. This file is compressed using gzip to reduce its size. `options` is an optional dictionary, which sets various configuration options. These are

- **coverage**
  
  Boolean (defaults to false). If this is enabled, only information about which lines are read and executed is stored. Enabling this is the same as calling `CoverageLineByLine (7.8.15)`. Using this ignores all other options.

- **wallTime**
  
  Boolean (defaults to true). Sets if time should be measured using wall-clock time (true) or CPU time (false). (measuring CPU-time has a higher overhead).

- **recordMem**
  
  Boolean (defaults to false). Instead of recording the CPU time taken by statements, record the total size of all new objects created by each line.

- **resolution**
  
  Integer (defaults to 0). By default profiling will record a trace of all executed code. When `resolution` non-zero, GAP instead samples which piece of code is being executed every `resolution` nanoseconds. Increasing this improves performance and produces smaller traces, at the cost of accuracy. GAP will still accurately record which statements are executed at least once.

7.8.15 CoverageLineByLine

CoverageLineByLine begins GAP recording code coverage to the file `filename`. This is equivalent to calling `ProfileLineByLine (7.8.14)` with `coverage=true`.

7.8.16 UnprofileLineByLine

UnprofileLineByLine() stops profiling which was previously started with `ProfileLineByLine (7.8.14)` or `CoverageLineByLine (7.8.15)`.

7.8.17 UncoverageLineByLine

UncoverageLineByLine() stops profiling which was previously started with `ProfileLineByLine (7.8.14)` or `CoverageLineByLine (7.8.15)`.
7.8.18 ActivateProfileColour

\[ \texttt{ActivateProfileColour(true)} \]

Called with argument \texttt{true}, \texttt{ActivateProfileColour} makes GAP colour functions when printing them to show which lines have been executed while profiling was active via \texttt{ProfileLineByLine (7.8.14)} at any time during this GAP session. Passing \texttt{false} disables this behaviour.

7.8.19 IsLineByLineProfileActive

\[ \texttt{IsLineByLineProfileActive()} \]

\texttt{IsLineByLineProfileActive} returns if line-by-line profiling is currently activated.

7.8.20 DisplayCacheStats

\[ \texttt{DisplayCacheStats()} \]

displays statistics about the different caches used by the method selection.

7.8.21 ClearCacheStats

\[ \texttt{ClearCacheStats()} \]

clears all statistics about the different caches used by the method selection.

7.9 Information about the version used

The global variable \texttt{GAPInfo.Version} (see \texttt{GAPInfo (3.5.1)}) contains the version number of the version of GAP. Its value can be checked other version number using \texttt{CompareVersionNumbers (76.3.9)}.

To produce sample citations for the used version of GAP or for a package available in this GAP installation, use \texttt{Cite (76.3.17)}.

If you wish to report a problem to GAP Support or GAP Forum, it may be useful to not only report the version used, but also to include the GAP banner displays the information about the architecture for which the GAP binary is built, used libraries and loaded packages.

7.10 Test Files

Test files are used to check that GAP produces correct results in certain computations. A selection of test files for the library can be found in the \texttt{tst} directory of the GAP distribution.

7.10.1 Starting and stopping test

\[ \texttt{START_TEST(id)} \]
\[ \texttt{STOP_TEST(file)} \]
START_TEST (7.10.1) and STOP_TEST (7.10.1) may be optionally used in files that are read via Test (7.10.2). If used, START_TEST (7.10.1) reinitialize the caches and the global random number generator, in order to be independent of the reading order of several test files. Furthermore, the assertion level (see Assert (7.5.3)) is set to 2 (if it was lower before) by START_TEST (7.10.1) and set back to the previous value in the subsequent STOP_TEST (7.10.1) call.

To use these options, a test file should be started with a line

```gap
Example
gap> START_TEST( "arbitrary identifier string" );
```

(Note that the gap> prompt is part of the line!) and should be finished with a line

```gap
Example
gap> STOP_TEST( "filename" );
```

Here the string "filename" should give the name of the test file.

Note that the functions in tst/testutil.g temporarily replace STOP_TEST (7.10.1) before they call Test (7.10.2).

If you want to run a quick test of your GAP installation (though this is not required), you can read in a test script that exercises some GAP's capabilities.

```gap
Example
gap> Read( Filename( DirectoriesLibrary( "tst" ), "testinstall.g" ) );
```

If you want to run a more advanced check (this is not required and make take up to an hour), you can read teststandard.g which is an extended test script performing all tests from the tst directory.

```gap
Example
gap> Read( Filename( DirectoriesLibrary( "tst" ), "teststandard.g" ) );
```

### 7.10.2 Test

#### Test (fname[, optrec])

**Returns:** true or false.

The argument fname must be the name of a file or an open input stream. The content of this file or stream should contain GAP input and output. The function Test runs the input lines, compares the actual output with the output stored in fname and reports differences. With an optional record as argument optrec details of this process can be adjusted. Note that the rewriteToFile option is especially useful for generating test files.

More precisely, the content of fname must have the following format.

Lines starting with "gap> " are considered as GAP input, they can be followed by lines starting with
"> " if the input is continued over several lines.

To allow for comments in `fname` the following lines are ignored by default: lines at the beginning of `fname` that start with "#" or are empty, and one empty line together with one or more lines starting with "#".

All other lines are considered as GAP output from the preceding GAP input.

Lines which begin "#@" define special configuration options for tests. The `#@local` and `#@exec` options can only be used before any GAP input, and the other commands can only be used between individual tests (just before a line starting `gap>`, or at end of the file). Currently defined options are:

`#@local identifierlist`

Run all the tests in the input as if it is in a function with local variable list `identifierlist`, which is a comma-separated list of identifiers. Multiple `#@local` lines may be used.

`#@exec gapcode`

Execute the code `gapcode` before any test in the input is run. This allows defining global variables when using `#@local`.

`#@if EXPR ... [#@else] ... #@fi`

A `#@if` allows to conditionally skip parts of the test input depending on the value of a boolean expression. The exact behavior is done as follows:

If the GAP expression `EXPR` evaluates to `true`, then the lines after the `#@if` are used until either a `#@else` or `#@fi` is reached. If a `#@else` is present then the code after the `#@else` is used if and only if `EXPR` evaluated to `false`. Finally, once `#@endif` is reached, evaluation continues normally.

By default the actual GAP output is compared exactly with the stored output, and if these are different some information about the differences is printed.

If any differences are found then `Test` returns `false`, otherwise `true`.

If the optional argument `optrec` is given it must be a record. The following components of `optrec` are recognized and can change the default behaviour of `Test`:

`ignoreComments`

If set to `false` then no lines in `fname` are ignored as explained above (default is `true`).

`width`

The screen width used for the new output (default is 80).

`compareFunction`

This must be a function that gets two strings as input, the newly generated and the stored output of some GAP input. The function must return `true` or `false`, indicating if the strings should be considered equivalent or not. By default `\( \neq (31.11.1) \)` is used.

Two strings are recognized as abbreviations in this component: "uptowhitespace" checks if the two strings become equal after removing all white space. And "uptonl" compares the string up to trailing newline characters.

`reportDiff`

A function that gets six arguments and reports a difference in the output: the GAP input, the expected GAP output, the newly generated output, the name of tested file, the line number of the input, the time to run the input. (The default is demonstrated in the example below.)
rewriteToFile
If this is bound to a string it is considered as a file name and that file is written with the same
input and comment lines as \texttt{fname} but the output substituted by the newly generated version;
if it is bound to \texttt{true}, then this is treated as if it was bound to \texttt{fname} (default is \texttt{false}). This
is especially useful for generating test files because it ensures that the test files are formatted
exactly as \texttt{Test} expects them to be.

writeTimings
If this is bound to a string it is considered as a file name, that file is written and contains timing
information for each input in \texttt{fname}.

compareTimings
If this is bound to a string it is considered as name of a file to which timing information was
stored via \texttt{writeTimings} in a previous call. The new timings are compared to the stored ones.
By default only commands which take more than a threshold of 100 milliseconds are consid-
ered, and only differences of more than 20\% are considered significant. These defaults can be
overwritten by assigning a list \texttt{[timingfile, threshold, percentage]} to this component.
(The default of \texttt{compareTimings} is \texttt{false}.)

reportTimeDiff
This component can be used to overwrite the default function to display timing differences. It
must be a function with 5 arguments: \texttt{GAP} input, name of test file, line number, stored time,
new time.

ignoreSTOP_TEST
By default set to \texttt{true}, in that case the output of \texttt{GAP} input starting with "STOP_TEST" is not
checked.

showProgress
If this is \texttt{true} then \texttt{GAP} prints position information and the input line before it is processed;
if set to "some", then \texttt{GAP} shows the current line number of the test being processed; if set to
\texttt{false}, no progress updates are displayed (default is "some" if \texttt{GAP}'s output goes to a terminal,
otherwise \texttt{false}).

subsWindowsLineBreaks
If this is \texttt{true} then \texttt{GAP} substitutes DOS/Windows style line breaks "\r\n" by UNIX style line
breaks "\n" after reading the test file. (default is \texttt{true}).

returnNumFailures
If this is \texttt{true} then \texttt{GAP} returns the number of input lines of the test file which had differences
in their output, instead of returning \texttt{true} or \texttt{false}.

--- Example ---
\begin{verbatim}
gap> tnam := Filename(DirectoriesLibrary(), "../doc/ref/demo.tst");;
gap> mask := function(str) return Concatenation("| ",
> JoinStringsWithSeparator(SplitString(str, "\n", ""), "\n| "),
> "\n"); end;;
gap> Print(mask(StringFile(tnam))); 
| # this is a demo file for the 'Test' function
| #
| gap> g := Group((1,2), (1,2,3));
\end{verbatim}
Group([ (1,2), (1,2,3) ])
#
# another comment following an empty line
# the following fails:
gap> a := 13+29;
41
gap> ss := InputTextString(StringFile(tnam));;
gap> Test(ss);
#
# the following fails:
gap> a := 13+29;
# Expected output:
41
# But found:
42
false
gap> RewindStream(ss);
true
gap> dtmp := DirectoryTemporary();;
gap> ftmp := Filename(dtmp,"demo.tst");;
gap> Test(ss, rec(reportDiff := Ignore, rewriteToFile := ftmp));
false
gap> Test(ftmp);
true
gap> Print(mask(StringFile(ftmp)));  
# this is a demo file for the 'Test' function
#
gap> g := Group((1,2), (1,2,3));
gap> Group([ (1,2), (1,2,3) ])
#
# another comment following an empty line
# the following fails:
gap> a := 13+29;
42
false

7.10.3 TestDirectory

TestDirectory(inlist [, optrec])

Returns: true or false.

The argument inlist must be either a single filename or directory name, or a list of filenames and directories. The function TestDirectory will take create a list of files to be tested by taking any files in inlist, and recursively searching any directories in inlist for files ending in .tst. Each of these files is then run through Test (7.10.2), and the results printed, and true returned if all tests passed.

If the optional argument optrec is given it must be a record. Note that the rewriteToFile option is especially useful for generating test files. The following components of optrec are recognized and can change the default behaviour of TestDirectory:

testOptions

A record which will be passed on as the second argument of Test (7.10.2) if present.
earlyStop
If true, stop as soon as any Test (7.10.2) fails (default to false).

showProgress
Print information about how tests are progressing (default to "some" if GAP’s output goes to a terminal, otherwise false).

suppressStatusMessage
Suppress displaying status messages #I Errors detected while testing and #I No errors detected while testing after the test (default to false).

rewriteToFile
If true, then rewrite each test file to disc, with the output substituted by the results of running the test (default to false). This is especially useful for generating test files because it ensures that the test files are formatted exactly as Test (7.10.2) expects them to be.

exclude
A list of file and directory names which will be excluded from testing (default to []).

exitGAP
Rather than returning true or false, exit GAP with the return value of GAP set to success or fail, depending on if all tests passed (default to false).

See also TestPackage (76.3.5) for the information on running standard tests for GAP packages.

7.11 Debugging Recursion
The GAP interpreter monitors the level of nesting of GAP functions during execution. By default, whenever this nesting reaches a multiple of 5000, GAP enters a break loop (6.4) allowing you to terminate the calculation, or enter RETURN; to continue it.

```
Example

gap> dive:= function(depth) if depth>1 then dive(depth-1); fi; return; end;
  function( depth ) ... end
gap> dive(100);
gap> OnBreak:= function() Where(1); end; # shorter traceback
  function( ) ... end
gap> dive(6000);
  recursion depth trap (5000)
at
dive( depth - 1 );
called from
dive( depth - 1 ); called from
...
Entering break read-eval-print loop ...
you can ’quit;’ to quit to outer loop, or
you may ’return;’ to continue
brk> return;
gap> dive(11000);
  recursion depth trap (5000)
at
dive( depth - 1 );
```
called from
dive( depth - 1 ); called from
...
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you may 'return;' to continue
brk> return;
recursion depth trap (10000)
at
dive( depth - 1 );
called from
dive( depth - 1 ); called from
...
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you may 'return;' to continue
brk> return;
gap>

This behaviour can be controlled using the following procedures.

7.11.1 SetRecursionTrapInterval

SetRecursionTrapInterval(interval)

GetRecursionDepth()    (function)

GetRecursionDepth returns the nesting level of the GAP interpreter. This is reset to 0 every time the break loop is entered. SetRecursionTrapInterval sets the depth of the stack at which GAP will enter the Break loop. interval must be a non-negative small integer (between 0 and $2^{28}$). An interval of 0 suppresses the monitoring of recursion altogether. In this case excessive recursion may cause GAP to crash.

Example

gap> GetRecursionDepth();
0
gap> dive := function(depth)
  > if depth>1 then
  >    dive(depth-1);
  > else
  >    Print("Depth ", GetRecursionDepth());
  > fi;
  > end;;
gap> SetRecursionTrapInterval(1000);
gap> dive(100);
Depth 100
gap> dive(2500);
recursion depth trap (10000)
at
dive( depth - 1 );
called from
dive( depth - 1 ); called from
...
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you may 'return;' to continue
> return;
recursion depth trap (2000)
at
dive( depth - 1 );
called from
dive( depth - 1 ); called from
...
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you may 'return;' to continue
> GetRecursionDepth();
0
> return;
> SetRecursionTrapInterval(-1);
SetRecursionTrapInterval( <interval> ): <interval> must be a non-negative small\n1 integer
not in any function
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you can replace <interval> via 'return <interval>;'; to continue
> return 0;
> dive(20000);
Depth 20000
> dive(2000000);
Segmentation fault

7.12 Global Memory Information

The GAP environment provides automatic memory management, so that the programmer does not need to concern themselves with allocating space for objects, or recovering space when objects are no longer needed. The component of the kernel which provides this is called GASMAN (GAP Storage MANager). Messages reporting garbage collections performed by GASMAN can be switched on by the -g command line option (see section 3.1). There are also some facilities to access information from GASMAN from GAP programs.

7.12.1 GasmanStatistics

GasmanStatistics returns a record containing some information from the garbage collection mechanism. The record may contain up to four components: full, partial, npartial, and nfull.

The full component will be present if a full garbage collection has taken place since GAP started. It contains information about the most recent full garbage collection. It is a record, with eight components: livebags contains the number of bags which survived the garbage collection; livekb contains the total number of kilobytes occupied by those bags; deadbags contains the total number of bags which were reclaimed by that garbage collection and all the partial garbage collections preceding it,
since the previous full garbage collection; \texttt{deadkb} contains the total number of kilobytes occupied by those bags; \texttt{freekb} reports the total number of kilobytes available in the GAP workspace for new objects; \texttt{totalkb} reports the actual size of the workspace; \texttt{time} reports the CPU time in milliseconds spent on the last garbage collection and \texttt{cumulative} the total CPU time in milliseconds spent on that type of garbage collection since GAP started.

These figures should be viewed with some caution. They are stored internally in fixed length integer formats, and \texttt{deadkb} and \texttt{deadbags} are liable to overflow if there are many partial collections before a full collection. Also, note that \texttt{livekb} and \texttt{freekb} will not usually add up to \texttt{totalkb}. The difference is essentially the space overhead of the memory management system.

The \texttt{partial} component will be present if there has been a partial garbage collection since the last full one. It is also a record with the same six components as \texttt{full}. In this case \texttt{deadbags} and \texttt{deadkb} refer only to the number and total size of the garbage bags reclaimed in this partial garbage collection and \texttt{livebags} and \texttt{livekb} only to the numbers and total size of the young bags that were considered for garbage collection, and survived.

The \texttt{npartial} and \texttt{nfull} components will contain the number of full and partial garbage collections performed since GAP started.

### 7.12.2 GasmanMessageStatus

- \texttt{GasmanMessageStatus()} (function)
- \texttt{SetGasmanMessageStatus(stat)} (function)

\texttt{GasmanMessageStatus} returns one of the strings "none", "full", or "all", depending on whether the garbage collector is currently set to print messages on no collections, full collections only, or all collections, respectively.

Calling \texttt{SetGasmanMessageStatus} with the argument \texttt{stat}, which should be one of the three strings mentioned above, sets the garbage collector messaging level.

### 7.12.3 GasmanLimits

- \texttt{GasmanLimits()} (function)

\texttt{GasmanLimits} returns a record with three components: \texttt{min} is the minimum workspace size as set by the \texttt{-m} command line option in kilobytes. The workspace size will never be reduced below this by the garbage collector. \texttt{max} is the maximum workspace size, as set by the \texttt{-o} command line option, also in kilobytes. If the workspace would need to grow past this point, GAP will enter a break loop to warn the user. A value of 0 indicates no limit. \texttt{kill} is the absolute maximum, set by the \texttt{-K} command line option. The workspace will never be allowed to grow past this limit.
Chapter 8

Options Stack

GAP supports a global options system. This is intended as a way for the user to provide guidance to various algorithms that might be used in a computation. Such guidance should not change mathematically the specification of the computation to be performed, although it may change the algorithm used. A typical example is the selection of a strategy for the Todd-Coxeter coset enumeration procedure. An example of something not suited to the options mechanism is the imposition of exponent laws in the $p$-Quotient algorithm.

The basis of this system is a global stack of records. All the entries of each record are thought of as options settings, and the effective setting of an option is given by the topmost record in which the relevant field is bound.

The reason for the choice of a stack is the intended pattern of use:

```
PushOptions( rec( stuff ) );
DoSomething( args );
PopOptions();
```

This can be abbreviated, to `DoSomething( args : stuff );` with a small additional abbreviation of `stuff` permitted. See 4.11.2 for details. The full form can be used where the same options are to run across several calls, or where the `DoSomething` procedure is actually an infix operator, or other function with special syntax.

An alternative to this system is the use of additional optional arguments in procedure calls. This is not felt to be sufficient because many procedure calls might cause, for example, a coset enumeration and each would need to make provision for the possibility of extra arguments. In this system the options are pushed when the user-level procedure is called, and remain in effect (unless altered) for all procedures called by it.

Note that in some places in the system optional records containing options which are valid only for the immediate function or method call are in fact used.

8.1 Functions Dealing with the Options Stack

8.1.1 PushOptions

```
▷ PushOptions(options, record)  (function)
```

This function pushes a record of options onto the global option stack. Note that `PushOptions( rec( opt := fail ) )` has the effect of resetting the option `opt`, since an option that has never been
set has the value `fail` returned by `ValueOption` (8.1.5).

Note that there is no check for misspelt or undefined options.

### 8.1.2 PopOptions

惇 `PopOptions()`

This function removes the top-most options record from the options stack if there is one.

### 8.1.3 ResetOptionsStack

惇 `ResetOptionsStack()`

unbinds (i.e. removes) all the options records from the options stack.

*Note*: `ResetOptionsStack` should not be used within a function. Its intended use is to clean up the options stack in the event that the user has `quit` from a `break` loop, so leaving a stack of no-longer-needed options (see 6.4.1).

### 8.1.4 OnQuit

惇 `OnQuit()`

called when a user selects to `quit`; a `break` loop entered via execution of `Error` (6.6.1). As GAP starts up, `OnQuit` is defined to do nothing, in case an error is encountered during GAP start-up. Later in the loading process we redefine `OnQuit` to do a variant of `ResetOptionsStack` (8.1.3) to ensure the options stack is empty after a user quits an `Error` (6.6.1)-induced break loop. (`OnQuit` differs from `ResetOptionsStack` (8.1.3) in that it warns when it does something rather than the other way round.) Currently, `OnQuit` is not advertised, since exception handling may make it obsolete.

### 8.1.5 ValueOption

惇 `ValueOption(opt)`

This function is a method for accessing the options stack without changing it; `opt` should be the name of an option, i.e. a string. A function which makes decisions that might be affected by options should examine the result of `ValueOption`. If `opt` is currently not set then `fail` is returned.

### 8.1.6 DisplayOptionsStack

惇 `DisplayOptionsStack()`

This function prints a human-readable display of the complete options stack.

### 8.1.7 InfoOptions

惇 `InfoOptions` (info class)
This info class can be used to enable messages about options being changed (level 1) or accessed (level 2).

### 8.2 Options Stack – an Example

The example below shows simple manipulation of the Options Stack, first using `PushOptions` (8.1.1) and `PopOptions` (8.1.2) and then using the special function calling syntax.

```gap
gap> foo := function()
>     Print("myopt1 = ", ValueOption("myopt1"),
>             " myopt2 = ",ValueOption("myopt2"),"\n");
> end;
function( ) ... end
gap> foo();
myopt1 = fail myopt2 = fail
gap> PushOptions(rec(myopt1 := 17));
gap> foo();
myopt1 = 17 myopt2 = fail
gap> DisplayOptionsStack();
[ rec(
    myopt1 := 17 ) ]
gap> PopOptions();
gap> foo();
myopt1 = fail myopt2 = fail
gap> foo( : myopt1, myopt2 := [Z(3),"aardvark"]);
myopt1 = true myopt2 = [ Z(3), "aardvark" ]
gap> DisplayOptionsStack();
[ ]
gap>
```
Chapter 9

Files and Filenames

Files are identified by filenames, which are represented in GAP as strings. Filenames can be created directly by the user or a program, but of course this is operating system dependent.

Filenames for some files can be constructed in a system independent way using the following functions. This is done by first getting a directory object for the directory the file shall reside in, and then constructing the filename. However, it is sometimes necessary to construct filenames of files in subdirectories relative to a given directory object. In this case the directory separator is always / even under DOS or MacOS.

Section 9.3 describes how to construct directory objects for the common GAP and system directories. Using the command Filename (9.4.1) it is possible to construct a filename pointing to a file in these directories. There are also functions to test for accessibility of files, see 9.6.

9.1 Portability

For portability filenames and directory names should be restricted to at most 8 alphanumerical characters optionally followed by a dot . and between 1 and 3 alphanumerical characters. Upper case letters should be avoided because some operating systems do not make any distinction between case, so that Name, Name and name all refer to the same file whereas some operating systems are case sensitive. To avoid problems only lower case characters should be used.

Another function which is system-dependent is LastSystemError (9.1.1).

9.1.1 LastSystemError

LastSystemError() (function)

LastSystemError returns a record describing the last system error that has occurred. This record contains at least the component message which is a string. This message is, however, highly operating system dependent and should only be used as an informational message for the user.

9.2 GAP Root Directories

When GAP is started it determines a list of directories which we call the GAP root directories. In a running GAP session this list can be found in GAPInfo.RootPaths.
The core part of GAP knows which files to read relative to its root directories. For example when GAP wants to read its library file `lib/group.gd`, it appends this path to each path in `GAPInfo.RootPaths` until it finds the path of an existing file. The first file found this way is read.

Furthermore, GAP looks for available packages by examining the subdirectories `pkg/` in each of the directories in `GAPInfo.RootPaths`.

The root directories are specified via one or several of the `-l` paths command line options, see 3.1. Furthermore, by default GAP automatically prepends a user specific GAP root directory to the list; this can be avoided by calling GAP with the `-r` option. The name of this user specific directory depends on your operating system, it can be found in `GAPInfo.UserGapRoot`. This directory can be used to tell GAP about personal preferences, to always load some additional code, to install additional packages, or to overwrite some GAP files. See 3.2 for more information how to do this.

### 9.3 Directories

#### 9.3.1 IsDirectory

```
▷ IsDirectory(obj)
```

*(Category)*

IsDirectory is a category of directories.

#### 9.3.2 Directory

```
▷ Directory(string)
```

*(operation)*

returns a directory object for the string `string`. Directory understands "." for "current directory", that is, the directory in which GAP was started. It also understands absolute paths.

If the variable `GAPInfo.UserHome` is defined (this may depend on the operating system) then `Directory` understands a string with a leading `~` (tilde) character for a path relative to the user’s home directory (but a string beginning with "~other_user" is not interpreted as a path relative to other_user’s home directory, as in a UNIX shell).

Paths are otherwise taken relative to the current directory.

#### 9.3.3 DirectoryTemporary

```
▷ DirectoryTemporary()
```

*(function)*

returns a directory object in the category IsDirectory (9.3.1) for a new temporary directory. This is guaranteed to be newly created and empty immediately after the call to `DirectoryTemporary`. GAP will make a reasonable effort to remove this directory upon termination of the GAP job that created the directory.

If `DirectoryTemporary` is unable to create a new directory, `fail` is returned. In this case `LastSystemError (9.1.1)` can be used to get information about the error.

A warning message is given if more than 1000 temporary directories are created in any GAP session.
9.3.4 DirectoryCurrent

\> DirectoryCurrent()

(function)

returns the directory object for the current directory.

9.3.5 DirectoriesLibrary

\> DirectoriesLibrary(\[name\])

(function)

DirectoriesLibrary returns the directory objects for the GAP library name as a list. name must be one of "lib" (the default), "doc", "tst", and so on.

The string "" is also legal and with this argument DirectoriesLibrary returns the list of GAP root directories. The return value of this call differs from GAPInfo.RootPaths in that the former is a list of directory objects and the latter a list of strings.

The directory name must exist in at least one of the root directories, otherwise fail is returned.

As the files in the GAP root directories (see 9.2) can be distributed into different directories in the filespace a list of directories is returned. In order to find an existing file in a GAP root directory you should pass that list to Filename (9.4.1) as the first argument. In order to create a filename for a new file inside a GAP root directory you should pass the first entry of that list. However, creating files inside the GAP root directory is not recommended, you should use DirectoryTemporary (9.3.3) instead.

9.3.6 DirectoriesSystemPrograms

\> DirectoriesSystemPrograms()

(function)

DirectoriesSystemPrograms returns the directory objects for the list of directories where the system programs reside, as a list. Under UNIX this would usually represent $PATH.

9.3.7 DirectoryContents

\> DirectoryContents(dir)

(function)

This function returns a list of filenames/directory names that reside in the directory dir. The argument dir can either be given as a string indicating the name of the directory or as a directory object (see IsDirectory (9.3.1)). If the specified directory does not exist, fail is returned.

The ordering of the list entries can depend on the operating system.

An interactive way to show the contents of a directory is provided by the function BrowseDirectory (Browse: BrowseDirectory) from the GAP package Browse.

9.3.8 DirectoryDesktop

\> DirectoryDesktop()

(function)

returns a directory object for the users desktop directory as defined on many modern operating systems. The function is intended to provide a cross-platform interface to a directory that is easily accessible by the user. Under Unix systems (including Mac OS X) this will be the Desktop directory.
in the users home directory if it exists, and the users home directory otherwise. Under Windows it will
the users Desktop folder (or the appropriate name under different languages).

### 9.3.9 DirectoryHome

DirectoryHome()  

returns a directory object for the users home directory, defined as a directory in which the user
will typically have full read and write access. The function is intended to provide a cross-platform
interface to a directory that is easily accessible by the user. Under Unix systems (including Mac OS
X) this will be the usual user home directory. Under Windows it will the users My Documents folder
(or the appropriate name under different languages).

### 9.4 File Names

#### 9.4.1 Filename

Filename(dir, name)  

Filename(list-of-dirs, name)  

If the first argument is a directory object dir, Filename returns the (system dependent) filename
as a string for the file with name name in the directory dir. Filename returns the filename regardless
of whether the directory contains a file with name name or not.

If the first argument is a list list-of-dirs (possibly of length 1) of directory objects, then
Filename searches the directories in order, and returns the filename for the file name in the first
directory which contains a file name or fail if no directory contains a file name.

For example, in order to locate the system program date use DirectoriesSystemPrograms
(9.3.6) together with the second form of Filename.

Example

```plaintext
gap> path := DirectoriesSystemPrograms();;
gap> date := Filename( path, "date" );
"/bin/date"
```

In order to locate the library file files.gd use DirectoriesLibrary (9.3.5) together with the
second form of Filename.

Example

```plaintext
gap> path := DirectoriesLibrary();
gap> Filename( path, "files.gd" );
"./lib/files.gd"
```

In order to construct filenames for new files in a temporary directory use DirectoryTemporary
(9.3.3) together with the first form of Filename.

Example

```plaintext
gap> tmpdir := DirectoryTemporary();
gap> Filename( [ tmpdir ], "file.new" );
fail
gap> Filename( tmpdir, "file.new" );
"/var/tmp/tmp.0.021738.0001/file.new"
```
9.5 Special Filenames

The special filename "*stdin*" denotes the standard input, i.e., the stream through which the user enters commands to GAP. The exact behaviour of reading from "*stdin*" is operating system dependent, but usually the following happens. If GAP was started with no input redirection, statements are read from the terminal stream until the user enters the end of file character, which is usually CTRL-D. Note that terminal streams are special, in that they may yield ordinary input after an end of file. Thus when control returns to the main read-eval-print loop the user can continue with GAP. If GAP was started with an input redirection, statements are read from the current position in the input file up to the end of the file. When control returns to the main read eval view loop the input stream will still return end of file, and GAP will terminate.

The special filename "*errin*" denotes the stream connected to the UNIX stderr output. This stream is usually connected to the terminal, even if the standard input was redirected, unless the standard error stream was also redirected, in which case opening of "*errin*" fails.

The special filename "*stdout*" can be used to print to the standard output.

The special filename "*errout*" can be used to print to the standard error output file, which is usually connected to the terminal, even if the standard output was redirected.

9.6 File Access

When the following functions return false one can use LastSystemError (9.1.1) to find out the reason (as provided by the operating system), see the examples.

9.6.1 IsExistingFile

\[ \text{IsExistingFile(filename)} \]

IsExistingFile returns true if a file with the filename filename exists and can be seen by the GAP process. Otherwise false is returned.

Example

\[
\begin{align*}
gap> \text{IsExistingFile( "/bin/date" );} & \quad \text{# file ‘/bin/date’ exists} \\
gap> \text{true} & \\
gap> \text{IsExistingFile( "/bin/date.new" );} & \quad \text{# non existing ‘/bin/date.new’} \\
gap> \text{false} & \\
gap> \text{IsExistingFile( "/bin/date/new" );} & \quad \text{‘/bin/date’ is not a directory} \\
gap> \text{false} & \\
gap> \text{LastSystemError().message;} & \\
\text{"Not a directory"} \\
\end{align*}
\]

9.6.2 IsReadableFile

\[ \text{IsReadableFile(filename)} \]

IsReadableFile returns true if a file with the filename filename exists and the GAP process has read permissions for the file, or false if this is not the case.

Example

\[
\begin{align*}
gap> \text{IsReadableFile( "/bin/date" );} & \quad \text{# file ‘/bin/date’ is readable} \\
gap> \text{true} & \\
\end{align*}
\]
gap> IsReadableFile( "/bin/date.new" ); # non-existing '/bin/date.new'
false
gap> LastSystemError().message;
"No such file or directory"

9.6.3 IsWritableFile

\[\text{IsWritableFile}(\text{filename})\]

IsWritableFile returns true if a file with the filename \textit{filename} exists and the GAP process has write permissions for the file, or false if this is not the case.

Example

\begin{verbatim}
gap> IsWritableFile( "/bin/date" ); # file '/bin/date' is not writable
false
\end{verbatim}

9.6.4 IsExecutableFile

\[\text{IsExecutableFile}(\text{filename})\]

IsExecutableFile returns true if a file with the filename \textit{filename} exists and the GAP process has execute permissions for the file, or false if this is not the case. Note that execute permissions do not imply that it is possible to execute the file, e.g., it may only be executable on a different machine.

Example

\begin{verbatim}
gap> IsExecutableFile( "/bin/date" ); # ... but executable
true
\end{verbatim}

9.6.5 IsDirectoryPath

\[\text{IsDirectoryPath}(\text{filename})\]

IsDirectoryPath returns true if the file with the filename \textit{filename} exists and is a directory, and false otherwise. Note that this function does not check if the GAP process actually has write or execute permissions for the directory. You can use IsWritableFile (9.6.3), resp. IsExecutableFile (9.6.4) to check such permissions.

9.7 File Operations

9.7.1 Read

\[\text{Read}(\text{filename})\]

reads the input from the file with the filename \textit{filename}, which must be given as a string.

Read first opens the file \textit{filename}. If the file does not exist, or if GAP cannot open it, e.g., because of access restrictions, an error is signalled.

Then the contents of the file are read and evaluated, but the results are not printed. The reading and evaluations happens exactly as described for the main loop (see 6.1).
If a statement in the file causes an error a break loop is entered (see 6.4). The input for this break loop is not taken from the file, but from the input connected to the stderr output of GAP. If stderr is not connected to a terminal, no break loop is entered. If this break loop is left with quit (or CTRL-D), GAP exits from the Read command, and from all enclosing Read commands, so that control is normally returned to an interactive prompt. The QUIT statement (see 6.7) can also be used in the break loop to exit GAP immediately.

Note that a statement must not begin in one file and end in another. I.e., eof (end-of-file) is not treated as whitespace, but as a special symbol that must not appear inside any statement.

Note that one file may very well contain a read statement causing another file to be read, before input is again taken from the first file. There is an upper limit of 15 on the number of files that may be open simultaneously.

### 9.7.2 ReadAsFunction

\[ \text{ReadAsFunction(filename)} \]  
(read operation)

reads the file with filename filename as a function and returns this function.

**Example**

Suppose that the file /tmp/example.g contains the following

```
local a;

a := 10;
return a*10;
```

Reading the file as a function will not affect a global variable a.

```
gap> a := 1;
1
gap> ReadAsFunction("/tmp/example.g")();
100
gap> a;
1
```

### 9.7.3 PrintTo and AppendTo

\[ \text{PrintTo(filename[, obj1, ...])} \]  
(function)

\[ \text{AppendTo(filename[, obj1, ...])} \]  
(function)

PrintTo works like Print (6.3.4), except that the arguments obj1, ... (if present) are printed to the file with the name filename instead of the standard output. This file must of course be writable by GAP. Otherwise an error is signalled. Note that PrintTo will overwrite the previous contents of this file if it already existed; in particular, PrintTo with just the filename argument empties that file.

AppendTo works like PrintTo, except that the output does not overwrite the previous contents of the file, but is appended to the file.

There is an upper limit of 15 on the number of output files that may be open simultaneously.

*Note* that one should be careful not to write to a logfile (see LogTo (9.7.4)) with PrintTo or AppendTo.
9.7.4 LogTo

▷ LogTo(filename) (operation)
▷ LogTo() (operation)

Calling LogTo with a string filename causes the subsequent interaction to be logged to the file with the name filename, i.e., everything you see on your terminal will also appear in this file. (LogTo (10.4.5) may also be used to log to a stream.) This file must of course be writable by GAP, otherwise an error is signalled. Note that LogTo will overwrite the previous contents of this file if it already existed.

Called without arguments, LogTo stops logging to a file or stream.

9.7.5 InputLogTo

▷ InputLogTo(filename) (operation)
▷ InputLogTo() (operation)

Calling InputLogTo with a string filename causes the subsequent input to be logged to the file with the name filename, i.e., everything you type on your terminal will also appear in this file. Note that InputLogTo and LogTo (9.7.4) cannot be used at the same time while InputLogTo and OutputLogTo (9.7.6) can. Note that InputLogTo will overwrite the previous contents of this file if it already existed.

Called without arguments, InputLogTo stops logging to a file or stream.

9.7.6 OutputLogTo

▷ OutputLogTo(filename) (operation)
▷ OutputLogTo() (operation)

Calling OutputLogTo with a string filename causes the subsequent output to be logged to the file with the name filename, i.e., everything GAP prints on your terminal will also appear in this file. Note that OutputLogTo and LogTo (9.7.4) cannot be used at the same time while InputLogTo (9.7.5) and OutputLogTo can. Note that OutputLogTo will overwrite the previous contents of this file if it already existed.

Called without arguments, OutputLogTo stops logging to a file or stream.

9.7.7 CrcFile

▷ CrcFile(filename) (function)

CRC (cyclic redundancy check) numbers provide a certain method of doing checksums. They are used by GAP to check whether files have changed.

CrcFile computes a checksum value for the file with filename filename and returns this value as an integer. The function returns fail if a system error occurred, say, for example, if filename does not exist. In this case the function LastSystemError (9.1.1) can be used to get information about the error.
9.7.8 RemoveFile

```plaintext
impl
```
RemoveFile(filename)
```plaintext
```

will remove the file with filename `filename` and returns `true` in case of success. The function returns `false` if a system error occurred, for example, if your permissions do not allow the removal of `filename`. In this case the function `LastSystemError` (9.1.1) can be used to get information about the error.

9.7.9 UserHomeExpand

```plaintext
impl
```
UserHomeExpand(str)
```plaintext
```

If the string `str` starts with a `'~'` character this function returns a new string with the leading `'~'` substituted by the users home directory as stored in `GAPInfo.UserHome`. Otherwise `str` is returned unchanged.

9.7.10 Reread

```plaintext
impl
```
Reread(filename)
```plaintext
```

In general, it is not possible to read the same GAP library file twice, or to read a compiled version after reading a GAP version, because crucial global variables are made read-only (see 4.9) and filters and methods are added to global tables.

A partial solution to this problem is provided by the function `Reread` (and related functions `RereadLib` etc.). `Reread( filename )` sets the global variable `REREADING` to `true`, reads the file named by `filename` and then resets `REREADING`. Various system functions behave differently when `REREADING` is set to `true`. In particular, assignment to read-only global variables is permitted, calls to `NewRepresentation` (13.4.4) and `NewInfoClass` (7.4.1) with parameters identical to those of an existing representation or info class will return the existing object, and methods installed with `InstallMethod` (78.3.1) may sometimes displace existing methods.

This function may not entirely produce the intended results, especially if what has changed is the super-representation of a representation or the requirements of a method. In these cases, it is necessary to restart GAP to read the modified file.

An additional use of `Reread` is to load the compiled version of a file for which the GAP language version had previously been read (or perhaps was included in a saved workspace). See 76.3.11 and 3.3 for more information.

It is not advisable to use `Reread` programmatically. For example, if a file that contains calls to `Reread` is read with `Reread` then `REREADING` may be reset too early.
Chapter 10

Streams

Streams provide flexible access to GAP’s input and output processing. An input stream takes characters from some source and delivers them to GAP which reads them from the stream. When an input stream has delivered all characters it is at end-of-stream. An output stream receives characters from GAP which writes them to the stream, and delivers them to some destination.

A major use of streams is to provide efficient and flexible access to files. Files can be read and written using Read (9.7.1) and AppendTo (9.7.3), however the former only allows a complete file to be read as GAP input and the latter imposes a high time penalty if many small pieces of output are written to a large file. Streams allow input files in other formats to be read and processed, and files to be built up efficiently from small pieces of output. Streams may also be used for other purposes, for example to read from and print to GAP strings, or to read input directly from the user.

Any stream is either a text stream, which translates the end-of-line character (\n) to or from the system’s representation of end-of-line (e.g., new-line under UNIX and carriage-return-new-line under DOS), or a binary stream, which does not translate the end-of-line character. The processing of other unprintable characters by text streams is undefined. Binary streams pass them unchanged.

Whereas it is cheap to append to a stream, streams do consume system resources, and only a limited number can be open at any time, therefore it is necessary to close a stream as soon as possible using CloseStream (10.2.1). If creating a stream failed then LastSystemError (9.1.1) can be used to get information about the failure.

10.1 Categories for Streams and the StreamsFamily

10.1.1 IsStream

\[\text{IsStream}(\text{obj})\] (Category)

Streams are GAP objects and all open streams, input, output, text and binary, lie in this category.

10.1.2 IsClosedStream

\[\text{IsClosedStream}(\text{obj})\] (Category)

When a stream is closed, its type changes to lie in IsClosedStream. This category is used to install methods that trap accesses to closed streams.
10.1.3 IsInputStream

\[\text{IsInputStream}(obj)\]  
(Category)

All input streams lie in this category, and support input operations such as \text{ReadByte} (10.3.3) (see Section 10.3).

10.1.4 IsInputTextStream

\[\text{IsInputTextStream}(obj)\]  
(Category)

All text input streams lie in this category. They translate new-line characters read.

10.1.5 IsInputTextNone

\[\text{IsInputTextNone}(obj)\]  
(Category)

It is convenient to use a category to distinguish dummy streams (see 10.9) from others. Other distinctions are usually made using representations.

10.1.6 IsOutputStream

\[\text{IsOutputStream}(obj)\]  
(Category)

All output streams lie in this category and support basic operations such as \text{WriteByte} (10.4.1) (see Section 10.4).

10.1.7 IsOutputTextStream

\[\text{IsOutputTextStream}(obj)\]  
(Category)

All text output streams lie in this category and translate new-line characters on output.

10.1.8 IsOutputTextNone

\[\text{IsOutputTextNone}(obj)\]  
(Category)

It is convenient to use a category to distinguish dummy streams (see 10.9) from others. Other distinctions are usually made using representations.

10.1.9 StreamsFamily

\[\text{StreamsFamily}\]  
(family)

All streams lie in the StreamsFamily.
10.2 Operations applicable to All Streams

10.2.1 CloseStream

\[ \text{CloseStream}(\text{stream}) \] (operation)

In order to preserve system resources and to flush output streams every stream should be closed as soon as it is no longer used using \text{CloseStream}.

It is an error to try to read characters from or write characters to a closed stream. Closing a stream tells the GAP kernel and/or the operating system kernel that the file is no longer needed. This may be necessary because the GAP kernel and/or the operating system may impose a limit on how many streams may be open simultaneously.

10.2.2 FileDescriptorOfStream

\[ \text{FileDescriptorOfStream}(\text{stream}) \] (operation)

returns the UNIX file descriptor of the underlying file. This is mainly useful for the \text{UNIXSelect} (10.2.3) function call. This is as of now only available on UNIX-like operating systems and only for streams to local processes and local files.

10.2.3 UNIXSelect

\[ \text{UNIXSelect}([\text{inlist, outlist, exclist, timeoutsec, timeoutusec}] \] (function)

makes the UNIX C-library function \text{select} accessible from GAP for streams. The functionality is as described in the man page (see UNIX file descriptors (integers) for streams. They can be obtained via \text{FileDescriptorOfStream} (10.2.2) for streams to local processes and to local files. The argument \text{timeoutsec} is a timeout in seconds as in the \text{struct timeval} on the C level. The argument \text{timeoutusec} is analogously in microseconds. The total timeout is the sum of both. If one of those timeout arguments is not a small integer then no timeout is applicable (\text{fail} is allowed for the timeout arguments).

The return value is the number of streams that are ready, this may be 0 if a timeout was specified. All file descriptors in the three lists that are not yet ready are replaced by \text{fail} in this function. So the lists are changed!

This function is only available if your operating system has \text{select}, which is detected during compilation of GAP.

10.3 Operations for Input Streams

Two operations normally used to read files: \text{Read} (9.7.1) and \text{ReadAsFunction} (9.7.2) can also be used to read GAP input from a stream. The input is immediately parsed and executed. When reading from a stream \text{str}, the GAP kernel generates calls to \text{ReadLine(str)} to supply text to the parser.

Three further operations: \text{.ReadByte} (10.3.3), \text{ReadLine} (10.3.4) and \text{ReadAll} (10.3.5), support reading characters from an input stream without parsing them. This can be used to read data in any format and process it in GAP.
Additional operations for input streams support detection of end of stream, and (for those streams for which it is appropriate) random access to the data.

10.3.1 Read (for streams)

\[
\text{Read(input-text-stream)} \quad \text{(operation)}
\]

reads the input-text-stream as input until end-of-stream occurs. See 9.7 for details.

10.3.2 ReadAsFunction (for streams)

\[
\text{ReadAsFunction(input-text-stream)} \quad \text{(operation)}
\]

reads the input-text-stream as function and returns this function. See 9.7 for details.

```
gap> # a function with local 'a' does not change the global one
gap> a := 1;;
gap> i := InputTextString( "local a; a := 10; return a*10;" );;
gap> ReadAsFunction(i)();
100
gap> a;
1
gap> # reading it via 'Read' does
gap> i := InputTextString( "a := 10;" );;
gap> Read(i);
gap> a;
10
```

10.3.3 ReadByte

\[
\text{ReadByte(input-stream)} \quad \text{(operation)}
\]

ReadByte returns one character (returned as integer) from the input stream input-stream. ReadByte returns fail if there is no character available, in particular if it is at the end of a file.

If input-stream is the input stream of a input/output process, ReadByte may also return fail if no byte is currently available.

ReadByte is the basic operation for input streams. If a ReadByte method is installed for a user-defined type of stream which does not block, then all the other input stream operations will work (although possibly not at peak efficiency).

ReadByte will wait (block) until a byte is available. For instance if the stream is a connection to another process, it will wait for the process to output a byte.

10.3.4 ReadLine

\[
\text{ReadLine(input-stream)} \quad \text{(operation)}
\]

ReadLine returns one line (returned as string with the newline) from the input stream input-stream. ReadLine reads in the input until a newline is read or the end-of-stream is encountered.
If `input-stream` is the input stream of a input/output process, `ReadLine` may also return `fail` or return an incomplete line if the other process has not yet written any more. It will always wait (block) for at least one byte to be available, but will then return as much input as is available, up to a limit of one line.

A default method is supplied for `ReadLine` which simply calls `ReadByte (10.3.3)` repeatedly. This is only safe for streams that cannot block. The kernel uses calls to `ReadLine` to supply input to the parser when reading from a stream.

### 10.3.5 `ReadAll`

\[ \texttt{ReadAll(input-stream[, limit])} \]

`ReadAll` returns all characters as string from the input stream `stream-in`. It waits (blocks) until at least one character is available from the stream, or until there is evidence that no characters will ever be available again. This last indicates that the stream is at end-of-stream. Otherwise, it reads as much input as it can from the stream without blocking further and returns it to the user. If the stream is already at end of file, so that no bytes are available, `fail` is returned. In the case of a file stream connected to a normal file (not a pseudo-tty or named pipe or similar), all the bytes should be immediately available and this function will read the remainder of the file.

With a second argument, at most `limit` bytes will be returned. Depending on the stream a bounded number of additional bytes may have been read into an internal buffer.

A default method is supplied for `ReadAll` which simply calls `ReadLine (10.3.4)` repeatedly. This is only really safe for streams which cannot block. Other streams should install a method for `ReadAll`:

```
Example

gap> i := InputTextString( "iHallo
You
i" );;

gap> ReadByte(i);
49
  'i'

gap> ReadLine(i);
  "Hallo\n"

gap> ReadLine(i);
  "You\n"

gap> ReadLine(i);
  "i"

gap> ReadLine(i);
  fail

gap> ReadAll(i);
  ""

  gap> RewindStream(i);;

gap> ReadAll(i);
  "iHallo\nYou\ni"
```

### 10.3.6 `IsEndOfStream`

\[ \texttt{IsEndOfStream(input-stream)} \]

`IsEndOfStream` returns `true` if the input stream is at `end-of-stream`, and `false` otherwise. Note that `IsEndOfStream` might return `false` even if the next `ReadByte (10.3.3)` fails.
10.3.7 PositionStream

\[ \text{PositionStream}(\text{input-stream}) \]

Some input streams, such as string streams and file streams attached to disk files, support a form of random access by way of the operations \text{PositionStream}, \text{SeekPositionStream} (10.3.9) and \text{RewindStream} (10.3.8). \text{PositionStream} returns a non-negative integer denoting the current position in the stream (usually the number of characters before the next one to be read).

If this is not possible, for example for an input stream attached to standard input (normally the keyboard), then \text{fail} is returned.

10.3.8 RewindStream

\[ \text{RewindStream}(\text{input-stream}) \]

\text{RewindStream} attempts to return an input stream to its starting condition, so that all the same characters can be read again. It returns \text{true} if the rewind succeeds and \text{fail} otherwise.

A default method implements \text{RewindStream} using \text{SeekPositionStream} (10.3.9).

10.3.9 SeekPositionStream

\[ \text{SeekPositionStream}(\text{input-stream, pos}) \]

\text{SeekPositionStream} attempts to rewind or wind forward an input stream to the specified position. This is not possible for all streams. It returns \text{true} if the seek is successful and \text{fail} otherwise.

10.4 Operations for Output Streams

10.4.1 WriteByte

\[ \text{WriteByte}(\text{output-stream, byte}) \]

writes the next character (given as \text{integer}) to the output stream \text{output-stream}. The function returns \text{true} if the write succeeds and \text{fail} otherwise.

\text{WriteByte} is the basic operation for output streams. If a \text{WriteByte} method is installed for a user-defined type of stream, then all the other output stream operations will work (although possibly not at peak efficiency).

10.4.2 WriteLine

\[ \text{WriteLine}(\text{output-stream, string}) \]

appends \text{string} to \text{output-stream}. A final newline is written. The function returns \text{true} if the write succeeds and \text{fail} otherwise.

A default method is installed which implements \text{WriteLine} by repeated calls to \text{WriteByte} (10.4.1).
10.4.3 WriteAll

\[ \text{WriteAll(output-stream, string)} \]

appends \text{string} to \text{output-stream}. No final newline is written. The function returns \text{true} if the write succeeds and \text{fail} otherwise. It will block as long as necessary for the write operation to complete (for example for a child process to clear its input buffer).

A default method is installed which implements \text{WriteAll} by repeated calls to \text{WriteByte} (10.4.1).

When printing or appending to a stream (using \text{PrintTo} (9.7.3), or \text{AppendTo} (9.7.3) or when logging to a stream), the kernel generates a call to \text{WriteAll} for each line output.

Example

\[
\begin{align*}
gap> \text{str := ""}; \ a := \text{OutputTextString(str,true)};; \\
gap> \text{WriteByte(a,INT\_CHAR('H'))}; \\
gap> \text{true} \\
gap> \text{WriteLine(a,"allo")}; \\
gap> \text{true} \\
gap> \text{WriteAll(a,"You\n")}; \\
gap> \text{true} \\
gap> \text{CloseStream(a)}; \\
gap> \text{Print(str)}; \\
\text{Hallo} \\
\text{You}
\end{align*}
\]

10.4.4 PrintTo and AppendTo (for streams)

\[ \text{PrintTo(output-stream, arg1, ...)} \] (function)
\[ \text{AppendTo(output-stream, arg1, ...)} \] (function)

These functions work like \text{Print} (6.3.4), except that the output is appended to the output stream \text{output-stream}.

Example

\[
\begin{align*}
gap> \text{str := ""}; \ a := \text{OutputTextString(str,true)};; \\
gap> \text{AppendTo( a, (1,2,3), ":", Z(3) )}; \\
gap> \text{CloseStream(a)}; \\
gap> \text{Print( str, ":\n" )}; \\
(1,2,3):Z(3)
\end{align*}
\]

10.4.5 LogTo (for streams)

\[ \text{LogTo(stream)} \] (operation)

causes the subsequent interaction to be logged to the output stream \text{stream}. It works in precisely the same way as it does for files (see \text{LogTo} (9.7.4)).

10.4.6 InputLogTo (for streams)

\[ \text{InputLogTo(stream)} \] (operation)
causes the subsequent input to be logged to the output stream stream. It works just like it does for files (see InputLogTo (9.7.5)).

10.4.7 OutputLogTo (for streams)

causes the subsequent output to be logged to the output stream stream. It works just like it does for files (see OutputLogTo (9.7.6)).

10.4.8 SetPrintFormattingStatus

SetPrintFormattingStatus sets whether output sent to the output stream stream via PrintTo (9.7.3), AppendTo (9.7.3), LogTo (10.4.5), etc., is by default formatted just as it would be were it being printed to the screen. Thus, it is broken into lines of reasonable length at (where possible) sensible places, lines containing elements of lists or records are indented, and so forth. This is appropriate if the output is eventually to be viewed by a human, and harmless if it to passed as input to GAP, but may be unhelpful if the output is to be passed as input to another program. It is possible to turn off this behaviour for a stream using the SetPrintFormattingStatus operation, and to test whether it is on or off using PrintFormattingStatus.

SetPrintFormattingStatus sets whether output sent to the output stream stream via PrintTo (9.7.3), AppendTo (9.7.3), etc. will be formatted with line breaks and indentation. If the second argument newstatus is true then output will be so formatted, and if false then it will not. If the stream is not a text stream, only false is allowed.

PrintFormattingStatus returns true if output sent to the output text stream stream via PrintTo (9.7.3), AppendTo (9.7.3), etc. will be formatted with line breaks and indentation, and false otherwise. For non-text streams, it returns false. If as argument stream the string "*stdout*" is given, these functions refer to the formatting status of the standard output (so usually the users terminal screen).

These functions do not influence the behaviour of the low level functions WriteByte (10.4.1), WriteLine (10.4.2) or WriteAll (10.4.3) which always write without formatting.

Example

```
gap> s := "";; str := OutputTextString(s,false);
gap> PrintTo(str,Primes([1..30]));
gap> s;
"[ 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61,
\n 67, 71, 73, 79, 83, 89, 97, 101, 103, 107, 109, 113 ]"
gap> Print(s,"\n");
[ 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61,
 67, 71, 73, 79, 83, 89, 97, 101, 103, 107, 109, 113 ]
gap> SetPrintFormattingStatus(str, false);
gap> PrintTo(str,Primes([1..30]));
gap> s;
"[ 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61,
\n 67, 71, 73, 79, 83, 89, 97, 101, 103, 107, 109, 113 ][ 2, 3, 5, 7,
 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 
```
10.5 File Streams

File streams are streams associated with files. An input file stream reads the characters it delivers from a file, an output file stream prints the characters it receives to a file. The following functions can be used to create such streams. They return fail if an error occurred, in this case LastSystemError (9.1.1) can be used to get information about the error.

10.5.1 InputTextFile

\[ \texttt{InputTextFile( filename )} \]

InputTextFile( filename ) returns an input stream in the category IsInputTextStream (10.1.4) that delivers the characters from the file filename. If filename ends in .gz and the file is a valid gzipped file, then the file will be transparently un compressed.

InputTextFile is designed for use with text files and automatically handles windows-style line endings. This means it should not be used for binary data. The \texttt{IO\_File (IO: IO\_File mode)} function from the IO package should be used to access binary data.

10.5.2 OutputTextFile

\[ \texttt{OutputTextFile( filename, append )} \]

OutputTextFile( filename, append ) returns an output stream in the category IsOutputTextFile that writes received characters to the file filename. If append is false, then the file is emptied first, otherwise received characters are added at the end of the file. If filename ends in .gz then the file will be written with gzip compression.

\begin{example}
\texttt{gap> # use a temporary directory}
\texttt{gap> name := Filename( DirectoryTemporary(), "test" );;}
\texttt{gap> # create an output stream, append output, and close again}
\texttt{gap> output := OutputTextFile( name, true );;}
\texttt{gap> AppendTo( output, "Hallo\n", "You\n" );}
\texttt{gap> CloseStream(output);}
\texttt{gap> # create an input, print complete contents of file, and close}
\texttt{gap> input := InputTextFile(name);;}
\texttt{gap> Print( ReadAll(input) );}
Hallo
You
\texttt{gap> CloseStream(input);}
\texttt{gap> # append a single line}
\texttt{gap> output := OutputTextFile( name, true );;}
\end{example}
10.6 User Streams

The commands described in this section create streams which accept characters from, or deliver characters to, the user, via the keyboard or the GAP session display.

10.6.1 InputTextUser

\[ \text{InputTextUser()} \]

returns an input text stream which delivers characters typed by the user (or from the standard input device if it has been redirected). In normal circumstances, characters are delivered one by one as they are typed, without waiting until the end of a line. No prompts are printed.

10.6.2 OutputTextUser

\[ \text{OutputTextUser()} \]

returns an output stream which delivers characters to the user’s display (or the standard output device if it has been redirected). Each character is delivered immediately it is written, without waiting for a full line of output. Text written in this way is not written to the session log (see LogTo (9.7.4)).

10.6.3 InputFromUser

\[ \text{InputFromUser(arg)} \]

prints the arg as a prompt, then waits until a text is typed by the user (or from the standard input device if it has been redirected). This text must be a single expression, followed by one enter. This is evaluated (see EvalString (27.9.5)) and the result is returned.

10.7 String Streams

String streams are streams associated with strings. An input string stream reads the characters it delivers from a string, an output string stream appends the characters it receives to a string. The following functions can be used to create such streams.
10.7.1 InputTextString

\>
\texttt{InputTextString(string)}

\texttt{InputTextString( string )} returns an input stream that delivers the characters from the string \texttt{string}. The \texttt{string} is not changed when reading characters from it and changing the \texttt{string} after the call to \texttt{InputTextString} has no influence on the input stream.

10.7.2 OutputTextString

\>
\texttt{OutputTextString(list, append)}

returns an output stream that puts all received characters into the list \texttt{list}. If \texttt{append} is \texttt{false}, then the list is emptied first, otherwise received characters are added at the end of the list.

\begin{verbatim}
gap> # read input from a string
gap> input := InputTextString( "Hallo\nYou\n" );;
gap> ReadLine(input);
"Hallo\n"
gap> ReadLine(input);
"You\n"
gap> # print to a string
gap> str := "";;
gap> out := OutputTextString( str, true );;
gap> PrintTo( out, 1, "\n", (1,2,3,4)(5,6), "\n" );
gap> CloseStream(out);
gap> Print( str );
1
(1,2,3,4)(5,6)
\end{verbatim}

10.8 Input-Output Streams

Input-output streams capture bidirectional communications between \texttt{GAP} and another process, either locally or (@as yet unimplemented@) remotely.

Such streams support the basic operations of both input and output streams. They should provide some buffering, allowing output data to be written to the stream, even when input data is waiting to be read, but the amount of this buffering is operating system dependent, and the user should take care not to get too far ahead in writing, or behind in reading, or deadlock may occur.

At present the only type of Input-Output streams that are implemented provide communication with a local child process, using a pseudo-tty.

Like other streams, write operations are blocking, read operations will block to get the first character, but not thereafter.

As far as possible, no translation is done on characters written to, or read from the stream, and no control characters have special effects, but the details of particular pseudo-tty implementations may effect this.
10.8.1 IsInputOutputStream

\( \text{IsInputOutputStream}(\text{obj}) \) (Category)

IsInputOutputStream is the Category of Input-Output Streams; it returns true if the obj is an input-output stream and false otherwise.

10.8.2 InputOutputLocalProcess

\( \text{InputOutputLocalProcess}(\text{dir}, \text{executable}, \text{args}) \) (function)

starts up a slave process, whose executable file is executable, with “command line” arguments args in the directory dir. (Suitable choices for dir are DirectoryCurrent() or DirectoryTemporary() (see Section 9.3); DirectoryTemporary() may be a good choice when executable generates output files that it doesn't itself remove afterwards.) InputOutputLocalProcess returns an InputOutputStream object. Bytes written to this stream are received by the slave process as if typed at a terminal on standard input. Bytes written to standard output by the slave process can be read from the stream.

When the stream is closed, the signal SIGTERM is delivered to the child process, which is expected to exit.

```
gap> d := DirectoryCurrent();
dir("./")
gap> f := Filename(DirectoriesSystemPrograms(), "rev");
"/usr/bin/rev"
gap> s := InputOutputLocalProcess(d,f,[[]]);
< input/output stream to rev >
gap> WriteLine(s,"The cat sat on the mat");
true
gap> Print(ReadLine(s));
tam eht no tam tac ehT
gap> x := ListWithIdenticalEntries(10000,'x');
gap> ConvertToStringRep(x);
true
gap> WriteByte(s,INT_CHAR('\n'));
true
gap> y := ReadAll(s);;
gap> Length(y);
4095
gap> CloseStream(s);
gap> s;
< closed input/output stream to rev >
```

10.8.3 ReadAllLine

\( \text{ReadAllLine}(\text{iostream}[, \text{nofail}][, \text{IsAllLine}]) \) (operation)

For an input/output stream iostream ReadAllLine reads until a newline character if any input is found or returns fail if no input is found, i.e. if any input is found ReadAllLine is non-blocking.
If the argument `nofail` (which must be `false` or `true`) is provided and it is set to `true` then `ReadAllLine` will wait, if necessary, for input and never return `fail`.

If the argument `IsAllLine` (which must be a function that takes a string argument and returns either `true` or `false`) then it is used to determine what constitutes a whole line. The default behaviour is equivalent to passing the function

```plaintext
line -> 0 < Length(line) and line[Length(line) - 1] = '\n'
```

for the `IsAllLine` argument. The purpose of the `IsAllLine` argument is to cater for the case where the input being read is from an external process that writes a “prompt” for data that does not terminate with a newline.

If the first argument is an input stream but not an input/output stream then `ReadAllLine` behaves as if `ReadLine` (10.3.4) was called with just the first argument and any additional arguments are ignored.

### 10.9 Dummy Streams

The following two commands create dummy streams which will consume all characters and never deliver one.

#### 10.9.1 InputTextNone

```plaintext
InputTextNone() (function)
```

returns a dummy input text stream, which delivers no characters, i.e., it is always at end of stream. Its main use is for calls to `Process` (11.1.1) when the started program does not read anything.

#### 10.9.2 OutputTextNone

```plaintext
OutputTextNone() (function)
```

returns a dummy output stream, which discards all received characters. Its main use is for calls to `Process` (11.1.1) when the started program does not write anything.

### 10.10 Handling of Streams in the Background

This section describes a feature of the GAP kernel that can be used to handle pending streams somehow “in the background”. This is only available on operating systems that have `select`.

Right before GAP reads a keypress from the keyboard it calls a little subroutine that can handle streams that are ready to be read or ready to be written. This means that GAP can handle these streams during user input on the command line. Note that this does not work when GAP is in the middle of some calculation.

This feature is used in the following way. One can install handler functions for reading or writing streams via `InstallCharReadHookFunc` (10.10.1). Handlers can be removed via `UnInstallCharReadHookFunc` (10.10.2).
Note that handler functions must not return anything and get one integer argument, which refers to an index in one of the following arrays (according to whether the function was installed for input, output or exceptions on the stream). Handler functions usually should not output anything on the standard output because this ruins the command line during command line editing.

10.10.1  InstallCharReadHookFunc

\[InstallCharReadHookFunc(stream, mode, func)\]

installs the function \(func\) as a handler function for the stream \(stream\). The argument \(mode\) decides, for what operations on the stream this function is installed. \(mode\) must be a string, in which a letter \(r\) means “read”, \(w\) means “write” and \(x\) means “exception”, according to the \select\ function call in the UNIX C-library (see \man select\ and UNIXSelect (10.2.3)). More than one letter is allowed in \(mode\). As described above the function is called in a situation when GAP is reading a character from the keyboard. Handler functions should not use much time to complete.

This functionality only works if the operating system has a \select\ function.

10.10.2  UnInstallCharReadHookFunc

\[UnInstallCharReadHookFunc(stream, func)\]

uninstalls the function \(func\) as a handler function for the stream \(stream\). All instances are deinstalled, regardless of the mode of operation (read, write, exception).

This functionality only works if the operating system has a \select\ function.

10.11  Comma separated files

In some situations it can be desirable to process data given in the form of a spreadsheet (such as Excel). GAP can do this using the CSV (comma separated values) format, which spreadsheet programs can usually read in or write out.

The first line of the spreadsheet is used as labels of record components, each subsequent line then corresponds to a record. Entries enclosed in double quotes are considered as strings and are permitted to contain the separation character (usually a comma).

10.11.1  ReadCSV

\[ReadCSV(filename[, nohead][, separator])\]

This function reads in a spreadsheet, saved in CSV format (comma separated values) and returns its entries as a list of records. The entries of the first line of the spreadsheet are used to denote the names of the record components. Blanks will be translated into underscore characters. If the parameter \(nohead\) is given as \true, instead the record components will be called \texttt{fieldn}. Each subsequent line will create one record. If given, \(separator\) is the character used to separate fields. Otherwise it defaults to a comma.
10.11.2 PrintCSV

\[ \text{PrintCSV}(\text{filename}, \text{list[, fields]} ) \]

This function prints a list of records as a spreadsheet in CSV format (which can be read in for example into Excel). The names of the record components will be printed as entries in the first line. If the argument \textit{fields} is given only the record fields listed in this list will be printed and they will be printed in the same arrangement as given in this list. If the option \textit{noheader} is set to true the line with the record field names will not be printed.
Chapter 11

Processes

GAP can call other programs, such programs are called *processes*. There are two kinds of processes: first there are processes that are started, run and return a result, while GAP is suspended until the process terminates. Then there are processes that will run in parallel to GAP as subprocesses and GAP can communicate and control the processes using streams (see `InputOutputLocalProcess` (10.8.2)).

11.1 Process and Exec

11.1.1 Process

\[
\text{\texttt{Process(dir, prg, stream-in, stream-out, options)}}
\]

Process runs a new process and returns when the process terminates. It returns the return value of the process if the operating system supports such a concept.

The first argument `dir` is a directory object (see 9.3) which will be the current directory (in the usual UNIX or MSDOS sense) when the program is run. This will only matter if the program accesses files (including running other programs) via relative path names. In particular, it has nothing to do with finding the binary to run.

In general the directory will either be the current directory, which is returned by `DirectoryCurrent` (9.3.4) –this was the behaviour of GAP 3– or a temporary directory returned by `DirectoryTemporary` (9.3.3). If one expects that the process creates temporary or log files the latter should be used because GAP will attempt to remove these directories together with all the files in them when quitting.

If a program of a GAP package which does not only consist of GAP code needs to be launched in a directory relative to certain data libraries, then the first entry of `DirectoriesPackageLibrary` (76.3.7) should be used. The argument of `DirectoriesPackageLibrary` (76.3.7) should be the path to the data library relative to the package directory.

If a program calls other programs and needs to be launched in a directory containing the executables for such a GAP package then the first entry of `DirectoriesPackagePrograms` (76.3.8) should be used.

The latter two alternatives should only be used if absolutely necessary because otherwise one risks accumulating log or core files in the package directory.
Example

```gap
gap> path := DirectoriesSystemPrograms();;
gap> ls := Filename( path, "ls" );;
gap> stdin := InputTextUser();;
gap> stdout := OutputTextUser();;
gap> Process( path[1], ls, stdin, stdout, ["-c"] );;
awk ls mkdir

gap> # current directory, here the root directory
gap> Process( DirectoryCurrent(), ls, stdin, stdout, ["-c"] );;
bin lib trans tst CVS grp prim thr two
src dev etc tbl doc pkg small tom

gap> # create a temporary directory
gap> tmpdir := DirectoryTemporary();;
gap> Process( tmpdir, ls, stdin, stdout, ["-c"] );;
gap> PrintTo( Filename( tmpdir, "emil" ) );
gap> Process( tmpdir, ls, stdin, stdout, ["-c"] );;
emil
```

`prg` is the filename of the program to launch, for portability it should be the result of `Filename` (9.4.1) and should pass `IsExecutableFile` (9.6.4). Note that `Process` does no searching through a list of directories, this is done by `Filename` (9.4.1).

`stream-in` is the input stream that delivers the characters to the process. For portability it should either be `InputTextNone` (10.9.1) (if the process reads no characters), `InputTextUser` (10.6.1), the result of a call to `InputTextFile` (10.5.1) from which no characters have been read, or the result of a call to `InputTextString` (10.7.1).

`Process` is free to consume all the input even if the program itself does not require any input at all.

`stream-out` is the output stream which receives the characters from the process. For portability it should either be `OutputTextNone` (10.9.2) (if the process writes no characters), `OutputTextUser` (10.6.2), the result of a call to `OutputTextFile` (10.5.2) to which no characters have been written, or the result of a call to `OutputTextString` (10.7.2).

`options` is a list of strings which are passed to the process as command line argument. Note that no substitutions are performed on the strings, i.e., they are passed immediately to the process and are not processed by a command interpreter (shell). Further note that each string is passed as one argument, even if it contains `space` characters. Note that input/output redirection commands are not allowed as `options`.

In order to find a system program use `DirectoriesSystemPrograms` (9.3.6) together with `Filename` (9.4.1).

```gap
Example

```

The next example shows how to execute `date` with no argument and no input, and collect the output into a string stream.

```gap
Example

```

```gap
Example
```
11.1.2 Exec

\[ \text{Exec}(\text{cmd}, \text{option}1, \ldots, \text{option}N) \] (function)

Exec runs a shell in the current directory to execute the command given by the string cmd with options option1,...,optionN.

Example

\[
\text{gap> Exec("date");}
\]

Thu Jul 24 10:04:13 BST 1997

Example

\[
\begin{align*}
\text{gap> Exec("echo \"GAP is great!\" > foo");} \\
\text{gap> Exec("cat foo");} \\
\text{GAP is great!} \\
\text{gap> Exec("rm foo");}
\end{align*}
\]

Exec calls the more general operation Process (11.1.1). The function Edit (6.10.1) should be used to call an editor from within GAP.
Chapter 12

Objects and Elements

An object is anything in GAP that can be assigned to a variable, so nearly everything in GAP is an object.

Different objects can be regarded as equal with respect to the equivalence relation “=”, in this case we say that the objects describe the same element.

12.1 Objects

Nearly all things one deals with in GAP are objects. For example, an integer is an object, as is a list of integers, a matrix, a permutation, a function, a list of functions, a record, a group, a coset or a conjugacy class in a group.

Examples of things that are not objects are comments which are only lexical constructs, while loops which are only syntactical constructs, and expressions, such as 1 + 1; but note that the value of an expression, in this case the integer 2, is an object.

Objects can be assigned to variables, and everything that can be assigned to a variable is an object. Analogously, objects can be used as arguments of functions, and can be returned by functions.

12.1.1 IsObject

\texttt{IsObject(obj)}

\texttt{IsObject} returns \texttt{true} if the object \texttt{obj} is an object. Obviously it can never return \texttt{false}.

It can be used as a filter in \texttt{InstallMethod (78.3.1)} when one of the arguments can be anything.

12.2 Elements as equivalence classes

The equality operation “=” defines an equivalence relation on all GAP objects. The equivalence classes are called elements.

There are basically three reasons to regard different objects as equal. Firstly the same information may be stored in different places. Secondly the same information may be stored in different ways; for example, a polynomial can be stored sparsely or densely. Thirdly different information may be equal modulo a mathematical equivalence relation. For example, in a finitely presented group with the relation $a^2 = 1$ the different objects $a$ and $a^3$ describe the same element.
As an example of all three reasons, consider the possibility of storing an integer in several places of the memory, of representing it as a fraction with denominator 1, or of representing it as a fraction with any denominator, and numerator a suitable multiple of the denominator.

12.3 Sets

In GAP there is no category whose definition corresponds to the mathematical property of being a set, however in the manual we will often refer to an object as a set in order to convey the fact that mathematically, we are thinking of it as a set. In particular, two sets $A$ and $B$ are equal if and only if, $x \in A \iff x \in B$.

There are two types of object in GAP which exhibit this kind of behaviour with respect to equality, namely domains (see Section 12.4) and lists whose elements are strictly sorted see IsSSortedList (21.17.4). In general, set in this manual will mean an object of one of these types.

More precisely: two domains can be compared with “$\{=\}$”, the answer being true if and only if the sets of elements are equal (regardless of any additional structure) and; a domain and a list can be compared with “$=\$”, the answer being true if and only if the list is equal to the strictly sorted list of elements of the domain.

A discussion about sorted lists and sets can be found in Section 21.19.

12.4 Domains

An especially important class of objects in GAP are those whose underlying mathematical abstraction is that of a structured set, for example a group, a conjugacy class, or a vector space. Such objects are called domains. The equality relation between domains is always equality as sets, so that two domains are equal if and only if they contain the same elements.

Domains play a central role in GAP. In a sense, the only reason that GAP supports objects such as integers and permutations is the wish to form domains of them and compute the properties of those domains.

Domains are described in Chapter 31.

12.5 Identical Objects

Two objects that are equal as objects (that is they actually refer to the same area of computer memory) and not only w.r.t. the equality relation “$=$” are called identical. Identical objects do of course describe the same element.

12.5.1 IsIdenticalObj

$\triangleright$ IsIdenticalObj(obj1, obj2) (function)

IsIdenticalObj tests whether the objects obj1 and obj2 are identical (that is they are either equal immediate objects or are both stored at the same location in memory.

If two copies of a simple constant object (see section 12.6) are created, it is not defined whether GAP will actually store two equal but non-identical objects, or just a single object. For mutable objects, however, it is important to know whether two values refer to identical or non-identical objects,
and the documentation of operations that return mutable values should make clear whether the values returned are new, or may be identical to values stored elsewhere.

```gap
Example

gap> IsIdenticalObj( 10^6, 10^6);
true
gap> IsIdenticalObj( 10^30, 10^30);
false
gap> IsIdenticalObj( true, true);
true
```

Generally, one may compute with objects but think of the results in terms of the underlying elements because one is not interested in locations in memory, data formats or information beyond underlying equivalence relations. But there are cases where it is important to distinguish the relations identity and equality. This is best illustrated with an example. (The reader who is not familiar with lists in GAP, in particular element access and assignment, is referred to Chapter 21.)

```gap
Example

gap> l1:= [ 1, 2, 3 ];; l2:= [ 1, 2, 3 ];;
gap> l1 = l2;
true
gap> IsIdenticalObj( l1, l2 );
false
gap> l1[3]:= 4;; l1; l2;
[ 1, 2, 4 ]
[ 1, 2, 3 ]
gap> l1 = l2;
false
```

The two lists `l1` and `l2` are equal but not identical. Thus a change in `l1` does not affect `l2`.

```gap
Example

gap> l1:= [ 1, 2, 3 ];; l2:= l1;;
gap> l1 = l2;
true
gap> IsIdenticalObj( l1, l2 );
true
gap> l1[3]:= 4;; l1; l2;
[ 1, 2, 4 ]
[ 1, 2, 4 ]
gap> l1 = l2;
true
```

Here, `l1` and `l2` are identical objects, so changing `l1` means a change to `l2` as well.

### 12.5.2 IsNotIdenticalObj

- **IsNotIdenticalObj**(obj1, obj2) (function)

  tests whether the objects `obj1` and `obj2` are not identical.
12.6 Mutability and Copyability

An object in GAP is said to be immutable if its mathematical value (as defined by =) does not change under any operation. More explicitly, suppose $a$ is immutable and $O$ is some operation on $a$, then if $a = b$ evaluates to true before executing $O(a)$, $a = b$ also evaluates to true afterwards. (Examples for operations $O$ that change mutable objects are Add (21.4.2) and Unbind (21.5.3) which are used to change list objects, see Chapter 21.) An immutable object may change, for example to store new information, or to adopt a more efficient representation, but this does not affect its behaviour under =.

There are two points here to note. Firstly, “operation” above refers to the functions and methods which can legitimately be applied to the object, and not the !. operation whereby virtually any aspect of any GAP level object may be changed. The second point which follows from this, is that when implementing new types of objects, it is the programmer’s responsibility to ensure that the functions and methods they write never change immutable objects mathematically.

In fact, most objects with which one deals in GAP are immutable. For instance, the permutation $(1,2)$ will never become a different permutation or a non-permutation (although a variable which previously had $(1,2)$ stored in it may subsequently have some other value).

For many purposes, however, mutable objects are useful. These objects may be changed to represent different mathematical objects during their life. For example, mutable lists can be changed by assigning values to positions or by unbinding values at certain positions. Similarly, one can assign values to components of a mutable record, or unbind them.

12.6.1 IsCopyable

$\triangleright$ IsCopyable(obj)

(Category)

If a mutable form of an object obj can be made in GAP, the object is called copyable. Examples of copyable objects are of course lists and records. A new mutable version of the object can always be obtained by the operation ShallowCopy (12.7.1).

Objects for which only an immutable form exists in GAP are called constants. Examples of constants are integers, permutations, and domains. Called with a constant as argument, Immutable (12.6.3) and ShallowCopy (12.7.1) return this argument.

12.6.2 IsMutable

$\triangleright$ IsMutable(obj)

(Category)

tests whether obj is mutable.

If an object is mutable then it is also copyable (see IsCopyable (12.6.1)), and a ShallowCopy (12.7.1) method should be supplied for it. Note that IsMutable must not be implied by another filter, since otherwise Immutable (12.6.3) would be able to create paradoxical objects in the sense that IsMutable for such an object is false but the filter that implies IsMutable is true.

In many situations, however, one wants to ensure that objects are immutable. For example, take the identity of a matrix group. Since this matrix may be referred to as the identity of the group in several places, it would be fatal to modify its entries, or add or unbind rows. We can obtain an immutable copy of an object with Immutable (12.6.3).
12.6.3 Immutable

\texttt{Immutable}(\texttt{obj}) (function)

returns an immutable structural copy (see \texttt{StructuralCopy} (12.7.2)) of \texttt{obj} in which the subobjects are immutable \textit{copies} of the subobjects of \texttt{obj}. If \texttt{obj} is immutable then \texttt{Immutable} returns \texttt{obj} itself.

\texttt{GAP} will complain with an error if one tries to change an immutable object.

12.6.4 MakeImmutable

\texttt{MakeImmutable}(\texttt{obj}) (function)

One can turn the (mutable or immutable) object \texttt{obj} into an immutable one with \texttt{MakeImmutable}; note that this also makes all subobjects of \texttt{obj} immutable, so one should call \texttt{MakeImmutable} only if \texttt{obj} and its mutable subobjects are newly created. If one is not sure about this, \texttt{Immutable} (12.6.3) should be used.

Note that it is \textit{not} possible to turn an immutable object into a mutable one; only mutable copies can be made (see 12.7).

Using \texttt{Immutable} (12.6.3), it is possible to store an immutable identity matrix or an immutable list of generators, and to pass around references to this immutable object safely. Only when a mutable copy is really needed does the actual object have to be duplicated. Compared to the situation without immutable objects, much unnecessary copying is avoided this way. Another advantage of immutability is that lists of immutable objects may remember whether they are sorted (see 21.19), which is not possible for lists of mutable objects.

Since the operation \texttt{Immutable} (12.6.3) must work for any object in \texttt{GAP}, it follows that an immutable form of every object must be possible, even if it is not sensible, and user-defined objects must allow for the possibility of becoming immutable without notice.

12.6.5 Mutability of Iterators

An interesting example of mutable (and thus copyable) objects is provided by \textit{iterators}, see 30.8. (Of course an immutable form of an iterator is not very useful, but clearly \texttt{Immutable} (12.6.3) will yield such an object.) Every call of \texttt{NextIterator} (30.8.5) changes a mutable iterator until it is exhausted, and this is the only way to change an iterator. \texttt{ShallowCopy} (12.7.1) for an iterator \texttt{iter} is defined so as to return a mutable iterator that has no mutable data in common with \texttt{iter}, and that behaves equally to \texttt{iter} w.r.t. \texttt{IsDoneIterator} (30.8.4) and (if \texttt{iter} is mutable) \texttt{NextIterator} (30.8.5). Note that this meaning of the “shallow copy” of an iterator that is returned by \texttt{ShallowCopy} (12.7.1) is not as obvious as for lists and records, and must be explicitly defined.

12.6.6 Mutability of Results of Arithmetic Operations

Many operations return immutable results, among those in particular attributes (see 13.5). Examples of attributes are \texttt{Size} (30.4.6), \texttt{Zero} (31.10.3), \texttt{AdditiveInverse} (31.10.9), \texttt{One} (31.10.2), and \texttt{Inverse} (31.10.8). Arithmetic operations, such as the binary infix operations $+$, $-$. $\cdot$, $/$, $\hat{}$, \texttt{mod}, the unary $\hat{}$, and operations such as \texttt{Comm} (31.12.3) and \texttt{LeftQuotient} (31.12.2), return \textit{mutable} results, except if all arguments are immutable. So the product of two matrices or of a vector and a matrix is immutable if and only if the two matrices or both the vector and the matrix are immutable (see
also 21.11). There is one exception to this rule, which arises where the result is less deeply nested
than at least one of the argument, where mutable arguments may sometimes lead to an immutable
result. For instance, a mutable matrix with immutable rows, multiplied by an immutable vector gives
an immutable vector result. The exact rules are given in 21.11.

It should be noted that $0 \ast obj$ is equivalent to \text{ZeroSM}(\text{obj}), \text{AdditiveInverseSM}(\text{obj})$ is equivalent to \text{AdditiveInverseSM}(\text{obj}), and $\text{obj}^{-1}$ is equivalent to \text{InverseSM}(\text{obj}). The “SM” stands for “same mutability”, and indicates that the result is mutable
if and only if the argument is mutable.

The operations \text{ZeroOp} (31.10.3), \text{AdditiveInverseOp} (31.10.9), \text{OneOp} (31.10.2), and \text{InverseOp} (31.10.8) return mutable results whenever a mutable version of the result exists, contrary
to the attributes \text{Zero} (31.10.3), AdditiveInverse (31.10.9), One (31.10.2), and Inverse (31.10.8).

If one introduces new arithmetic objects then one need not install methods for the attributes \text{One}
(31.10.2), \text{Zero} (31.10.3), etc. The methods for the associated operations \text{OneOp} (31.10.2) and \text{ZeroOp}
(31.10.3) will be called, and then the results made immutable.

All methods installed for the arithmetic operations must obey the rule about the mutability of the
result. This means that one may try to avoid the perhaps expensive creation of a new object if both
operands are immutable, and of course no problems of this kind arise at all in the (usual) case that the
objects in question do not admit a mutable form, i.e., that these objects are not copyable.

In a few, relatively low-level algorithms, one wishes to treat a matrix partly as a data structure,
and manipulate and change its entries. For this, the matrix needs to be mutable, and the rule that
attribute values are immutable is an obstacle. For these situations, a number of additional operations
are provided, for example \text{TransposedMatMutable} (24.5.6) constructs a mutable matrix (contrary to
the attribute \text{TransposedMat} (24.5.6)), while \text{TriangulizeMat} (24.7.3) modifies a mutable matrix
(in place) into upper triangular form.

Note that being immutable does not forbid an object to store knowledge. For example, if it is
found out that an immutable list is strictly sorted then the list may store this information. More
precisely, an immutable object may change in any way, provided that it continues to represent the
same mathematical object.

12.7 Duplication of Objects

12.7.1 ShallowCopy

\begin{verbatim}
▷ ShallowCopy(obj)
\end{verbatim}

ShallowCopy returns a new mutable object equal to its argument, if this is possible. The subobjects
of \textit{ShallowCopy( obj )} are identical to the subobjects of \textit{obj}.

If GAP does not support a mutable form of the immutable object \textit{obj} (see 12.6) then
\textit{ShallowCopy} returns \textit{obj} itself.

Since \textit{ShallowCopy} is an operation, the concrete meaning of “subobject” depends on the type of
\textit{obj}. But for any copyable object \textit{obj}, the definition should reflect the idea of “first level copying”.

The definition of \textit{ShallowCopy} for lists (in particular for matrices) can be found in 21.7.

12.7.2 StructuralCopy

\begin{verbatim}
▷ StructuralCopy(obj)
\end{verbatim}
In a few situations, one wants to make a *structural copy* \( scp \) of an object \( obj \). This is defined as follows. \( scp \) and \( obj \) are identical if \( obj \) is immutable. Otherwise, \( scp \) is a mutable copy of \( obj \) such that each subobject of \( scp \) is a structural copy of the corresponding subobject of \( obj \). Furthermore, if two subobjects of \( obj \) are identical then also the corresponding subobjects of \( scp \) are identical.

```gap
gap> obj:= [ [ 0, 1 ] ];;
gap> obj[2]:= obj[1];;
gap> obj[3]:= Immutable( obj[1] );;
gap> scp:= StructuralCopy( obj );;
gap> scp = obj; IsIdenticalObj( scp, obj );
true false
gap> IsIdenticalObj( scp[1], obj[1] );
false
gap> IsIdenticalObj( scp[3], obj[3] );
true
gap> IsIdenticalObj( scp[1], scp[2] );
true
```

That both `ShallowCopy` (12.7.1) and `StructuralCopy` return the argument \( obj \) itself if it is not copyable is consistent with this definition, since there is no way to change \( obj \) by modifying the result of any of the two functions, because in fact there is no way to change this result at all.

### 12.8 Other Operations Applicable to any Object

There are a number of general operations which can be applied, in principle, to any object in GAP. Some of these are documented elsewhere –see `String` (27.7.6), `PrintObj` (6.3.5) and `Display` (6.3.6). Others are mainly somewhat technical.

#### 12.8.1 SetName

```gap```
SetName(obj, name)
```

(operation)

for a suitable object \( obj \) sets that object to have name \( name \) (a string).

#### 12.8.2 Name

```gap```
Name(obj)
```

(attribute)

returns the name, a string, previously assigned to \( obj \) via a call to `SetName` (12.8.1). The name of an object is used *only* for viewing the object via this name.

There are no methods installed for computing names of objects, but the name may be set for suitable objects, using `SetName` (12.8.1).

```gap```
gap> R := PolynomialRing(Integers,2);
Integers[x_1,x_2]
gap> SetName(R,"Z[x,y]");
gap> R;
Z[x,y]
```
12.8.3 InfoText

\[ \text{InfoText}(\text{obj}) \]

is a mutable string with information about the object \textit{obj}. There is no default method to create an info text.

12.8.4 IsInternallyConsistent

\[ \text{IsInternallyConsistent}(\text{obj}) \]

For debugging purposes, it may be useful to check the consistency of an object \textit{obj} that is composed from other (composed) objects.

There is a default method of \text{IsInternallyConsistent}, with rank zero, that returns \text{true}. So it is possible (and recommended) to check the consistency of subobjects of \textit{obj} recursively by \text{IsInternallyConsistent}.

(Note that \text{IsInternallyConsistent} is not an attribute.)

12.8.5 MemoryUsage

\[ \text{MemoryUsage}(\text{obj}) \]

Returns the amount of memory in bytes used by the object \textit{obj} and its subobjects. Note that in general, objects can reference each other in very difficult ways such that determining the memory usage is a recursive procedure. In particular, computing the memory usage of a complicated structure itself uses some additional memory, which is however no longer used after completion of this operation. This procedure descends into lists and records, positional and component objects; however it deliberately does not take into account the type and family objects. For functions, it only takes the memory usage of the function body, not of the local context the function was created in, although the function keeps a reference to that as well.
Chapter 13

Types of Objects

Every GAP object has a type. The type of an object is the information which is used to decide whether an operation is admissible or possible with that object as an argument, and if so, how it is to be performed (see Chapter 78).

For example, the types determine whether two objects can be multiplied and what function is called to compute the product. Analogously, the type of an object determines whether and how the size of the object can be computed. It is sometimes useful in discussing the type system, to identify types with the set of objects that have this type. Partial types can then also be regarded as sets, such that any type is the intersection of its parts.

The type of an object consists of two main parts, which describe different aspects of the object.

The family determines the relation of the object to other objects. For example, all permutations form a family. Another family consists of all collections of permutations, this family contains the set of permutation groups as a subset. A third family consists of all rational functions with coefficients in a certain family.

The other part of a type is a collection of filters (actually stored as a bit-list indicating, from the complete set of possible filters, which are included in this particular type). These filters are all treated equally by the method selection, but, from the viewpoint of their creation and use, they can be divided (with a small number of unimportant exceptions) into categories, representations, attribute testers and properties. Each of these is described in more detail below.

This chapter does not describe how types and their constituent parts can be created. Information about this topic can be found in Chapter 79.

Note: Detailed understanding of the type system is not required to use GAP. It can be helpful, however, to understand how things work and why GAP behaves the way it does.

A discussion of the type system can be found in [BL98].

13.1 Families

The family of an object determines its relationship to other objects.

More precisely, the families form a partition of all GAP objects such that the following two conditions hold: objects that are equal w.r.t. = lie in the same family; and the family of the result of an operation depends only on the families of its operands.

The first condition means that a family can be regarded as a set of elements instead of a set of objects. Note that this does not hold for categories and representations (see below), two objects that are equal w.r.t. = need not lie in the same categories and representations. For example, a sparsely
represented matrix can be equal to a densely represented matrix. Similarly, each domain is equal w.r.t. \(=\) to the sorted list of its elements, but a domain is not a list, and a list is not a domain.

Families are probably the least obvious part of the GAP type system, so some remarks about the role of families are necessary. When one uses GAP as it is, one will (better: should) not meet families at all. The two situations where families come into play are the following.

First, since families are used to describe relations between arguments of operations in the method selection mechanism (see Chapter 78, and also Chapter 13), one has to prescribe such a relation in each method installation (see 78.3); usual relations are \texttt{ReturnTrue} (5.4.1) (which means that any relation of the actual arguments is admissible), \texttt{IsIdenticalObj} (12.5.1) (which means that there are two arguments that lie in the same family), and \texttt{IsCollsElms} (which means that there are two arguments, the first being a collection of elements that lie in the same family as the second argument).

Second—and this is the more complicated situation—whenever one creates a new kind of objects, one has to decide what its family shall be. If the new object shall be equal to existing objects, for example if it is just represented in a different way, there is no choice: The new object must lie in the same family as all objects that shall be equal to it. So only if the new object is different (w.r.t. the equality ‘\(=\)’) from all other GAP objects, we are likely to create a new family for it. Note that enlarging an existing family by such new objects may be problematic because of implications that have been installed for all objects of the family in question. The choice of families depends on the applications one has in mind. For example, if the new objects in question are not likely to be arguments of operations for which family relations are relevant (for example binary arithmetic operations), one could create one family for all such objects, and regard it as “the family of all those GAP objects that would in fact not need a family”. On the other extreme, if one wants to create domains of the new objects then one has to choose the family in such a way that all intended elements of a domain do in fact lie in the same family. (Remember that a domain is a collection, see Chapter 12.4, and that a collection consists of elements in the same family, see Chapter 30 and Section 13.1.)

Let us look at an example. Suppose that no permutations are available in GAP, and that we want to implement permutations. Clearly we want to support permutation groups, but it is not a priori clear how to distribute the new permutations into families. We can put all permutations into one family; this is how in fact permutations are implemented in GAP. But it would also be possible to put all permutations of a given degree into a family of their own; this would for example mean that for each degree, there would be distinguished trivial permutations, and that the stabilizer of the point 5 in the symmetric group on the points 1, 2, \ldots, 5 is not regarded as equal to the symmetric group on 1, 2, 3, 4. Note that the latter approach would have the advantage that it is no problem to construct permutations and permutation groups acting on arbitrary (finite) sets, for example by constructing first the symmetric group on the set and then generating any desired permutation group as a subgroup of this symmetric group.

So one aspect concerning a reasonable choice of families is to make the families large enough for being able to form interesting domains of elements in the family. But on the other hand, it is useful to choose the families small enough for admitting meaningful relations between objects. For example, the elements of different free groups in GAP lie in different families; the multiplication of free group elements is installed only for the case that the two operands lie in the same family, with the effect that one cannot erroneously form the product of elements from different free groups. In this case, families appear as a tool for providing useful restrictions.

As another example, note that an element and a collection containing this element never lie in the same family, by the general implementation of collections; namely, the family of a collection of elements in the family \(\text{Fam}\) is the collections family of \(\text{Fam}\) (see \texttt{CollectionsFamily} (30.2.1)).
means that for a collection, we need not (because we cannot) decide about its family.

A few functions in GAP return families, see CollectionsFamily (30.2.1) and ElementsFamily (30.2.3).

13.1.1 FamilyObj

\[ \text{FamilyObj}(\text{obj}) \]

returns the family of the object \text{obj}.

The family of the object \text{obj} is itself an object, its family is \text{FamilyOfFamilies}.

It should be emphasized that families may be created when they are needed. For example, the family of elements of a finitely presented group is created only after the presentation has been constructed. Thus families are the dynamic part of the type system, that is, the part that is not fixed after the initialisation of GAP.

Families can be parametrized. For example, the elements of each finitely presented group form a family of their own. Here the family of elements and the finitely presented group coincide when viewed as sets. Note that elements in different finitely presented groups lie in different families. This distinction allows GAP to forbid multiplications of elements in different finitely presented groups.

As a special case, families can be parametrized by other families. An important example is the family of \text{collections} that can be formed for each family. A collection consists of objects that lie in the same family, it is either a nonempty dense list of objects from the same family or a domain.

Note that every domain is a collection, that is, it is not possible to construct domains whose elements lie in different families. For example, a polynomial ring over the rationals cannot contain the integer 0 because the family that contains the integers does not contain polynomials. So one has to distinguish the integer zero from each zero polynomial.

Let us look at this example from a different viewpoint. A polynomial ring and its coefficients ring lie in different families, hence the coefficients ring cannot be embedded “naturally” into the polynomial ring in the sense that it is a subset. But it is possible to allow, e.g., the multiplication of an integer and a polynomial over the integers. The relation between the arguments, namely that one is a coefficient and the other a polynomial, can be detected from the relation of their families. Moreover, this analysis is easier than in a situation where the rationals would lie in one family together with all polynomials over the rationals, because then the relation of families would not distinguish the multiplication of two polynomials, the multiplication of two coefficients, and the multiplication of a coefficient with a polynomial. So the wish to describe relations between elements can be taken as a motivation for the introduction of families.

13.1.2 NewFamily

\[ \text{NewFamily}(\text{name}, \text{req}, \text{imp}, \text{famfilter}) \]

\text{NewFamily} returns a new family \text{fam} with name \text{name}. The argument \text{req}, if present, is a filter of which \text{fam} shall be a subset. If one tries to create an object in \text{fam} that does not lie in the filter \text{req}, an error message is printed. Also the argument \text{imp}, if present, is a filter of which \text{fam} shall be a subset. Any object that is created in the family \text{fam} will lie automatically in the filter \text{imp}.

The filter \text{famfilter}, if given, specifies a filter that will hold for the family \text{fam} (not for objects in \text{fam}).
Families are always represented as component objects (see 79.2). This means that components can be used to store and access useful information about the family.

13.2 Filters

A filter is a special unary GAP function that returns either true or false, depending on whether or not the argument lies in the set defined by the filter. Filters are used to express different aspects of information about a GAP object, which are described below (see 13.3, 13.4, 13.5, 13.6, 13.7, 13.8).

Presently any filter in GAP is implemented as a function which corresponds to a set of positions in the bitlist which forms part of the type of each GAP object, and returns true if and only if the bitlist of the type of the argument has the value true at all of these positions.

The intersection (or meet) of two filters filt1, filt2 is again a filter, it can be formed as filt1 and filt2

See 20.4 for more details.

For example, IsList and IsEmpty is a filter that returns true if its argument is an empty list, and false otherwise. The filter IsGroup (39.2.7) is defined as the intersection of the category IsMagmaWithInverses (35.1.4) and the property IsAssociative (35.4.7).

A filter that is not the meet of other filters is called a simple filter. For example, each attribute tester (see 13.6) is a simple filter. Each simple filter corresponds to a position in the bitlist currently used as part of the data structure representing a type.

Every filter has a rank, which is used to define a ranking of the methods installed for an operation, see Section 78.3. The rank of a filter can be accessed with RankFilter (13.2.1).

13.2.1 RankFilter

\[ \text{RankFilter} \] (function)

For simple filters, an incremental rank is defined when the filter is created, see the sections about the creation of filters: NewCategory (13.3.4), NewRepresentation (13.4.4), NewAttribute (13.5.3), NewProperty (13.7.4), NewFilter (13.8.1). For an arbitrary filter, its rank is given by the sum of the incremental ranks of the involved simple filters; in addition to the implied filters, these are also the required filters of attributes (again see the sections about the creation of filters). In other words, for the purpose of computing the rank and only for this purpose, attribute testers are treated as if they would imply the requirements of their attributes.

13.2.2 NamesFilter

\[ \text{NamesFilter} \] (function)

NamesFilter returns a list of names of the implied simple filters of the filter filt, these are all those simple filters imp such that every object in filt also lies in imp. For implications between filters, see ShowImpliedFilters (13.2.4) as well as sections 78.8, NewCategory (13.3.4), NewRepresentation (13.4.4), NewAttribute (13.5.3), NewProperty (13.7.4).
13.2.3 FilterByName

\[ \text{FilterByName}(\text{name}) \]

finds the filter with name \text{name} in the global FILTERS list. This is useful to find filters that were created but not bound to a global variable.

13.2.4 ShowImpliedFilters

\[ \text{ShowImpliedFilters} (\text{filter}) \]

Displays information about the filters that may be implied by \text{filter}. They are given by their names. \text{ShowImpliedFilters} first displays the names of all filters that are unconditionally implied by \text{filter}. It then displays implications that require further filters to be present (indicating by + the required further filters).

Example

\begin{verbatim}
gap> ShowImpliedFilters(IsNilpotentGroup);
Implies:
  IsListOrCollection
  IsCollection
  IsDuplicateFree
  IsExtLElement
  CategoryCollections(IsExtLElement)
  IsExtRElement
  CategoryCollections(IsExtRElement)
  CategoryCollections(IsMultiplicativeElement)
  CategoryCollections(IsMultiplicativeElementWithOne)
  CategoryCollections(IsMultiplicativeElementWithInverse)
  IsGeneralizedDomain
  IsMagma
  IsMagmaWithOne
  IsMagmaWithInversesIfNonzero
  IsMagmaWithInverses
  IsAssociative
  HasMultiplicativeNeutralElement
  IsGeneratorsOfSemigroup
  IsSimpleSemigroup
  IsRegularSemigroup
  IsInverseSemigroup
  IsCompletelyRegularSemigroup
  IsGroupAsSemigroup
  IsMonoidAsSemigroup
  IsOrthodoxSemigroup
  IsSupersolvableGroup
  IsSolvableGroup
  IsNilpotentByFinite

May imply with:
  +IsFinitelyGeneratedGroup
  IsPolycyclicGroup
\end{verbatim}
13.2.5 FiltersType

⊿ FiltersType(type)  
⊿ FiltersObj(object)

returns a list of the filters in the type type, or in the type of the object object respectively.

Example

```
gap> FiltersObj(fail);
[ <Category "IsBool">, <Representation "IsInternalRep"> ]
gap> FiltersType(TypeOfTypes);
[ <Representation "IsPositionalObjectRep">, <Category "IsType">, <Representation "IsTypeDefaultRep">, ...
```

13.3 Categories

The categories of an object are filters (see 13.2) that determine what operations an object admits. For example, all integers form a category, all rationals form a category, and all rational functions form a category. An object which claims to lie in a certain category is accepting the requirement that it should have methods for certain operations (and perhaps that their behaviour should satisfy certain axioms). For example, an object lying in the category IsList (21.1.1) must have methods for Length (21.17.5), IsBound \[
\] (21.2.1) and the list element access operation \[
\] (21.2.1).

An object can lie in several categories. For example, a row vector lies in the categories IsList (21.1.1) and IsVector (31.14.14); each list lies in the category IsCopyable (12.6.1), and depending on whether or not it is mutable, it may lie in the category IsMutable (12.6.2). Every domain lies in the category IsDomain (31.9.1).

Of course some categories of a mutable object may change when the object is changed. For example, after assigning values to positions of a mutable non-dense list, this list may become part of the category IsDenseList (21.1.2).

However, if an object is immutable then the set of categories it lies in is fixed.

All categories in the library are created during initialization, in particular they are not created dynamically at runtime.

The following list gives an overview of important categories of arithmetic objects. Indented categories are to be understood as subcategories of the non indented category listed above it.

```
IsObject
  IsExtLElement
  IsExtRElement
    IsMultiplicativeElement
      IsMultiplicativeElementWithOne
      IsMultiplicativeElementWithInverse
    IsExtAElement
    IsAdditiveElement
      IsAdditiveElementWithZero
      IsAdditiveElementWithInverse
```

Every object lies in the category IsObject (12.1.1).
The categories `IsExtLElement (31.14.8)` and `IsExtRElement (31.14.9)` contain objects that can be multiplied with other objects via `*` from the left and from the right, respectively. These categories are required for the operands of the operation `*`.

The category `IsMultiplicativeElement (31.14.10)` contains objects that can be multiplied from the left and from the right with objects from the same family. `IsMultiplicativeElementWithOne (31.14.11)` contains objects `obj` for which a multiplicatively neutral element can be obtained by taking the 0-th power `obj^0`. `IsMultiplicativeElementWithInverse (31.14.13)` contains objects `obj` for which a multiplicative inverse can be obtained by forming `obj^-1`.

Likewise, the categories `IsExtAElement (31.14.1)`, `IsAdditiveElement (31.14.3)`, `IsAdditiveElementWithZero (31.14.5)` and `IsAdditiveElementWithInverse (31.14.7)` contain objects that can be added via `+` to other objects, objects that can be added to objects of the same family, objects for which an additively neutral element can be obtained by multiplication with zero, and objects for which an additive inverse can be obtained by multiplication with `-1`.


As stated above it is not guaranteed by the categories of objects whether the result of an operation with these objects as arguments is defined. For example, the category `IsMatrix (24.2.1)` is a subcategory of `IsMultiplicativeElementWithInverse (31.14.13)`. Clearly not every matrix has a multiplicative inverse. But the category `IsMatrix (24.2.1)` makes each matrix an admissible argument of the operation `Inverse (31.10.8)`, which may sometimes return `fail`. Likewise, two matrices can be multiplied only if they are of appropriate shapes.

Analogous to the categories of arithmetic elements, there are categories of domains of these elements.

```
IsObject
 IsDomain
  IsMagma
   IsMagmaWithOne
    IsMagmaWithInversesIfNonzero
    IsMagmaWithInverses
  IsAdditiveMagma
   IsAdditiveMagmaWithZero
   IsAdditiveMagmaWithInverses
 IsExtLSet
 IsExtRSet
```

Of course `IsDomain (31.9.1)` is a subcategory of `IsObject (12.1.1)`. A domain that is closed under multiplication `*` is called a magma and it lies in the category `IsMagma (35.1.1)`. If a magma is closed under taking the identity, it lies in `IsMagmaWithOne (35.1.2)`, and if it is also closed under taking inverses, it lies in `IsMagmaWithInverses (35.1.4)`. The category `IsMagmaWithInversesIfNonzero (35.1.3)` denotes closure under taking inverses only for nonzero elements, every division ring lies in this category.

Note that every set of categories constitutes its own notion of generation, for example a group may be generated as a magma with inverses by some elements, but to generate it as a magma with one it may be necessary to take the union of these generators and their inverses.
13.3.1 IsCategory

\[\text{IsCategory}(\text{object})\]

returns true if \text{object} is a category (see 13.3), and false otherwise. Note that GAP categories are not categories in the usual mathematical sense.

13.3.2 CategoriesOfObject

\[\text{CategoriesOfObject}(\text{object})\]

returns a list of the names of the categories in which \text{object} lies.

Example

```gap
gap> g:=Group((1,2),(1,2,3));;
gap> CategoriesOfObject(g);
```

13.3.3 CategoryByName

\[\text{CategoryByName}(\text{name})\]

returns the category with name \text{name} if it is found, or fail otherwise.

13.3.4 NewCategory

\[\text{NewCategory}(\text{name}, \text{super}[, \text{rank}])\]

\text{NewCategory} returns a new category \text{cat} that has the name \text{name} and is contained in the filter \text{super}, see 13.2. This means that every object in \text{cat} lies automatically also in \text{super}. We say also that \text{super} is an implied filter of \text{cat}.

For example, if one wants to create a category of group elements then \text{super} should be \text{IsMultiplicativeElementWithInverse} (31.14.13) or a subcategory of it. If no specific supercategory of \text{cat} is known, \text{super} may be \text{IsObject} (12.1.1).

The optional third argument \text{rank} denotes the incremental rank (see 13.2) of \text{cat}, the default value is 1.

13.3.5 DeclareCategory

\[\text{DeclareCategory}(\text{name}, \text{super}[, \text{rank}])\]

does the same as \text{NewCategory} (13.3.4) and additionally makes the variable \text{name} read-only.
13.3.6 CategoryFamily

\texttt{CategoryFamily(cat)}

For a category \texttt{cat}, \texttt{CategoryFamily} returns the \textit{family category} of \texttt{cat}. This is a category in which all families lie that know from their creation that all their elements are in the category \texttt{cat}, see 13.1.

For example, a family of associative words is in the category \texttt{CategoryFamily(IsAssocWord)}, and one can distinguish such a family from others by this category. So it is possible to install methods for operations that require one argument to be a family of associative words.

\texttt{CategoryFamily} is quite technical, and in fact of minor importance.

See also \texttt{CategoryCollections (30.2.4)}.

13.4 Representation

The \textit{representation} of an object is a set of filters (see 13.2) that determines how an object is actually represented. For example, a matrix or a polynomial can be stored sparsely or densely; all dense polynomials form a representation. An object which claims to lie in a certain representation is accepting the requirement that certain fields in the data structure be present and have specified meanings.

13.4.1 Basic Representations of Objects

\texttt{IsInternalRep(obj)}

\texttt{IsDataObjectRep(obj)}

\texttt{IsPositionalObjectRep(obj)}

\texttt{IsComponentObjectRep(obj)}

\texttt{GAP} distinguishes four essentially different ways to represent objects. First there are the representations \texttt{IsInternalRep} for internal objects such as integers and permutations, and \texttt{IsDataObjectRep} for other objects that are created and whose data are accessible only by kernel functions. The data structures underlying such objects cannot be manipulated at the \texttt{GAP} level.

All other objects are either in the representation \texttt{IsComponentObjectRep} or in the representation \texttt{IsPositionalObjectRep}, see 79.2 and 79.3.

An object can belong to several representations in the sense that it lies in several subrepresentations of \texttt{IsComponentObjectRep} or of \texttt{IsPositionalObjectRep}. The representations to which an object belongs should form a chain and either two representations are disjoint or one is contained in the other. So the subrepresentations of \texttt{IsComponentObjectRep} and \texttt{IsPositionalObjectRep} each form trees. In the language of Object Oriented Programming, we support only single inheritance for representations.

These trees are typically rather shallow, since for one representation to be contained in another implies that all the components of the data structure implied by the containing representation, are present in, and have the same meaning in, the smaller representation (whose data structure presumably contains some additional components).

Objects may change their representation, for example a mutable list of characters can be converted into a string.

All representations in the library are created during initialization, in particular they are not created dynamically at runtime.
Examples of subrepresentations of IsPositionalObjectRep are IsModulusRep, which is used for residue classes in the ring of integers, and IsDenseCoeffVectorRep, which is used for elements of algebras that are defined by structure constants.

An important subrepresentation of IsComponentObjectRep is IsAttributeStoringRep (13.5.5), which is used for many domains and some other objects. It provides automatic storing of all attribute values (see Section 13.5).

13.4.2 IsRepresentation

▷ IsRepresentation(object) (function)

returns true if object is a representation (see 13.4), and false otherwise.

13.4.3 RepresentationsOfObject

▷ RepresentationsOfObject(object) (operation)

returns a list of the names of the representations object has.

Example

\[
gap> g:=Group([(1,2),(1,2,3)]);
gap> RepresentationsOfObject(g);
[ "IsComponentObjectRep", "IsAttributeStoringRep" ]
\]

13.4.4 NewRepresentation

▷ NewRepresentation(name, super, slots[, req]) (function)

NewRepresentation returns a new representation rep that has the name name and is a subrepresentation of the representation super. This means that every object in rep lies automatically also in super. We say also that super is an implied filter of rep.

Each representation in GAP is a subrepresentation of exactly one of the four representations IsInternalRep (13.4.1), IsDataObjectRep (13.4.1), IsComponentObjectRep (13.4.1), IsPositionalObjectRep (13.4.1). The data describing objects in the former two can be accessed only via GAP kernel functions, the data describing objects in the latter two is accessible also in library functions, see 79.2 and 79.3 for the details.

The third argument slots is a list either of integers or of strings. In the former case, rep must be IsPositionalObjectRep (13.4.1) or a subrepresentation of it, and slots tells what positions of the objects in the representation rep may be bound. In the latter case, rep must be IsComponentObjectRep (13.4.1) or a subrepresentation of, and slots lists the admissible names of components that objects in the representation rep may have. The admissible positions resp. component names of super need not be listed in slots.

The incremental rank (see 13.2) of rep is 1.

Note that for objects in the representation rep, of course some of the component names and positions reserved via slots may be unbound.

Examples for the use of NewRepresentation can be found in 79.2, 79.3, and also in 81.3.
13.4.5 DeclareRepresentation

\[
\text{DeclareRepresentation(name, super, slots[, req]) (function)}
\]

does the same as \text{NewRepresentation (13.4.4)} and additionally makes the variable \text{name} read-only.

13.5 Attributes

The attributes of an object describe knowledge about it.

An attribute is a unary operation without side-effects.

An object may store values of its attributes once they have been computed, and claim that it knows these values. Note that “store” and “know” have to be understood in the sense that it is very cheap to get such a value when the attribute is called again.

The stored value of an attribute is in general immutable (see 12.6), except if the attribute had been specially constructed as “mutable attribute”.

It depends on the representation of an object (see 13.4) which attribute values it stores. An immutable object in the representation \text{IsAttributeStoringRep (13.5.5)} stores \text{all} attribute values once they are computed.

Note that it is impossible to get rid of a stored attribute value because the system may have drawn conclusions from the old attribute value, and just removing the value might leave the data structures in an inconsistent state. If necessary, a new object can be constructed.

Each method that is installed for an attribute via \text{InstallMethod (78.3.1)} must require exactly one argument, and this must lie in the filter \text{filter} that was entered as second argument of \text{NewAttribute (13.5.3)} resp. \text{NewProperty (13.7.4)}.

As for any operation, for attributes one can install a method taking an argument that does not lie in \text{filt} via \text{InstallOtherMethod (78.3.2)}, or a method for more than one argument. For example, \text{IsTransitive (41.10.1)} is an attribute for a \(G\)-set that can also be called for the two arguments, being a group \(G\) and its action domain. If attributes are called with more than one argument then the return value is not stored in any of the arguments.

Properties are a special form of attributes that have the value \text{true} or \text{false}, see section 13.7.

Examples of attributes for multiplicative elements are \text{Inverse (31.10.8)}, \text{One (31.10.2)}, and \text{Order (31.10.10)}. \text{Size (30.4.6)} is an attribute for domains, \text{Centre (35.4.5)} is an attribute for magmas, and \text{DerivedSubgroup (39.12.3)} is an attribute for groups.

13.5.1 IsAttribute

\[
\text{IsAttribute(object)} (function)
\]

returns \text{true} if \text{object} is an attribute (see 13.5), and \text{false} otherwise.

13.5.2 KnownAttributesOfObject

\[
\text{KnownAttributesOfObject(object)} (operation)
\]

returns a list of the names of the attributes whose values are known for \text{object}.
Example

```gap
gap> g:=Group((1,2),(1,2,3));;Size(g);;
gap> KnownAttributesOfObject(g);
[ "Size", "OneImmutable", "NrMovedPoints", "MovedPoints",
  "GeneratorsOfMagmaWithInverses", "MultiplicativeNeutralElement",
  "HomePcgs", "Pcgs", "StabChainMutable", "StabChainOptions" ]
```

13.5.3 NewAttribute

NewAttribute returns a new attribute getter with name \texttt{name} that is applicable to objects with the property \texttt{filter}.

Contrary to the situation with categories and representations, the tester of the new attribute does not imply \texttt{filter}. This is exactly because of the possibility to install methods that do not require \texttt{filter}.

For example, the attribute \texttt{Size} (30.4.6) was created with second argument a list or a collection, but there is also a method for \texttt{Size} (30.4.6) that is applicable to a character table, which is neither a list nor a collection.

For the optional third and fourth arguments, there are the following possibilities.

- The integer argument \texttt{rank} causes the attribute tester to have this incremental rank (see 13.2).
- If the argument \texttt{mutable} is the string "mutable" or the boolean true, then the values of the attribute are mutable.
- If the argument \texttt{mutable} is the boolean false, then the values of the attribute are immutable.

When a value of such mutable attribute is set then this value itself is stored, not an immutable copy of it, and it is the user’s responsibility to set an object that is mutable. This is useful for an attribute whose value is some partial information that may be completed later. For example, there is an attribute \texttt{ComputedSylowSubgroups} for the list holding those Sylow subgroups of a group that have been computed already by the function \texttt{SylowSubgroup} (39.13.1), and this list is mutable because one may want to enter groups into it as they are computed.

If no argument for \texttt{rank} is given, then the rank of the tester is 1.

Each method for the new attribute that does not require its argument to lie in \texttt{filter} must be installed using \texttt{InstallOtherMethod} (78.3.2).

13.5.4 DeclareAttribute

DeclareAttribute does the same as \texttt{NewAttribute} (13.5.3), additionally makes the variable \texttt{name} read-only and also binds read-only global variables with names \texttt{Hasname} and \texttt{Setname} for the tester and setter of the attribute (see Section 13.6).
13.5.5  IsAttributeStoringRep

Objects in this representation have default methods to get stored values of attributes and –if they are immutable– to store attribute values automatically once they have been computed. (These methods are called the “system getter” and the “system setter” of the attribute, respectively.)

As a consequence, for immutable objects in IsAttributeStoringRep, subsequent calls to an attribute will return the same object.

Mutable objects in IsAttributeStoringRep are allowed, but attribute values are not stored automatically in them. Such objects are useful because they may later be made immutable using MakeImmutable (12.6.4), at which point they will start storing all attribute values.

Note that one can force an attribute value to be stored in a mutable object in IsAttributeStoringRep, by explicitly calling the attribute setter. This feature should be used with care. For example, think of a mutable matrix whose rank or trace gets stored, and the values later become wrong when somebody changes the matrix entries.

Example

```
gap> g:= Group( (1,2)(3,4), (1,3)(2,4) );;
gap> IsAttributeStoringRep( g );
true
gap> HasSize( g );  Size( g );  HasSize( g );
false
4
true
gap> r:= 7/4;;
gap> IsAttributeStoringRep( r );
false
gap> Int( r );  HasInt( r );
1
false
```

13.6  Setter and Tester for Attributes

For every attribute, the attribute setter and the attribute tester are defined.

To check whether an object belongs to an attribute attr, the tester of the attribute is used, see Tester (13.6.1). To store a value for the attribute attr in an object, the setter of the attribute is used, see Setter (13.6.2).

13.6.1  Tester

For an attribute attr, Tester(attr) is a filter (see 13.2) that returns true or false, depending on whether or not the value of attr for the object is known. For example, Tester( Size )( obj ) is true if the size of the object obj is known.
13.6.2 Setter

\[ \text{Setter(attr)} \]

For an attribute \( \text{attr} \), \( \text{Setter(attr)} \) is called automatically when the attribute value has been computed for an immutable object which does not already have a value stored for \( \text{attr} \). One can also call the setter explicitly, for example, \( \text{Setter( Size ) (obj, val)} \) sets \( \text{val} \) as size of the object \( \text{obj} \) if the size was not yet known.

For each attribute \( \text{attr} \) that is declared with \( \text{DeclareAttribute (13.5.4)} \) resp. \( \text{DeclareProperty (13.7.5)} \), tester and setter are automatically made accessible by the names \( \text{Hasattr} \) and \( \text{Setattr} \), respectively. For example, the tester for \( \text{Size} \) (30.4.6) is called \( \text{HasSize} \), and the setter is called \( \text{SetSize} \).

Example

\[
\text{gap> g:=Group((1,2,3,4),(1,2));;Size(g);} \\
24 \\
\text{gap> HasSize(g);} \\
\text{true} \\
\text{gap> SetSize(g,99);} \\
\text{gap> Size(g);} \\
24
\]

For two properties \( \text{prop1} \) and \( \text{prop2} \), the intersection \( \text{prop1 and prop2} \) (see 13.2) is again a property for which a setter and a tester exist. Setting the value of this intersection to true for a GAP object means to set the values of \( \text{prop1} \) and \( \text{prop2} \) to true for this object.

Example

\[
\text{gap> prop:= IsFinite and IsCommutative;} \\
<\text{Property "(IsFinite and IsCommutative)"}> \\
\text{gap> g:= Group((1,2,3), (4,5));;} \\
\text{gap> Tester( prop )( g );} \\
\text{false} \\
\text{gap> Setter( prop )( g, true );} \\
\text{gap> Tester( prop )( g );} \\
\text{prop( g );} \\
\text{true} \\
\text{true}
\]

It is not allowed to set the value of such an intersection to false for an object.

Example

\[
\text{gap> Setter( prop )( Rationals, false );} \\
\text{You cannot set an "and-filter" except to true} \\
\text{not in any function} \\
\text{Entering break read-eval-print loop ...} \\
\text{you can ’quit;' to quit to outer loop, or} \\
\text{you can type ’return true;' to set all components true} \\
\text{(but you might really want to reset just one component) to continue} \\
\text{brk>}
\]

13.6.3 AttributeValueNotSet

\[ \text{AttributeValueNotSet(attr, obj)} \]

(function)
If the value of the attribute \texttt{attr} is already stored for \texttt{obj}, \texttt{AttributeValueNotSet} simply
returns this value. Otherwise the value of \texttt{attr(obj)} is computed and returned \textit{without storing it}
in \texttt{obj}. This can be useful when “large” attribute values (such as element lists) are needed only once
and shall not be stored in the object.

\begin{example}
\begin{verbatim}
gap> HasAsSSortedList(g);
false
\end{verbatim}
\end{example}

The normal behaviour of attributes (when called with just one argument) is that once a method has
been selected and executed, and has returned a value the setter of the attribute is called, to (possibly)
store the computed value. In special circumstances, this behaviour can be altered dynamically on
an attribute-by-attribute basis, using the functions \texttt{DisableAttributeValueStoring} (13.6.5) and
\texttt{EnableAttributeValueStoring} (13.6.6).

In general, the code in the library assumes, for efficiency, but not for correctness, that attribute
values \textit{will} be stored (in suitable objects), so disabling storing may cause substantial computations to
be repeated.

\subsection{InfoAttributes}

\begin{function}
\texttt{InfoAttributes} (info class)
\end{function}

This info class (together with \texttt{InfoWarning} (7.4.8) is used for messages about attribute storing
being disabled (at level 2) or enabled (level 3). It may be used in the future for other messages
concerning changes to attribute behaviour.

\subsection{DisableAttributeValueStoring}

\begin{function}
\texttt{DisableAttributeValueStoring(attr)} (function)
\end{function}

disables the usual call of \texttt{Setter(attr)} when a method for \texttt{attr} returns a value. In conse-
quence the values will never be stored. Note that \texttt{attr} must be an attribute and \textit{not} a property.

\subsection{EnableAttributeValueStoring}

\begin{function}
\texttt{EnableAttributeValueStoring(attr)} (function)
\end{function}

enables the usual call of \texttt{Setter(attr)} when a method for \texttt{attr} returns a value. In conse-
quence the values may be stored. This will usually have no effect unless
\texttt{DisableAttributeValueStoring} (13.6.5) has previously been used for \texttt{attr}. Note that \texttt{attr} must
be an attribute and \textit{not} a property.

\begin{example}
\begin{verbatim}
gap> g := Group([1,2,3,4,5],[1,2,3]);
Group([ [1,2,3,4,5], [1,2,3] ])
gap> KnownAttributesOfObject(g);
\end{verbatim}
\end{example}
13.7 Properties

The properties of an object are those of its attributes (see 13.5) whose values can only be true or false.

The main difference between attributes and properties is that a property defines two sets of objects, namely the usual set of all objects for which the value is known, and the set of all objects for which the value is known to be true.

(Note that it makes no sense to consider a third set, namely the set of objects for which the value of a property is true whether or not it is known, since there may be objects for which the containment in this set cannot be decided.)

For a property prop, the containment of an object obj in the first set is checked again by applying Tester(prop) to obj, and obj lies in the second set if and only if Tester(prop)(obj) and prop(obj) is true.

If a property value is known for an immutable object then this value is also stored, as part of the type of the object. To some extent, property values of mutable objects also can be stored, for example a mutable list all of whose entries are immutable can store whether it is strictly sorted. When the object is mutated (for example by list assignment) the type may need to be adjusted.

Important properties for domains are IsAssociative (35.4.7), IsCommutative (35.4.9), IsAnticommutative (56.4.6), IsLDistributive (56.4.3) and IsRDistributive (56.4.4), which mean that the multiplication of elements in the domain satisfies \((ab)c = a(bc), ab = ba, a\cdot b = -(b\cdot a), a\cdot (b + c) = a\cdot b + a\cdot c, (a + b)\cdot c = a\cdot c + b\cdot c\), respectively, for all \(a, b, c\) in the domain.
13.7.1 IsProperty

\[\text{IsProperty}(\text{object})\]

This function returns true if \text{object} is a property (see 13.7), and false otherwise.

13.7.2 KnownPropertiesOfObject

\[\text{KnownPropertiesOfObject}(\text{object})\]

This operation returns a list of the names of the properties whose values are known for \text{object}.

13.7.3 KnownTruePropertiesOfObject

\[\text{KnownTruePropertiesOfObject}(\text{object})\]

This operation returns a list of the names of the properties known to be true for \text{object}.

Example

```
gap> g:=Group((1,2),(1,2,3));;
gap> KnownPropertiesOfObject(g);
[ "IsEmpty", "IsTrivial", "IsNonTrivial", "IsFinite", 
  "CanEasilyCompareElements", "CanEasilySortElements", 
  "IsDuplicateFree", "IsGeneratorsOfMagmaWithInverses", 
  "IsAssociative", "IsGeneratorsOfSemigroup", "IsSimpleSemigroup", 
  "IsRegularSemigroup", "IsInverseSemigroup", 
  "IsCompletelyRegularSemigroup", "IsCompletelySimpleSemigroup", 
  "IsGroupAsSemigroup", "IsMonoidAsSemigroup", "IsOrthodoxSemigroup", 
  "IsFinitelyGeneratedGroup", "IsSubsetLocallyFiniteGroup", 
  "KnowsHowToDecompose", "IsInfiniteAbelianizationGroup", 
  "IsNilpotentByFinite", "IsTorsionFree", "IsFreeAbelian" ]
gap> Size(g);
6
```

Example

```
gap> KnownTruePropertiesOfObject(g);
[ "IsNonTrivial", "IsFinite", "CanEasilyCompareElements", 
  "CanEasilySortElements", "IsDuplicateFree", 
  "IsGeneratorsOfMagmaWithInverses", "IsAssociative", 
  "IsGeneratorsOfSemigroup", "IsSimpleSemigroup", 
  "IsRegularSemigroup", "IsInverseSemigroup", 
  "IsCompletelyRegularSemigroup", "IsCompletelySimpleSemigroup", 
  "IsGroupAsSemigroup", "IsMonoidAsSemigroup", "IsOrthodoxSemigroup", 
  "IsFinitelyGeneratedGroup", "IsSubsetLocallyFiniteGroup", 
  "KnowsHowToDecompose", "IsPerfectGroup", "IsSolvableGroup", 
  "IsPolycyclicGroup", "IsInfiniteAbelianizationGroup", 
  "IsNilpotentByFinite", "IsTorsionFree", "IsFreeAbelian" ]
```

Example
13.7.4 NewProperty

\[ \texttt{NewProperty(name, filter[, rank])} \]

NewProperty returns a new property \texttt{prop} with name \texttt{name} (see also 13.7). The filter \texttt{filter} describes the involved filters of \texttt{prop}. As in the case of attributes, \texttt{filter} is not implied by \texttt{prop}.

The optional third argument \texttt{rank} denotes the incremental rank (see 13.2) of the property \texttt{prop} itself, i.e. not of its tester; the default value is 1.

13.7.5 DeclareProperty

\[ \texttt{DeclareProperty(name, filter[, rank])} \]

does the same as \texttt{NewProperty} (13.7.4), additionally makes the variable \texttt{name} read-only and also binds read-only global variables with names \texttt{Hasname} and \texttt{Setname} for the tester and setter of the property (see Section 13.6).

13.8 Other Filters

There are situations where one wants to express a kind of knowledge that is based on some heuristic.

For example, the filters (see 13.2) \texttt{CanEasilyTestMembership} (39.26.1) and \texttt{CanEasilyComputePcgs} (45.2.3) are defined in the \texttt{GAP} library. Note that such filters do not correspond to a mathematical concept, contrary to properties (see 13.7). Also it need not be defined what “easily” means for an arbitrary \texttt{GAP} object, and in this case one cannot compute the value for an arbitrary \texttt{GAP} object. In order to access this kind of knowledge as a part of the type of an object, \texttt{GAP} provides filters for which the value is \texttt{false} by default, and it is changed to \texttt{true} in certain situations, either explicitly (for the given object) or via a logical implication (see 78.8) from other filters.

For example, a \texttt{true} value of \texttt{CanEasilyComputePcgs} (45.2.3) for a group means that certain methods are applicable that use a pcgs (see 45.1) for the group. There are logical implications to set the filter value to \texttt{true} for permutation groups that are known to be solvable, and for groups that have already a (sufficiently nice) pcgs stored. In the case one has a solvable matrix group and wants to enable methods that use a pcgs, one can set the \texttt{CanEasilyComputePcgs} (45.2.3) value to \texttt{true} for this particular group.

A filter \texttt{filt} of the kind described here is different from the other filters introduced in the previous sections. In particular, \texttt{filt} is not a category (see 13.3) or a property (see 13.7) because its value may change for a given object, and \texttt{filt} is not a representation (see 13.4) because it has nothing to do with the way an object is made up from some data. \texttt{filt} is similar to an attribute tester (see 13.6), the only difference is that \texttt{filt} does not refer to an attribute value; note that \texttt{filt} is also used in the same way as an attribute tester; namely, the \texttt{true} value may be required for certain methods to be applicable.

In order to change the value of \texttt{filt} for an object \texttt{obj}, one can use logical implications (see 78.8) or \texttt{SetFilterObj} (13.8.3), \texttt{ResetFilterObj} (13.8.4).
13.8.1 NewFilter

\[ \texttt{NewFilter(name [, rank])} \]

\( \texttt{NewFilter} \) returns a simple filter with name \( \texttt{name} \) (see 13.8). The optional second argument \( \texttt{rank} \) denotes the incremental rank (see 13.2) of the filter, the default value is 1.

The default value of the new simple filter for each object is \( \texttt{false} \).

13.8.2 DeclareFilter

\[ \texttt{DeclareFilter(name [, rank])} \]

\( \texttt{DeclareFilter} \) does the same as \( \texttt{NewFilter} \) (13.8.1) and additionally makes the variable \( \texttt{name} \) read-only.

13.8.3 SetFilterObj

\[ \texttt{SetFilterObj(obj, filter)} \]

\( \texttt{SetFilterObj} \) sets the value of \( \texttt{filter} \) (and of all filters implied by \( \texttt{filter} \)) for \( \texttt{obj} \) to \( \texttt{true} \). This may trigger immediate methods.

13.8.4 ResetFilterObj

\[ \texttt{ResetFilterObj(obj, filter)} \]

\( \texttt{ResetFilterObj} \) sets the value of \( \texttt{filter} \) for \( \texttt{obj} \) to \( \texttt{false} \). (Implied filters of \( \texttt{filt} \) are not touched. This might create inconsistent situations if applied carelessly).

13.9 Types

We stated above (see 13) that, for an object \( \texttt{obj} \), its \textit{type} is formed from its family and its filters. There is a also a third component, used in a few situations, namely defining data of the type.

13.9.1 TypeObj

\[ \texttt{TypeObj(obj)} \]

\( \texttt{TypeObj} \) returns the type of the object \( \texttt{obj} \).

The type of an object is itself an object.

Two types are equal if and only if the two families are identical, the filters are equal, and, if present, also the defining data of the types are equal.

13.9.2 DataType

\[ \texttt{DataType(type)} \]

\( \texttt{DataType} \) returns the last part of the type, defining data, has not been mentioned before and seems to be of minor importance. It can be used, e.g., for cosets \( \texttt{Ug} \) of a group \( \texttt{U} \), where the type of each coset may contain
the group $U$ as defining data. As a consequence, two such cosets mod $U$ and $V$ can have the same type only if $U = V$. The defining data of the type type can be accessed via \texttt{DataType}.

### 13.9.3 NewType

\begin{verbatim}
\texttt{NewType(family, filter[, data])}
\end{verbatim}

\texttt{NewType} returns the type given by the family \texttt{family} and the filter \texttt{filter}. The optional third argument \texttt{data} is any object that denotes defining data of the desired type.

For examples where \texttt{NewType} is used, see 79.2, 79.3, and the example in Chapter 81.
Chapter 14

Integers

One of the most fundamental datatypes in every programming language is the integer type. GAP is no exception.

GAP integers are entered as a sequence of decimal digits optionally preceded by a “+” sign for positive integers or a “-” sign for negative integers. The size of integers in GAP is only limited by the amount of available memory, so you can compute with integers having thousands of digits.

Example

```
gap> -1234;
-1234

gap> 12345678901234567890123456789012345678901234567890;
12345678901234567890123456789012345678901234567890
```

Note that in a few places, only certain small integer values can be used. A small integer (also referred to as immediate integer) is an integer $n$ satisfying $\text{INTOBJ\_MIN} \leq n \leq \text{INTOBJ\_MAX}$, where $\text{INTOBJ\_MIN}$ and $\text{INTOBJ\_MAX}$ equal either $-2^{28}$ and $2^{28} - 1$ (on 32-bit systems) or $-2^{60}$ and $2^{60} - 1$ (on 64-bit systems). For example, the elements of a range are restricted to small integers (see 21.22).

Many more functions that are mainly related to the prime residue group of integers modulo an integer are described in chapter 15, and functions dealing with combinatorics can be found in chapter 16.

14.1 Integers: Global Variables

14.1.1 Integers (global variable)

These global variables represent the ring of integers and the semirings of positive and nonnegative integers, respectively.

Example

```
gap> Size( Integers ); 2 in Integers;
infinity
true
```
Integers is a subset of Rationals (17.1.1), which is a subset of Cyclotomics (18.1.2). See Chapter 18 for arithmetic operations and comparison of integers.

14.1.2 IsIntegers

\[
\text{IsIntegers}(\text{obj}) \quad \text{(Category)}
\]
\[
\text{IsPositiveIntegers}(\text{obj}) \quad \text{(Category)}
\]
\[
\text{IsNonnegativeIntegers}(\text{obj}) \quad \text{(Category)}
\]

are the defining categories for the domains Integers (14.1.1), PositiveIntegers (14.1.1), and NonnegativeIntegers (14.1.1).

Example

\begin{verbatim}
gap> IsIntegers( Integers ); IsIntegers( Rationals ); IsIntegers( 7 );
true
false
false
\end{verbatim}

14.2 Elementary Operations for Integers

14.2.1 IsInt

\[
\text{IsInt}(\text{obj}) \quad \text{(Category)}
\]

Every rational integer lies in the category IsInt, which is a subcategory of IsRat (17.2.1).

14.2.2 IsPosInt

\[
\text{IsPosInt}(\text{obj}) \quad \text{(Category)}
\]

Every positive integer lies in the category IsPosInt.

14.2.3 Int

\[
\text{Int}(\text{elm}) \quad \text{(attribute)}
\]

Int returns an integer int whose meaning depends on the type of elm. For example:

If \( elm \) is a rational number (see Chapter 17) then int is the integer part of the quotient of numerator and denominator of \( elm \) (see QuoInt (14.3.1)).

If \( elm \) is an element of a finite prime field (see Chapter 59) then int is the smallest nonnegative integer such that \( elm = \text{int} \times \text{One}(\text{elm}) \).

If \( elm \) is a string (see Chapter 27) consisting entirely of decimal digits '0', '1', ..., '9', and optionally a sign '-' (at the first position), then int is the integer described by this string. For all other strings, fail is returned. See Int (27.9.1).

The operation String (27.7.6) can be used to compute a string for rational integers, in fact for all cyclotomics.

Example

\begin{verbatim}
gap> Int( 4/3 ); Int( -2/3 );
1
\end{verbatim}
14.2.4  IsEvenInt

▷ IsEvenInt(n) (function)

tests if the integer \( n \) is divisible by 2.

14.2.5  IsOddInt

▷ IsOddInt(n) (function)

tests if the integer \( n \) is not divisible by 2.

14.2.6  AbsInt

▷ AbsInt(n) (function)

AbsInt returns the absolute value of the integer \( n \), i.e., \( n \) if \( n \) is positive, -\( n \) if \( n \) is negative and 0 if \( n \) is 0.

AbsInt is a special case of the general operation EuclideanDegree (56.6.2).
See also AbsoluteValue (18.1.8).

Example

\[
\begin{align*}
\text{gap> } & \text{AbsInt( 33 );} \\
& 33 \\
\text{gap> } & \text{AbsInt( -214378 );} \\
& 214378 \\
\text{gap> } & \text{AbsInt( 0 );} \\
& 0
\end{align*}
\]

14.2.7  SignInt

▷ SignInt(n) (function)

SignInt returns the sign of the integer \( n \), i.e., 1 if \( n \) is positive, -1 if \( n \) is negative and 0 if \( n \) is 0.

Example

\[
\begin{align*}
\text{gap> } & \text{SignInt( 33 );} \\
& 1 \\
\text{gap> } & \text{SignInt( -214378 );} \\
& -1 \\
\text{gap> } & \text{SignInt( 0 );} \\
& 0
\end{align*}
\]
14.2.8 LogInt

\[ \text{LogInt}\( n, \text{base} \)\]

LogInt returns the integer part of the logarithm of the positive integer \( n \) with respect to the positive integer \( \text{base} \), i.e., the largest positive integer \( e \) such that \( \text{base}^e \leq n \). The function LogInt will signal an error if either \( n \) or \( \text{base} \) is not positive.

For \( \text{base} = 2 \) this is very efficient because the internal binary representation of the integer is used.

\begin{verbatim}
gap> LogInt( 1030, 2 );
10
gap> 2^10;
1024
gap> LogInt( 1, 10 );
0
\end{verbatim}

14.2.9 RootInt

\[ \text{RootInt}\( n[, k] \)\]

RootInt returns the integer part of the \( k \) th root of the integer \( n \). If the optional integer argument \( k \) is not given it defaults to 2, i.e., RootInt returns the integer part of the square root in this case.

If \( n \) is positive, RootInt returns the largest positive integer \( r \) such that \( r^k \leq n \). If \( n \) is negative and \( k \) is odd RootInt returns \(-\text{RootInt}\( -n, k \)\). If \( n \) is negative and \( k \) is even RootInt will cause an error. RootInt will also cause an error if \( k \) is 0 or negative.

\begin{verbatim}
gap> RootInt( 361 );
19
gap> RootInt( 2 * 10^12 );
1414213
gap> RootInt( 17000, 5 );
7
gap> 7^5;
16807
\end{verbatim}

14.2.10 SmallestRootInt

\[ \text{SmallestRootInt}\( n \)\]

SmallestRootInt returns the smallest root of the integer \( n \).

The smallest root of an integer \( n \) is the integer \( r \) of smallest absolute value for which a positive integer \( k \) exists such that \( n = r^k \).

\begin{verbatim}
gap> SmallestRootInt( 2^30 );
2
gap> SmallestRootInt( -(2^30) );
-4
\end{verbatim}

Note that \((-2)^{30} = +(2^{30})\).
Example

```gap
gap> SmallestRootInt(279936); 6
gap> LogInt(279936,6); 7
gap> SmallestRootInt(1001); 1001
```

14.2.11 ListOfDigits

▷ ListOfDigits(n) (function)

For a positive integer \( n \) this function returns a list \( l \), consisting of the digits of \( n \) in decimal representation.

Example

```gap
gap> ListOfDigits(3142); [3,1,4,2]
```

14.2.12 Random (for integers)

▷ Random(Integers) (method)

Random for integers returns pseudo random integers between \(-10\) and \(10\) distributed according to a binomial distribution. To generate uniformly distributed integers from a range, use the construction `Random([low..high])` (see Random (30.7.1)).

14.3 Quotients and Remainders

14.3.1 QuoInt

▷ QuoInt(n, m) (function)

QuoInt returns the integer part of the quotient of its integer operands.

If \( n \) and \( m \) are positive, QuoInt returns the largest positive integer \( q \) such that \( q \times m \leq n \). If \( n \) or \( m \) or both are negative the absolute value of the integer part of the quotient is the quotient of the absolute values of \( n \) and \( m \), and the sign of it is the product of the signs of \( n \) and \( m \).

QuoInt is used in a method for the general operation EuclideanQuotient (56.6.3).

Example

```gap
gap> QuoInt(5,3); QuoInt(-5,3); QuoInt(5,-3); QuoInt(-5,-3);
1 -1 -1 1
```

14.3.2 BestQuoInt

▷ BestQuoInt(n, m) (function)
BestQuoInt returns the best quotient $q$ of the integers $n$ and $m$. This is the quotient such that $n - q \times m$ has minimal absolute value. If there are two quotients whose remainders have the same absolute value, then the quotient with the smaller absolute value is chosen.

Example

```
gap> BestQuoInt( 5, 3 ); BestQuoInt( -5, 3 );
2
-2
```

14.3.3 RemInt

RemInt returns the remainder of its two integer operands.

If $m$ is not equal to zero, RemInt returns $n - m \times QuoInt( n, m )$. Note that the rules given for QuoInt (14.3.1) imply that the return value of RemInt has the same sign as $n$ and its absolute value is strictly less than the absolute value of $m$. Note also that the return value equals $n \mod m$ when both $n$ and $m$ are nonnegative. Dividing by 0 signals an error.

RemInt is used in a method for the general operation EuclideanRemainder (56.6.4).

Example

```
gap> RemInt(5,3); RemInt(-5,3); RemInt(5,-3); RemInt(-5,-3);
2
-2
2
-2
```

14.3.4 GcdInt

GcdInt returns the greatest common divisor of its two integer operands $m$ and $n$, i.e., the greatest integer that divides both $m$ and $n$. The greatest common divisor is never negative, even if the arguments are. We define $GcdInt( m, 0 ) = GcdInt( 0, m ) = AbsInt( m )$ and $GcdInt( 0, 0 ) = 0$.

GcdInt is a method used by the general function Gcd (56.7.1).

Example

```
gap> GcdInt(123,66);
3
```

14.3.5 Gcdex

Gcdex returns a record $g$ describing the extended greatest common divisor of $m$ and $n$. The component gcd is this gcd, the components coeff1 and coeff2 are integer cofactors such that $g.gcd = g.coeff1 \times m + g.coeff2 \times n$, and the components coeff3 and coeff4 are integer cofactors such that $0 = g.coeff3 \times m + g.coeff4 \times n$.

If $m$ and $n$ both are nonzero, $AbsInt( g.coeff1 )$ is less than or equal to $AbsInt(n) / (2 \times g.gcd)$, and $AbsInt( g.coeff2 )$ is less than or equal to $AbsInt(m) / (2 \times g.gcd)$. 
If \( m \) or \( n \) or both are zero, \( \text{coeff3} \) is \(-\frac{n}{\text{gcd}}\) and \( \text{coeff4} \) is \(\frac{m}{\text{gcd}}\).

The coefficients always form a unimodular matrix, i.e., the determinant \(\text{g.coeff1} \times \text{g.coeff4} - \text{g.coeff3} \times \text{g.coeff2}\) is 1 or -1.

Example

\[
\text{gap> Gcdex( 123, 66 );}
\text{rec( coeff1 := 7, coeff2 := -13, coeff3 := -22, coeff4 := 41, gcd := 3 )}
\]

This means \( 3 = 7 \times 123 - 13 \times 66, 0 = -22 \times 123 + 41 \times 66. \)

Example

\[
\text{gap> Gcdex( 0, -3 );}
\text{rec( coeff1 := 0, coeff2 := -1, coeff3 := 1, coeff4 := 0, gcd := 3 )}
\text{gap> Gcdex( 0, 0 );}
\text{rec( coeff1 := 1, coeff2 := 0, coeff3 := 0, coeff4 := 1, gcd := 0 )}
\]

GcdRepresentation (56.7.3) provides similar functionality over arbitrary Euclidean rings.

### 14.3.6 LcmInt

\( \star \) \text{LcmInt}(m, n) \hspace{100pt} \text{(function)}

returns the least common multiple of the integers \( m \) and \( n \).

\text{LcmInt} \ is \ a \ method \ used \ by \ the \ general \ operation \text{Lcm} \ (56.7.6).

Example

\[
\text{gap> LcmInt( 123, 66 );}
2706
\]

### 14.3.7 CoefficientsQadic

\( \star \) \text{CoefficientsQadic}(i, q) \hspace{100pt} \text{(operation)}

returns the \( q \)-adic representation of the integer \( i \) as a list \( l \) of coefficients satisfying the equality \( i = \sum_{j=0}^{\infty} q^j \cdot l[j+1] \) for an integer \( q > 1. \)

Example

\[
\text{gap> l:=CoefficientsQadic(462,3);}
\text{[ 0, 1, 0, 2, 2, 1 ]}
\]

### 14.3.8 CoefficientsMultiadic

\( \star \) \text{CoefficientsMultiadic}(ints, int) \hspace{100pt} \text{(function)}

returns the multiadic expansion of the integer \( \text{int} \) modulo the integers given in \( \text{ints} \) (in ascending order). It returns a list of coefficients in the \textit{reverse} order to that in \( \text{ints} \).
14.3.9 ChineseRem

- **ChineseRem(moduli, residues)** (function)

ChineseRem returns the combination of the residues modulo the moduli, i.e., the unique integer \( c \) from \([0..\text{Lcm}(\text{moduli})-1]\) such that \( c \equiv \text{residues}[i] \mod \text{moduli}[i] \) for all \( i \), if it exists. If no such combination exists ChineseRem signals an error.

Such a combination does exist if and only if \( \text{residues}[i] \equiv \text{residues}[k] \mod \text{Gcd}(\text{moduli}[i], \text{moduli}[k]) \) for every pair \( i, k \). Note that this implies that such a combination exists if the moduli are pairwise relatively prime. This is called the Chinese remainder theorem.

**Example**

```gap
gap> ChineseRem([2, 3, 5, 7], [1, 2, 3, 4]);
53
gap> ChineseRem([6, 10, 14], [1, 3, 5]);
103
```

14.3.10 PowerModInt

- **PowerModInt(r, e, m)** (function)

returns \( r^e \mod m \) for integers \( r, e \) and \( m \).

Note that PowerModInt can reduce intermediate results and thus will generally be faster than using \( r^e \mod m \), which would compute \( r^e \) first and reduces the result afterwards.

PowerModInt is a method for the general operation PowerMod (56.7.9).

14.4 Prime Integers and Factorization

14.4.1 Primes

- **Primes** (global variable)

Primes is a strictly sorted list of the 168 primes less than 1000.

This is used in IsPrimeInt (14.4.2) and FactorsInt (14.4.7) to cast out small primes quickly.

**Example**

```gap
gap> Primes[1];
2
gap> Primes[100];
541
```
14.4.2 IsPrimeInt

\[ \text{IsPrimeInt}(n) \] (function)

\[ \text{IsProbablyPrimeInt}(n) \] (function)

IsPrimeInt returns false if it can prove that the integer \( n \) is composite and true otherwise. By convention IsPrimeInt(0) = IsPrimeInt(1) = false and we define IsPrimeInt(-n) = IsPrimeInt(n).

IsPrimeInt will return true for every prime \( n \). IsPrimeInt will return false for all composite \( n < 10^{18} \) and for all composite \( n \) that have a factor \( p < 1000 \). So for integers \( n < 10^{18} \), IsPrimeInt is a proper primality test. It is conceivable that IsPrimeInt may return true for some composite \( n > 10^{18} \), but no such \( n \) is currently known. So for integers \( n > 10^{18} \), IsPrimeInt is a probable-primality test. IsPrimeInt will issue a warning when its argument is probably prime but not a proven prime. (The function IsProbablyPrimeInt will do a similar calculation but not issue a warning.) The warning can be switched off by SetInfoLevel( InfoPrimeInt, 0 );, the default level is 1 (also see SetInfoLevel (7.4.3)).

If composites that fool IsPrimeInt do exist, they would be extremely rare, and finding one by pure chance might be less likely than finding a bug in GAP. We would appreciate being informed about any example of a composite number \( n \) for which IsPrimeInt returns true.

IsPrimeInt is a deterministic algorithm, i.e., the computations involve no random numbers, and repeated calls will always return the same result. IsPrimeInt first does trial divisions by the primes less than 1000. Then it tests that \( n \) is a strong pseudoprime w.r.t. the base 2. Finally it tests whether \( n \) is a Lucas pseudoprime w.r.t. the smallest quadratic nonresidue of \( n \). A better description can be found in the comment in the library file primality.gi.

The time taken by IsPrimeInt is approximately proportional to the third power of the number of digits of \( n \). Testing numbers with several hundreds digits is quite feasible.

IsPrimeInt is a method for the general operation IsPrime (56.5.8).

Remark: In future versions of GAP we hope to change the definition of IsPrimeInt to return true only for proven primes (currently, we lack a sufficiently good primality proving function). In applications, use explicitly IsPrimeInt or IsProbablyPrimeInt with this change in mind.

\[
\text{gap}\>\text{IsPrimeInt}(2^{31} - 1);\quad \text{true}
\]

\[
\text{gap}\>\text{IsPrimeInt}(10^{42} + 1);\quad \text{false}
\]

14.4.3 PrimalityProof

\[ \text{PrimalityProof}(n) \] (function)

Construct a machine verifiable proof of the primality of (the probable prime) \( n \), following the ideas of [BLS75]. The proof consists of various Fermat and Lucas pseudoprimality tests, which taken as a whole prove the primality. The proof is represented as a list of witnesses of two kinds. The first kind, \[ ["F", \text{divisor}, \text{base}] \], indicates a successful Fermat pseudoprimality test, where \( n \) is a strong pseudoprime at base with order not divisible by \((n - 1)/\text{divisor}\). The second kind, \[ ["L", \text{divisor}, \text{discriminant}, \text{P}] \] indicates a successful Lucas pseudoprimality test, for a quadratic form of given discriminant and middle term P with an extra check at \((n + 1)/\text{divisor}\).
14.4.4 IsPrimePowerInt

IsPrimePowerInt returns true if the integer \( n \) is a prime power and false otherwise.

An integer \( n \) is a prime power if there exists a prime \( p \) and a positive integer \( i \) such that \( p^i = n \). If \( n \) is negative the condition is that there must exist a negative prime \( p \) and an odd positive integer \( i \) such that \( p^i = n \). The integers 1 and -1 are not prime powers.

Note that IsPrimePowerInt uses SmallestRootInt (14.2.10) and a probable-primality test (see IsPrimeInt (14.4.2)).

Example

\[
\text{gap> IsPrimePowerInt}(31^5); \\
\text{true} \\
\text{gap> IsPrimePowerInt}(2^{31}-1); \ # 2^{31}-1 \text{ is actually a prime} \\
\text{true} \\
\text{gap> IsPrimePowerInt}(2^63-1); \\
\text{false} \\
\text{gap> Filtered([-10..10], IsPrimePowerInt);} \\
\text{[ -8, -7, -5, -3, -2, 2, 3, 4, 5, 7, 8, 9 ]}
\]

14.4.5 NextPrimeInt

NextPrimeInt returns the smallest prime which is strictly larger than the integer \( n \).

Note that NextPrimeInt uses a probable-primality test (see IsPrimeInt (14.4.2)).

Example

\[
\text{gap> NextPrimeInt(541); NextPrimeInt(-1);} \\
547 \ 2
\]

14.4.6 PrevPrimeInt

PrevPrimeInt returns the largest prime which is strictly smaller than the integer \( n \).

Note that PrevPrimeInt uses a probable-primality test (see IsPrimeInt (14.4.2)).

Example

\[
\text{gap> PrevPrimeInt(541); PrevPrimeInt(1);} \\
523 \ -2
\]

14.4.7 FactorsInt

FactorsInt(n)
FactorsInt(n: RhoTrials := trials)
FactorsInt returns a list of factors of a given integer \( n \) such that \( \text{Product}( \text{FactorsInt}( n ) ) = n \). If \( |n| \leq 1 \) the list \([n]\) is returned. Otherwise the result contains probable primes, sorted by absolute value. The entries will all be positive except for the first one in case of a negative \( n \).

See PrimeDivisors (14.4.8) for a function that returns a set of (probable) primes dividing \( n \).

Note that FactorsInt uses a probable-primality test (see IsPrimeInt (14.4.2)). Thus FactorsInt might return a list which contains composite integers. In such a case you will get a warning about the use of a probable prime. You can switch off these warnings by SetInfoLevel( InfoPrimeInt, 0 ); (also see SetInfoLevel (7.4.3)).

The time taken by FactorsInt is approximately proportional to the square root of the second largest prime factor of \( n \), which is the last one that FactorsInt has to find, since the largest factor is simply what remains when all others have been removed. Thus the time is roughly bounded by the fourth root of \( n \). FactorsInt is guaranteed to find all factors less than \( 10^6 \) and will find most factors less than \( 10^{10} \). If \( n \) contains multiple factors larger than that FactorsInt may not be able to factor \( n \) and will then signal an error.

FactorsInt is used in a method for the general operation Factors (56.5.9).

In the second form, FactorsInt calls FactorsRho with a limit of trials on the number of trials it performs. The default is 8192. Note that Pollard’s Rho is the fastest method for finding prime factors with roughly 5-10 decimal digits, but becomes more and more inferior to other factorization techniques like e.g. the Elliptic Curves Method (ECM) the bigger the prime factors are. Therefore instead of performing a huge number of Rho trials, it is usually more advisable to install the FactInt package and then simply to use the operation Factors (56.5.9). The factorization of the 8-th Fermat number by Pollard’s Rho below takes already a while.

```gap
gap> FactorsInt( -Factorial(6) );
[ -2, 2, 2, 2, 2, 3, 3, 5 ]
gap> Set( FactorsInt( Factorial(13)/11 ) );
[ 2, 3, 5, 7, 13 ]
gap> FactorsInt( 2^63 - 1 );
[ 7, 7, 73, 127, 92737, 649657 ]
gap> FactorsInt( 10^42 + 1 );
[ 29, 101, 281, 9901, 226549, 12149949, 445819223320340849 ]
gap> FactorsInt(2^256+1:RhoTrials:=100000000);
[ 1238926361552897, 934616397135679777691 63558199606896684051237641638188680280321 ]
```

### 14.4.8 PrimeDivisors

\[ \text{PrimeDivisors}(n) \]

(\text{attribute})

PrimeDivisors returns for a non-zero integer \( n \) a set of its positive (probable) primes divisors. In rare cases the result could contain a composite number which passed certain primality tests, see IsProbablyPrimeInt (14.4.2) and FactorsInt (14.4.7) for more details.

```gap
gap> PrimeDivisors(-12);
[ 2, 3 ]
gap> PrimeDivisors(1);
[ ]
```
14.4.9 PartialFactorization

PartialFactorization returns a partial factorization of the integer \( n \). No assertions are made about the primality of the factors, except of those mentioned below.

The argument \( effort \), if given, specifies how intensively the function should try to determine factors of \( n \). The default is \( effort = 5 \).

- If \( effort = 0 \), trial division by the primes below 100 is done. Returned factors below \( 10^4 \) are guaranteed to be prime.
- If \( effort = 1 \), trial division by the primes below 1000 is done. Returned factors below \( 10^6 \) are guaranteed to be prime.
- If \( effort = 2 \), additionally trial division by the numbers in the lists Primes2 and ProbablePrimes2 is done, and perfect powers are detected. Returned factors below \( 10^6 \) are guaranteed to be prime.
- If \( effort = 3 \), additionally FactorsRho (Pollard’s Rho) with RhoTrials = 256 is used.
- If \( effort = 4 \), as above, but RhoTrials = 2048.
- If \( effort = 5 \), as above, but RhoTrials = 8192. Returned factors below \( 10^{12} \) are guaranteed to be prime, and all prime factors below \( 10^6 \) are guaranteed to be found.
- If \( effort = 6 \) and the package FactInt is loaded, in addition to the above quite a number of special cases are handled.
- If \( effort = 7 \) and the package FactInt is loaded, the only thing which is not attempted to obtain a full factorization into Baillie-Pomerance-Selfridge-Wagstaff pseudoprimes is the application of the MPQS to a remaining composite with more than 50 decimal digits.

Increasing the value of the argument \( effort \) by one usually results in an increase of the runtime requirements by a factor of (very roughly!) 3 to 10. (Also see CheapFactorsInt (EDIM: CheapFactorsInt)).

Example:

```gap
List([0..5],i->PartialFactorization(97^35-1,i));
```

```
[ [ 2, 2, 2, 2, 2, 3, 11, 31, 43, 24463389590696215209019263651689171101059782024229656319002965029 ],
  [ 2, 2, 2, 2, 2, 3, 11, 31, 43, 967, 25298231220894004229764877473817798356367065687337671812787 ],
  [ 2, 2, 2, 2, 3, 3, 31, 31, 43, 967, 25298231220894004229764877473817798356367065687337671812787 ],
  [ 2, 2, 2, 2, 2, 3, 3, 31, 31, 43, 967, 25298231220894004229764877473817798356367065687337671812787 ],
  [ 2, 2, 2, 2, 3, 3, 31, 31, 43, 967, 2426591739503269218697694214365631534465616962914227 ],
  [ 2, 2, 2, 2, 3, 3, 31, 31, 43, 967, 25298231220894004229764877473817798356367065687337671812787 ],
  [ 2, 2, 2, 2, 3, 3, 31, 31, 43, 967, 39761, 262321, 24265917395032692186976942143656311534465616962914227 ],
  [ 2, 2, 2, 2, 3, 3, 31, 31, 43, 967, 39761, 262321, 687121, 3529939410427846312333513593170858474160787 ],
  [ 2, 2, 2, 2, 2, 3, 3, 31, 31, 43, 967, 39761, 262321, 687121, 20241187, 504769301, 345649173943451574629911361501 ] ]
```
14.4.10 PrintFactorsInt

- **PrintFactorsInt(n)** (function)

prints the prime factorization of the integer \( n \) in human-readable form. See also StringPP (27.7.9).

Example

```gap
gap> PrintFactorsInt( Factorial( 7 ) ); Print( "\n" );
2^4*3^2*5*7
```

14.4.11 PrimePowersInt

- **PrimePowersInt(n)** (function)

returns the prime factorization of the integer \( n \) as a list \([p_1, e_1, \ldots, p_k, e_k] \) with \( n = p_1^{e_1} \cdot p_2^{e_2} \cdot \ldots \cdot p_k^{e_k} \). For negative integers, the absolute value is taken. Zero is not allowed as input.

Example

```gap
gap> PrimePowersInt( Factorial( 7 ) );
[ 2, 4, 3, 2, 5, 1, 7, 1 ]
gap> PrimePowersInt( 1 );
[ ]
```

14.4.12 DivisorsInt

- **DivisorsInt(n)** (function)

DivisorsInt returns a list of all divisors of the integer \( n \). The list is sorted, so that it starts with 1 and ends with \( n \). We define that \( \text{DivisorsInt}( -n ) = \text{DivisorsInt}( n ) \).

Since the set of divisors of 0 is infinite calling \( \text{DivisorsInt}( 0 ) \) causes an error.

DivisorsInt may call FactorsInt (14.4.7) to obtain the prime factors. Sigma (15.5.1) and Tau (15.5.2) compute the sum and the number of positive divisors, respectively.

Example

```gap
gap> DivisorsInt( 1 ); DivisorsInt( 20 ); DivisorsInt( 541 );
[ 1 ]
[ 1, 2, 4, 5, 10, 20 ]
[ 1, 541 ]
```

14.5 Residue Class Rings

\texttt{ZmodnZ} (14.5.2) returns a residue class ring of \texttt{Integers} (14) modulo an ideal. These residue class rings are rings, thus all operations for rings (see Chapter 56) apply. See also Chapters 59 and 15.

14.5.1 \mod (for residue class rings)

- **\mod(r/s, n)** (operation)
If \( r, s \) and \( n \) are integers, \( r / s \) as a reduced fraction is \( p/q \), where \( q \) and \( n \) are coprime, then \( r / s \mod n \) is defined to be the product of \( p \) and the inverse of \( q \) modulo \( n \). See Section 4.13 for more details and definitions.

With the above definition, \( 4 / 6 \mod 32 \) equals \( 2 / 3 \mod 32 \) and hence exists (and is equal to 22), despite the fact that 6 has no inverse modulo 32.

### 14.5.2 ZmodnZ

- \( \text{ZmodnZ}(n) \) (function)
- \( \text{ZmodpZ}(p) \) (function)
- \( \text{ZmodpZN}C(p) \) (function)

\( \text{ZmodnZ} \) returns a ring \( R \) isomorphic to the residue class ring of the integers modulo the ideal generated by \( n \). The element corresponding to the residue class of the integer \( i \) in this ring can be obtained by \( i \ast \text{One}(R) \), and a representative of the residue class corresponding to the element \( x \in R \) can be computed by \( \text{Int}(x) \).

\( \text{ZmodnZ}(n) \) is equal to \( \text{Integers \ mod \ } n \).

\( \text{ZmodpZ} \) does the same if the argument \( p \) is a prime integer, additionally the result is a field.

\( \text{ZmodpZNC} \) omits the check whether \( p \) is a prime.

Each ring returned by these functions contains the whole family of its elements if \( n \) is not a prime, and is embedded into the family of finite field elements of characteristic \( n \) if \( n \) is a prime.

### 14.5.3 ZmodnZObj (for a residue class family and integer)

- \( \text{ZmodnZObj}(\text{Fam}, r) \) (operation)
- \( \text{ZmodnZObj}(r, n) \) (operation)

If the first argument is a residue class family \( \text{Fam} \) then \( \text{ZmodnZObj} \) returns the element in \( \text{Fam} \) whose coset is represented by the integer \( r \).

If the two arguments are an integer \( r \) and a positive integer \( n \) then \( \text{ZmodnZObj} \) returns the element in \( \text{ZmodnZ}(n) \) (see \( \text{ZmodnZ} \) (14.5.2)) whose coset is represented by the integer \( r \).

**Example**

```gap
gap> r := ZmodnZ(15);
(\text{Integers \ mod \ } 15)
gap> fam := ElementsFamily(FamilyObj(r));;
gap> a := ZmodnZObj(fam, 9);
ZmodnZObj( 9, 15 )
gap> a+a;
ZmodnZObj( 3, 15 )
gap> Int(a+a);
3
```

### 14.5.4 IsZmodnZObj

- \( \text{IsZmodnZObj}(\text{obj}) \) (Category)
- \( \text{IsZmodnZObjNonprime}(\text{obj}) \) (Category)
- \( \text{IsZmodpZObj}(\text{obj}) \) (Category)
- \( \text{IsZmodpZObjSmall}(\text{obj}) \) (Category)
(The elements in the rings $\mathbb{Z}/n\mathbb{Z}$ are in the category `IsZmodnZObj`. If $n$ is a prime then the elements are of course also in the category `IsFFE (59.1.1)`, otherwise they are in `IsZmodnZObjNonprime`. `IsZmodpZObjLarge` is an abbreviation of `IsZmodnZObj` and `IsFFE`. This category is the disjoint union of `IsZmodpZObjSmall` and `IsZmodpZObjLarge`, the former containing all elements with $n$ at most `MAXSIZE_GF_INTERNAL`.

The reasons to distinguish the prime case from the nonprime case are:

- that objects in `IsZmodnZObjNonprime` have an external representation (namely the residue in the range $[0, 1, \ldots, n - 1]$),
- that the comparison of elements can be defined as comparison of the residues, and
- that the elements lie in a family of type `IsZmodnZObjNonprimeFamily` (note that for prime $n$, the family must be an `IsFFEFamily`).

The reasons to distinguish the small and the large case are that for small $n$ the elements must be compatible with the internal representation of finite field elements, whereas we are free to define comparison as comparison of residues for large $n$.

Note that we cannot claim that every finite field element of degree 1 is in `IsZmodnZObj`, since finite field elements in internal representation may not know that they lie in the prime field.

### 14.6 Check Digits

#### 14.6.1 CheckDigitISBN

- `CheckDigitISBN(n)` (function)
- `CheckDigitISBN13(n)` (function)
- `CheckDigitPostalMoneyOrder(n)` (function)
- `CheckDigitUPC(n)` (function)

These functions can be used to compute, or check, check digits for some everyday items. In each case what is submitted as input is either the number with check digit (in which case the function returns `true` or `false`), or the number without check digit (in which case the function returns the missing check digit). The number can be specified as integer, as string (for example in case of leading zeros) or as a sequence of arguments, each representing a single digit. The check digits tested are the 10-digit ISBN (International Standard Book Number) using `CheckDigitISBN` (since arithmetic is module 11, a digit 11 is represented by an X); the newer 13-digit ISBN-13 using `CheckDigitISBN13`; the numbers of 11-digit US postal money orders using `CheckDigitPostalMoneyOrder`; and the 12-digit UPC bar code found on groceries using `CheckDigitUPC`.

```bash
gap> CheckDigitISBN("0621661039");
Check Digit is 'X'
'X'
gap> CheckDigitISBN("062166103X");
Checksum test satisfied
true
gap> CheckDigitISBN(0,5,2,1,6,6,1,0,3,1);
```
Checksum test failed
false

\texttt{gap> CheckDigitISBN(0,5,2,1,6,6,1,0,3,'X');} # note single quotes!
Checksum test satisfied
true

\texttt{gap> CheckDigitISBN13("9781420094527");}
Checksum test satisfied
true

\texttt{gap> CheckDigitUPC("07164183001");}
Check Digit is 1
1

\texttt{gap> CheckDigitPostalMoneyOrder(16786457155);}
Checksum test satisfied
true

\subsection*{14.6.2 \texttt{CheckDigitTestFunction}}
\begin{quote}
\texttt{CheckDigitTestFunction(l, m, f)} \hfill (function)
\end{quote}

This function creates check digit test functions such as \texttt{CheckDigitISBN} \hspace{0.5cm} (14.6.1) for check digit schemes that use the inner products with a fixed vector modulo a number. The scheme creates will use strings of \texttt{l} digits (including the check digits), the check consists of taking the standard product of the vector of digits with the fixed vector \texttt{f} modulo \texttt{m}; the result needs to be 0. The function returns a function that then can be used for testing or determining check digits.

\begin{verbatim}
\texttt{gap> isbntest:=CheckDigitTestFunction(10,11,[1,2,3,4,5,6,7,8,9,-1]);}
\texttt{function( arg... ) ... end}
\texttt{gap> isbntest("038794680");}
Check Digit is 2
2
\end{verbatim}

\subsection*{14.7 Random Sources}

\texttt{GAP} provides \texttt{Random} \hspace{0.5cm} (30.7.1) methods for many collections of objects. On a lower level these methods use \textit{random sources} which provide random integers and random choices from lists.

\subsubsection*{14.7.1 \texttt{IsRandomSource}}
\begin{quote}
\texttt{IsRandomSource(obj)} \hfill (Category)
\end{quote}

This is the category of random source objects which are defined to have, for an object \texttt{rs} in this category, methods available for the following operations which are explained in more detail below: \texttt{Random(rs, list)} giving a random element of a list, \texttt{Random(rs, low, high)} giving a random integer between \texttt{low} and \texttt{high} (inclusive), \texttt{Init} \hspace{0.5cm} (14.7.3), \texttt{State} \hspace{0.5cm} (14.7.3) and \texttt{Reset} \hspace{0.5cm} (14.7.3).

Use \texttt{RandomSource} \hspace{0.5cm} (14.7.5) to construct new random sources.

One idea behind providing several independent (pseudo) random sources is to make algorithms which use some sort of random choices deterministic. They can use their own new random source created with a fixed seed and so do exactly the same in different calls.
Random source objects lie in the family RandomSourcesFamily.

### 14.7.2 Random (for random source and list)

- Random(\(rs\), \(list\))
- Random(\(rs\), \(coll\))
- Random(\(rs\), \(low\), \(high\))

This operation returns a random element from the list \(list\) or the collection \(coll\), or an integer in the range from the given (possibly large) integers \(low\) to \(high\), respectively.

The choice should only depend on the random source \(rs\) and have no effect on other random sources.

#### Example

```gap
gap> mysource := RandomSource(IsMersenneTwister, 42);;
gap> Random(mysource, 1, 10^60);
999331861769949319194941485000557997842686717712196687315183
```

### 14.7.3 State

- State(\(rs\))
- Reset(\(rs\)[, \(seed\)])
- Init(\(prers\)[, \(seed\)])

These are the basic operations for which random sources (see IsRandomSource (14.7.1)) must have methods.

State should return a data structure which allows to recover the state of the random source such that a sequence of random calls using this random source can be reproduced. If a random source cannot be reset (say, it uses truly random physical data) then State should return fail.

Reset(\(rs\), \(seed\)) resets the random source \(rs\) to a state described by \(seed\), if the random source can be reset (otherwise it should do nothing). Here \(seed\) can be an output of State and then should reset to that state. Also, the methods should always allow integers as \(seed\). Without the \(seed\) argument the default \(seed\) = 1 is used.

Init is the constructor of a random source, it gets an empty component object \(prers\) which has already the correct type and should fill in the actual data which are needed. Optionally, it should allow one to specify a \(seed\) for the initial state, as explained for Reset.

Most methods for Random (30.7.1) in the GAP library use the GlobalMersenneTwister (14.7.4) as random source. It can be reset into a known state as in the following example.

#### Example

```gap
gap> seed := Reset(GlobalMersenneTwister);;
gap> seed = State(GlobalMersenneTwister);
true
gap> List([1..10], i->Random(Integers));
[ -3, 2, -1, -2, -1, 1, -4, 1, 0 ]
gap> List([1..10], i->Random(Integers));
[ -1, -1, -1, 1, -1, 1, -2, -1, -2, 0 ]
gap> Reset(GlobalMersenneTwister, seed);;
gap> List([1..10], i->Random(Integers));
[ -3, 2, -1, -2, -1, 1, -4, 1, 0 ]```
14.7.4 IsMersenneTwister

- IsMersenneTwister(rs)  (Category)
- IsGAPRandomSource(rs)  (Category)
- IsGlobalRandomSource(rs)  (Category)
- GlobalMersenneTwister  (global variable)
- GlobalRandomSource  (global variable)

Currently, the GAP library provides three types of random sources, distinguished by the three listed categories.

IsMersenneTwister are random sources which use a fast random generator of 32 bit numbers, called the Mersenne twister. The pseudo random sequence has a period of $2^{19937} - 1$ and the numbers have a 623-dimensional equidistribution. For more details and the origin of the code used in the GAP kernel, see: http://www.math.sci.hiroshima-u.ac.jp/~m-mat/MT/emt.html.

Use the Mersenne twister if possible, in particular for generating many large random integers.

There is also a predefined global random source GlobalMersenneTwister which is used by most of the library methods for Random (30.7.1).

IsGAPRandomSource uses the same number generator as IsGlobalRandomSource, but you can create several of these random sources which generate their random numbers independently of all other random sources.

IsGlobalRandomSource gives access to the classical global random generator which was used by GAP in former releases. You do not need to construct new random sources of this kind which would all use the same global data structure. Just use the existing random source GlobalRandomSource. This uses the additive random number generator described in [Knu98] (Algorithm A in 3.2.2 with lag 30).

14.7.5 RandomSource

- RandomSource(cat [, seed])  (operation)

This operation is used to create new random sources. The first argument cat is the category describing the type of the random generator, an optional seed which can be an integer or a type specific data structure can be given to specify the initial state.

Example

```gap
gap> rs1 := RandomSource(IsMersenneTwister);
<RandomSource in IsMersenneTwister>
gap> state1 := State(rs1);

gap> l1 := List([1..10000], i-> Random(rs1, [1..6]));
gap> rs2 := RandomSource(IsMersenneTwister);
gap> l2 := List([1..10000], i-> Random(rs2, [1..6]));
gap> l1 = l2;
true

gap> n := Random(rs1, 1, 2^220);
107726777923092117987668044202944212469136000816111066409337432400
```
14.8 Bitfields

Bitfields are a low-level feature intended to support efficient subdivision of immediate integers into bitfields of various widths. This is typically useful in implementing space-efficient and/or cache-efficient data structures. This feature should be used with care because (inter alia) it has different limitations on 32-bit and 64-bit architectures.

14.8.1 MakeBitfields

\[ \texttt{MakeBitfields(width...,)} \]

This function sets up the machinery for a set of bitfields of the given widths. All bitfield values are treated as unsigned. The total of the widths must not exceed 60 bits on 64-bit architecture or 28 bits on a 32-bit architecture. For performance reasons some checks that one might wish to do are omitted. In particular, the builder and setter functions do not check if the value[s] passed to them are negative or too large (unless GAP is specially compiled for debugging). Behaviour when such arguments are passed is undefined. You can tell which type of architecture you are running on by accessing GAPInfo.BytesPerVariable which is 8 on 64-bits and 4 on 32. The return value when \( n \) widths are given is a record whose fields are

- \texttt{widths} a copy of the arguments, for convenience,
- \texttt{getters} a list of \( n \) functions of one argument each of which extracts one of the fields from an immediate integer
- \texttt{setters} a list of \( n \) functions each taking two arguments: a packed value and a new value for one of its fields and returning a new packed value. The \( i \)th function returned the new packed value in which the \( i \)th field has been replaced by the new value. Note that this does NOT modify the original packed value.

Two additional fields may be present if any of the field widths is one. Each is a list and only has entryed bound in the positions corresponding to the width 1 fields.

- \texttt{booleanGetters} if the \( i \)th position of this list is set, it contains a function which extracts the \( i \)th field (which will have width one) and returns \texttt{true} if it contains 1 and \texttt{false} if it contains 0
- \texttt{booleanSetters} if the \( i \)th position of this list is set, it contains a function of two arguments. The first argument is a packed value, the second is \texttt{true} or \texttt{false}. It returns a new packed value in which the \( i \)th field is set to 1 if the second argument was \texttt{true} and 0 if it was \texttt{false}. Behaviour for any other value is undefined.

14.8.2 BuildBitfields

\[ \texttt{BuildBitfields(widths, vals...)} \]
This function takes one or more argument. It’s first argument is a list of field widths, as found in the widths entry of a record returned by MakeBitfields. The remaining arguments are unsigned integer values, equal in number to the entries of the list of field widths. It returns a small integer in which those entries are packed into bitfields of the given widths. The first entry occupies the least significant bits. DeclareGlobalFunction("BuildBitfields");

```
Example
```

```
gap> bf := MakeBitfields(1,2,3);
  rec( booleanGetters := [ function( data ) ... end ],
       booleanSetters := [ function( data, val ) ... end ],
       getters := [ function( data ) ... end, function( data ) ... end,
                    function( data ) ... end ],
       setters := [ function( data, val ) ... end, function( data, val ) ... end,
                    function( data, val ) ... end ],
       widths := [ 1, 2, 3 ]
  )
gap> x := BuildBitfields(bf.widths,0,3,5);
   46
gap> bf.getters[3](x);
   5
gap> y := bf.setters[1](x,1);
   47
gap> x;
   46
gap> bf.booleanGetters[1](x);
false
gap> bf.booleanGetters[1](y);
true
```
Chapter 15

Number Theory

GAP provides a couple of elementary number theoretic functions. Most of these deal with the group of integers coprime to \( m \), called the prime residue group. The order of this group is \( \phi(m) \) (see \Phi (15.2.2)), and \( \lambda(m) \) (see \Lambda (15.2.3)) is its exponent. This group is cyclic if and only if \( m \) is 2, 4, an odd prime power \( p^n \), or twice an odd prime power \( 2p^n \). In this case the generators of the group, i.e., elements of order \( \phi(m) \), are called primitive roots (see \PrimitiveRootMod (15.3.3)).

Note that neither the arguments nor the return values of the functions listed below are groups or group elements in the sense of GAP. The arguments are simply integers.

15.1  InfoNumtheor (Info Class)

15.1.1  InfoNumtheor

\( \text{InfoNumtheor} \)

\( \text{InfoNumtheor} \) is the info class (see 7.4) for the functions in the number theory chapter.

15.2  Prime Residues

15.2.1  PrimeResidues

\( \text{PrimeResidues}(m) \)

PrimeResidues returns the set of integers from the range \( [ 0 \ldots \text{Abs}(m)-1 ] \) that are coprime to the integer \( m \).

\( \text{Abs}(m) \) must be less than \( 2^{28} \), otherwise the set would probably be too large anyhow.

\begin{verbatim}
Example

gap> PrimeResidues(0); PrimeResidues(1); PrimeResidues(20);
[ ]
[ 0 ]
[ 1, 3, 7, 9, 11, 13, 17, 19 ]
\end{verbatim}
15.2.2 Phi

\textbullet{} \Phi(m) \quad \text{(operation)}

\Phi returns the number \( \phi(m) \) of positive integers less than the positive integer \( m \) that are coprime to \( m \).

Suppose that \( m = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k} \). Then \( \phi(m) = p_1^{e_1-1}(p_1-1)p_2^{e_2-1}(p_2-1) \cdots p_k^{e_k-1}(p_k-1) \).

Example

\begin{verbatim}
gap> Phi( 12 );
4
gap> Phi( 2^13-1 ); # this proves that 2^(13)-1 is a prime
8190
gap> Phi( 2^15-1 );
27000
\end{verbatim}

15.2.3 Lambda

\textbullet{} \Lambda(m) \quad \text{(operation)}

\Lambda returns the exponent \( \lambda(m) \) of the group of prime residues modulo the integer \( m \).

\( \lambda(m) \) is the smallest positive integer \( l \) such that for every \( a \) relatively prime to \( m \) we have \( a^l \equiv 1 \pmod{m} \); thus \( \lambda(m) \) divides \( \phi(m) \) (see \Phi (15.2.2)).

Carmichael’s theorem states that \( \lambda \) can be computed as follows: \( \lambda(2) = 1, \lambda(4) = 2 \) and \( \lambda(2^e) = 2^{e-2} \) if \( 3 \leq e, \lambda(p^e) = (p-1)p^{e-1} \) (i.e. \( \phi(m) \)) if \( p \) is an odd prime and \( \lambda(m \cdot n) = \text{Lcm}(\lambda(m), \lambda(n)) \) if \( m, n \) are coprime.

Composites for which \( \lambda(m) \) divides \( m-1 \) are called Carmichaels. If \( 6k+1, 12k+1 \) and \( 18k+1 \) are primes their product is such a number. There are only 1547 Carmichaels below \( 10^{10} \) but 455052511 primes.

Example

\begin{verbatim}
gap> Lambda( 10 );
4
gap> Lambda( 30 );
4
gap> Lambda( 561 ); # 561 is the smallest Carmichael number
80
\end{verbatim}

15.2.4 GeneratorsPrimeResidues

\textbullet{} GeneratorsPrimeResidues(n) \quad \text{(function)}

Let \( n \) be a positive integer. GeneratorsPrimeResidues returns a description of generators of the group of prime residues modulo \( n \). The return value is a record with components

\textbf{primes:}

a list of the prime factors of \( n \),

\textbf{exponents:}

a list of the exponents of these primes in the factorization of \( n \), and
generators:
a list describing generators of the group of prime residues; for the prime factor 2, either a
primitive root or a list of two generators is stored, for each other prime factor of \( n \), a primitive
root is stored.

Example

\begin{verbatim}
gap> GeneratorsPrimeResidues( 1 );
rec( exponents := [ ], generators := [ ], primes := [ ] )
gap> GeneratorsPrimeResidues( 4*3 );
rec( exponents := [ 2, 1 ], generators := [ 7, 5 ],
    primes := [ 2, 3 ] )
gap> GeneratorsPrimeResidues( 8*9*5 );
rec( exponents := [ 3, 2, 1 ],
    generators := [ [ 271, 181 ], 281, 217 ], primes := [ 2, 3, 5 ] )
\end{verbatim}

15.3 Primitive Roots and Discrete Logarithms

15.3.1 OrderMod

\begin{verbatim}
OrderMod( \( n, m \) )
\end{verbatim}

OrderMod returns the multiplicative order of the integer \( n \) modulo the positive integer \( m \). If \( n \) and
\( m \) are not coprime the order of \( n \) is not defined and OrderMod will return 0.

If \( n \) and \( m \) are relatively prime the multiplicative order of \( n \) modulo \( m \) is the smallest positive
integer \( i \) such that \( n^i \equiv 1 \pmod{m} \). If the group of prime residues modulo \( m \) is cyclic then each
element of maximal order is called a primitive root modulo \( m \) (see IsPrimitiveRootMod (15.3.4)).

OrderMod usually spends most of its time factoring \( m \) and \( \phi(m) \) (see FactorsInt (14.4.7)).

Example

\begin{verbatim}
gap> OrderMod( 2, 7 );
3
\end{verbatim}

Example

\begin{verbatim}
gap> OrderMod( 3, 7 );  # 3 is a primitive root modulo 7
6
\end{verbatim}

15.3.2 LogMod

\begin{verbatim}
LogMod( \( n, r, m \) )
LogModShanks( \( n, r, m \) )
\end{verbatim}

computes the discrete \( r \)-logarithm of the integer \( n \) modulo the integer \( m \). It returns a number \( l \)
such that \( r^l \equiv n \pmod{m} \) if such a number exists. Otherwise \texttt{fail} is returned.

\texttt{LogModShanks} uses the Baby Step - Giant Step Method of Shanks (see for example [Coh93,
section 5.4.1]) and in general requires more memory than a call to \texttt{LogMod}.

Example

\begin{verbatim}
gap> l:= LogMod( 2, 5, 7 ); 5^l mod 7 = 2;
4
true
\end{verbatim}
15.3.3 PrimitiveRootMod

\[ \text{PrimitiveRootMod}(m[, \text{start}]) \]

PrimitiveRootMod returns the smallest primitive root modulo the positive integer \( m \) and fail if no such primitive root exists. If the optional second integer argument \( \text{start} \) is given, PrimitiveRootMod returns the smallest primitive root that is strictly larger than \( \text{start} \).

Example

\begin{verbatim}
gap> # largest primitive root for a prime less than 2000:
gap> PrimitiveRootMod( 409 );
21
gap> PrimitiveRootMod( 541, 2 );
10
gap> # 327 is the largest primitive root mod 337:
gap> PrimitiveRootMod( 337, 327 );
fail
gap> # there exists no primitive root modulo 30:
gap> PrimitiveRootMod( 30 );
fail
\end{verbatim}

15.3.4 IsPrimitiveRootMod

\[ \text{IsPrimitiveRootMod}(r, m) \]

IsPrimitiveRootMod returns true if the integer \( r \) is a primitive root modulo the positive integer \( m \), and false otherwise. If \( r \) is less than 0 or larger than \( m \) it is replaced by its remainder.

Example

\begin{verbatim}
gap> IsPrimitiveRootMod( 2, 541 );
true
gap> IsPrimitiveRootMod( -539, 541 ); # same computation as above;
true
gap> IsPrimitiveRootMod( 4, 541 );
false
gap> ForAny( [1..29], r -> IsPrimitiveRootMod( r, 30 ) );
false
\end{verbatim}

15.4 Roots Modulo Integers

15.4.1 Jacobi

\[ \text{Jacobi}(n, m) \]

Jacobi returns the value of the Kronecker-Jacobi symbol \( J(n,m) \) of the integer \( n \) modulo the integer \( m \). It is defined as follows:

If \( n \) and \( m \) are not coprime then \( J(n,m) = 0 \). Furthermore, \( J(n,1) = 1 \) and \( J(n,-1) = -1 \) if \( m < 0 \) and \( +1 \) otherwise. And for odd \( n \) it is \( J(n,2) = (-1)^k \) with \( k = (n^2 - 1)/8 \). For odd primes \( m \) which are coprime to \( n \) the Kronecker-Jacobi symbol has the same value as the Legendre symbol (see Legendre (15.4.2)).
For the general case suppose that \( m = p_1 \cdot p_2 \cdot \cdots \cdot p_k \) is a product of \(-1\) and of primes, not necessarily distinct, and that \( n \) is coprime to \( m \). Then \( J(n,m) = J(n,p_1) \cdot J(n,p_2) \cdot \cdots \cdot J(n,p_k) \).

Note that the Kronecker-Jacobi symbol coincides with the Jacobi symbol that is defined for odd \( m \) in many number theory books. For odd primes \( m \) and \( n \) coprime to \( m \) it coincides with the Legendre symbol.

Jacobi is very efficient, even for large values of \( n \) and \( m \), it is about as fast as the Euclidean algorithm (see `Gcd` (56.7.1)).

Example

```gap
gap> Jacobi( 11, 35 ); # 9^2 = 11 mod 35
1
gap> # this is -1, thus there is no r such that r^2 = 6 mod 35
gap> Jacobi( 6, 35 );
-1
gap> # this is 1 even though there is no r with r^2 = 3 mod 35
gap> Jacobi( 3, 35 );
1
```

15.4.2 Legendre

\[\text{Legendre}(n, m)\]

Legendre returns the value of the Legendre symbol of the integer \( n \) modulo the positive integer \( m \).

The value of the Legendre symbol \( L(n/m) \) is 1 if \( n \) is a quadratic residue modulo \( m \), i.e., if there exists an integer \( r \) such that \( r^2 \equiv n \pmod{m} \) and \(-1\) otherwise.

If a root of \( n \) exists it can be found by `RootMod` (15.4.3).

While the value of the Legendre symbol usually is only defined for \( m \) a prime, we have extended the definition to include composite moduli too. The Jacobi symbol (see `Jacobi` (15.4.1)) is another generalization of the Legendre symbol for composite moduli that is much cheaper to compute, because it does not need the factorization of \( m \) (see `FactorsInt` (14.4.7)).

A description of the Jacobi symbol, the Legendre symbol, and related topics can be found in [Bak84].

Example

```gap
gap> Legendre( 5, 11 ); # 4^2 = 5 mod 11
1
gap> # this is -1, thus there is no r such that r^2 = 6 mod 11
gap> Legendre( 6, 11 );
-1
gap> # this is -1, thus there is no r with r^2 = 3 mod 35
gap> Legendre( 3, 35 );
-1
```

15.4.3 RootMod

\[\text{RootMod}(n[, k], m)\]

RootMod computes a \( k \)th root of the integer \( n \) modulo the positive integer \( m \), i.e., a \( r \) such that \( r^k \equiv n \pmod{m} \). If no such root exists `RootMod` returns `fail`. If only the arguments \( n \) and \( m \) are given, the default value for \( k \) is 2.
A square root of \( n \) exists only if \( \text{Legendre}(n, m) = 1 \) (see \text{Legendre} (15.4.2)). If \( m \) has \( r \) different prime factors then there are \( 2^r \) different roots of \( n \mod m \). It is unspecified which one \text{RootMod} returns. You can, however, use \text{RootsMod} (15.4.4) to compute the full set of roots.

\text{RootMod} is efficient even for large values of \( m \), in fact the most time is usually spent factoring \( m \) (see \text{FactorsInt} (14.4.7)).

**Example**

\begin{verbatim}
gap> # note 'RootMod' does not return 8 in this case but -8:
gap> RootMod( 64, 1009 );
1001
gap> RootMod( 64, 3, 1009 );
518
gap> RootMod( 64, 5, 1009 );
656
gap> List( RootMod( 64, 1009 ) * RootsUnityMod( 1009 ),
> x -> x mod 1009 ); # set of all square roots of 64 mod 1009
[ 1001, 8 ]
\end{verbatim}

### 15.4.4 RootsMod

\begin{function}
\texttt{RootsMod}( n[, k], m )
\end{function}

\text{RootsMod} computes the set of \( k \)th roots of the integer \( n \) modulo the positive integer \( m \), i.e., the list of all \( r \) such that \( r^k \equiv n \pmod{m} \). If only the arguments \( n \) and \( m \) are given, the default value for \( k \) is 2.

**Example**

\begin{verbatim}
gap> RootsMod( 1, 7*31 ); # the same as 'RootsUnityMod( 7*31 )'
[ 1, 92, 125, 216 ]
gap> RootsMod( 7, 7*31 );
[ 21, 196 ]
gap> RootsMod( 5, 7*31 );
[ ]
gap> RootsMod( 1, 5, 7*31 );
[ 1, 8, 64, 78, 190 ]
\end{verbatim}

### 15.4.5 RootsUnityMod

\begin{function}
\texttt{RootsUnityMod}( k[, ]m )
\end{function}

\text{RootsUnityMod} returns the set of \( k \)-th roots of unity modulo the positive integer \( m \), i.e., the list of all solutions \( r \) of \( r^k \equiv 1 \pmod{m} \). If only the argument \( m \) is given, the default value for \( k \) is 2.

In general there are \( k^n \) such roots if the modulus \( m \) has \( n \) different prime factors \( p \) such that \( p \equiv 1 \pmod{k} \). If \( k^2 \) divides \( m \), then there are \( k^{n+1} \) such roots; and especially if \( k = 2 \) and 8 divides \( m \) there are \( 2^{n+2} \) such roots.

In the current implementation \( k \) must be a prime.

**Example**

\begin{verbatim}
gap> RootsUnityMod( 7*31 ); RootsUnityMod( 3, 7*31 );
[ 1, 92, 125, 216 ]
[ 1, 25, 32, 67, 149, 156, 191, 211 ]
gap> RootsUnityMod( 5, 7*31 );
[ 1, 8, 64, 78, 190 ]
\end{verbatim}
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15.5 Multiplicative Arithmetic Functions

15.5.1 Sigma

\[ \text{Sigma}(n) \]

Sigma returns the sum of the positive divisors of the nonzero integer \( n \).
Sigma is a multiplicative arithmetic function, i.e., if \( n \) and \( m \) are relatively prime we have that 
\[ \sigma(n \cdot m) = \sigma(n)\sigma(m). \]
Together with the formula \( \sigma(p^k) = \frac{p^{k+1} - 1}{p - 1} \) this allows us to compute \( \sigma(n) \).

Integers \( n \) for which \( \sigma(n) = 2n \) are called perfect. Even perfect integers are exactly of the form \( 2^{n-1}(2^n - 1) \) where \( 2^n - 1 \) is prime. Primes of the form \( 2^n - 1 \) are called Mersenne primes, and 42 among the known Mersenne primes are obtained for \( n = 2, 3, 5, 7, 13, 17, 19, 31, 61, 89, 107, 127, 521, 607, 1279, 2203, 2281, 3217, 4253, 4423, 44497, 6972593, 13466917, 20996011, 24036583 and 25964951. Please find more up to date information about Mersenne primes at https://www.mersenne.org. It is not known whether odd perfect integers exist, however [BC89] show that any such integer must have at least 300 decimal digits.

Sigma usually spends most of its time factoring \( n \) (see FactorsInt (14.4.7)).

Example

\[
\begin{align*}
\text{gap> } \text{Sigma}(1) ; \\
1 \\
\text{gap> } \text{Sigma}(1009) ; \quad \# \text{ 1009 is a prime} \\
1010 \\
\text{gap> } \text{Sigma}(8128) = 2 \cdot 8128; \quad \# \text{ 8128 is a perfect number} \\
\text{true}
\end{align*}
\]

15.5.2 Tau

\[ \text{Tau}(n) \]

Tau returns the number of the positive divisors of the nonzero integer \( n \).
Tau is a multiplicative arithmetic function, i.e., if \( n \) and \( m \) are relatively prime we have \( \tau(n \cdot m) = \tau(n)\tau(m) \). Together with the formula \( \tau(p^k) = k + 1 \) this allows us to compute \( \tau(n) \).

Tau usually spends most of its time factoring \( n \) (see FactorsInt (14.4.7)).

Example

\[
\begin{align*}
\text{gap> } \text{Tau}(1) ; \\
1 \\
\text{gap> } \text{Tau}(1013) ; \quad \# \text{ thus 1013 is a prime} \\
2 \\
\text{gap> } \text{Tau}(8128) ; \\
14 \\
\text{gap> } \# \text{ result is odd if and only if argument is a perfect square:}
\end{align*}
\]
gap> Tau( 36 );
9

15.5.3 MoebiusMu

MoebiusMu computes the value of Moebius inversion function for the nonzero integer \( n \). This is 0 for integers which are not squarefree, i.e., which are divided by a square \( r^2 \). Otherwise it is 1 if \( n \) has an even number and \(-1\) if \( n \) has an odd number of prime factors.

The importance of \( \mu \) stems from the so-called inversion formula. Suppose \( f \) is a multiplicative arithmetic function defined on the positive integers and let \( g(n) = \sum_d f(d) \). Then \( f(n) = \sum_{d|n} \mu(d) g(n/d) \). As a special case we have \( \phi(n) = \sum_{d|n} \mu(d) n/d \) since \( n = \sum_{d|n} \phi(d) \) (see Phi (15.2.2)).

MoebiusMu usually spends all of its time factoring \( n \) (see FactorsInt (14.4.7)).

Example

```gap
gap> MoebiusMu( 60 ); MoebiusMu( 61 ); MoebiusMu( 62 );
0
-1
1
```

15.6 Continued Fractions

15.6.1 ContinuedFractionExpansionOfRoot

ContinuedFractionExpansionOfRoot(\( f, n \)) (function)

The first \( n \) terms of the continued fraction expansion of the only positive real root of the polynomial \( f \) with integer coefficients. The leading coefficient of \( f \) must be positive and the value of \( f \) at 0 must be negative. If the degree of \( f \) is 2 and \( n = 0 \), the function computes one period of the continued fraction expansion of the root in question. Anything may happen if \( f \) has three or more positive real roots.

Example

```gap
x := Indeterminate(Integers);
gap> ContinuedFractionExpansionOfRoot(x^2-7,20);
[ 2, 1, 1, 1, 4, 1, 1, 1, 4, 1, 1, 1, 4, 1, 1, 1, 4, 1, 1, 1 ]
gap> ContinuedFractionExpansionOfRoot(x^2-7,0);
[ 2, 1, 1, 1, 4 ]
gap> ContinuedFractionExpansionOfRoot(x^3-2,20);
[ 1, 3, 1, 5, 1, 1, 4, 1, 1, 8, 1, 14, 1, 10, 2, 1, 4, 12, 2, 3 ]
gap> ContinuedFractionExpansionOfRoot(x^5-x-1,50);
[ 1, 5, 1, 42, 1, 3, 24, 2, 2, 1, 16, 1, 11, 1, 1, 2, 31, 1, 12, 5,
  1, 7, 11, 1, 4, 1, 4, 2, 2, 3, 4, 2, 1, 11, 1, 1, 41, 12, 1, 8, 1,
  1, 1, 1, 9, 2, 1, 5, 4 ]
```

15.6.2 ContinuedFractionApproximationOfRoot

ContinuedFractionApproximationOfRoot(\( f, n \)) (function)
The $n$th continued fraction approximation of the only positive real root of the polynomial $f$ with integer coefficients. The leading coefficient of $f$ must be positive and the value of $f$ at 0 must be negative. Anything may happen if $f$ has three or more positive real roots.

```
Example
```

```gap
ContinuedFractionApproximationOfRoot(x^2-2,10);
3363/2378
ContinuedFractionApproximationOfRoot(x^5-x-1,20);
49989783527/428250732317
```

```
Example
```
<table>
<thead>
<tr>
<th>Command</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>gap&gt; TwoSquares(11); # there is no representation</td>
<td>fail</td>
</tr>
<tr>
<td>gap&gt; TwoSquares(16);</td>
<td>[0, 4]</td>
</tr>
<tr>
<td>gap&gt; # 3 is the minimal possible gcd because 9 divides 45:</td>
<td></td>
</tr>
<tr>
<td>gap&gt; TwoSquares(45);</td>
<td>[3, 6]</td>
</tr>
<tr>
<td>gap&gt; # it is not [5,10] because their gcd is not minimal:</td>
<td></td>
</tr>
<tr>
<td>gap&gt; TwoSquares(125);</td>
<td>[2, 11]</td>
</tr>
<tr>
<td>gap&gt; # [10,11] would be the other possible representation:</td>
<td></td>
</tr>
<tr>
<td>gap&gt; TwoSquares(13*17);</td>
<td>[5, 14]</td>
</tr>
<tr>
<td>gap&gt; TwoSquares(8486544683879497562821); # argument is prime</td>
<td>[6305894639, 28440994650]</td>
</tr>
</tbody>
</table>
Chapter 16

Combinatorics

This chapter describes functions that deal with combinatorics. We mainly concentrate on two areas. One is about selections, that is the ways one can select elements from a set. The other is about partitions, that is the ways one can partition a set into the union of pairwise disjoint subsets.

16.1 Combinatorial Numbers

16.1.1 Factorial

\( \text{Factorial}(n) \) (function)

returns the factorial \( n! \) of the positive integer \( n \), which is defined as the product \( 1 \cdot 2 \cdot 3 \cdots n \). \( n! \) is the number of permutations of a set of \( n \) elements. \( 1/n! \) is the coefficient of \( x^n \) in the formal series \( \exp(x) \), which is the generating function for factorial.

Example

\[
\text{gap> List( [0..10], Factorial );}
\]
[ 1, 1, 2, 6, 24, 120, 720, 5040, 40320, 362880, 3628800 ]
\[
\text{gap> Factorial( 30 );}
265252859812191058636308480000000
\]

\text{PermutationsList (16.2.12)} computes the set of all permutations of a list.

16.1.2 Binomial

\( \text{Binomial}(n, k) \) (function)

returns the binomial coefficient \( \binom{n}{k} \) of integers \( n \) and \( k \). This is defined by the conditions \( \binom{n}{0} = 0 \) for \( k < 0 \), \( \binom{0}{k} = 0 \) for \( k \neq 0 \), \( \binom{0}{0} = 1 \) and the relation \( \binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1} \) for all \( n \) and \( k \).

There are many ways of describing this function. For example, if \( n \geq 0 \) and \( 0 \leq k \leq n \), then \( \binom{n}{k} = n! / (k!(n-k)!) \) and for \( n < 0 \) and \( k \geq 0 \) we have \( \binom{n}{k} = (-1)^k \binom{-n+k-1}{k} \).

If \( n \geq 0 \) then \( \binom{n}{k} \) is the number of subsets with \( k \) elements of a set with \( n \) elements. Also, \( \binom{n}{k} \) is the coefficient of \( x^k \) in the polynomial \( (x+1)^n \), which is the generating function for \( \binom{n}{k} \), hence the name.

Example

\[
\text{gap> # Knuth calls this the trademark of Binomial:}
\]
\[
\text{gap> List( [0..4], k->Binomial( 4, k ) );}
\]

218
1, 4, 6, 4, 1
gap> List( [0..6], n->List( [0..6], k->Binomial( n, k ) ) );
# the lower triangle is called Pascal's triangle:
PrintArray( last );
[ [ 1, 0, 0, 0, 0, 0, 0 ],
  [ 1, 1, 0, 0, 0, 0, 0 ],
  [ 1, 2, 1, 0, 0, 0, 0 ],
  [ 1, 3, 3, 1, 0, 0, 0 ],
  [ 1, 4, 6, 4, 1, 0, 0 ],
  [ 1, 5, 10, 10, 5, 1, 0 ],
  [ 1, 6, 15, 20, 15, 6, 1 ] ]
gap> Binomial( 50, 10 );
10272278170

NrCombinations (16.2.3) is the generalization of Binomial for multisets. Combinations (16.2.1) computes the set of all combinations of a multiset.

16.1.3 Bell

\texttt{Bell(n)}

returns the Bell number $B(n)$. The Bell numbers are defined by $B(0) = 1$ and the recurrence $B(n+1) = \sum_{k=0}^{n} \binom{n}{k} B(k)$.

$B(n)$ is the number of ways to partition a set of $n$ elements into pairwise disjoint nonempty subsets (see PartitionsSet (16.2.16)). This implies of course that $B(n) = \sum_{k=0}^{n} S_2(n,k)$ (see Stirling2 (16.1.6)). $B(n)/n!$ is the coefficient of $x^n$ in the formal series $\exp(\exp(x) - 1)$, which is the generating function for $B(n)$.

\texttt{gap> List( [0..6], n -> Bell( n ) );}
[ 1, 1, 2, 5, 15, 52, 203 ]
gap> Bell( 14 );
190899322

16.1.4 Bernoulli

\texttt{Bernoulli(n)}

returns the $n$-th Bernoulli number $B_n$, which is defined by $B_0 = 1$ and $B_n = -\sum_{k=0}^{n-1} \binom{n+1}{k} B_k / (n+1)$.

$B_n/n!$ is the coefficient of $x^n$ in the power series of $x/\exp(x) - 1)$. Except for $B_1 = -1/2$ the Bernoulli numbers for odd indices are zero.

\texttt{gap> Bernoulli( 4 );}
-1/30
\texttt{gap> Bernoulli( 10 );}
5/66
\texttt{gap> Bernoulli( 12 ); # there is no simple pattern in Bernoulli numbers}
-691/2730
\texttt{gap> Bernoulli( 50 ); # and they grow fairly fast}
4950670620544968212477525/66
16.1.5 Stirling1

\( \text{Stirling1}(n, k) \)

returns the Stirling number of the first kind \( S_1(n, k) \) of the integers \( n \) and \( k \). Stirling numbers of the first kind are defined by \( S_1(0, 0) = 1 \), \( S_1(n, 0) = S_1(0, k) = 0 \) if \( n, k \neq 0 \) and the recurrence \( S_1(n, k) = (n - 1)S_1(n - 1, k) + S_1(n - 1, k - 1) \).

\( S_1(n, k) \) is the number of permutations of \( n \) points with \( k \) cycles. Stirling numbers of the first kind appear as coefficients in the series \( n! \binom{x}{n} = \sum_{k=0}^{n} S_1(n, k) x^k \) which is the generating function for Stirling numbers of the first kind. Note the similarity to \( x^n = \sum_{k=0}^{n} S_2(n, k) k! \binom{x}{k} \) (see Stirling2 (16.1.6)). Also the definition of \( S_1 \) implies \( S_1(n, k) = S_2(-k, -n) \) if \( n, k < 0 \). There are many formulae relating Stirling numbers of the first kind to Stirling numbers of the second kind, Bell numbers, and Binomial coefficients.

Example

gap> # Knuth calls this the trademark of S_1:
gap> List( [0..4], k -> Stirling1( 4, k ) );
[ 0, 6, 11, 6, 1 ]
gap> List( [0..6], n->List( [0..6], k->Stirling1( n, k ) ) );;
gap> # note the similarity with Pascal's triangle for Binomial numbers
gap> PrintArray( last );
[ [ 1, 0, 0, 0, 0, 0, 0 ],
  [ 0, 1, 0, 0, 0, 0, 0 ],
  [ 0, 1, 1, 0, 0, 0, 0 ],
  [ 0, 2, 3, 1, 0, 0, 0 ],
  [ 0, 6, 11, 6, 1, 0, 0 ],
  [ 0, 24, 50, 225, 85, 15, 1 ] ]
gap> Stirling1(50,10);
10162302092636749005904379711930994043405650538053666627366376

16.1.6 Stirling2

\( \text{Stirling2}(n, k) \)

returns the Stirling number of the second kind \( S_2(n, k) \) of the integers \( n \) and \( k \). Stirling numbers of the second kind are defined by \( S_2(0, 0) = 1 \), \( S_2(n, 0) = S_2(0, k) = 0 \) if \( n, k \neq 0 \) and the recurrence \( S_2(n, k) = kS_2(n - 1, k) + S_2(n - 1, k - 1) \).

\( S_2(n, k) \) is the number of ways to partition a set of \( n \) elements into \( k \) pairwise disjoint nonempty subsets (see PartitionsSet (16.2.16)). Stirling numbers of the second kind appear as coefficients in the expansion of \( x^n = \sum_{k=0}^{n} S_2(n, k) k! \binom{x}{k} \). Note the similarity to \( n! \binom{x}{n} = \sum_{k=0}^{n} S_1(n, k) x^k \) (see Stirling1 (16.1.5)). Also the definition of \( S_2 \) implies \( S_2(n, k) = S_1(-k, -n) \) if \( n, k < 0 \). There are many formulae relating Stirling numbers of the second kind to Stirling numbers of the first kind, Bell numbers, and Binomial coefficients.

Example

gap> # Knuth calls this the trademark of S_2:
gap> List( [0..4], k -> Stirling2( 4, k ) );
[ 0, 1, 7, 6, 1 ]
gap> List( [0..6], n->List( [0..6], k->Stirling2( n, k ) ) );;
gap> # note the similarity with Pascal's triangle for Binomial numbers

gap> PrintArray( last );
[  [  1,  0,  0,  0,  0,  0,  0 ],
[  0,  1,  0,  0,  0,  0,  0 ],
[  0,  1,  1,  0,  0,  0,  0 ],
[  0,  1,  3,  1,  0,  0,  0 ],
[  0,  1,  7,  6,  1,  0,  0 ],
[  0,  1, 15, 25, 10,  1,  0 ],
[  0,  1, 31, 90, 65, 15,  1 ] ]
gap> Stirling2( 50, 10 );
2615471651586288129201277396577993781727011

16.2 Combinations, Arrangements and Tuples

16.2.1 Combinations

\textbf{Combinations}(mset[, k]) \hspace{1em} \text{(function)}

returns the set of all combinations of the multiset \textit{mset} (a list of objects which may contain the same object several times) with \textit{k} elements; if \textit{k} is not given it returns all combinations of \textit{mset}.

A combination of \textit{mset} is an unordered selection without repetitions and is represented by a sorted sublist of \textit{mset}. If \textit{mset} is a proper set, there are \binom{|mset|}{k} (see \textbf{Binomial} (16.1.2)) combinations with \textit{k} elements, and the set of all combinations is just the \textit{power set} of \textit{mset}, which contains all \textit{subsets} of \textit{mset} and has cardinality \(2^{|mset|}\).

To loop over combinations of a larger multiset use \textbf{IteratorOfCombinations} (16.2.2) which produces combinations one by one and may save a lot of memory. Another memory efficient representation of the list of all combinations is provided by \textbf{EnumeratorOfCombinations} (16.2.2).

16.2.2 Iterator and enumerator of combinations

\textbf{IteratorOfCombinations}(mset[, k]) \hspace{1em} \text{(function)}

\textbf{EnumeratorOfCombinations}(mset) \hspace{1em} \text{(function)}

\textbf{IteratorOfCombinations} returns an \textit{Iterator} (30.8.1) for combinations (see \textbf{Combinations} (16.2.1)) of the given multiset \textit{mset}. If a non-negative integer \textit{k} is given as second argument then only the combinations with \textit{k} entries are produced, otherwise all combinations.

\textbf{EnumeratorOfCombinations} returns an \textit{Enumerator} (30.3.2) of the given multiset \textit{mset}. Currently only a variant without second argument \textit{k} is implemented.

The ordering of combinations from these functions can be different and also different from the list returned by \textbf{Combinations} (16.2.1).

\begin{verbatim}
gap> m:=[1..15];; Add(m, 15);
gap> NrCombinations(m);
49152
gap> i := 0;; for c in Combinations(m) do i := i+1; od;
gap> i;
49152
gap> cm := EnumeratorOfCombinations(m);

gap> cm[1000];
\end{verbatim}
16.2.3 NrCombinations

\begin{verbatim}
>= NrCombinations(mset[, k])
\end{verbatim}
returns the number of Combinations(mset,k).

\begin{verbatim}
gap> Combinations([1,2,2,3]);
[ [  ], [ 1 ], [ 1, 2 ], [ 1, 2, 2 ], [ 1, 2, 2, 3 ], [ 1, 2, 3 ],
  [ 1, 3 ], [ 2 ], [ 2, 2 ], [ 2, 2, 3 ], [ 2, 3 ], [ 3 ] ]
gap> # number of different hands in a game of poker:
gap> NrCombinations([1..52], 5);
2598960
\end{verbatim}

The function Arrangements (16.2.4) computes ordered selections without repetitions, UnorderedTuples (16.2.6) computes unordered selections with repetitions, and Tuples (16.2.8) computes ordered selections with repetitions.

16.2.4 Arrangements

\begin{verbatim}
>= Arrangements(mset[, k])
\end{verbatim}
returns the set of arrangements of the multiset mset that contain k elements. If k is not given it returns all arrangements of mset.

An arrangement of mset is an ordered selection without repetitions and is represented by a list that contains only elements from mset, but maybe in a different order. If mset is a proper set there are |mset|!/(|mset|−k)! (see Factorial (16.1.1)) arrangements with k elements.

16.2.5 NrArrangements

\begin{verbatim}
>= NrArrangements(mset[, k])
\end{verbatim}
returns the number of Arrangements(mset,k).

As an example of arrangements of a multiset, think of the game Scrabble. Suppose you have the six characters of the word "settle" and you have to make a four letter word. Then the possibilities are given by

\begin{verbatim}
gap> Arrangements(["s","e","t","t","l","e"], 4);
[ [ "e", "e", "l", "s" ], [ "e", "e", "l", "t" ], [ "e", "e", "l", "e" ],
  [ "e", "e", "t", "t" ], [ "e", "e", "t", "l" ],
  ... 93 more possibilities ...
[ "t", "t", "l", "e" ], [ "t", "t", "s", "e" ], [ "t", "t", "s", "l" ] ]
\end{verbatim}

Can you find the five proper English words, where "lets" does not count? Note that the fact that the list returned by Arrangements (16.2.4) is a proper set means in this example that the possibilities are listed in the same order as they appear in the dictionary.
The function Combinations (16.2.1) computes unordered selections without repetitions, UnorderedTuples (16.2.6) computes unordered selections with repetitions, and Tuples (16.2.8) computes ordered selections with repetitions.

16.2.6 UnorderedTuples

\( \text{UnorderedTuples}(set, k) \)

returns the set of all unordered tuples of length \( k \) of the set \( set \).

An unordered tuple of length \( k \) of \( set \) is an unordered selection with repetitions of \( set \) and is represented by a sorted list of length \( k \) containing elements from \( set \). There are \( (|set|+k-1) \) such unordered tuples.

Note that the fact that UnorderedTuples returns a set implies that the last index runs fastest. That means the first tuple contains the smallest element from \( set \) \( k \) times, the second tuple contains the smallest element of \( set \) at all positions except at the last positions, where it contains the second smallest element from \( set \) and so on.

16.2.7 NrUnorderedTuples

\( \text{NrUnorderedTuples}(set, k) \)

returns the number of UnorderedTuples\( (set,k) \).

As an example for unordered tuples think of a poker-like game played with 5 dice. Then each possible hand corresponds to an unordered five-tuple from the set \{1,2,..,6\}.

The function Combinations (16.2.1) computes unordered selections without repetitions, Arrangements (16.2.4) computes ordered selections without repetitions, and Tuples (16.2.8) computes ordered selections with repetitions.

16.2.8 Tuples

\( \text{Tuples}(set, k) \)

returns the set of all ordered tuples of length \( k \) of the set \( set \).
returns the set of all ordered tuples of length $k$ of the set $\text{set}$.  

An ordered tuple of length $k$ of $\text{set}$ is an ordered selection with repetition and is represented by a list of length $k$ containing elements of $\text{set}$. There are $|\text{set}|^k$ such ordered tuples.

Note that the fact that $\text{Tuples}$ returns a set implies that the last index runs fastest. That means

the first tuple contains the smallest element from $\text{set}$ $k$ times, the second tuple contains the smallest element of $\text{set}$ at all positions except at the last positions, where it contains the second smallest element from $\text{set}$ and so on.

16.2.9 EnumeratorOfTuples

$\textbf{EnumeratorOfTuples} (\text{set}, k)$ (function)

This function is referred to as an example of enumerators that are defined by functions but are not constructed from a domain. The result is equal to that of $\text{Tuples} (\text{set}, k)$. However, the entries are not stored physically in the list but are created/identified on demand.

16.2.10 IteratorOfTuples

$\textbf{IteratorOfTuples} (\text{set}, k)$ (function)

For a set $\text{set}$ and a positive integer $k$, $\text{IteratorOfTuples}$ returns an iterator (see 30.8) of the set of all ordered tuples (see $\text{Tuples}$ (16.2.8)) of length $k$ of the set $\text{set}$. The tuples are returned in lexicographic order.

16.2.11 NrTuples

$\textbf{NrTuples} (\text{set}, k)$ (function)

returns the number of $\text{Tuples} (\text{set}, k)$.

Example

\begin{verbatim}
gap> Tuples( [1,2,3], 2 );
[ [ 1, 1 ], [ 1, 2 ], [ 1, 3 ], [ 2, 1 ], [ 2, 2 ], [ 2, 3 ],
  [ 3, 1 ], [ 3, 2 ], [ 3, 3 ] ]
gap> NrTuples( [1..10], 5 );
100000
\end{verbatim}

$\text{Tuples} (\text{set}, k)$ can also be viewed as the $k$-fold cartesian product of $\text{set}$ (see $\text{Cartesian}$ (21.20.16)).

The function $\text{Combinations}$ (16.2.1) computes unordered selections without repetitions, $\text{Arrangements}$ (16.2.4) computes ordered selections without repetitions, and finally the function $\text{UnorderedTuples}$ (16.2.6) computes unordered selections with repetitions.

16.2.12 PermutationsList

$\textbf{PermutationsList} (\text{mset})$ (function)

$\text{PermutationsList}$ returns the set of permutations of the multiset $\text{mset}$.
A *permutation* is represented by a list that contains exactly the same elements as \(mset\), but possibly in different order. If \(mset\) is a proper set there are \(|mset|!\) (see Factorial (16.1.1)) such permutations. Otherwise if the first elements appears \(k_1\) times, the second element appears \(k_2\) times and so on, the number of permutations is \(|mset|!/(k_1!k_2!\ldots)\), which is sometimes called multinomial coefficient.

### 16.2.13 NrPermutationsList

\[\text{NrPermutationsList(} \text{mset} \text{)}\]

returns the number of \(\text{PermutationsList(} \text{mset} \text{)}\).

**Example**

```gap
gap> PermutationsList([1,2,3]);
[[1, 2, 3], [1, 3, 2], [2, 1, 3], [2, 3, 1], [3, 1, 2], [3, 2, 1]]
gap> PermutationsList([1,1,2,2]);
[[1, 1, 2, 2], [1, 2, 1, 2], [1, 2, 2, 1], [2, 1, 1, 2], [2, 1, 2, 1], [2, 2, 1, 1]]
gap> NrPermutationsList([1,2,2,3,3,3,4,4,4,4]);
12600
```

The function \(\text{Arrangements(} \text{16.2.4)}\) is the generalization of \(\text{PermutationsList(} \text{16.2.12)}\) that allows you to specify the size of the permutations. \(\text{Derangements(} \text{16.2.14)}\) computes permutations that have no fixed points.

### 16.2.14 Derangements

\[\text{Derangements(} \text{list} \text{)}\]

returns the set of all derangements of the list \(\text{list}\).

A *derangement* is a fixpointfree permutation of \(\text{list}\) and is represented by a list that contains exactly the same elements as \(\text{list}\), but in such an order that the derangement has at no position the same element as \(\text{list}\). If the list \(\text{list}\) contains no element twice there are exactly \(|\text{list}|!(1/2! - 1/3! + 1/4! - \cdots + (-1)^n/n!)\) derangements.

Note that the ratio \(\text{NrPermutationsList(} [1..n]\text{) / NrDerangements(} [1..n]\text{)}\), which is \(n!/n!(1/2! - 1/3! + 1/4! - \cdots + (-1)^n/n!))\), is an approximation for the base of the natural logarithm \(e = 2.7182818285\ldots\), which is correct to about \(n\) digits.

### 16.2.15 NrDerangements

\[\text{NrDerangements(} \text{list} \text{)}\]

returns the number of \(\text{Derangements(} \text{list} \text{)}\).

As an example of derangements suppose that you have to send four different letters to four different people. Then a derangement corresponds to a way to send those letters such that no letter reaches the intended person.
The function `PermutationsList` (16.2.12) computes all permutations of a list.

### 16.2.16 PartitionsSet

\[ \text{PartitionsSet}(set[, k]) \]

returns the set of all unordered partitions of the set `set` into `k` pairwise disjoint nonempty sets. If `k` is not given it returns all unordered partitions of `set` for all `k`.

An **unordered partition** of `set` is a set of pairwise disjoint nonempty sets with union `set` and is represented by a sorted list of such sets. There are \( B(|set|) \) (see Bell (16.1.3)) partitions of the set `set` and \( S_2(|set|, k) \) (see Stirling2 (16.1.6)) partitions with `k` elements.

### 16.2.17 NrPartitionsSet

\[ \text{NrPartitionsSet}(set[, k]) \]

returns the number of `PartitionsSet(set,k)`.

Note that `PartitionsSet` (16.2.16) does currently not support multisets and that there is currently no ordered counterpart.
16.2.18 Partitions

\[ \text{Partitions}(n[, k]) \]

returns the set of all (unordered) partitions of the positive integer \( n \) into sums with \( k \) summands. If \( k \) is not given it returns all unordered partitions of \( n \) for all \( k \).

An unordered partition is an unordered sum \( n = p_1 + p_2 + \cdots + p_k \) of positive integers and is represented by the list \( p = [p_1, p_2, \ldots, p_k] \), in nonincreasing order, i.e., \( p_1 \geq p_2 \geq \ldots \geq p_k \). We write \( p \vdash n \). There are approximately \( \exp(\pi \sqrt{\frac{2}{3n}})/(4\sqrt{3n}) \) such partitions, use \( \text{NrPartitions}(16.2.20) \) to compute the precise number.

If you want to loop over all partitions of some larger \( n \) use the more memory efficient \( \text{IteratorOfPartitions}(16.2.19) \).

It is possible to associate with every partition of the integer \( n \) a conjugacy class of permutations in the symmetric group on \( n \) points and vice versa. Therefore \( p(n) := \text{NrPartitions}(n) \) is the number of conjugacy classes of the symmetric group on \( n \) points.

Ramanujan found the identities \( p(5i + 4) = 0 \mod 5 \), \( p(7i + 5) = 0 \mod 7 \) and \( p(11i + 6) = 0 \mod 11 \) and many other fascinating things about the number of partitions.

16.2.19 IteratorOfPartitions

\[ \text{IteratorOfPartitions}(n) \]

For a positive integer \( n \), \( \text{IteratorOfPartitions} \) returns an iterator (see 30.8) of the set of partitions of \( n \) (see \( \text{Partitions}(16.2.18) \)). The partitions of \( n \) are returned in lexicographic order.

16.2.20 NrPartitions

\[ \text{NrPartitions}(n[, k]) \]

returns the number of \( \text{Partitions}(\text{set}, k) \).

Example

\[
\begin{array}{l}
gap> \text{Partitions}(7);
gap> [ [ 1, 1, 1, 1, 1, 1, 1 ] , [ 2, 1, 1, 1, 1, 1, 1 ] , [ 2, 2, 1, 1, 1, 1, 1 ] , [ 3, 1, 1, 1, 1, 1, 1 ] , [ 3, 2, 1, 1, 1, 1, 1 ] , [ 4, 1, 1, 1, 1, 1, 1 ] , [ 4, 2, 1, 1, 1, 1, 1 ] , [ 4, 3, 1, 1, 1, 1, 1 ] , [ 5, 1, 1, 1, 1, 1, 1 ] , [ 5, 2, 1, 1, 1, 1, 1 ] , [ 6, 1, 1, 1, 1, 1, 1 ] , [ 7 ] ]
gap> \text{Partitions}(8, 3);
gap> [ [ 3, 3, 2, 1, 1, 1, 1 ] , [ 4, 2, 2, 1, 1, 1, 1 ] , [ 4, 3, 1, 1, 1, 1, 1 ] , [ 5, 2, 1, 1, 1, 1, 1 ] , [ 6, 1, 1, 1, 1, 1, 1 ] ]
gap> \text{NrPartitions}(7);
gap> 15
\end{array}
\]

The function \( \text{OrderedPartitions}(16.2.21) \) is the ordered counterpart of \( \text{Partitions}(16.2.18) \).

16.2.21 OrderedPartitions

\[ \text{OrderedPartitions}(n[, k]) \]

returns the number of \( \text{Partitions}(\text{set}, k) \).
returns the set of all ordered partitions of the positive integer \(n\) into sums with \(k\) summands. If \(k\) is not given it returns all ordered partitions of \(set\) for all \(k\).

An ordered partition is an ordered sum \(n = p_1 + p_2 + \ldots + p_k\) of positive integers and is represented by the list \([p_1, p_2, \ldots, p_k]\). There are totally \(2^{n-1}\) ordered partitions and \(\binom{n-1}{k-1}\) (see Binomial (16.1.2)) ordered partitions with \(k\) summands.

Do not call \texttt{OrderedPartitions} with an \(n\) much larger than 15, the list will simply become too large.

### 16.2.22 \texttt{NrOrderedPartitions}

\texttt{NrOrderedPartitions}(\(n[, k]\))

returns the number of \texttt{OrderedPartitions}(\(set, k\)).

```
gap> OrderedPartitions(5);
[ [ 1, 1, 1, 1, 1 ], [ 1, 1, 1, 2 ], [ 1, 1, 2, 1 ], [ 1, 1, 3 ], [ 1, 2, 1, 1 ], [ 1, 2, 2 ], [ 1, 3, 1 ], [ 1, 4 ], [ 2, 1, 1, 1 ], [ 2, 1, 2 ], [ 2, 2, 1 ], [ 2, 3 ], [ 3, 1, 1 ], [ 3, 2 ], [ 4, 1 ], [ 5 ] ]
gap> OrderedPartitions(6,3);
[ [ 1, 1, 4 ], [ 1, 2, 3 ], [ 1, 3, 2 ], [ 1, 4, 1 ], [ 2, 1, 3 ], [ 2, 2, 2 ], [ 2, 3, 1 ], [ 3, 1, 2 ], [ 3, 2, 1 ], [ 4, 1, 1 ] ]
gap> NrOrderedPartitions(20);
524288
```

The function \texttt{Partitions} (16.2.18) is the unordered counterpart of \texttt{OrderedPartitions} (16.2.21).

### 16.2.23 \texttt{PartitionsGreatestLE}

\texttt{PartitionsGreatestLE}(\(n, m\))

returns the set of all (unordered) partitions of the integer \(n\) having parts less or equal to the integer \(m\).

### 16.2.24 \texttt{PartitionsGreatestEQ}

\texttt{PartitionsGreatestEQ}(\(n, m\))

returns the set of all (unordered) partitions of the integer \(n\) having greatest part equal to the integer \(m\).

### 16.2.25 \texttt{RestrictedPartitions}

\texttt{RestrictedPartitions}(\(n, set[, k]\))

In the first form \texttt{RestrictedPartitions} returns the set of all restricted partitions of the positive integer \(n\) into sums with \(k\) summands with the summands of the partition coming from the set \(set\). If \(k\) is not given all restricted partitions for all \(k\) are returned.
A restricted partition is like an ordinary partition (see Partitions (16.2.18)) an unordered sum \( n = p_1 + p_2 + \ldots + p_k \) of positive integers and is represented by the list \( p = [p_1, p_2, \ldots, p_k] \), in non-increasing order. The difference is that here the \( p_i \) must be elements from the set \( \text{set} \), while for ordinary partitions they may be elements from \([ 1 \ldots n ]\).

### 16.2.26 NrRestrictedPartitions

\( \text{NrRestrictedPartitions}(n, \text{set}[, k]) \)

returns the number of \( \text{RestrictedPartitions}(n, \text{set}, k) \).

**Example**

\[
gap> \text{RestrictedPartitions}(8, [1,3,5,7]);
\[
[ [ 1, 1, 1, 1, 1, 1, 1, 1 ], [ 3, 1, 1, 1, 1, 1 ], [ 3, 3, 1, 1 ],
  [ 5, 1, 1, 1 ], [ 5, 3 ], [ 7, 1 ] ]
\]

\[
gap> \text{NrRestrictedPartitions}(50,[1,2,5,10,20,50]);
451
\]

The last example tells us that there are 451 ways to return 50 pence change using 1, 2, 5, 10, 20 and 50 pence coins.

### 16.2.27 SignPartition

\( \text{SignPartition}(\pi) \)

returns the sign of a permutation with cycle structure \( \pi \).

This function actually describes a homomorphism from the symmetric group \( S_n \) into the cyclic group of order 2, whose kernel is exactly the alternating group \( A_n \) (see SignPerm (42.4.1)). Partitions of sign 1 are called even partitions while partitions of sign \(-1\) are called odd.

**Example**

\[
gap> \text{SignPartition([6,5,4,3,2,1])};
-1
\]

### 16.2.28 AssociatedPartition

\( \text{AssociatedPartition}(\pi) \)

returns the associated partition of the partition \( \pi \) which is obtained by transposing the corresponding Young diagram.

**Example**

\[
gap> \text{AssociatedPartition([4,2,1])};
[ 3, 2, 1, 1 ]
\]

\[
gap> \text{AssociatedPartition([6])};
[ 1, 1, 1, 1, 1, 1 ]
\]
16.2.29 PowerPartition

PowerPartition returns the partition corresponding to the \(k\)-th power of a permutation with cycle structure \(pi\).

Each part \(l\) of \(pi\) is replaced by \(d = \gcd(l, k)\) parts \(l/d\). So if \(pi\) is a partition of \(n\) then \(pi^k\) also is a partition of \(n\). PowerPartition describes the power map of symmetric groups.

Example

```
gap> PowerPartition([6,5,4,3,2,1], 3);  
[ 5, 4, 2, 2, 2, 2, 1, 1, 1, 1 ]  
```

16.2.30 PartitionTuples

PartitionTuples returns the list of all \(r\)-tuples of partitions which together form a partition of \(n\).

\(r\)-tuples of partitions describe the classes and the characters of wreath products of groups with \(r\) conjugacy classes with the symmetric group on \(n\) points, see CharacterTableWreathSymmetric (71.20.6) and CharacterValueWreathSymmetric (71.20.7).

16.2.31 NrPartitionTuples

NrPartitionTuples returns the number of PartitionTuples(\(n, r\)).

Example

```
gap> PartitionTuples(3, 2);  
[ [ [ 1, 1, 1 ], [ ] ], [ [ 1, 1 ], [ 1 ] ], [ [ 1 ], [ 1, 1 ] ],  
 [ [ 1, 1, 1 ] ], [ [ 2, 1 ], [ 1 ] ], [ [ 1 ], [ 2 ] ],  
 [ [ 2 ], [ 1, 1 ] ], [ [ ], [ 2, 1 ] ], [ [ 3 ], [ ] ],  
 [ [ ], [ 3 ] ] ]  
```

16.2.32 BetaSet

BetaSet returns the list of integers obtained by reversing the order of \(alpha\) and then adding the sequence \([0, 1, 2, \ldots]\) of the same length, cf. [JK81, Section 2.7].

Example

```
gap> BetaSet([4, 2, 1]);  
[ 1, 3, 6 ]  
gap> BetaSet([]);  
[ ]  
```
16.3 Fibonacci and Lucas Sequences

16.3.1 Fibonacci

\[ \text{Fibonacci}(n) \]

returns the \( n \)-th number of the Fibonacci sequence. The Fibonacci sequence \( F_n \) is defined by the initial conditions \( F_1 = F_2 = 1 \) and the recurrence relation \( F_{n+2} = F_{n+1} + F_n \). For negative \( n \) we define \( F_n = (-1)^{n+1} F_{-n} \), which is consistent with the recurrence relation.

Using generating functions one can prove that \( F_n = \phi^n - \frac{1}{\phi^n} \), where \( \phi = \frac{\sqrt{5} + 1}{2} \), i.e., one root of \( x^2 - x - 1 = 0 \). Fibonacci numbers have the property \( \gcd(F_m, F_n) = F_{\gcd(m,n)} \).

\[ \text{Fibonacci}(k) \]

is the special case \( \text{Lucas}(1, -1, k) \) (see Lucas (16.3.2)).

Example

\[
\begin{align*}
gap> \text{Fibonacci}(10); & \quad 55 \\
gap> \text{Fibonacci}(36); & \quad 9227465 \\
gap> \text{Fibonacci}(-10); & \quad -55
\end{align*}
\]

16.3.2 Lucas

\[ \text{Lucas}(P, Q, k) \]

returns the \( k \)-th values of the Lucas sequence with parameters \( P \) and \( Q \), which must be integers, as a list of three integers. If \( k \) is a negative integer, then the values of the Lucas sequence may be nonintegral rational numbers, with denominator roughly \( Q^k \).

Let \( \alpha, \beta \) be the two roots of \( x^2 - Px + Q \) then we define \( \text{Lucas}(P, Q, k) \) \([1]\) = \( U_k = (\alpha^k - \beta^k)/(\alpha - \beta) \) and \( \text{Lucas}(P, Q, k) \) \([2]\) = \( V_k = (\alpha^k + \beta^k) \) and as a convenience \( \text{Lucas}(P, Q, k) \) \([3]\) = \( Q^k \).

The following recurrence relations are easily derived from the definition \( U_0 = 0, U_1 = 1, U_k = PU_{k-1} - QU_{k-2} \) and \( V_0 = 2, V_1 = P, V_k = PV_{k-1} - QV_{k-2} \). Those relations are actually used to define Lucas if \( \alpha = \beta \).

Also the more complex relations used in Lucas can be easily derived \( U_{2k} = U_k V_k, U_{2k+1} = (PU_{2k} + V_{2k})/2 \) and \( V_{2k} = V_k^2 - 2Q^k, V_{2k+1} = ((P^2 - 4Q)U_{2k} + PV_{2k})/2 \).

Fibonacci \((k)\) (see Fibonacci (16.3.1)) is simply Lucas \((1, -1, k) \) \([1]\). In an abuse of notation, the sequence Lucas \((1, -1, k) \) \([2]\) is sometimes called the Lucas sequence.

Example

\[
\begin{align*}
gap> \text{List}([0..10], i -> \text{Lucas}(1,-2,i)[1]); & \quad \# 2^k - (-1)^k/3 \\
[ & 0, 1, 1, 3, 5, 11, 21, 43, 85, 171, 341 ] \\
gap> \text{List}([0..10], i -> \text{Lucas}(1,-2,i)[2]); & \quad \# 2^k + (-1)^k \\
[ & 2, 1, 5, 7, 17, 31, 65, 127, 257, 511, 1025 ] \\
gap> \text{List}([0..10], i -> \text{Lucas}(1,-1,i)[1]); & \quad \# \text{Fibonacci sequence} \\
[ & 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55 ] \\
gap> \text{List}([0..10], i -> \text{Lucas}(2,1,i)[1]); & \quad \# \text{the roots are equal} \\
[ & 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ]
\end{align*}
\]
16.4 Permanent of a Matrix

16.4.1 Permanent

\[ \text{Permanent(mat)} \]

returns the permanent of the matrix mat. The permanent is defined by \( \sum_{p \in \text{Sym}(n)} \prod_{i=1}^{n} mat[i][p] \).

Note the similarity of the definition of the permanent to the definition of the determinant (see DeterminantMat (24.4.4)). In fact the only difference is the missing sign of the permutation. However the permanent is quite unlike the determinant, for example it is not multilinear or alternating. It has however important combinatorial properties.

Example

\begin{verbatim}
gap> Permanent( [[0,1,1,1], [1,0,1,1], [1,1,0,1], [1,1,1,0]]; # inefficient way to compute NrDerangements([1..4])
gap> 9

gap> Permanent( [[1,1,0,1,0,0,0], [0,1,1,0,1,0,0], [0,0,1,1,0,1,0], [0,0,0,1,1,0,1], 
    [1,0,0,0,1,1,0], [0,1,0,0,0,1,1], [1,0,1,0,0,0,1]]; 
    # 24 permutations fit the projective plane of order 2:
gap> 24
\end{verbatim}
Chapter 17

Rational Numbers

The *rationals* form a very important field. On the one hand it is the quotient field of the integers (see chapter 14). On the other hand it is the prime field of the fields of characteristic zero (see chapter 60).

The former comment suggests the representation actually used. A rational is represented as a pair of integers, called *numerator* and *denominator*. Numerator and denominator are *reduced*, i.e., their greatest common divisor is 1. If the denominator is 1, the rational is in fact an integer and is represented as such. The numerator holds the sign of the rational, thus the denominator is always positive.

Because the underlying integer arithmetic can compute with arbitrary size integers, the rational arithmetic is always exact, even for rationals whose numerators and denominators have thousands of digits.

```
gap> 2/3;
2/3
gap> 66/123;  # numerator and denominator are made relatively prime
22/41
gap> 17/-13;  # the numerator carries the sign;
-17/13
gap> 121/11;  # rationals with denominator 1 (when canceled) are integers
11
```

### 17.1 Rationals: Global Variables

#### 17.1.1 Rationals

* Rationals (global variable)
* IsRationals(obj) (filter)

Rationals is the field \( \mathbb{Q} \) of rational integers, as a set of cyclotomic numbers, see Chapter 18 for basic operations, Functions for the field Rationals can be found in the chapters 58 and 60.

IsRationals returns true for a prime field that consists of cyclotomic numbers – for example the GAP object Rationals – and false for all other GAP objects.

```
gap> Size( Rationals ); 2/3 in Rationals;
infinity
```
17.2 Elementary Operations for Rationals

17.2.1 IsRat

\(\texttt{IsRat(obj)}\) (Category)

Every rational number lies in the category \texttt{IsRat}, which is a subcategory of \texttt{IsCyc} (18.1.3).

\begin{verbatim}
gap> IsRat( 2/3 );
true
gap> IsRat( 17/-13 );
true
gap> IsRat( 11 );
true
gap> IsRat( IsRat ); # 'IsRat' is a function, not a rational
false
\end{verbatim}

17.2.2 IsPosRat

\(\texttt{IsPosRat(obj)}\) (Category)

Every positive rational number lies in the category \texttt{IsPosRat}.

17.2.3 IsNegRat

\(\texttt{IsNegRat(obj)}\) (Category)

Every negative rational number lies in the category \texttt{IsNegRat}.

17.2.4 NumeratorRat

\(\texttt{NumeratorRat(rat)}\) (function)

\texttt{NumeratorRat} returns the numerator of the rational \texttt{rat}. Because the numerator holds the sign of the rational it may be any integer. Integers are rationals with denominator 1, thus \texttt{NumeratorRat} is the identity function for integers.

\begin{verbatim}
gap> NumeratorRat( 2/3 );
2
gap> # numerator and denominator are made relatively prime:
gap> NumeratorRat( 66/123 );
22
gap> NumeratorRat( 17/-13 ); # numerator holds the sign of the rational
-17
gap> NumeratorRat( 11 ); # integers are rationals with denominator 1
11
\end{verbatim}
17.2.5 DenominatorRat

\[ \text{DenominatorRat}(\text{rat}) \]

DenominatorRat returns the denominator of the rational \text{rat}. Because the numerator holds the sign of the rational the denominator is always a positive integer. Integers are rationals with the denominator 1, thus \text{DenominatorRat} returns 1 for integers.

Example

\begin{verbatim}
\gap\> \text{DenominatorRat}( 2/3 );
3
\gap\> \# numerator and denominator are made relatively prime:
\gap\> \text{DenominatorRat}( 66/123 );
41
\gap\> \# the denominator holds the sign of the rational:
\gap\> \text{DenominatorRat}( 17/-13 );
13
\gap\> \text{DenominatorRat}( 11 ); \# integers are rationals with denominator 1
1
\end{verbatim}

17.2.6 Rat

\[ \text{Rat}(\text{elm}) \]

Rat returns a rational number \text{rat} whose meaning depends on the type of \text{elm}.

If \text{elm} is a string consisting of digits '0', '1', ..., '9' and ' −' (at the first position), '/ ' and the decimal dot ',', then \text{rat} is the rational described by this string. If \text{elm} is a rational number, then \text{Rat} returns \text{elm}. The operation \text{String} (27.7.6) can be used to compute a string for rational numbers, in fact for all cyclotomics.

Example

\begin{verbatim}
\gap\> \text{Rat}( "1/2" ); \text{Rat}( "35/14" ); \text{Rat}( "35/-27" ); \text{Rat}( "3.14159" );
1/2
5/2
-35/27
314159/100000
\end{verbatim}

17.2.7 Random (for rationals)

\[ \text{Random}(\text{Rationals}) \]

Random for rationals returns pseudo random rationals which are the quotient of two random integers. See the description of \text{Random} (14.2.12) for details. (Also see \text{Random} (30.7.1).)
Chapter 18

Cyclotomic Numbers

GAP admits computations in abelian extension fields of the rational number field \( \mathbb{Q} \), that is fields with abelian Galois group over \( \mathbb{Q} \). These fields are subfields of cyclotomic fields \( \mathbb{Q}(e_n) \) where \( e_n = \exp(2\pi i/n) \) is a primitive complex \( n \)-th root of unity. The elements of these fields are called cyclotomics.

Information concerning operations for domains of cyclotomics, for example certain integral bases of fields of cyclotomics, can be found in Chapter 60. For more general operations that take a field extension as a –possibly optional– argument, e.g., Trace (58.3.5) or Coefficients (61.6.3), see Chapter 58.

18.1 Operations for Cyclotomics

18.1.1 \( E \)

\( E \) returns the primitive \( n \)-th root of unity \( e_n = \exp(2\pi i/n) \). Cyclotomics are usually entered as sums of roots of unity, with rational coefficients, and irrational cyclotomics are displayed in such a way. (For special cyclotomics, see 18.4.)

```gap
gap> E(9); E(9)^3; E(6); E(12) / 3;
-E(9)^4-E(9)^7
E(3)
-E(3)^2
-1/3*E(12)^7
```

A particular basis is used to express cyclotomics, see 60.3; note that \( E(9) \) is not a basis element, as the above example shows.

18.1.2 Cyclotomics

\( \text{Cyclotomics} \) is the domain of all cyclotomics.
As the cyclotomics are field elements, the usual arithmetic operators +, -, *, and / (and ^ to take powers by integers) are applicable. Note that ^ does not denote the conjugation of group elements, so it is not possible to explicitly construct groups of cyclotomics. (However, it is possible to compute the inverse and the multiplicative order of a nonzero cyclotomic.) Also, taking the k-th power of a root of unity z defines a Galois automorphism if and only if k is coprime to the conductor (see Conductor (18.1.7)) of z.

Example

```
gap> E(9) in Cyclotomics; 37 in Cyclotomics; true in Cyclotomics;
true
true
false
```

Example

```
gap> E(5) + E(3); (E(5) + E(5)^4) ^ 2; E(5) / E(3); E(5) * E(3);
-E(15)^2-2*E(15)^8-E(15)^11-E(15)^13-E(15)^14
-2*E(5)-E(5)^2-E(5)^3-2*E(5)^4
E(15)^13
E(15)^8

gap> Order( E(5) ); Order( 1+E(5) );
5
infinity
```

18.1.3 IsCyclotomic

▷ IsCyclotomic(obj) (Category)  
▷ IsCyc(obj) (Category)

Every object in the family CyclotomicsFamily lies in the category IsCyclotomic. This covers integers, rationals, proper cyclotomics, the object infinity (18.2.1), and unknowns (see Chapter 74). All these objects except infinity (18.2.1) and unknowns lie also in the category IsCyc, infinity (18.2.1) lies in (and can be detected from) the category IsInfinity (18.2.1), and unknowns lie in IsUnknown (74.1.3).

Example

```
gap> IsCyclotomic(0); IsCyclotomic(1/2*E(3)); IsCyclotomic( infinity );
true
true
true

gap> IsCyc(0); IsCyc(1/2*E(3)); IsCyc( infinity );
true
true
false
```

18.1.4 IsIntegralCyclotomic

▷ IsIntegralCyclotomic(obj) (property)

A cyclotomic is called integral or a cyclotomic integer if all coefficients of its minimal polynomial over the rationals are integers. Since the underlying basis of the external representation of cyclotomics
is an integral basis (see 60.3), the subring of cyclotomic integers in a cyclotomic field is formed by those cyclotomics for which the external representation is a list of integers. For example, square roots of integers are cyclotomic integers (see 18.4), any root of unity is a cyclotomic integer, character values are always cyclotomic integers, but all rationals which are not integers are not cyclotomic integers.

Example

```gap
gap> r:= ER( 5 ); # The square root of 5 ...  E(5)-E(5)^2-E(5)^3+E(5)^4
gap> IsIntegralCyclotomic( r ); # ... is a cyclotomic integer.  true
gap> r2:= 1/2 * r; # This is not a cyclotomic integer, ...
1/2*E(5)-1/2*E(5)^2-1/2*E(5)^3+1/2*E(5)^4
gap> IsIntegralCyclotomic( r2 );
false
gap> r3:= 1/2 * r - 1/2; # ... but this is one.
E(5)+E(5)^4
gap> IsIntegralCyclotomic( r3 );
true
```

18.1.5 Int (for a cyclotomic)

\texttt{Int(cyc)}  

The operation \texttt{Int} can be used to find a cyclotomic integer near to an arbitrary cyclotomic, by applying \texttt{Int} to the coefficients.

Example

```gap
gap> Int( E(5)+1/2*E(5)^2 ); Int( 2/3*E(7)-3/2*E(4) );  E(5)
-E(4)
```

18.1.6 String (for a cyclotomic)

\texttt{String(cyc)}  

The operation \texttt{String} returns for a cyclotomic \texttt{cyc} a string corresponding to the way the cyclotomic is printed by \texttt{ViewObj} and \texttt{PrintObj}.

Example

```gap
gap> String( E(5)+1/2*E(5)^2 ); String( 17/3 );  "E(5)+1/2*E(5)^2"
"17/3"
```

18.1.7 Conductor (for a cyclotomic)

\texttt{Conductor(cyc)}  
\texttt{Conductor(C)}  

For an element \texttt{cyc} of a cyclotomic field, \texttt{Conductor} returns the smallest integer \( n \) such that \texttt{cyc} is contained in the \( n \)-th cyclotomic field. For a collection \( C \) of cyclotomics (for example a dense list of cyclotomics or a field of cyclotomics), \texttt{Conductor} returns the smallest integer \( n \) such that all elements of \( C \) are contained in the \( n \)-th cyclotomic field.
Example

\[
gap> \text{Conductor( 0 ); Conductor( E(10) ); Conductor( E(12) );}
\]
1
5
12

18.1.8 AbsoluteValue

\[\text{AbsoluteValue(cyc)}\]

returns the absolute value of a cyclotomic number \textit{cyc}. At the moment only methods for rational numbers exist.

Example

\[
gap> \text{AbsoluteValue(-3);}
\]
3

18.1.9 RoundCyc

\[\text{RoundCyc(cyc)}\]

is a cyclotomic integer \(z\) (see \texttt{IsIntegralCyclotomic (18.1.4)}) near to the cyclotomic \textit{cyc} in the following sense: Let \(c\) be the \(i\)-th coefficient in the external representation (see \texttt{CoeffsCyc (18.1.10)}) of \textit{cyc}. Then the \(i\)-th coefficient in the external representation of \(z\) is \texttt{Int( c + 1/2 )} or \texttt{Int( c - 1/2 )}, depending on whether \(c\) is nonnegative or negative, respectively.

Expressed in terms of the Zumbroich basis (see 60.3), rounding the coefficients of \textit{cyc} w.r.t. this basis to the nearest integer yields the coefficients of \(z\).

Example

\[
gap> \text{RoundCyc( E(5)+1/2*E(5)^2 ); RoundCyc( 2/3*E(7)+3/2*E(4) );}
\]
\[
E(5)+E(5)^2
\]
\[
\]
\[
-2*E(28)^27
\]

18.1.10 CoeffsCyc

\[\text{CoeffsCyc(cyc, N)}\]

Let \textit{cyc} be a cyclotomic with conductor \(n\) (see \texttt{Conductor (18.1.7)}). If \(N\) is not a multiple of \(n\) then \texttt{CoeffsCyc} returns \texttt{fail} because \textit{cyc} cannot be expressed in terms of \(N\)-th roots of unity. Otherwise \texttt{CoeffsCyc} returns a list of length \(N\) with entry at position \(j\) equal to the coefficient of \(\exp(2\pi i (j-1)/N)\) if this root belongs to the \(N\)-th Zumbroich basis (see 60.3), and equal to zero otherwise. So we have \(\textit{cyc} = \text{CoeffsCyc( \textit{cyc}, N )} \ast \text{List( [1..N], \(j \rightarrow E(N)^j\))} \).

Example

\[
gap> \text{cyc:= E(5)+E(5)^2;}
\]
\[
E(5)+E(5)^2
\]
\[
\text{CoeffsCyc( \textit{cyc}, 5 ); CoeffsCyc( \textit{cyc}, 15 ); CoeffsCyc( \textit{cyc}, 7 );}
\]
\[
[ 0, 1, 1, 0, 0 ]
\]
\[
[ 0, -1, 0, 0, 0, 0, -1, 0, 0, -1, 0, -1, 0, -1, 0 ]
\]
\[
\text{fail}
\]
18.1.11 DenominatorCyc

\texttt{DenominatorCyc(cyc)} (function)

For a cyclotomic number \texttt{cyc} (see \texttt{IsCyclotomic} (18.1.3)), this function returns the smallest positive integer \texttt{n} such that \texttt{ncyc} is a cyclotomic integer (see \texttt{IsIntegralCyclotomic} (18.1.4)). For rational numbers \texttt{cyc}, the result is the same as that of \texttt{DenominatorRat} (17.2.5).

18.1.12 ExtRepOfObj (for a cyclotomic)

\texttt{ExtRepOfObj(cyc)} (method)

The external representation of a cyclotomic \texttt{cyc} with conductor \texttt{n} (see \texttt{Conductor} (18.1.7)) is the list returned by \texttt{CoeffsCyc} (18.1.10), called with \texttt{cyc} and \texttt{n}.

Example

\begin{verbatim}
gap> ExtRepOfObj( E(5) ); CoeffsCyc( E(5), 5 );
[ 0, 1, 0, 0, 0 ]
[ 0, 1, 0, 0, 0 ]
gap> CoeffsCyc( E(5), 15 );
[ 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, -1, 0 ]
\end{verbatim}

18.1.13 DescriptionOfRootOfUnity

\texttt{DescriptionOfRootOfUnity(root)} (function)

Given a cyclotomic \texttt{root} that is known to be a root of unity (this is not checked), \texttt{DescriptionOfRootOfUnity} returns a list \texttt{[n,e]} of coprime positive integers such that \texttt{root = E(n)^e} holds.

Example

\begin{verbatim}
gap> E(9); DescriptionOfRootOfUnity( E(9) );
-E(9)^4-E(9)^7
[ 9, 1 ]
gap> DescriptionOfRootOfUnity( -E(3) );
[ 6, 5 ]
\end{verbatim}

18.1.14 IsGaussInt

\texttt{IsGaussInt(x)} (function)

\texttt{IsGaussInt} returns true if the object \texttt{x} is a Gaussian integer (see \texttt{GaussianIntegers} (60.5.1)), and false otherwise. Gaussian integers are of the form \texttt{a + b\cdotE(4)}, where \texttt{a} and \texttt{b} are integers.

18.1.15 IsGaussRat

\texttt{IsGaussRat(x)} (function)

\texttt{IsGaussRat} returns true if the object \texttt{x} is a Gaussian rational (see \texttt{GaussianRationals} (60.1.3)), and false otherwise. Gaussian rationals are of the form \texttt{a + b\cdotE(4)}, where \texttt{a} and \texttt{b} are rationals.
18.1.16 DefaultField (for cyclotomics)

DefaultField for cyclotomics is defined to return the smallest cyclotomic field containing the given elements. Note that Field (58.1.3) returns the smallest field containing all given elements, which need not be a cyclotomic field. In both cases, the fields represent vector spaces over the rationals (see 60.3).

Example

```
gap> Field( E(5)+E(5)^4 ); DefaultField( E(5)+E(5)^4 );
NF(5,[ 1, 4 ])
CF(5)
```

18.2 Infinity and negative Infinity

18.2.1 IsInfinity

• IsInfinity(obj) (Category)
• IsNegInfinity(obj) (Category)
• infinity (global variable)
• -infinity (global variable)

infinity and -infinity are special GAP objects that lie in CyclotomicsFamily. They are larger or smaller than all other objects in this family respectively. infinity is mainly used as return value of operations such as Size (30.4.6) and Dimension (57.3.3) for infinite and infinite dimensional domains, respectively.

Some arithmetic operations are provided for convenience when using infinity and -infinity as top and bottom element respectively.

Example

```
gap> -infinity + 1;
-inf

gap> infinity + infinity;
inf
```

Often it is useful to distinguish infinity from “proper” cyclotomics. For that, infinity lies in the category IsInfinity but not in IsCyc (18.1.3), and the other cyclotomics lie in the category IsCyc (18.1.3) but not in IsInfinity.

Example

```
gap> s:= Size( Rationals );
inf

gap> s = infinity; IsCyclotomic( s ); IsCyc( s ); IsInfinity( s );
true
true
false
true

gap> s in Rationals; s > 17;
false
true

gap> Set( [ s, 2, s, E(17), s, 19 ] );
[ 2, 19, E(17), infinity ]
```
18.3 Comparisons of Cyclotomics

To compare cyclotomics, the operators `<`, `<=`, `=`, `>=`, `>`, and `<>` can be used, the result will be `true` if the first operand is smaller, smaller or equal, equal, larger or equal, larger, or unequal, respectively, and `false` otherwise.

Cyclotomics are ordered as follows: The relation between rationals is the natural one, rationals are smaller than irrational cyclotomics, and `infinity` (18.2.1) is the largest cyclotomic. For two irrational cyclotomics with different conductors (see `Conductor` (18.1.7)), the one with smaller conductor is regarded as smaller. Two irrational cyclotomics with same conductor are compared via their external representation (see `ExtRepOfObj` (18.1.12)).

For comparisons of cyclotomics and other GAP objects, see Section 4.12.

Example

```gap
gap> E(5) < E(6); # the latter value has conductor 3
false
gap> E(3) < E(3)^2; # both have conductor 3, compare the ext. repr.
falso
gap> 3 < E(3); E(5) < E(7);
true
true
```

18.4 ATLAS Irrationalities

18.4.1 EB, EC, ... , EH

For a positive integer $N$, let $z = E(N) = \exp(2\pi i/N)$. The following so-called atomic irrationalities (see [CCN+85, Chapter 7, Section 10]) can be entered using functions. (Note that the values are not necessary irrational.)

\[
\begin{align*}
EB(N) & = b_N = \frac{\sum_{j=1}^{N-1} z^{j^2}}{2}, \quad N \equiv 1 \pmod{2} \\
EC(N) & = c_N = \frac{\sum_{j=1}^{N-1} z^{j^3}}{3}, \quad N \equiv 1 \pmod{3} \\
ED(N) & = d_N = \frac{\sum_{j=1}^{N-1} z^{j^4}}{4}, \quad N \equiv 1 \pmod{4} \\
EE(N) & = e_N = \frac{\sum_{j=1}^{N-1} z^{j^5}}{5}, \quad N \equiv 1 \pmod{5} \\
EF(N) & = f_N = \frac{\sum_{j=1}^{N-1} z^{j^6}}{6}, \quad N \equiv 1 \pmod{6} \\
EG(N) & = g_N = \frac{\sum_{j=1}^{N-1} z^{j^7}}{7}, \quad N \equiv 1 \pmod{7} \\
EH(N) & = h_N = \frac{\sum_{j=1}^{N-1} z^{j^8}}{8}, \quad N \equiv 1 \pmod{8}
\end{align*}
\]

(Note that in `EC(N), ... , EH(N), N must be a prime.)
18.4.2 EI and ER

For a rational number \( N \), ER returns the square root \( \sqrt{N} \) of \( N \), and EI returns \( \sqrt{-N} \). By the chosen embedding of cyclotomic fields into the complex numbers, ER returns the positive square root if \( N \) is positive, and if \( N \) is negative then \( \text{ER}(N) = \text{EI}(-N) \) holds. In any case, \( \text{EI}(N) = \text{E}(4) \times \text{ER}(N) \).

ER is installed as method for the operation \( \text{Sqrt} \) (31.12.5), for rational argument.

From a theorem of Gauss we know that
\[
\sqrt{N} = \frac{-1 + \sqrt{N}}{2} \quad \text{if} \quad N \equiv 1 \pmod{4} \\
\sqrt{N} = \frac{-1 + i\sqrt{N}}{2} \quad \text{if} \quad N \equiv -1 \pmod{4}
\]

So \( \sqrt{N} \) can be computed from \( b_N \), see EB (18.4.1).

18.4.3 EY, EX, \ldots, ES

For the given integer \( N > 2 \), let \( N_k \) denote the first integer with multiplicative order exactly \( k \) modulo \( N \), chosen in the order of preference

1, \(-1\), 2, \(-2\), 3, \(-3\), 4, \(-4\), \ldots.

We define (with \( z = \exp(2\pi i/N) \))

\[
\begin{align*}
\text{EY}(N) &= y_N = z + z^n & (n = N_2) \\
\text{EX}(N) &= x_N = z + z^n + z^{n_2} & (n = N_3) \\
\text{EW}(N) &= w_N = z + z^n + z^{n_2} + z^{n_3} & (n = N_4) \\
\text{EV}(N) &= v_N = z + z^n + z^{n_2} + z^{n_3} + z^{n_4} & (n = N_5) \\
\text{EU}(N) &= u_N = z + z^n + z^{n_2} + \ldots + z^{n_5} & (n = N_6) \\
\text{ET}(N) &= t_N = z + z^n + z^{n_2} + \ldots + z^{n_6} & (n = N_7) \\
\text{ES}(N) &= s_N = z + z^n + z^{n_2} + \ldots + z^{n_7} & (n = N_8)
\end{align*}
\]
For the two-argument versions of the functions, see Section \texttt{NK} (18.4.5).

\begin{verbatim}
gap> EY(5);  E(5)+E(5)^4
gap> EW(16,3); EW(17,2);  0
E(17)+E(17)^4+E(17)^13+E(17)^16
\end{verbatim}

\section{18.4.4 \texttt{EM}, \texttt{EL}, \ldots, \texttt{EJ}}

- \texttt{EM}(	exttt{N}[, \texttt{d}])  \quad (function)
- \texttt{EL}(	exttt{N}[, \texttt{d}])  \quad (function)
- \texttt{EK}(	exttt{N}[, \texttt{d}])  \quad (function)
- \texttt{EJ}(	exttt{N}[, \texttt{d}])  \quad (function)

Let \( N \) be an integer, \( N > 2 \). We define (with \( z = \exp(2\pi i/N) \))
\[
\text{EM}(N) = m_N = z - z^n \quad (n = N_2) \\
\text{EL}(N) = l_N = z - z^n + z^{2n} - z^3 \quad (n = N_4) \\
\text{EK}(N) = k_N = z - z^n + \ldots - z^5 \quad (n = N_6) \\
\text{EJ}(N) = j_N = z - z^n + \ldots - z^7 \quad (n = N_8)
\]

For the two-argument versions of the functions, see Section \texttt{NK} (18.4.5).

\section{18.4.5 \texttt{NK}}

- \texttt{NK}(\texttt{N}, \texttt{k}, \texttt{d})  \quad (function)

Let \( N_k^{(d)} \) be the \( (d + 1) \)-th integer with multiplicative order exactly \( k \) modulo \( N \), chosen in the order of preference defined in Section 18.4.3; \texttt{NK} returns \( N_k^{(d)} \); if there is no integer with the required multiplicative order, \texttt{NK} returns \texttt{fail}.

We write \( N_1 = N_1^{(0)}, N_1' = N_1^{(1)}, N_1'' = N_1^{(2)} \) and so on.

The algebraic numbers
\[
y_1' = y_1^{(1)}, y_1'' = y_1^{(2)}, \ldots, x_1', x_1'', \ldots, j_1', j_1'', \ldots
\]
are obtained on replacing \( N_k \) in the definitions in the sections 18.4.3 and 18.4.4 by \( N_k', N_k'', \ldots \); they can be entered as
\[
\text{EY}(N,d) = y_1^{(d)} \\
\text{EX}(N,d) = x_1^{(d)} \\
\text{EJ}(N,d) = j_1^{(d)}
\]
18.4.6 AtlasIrrationality

\[ \text{AtlasIrrationality}(\text{irratname}) \]

Let \textit{irratname} be a string that describes an irrational value as a linear combination in terms of the atomic irrationalities introduced in the sections 18.4.1, 18.4.2, 18.4.3, 18.4.4. These irrational values are defined in [CCN+85, Chapter 6, Section 10], and the following description is mainly copied from there. If \( q_N \) is such a value (e.g. \( y''_{24} \)) then linear combinations of algebraic conjugates of \( q_N \) are abbreviated as in the following examples:

\[
\begin{align*}
2qN+3&5-4&7+&9 & \text{means} & 2q_N^5 - 4q_N^7 + q_N^9 \\
4qN&3&5&7-3&4 & \text{means} & 4(q_N^3 + q_N^5 + q_N^7 - 3q_N^4) \\
4qN+3&5&7 & \text{means} & 4(q_N^3 + q_N^5 + q_N^7)
\end{align*}
\]

To explain the “ampersand” syntax in general we remark that “&k” is interpreted as \( q_N^k \), where \( q_N \) is the most recently named atomic irrationality, and that the scope of any premultiplying coefficient is broken by a + or − sign, but not by & or ∗k. The algebraic conjugations indicated by the ampersands apply directly to the \textit{atomic} irrationality \( q_N \), even when, as in the last example, \( q_N \) first appears with another conjugacy ∗k.

Example

\[
\begin{align*}
gap> \text{AtlasIrrationality}(\ "b7*3" ); \\
E(7)^3+E(7)^5+E(7)^6 \\
gap> \text{AtlasIrrationality}(\ "y'''24" ); \\
E(24)^{-19} \\
gap> \text{AtlasIrrationality}(\ "-3y'''24*13&5" ); \\
3\times E(8)-3\times E(8)^3 \\
gap> \text{AtlasIrrationality}(\ "3y'''24*13-2&5" ); \\
-3\times E(24)^{-2}+2\times E(24)^{11}+2\times E(24)^{17}+3\times E(24)^{19} \\
gap> \text{AtlasIrrationality}(\ "3y'''24*13&5" ); \\
-3\times E(24)-E(24)^{11}+E(24)^{17}+3\times E(24)^{19} \\
gap> \text{AtlasIrrationality}(\ "3y'''24*13-4&5&7" ); \\
-7\times E(24)-4\times E(24)^{11}+4\times E(24)^{17}+7\times E(24)^{19} \\
gap> \text{AtlasIrrationality}(\ "3y'''24&7" ); \\
6\times E(24)-6\times E(24)^{19}
\end{align*}
\]

18.5 Galois Conjugacy of Cyclotomics

18.5.1 GaloisCyc (for a cyclotomic)

\[ \text{GaloisCyc}(\text{cyc, k}) \]

For a cyclotomic \textit{cyc} and an integer \textit{k}, \text{GaloisCyc} returns the cyclotomic obtained by raising the roots of unity in the Zumbroich basis representation of \textit{cyc} to the \textit{k}-th power. If \textit{k} is coprime to the integer \textit{n}, \text{GaloisCyc}(\textit{cyc, k}) acts as a Galois automorphism of the \textit{n}-th cyclotomic field (see 60.4); to get the Galois automorphisms themselves, use \text{GaloisGroup} (58.3.1).

The complex conjugate of \textit{cyc} is \text{GaloisCyc}(\textit{cyc, -1}), which can also be computed using \text{ComplexConjugate} (18.5.2).

For a list or matrix \textit{list} of cyclotomics, \text{GaloisCyc} returns the list obtained by applying \text{GaloisCyc} to the entries of \textit{list}.
18.5.2 ComplexConjugate

- ComplexConjugate(z) (attribute)
- RealPart(z) (attribute)
- ImaginaryPart(z) (attribute)

For a cyclotomic number \( z \), ComplexConjugate returns \( \text{GaloisCyc}( z, -1) \), see GaloisCyc (18.5.1). For a quaternion \( z = c_1e + c_2i + c_3j + c_4k \), ComplexConjugate returns \( c_1e - c_2i - c_3j - c_4k \), see IsQuaternion (62.8.8).

When ComplexConjugate is called with a list then the result is the list of return values of ComplexConjugate for the list entries in the corresponding positions.

When ComplexConjugate is defined for an object \( z \) then RealPart and ImaginaryPart return \( (z + \text{ComplexConjugate}(z)) / 2 \) and \( (z - \text{ComplexConjugate}(z)) / 2 i \), respectively, where \( i \) denotes the corresponding imaginary unit.

Example

```
gap> \text{GaloisCyc}( \text{E}(5) + \text{E}(5)^4, 2 );
\text{E}(5)^2+\text{E}(5)^3

gap> \text{GaloisCyc}( \text{E}(5), -1 ); \hspace{1em} \# \text{the complex conjugate}
\text{E}(5)^4

gap> \text{GaloisCyc}( \text{E}(5) + \text{E}(5)^4, -1 ); \hspace{1em} \# \text{this value is real}
\text{E}(5)+\text{E}(5)^4

gap> \text{GaloisCyc}( \text{E}(15) + \text{E}(15)^4, 3 );
\text{E}(5)+\text{E}(5)^4

gap> \text{ComplexConjugate}( \text{E}(7) );
\text{E}(7)^6
```

18.5.3 StarCyc

- StarCyc(cyc) (function)

If the cyclotomic \( cyc \) is an irrational element of a quadratic extension of the rationals then StarCyc returns the unique Galois conjugate of \( cyc \) that is different from \( cyc \), otherwise fail is returned. In the first case, the return value is often called \( cyc^* \) (see 71.13).

Example

```
gap> \text{StarCyc}( \text{EB}(5) ); \text{StarCyc}( \text{E}(5) );
\text{E}(5)^2+\text{E}(5)^3
fail
```

18.5.4 Quadratic

- Quadratic(cyc) (function)

Let \( cyc \) be a cyclotomic integer that lies in a quadratic extension field of the rationals. Then we have \( cyc = (a + b\sqrt{n})/d \), for integers \( a, b, n, d \), such that \( d \) is either 1 or 2. In this case, Quadratic returns a record with the components \( a, b, \text{root}, d, \text{ATLAS}, \) and \( \text{display} \); the values of the first four are \( a, b, n, \) and \( d \), the ATLAS value is a (not necessarily shortest) representation of \( cyc \) in terms of the Atlas irrationalities \( b|n|, l|n|, r|n| \), and the display value is a string that expresses \( cyc \) in GAP notation, corresponding to the value of the ATLAS component.
If \( \text{cyc} \) is not a cyclotomic integer or does not lie in a quadratic extension field of the rationals then \( \text{fail} \) is returned.

If the denominator \( d \) is 2 then necessarily \( n \) is congruent to 1 modulo 4, and \( r_n, i_n \) are not possible; we have \( \text{cyc} = x + y \ast \text{EB}(\text{root}) \) with \( y = b, x = (a + b) / 2 \).

If \( d = 1 \), we have the possibilities \( i_n \lvert n \lvert \) for \( n < -1 \), \( a + b \ast i \) for \( n = -1 \), \( a + b \ast r_n \) for \( n > 0 \).

Furthermore if \( n \) is congruent to 1 modulo 4, also \( \text{cyc} = (a + b) + 2 \ast b \ast b_{[n]} \) is possible; the shortest string of these is taken as the value for the component \( \text{ATLAS} \).

```
Example

gap> Quadratic( EB(5) ); Quadratic( EB(27) );
rec( ATLAS := "b5", a := -1, b := 1, d := 2,
    display := "(-1+Sqrt(5))/2", root := 5 )
rec( ATLAS := "1+3b3", a := -1, b := 3, d := 2,
    display := "(-1+3*Sqrt(-3))/2", root := -3 )

fail
```

### 18.5.5 GaloisMat

\( \triangledown \) \text{GaloisMat(mat)}

Let \( \text{mat} \) be a matrix of cyclotomics. \text{GaloisMat} calculates the complete orbits under the operation of the Galois group of the (irrational) entries of \( \text{mat} \), and the permutations of rows corresponding to the generators of the Galois group.

If some rows of \( \text{mat} \) are identical, only the first one is considered for the permutations, and a warning will be printed.

\text{GaloisMat} returns a record with the components \( \text{mat} \), \( \text{galoisfams} \), and \( \text{generators} \).

- \( \text{mat} \) a list with initial segment being the rows of \( \text{mat} \) (not shallow copies of these rows); the list consists of full orbits under the action of the Galois group of the entries of \( \text{mat} \) defined above.
  The last rows in the list are those not contained in \( \text{mat} \) but must be added in order to complete the orbits; so if the orbits were already complete, \( \text{mat} \) and \( \text{mat} \) have identical rows.

- \( \text{galoisfams} \) a list that has the same length as the \( \text{mat} \) component, its entries are either 1, 0, -1, or lists.
  
  \( \text{galoisfams}[i] = 1 \) means that \( \text{mat}[i] \) consists of rationals, i.e., \( [\text{mat}[i]] \) forms an orbit;
  
  \( \text{galoisfams}[i] = -1 \) means that \( \text{mat}[i] \) contains unknowns (see Chapter 74); in this case \( [\text{mat}[i]] \) is regarded as an orbit, too, even if \( \text{mat}[i] \) contains irrational entries;
  
  \( \text{galoisfams}[i] = [l_1, l_2] \)
  (a list) means that \( \text{mat}[i] \) is the first element of its orbit in \( \text{mat} \), \( l_1 \) is the list of positions of rows that form the orbit, and \( l_2 \) is the list of corresponding Galois automorphisms (as exponents, not as functions); so we have \( \text{mat}[l_1[j]][k] = \text{GaloisCyc}(\text{mat}[i][k], l_2[j]) \);
  
  \( \text{galoisfams}[i] = 0 \) means that \( \text{mat}[i] \) is an element of a nontrivial orbit but not the first element of it.
generators
  a list of permutations generating the permutation group corresponding to the action of the Galois
group on the rows of mat.

Example

\[
\text{gap> GaloisMat( [ [ E(3), E(4) ] ] );}
\]
\[
\text{rec( galoisfams := [ [ 1, 2, 3, 4 ], [ 1, 7, 5, 11 ] ], 0, 0, 0 ],}
\]
\[
\text{generators := [ (1,2)(3,4), (1,3)(2,4) ],}
\]
\[
\text{mat := [ [ E(3), E(4) ], [ E(3), -E(4) ], [ E(3)^2, E(4) ],}
\]
\[
[ E(3)^2, -E(4) ] ] )
\]
\[
\text{gap> GaloisMat( [ [ 1, 1, 1 ], [ 1, E(3), E(3)^2 ] ] );}
\]
\[
\text{rec( galoisfams := [ 1, [ [ 2, 3 ], [ 1, 2 ] ], 0 ],}
\]
\[
\text{generators := [ (2,3) ],}
\]
\[
\text{mat := [ [ 1, 1, 1 ], [ 1, E(3), E(3)^2 ], [ 1, E(3)^2, E(3) ] ] )}
\]

18.5.6 RationalizedMat

\[\text{RationalizedMat(mat)}\]

returns the list of rationalized rows of mat, which must be a matrix of cyclotomics. This is the
set of sums over orbits under the action of the Galois group of the entries of mat (see GaloisMat
(18.5.5)), so the operation may be viewed as a kind of trace on the rows.

Note that no two rows of mat should be equal.

Example

\[
\text{gap> mat:= [ [ 1, 1, 1 ], [ 1, E(3), E(3)^2 ], [ 1, E(3)^2, E(3) ] ] ];}
\]
\[
\text{gap> RationalizedMat( mat );}
\]
\[
[ [ 1, 1, 1 ], [ 2, -1, -1 ] ]
\]

18.6 Internally Represented Cyclotomics

The implementation of an \textit{internally represented cyclotomic} is based on a list of length equal to its
conductor. This means that the internal representation of a cyclotomic does \textit{not} refer to the smallest
number field but the smallest \textit{cyclotomic} field containing it. The reason for this is the wish to reflect
the natural embedding of two cyclotomic fields into a larger one that contains both. With such embed-
dings, it is easy to construct the sum or the product of two arbitrary cyclotomics (in possibly different
fields) as an element of a cyclotomic field.

The disadvantage of this approach is that the arithmetical operations are quite expensive, so the use
of internally represented cyclotomics is not recommended for doing arithmetics over number fields,
such as calculations with matrices of cyclotomics. But internally represented cyclotomics are good
enough for dealing with irrationalities in character tables (see chapter 71).

For the representation of cyclotomics one has to recall that the \( n \)-th cyclotomic field \( \mathbb{Q}(e_n) \) is
a vector space of dimension \( \varphi(n) \) over the rationals where \( \varphi \) denotes Euler’s phi-function (see \( \Phi \)(15.2.2)).

A special integral basis of cyclotomic fields is chosen that allows one to easily convert arbitrary
sums of roots of unity into the basis, as well as to convert a cyclotomic represented w.r.t. the basis into
the smallest possible cyclotomic field. This basis is accessible in GAP, see 60.3 for more information
and references.
Note that the set of all $n$-th roots of unity is linearly dependent for $n > 1$, so multiplication is not the multiplication of the group ring $\mathbb{Q}[e_n]$; given a $\mathbb{Q}$-basis of $\mathbb{Q}(e_n)$ the result of the multiplication (computed as multiplication of polynomials in $e_n$, using $(e_n)^n = 1$) will be converted to the basis.

Example

```gap
gap> E(5) * E(5)^2; ( E(5) + E(5)^4 ) * E(5)^2;
E(5)^3
E(5)+E(5)^3
```
```
```gap
gap> ( E(5) + E(5)^4 ) * E(5);
-E(5)-E(5)^3-E(5)^4
```
An internally represented cyclotomic is always represented in the smallest cyclotomic field it is contained in. The internal coefficients list coincides with the external representation returned by `ExtRepOfObj` (18.1.12).

To avoid calculations becoming unintentionally very long, or consuming very large amounts of memory, there is a limit on the conductor of internally represented cyclotomics, by default set to one million. This can be raised (although not lowered) using `SetCyclotomicsLimit` (18.6.1) and accessed using `GetCyclotomicsLimit` (18.6.1). The maximum value of the limit is $2^{28} - 1$ on 32 bit systems, and $2^{32} - 1$ on 64 bit systems. So the maximal cyclotomic field implemented in GAP is not really the field $\mathbb{Q}_{ab}$.

It should be emphasized that one disadvantage of representing a cyclotomic in the smallest cyclotomic field (and not in the smallest field) is that arithmetic operations in a fixed small extension field of the rational number field are comparatively expensive. For example, take a prime integer $p$ and suppose that we want to work with a matrix group over the field $\mathbb{Q}(\sqrt{p})$. Then each matrix entry could be described by two rational coefficients, whereas the representation in the smallest cyclotomic field requires $p - 1$ rational coefficients for each entry. So it is worth thinking about using elements in a field constructed with `AlgebraicExtension` (67.1.1) when natural embeddings of cyclotomic fields are not needed.

18.6.1 SetCyclotomicsLimit

SetCyclotomicsLimit(newlimit) (function)

GetCyclotomicsLimit() (function)

GetCyclotomicsLimit returns the current limit on conductors of internally represented cyclotomic numbers.

SetCyclotomicsLimit can be called to increase the limit on conductors of internally represented cyclotomic numbers. Note that computing in large cyclotomic fields using this representation can be both slow and memory-consuming, and that other approaches may be better for some problems. See 18.6.
Chapter 19

Floats

Starting with version 4.5, GAP has built-in support for floating-point numbers in machine format, and allows package to implement arbitrary-precision floating-point arithmetic in a uniform manner. For now, one such package, Float exists, and is based on the arbitrary-precision routines in mpfr.

A word of caution: GAP deals primarily with algebraic objects, which can be represented exactly in a computer. Numerical imprecision means that floating-point numbers do not form a ring in the strict GAP sense, because addition is in general not associative ($1.0e^{-100}+1.0-1.0$ is not the same as $1.0e^{-100}+(1.0-1.0)$, in the default precision setting).

Most algorithms in GAP which require ring elements will therefore not be applicable to floating-point elements. In some cases, such a notion would not even make any sense (what is the greatest common divisor of two floating-point numbers?)

19.1 A sample run

Floating-point numbers can be input into GAP in the standard floating-point notation:

```
Example

gap> 3.14;
3.14

Example

gap> last^2/6;
1.64327

Example

gap> h := 6.62606896e-34;
6.62607e-34

Example

gap> pi := 4*Atan(1.0);
3.14159

Example

gap> hbar := h/(2*pi);
1.05457e-34
```

Floating-point numbers can also be created using Float, from strings or rational numbers; and can be converted back using String,Rat,Int.

GAP allows rational and floating-point numbers to be mixed in the elementary operations $+,-,*,/$. However, floating-point numbers and rational numbers may not be compared. Conversions are performed using the creator Float:

```
Example

gap> Float("3.1416");
3.1416
```

250
19.2 Methods

Floating-point numbers may be directly input, as in any usual mathematical software or language; with the exception that every floating-point number must contain a decimal digit. Therefore .1, .1e1, -.999 etc. are all valid GAP inputs.

Floating-point numbers so entered in GAP are stored as strings. They are converted to floating-point when they are first used. This means that, if the floating-point precision is increased, the constants are reevaluated to fit the new format.

Floating-point numbers may be followed by an underscore, as in 1._. This means that they are to be immediately converted to the current floating-point format. The underscore may be followed by a single letter, which specifies which format/precision to use. By default, GAP has a single floating-point handler, with fixed (53 bits) precision, and its format specifier is ‘l’ as in 1._l. Higher-precision floating-point computations is available via external packages, float for example.

A record, FLOAT (19.2.5), contains all relevant constants for the current floating-point format; see its documentation for details. Typical fields are FLOAT.MANT_DIG=53, the constant FLOAT.VIEW_DIG=6 specifying the number of digits to view, and FLOAT.PI for the constant π. The constants have the same name as their C counterparts, except for the missing initial DBL_ or M_.

Floating-point numbers may be created using the single function Float (19.2.1), which accepts as arguments rational, string, or floating-point numbers. Floating-point numbers may also be created, in any floating-point representation, using NewFloat (19.2.1) as in NewFloat(IsIEEE754FloatRep,355/113), by supplying the category filter of the desired new floating-point number; or using MakeFloat (19.2.1) as in NewFloat(1.0,355/113), by supplying a sample floating-point number.

Floating-point numbers may also be converted to other GAP formats using the usual commands Int (14.2.3), Rat (17.2.6), String (27.7.6).

Exact conversion to and from floating-point format may be done using external representations. The "external representation" of a floating-point number $x$ is a pair $[m,e]$ of integers, such that $x=m*2^{(-1+e-\text{LogInt(AbsInt}(m),2))}$. Conversion to and from external representation is performed as usual using ExtRepOfObj (79.8.1) and ObjByExtRep (79.8.1):
Computations with floating-point numbers never raise any error. Division by zero is allowed, and produces a signed infinity. Illegal operations, such as \( 0 ./ 0. \), produce \( \text{NaN} \)’s (not-a-number); this is the only floating-point number \( x \) such that \( \text{not EqFloat}(x+0.0,x) \).

The IEEE754 standard requires \( \text{NaN} \) to be non-equal to itself. On the other hand, GAP requires every object to be equal to itself. To respect the IEEE754 standard, the function \( \text{EqFloat} \) should be used instead of \( = \).

The category a floating-point belongs to can be checked using the filters \( \text{IsFinite} \), \( \text{IsPInfinity} \), \( \text{IsNInfinity} \), \( \text{IsXInfinity} \), \( \text{IsNaN} \).

Comparisons between floating-point numbers and rationals are explicitly forbidden. The rationale is that objects belonging to different families should in general not be comparable in GAP. Floating-point numbers are also approximations of real numbers, and don’t follow the same rules; consider for example, using the default GAP implementation of floating-point numbers,

```
gap> 1.0/3.0 = Float(1/3);
true
```

```
gap> (1.0/3.0)^5 = Float((1/3)^5);
false
```

### 19.2.1 Float creators

- \( \text{Float}(\text{obj}) \) (function)
- \( \text{NewFloat} (\text{filter}, \text{obj}) \) (constructor)
- \( \text{MakeFloat} (\text{sample}, \text{obj}, \text{obj}) \) (operation)

**Returns:** A new floating-point number, based on \( \text{obj} \)

This function creates a new floating-point number.

If \( \text{obj} \) is a rational number, the created number is created with sufficient precision so that the number can (usually) be converted back to the original number (see \( \text{Rat} \) and \( \text{Rat} \)). For an integer, the precision, if unspecified, is chosen sufficient so that \( \text{Int(Float(obj))==obj} \) always holds, but at least 64 bits.

\( \text{obj} \) may also be a string, which may be of the form \( "3.14e0" \) or \( "0.314e1" \) or \( "0.314@1" \) etc.

An option may be passed to specify, it bits, a desired precision. The format is \( \text{Float("3.14":PrecisionFloat:=1000)} \) to create a 1000-bit approximation of 3.14.

In particular, if \( \text{obj} \) is already a floating-point number, then \( \text{Float(obj:PrecisionFloat:=prec)} \) creates a copy of \( \text{obj} \) with a new precision. \( \text{prec} \)

### 19.2.2 Rat (for floats)

- \( \text{Rat}(f) \) (attribute)

**Returns:** A rational approximation to \( f \)

This command constructs a rational approximation to the floating-point number \( f \). Of course, it is not guaranteed to return the original rational number \( f \) was created from, though it returns the most ‘reasonable’ one given the precision of \( f \).

Two options control the precision of the rational approximation: In the form \( \text{Rat}(f:\text{maxdenom:=md, maxpartial:=mp}) \), the rational returned is such that the denominator is at most \( \text{md} \) and the partials in its continued fraction expansion are at most \( \text{mp} \). The default values are \( \text{maxpartial:=10000 and maxdenom:=2^\text{precision/2}} \).
19.2.3 Cyc (for floats)

\[ \text{Cyc}(f[, \text{degree}]) \]  

\textbf{Returns:} A cyclotomic approximation to \( f \)

This command constructs a cyclotomic approximation to the floating-point number \( f \). Of course, it is not guaranteed to return the original rational number \( f \) was created from, though it returns the most 'reasonable' one given the precision of \( f \). An optional argument \textit{degree} specifies the maximal degree of the cyclotomic to be constructed.

The method used is LLL lattice reduction.

19.2.4 SetFloats

\[ \text{SetFloats}(\text{rec}[, \text{bits}][, \text{install}]) \]  

\textbf{(function)}

Installs a new interface to floating-point numbers in GAP, optionally with a desired precision \textit{bits} in binary digits. The last optional argument \textit{install} is a boolean value; if false, it only installs the eager handler and the precision for the floateans, without making them the default.

19.2.5 FLOAT (constants)

\[ \text{FLOAT} \]  

\textbf{(global variable)}

This record contains useful floating-point constants:

\textbf{DECIMAL\_DIG}  
Maximal number of useful digits;

\textbf{DIG}  
Number of significant digits;

\textbf{VIEW\_DIG}  
Number of digits to print in short view;

\textbf{EPSILON}  
Smallest number such that \( 1 \neq 1 + \varepsilon \);

\textbf{MANT\_DIG}  
Number of bits in the mantissa;

\textbf{MAX}  
Maximal representable number;

\textbf{MAX\_10\_EXP}  
Maximal decimal exponent;

\textbf{MAX\_EXP}  
Maximal binary exponent;

\textbf{MIN}  
Minimal positive representable number;
\( \text{MIN\_10\_EXP} \)
Minimal decimal exponent;

\( \text{MIN\_EXP} \)
Minimal exponent;

\( \text{INFINITY} \)
Positive infinity;

\( \text{NINFINITY} \)
Negative infinity;

\( \text{NAN} \)
Not-a-number,

as well as mathematical constants \( E, \log_2 E, \log_{10} E, \ln 2, \ln 10, \pi, \pi_2, \pi_4, 1_\pi, 2_\pi, 2_\sqrt{\pi}, \sqrt{2}, \sqrt{1/2} \).

19.2.6 EqFloat

\[ \text{EqFloat}(x, y) \]  
(operation)

Returns: Whether the floats \( x \) and \( y \) are equal

This function compares two floating-point numbers, and returns \texttt{true} if they are equal, and \texttt{false} otherwise; with the exception that \texttt{NaN} is always considered to be different from itself.

19.2.7 PrecisionFloat

\[ \text{PrecisionFloat}(x) \]  
(attribute)

Returns: The precision of \( x \)

This function returns the precision, counted in number of binary digits, of the floating-point number \( x \).

19.2.8 SignBit

\[ \text{SignBit}(x) \]  
(attribute)

\[ \text{SignFloat}(x) \]  
(attribute)

Returns: The sign of \( x \).

The first function \texttt{SignBit} returns the sign bit of the floating-point number \( x \): \texttt{true} if \( x \) is negative (including \( -0. \)) and \texttt{false} otherwise.

The second function \texttt{SignFloat} returns the integer \(-1\) if \( x<0 \), \( 0 \) if \( x=0 \) and \( 1 \) if \( x>0 \).

19.2.9 Infinity testers

\[ \text{IsPInfinity}(x) \]  
(property)

\[ \text{IsNInfinity}(x) \]  
(property)

\[ \text{IsXInfinity}(x) \]  
(property)

\[ \text{IsFinite}(x) \]  
(property)

\[ \text{IsNaN}(x) \]  
(property)
Returns \texttt{true} if the floating-point number \( x \) is respectively \(+\infty\), \(-\infty\), \(\pm \infty\), finite, or \('not a number'\), such as the result of \(0.0/0.0\).

### 19.2.10 Standard mathematical operations

- \( \cos(f) \) (attribute)
- \( \sin(f) \) (attribute)
- \( \tan(f) \) (attribute)
- \( \sec(f) \) (attribute)
- \( \csc(f) \) (attribute)
- \( \cot(f) \) (attribute)
- \( \arcsin(f) \) (attribute)
- \( \arccos(f) \) (attribute)
- \( \arctan(f) \) (attribute)
- \( \cosh(f) \) (attribute)
- \( \sinh(f) \) (attribute)
- \( \tanh(f) \) (attribute)
- \( \sech(f) \) (attribute)
- \( \csch(f) \) (attribute)
- \( \coth(f) \) (attribute)
- \( \text{asinh}(f) \) (attribute)
- \( \text{acosh}(f) \) (attribute)
- \( \text{atanh}(f) \) (attribute)
- \( \log(f) \) (operation)
- \( \log_{2}(f) \) (attribute)
- \( \log_{10}(f) \) (attribute)
- \( \log_{1+}(f) \) (attribute)
- \( \exp(f) \) (attribute)
- \( \exp_{2}(f) \) (attribute)
- \( \exp_{10}(f) \) (attribute)
- \( \exp_{1+}(f) \) (attribute)
- \( \text{cubecube}(f) \) (attribute)
- \( \text{square}(f) \) (attribute)
- \( \text{ceil}(f) \) (attribute)
- \( \text{floor}(f) \) (attribute)
- \( \text{round}(f) \) (attribute)
- \( \text{trunc}(f) \) (attribute)
- \( \text{atan2}(y, x) \) (operation)
- \( \text{frexp}(f) \) (attribute)
- \( \text{ldec}(f, \text{exp}) \) (operation)
- \( \text{absolutevalue}(f) \) (attribute)
- \( \text{norm}(f) \) (attribute)
- \( \text{hypotheneuse}(x, y) \) (operation)
- \( \text{frac}(f) \) (attribute)
- \( \text{sin}\cos(f) \) (attribute)
- \( \text{erf}(f) \) (attribute)
- \( \text{ greentea}(f) \) (attribute)
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\[ \Gamma(f) \]  

(attribut)

Standard math functions.

19.3 High-precision-specific methods

GAP provides a mechanism for packages to implement new floating-point numerical interfaces. The following describes that mechanism, actual examples of packages are documented separately.

A package must create a record with fields (all optional)

creator  
a function converting strings to floating-point;

eager  
a character allowing immediate conversion to floating-point;

objbyextrep  
a function creating a floating-point number out of a list [mantissa, exponent];

filter  
a filter for the new floating-point objects;

constants  
a record containing numerical constants, such as MANT\_DIG, MAX, MIN, NAN.

The package must install methods Int, Rat, String for its objects, and creators NewFloat(filter, IsRat), NewFloat(IsString). It must then install methods for all arithmetic and numerical operations: SUM, Exp, ...

The user chooses that implementation by calling SetFloats (19.2.4) with the record as argument, and with an optional second argument requesting a precision in binary digits.

19.4 Complex arithmetic

Complex arithmetic may be implemented in packages, and is present in float. Complex numbers are treated as usual numbers; they may be input with an extra "i" as in \(-0.5 + 0.866i\). They may also be created using NewFloat (19.2.1) with three arguments: the float filter, the real part, and the imaginary part.

Methods should then be implemented for Norm, RealPart, ImaginaryPart, ComplexConjugate, ...

19.4.1 Argument (for complex floats)

\[ \arg(z) \]  

(attribut)

Returns the argument of the complex number \( z \), namely the value \( \text{Atan2}(\text{ImaginaryPart}(z), \text{RealPart}(z)) \).
19.5 Interval-specific methods

Interval arithmetic may also be implemented in packages. Intervals are in fact efficient implementations of sets of real numbers. The only non-trivial issue is how they should be compared. The standard EQ tests if the intervals are equal; however, it is usually more useful to know if intervals overlap, or are disjoint, or are contained in each other.

Note the usual convention that intervals are compared as in $[a, b] \leq [c, d]$ if and only if $a \leq c$ and $b \leq d$.

19.5.1 Sup

\[ \text{Sup}(x) \]

( attribute)

Returns the supremum of the interval $x$.

19.5.2 Inf

\[ \text{Inf}(x) \]

( attribute)

Returns the infimum of the interval $x$.

19.5.3 Mid

\[ \text{Mid}(x) \]

( attribute)

Returns the midpoint of the interval $x$.

19.5.4 AbsoluteDiameter

\[ \text{AbsoluteDiameter}(x) \]

( attribute)

\[ \text{Diameter}(x) \]

( operation)

Returns the absolute diameter of the interval $x$, namely the difference $\text{Sup}(x) - \text{Inf}(x)$.

19.5.5 RelativeDiameter

\[ \text{RelativeDiameter}(x) \]

( attribute)

Returns the relative diameter of the interval $x$, namely $(\text{Sup}(x) - \text{Inf}(x))/\text{AbsoluteValue}(\text{Min}(x))$.

19.5.6 IsDisjoint

\[ \text{IsDisjoint}(x1, x2) \]

( operation)

Returns true if the two intervals $x1, x2$ are disjoint.
19.5.7 IsSubset (for interval floats)

\[ \text{IsSubset}(x1, x2) \]

Returns \textbf{true} if the interval \( x1 \) contains \( x2 \).

19.5.8 IncreaseInterval

\[ \text{IncreaseInterval}(x, \text{delta}) \]

Returns an interval with same midpoint as \( x \) but absolute diameter increased by \( \text{delta} \).

19.5.9 BlowupInterval

\[ \text{BlowupInterval}(x, \text{ratio}) \]

Returns an interval with same midpoint as \( x \) but relative diameter increased by \( \text{ratio} \).

19.5.10 BisectInterval

\[ \text{BisectInterval}(x) \]

Returns a list of two intervals whose union equals the interval \( x \).
Chapter 20

Booleans

The two main boolean values are true and false. They stand for the logical values of the same name. They appear as values of the conditions in if-statements and while-loops. Booleans are also important as return values of filters (see 13.2) such as IsFinite (30.4.2) and IsBool (20.1.1). Note that it is a convention that the name of a function that returns true or false according to the outcome, starts with Is.

For technical reasons, also the value fail (see 20.2) is regarded as a boolean.

20.1 IsBool (Filter)

20.1.1 IsBool

\[ \text{IsBool}(\text{obj}) \]  
(Category)

Tests whether \( \text{obj} \) is true, false or fail.

Example

\[
\text{gap> IsBool( true ); IsBool( false ); IsBool( 17 );}
\]

true
true
false

20.2 Fail (Variable)

20.2.1 fail

\[ \text{fail} \]  
(global variable)

The value fail is used to indicate situations when an operation could not be performed for the given arguments, either because of shortcomings of the arguments or because of restrictions in the implementation or computability. So for example Position (21.16.1) will return fail if the point searched for is not in the list.

fail is simply an object that is different from every other object than itself.

For technical reasons, fail is a boolean value. But note that fail cannot be used to form boolean expressions with and, or, and not (see 20.4 below), and fail cannot appear in boolean lists (see Chapter 22).
20.3 Comparisons of Booleans

20.3.1 Equality and inequality of Booleans

\begin{verbatim}
bool1 = bool2

bool1 <> bool2

The equality operator = evaluates to true if the two boolean values bool1 and bool2 are equal, i.e., both are true or both are false or both fail, and false otherwise. The inequality operator <> evaluates to true if the two boolean values bool1, bool2 are different, and false otherwise. This operation is also called the exclusive or, because its value is true if exactly one of bool1 or bool2 is true.

You can compare boolean values with objects of other types. Of course they are never equal.
\end{verbatim}

\begin{verbatim}
gap> true = false;
fake

gap> false = (true = fail);
true

gap> true <> 17;
true
\end{verbatim}

20.3.2 Ordering of Booleans

\begin{verbatim}
bool1 < bool2

The ordering of boolean values is defined by true < false < fail. For the comparison of booleans with other GAP objects, see Section 4.12.
\end{verbatim}

\begin{verbatim}
gap> true < false; fail >= false;
true
true
\end{verbatim}

20.4 Operations for Booleans

The following boolean operations are only applicable to true and false.

20.4.1 Logical disjunction

\begin{verbatim}
bool1 or bool2

The logical operator or evaluates to true if at least one of the two boolean operands bool1 and bool2 is true, and to false otherwise.

or first evaluates bool1. If the value is neither true nor false an error is signalled. If the value is true, then or returns true without evaluating bool2. If the value is false, then or evaluates bool2. Again, if the value is neither true nor false an error is signalled. Otherwise or returns the value of bool2. This short-circuited evaluation is important if the value of bool1 is true and evaluation of bool2 would take much time or cause an error.

or is associative, i.e., it is allowed to write b1 or b2 or b3, which is interpreted as (b1 or b2) or b3. or has the lowest precedence of the logical operators. All logical operators have lower precedence than the comparison operators =, <, in, etc.
\end{verbatim}
20.4.2 Logical conjunction

bool1 and bool2
fil1 and fil2

The logical operator and evaluates to true if both boolean operands bool1, bool2 are true, and to false otherwise. and first evaluates bool1. If the value is neither true nor false an error is signalled. If the value is false, then and returns false without evaluating bool2. If the value is true, then and evaluates bool2. Again, if the value is neither true nor false an error is signalled. Otherwise and returns the value of bool2. This short-circuited evaluation is important if the value of bool1 is false and evaluation of bool2 would take much time or cause an error.

and is associative, i.e., it is allowed to write b1 and b2 and b3, which is interpreted as (b1 and b2) and b3. and has higher precedence than the logical or operator, but lower than the unary logical not operator. All logical operators have lower precedence than the comparison operators =, <, in, etc.

and can also be applied to filters. It returns a filter that when applied to some argument x, tests fil1(x) and fil2(x).

20.4.3 Logical negation

not bool

The logical operator not returns true if the boolean value bool is false, and true otherwise. An error is signalled if bool does not evaluate to true or false.

not has higher precedence than the other logical operators, or and and. All logical operators have lower precedence than the comparison operators =, <, in, etc.
Example

```gap
gap> true and false;
false
gap> not true;
false
gap> not false;
true
```
Chapter 21

Lists

Lists are the most important way to treat objects together. A list arranges objects in a definite order. So each list implies a partial mapping from the integers to the elements of the list. I.e., there is a first element of a list, a second, a third, and so on. Lists can occur in mutable or immutable form, see 12.6 for the concept of mutability, and 21.7 for the case of lists.

This chapter deals mainly with the aspect of lists in GAP as data structures. Chapter 30 tells more about the collection aspect of certain lists, and more about lists as arithmetic objects can be found in the chapters 23 and 24.

Lists are used to implement ranges (see 21.22), sets (see 21.19), strings (see 27), row vectors and matrices (see 23 and 24, but note that GAP supports also linear algebra for objects which are not lists, see 26); boolean lists (see 22) are a further special kind of lists.

Several operations for lists, such as Intersection (30.5.2) and Random (30.7.1), will be described in Chapter 30, in particular see 30.3.

21.1 List Categories

A list can be written by writing down the elements in order between square brackets [, ], and separating them with commas ,. An empty list, i.e., a list with no elements, is written as [].

Example

```gap
gap> [ 1, 3, 5, 7 ];  # a list with three elements
[ 1, 3, 5, 7 ]
gap> [ [ ] , [ 1 ], [ 1, 2 ] ];  # a list may contain other lists
[ [ ], [ 1 ], [ 1, 2 ] ]
```

Each list constructed this way is mutable (see 12.6).

21.1.1 IsList

> IsList(obj)

(Category)

tests whether obj is a list.

Example

```gap
gap> IsList([ 1, 3, 5 ]);  IsList( 1 );
true
false
```
21.1.2 IsDenseList

\[ \text{IsDenseList}(\text{obj}) \]

A list is dense if it has no holes, i.e., contains an element at every position up to the length. It is absolutely legal to have lists with holes. They are created by leaving the entry between the commas empty. Holes at the end of a list are ignored. Lists with holes are sometimes convenient when the list represents a mapping from a finite, but not consecutive, subset of the positive integers.

\begin{verbatim}
gap> IsDenseList( [ 1, 2, 3 ]); true
gap> l := [ , 4, 9,, 25,, 49,,,, 121 ];; IsDenseList( l ); false
gap> l[3]; 9
gap> l[4]; List Element: <list>[4] must have an assigned value not in any function
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or you can 'return;' after assigning a value to continue
brk> l[4] := 16;; # assigning a value
brk> return; # to escape the break-loop
16
gap>
\end{verbatim}

Observe that requesting the value of \( l[4] \), which was not assigned, caused the entry of a break-loop (see Section 6.4). After assigning a value and typing \text{return;}\), GAP is finally able to comply with our request (by responding with 16).

21.1.3 IsHomogeneousList

\[ \text{IsHomogeneousList}(\text{obj}) \]

returns \text{true} if \( \text{obj} \) is a list and it is homogeneous, and \text{false} otherwise. A homogeneous list is a dense list whose elements lie in the same family (see 13.1). The empty list is homogeneous but not a collection (see 30), a nonempty homogeneous list is also a collection.

\begin{verbatim}
gap> IsHomogeneousList( [ 1, 2, 3 ] ); IsHomogeneousList( [] ); true true
gap> IsHomogeneousList( [ 1, false, () ] ); false
\end{verbatim}

21.1.4 IsTable

\[ \text{IsTable}(\text{obj}) \]

A table is a nonempty list of homogeneous lists which lie in the same family. Typical examples of tables are matrices (see 24).
21.1.5 IsRectangularTable

\( \text{IsRectangularTable}(\text{list}) \) (property)

A list lies in IsRectangularTable when it is nonempty and its elements are all homogeneous lists of the same family and the same length.

21.1.6 IsConstantTimeAccessList

\( \text{IsConstantTimeAccessList}(\text{list}) \) (Category)

This category indicates whether the access to each element of the list \( \text{list} \) will take roughly the same time. This is implied for example by IsList and IsInternalRep, so all strings, Boolean lists, ranges, and internally represented plain lists are in this category.

But also other enumerators (see 21.23) can lie in this category if they guarantee constant time access to their elements.

21.2 Basic Operations for Lists

The basic operations for lists are element access (see 21.3), assignment of elements to a list (see 21.4), fetching the length of a list (see Length (21.17.5)), the test for a hole at a given position, and unbinding an element at a given position (see 21.5).

The term basic operation means that each other list operation can be formulated in terms of the basic operations. (But note that often a more efficient method than this one is implemented.)

Any GAP object \( \text{list} \) in the category IsList (21.1.1) is regarded as a list, and if methods for the basic list operations are installed for \( \text{list} \) then \( \text{list} \) can be used also for the other list operations.

For internally represented lists, kernel methods are provided for the basic list operations with positive integer indices. For other lists or other indices, it is possible to install appropriate methods for these operations. This permits the implementation of lists that do not need to store all list elements (see also 21.23); for example, the elements might be described by an algorithm, such as the elements list of a group. For this reduction of space requirements, however, a price in access time may have to be paid (see ConstantTimeAccessList (21.17.6)).

21.2.1 \( \text{\textbackslash [\text{\textbackslash}]\text{\textbackslash}} \)

\( \text{\textbackslash [\text{\textbackslash}]\text{\textbackslash}(\text{list}, \text{ix})} \) (operation)

\( \text{IsBound\textbackslash [\text{\textbackslash}]\text{\textbackslash}(\text{list}, \text{ix})} \) (operation)

\( \text{\textbackslash [\text{\textbackslash}]\text{\textbackslash:\textbackslash=(\text{list}, \text{pos}, \text{ix})} \) (operation)
Unbind\[\](list, ix)

These operations implement element access, test for element boundedness, list element assignment, and removal of the element with index ix.

Note that the special characters \[\], :, and = must be escaped with a backslash \ (see 4.3); so \[\] (21.2.1) denotes the operation for element access in a list, whereas [] denotes an empty list. (Maybe the variable names involving special characters look strange, but nevertheless they are quite suggestive.)

\[\](list, ix) is equivalent to list [ ix ], which clearly will usually be preferred; the former is useful mainly if one wants to access the operation itself, for example if one wants to install a method for element access in a special kind of lists.

Similarly, IsBound\[\] (21.2.1) is used explicitly mainly in method installations. In other situations, one can simply call IsBound (21.5.1), which then delegates to IsBound\[\] (21.2.1) if the first argument is a list, and to IsBound\.[ (29.7.3) if the first argument is a record.

Analogous statements hold for \[\]:= (21.2.1) and Unbind\[\] (21.2.1).

21.3 List Elements

list [ ix ]

The above construct evaluates to the element of the list list with index ix. For built-in list types and collections, indexing is done with origin 1, i.e., the first element of the list is the element with index 1.

Example

```gap
gap> l := [ 2, 3, 5, 7, 11, 13 ];; l[1]; l[2]; l[6];
gap> 2
2
3
13
```

If list is not a built-in list, or ix does not evaluate to a positive integer, method selection is invoked to try and find a way of indexing list with index ix. If this fails, or the selected method finds that list [ix] is unbound, an error is signalled.

list{ poss }

The above construct evaluates to a new list new whose first element is list [poss [1]], whose second element is list [poss [2]], and so on. However, it does not need to be sorted and may contain duplicate elements. If for any i, list [ poss [i] ] is unbound, an error is signalled.

Example

```gap
gap> l := [ 2, 3, 5, 7, 11, 13, 17, 19 ];
gap> l{[4..6]}; l{[1,7,1,8]};
gap> [ 7, 11, 13 ]
gap> [ 2, 17, 2, 19 ]
```

The result is a new list, that is not identical to any other list. The elements of that list, however, are identical to the corresponding elements of the left operand (see 21.6).

It is possible to nest such sublist extractions, as can be seen in the example below.

Example

```gap
gap> m := [ [1,2],[2,5],[7,8],[10,11,12] ];; m{[1,2]};{[3,2]};
gap> [ [ 1, 2 ], [ 2, 5 ], [ 7, 8 ], [ 10, 11, 12 ] ]
gap> [ [ 1, 2 ] ]
gap> [ [ 3, 2 ], [ 6, 5 ], [ 9, 8 ] ]
```
Note the difference between the two examples. The latter extracts elements 1, 2, and 3 from \( m \) and then extracts the elements 3 and 2 from this list. The former extracts elements 1, 2, and 3 from \( m \) and then extracts the elements 3 and 2 from each of those element lists.

To be precise: With each selector \([\text{pos}]\) or \(\{\text{poss}\}\) we associate a level that is defined as the number of selectors of the form \(\{\text{poss}\}\) to its left in the same expression. For example

\[
\begin{array}{c|cccccc}
\text{level} & 0 & 0 & 1 & 2 & 2 & 3 \\
\hline
\text{1[pos1]{pos2}{pos3}[pos4}{pos5}[pos6]} & & & & & & \\
\end{array}
\]

Then a selector \([\text{pos}]\) of level level is computed as \(\text{ListElement}(\text{list}, \text{pos}, \text{level})\), where \(\text{ListElement} \) is defined as follows. (Note that \(\text{ListElement} \) is not a GAP function.)

\[
\text{ListElement} := \text{function} ( \text{list}, \text{pos}, \text{level} ) \\
\text{if level = 0 then} \\
\text{return list[pos];} \\
\text{else} \\
\text{return List( list, elm -> ListElement(elm,pos,level-1) );} \\
\text{fi;} \\
\text{end;}
\]

and a selector \(\text{list}\{\text{poss}\}\) of level level is computed as \(\text{ListElements}(\text{list}, \text{poss}, \text{level})\), where \(\text{ListElements} \) is defined as follows. (Note that \(\text{ListElements} \) is not a GAP function.)

\[
\text{ListElements} := \text{function} ( \text{list}, \text{poss}, \text{level} ) \\
\text{if level = 0 then} \\
\text{return list{poss};} \\
\text{else} \\
\text{return List( list, elm -> ListElements(elm,poss,level-1) );} \\
\text{fi;} \\
\text{end;}
\]

21.3.1 \(\{\}\) \(\{\}\)(list, poss)

This operation implements sublist access. For any list, the default method is to loop over the entries in the list \(\text{poss}\), and to delegate to the element access operation. (For the somewhat strange variable name, cf. 21.2.)

21.4 List Assignment

\text{\text{list}{\text{ix}} := \text{object};}

The list element assignment assigns the object \text{object}, which can be of any type, to the list with index \text{ix}, in the mutable (see 12.6) list \text{list}. That means that accessing the \text{ix}-th element of the list \text{list} will return \text{object} after this assignment.
Example

```gap
gap> l := [ 1, 2, 3 ];;
[ 3, 2, 3 ]
gap> l[1] := 3;; l; # assign a new object
[ 3, 2, 3 ]
gap> l[2] := [ 4, 5, 6 ];; l; # <object> may be of any type
[ 3, [ 4, 5, 6 ], 3 ]
gap> l[l[1]] := 10;; l; # <index> may be an expression
[ 3, [ 4, 5, 6 ], 10 ]
```

If the index \( ix \) is an integer larger than the length of the list \( list \) (see \texttt{Length} (21.17.5)), the list is automatically enlarged to make room for the new element. Note that it is possible to generate lists with holes that way.

Example

```gap
gap> l[4] := "another entry";; l; # <list> is enlarged
[ 3, [ 4, 5, 6 ], 10, "another entry" ]
gap> l[10] := 1;; l; # now <list> has a hole
[ 3, [ 4, 5, 6 ], 10, "another entry",,,,,,, 1 ]
```

The function \texttt{Add} (21.4.2) should be used if you want to add an element to the end of the list. Note that assigning to a list changes the list, thus this list must be mutable (see 12.6). See 21.6 for subtleties of changing lists.

If \( list \) does not evaluate to a list, \( pos \) does not evaluate to a positive integer, method selection is invoked to try and find a way of indexing \( list \) with index \( pos \). If this fails, or the selected method finds that \( list[\text{pos}] \) is unbound, or if \( object \) is a call to a function which does not return a value (for example \texttt{Print} ) an error is signalled.

\[
\text{list}\{\text{pos}\} := \text{objects};
\]

The sublist assignment assigns the object \( \text{objects}[1] \), which can be of any type, to the list \( \text{list} \) at the position \( \text{pos}[1] \), the object \( \text{objects}[2] \) to \( \text{list}[\text{pos}[2]] \), and so on. \( \text{pos} \) must be a dense list of positive integers, it need, however, not be sorted and may contain duplicate elements. \( \text{objects} \) must be a dense list and must have the same length as \( \text{pos} \).

Example

```gap
gap> l := [ 2, 3, 5, 7, 11, 13, 17, 19 ];;
gap> l{[1..4]} := [10..13];; l;
[ 10, 11, 12, 13, 11, 13, 17, 19 ]
gap> l{[1,7,1,10]} := [ 1, 2, 3, 4 ];; l;
[ 3, 11, 12, 13, 11, 13, 2, 19,, 4 ]
```

The next example shows that it is possible to nest such sublist assignments.

Example

```gap
gap> m := [ [1,2,3], [4,5,6], [7,8,9], [10,11,12] ];;
gap> m{[1,2,3]}{[3,2]} := [ 11,12, [13,14], [15,16] ];; m;
[ [ 1, 12, 11 ], [ 4, 14, 13 ], [ 7, 16, 15 ], [ 10, 11, 12 ] ]
```

The exact behaviour is defined in the same way as for list extractions (see 21.3). Namely, with each selector \( \{\text{pos}\} \) or \( \{\text{pos}\} \) we associate a level that is defined as the number of selectors of the form \( \{\text{pos}\} \) to its left in the same expression. For example
Then a list assignment `list[pos] := vals; of level level is computed as `ListAssignment(list, pos, vals, level), where `ListAssignment is defined as follows. (Note that `ListAssignment is not a GAP function.)

```
Example

ListAssignment := function ( list, pos, vals, level )
local i;
if level = 0 then
    list[pos] := vals;
else
    for i in [1..Length(list)] do
        ListAssignment( list[i], pos, vals[i], level-1 );
    od;
fi;
end;
```

and a list assignment `list{poss} := vals of level level is computed as `ListAssignments(list, poss, vals, level), where `ListAssignments is defined as follows. (Note that `ListAssignments is not a GAP function.)

```
Example

ListAssignments := function ( list, poss, vals, level )
local i;
if level = 0 then
    list{poss} := vals;
else
    for i in [1..Length(list)] do
        ListAssignments( list[i], poss, vals[i], level-1 );
    od;
fi;
end;
```

21.4.1 `{}` :=

`{}` := (list, poss, val)

This operation implements sublist assignment. For any list, the default method is to loop over the entries in the list `poss, and to delegate to the element assignment operation. (For the somewhat strange variable name, cf. 21.2.)

21.4.2 Add

`Add(list, obj[, pos])`

adds the element `obj to the mutable list `list. The two argument version adds `obj at the end of `list, i.e., it is equivalent to the assignment `list[ Length(list) + 1 ] := obj, see 21.4.
The three argument version adds \texttt{obj} in position \texttt{pos}, moving all later elements of the list (if any) up by one position. Any holes at or after position \texttt{pos} are also moved up by one position, and new holes are created before \texttt{pos} if they are needed.

Nothing is returned by \texttt{Add}, the function is only called for its side effect.

### 21.4.3 Remove

\texttt{Remove(list [, pos])}

removes an element from \texttt{list}. The one argument form removes the last element. The two argument form removes the element in position \texttt{pos}, moving all subsequent elements down one position. Any holes after position \texttt{pos} are also moved down by one position.

The one argument form always returns the removed element. In this case \texttt{list} must be non-empty.

The two argument form returns the old value of \texttt{list[pos]} if it was bound, and nothing if it was not. Note that accessing or assigning the return value of this form of the \texttt{Remove} operation is only safe when you know that there will be a value, otherwise it will cause an error.

\begin{verbatim}
 gap> l := [ 2, 3, 5 ];; Add( l, 7 ); l;
 [ 2, 3, 5, 7 ]
 gap> Add(l,4,2); l;
 [ 2, 4, 3, 5, 7 ]
 gap> Remove(l,2); l;
 4
 [ 2, 3, 5, 7 ]
 gap> Remove(l); l;
 7
 [ 2, 3, 5 ]
 gap> Remove(l,5); l;
 [ 2, 3, 5 ]
\end{verbatim}

### 21.4.4 CopyListEntries

\texttt{CopyListEntries(fromlst, fromind, fromstep, tolst, toind, tostep, n)}

This function copies \texttt{n} elements from \texttt{fromlst}, starting at position \texttt{fromind} and incrementing the position by \texttt{fromstep} each time, into \texttt{tolst} starting at position \texttt{toind} and incrementing the position by \texttt{tostep} each time. \texttt{fromlst} and \texttt{tolst} must be plain lists. \texttt{fromstep} and/or \texttt{tostep} can be negative. Unbound positions of \texttt{fromlst} are simply copied to \texttt{tolst}.

\texttt{CopyListEntries} is used in methods for the operations \texttt{Add} (21.4.2) and \texttt{Remove} (21.4.3).

### 21.4.5 Append

\texttt{Append(list1, list2)}

adds the elements of the list \texttt{list2} to the end of the mutable list \texttt{list1}, see 21.4. \texttt{list2} may contain holes, in which case the corresponding entries in \texttt{list1} will be left unbound. \texttt{Append} returns nothing, it is only called for its side effect.

Note that \texttt{Append} changes its first argument, while \texttt{Concatenation} (21.20.1) creates a new list and leaves its arguments unchanged.
21.5 IsBound and Unbind for Lists

21.5.1 IsBound (for a list index)

\[
\text{IsBound}(\text{list}[, \, n])
\]

IsBound returns true if the list list has an element at index \(n\), and false otherwise. list must evaluate to a list, or to an object for which a suitable method for IsBound has been installed, otherwise an error is signalled.

Example

\[
\begin{align*}
gap> 1 & := [\, 2, 3, 5\, ]; \text{ Append}(1, [\, 7, 11, 13\, ]); 1; \\
& [2, 3, 5, 7, 11, 13] \\
gap> \text{Append}(1, [\, 17,\, 23\, ]); 1; \\
& [2, 3, 5, 7, 11, 13, 17,\, 23]
\end{align*}
\]

\[
\begin{align*}
gap> l & := [\, , 2, 3,\, , 5,\, , 7,\, ,\, ,\, , 11\, ];; \\
gap> \text{IsBound}(l[7]); \\
true \\
gap> \text{IsBound}(l[4]); \\
false \\
gap> \text{IsBound}(l[101]); \\
false
\end{align*}
\]

21.5.2 GetWithDefault

\[
\text{GetWithDefault}(\text{list}, \, n, \text{default})
\]

GetWithDefault returns the \(n\)th element of the list list, if list has a value at index \(n\), and default otherwise.

While this method can be used on any list, it is particularly useful for Weak Pointer lists \texttt{86.1} where the value of the list can change.

To distinguish between the \(n\)th element being unbound, or default being in list, users can create a new mutable object, such as a string. IsIdenticalObj(12.5.1) returns false for different mutable strings, even if their contents are the same.

Example

\[
\begin{align*}
gap> l & := [1, 2,, "a"];
[1, 2,, "a"] \\
gap> \text{newobj} & := "a";
"a" \\
gap> \text{GetWithDefault}(1, 2, \text{newobj}); \\
2 \\
gap> \text{GetWithDefault}(1, 3, \text{newobj}); \\
"a" \\
gap> \text{GetWithDefault}(1, 4, \text{newobj}); \\
"a" \\
gap> \text{IsIdenticalObj}\left(\text{GetWithDefault}(1, 3, \text{newobj}), \text{newobj}\right); \\
true
\end{align*}
\]
gap> IsIdenticalObj(GetWithDefault(l, 4, newobj), newobj);  
false

21.5.3  Unbind (unbind a list entry)

Unbind deletes the element with index \( n \) in the mutable list \( \text{list} \). That is, after execution of Unbind, \( \text{list} \) no longer has an assigned value with index \( n \). Thus Unbind can be used to produce holes in a list. Note that it is not an error to unbind a nonexistent list element. \( \text{list} \) must evaluate to a list, or to an object for which a suitable method for Unbind\[\] has been installed, otherwise an error is signalled.

Example

\[
\begin{align*}
gap> & 1 := [ , 2, 3, 5, , 7, , , , 11 ];; \\
gap> & \text{Unbind}( l[3] ); \ 1; \\
& [ , 2, , 7, , , 11 ] \\
gap> & \text{Unbind}( l[4] ); \ 1; \\
& [ , 2,,,, 7,,,, 11 ]
\end{align*}
\]

Note that IsBound (21.5.1) and Unbind are special in that they do not evaluate their argument, otherwise IsBound (21.5.1) would always signal an error when it is supposed to return \texttt{false} and there would be no way to tell Unbind which component to remove.

21.6  Identical Lists

With the list assignment (see 21.4) it is possible to change a mutable list. This section describes the semantic consequences of this fact. (See also 12.5.)

First we define what it means when we say that “an object is changed”. You may think that in the following example the second assignment changes the integer.

Example

\[
\begin{align*}
i := & 3; \\
i := i + 1;
\end{align*}
\]

But in this example it is not the \texttt{integer} 3 which is changed, by adding one to it. Instead the \texttt{variable} \( i \) is changed by assigning the value of \( i+1 \), which happens to be 4, to \( i \). The same thing happens in the example below.

Example

\[
\begin{align*}
i := & [ 1, 2 ]; \\
i := [ 1, 2, 3 ];
\end{align*}
\]

The second assignment does not change the first list, instead it assigns a new list to the variable \( i \). On the other hand, in the following example the list \( \text{is} \) changed by the second assignment.

Example

\[
\begin{align*}
i := & [ 1, 2 ]; \\
i[3] := 3;
\end{align*}
\]
To understand the difference, think of a variable as a name for an object. The important point is that a list can have several names at the same time. An assignment `var := list;` means in this interpretation that `var` is a name for the object `list`. At the end of the following example 12 still has the value `[ 1, 2 ]` as this list has not been changed and nothing else has been assigned to it.

```
11 := [ 1, 2 ];
12 := 11;
11 := [ 1, 2, 3 ];
```

But after the following example the list for which 12 is a name has been changed and thus the value of 12 is now `[ 1, 2, 3 ]`.

```
11 := [ 1, 2 ];
12 := 11;
11[3] := 3;
```

We say that two lists are _identical_ if changing one of them by a list assignment also changes the other one. This is slightly incorrect, because if two lists are identical, there are actually only two names for one list. However, the correct usage would be very awkward and would only add to the confusion. Note that two identical lists must be equal, because there is only one list with two different names. Thus identity is an equivalence relation that is a refinement of equality. Identity of objects can be detected using `IsIdenticalObj (12.5.1)`.

Let us now consider under which circumstances two lists are identical.

If you enter a list literal then the list denoted by this literal is a new list that is not identical to any other list. Thus in the following example 11 and 12 are not identical, though they are equal of course.

```
11 := [ 1, 2 ];
12 := [ 1, 2 ];
```

Also in the following example, no lists in the list 1 are identical.

```
1 := [];
for i in [1..10] do 1[i] := [ 1, 2 ]; od;
```

If you assign a list to a variable no new list is created. Thus the list value of the variable on the left hand side and the list on the right hand side of the assignment are identical. So in the following example 11 and 12 are identical lists.

```
11 := [ 1, 2 ];
12 := 11;
```

If you pass a list as an argument no new list is created. Thus the list value of the variable on the left hand side and the list on the right hand side of the assignment are identical. So in the following example 11 and 12 are identical lists.

```
11 := [ 1, 2 ];
f := function ( l ) return l; end;
12 := f( 11 );
```
If you change a list it keeps its identity. Thus if two lists are identical and you change one of them, you also change the other, and they are still identical afterwards. On the other hand, two lists that are not identical will never become identical if you change one of them. So in the following example both 11 and 12 are changed, and are still identical.

```
11 := [ 1, 2 ];
12 := 11;
11[1] := 2;
```

### 21.7 Duplication of Lists

Here we describe the meaning of `ShallowCopy (12.7.1)` and `StructuralCopy (12.7.2)` for lists. For the general definition of these functions, see 12.7.

The subobjects (see `ShallowCopy (12.7.1)`) of a list are exactly its elements.

This means that for any list `list`, `ShallowCopy (12.7.1)` returns a mutable new list `new` that is not identical to any other list (see 21.6), and whose elements are identical to the elements of `list`.

Analogously, for a mutable list `list`, `StructuralCopy (12.7.2)` returns a mutable new list `scp` that is not identical to any other list, and whose elements are structural copies (defined recursively) of the elements of `list`; an element of `scp` is mutable (and then a new list) if and only if the corresponding element of `list` is mutable.

In both cases, modifying the copy `new` resp. `scp` by assignments (see 21.4) does not modify the original object `list`.

`ShallowCopy (12.7.1)` basically executes the following code for lists.

```
gap> list1 := [ [ 1, 2 ], [ 3, 4 ] ];; list2 := ShallowCopy( list1 );;
gap> IsIdenticalObj( list1, list2 );
false
```

```
gap> IsIdenticalObj( list1[1], list2[1] );
true
```

```
gap> list2[1] := 0;; list1; list2;
[ [ 1, 2 ], [ 3, 4 ] ]
[ 0, [ 3, 4 ] ]
```

`StructuralCopy (12.7.2)` basically executes the following code for lists.

```
gap> new := [ ];
for i in [ 1 .. Length( list ) ] do
  if IsBound( list[i] ) then
    new[i] := StructuralCopy( list[i] );
  fi;
od;
```

```
gap> list1 := [ [ 1, 2 ], [ 3, 4 ] ];; list2 := StructuralCopy( list1 );;
gap> IsIdenticalObj( list1[1], list2[1] );
true
```

```
gap> list2[1] := 0;; list1; list2;
[ [ 1, 2 ], [ 3, 4 ] ]
[ [ 1, 2 ], [ 0, 4 ] ]
```
Example

```gap
gap> list1 := [ [ 1, 2 ], [ 3, 4 ] ];; list2 := StructuralCopy( list1 );;
gap> IsIdenticalObj( list1, list2 );
false

gap> IsIdenticalObj( list1[1], list2[1] );
false

gap> list2[1][1] := 0;; list1; list2;
[ [ 1, 2 ], [ 3, 4 ] ]
[ [ 0, 2 ], [ 3, 4 ] ]
```

The above code is not entirely correct. If the object `list` contains a mutable object twice this object is not copied twice, as would happen with the above definition, but only once. This means that the copy `new` and the object `list` have exactly the same structure when viewed as a general graph.

Example

```gap
gap> sub := [ 1, 2 ];; list1 := [ sub, sub ];;
gap> list2 := StructuralCopy( list1 );
[ [ 1, 2 ], [ 1, 2 ] ]

gap> list2[1][1] := 0;; list2;
[ [ 0, 2 ], [ 0, 2 ] ]
gap> list1;
[ [ 1, 2 ], [ 1, 2 ] ]
```

### 21.8 Membership Test for Lists

#### 21.8.1 `\in` (element test for lists)

<table>
<thead>
<tr>
<th><code>\in(obj, list)</code></th>
<th>(operation)</th>
</tr>
</thead>
</table>

This function call or the infix variant `obj in list` tests whether there is a positive integer `i` such that `list[i] = obj` holds.

If the list `list` knows that it is strictly sorted (see `IsSSortedList (21.17.4)`), the membership test is much quicker, because a binary search can be used instead of the linear search used for arbitrary lists, see `\in (21.19.1)`.

Example

```gap
gap> 1 in [ 2, 2, 1, 3 ]; 1 in [ 4, -1, 0, 3 ];
true false

gap> s := SSortedList( [2,4,6,8,10,12,14,16,18,20,22,24,26,28,30,32] );;
gap> 17 in s; # uses binary search and only 4 comparisons
false
```

For finding the position of an element in a list, see 21.16.

### 21.9 Enlarging Internally Represented Lists

Section 21.4 told you (among other things) that it is possible to assign beyond the logical end of a mutable list, automatically enlarging the list. This section tells you how this is done for internally represented lists.
It would be extremely wasteful to make all lists large enough so that there is room for all assignments, because some lists may have more than 100000 elements, while most lists have less than 10 elements.

On the other hand suppose every assignment beyond the end of a list would be done by allocating new space for the list and copying all entries to the new space. Then creating a list of 1000 elements by assigning them in order, would take half a million copy operations and also create a lot of garbage that the garbage collector would have to reclaim.

So the following strategy is used. If a list is created it is created with exactly the correct size. If a list is enlarged, because of an assignment beyond the end of the list, it is enlarged by at least $\text{length} / 8 + 4$ entries. Therefore the next assignments beyond the end of the list do not need to enlarge the list. For example creating a list of 1000 elements by assigning them in order, would now take only 32 enlargements.

The result of this is of course that the physical length of a list may be larger than the logical length, which is usually called simply the length of the list. Aside from the implications for the performance you need not be aware of the physical length. In fact all you can ever observe, for example by calling Length (21.17.5), is the logical length.

Suppose that Length (21.17.5) would have to take the physical length and then test how many entries at the end of a list are unassigned, to compute the logical length of the list. That would take too much time. In order to make Length (21.17.5), and other functions that need to know the logical length, more efficient, the length of a list is stored along with the list.

For fine tuning code dealing with plain lists we provide the following two functions.

### 21.9.1 EmptyPlist

| EmptyPlist(len) | (function) |
| Returns: a plain list |

| ShrinkAllocationPlist(l) | (function) |
| Returns: nothing |

The function EmptyPlist returns an empty plain list which has enough memory allocated for `len` entries. This can be useful for creating and filling a plain list with a known number of entries.

The function ShrinkAllocationPlist gives back to GAP’s memory manager the physical memory which is allocated for the plain list `l` but not needed by the current number of entries.

Note that there are similar functions EmptyString (27.4.5) and ShrinkAllocationString (27.4.5) for strings instead of plain lists.

#### Example

```gap
gap> l:=[ ]; for i in [1..160] do Add(l, i^2); od;
[ ]
gap> m:=EmptyPlist(160); for i in [1..160] do Add(m, i^2); od;
[ ]
gap> # now l uses about 25% more memory than the equal list m
gap> ShrinkAllocationPlist(l);
gap> # now l and m use the same amount of memory
```

### 21.10 Comparisons of Lists

```gap
list1 = list2
list1 <> list2
```
Two lists \texttt{list1} and \texttt{list2} are equal if and only if for every index \texttt{i}, either both entries \texttt{list1[i]} and \texttt{list2[i]} are unbound, or both are bound and are equal, i.e., \texttt{list1[i] = list2[i]} is true.

\begin{verbatim}
gap> [ 1, 2, 3 ] = [ 1, 2, 3 ];
true
gap> [ , 2, 3 ] = [ 1, 2, ];
false
gap> [ 1, 2, 3 ] = [ 3, 2, 1 ];
false
\end{verbatim}

This definition will cause problems with lists which are their own entries. Comparing two such lists for equality may lead to an infinite recursion in the kernel if the list comparison has to compare the list entries which are in fact the lists themselves, and then \texttt{GAP} crashes.

\texttt{list1 < list2}

\texttt{list1 <= list2}

Lists are ordered \textit{lexicographically}. Unbound entries are smaller than any bound entry. That implies the following behaviour. Let \texttt{i} be the smallest positive integer \texttt{i} such that \texttt{list1[i]} and \texttt{list2[i]} at position \texttt{i} differ, i.e., either exactly one of \texttt{list1[i]}, \texttt{list2[i]} is bound or both entries are bound and differ. Then \texttt{list1} is less than \texttt{list2} if either \texttt{list1[i]} is unbound (and \texttt{list2[i]} is not) or both are bound and \texttt{list1[i]} < \texttt{list2[i]} is true.

\begin{verbatim}
gap> [ 1, 2, 3, 4 ] < [ 1, 2, 4, 8 ]; # <list1>[3] < <list2>[3]
true
gap> [ 1, 2, 3 ] < [ 1, 2, 3, 5 ]; # <list1>[4] is unbound and thus < 5
true
gap> [ 1, , 3, 4 ] < [ 1, -1, 3 ]; # <list1>[2] is unbound and thus < -1
true
\end{verbatim}

Note that for comparing two lists with \texttt{<} or \texttt{<=}, the (relevant) list elements must be comparable with \texttt{<}, which is usually \textit{not} the case for objects in different families, see \texttt{13.1}. Also for the possibility to compare lists with other objects, see \texttt{13.1}.

### 21.11 Arithmetic for Lists

It is convenient to have arithmetic operations for lists, in particular because in \texttt{GAP} row vectors and matrices are special kinds of lists. However, it is the wide variety of list objects because of which we prescribe arithmetic operations \textit{not for all} of them. (Keep in mind that “list” means just an object in the category \texttt{IsList (21.1.1)).}

(Due to the intended generality and flexibility, the definitions given in the following sections are quite technical. But for not too complicated cases such as matrices (see \texttt{24.3}) and row vectors (see \texttt{23.2}) whose entries aren’t lists, the resulting behaviour should be intuitive.)

For example, we want to deal with matrices which can be added and multiplied in the usual way, via the infix operators \texttt{+} and \texttt{*}; and we want also Lie matrices, with the same additive behaviour but with the multiplication defined by the Lie bracket. Both kinds of matrices shall be lists, with the usual access to their rows, with \texttt{Length (21.17.5)} returning the number of rows etc.

For the categories and attributes that control the arithmetic behaviour of lists, see \texttt{21.12}.
For the definition of return values of additive and multiplicative operations whose arguments are lists in these filters, see 21.13 and 21.14, respectively. It should be emphasized that these sections describe only what the return values are, and not how they are computed.

For the mutability status of the return values, see 21.15. (Note that this is not dealt with in the sections about the result values.)

Further details about the special cases of row vectors and matrices can be found in 23.2 and in 24.3, the compression status is dealt with in 23.3 and 24.14.

21.12 Filters Controlling the Arithmetic Behaviour of Lists

The arithmetic behaviour of lists is controlled by their types. The following categories and attributes are used for that.

Note that we distinguish additive and multiplicative behaviour. For example, Lie matrices have the usual additive behaviour but not the usual multiplicative behaviour.

21.12.1 IsGeneralizedRowVector

For a list \texttt{list}, the value \texttt{true} for \texttt{IsGeneralizedRowVector} indicates that the additive arithmetic behaviour of \texttt{list} is as defined in 21.13, and that the attribute \texttt{NestingDepthA} (21.12.4) will return a nonzero value when called with \texttt{list}.

\begin{verbatim}
Example
gap> IsList( "abc" ); IsGeneralizedRowVector( "abc" );
true false
gap> liemat:= LieObject( [ [ 1, 2 ], [ 3, 4 ] ] );
LieObject( [ [ 1, 2 ], [ 3, 4 ] ] )
gap> IsGeneralizedRowVector( liemat );
true
\end{verbatim}

21.12.2 IsMultiplicativeGeneralizedRowVector

For a list \texttt{list}, the value \texttt{true} for \texttt{IsMultiplicativeGeneralizedRowVector} indicates that the multiplicative arithmetic behaviour of \texttt{list} is as defined in 21.14, and that the attribute \texttt{NestingDepthM} (21.12.5) will return a nonzero value when called with \texttt{list}.

\begin{verbatim}
Example
gap> IsMultiplicativeGeneralizedRowVector( liemat );
false
gap> bas:= CanonicalBasis( FullRowSpace( Rationals, 3 ) );
CanonicalBasis( ( Rationals^3 ) )
gap> IsMultiplicativeGeneralizedRowVector( bas );
true
\end{verbatim}

Note that the filters \texttt{IsGeneralizedRowVector} (21.12.1), \texttt{IsMultiplicativeGeneralizedRowVector} do not enable default methods for addition or multiplication (cf. \texttt{IsListDefault} (21.12.3)).
21.12.3 IsListDefault

\[ \text{IsListDefault(list)} \] (Category)

For a list \texttt{list}, \texttt{IsListDefault} indicates that the default methods for arithmetic operations of lists, such as pointwise addition and multiplication as inner product or matrix product, shall be applicable to \texttt{list}.

\texttt{IsListDefault} implies \texttt{IsGeneralizedRowVector (21.12.1)} and \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)}.

All internally represented lists are in this category, and also all lists in the representations \texttt{IsGF2VectorRep}, \texttt{Is8BitVectorRep}, \texttt{IsGF2MatrixRep}, and \texttt{Is8BitMatrixRep} (see 23.3 and 24.14). Note that the result of an arithmetic operation with lists in \texttt{IsListDefault} will in general be an internally represented list, so most “wrapped list objects” will not lie in \texttt{IsListDefault}.

\begin{verbatim}
Example
\gap> v := [ 1, 2 ];; m := [ v, 2*v ];;
\gap> IsListDefault( v ); IsListDefault( m );
true true
\gap> IsListDefault( bas ); IsListDefault( liemat );
true false
\end{verbatim}

21.12.4 NestingDepthA

\[ \text{NestingDepthA(obj)} \] (attribute)

For a \texttt{GAP} object \texttt{obj}, \texttt{NestingDepthA} returns the \textit{additive nesting depth} of \texttt{obj}. This is defined recursively as the integer 0 if \texttt{obj} is not in \texttt{IsGeneralizedRowVector (21.12.1)}, as the integer 1 if \texttt{obj} is an empty list in \texttt{IsGeneralizedRowVector (21.12.1)}, and as 1 plus the additive nesting depth of the first bound entry in \texttt{obj} otherwise.

\begin{verbatim}
Example
\gap> NestingDepthA( v ); NestingDepthM( v );
1 1
\gap> NestingDepthA( m ); NestingDepthM( m );
2 2
\gap> NestingDepthA( liemat ); NestingDepthM( liemat );
2 0
\end{verbatim}

21.12.5 NestingDepthM

\[ \text{NestingDepthM(obj)} \] (attribute)

For a \texttt{GAP} object \texttt{obj}, \texttt{NestingDepthM} returns the \textit{multiplicative nesting depth} of \texttt{obj}. This is defined recursively as the integer 0 if \texttt{obj} is not in \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)}, as the integer 1 if \texttt{obj} is an empty list in \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)}, and as 1 plus the multiplicative nesting depth of the first bound entry in \texttt{obj} otherwise.
21.13 Additive Arithmetic for Lists

In this general context, we define the results of additive operations only in the following situations. For unary operations (zero and additive inverse), the unique argument must be in \texttt{IsGeneralizedRowVector} (21.12.1); for binary operations (addition and subtraction), at least one argument must be in \texttt{IsGeneralizedRowVector} (21.12.1), and the other either is not a list or also in \texttt{IsGeneralizedRowVector} (21.12.1).

(For non-list GAP objects, defining the results of unary operations is not an issue here, and if at least one argument is a list not in \texttt{IsGeneralizedRowVector} (21.12.1), it shall be left to this argument whether the result in question is defined and what it is.)

21.13.1 Zero for lists

The zero (see \texttt{Zero} (31.10.3)) of a list \texttt{x} in \texttt{IsGeneralizedRowVector} (21.12.1) is defined as the list whose entry at position \texttt{i} is the zero of \texttt{x[i]} if this entry is bound, and is unbound otherwise.

```gap
gap> Zero( [ 1, 2, 3 ] ); Zero( [ [ 1, 2 ], 3 ] ); Zero( liemat );
[ 0, 0, 0 ]
[ [ 0, 0 ], 0 ]
LieObject( [ [ 0, 0 ], [ 0, 0 ] ] )
```

21.13.2 AdditiveInverse for lists

The additive inverse (see \texttt{AdditiveInverse} (31.10.9)) of a list \texttt{x} in \texttt{IsGeneralizedRowVector} (21.12.1) is defined as the list whose entry at position \texttt{i} is the additive inverse of \texttt{x[i]} if this entry is bound, and is unbound otherwise.

```gap
gap> AdditiveInverse( [ 1, 2, 3 ] ); AdditiveInverse( [ [ 1, 2 ], 3 ] );
[ -1, -2, -3 ]
[ [ -1, -2 ], -3 ]
```

21.13.3 Addition of lists

If \texttt{x} and \texttt{y} are in \texttt{IsGeneralizedRowVector} (21.12.1) and have the same additive nesting depth (see \texttt{NestingDepthA} (21.12.4)), the sum \texttt{x + y} is defined \textit{pointwise}, in the sense that the result is a list whose entry at position \texttt{i} is \texttt{x[i] + y[i]} if these entries are bound, is a shallow copy (see \texttt{ShallowCopy} (12.7.1)) of \texttt{x[i]} or \texttt{y[i]} if the other argument is not bound at position \texttt{i}, and is unbound if both \texttt{x} and \texttt{y} are unbound at position \texttt{i}.

```gap
gap> l1 := [ [ 1, 2 ], 3 ]; l2 := [ 1, [ 2, 3 ] ];
gap> NestingDepthA( l1 ); NestingDepthM( l1 );
2
2
gap> NestingDepthA( l2 ); NestingDepthM( l2 );
1
1
```
If \( x \) is in \textbf{IsGeneralizedRowVector} (21.12.1) and \( y \) is in \textbf{IsGeneralizedRowVector} (21.12.1) and has lower additive nesting depth, or is neither a list nor a domain, the sum \( x + y \) is defined as a list whose entry at position \( i \) is \( x[i] + y \) if \( x \) is bound at position \( i \), and is unbound if not. The equivalent holds in the reversed case, where the order of the summands is kept, as addition is not always commutative.

**Example**

\[
\text{gap> } 1 + [1, 2, 3]; \quad [1, 2, 3] + [0, 2, 4]; \quad [1, 2] + [Z(2)]; \\
[2, 3, 4] \\
[1, 4, 7] \\
[0*Z(2), 2] \\
\text{gap> } 11 := [1, , 3, 4];; 12 := [2, 3, 4, 5];; \\
\text{gap> } 13 := [ [1, 2], , [5, 6]]; 14 := [ , [3, 4], [5, 6]];; \\
\text{gap> NestingDepthA( 11 ); NestingDepthA( 12 );} \\
1 \\
2 \\
\text{gap> } NestingDepthA( 13 ); NestingDepthA( 14 ); \\
2 \\
2 \\
\text{gap> } 11 + 12; \\
[1, 2, 6, 8, 5] \\
\text{gap> } 11 + 13; \\
[2, 2, 3, 4],, [6, 6, 3, 4] \\
\text{gap> } 12 + 14; \\
[ , [3, 6, 3, 4, 5], [5, 8, 3, 4, 5]] \\
\text{gap> } 13 + 14; \\
[1, 2], [3, 4], [10, 12] \\
\text{gap> } 11 + [ ]; \\
[1,, 3, 4]
\]

21.13.4 Subtraction of lists

For two GAP objects \( x \) and \( y \) of which one is in \textbf{IsGeneralizedRowVector} (21.12.1) and the other is also in \textbf{IsGeneralizedRowVector} (21.12.1) or is neither a list nor a domain, \( x - y \) is defined as \( x + (-y) \).

**Example**

\[
\text{gap> } 11 - 12; \\
[1, -2, 0, 0, -5] \\
\text{gap> } 11 - 13; \\
[0, -2, 3, 4],, [-4, -6, 3, 4] \\
\text{gap> } 12 - 14; \\
[ , [-3, -2, 3, 4, 5], [-5, -4, 3, 4, 5]] \\
\text{gap> } 13 - 14; \\
[1, 2], [-3, -4], [0, 0] \\
\text{gap> } 11 - [ ]; \\
[1,, 3, 4]
\]

21.14 Multiplicative Arithmetic for Lists

In this general context, we define the results of multiplicative operations only in the following situations. For unary operations (one and inverse), the unique argument must be in
IsMultiplicativeGeneralizedRowVector (21.12.2); for binary operations (multiplication and division), at least one argument must be in IsMultiplicativeGeneralizedRowVector (21.12.2), and the other either not a list or also in IsMultiplicativeGeneralizedRowVector (21.12.2).

(For non-list GAP objects, defining the results of unary operations is not an issue here, and if at least one argument is a list not in IsMultiplicativeGeneralizedRowVector (21.12.2), it shall be left to this argument whether the result in question is defined and what it is.)

21.14.1 One for lists

The one (see One (31.10.2)) of a dense list \( x \) in IsMultiplicativeGeneralizedRowVector (21.12.2) such that \( x \) has even multiplicative nesting depth and has the same length as each of its rows is defined as the usual identity matrix on the outer two levels, that is, an identity matrix of the same dimensions, with diagonal entries \( \text{One}( x[1][1] ) \) and off-diagonal entries \( \text{Zero}( x[1][1] ) \).

Example

\[
gap> \text{One}( \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} ); \\
\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\
\gap> \text{One}( \begin{bmatrix} \begin{bmatrix} 1 \end{bmatrix} & \begin{bmatrix} 2 \end{bmatrix} \\ \begin{bmatrix} 3 \end{bmatrix} & \begin{bmatrix} 4 \end{bmatrix} \end{bmatrix} ); \\
\begin{bmatrix} \begin{bmatrix} 1 \end{bmatrix} & \begin{bmatrix} 0 \end{bmatrix} \\ \begin{bmatrix} 0 \end{bmatrix} & \begin{bmatrix} 1 \end{bmatrix} \end{bmatrix} \\
\]

21.14.2 Inverse for lists

The inverse (see Inverse (31.10.8)) of an invertible square table \( x \) in IsMultiplicativeGeneralizedRowVector (21.12.2) whose entries lie in a common field is defined as the usual inverse \( y \), i.e., a square matrix over the same field such that \( x \cdot y \) and \( y \cdot x \) is equal to \( \text{One}( x ) \).

Example

\[
gap> \text{Inverse}( \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} ); \\
\begin{bmatrix} -2 & 1 \\ 3/2 & -1/2 \end{bmatrix} \\
\]

21.14.3 Multiplication of lists

There are three possible computations that might be triggered by a multiplication involving a list in IsMultiplicativeGeneralizedRowVector (21.12.2). Namely, \( x \cdot y \) might be

(I) the inner product \( x[1] \cdot y[1] + x[2] \cdot y[2] + \cdots + x[n] \cdot y[n] \), where summands are omitted for which the entry in \( x \) or \( y \) is unbound (if this leaves no summand then the multiplication is an error), or

(L) the left scalar multiple, i.e., a list whose entry at position \( i \) is \( x[i] \cdot y[i] \) if \( y \) is bound at position \( i \), and is unbound if not, or

(R) the right scalar multiple, i.e., a list whose entry at position \( i \) is \( x[i] \cdot y[i] \) if \( x \) is bound at position \( i \), and is unbound if not.

Our aim is to generalize the basic arithmetic of simple row vectors and matrices, so we first summarize the situations that shall be covered.

<table>
<thead>
<tr>
<th></th>
<th>scl</th>
<th>vec</th>
<th>mat</th>
</tr>
</thead>
<tbody>
<tr>
<td>scl</td>
<td>(L)</td>
<td>(L)</td>
<td></td>
</tr>
<tr>
<td>vec</td>
<td>(R)</td>
<td>(I)</td>
<td></td>
</tr>
<tr>
<td>mat</td>
<td>(R)</td>
<td>(R)</td>
<td></td>
</tr>
</tbody>
</table>
This means for example that the product of a scalar \( (\text{scl}) \) with a vector \( (\text{vec}) \) or a matrix \( (\text{mat}) \) is computed according to \( (L) \). Note that this is asymmetric.

Now we can state the general multiplication rules.

If exactly one argument is in \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)} then we regard the other argument (which is then neither a list nor a domain) as a scalar, and specify result \( (L) \) or \( (R) \), depending on ordering.

In the remaining cases, both \( x \) and \( y \) are in \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)}, and we distinguish the possibilities by their multiplicative nesting depths. An argument with \textit{odd} multiplicative nesting depth is regarded as a vector, and an argument with \textit{even} multiplicative nesting depth is regarded as a scalar or a matrix.

So if both arguments have odd multiplicative nesting depth, we specify result \( (I) \).

If exactly one argument has odd nesting depth, the other is treated as a scalar if it has lower multiplicative nesting depth, and as a matrix otherwise. In the former case, we specify result \( (L) \) or \( (R) \), depending on ordering; in the latter case, we specify result \( (L) \) or \( (I) \), depending on ordering.

We are left with the case that each argument has even multiplicative nesting depth. If the two depths are equal, we treat the computation as a matrix product, and specify result \( (R) \). Otherwise, we treat the less deeply nested argument as a scalar and the other as a matrix, and specify result \( (L) \) or \( (R) \), depending on ordering.

\begin{verbatim}
Example

gap> [ () , (2,3) , (1,2) , (1,2,3) , (1,3,2) , (1,3) ] * (1,4);
[ (1,4), (1,4)(2,3), (1,2,4), (1,2,3,4), (1,3,2,4), (1,3,4) ]

gap> [ 1, 2, , 4 ] * 2;
[ 2, 4,, 8 ]

gap> [ 1, 2, 3 ] * [ 1, 3, 5, 7 ];
22

gap> m:= [ [ 1, 2 ], 3 ];; m * m;
[ [ 7, 8 ], [ 3, 6 ], 9 ]

gap> m * m = [ m[1] * m, m[2] * m ];
true

gap> n:= [ 1, [ 2, 3 ] ];; n * n;
14

true

\end{verbatim}

### 21.14.4 Division of lists

For two \texttt{GAP} objects \( x \) and \( y \) of which one is in \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)} and the other is also in \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)} or is neither a list nor a domain, \( x/y \) is defined as \( x \cdot y^{-1} \).

\begin{verbatim}
Example

gap> [ 1, 2, 3 ] / 2;  [ 1, 2 ] / [ [ 1, 2 ], [ 3, 4 ] ];
[ 1/2, 1, 3/2 ]
[ 1, 0 ]

\end{verbatim}

### 21.14.5 mod for lists

If \( x \) and \( y \) are in \texttt{IsMultiplicativeGeneralizedRowVector (21.12.2)} and have the same multiplicative nesting depth (see \texttt{NestingDepthM (21.12.5)}), \( x \mod y \) is defined \textit{pointwise}, in the sense
that the result is a list whose entry at position \( i \) is \( x[i] \mod y[i] \) if these entries are bound, is a shallow copy (see ShallowCopy (12.7.1)) of \( x[i] \) or \( y[i] \) if the other argument is not bound at position \( i \), and is unbound if both \( x \) and \( y \) are unbound at position \( i \).

If \( x \) is in IsMultiplicativeGeneralizedRowVector (21.12.2) and \( y \) is in IsMultiplicativeGeneralizedRowVector (21.12.2) and has lower multiplicative nesting depth or is neither a list nor a domain, \( x \mod y \) is defined as a list whose entry at position \( i \) is \( x[i] \mod y \) if \( x \) is bound at position \( i \), and is unbound if not. The equivalent holds in the reversed case, where the order of the arguments is kept.

Example

\[
\begin{align*}
gap & \text{gap> 4711 mod [ 2, 3,, 5, 7 ];} \\
& \{ 1, 1,, 1, 0 \} \\
gap & \text{gap> [ 2, 3, 4, 5, 6 ] mod 3;} \\
& \{ 2, 0, 1, 2, 0 \} \\
gap & \text{gap> [ 10, 12, 14, 16 ] mod [ 3, 5, 7 ];} \\
& \{ 1, 2, 0, 16 \} 
\end{align*}
\]

21.14.6 Left quotients of lists

For two GAP objects \( x \) and \( y \) of which one is in IsMultiplicativeGeneralizedRowVector (21.12.2) and the other is also in IsMultiplicativeGeneralizedRowVector (21.12.2) or is neither a list nor a domain, LeftQuotient( \( x \), \( y \) ) is defined as \( x^{-1} \ast y \).

Example

\[
\text{gap> LeftQuotient( [ [ 1, 2 ], [ 3, 4 ] ], [ 1, 2 ] );} \\
\{ 0, 1/2 \}
\]

21.15 Mutability Status and List Arithmetic

Many results of arithmetic operations, when applied to lists, are again lists, and it is of interest whether their entries are mutable or not (if applicable). Note that the mutability status of the result itself is already defined by the general rule for any result of an arithmetic operation, not only for lists (see 12.6).

However, we do not define exactly the mutability status for each element on each level of a nested list returned by an arithmetic operation. (Of course it would be possible to define this recursively, but since the methods used are in general not recursive, in particular for efficient multiplication of compressed matrices, such a general definition would be a burden in these cases.) Instead we consider, for a list \( x \) in IsGeneralizedRowVector (21.12.1), the sequence \( x = x_1, x_2, \ldots, x_n \) where \( x_{i+1} \) is the first bound entry in \( x_i \) if exists (that is, if \( x_i \) is a nonempty list), and \( n \) is the largest \( i \) such that \( x_i \) lies in IsGeneralizedRowVector (21.12.1). The immutability level of \( x \) is defined as infinity if \( x \) is immutable, and otherwise the number of \( x_i \) which are immutable. (So the immutability level of a mutable empty list is 0.)

Thus a fully mutable matrix has immutability level 0, and a mutable matrix with immutable first row has immutability level 1 (independent of the mutability of other rows).

The immutability level of the result of any of the binary operations discussed here is the minimum of the immutability levels of the arguments, provided that objects of the required mutability status exist in GAP.
Moreover, the results have a “homogeneous” mutability status, that is, if the first bound entry at nesting depth \( i \) is immutable (mutable) then all entries at nesting depth \( i \) are immutable (mutable, provided that a mutable version of this entry exists in GAP).

Thus the sum of two mutable matrices whose first rows are mutable is a matrix all of whose rows are mutable, and the product of two matrices whose first rows are immutable is a matrix all of whose rows are immutable, independent of the mutability status of the other rows of the arguments.

For example, the sum of a matrix (mutable or immutable, i.e., of immutability level one of 0, 1, or 2) and a mutable row vector (i.e., immutability level 0) is a fully mutable matrix. The product of two mutable row vectors of integers is an integer, and since GAP does not support mutable integers, the result is immutable.

For unary arithmetic operations, there are three operations available, an attribute that returns an immutable result (Zero (31.10.3), AdditiveInverse (31.10.9), One (31.10.2), Inverse (31.10.8)), an operation that returns a result that is mutable (ZeroOp (31.10.3), AdditiveInverseOp (31.10.9), OneOp (31.10.2), InverseOp (31.10.8)), and an operation whose result has the same immutability level as the argument (ZeroSM (31.10.3), AdditiveInverseSM (31.10.9), OneSM (31.10.2), InverseSM (31.10.8)). The last kind of operations is equivalent to the corresponding infix operations \( 0 \ast \text{list} \), \( \text{list} \ast -1 \), and \( \text{list} \ast 0 \). (This holds not only for lists, see 12.6.)

An example motivating the mutability rule is the use of syntactic constructs such as \( \text{obj} \ast \text{list} \) and \( \text{list} \ast -1 \) as an elegant and efficient way to create mutable lists needed for further manipulations from mutable lists. In particular one can construct a mutable zero vector of length \( n \) by \( 0 \ast [1 .. n] \). The latter can be done also using ListWithIdenticalEntries (21.15.1).

### 21.15.1 ListWithIdenticalEntries

\[ \text{ListWithIdenticalEntries}(n, \text{obj}) \]

\( n \) is a list of length \( n \) that has the object \( \text{obj} \) stored at each of the positions from \( 1 \) to \( n \). Note that all elements of lists are identical, see 21.6.

#### Example

\[
\text{gap> ListWithIdenticalEntries}(10,0);
\]
\[
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
\]

### 21.16 Finding Positions in Lists

#### 21.16.1 Position

\[ \text{Position}(\text{list}, \text{obj}[, \text{from}]) \]

\( \text{list} \) is a list of length \( n \) that has the object \( \text{obj} \) stored at each of the positions from \( 1 \) to \( n \). Note that all elements of lists are identical, see 21.6.
returns the position of the first occurrence obj in list, or fail if obj is not contained in list. If a starting index from is given, it returns the position of the first occurrence starting the search after position from.

Each call to the two argument version is translated into a call of the three argument version, with third argument the integer zero 0. (Methods for the two argument version must be installed as methods for the version with three arguments, the third being described by IsZeroCyc.)

Example

```
gap> Position( [ 2, 2, 1, 3 ], 1 );
3
gap> Position( [ 2, 1, 1, 3 ], 1 );
2
gap> Position( [ 2, 1, 1, 3 ], 1, 2 );
3
gap> Position( [ 2, 1, 1, 3 ], 1, 3 );
fail
```

21.16.2 Positions

\textbf{Example}

```
gap> Positions([1,2,1,2,3,2,2],2);
[ 2, 4, 6, 7 ]
gap> Positions([1,2,1,2,3,2,2],4);
[ ]
```

21.16.3 PositionCanonical

\textbf{Example}

```
gap> g:=Group((1,2,3,4),(1,2));;u:=Subgroup(g,[](1,2)(3,4),(1,3)(2,4)];;
gap> rt:=RightTransversal(g,u);;AsList(rt);
[ (), (3,4), (2,3), (2,3,4), (2,4,3), (2,4) ]
gap> Position(rt,(1,2));
fail
gap> PositionCanonical(rt,(1,2));
2
```
21.16.4 PositionNthOccurrence

\[ \text{PositionNthOccurrence} \left( \text{list}, \text{obj}, n \right) \]

returns the position of the \( n \)-th occurrence of \( \text{obj} \) in \( \text{list} \) and returns \text{fail} if \( \text{obj} \) does not occur \( n \) times.

Example

\[
\begin{align*}
gap & \text{PositionNthOccurrence}([1,2,3,2,4,2,1],1,1); \\
gap & 1 \\
gap & \text{PositionNthOccurrence}([1,2,3,2,4,2,1],1,2); \\
gap & 7 \\
gap & \text{PositionNthOccurrence}([1,2,3,2,4,2,1],2,3); \\
gap & 6 \\
gap & \text{PositionNthOccurrence}([1,2,3,2,4,2,1],2,4); \\
& \text{fail}
\end{align*}
\]

21.16.5 PositionSorted

\[ \text{PositionSorted} \left( \text{list}, \text{elm}[\text{func}] \right) \]

Called with two arguments, \text{PositionSorted} returns the position of the element \( \text{elm} \) in the sorted list \( \text{list} \).

Called with three arguments, \text{PositionSorted} returns the position of the element \( \text{elm} \) in the list \( \text{list} \), which must be sorted with respect to \( \text{func} \). \( \text{func} \) must be a function of two arguments that returns \text{true} if the first argument is less than the second argument, and \text{false} otherwise.

\text{PositionSorted} returns \( \text{pos} \) such that \( \text{list[pos-1]} < \text{elm} \leq \text{list[pos]} \) holds. That means, if \( \text{elm} \) appears once in \( \text{list} \), its position is returned. If \( \text{elm} \) appears several times in \( \text{list} \), the position of the first occurrence is returned. If \( \text{elm} \) is not an element of \( \text{list} \), the index where \( \text{elm} \) must be inserted to keep the list sorted is returned.

\text{PositionSorted} uses binary search, whereas \text{Position} (21.16.1) can in general use only linear search, see the remark at the beginning of 21.19. For sorting lists, see 21.18, for testing whether a list is sorted, see \text{IsSortedList} (21.17.3) and \text{IsSSortedList} (21.17.4).

Specialized functions for certain kinds of lists must be installed as methods for the operation \text{PositionSortedOp}.

Example

\[
\begin{align*}
gap & \text{PositionSorted}([1,4,5,5,6,7], 0 ); \\
& 1 \\
gap & \text{PositionSorted}([1,4,5,5,6,7], 2 ); \\
& 2 \\
gap & \text{PositionSorted}([1,4,5,5,6,7], 4 ); \\
& 2 \\
gap & \text{PositionSorted}([1,4,5,5,6,7], 5 ); \\
& 3 \\
gap & \text{PositionSorted}([1,4,5,5,6,7], 8 ); \\
& 7
\end{align*}
\]
21.16.6 PositionSortedBy

\[ \text{PositionSortedBy}(\text{list}, \text{val}, \text{func}) \]

This function returns the same value that would be returned by \text{PositionSorted}(\text{List(list, func)}, \text{val}), but computes it in a more efficient way.

To be more precise, \text{func} must be a function on one argument which returns values that can be compared to \text{val}, and \text{list} must be a list for which \( \text{func(list[i])} \leq \text{func(list[i+1])} \) holds for all relevant \( i \). This property is not verified, and if the input violates it, then the result is undefined.

\text{PositionSortedBy} returns \( pos \) such that \( \text{func(list[pos - 1])} < \text{val} \leq \text{func(list[pos])} \) holds. That means, if there are elements \( \text{elm} \) in \text{list} for which \( \text{func(elm)} = \text{val} \) holds, then the position of the first such element is returned. If no element of \text{list} satisfies this condition, then the lowest index where an element \( \text{elm} \) satisfying \( \text{func(elm)} = \text{val} \) must be inserted to preserve the property \( \text{func(list[i])} \leq \text{func(list[i+1])} \) is returned.

\text{PositionSortedBy} uses binary search. Each \( \text{func(list[i])} \) is computed at most once.

Example

\begin{verbatim}
gap> PositionSortedBy( [ "", "ab", ], -1, Length );
1
gap> PositionSortedBy( [ "", "ab", ], 0, Length );
1
gap> PositionSortedBy( [ "", "ab", ], 1, Length );
2
gap> PositionSortedBy( [ "", "ab", ], 2, Length );
2
gap> PositionSortedBy( [ "", "ab", ], 3, Length );
3
\end{verbatim}

21.16.7 PositionSet

\[ \text{PositionSet}(\text{list}, \text{obj}[, \text{func}]) \]

\text{PositionSet} is a slight variation of \text{PositionSorted} (21.16.5). The only difference to \text{PositionSorted} (21.16.5) is that \text{PositionSet} returns \text{fail} if \text{obj} is not in \text{list}.

Example

\begin{verbatim}
gap> PositionSet( [1,4,5,5,6,7], 0 );
fail
gap> PositionSet( [1,4,5,5,6,7], 2 );
fail
gap> PositionSet( [1,4,5,5,6,7], 4 );
2
gap> PositionSet( [1,4,5,5,6,7], 5 );
3
gap> PositionSet( [1,4,5,5,6,7], 8 );
fail
\end{verbatim}
21.16.8 PositionMaximum

\[ \text{PositionMaximum}( \text{list}[, \text{func}]) \]

returns the position of maximum (with PositionMaximum) or minimum (with PositionMinimum) entry in the list list. If a second argument func is passed, then return instead the position of the largest/smallest entry in List( list, func ). If several entries of the list are equal to the maximum/minimum, the first such position is returned.

\begin{verbatim}
gap> PositionMaximum( [2,4,-6,2,4] ); 2
gap> PositionMinimum( [2,4,-6,2,4] ); 3
gap> PositionMaximum( [2,4,-6,2,4], x -> -x); 3
gap> PositionMinimum( [2,4,-6,2,4], x -> -x); 2
\end{verbatim}

\textbf{Maximum} (21.20.13) and \textbf{Minimum} (21.20.14) allow you to find the maximum or minimum element of a list directly.

21.16.9 PositionProperty

\[ \text{PositionProperty}( \text{list}, \text{func}[, \text{from}]) \]

returns the position of the first entry in the list list for which the property tester function func returns \text{true}, or \text{fail} if no such entry exists. If a starting index from is given, it returns the position of the first entry satisfying func, starting the search \text{after} position from.

\begin{verbatim}
gap> PositionProperty( [10^7..10^8], IsPrime ); 20
gap> PositionProperty( [10^5..10^6], n -> not IsPrime(n) and IsPrimePowerInt(n) );
490
\end{verbatim}

\textbf{First} (21.20.22) allows you to extract the first element of a list that satisfies a certain property.

21.16.10 PositionsProperty

\[ \text{PositionsProperty}( \text{list}, \text{func}) \]

returns the set of all those positions in the list list which are bound and for which the property tester function func returns \text{true}.

\begin{verbatim}
gap> l:= [ -5 .. 5 ];
gap> PositionsProperty( l, IsPosInt ); [ 7, 8, 9, 10, 11 ]
gap> PositionsProperty( l, IsPrimeInt ); [ 1, 3, 4, 8, 9, 11 ]
\end{verbatim}
PositionProperty (21.16.9) allows you to extract the position of the first element in a list that satisfies a certain property.

21.16.11 PositionBound

\> PositionBound(list)

(operation)

returns the first bound position of the list list. For the empty list it returns fail.

\begin{verbatim}
gap> PositionBound([1,2,3]);
1
\end{verbatim}

\begin{verbatim}
gap> PositionBound([,1,2,3]);
2
\end{verbatim}

21.16.12 PositionsBound

\> PositionsBound(list)

(function)

returns the set of all bound positions in the list list.

\begin{verbatim}
gap> PositionsBound([1,2,3]);
[ 1 .. 3 ]
gap> PositionsBound([,1,,3]);
[ 2, 4 ]
gap> PositionsBound([]);
[]
\end{verbatim}

21.16.13 PositionNot

\> PositionNot(list, val[, from])

(operation)

For a list list and an object val, PositionNot returns the smallest nonnegative integer n such that list[n] is either unbound or not equal to val. If a starting index from is given, it returns the first position with this property starting the search after position from.

\begin{verbatim}
gap> l:= [ 1, 1, 2, 3, 2 ];; PositionNot( l, 1 );
3
\end{verbatim}

\begin{verbatim}
gap> PositionNot( l, 1, 4 ); PositionNot( l, 2, 4 );
5
6
\end{verbatim}

21.16.14 PositionNonZero

\> PositionNonZero(vec[, from])

(operation)

For a row vector vec, PositionNonZero returns the position of the first non-zero element of vec, or Length(vec)+1 if all entries of vec are zero.
If a starting index \( \text{from} \) is given, it returns the position of the first occurrence starting the search after position \( \text{from} \).

\text{PositionNonZero} \text{ implements a special case of PositionNot} (21.16.13). Namely, the element to be avoided is the zero element, and the list must be (at least) homogeneous because otherwise the zero element cannot be specified implicitly.

\begin{verbatim}
gap> PositionNonZero( [ 1, 1, 2, 3, 2 ] );
1
gap> PositionNonZero( [ 2, 3, 4, 5 ] * Z(2) );
2
\end{verbatim}

\textbf{21.16.15 \text{PositionSublist}}

\begin{verbatim}
\triangleright \text{PositionSublist} ( \text{list, sub[, from]} ) \text{ (operation)}
\end{verbatim}

returns the smallest index in the list \text{list} at which a sublist equal to \text{sub} starts. If \text{sub} does not occur the operation returns \text{fail}. The version with given \text{from} starts searching after position \text{from}.

To determine whether \text{sub} matches \text{list} at a particular position, use \text{IsMatchingSublist} (21.17.1) instead.

\section{21.17 \text{Properties and Attributes for Lists}}

A list that contains mutable objects (like lists or records) \text{cannot} store attribute values that depend on the values of its entries, such as whether it is homogeneous, sorted, or strictly sorted, as changes in any of its entries could change such property values, like the following example shows.

\begin{verbatim}
\text{Example}
gap> l:=[[1],[2]];
[ [ 1 ], [ 2 ] ]
gap> IsSSortedList(l);
true
gap> l[1][1]:=3;
3
gap> IsSSortedList(l);
false
\end{verbatim}

For such lists these property values must be computed anew each time the property is asked for. For example, if \text{list} is a list of mutable row vectors then the call of \text{Position} (21.16.1) with \text{list} as first argument cannot take advantage of the fact that \text{list} is in fact sorted. One solution is to call explicitly \text{PositionSorted} (21.16.5) in such a situation, another solution is to replace \text{list} by an immutable copy using \text{Immutable} (12.6.3).

\subsection{21.17.1 \text{IsMatchingSublist}}

\begin{verbatim}
\triangleright \text{IsMatchingSublist} ( \text{list, sub[, at]} ) \text{ (operation)}
\end{verbatim}

returns \text{true} if \text{sub} matches a sublist of \text{list} from position 1 (or position \text{at}, in the case of three arguments), or \text{false}, otherwise. If \text{sub} is empty \text{true} is returned. If \text{list} is empty but \text{sub} is non-empty \text{false} is returned.
If you actually want to know whether there is an at for which IsMatchingSublist( list, sub, at ) is true, use a construction like PositionSublist( list, sub ) <> fail instead (see PositionSublist (21.16.15)); it’s more efficient.

### 21.17.2 IsDuplicateFree

- **IsDuplicateFree**(obj) (property)
- **IsDuplicateFreeList**(obj) (filter)

IsDuplicateFree returns true if obj is both a list or collection, and it is duplicate free; otherwise it returns false. IsDuplicateFreeList is a synonym for IsDuplicateFree and IsList.

A list is duplicate free if it is dense and does not contain equal entries in different positions. Every domain (see 12.4) is duplicate free.

Note that GAP cannot compare arbitrary objects (by equality). This can cause that IsDuplicateFree runs into an error, if obj is a list with some non-comparable entries.

### 21.17.3 IsSortedList

- **IsSortedList**(obj) (property)

returns true if obj is a list and it is sorted, and false otherwise.

A list list is sorted if it is dense (see IsDenseList (21.1.2)) and satisfies the relation list[i] \leq list[j] whenever i < j. Note that a sorted list is not necessarily duplicate free (see IsDuplicateFree (21.17.2) and IsSSortedList (21.17.4)).

Many sorted lists are in fact homogeneous (see IsHomogeneousList (21.1.3)), but also non-homogeneous lists may be sorted (see 31.11).

In sorted lists, membership test and computing of positions can be done by binary search, see 21.19.

Note that GAP cannot compare (by less than) arbitrary objects. This can cause that IsSortedList runs into an error, if obj is a list with some non-comparable entries.

### 21.17.4 IsSSortedList

- **IsSSortedList**(obj) (property)
- **iset**(obj) (property)

returns true if obj is a list and it is strictly sorted, and false otherwise. IsSSortedList is short for “is strictly sorted list”; IsSet is just a synonym for IsSSortedList.

A list list is strictly sorted if it is sorted (see IsSortedList (21.17.3)) and satisfies the relation list[i] < list[j] whenever i < j. In particular, such lists are duplicate free (see IsDuplicateFree (21.17.2)).

(Currently there is little special treatment of lists that are sorted but not strictly sorted. In particular, internally represented lists will not store that they are sorted but not strictly sorted.)

Note that GAP cannot compare (by less than) arbitrary objects. This can cause that IsSSortedList runs into an error, if obj is a list with some non-comparable entries.
21.17.5 Length

\[ \text{Length}(\text{list}) \]

returns the length of the list \text{list}, which is defined to be the index of the last bound entry in \text{list}.

21.17.6 ConstantTimeAccessList

\[ \text{ConstantTimeAccessList}(\text{list}) \]

\text{ConstantTimeAccessList} returns an immutable list containing the same elements as the list \text{list} (which may have holes) in the same order. If \text{list} is already a constant time access list, \text{ConstantTimeAccessList} returns an immutable copy of \text{list} directly. Otherwise it puts all elements and holes of \text{list} into a new list and makes that list immutable.

21.18 Sorting Lists

GAP implements three different families of sorting algorithms. The default algorithm is pattern-defeating quicksort, a variant of quicksort which performs better on partially sorted lists and has good worst-case behaviour. The functions which begin \texttt{Stable} are stable (equal elements keep the same relative order in the sorted list) and use merge sort. Finally, the functions which begin \texttt{Shell} use the shell sort which was GAP’s default search algorithm before 4.9. \texttt{Sortex} (21.18.3) and \texttt{SortingPerm} (21.18.4) are also stable.

21.18.1 Sort

\[ \text{Sort}(\text{list}, \text{func}) \]

\[ \text{SortBy}(\text{list}, \text{func}) \]

\[ \text{StableSort}(\text{list}, \text{func}) \]

\[ \text{StableSortBy}(\text{list}, \text{func}) \]

\text{Sort} sorts the list \text{list} in increasing order. In the one argument form \text{Sort} uses the operator \(<\) to compare the elements. (If the list is not homogeneous it is the users responsibility to ensure that \(<\) is defined for all element pairs, see 31.11) In the two argument form \text{Sort} uses the function \text{func} to compare elements. \text{func} must be a function taking two arguments that returns \texttt{true} if the first is regarded as strictly smaller than the second, and \texttt{false} otherwise.\text{StableSort} behaves identically to \text{Sort}, except that \text{StableSort} will keep elements which compare equal in the same relative order, while \text{Sort} may change their relative order.\text{Sort} does not return anything, it just changes the argument \text{list}. Use \text{ShallowCopy} (12.7.1) if you want to keep \text{list}. Use \text{Reversed} (21.20.7) if you want to get a new list that is sorted in decreasing order.\text{SortBy} sorts the list \text{list} into an order such that \text{func}(\text{list}[i]) \leq \text{func}(\text{list}[i+1]) for all relevant \text{i}. \text{func} must thus be a function on one argument which returns values that can be compared. Each \text{func}(\text{list}[i]) is computed just once and stored, making this more efficient than using the two-argument version of \text{Sort} in many cases.
StableSortBy behaves the same as SortBy except that, like StableSort, it keeps pairs of values which compare equal when func is applied to them in the same relative order.

```gap
gap> list := [ 5, 4, 6, 1, 7, 5 ];; Sort( list ); list;
[ 1, 4, 5, 5, 6, 7 ]
gap> SortBy(list, x -> x mod 3);
gap> list; # Sorted by mod 3
[ 6, 1, 4, 7, 5, 5 ]
gap> list := [ [0,6], [1,2], [1,3], [1,5], [0,4], [3,4] ];;
gap> Sort( list, function(v,w) return v*v < w*w; end );
gap> list; # sorted according to the Euclidean distance from [0,0]
[ [ 1, 2 ], [ 1, 3 ], [ 0, 4 ], [ 3, 4 ], [ 1, 5 ], [ 0, 6 ] ]
gap> SortBy( list, function(v) return v[1] + v[2]; end );
gap> list; # sorted according to Manhattan distance from [0,0]
[ [ 0, 6 ], [ 0, 4 ], [ 1, 3 ], [ 1, 5 ], [ 1, 2 ], [ 3, 4 ] ]
gap> list := [ [0,6], [1,3], [3,4], [1,5], [1,2], [0,4], ];;
gap> Sort( list, function(v,w) return v[1] < w[1]; end );
gap> # note the random order of the elements with equal first component:
gap> list;
[ [ 0, 6 ], [ 0, 4 ], [ 1, 3 ], [ 1, 5 ], [ 1, 2 ], [ 3, 4 ] ]
```

21.18.2 SortParallel

▷ SortParallel(list1, list2[, func])

▷ StableSortParallel(list1, list2[, func])

SortParallel sorts the list list1 in increasing order just as Sort (21.18.1) does. In parallel it applies the same exchanges that are necessary to sort list1 to the list list2, which must of course have at least as many elements as list1 does.

StableSortParallel behaves identically to SortParallel, except it keeps elements in list1 which compare equal in the same relative order.

```gap
gap> list1 := [ 5, 4, 6, 1, 7, 5 ];;
gap> list2 := [ 2, 3, 5, 7, 8, 9 ];
gap> SortParallel( list1, list2 );
gap> list1;
[ 1, 4, 5, 5, 6, 7 ]
gap> list2;
[ 7, 3, 2, 9, 5, 8 ]
```

Note that [ 7, 3, 2, 9, 5, 8 ] or [ 7, 3, 9, 2, 5, 8 ] are possible results. StableSortParallel will always return [ 7, 3, 2, 9, 5, 8 ].

21.18.3 Sortex

▷ Sortex(list[, func])

sorts the list list and returns a permutation that can be applied to list to obtain the sorted list. The one argument form sorts via the operator <, the two argument form sorts w.r.t. the function func.
The permutation returned by \texttt{Sortex} will keep elements which compare equal in the same relative order. (If the list is not homogeneous it is the user's responsibility to ensure that $<$ is defined for all element pairs, see 31.11)

\texttt{Permuted} (21.20.18) allows you to rearrange a list according to a given permutation.

Example

\begin{verbatim}
gap> list1 := [ 5, 4, 6, 1, 7, 5 ];;
gap> list2 := ShallowCopy( list1 );;
gap> perm := Sortex( list1 );
(1,3,5,6,4)
gap> list1;
[ 1, 4, 5, 5, 6, 7 ]
gap> Permuted( list2, perm );
[ 1, 4, 5, 5, 6, 7 ]
\end{verbatim}

21.18.4 \texttt{SortingPerm}

\texttt{SortingPerm(list)}

\texttt{SortingPerm} returns the same as \texttt{Sortex} (21.18.3) but does not change the argument.

Example

\begin{verbatim}
gap> list1 := [ 5, 4, 6, 1, 7, 5 ];;
gap> list2 := ShallowCopy( list1 );;
gap> perm := SortingPerm( list1 );
(1,3,5,6,4)
gap> list1;
[ 5, 4, 6, 1, 7, 5 ]
gap> Permuted( list2, perm );
[ 1, 4, 5, 5, 6, 7 ]
\end{verbatim}

21.19 Sorted Lists and Sets

Searching objects in a list works much quicker if the list is known to be sorted. Currently \texttt{GAP} exploits the sortedness of a list automatically only if the list is \textit{strictly sorted}, which is indicated by the property \texttt{IsSSortedList} (21.17.4).

Remember that a list of \textit{mutable} objects cannot store that it is strictly sorted but has to test it anew whenever it is asked whether it is sorted, see the remark in 21.17. Therefore \texttt{GAP} cannot take advantage of the sortedness of a list if this list has mutable entries. Moreover, if a sorted list \texttt{list} with mutable elements is used as an argument of a function that \textit{expects} this argument to be sorted, for example \texttt{UniteSet} (21.19.6) or \texttt{RemoveSet} (21.19.5), then it is checked whether \texttt{list} is in fact sorted; this check can have the effect actually to slow down the computations, compared to computations with sorted lists of immutable elements or computations that do not involve functions that do automatically check sortedness.

Strictly sorted lists are used to represent \textit{sets} in \texttt{GAP}. More precisely, a strictly sorted list is called a \textit{proper set} in the following, in order to avoid confusion with domains (see 12.4) which also represent sets.

In short proper sets are represented by sorted lists without holes and duplicates in \texttt{GAP}. Note that we guarantee this representation, so you may make use of the fact that a set is represented by a sorted list in your functions.
In some contexts (for example see 16), we also want to talk about multisets. A multiset is like a set, except that an element may appear several times in a multiset. Such multisets are represented by sorted lists without holes that may have duplicates.

This section lists only those functions that are defined exclusively for proper sets. Set theoretic functions for general collections, such as Intersection (30.5.2) and Union (30.5.3), are described in Chapter 30. In particular, for the construction of proper sets, see SSortedList (30.3.7) and AsSSortedList (30.3.10). For finding positions in sorted lists, see PositionSorted (21.16.5).

There are nondestructive counterparts of the functions UniteSet (21.19.6), IntersectSet (21.19.7), and SubtractSet (21.19.8) available for proper sets. These are UnionSet, IntersectionSet, and Difference (30.5.4). The former two are methods for the more general operations Union (30.5.3) and Intersection (30.5.2), the latter is itself an operation (see Difference (30.5.4)).

The result of IntersectionSet and UnionSet is always a new list, that is not identical to any other list. The elements of that list however are identical to the corresponding elements of the first argument set. If set is not a proper set it is not specified to which of a number of equal elements in set the element in the result is identical (see 21.6). The following functions, if not explicitly stated differently, take two arguments, set and obj, where set must be a proper set, otherwise an error is signalled; If the second argument obj is a list that is not a proper set then Set (30.3.7) is silently applied to it first.

21.19.1 \in (for strictly sorted lists)

\in(obj, list)

For a list list that stores that it is strictly sorted, the test with \in (21.19.1) whether the object obj is an entry of list uses binary search. This test can be entered also with the infix notation obj in list.

21.19.2 IsEqualSet

IsEqualSet(list1, list2)

tests whether list1 and list2 are equal when viewed as sets, that is if every element of list1 is an element of list2 and vice versa. Either argument of IsEqualSet may also be a list that is not a proper set, in which case Set (30.3.7) is applied to it first.

If both lists are proper sets then they are of course equal if and only if they are also equal as lists. Thus IsEqualSet( list1, list2 ) is equivalent to Set( list1 ) = Set( list2 ) (see Set (30.3.7)), but the former is more efficient.

Example

\begin{verbatim}
gap> IsEqualSet( [2,3,5,7,11], [11,7,5,3,2] );
true
\end{verbatim}

\begin{verbatim}
gap> IsEqualSet( [2,3,5,7,11], [2,3,5,7,11,13] );
false
\end{verbatim}

21.19.3 IsSubsetSet

IsSubsetSet(list1, list2)

tests whether list1 is a subset of list2.
tests whether every element of `list2` is contained in `list1`. Either argument of `IsSubsetSet` may also be a list that is not a proper set, in which case `Set` (30.3.7) is applied to it first.

21.19.4 AddSet

▷ `AddSet(set, obj)` (operation)

adds the element `obj` to the proper set `set`. If `obj` is already contained in `set` then `set` is not changed. Otherwise `obj` is inserted at the correct position such that `set` is again a proper set afterwards.

Note that `obj` must be in the same family as each element of `set`.

Example

```gap
gap> s := [2,3,7,11];;
gap> AddSet( s, 5 ); s;
[ 2, 3, 5, 7, 11 ]
gap> AddSet( s, 13 ); s;
[ 2, 3, 5, 7, 11, 13 ]
gap> AddSet( s, 3 ); s;
[ 2, 3, 5, 7, 11, 13 ]
```

21.19.5 RemoveSet

▷ `RemoveSet(set, obj)` (operation)

removes the element `obj` from the proper set `set`. If `obj` is not contained in `set` then `set` is not changed. If `obj` is an element of `set` it is removed and all the following elements in the list are moved one position forward.

Example

```gap
gap> s := [ 2, 3, 4, 5, 6, 7 ];;
gap> RemoveSet( s, 6 ); s;
[ 2, 3, 4, 5, 7 ]
gap> RemoveSet( s, 10 ); s;
[ 2, 3, 4, 5, 7 ]
```

21.19.6 UniteSet

▷ `UniteSet(set, list)` (operation)

unites the proper set `set` with `list`. This is equivalent to adding all elements of `list` to `set` (see `AddSet` (21.19.4)).

Example

```gap
gap> set := [ 2, 3, 5, 7, 11 ];;
gap> UniteSet( set, [ 4, 8, 9 ] ); set;
[ 2, 3, 4, 5, 7, 8, 9, 11 ]
gap> UniteSet( set, [ 16, 9, 25, 13, 16 ] ); set;
[ 2, 3, 4, 5, 7, 8, 9, 11, 13, 16, 25 ]
```
21.19.7 IntersectSet

▷ IntersectSet(set, list) (operation)

intersects the proper set set with list. This is equivalent to removing from set all elements of set that are not contained in list.

Example

```
gap> set := [ 2, 3, 4, 5, 7, 8, 9, 11, 13, 16 ];;
gap> IntersectSet( set, [ 3, 5, 7, 9, 11, 13, 15, 17 ] ); set;
[ 3, 5, 7, 9, 11, 13 ]
gap> IntersectSet( set, [ 9, 4, 6, 8 ] ); set;
[ 9 ]
```

21.19.8 SubtractSet

▷ SubtractSet(set, list) (operation)

subtracts list from the proper set set. This is equivalent to removing from set all elements of list.

Example

```
gap> set := [ 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 ];;
gap> SubtractSet( set, [ 6, 10 ] ); set;
[ 2, 3, 4, 5, 7, 8, 9, 11 ]
gap> SubtractSet( set, [ 9, 4, 6, 8 ] ); set;
[ 2, 3, 5, 7, 11 ]
```

21.20 Operations for Lists

Several of the following functions expect the first argument to be either a list or a collection (see 30), with possibly slightly different meaning for lists and non-list collections.

21.20.1 Concatenation (for several lists)

▷ Concatenation(list1, list2, ... ) (function)
▷ Concatenation(list) (function)

In the first form Concatenation returns the concatenation of the lists list1, list2, etc. The concatenation is the list that begins with the elements of list1, followed by the elements of list2, and so on. Each list may also contain holes, in which case the concatenation also contains holes at the corresponding positions.

In the second form list must be a dense list of lists list1, list2, etc., and Concatenation returns the concatenation of those lists.

The result is a new mutable list, that is not identical to any other list. The elements of that list however are identical to the corresponding elements of list1, list2, etc. (see 21.6).

Note that Concatenation creates a new list and leaves its arguments unchanged, while Append (21.4.5) changes its first argument. For computing the union of proper sets, Union (30.5.3) can be used, see also 21.19.
21.20.2 Compacted

\[ \textsc{Compacted(list)} \]

returns a new mutable list that contains the elements of \textit{list} in the same order but omitting the holes.

\begin{verbatim}
gap> 1:=[,1,,,3,,,4,[5,,,6],7];; Compacted( 1 );
[ 1, 3, 4, [ 5,,, 6 ], 7 ]
\end{verbatim}

21.20.3 Collected

\[ \textsc{Collected(list)} \]

returns a new list \textit{new} that contains for each element \textit{elm} of the list \textit{list} a list of length two, the first element of this is \textit{elm} itself and the second element is the number of times \textit{elm} appears in \textit{list}. The order of those pairs in \textit{new} corresponds to the ordering of the elements \textit{elm}, so that the result is sorted.

For all pairs of elements in \textit{list} the comparison via < must be defined.

\begin{verbatim}
gap> Factors( Factorial( 10 ) );
[ 2, 2, 2, 2, 2, 2, 2, 3, 3, 3, 3, 5, 5, 7 ]
gap> Collected( last );
[ [ 2, 8 ], [ 3, 4 ], [ 5, 2 ], [ 7, 1 ] ]
gap> Collected( last );
[ [ [ 2, 8 ], 1 ], [ [ 3, 4 ], 1 ], [ [ 5, 2 ], 1 ], [ [ 7, 1 ], 1 ] ]
\end{verbatim}

21.20.4 DuplicateFreeList

\[ \textsc{DuplicateFreeList(list)} \]

returns a new mutable list whose entries are the elements of the list \textit{list} with duplicates removed. \textsc{DuplicateFreeList} only uses the = comparison and will not sort the result. Therefore \textsc{DuplicateFreeList} can be used even if the elements of \textit{list} do not lie in the same family. Otherwise, if \textit{list} contains objects that can be compared with \textless (31.11.1) then it is much more efficient to use \textsc{Set} (30.3.7) instead of \textsc{DuplicateFreeList}.

\textsc{Unique} is a synonym for \textsc{DuplicateFreeList}.
Example

gap> l:=[1,Z(3),1,"abc",Group((1,2,3),(1,2)),Z(3),Group((1,2),(2,3))];;
gap> DuplicateFreeList( l );
[ 1, Z(3), "abc", Group([ (1,2,3), (1,2) ]) ]

21.20.5 AsDuplicateFreeList

▷ AsDuplicateFreeList(list) (attribute)

returns the same result as DuplicateFreeList (21.20.4), except that the result is immutable.

21.20.6 Flat

▷ Flat(list) (operation)

returns the list of all elements that are contained in the list list or its sublists. That is, Flat first makes a new empty list new. Then it loops over the elements elm of list. If elm is not a list it is added to new, otherwise Flat appends Flat( elm ) to new.

Example

gap> Flat( [ 1, [ 2, 3 ], [ [ 1, 2 ], 3 ] ] );
[ 1, 2, 3, 1, 2, 3 ]
gap> Flat( [ ] );
[ ]

To reconstruct a matrix from the list obtained by applying Flat to the matrix, the sublist operator can be used, as follows.

Example

gap> 1:=[9..14];;w:=2;; # w is the length of each row
gap> sub:=[1..w];;List([1..Length(1)/w],i->1{(i-1)*w+sub});
[ [ 9, 10 ], [ 11, 12 ], [ 13, 14 ] ]

21.20.7 Reversed

▷ Reversed(list) (function)

returns a new mutable list, containing the elements of the dense list list in reversed order. The argument list is unchanged. The result list is a new list, that is not identical to any other list. The elements of that list however are identical to the corresponding elements of the argument list (see 21.6).

Reversed implements a special case of list assignment, which can also be formulated in terms of the {} operator (see 21.4).

Example

gap> Reversed( [ 1, 4, 9, 5, 6, 7 ] );
[ 7, 6, 5, 9, 4, 1 ]
21.20.8 Shuffle

\[\text{Shuffle(list)}\] (operation)

The argument list must be a dense mutable list. This operation permutes the entries of list randomly (in place), and returns list.

Example

```
gap> Reset(GlobalMersenneTwister, 12345);; # make manual tester happy
gap> l := [1..20];
[ 1 .. 20 ]
gap> m := Shuffle(ShallowCopy(l));
[ 8, 13, 1, 3, 20, 15, 4, 7, 5, 18, 6, 12, 16, 11, 2, 10, 19, 17, 9, 14 ]
gap> l;
[ 1 .. 20 ]
gap> Shuffle(l);
gap> l;
[ 19, 5, 7, 20, 16, 1, 10, 15, 12, 11, 13, 2, 14, 3, 4, 17, 6, 8, 9, 18 ]
```

21.20.9 Is LexicographicallyLess

\[\text{IsLexicographicallyLess(list1, list2)}\] (function)

Let list1 and list2 be two dense, but not necessarily homogeneous lists (see IsDenseList (21.1.2), IsHomogeneousList (21.1.3)), such that for each i, the entries in both lists at position i can be compared via \(<\). IsLexicographicallyLess returns true if list1 is smaller than list2 w.r.t. lexicographical ordering, and false otherwise.

21.20.10 Apply

\[\text{Apply(list, func)}\] (function)

Apply applies the function func to every element of the dense and mutable list list, and replaces each element entry by the corresponding return value. Apply changes its argument. The nondestructive counterpart of Apply is List (30.3.5).

Example

```
gap> l:= [ 1, 2, 3 ];; Apply( l, i -> i^2 ); l;
[ 1, 4, 9 ]
```

21.20.11 Perform

\[\text{Perform(list, func)}\] (function)

Perform applies the function func to every element of the list list, discarding any return values. It does not return a value.

Example

```
gap> l := [1, 2, 3];; Perform(l, function(x) if IsPrimeInt(x) then Print(x,"
\n"); fi; end)
```
21.20.12 PermListList

\[\texttt{PermListList}(\text{list1}, \text{list2})\]

returns a permutation \( p \) of \([1 \ldots \text{Length}(\text{list1})]\) such that \( \text{list1}[i^p] = \text{list2}[i] \). It returns \texttt{fail} if there is no such permutation.

Example

\begin{verbatim}
gap> list1 := [ 5, 4, 6, 1, 7, 5 ];;
gap> list2 := [ 4, 1, 7, 5, 5, 6 ];;
gap> perm := PermListList(list1, list2);
(1,2,4)(3,5,6)
gap> Permuted( list2, perm );
[ 5, 4, 6, 1, 7, 5 ]
\end{verbatim}

21.20.13 Maximum

\[\texttt{Maximum}(\text{obj1}, \text{obj2}, \ldots)\]  
\[\texttt{Maximum}(\text{list})\]

In the first form \texttt{Maximum} returns the maximum of its arguments, i.e., one argument \( \text{obj} \) for which \( \text{obj} \geq \text{obj1}, \text{obj} \geq \text{obj2} \) etc.

In the second form \texttt{Maximum} takes a homogeneous list \( \text{list} \) and returns the maximum of the elements in this list.

Example

\begin{verbatim}
gap> Maximum( -123, 700, 123, 0, -1000 );
700
gap> Maximum( [ -123, 700, 123, 0, -1000 ] );
700
gap> # lists are compared elementwise:
gap> Maximum( [1,2], [0,15], [1,5], [2,-11] );
[ 2, -11 ]
\end{verbatim}

To get the index of the maximum element use \texttt{PositionMaximum} (21.16.8)

21.20.14 Minimum

\[\texttt{Minimum}(\text{obj1}, \text{obj2}, \ldots)\]  
\[\texttt{Minimum}(\text{list})\]

In the first form \texttt{Minimum} returns the minimum of its arguments, i.e., one argument \( \text{obj} \) for which \( \text{obj} \leq \text{obj1}, \text{obj} \leq \text{obj2} \) etc.

In the second form \texttt{Minimum} takes a homogeneous list \( \text{list} \) and returns the minimum of the elements in this list.

Note that for both \texttt{Maximum} (21.20.13) and \texttt{Minimum} the comparison of the objects \( \text{obj1}, \text{obj2} \) etc. must be defined; for that, usually they must lie in the same family (see 13.1).
Example

```gap
gap> Minimum( -123, 700, 123, 0, -1000 );
-1000
gap> Minimum( [ -123, 700, 123, 0, -1000 ] );
-1000
gap> Minimum( [ 1, 2 ], [ 0, 15 ], [ 1, 5 ], [ 2, -11 ] );
[ 0, 15 ]
```

To get the index of the minimum element use `PositionMinimum (21.16.8)`

### 21.20.15 MaximumList and MinimumList

- `MaximumList(list [, seed])` (operation)
- `MinimumList(list [, seed])` (operation)

return the maximum resp. the minimum of the elements in the list `list`. They are the operations called by `Maximum (21.20.13)` resp. `Minimum (21.20.14)`. Methods can be installed for special kinds of lists. For example, there are special methods to compute the maximum resp. the minimum of a range (see 21.22).

If a second argument `seed` is supplied, then the result is the maximum resp. minimum of the union of `list` and `seed`. In this manner, the operations may be applied to empty lists.

### 21.20.16 Cartesian

- `Cartesian(list [, list2, ...])` (function)
- `Cartesian(list)` (function)

In the first form `Cartesian` returns the cartesian product of the lists `list1`, `list2`, etc. In the second form `list` must be a list of lists `list1`, `list2`, etc., and `Cartesian` returns the cartesian product of those lists.

The cartesian product is a list `cart` of lists `tup`, such that the first element of `tup` is an element of `list1`, the second element of `tup` is an element of `list2`, and so on. The total number of elements in `cart` is the product of the lengths of the argument lists. In particular `cart` is empty if and only if at least one of the argument lists is empty. Also `cart` contains duplicates if and only if no argument list is empty and at least one contains duplicates.

The last index runs fastest. That means that the first element `tup1` of `cart` contains the first element from `list1`, from `list2` and so on. The second element `tup2` of `cart` contains the first element from `list1`, the first from `list2`, and so on, but the last element of `tup2` is the second element of the last argument list. This implies that `cart` is a proper set if and only if all argument lists are proper sets (see 21.19).

The function `Tuples (16.2.8)` computes the k-fold cartesian product of a list.

Example

```gap
gap> Cartesian( [ [1,2], [3,4], [5,6] ] );
[ [ 1, 3, 5 ], [ 1, 3, 6 ], [ 1, 4, 5 ], [ 1, 4, 6 ], [ 2, 3, 5 ],
  [ 2, 3, 6 ], [ 2, 4, 5 ], [ 2, 4, 6 ] ]
gap> Cartesian( [ [1,2,2], [1,1,2] ] );
[ [ 1, 1 ], [ 1, 1 ], [ 1, 2 ], [ 2, 1 ], [ 2, 1 ], [ 2, 2 ],
  [ 2, 1 ], [ 2, 1 ], [ 2, 2 ] ]
```
21.20.17  IteratorOfCartesianProduct

\> IteratorOfCartesianProduct(list1, list2, ...)
\> IteratorOfCartesianProduct(list)

(function)

In the first form \texttt{IteratorOfCartesianProduct} returns an iterator (see 30.8) of all elements of the cartesian product (see \texttt{Cartesian} (21.20.16)) of the lists \texttt{list1}, \texttt{list2}, etc.

In the second form \texttt{list} must be a list of lists \texttt{list1}, \texttt{list2}, etc., and \texttt{IteratorOfCartesianProduct} returns an iterator of the cartesian product of those lists.

Resulting tuples will be returned in the lexicographic order. Usage of iterators of cartesian products is recommended in the case when the resulting cartesian product is big enough, so its generating and storage will require essential amount of runtime and memory. For smaller cartesian products it is faster to generate the full set of tuples using \texttt{Cartesian} (21.20.16) and then loop over its elements (with some minor overhead of needing more memory).

21.20.18  Permuted

\> Permuted(list, perm)

(operation)

returns a new list \texttt{new} that contains the elements of the list \texttt{list} permuted according to the permutation \texttt{perm}. That is \texttt{new}[i \cdot \texttt{perm}] = \texttt{list}[i].

\texttt{Sortex} (21.18.3) allows you to compute a permutation that must be applied to a list in order to get the sorted list.

Example

\begin{verbatim}
gap> Permuted([5, 4, 6, 1, 7, 5], (1,3,5,6,4));
[1, 4, 5, 5, 6, 7]
\end{verbatim}

21.20.19  List (for a list (and a function))

\> List(list[, func])

(function)

This function returns a new mutable list \texttt{new} of the same length as the list \texttt{list} (which may have holes). The entry \texttt{new}[i] is unbound if \texttt{list}[i] is unbound. Otherwise \texttt{new}[i] = \texttt{func(list[i])}. If the argument \texttt{func} is omitted, its default is \texttt{IdFunc} (5.4.6), so this function does the same as \texttt{ShallowCopy} (12.7.1) (see also 21.7).

Example

\begin{verbatim}
gap> List([1,2,3], i -> i^2);
[1, 4, 9]
gap> List([1..10], IsPrime);
[false, true, true, false, true, false, false, false, false, false]
gap> List([1,,3,4], x -> x > 2);
[false,,true, true]
\end{verbatim}

(See also \texttt{List} (30.3.5).)
21.20.20 Filtered

\texttt{\textbackslash> \textup{\texttt{Filtered(listorcoll, func)}} (function)}

returns a new list that contains those elements of the list or collection \texttt{listorcoll} (see 30), respectively, for which the unary function \texttt{func} returns \texttt{true}.

If the first argument is a list, the order of the elements in the result is the same as the order of the corresponding elements of this list. If an element for which \texttt{func} returns \texttt{true} appears several times in the list it will also appear the same number of times in the result. The argument list may contain holes, they are ignored by \texttt{Filtered}.

For each element of \texttt{listorcoll}, \texttt{func} must return either \texttt{true} or \texttt{false}, otherwise an error is signalled.

The result is a new list that is not identical to any other list. The elements of that list however are identical to the corresponding elements of the argument list (see 21.6).

List assignment using the operator \texttt{\{}\texttt{\}} (21.3.1) (see 21.4) can be used to extract elements of a list according to indices given in another list.

\begin{verbatim}
Example

\texttt{gap> Filtered([1..20], IsPrime );}
\texttt{[ 2, 3, 5, 7, 11, 13, 17, 19 ]}
\texttt{gap> Filtered([1, 3, 4, -4, 4, 7, 10, 6], IsPrimePowerInt );}
\texttt{[ 3, 4, 4, 7 ]}
\texttt{gap> Filtered([1, 3, 4, -4, 4, 7, 10, 6],
\texttt{    n -> IsPrimePowerInt(n) and n mod 2 <> 0 );}
\texttt{[ 3, 7 ]}
\texttt{gap> Filtered(Group([1,2], (1,2,3)), x -> Order(x) = 2 );}
\texttt{[ (2,3), (1,2), (1,3) ]}
\end{verbatim}

21.20.21 Number

\texttt{\textbackslash> \textup{\texttt{Number(listorcoll[, func])}} (function)}

Called with a list \texttt{listorcoll}, \texttt{Number} returns the number of bound entries in this list. For dense lists \texttt{Number}, \texttt{Length} (21.17.5), and \texttt{Size} (30.4.6) return the same value; for lists with holes \texttt{Number} returns the number of bound entries, \texttt{Length} (21.17.5) returns the largest index of a bound entry, and \texttt{Size} (30.4.6) signals an error.

Called with two arguments, a list or collection \texttt{listorcoll} and a unary function \texttt{func}, \texttt{Number} returns the number of elements of \texttt{listorcoll} for which \texttt{func} returns \texttt{true}. If an element for which \texttt{func} returns \texttt{true} appears several times in \texttt{listorcoll} it will also be counted the same number of times.

For each element of \texttt{listorcoll}, \texttt{func} must return either \texttt{true} or \texttt{false}, otherwise an error is signalled.

\texttt{Filtered} (21.20.20) allows you to extract the elements of a list that have a certain property.

\begin{verbatim}
Example

\texttt{gap> Number([2, 3, 5, 7]);}
\texttt{4}
\texttt{gap> Number([], 2, 3, 5, 7, 11]);}
\texttt{5}
\texttt{gap> Number([1..20], IsPrime );}
\end{verbatim}
8
gap> Number( [ 1, 3, 4, -4, 4, 7, 10, 6 ], IsPrimePowerInt );
4
gap> Number( [ 1, 3, 4, -4, 4, 7, 10, 6 ],
    n -> IsPrimePowerInt(n) and n mod 2 <> 0 );
2
gap> Number( Group( (1,2), (1,2,3) ), x -> Order( x ) = 2 );
3

21.20.22 First

First returns the first element of the list list for which the unary function func returns true; if func is not given, the first element is returned. list may contain holes. func must return either true or false for each element of list, otherwise an error is signalled. If func returns false for all elements of list then First returns fail.

PositionProperty (21.16.9) allows you to find the position of the first element in a list that satisfies a certain property.

Example

\begin{verbatim}
gap> First( [10^7..10^8], IsPrime );
10000019
gap> First( [10^5..10^6],
    n -> not IsPrime(n) and IsPrimePowerInt(n) );
100489
gap> First( [ 1 .. 20 ], x -> x < 0 );
fail
gap> First( [ fail ], x -> x = fail );
fail
\end{verbatim}

21.20.23 Last

Last returns the last element of the list list for which the unary function func returns true; if func is not given, the first element is returned. list may contain holes. func must return either true or false for each element of list, otherwise an error is signalled. If func returns false for all elements of list then Last returns fail.

Example

\begin{verbatim}
gap> Last( [10^7..10^8], IsPrime );
99999989
gap> Last( [10^5..10^6],
    n -> not IsPrime(n) and IsPrimePowerInt(n) );
994009
gap> Last( [ 1 .. 20 ], x -> x < 0 );
fail
gap> Last( [ fail ], x -> x = fail );
fail
\end{verbatim}
21.20.24 ForAll

\[
\text{ForAll(listorcoll, func)}
\]

tests whether the unary function \( \text{func} \) returns \( \text{true} \) for all elements in the list or collection \( \text{listorcoll} \).

Example

```gap
gap> ForAll([1..20], IsPrime );
false
gap> ForAll([2,3,4,5,8,9], IsPrimePowerInt );
true
gap> ForAll([2..14], n -> IsPrimePowerInt(n) or n mod 2 = 0 );
true
gap> ForAll( Group([ (1,2), (1,2,3) ], i -> SignPerm(i) = 1 );
false
```

21.20.25 ForAny

\[
\text{ForAny(listorcoll, func)}
\]

tests whether the unary function \( \text{func} \) returns \( \text{true} \) for at least one element in the list or collection \( \text{listorcoll} \).

Example

```gap
gap> ForAny([1..20], IsPrime );
true
gap> ForAny([2,3,4,5,8,9], IsPrimePowerInt );
true
gap> ForAny([2..14], n -> IsPrimePowerInt(n) and n mod 5 = 0 and not IsPrime(n ));
false
gap> ForAny( Integers, i -> i > 0 and ForAll([0,2..4], j -> IsPrime(i+j) ) );
true
```

21.20.26 Product

\[
\text{Product(listorcoll[, func][, init])}
\]

Called with one argument, a dense list or collection \( \text{listorcoll} \), Product returns the product of the elements of \( \text{listorcoll} \) (see 30).

Called with a dense list or collection \( \text{listorcoll} \) and a function \( \text{func} \), which must be a function taking one argument, Product applies the function \( \text{func} \) to the elements of \( \text{listorcoll} \), and returns the product of the results. In either case Product returns 1 if the first argument is empty.

The general rules for arithmetic operations apply (see 21.15), so the result is immutable if and only if all summands are immutable.

If \( \text{listorcoll} \) contains exactly one element then this element (or its image under \( \text{func} \) if applicable) itself is returned, not a shallow copy of this element.

If an additional initial value \( \text{init} \) is given, Product returns the product of \( \text{init} \) and the elements of the first argument resp. of their images under the function \( \text{func} \). This is useful for example if the first argument is empty and a different identity than 1 is desired, in which case \( \text{init} \) is returned.
21.20.27 Sum

\(\text{Sum(listorcoll[, func[, init]])}\)

Called with one argument, a dense list or collection \texttt{listorcoll}, \texttt{Sum} returns the sum of the elements of \texttt{listorcoll} (see 30).

Called with a dense list or collection \texttt{listorcoll} and a function \texttt{func}, which must be a function taking one argument, \texttt{Sum} applies the function \texttt{func} to the elements of \texttt{listorcoll}, and returns the sum of the results. In either case \texttt{Sum} returns 0 if the first argument is empty.

The general rules for arithmetic operations apply (see 21.15), so the result is immutable if and only if all summands are immutable.

If \texttt{listorcoll} contains exactly one element then this element (or its image under \texttt{func} if applicable) itself is returned, not a shallow copy of this element.

If an additional initial value \texttt{init} is given, \texttt{Sum} returns the sum of \texttt{init} and the elements of the first argument resp. of their images under the function \texttt{func}. This is useful for example if the first argument is empty and a different zero than 0 is desired, in which case \texttt{init} is returned.

Example

\begin{verbatim}
gap> Sum( [ 2, 3, 5, 7, 11, 13, 17, 19 ] ); 77
\end{verbatim}

\begin{verbatim}
gap> Sum( [1..10], x->x^2 ); 385
\end{verbatim}

\begin{verbatim}
gap> Sum( [ [1,2], [3,4], [5,6] ] ); [ 9, 12 ]
\end{verbatim}

\begin{verbatim}
gap> Sum( GF(8) ); 0*Z(2)
\end{verbatim}

21.20.28 Iterated

\(\text{Iterated(list, f)}\)

returns the result of the iterated application of the function \texttt{f}, which must take two arguments, to the elements of the list \texttt{list}. More precisely, if \texttt{list} has length \(n\) then \texttt{Iterated} returns the result of the following application: \(f(...f(f(list[1],list[2]),list[3]),...,list[n])\).

Example

\begin{verbatim}
gap> Iterated( [ 126, 66, 105 ], Gcd ); 3
\end{verbatim}
21.20.29 ListN

\texttt{ListN(} \texttt{list1, list2, ...}, \texttt{listn, f) (function)}

applies the \textit{n}-argument function \textit{f} to the lists. That is, \texttt{ListN} returns the list whose \textit{i}-th entry is 
\(f(\texttt{list1[i]}, \texttt{list2[i]}, ..., \texttt{listn[i]}).\)

\begin{example}
\texttt{gap> ListN( [1,2], [3,4], \+ );}
\texttt{[ 4, 6 ]}
\end{example}

21.21 Advanced List Manipulations

The following functions are generalizations of \texttt{List} (30.3.5), \texttt{Set} (30.3.7), \texttt{Sum} (21.20.27), and \texttt{Product} (21.20.26).

21.21.1 ListX

\texttt{ListX(} \texttt{arg1, arg2, ...}, \texttt{argn, func) (function)}

\texttt{ListX} returns a new list constructed from the arguments.
Each of the arguments \texttt{arg1}, \texttt{arg2}, ... \texttt{argn} must be one of the following:

\textbf{a list or collection}
this introduces a new for-loop in the sequence of nested for-loops and if-statements;

\textbf{a function returning a list or collection}
this introduces a new for-loop in the sequence of nested for-loops and if-statements, where the loop-range depends on the values of the outer loop-variables; or

\textbf{a function returning true or false}
this introduces a new if-statement in the sequence of nested for-loops and if-statements.

The last argument \texttt{func} must be a function, it is applied to the values of the loop-variables and the results are collected.
Thus \texttt{ListX( list, func )} is the same as \texttt{List( list, func )}, and \texttt{ListX( list, func, x -> x )} is the same as \texttt{Filtered( list, func )}.

As a more elaborate example, assume \texttt{arg1} is a list or collection, \texttt{arg2} is a function returning true or false, \texttt{arg3} is a function returning a list or collection, and \texttt{arg4} is another function returning true or false, then
\texttt{result := ListX( arg1, arg2, arg3, arg4, func );}
is equivalent to

\begin{verbatim}
result := ;
for v1 in arg1 do
  if arg2( v1 ) then
    for v2 in arg3( v1 ) do
      if arg4( v1, v2 ) then
        Add( result, func( v1, v2 ) );
      fi;
  fi;
fi;
\end{verbatim}
The following example shows how \texttt{ListX} can be used to compute all pairs and all strictly sorted pairs of elements in a list.

\begin{verbatim}
gap> l := [ 1, 2, 3, 4 ];
gap> pair := function( x, y ) return [ x, y ]; end;

\texttt{ListX( l, l, pair )};
\end{verbatim}

\begin{verbatim}
\[ [ [ 1, 1 ], [ 1, 2 ], [ 1, 3 ], [ 1, 4 ], [ 2, 1 ], [ 2, 2 ],
   [ 2, 3 ], [ 2, 4 ], [ 3, 1 ], [ 3, 2 ], [ 3, 3 ], [ 3, 4 ],
   [ 4, 1 ], [ 4, 2 ], [ 4, 3 ], [ 4, 4 ] ]
\end{verbatim}

In the following example, $\prec$ (31.11.1) is the comparison operation:

\begin{verbatim}
gap> \texttt{ListX( l, l, \prec, pair )};
\end{verbatim}

\begin{verbatim}
\[ [ [ 1, 2 ], [ 1, 3 ], [ 1, 4 ], [ 2, 3 ], [ 2, 4 ], [ 3, 4 ] ]
\end{verbatim}

21.21.2 \textbf{SetX}

\texttt{SetX( arg1, arg2, ..., func )}

The only difference between \texttt{SetX} and \texttt{ListX} (21.21.1) is that the result list of \texttt{SetX} is strictly sorted.

21.21.3 \textbf{SumX}

\texttt{SumX( arg1, arg2, ..., func )}

\texttt{SumX} returns the sum of the elements in the list obtained by \texttt{ListX} (21.21.1) when this is called with the same arguments.

21.21.4 \textbf{ProductX}

\texttt{ProductX( arg1, arg2, ..., func )}

\texttt{ProductX} returns the product of the elements in the list obtained by \texttt{ListX} (21.21.1) when this is called with the same arguments.

21.22 \textbf{Ranges}

A \textit{range} is a dense list of integers in arithmetic progression (or degression). This is a list of integers such that the difference between consecutive elements is a nonzero constant. Ranges can be abbreviated with the syntactic construct

\begin{verbatim}
[ first, second .. last ]
\end{verbatim}

or, if the difference between consecutive elements is 1, as
[first .. last].

If first > last, [first .. last] is the empty list, which by definition is also a range; also, if second > first > last or second < first < last, then [first, second .. last] is the empty list. If first = last, [first, second .. last] is a singleton list, which is a range, too. Note that last - first must be divisible by the increment second - first, otherwise an error is signalled.

Currently, the integers first, second and last and the length of a range must be small integers as defined in chapter 14.

Note also that a range is just a special case of a list. Thus you can access elements in a range (see 21.3), test for membership etc. You can even assign to such a range if it is mutable (see 21.4). Of course, unless you assign last + second - first to the entry range[Length(range) + 1], the resulting list will no longer be a range. Note that assigning to an entry of range will convert it back into a plain list.

Most often ranges are used in connection with the for-loop see 4.20). Here the construct for var in [first .. last] do statements od replaces the
for var from first to last do statements od
which is more usual in other programming languages.
Example

```gap
s := [];; for i in [10..20] do Add( s, i^2 ); od; s;
[ 100, 121, 144, 169, 196, 225, 256, 289, 324, 361, 400 ]
```

Note that a range with \texttt{last} $\geq$ \texttt{first} is at the same time also a proper set (see 21.19), because it contains no holes or duplicates and is sorted, and also a row vector (see 23), because it contains no holes and all elements are integers.

### 21.22.1 \texttt{IsRange}

\texttt{IsRange(obj)}

(tests if the object \texttt{obj} is a range, i.e. is a dense list of integers that is also a range (see 21.22 for a definition of “range”).)

Example

```gap
IsRange([1,2,3]); IsRange([7,5,3,1]);
true
true
gap> IsRange([1 .. 3]);
true
gap> IsRange([1,2,4,5]); IsRange([1,,3,,5,,7]);
false
false
gap> IsRange([]); IsRange([1]);
true
true
```

### 21.22.2 \texttt{IsRangeRep}

\texttt{IsRangeRep(obj)}

Tests whether \texttt{obj} is represented as a range, that is by internally storing only the first value, the in- or decrement, and the last value of the range.

To test whether a list is a range in the mathematical sense see \texttt{IsRange (21.22.1)}.

Lists created by the syntactic construct \texttt{[first, second .. last]}, see 21.22, are in \texttt{IsRangeRep}.

Note that if you modify an \texttt{IsRangeRep} object by assigning to one of its entries, or by using \texttt{Add (21.4.2)} or \texttt{Append (21.4.5)}, then the range may be converted into a plain list, even though the resulting list may still be a range, mathematically.

Example

```gap
IsRangeRep([1 .. 3]);
true
gap> IsRangeRep([1, 2, 3]);
false
gap> l := [1..3];;
gap> l[1] := 1;;
gap> l;
[ 1, 2, 3 ]
```
21.22.3 ConvertToRangeRep

\[ \text{ConvertToRangeRep}(\text{list}) \]

For some lists the GAP kernel knows that they are in fact ranges. Those lists are represented internally in a compact way, namely in IsRangeRep (21.22.2), instead of as plain lists. A list that is represented as a plain list might still be a range but GAP may not know this.

If \text{list} is a range then \text{ConvertToRangeRep} changes the representation of \text{list} to IsRangeRep (21.22.2). A call of \text{ConvertToRangeRep} for a list that is not a range is ignored.

Example

\begin{verbatim}
gap> r := [ 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ];
[ 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ]
gap> ConvertToRangeRep( r ); r;
[ 1 .. 10 ]
gap> l := [ 1, 2, 4, 5 ];;
gap> ConvertToRangeRep( l ); l;
[ 1, 2, 4, 5 ]
\end{verbatim}

21.23 Enumerators

An enumerator is an immutable list that need not store its elements explicitly but knows, from a set of basic data, how to determine the \(i\)-th element and the position of a given object. A typical example of this is a vector space over a finite field with \(q\) elements, say, for which it is very easy to enumerate all elements using \(q\)-adic expansions of integers.

Using this enumeration can be even quicker than a binary search in a sorted list of vectors, see IsQuickPositionList (21.23.1).

On the one hand, element access to an enumerator may take more time than element access to an internally represented list containing the same elements. On the other hand, an enumerator may save a vast amount of memory. Take for example a permutation group of size a few millions. Even for moderate degree it is unlikely that a list of all its elements will fit into memory whereas it is no problem to construct an enumerator from a stabilizer chain (see 43.6).

There are situations where one only wants to loop over the elements of a domain, without using the special facilities of an enumerator, namely the particular order of elements and the possibility to find the position of elements. For such cases, GAP provides iterators (see 30.8).

The functions Enumerator (30.3.2) and EnumeratorSorted (30.3.3) return enumerators of domains. Most of the special implementations of enumerators in the GAP library are based on the general interface that is provided by EnumeratorByFunctions (30.3.4); one generic example is EnumeratorByBasis (61.6.5), which can be used to get an enumerator of a finite dimensional free module.

Also enumerators for non-domains can be implemented via EnumeratorByFunctions (30.3.4); for a discussion, see 79.5.

21.23.1 IsQuickPositionList

\[ \text{IsQuickPositionList}(\text{list}) \]

(function)
This filter indicates that a position test in list is quicker than about 5 or 6 element comparisons for “smaller”. If this is the case it can be beneficial to use Position (21.16.1) in list and a bit list than ordered lists to represent subsets of list.

21.24 Plain Lists

Plain lists are the default kind of lists in GAP, in the sense that GAP stores the list entries and does not know how to do better (as opposed to ranges or strings, which are also lists). Often it is not necessary to know how a given list is represented internally, the operations defined for lists apply to all lists.

Typical situations where the representation matters are when one wants to make sure that the given list is not a plain list and thus will be handled more efficiently, for example when one installs a method for a particular operation, where an argument is required to be a list in a particular representation.

21.24.1 IsPlistRep

▷ IsPlistRep(obj) (representation)

GAP lists created by entering comma separated values in square brackets are usually represented internally as so-called plain lists. Other representations of lists are IsBlistRep (22.5.1), IsRangeRep (21.22.2), IsStringRep (27.4.1), or the ones that are chosen for implementing enumerators, see Section 21.23.

| gap> IsPlistRep( [ 1, 2, 3 ] ); | true |
gap> IsPlistRep( "abc" );  false  
gap> IsPlistRep( [ 1 .. 5 ] );  false  
gap> IsPlistRep( BlistList( [ 1 .. 5 ], [ 1 ] ) );  false  
gap> IsPlistRep( 0 );  false  |
Chapter 22

Boolean Lists

This chapter describes boolean lists. A boolean list is a list that has no holes and contains only the boolean values true and false (see Chapter 20). In function names we call boolean lists blists for brevity.

22.1 IsBlist (Filter)

22.1.1 IsBlist

\begin{verbatim}
> IsBlist([true, true, false, false]);
true
> IsBlist([]);
true
> IsBlist([false,,true]);  # has holes
false
> IsBlist([1,1,0,0]);     # contains not only boolean values
false
> IsBlist(17);            # is not even a list
false
\end{verbatim}

A boolean list ("blist") is a list that has no holes and contains only true and false. Boolean lists can be represented in an efficient compact form, see 22.5 for details.

Boolean lists are lists and all operations for lists are therefore applicable to boolean lists.

Boolean lists can be used in various ways, but maybe the most important application is their use for the description of subsets of finite sets. Suppose set is a finite set, represented as a list. Then a subset sub of set is represented by a boolean list blist of the same length as set such that blist[i] is true if set[i] is in sub, and false otherwise.
22.2 Boolean Lists Representing Subsets

22.2.1 BlistList

\( \text{BlistList(list, sub)} \) (function)

returns a new boolean list that describes the list \( \text{sub} \) as a sublist of the dense list \( \text{list} \). That is BlistList returns a boolean list \( \text{blist} \) of the same length as \( \text{list} \) such that \( \text{blist}[i] \) is \( \text{true} \) if \( \text{list}[i] \) is in \( \text{sub} \) and \( \text{false} \) otherwise.

\( \text{list} \) need not be a proper set (see 21.19), even though in this case BlistList is most efficient. In particular \( \text{list} \) may contain duplicates. \( \text{sub} \) need not be a proper sublist of \( \text{list} \), i.e., \( \text{sub} \) may contain elements that are not in \( \text{list} \). Those elements of course have no influence on the result of BlistList.

Example

\[
\text{gap> BlistList( [1..10], [2,3,5,7] );}
\[
[ \text{false, true, true, false, true, false, true, false, false, false} ]
\]
\[
\text{gap> BlistList( [1,2,3,4,5,2,8,6,4,10], [4,8,9,16] );}
\[
[ \text{false, false, false, true, false, true, false, true, false, true} ]
\]

See also \text{UniteBlistList (22.4.2)}.

22.2.2 ListBlist

\( \text{ListBlist(list, blist)} \) (function)

returns the sublist \( \text{sub} \) of the list \( \text{list} \), which must have no holes, represented by the boolean list \( \text{blist} \), which must have the same length as \( \text{list} \).

\( \text{sub} \) contains the element \( \text{list}[i] \) if \( \text{blist}[i] \) is \( \text{true} \) and does not contain the element if \( \text{blist}[i] \) is \( \text{false} \). The order of the elements in \( \text{sub} \) is the same as the order of the corresponding elements in \( \text{list} \).

Example

\[
\text{gap> ListBlist([1..8],[false,true,true,true,true,false,true,true]);}
\[
[ 2, 3, 4, 5, 7, 8 ]
\]
\[
\text{gap> ListBlist( [1,2,3,4,5,2,8,6,4,10],}
\[
> [\text{false,false,false,true,false,false,true,false,true,false}] );
\[
[ 4, 8, 4 ]
\]

22.2.3 SizeBlist

\( \text{SizeBlist(blist)} \) (function)

returns the number of entries of the boolean list \( \text{blist} \) that are \( \text{true} \). This is the size of the subset represented by the boolean list \( \text{blist} \).

Example

\[
\text{gap> SizeBlist( [ false, true, false, true, false ] );}
\[
2
\]
22.2.4 IsSubsetBlist

\[ \text{Yes} \]
\begin{verbatim}
function IsSubsetBlist(blist1, blist2)
  returns true if the boolean list blist2 is a subset of the boolean list blist1, which must have equal length, and false otherwise. blist2 is a subset of blist1 if \( \text{blist1}[i] = \text{blist1}[i] \) or \( \text{blist2}[i] \) for all \( i \).
  Example
  gap> blist1 := [ true, true, false, false ];
  gap> blist2 := [ true, false, true, false ];
  gap> IsSubsetBlist( blist1, blist2 );
  false
  gap> blist2 := [ true, false, false, false ];
  gap> IsSubsetBlist( blist1, blist2 );
  true
\end{verbatim}

22.3 Set Operations via Boolean Lists

22.3.1 UnionBlist

\[ \text{Yes} \]
\begin{verbatim}
function UnionBlist(blist1, blist2[, ...])
  returns the union of the boolean lists blist1, blist2, etc., which must have equal length. The union is a new boolean list that contains at position \( i \) the value \( \text{blist1}[i] \) or \( \text{blist2}[i] \) or ....
  The second form takes the union of all blists (which as for the first form must have equal length) in the list list.
function UnionBlist(list)
\end{verbatim}

22.3.2 IntersectionBlist

\[ \text{Yes} \]
\begin{verbatim}
function IntersectionBlist(blist1, blist2[, ...])
  returns the intersection of the boolean lists blist1, blist2, etc., which must have equal length. The intersection is a new blist that contains at position \( i \) the value \( \text{blist1}[i] \) and \( \text{blist2}[i] \) and ....
  In the second form list must be a list of boolean lists blist1, blist2, etc., which must have equal length, and IntersectionBlist returns the intersection of those boolean lists.
function IntersectionBlist(list)
\end{verbatim}

22.3.3 DifferenceBlist

\[ \text{Yes} \]
\begin{verbatim}
function DifferenceBlist(blist1, blist2)
  returns the asymmetric set difference of the two boolean lists blist1 and blist2, which must have equal length. The asymmetric set difference is a new boolean list that contains at position \( i \) the value \( \text{blist1}[i] \) and not \( \text{blist2}[i] \).
\end{verbatim}
Example

```gap
gap> blist1 := [ true, true, false, false ];
gap> blist2 := [ true, false, true, false ];
gap> UnionBlist( blist1, blist2 );
[ true, true, true, false ]
gap> IntersectionBlist( blist1, blist2 );
[ true, false, false, false ]
gap> DifferenceBlist( blist1, blist2 );
[ false, true, false, false ]
```

22.4 Function that Modify Boolean Lists

22.4.1 UnionBlist

`UnionBlist(blist1, blist2)`  

`UnionBlist` unites the boolean list `blist1` with the boolean list `blist2`, which must have the same length. This is equivalent to assigning `blist1[i] := blist1[i] or blist2[i]` for all `i`. `UnionBlist` returns nothing, it is only called to change `blist1`.  

Example

```gap
gap> blist1 := [ true, true, false, false ];
gap> blist2 := [ true, false, true, false ];
gap> UnionBlist( blist1, blist2 );
gap> blist1;
[ true, true, true, false ]
```

The function `UnionBlist` (22.3.1) is the nondestructive counterpart to `UnionBlist`.  

22.4.2 UnionBlistList

`UnionBlistList(list, blist, sub)`  

works like `UnionBlist(blist, BlistList(list, sub))`. As no intermediate blist is created, the performance is better than the separate function calls.  

22.4.3 IntersectBlist

`IntersectBlist(blist1, blist2)`  

intersects the boolean list `blist1` with the boolean list `blist2`, which must have the same length. This is equivalent to assigning `blist1[i] := blist1[i] and blist2[i]` for all `i`. `IntersectBlist` returns nothing, it is only called to change `blist1`.  

Example

```gap
gap> blist1 := [ true, true, false, false ];
gap> blist2 := [ true, false, true, false ];
gap> IntersectBlist( blist1, blist2 );
gap> blist1;
[ true, false, false, false ]
```
The function `IntersectionBlist` (22.3.2) is the nondestructive counterpart to `IntersectBlist`.

### 22.4.4 SubtractBlist

`SubtractBlist(blist1, blist2)` (function)

subtracts the boolean list `blist2` from the boolean list `blist1`, which must have equal length.

This is equivalent to assigning `blist1[i] := blist1[i] and not blist2[i]` for all `i`.

`SubtractBlist` returns nothing, it is only called to change `blist1`.

Example

```gap
gap> blist1 := [ true, true, false, false ];;
gap> blist2 := [ true, false, true, false ];;
gap> SubtractBlist( blist1, blist2 );
gap> blist1;
[ false, true, false, false ]
```

The function `DifferenceBlist` (22.3.3) is the nondestructive counterpart to `SubtractBlist`.

### 22.4.5 FlipBlist

`FlipBlist(blist)` (function)

Changes every entry in `blist` that equals `true` to `false` and vice versa. If `blist1` and `blist2` are boolean lists with equal length and every value in `blist2` is `true`, then `FlipBlist(blist1)` is equivalent to `SubtractBlist(blist2, blist1); blist1 := blist2;` but `FlipBlist` is faster, and simpler to type.

`FlipBlist` returns nothing, it is only called to change `blist` in-place.

Example

```gap
gap> blist1 := [ true, true, true, true ];;
gap> blist2 := [ true, false, true, false ];;
gap> SubtractBlist( blist1, blist2 );
gap> blist1;
[ false, true, false, true ]
gap> FlipBlist( blist2 );
gap> blist2;
[ false, true, false, true ]
```

### 22.4.6 SetAllBlist

`SetAllBlist(blist)` (function)

Changes every entry in `blist` to `true`. If `blist1` and `blist2` are boolean lists with equal length and every value in `blist2` is `true`, then `SetAllBlist(blist1)` is equivalent to `UniteBlist(blist1, blist2);` but is faster, and simpler to type.

`SetAllBlist` returns nothing, it is only called to change `blist` in-place.
22.4.7 ClearAllBlist

Example

\begin{verbatim}
gap> blist1 := [ true, true, true, true ];;
gap> blist2 := [ true, false, true, false ];;
gap> SetAllBlist( blist1 );
gap> blist1;
[ true, true, true, true ]
gap> SetAllBlist(blist2);
gap> blist2;
[ true, true, true, true ]
\end{verbatim}

Changes every entry in blist to false. If blist1 and blist2 are boolean lists with equal length and every value in blist2 is false, then ClearAllBlist( blist1 ) is equivalent to IntersectBlist( blist1, blist2 ); but is faster, and simpler to type.

ClearAllBlist returns nothing, it is only called to change blist in-place.

Example

\begin{verbatim}
gap> blist1 := [ true, true, true, true ];;
gap> blist2 := [ true, false, true, false ];;
gap> ClearAllBlist( blist1 );
gap> blist1;
[ false, false, false, false ]
gap> ClearAllBlist(blist2);
gap> blist2;
[ false, false, false, false ]
\end{verbatim}

22.5 More about Boolean Lists

We defined a boolean list as a list that has no holes and contains only true and false. There is a special internal representation for boolean lists that needs only 1 bit for each entry. This bit is set if the entry is true and reset if the entry is false. This representation is of course much more compact than the ordinary representation of lists, which needs 32 or 64 bits per entry.

Not every boolean list is represented in this compact representation. It would be too much work to test every time a list is changed, whether this list has become a boolean list. This section tells you under which circumstances a boolean list is represented in the compact representation, so you can write your functions in such a way that you make best use of the compact representation.

If a dense list containing only true and false is read, it is stored in the compact representation. Furthermore, the results of BlistList (22.2.1), UnionBlist (22.3.1), IntersectionBlist (22.3.2) and DifferenceBlist (22.3.3) are known to be boolean lists by construction, and thus are represented in the compact representation upon creation.

If an argument of IsSubsetBlist (22.2.4), ListBlist (22.2.2), UnionBlist (22.3.1), IntersectionBlist (22.3.2), DifferenceBlist (22.3.3), UniteBlist (22.4.1), IntersectBlist (22.4.3) and SubtractBlist (22.4.4) is a list represented in the ordinary representation, it is tested to see if it is in fact a boolean list. If it is not, an error is signalled. If it is, the representation of the list is changed to the compact representation.
If you change a boolean list that is represented in the compact representation by assignment (see 21.4) or Add (21.4.2) in such a way that the list remains a boolean list it will remain represented in the compact representation. Note that changing a list that is not represented in the compact representation, whether it is a boolean list or not, in such a way that the resulting list becomes a boolean list, will never change the representation of the list.

22.5.1 IsBlistRep

\begin{verbatim}
▷ IsBlistRep(obj)
\end{verbatim}

\begin{verbatim}
▷ ConvertToBlistRep(blist)
\end{verbatim}

\textbf{Returns:} true or false

The first function is a filter that returns \texttt{true} if the object \texttt{obj} is a boolean list in compact representation and \texttt{false} otherwise, see 22.5.

The second function converts the object \texttt{blist} to a boolean list in compact representation and returns \texttt{true} if this is possible. Otherwise \texttt{blist} is unchanged and \texttt{false} is returned.

\begin{example}
\begin{verbatim}
gap> l := [true, false, true];
[ true, false, true ]

\texttt{true}
\end{verbatim}

\begin{verbatim}
gap> IsBlistRep(l);
true
\end{verbatim}

\begin{verbatim}
gap> l := [true, false, 1];
[ true, false, 1 ]

\texttt{false}
\end{verbatim}

\begin{verbatim}
false
\end{verbatim}

\begin{verbatim}
\texttt{false}
\end{verbatim}

\begin{verbatim}
gap> IsBlistRep(l);
false
\end{verbatim}

\begin{verbatim}
\texttt{false}
\end{verbatim}

\begin{verbatim}
gap> ConvertToBlistRep(l);
true
\end{verbatim}

\texttt{true}
\end{example}
Chapter 23

Row Vectors

Just as in mathematics, a vector in GAP is any object which supports appropriate addition and scalar multiplication operations (see Chapter 61). As in mathematics, an especially important class of vectors are those represented by a list of coefficients with respect to some basis. These correspond roughly to the GAP concept of row vectors.

23.1 IsRowVector (Filter)

23.1.1 IsRowVector

\texttt{IsRowVector(obj)}

\texttt{IsRowVector}\ (Category)

A row vector is a vector (see \texttt{IsVector (31.14.14)}) that is also a homogeneous list of odd additive nesting depth (see 21.12). Typical examples are lists of integers and rationals, lists of finite field elements of the same characteristic, and lists of polynomials from a common polynomial ring. Note that matrices are not regarded as row vectors, because they have even additive nesting depth.

The additive operations of the vector must thus be compatible with that for lists, implying that the list entries are the coefficients of the vector with respect to some basis.

Note that not all row vectors admit a multiplication via \texttt{\*} (which is to be understood as a scalar product); for example, class functions are row vectors but the product of two class functions is defined in a different way. For the installation of a scalar product of row vectors, the entries of the vector must be ring elements; note that the default method expects the row vectors to lie in \texttt{IsRingElementList}, and this category may not be implied by \texttt{IsRingElement (31.14.16)} for all entries of the row vector (see the comment in \texttt{IsVector (31.14.14)}).

Note that methods for special types of row vectors really must be installed with the requirement \texttt{IsRowVector}, since \texttt{IsVector (31.14.14)} may lead to a rank of the method below that of the default method for row vectors (see file \texttt{lib/vecmat.gi}).

\texttt{gap> IsRowVector([1,2,3]);}
\texttt{true}

Because row vectors are just a special case of lists, all operations and functions for lists are applicable to row vectors as well (see Chapter 21). This especially includes accessing elements of a row vector (see 21.3), changing elements of a mutable row vector (see 21.4), and comparing row vectors (see 21.10).
Note that, unless your algorithms specifically require you to be able to change entries of your vectors, it is generally better and faster to work with immutable row vectors. See Section 12.6 for more details.

### 23.2 Operators for Row Vectors

The rules for arithmetic operations involving row vectors are in fact special cases of those for the arithmetic of lists, as given in Section 21.11 and the following sections, here we reiterate that definition, in the language of vectors.

Note that the additive behaviour sketched below is defined only for lists in the category `IsGeneralizedRowVector (21.12.1)`, and the multiplicative behaviour is defined only for lists in the category `IsMultiplicativeGeneralizedRowVector (21.12.2)`.

\[ \text{vec1} + \text{vec2} \]

returns the sum of the two row vectors `vec1` and `vec2`. Probably the most usual situation is that `vec1` and `vec2` have the same length and are defined over a common field; in this case the sum is a new row vector over the same field where each entry is the sum of the corresponding entries of the vectors.

In more general situations, the sum of two row vectors need not be a row vector, for example adding an integer vector `vec1` and a vector `vec2` over a finite field yields the list of pointwise sums, which will be a mixture of finite field elements and integers if `vec1` is longer than `vec2`.

\[ \text{scalar} + \text{vec} \]
\[ \text{vec} + \text{scalar} \]

returns the sum of the scalar `scalar` and the row vector `vec`. Probably the most usual situation is that the elements of `vec` lie in a common field with `scalar`; in this case the sum is a new row vector over the same field where each entry is the sum of the scalar and the corresponding entry of the vector.

More general situations are for example the sum of an integer scalar and a vector over a finite field, or the sum of a finite field element and an integer vector.

\[
\text{Example}
\]
\[
\text{gap> } [1, 2, 3] + [1/2, 1/3, 1/4];
[3/2, 7/3, 13/4]
\]
\[
\text{gap> } [1/2, 3/2, 1/2] + 1/2;
[1, 2, 1]
\]

\[\text{vec1} - \text{vec2}\]
\[\text{scalar} - \text{vec}\]
\[\text{vec} - \text{scalar}\]

Subtracting a vector or scalar is defined as adding its additive inverse, so the statements for the addition hold likewise.

\[
\text{Example}
\]
\[
\text{gap> } [1, 2, 3] - [1/2, 1/3, 1/4];
[1/2, 5/3, 11/4]
\]
\[
\text{gap> } [1/2, 3/2, 1/2] - 1/2;
[0, 1, 0]
\]

\[\text{scalar} * \text{vec}\]
\[\text{vec} * \text{scalar}\]
returns the product of the scalar \texttt{scalar} and the row vector \texttt{vec}. Probably the most usual situation is that the elements of \texttt{vec} lie in a common field with \texttt{scalar}; in this case the product is a new row vector over the same field where each entry is the product of the scalar and the corresponding entry of the vector.

More general situations are for example the product of an integer scalar and a vector over a finite field, or the product of a finite field element and an integer vector.

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
geap> [ 1/2, 3/2, 1/2 ] * 2;
[ 1, 3, 1 ]
\end{verbatim}

\texttt{vec1 * vec2}

returns the standard scalar product of \texttt{vec1} and \texttt{vec2}, i.e., the sum of the products of the corresponding entries of the vectors. Probably the most usual situation is that \texttt{vec1} and \texttt{vec2} have the same length and are defined over a common field; in this case the sum is an element of this field.

More general situations are for example the inner product of an integer vector and a vector over a finite field, or the inner product of two row vectors of different lengths.

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
geap> [ 1, 2, 3 ] * [ 1/2, 1/3, 1/4 ];
23/12
\end{verbatim}

For the mutability of results of arithmetic operations, see 12.6.

Further operations with vectors as operands are defined by the matrix operations, see 24.3.

\section{23.2.1 NormedRowVector}
\begin{verbatim}
\texttt{NormedRowVector(v)}
\end{verbatim}

returns a scalar multiple \( w = c \times v \) of the row vector \( v \) with the property that the first nonzero entry of \( w \) is an identity element in the sense of \texttt{IsOne (31.10.5)}.

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
geap> NormedRowVector( [ 5, 2, 3 ] );
[ 1, 2/5, 3/5 ]
\end{verbatim}

\section{23.3 Row Vectors over Finite Fields}

GAP can use compact formats to store row vectors over fields of order at most 256, based on those used by the Meat-Axe [Rin93]. This format also permits extremely efficient vector arithmetic. On the other hand element access and assignment is significantly slower than for plain lists.

The function \texttt{ConvertToVectorRep (23.3.1)} is used to convert a list into a compressed vector, or to rewrite a compressed vector over another field. Note that this function is \textit{much} faster when it is given a field (or field size) as an argument, rather than having to scan the vector and try to decide the field. Supplying the field can also avoid errors and/or loss of performance, when one vector from some collection happens to have all of its entries over a smaller field than the “natural” field of the problem.
23.3.1 ConvertToVectorRep

Called with one argument \texttt{list}, \texttt{ConvertToVectorRep} converts \texttt{list} to an internal row vector representation if possible.

Called with a list \texttt{list} and a finite field \texttt{field}, \texttt{ConvertToVectorRep} converts \texttt{list} to an internal row vector representation appropriate for a row vector over \texttt{field}.

Instead of a field also its size \texttt{fieldsize} may be given.

It is forbidden to call this function unless \texttt{list} is a plain list or a row vector, \texttt{field} is a field, and all elements of \texttt{list} lie in \texttt{field}. Violation of this condition can lead to unpredictable behaviour or a system crash. (Setting the assertion level to at least 2 might catch some violations before a crash, see \texttt{SetAssertionLevel} (7.5.1).)

\texttt{list} may already be a compressed vector. In this case, if no \texttt{field} or \texttt{fieldsize} is given, then nothing happens. If one is given then the vector is rewritten as a compressed vector over the given \texttt{field} unless it has the filter \texttt{IsLockedRepresentationVector}, in which case it is not changed.

The return value is the size of the field over which the vector ends up written, if it is written in a compressed representation.

In this example, we first create a row vector and then ask \texttt{GAP} to rewrite it, first over \texttt{GF(2)} and then over \texttt{GF(4)}.

\begin{verbatim}
gap> v := [Z(2)^0,Z(2),Z(2),0*Z(2)];
[ Z(2)^0, Z(2)^0, Z(2)^0, 0*Z(2) ]
gap> RepresentationsOfObject(v);
[ "IsPlistRep", "IsInternalRep" ]
gap> ConvertToVectorRep(v);
2
gap> v;
<a GF2 vector of length 4>
gap> ConvertToVectorRep(v,4);
4
gap> v;
[ Z(2)^0, Z(2)^0, Z(2)^0, 0*Z(2) ]
gap> RepresentationsOfObject(v);
[ "IsDataObjectRep", "Is8BitVectorRep" ]
\end{verbatim}

A vector in the special representation over \texttt{GF(2)} is always viewed as <a GF2 vector of length \ldots>. Over fields of orders 3 to 256, a vector of length 10 or less is viewed as the list of its coefficients, but a longer one is abbreviated.

Arithmetic operations (see 21.11 and the following sections) preserve the compression status of row vectors in the sense that if all arguments are compressed row vectors written over the same field and the result is a row vector then also the result is a compressed row vector written over this field.
23.3.2 ImmutableVector

\[ \text{\texttt{\textit{ImmutableVector(field, vector[, change]}}} (\text{operation}) \]

returns an immutable vector equal to \textit{vector} which is in the optimal (concerning space and run-time) representation for vectors defined over \textit{field}. This means that vectors obtained by several calls of \texttt{ImmutableVector} for the same \textit{field} are compatible for fast arithmetic without need for field conversion.

The input vector \textit{vector} might change its representation as a side effect of this function, however the result of \texttt{ImmutableVector} is not necessarily \textit{identical} to \textit{vector} if a conversion is not possible.

If \textit{change} is \texttt{true}, then \textit{vector} may be changed to become immutable; otherwise it is copied first.

23.3.3 NumberFFVector

\[ \text{\texttt{\textit{NumberFFVector(vec, sz}}} (\text{operation}) \]

returns an integer that gives the position minus one of the finite field row vector \textit{vec} in the sorted list of all row vectors over the field with \textit{sz} elements in the same dimension as \textit{vec}. \texttt{NumberFFVector} returns \texttt{fail} if the vector cannot be represented over the field with \textit{sz} elements.

\begin{verbatim}
Example

gap> v:=[0,1,2,0]*Z(3);;
gap> NumberFFVector(v, 3);
21
gap> NumberFFVector(Zero(v),3);
0
gap> V:=EnumeratorSorted(GF(3)^4);
<enumerator of ( GF(3)^4 )>
gap> V[21+1] = v;
true
\end{verbatim}

23.4 Coefficient List Arithmetic

The following operations all perform arithmetic on row vectors, given as homogeneous lists of the same length, containing elements of a commutative ring.

There are two reasons for using \texttt{AddRowVector} (23.4.1) in preference to arithmetic operators. Firstly, the three argument form has no single-step equivalent. Secondly \texttt{AddRowVector} (23.4.1) changes its first argument in-place, rather than allocating a new vector to hold the result, and may thus produce less garbage.

23.4.1 AddRowVector

\[ \text{\texttt{\textit{AddRowVector(dst, src[, mul[, from, to]]}}} (\text{operation}) \]

Adds the product of \textit{src} and \textit{mul} to \textit{dst}, changing \textit{dst}. If \textit{from} and \textit{to} are given then only the index range [ \textit{from} .. \textit{to} ] is guaranteed to be affected. Other indices \textit{may} be affected, if it is more convenient to do so. Even when \textit{from} and \textit{to} are given, \textit{dst} and \textit{src} must be row vectors of the same length.
If \( \text{mul} \) is not given either then this operation simply adds \( \text{src} \) to \( \text{dst} \).

### 23.4.2 AddCoeffs

\[
\text{AddCoeffs(list1[, poss1], list2[, poss2[, mul]])}
\]

AddCoeffs adds the entries of \( \text{list2} \{ \text{poss2} \} \), multiplied by the scalar \( \text{mul} \), to \( \text{list1} \{ \text{poss1} \} \). Unbound entries in \( \text{list1} \) are assumed to be zero. The position of the right-most non-zero element is returned.

If the ranges \( \text{poss1} \) and \( \text{poss2} \) are not given, they are assumed to span the whole vectors. If the scalar \( \text{mul} \) is omitted, one is used as a default.

Note that it is the responsibility of the caller to ensure that \( \text{list2} \) has elements at position \( \text{poss2} \) and that the result (in \( \text{list1} \)) will be a dense list.

The function is free to remove trailing (right-most) zeros.

#### Example

\[
gap> \text{l:=[1,2,3,4];}\text{;}\text{m:=[5,6,7];};\text{AddCoeffs(l,m);} \\
gap> \text{l;} \\
[ 6, 8, 10, 4 ]
\]

### 23.4.3 MultVector

\[
\text{MultVector(list1, mul)}
\]

\[
\text{MultVectorLeft(list1, mul)}
\]

Returns: nothing

This operation calculates \( \text{mul} \* \text{list1} \) in-place.

Note that \text{MultVector} is just a synonym for \text{MultVectorLeft}.

### 23.4.4 CoeffsMod

\[
\text{CoeffsMod(list1[, len1], modulus)}
\]

returns the coefficient list obtained by reducing the entries in \( \text{list1} \) modulo \( \text{modulus} \). After reducing it shrinks the list to remove trailing zeroes. If the optional argument \( \text{len1} \) is used, it reduces only first \( \text{len1} \) elements of the list.

#### Example

\[
gap> l:=[1,2,3,4];\text{;}\text{CoeffsMod(l,2);} \\
[ 1, 0, 1 ]
\]

### 23.5 Shifting and Trimming Coefficient Lists

The following functions change coefficient lists by shifting or trimming.

#### 23.5.1 LeftShiftRowVector

\[
\text{LeftShiftRowVector(list, shift)}
\]
changes \texttt{list} by assigning \texttt{list[i]:= list[i+shift]} and removing the last \texttt{shift} entries of the result.

### 23.5.2 RightShiftRowVector

\begin{verbatim}
\texttt{RightShiftRowVector(list, shift, fill)}
\end{verbatim}

changes \texttt{list} by assigning \texttt{list[i+shift]:= list[i]} and filling each of the \texttt{shift} first entries with \texttt{fill}.

### 23.5.3 ShrinkRowVector

\begin{verbatim}
\texttt{ShrinkRowVector(list)}
\end{verbatim}

removes trailing zeroes from the list \texttt{list}.

#### Example

\begin{verbatim}
gap> l:=[1,0,0];;ShrinkRowVector(l);l;
[ 1 ]
\end{verbatim}

### 23.5.4 RemoveOuterCoeffs

\begin{verbatim}
\texttt{RemoveOuterCoeffs(list, coef)}
\end{verbatim}

removes \texttt{coef} at the beginning and at the end of \texttt{list} and returns the number of elements removed at the beginning.

#### Example

\begin{verbatim}
gap> l:=[1,1,2,1,1,2,1,1,2,1];; RemoveOuterCoeffs(l,1);
2
\end{verbatim}

### 23.6 Functions for Coding Theory

The following functions perform operations on finite fields vectors considered as code words in a linear code.

#### 23.6.1 WeightVecFFE

\begin{verbatim}
\texttt{WeightVecFFE(vec)}
\end{verbatim}

returns the weight of the finite field vector \texttt{vec}, i.e. the number of nonzero entries.

### 23.6.2 DistanceVecFFE

\begin{verbatim}
\texttt{DistanceVecFFE(vec1, vec2)}
\end{verbatim}


returns the distance between the two vectors \texttt{vec1} and \texttt{vec2}, which must have the same length and whose elements must lie in a common field. The distance is the number of places where \texttt{vec1} and \texttt{vec2} differ.

23.6.3 \textbf{DistancesDistributionVecFFEsVecFFE}

\begin{verbatim}
\DontPrintSemicolon
\textbf{DistancesDistributionVecFFEsVecFFE}(vecs, vec)
\end{verbatim}

returns the distances distribution of the vector \texttt{vec} to the vectors in the list \texttt{vecs}. All vectors must have the same length, and all elements must lie in a common field. The distances distribution is a list \(d\) of length \(\text{Length}(\texttt{vec})+1\), such that the value \(d[i]\) is the number of vectors in \texttt{vecs} that have distance \(i+1\) to \texttt{vec}.

23.6.4 \textbf{DistancesDistributionMatFFEVecFFE}

\begin{verbatim}
\DontPrintSemicolon
\textbf{DistancesDistributionMatFFEVecFFE}(mat, F, vec)
\end{verbatim}

returns the distances distribution of the vector \texttt{vec} to the vectors in the vector space generated by the rows of the matrix \texttt{mat} over the finite field \texttt{F}. The length of the rows of \texttt{mat} and the length of \texttt{vec} must be equal, and all entries must lie in \texttt{F}. The rows of \texttt{mat} must be linearly independent. The distances distribution is a list \(d\) of length \(\text{Length}(\texttt{vec})+1\), such that the value \(d[i]\) is the number of vectors in the vector space generated by the rows of \texttt{mat} that have distance \(i+1\) to \texttt{vec}.

23.6.5 \textbf{AClosestVectorCombinationsMatFFEVecFFE}

\begin{verbatim}
\DontPrintSemicolon
\textbf{AClosestVectorCombinationsMatFFEVecFFE}\((mat, f, vec, l, stop)\)
\end{verbatim}

\begin{verbatim}
\DontPrintSemicolon
\textbf{AClosestVectorCombinationsMatFFEVecFFECoords}\((mat, f, vec, l, stop)\)
\end{verbatim}

These functions run through the \(f\)-linear combinations of the vectors in the rows of the matrix \texttt{mat} that can be written as linear combinations of exactly \(l\) rows (that is without using zero as a coefficient). The length of the rows of \texttt{mat} and the length of \texttt{vec} must be equal, and all elements must lie in the field \texttt{f}. The rows of \texttt{mat} must be linearly independent. \textbf{AClosestVectorCombinationsMatFFEVecFFE} returns a vector from these that is closest to the vector \texttt{vec}. If it finds a vector of distance at most \texttt{stop}, which must be a nonnegative integer, then it stops immediately and returns this vector.

\textbf{AClosestVectorCombinationsMatFFEVecFFECoords} returns a length 2 list containing the same closest vector and also a vector \texttt{v} with exactly \(l\) non-zero entries, such that \texttt{v} times \texttt{mat} is the closest vector.

23.6.6 \textbf{CosetLeadersMatFFE}

\begin{verbatim}
\DontPrintSemicolon
\textbf{CosetLeadersMatFFE}(mat, f)
\end{verbatim}

returns a list of representatives of minimal weight for the cosets of a code. \texttt{mat} must be a check matrix for the code, the code is defined over the finite field \texttt{f}. All rows of \texttt{mat} must have the same length, and all elements must lie in the field \texttt{f}. The rows of \texttt{mat} must be linearly independent.
23.7 Vectors as coefficients of polynomials

A list of ring elements can be interpreted as a row vector or the list of coefficients of a polynomial. There are a couple of functions that implement arithmetic operations based on these interpretations. GAP contains proper support for polynomials (see 66), the operations described in this section are on a lower level.

The following operations all perform arithmetic on univariate polynomials given by their coefficient lists. These lists can have different lengths but must be dense homogeneous lists containing elements of a commutative ring. Not all input lists may be empty.

In the following descriptions we will always assume that list1 is the coefficient list of the polynomial pol1 and so forth. If length parameter leni is not given, it is set to the length of listi by default.

23.7.1 ValuePol

\[ \text{ValuePol(coeff, } x) \]

Let coeff be the coefficients list of a univariate polynomial \( f \), and \( x \) a ring element. Then ValuePol returns the value \( f(x) \).

The coefficient of \( x^i \) is assumed to be stored at position \( i+1 \) in the coefficients list.

Example

\text{gap> } \text{ValuePol([1,2,3],4)};
57

23.7.2 ProductCoeffs

\[ \text{ProductCoeffs(list1[, len1], list2[, len2])} \]

Let \( p_1 \) (and \( p_2 \)) be polynomials given by the first len1 (len2) entries of the coefficient list list2 (list2). If len1 and len2 are omitted, they default to the lengths of list1 and list2. This operation returns the coefficient list of the product of \( p_1 \) and \( p_2 \).

Example

\text{gap> } l:=[1,2,3,4];;m:=[5,6,7];;\text{ProductCoeffs(l,m)};
[ 5, 16, 34, 52, 45, 28 ]

23.7.3 ReduceCoeffs

\[ \text{ReduceCoeffs(list1[, len1], list2[, len2])} \]

Let \( p_1 \) (and \( p_2 \)) be polynomials given by the first len1 (len2) entries of the coefficient list list1 (list2). If len1 and len2 are omitted, they default to the lengths of list1 and list2. ReduceCoeffs changes list1 to the coefficient list of the remainder when dividing \( p_1 \) by \( p_2 \). This operation changes list1 which therefore must be a mutable list. The operation returns the position of the last non-zero entry of the result but is not guaranteed to remove trailing zeroes.

Example

\text{gap> } l:=[1,2,3,4];;m:=[5,6,7];;\text{ReduceCoeffs(l,m)};
2
\text{gap> } l;
[ 64/49, -24/49, 0, 0 ]
23.7.4 ReduceCoeffsMod

\[ \text{ReduceCoeffsMod(} \text{list1[, } \text{len1}] , \text{list2[, } \text{len2}], \text{modulus}) \]  

Let \( p_1 \) (and \( p_2 \)) be polynomials given by the first \( \text{len1} \) (\( \text{len2} \)) entries of the coefficient list \( \text{list1} \) (\( \text{list2} \)). If \( \text{len1} \) and \( \text{len2} \) are omitted, they default to the lengths of \( \text{list1} \) and \( \text{list2} \). \text{ReduceCoeffsMod} changes \( \text{list1} \) to the coefficient list of the remainder when dividing \( p_1 \) by \( p_2 \) modulo \( \text{modulus} \), which must be a positive integer. This operation changes \( \text{list1} \) which therefore must be a mutable list. The operation returns the position of the last non-zero entry of the result but is not guaranteed to remove trailing zeroes.

Example

```gap
gap> l:=[1,2,3,4];;m:=[5,6,7];;ReduceCoeffsMod(l,m,3);
1
gap> l;
[ 1, 0, 0, 0 ]
```

23.7.5 PowerModCoeffs

\[ \text{PowerModCoeffs(} \text{list1[, } \text{len1}], \text{exp, list2[, } \text{len2}]) \]  

Let \( p_1 \) and \( p_2 \) be polynomials whose coefficients are given by the first \( \text{len1} \) resp. \( \text{len2} \) entries of the lists \( \text{list1} \) and \( \text{list2} \), respectively. If \( \text{len1} \) and \( \text{len2} \) are omitted, they default to the lengths of \( \text{list1} \) and \( \text{list2} \). Let \( \text{exp} \) be a positive integer. \text{PowerModCoeffs} returns the coefficient list of the remainder when dividing the \( \text{exp} \)-th power of \( p_1 \) by \( p_2 \). The coefficients are reduced already while powers are computed, therefore avoiding an explosion in list length.

Example

```gap
gap> l:=[1,2,3,4];;m:=[5,6,7];;PowerModCoeffs(l,5,m);
[ -839462813696/678223072849, -7807439437824/678223072849 ]
```

23.7.6 ShiftedCoeffs

\[ \text{ShiftedCoeffs(list, shift)} \]  

produces a new coefficient list \( \text{new} \) obtained by the rule \( \text{new[i+shift]}:= \text{list[i]} \) and filling initial holes by the appropriate zero.

Example

```gap
gap> l:=[1,2,3];;ShiftedCoeffs(l,2);ShiftedCoeffs(l,-2);
[ 0, 0, 1, 2, 3 ]
[ 3 ]
```
Chapter 24

Matrices

Matrices are represented in GAP by lists of row vectors (see 23) (for future changes to this policy see Chapter 26). The vectors must all have the same length, and their elements must lie in a common ring. However, since checking rectangularness can be expensive functions and methods of operations for matrices often will not give an error message for non-rectangular lists of lists—in such cases the result is undefined.

Because matrices are just a special case of lists, all operations and functions for lists are applicable to matrices also (see chapter 21). This especially includes accessing elements of a matrix (see 21.3), changing elements of a matrix (see 21.4), and comparing matrices (see 21.10).

Note that, since a matrix is a list of lists, the behaviour of ShallowCopy (12.7.1) for matrices is just a special case of ShallowCopy (12.7.1) for lists (see 21.7); called with an immutable matrix mat, ShallowCopy (12.7.1) returns a mutable matrix whose rows are identical to the rows of mat. In particular the rows are still immutable. To get a matrix whose rows are mutable, one can use List(mat, ShallowCopy).

24.1 InfoMatrix (Info Class)

24.1.1 InfoMatrix

\texttt{InfoMatrix (info class)}

The info class for matrix operations is \texttt{InfoMatrix}.

24.2 Categories of Matrices

24.2.1 IsMatrix

\texttt{IsMatrix(obj)}

By convention \textit{matrix} is a list of lists of equal length whose entries lie in a common ring.

For technical reasons laid out at the top of Chapter 24, the filter IsMatrix is a synonym for a table of ring elements, (see IsTable (21.1.4) and IsRingElement (31.14.16)). This means that IsMatrix returns true for tables such as \([[[1,2],[3]]\). If necessary, IsRectangularTable (21.1.5) can be used to test whether an object is a list of homogenous lists of equal lengths manually.
Note that matrices may have different multiplications, besides the usual matrix product there is for example the Lie product. So there are categories such as `IsOrdinaryMatrix` (24.2.2) and `IsLieMatrix` (24.2.3) that describe the matrix multiplication. One can form the product of two matrices only if they support the same multiplication.

```
Example

gap> mat:=[[1,2,3],[4,5,6],[7,8,9]];
[ [ 1, 2, 3 ], [ 4, 5, 6 ], [ 7, 8, 9 ] ]
gap> IsMatrix(mat);
true
gap> mat:=[[1,2],[3]];
[ [ 1, 2 ], [ 3 ] ]
gap> IsMatrix(mat);
true
gap> IsRectangularTable(mat);
false
```

Note that the empty list `[]` and more complex “empty” structures such as `[[[]]]` are not matrices, although special methods allow them be used in place of matrices in some situations. See `EmptyMatrix` (24.5.3) below.

```
Example

gap> [[0]]*[[[]]];
[ [ 0 ] ]
gap> IsMatrix([[[]]]);
false
```

### 24.2.2 `IsOrdinaryMatrix`

An ordinary matrix is a matrix whose multiplication is the ordinary matrix multiplication. Each matrix in internal representation is in the category `IsOrdinaryMatrix`, and arithmetic operations with objects in `IsOrdinaryMatrix` produce again matrices in `IsOrdinaryMatrix`.

Note that we want that Lie matrices shall be matrices that behave in the same way as ordinary matrices, except that they have a different multiplication. So we must distinguish the different matrix multiplications, in order to be able to describe the applicability of multiplication, and also in order to form a matrix of the appropriate type as the sum, difference etc. of two matrices which have the same multiplication.

### 24.2.3 `IsLieMatrix`

A Lie matrix is a matrix whose multiplication is given by the Lie bracket. (Note that a matrix with ordinary matrix multiplication is in the category `IsOrdinaryMatrix` (24.2.2).)

Each matrix created by `LieObject` (64.1.1) is in the category `IsLieMatrix`, and arithmetic operations with objects in `IsLieMatrix` produce again matrices in `IsLieMatrix`. 
24.3 Operators for Matrices

The rules for arithmetic operations involving matrices are in fact special cases of those for the arithmetic of lists, given in Section 21.11 and the following sections, here we reiterate that definition, in the language of vectors and matrices.

Note that the additive behaviour sketched below is defined only for lists in the category IsGeneralizedRowVector (21.12.1), and the multiplicative behaviour is defined only for lists in the category IsMultiplicativeGeneralizedRowVector (21.12.2) (see 21.12).

\[ \text{mat1} + \text{mat2} \]
returns the sum of the two matrices \text{mat1} and \text{mat2}, Probably the most usual situation is that \text{mat1} and \text{mat2} have the same dimensions and are defined over a common field; in this case the sum is a new matrix over the same field where each entry is the sum of the corresponding entries of the matrices.

In more general situations, the sum of two matrices need not be a matrix, for example adding an integer matrix \text{mat1} and a matrix \text{mat2} over a finite field yields the table of pointwise sums, which will be a mixture of finite field elements and integers if \text{mat1} has bigger dimensions than \text{mat2}.

\[ \text{scalar} + \text{mat} \]
\[ \text{mat} + \text{scalar} \]
returns the sum of the scalar \text{scalar} and the matrix \text{mat}. Probably the most usual situation is that the entries of \text{mat} lie in a common field with \text{scalar}; in this case the sum is a new matrix over the same field where each entry is the sum of the scalar and the corresponding entry of the matrix.

More general situations are for example the sum of an integer scalar and a matrix over a finite field, or the sum of a finite field element and an integer matrix.

\[ \text{mat1} - \text{mat2} \]
\[ \text{scalar} - \text{mat} \]
\[ \text{mat} - \text{scalar} \]
Subtracting a matrix or scalar is defined as adding its additive inverse, so the statements for the addition hold likewise.

\[ \text{scalar} \times \text{mat} \]
\[ \text{mat} \times \text{scalar} \]
returns the product of the scalar \text{scalar} and the matrix \text{mat}. Probably the most usual situation is that the elements of \text{mat} lie in a common field with \text{scalar}; in this case the product is a new matrix over the same field where each entry is the product of the scalar and the corresponding entry of the matrix.

More general situations are for example the product of an integer scalar and a matrix over a finite field, or the product of a finite field element and an integer matrix.

\[ \text{vec} \times \text{mat} \]
returns the product of the row vector \text{vec} and the matrix \text{mat}. Probably the most usual situation is that \text{vec} and \text{mat} have the same lengths and are defined over a common field, and that all rows of \text{mat} have the same length \( m \), say; in this case the product is a new row vector of length \( m \) over the same field which is the sum of the scalar multiples of the rows of \text{mat} with the corresponding entries of \text{vec}.

More general situations are for example the product of an integer vector and a matrix over a finite field, or the product of a vector over a finite field and an integer matrix.

\[ \text{mat} \times \text{vec} \]
returns the product of the matrix \text{mat} and the row vector \text{vec}. (This is the standard product of a matrix with a column vector.) Probably the most usual situation is that the length of \text{vec} and of all rows of \text{mat} are equal, and that the elements of \text{mat} and \text{vec} lie in a common field; in this case the
product is a new row vector of the same length as mat and over the same field which is the sum of the scalar multiples of the columns of mat with the corresponding entries of vec.

More general situations are for example the product of an integer matrix and a vector over a finite field, or the product of a matrix over a finite field and an integer vector.

\[ \text{mat1} \times \text{mat2} \]

This form evaluates to the (Cauchy) product of the two matrices mat1 and mat2. Probably the most usual situation is that the number of columns of mat1 equals the number of rows of mat2, and that the elements of mat and vec lie in a common field; if mat1 is a matrix with \( m \) rows and \( n \) columns, say, and mat2 is a matrix with \( n \) rows and \( o \) columns, the result is a new matrix with \( m \) rows and \( o \) columns. The element in row \( i \) at position \( j \) of the product is the sum of \( \text{mat1}[i][l] \times \text{mat2}[l][j] \), with \( l \) running from 1 to \( n \).

\[ \text{Inverse( mat )} \]

returns the inverse of the matrix mat, which must be an invertible square matrix. If mat is not invertible then fail is returned.

\[ \text{mat1} / \text{mat2} \]
\[ \text{scalar} / \text{mat} \]
\[ \text{mat} / \text{scalar} \]
\[ \text{vec} / \text{mat} \]

In general, \( \text{left} / \text{right} \) is defined as \( \text{left} \times \text{right}^{-1} \). Thus in the above forms the right operand must always be invertible.

\[ \text{mat} ^ \text{int} \]
\[ \text{mat1} ^ \text{mat2} \]
\[ \text{vec} ^ \text{mat} \]

Powering a square matrix mat by an integer int yields the int-th power of mat; if int is negative then mat must be invertible, if int is 0 then the result is the identity matrix One(mat), even if mat is not invertible.

Powering a square matrix mat1 by an invertible square matrix mat2 of the same dimensions yields the conjugate of mat1 by mat2, i.e., the matrix mat2^{-1} \times mat1 \times mat2.

Powering a row vector vec by a matrix mat is in every respect equivalent to vec \times mat. This operations reflects the fact that matrices act naturally on row vectors by multiplication from the right, and that the powering operator is GAP's standard for group actions.

\[ \text{Comm( mat1, mat2 )} \]

returns the commutator of the square invertible matrices mat1 and mat2 of the same dimensions and over a common field, which is the matrix mat1^{-1} \times mat2^{-1} \times mat1 \times mat2.

The following cases are still special cases of the general list arithmetic defined in 21.11.

\[ \text{scalar + matlist} \]
\[ \text{matlist + scalar} \]
\[ \text{scalar - matlist} \]
\[ \text{matlist - scalar} \]
\[ \text{scalar \times matlist} \]
\[ \text{matlist \times scalar} \]
\[ \text{matlist \div scalar} \]

A scalar scalar may also be added, subtracted, multiplied with, or divided into a list matlist of matrices. The result is a new list of matrices where each matrix is the result of performing the operation with the corresponding matrix in matlist.

\[ \text{mat \times matlist} \]
A matrix \( \mat \) may also be multiplied with a list \( \matlist \) of matrices. The result is a new list of matrices, where each entry is the product of \( \mat \) and the corresponding entry in \( \matlist \).

Dividing a list \( \matlist \) of matrices by an invertible matrix \( \mat \) evaluates to \( \matlist * \mat^{-1} \). The result returns the product of the vector \( \vec \) and the list of matrices \( \mat \). The lengths \( l \) of \( \vec \) and \( \matlist \) must be equal. All matrices in \( \matlist \) must have the same dimensions. The elements of \( \vec \) and the elements of the matrices in \( \matlist \) must lie in a common ring. The product is the sum over \( \vec[i] * \matlist[i] \) with \( i \) running from 1 to \( l \).

For the mutability of results of arithmetic operations, see 12.6.

### 24.4 Properties and Attributes of Matrices

#### 24.4.1 DimensionsMat

\[ \text{DimensionsMat}(\mat) \]

is a list of length 2, the first being the number of rows, the second being the number of columns of the matrix \( \mat \). If \( \mat \) is malformed, that is, it is not a RectangularTable (21.1.5), returns fail.

**Example**

\[ \text{gap> DimensionsMat([[1,2,3],[4,5,6]]);} \]

\[ [2, 3] \]

\[ \text{gap> DimensionsMat([[1,2,3],[4,5]]);} \]

fail

#### 24.4.2 DefaultFieldOfMatrix

\[ \text{DefaultFieldOfMatrix}(\mat) \]

For a matrix \( \mat \), \text{DefaultFieldOfMatrix} returns either a field (not necessarily the smallest one) containing all entries of \( \mat \), or fail.

If \( \mat \) is a matrix of finite field elements or a matrix of cyclotomics, \text{DefaultFieldOfMatrix} returns the default field generated by the matrix entries (see 59.3 and 18.1).

**Example**

\[ \text{gap> DefaultFieldOfMatrix([[Z(4),Z(8)]]);} \]

\[ GF(2^6) \]

#### 24.4.3 TraceMat

\[ \text{TraceMat}(\mat) \]

The trace of a square matrix is the sum of its diagonal entries.

**Example**

\[ \text{gap> TraceMat([[1,2,3],[4,5,6],[7,8,9]]);} \]

15
### 24.4.4 DeterminantMat

▷ DeterminantMat(mat) \hspace{1cm} \text{(attribute)}
▷ Determinant(mat) \hspace{1cm} \text{(operation)}

returns the determinant of the square matrix \( \text{mat} \).

These methods assume implicitly that \( \text{mat} \) is defined over an integral domain whose quotient field is implemented in GAP. For matrices defined over an arbitrary commutative ring with one see DeterminantMatDivFree (24.4.6).

### 24.4.5 DeterminantMatDestructive

▷ DeterminantMatDestructive(mat) \hspace{1cm} \text{(operation)}

Does the same as DeterminantMat (24.4.4), with the difference that it may destroy its argument. The matrix \( \text{mat} \) must be mutable.

```
gap> DeterminantMat([[1,2],[2,1]]);  
-3
```

```
gap> mm:= [[1,2],[2,1]];;
gap> DeterminantMatDestructive( mm );
-3
```

```
[ [ 1, 2 ], [ 0, -3 ] ]
```

### 24.4.6 DeterminantMatDivFree

▷ DeterminantMatDivFree(mat) \hspace{1cm} \text{(operation)}

returns the determinant of a square matrix \( \text{mat} \) over an arbitrary commutative ring with one using the division free method of Mahajan and Vinay [MV97].

### 24.4.7 IsEmptyMatrix (for matrices)

▷ IsEmptyMatrix(M) \hspace{1cm} \text{(property)}

Returns: A boolean
Is true if \( M \) either has zero columns or zero rows and false otherwise. In other words, a matrix is empty if it has no entries.

### 24.4.8 IsMonomialMatrix

▷ IsMonomialMatrix(mat) \hspace{1cm} \text{(property)}

A matrix is monomial if and only if it has exactly one nonzero entry in every row and every column.

```
gap> IsMonomialMatrix([[0,1],[1,0]]);
true
```
24.4.9  IsDiagonalMatrix

$\text{IsDiagonalMatrix}(\text{mat})$

return true if the matrix \text{mat} has only zero entries off the main diagonal, and false otherwise.

```gap
gap> IsDiagonalMatrix( [ [ 1 ] ] );
true
gap> IsDiagonalMatrix( [ [ 1, 0, 0 ], [ 0, 1, 0 ] ] );
true
gap> IsDiagonalMatrix( [ [ 0, 1 ], [ 1, 0 ] ] );
false
```

24.4.10  IsUpperTriangularMatrix

$\text{IsUpperTriangularMatrix}(\text{mat})$

return true if the matrix \text{mat} has only zero entries below the main diagonal, and false otherwise.

```gap
gap> IsUpperTriangularMatrix( [ [ 1 ] ] );
true
gap> IsUpperTriangularMatrix( [ [ 1, 2, 3 ], [ 0, 5, 6 ] ] );
true
gap> IsUpperTriangularMatrix( [ [ 0, 1 ], [ 1, 0 ] ] );
false
```

24.4.11  IsLowerTriangularMatrix

$\text{IsLowerTriangularMatrix}(\text{mat})$

return true if the matrix \text{mat} has only zero entries above the main diagonal, and false otherwise.

```gap
gap> IsLowerTriangularMatrix( [ [ 1 ] ] );
true
gap> IsLowerTriangularMatrix( [ [ 1, 0, 0 ], [ 2, 3, 0 ] ] );
true
gap> IsLowerTriangularMatrix( [ [ 0, 1 ], [ 1, 0 ] ] );
false
```

24.5  Matrix Constructions

24.5.1  IdentityMat

$\text{IdentityMat}(m[, R])$


returns a (mutable) $m \times m$ identity matrix over the ring given by $R$. Here, $R$ can be either a ring, or an element of a ring. By default, an integer matrix is created.

```gap
gap> IdentityMat(3);
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ]
gap> IdentityMat(2,Integers mod 15);
[ [ ZmodnZObj( 1, 15 ), ZmodnZObj( 0, 15 ) ],
  [ ZmodnZObj( 0, 15 ), ZmodnZObj( 1, 15 ) ] ]
gap> IdentityMat(2,Z(3));
[ [ Z(3)^0, 0*Z(3) ], [ 0*Z(3), Z(3)^0 ] ]
```

### 24.5.2 NullMat

returns a (mutable) $m \times n$ null matrix over the ring given by $R$. Here, $R$ can be either a ring, or an element of a ring. By default, an integer matrix is created.

```gap
gap> NullMat(3,2);
[ [ 0, 0 ], [ 0, 0 ], [ 0, 0 ] ]
gap> NullMat(2,2,Integers mod 15);
[ [ ZmodnZObj( 0, 15 ), ZmodnZObj( 0, 15 ) ],
  [ ZmodnZObj( 0, 15 ), ZmodnZObj( 0, 15 ) ] ]
gap> NullMat(3,2,Z(3));
[ [ 0*Z(3), 0*Z(3) ], [ 0*Z(3), 0*Z(3) ], [ 0*Z(3), 0*Z(3) ] ]
```

### 24.5.3 EmptyMatrix

is an empty (ordinary) matrix in characteristic `char` that can be added to or multiplied with empty lists (representing zero-dimensional row vectors). It also acts (via the operation `\^` (31.12.1)) on empty lists.

```gap
gap> EmptyMatrix(5);
EmptyMatrix( 5 )
gap> AsList(last);
[ ]
```

### 24.5.4 DiagonalMat

returns a diagonal matrix `mat` with the diagonal entries given by `vector`.

```gap
gap> DiagonalMat([1,2,3]);
[ [ 1, 0, 0 ], [ 0, 2, 0 ], [ 0, 0, 3 ] ]
```
24.5.5 PermutationMat

\[ \text{PermutationMat}(\text{perm}, \text{dim}[, \text{F}]) \]

returns a matrix in dimension \( \text{dim} \) over the field given by \( \text{F} \) (i.e. the smallest field containing the element \( \text{F} \) or \( \text{F} \) itself if it is a field) that represents the permutation \( \text{perm} \) acting by permuting the basis vectors as it permutes points.

\begin{verbatim}
gap> PermutationMat((1,2,3),4,1);
[ [ 0, 1, 0, 0 ], [ 0, 0, 1, 0 ], [ 1, 0, 0, 0 ], [ 0, 0, 0, 1 ] ]
\end{verbatim}

24.5.6 TransposedMatImmutable

\begin{verbatim}
\text{TransposedMatImmutable}(\text{mat}) \quad \text{(attribute)}
\text{TransposedMatAttr}(\text{mat}) \quad \text{(attribute)}
\text{TransposedMat}(\text{mat}) \quad \text{(attribute)}
\text{TransposedMatMutable}(\text{mat}) \quad \text{(operation)}
\text{TransposedMatOp}(\text{mat}) \quad \text{(operation)}
\end{verbatim}

These functions all return the transposed of the matrix \( \text{mat} \), i.e., a matrix \( \text{trans} \) such that \( \text{trans}[i][k] = \text{mat}[k][i] \) holds. They differ only w.r.t. the mutability of the result. \text{TransposedMat} is an attribute and hence returns an immutable result. \text{TransposedMatMutable} is guaranteed to return a new mutable matrix. \text{TransposedMatImmutable} and \text{TransposedMatAttr} are synonyms of \text{TransposedMat}, and \text{TransposedMatOp} is a synonym of \text{TransposedMatMutable}, in analogy to operations such as \text{Zero} (31.10.3).

24.5.7 TransposedMatDestructive

\begin{verbatim}
\text{TransposedMatDestructive}(\text{mat}) \quad \text{(operation)}
\end{verbatim}

If \( \text{mat} \) is a mutable matrix, then the transposed is computed by swapping the entries in \( \text{mat} \). In this way \( \text{mat} \) gets changed. In all other cases the transposed is computed by \text{TransposedMat} (24.5.6).

\begin{verbatim}
gap> TransposedMat([[1,2,3],[4,5,6],[7,8,9]]);
[ [ 1, 4, 7 ], [ 2, 5, 8 ], [ 3, 6, 9 ] ]
gap> mm:= [[1,2,3],[4,5,6],[7,8,9]];
gap> TransposedMatDestructive( mm );
[ [ 1, 4, 7 ], [ 2, 5, 8 ], [ 3, 6, 9 ] ]
gap> mm;
[ [ 1, 4, 7 ], [ 2, 5, 8 ], [ 3, 6, 9 ] ]
\end{verbatim}

24.5.8 KroneckerProduct

\begin{verbatim}
\text{KroneckerProduct}(\text{mat1}, \text{mat2}) \quad \text{(operation)}
\end{verbatim}

The Kronecker product of two matrices is the matrix obtained when replacing each entry \( a \) of \( \text{mat1} \) by the product \( a*\text{mat2} \) in one matrix.
24.5.9 ReflectionMat

\texttt{ReflectionMat(coeffs[, conj[, root]])}

Let \texttt{coeffs} be a row vector. \texttt{ReflectionMat} returns the matrix of the reflection in this vector.

More precisely, if \texttt{coeffs} is the coefficients list of a vector \( v \) w.r.t. a basis \( B \) (see \texttt{Basis(61.5.2)}) say, then the returned matrix describes the reflection in \( v \) w.r.t. \( B \) as a map on a row space, with action from the right.

The optional argument \texttt{root} is a root of unity that determines the order of the reflection. The default is a reflection of order 2. For triflections one should choose a third root of unity etc. (see \texttt{E(18.1.1)}).

\texttt{conj} is a function of one argument that conjugates a ring element. The default is \texttt{ComplexConjugate(18.5.2)}.

The matrix of the reflection in \( v \) is defined as

\[ M = I_n + v^\top \cdot (w - 1)/(v^\top v) \cdot v \]

where \( w \) equals \texttt{root}, \( n \) is the length of the coefficient list, and \( ^\top \) denotes the conjugation.

So \( v \) is mapped to \( wv \), with default \(-v\), and any vector \( x \) with the property \( x^\top v = 0 \) is fixed by the reflection.

24.5.10 PrintArray

\texttt{PrintArray(array)}

pretty-prints the array \texttt{array}.

24.6 Random Matrices

24.6.1 RandomMat

\texttt{RandomMat([rs, , m, n[, R]])}

\texttt{RandomMat} returns a new mutable random matrix with \( m \) rows and \( n \) columns with elements taken from the ring \( R \), which defaults to \texttt{Integers(14)}. Optionally, a random source \( rs \) can be supplied.
RandomInvertibleMat returns a new mutable invertible random matrix with \( m \) rows and columns with elements taken from the ring \( R \), which defaults to \texttt{Integers} (14). Optionally, a random source \( rs \) can be supplied.

```gap
gap> m := RandomInvertibleMat(4);
[ [ -4, 1, 0, -1 ], [ -1, -1, 1, -1 ], [ 1, -2, -1, -2 ],
  [ 0, -1, 2, -2 ] ]
gap> m^{-1};
[ [ -1/8, -11/24, 1/24, 1/4 ], [ 1/4, -13/12, -1/12, 1/2 ],
  [ -1/8, 5/24, -7/24, 1/4 ], [ -1/4, 3/4, -1/4, -1/2 ] ]
```

24.6.3 RandomUnimodularMat

\[ \text{RandomUnimodularMat}(rs, m) \]

returns a new random mutable \( m \times m \) matrix with integer entries that is invertible over the integers. Optionally, a random source \( rs \) can be supplied.

```gap
gap> m := RandomUnimodularMat(3);
[ [ -5, 1, 0 ], [ 12, -2, -1 ], [ -14, 3, 0 ] ]
gap> m^{-1};
[ [ -3, 0, 1 ], [ -14, 0, 5 ], [ -8, -1, 2 ] ]
```

24.7 Matrices Representing Linear Equations and the Gaussian Algorithm

24.7.1 RankMat

\[ \text{RankMat}(mat) \]

If \( mat \) is a matrix whose rows span a free module over the ring generated by the matrix entries and their inverses then \text{RankMat} returns the dimension of this free module. Otherwise \texttt{fail} is returned.

Note that \text{RankMat} may perform a Gaussian elimination. For large rational matrices this may take very long, because the entries may become very large.

```gap
gap> mat:=[[1,2,3],[4,5,6],[7,8,9]];;
gap> RankMat(mat);
2
```

24.7.2 TriangulizedMat

\[ \text{TriangulizedMat(mat)} \]

 Computes an upper triangular form of the matrix \( mat \) via the Gaussian Algorithm. It returns a mutable matrix in upper triangular form. This is sometimes also called “Hermite normal form” or “Reduced Row Echelon Form”. \texttt{RREF} is a synonym for \text{TriangulizedMat}. 

24.7.3 TriangulizeMat

\> TriangulizeMat(mat)

Applies the Gaussian Algorithm to the mutable matrix \texttt{mat} and changes \texttt{mat} such that it is in upper triangular normal form (sometimes called “Hermite normal form” or “Reduced Row Echelon Form”).

\begin{verbatim}
  gap> m:=TransposedMatMutable(mat);
  [ [ 1, 4, 7 ], [ 2, 5, 8 ], [ 3, 6, 9 ] ]
  gap> TriangulizeMat(m);m;
  [ [ 1, 0, -1 ], [ 0, 1, 2 ], [ 0, 0, 0 ] ]
  gap> m:=TransposedMatMutable(mat);
  [ [ 1, 4, 7 ], [ 2, 5, 8 ], [ 3, 6, 9 ] ]
  gap> TriangulizedMat(m);m;
  [ [ 1, 0, -1 ], [ 0, 1, 2 ], [ 0, 0, 0 ] ]
\end{verbatim}

24.7.4 NullspaceMat

\> NullspaceMat(mat)

\> TriangulizedNullspaceMat(mat)

returns a list of row vectors that form a basis of the vector space of solutions to the equation \texttt{vec * mat} = 0. The result is an immutable matrix. This basis is not guaranteed to be in any specific form.

The variant \texttt{TriangulizedNullspaceMat} returns a basis of the nullspace in triangulized form as is often needed for algorithms.

24.7.5 NullspaceMatDestructive

\> NullspaceMatDestructive(mat)

\> TriangulizedNullspaceMatDestructive(mat)

This function does the same as \texttt{NullspaceMat} (24.7.4). However, the latter function makes a copy of \texttt{mat} to avoid having to change it. This function does not do that; it returns the nullspace and may destroy \texttt{mat}; this saves a lot of memory in case \texttt{mat} is big. The matrix \texttt{mat} must be mutable.

The variant \texttt{TriangulizedNullspaceMatDestructive} returns a basis of the nullspace in triangulized form. It may destroy the matrix \texttt{mat}.

\begin{verbatim}
  gap> mat:=[[1,2,3],[4,5,6],[7,8,9]];
  gap> NullspaceMat(mat); [ [ 1, -2, 1 ] ]
  gap> mm:=[[1,2,3],[4,5,6],[7,8,9]];
  gap> NullspaceMatDestructive( mm ); [ [ 1, -2, 1 ] ]
  gap> mm;
  [ [ 1, 2, 3 ], [ 0, -3, -6 ], [ 0, 0, 0 ] ]
\end{verbatim}
24.7.6 SolutionMat

\[ \text{SolutionMat}(\text{mat}, \text{vec}) \]

returns a row vector \( x \) that is a solution of the equation \( x \cdot \text{mat} = \text{vec} \). It returns \text{fail} if no such vector exists.

24.7.7 SolutionMatDestructive

\[ \text{SolutionMatDestructive}(\text{mat}, \text{vec}) \]

Does the same as \text{SolutionMat}(\text{mat}, \text{vec}) except that it may destroy the matrix \text{mat} and the vector \text{vec}. The matrix \text{mat} must be mutable.

Example

```
gap> \text{mat}:=[[1,2,3],[4,5,6],[7,8,9]];;
gap> \text{SolutionMat}(\text{mat},[3,5,7]);
[ 5/3, 1/3, 0 ]
gap> \text{mm}:=[[1,2,3],[4,5,6],[7,8,9]];;
gap> v:=[3,5,7];;
gap> \text{SolutionMatDestructive}(\text{mm},v);
[ 5/3, 1/3, 0 ]
gap> \text{mm};
[ [ 1, 2, 3 ], [ 0, -3, -6 ], [ 0, 0, 0 ] ]
gap> v;
[ 0, 0, 0 ]
```

24.7.8 BaseFixedSpace

\[ \text{BaseFixedSpace}(\text{mats}) \]

\text{BaseFixedSpace} returns a list of row vectors that form a base of the vector space \( V \) such that \( vM = v \) for all \( v \) in \( V \) and all matrices \( M \) in the list \( \text{mats} \). (This is the common eigenspace of all matrices in \( \text{mats} \) for the eigenvalue 1.)

Example

```
gap> \text{BaseFixedSpace}([[1,2],[0,1]]);
[ [ 0, 1 ] ]
```

24.8 Eigenvectors and eigenvalues

24.8.1 GeneralisedEigenvalues

\[ \text{GeneralisedEigenvalues}(\text{F}, \text{A}) \]

\[ \text{GeneralizedEigenvalues}(\text{F}, \text{A}) \]

The generalised eigenvalues of the matrix \( A \) over the field \( F \).
24.8.2 GeneralisedEigenspaces

\( \text{GeneralisedEigenspaces}(F, A) \) (operation)
\( \text{GeneralizedEigenspaces}(F, A) \) (operation)

The generalised eigenspaces of the matrix \( A \) over the field \( F \).

24.8.3 Eigenvalues

\( \text{Eigenvalues}(F, A) \) (operation)

The eigenvalues of the matrix \( A \) over the field \( F \).

24.8.4 Eigenspaces

\( \text{Eigenspaces}(F, A) \) (operation)

The eigenspaces of the matrix \( A \) over the field \( F \).

24.8.5 Eigenvectors

\( \text{Eigenvectors}(F, A) \) (operation)

The eigenvectors of the matrix \( A \) over the field \( F \).

24.9 Elementary Divisors

See also chapter 25.

24.9.1 ElementaryDivisorsMat

\( \text{ElementaryDivisorsMat}(\text{mat}) \) (operation)
\( \text{ElementaryDivisorsMatDestructive}(\text{mat}) \) (function)

returns a list of the elementary divisors, i.e., the unique \( d \) with \( d[i] \) divides \( d[i+1] \) and \( \text{mat} \) is equivalent to a diagonal matrix with the elements \( d[i] \) on the diagonal. The operations are performed over the euclidean ring \( \text{ring} \), which must contain all matrix entries. For compatibility reasons it can be omitted and defaults to the DefaultRing (56.1.3) of the matrix entries.

The function ElementaryDivisorsMatDestructive produces the same result but in the process may destroy the contents of \( \text{mat} \).

Example

\begin{verbatim}
gap> mat:=[[1,2,3],[4,5,6],[7,8,9]];
gap> ElementaryDivisorsMat(mat); [ 1, 3, 0 ]
gap> x:=Indeterminate(Rationals,"x");
gap> mat:=mat*One(x)-x*mat^0;
[ [ -x+1, 2, 3 ], [ 4, -x+5, 6 ], [ 7, 8, -x+9 ] ]
gap> ElementaryDivisorsMat(PolynomialRing(Rationals,1),mat);
[ 1, 1, x^3-15*x^2-18*x ]
\end{verbatim}
gap> mat:=KroneckerProduct(CompanionMat((x-1)^2),
    CompanionMat((x^3-1)*(x-1)));;

gap> mat:=mat*One(x)-x*mat^0;
[ [ -x, 0, 0, 0, 0, 0, 0, 1 ], [ 0, -x, 0, 0, -1, 0, 0, -1 ],
  [ 0, 0, -x, 0, 0, -1, 0, 0 ], [ 0, 0, 0, -x, 0, 0, -1, -1 ],
  [ 0, 0, 0, -1, -x, 0, 0, -2 ], [ 1, 0, 0, 1, 2, -x, 0, 2 ],
  [ 0, 1, 0, 0, 2, -x, 0, 0 ], [ 0, 0, 1, 1, 0, 0, 2, -x+2 ] ]

gap> ElementaryDivisorsMat(PolynomialRing(Rationals,1),mat);
[ 1, 1, 1, 1, 1, 1, x-1, x^7-x^6-2*x^4+2*x^3+x-1 ]

24.9.2 ElementaryDivisorsTransformationsMat

Example

gap> mat:=KroneckerProduct(CompanionMat((x-1)^2),CompanionMat((x^3-1)*(x-1)));;

gap> mat:=mat*One(x)-x*mat^0;
[ [ -x, 0, 0, 0, 0, 0, 0, 1 ], [ 0, -x, 0, 0, -1, 0, 0, -1 ],
  [ 0, 0, -x, 0, 0, -1, 0, 0 ], [ 0, 0, 0, -x, 0, 0, -1, -1 ],
  [ 0, 0, 0, -1, -x, 0, 0, -2 ], [ 1, 0, 0, 1, 2, -x, 0, 2 ],
  [ 0, 1, 0, 0, 2, -x, 0, 0 ], [ 0, 0, 1, 1, 0, 0, 2, -x+2 ] ]

gap> t:=ElementaryDivisorsTransformationsMat(PolynomialRing(Rationals,1),mat);
rec( coltrans := [ [ 0, 0, 0, 0, 0, 0, 0, 1/6*x^2-7/9*x-1/18, -3*x^3-x^2-x-1 ],
  [ 0, 0, 0, 0, 0, 0, 0, -1/6*x^2+x-1, 3*x^3-3*x^2-2*x ],
  [ 0, 0, 0, 0, 0, 0, 1, -1/9*x^3+1/2*x^2+1/9*x, 2*x^4+x^3+x^2+2*x ],
  [ 0, -1, 0, 0, 0, 0, -2/9*x^2+19/18*x, 4*x^3-3*x^2-3*x ],
  [ 0, 0, -1, 0, 0, 0, 1/18*x^5-1/3*x^4+1/3*x^3+1/9*x^2,
    -x^6+5*x^5-x^4+2*x^3+2*x^2 ],
  [ 0, 0, 0, 0, 0, 0, 0, -1/6*x^2+7/9*x+1/18, -3*x^3+x^2-x+1 ],
  [ 1, 0, 0, 0, 0, 0, 0, x-1, x^7-x^6-2*x^4+2*x^3+x-1 ] ],
  normal := [ [ 1, 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 1, 0, 0, 0, 0, 0, 0, 0 ],
  [ 0, 0, 1, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 1, 0, 0, 0, 0 ],
  [ 0, 0, 0, 0, 0, 0, 1, 0, 0 ], [ 0, 0, 0, 0, 0, 0, x-1, 0 ],
  [ 0, 0, 0, 0, 0, 0, 0, x^7-x^6-2*x^4+2*x^3+x-1 ] ],
  rowtrans := [ [ 1, 0, 0, 0, 0, 0, 0, 0, 0 ], [ 1, 0, 0, 0, 0, 0, 0, 0, 0 ],
  [ 0, 0, 1, 0, 0, 0, 0, 0, 0 ], [ 1, 0, 0, 1, 0, 0, 0, 0, 0 ],
  [ -x^2, -x, 0, 0, 1, 0, 0, 0, 0 ], [ 2*x^2-2*x+2, 2*x^2-x, 0, 2, -2*x+1, 0, 0, 1 ],
  [ 3*x^3-6*x^2+3*x, 3*x^3-2*x^2-2*x, 0, 1, 2*x ] ] )
\[
\begin{align*}
\frac{1}{6}x^8-\frac{7}{6}x^7+2x^6-\frac{4}{3}x^5+\frac{7}{3}x^4-4x^3+\frac{13}{6}x^2-\frac{7}{6}x+2, \\
\frac{1}{6}x^8-\frac{7}{18}x^7+\frac{13}{18}x^6-\frac{5}{18}x^5+\frac{35}{18}x^4-\frac{31}{18}x^3+\frac{1}{9}x^2-\frac{2}{9}x+1, \\
\frac{1}{6}x^6-\frac{5}{6}x^5+\frac{1}{6}x^4-\frac{1}{6}x^3+\frac{11}{6}x^2-\frac{1}{6}x, \\
-\frac{1}{6}x^7+\frac{17}{18}x^6-\frac{13}{18}x^5+\frac{5}{18}x^4-\frac{35}{18}x^3+\frac{31}{18}x^2-\frac{2}{9}x+1, \\
\frac{1}{18}x^5-\frac{5}{18}x^4+\frac{1}{18}x^3-\frac{1}{18}x^2+\frac{23}{18}x-\frac{1}{18}, \\
\frac{1}{9}x^6-\frac{5}{9}x^5+\frac{1}{9}x^4-\frac{1}{9}x^3+\frac{14}{9}x^2-\frac{1}{9}x \\
\end{align*}
\]

\[
\text{gap> t.rowtrans*mat*t.coltrans;}
\begin{bmatrix}
1, 0, 0, 0, 0, 0, 0, 0 \\
0, 1, 0, 0, 0, 0, 0, 0 \\
0, 0, 1, 0, 0, 0, 0, 0 \\
0, 0, 0, 1, 0, 0, 0, 0 \\
0, 0, 0, 0, 0, 0, x-1, 0 \\
0, 0, 0, 0, 0, 0, 0, x^7-x^6-2x^4+2x^3+x-1 
\end{bmatrix}
\]

### 24.9.3 DiagonalizeMat

\[\text{DiagonalizeMat}(\text{ring, mat})\] (operation)

brings the mutable matrix \(\text{mat}\), considered as a matrix over \(\text{ring}\), into diagonal form by elementary row and column operations.

**Example**

\[
\text{gap> m:=[[1,2],[2,1]];;}
\text{gap> DiagonalizeMat(Integers,m);m;}
\begin{bmatrix}
1, 0 \\
0, 3 
\end{bmatrix}
\]

### 24.10 Echelonized Matrices

#### 24.10.1 SemiEchelonMat

\[\text{SemiEchelonMat}(\text{mat})\] (attribute)

A matrix over a field \(F\) is in semi-echelon form if the first nonzero element in each row is the identity of \(F\), and all values exactly below these pivots are the zero of \(F\).

SemiEchelonMat returns a record that contains information about a semi-echelonized form of the matrix \(\text{mat}\).

The components of this record are

- **vectors**
  - list of row vectors, each with pivot element the identity of \(F\),

- **heads**
  - list that contains at position \(i\), if nonzero, the number of the row for that the pivot element is in column \(i\).

#### 24.10.2 SemiEchelonMatDestructive

\[\text{SemiEchelonMatDestructive}(\text{mat})\] (operation)
This does the same as \texttt{SemiEchelonMat( mat )}, except that it may (and probably will) destroy the matrix \texttt{mat}.

Example

\begin{verbatim}
gap> mm:=[[1,2,3],[4,5,6],[7,8,9]];;
gap> SemiEchelonMatDestructive( mm );
rec( heads := [ 1, 2, 0 ], vectors := [ [ 1, 2, 3 ], [ 0, 1, 2 ] ] )
gap> mm;
[ [ 1, 2, 3 ], [ 0, 1, 2 ], [ 0, 0, 0 ] ]
\end{verbatim}

\subsection{SemiEchelonMatTransformation}

\texttt{SemiEchelonMatTransformation( mat )}

(\texttt{attribute})

does the same as \texttt{SemiEchelonMat (24.10.1)} but additionally stores the linear transformation \( T \) performed on the matrix. The additional components of the result are

\begin{itemize}
\item \texttt{coeffs} a list of coefficients vectors of the \texttt{vectors} component, with respect to the rows of \texttt{mat}, that is, \texttt{coeffs * mat} is the \texttt{vectors} component.
\item \texttt{relations} a list of basis vectors for the (left) null space of \texttt{mat}.
\end{itemize}

Example

\begin{verbatim}
gap> SemiEchelonMatTransformation( [[1,2,3],[0,0,1]] );
rec( coeffs := [ [ 1, 0 ], [ 0, 1 ] ], heads := [ 1, 0, 2 ],
relations := [ ], vectors := [ [ 1, 2, 3 ], [ 0, 0, 1 ] ] )
\end{verbatim}

\subsection{SemiEchelonMats}

\texttt{SemiEchelonMats(mats)}

(\texttt{operation})

A list of matrices over a field \( F \) is in semi-echelon form if the list of row vectors obtained on concatenating the rows of each matrix is a semi-echelonized matrix (see \texttt{SemiEchelonMat (24.10.1)}). \texttt{SemiEchelonMats} returns a record that contains information about a semi-echelonized form of the list \texttt{mats} of matrices.

The components of this record are

\begin{itemize}
\item \texttt{vectors} list of matrices, each with pivot element the identity of \( F \),
\item \texttt{heads} matrix that contains at position \([i,j]\), if nonzero, the number of the matrix that has the pivot element in this position
\end{itemize}

\subsection{SemiEchelonMatsDestructive}

\texttt{SemiEchelonMatsDestructive(mats)}

(\texttt{operation})

Does the same as \texttt{SemiEchelonMats}, except that it may destroy its argument. Therefore the argument must be a list of matrices that re mutable.
24.11 Matrices as Basis of a Row Space

See also chapter 25

24.11.1 BaseMat

d BaseMat(mat)

(attribut)

returns a basis for the row space generated by the rows of mat in the form of an immutable matrix.

24.11.2 BaseMatDestructive

d BaseMatDestructive(mat)

(operation)

Does the same as BaseMat (24.11.1), with the difference that it may destroy the matrix mat. The matrix mat must be mutable.

Example

\begin{verbatim}
gap> mat:=[[1,2,3],[4,5,6],[7,8,9]];;
gap> BaseMat(mat);
[ [ 1, 2, 3 ], [ 0, 1, 2 ] ]
gap> mm:= [[1,2,3],[4,5,6],[5,7,9]];;
gap> BaseMatDestructive( mm );
[ [ 1, 2, 3 ], [ 0, 1, 2 ] ]
gap> mm;
[ [ 1, 2, 3 ], [ 0, 1, 2 ], [ 0, 0, 0 ] ]
\end{verbatim}

24.11.3 BaseOrthogonalSpaceMat

d BaseOrthogonalSpaceMat(mat)

(attribut)

Let V be the row space generated by the rows of mat (over any field that contains all entries of mat). BaseOrthogonalSpaceMat(mat) computes a base of the orthogonal space of V.

The rows of mat need not be linearly independent.

24.11.4 SumIntersectionMat

d SumIntersectionMat(M1, M2)

(operation)

performs Zassenhaus’ algorithm to compute bases for the sum and the intersection of spaces generated by the rows of the matrices M1, M2.

returns a list of length 2, at first position a base of the sum, at second position a base of the intersection. Both bases are in semi-echelon form (see 24.10).

Example

\begin{verbatim}
gap> SumIntersectionMat(mat,[[2,7,6],[5,9,4]]);
[ [ [ 1, 2, 3 ], [ 0, 1, 2 ], [ 0, 0, 1 ] ], [ [ 1, -3/4, -5/2 ] ] ]
\end{verbatim}
24.11.5 BaseSteinitzVectors

\[ \text{BaseSteinitzVectors}(\text{bas}, \text{mat}) \]

find vectors extending \text{mat} to a basis spanning the span of \text{bas}. Both \text{bas} and \text{mat} must be matrices of full (row) rank. It returns a record with the following components:

- \text{subspace}
  - a basis of the space spanned by \text{mat} in upper triangular form with leading ones at all echelon steps and zeroes above these ones.
- \text{factorspace}
  - a list of extending vectors in upper triangular form.
- \text{factorzero}
  - is a zero vector.
- \text{heads}
  - is a list of integers which can be used to decompose vectors in the basis vectors. The \(i\)th entry indicating the vector that gives an echelon step at position \(i\). A negative number indicates an echelon step in the subspace, a positive number an echelon step in the complement, the absolute value gives the position of the vector in the lists \text{subspace} and \text{factorspace}.

Example

\[
\text{gap> BaseSteinitzVectors(IdentityMat(3,1),[[11,13,15]]);}
\]

\[ \text{rec( factorspace := [ [ 0, 1, 15/13 ], [ 0, 0, 1 ] ],}
\]

\[ \text{factorzero := [ 0, 0, 0 ], heads := [ -1, 1, 2 ],}
\]

\[ \text{subspace := [ [ 1, 13/11, 15/11 ] ] )} \]

24.12 Triangular Matrices

24.12.1 DiagonalOfMatrix

\[ \text{DiagonalOfMatrix}(\text{mat}) \]

\[ \text{DiagonalOfMat}(\text{mat}) \]

return the diagonal of the matrix \text{mat}. If \text{mat} is not a square matrix, then the result has the same length as the rows of \text{mat}, and is padded with zeros if \text{mat} has fewer rows than columns.

Example

\[
\text{gap> DiagonalOfMatrix( [ [ 1, 2, 3 ], [ 4, 5, 6 ] ] );}
\]

\[ [ 1, 5, 0 ] \]

24.12.2 UpperSubdiagonal

\[ \text{UpperSubdiagonal}(\text{mat}, \text{pos}) \]

returns a mutable list containing the entries of the \text{pos}th upper subdiagonal of the matrix \text{mat}.

Example

```gap
gap> UpperSubdiagonal( [ [ 1, 2, 3 ], [ 4, 5, 6 ], [ 7, 8, 9 ] ], 1 );
[ 2, 6 ]
gap> UpperSubdiagonal( [ [ 1, 2 ], [ 3, 4 ], [ 5, 6 ] ], 1 );
[ 2 ]
gap> UpperSubdiagonal( [ [ 1, 2, 3, 4 ], [ 5, 6, 7, 8 ] ], 1 );
[ 2, 7 ]
```

24.12.3 DepthOfUpperTriangularMatrix

▷ DepthOfUpperTriangularMatrix(mat) (attribute)

If `mat` is an upper triangular matrix this attribute returns the index of the first nonzero diagonal.

Example

```gap
gap> DepthOfUpperTriangularMatrix([[0,1,2],[0,0,1],[0,0,0]]);
1
gap> DepthOfUpperTriangularMatrix([[0,0,2],[0,0,0],[0,0,0]]);
2
```

24.13 Matrices as Linear Mappings

24.13.1 CharacteristicPolynomial

▷ CharacteristicPolynomial([F, E, ]mat [, ind]) (attribute)

For a square matrix `mat`, `CharacteristicPolynomial` returns the characteristic polynomial of `mat`, that is, the StandardAssociate (56.5.5) of the determinant of the matrix `mat - X \cdot I`, where `X` is an indeterminate and `I` is the appropriate identity matrix.

If fields `F` and `E` are given, then `F` must be a subfield of `E`, and `mat` must have entries in `E`. Then `CharacteristicPolynomial` returns the characteristic polynomial of the `F`-linear mapping induced by `mat` on the underlying `E`-vector space of `mat`. In this case, the characteristic polynomial is computed using `BlownUpMat` (24.13.4) for the field extension of `E/F` generated by the default field. Thus, if `F = E`, the result is the same as for the one argument version.

The returned polynomials are expressed in the indeterminate number `ind`. If `ind` is not given, it defaults to 1.

`CharacteristicPolynomial(F, E, mat)` is a multiple of the minimal polynomial `MinimalPolynomial(F, mat)` (see `MinimalPolynomial` (66.8.1)).

Note that, up to GAP version 4.4.6, `CharacteristicPolynomial` only allowed to specify one field (corresponding to `F`) as an argument. That usage has been disabled because its definition turned out to be ambiguous and may have lead to unexpected results. (To ensure backward compatibility, it is still possible to use the old form if `F` contains the default field of the matrix, see `DefaultFieldOfMatrix` (24.4.2), but this feature will disappear in future versions of GAP.)

Example

```gap
gap> CharacteristicPolynomial( [ [ 1, 1 ], [ 0, 1 ] ] );
x^2-2*x+1
gap> mat := [[0,1],[E(4)-1,E(4)]];;
gap> CharacteristicPolynomial( mat );
x^2+(-E(4))*x+(1-E(4))
```
gap> CharacteristicPolynomial( Rationals, CF(4), mat );
\texttt{x}^4+3x^2+2x+2

\texttt{gap> mat:= [ [ E(4), 1 ], [ 0, -E(4) ] ];}
\texttt{x}^2+1

\texttt{gap> CharacteristicPolynomial( mat );}
\texttt{x}^4+2x^2+1

\subsection*{24.13.2 RationalCanonicalFormTransform}
\texttt{RationalCanonicalFormTransform(mat)} (function)

For a matrix \( A \), return a matrix \( P \) such that \( AP \) is in rational canonical form (also called Frobenius normal form). The algorithm used is the basic textbook version and thus not of optimal complexity.

\texttt{gap> aa:=[[0,-8,12,40,-36,4,0,59,15,-9],[-2,-2,-2,6,-11,1,-1,10,1,0],}
\texttt{[0,2,-3,-7,8,-1,0,-7,-3,2],[-5,-4,-6,18,-30,2,-2,35,5,-1],}
\texttt{[-1,-6,6,20,-28,3,0,24,10,-6],[0,0,0,-1,0,0,0,-3,0,0],}
\texttt{[0,0,-1,-2,2,0,-1,-7,0,0],[0,-8,9,21,-36,4,-2,12,12,-8]];;}
\texttt{gap> t:=RationalCanonicalFormTransform(aa);;}
\texttt{gap> aa^t;}
\[
\begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\
\end{bmatrix}
\]

\subsection*{24.13.3 JordanDecomposition}
\texttt{JordanDecomposition(mat)} (attribute)

\texttt{JordanDecomposition(mat)} returns a list \([S,N]\) such that \(S\) is a semisimple matrix and \(N\) is nilpotent. Furthermore, \(S\) and \(N\) commute and \(mat=S+N\).

\texttt{gap> mat:=[[1,2,3],[4,5,6],[7,8,9]];;}
\texttt{gap> JordanDecomposition(mat);}
\[
\begin{bmatrix}
1 & 2 & 3 \\
4 & 5 & 6 \\
7 & 8 & 9 \\
\end{bmatrix},
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\]

\subsection*{24.13.4 BlownUpMat}
\texttt{BlownUpMat(B, mat)} (function)

Let \(B\) be a basis of a field extension \(F/K\), and \(mat\) a matrix whose entries are all in \(F\). (This is not checked.) \texttt{BlownUpMat} returns a matrix over \(K\) that is obtained by replacing each entry of \(mat\) by its regular representation w.r.t. \(B\).
More precisely, regard mat as the matrix of a linear transformation on the row space $F^n$ w.r.t. the $F$-basis with vectors $(v_1, \ldots, v_n)$, say, and suppose that the basis $B$ consists of the vectors $(b_1, \ldots, b_m)$; then the returned matrix is the matrix of the linear transformation on the row space $K^{mn}$ w.r.t. the $K$-basis whose vectors are $(b_1 v_1, \ldots, b_m v_1, \ldots, b_m v_n)$.

Note that the linear transformations act on row vectors, i.e., each row of the matrix is a concatenation of vectors of $B$-coefficients.

### 24.13.5 BlownUpVector

\[ \text{BlownUpVector}(B, \text{vector}) \]  

Let $B$ be a basis of a field extension $F/K$, and vector a row vector whose entries are all in $F$. BlownUpVector returns a row vector over $K$ that is obtained by replacing each entry of vector by its coefficients w.r.t. $B$.

So BlownUpVector and BlownUpMat (24.13.4) are compatible in the sense that for a matrix mat over $F$, BlownUpVector($B$, mat * vector) is equal to BlownUpMat($B$, mat) * BlownUpVector($B$, vector).

**Example**

\[\begin{align*}
gap> & B:= \text{Basis}(\text{CF}(4), [1, \text{E}(4)]);; \\
gap> & \text{mat}:= \begin{bmatrix} 1, \text{E}(4) \end{bmatrix};; \text{vec}:= \begin{bmatrix} 1, \text{E}(4) \end{bmatrix};; \\
gap> & \text{bmat}:= \text{BlownUpMat}(B, \text{mat} );; \text{bvec}:= \text{BlownUpVector}(B, \text{vec} );; \\
gap> & \text{Display}(\text{bmat}); \quad \text{bvec}; \\
& \begin{bmatrix} 1, 0, 0, 1 \end{bmatrix}, \\
& \begin{bmatrix} 0, 1, -1, 0 \end{bmatrix}, \\
& \begin{bmatrix} 0, 0, 1, 0 \end{bmatrix}, \\
& \begin{bmatrix} 0, 0, 0, 1 \end{bmatrix} \\
gap> & \text{bvec} * \text{bmat} = \text{BlownUpVector}(B, \text{vec} * \text{mat} );; \\
true
\end{align*}\]

### 24.13.6 CompanionMat

\[ \text{CompanionMat}(\text{poly}) \]  

computes a companion matrix of the polynomial poly. This matrix has poly as its minimal polynomial.

### 24.14 Matrices over Finite Fields

Just as for row vectors, (see section 23.3), GAP has a special representation for matrices over small finite fields.

To be eligible to be represented in this way, each row of a matrix must be able to be represented as a compact row vector of the same length over the same finite field.

**Example**

\[\begin{align*}
gap> & v := \text{Z}(2)[1,0,0,1,1]; \\
& [Z(2)^0, 0*Z(2), 0*Z(2), Z(2)^0, Z(2)^0 ] \\
gap> & \text{ConvertToVectorRep}(v,2); \quad \text{Example} \\
2
\end{align*}\]
All compressed matrices over GF(2) are viewed as `<a nxm matrix over GF2>`, while over fields GF(q) for q between 3 and 256, matrices with 25 or more entries are viewed in this way, and smaller ones as lists of lists.

Matrices can be converted to this special representation via the following functions.

Note that the main advantage of this special representation of matrices is in low dimensions, where various overheads can be reduced. In higher dimensions, a list of compressed vectors will be almost as fast. Note also that list access and assignment will be somewhat slower for compressed matrices than for plain lists.

In order to form a row of a compressed matrix a vector must accept certain restrictions. Specifically, it cannot change its length or change the field over which it is compressed. The main consequences of this are: that only elements of the appropriate field can be assigned to entries of the vector, and only to positions between 1 and the original length; that the vector cannot be shared between two matrices compressed over different fields.

This is enforced by the filter `IsLockedRepresentationVector`. When a vector becomes part of a compressed matrix, this filter is set for it. Assignment, `Unbind` (21.5.3), `ConvertToVectorRep` (23.3.1) and `ConvertToMatrixRep` (24.14.2) are all prevented from altering a vector with this filter.

```
gap> v := [Z(2),Z(2)];; ConvertToVectorRep(v,GF(2));; v;
<a GF2 vector of length 2>
gap> m := [v,v];
[ <a GF2 vector of length 2>, <a GF2 vector of length 2> ]
gap> ConvertToMatrixRep(m,GF(2));
2
gap> m2 := [m[1], [Z(4),Z(4)]]; # now try and mix in some GF(4)
[ <a GF2 vector of length 2>, [ Z(2^2), Z(2^2) ] ]
gap> ConvertToMatrixRep(m2); # but m2[1] is locked
#I ConvertToVectorRep: locked vector not converted to different field
fail
gap> m2 := [ShallowCopy(m[1]), [Z(4),Z(4)]]; # a fresh copy of row 1
[ <a GF2 vector of length 2>, [ Z(2^2), Z(2^2) ] ]
gap> ConvertToMatrixRep(m2); # now it works
```
gap> m2;  
[ [ Z(2)^0, Z(2)^0 ], [ Z(2^2), Z(2^2) ] ]

gap> RepresentationsOfObject(m2);  
[ "IsPositionalObjectRep", "Is8BitMatrixRep" ]

Arithmetic operations (see 21.11 and the following sections) preserve the compression status of matrices in the sense that if all arguments are compressed matrices written over the same field and the result is a matrix then also the result is a compressed matrix written over this field.

There are also two operations that are only available for matrices written over finite fields.

### 24.14.1 ImmutableMatrix

\[\text{ImmutableMatrix}(\text{field}, \text{matrix}[, \text{change}])\]

returns an immutable matrix equal to \text{matrix} which is in the optimal (concerning space and runtime) representation for matrices defined over \text{field}. This means that matrices obtained by several calls of \text{ImmutableMatrix} for the same \text{field} are compatible for fast arithmetic without need for field conversion.

The input matrix \text{matrix} or its rows might change their representation as a side effect of this function, however the result of \text{ImmutableMatrix} is not necessarily identical to \text{matrix} if a conversion is not possible.

If \text{change} is true, the rows of \text{matrix} (or \text{matrix} itself) may be changed to become immutable; otherwise they are copied first.

### 24.14.2 ConvertToMatrixRep (for a list (and a field))

\[\text{ConvertToMatrixRep}(\text{list}[, \text{field}])\]

\[\text{ConvertToMatrixRep}(\text{list}[, \text{fieldsize}])\]

\[\text{ConvertToMatrixRepNC}(\text{list}[, \text{field}])\]

\[\text{ConvertToMatrixRepNC}(\text{list}[, \text{fieldsize}])\]

This function is more technical version of \text{ImmutableMatrix} (24.14.1), which will never copy a matrix (or any rows of it) but may fail if it encounters rows locked in the wrong representation, or various other more technical problems. Most users should use \text{ImmutableMatrix} (24.14.1) instead. The NC versions of the function do less checking of the argument and may cause unpredictable results or crashes if given unsuitable arguments. Called with one argument \text{list}, \text{ConvertToMatrixRep} converts \text{list} to an internal matrix representation if possible.

Called with a list \text{list} and a finite field \text{field}, \text{ConvertToMatrixRep} converts \text{list} to an internal matrix representation appropriate for a matrix over \text{field}.

Instead of a \text{field} also its size \text{fieldsize} may be given.

It is forbidden to call this function unless all elements of \text{list} are row vectors with entries in the field \text{field}. Violation of this condition can lead to unpredictable behaviour or a system crash. (Setting the assertion level to at least 2 might catch some violations before a crash, see \text{SetAssertionLevel} (7.5.1).)

\text{list} may already be a compressed matrix. In this case, if no \text{field} or \text{fieldsize} is given, then nothing happens.
The return value is the size of the field over which the matrix ends up written, if it is written in a compressed representation.

### 24.14.3 ProjectiveOrder

\[
\text{ProjectiveOrder}(\text{mat})
\]

Returns an integer \( n \) and a finite field element \( e \) such that \( A^n = eI \). \text{mat} must be a matrix defined over a finite field.

**Example**

\[
\text{gap> ProjectiveOrder([[1,4],[5,2]]*Z(11)^0);}
\]

\[
\begin{bmatrix}
5, Z(11)^5
\end{bmatrix}
\]

### 24.14.4 SimultaneousEigenvalues

\[
\text{SimultaneousEigenvalues}(\text{matlist}, \text{expo})
\]

The matrices in \text{matlist} must be matrices over \( \text{GF}(q) \) for some prime \( q \). Together, they must generate an abelian p-group of exponent \( \text{expo} \). Then the eigenvalues of \text{mat} in the splitting field \( \text{GF}(q^r) \) for some \( r \) are powers of an element \( \xi \) in the splitting field, which is of order \( \text{expo} \). SimultaneousEigenvalues returns a matrix of integers mod \( \text{expo} \), say \((a_{i,j})\), such that the power \( \xi^{a_{i,j}} \) is an eigenvalue of the \( i \)-th matrix in \text{matlist} and the eigenspaces of the different matrices to the eigenvalues \( \xi^{a_{i,j}} \) for fixed \( j \) are equal.

### 24.15 Inverse and Nullspace of an Integer Matrix Modulo an Ideal

The following operations deal with matrices over a ring, but only care about the residues of their entries modulo some ring element. In the case of the integers and a prime number \( p \), say, this is effectively computation in a matrix over the prime field in characteristic \( p \).

#### 24.15.1 InverseMatMod

\[
\text{InverseMatMod}(\text{mat}, \text{obj})
\]

For a square matrix \text{mat}, \text{InverseMatMod} returns a matrix \text{inv} such that \( \text{inv} \star \text{mat} \) is congruent to the identity matrix modulo \text{obj}, if such a matrix exists, and \text{fail} otherwise.

**Example**

\[
\text{gap> mat:= [ [ 1, 2 ], [ 3, 4 ] ]; inv:= InverseMatMod( mat, 5 );}
\]

\[
\begin{bmatrix}
11, 5 \\
25, 11
\end{bmatrix}
\]

#### 24.15.2 BasisNullspaceModN

\[
\text{BasisNullspaceModN}(M, n)
\]

(function)
$M$ must be a matrix of integers and $n$ a positive integer. Then $\text{BasisNullspaceModN}$ returns a set $B$ of vectors such that every vector $v$ of integer modulo $n$ satisfying $v \cdot M \equiv 0 \pmod{n}$ can be expressed by a $\mathbb{Z}$-linear combination of elements of $B$.

### 24.15.3 NullspaceModQ

- $\text{NullspaceModQ}(M, q)$
- $\text{NullspaceModN}(M, n)$

$M$ must be a matrix of integers and $n$ a positive integer. Then $\text{NullspaceModN}$ returns the set of all vectors of integers modulo $n$, which solve the homogeneous equation system $v \cdot M \equiv 0 \pmod{n}$. $\text{NullspaceModQ}$ is a synonym for $\text{NullspaceModN}$.

**Example**

```gap
gap> NullspaceModN([ [ 2 ] ], 8);
[ [ 0 ], [ 4 ] ]
gap> NullspaceModN([ [ 2, 1 ], [ 0, 2 ] ], 6);
[ [ 0, 0 ], [ 0, 3 ] ]
gap> mat:= [ [ 1, 3 ], [ 1, 2 ], [ 1, 1 ] ];;
gap> NullspaceModN(mat, 5);
[ [ 0, 0, 0 ], [ 1, 3, 1 ], [ 2, 1, 2 ], [ 3, 4, 3 ], [ 4, 2, 4 ] ]
```

### 24.16 Special Multiplication Algorithms for Matrices over GF(2)

When multiplying two compressed matrices $M$ and $N$ over GF(2) of dimensions $a \times b$ and $b \times c$, say, where $a$, $b$ and $c$ are all greater than or equal to 128, GAP by default uses a more sophisticated matrix multiplication algorithm, in which linear combinations of groups of 8 rows of $M$ are remembered and re-used in constructing various rows of the product. This is called level 8 grease. To optimise memory access patterns, these combinations are stored for $(b + 255)/256$ sets of 8 rows at once. This number is called the blocking level.

These levels of grease and blocking are found experimentally to give good performance across a range of processors and matrix sizes, but other levels may do even better in some cases. You can control the levels exactly using the functions below.

We plan to include greased blocked matrix multiplication for other finite fields, and greased blocked algorithms for inversion and other matrix operations in a future release.

#### 24.16.1 PROD_GF2MAT_GF2MAT_SIMPLE

- $\text{PROD_GF2MAT_GF2MAT_SIMPLE}(m1, m2)$

This function performs the standard unblocked and ungreased matrix multiplication for matrices of any size.

#### 24.16.2 PROD_GF2MAT_GF2MAT_ADVANCED

- $\text{PROD_GF2MAT_GF2MAT_ADVANCED}(m1, m2, g, b)$

This function computes the product of $m1$ and $m2$, which must be compressed matrices over GF(2) of compatible dimensions, using level $g$ grease and level $b$ blocking.
24.17 Block Matrices

Block matrices are a special representation of matrices which can save a lot of memory if large matrices have a block structure with lots of zero blocks. GAP uses the representation `IsBlockMatrixRep` to store block matrices.

24.17.1 AsBlockMatrix

\[ \text{AsBlockMatrix}(m, nrb, ncb) \]

returns a block matrix with \( nrb \) row blocks and \( ncb \) column blocks which is equal to the ordinary matrix \( m \).

24.17.2 BlockMatrix

\[ \text{BlockMatrix}(\text{blocks, nrb, ncb[, rpb, cpb, zero]}) \]

BlockMatrix returns an immutable matrix in the sparse representation `IsBlockMatrixRep`. The nonzero blocks are described by the list `blocks` of triples \([i, j, M(i, j)]\) each consisting of a matrix \( M(i, j) \) and its block coordinates in the block matrix to be constructed. All matrices \( M(i, j) \) must have the same dimensions. As usual the first coordinate specifies the row and the second one the column. The resulting matrix has \( nrb \) row blocks and \( ncb \) column blocks.

If `blocks` is empty (i.e., if the matrix is a zero matrix) then the dimensions of the blocks must be entered as \( rpb \) and \( cpb \), and the zero element as \( \text{zero} \).

Note that all blocks must be ordinary matrices (see `IsOrdinaryMatrix (24.2.2)`), and also the block matrix is an ordinary matrix.

**Example**

\[
\text{gap> M := BlockMatrix([[1,1,[[1, 2],[3, 4]]], [1,2,[[9,10],[11,12]]], [2,2,[[5, 6],[7, 8]]]],2,2);}
\]

\[
\text{<block matrix of dimensions (2*2)x(2*2)>}
\]

\[
\text{Display(M);}
\]

\[
\begin{array}{cccc}
1 & 2 & 9 & 10 \\
3 & 4 & 11 & 12 \\
0 & 0 & 5 & 6 \\
0 & 0 & 7 & 8 \\
\end{array}
\]

24.17.3 MatrixByBlockMatrix

\[ \text{MatrixByBlockMatrix}(\text{blockmat}) \]

returns a plain ordinary matrix that is equal to the block matrix `blockmat`.

24.18 Linear Programming

24.18.1 SimplexMethod

\[ \text{SimplexMethod}(A, b, c) \]

\( A \), \( b \), and \( c \) are matrices and vectors.
Find a rational vector $x$ that maximizes $\mathbf{x} \cdot \mathbf{c}$, subject to the constraint $\mathbf{A} \cdot \mathbf{x} \leq \mathbf{b}$.

Example

```gap
gap> A:=[[3,1,1,4],[1,-3,2,3],[2,1,3,-1]];;
gap> b:=[12,7,10];;c:=[2,4,3,1];;
gap> SimplexMethod(A,b,c);
[ [ 0, 52/5, 0, 2/5 ], 42 ]
```
Chapter 25

Integral matrices and lattices

25.1 Linear equations over the integers and Integral Matrices

25.1.1 NullspaceIntMat

\[
\text{NullspaceIntMat(mat)}
\]

If \( \text{mat} \) is a matrix with integral entries, this function returns a list of vectors that forms a basis of the integral nullspace of \( \text{mat} \), i.e., of those vectors in the nullspace of \( \text{mat} \) that have integral entries.

Example

\[ \text{gap> mat := \begin{bmatrix} 1,2,7,4,5,6,7,8,9,10,11,19,5,7,12 \end{bmatrix};} \]
\[ \text{gap> NullspaceMat(mat); } \begin{bmatrix} -7/4, 9/2, -15/4, 1, 0 \end{bmatrix}, \begin{bmatrix} -3/4, -3/2, 1/4, 0, 1 \end{bmatrix} \]
\[ \text{gap> NullspaceIntMat(mat); } \begin{bmatrix} 1, 18, -9, 2, -6 \end{bmatrix}, \begin{bmatrix} 0, 24, -13, 3, -7 \end{bmatrix} \]

25.1.2 SolutionIntMat

\[
\text{SolutionIntMat(mat, vec)}
\]

If \( \text{mat} \) is a matrix with integral entries and \( \text{vec} \) a vector with integral entries, this function returns a vector \( x \) with integer entries that is a solution of the equation \( x \times \text{mat} = \text{vec} \). It returns \text{fail} if no such vector exists.

Example

\[ \text{gap> mat := \begin{bmatrix} 1,2,7,4,5,6,7,8,9,10,11,19,5,7,12 \end{bmatrix};} \]
\[ \text{gap> SolutionMat(mat, \begin{bmatrix} 95,115,182 \end{bmatrix}); } \begin{bmatrix} 47/4, -17/2, 67/4, 0, 0 \end{bmatrix} \]
\[ \text{gap> SolutionIntMat(mat, \begin{bmatrix} 95,115,182 \end{bmatrix}); } \begin{bmatrix} 2285, -5864, 4888, -1299, 0 \end{bmatrix} \]

25.1.3 SolutionNullspaceIntMat

\[
\text{SolutionNullspaceIntMat(mat, vec)}
\]

This function returns a list of length two, its first entry being the result of a call to \text{SolutionIntMat (25.1.2)} with same arguments, the second the result of \text{NullspaceIntMat (25.1.1)}
applied to the matrix `mat`. The calculation is performed faster than if two separate calls would be used.

```
Example

gap> mat:=[[1,2,7],[4,5,6],[7,8,9],[10,11,19],[5,7,12]];;
gap> SolutionNullspaceIntMat(mat,[95,115,182]);
[ [ 1, 18, -9, 2, -6 ], [ 0, 24, -13, 3, -7 ] ]
```

### 25.1.4 BaseIntMat

▷ `BaseIntMat(mat)`  

If `mat` is a matrix with integral entries, this function returns a list of vectors that forms a basis of the integral row space of `mat`, i.e. of the set of integral linear combinations of the rows of `mat`.

```
Example

gap> mat:=[[1,2,7],[4,5,6],[10,11,19]];;
gap> BaseIntMat(mat);
[ [ 1, 2, 7 ], [ 0, 3, 7 ], [ 0, 0, 15 ] ]
```

### 25.1.5 BaseIntersectionIntMats

▷ `BaseIntersectionIntMats(m, n)`  

If `m` and `n` are matrices with integral entries, this function returns a list of vectors that forms a basis of the intersection of the integral row spaces of `m` and `n`.

```
Example

gap> nat:=[[5,7,2],[4,2,5],[7,1,4]];;
gap> BaseIntMat(nat);
[ [ 1, 2, 7 ], [ 0, 3, 7 ], [ 0, 0, 15 ] ]
gap> BaseIntersectionIntMats(mat,nat);
[ [ 1, 5, 509 ], [ 0, 6, 869 ], [ 0, 0, 960 ] ]
```

### 25.1.6 ComplementIntMat

▷ `ComplementIntMat(full, sub)`  

Let `full` be a list of integer vectors generating an integral row module `M` and `sub` a list of vectors defining a submodule `S` of `M`. This function computes a free basis for `M` that extends `S`. I.e., if the dimension of `S` is `n` it determines a basis `B = \{ b_1, ..., b_m \}` for `M`, as well as `n` integers `x_i` such that the `n` vectors `s_i := x_i \cdot b_i` form a basis for `S`.

It returns a record with the following components:

- `complement`: the vectors `b_{n+1}` up to `b_m` (they generate a complement to `S`).
- `sub`: the vectors `s_i` (a basis for `S`).
- `moduli`: the factors `x_i`.
25.2 Normal Forms over the Integers

This section describes the computation of the Hermite and Smith normal form of integer matrices.

The Hermite Normal Form (HNF) $H$ of an integer matrix $A$ is a row equivalent upper triangular form such that all off-diagonal entries are reduced modulo the diagonal entry of the column they are in. There exists a unique unimodular matrix $Q$ such that $QA = H$.

The Smith Normal Form $S$ of an integer matrix $A$ is the unique equivalent diagonal form with $S_i$ dividing $S_j$ for $i < j$. There exist unimodular integer matrices $P, Q$ such that $PAQ = S$.

All routines described in this section build on the “workhorse” routine NormalFormIntMat (25.2.9).

25.2.1 TriangulizedIntegerMat

$\triangledown$ TriangulizedIntegerMat(mat) (operation)

Computes an upper triangular form of a matrix with integer entries. It returns a mutable matrix in upper triangular form.

25.2.2 TriangulizedIntegerMatTransform

$\triangledown$ TriangulizedIntegerMatTransform(mat) (operation)

Computes an upper triangular form of a matrix with integer entries. It returns a record with a component normal (an immutable matrix in upper triangular form) and a component rowtrans that gives the transformations done to the original matrix to bring it into upper triangular form.

25.2.3 TriangulizeIntegerMat

$\triangledown$ TriangulizeIntegerMat(mat) (operation)

Changes mat to be in upper triangular form. (The result is the same as that of TriangulizedIntegerMat (25.2.1), but mat will be modified, thus using less memory.) If mat is immutable an error will be triggered.

```
Example

gap> m:=IdentityMat(3);
gap> n:=[[1,2,3],[4,5,6]];
gap> ComplementIntMat(m,n);
rec( complement := [ [ 0, 0, 1 ] ], moduli := [ 1, 3 ],
    sub := [ [ 1, 2, 3 ], [ 0, 3, 6 ] ] )
```

```
Example

gap> m:=[[1,15,28],[4,5,6],[7,8,9]];
gap> TriangulizedIntegerMat(m);
[ [ 1, 15, 28 ], [ 0, 1, 1 ], [ 0, 0, 3 ] ]
gap> n:=TriangulizedIntegerMatTransform(m);
rec( normal := [ [ 1, 15, 28 ], [ 0, 1, 1 ], [ 0, 0, 3 ] ],
    rank := 3, rowC := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ],
    rowQ := [ [ 1, 0, 0 ], [ -30, 17 ], [ -3, 97, -55 ] ],
```
25.2.4 HermiteNormalFormIntegerMat

\texttt{HermiteNormalFormIntegerMat(mat)}

This operation computes the Hermite normal form of a matrix \texttt{mat} with integer entries. It returns an immutable matrix in HNF.

25.2.5 HermiteNormalFormIntegerMatTransform

\texttt{HermiteNormalFormIntegerMatTransform(mat)}

This operation computes the Hermite normal form of a matrix \texttt{mat} with integer entries. It returns a record with components \texttt{normal} (a matrix \(H\)) and \texttt{rowtrans} (a matrix \(Q\)) such that \(QA = H\).

Example

\begin{verbatim}
gap> m:=[[1,15,28],[4,5,6],[7,8,9]];
gap> HermiteNormalFormIntegerMat(m);
[ [ 1, 0, 1 ], [ 0, 1, 1 ], [ 0, 0, 3 ] ]
gap> n:=HermiteNormalFormIntegerMatTransform(m);
rec( normal := [ [ 1, 0, 1 ], [ 0, 1, 1 ], [ 0, 0, 3 ] ], rank := 3,
  rowC := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ],
  rowQ := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ],
  rowtrans := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ],
  signdet := 1 )
gap> n.rowtrans*m=n.normal;
true
\end{verbatim}

25.2.6 SmithNormalFormIntegerMat

\texttt{SmithNormalFormIntegerMat(mat)}

This operation computes the Smith normal form of a matrix \texttt{mat} with integer entries. It returns a new immutable matrix in the Smith normal form.

25.2.7 SmithNormalFormIntegerMatTransforms

\texttt{SmithNormalFormIntegerMatTransforms(mat)}

This operation computes the Smith normal form of a matrix \texttt{mat} with integer entries. It returns a record with components \texttt{normal} (a matrix \(S\)), \texttt{rowtrans} (a matrix \(P\)), and \texttt{coltrans} (a matrix \(Q\)) such that \(PAQ = S\).
25.2.8 DiagonalizeIntMat

\[ \text{DiagonalizeIntMat(mat)} \]

This function changes \( \text{mat} \) to its SNF. (The result is the same as that of \text{SmithNormalFormIntegerMat} (25.2.6), but \( \text{mat} \) will be modified, thus using less memory.) If \( \text{mat} \) is immutable an error will be triggered.

Example

\[
\begin{align*}
gap> m:=&[[1,15,28],[4,5,6],[7,8,9]]; \\
gap> \text{SmithNormalFormIntegerMat}(m); \\
&[[ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 3 ]] \\
gap> n:=\text{SmithNormalFormIntegerMatTransforms}(m); \\
rec( \text{colC} := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ], \\
    \text{colQ} := [ [ 1, 0, -1 ], [ 0, 1, -1 ], [ 0, 0, 1 ] ], \\
    \text{coltrans} := [ [ 1, 0, -1 ], [ 0, 1, -1 ], [ 0, 0, 1 ] ], \\
    \text{normal} := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 3 ] ], \text{rank} := 3, \\
    \text{rowC} := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ], \\
    \text{rowQ} := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ], \\
    \text{rowtrans} := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ], \\
    \text{signdet} := 1 ) \\
gap> n.\text{rowtrans} * m * n.\text{coltrans} = n.\text{normal}; \\
true \\
gap> \text{DiagonalizeIntMat}(m); m; \\
&[[ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 3 ]] \\
\end{align*}
\]

25.2.9 NormalFormIntMat

\[ \text{NormalFormIntMat(mat, options)} \]

This general operation for computation of various Normal Forms is probably the most efficient.

Options bit values:

- **0/1**: Triangular Form / Smith Normal Form.
- **2**: Reduce off diagonal entries.
- **4**: Row Transformations.
- **8**: Col Transformations.
- **16**: Destructive (the original matrix may be destroyed)

Compute a Triangular, Hermite or Smith form of the \( n \times m \) integer input matrix \( A \). Optionally, compute \( n \times n \) and \( m \times m \) unimodular transforming matrices \( Q, P \) which satisfy \( QA = H \) or \( QAP = S \).

Note option is a value ranging from 0 to 15 but not all options make sense (e.g., reducing off diagonal entries with SNF option selected already). If an option makes no sense it is ignored.

Returns a record with component \text{normal} containing the computed normal form and optional components \text{rowtrans} and/or \text{coltrans} which hold the respective transformation matrix. Also in the record are components holding the sign of the determinant, \text{signdet}, and the rank of the matrix, \text{rank}.
Example

\begin{verbatim}
gap> m:=[[1,15,28],[4,5,6],[7,8,9]];;

Example

\begin{verbatim}
gap> NormalFormIntMat(m,0); # Triangular, no transforms
rec( normal := [ [ 1, 15, 28 ], [ 0, 1, 1 ], [ 0, 0, 3 ] ],
    rank := 3, signdet := 1 )

gap> NormalFormIntMat(m,6); # Hermite Normal Form with row transforms
rec( normal := [ [ 1, 0, 1 ], [ 0, 1, 1 ], [ 0, 0, 3 ] ], rank := 3,
    rowC := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ],
    rowQ := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ],
    rowtrans := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ],
    signdet := 1 )

gap> NormalFormIntMat(m,13); # Smith Normal Form with both transforms
rec( colC := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ],
    colQ := [ [ 1, 0, -1 ], [ 0, 1, -1 ], [ 0, 0, 1 ] ],
    coltrans := [ [ 1, 0, -1 ], [ 0, 1, -1 ], [ 0, 0, 1 ] ],
    normal := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 3 ] ], rank := 3,
    rowC := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ],
    rowQ := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ],
    rowtrans := [ [ -2, 62, -35 ], [ 1, -30, 17 ], [ -3, 97, -55 ] ],
    signdet := 1 )

gap> last.rowtrans*m*last.coltrans;
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 3 ] ]
\end{verbatim}

25.2.10 AbelianInvariantsOfList

\begin{verbatim}
\textbf{AbelianInvariantsOfList(list)}
\end{verbatim}

Given a list of nonnegative integers, this routine returns a sorted list containing the prime power factors of the positive entries in the original list, as well as all zeroes of the original list.

Example

\begin{verbatim}
gap> AbelianInvariantsOfList([4,6,2,0,12]);
[ 0, 2, 2, 3, 3, 4, 4 ]
\end{verbatim}

25.3 Determinant of an integer matrix

25.3.1 DeterminantIntMat

\begin{verbatim}
\textbf{DeterminantIntMat(mat)}
\end{verbatim}

Computes the determinant of an integer matrix using the same strategy as \texttt{NormalFormIntMat} (25.2.9). This method is faster in general for matrices greater than 20 \times 20 but quite a lot slower for smaller matrices. It therefore passes the work to the more general \texttt{DeterminantMat} (24.4.4) for these smaller matrices.

25.4 Decompositions

For computing the decomposition of a vector of integers into the rows of a matrix of integers, with integral coefficients, one can use \textit{p}-adic approximations, as follows.
Let $A$ be a square integral matrix, and $p$ an odd prime. The reduction of $A$ modulo $p$ is $\overline{A}$, its entries are chosen in the interval $[-(p-1)/2, (p-1)/2]$. If $\overline{A}$ is regular over the field with $p$ elements, we can form $A^t = \overline{A}^{-1}$. Now we consider the integral linear equation system $xA = b$, i.e., we look for an integral solution $x$. Define $b_0 = b$, and then iteratively compute $x_i = (b_i A^t) \mod p, b_{i+1} = (b_i - x_i A) / p, i = 0, 1, 2, \ldots$.

By induction, we get $p^i + 1 b_{i+1} + \left( \sum_{j=0}^{i} p^j x_j \right) A = b$.

If there is an integral solution $x$ then it is unique, and there is an index $l$ such that $b_{l+1}$ is zero and $x = \sum_{j=0}^{l} p^j x_j$.

There are two useful generalizations of this idea. First, $A$ need not be square; it is only necessary that there is a square regular matrix formed by a subset of columns of $A$. Second, $A$ does not need to be integral; the entries may be cyclotomic integers as well, in this case one can replace each column of $A$ by the columns formed by the coefficients w.r.t. an integral basis (which are integers). Note that this preprocessing must be performed compatibly for $A$ and $b$.

GAP provides the following functions for this purpose (see also InverseMatMod (24.15.1)).

### 25.4.1 Decomposition

**Decomposition**($A$, $B$, $\text{depth}$)

For a $m \times n$ matrix $A$ of cyclotomics that has rank $m \leq n$, and a list $B$ of cyclotomic vectors, each of length $n$, Decomposition tries to find integral solutions of the linear equation systems $x * A = B[i]$, by computing the $p$-adic series of hypothetical solutions.

Decomposition($A$, $B$, $\text{depth}$), where $\text{depth}$ is a nonnegative integer, computes for each vector $B[i]$ the initial part $\sum_{k=0}^{\text{depth}} x_k p^k$, with all $x_k$ vectors of integers with entries bounded by $\pm (p-1)/2$. The prime $p$ is set to 83 first; if the reduction of $A$ modulo $p$ is singular, the next prime is chosen automatically.

A list $X$ is returned. If the computed initial part for $x * A = B[i]$ is a solution, we have $X[i] = x$, otherwise $X[i] = \text{fail}$.

If $\text{depth}$ is not an integer then it must be the string "nonnegative". Decomposition($A$, $B$, "nonnegative") assumes that the solutions have only nonnegative entries, and that the first column of $A$ consists of positive integers. This is satisfied, e.g., for the decomposition of ordinary characters into Brauer characters. In this case the necessary number $\text{depth}$ of iterations can be computed; the $i$-th entry of the returned list is $\text{fail}$ if there exists no nonnegative integral solution of the system $x * A = B[i]$, and it is the solution otherwise.

*Note* that the result is a list of $\text{fail}$ if $A$ has not full rank, even if there might be a unique integral solution for some equation system.

### 25.4.2 LinearIndependentColumns

**LinearIndependentColumns**($\text{mat}$)

Called with a matrix $\text{mat}$, LinearIndependentColumns returns a maximal list of column positions such that the restriction of $\text{mat}$ to these columns has the same rank as $\text{mat}$. 
25.4.3 PadicCoefficients

\[ \text{PadicCoefficients}(A, \text{Amotpinv}, b, \text{prime}, \text{depth}) \]

Let \( A \) be an integral matrix, \( \text{prime} \) a prime integer, \( \text{Amotpinv} \) an inverse of \( A \) modulo \( \text{prime} \), \( b \) an integral vector, and \( \text{depth} \) a nonnegative integer. \text{PadicCoefficients} returns the list \([x_0, x_1, \ldots, x_l, b_{l+1}]\) describing the \( \text{prime} \)-adic approximation of \( b \) (see above), where \( l = \text{depth} \) or \( l \) is minimal with the property that \( b_{l+1} = 0 \).

25.4.4 IntegralizedMat

\[ \text{IntegralizedMat}(A[, \text{inforec}]) \]

\text{IntegralizedMat} returns, for a matrix \( A \) of cyclotomics, a record \text{intmat} with components \text{mat} and \text{inforec}. Each family of algebraic conjugate columns of \( A \) is encoded in a set of columns of the rational matrix \text{intmat}.\text{mat} by replacing cyclotomics in \( A \) by their coefficients w.r.t. an integral basis. \text{intmat}.\text{inforec} is a record containing the information how to encode the columns.

If the only argument is \( A \), the value of the component \text{inforec} is computed that can be entered as second argument \text{inforec} in a later call of \text{IntegralizedMat} with a matrix \( B \) that shall be encoded compatibly with \( A \).

25.4.5 DecompositionInt

\[ \text{DecompositionInt}(A, B, \text{depth}) \]

\text{DecompositionInt} does the same as \text{Decomposition} (25.4.1), except that \( A \) and \( B \) must be integral matrices, and \( \text{depth} \) must be a nonnegative integer.

25.5 Lattice Reduction

25.5.1 LLLReducedBasis

\[ \text{LLLReducedBasis}(L[, \text{vectors}[, y [, "linearcomb"]], \text{lllout}]) \]

provides an implementation of the LLL algorithm by Lenstra, Lenstra and Lovász (see [LLJL82], [Poh87]). The implementation follows the description in [Coh93, p. 94f.].

\text{LLLReducedBasis} returns a record whose component \text{basis} is a list of LLL reduced linearly independent vectors spanning the same lattice as the list \text{vectors}. \( L \) must be a lattice, with scalar product of the vectors \( v \) and \( w \) given by \text{ScalarProduct}(L, v, w). If no lattice is specified then the scalar product of vectors given by \text{ScalarProduct}(v, w) is used.

In the case of the option "linearcomb", the result record contains also the components \text{relations} and \text{transformation}, with the following meaning. \text{relations} is a basis of the relation space of \text{vectors}, i.e., of vectors \( x \) such that \( x \ast \text{vectors} \) is zero. \text{transformation} gives the expression of the new lattice basis in terms of the old, i.e., \( \text{transformation} \ast \text{vectors} \) equals the basis component of the result.

Another optional argument is \( y \), the “sensitivity” of the algorithm, a rational number between 1/4 and 1 (the default value is 3/4).
The optional argument \texttt{lllout} is a record with the components \texttt{mue} and \texttt{B}, both lists of length \(k\), with the meaning that if \texttt{lllout} is present then the first \(k\) vectors in \texttt{vectors} form an LLL reduced basis of the lattice they generate, and \texttt{lllout.mue} and \texttt{lllout.B} contain their scalar products and norms used internally in the algorithm, which are also present in the output of \texttt{LLLReducedBasis}. So \texttt{lllout} can be used for “incremental” calls of \texttt{LLLReducedBasis}.

The function \texttt{LLLReducedGramMat} (25.5.2) computes an LLL reduced Gram matrix.

Example

\begin{verbatim}
gap> vectors:= [ [ 9, 1, 0, -1, -1 ], [ 16, 0, 1, 1, 1 ], [ 20, 0, -1, 0, 0 ],
     [ 25, 1, 1, 0, 0 ] ];;

gap> LLLReducedBasis( vectors, "linearcomb" );
rec( B := [ 5, 36/5, 12, 50/3 ],
    basis := [ [ 1, 1, 1, 1, 1 ], [ 1, 1, -2, 1, 1 ],
              [ -1, 3, -1, -1, -1 ], [ -3, 1, 0, 2, 2 ] ],
    mue := [ [ ], [ 2/5 ], [ -1/5, 1/3 ], [ 2/5, 1/6, 1/6 ] ],
    relations := [ [ -1, 0, -1, 0, 1 ] ],
    transformation := [ [ 0, -1, 1, 0, 0 ], [ -1, -2, 0, 2, 0 ],
                        [ 1, -2, 0, 1, 0 ] ] )
\end{verbatim}

25.5.2 \texttt{LLLReducedGramMat}

\begin{verbatim}
> LLLReducedGramMat( g[, y] )
\end{verbatim}

\texttt{LLLReducedGramMat} provides an implementation of the \textit{LLL algorithm} by Lenstra, Lenstra and Lovász (see [LLJL82], [Poh87]). The implementation follows the description in [Coh93, p. 94f.].

Let \(G\) the Gram matrix of the vectors \((b_1, b_2, \ldots, b_n)\); this means \(G\) is either a square symmetric matrix or lower triangular matrix (only the entries in the lower triangular half are used by the program).

\texttt{LLLReducedGramMat} returns a record whose component \texttt{remainder} is the Gram matrix of the LLL reduced basis corresponding to \((b_1, b_2, \ldots, b_n)\). If \(G\) is a lower triangular matrix then also the \texttt{remainder} component of the result record is a lower triangular matrix.

The result record contains also the components \texttt{relations} and \texttt{transformation}, which have the following meaning.

\texttt{relations} is a basis of the space of vectors \((x_1, x_2, \ldots, x_n)\) such that \(\sum_{i=1}^{n} x_i b_i\) is zero, and \texttt{transformation} gives the expression of the new lattice basis in terms of the old, i.e., \texttt{transformation} is the matrix \(T\) such that \(T \cdot G \cdot T^t\) is the \texttt{remainder} component of the result.

The optional argument \(y\) denotes the “sensitivity” of the algorithm, it must be a rational number between 1/4 and 1; the default value is \(y = 3/4\).

The function \texttt{LLLReducedBasis} (25.5.1) computes an LLL reduced basis.

Example

\begin{verbatim}
 gap> g:= [ [ 4, 6, 5, 2, 2 ], [ 6, 13, 7, 4, 4 ],
        [ 5, 7, 11, 2, 0 ], [ 2, 4, 2, 8, 4 ], [ 2, 4, 0, 4, 8 ] ];;

 gap> LLLReducedGramMat( g );
 rec( B := [ 4, 4, 75/16, 168/25, 32/7 ],
     mue := [ [ ], [ 1/2 ], [ 1/4, -1/8 ], [ 1/4, 1/8, 37/75, 8/21 ] ],
     relations := [ ],
     remainder := [ [ 4, 2, 1, 2, -1 ], [ 2, 5, 0, 2, 0 ],
                    [ 1, 0, 5, 0, 2 ], [ 2, 2, 0, 8, 2 ], [ -1, 0, 2, 2, 7 ] ],
     transformation := [ [ 1, 0, 0, 0, 0 ], [ -1, 1, 0, 0, 0 ],
                         [ -1, 0, 1, 0, 0 ], [ 0, 0, 0, 1, 0 ], [ -2, 0, 1, 0, 1 ] ] )
\end{verbatim}
25.6 Orthogonal Embeddings

25.6.1 OrthogonalEmbeddings

OrthogonalEmbeddings(gram[, "positive"][, maxdim])

computes all possible orthogonal embeddings of a lattice given by its Gram matrix gram, which must be a regular symmetric matrix of integers. In other words, all integral solutions \(X\) of the equation \(X^t \cdot X = \text{gram}\) are calculated. The implementation follows the description in [Ple95].

Usually there are many solutions \(X\) but all their rows belong to a small set of vectors, so OrthogonalEmbeddings returns the solutions encoded by a record with the following components.

- vectors the list \(L = [x_1, x_2, \ldots, x_n]\) of vectors that may be rows of a solution, up to sign; these are exactly the vectors with the property \(x_i \cdot \text{gram}^{-1} \cdot x_i^t \leq 1\), see ShortestVectors (25.6.2).

- norms the list of values \(x_i \cdot \text{gram}^{-1} \cdot x_i^t\), and

- solutions a list \(S\) of index lists; the \(i\)-th solution matrix is \(L\{S[i]\}\), so the dimension of the \(i\)-th solution is the length of \(S[i]\), and we have \(\text{gram} = \sum_{j \in S[i]} x_j^t \cdot x_j\).

The optional argument "positive" will cause OrthogonalEmbeddings to compute only vectors \(x_i\) with nonnegative entries. In the context of characters this is allowed (and useful) if \(\text{gram}\) is the matrix of scalar products of some virtual characters. From the characters and the embedding given by the matrix \(X\), Decreased (72.10.7) may be able to compute irreducibles.

Example

\[
\text{gap> } b := [ [ 3, -1, -1 ], [ -1, 3, -1 ], [ -1, -1, 3 ] ];
\]
\[
\text{gap> } c := \text{OrthogonalEmbeddings}(b);
\]
\[
\text{rec( norms := [ 1, 1, 1, 1/2, 1/2, 1/2, 1/2, 1/2, 1/2 ],}
\text{ solutions := [ [ 1, 2, 3 ], [ 1, 6, 6, 7, 7 ], [ 2, 5, 5, 8, 8 ],}
\text{ [ 3, 4, 4, 9, 9 ], [ 4, 5, 6, 7, 8, 9 ] ],}
\text{ vectors := [ [ -1, 1, 1 ], [ 1, -1, 1 ], [ -1, -1, 1 ],}
\text{ [ -1, 1, 0 ], [ -1, 0, 1 ], [ 1, 0, 0 ], [ 0, -1, 1 ],}
\text{ [ 0, 1, 0 ], [ 0, 0, 1 ] ] }
\text{gap> } c \text{.vectors[ c.solutions[1] ]};
\text{[ [ -1, 1, 1 ], [ 1, -1, 1 ], [ -1, -1, 1 ] ] }
\]

\(\text{gram}\) may be the matrix of scalar products of some virtual characters. From the characters and the embedding given by the matrix \(X\), Decreased (72.10.7) may be able to compute irreducibles.

25.6.2 ShortestVectors

ShortestVectors(G, m[, "positive"])

Let \(G\) be a regular matrix of a symmetric bilinear form, and \(m\) a nonnegative integer. ShortestVectors computes the vectors \(x\) that satisfy \(x \cdot G \cdot x^t \leq m\), and returns a record describing these vectors. The result record has the components
vectors

list of the nonzero vectors \( x \), but only one of each pair \( (x, -x) \),

norms

list of norms of the vectors according to the Gram matrix \( G \).

If the optional argument "positive" is entered, only those vectors \( x \) with nonnegative entries are computed.

```
Example

gap> g := [ [ 2, 1, 1 ], [ 1, 2, 1 ], [ 1, 1, 2 ] ];;
gap> ShortestVectors(g,4);
rec( norms := [ 4, 2, 2, 4, 2, 4, 2, 2, 2 ],
    vectors := [ [ -1, 1, 1 ], [ 0, 0, 1 ], [ -1, 0, 1 ], [ 1, -1, 1 ],
                  [ 0, -1, 1 ], [ -1, -1, 1 ], [ 0, 1, 0 ], [ -1, 1, 0 ],
                  [ 1, 0, 0 ] ] )
```
Chapter 26

Vector and Matrix Objects

This chapter is work in progress. It will eventually describe the new interface to vector and matrix objects.

Traditionally, vectors in GAP have been lists and matrices have been lists of lists (of equal length). Unfortunately, such lists cannot store their type and so it is impossible to use the full advantages of GAP’s method selection on them. This situation is unsustainable in the long run since more special representations (compressed, sparse, etc.) have already been and even more will be implemented. To eventually solve this problem, this chapter describes a new programming interface to vectors and matrices.

26.1 Fundamental Ideas and Rules

The whole idea of this interface is that vectors and matrices must be proper objects with a stored type (i.e. created by Objectify allowing inheritance) to benefit from method selection. We therefore refer to the new style vectors and matrices as “vector objects” and “matrix objects” respectively.

It should be possible to write (efficient) code that is independent of the actual representation (in the sense of GAP’s representation filters) and preserves it.

This latter requirement makes it necessary to distinguish between (at least) two classes of matrices:

- “RowList”-Matrices which behave basically like lists of rows, in particular are the rows individual GAP objects that can be shared between different matrix objects.
- “Flat” matrices which behave basically like one GAP object that cannot be split up further. In particular a row is only a part of a matrix and no GAP object in itself.

For various reasons these two classes have to be distinguished already with respect to the definition of the operations for them.

In particular vectors and matrices know their BaseDomain and their dimensions. Note that the basic condition is that the elements of vectors and matrices must either lie in the BaseDomain or naturally embed in the sense that + and * and = automatically work with all elements of the base domain (example: integers in polynomials over integers).

Vectors are equal with respect to “=” if they have the same length and the same entries. It is not necessary that they have the same BaseDomain. Matrices are equal with respect to “=” if they have the same dimensions and the same entries. It is possible that not for all pairs of representations methods exist.
It is not guaranteed that all rows of a matrix have the same vector type! It is for example thinkable
that a matrix stores some of its rows in a sparse representation and some in a dense one! However, it
is guaranteed that the rows of matrices in the same representation are compatible in the sense that all
vector operations defined in this interface can be applied to them and that new matrices in the same
representation as the original matrix can be formed out of them.

Note that there is neither a default mapping from the set of matrix representations to the set of
vector representations nor one in the reverse direction! There is nothing like an "associated" vector
representation to a matrix representation or vice versa.

The way to write code that preserves the representation basically works by using constructing
operations that take template objects to decide about the actual representation of the new object.
Vectors do not have to be lists in the sense that they do not have to support all list operations. The
same holds for matrices. However, RowList matrices behave nearly like lists of row vectors that insist
on being dense and containing only vectors of the same length and with the same BaseDomain.

There are some rules embedded in the comments to the following code. They are marked with the
word "Rule". FIXME: Collect all rules here.

26.2 Categories of Vectors and Matrices

26.3 Constructing Vector and Matrix Objects

26.4 Operations for Vector Objects

26.4.1 PositionNonZero (for vectors)

\[ \text{PositionNonZero}(V) \] (operation)

Returns: An integer

Returns the index of the first entry in the vector \( V \) which is not zero. If all entries are zero, the
function returns \( \text{Length}(V) + 1 \).

26.4.2 PositionLastNonZero

\[ \text{PositionLastNonZero}(V) \] (operation)

Returns: An integer

Returns the index of the last entry in the vector \( V \) which is not zero. If all entries are zero, the
function returns 0.

26.4.3 ListOp (for IsVectorObj, IsFunction)

\[ \text{ListOp}(V[, \text{func}]) \] (operation)

Returns: A plain list

Applies \( \text{func} \) to each entry of the vector \( V \) and returns the results as a plain list. This allows for
calling \text{List} (30.3.5) on vectors. If the argument \( \text{func} \) is not provided, applies \text{IdFunc} (5.4.6) to all
entries.
26.4.4 Unpack (for IsVectorObj)

\[ \text{Unpack}(V) \]

\textbf{Returns:} A plain list

Returns a new plain list containing the entries of \( V \). Guarantees to return a new list which can be manipulated without changing \( V \). The entries itself are not copied.

26.4.5 ConcatenationOfVectors (for IsVectorObj)

\[ \text{ConcatenationOfVectors}(V_1, V_2, ...) \]

\[ \text{ConcatenationOfVectors}(V\text{list}) \]

\textbf{Returns:} a vector object

Returns a new vector containing the entries of \( V_1, V_2, \text{etc.} \) As prototype \( V_1 \) is used.

26.4.6 ExtractSubVector (for IsVectorObj, IsList)

\[ \text{ExtractSubVector}(V, l) \]

\textbf{Returns:} a vector object

Returns a new vector containing the entries of \( V \) at the positions in \( l \).

26.4.7 ZeroVector (for IsInt, IsVectorObj)

\[ \text{ZeroVector}(1, V) \]

\textbf{Returns:} a vector object

Returns a new vector of length \( 1 \) in the same representation as \( V \) containing only zeros.

26.4.8 ConstructingFilter (for IsVectorObj)

\[ \text{ConstructingFilter}(V) \]

\textbf{Returns:} a filter

Returns a filter \( f \) such that if \text{NewVector} is called with \( f \) a vector in the same representation as \( V \) is produced.

26.4.9 Randomize

\[ \text{Randomize}([Rs, ]v) \]

\[ \text{Randomize}([Rs, ]m) \]

Replaces every entry in the mutable vector object \( v \) or matrix object \( m \), respectively, with a random one from the base domain of \( v \) or \( m \), respectively, and returns the argument.

If given, the random source \( Rs \) is used to compute the random elements. Note that in this case, a \text{Random} (14.7.2) method must be available that takes a random source as its first argument and the base domain as its second argument.

26.4.10 WeightOfVector (for IsVectorObj)

\[ \text{WeightOfVector}(V) \]

\textbf{Returns:} an integer

Computes the Hamming weight of the vector \( V \), i.e., the number of nonzero entries.
26.4.11 DistanceOfVectors (for IsVectorObj,IsVectorObj)

\[ \text{DistanceOfVectors}(V_1, V_2) \] (operation)

**Returns:** an integer

Computes the Hamming distance of the vectors \( V_1 \) and \( V_2 \), i.e., the number of entries in which the vectors differ. The vectors must be of equal length.

26.5 Operations for Row List Matrix Objects

26.6 Operations for Flat Matrix Objects
Chapter 27

Strings and Characters

27.1 IsChar and IsString

27.1.1 IsChar

\[ \text{IsChar}(\text{obj}) \] (Category)

\[ \text{IsCharCollection}(\text{obj}) \] (Category)

A character is simply an object in GAP that represents an arbitrary character from the character set of the operating system. Character literals can be entered in GAP by enclosing the character in singlequotes `.

Example

```gap
gap> x := 'a'; IsChar( x );
'a'
true
gap> '*',
'*'
```

27.1.2 IsString

\[ \text{IsString}(\text{obj}) \] (filter)

A string is a dense list (see IsList (21.1.1), IsDenseList (21.1.2)) of characters (see IsChar (27.1.1)); thus strings are always homogeneous (see IsHomogeneousList (21.1.3)).

A string literal can either be entered as the list of characters or by writing the characters between doublequotes "". GAP will always output strings in the latter format. However, the input via the double quote syntax enables GAP to store the string in an efficient compact internal representation. See IsStringRep (27.4.1) below for more details.

Each character, in particular those which cannot be typed directly from the keyboard, can also be typed in three digit octal notation, or two digit hexadecimal notation. And for some special characters (like the newline character) there is a further possibility to type them, see section 27.2.

Example

```gap
gap> s1 := ['H','e','l','l','o',' ','w','o','r','l','d','.'];
"Hello world."
gap> IsString( s1 );
true
```
gap> s2 := "Hello world.";
"Hello world."

gap> s1 = s2;
true

gap> s3 := "";  # the empty string
"

gap> s3 = [];
true

gap> IsString([]);
true

gap> IsString( "123" ); IsString( 123 );
true false

gap> IsString( ['1', '2', '3'] );
true

gap> IsString( ['1', '2', ', '4'] );  # strings must be dense
false

gap> IsString( ['1', '2', 3] );  # strings must only contain characters
false

27.1.3 Strings As Lists

Note that a string is just a special case of a list. So everything that is possible for lists (see 21) is also possible for strings. Thus you can access the characters in such a string (see 21.3), test for membership (see 30.6), ask for the length, concatenate strings (see Concatenation (21.20.1)), form substrings etc. You can even assign to a mutable string (see 21.4). Of course unless you assign a character in such a way that the list stays dense, the resulting list will no longer be a string.

Example

```gap
Example
```

```gap
Example
```

27.1.4 Printing Strings

ViewObj(str) (method)
PrintObj(str) (method)

If a string is displayed by View (6.3.3), for example as result of an evaluation (see 6.1), or by ViewObj (6.3.5) and PrintObj (6.3.5), it is displayed with enclosing doublequotes. (But note that there is an ambiguity for the empty string which is also an empty list of arbitrary GAP ob-
jects; it is only printed like a string if it was input as empty string or converted to a string with ConvertToStringRep (27.4.2).) The output of PrintObj can be read back into GAP.

Strings behave differently from other GAP objects with respect to Print (6.3.4), PrintTo (9.7.3), or AppendTo (9.7.3). These commands interpret a string in the sense that they essentially send the characters of the string directly to the output stream/file. (But depending on the type of the stream and the presence of some special characters used as hints for line breaks there may be sent some additional newline (or backslash and newline) characters.

Example

```gap
gap> s4 := "abc\"def\nghi";;
gap> View( s4 ); Print( "\n" );
"abc\"def\nghi"
gap> ViewObj( s4 ); Print( "\n" );
"abc\"def\nghi"
gap> PrintObj( s4 ); Print( "\n" );
"abc\"def\nghi"
gap> Print( s4 ); Print( "\n" );
abc\ndef\nghi
gap> s := "German uses strange characters: äöü\n";
"German uses strange characters: äöü\n"
gap> Print(s);
German uses strange characters: äöü

gap> PrintObj(s); Print( "\n" );
"German uses strange characters: \303\244\303\266\303\274\303\237\n"
gap> s := "\007";
"\007"
gap> Print(s); # rings bell in many terminals
```

Note that only those line breaks are printed by Print (6.3.4) that are contained in the string (\n characters, see 27.2), as is shown in the example below.

Example

```gap
gap> s1;  
"Hello world."
gap> Print( s1 );
Hello world.
gap> Print( s1, "\n" );
Hello world.
gap> Print( s1, "\nnext line\n" );
Hello world.
ext line
```

27.2 Special Characters

There are a number of special character sequences that can be used between the singlequotes of a character literal or between the doublequotes of a string literal to specify characters. They consist of a backslash \ followed by a second character indicating the type of special character sequence, and possibly more characters. The following special character sequences are currently defined. For any other sequence starting with a backslash, the backslash is ignored.
newline character. This is the character that, at least on UNIX systems, separates lines in a text file. Printing of this character in a string has the effect of moving the cursor down one line and back to the beginning of the line.

doublequote character. Inside a string a doublequote must be escaped by the backslash, because it is otherwise interpreted as end of the string.

singlequote character. Inside a character a singlequote must escaped by the backslash, because it is otherwise interpreted as end of the character.

backslash character. Inside a string a backslash must be escaped by another backslash, because it is otherwise interpreted as first character of an escape sequence.

backspace character. Printing this character should have the effect of moving the cursor back one character. Whether it works or not is system dependent and should not be relied upon.

carriage return character. Printing this character should have the effect of moving the cursor back to the beginning of the same line. Whether this works or not is again system dependent.

flush character. This character is not printed. Its purpose is to flush the output queue. Usually GAP waits until it sees a newline before it prints a string. If you want to display a string that does not include this character use \c.

XYZ
with X, Y, Z three octal digits, that is one of "01234567". This is translated to the character corresponding to the number X * 64 + Y * 8 + Z modulo 256. This can be used to specify and store arbitrary binary data as a string in GAP.

0xYZ
with Y, and Z hexadecimal digits, that is one of "0123456789abcdefABCDEFabcdef", where a to f and A to F are interpreted as the numbers 10 to 15. This is translated to the character corresponding to the number Y*16 + Z.

other
For any other character the backslash is ignored.

Again, if the line is displayed as result of an evaluation, those escape sequences are displayed in the same way that they are input.

Only Print (6.3.4), PrintTo (9.7.3), or AppendTo (9.7.3) send the characters directly to the output stream.

Example

gap> "This is one line.\nThis is another line.\n";  "This is one line.\nThis is another line.\n"
gap> Print( last );
This is one line.
This is another line.

Note in particular that it is not allowed to enclose a newline inside the string. You can use the special character sequence \n to write strings that include newline characters. If, however, an input string is too long to fit on a single line it is possible to continue it over several lines. In this case the
last character of each input line, except the last line must be a backslash. Both backslash and newline are thrown away by GAP while reading the string. Note that the same continuation mechanism is available for identifiers and integers, see 6.2. The rules on escaping are ignored in a triple quoted string, see 27.3

### 27.3 Triple Quoted Strings

Another method of entering strings in GAP is triple quoted strings. Triple quoted strings ignore the rules on escaping given in 27.2. Triple quoted strings begin an end with three doublequotes. Inside the triple quotes no escaping is done, and the string continues, including newlines, until three doublequotes are found.

```gap
  gap> """Print("\n")"";
  "Print("\n")"
```

Triple quoted strings are represented internally identically to all other strings, they only provide an alternative method of giving strings to GAP. Triple quoted strings still follow GAP’s line editing rules (6.2), which state that in normal line editing mode, lines starting `gap>`, `>` or `brk>` will have this beginning part removed.

### 27.4 Internally Represented Strings

#### 27.4.1 IsStringRep

```gap
def IsStringRep(obj)
  (Representation)
```

IsStringRep is a special (internal) representation of dense lists of characters. Dense lists of characters can be converted into this representation using ConvertToStringRep (27.4.2). Note that calling IsString (27.1.2) does not change the representation.

#### 27.4.2 ConvertToStringRep

```gap
def ConvertToStringRep(obj)
  (function)
```

If `obj` is a dense internally represented list of characters then ConvertToStringRep changes the representation to IsStringRep (27.4.1). This is useful in particular for converting the empty list `[]`, which usually is in IsPlistRep (21.24.1), to IsStringRep (27.4.1). If `obj` is not a string then ConvertToStringRep signals an error.

#### 27.4.3 CopyToStringRep

```gap
def CopyToStringRep(obj)
  (function)
```

If `obj` is a dense internally represented list of characters then CopyToStringRep copies `obj` to a new object with representation IsStringRep (27.4.1). If `obj` is not a string then CopyToStringRep signals an error.
27.4.4IsEmptyString

> IsEmptyString(str) (function)

IsEmptyString returns true if str is the empty string in the representation IsStringRep (27.4.1), and false otherwise. Note that the empty list [] and the empty string "" have the same type, the recommended way to distinguish them is via IsEmptyString. For formatted printing, this distinction is sometimes necessary.

Example

```
gap> l:= [];; IsString(l); IsEmptyString(l); IsEmpty(l);
true false true
gap> l; ConvertToStringRep(l); l;
[ ] ""

gap> IsEmptyString(l); IsEmptyString("" ); IsEmptyString("abc ");
true true false

gap> ll:= [ 'a', 'b' ]; IsStringRep(ll); ConvertToStringRep(ll);
"ab" false

gap> ll; IsStringRep(ll);
"ab" true
```

27.4.5EmptyString

> EmptyString(len) (function)

Returns: a string

> ShrinkAllocationString(str) (function)

Returns: nothing

The function EmptyString returns an empty string in internal representation which has enough memory allocated for len characters. This can be useful for creating and filling a string with a known number of entries.

The function ShrinkAllocationString gives back to GAP's memory manager the physical memory which is allocated for the string str in internal representation but not needed by its current number of characters.

These functions are intended for saving some of GAP's memory in certain situations, see the explanations and the example for the analogous functions EmptyPlist (21.9.1) and ShrinkAllocationPlist (21.9.1) for plain lists.

27.4.6CharsFamily

> CharsFamily (family)
Each character lies in the family \texttt{CharsFamily}, each nonempty string lies in the collections family of this family. Note the subtle differences between the empty list \texttt{[]} and the empty string "" when both are printed.

### 27.5 Recognizing Characters

#### 27.5.1 \texttt{IsDigitChar}

\[ \texttt{IsDigitChar(}c\texttt{)} \]

checks whether the character \( c \) is a digit, i.e., occurs in the string "0123456789".

#### 27.5.2 \texttt{IsLowerAlphaChar}

\[ \texttt{IsLowerAlphaChar(}c\texttt{)} \]

checks whether the character \( c \) is a lowercase alphabet letter, i.e., occurs in the string "abcdefghijklmnopqrstuvwxyz".

#### 27.5.3 \texttt{IsUpperAlphaChar}

\[ \texttt{IsUpperAlphaChar(}c\texttt{)} \]

checks whether the character \( c \) is an uppercase alphabet letter, i.e., occurs in the string "ABCDEFGHIJKLMNOPQRSTUVWXYZ".

#### 27.5.4 \texttt{IsAlphaChar}

\[ \texttt{IsAlphaChar(}c\texttt{)} \]

checks whether the character \( c \) is either a lowercase or an uppercase alphabet letter.

### 27.6 Comparisons of Strings

#### 27.6.1 \texttt{=} (for two strings)

\[ \texttt{=}(\texttt{string1, string2}) \]

The equality operator \texttt{=} returns \texttt{true} if the two strings \texttt{string1} and \texttt{string2} are equal and \texttt{false} otherwise. The inequality operator \texttt{<>} returns \texttt{true} if the two strings \texttt{string1} and \texttt{string2} are not equal and \texttt{false} otherwise.

```
Example

\begin{verbatim}
gap> "Hello world.\n" = "Hello world.\n";  
true  
gap> "Hello World.\n" = "Hello world.\n";  # comparison is case sensitive  
false 
gap> "Hello world." = "Hello world.\n";  # first string has no <newline>  
false
\end{verbatim}
```
gap> "Goodbye world.\n" = "Hello world.\n";
false
gap> [ 'a', 'b' ] = "ab";
true

27.6.2  \< (for two strings)

\< (string1, string2) (method)

The ordering of strings is lexicographically according to the order implied by the underlying, system dependent, character set.

Example

gap> "Hello world.\n" < "Hello world.\n"; # the strings are equal
false
gap> "Hello World." < "Hello world.";
true
gap> "Hello world." < "Hello world.\n"; # prefixes are always smaller
true
gap> "Goodbye world.\n" < "Hello world.\n";
true

Strings can be compared via < with certain GAP objects that are not strings, see 4.12 for the details.

27.7 Operations to Produce or Manipulate Strings

For the possibility to print GAP objects to strings, see 10.7.

27.7.1 DisplayString

DisplayString(obj) (operation)

Returns a string which could be used to display the object obj in a nice, formatted way which is easy to read (but might be difficult for machines to understand). The actual format used for this depends on the type of obj. Each method should include a newline character as last character. Note that no method for DisplayString may delegate to any of the operations Display (6.3.6), ViewObj (6.3.5) or PrintObj (6.3.5) to avoid circular delegations.

27.7.2 DEFAULTDISPLAYSTRING

DEFAULTDISPLAYSTRING (global variable)

This is the default value for DisplayString (27.7.1).
27.7.3 ViewString

\texttt{ViewString(obj)} \hspace{1cm} \text{(operation)}

\textit{ViewString} returns a string which would be displayed by \texttt{ViewObj} (6.3.5) for an object. Note that no method for \textit{ViewString} may delegate to any of the operations \texttt{Display} (6.3.6), \texttt{ViewObj} (6.3.5), \texttt{DisplayString} (27.7.1) or \texttt{PrintObj} (6.3.5) to avoid circular delegations.

27.7.4 DEFAULTVIEWSTRING

\texttt{DEFAULTVIEWSTRING} \hspace{1cm} \text{(global variable)}

This is the default value for \textit{ViewString} (27.7.3).

27.7.5 PrintString

\texttt{PrintString(obj[, length])} \hspace{1cm} \text{(operation)}

\textit{PrintString} returns a representation of \texttt{obj}, which may be an object of arbitrary type, as a string. This string should approximate as closely as possible the character sequence you see if you print \texttt{obj} using \texttt{PrintObj} (6.3.5).

If \texttt{length} is given it must be an integer. The absolute value gives the minimal length of the result. If the string representation of \texttt{obj} takes less than that many characters it is filled with blanks. If \texttt{length} is positive it is filled on the left, if \texttt{length} is negative it is filled on the right.

In the two argument case, the string returned is a new mutable string (in particular not a part of any other object); it can be modified safely, and \texttt{MakeImmutable} (12.6.4) may be safely applied to it.

\begin{example}
\begin{verbatim}
gap> PrintString(123);PrintString([1,2,3]);
"123"
"[ 1, 2, 3 ]"
\end{verbatim}
\end{example}

\textit{PrintString} is entitled to put in additional control characters \textless (ASCII 1) and \textgreater (ASCII 2) that allow proper line breaks. See \texttt{StripLineBreakCharacters} (27.7.7) for a function to get rid of these control characters.

27.7.6 String

\texttt{String(obj[, length])} \hspace{1cm} \text{(attribute)}

\textit{String} returns a representation of \texttt{obj}, which may be an object of arbitrary type, as a string. This string should approximate as closely as possible the character sequence you see if you print \texttt{obj}.

If \texttt{length} is given it must be an integer. The absolute value gives the minimal length of the result. If the string representation of \texttt{obj} takes less than that many characters it is filled with blanks. If \texttt{length} is positive it is filled on the left, if \texttt{length} is negative it is filled on the right.

In the two argument case, the string returned is a new mutable string (in particular not a part of any other object); it can be modified safely, and \texttt{MakeImmutable} (12.6.4) may be safely applied to it.
Example

```gap
gap> String(123); String([1,2,3]);
"123"
"[ 1, 2, 3 ]"
```

String must not put in additional control characters \< (ASCII 1) and \> (ASCII 2) that allow proper line breaks.

### 27.7.7 StripLineBreakCharacters

This function takes a string `st` as an argument and removes all control characters \< (ASCII 1) and \> (ASCII 2) which are used by `PrintString` (27.7.5) and `PrintObj` (6.3.5) to ensure proper line breaking. A new string with these characters removed is returned.

### 27.7.8 HexStringInt

```
returns a string which represents the integer `int` with hexadecimal digits (using A to F as digits 10 to 15). The inverse translation can be achieved with `IntHexString` (27.9.3).
```

### 27.7.9 StringPP

```
returns a string representing the prime factor decomposition of the integer `int`. See also `PrintFactorsInt` (14.4.10).
```

### 27.7.10 WordAlp

```
returns a string that is the `nr`-th word over the alphabet list `alpha`, w.r.t. word length and lexicographical order. The empty word is `WordAlp(alpha, 0)`.
```

### 27.7.11 LowercaseString

```
Returns a lowercase version of the string `string`, that is, a string in which each uppercase alphabet character is replaced by the corresponding lowercase character.
```
27.7.12 LowercaseChar

\[ \text{LowercaseChar(character)} \]

Returns the lowercase version of the character `character`.

27.7.13 UppercaseString

\[ \text{UppercaseString(string)} \]

Returns a uppercase version of the string `string`, that is, a string in which each lowercase alphabet character is replaced by the corresponding uppercase character.

Example

```gap
LowercaseString("This Is UpperCase");
"this is uppercase"
```

```gap
UppercaseString("This Is UpperCase");
"THIS IS UPPERCASE"
```

27.7.14 UppercaseChar

\[ \text{UppercaseChar(character)} \]

Returns the uppercase version of the character `character`.

27.7.15 SplitString

\[ \text{SplitString(string, seps[, wspace])} \]

This function accepts a string `string` and lists `seps` and, optionally, `wspace` of characters. Now `string` is split into substrings at each occurrence of a character in `seps` or `wspace`. The characters in `wspace` are interpreted as white space characters. Substrings of characters in `wspace` are treated as one white space character and they are ignored at the beginning and end of a string.

Both arguments `seps` and `wspace` can be single characters.

Each string in the resulting list of substring does not contain any characters in `seps` or `wspace`.

A character that occurs both in `seps` and `wspace` is treated as a white space character.

A separator at the end of a string is interpreted as a terminator; in this case, the separator does not produce a trailing empty string. Also see `Chomp (27.7.21)`.

Example

```gap
SplitString( "sub1:sub2::sub4", ";" );
[ "sub1", "sub2", ",", "sub4" ]
```

```gap
SplitString( "a;b;c;d;", ";" );
[ "a", "b", "c", "d" ]
```

```gap
SplitString( "/home//user//dir/", ",", "/" );
[ "home", "user", "dir" ]
```
27.7.16  ReplacedString

\texttt{ReplacedString(string, old, new)} (function)

replaces occurrences of the string \texttt{old} in \texttt{string} by \texttt{new}, starting from the left and always replacing the first occurrence. To avoid infinite recursion, characters which have been replaced already, are not subject to renewed replacement.

Example

\begin{verbatim}
gap> ReplacedString("abacab","a","zl"); "zlbzlczlb"
gap> ReplacedString("ababa", "aba","c"); "cba"
gap> ReplacedString("abacab","a","ba"); "babbacbab"
\end{verbatim}

27.7.17  NormalizeWhitespace

\texttt{NormalizeWhitespace(string)} (function)

This function changes the string \texttt{string} in place. The characters (space), \texttt{\n}, \texttt{\r} and \texttt{\t} are considered as white space. Leading and trailing white space characters in \texttt{string} are removed. Sequences of white space characters between other characters are replaced by a single space character. See \texttt{NormalizedWhitespace (27.7.18)} for a non-destructive version.

Example

\begin{verbatim}
gap> s := " x y \n\n\t\r z\n \n"; " x y \n\n\t\r z\n \n"
gap> NormalizeWhitespace(s); gap> s; "x y z"
\end{verbatim}

27.7.18  NormalizedWhitespace

\texttt{NormalizedWhitespace(str)} (function)

This function returns a copy of string \texttt{str} to which \texttt{NormalizeWhitespace (27.7.17)} was applied.

27.7.19  RemoveCharacters

\texttt{RemoveCharacters(string, chars)} (function)

Both arguments must be strings. This function efficiently removes all characters given in \texttt{chars} from \texttt{string}.

Example

\begin{verbatim}
gap> s := "ab c\ndef\ng h i .\n"; "ab c\ndef\ng h i .\n"
gap> RemoveCharacters(s, " \n\t\r"); # remove all whitespace characters gap> s; "abcdefghi."
\end{verbatim}
27.7.20 JoinStringsWithSeparator

\[ \text{JoinStringsWithSeparator}(\text{list}, \text{sep}) \]

Joins list (a list of strings) after interpolating sep (or "," if the second argument is omitted) between each adjacent pair of strings; sep should be a string.

Example

```gap
gap> list := List([1..10], String);
[ "1", "2", "3", "4", "5", "6", "7", "8", "9", "10" ]
gap> JoinStringsWithSeparator(list);
"1,2,3,4,5,6,7,8,9,10"
gap> JoinStringsWithSeparator(\["The", "quick", "brown", "fox"\], ",");
"The quick brown fox"
gap> new:= JoinStringsWithSeparator(\["a", "b", "c", "d"\], ",\n");
"a,\n b,\n c,\n d"
gap> Print(" 
	a, 
b, 
c, 
d
")
```

27.7.21 Chomp

\[ \text{Chomp}(\text{str}) \]

Like the similarly named Perl function, Chomp removes a trailing newline character (or carriage-return line-feed couplet) from a string argument str if present and returns the result. If str is not a string or does not have such trailing character(s) it is returned unchanged. This latter property means that Chomp is safe to use in cases where one is manipulating the result of another function which might sometimes return fail.

Example

```gap
gap> Chomp("The quick brown fox jumps over the lazy dog.\n");
"The quick brown fox jumps over the lazy dog."
gap> Chomp("The quick brown fox jumps over the lazy dog.\r\n");
"The quick brown fox jumps over the lazy dog."
gap> Chomp("The quick brown fox jumps over the lazy dog.");
"The quick brown fox jumps over the lazy dog."
gap> Chomp(fail); 
fail
gap> Chomp(32); 
32
```

Note: Chomp only removes a trailing newline character from str. If your string contains several newline characters and you really want to split str into lines at the newline characters (and remove those newline characters) then you should use SplitString (27.7.15), e.g.

Example

```gap
gap> str := "The quick brown fox\njumps over the lazy dog.\n";
"The quick brown fox\njumps over the lazy dog.\n"
gap> SplitString(str, ",", "\n");
[ "The quick brown fox", "jumps over the lazy dog." ]
```
gap> Chomp(str);
"The quick brown fox\n  jumps over the lazy dog."

27.7.22  StartsWith

\(\text{StartsWith}(\text{string, prefix})\)

\(\text{EndsWith}(\text{string, suffix})\)

Determines whether a string starts or ends with another string.

27.7.23  StringFormatted

\(\text{StringFormatted}(\text{string, data...})\)

\(\text{PrintFormatted}(\text{string, data...})\)

\(\text{PrintToFormatted}(\text{stream, string, data...})\)

These functions perform a string formatting operation. They accept a format string, which can contain replacement fields which are delimited by braces \{\}. Each replacement field contains a numeric or positional argument, describing the element of data to replace the braces with.

There are three formatting functions, which differ only in how they output the formatted string. StringFormatted returns the formatted string, PrintFormatted prints the formatted string and PrintToFormatted appends the formatted string to stream, which can be either an output stream or a filename.

The arguments after string form a list data of values used to substitute the replacement fields in string, using the following formatting rules:

string is treated as a normal string, except for occurrences of \{ and \}, which follow special rules, as follows:

The contents of \{ \} is split by a ! into \{id!format\}, where both id and format are optional. If the ! is omitted, the bracket is treated as \{id\} with no format.

id is interpreted as follows:

An integer i

Take the i th element of data.

A string str

If this is used, the first element of data must be a record r. In this case, the value r.(str) is taken.

No id given

Take the jth element of data, where j is the number of replacement fields with no id in the format string so far. If any replacement field has no id, then all replacement fields must have no id.

A single brace can be outputted by doubling, so {{ in the format string produces \{ and \}} produces \}.

The format decides how the variable is printed. format must be one of s (which uses String (27.7.6)), v (which uses ViewString (27.7.3)) or d (which calls DisplayString (27.7.1)). The default value for format is s.
The following two functions convert basic strings to lists of numbers and vice versa. They are useful for examples of text encryption.

### 27.7.24 NumbersString

```gap
NumbersString(s, m[, table])
```

NumbersString takes a string message `s` and returns a list of integers, each not exceeding the integer `m` that encode the message using the scheme $A = 11$, $B = 12$ and so on (and converting lower case to upper case). If a list of characters is given in `table`, it is used instead for encoding.

**Example**

```gap
gap> l:=NumbersString("Twas brillig and the slithy toves",1000000);
[ 303311, 291012, 281922, 221917, 101124, 141030, 181510, 292219, 301835, 103025, 321529 ]
```

### 27.7.25 StringNumbers

```gap
StringNumbers(l, m[, table])
```

StringNumbers takes a list `l` of integers that was encoded using NumbersString (27.7.24) and the size integer `m`, and returns a message string, using the scheme $A = 11$, $B = 12$ and so on. If a list of characters is given in `table`, it is used instead for decoding.

**Example**

```gap
gap> StringNumbers(l,1000000);
"TWAS BRILLIG AND THE SLITHY TÖVES"
```

### 27.7.26 StringOfMemoryAmount

```gap
StringOfMemoryAmount(numbytes)
```

This function returns a human-readable string representing `numbytes` of memory. It is used in printing amounts of memory allocated by tests and benchmarks. Binary prefixes (representing powers of 1024) are used.

**Example**

```gap
gap> StringOfMemoryAmount(123456789);
"117MB"
```
27.8 Character Conversion

The following functions convert characters in their internal integer values and vice versa. Note that the number corresponding to a particular character might depend on the system used. While most systems use an extension of ASCII, in particular character values outside the range \([ \text{32 .. 126} \)] might differ between architectures.

27.8.1 IntChar

\[ \text{IntChar} \( \text{char} \) \]

returns an integer value in the range \([ 0 .. 255 ]\) that corresponds to \text{char}.

27.8.2 CharInt

\[ \text{CharInt} \( \text{int} \) \]

returns a character that corresponds to the integer value \text{int}, which must be in the range \([ 0 .. 255 ]\).

Example

\[
\begin{array}{l}
gap> c := \text{CharInt}(65);
gap> 'A';
gap> \text{IntChar}(c);
\end{array}
\]

27.8.3 SIntChar

\[ \text{SIntChar} \( \text{char} \) \]

returns a signed integer value in the range \([ -128 .. 127 ]\) that corresponds to \text{char}.

27.8.4 CharSInt

\[ \text{CharSInt} \( \text{int} \) \]

returns a character which corresponds to the signed integer value \text{int}, which must be in the range \([ -128 .. 127 ]\).

The signed and unsigned integer functions behave the same for values in the range \([ 0 .. 127 ]\).

Example

\[
\begin{array}{l}
gap> \text{SIntChar}(c);
65
gap> c := \text{CharSInt}(-20);
gap> \text{SIntChar}(c);
-20
gap> \text{IntChar}(c);
236
gap> \text{SIntChar}(\text{CharInt}(255));
-1
\end{array}
\]
27.9 Operations to Evaluate Strings

27.9.1 Int (for strings)

\[ \text{Int}(\text{str}) \]  

returns an integer as represented by the string \text{str}. The argument string may optionally start with the sign character \ -, followed by a sequence of decimal digits. For any other input \text{fail} is returned. For backwards compatibility, the empty string is accepted, in which case 0 is returned as result.

\begin{verbatim}
gap> Int("12345"); 12345
gap> Int("123/45"); fail
gap> Int("1+2"); fail
gap> Int("-12"); -12
gap> Int("""); 0
\end{verbatim}

27.9.2 Rat (for strings)

\[ \text{Rat}(\text{str}) \]  

returns a rational as represented by the string \text{str}. The argument string may optionally start with the sign character \ -, followed by either a sequence of decimal digits or by two sequences of decimal digits that are separated by one of the characters / or ., where the latter stands for a decimal dot. For any other input \text{fail} is returned.

\begin{verbatim}
gap> Rat("123/45"); 41/15
gap> Rat("-123.45"); -2469/20
\end{verbatim}

27.9.3 IntHexString

\[ \text{IntHexString}(\text{str}) \]  

returns an integer as represented by the string \text{str}. The argument string may optionally start with the sign character \ -, followed by a sequence of hexadecimal digits. Here the letters a-f or A-F are used as digits 10 to 15. Any other input results in an error.

This function can be used (together with HexStringInt (27.7.8)) for efficiently storing and reading large integers from respectively into GAP. Note that the translation between integers and their hexadecimal representation costs linear computation time in terms of the number of digits, while translation from and into decimal representation needs substantial computations.

\begin{verbatim}
gap> IntHexString("-abcdef0123456789"); -12379813738877118345
\end{verbatim}
gap> HexStringInt(last);
"-ABCDEF0123456789"

27.9.4 Ordinal

\[ \text{Ordinal}(n) \] (function)

returns the ordinal of the integer \( n \) as a string.

Example

\[
gap> \text{Ordinal}(2); \ \text{Ordinal}(21); \ \text{Ordinal}(33); \ \text{Ordinal}(-33);
\]

"2nd"
"21st"
"33rd"
"-33rd"

27.9.5 EvalString

\[ \text{EvalString}(\text{expr}) \] (function)

passes the string \( \text{expr} \) through an input text stream so that GAP interprets it, and returns the result.

Example

\[
gap> a:=10;
10
gap> \text{EvalString("a^2")};
100
\]

EvalString is intended for single expressions. A sequence of commands may be interpreted by using the functions \text{InputTextString} (10.7.1) and \text{ReadAsFunction} (10.3.2) together; see 10.3 for an example.

If EvalString is used inside a function, then it doesn’t know about the local variables and the arguments of the function. A possible workaround is to define global variables in advance, and then to assign the values of the local variables to the global ones, like in the example below.

Example

\[
gap> \text{global}_a := 0;;
gap> \text{global}_b := 0;;
gap> \text{example} := \text{function ( local}_a \)
> \text{local local}_b;
> \text{local}_b := 5;
> \text{global}_a := \text{local}_a;
> \text{global}_b := \text{local}_b;
> \text{return EvalString("global}_a * \text{global}_b")};
> \text{end};;
gap> \text{example}(2);
10
\]
27.9.6 CrcString

➤ CrcString(str) (function)

Returns: an integer

This function computes a cyclic redundancy check number from a string str. See also CrcFile (9.7.7).

Example

\[
\text{gap> CrcString("GAP example string");} \\
-50451670
\]

27.10 Calendar Arithmetic

All calendar functions use the Gregorian calendar.

27.10.1 DaysInYear

➤ DaysInYear(year) (function)

returns the number of days in the year year.

27.10.2 DaysInMonth

➤ DaysInMonth(month, year) (function)

returns the number of days in month number month of year, and fail if month is not in the valid range.

Example

\[
\text{gap> DaysInYear(1998);} \\
365 \\
\text{gap> DaysInMonth(3,1998);} \\
31
\]

27.10.3 DMYDay

➤ DMYDay(day) (function)

converts a number of days, starting 1-Jan-1970, to a list \[ \text{day, month, year} \] in Gregorian calendar counting.

27.10.4 DayDMY

➤ DayDMY(dmy) (function)

returns the number of days from 01-Jan-1970 to the day given by dmy, which must be a list of the form \[ \text{day, month, year} \] in Gregorian calendar counting. The result is fail on input outside valid ranges.

Note that this makes not much sense for early dates like: before 1582 (no Gregorian calendar at all), or before 1753 in many English speaking countries or before 1917 in Russia.
27.10.5 WeekDay

\[ \text{WeekDay}(\text{date}) \]

returns the weekday of a day given by \text{date}, which can be a number of days since 1-Jan-1970 or a list \([\text{day, month, year}]\).

27.10.6 StringDate

\[ \text{StringDate}(\text{date}) \]

converts \text{date} to a readable string. \text{date} can be a number of days since 1-Jan-1970 or a list \([\text{day, month, year}]\).

\begin{verbatim}
gap> DayDMY([1,1,1970]); DayDMY([2,1,1970]);
0
1
gap> DMYDay(12345);
[ 20, 10, 2003 ]
gap> WeekDay([11,3,1998]);
"Wed"
gap> StringDate([11,3,1998]);
"11-Mar-1998"
\end{verbatim}

27.10.7 HMSMSec

\[ \text{HMSMSec}(\text{msec}) \]

converts a number \text{msec} of milliseconds into a list \([\text{hour, min, sec, milli}]\).

27.10.8 SecHMSM

\[ \text{SecHMSM}(\text{hmsm}) \]

is the reverse of \text{HMSMSec} (27.10.7).

27.10.9 StringTime

\[ \text{StringTime}(\text{time}) \]

converts \text{time} (given as a number of milliseconds or a list \([\text{hour, min, sec, milli}]\)) to a readable string.

\begin{verbatim}
gap> HMSMSec(Factorial(10));
[ 1, 0, 28, 800 ]
gap> SecHMSM([1,10,5,13]);
4205013
gap> StringTime([1,10,5,13]);
"1:10:05.013"
\end{verbatim}
27.10.10  SecondsDMYhms

\(\text{SecondsDMYhms(DMYhms)}\) (function)

returns the number of seconds from 01-Jan-1970, 00:00:00, to the time given by \(\text{DMYhms}\), which must be a list of the form \([\text{day}, \text{month}, \text{year}, \text{hour}, \text{minute}, \text{second}]\). The remarks on the Gregorian calendar in the section on \(\text{DayDMY (27.10.4)}\) apply here as well. The last three arguments must lie in the appropriate ranges.

27.10.11  DMYhmsSeconds

\(\text{DMYhmsSeconds(secs)}\) (function)

This is the inverse function to \(\text{SecondsDMYhms (27.10.10)}\).

Example

\begin{verbatim}
gap> SecondsDMYhms([ 9, 9, 2001, 1, 46, 40 ]); 1000000000
gap> DMYhmsSeconds(-1000000000); [ 24, 4, 1938, 22, 13, 20 ]
\end{verbatim}

27.11  Obtaining LaTeX Representations of Objects

For the purpose of generating \(\LaTeX\) source code with \GAP{} it is recommended to add new functions which will print the \(\LaTeX\) source or return \(\LaTeX\) strings for further processing.

An alternative approach could be based on methods for the default \(\LaTeX\) representation for each appropriate type of objects. However, there is no clear notion of a default \(\LaTeX\) code for any non-trivial mathematical object; moreover, different output may be required in different contexts.

While customisation of such an operation may require changes in a variety of methods that may be distributed all over the library, the user will have a clean overview of the whole process of \(\LaTeX\) code generation if it is contained in a single function. Furthermore, there may be kinds of objects which are not detected by the method selection, or there may be a need in additional parameters specifying requirements for the output.

This is why having a special purpose function for each particular case is more suitable. \GAP{} provides several functions that produce \(\LaTeX\) strings for those situations where this is nontrivial and reasonable. A useful example is \(\text{LaTeXStringDecompositionMatrix (71.11.5)}\) from the \GAP{} library, others can be found entering \(\text{?LaTeX}\) at the \GAP{} prompt. Package authors are encouraged to add an index entry \(\text{LaTeX}\) to the documentation of all \(\LaTeX\) string producing functions. This way, entering \(\text{?LaTeX}\) will give an overview of all documented functionality in this direction.
Chapter 28

Dictionaries and General Hash Tables

People and computers spend a large amount of time with searching. Dictionaries are an abstract data structure which facilitates searching for objects. Depending on the kind of objects the implementation will use a variety of possible internal storage methods that will aim to provide the fastest possible access to objects. These internal methods include

**Hash Tables**
- for objects for which a hash function has been defined.

**Direct Indexing**
- if the domain is small and cheaply enumerable

**Sorted Lists**
- if a total order can be computed easily

**Plain lists**
- for objects for which nothing but an equality test is available.

28.1 Using Dictionaries

The standard way to use dictionaries is to first create a dictionary (using `NewDictionary` (28.2.1), and then to store objects (and associated information) in it and look them up.

For the creation of objects the user has to make a few choices: Is the dictionary only to be used to check whether objects are known already, or whether associated information is to be stored with the objects. This second case is called a *lookup dictionary* and is selected by the second parameter of `NewDictionary` (28.2.1).

The second choice is to indicate which kind of objects are to be stored. This choice will decide the internal storage used. This kind of objects is specified by the first parameter to `NewDictionary` (28.2.1), which is a “sample” object.

In some cases however such a sample object is not specific enough. For example when storing vectors over a finite field, it would not be clear whether all vectors will be over a prime field or over a field extension. Such an issue can be resolved by indicating in an (optional) third parameter to `NewDictionary` (28.2.1) a *domain* which has to be a collection that will contain all objects to be used with this dictionary. (Such a domain may also be used internally to decide that direct indexing can be used).
The reason for this choice of giving two parameters is that in some cases no suitable collection of objects has been defined in GAP - for example for permutations there is no object representing the symmetric group on infinitely many points.

Once a dictionary has been created, it is possible to use RepresentationsOfObject (13.4.3) to check which representation is used by GAP.

In the following example, we create a dictionary to store permutations with associated information.

```gap
Example

gap> d:=NewDictionary((1,2,3),true,Elements(SymmetricGroup(5)));;
gap> RepresentationsOfObject(d);
[ "IsComponentObjectRep", "IsNonAtomicComponentObjectRep",
  "IsDictionaryDefaultRep", "IsListDictionary",
  "IsListLookupDictionary", "IsSortDictionary",
  "IsSortLookupDictionary" ]

(Just indicating SymmetricGroup(5) as a third parameter would still keep the first storage method, as indexing would be too expensive if no explicit element list is known.)

The same effect happens in the following example, in which we work with vectors: Indicating only a vector only enables sorted index, as it cannot be known whether all vectors will be defined over the prime field. On the other hand, providing the vector space (and thus limiting the domain) enables the use of hashing (which will be faster).

```
28.2 Dictionaries

This section contains the formal declarations for dictionaries. For information on how to use them, please refer to the previous section 28.1. There are several ways how dictionaries are implemented: As lists, as sorted lists, as hash tables or via binary lists. A user however will just have to call NewDictionary (28.2.1) and obtain a “suitable” dictionary for the kind of objects she wants to create. It is possible however to create hash tables (see 28.4) and dictionaries using binary lists (see DictionaryByPosition (28.3.1)).

The use of two objects, obj and objcoll to parametrize the objects a dictionary is able to store might look confusing. However there are situations where either of them might be needed:

The first situation is that of objects, for which no formal “collection object” has been defined. A typical example here might be subspaces of a vector space. GAP does not formally define a “Grassmannian” or anything else to represent the multitude of all subspaces. So it is only possible to give the dictionary a “sample object”.

The other situation is that of an object which might represent quite varied domains. The permutation (1,10^6) might be the nontrivial element of a cyclic group of order 2, it might be a representative of S_{10^6}. In the first situation the best approach might be just to have two entries for the two possible objects, in the second situation a much more elaborate approach might be needed.

An algorithm that creates a dictionary will usually know a priori, from what domain all the objects will be, giving this domain permits to use a more efficient dictionary.

This is particularly true for vectors. From a single vector one cannot decide whether a calculation will take place over the smallest field containing all its entries or over a larger field.

28.2.1 NewDictionary

\[ \text{NewDictionary(}obj, \text{look[, objcoll]}) \]

creates a new dictionary for objects such as \texttt{obj}. If \texttt{objcoll} is given the dictionary will be for objects only from this collection, knowing this can improve the performance. If \texttt{objcoll} is given, \texttt{obj} may be replaced by \texttt{false}, i.e. no sample object is needed.

The function tries to find the right kind of dictionary for the basic dictionary functions to be quick. If \texttt{look} is \texttt{true}, the dictionary will be a lookup dictionary, otherwise it is an ordinary dictionary.

28.3 Dictionaries via Binary Lists

As there are situations where the approach via binary lists is explicitly desired, such dictionaries can be created deliberately.

28.3.1 DictionaryByPosition

\[ \text{DictionaryByPosition(}list, \text{lookup}) \]

creates a new (lookup) dictionary which uses PositionCanonical (21.16.3) in \texttt{list} for indexing. The dictionary will have an entry \texttt{dict!.blist} which is a bit list corresponding to \texttt{list} indicating the known values. If \texttt{look} is \texttt{true}, the dictionary will be a lookup dictionary, otherwise it is an ordinary dictionary.
28.3.2 IsDictionary

\[\text{IsDictionary}(obj)\] (Category)

A dictionary is a growable collection of objects that permits to add objects (with associated values) and to check whether an object is already known.

28.3.3 IsLookupDictionary

\[\text{IsLookupDictionary}(obj)\] (Category)

A lookup dictionary is a dictionary, which permits not only to check whether an object is contained, but also to retrieve associated values, using the operation \text{LookupDictionary} (28.3.6).

28.3.4 AddDictionary

\[\text{AddDictionary}(dict, key[, val])\] (operation)

adds \textit{key} to the dictionary \textit{dict}, storing the associated value \textit{val} in case \textit{dict} is a lookup dictionary. If \textit{key} is not an object of the kind for which the dictionary was specified, or if \textit{key} is known already to \textit{dict}, the results are unpredictable.

28.3.5 KnowsDictionary

\[\text{KnowsDictionary}(dict, key)\] (operation)

checks, whether \textit{key} is known to the dictionary \textit{dict}, and returns \texttt{true} or \texttt{false} accordingly. \textit{key} must be an object of the kind for which the dictionary was specified, otherwise the results are unpredictable.

28.3.6 LookupDictionary

\[\text{LookupDictionary}(dict, key)\] (operation)

looks up \textit{key} in the lookup dictionary \textit{dict} and returns the associated value. If \textit{key} is not known to the dictionary, \texttt{fail} is returned.

28.4 General Hash Tables

These sections describe some particularities for hash tables. These are intended mainly for extending the implementation - programs requiring hash functionality ought to use the dictionary interface described above.

We hash by keys and also store a value. Keys cannot be removed from the table, but the corresponding value can be changed. Fast access to last hash index allows you to efficiently store more than one array of values –this facility should be used with care.

This code works for any kind of object, provided you have a \texttt{DenseIntKey} (28.5.1) method to convert the key into a positive integer. This method should ideally be implemented efficiently in the core.
Note that, for efficiency, it is currently impossible to create a hash table with non-positive integers.

### 28.5 Hash keys

The crucial step of hashing is to transform key objects into integers such that equal objects produce the same integer.

The actual function used will vary very much on the type of objects. However GAP provides already key functions for some commonly encountered objects.

#### 28.5.1 DenseIntKey

\[\text{DenseIntKey}(\text{objcoll}, \text{obj})\]

returns a function that can be used as hash key function for objects such as \text{obj} in the collection \text{objcoll}. Typically, \text{objcoll} will be a large domain. If the domain is not available, it can be given as \text{false} in which case the hash key function will be determined only based on \text{obj}. (For a further discussion of these two arguments see \text{NewDictionary} (28.2.1)).

The function returned by \text{DenseIntKey} is guaranteed to give different values for different objects. If no suitable hash key function has been predefined, \text{fail} is returned.

#### 28.5.2 SparseIntKey

\[\text{SparseIntKey}(\text{objcoll}, \text{obj})\]

returns a function that can be used as hash key function for objects such as \text{obj} in the collection \text{objcoll}. In contrast to \text{DenseIntKey} (28.5.1), the function returned may return the same key value for different objects. If no suitable hash key function has been predefined, \text{fail} is returned.

### 28.6 Dense hash tables

Dense hash tables are used for hashing dense sets without collisions, in particular integers. Keys are stored as an unordered list and values as an array with holes. The position of a value is given by the function returned by \text{DenseIntKey} (28.5.1), and so \text{KeyIntDense} must be one-to-one.

#### 28.6.1 DenseHashTable

\[\text{DenseHashTable}()\]

Construct an empty dense hash table. This is the only correct way to construct such a table.

### 28.7 Sparse hash tables

Sparse hash tables are used for hashing sparse sets. Stores keys as an array with fail denoting an empty position, stores values as an array with holes. Uses the result of calling \text{SparseIntKey} (28.5.2) of the key. \text{DefaultHashLength} is the default starting hash table length; the table is doubled when it becomes half full.
In sparse hash tables, the integer obtained from the hash key is then transformed to an index position by taking it modulo the length of the hash array.

28.7.1 SparseHashTable

SparseHashTable([intkeyfun[, startlength]]) (function)

Construct an empty sparse hash table. This is the only correct way to construct such a table. If the argument intkeyfun is given, this function will be used to obtain numbers for the keys passed to it. If also startlength is given, the hash table will be initialized at that size.

28.7.2 DoubleHashArraySize

DoubleHashArraySize(hash) (function)

Double the size of the hash array and rehash all the entries. This will also happen automatically when the hash array is half full.
Chapter 29

Records

Records are next to lists the most important way to collect objects together. A record is a collection of components. Each component has a unique name, which is an identifier that distinguishes this component, and a value, which is an object of arbitrary type. We often abbreviate value of a component to element. We also say that a record contains its elements. You can access and change the elements of a record using its name.

Record literals are written by writing down the components in order between “rec(“ and “)”, and separating them by commas “,”. Each component consists of the name, the assignment operator “:=”, and the value. The empty record, i.e., the record with no components, is written as rec().

```
Example
gap> rec( a := 1, b := "2" ); # a record with two components
rec( a := 1, b := "2" )
gap> rec( a := 1, b := rec( c := 2 ) ); # record may contain records
rec( a := 1, b := rec( c := 2 ) )
```

We may use the Display (6.3.6) function to illustrate the hierarchy of the record components.

```
Example
gap> Display( last );
rec(  
a := 1,
b := rec(  
    c := 2  )
  )
```

Records usually contain elements of various types, i.e., they are usually not homogeneous like lists.

29.1 IsRecord and RecNames

29.1.1 IsRecord
Example

\begin{verbatim}
gap> IsRecord( rec( a := 1, b := 2 ) );
true
gap> IsRecord( IsRecord );
false
\end{verbatim}

### 29.1.2 RecNames

\begin{verbatim}
\textbf{RecNames}(record)
\end{verbatim}

returns a list of strings corresponding to the names of the record components of the record `record`.

Example

\begin{verbatim}
gap> r := rec( a := 1, b := 2 );;
gap> Set(RecNames( r )); # 'Set' because ordering depends on GAP session
[ "a", "b" ]
\end{verbatim}

Note that you cannot use the string result in the ordinary way to access or change a record component. You can use the `record.(name)` construct for that, see 29.2 and 29.3.

### 29.2 Accessing Record Elements

\begin{verbatim}
r.name
\end{verbatim}

The above construct evaluates to the value of the record component with the name `name` in the record `r`. Note that the name is not evaluated, i.e. it is taken literal.

Example

\begin{verbatim}
gap> r := rec( a := 1, b := 2 );;
gap> r.a;
1
gap> r.b;
2
\end{verbatim}

\begin{verbatim}
r.(name)
\end{verbatim}

This construct is similar to the above construct. The difference is that the second operand `name` is evaluated. It must evaluate to a string or an integer otherwise an error is signalled. The construct then evaluates to the element of the record `r` whose name is, as a string, equal to `name`.

Example

\begin{verbatim}
gap> old := rec( a := 1, b := 2 );;
gap> new := rec();
rec( )
gap> for i in RecNames( old ) do
> new.(i) := old.(i);
> od;
gap> Display( new );
rec(  
a := 1,
b := 2 )
\end{verbatim}
### 29.3 Record Assignment

\[ r . \text{name} := \text{obj} \]

The record assignment assigns the object \( \text{obj} \), which may be an object of arbitrary type, to the record component with the name \( \text{name} \), which must be an identifier, of the record \( r \). That means that accessing the element with name \( \text{name} \) of the record \( r \) will return \( \text{obj} \) after this assignment. If the record \( r \) has no component with the name \( \text{name} \), the record is automatically extended to make room for the new component.

```gap
gap> r := rec( a := 1, b := 2 );;
gap> r.a := 10;;
gap> Display( r ); rec( a := 10, b := 2 )
gap> r.c := 3;;
gap> Display( r ); rec( a := 10, b := 2, c := 3 )
```

Note that assigning to a record changes the record.

The function \texttt{IsBound} (29.6.1) can be used to test if a record has a component with a certain name, the function \texttt{Unbind} (29.6.2) can be used to remove a component with a certain name again.

```gap
gap> IsBound(r.a); true
gap> IsBound(r.d); false
gap> Unbind(r.b);
gap> Display( r ); rec( a := 10, c := 3 )
```

\[ r . (\text{name}) := \text{obj} \]

This construct is similar to the above construct. The difference is that the second operand \( \text{name} \) is evaluated. It must evaluate to a string or an integer otherwise an error is signalled. The construct then assigns \( \text{obj} \) to the record component of the record \( r \) whose name is, as a string, equal to \( \text{name} \).

### 29.4 Identical Records

With the record assignment (see 29.3) it is possible to change a record. This section describes the semantic consequences of this fact which are essentially the same as for lists (see 21.6).

```gap
r := rec( a := 1 );
r := rec( a := 1, b := 2 );
```
The second assignment does not change the first record, instead it assigns a new record to the variable \( r \). On the other hand, in the following example the record is changed by the second assignment.

\[
\begin{align*}
r &:= \text{rec}( a := 1 ); \\
r.b &:= 2;
\end{align*}
\]

To understand the difference first think of a variable as a name for an object. The important point is that a record can have several names at the same time. An assignment \( \text{var} := r \) means in this interpretation that \( \text{var} \) is a name for the object \( r \). At the end of the following example \( r2 \) still has the value \( \text{rec}( a := 1 ) \) as this record has not been changed and nothing else has been assigned to \( r2 \).

\[
\begin{align*}
r1 &:= \text{rec}( a := 1 ); \\
r2 &:= r1; \\
r1 &:= \text{rec}( a := 1, b := 2 );
\end{align*}
\]

But after the following example the record for which \( r2 \) is a name has been changed and thus the value of \( r2 \) is now \( \text{rec}( a := 1, b := 2 ) \).

\[
\begin{align*}
r1 &:= \text{rec}( a := 1 ); \\
r2 &:= r1; \\
r1.b &:= 2;
\end{align*}
\]

We shall say that two records are \textit{identical} if changing one of them by a record assignment also changes the other one. This is slightly incorrect, because if two records are identical, there are actually only two names for one record. However, the correct usage would be very awkward and would only add to the confusion. Note that two identical records must be equal, because there is only one record with two different names. Thus identity is an equivalence relation that is a refinement of equality.

Let us now consider under which circumstances two records are identical.

If you enter a record literal then the record denoted by this literal is a new record that is not identical to any other record. Thus in the following example \( r1 \) and \( r2 \) are not identical, though they are equal of course.

\[
\begin{align*}
r1 &:= \text{rec}( a := 1 ); \\
r2 &:= \text{rec}( a := 1 );
\end{align*}
\]

Also in the following example, no records in the list \( l \) are identical.

\[
\begin{align*}
l &:= []; \\
\text{for } i \text{ in } [1..10] \text{ do} \\
\quad l[i] &:= \text{rec}( a := 1 );
\text{od};
\end{align*}
\]

If you assign a record to a variable no new record is created. Thus the record value of the variable on the left hand side and the record on the right hand side of the assignment are identical. So in the following example \( r1 \) and \( r2 \) are identical records.
If you pass a record as argument, the old record and the argument of the function are identical. Also if you return a record from a function, the old record and the value of the function call are identical. So in the following example \( r1 \) and \( r2 \) are identical records.

\[
\begin{align*}
   r1 &:= \text{rec}( a := 1 ); \\
   f &:= \text{function}( r ) \text{return } r; \text{ end}; \\
   r2 &:= f( r1 );
\end{align*}
\]

The functions \texttt{StructuralCopy (12.7.2)} and \texttt{ShallowCopy (12.7.1)} accept a record and return a new record that is equal to the old record but that is \textit{not} identical to the old record. The difference between \texttt{StructuralCopy (12.7.2)} and \texttt{ShallowCopy (12.7.1)} is that in the case of \texttt{ShallowCopy (12.7.1)} the corresponding components of the new and the old records will be identical, whereas in the case of \texttt{StructuralCopy (12.7.2)} they will only be equal. So in the following example \( r1 \) and \( r2 \) are not identical records.

\[
\begin{align*}
   r1 &:= \text{rec}( a := 1 ); \\
   r2 &:= \text{ShallowCopy}( r1 );
\end{align*}
\]

If you change a record it keeps its identity. Thus if two records are identical and you change one of them, you also change the other, and they are still identical afterwards. On the other hand, two records that are not identical will never become identical if you change one of them. So in the following example both \( r1 \) and \( r2 \) are changed, and are still identical.

\[
\begin{align*}
   r1 &:= \text{rec}( a := 1 ); \\
   r2 &:= r1; \\
   r1.b &:= 2;
\end{align*}
\]

### 29.5 Comparisons of Records

\[
\begin{align*}
   \text{rec1} &\equiv \text{rec2} \\
   \text{rec1} &\neq \text{rec2}
\end{align*}
\]

Two records are considered equal, if for each component of one record the other record has a component of the same name with an equal value and vice versa.

\[
\begin{align*}
   \text{gap} &> \text{rec}( a := 1, b := 2 ) = \text{rec}( b := 2, a := 1 ); \\
   \text{true} &> \text{rec}( a := 1, b := 2 ) = \text{rec}( a := 2, b := 1 ); \\
   \text{false} &> \text{rec}( a := 1 ) = \text{rec}( a := 1, b := 2 ); \\
   \text{false} &> \text{rec}( a := 1 ) = 1; \\
   \text{false}
\end{align*}
\]
To compare records we imagine that the components of both records are sorted according to their names (the sorting depends on the GAP session, more precisely the order in which component names were first used). Then the records are compared lexicographically with unbound elements considered smaller than anything else. Precisely one record \texttt{rec1} is considered less than another record \texttt{rec2} if \texttt{rec2} has a component with name \texttt{name2} and either \texttt{rec1} has no component with this name or \texttt{rec1.name2 < rec2.name2} and for each component of \texttt{rec1} with name \texttt{name1 < name2 rec2} has a component with this name and \texttt{rec1.name1 = rec2.name1}.

\begin{verbatim}
gap> rec( axy := 1, bxy := 2 ) < rec( bxy := 2, axy := 1 ); # are equal false

gap> rec( axy := 1 ) < rec( axy := 1, bxy := 2 ); # unbound is < 2 true

gap> # in new session the .axy components are compared first

gap> rec( axy := 1, bxy := 2 ) < rec( axy := 2, bxy := 0 ); # 1 < 2 true

gap> rec( axy := 1 ) < rec( axy := 0, bxy := 2 ); # 0 < 1 false

gap> rec( bxy := 1 ) < rec( bxy := 0, axy := 2 ); # unbound is < 2 true
\end{verbatim}

\section{29.6 \texttt{IsBound} and \texttt{Unbind} for Records}

\subsection{29.6.1 \texttt{IsBound} (for a record component)}

\begin{verbatim}
▷ IsBound(r.name)
\end{verbatim}

\texttt{IsBound} returns \texttt{true} if the record \texttt{r} has a component with the name \texttt{name} (which must be an identifier) and \texttt{false} otherwise. \texttt{r} must evaluate to a record, otherwise an error is signalled.

\begin{verbatim}
gap> r := rec( a := 1, b := 2 );;

gap> IsBound( r.a );
true

gap> IsBound( r.c );
false
\end{verbatim}

\subsection{29.6.2 \texttt{Unbind} (unbind a record component)}

\begin{verbatim}
▷ Unbind(r.name)
\end{verbatim}

\texttt{Unbind} deletes the component with the name \texttt{name} in the record \texttt{r}. That is, after execution of \texttt{Unbind}, \texttt{r} no longer has a record component with this name. Note that it is not an error to unbind a nonexisting record component. \texttt{r} must evaluate to a record, otherwise an error is signalled.

\begin{verbatim}
gap> r := rec( a := 1, b := 2 );;

gap> Unbind( r.a ); r;
rec( b := 2 )
\end{verbatim}
Note that IsBound (29.6.1) and Unbind are special in that they do not evaluate their argument, otherwise IsBound (29.6.1) would always signal an error when it is supposed to return false and there would be no way to tell Unbind which component to remove.

29.7 Record Access Operations

Internally, record accesses are done using the operations listed in this section. For the records implemented in the kernel, kernel methods are provided for all these operations but otherwise it is possible to install methods for these operations for any object. This permits objects to simulate record behavior.

To save memory, records do not store a list of all component names, but only numbers identifying the components. There numbers are called RNams. GAP keeps a global list of all RNams that are used and provides the functions NameRNam (29.7.1) and RNamObj (29.7.2) to translate RNams to strings that give the component names and vice versa.

29.7.1 NameRNam

\( \text{NameRNam}(nr) \)

returns a string representing the component name corresponding to the RNam \( nr \).

29.7.2 RNamObj (for a string)

\( \text{RNamObj}(str) \)
\( \text{RNamObj}(int) \)

returns a number (the RNam) corresponding to the string \( str \). It is also possible to pass a positive integer \( int \) in which case the decimal expansion of \( int \) is used as a string.

Example

\[
gap> \text{NameRNam}(798); \\
"BravaisSupergroups" \\
gap> \text{RNamObj}("blubberflutsch"); \\
2075 \\
gap> \text{NameRNam}(last); \\
"blubberflutsch"
\]

The correspondence between strings and RNams is not predetermined ab initio, but RNams are assigned to component names dynamically on a “first come, first serve” basis. Therefore, depending on the version of the library you are using and on the assignments done so far, the same component name may be represented by different RNams in different GAP sessions.

29.7.3 \.

\( \text{\.}(obj, rnam) \)
\( \text{IsBound\.}(obj, rnam) \)
These operations are called for record accesses to arbitrary objects. If applicable methods are installed, they are called when the object is accessed as a record.

For records, the operations implement component access, test for element boundness, component assignment and removal of the component represented by the RNam \textit{rnam}.

The component identifier \textit{rnam} is always required to be in \texttt{IsPosInt (14.2.2)}.

Example:

```gap
gap> r:= rec( a:= 1 );;
gap> IsBound\.( r, RNamObj( "a" ) );
true
gap> \.( r, RNamObj( "a" ) );
1
gap> IsBound\.( r, RNamObj( "b" ) );
false
gap> \.:=( r, RNamObj( "b" ), 2 );
gap> r;
rec( a := 1, b := 2 )
gap> Unbind\.( r, RNamObj( "b" ) );
gap> r;
rec(a := 1)
gap> G:= SymmetricGroup( 4 );;
gap> G.1;
(1,2,3,4)
gap> \.( G, RNamObj( 1 ) );
(1,2,3,4)
gap> meth:= ApplicableMethod( \., [ G, 4711 ] );;
gap> meth(G, RNamObj( 1 ));
(1,2,3,4)
```
Chapter 30

Collections

A collection in GAP consists of elements in the same family (see 13.1). The most important kinds of collections are homogeneous lists (see 21) and domains (see 12.4). Note that a list is never a domain, and a domain is never a list. A list is a collection if and only if it is nonempty and homogeneous.

Basic operations for collections are Size (30.4.6) and Enumerator (30.3.2); for finite collections, Enumerator (30.3.2) admits to delegate the other operations for collections (see 30.4 and 30.5) to functions for lists (see 21). Obviously, special methods depending on the arguments are needed for the computation of e.g. the intersection of two infinite domains.

30.1 IsCollection (Filter)

30.1.1 IsCollection

\[ \text{IsCollection(obj)} \]  

(Category)

tests whether an object is a collection.

Some of the functions for lists and collections are described in the chapter about lists, mainly in Section 21.20. In the current chapter, we describe those functions for which the “collection aspect” seems to be more important than the “list aspect”.

30.2 Collection Families

30.2.1 CollectionsFamily

\[ \text{CollectionsFamily(Fam)} \]  

(attribute)

For a family Fam, CollectionsFamily returns the family of all collections over Fam, that is, of all dense lists and domains that consist of objects in Fam.

The NewFamily (13.1.2) call in the standard method of CollectionsFamily is executed with second argument IsCollection (30.1.1), since every object in the collections family must be a collection, and with third argument the collections categories of the involved categories in the implied filter of Fam.

Note that families (see 13.1) are used to describe relations between objects. Important such relations are that between an element e and each collection of elements that lie in the same family as e,
and that between two collections whose elements lie in the same family. Therefore, all collections of elements in the family \( \text{Fam} \) form the new family \( \text{CollectionsFamily}(\ \text{Fam}) \).

### 30.2.2 IsCollectionFamily

\[ \text{IsCollectionFamily}(\text{obj}) \] (Category)

is true if \( \text{Fam} \) is a family of collections, and false otherwise.

### 30.2.3 ElementsFamily

\[ \text{ElementsFamily}(\text{Fam}) \] (attribute)

If \( \text{Fam} \) is a collections family (see IsCollectionFamily (30.2.2)) then ElementsFamily returns the family from which \( \text{Fam} \) was created by CollectionsFamily (30.2.1). The way a collections family is created, it always has its elements family stored. If \( \text{Fam} \) is not a collections family then an error is signalled.

#### Example

```gap
gap> fam:=FamilyObj( (1,2) );;
gap> collfam:=CollectionsFamily( fam );;
gap> fam = collfam; fam = ElementsFamily( collfam );
false true
gap> collfam = FamilyObj( [ (1,2,3) ] );
true
gap> collfam = FamilyObj( Group( () ) );
true
gap> collfam = CollectionsFamily( collfam );
false
```

### 30.2.4 CategoryCollections

\[ \text{CategoryCollections}(\text{filter}) \] (function)

Let \( \text{filter} \) be a filter that is true for all elements of a family \( \text{Fam} \), by the construction of \( \text{Fam} \). Then CategoryCollections returns the collections category of \( \text{filter} \). This is a category that is true for all elements in CollectionsFamily( \( \text{Fam} \) ).

For example, the construction of PermutationsFamily (42.1.3) guarantees that each of its elements lies in the filter IsPerm (42.1.1), and each collection of permutations (permutation group or dense list of permutations) lies in the category CategoryCollections( IsPerm ). Note that this works only if the collections category is created before the collections family. So it is necessary to construct interesting collections categories immediately after the underlying category has been created.

### 30.2.5 DeclareCategoryCollections

\[ \text{DeclareCategoryCollections}(\text{filter}) \] (function)
Calls \texttt{CategoryCollections} (30.2.4) on the category that is bound to the global variable with name \texttt{name} to obtain its collections category, and binds the latter to the global variable with name \texttt{nname}. This name is defined as follows: If \texttt{name} is of the form \texttt{Something}\texttt{Coll} then \texttt{nname} is set to \texttt{Something}\texttt{Coll}\texttt{Coll}, if \texttt{name} is of the form \texttt{Something}\texttt{Coll} then \texttt{nname} is set to \texttt{Something}\texttt{Coll}\texttt{Coll}, otherwise we set \texttt{nname} to \texttt{name}\texttt{Collection}.

### 30.3 Lists and Collections

The following functions take a \textit{list or collection} as argument, and return a corresponding \textit{list}. They differ in whether or not the result is mutable or immutable (see 12.6), guaranteed to be sorted, or guaranteed to admit list access in constant time (see \texttt{IsConstantTimeAccessList} (21.1.6)).

#### 30.3.1 IsListOrCollection

\begin{verbatim}
\texttt{IsListOrCollection(obj)} (Category)
\end{verbatim}

Several functions are defined for both lists and collections, for example \texttt{Intersection} (30.5.2), \texttt{Iterator} (30.8.1), and \texttt{Random} (30.7.1). \texttt{IsListOrCollection} is a supercategory of \texttt{IsList} (21.1.1) and \texttt{IsCollection} (30.1.1) (that is, all lists and collections lie in this category), which is used to describe the arguments of functions such as the ones listed above.

#### 30.3.2 Enumerator

\begin{verbatim}
\texttt{Enumerator(listorcoll)} (attribute)
\end{verbatim}

\texttt{Enumerator} returns an immutable list \textit{enum}. If the argument is a list (which may contain holes), then \texttt{Length()} is the length of this list, and \textit{enum} contains the elements (and holes) of this list in the same order. If the argument is a collection that is not a list, then \texttt{Length()} is the number of different elements of \textit{C}, and \textit{enum} contains the different elements of the collection in an unspecified order, which may change for repeated calls of \texttt{Enumerator}. \texttt{enum[pos]} may not execute in constant time (see \texttt{IsConstantTimeAccessList} (21.1.6)), and the size of \textit{enum} in memory is as small as is feasible.

For lists, the default method is \texttt{Immutable} (12.6.3). For collections that are not lists, there is no default method.

#### 30.3.3 EnumeratorSorted

\begin{verbatim}
\texttt{EnumeratorSorted(listorcoll)} (attribute)
\end{verbatim}

\texttt{EnumeratorSorted} returns an immutable list \textit{enum}. The argument must be a collection or a list \textit{listorcoll} which may contain holes but whose elements lie in the same family (see 13.1). \texttt{Length()} is the number of different elements of the argument, and \textit{enum} contains the different elements in sorted order, w.r.t. \texttt{<}. \texttt{enum[pos]} may not execute in constant time (see \texttt{IsConstantTimeAccessList} (21.1.6)), and the size of \textit{enum} in memory is as small as is feasible.
Example

```gap
gap> Enumerator([1, 3,, 2]);
[ 1, 3,, 2 ]
gap> enum := Enumerator( Rationals );; elm := enum[10^6];
-69/907
gap> Position( enum, elm );
1000000
gap> IsMutable( enum ); IsSortedList( enum );
false false
gap> IsConstantTimeAccessList( enum );
false
gap> EnumeratorSorted([1, 3,, 2]);
[ 1, 2, 3 ]
```

### 30.3.4 EnumeratorByFunctions (for a domain and a record)

* EnumeratorByFunctions(D, record) (function)
* EnumeratorByFunctions(Fam, record) (function)

`EnumeratorByFunctions` returns an immutable, dense, and duplicate-free list `enum` for which `IsBound` (21.5.1), element access via `\[\]` (21.2.1), `Length` (21.17.5), and `Position` (21.16.1) are computed via prescribed functions.

Let `record` be a record with at least the following components.

**ElementNumber**
A function taking two arguments `enum` and `pos`, which returns `enum[pos]` (see 21.2); it can be assumed that the argument `pos` is a positive integer, but `pos` may be larger than the length of `enum` (in which case an error must be signalled); note that the result must be immutable since `enum` itself is immutable.

**NumberElement**
A function taking two arguments `enum` and `elm`, which returns `Position(enum, elm)` (see `Position` (21.16.1)); it cannot be assumed that `elm` is really contained in `enum` (and `fail` must be returned if not); note that for the three argument version of `Position` (21.16.1), the method that is available for duplicate-free lists suffices.

Further (data) components may be contained in `record` which can be used by these function.

If the first argument is a domain `D` then `enum` lists the elements of `D` (in general `enum` is not sorted), and methods for `Length` (21.17.5), `IsBound` (21.5.1), and `PrintObj` (6.3.5) may use `D`.

If one wants to describe the result without creating a domain then the elements are given implicitly by the functions in `record`, and the first argument must be a family `Fam` which will become the family of `enum`; if `enum` is not homogeneous then `Fam` must be `ListsFamily`, otherwise it must be the collections family of any element in `enum`. In this case, additionally the following component in `record` is needed.

**Length**
A function taking the argument `enum`, which returns the length of `enum` (see `Length` (21.17.5)).
The following components are optional; they are used if they are present but default methods are installed for the case that they are missing.

**IsBound**

a function taking two arguments `enum` and `k`, which returns `IsBound( enum[ k ] )` (see 21.2); if this component is missing then `Length` (21.17.5) is used for computing the result.

**Membership**

a function taking two arguments `elm` and `enum`, which returns `true` if `elm` is an element of `enum`, and `false` otherwise (see 21.2); if this component is missing then `NumberElement` is used for computing the result.

**AsList**

a function taking one argument `enum`, which returns a list with the property that the access to each of its elements will take roughly the same time (see `IsConstantTimeAccessList` (21.1.6)); if this component is missing then `ConstantTimeAccessList` (21.17.6) is used for computing the result.

**ViewObj** and **PrintObj**

two functions that print what one wants to be printed when `View( enum )` or `Print( enum )` is called (see 6.3), if the `ViewObj` component is missing then the `PrintObj` method is used as a default.

If the result is known to have additional properties such as being strictly sorted (see `IsSSortedList` (21.17.4)) then it can be useful to set these properties after the construction of the enumerator, before it is used for the first time. And in the case that a new sorted enumerator of a domain is implemented via `EnumeratorByFunctions`, and this construction is installed as a method for the operation `Enumerator` (30.3.2), then it should be installed also as a method for `EnumeratorSorted` (30.3.3).

Note that it is not checked that `EnumeratorByFunctions` really returns a dense and duplicate-free list. `EnumeratorByFunctions` does not make a shallow copy of `record`, this record is changed in place, see 79.1.

It would be easy to implement a slightly generalized setup for enumerators that need not be duplicate-free (where the three argument version of `Position` (21.16.1) is supported), but the resulting overhead for the methods seems not to be justified.

### 30.3.5 List (for a collection)

**List(C)** (function)

For a collection `C` (see 30) that is not a list, `List` returns a new mutable list `new` such that `Length( new )` is the number of different elements of `C`, and `new` contains the different elements of `C` in an unspecified order which may change for repeated calls. `new[ pos ]` executes in constant time (see `IsConstantTimeAccessList` (21.1.6)), and the size of `new` is proportional to its length. The generic method for this case is `ShallowCopy( Enumerator( C ) )`.

Example

```
gap> l:= List( Group( (1,2,3) ) );
[ (), (1,3,2), (1,2,3) ]
```
gap> IsMutable( 1 );  IsSortedList( 1 );  IsConstantTimeAccessList( 1 );
true
false
true

(See also List (21.20.19)).

### 30.3.6 SortedList

**SortedList**

\[ \text{SortedList} \text{\([listorcoll[, \text{func}]\])} \]

\text{SortedList} \ returns \ a \ new \ mutable \ and \ dense \ list \ \textit{new}. \ The \ argument \ must \ be \ a \ collection \ or \ list \ \textit{listorcoll} \ which \ may \ contain \ holes \ but \ whose \ elements \ lie \ in \ the \ same \ family \ (see \ 13.1). \ \text{Length} (\ \textit{new}) \ \text{is} \ \text{the} \ \text{number} \ \text{of} \ \text{elements} \ \text{of} \ \textit{listorcoll}, \ \text{and} \ \textit{new} \ \text{contains} \ \text{the} \ \text{elements} \ \text{in} \ \text{sorted} \ \text{order,} \ \text{w.r.t.} < \ \text{or} \ \text{func} \ \text{if} \ \text{it} \ \text{is} \ \text{specified}. \ \text{For} \ \text{details}, \ \text{please} \ \text{refer} \ \text{to} \ \text{Sort} (21.18.1). \ \text{new} [\text{pos}] \ \text{executes} \ \text{in} \ \text{constant} \ \text{time} \ (\text{see IsConstantTimeAccessList} (21.1.6)), \ \text{and} \ \text{the} \ \text{size} \ \text{of} \ \textit{new} \ \text{in} \ \text{memory} \ \text{is} \ \text{proportional} \ \text{to} \ \text{its} \ \text{length}.

Example

\[
gap> l:= \text{SortedList}( \text{Group}( (1,2,3) ) );
[ () , (1,2,3) , (1,3,2) ]
gap> \text{IsMutable}( 1 );  \text{IsSortedList}( 1 );  \text{IsConstantTimeAccessList}( 1 );
true
true
true
\]

\[
gap> \text{SortedList}( [ 1, 2, 1,, 3, 2 ] );
[ 1, 1, 2, 2, 3 ]
\]

### 30.3.7 SSortedList

**SSortedList**

\[ \text{SSortedList} \text{\([listorcoll[, \text{func}]\])} \]

SSortedList \( (\text{"strictly sorted list"}) \) \ returns \ a \ new \ dense, \ mutable, \ and \ duplicate \ free \ list \ \textit{new}. \ The \ argument \ must \ be \ a \ collection \ or \ list \ \textit{listorcoll} \ which \ may \ contain \ holes.

If \ the \ optional \ argument \ \textit{func} \ is \ not \ given \ then \ \text{Length} (\ \textit{new}) \ \text{is} \ \text{the} \ \text{number} \ \text{of} \ \text{different} \ \text{elements} \ \text{of} \ \textit{listorcoll}, \ \text{and} \ \textit{new} \ \text{contains} \ \text{the} \ \text{different} \ \text{elements} \ \text{in} \ \text{strictly} \ \text{sorted} \ \text{order,} \ \text{w.r.t.} \ \textless \ (31.11.1). \ \text{For} \ \text{that}, \ \text{any} \ \text{two} \ \text{entries} \ \text{of} \ \textit{listorcoll} \ \text{must} \ \text{be} \ \text{comparable} \ \text{via} \ \textless \ (31.11.1). \ (\text{Typically,} \ \text{the} \ \text{entries} \ \text{lie} \ \text{in} \ \text{the} \ \text{same} \ \text{family,} \ \text{see} \ 13.1.)

If \ \textit{func} \ is \ given \ then \ it \ must \ be \ a \ unary \ function. \ In \ this \ case, \ \textit{func} \ \text{is} \ \text{applied} \ \text{to} \ \text{all} \ \text{elements} \ \text{of} \ \textit{listorcoll}, \ \textit{new} \ \text{contains} \ \text{the} \ \text{different} \ \text{return} \ \text{values} \ \text{in} \ \text{strictly} \ \text{sorted} \ \text{order,} \ \text{and} \ \text{Length} (\ \textit{new}) \ \text{is} \ \text{the} \ \text{number} \ \text{of} \ \text{different} \ \text{such} \ \text{values}. \ \text{For} \ \text{that}, \ \text{any} \ \text{two} \ \text{return} \ \text{values} \ \text{must} \ \text{be} \ \text{comparable} \ \text{via} \ \textless \ (31.11.1).

\text{new} [\text{pos}] \ \text{executes} \ \text{in} \ \text{constant} \ \text{time} \ (\text{see IsConstantTimeAccessList} (21.1.6)), \ \text{and} \ \text{the} \ \text{size} \ \text{of} \ \textit{new} \ \text{in} \ \text{memory} \ \text{is} \ \text{proportional} \ \text{to} \ \text{its} \ \text{length}.

Set \ is \ simply \ a \ synonym \ for \ SSortedList.

Example

\[
gap> 1:= \text{SSortedList}( \text{Group}( (1,2,3) ) );
[ () , (1,2,3) , (1,3,2) ]
\]
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30.3.8 AsList

AsList returns a immutable list imm. If the argument is a list (which may contain holes), then Length(imm) is the Length (21.17.5) value of this list, and imm contains the elements (and holes) of of the list in the same order. If the argument is a collection that is not a list, then Length(imm) is the number of different elements of this collection, and imm contains the different elements of the collection in an unspecified order, which may change for repeated calls of AsList. imm[pos] executes in constant time (see IsConstantTimeAccessList (21.1.6)), and the size of imm in memory is proportional to its length.

If you expect to do many element tests in the resulting list, it might be worth to use a sorted list instead, using AsSSortedList (30.3.10).

Example

```gap]
gap> l:= AsList( [ 1, 3, 3,, 2 ] );
[ 1, 3, 3,, 2 ]
gap> IsMutable( l ); IsSortedList( l ); IsConstantTimeAccessList( l );
false false true
gap> AsList( Group( (1,2,3), (1,2) ) );
[ (1), (2,3), (1,2), (1,2,3), (1,3,2), (1,3) ]
```

30.3.9 AsSortedList

AsSortedList returns a dense and immutable list imm. The argument must be a collection or list listorcoll which may contain holes but whose elements lie in the same family (see 13.1). Length(imm) is the number of elements of the argument, and imm contains the elements in sorted order, w.r.t. <=. new[pos] executes in constant time (see IsConstantTimeAccessList (21.1.6)), and the size of imm in memory is proportional to its length.

The only difference to the operation SortedList (30.3.6) is that AsSortedList returns an immutable list.

Example

```gap]
gap> l:= AsSortedList( [ 1, 3, 3,, 2 ] );
[ 1, 2, 3, 3 ]
gap> IsMutable( l ); IsSortedList( l ); IsConstantTimeAccessList( l );
true true true
```
false
true
true
gap> IsSSortedList( l );
false

30.3.10 AsSSortedList

AsSSortedList ("as strictly sorted list") returns a dense, immutable, and duplicate free list \textit{imm}. The argument must be a collection or list \textit{listorcoll} which may contain holes but whose elements lie in the same family (see 13.1). \texttt{Length( imm )} is the number of different elements of \textit{listorcoll}, and \textit{imm} contains the different elements in strictly sorted order, w.r.t. \texttt{<} (31.11.1). \textit{imm}[\textit{pos}] executes in constant time (see \texttt{IsConstantTimeAccessList} (21.1.6)), and the size of \textit{imm} in memory is proportional to its length.

Because the comparisons required for sorting can be very expensive for some kinds of objects, you should use \texttt{AsList} (30.3.8) instead if you do not require the result to be sorted.

The only difference to the operation \texttt{SSortedList} (30.3.7) is that AsSSortedList returns an \textit{immutable} list.

AsSet is simply a synonym for AsSSortedList.

In general a function that returns a set of elements is free, in fact encouraged, to return a domain instead of the proper set of its elements. This allows one to keep a given structure, and moreover the representation by a domain object is usually more space efficient. AsSSortedList must of course \textit{not} do this, its only purpose is to create the proper set of elements.

\begin{verbatim}
gap> l:= AsSSortedList( l );
[ 1, 2, 3 ]
gap> IsMutable( l ); IsSSortedList( l ); IsConstantTimeAccessList( l );
false
true
true
gap> AsSSortedList( Group( (1,2,3), (1,2) ) );
[ (), (2,3), (1,2), (1,2,3), (1,3,2), (1,3) ]
\end{verbatim}

30.3.11 Elements

Elements does the same as AsSSortedList (30.3.10), that is, the return value is a strictly sorted list of the elements in the list or collection \textit{C}.

Elements is only supported for backwards compatibility. In many situations, the sortedness of the "element list" for a collection is in fact not needed, and one can save a lot of time by asking for a list that is \textit{not} necessarily sorted, using AsList (30.3.8). If one is really interested in the strictly sorted list of elements in \textit{C} then one should use AsSet (30.3.10) or AsSSortedList (30.3.10) instead.
30.4 Attributes and Properties for Collections

30.4.1 IsEmpty

IsEmpty(listorcoll)

IsEmpty returns true if the collection or list listorcoll is empty (that is it contains no elements), and false otherwise.

30.4.2 IsFinite

IsFinite(C)

IsFinite returns true if the collection C is finite, and false otherwise. The default method for IsFinite checks the size (see Size (30.4.6)) of C. Methods for IsFinite may call Size (30.4.6), but methods for Size (30.4.6) must not call IsFinite.

30.4.3 IsTrivial

IsTrivial(C)

IsTrivial returns true if the collection C consists of exactly one element.

30.4.4 IsNonTrivial

IsNonTrivial(C)

IsNonTrivial returns true if the collection C is empty or consists of at least two elements (see IsTrivial (30.4.3)).

Example

```gap
gap> IsEmpty( [] ); IsEmpty( [ 1 .. 100 ] ); IsEmpty( Group( (1,2,3) ) );
true false false

gap> IsFinite( [ 1 .. 100 ] ); IsFinite( Integers );
true false

gap> IsTrivial( Integers ); IsTrivial( Group( () ) );
false true

gap> IsNonTrivial( Integers ); IsNonTrivial( Group( () ) );
true false
```

30.4.5 IsWholeFamily

IsWholeFamily(C)

IsWholeFamily returns true if the collection C is a whole family.
IsWholeFamily returns true if the collection $C$ contains the whole family (see 13.1) of its elements.

```gap
gap> IsWholeFamily( Integers );
false
gap> IsWholeFamily( Integers mod 3 );
false
gap> IsWholeFamily( Integers mod 4 );
true
gap> IsWholeFamily( FreeGroup( 2 ) );
true
```

### 30.4.6 Size

Size returns the size of the list or collection $listorcoll$, which is either an integer or infinity (18.2.1). If the argument is a list then the result is its length (see Length (21.17.5)).

The default method for Size checks the length of an enumerator of $listorcoll$.

Methods for IsFinite (30.4.2) may call Size, but methods for Size must not call IsFinite (30.4.2).

```gap
gap> Size( [1,2,3] ); Size( Group( () ) ); Size( Integers );
3
1
infinity
```

### 30.4.7 Representative

Representative returns a representative of the collection $C$.

Note that Representative is free in choosing a representative if there are several elements in $C$. It is not even guaranteed that Representative returns the same representative if it is called several times for one collection. The main difference between Representative and Random (30.7.1) is that Representative is free to choose a value that is cheap to compute, while Random (30.7.1) must make an effort to randomly distribute its answers.

If $C$ is a domain then there are methods for Representative that try to fetch an element from any known generator list of $C$, see 31. Note that Representative does not try to compute generators of $C$, thus Representative may give up and signal an error if $C$ has no generators stored at all.

### 30.4.8 RepresentativeSmallest

returns the smallest element in the collection $C$, w.r.t. the ordering $\prec$ (31.11.1). While the operation defaults to comparing all elements, better methods are installed for some collections.
Example

```gap
gap> Representative( Rationals );
0
gap> Representative( [ -1, -2 .. -100 ] );
-1
gap> RepresentativeSmallest( [ -1, -2 .. -100 ] );
-100
```

30.5 Operations for Collections

30.5.1 IsSubset

▷ IsSubset(C1, C2)

IsSubset returns true if C2, which must be a collection, is a subset of C1, which also must be a collection, and false otherwise.

C2 is considered a subset of C1 if and only if each element of C2 is also an element of C1. That is IsSubset behaves as if implemented as IsSubsetSet( AsSSortedList( C1 ), AsSSortedList( C2 ) ), except that it will also sometimes, but not always, work for infinite collections, and that it will usually work much faster than the above definition. Either argument may also be a proper set (see 21.19).

Example

```gap
gap> IsSubset( Rationals, Integers );
true
gap> IsSubset( Integers, [ 1, 2, 3 ] );
true
gap> IsSubset( Group( (1,2,3,4) ), [ (1,2,3) ] );
false
```

30.5.2 Intersection

▷ Intersection(C1, C2, ...)

▷ Intersection(list)

▷ Intersection2(C1, C2)

In the first form Intersection returns the intersection of the collections C1, C2, etc. In the second form list must be a nonempty list of collections and Intersection returns the intersection of those collections. Each argument or element of list respectively may also be a homogeneous list that is not a proper set, in which case Intersection silently applies Set (30.3.7) to it first.

The result of Intersection is the set of elements that lie in every of the collections C1, C2, etc. If the result is a list then it is mutable and new, i.e., not identical to any of C1, C2, etc.

Methods can be installed for the operation Intersection2 that takes only two arguments. Intersection calls Intersection2.

Methods for Intersection2 should try to maintain as much structure as possible, for example the intersection of two permutation groups is again a permutation group.

Example

```gap
# this is one of the rare cases where the intersection of two
# infinite domains works ('CF' is a shorthand for 'CyclotomicField'):
```
gap> Intersection( CyclotomicField(9), CyclotomicField(12) );
CF(3)
gap> D12 := Group( (2,6)(3,5), (1,2)(3,6)(4,5) );;
gap> Intersection( D12, Group( (1,2), (1,2,3,4,5) ) );
Group([ (1,5)(2,4) ])
gap> Intersection( D12, [ (1,3)(4,6), (1,2)(3,4) ] )
> ; # note that the second argument is not a proper set
[ (1,3)(4,6) ]
gap> # although the result is mathematically a group it is returned as a
gap> # proper set because the second argument is not regarded as a group:
gap> Intersection( D12, [ (), (1,2)(3,4), (1,3)(4,6), (1,4)(5,6) ] );
[ (), (1,3)(4,6) ]
gap> Intersection( Group( () ), [1,2,3] );
[ ]
gap> Intersection( [2,4,6,8,10], [3,6,9,12,15], [5,10,15,20,25] )
> ; # two or more lists or collections as arguments are legal
[ ]
gap> Intersection( [ [1,2,4], [2,3,4], [1,3,4] ] )
> ; # or one list of lists or collections
[ 4 ]

30.5.3 Union

\begin{itemize}
\item \textbf{Union}(C1, C2, ...)
\item \textbf{Union}(list)
\item \textbf{Union2}(C1, C2)
\end{itemize}

In the first form \textbf{Union} returns the union of the collections \textit{C1}, \textit{C2}, etc. In the second form \textit{list} must be a list of collections and \textbf{Union} returns the union of those collections. Each argument or element of \textit{list} respectively may also be a homogeneous list that is not a proper set, in which case \textbf{Union} silently applies \textbf{Set} (30.3.7) to it first.

The result of \textbf{Union} is the set of elements that lie in any of the collections \textit{C1}, \textit{C2}, etc. If the result is a list then it is mutable and new, i.e., not identical to any of \textit{C1}, \textit{C2}, etc.

Methods can be installed for the operation \textbf{Union2} that takes only two arguments. \textbf{Union} calls \textbf{Union2}.

\begin{verbatim}
gap> Union( [ (1,2,3), (1,2,3,4) ], Group( (1,2,3), (1,2) ) );
[ (1,2,3), (1,2,3,4), (1,2,3), (1,3,2), (1,3), (1,3,2), (1,3,2) ]
gap> Union( [2,4,6,8,10], [3,6,9,12,15], [5,10,15,20,25] )
> ; # two or more lists or collections as arguments are legal
[ 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, 20, 25 ]
gap> Union( [ [1,2,4], [2,3,4], [1,3,4] ] )
> ; # or one list of lists or collections
[ 1 .. 4 ]
gap> Union( [ ] );
[ ]
\end{verbatim}

When computing the Union of lists or sets of small integers and ranges, every attempt is made to return the result as a range and to avoid expanding ranges provided as input.
30.5.4 Difference

\texttt{Difference(C1, C2)}

\texttt{Difference} returns the set difference of the collections \texttt{C1} and \texttt{C2}. Either argument may also be a homogeneous list that is not a proper set, in which case \texttt{Difference} silently applies \texttt{Set} (30.3.7) to it first.

The result of \texttt{Difference} is the set of elements that lie in \texttt{C1} but not in \texttt{C2}. Note that \texttt{C2} need not be a subset of \texttt{C1}. The elements of \texttt{C2}, however, that are not elements of \texttt{C1} play no role for the result. If the result is a list then it is mutable and new, i.e., not identical to \texttt{C1} or \texttt{C2}.

**Example**

\begin{verbatim}
gap> Difference([ (1,2,3), (1,2,3,4) ], Group( (1,2,3), (1,2) ));
[ (1,2,3,4) ]
gap> Difference( [ (1,2,3), (1,2,3,4) ], Group( (1,2,3), (1,2) ) );
[ (1,2,3,4) ]
gap> Difference( [ (1,2,3), (1,2,3,4) ], Group( (1,2,3), (1,2) ) );
[ (1,2,3,4) ]
\end{verbatim}

30.6 Membership Test for Collections

30.6.1 \texttt{\_in (for a collection)}

\texttt{\_in(obj, C)}

returns \texttt{true} if the object \texttt{obj} lies in the collection \texttt{C}, and \texttt{false} otherwise.

The infix version of the command

\texttt{obj in C}

calls the operation \texttt{\_in (30.6.1)}, for which methods can be installed.

**Example**

\begin{verbatim}
gap> 13 in Integers; [ 1, 2 ] in Integers;
true
false
gap> g:= Group( (1,2) );; (1,2) in g; (1,2,3) in g;
true
false
gap> g:= Group( (1,2) );; (1,2) in g; (1,2,3) in g;
true
false
gap> g:= Group( (1,2) );; (1,2) in g; (1,2,3) in g;
true
false
gap> g:= Group( (1,2) );; (1,2) in g; (1,2,3) in g;
true
false
\end{verbatim}

30.7 Random Elements

The method used by \texttt{GAP} to obtain random elements may depend on the type \texttt{object}.

Most methods which produce random elements in \texttt{GAP} use a global random number generator (see \texttt{GlobalMersenneTwister (14.7.4)}). This random number generator is (deliberately) initialized to the same values when \texttt{GAP} is started, so different runs of \texttt{GAP} with the same input will always produce the same result, even if random calculations are involved.

See \texttt{Reset (14.7.3)} for a description of how to reset the random number generator to a previous state.

30.7.1 Random (for a list or collection)

\texttt{Random(listorcoll)}

\texttt{Random(from, to)}
Random returns a (pseudo-)random element of the list or collection listorcoll.

As lists or ranges are restricted in length ($2^{28} - 1$ or $2^{60} - 1$ depending on your system), the second form returns a random integer in the range from to to (inclusive) for arbitrary integers from and to.

The distribution of elements returned by Random depends on the argument. For a list the distribution is uniform (all elements are equally likely). The same holds usually for finite collections that are not lists. For infinite collections some reasonable distribution is used.

See the chapters of the various collections to find out which distribution is being used.

For some collections ensuring a reasonable distribution can be difficult and require substantial runtime (for example for large finite groups). If speed is more important than a guaranteed distribution, the operation PseudoRandom (30.7.2) should be used instead.

Note that Random is of course not an attribute.

Example

```
gap> Random([1..6]);
6
gap> Random(1, 2^100);
8662701568286902862304086250
```

30.7.2 PseudoRandom

PseudoRandom returns a pseudo random element of the list or collection listorcoll, which can be roughly described as follows. For a list, PseudoRandom returns the same as Random (30.7.1). For collections that are not lists, the elements returned by PseudoRandom are not necessarily equally distributed, even for finite collections; the idea is that Random (30.7.1) returns elements according to a reasonable distribution, PseudoRandom returns elements that are cheap to compute but need not satisfy this strong condition, and Representative (30.4.7) returns arbitrary elements, probably the same element for each call.

30.7.3 RandomList

RandomList([rs, ]list) (function)

For a dense list list, RandomList returns a (pseudo-)random element with equal distribution.

The random source rs is used to choose a random number. If rs is absent, this function uses the GlobalMersenneTwister (14.7.4) to produce the random elements (a source of high quality random numbers).
30.8 Iterators

30.8.1 Iterator

\begin{verbatim}
\textbf{Iterator} \textbf{(listorcoll)} \hspace{1cm} \textbf{(operation)}
\textbf{IsStandardIterator} \textbf{(listorcoll)} \hspace{1cm} \textbf{(filter)}
\end{verbatim}

Iterators provide a possibility to loop over the elements of a (countable) collection or list \texttt{listorcoll}, without repetition. For many collections \( C \), an iterator of \( C \) need not store all elements of \( C \), for example it is possible to construct an iterator of some infinite domains, such as the field of rational numbers.

\textbf{Iterator} returns a mutable iterator \texttt{iter} for its argument. If this argument is a list (which may contain holes), then \texttt{iter} iterates over the elements (but not the holes) of this list in the same order (see \textbf{IteratorList} (30.8.6) for details). If this argument is a collection but not a list then \texttt{iter} iterates over the elements of this collection in an unspecified order, which may change for repeated calls of \textbf{Iterator}. Because iterators returned by \textbf{Iterator} are mutable (see 12.6), each call of \textbf{Iterator} for the same argument returns a new iterator. Therefore \textbf{Iterator} is not an attribute (see 13.5).

The only operations for iterators are \textbf{IsDoneIterator} (30.8.4), \textbf{NextIterator} (30.8.5), and \textbf{ShallowCopy} (12.7.1). In particular, it is only possible to access the next element of the iterator with \textbf{NextIterator} (30.8.5) if there is one, and this can be checked with \textbf{IsDoneIterator} (30.8.4). For an iterator \texttt{iter}, \textbf{ShallowCopy} (12.7.1) returns a mutable iterator \texttt{new} that iterates over the remaining elements independent of \texttt{iter}; the results of \textbf{IsDoneIterator} (30.8.4) for \texttt{iter} and \texttt{new} are equal, and if \texttt{iter} is mutable then also the results of \textbf{NextIterator} (30.8.5) for \texttt{iter} and \texttt{new} are equal; note that \texttt{=} is not defined for iterators, so the equality of two iterators cannot be checked with \texttt{=}. When \textbf{Iterator} is called for a mutable collection \( C \) then it is not defined whether \texttt{iter} respects changes to \( C \) occurring after the construction of \texttt{iter}, except if the documentation explicitly promises a certain behaviour. The latter is the case if the argument is a mutable list (see \textbf{IteratorList} (30.8.6) for subtleties in this case).

It is possible to have for-loops run over mutable iterators instead of lists.

In some situations, one can construct iterators with a special succession of elements, see \textbf{IteratorByBasis} (61.6.6) for the possibility to loop over the elements of a vector space w.r.t. a given basis.

For lists, \textbf{Iterator} is implemented by \textbf{IteratorList} (30.8.6). For collections \( C \) that are not lists, the default method is \textbf{IteratorList( Enumerator( \( C \) ) )}. Better methods depending on \( C \) should be provided if possible.

For random access to the elements of a (possibly infinite) collection, enumerators are used. See 21.23 for the facility to compute a list from \( C \), which provides a (partial) mapping from \( C \) to the positive integers.

The filter \textbf{IsStandardIterator} means that the iterator is implemented as a component object and has components \textbf{IsDoneIterator} and \textbf{NextIterator} which are bound to the methods of the operations of the same name for this iterator.

\begin{verbatim}
gap> iter:= Iterator( GF(5) );
<iterator>
gap> l:= [];;
gap> for i in iter do Add( l, i ); od; l;
[ 0*Z(5), Z(5)^0, Z(5), Z(5)^2, Z(5)^3 ]
gap> l:= [];;
gap> iter:= Iterator( [ 1, 2, 3, 4 ] );; l:= [];;
\end{verbatim}
30.8.2 IteratorSorted

\textit{IteratorSorted} returns a mutable iterator. The argument must be a collection or a list that is not necessarily dense but whose elements lie in the same family (see 13.1). It loops over the different elements in sorted order.

For a collection \( C \) that is not a list, the generic method is \textit{IteratorList}( \textit{EnumeratorSorted}( \( C \) )).

30.8.3 IsIterator

\textit{IsIterator} lies in the category \textit{IsIterator}.

30.8.4 IsDoneIterator

\textit{IsDoneIterator} is true if all elements of \( C \) have been returned already by \textit{NextIterator}( \textit{iter} ), and false otherwise.

30.8.5 NextIterator

\textit{NextIterator} is applicable to \textit{iter}, and the result is the next element of \( C \), according to the succession defined by \textit{iter}.

If \textit{IsDoneIterator} is true then it is not defined what happens when \textit{NextIterator} is called for \textit{iter}; that is, it may happen that an error is signalled or that something meaningless is returned, or even that \textit{GAP} crashes.

Example

\begin{verbatim}
gap> iter := Iterator( [ 1, 2, 3, 4 ] );
<iterator>
gap> sum := 0;
gap> while not IsDoneIterator( iter ) do
>     sum := sum + NextIterator( iter );
>   od;
gap> IsDoneIterator( iter ); sum;
true
10
\end{verbatim}
gap> ir:= Iterator( Rationals );;
gap> l:= [ ];; for i in [1..20] do Add( l, NextIterator( ir ) ); od; l;
[ 0, 1, -1, 1/2, 2, -1/2, -2, 1/3, 2/3, 3/2, 3, -1/3, -2/3, -3/2, -3, 1/4, 3/4, 4/3, 4, -1/4 ]
gap> for i in ir do
> if DenominatorRat( i ) > 10 then break; fi;
> od;
gap> i;
1/11

30.8.6 IteratorList

IteratorList returns a new iterator that allows iteration over the elements of the list list (which may have holes) in the same order.

If list is mutable then it is in principle possible to change list after the call of IteratorList. In this case all changes concerning positions that have not yet been reached in the iteration will also affect the iterator. For example, if list is enlarged then the iterator will iterate also over the new elements at the end of the changed list.

Note that changes of list will also affect all shallow copies of list.

30.8.7 TrivialIterator

TrivialIterator( elm ) (function)
is a mutable iterator for the collection [ elm ] that consists of exactly one element elm (see IsTrivial (30.4.3)).

30.8.8 IteratorByFunctions

IteratorByFunctions returns a (mutable) iterator iter for which NextIterator (30.8.5), IsDoneIterator (30.8.4), and ShallowCopy (12.7.1) are computed via prescribed functions.

Let record be a record with at least the following components.

NextIterator
a function taking one argument iter, which returns the next element of iter (see NextIterator (30.8.5)); for that, the components of iter are changed.

IsDoneIterator
a function taking one argument iter, which returns the IsDoneIterator (30.8.4) value of iter.

ShallowCopy
a function taking one argument iter, which returns a record for which IteratorByFunctions can be called in order to create a new iterator that is independent of iter but behaves like iter w.r.t. the operations NextIterator (30.8.5) and IsDoneIterator (30.8.4).
ViewObj and PrintObj

two functions that print what one wants to be printed when View( iter ) or Print( item ) is called (see 6.3), if the ViewObj component is missing then the PrintObj method is used as a default.

Further (data) components may be contained in record which can be used by these function.

IteratorByFunctions does not make a shallow copy of record, this record is changed in place (see Section 79.1).

Iterators constructed with IteratorByFunctions are in the filter IsStandardIterator (30.8.1).
Chapter 31
Domains and their Elements

Domain is GAP’s name for structured sets. The ring of Gaussian integers \( \mathbb{Z}[\sqrt{-1}] \) is an example of a domain, the group \( D_{12} \) of symmetries of a regular hexahedron is another.

The GAP library predefines some domains. For example the ring of Gaussian integers is predefined as \texttt{GaussianIntegers} (60.5.1) (see 60.5) and the field of rationals is predefined as \texttt{Rationals} (17.1.1) (see 17). Most domains are constructed by functions, which are called domain constructors (see 31.3). For example the group \( D_{12} \) is constructed by the construction \texttt{Group( (1,2,3,4,5,6), (2,6)(3,5) )} (see \texttt{Group (39.2.1)}) and the finite field with 16 elements is constructed by \texttt{GaloisField( 16 )} (see \texttt{GaloisField (59.3.2)}).

The first place where you need domains in GAP is the obvious one. Sometimes you simply want to deal with a domain. For example if you want to compute the size of the group \( D_{12} \), you had better be able to represent this group in a way that the \texttt{Size} (30.4.6) function can understand.

The second place where you need domains in GAP is when you want to be able to specify that an operation or computation takes place in a certain domain. For example suppose you want to factor 10 in the ring of Gaussian integers. Saying \texttt{Factors( 10 )} will not do, because this will return the factorization \([ 2, 5 ]\) in the ring of integers. To allow operations and computations to happen in a specific domain, \texttt{Factors (56.5.9)}, and many other functions as well, accept this domain as optional first argument. Thus \texttt{Factors( GaussianIntegers, 10 )} yields the desired result \([ 1+E(4), 1-E(4), 2+E(4), 2-E(4) ]\). (The imaginary unit \( \sqrt{-1} \) is written as \texttt{E(4)} in GAP, see \texttt{E (18.1.1)}.)

An introduction to the most important facts about domains is given in Chapter (Tutorial: Domains).

There are only few operations especially for domains (see 31.9), operations such as \texttt{Intersection} (30.5.2) and \texttt{Random} (30.7.1) are defined for the more general situation of collections (see Chapter 30).

31.1 Operational Structure of Domains

Domains have an operational structure, that is, a collection of operations under which the domain is closed. For example, a group is closed under multiplication, taking the zeroth power of elements, and taking inverses of elements. The operational structure may be empty, examples of domains without additional structure are the underlying relations of general mappings (see 32.3).

The operations under which a domain is closed are a subset of the operations that the elements of a domain admit. It is possible that the elements admit more operations. For example, matrices can be
multiplied and added. But addition plays no role in a group of matrices, and multiplication plays no role in a vector space of matrices. In particular, a matrix group is not closed under addition.

Note that the elements of a domain exist independently of this domain, usually they existed already before the domain was created. So it makes sense to say that a domain is generated by some elements with respect to certain operations.

Of course, different sets of operations yield different notions of generation. For example, the group generated by some matrices is different from the ring generated by these matrices, and these two will in general be different from the vector space generated by the same matrices, over a suitable field.

The other way round, the same set of elements may be obtained by generation w.r.t. different notions of generation. For example, one can get the group generated by two elements \( g \) and \( h \) also as the monoid generated by the elements \( g, g^{-1}, h, h^{-1} \); if both \( g \) and \( h \) have finite order then of course the group generated by \( g \) and \( h \) coincides with the monoid generated by \( g \) and \( h \).

Additionally to the operational structure, a domain can have properties. For example, the multiplication of a group is associative, and the multiplication in a field is commutative.

Note that associativity and commutativity depend on the set of elements for which one considers the multiplication, i.e., it depends on the domain. For example, the multiplication in a full matrix ring over a field is not commutative, whereas its restriction to the set of diagonal matrices is commutative.

One important difference between the operational structure and the properties of a domain is that the operational structure is fixed when the domain is constructed, whereas properties can be discovered later. For example, take a domain whose operational structure is given by closure under multiplication. If it is discovered that the inverses of all its elements also do (by chance) lie in this domain, being closed under taking inverses is not added to the operational structure. But a domain with operational structure of multiplication, taking the identity, and taking inverses will be treated as a group as soon as the multiplication is found out to be associative for this domain.

The operational structures available in GAP form a hierarchy, which is explicitly formulated in terms of domain categories, see 31.6.

### 31.2 Equality and Comparison of Domains

*Equality* and *comparison* of domains are defined as follows.

Two domains are considered equal if and only if the sets of their elements as computed by \texttt{AsSSortedList (30.3.10)} are equal. Thus, in general \texttt{=} behaves as if each domain operand were replaced by its set of elements. Except that \texttt{=} will also sometimes, but not always, work for infinite domains, for which of course GAP cannot compute the set of elements. Note that this implies that domains with different algebraic structure may well be equal. As a special case of this, either operand of \texttt{=} may also be a proper set (see 21.19), i.e., a sorted list without holes or duplicates (see \texttt{AsSSortedList (30.3.10)}), and \texttt{=} will return \texttt{true} if and only if this proper set is equal to the set of elements of the argument that is a domain.

No general ordering of arbitrary domains via \texttt{<} is defined in GAP 4. This is because a well-defined \texttt{<} for domains or, more general, for collections, would have to be compatible with \texttt{=} and would need to be transitive and antisymmetric in order to be used to form ordered sets. In particular, \texttt{<} would have to be independent of the algebraic structure of its arguments because this holds for \texttt{=}, and thus there would be hardly a situation where one could implement an efficient comparison method. (Note that in the case that two domains are comparable with \texttt{<}, the result is in general not compatible with the set theoretical subset relation, which can be decided with \texttt{IsSubset (30.5.1)},.)
31.3 Constructing Domains

For several operational structures (see 31.1), GAP provides functions to construct domains with this structure (note that such functions do not exist for all operational structures). For example, Group (39.2.1) returns groups, VectorSpace (61.2.1) returns vector spaces etc.:

\[
\text{Struct} \left( \text{arg1}, \text{arg2}, \ldots \right)
\]

The syntax of these functions may vary, dependent on the structure in question. Usually a domain is constructed as the closure of some elements under the given operations, that is, the domain is given by its \textit{generators}. For example, a group can be constructed from a list of generating permutations or matrices or whatever is admissible as group elements, and a vector space over a given field \( F \) can be constructed from \( F \) and a list of appropriate vectors.

The idea of generation and generators in GAP is that the domain returned by a function such as Group, Algebra, or FreeLeftModule contains the given generators. This implies that the generators of a group must know how they are multiplied and inverted, the generators of a module must know how they are added and how scalar multiplication works, and so on. Thus one cannot use for example permutations as generators of a vector space.

The function \text{Struct} first checks whether the arguments admit the construction of a domain with the desired structure. This is done by calling the operation

\[
\text{IsGeneratorsOfStruct} \left( [\text{info}], \text{gens} \right)
\]

where \text{arglist} is the list of given generators and \text{info} an argument of \text{Struct}, for example the field of scalars in the case that a vector space shall be constructed. If the check failed then \text{Struct} returns fail, otherwise it returns the result of \text{StructByGenerators} (see below). (So if one wants to omit the check then one should call \text{StructByGenerators} directly.)

\[
\text{GeneratorsOfStruct} \left( D \right)
\]

For a domain \( D \) with operational structure corresponding to \text{Struct}, the attribute \text{GeneratorsOfStruct} returns a list of corresponding generators of \( D \). If these generators were not yet stored in \( D \) then \( D \) must know some generators if \text{GeneratorsOfStruct} shall have a chance to compute the desired result; for example, monoid generators of a group can be computed from known group generators (and vice versa). Note that several notions of generation may be meaningful for a given domain, so it makes no sense to ask for “the generators of a domain”. Further note that the generators may depend on other information about \( D \). For example the generators of a vector space depend on the underlying field of scalars; the vector space generators of a vector space over the field with four elements need not generate the same vector space when this is viewed as a space over the field with two elements.

\[
\text{StructByGenerators} \left( [\text{info}], \text{gens} \right)
\]

Domain construction from generators \text{gens} is implemented by operations \text{StructByGenerators}, which are called by the simple functions \text{Struct}; methods can be installed only for the operations. Note that additional information \text{info} may be necessary to construct the domain; for example, a vector space needs the underlying field of scalars in addition to the list of vector space generators. The \text{GeneratorsOfStruct} value of the returned domain need not be equal to \text{gens}. But if a domain \( D \) is printed as \text{Struct}([\text{a}, \text{b}, \ldots]) and if there is an attribute \text{GeneratorsOfStruct} then the list \text{GeneratorsOfStruct} \left( D \right) is guaranteed to be equal to [ \text{a}, \text{b}, \ldots ].

\[
\text{StructWithGenerators} \left( [\text{info}], \text{gens} \right)
\]

The only difference between \text{StructByGenerators} and \text{StructWithGenerators} is that the latter guarantees that the \text{GeneratorsOfStruct} value of the result is equal to the given generators \text{gens}.

\[
\text{ClosureStruct} \left( D, \text{obj} \right)
\]
For constructing a domain as the closure of a given domain with an element or another domain, one can use the operation \texttt{ClosureStruct}. It returns the smallest domain with operational structure corresponding to \texttt{Struct} that contains \texttt{D} as a subset and \texttt{obj} as an element.

### 31.4 Changing the Structure

The same set of elements can have different operational structures. For example, it may happen that a monoid \( M \) does in fact contain the inverses of all of its elements; if \( M \) has not been constructed as a group (see 31.6) then it is reasonable to ask for the group that is equal to \( M \).

\texttt{AsStruct( [info, ]D )}

If \( D \) is a domain that is closed under the operational structure given by \texttt{Struct} then \texttt{AsStruct} returns a domain \( E \) that consists of the same elements (that is, \( D = E \)) and that has this operational structure (that is, \texttt{IsStruct( E )} is true); if \( D \) is not closed under the structure given by \texttt{Struct} then \texttt{AsStruct} returns \texttt{fail}.

If additional information besides generators are necessary to define \( D \) then the argument \texttt{info} describes the value of this information for the desired domain. For example, if we want to view \( D \) as a vector space over the field with two elements then we may call \texttt{AsVectorSpace( GF(2), D )}; this allows us to change the underlying field of scalars, for example if \( D \) is a vector space over the field with four elements. Again, if \( D \) is not equal to a domain with the desired structure and additional information then \texttt{fail} is returned.

In the case that no additional information \texttt{info} is related to the structure given by \texttt{Struct}, the operation \texttt{AsStruct} is in fact an attribute (see 13.5).

See the index of the GAP Reference Manual for an overview of the available \texttt{AsStruct} functions.

### 31.5 Changing the Representation

Often it is useful to answer questions about a domain via computations in a different but isomorphic domain. In the sense that this approach keeps the structure and changes the underlying set of elements, it can be viewed as a counterpart of keeping the set of elements and changing its structure (see 31.4).

One reason for doing so can be that computations with the elements in the given domain are not very efficient. For example, if one is given a solvable matrix group (see Chapter 44) then one can compute an isomorphism to a polycyclicly presented group \( G \), say (see Chapter 45); the multiplication of two matrices—which is essentially determined by the dimension of the matrices—is much more expensive than the multiplication of two elements in \( G \)—which is essentially determined by the composition length of \( G \).

\texttt{IsomorphismRepStruct( D )}

If \( D \) is a domain that is closed under the operational structure given by \texttt{Struct} then \texttt{IsomorphismRepStruct} returns a mapping \( \text{hom} \) from \( D \) to a domain \( E \) having structure given by \texttt{Struct}, such that \( \text{hom} \) respects the structure \texttt{Struct} and \texttt{Rep} describes the representation of the elements in \( E \). If no domain \( E \) with the required properties exists then \texttt{fail} is returned.

For example, \texttt{IsomorphismPermGroup (43.3.1)} takes a group as its argument and returns a group homomorphism (see 40) onto an isomorphic permutation group (see Chapter 43) provided the original group is finite; for infinite groups, \texttt{IsomorphismPermGroup (43.3.1)} returns \texttt{fail}. Similarly, \texttt{IsomorphismPcGroup (46.5.2)} returns a group homomorphism from its argument to a polycyclicly presented group (see 46) if the argument is polycyclic, and \texttt{fail} otherwise.
See the index of the GAP Reference Manual for an overview of the available IsomorphismRepStruct functions.

### 31.6 Domain Categories

As mentioned in 31.1, the operational structure of a domain is fixed when the domain is constructed. For example, if \( D \) was constructed by Monoid (51.2.2) then \( D \) is in general not regarded as a group in GAP, even if \( D \) is in fact closed under taking inverses. In this case, IsGroup (39.2.7) returns `false` for \( D \). The operational structure determines which operations are applicable for a domain, so for example SylowSubgroup (39.13.1) is not defined for \( D \) and therefore will signal an error.

\[ \text{IsStruct}(D) \]

The functions IsStruct implement the tests whether a domain \( D \) has the respective operational structure (upon construction). IsStruct is a filter (see 13) that involves certain categories (see 13.3) and usually also certain properties (see 13.7). For example, IsGroup (39.2.7) is equivalent to IsMagmaWithInverses and IsAssociative, the first being a category and the second being a property.

Implications between domain categories describe the hierarchy of operational structures available in GAP. Here are some typical examples.

- **IsDomain (31.9.1)** is implied by each domain category,
- **IsMagma** (35.1.1) is implied by each category that describes the closure under multiplication `*`,
- **IsAdditiveMagma** (55.1.4) is implied by each category that describes the closure under addition `+`,
- **IsMagmaWithOne** (35.1.2) implies **IsMagma** (35.1.1); a magma-with-one is a magma such that each element (and thus also the magma itself) can be asked for its zeroth power,
- **IsMagmaWithInverses** (35.1.4) implies **IsMagmaWithOne** (35.1.2); a magma-with-inverses is a magma such that each element can be asked for its inverse; important special cases are groups, which in addition are associative,
- a **ring** is a magma that is also an additive group,
- a **ring-with-one** is a ring that is also a magma-with-one,
- a **division ring** is a ring-with-one that is also closed under taking inverses of nonzero elements,
- a **field** is a commutative division ring.

Each operational structure Struct has associated with it a domain category IsStruct, and operations StructByGenerators for constructing a domain from generators, GeneratorsOfStruct for storing and accessing generators w.r.t. this structure, ClosureStruct for forming the closure, and AsStruct for getting a domain with the desired structure from one with weaker operational structure and for testing whether a given domain can be regarded as a domain with Struct.

The functions applicable to domains with the various structures are described in the corresponding chapters of the Reference Manual. For example, functions for rings, fields, groups, and vector spaces are described in Chapters 56, 58, 39, and 61, respectively. More general functions for arbitrary collections can be found in Chapter 30.
31.7 Parents

31.7.1 Parent

- `Parent(D)`  
  (function)
- `SetParent(D, P)`  
  (operation)
- `HasParent(D)`  
  (filter)

It is possible to assign to a domain `D` one other domain `P` containing `D` as a subset, in order to exploit this subset relation between `D` and `P`. Note that `P` need not have the same operational structure as `D`, for example `P` may be a magma and `D` a field.

The assignment is done by calling `SetParent`, and `P` is called the parent of `D`. If `D` has already a parent, calls to `SetParent` will be ignored.

If `D` has a parent `P` – this can be checked with `HasParent` – then `P` can be used to gain information about `D`. First, the call of `SetParent` causes `UseSubsetRelation (31.13.1)` to be called. Second, for a domain `D` with parent, information relative to the parent can be stored in `D`; for example, there is an attribute `NormalizerInParent` for storing `Normalizer(P, D)` in the case that `D` is a group. (More about such parent dependent attributes can be found in 85.2.) Note that because of this relative information, one cannot change the parent; that is, one can set the parent only once, subsequent calls to `SetParent` for the same domain `D` are ignored. Further note that contrary to `UseSubsetRelation (31.13.1)`, also knowledge about the parent `P` might be used that is discovered after the `SetParent` call.

A stored parent can be accessed using `Parent`. If `D` has no parent then `Parent` returns `D` itself, and `HasParent` will return `false` also after a call to `Parent`. So `Parent` is not an attribute, the underlying attribute to store the parent is `ParentAttr`.

Certain functions that return domains with parent already set, for example `Subgroup (39.3.1)`, are described in Section 31.8. Whenever a function has this property, the GAP Reference Manual states this explicitly. Note that these functions do not guarantee a certain parent, for example `DerivedSubgroup (39.12.3)` for a perfect group `G` may return `G` itself, and if `G` had already a parent then this is not replaced by `G`. As a rule of thumb, GAP avoids to set a domain as its own parent, which is consistent with the behaviour of `Parent`, at least until a parent is set explicitly with `SetParent`.

```gap
> g:= Group( (1,2,3), (1,2) );;
> h:= Group( (1,2) );;
> HasParent( g ); HasParent( h );
false
false
> SetParent( h, g );
> Parent( g ); Parent( h );
Group([ (1,2,3), (1,2) ])
Group([ (1,2,3), (1,2) ])
> HasParent( g ); HasParent( h );
false
true
```

31.8 Constructing Subdomains

For many domains `D`, there are functions that construct certain subsets `S` of `D` as domains with parent (see 31.7) already set to `D`. For example, if `G` is a group that contains the elements in the list `gens`
then \texttt{Subgroup(} \texttt{G, gens }\texttt{)} returns a group \texttt{S} that is generated by the elements in \texttt{gens} and with \texttt{Parent(} \texttt{S }\texttt{)} = \texttt{G}.

\begin{verbatim}
Substruct( D, gens )

More general, if \texttt{D} is a domain whose algebraic structure is given by the function \texttt{Struct} (for example \texttt{Group}, \texttt{Algebra}, \texttt{Field}) then the function \texttt{Substruct} (for example \texttt{Subgroup}, \texttt{Subalgebra}, \texttt{Subfield}) returns domains with structure \texttt{Struct} and parent set to the first argument.

\begin{verbatim}
SubstructNC( D, gens )

Each function \texttt{Substruct} checks that the \texttt{Struct} generated by \texttt{gens} is in fact a subset of \texttt{D}. If one wants to omit this check then one can call \texttt{SubstructNC} instead; the suffix \texttt{NC} stands for "no check".

\begin{verbatim}
AsSubstruct( D, S )

first constructs \texttt{AsStruct( [info, ]S )}, where \texttt{info} depends on \texttt{D} and \texttt{S}, and then sets the parent (see 31.7) of this new domain to \texttt{D}.

\begin{verbatim}
IsSubstruct( D, S )

There is no real need for functions that check whether a domain \texttt{S} is a \texttt{Substruct} of a domain \texttt{D}, since this is equivalent to the checks whether \texttt{S} is a \texttt{Struct} and \texttt{S} is a subset of \texttt{D}. Note that in many cases, only the subset relation is what one really wants to check, and that appropriate methods for the operation \texttt{IsSubset} (30.5.1) are available for many special situations, such as the test whether a group is contained in another group, where only generators need to be checked.

If a function \texttt{IsSubstruct} is available in \texttt{GAP} then it is implemented as first a call to \texttt{IsStruct} for the second argument and then a call to \texttt{IsSubset} (30.5.1) for the two arguments.

\end{verbatim}
\end{verbatim}
\end{verbatim}

\section{31.9 Operations for Domains}

For the meaning of the attributes \texttt{Characteristic} (31.10.1), \texttt{One} (31.10.2), \texttt{Zero} (31.10.3) in the case of a domain argument, see 31.10.

\subsection{31.9.1 \texttt{IsGeneralizedDomain}}

\begin{verbatim}
▷ IsGeneralizedDomain( obj )
▷ IsDomain( obj )

(Category)

(Category)
\end{verbatim}

For some purposes, it is useful to deal with objects that are similar to domains but that are not collections in the sense of \texttt{GAP} because their elements may lie in different families; such objects are called \textit{generalized domains}. An instance of generalized domains are "operation domains", for example any \texttt{G}-set for a permutation group \texttt{G} consisting of some union of points, sets of points, sets of sets of points etc., under a suitable action.

\texttt{IsDomain} is a synonym for \texttt{IsGeneralizedDomain} and \texttt{IsCollection}.

\subsection{31.9.2 \texttt{GeneratorsOfDomain}}

\begin{verbatim}
▷ GeneratorsOfDomain( D )

(attribute)
\end{verbatim}

For a domain \texttt{D}, \texttt{GeneratorsOfDomain} returns a list containing generators of \texttt{D} with respect to the trivial operational structure, that is interpreting \texttt{D} as a set. The returned list may contain repetitions.

See 31.3 and for \texttt{GeneratorsOfStruct} methods with respect to other available operational structures.
For many domains that have natural generators by construction (for example, the natural generators of a free group of rank two are the two generators stored as value of the attribute GeneratorsOfGroup (39.2.4), and the natural generators of a free associative algebra are those generators stored as value of the attribute GeneratorsOfAlgebra (62.9.1)), each natural generator can be accessed using the . operator. For a domain D, D.i returns the i-th generator if i is a positive integer, and if name is the name of a generator of D then D.name returns this generator.

Example

```
gap> G := DihedralGroup(IsPermGroup, 4);;
gap> GeneratorsOfGroup(G);
[ (1,2), (3,4) ]
gap> GeneratorsOfDomain(G);
[ (), (3,4), (1,2), (1,2)(3,4) ]
gap> F := FreeGroup("x");
gap> GeneratorsOfGroup(F);
[ x ]
gap> GeneratorsOfDomain(F); Error, resulting list would be too large (length infinity)
```

31.9.3 Domain

`Domain([Fam, ]generators)` (function)
`DomainByGenerators(Fam, generators)` (operation)

Domain returns the domain consisting of the elements in the homogeneous list generators. If `generators` is empty then a family `Fam` must be entered as the first argument, and the returned (empty) domain lies in the collections family of `Fam`.

DomainByGenerators is the operation called by Domain.

31.10 Attributes and Properties of Elements

The following attributes and properties for elements and domains correspond to the operational structure.

31.10.1 Characteristic

`Characteristic(obj)` (attribute)

Characteristic returns the characteristic of `obj`.

If `obj` is a family, all of whose elements lie in IsAdditiveElementWithZero (31.14.5) then its characteristic is the least positive integer n, if any, such that IsZero(n*x) is true for all x in the family `obj`, otherwise it is 0.

If `obj` is a collections family of a family g which has a characteristic, then the characteristic of `obj` is the same as the characteristic of `g`.

For other families `obj` the characteristic is not defined and fail will be returned.

For any object `obj` which is in the filter IsAdditiveElementWithZero (31.14.5) or in the filter IsAdditiveMagmaWithZero (55.1.5) the characteristic of `obj` is the same as the characteristic of its family if that is defined and undefined otherwise.
For all other objects \( \text{obj} \) the characteristic is undefined and may return \text{fail} or a “no method found” error.

### 31.10.2 OneImmutable

\[ \text{OneImmutable}(\text{obj}) \]
\[ \text{OneAttr}(\text{obj}) \]
\[ \text{One}(\text{obj}) \]
\[ \text{Identity}(\text{obj}) \]
\[ \text{OneMutable}(\text{obj}) \]
\[ \text{OneOp}(\text{obj}) \]
\[ \text{OneSameMutability}(\text{obj}) \]
\[ \text{OneSM}(\text{obj}) \]

\text{OneImmutable}, \text{OneMutable}, and \text{OneSameMutability} return the multiplicative neutral element of the multiplicative element \( \text{obj} \).

They differ only w.r.t. the mutability of the result. \text{OneImmutable} is an attribute and hence returns an immutable result. \text{OneMutable} is guaranteed to return a new \textit{mutable} object whenever a mutable version of the required element exists in \textsc{GAP} (see \texttt{IsCopyable (12.6.1)}). \text{OneSameMutability} returns a result that is mutable if \( \text{obj} \) is mutable and if a mutable version of the required element exists in \textsc{GAP}; for lists, it returns a result of the same immutability level as the argument. For instance, if the argument is a mutable matrix with immutable rows, it returns a similar object.

If \( \text{obj} \) is a multiplicative element then \text{OneSameMutability}(\text{obj}) is equivalent to \( \text{obj}^{-0} \).

\text{OneAttr}, \text{One} and \text{Identity} are synonyms of \text{OneImmutable}. \text{OneSM} is a synonym of \text{OneSameMutability}. \text{OneOp} is a synonym of \text{OneMutable}.

If \( \text{obj} \) is a domain or a family then \text{One} is defined as the identity element of all elements in \( \text{obj} \), provided that all these elements have the same identity. For example, the family of all cyclotomics has the identity element \( 1 \), but a collections family (see \texttt{CollectionsFamily (30.2.1)}) may contain matrices of all dimensions and then it cannot have a unique identity element. Note that \text{One} is applicable to a domain only if it is a \textit{magma-with-one} (see \texttt{IsMagmaWithOne (35.1.2)}); use \texttt{MultiplicativeNeutralElement (35.4.10)} otherwise.

The identity of an object need not be distinct from its zero, so for example a ring consisting of a single element can be regarded as a ring-with-one (see \texttt{56}). This is particularly useful in the case of finitely presented algebras, where any factor of a free algebra-with-one is again an algebra-with-one, no matter whether or not it is a zero algebra.

The default method of \text{One} for multiplicative elements calls \text{OneMutable} (note that methods for \text{OneMutable} must \textit{not} delegate to \text{One}); so other methods to compute identity elements need to be installed only for \text{OneOp} and (in the case of copyable objects) \text{OneSameMutability}.

For domains, \text{One} may call \texttt{Representative (30.4.7)}, but \texttt{Representative (30.4.7)} is allowed to fetch the identity of a domain \( \text{D} \) only if \texttt{HasOne( D )} is true.

### 31.10.3 ZeroImmutable

\[ \text{ZeroImmutable}(\text{obj}) \]
\[ \text{ZeroAttr}(\text{obj}) \]
\[ \text{Zero}(\text{obj}) \]
\[ \text{ZeroMutable}(\text{obj}) \]

\text{ZeroImmutable}, \text{ZeroMutable}, and \text{ZeroSameMutability} return the additive neutral element of the additive element \( \text{obj} \).

They differ only w.r.t. the mutability of the result. \text{ZeroImmutable} is an attribute and hence returns an immutable result. \text{ZeroMutable} is guaranteed to return a new \textit{mutable} object whenever a mutable version of the required element exists in \textsc{GAP} (see \texttt{IsCopyable (12.6.1)}). \text{ZeroSameMutability} returns a result that is mutable if \( \text{obj} \) is mutable and if a mutable version of the required element exists in \textsc{GAP}; for lists, it returns a result of the same immutability level as the argument. For instance, if the argument is a mutable matrix with immutable rows, it returns a similar object.

If \( \text{obj} \) is a multiplicative element then \text{ZeroSameMutability}(\text{obj}) is equivalent to \( \text{obj}+0 \).

\text{ZeroAttr}, \text{Zero} and \text{Identity} are synonyms of \text{ZeroImmutable}. \text{ZeroSM} is a synonym of \text{ZeroSameMutability}. \text{ZeroOp} is a synonym of \text{ZeroMutable}.

If \( \text{obj} \) is a domain or a family then \text{Zero} is defined as the identity element of all elements in \( \text{obj} \), provided that all these elements have the same identity. For example, the family of all cyclotomics has the identity element \( 0 \), but a collections family (see \texttt{CollectionsFamily (30.2.1)}) may contain matrices of all dimensions and then it cannot have a unique identity element. Note that \text{Zero} is applicable to a domain only if it is a \textit{magma-with-one} (see \texttt{IsMagmaWithOne (35.1.2)}); use \texttt{AdditiveNeutralElement (35.4.10)} otherwise.

The identity of an object need not be distinct from its zero, so for example a ring consisting of a single element can be regarded as a ring-with-one (see \texttt{56}). This is particularly useful in the case of finitely presented algebras, where any factor of a free algebra-with-one is again an algebra-with-one, no matter whether or not it is a zero algebra.

The default method of \text{Zero} for additive elements calls \text{ZeroMutable} (note that methods for \text{ZeroMutable} must \textit{not} delegate to \text{Zero}); so other methods to compute identity elements need to be installed only for \text{ZeroOp} and (in the case of copyable objects) \text{ZeroSameMutability}.

For domains, \text{Zero} may call \texttt{Representative (30.4.7)}, but \texttt{Representative (30.4.7)} is allowed to fetch the identity of a domain \( \text{D} \) only if \texttt{HasOne( D )} is true.
ZeroImmutable, ZeroMutable, and ZeroSameMutability all return the additive neutral element of the additive element obj.

They differ only w.r.t. the mutability of the result. ZeroImmutable is an attribute and hence returns an immutable result. ZeroMutable is guaranteed to return a new mutable object whenever a mutable version of the required element exists in GAP (see IsCopyable (12.6.1)). ZeroSameMutability returns a result that is mutable if obj is mutable and if a mutable version of the required element exists in GAP; for lists, it returns a result of the same immutability level as the argument. For instance, if the argument is a mutable matrix with immutable rows, it returns a similar object.

ZeroSameMutability( obj ) is equivalent to 0 * obj.

ZeroAttr and Zero are synonyms of ZeroImmutable. ZeroSM is a synonym of ZeroSameMutability. ZeroOp is a synonym of ZeroMutable.

If obj is a domain or a family then Zero is defined as the zero element of all elements in obj, provided that all these elements have the same zero. For example, the family of all cyclotomics has the zero element 0, but a collections family (see CollectionsFamily (30.2.1)) may contain matrices of all dimensions and then it cannot have a unique zero element. Note that Zero is applicable to a domain only if it is an additive magma-with-zero (see IsAdditiveMagmaWithZero (55.1.5)); use AdditiveNeutralElement (55.3.5) otherwise.

The default method of Zero for additive elements calls ZeroMutable (note that methods for ZeroMutable must not delegate to Zero); so other methods to compute zero elements need to be installed only for ZeroMutable and (in the case of copyable objects) ZeroSameMutability.

For domains, Zero may call Representative (30.4.7), but Representative (30.4.7) is allowed to fetch the zero of a domain D only if HasZero( D ) is true.

### 31.10.4 MultiplicativeZeroOp

- **MultiplicativeZeroOp(elt)**

  **Returns:** A multiplicative zero element.

  for an element elt in the category IsMultiplicativeElementWithZero (31.14.12), MultiplicativeZeroOp returns the element z in the family F of elt with the property that \( z \cdot m = z = m \cdot z \) holds for all \( m \in F \), if such an element can be determined.

  Families of elements in the category IsMultiplicativeElementWithZero (31.14.12) often arise from adjoining a new zero to an existing magma. See InjectionZeroMagma (35.2.13) or MagmaWithZeroAdjoined (35.2.13) for details.

```gap
gap> G:=AlternatingGroup(5);;
gap> x:=Representative(MagmaWithZeroAdjoined(G));
<group with 0 adjoined elt: ()>
gap> MultiplicativeZeroOp(x); 
<group with 0 adjoined elt: 0>
```
31.10.5 IsOne
\[\text{IsOne(elm)}\] (property)

is true if \(\text{elm} = \text{One(elm)}\), and false otherwise.

31.10.6 IsZero
\[\text{IsZero(elm)}\] (property)

is true if \(\text{elm} = \text{Zero(elm)}\), and false otherwise.

31.10.7 IsIdempotent
\[\text{IsIdempotent(elt)}\] (property)

returns true iff \(\text{elt}\) is its own square. (Even if \text{IsZero} (31.10.6) returns true for \(\text{elt}\).)

31.10.8 InverseImmutable
\[\text{InverseImmutable(elm)}\] (attribute)
\[\text{InverseAttr(elm)}\] (attribute)
\[\text{Inverse(elm)}\] (attribute)
\[\text{InverseMutable(elm)}\] (operation)
\[\text{InverseOp(elm)}\] (operation)
\[\text{InverseSameMutability(elm)}\] (operation)
\[\text{InverseSM(elm)}\] (operation)

\text{InverseImmutable}, \text{InverseMutable}, and \text{InverseSameMutability} all return the multiplicative inverse of an element \(\text{elm}\), that is, an element \(\text{inv}\) such that \(\text{elm} \ast \text{inv} = \text{inv} \ast \text{elm} = \text{One(elm)}\) holds; if \(\text{elm}\) is not invertible then fail (see 20.2) is returned.

Note that the above definition implies that a (general) mapping is invertible in the sense of \text{Inverse} only if its source equals its range (see 32.14). For a bijective mapping \(f\) whose source and range differ, \text{InverseGeneralMapping} (32.2.3) can be used to construct a mapping \(g\) with the property that \(f \ast g\) is the identity mapping on the source of \(f\) and \(g \ast f\) is the identity mapping on the range of \(f\).

The operations differ only w.r.t. the mutability of the result. \text{InverseImmutable} is an attribute and hence returns an immutable result. \text{InverseMutable} is guaranteed to return a new \text{mutable} object whenever a mutable version of the required element exists in \text{GAP}. \text{InverseSameMutability} returns a result that is mutable if \(\text{elm}\) is mutable and if a mutable version of the required element exists in \text{GAP}; for lists, it returns a result of the same immutability level as the argument. For instance, if the argument is a mutable matrix with immutable rows, it returns a similar object.

\text{InverseSameMutability(elt)} is equivalent to \(elt^{-1}\).

\text{InverseAttr} and \text{Inverse} are synonyms of \text{InverseImmutable}. \text{InverseSM} is a synonym of \text{InverseSameMutability}. \text{InverseOp} is a synonym of \text{InverseMutable}.

The default method of \text{InverseImmutable} calls \text{InverseMutable} (note that methods for \text{InverseMutable} must not delegate to \text{InverseImmutable}); other methods to compute inverses need to be installed only for \text{InverseMutable} and (in the case of copyable objects) \text{InverseSameMutability}.
31.10.9 AdditiveInverseImmutable

- AdditiveInverseImmutable(elm) (attribute)
- AdditiveInverseAttr(elm) (attribute)
- AdditiveInverse(elm) (attribute)
- AdditiveInverseMutable(elm) (operation)
- AdditiveInverseOp(elm) (operation)
- AdditiveInverseSameMutability(elm) (operation)
- AdditiveInverseSM(elm) (operation)

AdditiveInverseImmutable, AdditiveInverseMutable, and AdditiveInverseSameMutability all return the additive inverse of elm.

They differ only w.r.t. the mutability of the result. AdditiveInverseImmutable is an attribute and hence returns an immutable result. AdditiveInverseMutable is guaranteed to return a new mutable object whenever a mutable version of the required element exists in GAP (see IsCopyable (12.6.1)). AdditiveInverseSameMutability returns a result that is mutable if elm is mutable and if a mutable version of the required element exists in GAP; for lists, it returns a result of the same immutability level as the argument. For instance, if the argument is a mutable matrix with immutable rows, it returns a similar object.

AdditiveInverseSameMutability(elm) is equivalent to -elm.

AdditiveInverseAttr and AdditiveInverse are synonyms of AdditiveInverseImmutable. AdditiveInverseSM is a synonym of AdditiveInverseSameMutability. AdditiveInverseOp is a synonym of AdditiveInverseMutable.

The default method of AdditiveInverse calls AdditiveInverseMutable (note that methods for AdditiveInverseMutable must not delegate to AdditiveInverse); so other methods to compute additive inverses need to be installed only for AdditiveInverseMutable and (in the case of copyable objects) AdditiveInverseSameMutability.

31.10.10 Order

- Order(elm) (attribute)

is the multiplicative order of elm. This is the smallest positive integer n such that elm ^ n = One(elm) if such an integer exists. If the order is infinite, Order may return the value infinity (18.2.1), but it also might run into an infinite loop trying to test the order.

31.11 Comparison Operations for Elements

Binary comparison operations have been introduced already in 4.12. The underlying operations for which methods can be installed are the following.

31.11.1 \= and \<

- \=(left-expr, right-expr) (operation)
- \<(left-expr, right-expr) (operation)
Note that the comparisons via \(<\), \(\leq\), \(>\), and \(\geq\) are delegated to the operations \(\leq\) (31.11.1) and \(<\) (31.11.1).

In general, objects in different families cannot be compared with \(<\) (31.11.1). For the reason and for exceptions from this rule, see 4.12.

### 31.11.2 CanEasilyCompareElements

- CanEasilyCompareElements(obj)
- CanEasilyCompareElementsFamily(fam)
- CanEasilySortElements(obj)
- CanEasilySortElementsFamily(fam)

For some objects a “normal form” is hard to compute and thus equality of elements of a domain might be expensive to test. Therefore GAP provides a (slightly technical) property with which an algorithm can test whether an efficient equality test is available for elements of a certain kind.

CanEasilyCompareElements indicates whether the elements in the family fam of obj can be easily compared with \(\leq\) (31.11.1).

The default method for this property is to ask the family of obj, the default method for the family is to return false.

The ability to compare elements may depend on the successful computation of certain information. (For example for finitely presented groups it might depend on the knowledge of a faithful permutation representation.) This information might change over time and thus it might not be a good idea to store a value false too early in a family. Instead the function CanEasilyCompareElementsFamily should be called for the family of obj which returns false if the value of CanEasilyCompareElements is not known for the family without computing it. (This is in fact what the above mentioned family dispatch does.)

If a family knows ab initio that it can compare elements this property should be set as implied filter and filter for the family (the 3rd and 4th argument of NewFamily (13.1.2) respectively). This guarantees that code which directly asks the family gets a right answer.

The property CanEasilySortElements and the function CanEasilySortElementsFamily behave exactly in the same way, except that they indicate that objects can be compared via \(<\) (31.11.1). This property implies CanEasilyCompareElements, as the ordering must be total.

### 31.12 Arithmetic Operations for Elements

Binary arithmetic operations have been introduced already in 4.13. The underlying operations for which methods can be installed are the following.

#### 31.12.1 \(\oplus, \otimes, \div, \neg, \mod\)

- \(+\)(left-expr, right-expr)
- \(*\)(left-expr, right-expr)
- \(/\)(left-expr, right-expr)
- \(^\)(left-expr, right-expr)
- \(\mod\)(left-expr, right-expr)
For details about special methods for \* (31.12.1), \slash (31.12.1), \^ (31.12.1) and \mod (31.12.1), consult the appropriate index entries for them.

### 31.12.2 LeftQuotient

\[
\text{\texttt{LeftQuotient(elm1, elm2)}}
\]

returns the product \( elm1^{-1} \ast elm2 \). For some types of objects (for example permutations) this product can be evaluated more efficiently than by first inverting \( elm1 \) and then forming the product with \( elm2 \).

### 31.12.3 Comm

\[
\text{\texttt{Comm(elm1, elm2)}}
\]

returns the commutator of \( elm1 \) and \( elm2 \). The commutator is defined as the product \( elm1^{-1} \ast elm2^{-1} \ast elm1 \ast elm2 \).

**Example**

```gap
gap> a := (1,3)(4,6);; b := (1,6,5,4,3,2);;
gap> Comm( a, b );
(1,5,3)(2,6,4)
gap> LeftQuotient( a, b );
(1,2)(3,6)(4,5)
```

### 31.12.4 LieBracket

\[
\text{\texttt{LieBracket(elm1, elm2)}}
\]

returns the element \( elm1 \ast elm2 - elm2 \ast elm1 \).

The addition \slash (31.12.1) is assumed to be associative but not assumed to be commutative (see IsAdditivelyCommutative (55.3.1)). The multiplication \* (31.12.1) is not assumed to be commutative or associative (see IsCommutative (35.4.9), IsAssociative (35.4.7)).

### 31.12.5 Sqrt

\[
\text{\texttt{Sqrt(obj)}}
\]

\( \text{Sqrt} \) returns a square root of \( obj \), that is, an object \( x \) with the property that \( x \ast x = obj \) holds. If such an \( x \) is not unique then the choice of \( x \) depends on the type of \( obj \). For example, \( \text{ER} \) (18.4.2) is the \( \text{Sqrt} \) method for rationals (see IsRat (17.2.1)).

### 31.13 Relations Between Domains

Domains are often constructed relative to other domains. The probably most usual case is to form a subset of a domain, for example the intersection (see Intersection (30.5.2)) of two domains, or a Sylow subgroup of a given group (see SylowSubgroup (39.13.1)).
In such a situation, the new domain can gain knowledge by exploiting that several attributes are maintained under taking subsets. For example, the intersection of an arbitrary domain with a finite domain is clearly finite, a Sylow subgroup of an abelian group is abelian, too, and so on.

Since usually the new domain has access to the knowledge of the old domain(s) only when it is created (see 31.8 for the exception), this is the right moment to take advantage of the subset relation, using UseSubsetRelation (31.13.1).

Analogous relations occur when a factor structure is created from a domain and a subset (see UseFactorRelation (31.13.2)), and when a domain isomorphic to a given one is created (see UseIsomorphismRelation (31.13.3)).

The functions InstallSubsetMaintenance (31.13.4), InstallIsomorphismMaintenance (31.13.6), and InstallFactorMaintenance (31.13.5) are used to tell GAP under what conditions an attribute is maintained under taking subsets, or forming factor structures or isomorphic domains. This is used only when a new attribute or property is created, see NewAttribute (13.5.3) and NewProperty (13.7.4). For the attributes already available, such as IsFinite (30.4.2) and IsCommutative (35.4.9), the maintenances are already notified.

### 31.13.1 UseSubsetRelation

UseSubsetRelation(super, sub)  
(operation)

Methods for this operation transfer possibly useful information from the domain super to its subset sub, and vice versa.

UseSubsetRelation is designed to be called automatically whenever substructures of domains are constructed. So the methods must be cheap, and the requirements should be as sharp as possible!

To achieve that all applicable methods are executed, all methods for this operation except the default method must end with TryNextMethod(). This default method deals with the information that is available by the calls of InstallSubsetMaintenance (31.13.4) in the GAP library.

```
Example

gap> g:= Group( (1,2), (3,4), (5,6) );; h:= Group( (1,2), (3,4) );;
gap> IsAbelian( g ); HasIsAbelian( h );
true false
gap> UseSubsetRelation( g, h );; HasIsAbelian( h ); IsAbelian( h );
true true
```

### 31.13.2 UseFactorRelation

UseFactorRelation(numer, denom, factor)  
(operation)

Methods for this operation transfer possibly useful information from the domain numer or its subset denom to the domain factor that is isomorphic to the factor of numer by denom, and vice versa. denom may be fail, for example if factor is just known to be a factor of numer but denom is not available as a GAP object; in this case those factor relations are used that are installed without special requirements for denom.

UseFactorRelation is designed to be called automatically whenever factor structures of domains are constructed. So the methods must be cheap, and the requirements should be as sharp as possible!
To achieve that all applicable methods are executed, all methods for this operation except the default method must end with a call to \texttt{TryNextMethod (78.5.1)}. This default method deals with the information that is available by the calls of \texttt{InstallFactorMaintenance (31.13.5)} in the \texttt{GAP} library.

\begin{example}
\begin{verbatim}
gap> g := Group( (1,2,3,4), (1,2) );; h := Group( (1,2,3), (1,2) );;
gap> IsSolvableGroup( g ); HasIsSolvableGroup( h );
true
false

gap> UseFactorRelation(g, Subgroup( g, [ (1,2)(3,4), (1,3)(2,4) ] ), h);
true
false
\end{verbatim}
\end{example}

31.13.3 \textbf{UseIsomorphismRelation}

\begin{verbatim}$\triangleright$ UseIsomorphismRelation(old, new)
\end{verbatim}(operation)

Methods for this operation transfer possibly useful information from the domain \texttt{old} to the isomorphic domain \texttt{new}.

\texttt{UseIsomorphismRelation} is designed to be called automatically whenever isomorphic structures of domains are constructed. So the methods must be \textit{cheap}, and the requirements should be as sharp as possible!

To achieve that \textit{all} applicable methods are executed, all methods for this operation except the default method must end with a call to \texttt{TryNextMethod (78.5.1)}. This default method deals with the information that is available by the calls of \texttt{InstallIsomorphismMaintenance (31.13.6)} in the \texttt{GAP} library.

\begin{example}
\begin{verbatim}
gap> g := Group( (1,2) );; h := Group( [ [ -1 ] ] );;
gap> Size( g ); HasSize( h );
2
false

gap> UseIsomorphismRelation( g, h ); HasSize( h ); Size( h );
true
2
\end{verbatim}
\end{example}

31.13.4 \textbf{InstallSubsetMaintenance}

\begin{verbatim}$\triangleright$ InstallSubsetMaintenance(opr, super_req, sub_req)
\end{verbatim}(function)

\texttt{opr} must be a property or an attribute. The call of \texttt{InstallSubsetMaintenance} has the effect that for a domain $D$ in the filter \texttt{super\_req}, and a domain $S$ in the filter \texttt{sub\_req}, the call \texttt{UseSubsetRelation(D,S)} (see \texttt{UseSubsetRelation (31.13.1)}) sets a known value of \texttt{opr} for $D$ as value of \texttt{opr} also for $S$. A typical example for which \texttt{InstallSubsetMaintenance} is applied is given by \texttt{opr = IsFinite, super\_req = IsCollection} and \texttt{IsFinite}, and \texttt{sub\_req = IsCollection}.

If \texttt{opr} is a property and the filter \texttt{super\_req} lies in the filter \texttt{opr} then we can use also the following inverse implication. If $D$ is in the filter whose intersection with \texttt{opr} is \texttt{super\_req} and if $S$
is in the filter sub_req, S is a subset of D, and the value of opr for S is false then the value of opr for D is also false.

31.13.5 InstallFactorMaintenance

InstallFactorMaintenance(opr, numer_req, denom_req, factor_req) (function)

opr must be a property or an attribute. The call of InstallFactorMaintenance has the effect that for collections N, D, F in the filters numer_req, denom_req, and factor_req, respectively, the call UseFactorRelation(N,D,F) (see UseFactorRelation (31.13.2)) sets a known value of opr for N as value of opr also for F. A typical example for which InstallFactorMaintenance is applied is given by opr = IsFinite, numer_req = IsCollection and IsFinite, denom_req = IsCollection, and factor_req = IsCollection.

For the other direction, if numer_req involves the filter opr then a known false value of opr for F implies a false value for D provided that D lies in the filter obtained from numer_req by removing opr.

Note that an implication of a factor relation holds in particular for the case of isomorphisms. So one need not install an isomorphism maintained method when a factor maintained method is already installed. For example, UseIsomorphismRelation (31.13.3) will transfer a known IsFinite (30.4.2) value because of the installed factor maintained method.

31.13.6 InstallIsomorphismMaintenance

InstallIsomorphismMaintenance(opr, old_req, new_req) (function)

opr must be a property or an attribute. The call of InstallIsomorphismMaintenance has the effect that for a domain D in the filter old_req, and a domain E in the filter new_req, the call UseIsomorphismRelation(D,E) (see UseIsomorphismRelation (31.13.3)) sets a known value of opr for D as value of opr also for E. A typical example for which InstallIsomorphismMaintenance is applied is given by opr = Size, old_req = IsCollection, and new_req = IsCollection.

31.14 Useful Categories of Elements

This section and the following one are rather technical, and may be interesting only for those GAP users who want to implement new kinds of elements.

It deals with certain categories of elements that are useful mainly for the design of elements, from the viewpoint that one wants to form certain domains of these elements. For example, a domain closed under multiplication * (a so-called magma, see Chapter 35) makes sense only if its elements can be multiplied, and the latter is indicated by the category IsMultiplicativeElement (31.14.10) for each element. Again note that the underlying idea is that a domain is regarded as generated by given elements, and that these elements carry information about the desired domain. For general information on categories and their hierarchies, see 13.3.

More special categories of this kind are described in the contexts where they arise, they are IsRowVector (23.1.1), IsMatrix (24.2.1), IsOrdinaryMatrix (24.2.2), and IsLieMatrix (24.2.3).
31.14.1 IsExtAElement

\[ \text{IsExtAElement}(\text{obj}) \] (Category)

An external additive element is an object that can be added via + with other elements (not necessarily in the same family, see 13.1).

31.14.2 IsNearAdditiveElement

\[ \text{IsNearAdditiveElement}(\text{obj}) \] (Category)

A near-additive element is an object that can be added via + with elements in its family (see 13.1); this addition is not necessarily commutative.

31.14.3 IsAdditiveElement

\[ \text{IsAdditiveElement}(\text{obj}) \] (Category)

An additive element is an object that can be added via + with elements in its family (see 13.1); this addition is commutative.


\[ \text{IsNearAdditiveElementWithZero}(\text{obj}) \] (Category)

A near-additive element-with-zero is an object that can be added via + with elements in its family (see 13.1), and that is an admissible argument for the operation \text{Zero} (31.10.3); this addition is not necessarily commutative.

31.14.5 IsAdditiveElementWithZero

\[ \text{IsAdditiveElementWithZero}(\text{obj}) \] (Category)

An additive element-with-zero is an object that can be added via + with elements in its family (see 13.1), and that is an admissible argument for the operation \text{Zero} (31.10.3); this addition is commutative.

31.14.6 IsNearAdditiveElementWithInverse

\[ \text{IsNearAdditiveElementWithInverse}(\text{obj}) \] (Category)

A near-additive element-with-inverse is an object that can be added via + with elements in its family (see 13.1), and that is an admissible argument for the operations \text{Zero} (31.10.3) and \text{AdditiveInverse} (31.10.9); this addition is not necessarily commutative.
31.14.7  IsAdditiveElementWithInverse

\( \text{IsAdditiveElementWithInverse}(\text{obj}) \) (Category)

An additive element-with-inverse is an object that can be added via \( + \) with elements in its family (see 13.1), and that is an admissible argument for the operations \( \text{Zero} \) (31.10.3) and \( \text{AdditiveInverse} \) (31.10.9); this addition is commutative.

31.14.8  IsExtLElement

\( \text{IsExtLElement}(\text{obj}) \) (Category)

An external left element is an object that can be multiplied from the left, via \( \ast \), with other elements (not necessarily in the same family, see 13.1).

31.14.9  IsExtRElement

\( \text{IsExtRElement}(\text{obj}) \) (Category)

An external right element is an object that can be multiplied from the right, via \( \ast \), with other elements (not necessarily in the same family, see 13.1).

31.14.10  IsMultiplicativeElement

\( \text{IsMultiplicativeElement}(\text{obj}) \) (Category)

A multiplicative element is an object that can be multiplied via \( \ast \) with elements in its family (see 13.1).

31.14.11  IsMultiplicativeElementWithOne

\( \text{IsMultiplicativeElementWithOne}(\text{obj}) \) (Category)

A multiplicative element-with-one is an object that can be multiplied via \( \ast \) with elements in its family (see 13.1), and that is an admissible argument for the operation \( \text{One} \) (31.10.2).


\( \text{IsMultiplicativeElementWithZero}(\text{elt}) \) (Category)

\textbf{Returns:} \textit{true} or \textit{false}.

This is the category of elements in a family which can be the operands of \( \ast \) (multiplication) and the operation \text{MultiplicativeZeroOp} (31.10.4).

```gap
gap> S:=Semigroup(Transformation([1,1,1]));;
gap> M:=MagmaWithZeroAdjoined(S);
<<commutative transformation semigroup of degree 3 with 1 generator>
   with 0 adjoined>>
gap> x:=Representative(M);
<semigroup with 0 adjoined elt: Transformation([1,1,1])>
```
31.14.13  IsMultiplicativeElementWithInverse

\[\text{IsMultiplicativeElementWithInverse}(\text{obj})\] (Category)

A multiplicative element-with-inverse is an object that can be multiplied via \(*\) with elements in its family (see 13.1), and that is an admissible argument for the operations \texttt{One}(31.10.2) and \texttt{Inverse}(31.10.8). (Note the word “admissible”: an object in this category does not necessarily have an inverse, \texttt{Inverse}(31.10.8) may return \texttt{fail}.)

31.14.14  IsVector

\[\text{IsVector}(\text{obj})\] (Category)

A vector is an additive-element-with-inverse that can be multiplied from the left and right with other objects (not necessarily of the same type). Examples are cyclotomics, finite field elements, and of course row vectors (see below).

Note that not all lists of ring elements are regarded as vectors, for example lists of matrices are not vectors. This is because although the category \texttt{IsAdditiveElementWithInverse}(31.14.7) is implied by the meet of its collections category and \texttt{IsList}(21.1.1), the family of a list entry may not imply \texttt{IsAdditiveElementWithInverse}(31.14.7) for all its elements.

31.14.15  IsNearRingElement

\[\text{IsNearRingElement}(\text{obj})\] (Category)

\texttt{IsNearRingElement} is just a synonym for the meet of \texttt{IsNearAdditiveElementWithInverse}(31.14.6) and \texttt{IsMultiplicativeElement}(31.14.10).

31.14.16  IsRingElement

\[\text{IsRingElement}(\text{obj})\] (Category)

\texttt{IsRingElement} is just a synonym for the meet of \texttt{IsAdditiveElementWithInverse}(31.14.7) and \texttt{IsMultiplicativeElement}(31.14.10).

31.14.17  IsNearRingElementWithOne

\[\text{IsNearRingElementWithOne}(\text{obj})\] (Category)

\texttt{IsNearRingElementWithOne} is just a synonym for the meet of \texttt{IsNearAdditiveElementWithInverse}(31.14.6) and \texttt{IsMultiplicativeElementWithOne}(31.14.11).
31.14.18 IsRingElementWithOne

\[ \text{IsRingElementWithOne}(\text{obj}) \] (Category)

IsRingElementWithOne is just a synonym for the meet of IsAdditiveElementWithInverse (31.14.7) and IsMultiplicativeElementWithOne (31.14.11).

31.14.19 IsNearRingElementWithInverse

\[ \text{IsNearRingElementWithInverse}(\text{obj}) \] (Category)

IsNearRingElementWithInverse is just a synonym for the meet of IsNearAdditiveElementWithInverse (31.14.6) and IsMultiplicativeElementWithInverse (31.14.13).

31.14.20 IsRingElementWithInverse

\[ \text{IsRingElementWithInverse}(\text{obj}) \] (Category)
\[ \text{IsScalar}(\text{obj}) \] (Category)

IsRingElementWithInverse and IsScalar are just synonyms for the meet of IsAdditiveElementWithInverse (31.14.7) and IsMultiplicativeElementWithInverse (31.14.13).

31.15 Useful Categories for all Elements of a Family

The following categories of elements are to be understood mainly as categories for all objects in a family, they are usually used as third argument of NewFamily (13.1.2). The purpose of each of the following categories is then to guarantee that each collection of its elements automatically lies in its collections category (see CategoryCollections (30.2.4)).

For example, the multiplication of permutations is associative, and it is stored in the family of permutations that each permutation lies in IsAssociativeElement (31.15.1). As a consequence, each magma consisting of permutations (more precisely: each collection that lies in the family CollectionsFamily( PermutationsFamily ), see CollectionsFamily (30.2.1)) automatically lies in CategoryCollections( IsAssociativeElement ). A magma in this category is always known to be associative, via a logical implication (see 78.8).

Similarly, if a family knows that all its elements are in the categories IsJacobianElement (31.15.5) and IsZeroSquaredElement (31.15.6), then each algebra of these elements is automatically known to be a Lie algebra (see Chapter 62).

31.15.1 IsAssociativeElement

\[ \text{IsAssociativeElement}(\text{obj}) \] (Category)
\[ \text{IsAssociativeElementCollection}(\text{obj}) \] (Category)
\[ \text{IsAssociativeElementCollColl}(\text{obj}) \] (Category)
An element \emph{obj} in the category \texttt{IsAssociativeElement} knows that the multiplication of any elements in the family of \emph{obj} is associative. For example, all permutations lie in this category, as well as those ordinary matrices (see \texttt{IsOrdinaryMatrix (24.2.2)}) whose entries are also in \texttt{IsAssociativeElement}.

\subsection{31.15.2 \texttt{IsAdditivelyCommutativeElement}}

\begin{itemize}
  \item \texttt{IsAdditivelyCommutativeElement(obj)}
  \item \texttt{IsAdditivelyCommutativeElementCollection(obj)}
  \item \texttt{IsAdditivelyCommutativeElementCollColl(obj)}
  \item \texttt{IsAdditivelyCommutativeElementFamily(obj)}
\end{itemize}

An element \emph{obj} in the category \texttt{IsAdditivelyCommutativeElement} knows that the addition of any elements in the family of \emph{obj} is commutative. For example, each finite field element and each rational number lies in this category.

\subsection{31.15.3 \texttt{IsCommutativeElement}}

\begin{itemize}
  \item \texttt{IsCommutativeElement(obj)}
  \item \texttt{IsCommutativeElementCollection(obj)}
  \item \texttt{IsCommutativeElementCollColl(obj)}
\end{itemize}

An element \emph{obj} in the category \texttt{IsCommutativeElement} knows that the multiplication of any elements in the family of \emph{obj} is commutative. For example, each finite field element and each rational number lies in this category.

\subsection{31.15.4 \texttt{IsFiniteOrderElement}}

\begin{itemize}
  \item \texttt{IsFiniteOrderElement(obj)}
  \item \texttt{IsFiniteOrderElementCollection(obj)}
  \item \texttt{IsFiniteOrderElementCollColl(obj)}
\end{itemize}

An element \emph{obj} in the category \texttt{IsFiniteOrderElement} knows that it has finite multiplicative order. For example, each finite field element and each permutation lies in this category. However the value may be \texttt{false} even if \emph{obj} has finite order, but if this was not known when \emph{obj} was constructed.

Although it is legal to set this filter for any object with finite order, this is really useful only in the case that all elements of a family are known to have finite order.

\subsection{31.15.5 \texttt{IsJacobianElement}}

\begin{itemize}
  \item \texttt{IsJacobianElement(obj)}
  \item \texttt{IsJacobianElementCollection(obj)}
  \item \texttt{IsJacobianElementCollColl(obj)}
  \item \texttt{IsRestrictedJacobianElement(obj)}
  \item \texttt{IsRestrictedJacobianElementCollection(obj)}
  \item \texttt{IsRestrictedJacobianElementCollColl(obj)}
\end{itemize}
An element \( \text{obj} \) in the category \IsJacobianElement knows that the multiplication of any elements in the family \( F \) of \( \text{obj} \) satisfies the Jacobi identity, that is, \( x * y * z + z * x * y + y * z * x \) is zero for all \( x, y, z \) in \( F \).

For example, each Lie matrix (see \IsLieMatrix (24.2.3)) lies in this category.

### 31.15.6 \IsZeroSquaredElement

\IsZeroSquaredElement(\text{obj})
\IsZeroSquaredElementCollection(\text{obj})
\IsZeroSquaredElementCollColl(\text{obj})

An element \( \text{obj} \) in the category \IsZeroSquaredElement knows that \( \text{obj}^2 = \text{Zero}(\text{obj}) \). For example, each Lie matrix (see \IsLieMatrix (24.2.3)) lies in this category.

Although it is legal to set this filter for any zero squared object, this is really useful only in the case that all elements of a family are known to have square zero.
Chapter 32

Mappings

A mapping in GAP is what is called a “function” in mathematics. GAP also implements generalized mappings in which one element might have several images, these can be imagined as subsets of the cartesian product and are often called “relations”.

Most operations are declared for general mappings and therefore this manual often refers to “(general) mappings”, unless you deliberately need the generalization you can ignore the “general” bit and just read it as “mappings”.

A general mapping $F$ in GAP is described by its source $S$, its range $R$, and a subset $Rel$ of the direct product $S \times R$, which is called the underlying relation of $F$. $S$, $R$, and $Rel$ are generalized domains (see 12.4). The corresponding attributes for general mappings are Source (32.3.8), Range (32.3.7), and UnderlyingRelation (32.3.9).

Note that general mappings themselves are not domains. One reason for this is that two general mappings with same underlying relation are regarded as equal only if also the sources are equal and the ranges are equal. Other, more technical, reasons are that general mappings and domains have different basic operations, and that general mappings are arithmetic objects (see 32.6); both should not apply to domains.

Each element of an underlying relation of a general mapping lies in the category of direct product elements (see IsDirectProductElement (32.1.1)).

For each $s \in S$, the set $\{ r \in R | (s, r) \in Rel \}$ is called the set of images of $s$. Analogously, for $r \in R$, the set $\{ s \in S | (s, r) \in Rel \}$ is called the set of preimages of $r$.

The ordering of general mappings via $<$ is defined by the ordering of source, range, and underlying relation. Specifically, if the source and range domains of $map1$ and $map2$ are the same, then one considers the union of the preimages of $map1$ and $map2$ as a strictly ordered set. The smaller of $map1$ and $map2$ is the one whose image is smaller on the first point of this sequence where they differ.

For mappings which preserve an algebraic structure a kernel is defined. Depending on the structure preserved the operation to compute this kernel is called differently, see Section 32.7.

Some technical details of general mappings are described in section 32.13.

32.1 Direct Products and their Elements

32.1.1 IsDirectProductElement

$\triangleright$ IsDirectProductElement(obj) (Category)
IsDirectProductElement is a subcategory of the meet of IsDenseList (21.1.2), IsMultiplicativeElementWithInverse (31.14.13), IsAdditiveElementWithInverse (31.14.7), and IsCopyable (12.6.1), where the arithmetic operations (addition, zero, additive inverse, multiplication, powering, one, inverse) are defined componentwise.

Note that each of these operations will cause an error message if its result for at least one component cannot be formed.

For an object in the filter IsDirectProductElement, ShallowCopy (12.7.1) returns a mutable plain list with the same entries. The sum and the product of a direct product element and a list in IsListDefault (21.12.3) is the list of sums and products, respectively. The sum and the product of a direct product element and an object that is neither a list nor a collection is the direct product element of componentwise sums and products, respectively.

### 32.1.2 DirectProductFamily

- **DirectProductFamily(args)** (function)

  args must be a dense list of CollectionsFamily (30.2.1) families, otherwise the function raises an error.

  DirectProductFamily returns fam, a collections family of IsDirectProductElement (32.1.1) objects.

  fam is the CollectionsFamily (30.2.1) of IsDirectProductElement (32.1.1) objects whose i-th component is in ElementsFamily(args[i]).

  Note that a collection in fam may not itself be a direct product; it just is a subcollection of a direct product.

  **Example**

  ```
  gap> D8 := DihedralGroup(IsPermGroup, 8);;
  gap> FamilyObj(D8) = CollectionsFamily(PermutationsFamily);
  true
  gap> fam := DirectProductFamily([FamilyObj(D8), FamilyObj(D8)]);
  gap> ComponentsOfDirectProductElementsFamily(ElementsFamily(fam));
  [ <Family: "PermutationsFamily">, <Family: "PermutationsFamily"> ]
  ```

Also note that not all direct products in GAP are created via these families. For example if the arguments to DirectProduct (49.1.1) are permutation groups, then it returns a permutation group as well, whose elements are not IsDirectProductElement (32.1.1) objects.

**Example**

```
gap> fam = FamilyObj(DirectProduct(D8, D8));
false
gap> D4 := DihedralGroup(IsPcGroup, 4);;
gap> fam2 := DirectProductFamily([FamilyObj(D8), FamilyObj(D4)]);
gap> fam2 := FamilyObj(DirectProduct(D8, D4));
true
```
32.2 Creating Mappings

32.2.1 GeneralMappingByElements

`GeneralMappingByElements(S, R, elms)`

is the general mapping with source $S$ and range $R$, and with underlying relation consisting of the collection $elms$ of direct product elements.

32.2.2 MappingByFunction

`MappingByFunction(S, R, fun[, invfun])`

`MappingByFunction(S, R, fun, false, prefun)`

`MappingByFunction` returns a mapping $map$ with source $S$ and range $R$, such that each element $s$ of $S$ is mapped to the element $fun(s)$, where $fun$ is a GAP function.

If the argument $invfun$ is bound then $map$ is a bijection between $S$ and $R$, and the preimage of each element $r$ of $R$ is given by $invfun(r)$, where $invfun$ is a GAP function.

If five arguments are given and the fourth argument is $false$ then the GAP function $prefun$ can be used to compute a single preimage also if $map$ is not bijective.

The mapping returned by `MappingByFunction` lies in the filter `IsNonSPGeneralMapping (32.14.1)`, see 32.14.

32.2.3 InverseGeneralMapping

`InverseGeneralMapping(map)`

The inverse general mapping of a general mapping $map$ is the general mapping whose underlying relation (see `UnderlyingRelation (32.3.9)`) contains a pair $(r, s)$ if and only if the underlying relation of $map$ contains the pair $(s, r)$.

See the introduction to Chapter 32 for the subtleties concerning the difference between `InverseGeneralMapping` and `Inverse (31.10.8)`.

Note that the inverse general mapping of a mapping $map$ is in general only a general mapping. If $map$ knows to be bijective its inverse general mapping will know to be a mapping. In this case also `Inverse (map)` works.

32.2.4 RestrictedInverseGeneralMapping

`RestrictedInverseGeneralMapping(map)`

The restricted inverse general mapping of a general mapping $map$ is the general mapping whose underlying relation (see `UnderlyingRelation (32.3.9)`) contains a pair $(r, s)$ if and only if the underlying relation of $map$ contains the pair $(s, r)$, and whose domain is restricted to the image of $map$ and whose range is the domain of $map$. 
### 32.2.5 CompositionMapping

> CompositionMapping(map1, map2, ...)

 CompositionMapping allows one to compose arbitrarily many general mappings, and delegates each step to CompositionMapping2 (32.2.6). The result is a map that maps an element first under the last argument, then under the penultimate argument and so forth.

Additionally, the properties IsInjective (32.3.4) and IsSingleValued (32.3.2) are maintained. If the range of the \( i + 1 \)-th argument is identical to the range of the \( i \)-th argument, also IsTotal (32.3.1) and IsSurjective (32.3.5) are maintained. (So one should not call CompositionMapping2 (32.2.6) directly if one wants to maintain these properties.)

Depending on the types of \( \text{map1} \) and \( \text{map2} \), the returned mapping might be constructed completely new (for example by giving domain generators and their images, this is for example the case if both mappings preserve the same algebraic structures and GAP can decompose elements of the source of \( \text{map2} \) into generators) or as an (iterated) composition (see IsCompositionMappingRep (32.2.7)).

#### Example

```gap
gap> f := GroupHomomorphismByImages(CyclicGroup(IsPermGroup, 2),
   CyclicGroup(IsPermGroup, 1));
[ (1,2) ] -> [ () ]
gap> g := GroupHomomorphismByImages(CyclicGroup(IsPermGroup, 6),
   CyclicGroup(IsPermGroup, 2));
[ (1,2,3,4,5,6) ] -> [ (1,2) ]
gap> CompositionMapping(f, g);
[ (1,2,3,4,5,6) ] -> [ () ]
gap> CompositionMapping(g, f);
[ (1,2) ] -> [ () ]
```

### 32.2.6 CompositionMapping2

> CompositionMapping2(map2, map1)

CompositionMapping2 returns the composition of \( \text{map2} \) and \( \text{map1} \), this is the general mapping that maps an element first under \( \text{map1} \), and then maps the images under \( \text{map2} \).

(Note the reverse ordering of arguments in the composition via the multiplication \( \ast \) (31.12.1). CompositionMapping2General is the method that forms a composite mapping with two constituent mappings. (This is used in some algorithms.)

### 32.2.7 IsCompositionMappingRep

> IsCompositionMappingRep(map)

Mappings in this representation are stored as composition of two mappings, (pre)images of elements are computed in a two-step process. The constituent mappings of the composition can be obtained via ConstituentsCompositionMapping (32.2.8).
32.2.8 ConstituentsCompositionMapping

If `map` is stored in the representation `IsCompositionMappingRep` (32.2.7) as composition of two mappings `map1` and `map2`, this function returns the two constituent mappings in a list `[map1, map2]`.

32.2.9 ZeroMapping

A zero mapping is a total general mapping that maps each element of its source to the zero element of its range.

(Each mapping with empty source is a zero mapping.)

32.2.10 IdentityMapping

is the bijective mapping with source and range equal to the collection `D`, which maps each element of `D` to itself.

32.2.11 Embedding

returns the embedding of the domain `S` in the domain `T`, or in the second form, some domain indexed by the positive integer `i`. The precise natures of the various methods are described elsewhere: for Lie algebras, see `LieFamily` (64.1.3); for group products, see 49.6 for a general description, or for examples see 49.1 for direct products, 49.2 for semidirect products, or 49.4 for wreath products; or for magma rings see 65.3.

32.2.12 Projection

returns the projection of the domain `S` onto the domain `T`, or in the second form, some domain indexed by the positive integer `i`, or in the third form, some natural quotient domain of `S`. Various methods are defined for group products; see 49.6 for a general description, or for examples see 49.1 for direct products, 49.2 for semidirect products, 49.3 for subdirect products, or 49.4 for wreath products.
32.2.13 RestrictedMapping

\[ \text{RestrictedMapping} (\text{map}, \text{subdom}) \]

If \( \text{subdom} \) is a subdomain of the source of the general mapping \( \text{map} \), this operation returns the restriction of \( \text{map} \) to \( \text{subdom} \).

32.3 Properties and Attributes of (General) Mappings

32.3.1 IsTotal

\[ \text{IsTotal} (\text{map}) \]

is true if each element in the source \( S \) of the general mapping \( \text{map} \) has images, i.e., \( s^{\text{map}} \neq \emptyset \) for all \( s \in S \), and false otherwise.

32.3.2 IsSingleValued

\[ \text{IsSingleValued} (\text{map}) \]

is true if each element in the source \( S \) of the general mapping \( \text{map} \) has at most one image, i.e., \( |s^{\text{map}}| \leq 1 \) for all \( s \in S \), and false otherwise.

Equivalently, \( \text{IsSingleValued} (\text{map}) \) is true if and only if the preimages of different elements in \( R \) are disjoint.

32.3.3 IsMapping

\[ \text{IsMapping} (\text{map}) \]

A mapping \( \text{map} \) is a general mapping that assigns to each element \( \text{elm} \) of its source a unique element \( \text{Image} (\text{map}, \text{elm}) \) of its range.

Equivalently, the general mapping \( \text{map} \) is a mapping if and only if it is total and single-valued (see IsTotal (32.3.1), IsSingleValued (32.3.2)).

32.3.4 IsInjective

\[ \text{IsInjective} (\text{map}) \]

is true if the images of different elements in the source \( S \) of the general mapping \( \text{map} \) are disjoint, i.e., \( x^{\text{map}} \cap y^{\text{map}} = \emptyset \) for \( x \neq y \in S \), and false otherwise.

Equivalently, \( \text{IsInjective} (\text{map}) \) is true if and only if each element in the range of \( \text{map} \) has at most one preimage in \( S \).

32.3.5 IsSurjective

\[ \text{IsSurjective} (\text{map}) \]

is true if each element in the range \( R \) of the general mapping \( \text{map} \) has at least one preimage in \( S \), and false otherwise.
is true if each element in the range \( R \) of the general mapping \( \text{map} \) has preimages in the source \( S \) of \( \text{map} \), i.e., \( \{ s \in S \mid x \in s^{\text{map}} \} \neq \emptyset \) for all \( x \in R \), and false otherwise.

### 32.3.6 IsBijective

\( \triangleright \) IsBijective\( (\text{map}) \)  (property)

A general mapping \( \text{map} \) is bijective if and only if it is an injective and surjective mapping (see IsMapping (32.3.3), IsInjective (32.3.4), IsSurjective (32.3.5)).

### 32.3.7 Range (of a general mapping)

\( \triangleright \) Range\( (\text{map}) \)  (attribute)

The range of a general mapping.

### 32.3.8 Source

\( \triangleright \) Source\( (\text{map}) \)  (attribute)

The source of a general mapping.

### 32.3.9 UnderlyingRelation

\( \triangleright \) UnderlyingRelation\( (\text{map}) \)  (attribute)

The underlying relation of a general mapping \( \text{map} \) is the domain of pairs \((s, r)\), with \( s \) in the source and \( r \) in the range of \( \text{map} \) (see Source (32.3.8), Range (32.3.7)), and \( r \in \text{ImagesElm( map, s )} \).

Each element of the underlying relation is represented by a direct product element (see IsDirectProductElement (32.1.1)).

### 32.3.10 UnderlyingGeneralMapping

\( \triangleright \) UnderlyingGeneralMapping\( (\text{map}) \)  (attribute)

attribute for underlying relations of general mappings

### 32.4 Images under Mappings

#### 32.4.1 ImagesSource

\( \triangleright \) ImagesSource\( (\text{map}) \)  (attribute)

is the set of images of the source of the general mapping \( \text{map} \).

ImagesSource delegates to ImagesSet (32.4.4), it is introduced only to store the image of \( \text{map} \) as attribute value.
32.4.2 ImagesRepresentative

\[ \text{ImagesRepresentative}(\text{map}, \text{elm}) \] (operation)

If \( \text{elm} \) is an element of the source of the general mapping \( \text{map} \) then \( \text{ImagesRepresentative} \) returns either a representative of the set of images of \( \text{elm} \) under \( \text{map} \) or \text{fail}, the latter if and only if \( \text{elm} \) has no images under \( \text{map} \).

Anything may happen if \( \text{elm} \) is not an element of the source of \( \text{map} \).

32.4.3 ImagesElm

\[ \text{ImagesElm}(\text{map}, \text{elm}) \] (operation)

If \( \text{elm} \) is an element of the source of the general mapping \( \text{map} \) then \( \text{ImagesElm} \) returns the set of all images of \( \text{elm} \) under \( \text{map} \).

Anything may happen if \( \text{elm} \) is not an element of the source of \( \text{map} \).

32.4.4 ImagesSet

\[ \text{ImagesSet}(\text{map}, \text{elms}) \] (operation)

If \( \text{elms} \) is a subset of the source of the general mapping \( \text{map} \) then \( \text{ImagesSet} \) returns the set of all images of \( \text{elms} \) under \( \text{map} \).

The result will be either a proper set or a domain. Anything may happen if \( \text{elms} \) is not a subset of the source of \( \text{map} \).

32.4.5 ImageElm

\[ \text{ImageElm}(\text{map}, \text{elm}) \] (operation)

If \( \text{elm} \) is an element of the source of the total and single-valued mapping \( \text{map} \) then \( \text{ImageElm} \) returns the unique image of \( \text{elm} \) under \( \text{map} \).

Anything may happen if \( \text{elm} \) is not an element of the source of \( \text{map} \).

32.4.6 Image

\[ \text{Image}(\text{map}) \] (function)
\[ \text{Image}(\text{map}, \text{elm}) \] (function)
\[ \text{Image}(\text{map}, \text{coll}) \] (function)

\( \text{Image}(\text{map}) \) is the image of the general mapping \( \text{map} \), i.e., the subset of elements of the range of \( \text{map} \) that are actually values of \( \text{map} \). Note that in this case the argument may also be multi-valued.

\( \text{Image}(\text{map}, \text{elm}) \) is the image of the element \( \text{elm} \) of the source of the mapping \( \text{map} \) under \( \text{map} \), i.e., the unique element of the range to which \( \text{map} \) maps \( \text{elm} \). This can also be expressed as \( \text{elm} \sim \text{map} \). Note that \( \text{map} \) must be total and single valued, a multi valued general mapping is not allowed (see Images (32.4.7)).

\( \text{Image}(\text{map}, \text{coll}) \) is the image of the subset \( \text{coll} \) of the source of the mapping \( \text{map} \) under \( \text{map} \), i.e., the subset of the range to which \( \text{map} \) maps elements of \( \text{coll} \). \( \text{coll} \) may be a proper set
or a domain. The result will be either a proper set or a domain. Note that in this case $\text{map}$ may also be multi-valued. (If $\text{coll}$ and the result are lists then the positions of entries do in general not correspond.)

$\text{Image}$ delegates to $\text{ImagesSource}$ (32.4.1) when called with one argument, and to $\text{ImageElm}$ (32.4.5) resp. $\text{ImagesSet}$ (32.4.4) when called with two arguments.

If the second argument is not an element or a subset of the source of the first argument, an error is signalled.

### 32.4.7 Images

- $\text{Images}(\text{map})$ (function)
- $\text{Images}(\text{map}, \text{elm})$ (function)
- $\text{Images}(\text{map}, \text{coll})$ (function)

$\text{Images}(\text{map})$ is the image of the general mapping $\text{map}$, i.e., the subset of elements of the range of $\text{map}$ that are actually values of $\text{map}$.

$\text{Images}(\text{map}, \text{elm})$ is the set of images of the element $\text{elm}$ of the source of the general mapping $\text{map}$ under $\text{map}$, i.e., the set of elements of the range to which $\text{map}$ maps $\text{elm}$.

$\text{Images}(\text{map}, \text{coll})$ is the set of images of the subset $\text{coll}$ of the source of the general mapping $\text{map}$ under $\text{map}$, i.e., the subset of the range to which $\text{map}$ maps elements of $\text{coll}$. $\text{coll}$ may be a proper set or a domain. The result will be either a proper set or a domain. (If $\text{coll}$ and the result are lists then the positions of entries do in general not correspond.)

$\text{Images}$ delegates to $\text{ImagesSource}$ (32.4.1) when called with one argument, and to $\text{ImageElm}$ (32.4.5) resp. $\text{ImagesSet}$ (32.4.4) when called with two arguments.

If the second argument is not an element or a subset of the source of the first argument, an error is signalled.

### 32.5 Preimages under Mappings

#### 32.5.1 PreImagesRange

- $\text{PreImagesRange}(\text{map})$ (attribute)

$\text{PreImagesRange}(\text{map})$ is the set of preimages of the range of the general mapping $\text{map}$.

$\text{PreImagesRange}$ delegates to $\text{PreImagesSet}$ (32.5.5), it is introduced only to store the preimage of $\text{map}$ as attribute value.

#### 32.5.2 PreImagesElm

- $\text{PreImagesElm}(\text{map}, \text{elm})$ (operation)

If $\text{elm}$ is an element of the range of the general mapping $\text{map}$ then $\text{PreImagesElm}$ returns the set of all preimages of $\text{elm}$ under $\text{map}$.

Anything may happen if $\text{elm}$ is not an element of the range of $\text{map}$. 
32.5.3 PreImageElm

\[ \text{PreImageElm}(\text{map}, \text{elm}) \] (operation)

If \(\text{elm}\) is an element of the range of the injective and surjective general mapping \(\text{map}\) then \(\text{PreImageElm}\) returns the unique preimage of \(\text{elm}\) under \(\text{map}\).

Anything may happen if \(\text{elm}\) is not an element of the range of \(\text{map}\).

32.5.4 PreImagesRepresentative

\[ \text{PreImagesRepresentative}(\text{map}, \text{elm}) \] (operation)

If \(\text{elm}\) is an element of the range of the general mapping \(\text{map}\) then \(\text{PreImagesRepresentative}\) returns either a representative of the set of preimages of \(\text{elm}\) under \(\text{map}\) or \text{fail}, the latter if and only if \(\text{elm}\) has no preimages under \(\text{map}\).

Anything may happen if \(\text{elm}\) is not an element of the range of \(\text{map}\).

32.5.5 PreImagesSet

\[ \text{PreImagesSet}(\text{map}, \text{elms}) \] (operation)

If \(\text{elms}\) is a subset of the range of the general mapping \(\text{map}\) then \(\text{PreImagesSet}\) returns the set of all preimages of \(\text{elms}\) under \(\text{map}\).

Anything may happen if \(\text{elms}\) is not a subset of the range of \(\text{map}\).

32.5.6 PreImage

\[ \text{PreImage}(\text{map}) \] (function)
\[ \text{PreImage}(\text{map}, \text{elm}) \] (function)
\[ \text{PreImage}(\text{map}, \text{coll}) \] (function)

\(\text{PreImage}(\text{map})\) is the preimage of the general mapping \(\text{map}\), i.e., the subset of elements of the source of \(\text{map}\) that actually have values under \(\text{map}\). Note that in this case the argument may also be non-injective or non-surjective.

\(\text{PreImage}(\text{map}, \text{elm})\) is the preimage of the element \(\text{elm}\) of the range of the injective and surjective mapping \(\text{map}\) under \(\text{map}\), i.e., the unique element of the source which is mapped under \(\text{map}\) to \(\text{elm}\). Note that \(\text{map}\) must be injective and surjective (see \text{PreImages} (32.5.7)).

\(\text{PreImage}(\text{map}, \text{coll})\) is the preimage of the subset \(\text{coll}\) of the range of the general mapping \(\text{map}\) under \(\text{map}\), i.e., the subset of the source which is mapped under \(\text{map}\) to elements of \(\text{coll}\). \(\text{coll}\) may be a proper set or a domain. The result will be either a proper set or a domain. Note that in this case \(\text{map}\) may also be non-injective or non-surjective. (If \(\text{coll}\) and the result are lists then the positions of entries do in general not correspond.)

\(\text{PreImage}\) delegates to \text{PreImagesRange} (32.5.1) when called with one argument, and to \text{PreImageElm} (32.5.3) resp. \text{PreImagesSet} (32.5.5) when called with two arguments.

If the second argument is not an element or a subset of the range of the first argument, an error is signalled.
32.5.7 PreImages

\[\text{PreImages}(\text{map})\] is the preimage of the general mapping \text{map}, i.e., the subset of elements of the source of \text{map} that have actually values under \text{map}.

\[\text{PreImages}(\text{map}, \text{elm})\] is the set of preimages of the element \text{elm} of the range of the general mapping \text{map} under \text{map}, i.e., the set of elements of the source which \text{map} maps to \text{elm}.

\[\text{PreImages}(\text{map}, \text{coll})\] is the set of images of the subset \text{coll} of the range of the general mapping \text{map} under \text{map}, i.e., the subset of the source which \text{map} maps to elements of \text{coll}. \text{coll} may be a proper set or a domain. The result will be either a proper set or a domain. (If \text{coll} and the result are lists then the positions of entries do in general not correspond.)

\text{PreImages} delegates to \text{PreImagesRange} (32.5.1) when called with one argument, and to \text{PreImagesElm} (32.5.2) resp. \text{PreImagesSet} (32.5.5) when called with two arguments.

If the second argument is not an element or a subset of the range of the first argument, an error is signalled.

32.6 Arithmetic Operations for General Mappings

General mappings are arithmetic objects. One can form groups and vector spaces of general mappings provided that they are invertible or can be added and admit scalar multiplication, respectively.

For two general mappings with same source, range, preimage, and image, the \textit{sum} is defined pointwise, i.e., the images of a point under the sum is the set of all sums with first summand in the images of the first general mapping and second summand in the images of the second general mapping.

\textit{Scalar multiplication} of general mappings is defined likewise.

The \textit{product} of two general mappings is defined as the composition. This multiplication is always associative. In addition to the composition via \*, general mappings can be composed –in reversed order– via \text{CompositionMapping} (32.2.5).

General mappings are in the category of multiplicative elements with inverses. Similar to matrices, not every general mapping has an inverse or an identity, and we define the behaviour of \text{One} (31.10.2) and \text{Inverse} (31.10.8) for general mappings as follows. \text{One} (31.10.2) returns \text{fail} when called for a general mapping whose source and range differ, otherwise \text{One} (31.10.2) returns the identity mapping of the source. (Note that the source may differ from the preimage). \text{Inverse} (31.10.8) returns \text{fail} when called for a non-bijective general mapping or for a general mapping whose source and range differ; otherwise \text{Inverse} (31.10.8) returns the inverse mapping.

Besides the usual inverse of multiplicative elements, which means that \text{Inverse} (\text{g}) \* \text{g} = \text{g} \* \text{Inverse} (\text{g}) = \text{One} (\text{g}), for general mappings we have the attribute \text{InverseGeneralMapping} (32.2.3). If \text{F} is a general mapping with source \text{S}, range \text{R}, and underlying relation \text{Rel} then \text{InverseGeneralMapping} (\text{F}) has source \text{R}, range \text{S}, and underlying relation \{(r,s) \mid (s,r) \in \text{Rel}\}. For a general mapping that has an inverse in the usual sense, i.e., for a bijection of the source, of course both concepts coincide.

\text{Inverse} (31.10.8) may delegate to \text{InverseGeneralMapping} (32.2.3). \text{InverseGeneralMapping} (32.2.3) must not delegate to \text{Inverse} (31.10.8), but a known value of \text{Inverse} (31.10.8) may be fetched. So methods to compute the inverse of a general mapping
should be installed for \texttt{InverseGeneralMapping} (32.2.3).
(Note that in many respects, general mappings behave similar to matrices, for example one can define left and right identities and inverses, which do not fit into the current concepts of \textsc{GAP}.)

32.7 Mappings which are Compatible with Algebraic Structures

From an algebraical point of view, the most important mappings are those which are compatible with a structure. For Magmas, Groups and Rings, \textsc{GAP} supports the following four types of such mappings:

1. General mappings that respect multiplication
2. General mappings that respect addition
3. General mappings that respect scalar mult.
4. General mappings that respect multiplicative and additive structure

(Very technical note: \textsc{GAP} defines categories \texttt{IsSPGeneralMapping} and \texttt{IsNonSPGeneralMapping}. The distinction between these is orthogonal to the structure compatibility described here and should not be confused.)

32.8 Magma Homomorphisms

32.8.1 \texttt{IsMagmaHomomorphism}

\begin{verbatim}
\textbf{\texttt{IsMagmaHomomorphism}}(mapp)
\end{verbatim}

A magma homomorphism is a total single valued mapping which respects multiplication.

32.8.2 \texttt{MagmaHomomorphismByFunctionNC}

\begin{verbatim}
\textbf{\texttt{MagmaHomomorphismByFunctionNC}}(G, H, fn)
\end{verbatim}

Creates the homomorphism from \texttt{G} to \texttt{H} without checking that \texttt{fn} is a homomorphism.

32.8.3 \texttt{NaturalHomomorphismByGenerators}

\begin{verbatim}
\textbf{\texttt{NaturalHomomorphismByGenerators}}(f, s)
\end{verbatim}

returns a mapping from the magma \texttt{f} with \texttt{n} generators to the magma \texttt{s} with \texttt{n} generators, which maps the \texttt{i}-th generator of \texttt{f} to the \texttt{i}-th generator of \texttt{s}.

32.9 Mappings that Respect Multiplication

32.9.1 \texttt{RespectsMultiplication}

\begin{verbatim}
\textbf{\texttt{RespectsMultiplication}}(mapp)
\end{verbatim}
Let \( mapp \) be a general mapping with underlying relation \( F \subseteq S \times R \), where \( S \) and \( R \) are the source and the range of \( mapp \), respectively. Then \( \text{RespectsMultiplication} \) returns \( \text{true} \) if \( S \) and \( R \) are magmas such that \((s_1, r_1), (s_2, r_2) \in F \) implies \((s_1 * s_2, r_1 * r_2) \in F \), and \( \text{false} \) otherwise.

If \( mapp \) is single-valued then \( \text{RespectsMultiplication} \) returns \( \text{true} \) if and only if the equation \( s_1 \uparrow mapp \star s_2 \uparrow mapp = (s_1 \star s_2) \uparrow mapp \) holds for all \( s_1, s_2 \) in \( S \).

### 32.9.2 RespectsOne

\( \triangleright \text{RespectsOne}(mapp) \)  

Let \( mapp \) be a general mapping with underlying relation \( F \subseteq S \times R \), where \( S \) and \( R \) are the source and the range of \( mapp \), respectively. Then \( \text{RespectsOne} \) returns \( \text{true} \) if \( S \) and \( R \) are magmas-with-one such that \((\text{One}(S), \text{One}(R)) \in F \), and \( \text{false} \) otherwise.

If \( mapp \) is single-valued then \( \text{RespectsOne} \) returns \( \text{true} \) if and only if the equation \( \text{One}(S) \uparrow mapp = \text{One}(R) \) holds.

### 32.9.3 RespectsInverses

\( \triangleright \text{RespectsInverses}(mapp) \)  

Let \( mapp \) be a general mapping with underlying relation \( F \subseteq S \times R \), where \( S \) and \( R \) are the source and the range of \( mapp \), respectively. Then \( \text{RespectsInverses} \) returns \( \text{true} \) if \( S \) and \( R \) are magmas-with-inverses such that, for \( s \in S \) and \( r \in R \), \((s, r) \in F \) implies \((s^{-1}, r^{-1}) \in F \), and \( \text{false} \) otherwise.

If \( mapp \) is single-valued then \( \text{RespectsInverses} \) returns \( \text{true} \) if and only if the equation \( \text{Inverse}(s) \uparrow mapp = \text{Inverse}(s \uparrow mapp) \) holds for all \( s \) in \( S \).

### 32.9.4 IsGroupGeneralMapping

\( \triangleright \text{IsGroupGeneralMapping}(mapp) \)  

A group general mapping is a mapping which respects multiplication and inverses. If it is total and single valued it is called a group homomorphism.

Chapter 40 explains group homomorphisms in more detail.

### 32.9.5 KernelOfMultiplicativeGeneralMapping

\( \triangleright \text{KernelOfMultiplicativeGeneralMapping}(mapp) \)  

Let \( mapp \) be a general mapping. Then \( \text{KernelOfMultiplicativeGeneralMapping} \) returns the set of all elements in the source of \( mapp \) that have the identity of the range in their set of images.

(This is a monoid if \( mapp \) respects multiplication and one, and if the source of \( mapp \) is associative.)

### 32.9.6 CoKernelOfMultiplicativeGeneralMapping

\( \triangleright \text{CoKernelOfMultiplicativeGeneralMapping}(mapp) \)  

Let \texttt{mapp} be a general mapping. Then \texttt{CoKernelOfMultiplicativeGeneralMapping} returns the set of all elements in the range of \texttt{mapp} that have the identity of the source in their set of preimages. (This is a monoid if \texttt{mapp} respects multiplication and one, and if the range of \texttt{mapp} is associative.)

### 32.10 Mappings that Respect Addition

#### 32.10.1 \texttt{RespectsAddition}

\texttt{RespectsAddition(mapp)} (property)

Let \texttt{mapp} be a general mapping with underlying relation \(F \subseteq S \times R\), where \(S\) and \(R\) are the source and the range of \texttt{mapp}, respectively. Then \texttt{RespectsAddition} returns \texttt{true} if \(S\) and \(R\) are additive magmas such that \((s_1, r_1), (s_2, r_2) \in F\) implies \((s_1 + s_2, r_1 + r_2) \in F\), and \texttt{false} otherwise.

If \texttt{mapp} is single-valued then \texttt{RespectsAddition} returns \texttt{true} if and only if the equation \(s_1 \sim \texttt{mapp} + s_2 \sim \texttt{mapp} = (s_1 + s_2) \sim \texttt{mapp}\) holds for all \(s_1, s_2\) in \(S\).

#### 32.10.2 \texttt{RespectsAdditiveInverses}

\texttt{RespectsAdditiveInverses(mapp)} (property)

Let \texttt{mapp} be a general mapping with underlying relation \(F \subseteq S \times R\), where \(S\) and \(R\) are the source and the range of \texttt{mapp}, respectively. Then \texttt{RespectsAdditiveInverses} returns \texttt{true} if \(S\) and \(R\) are additive-magmas-with-inverses such that \((s, r) \in F\) implies \((-s, -r) \in F\), and \texttt{false} otherwise.

If \texttt{mapp} is single-valued then \texttt{RespectsAdditiveInverses} returns \texttt{true} if and only if the equation \(\text{AdditiveInverse}(s) \sim \texttt{mapp} = \text{AdditiveInverse}(s \sim \texttt{mapp})\) holds for all \(s\) in \(S\).

#### 32.10.3 \texttt{RespectsZero}

\texttt{RespectsZero(mapp)} (property)

Let \texttt{mapp} be a general mapping with underlying relation \(F \subseteq S \times R\), where \(S\) and \(R\) are the source and the range of \texttt{mapp}, respectively. Then \texttt{RespectsZero} returns \texttt{true} if \(S\) and \(R\) are additive-magmas-with-zero such that \((\text{Zero}(S), \text{Zero}(R)) \in F\), and \texttt{false} otherwise.

If \texttt{mapp} is single-valued then \texttt{RespectsZero} returns \texttt{true} if and only if the equation \(\text{Zero}(S) \sim \texttt{mapp} = \text{Zero}(R)\) holds.

#### 32.10.4 \texttt{IsAdditiveGroupGeneralMapping}

\texttt{IsAdditiveGroupGeneralMapping(mapp)} (filter)
\texttt{IsAdditiveGroupHomomorphism(mapp)} (filter)

\texttt{IsAdditiveGroupGeneralMapping} specifies whether a general mapping \texttt{mapp} respects addition (see \texttt{RespectsAddition} (32.10.1)) and respects additive inverses (see \texttt{RespectsAdditiveInverses} (32.10.2)).

\texttt{IsAdditiveGroupHomomorphism} is a synonym for the meet of \texttt{IsAdditiveGroupGeneralMapping} and \texttt{IsMapping} (32.3.3).
32.10.5 KernelOfAdditiveGeneralMapping

\[ \text{KernelOfAdditiveGeneralMapping}(\text{mapp}) \] (attribute)

Let \( \text{mapp} \) be a general mapping. Then \( \text{KernelOfAdditiveGeneralMapping} \) returns the set of all elements in the source of \( \text{mapp} \) that have the zero of the range in their set of images.

32.10.6 CoKernelOfAdditiveGeneralMapping

\[ \text{CoKernelOfAdditiveGeneralMapping}(\text{mapp}) \] (attribute)

Let \( \text{mapp} \) be a general mapping. Then \( \text{CoKernelOfAdditiveGeneralMapping} \) returns the set of all elements in the range of \( \text{mapp} \) that have the zero of the source in their set of preimages.

32.11 Linear Mappings

Also see Sections 32.9, 32.10, and KernelOfMultiplicativeGeneralMapping (32.9.5), CoKernelOfMultiplicativeGeneralMapping (32.9.6).

32.11.1 RespectsScalarMultiplication

\[ \text{RespectsScalarMultiplication}(\text{mapp}) \] (property)

Let \( \text{mapp} \) be a general mapping, with underlying relation \( F \subseteq S \times R \), where \( S \) and \( R \) are the source and the range of \( \text{mapp} \), respectively. Then \( \text{RespectsScalarMultiplication} \) returns true if \( S \) and \( R \) are left modules with the left acting domain \( D \) of \( S \) contained in the left acting domain of \( R \) and such that \( (s, r) \in F \) implies \( (c \cdot s, c \cdot r) \in F \) for all \( c \in D \), and false otherwise.

If \( \text{mapp} \) is single-valued then \( \text{RespectsScalarMultiplication} \) returns true if and only if the equation \( c \cdot s^{\text{mapp}} = (c \cdot s)^{\text{mapp}} \) holds for all \( c \) in \( D \) and \( s \) in \( S \).

32.11.2 IsLeftModuleGeneralMapping

\[ \text{IsLeftModuleGeneralMapping}(\text{mapp}) \] (filter)
\[ \text{IsLeftModuleHomomorphism}(\text{mapp}) \] (filter)

\( \text{IsLeftModuleGeneralMapping} \) specifies whether a general mapping \( \text{mapp} \) satisfies the property \( \text{IsAdditiveGroupGeneralMapping} \) (32.10.4) and respects scalar multiplication (see RespectsScalarMultiplication (32.11.1)).

\( \text{IsLeftModuleHomomorphism} \) is a synonym for the meet of \( \text{IsLeftModuleGeneralMapping} \) and \( \text{IsMapping} \) (32.3.3).

32.11.3 IsLinearMapping

\[ \text{IsLinearMapping}(F, \text{mapp}) \] (operation)

For a field \( F \) and a general mapping \( \text{mapp} \), \( \text{IsLinearMapping} \) returns true if \( \text{mapp} \) is an \( F \)-linear mapping, and false otherwise.
A mapping \( f \) is a linear mapping (or vector space homomorphism) if the source and range are vector spaces over the same division ring \( D \), and if \( f(a + b) = f(a) + f(b) \) and \( f(s \cdot a) = s \cdot f(a) \) hold for all elements \( a, b \) in the source of \( f \) and \( s \in D \).

### 32.12 Ring Homomorphisms

#### 32.12.1 IsRingGeneralMapping

\[ \text{IsRingGeneralMapping}(\text{mapp}) \]

\[ \text{IsRingHomomorphism}(\text{mapp}) \]

\text{IsRingGeneralMapping} specifies whether a general mapping \( \text{mapp} \) satisfies the property \text{IsAdditiveGroupGeneralMapping} (32.10.4) and respects multiplication (see \text{RespectsMultiplication} (32.9.1)).

\text{IsRingHomomorphism} is a synonym for the meet of \text{IsRingGeneralMapping} and \text{IsMapping} (32.3.3).

#### 32.12.2 IsRingWithOneGeneralMapping

\[ \text{IsRingWithOneGeneralMapping}(\text{mapp}) \]

\[ \text{IsRingWithOneHomomorphism}(\text{mapp}) \]

#### 32.12.3 IsAlgebraGeneralMapping

\[ \text{IsAlgebraGeneralMapping}(\text{mapp}) \]

\[ \text{IsAlgebraHomomorphism}(\text{mapp}) \]

\text{IsAlgebraGeneralMapping} specifies whether a general mapping \( \text{mapp} \) satisfies both properties \text{IsRingGeneralMapping} (32.12.1) and (see \text{IsLeftModuleGeneralMapping} (32.11.2)).

\text{IsAlgebraHomomorphism} is a synonym for the meet of \text{IsAlgebraGeneralMapping} and \text{IsMapping} (32.3.3).

#### 32.12.4 IsAlgebraWithOneGeneralMapping

\[ \text{IsAlgebraWithOneGeneralMapping}(\text{mapp}) \]

\[ \text{IsAlgebraWithOneHomomorphism}(\text{mapp}) \]

\text{IsAlgebraWithOneGeneralMapping} specifies whether a general mapping \( \text{mapp} \) satisfies both properties \text{IsAlgebraGeneralMapping} (32.12.3) and \text{RespectsOne} (32.9.2).

\text{IsAlgebraWithOneHomomorphism} is a synonym for the meet of \text{IsAlgebraWithOneGeneralMapping} and \text{IsMapping} (32.3.3).

#### 32.12.5 IsFieldHomomorphism

\[ \text{IsFieldHomomorphism}(\text{mapp}) \]


A general mapping is a field homomorphism if and only if it is a ring homomorphism with source a field.

### 32.13 General Mappings

#### 32.13.1 IsGeneralMapping

\[ \text{IsGeneralMapping}(\text{map}) \] (Category)

Each general mapping lies in the category IsGeneralMapping. It implies the categories IsMultiplicativeElementWithInverse (31.14.13) and IsAssociativeElement (31.15.1); for a discussion of these implications, see 32.6.

#### 32.13.2 IsConstantTimeAccessGeneralMapping

\[ \text{IsConstantTimeAccessGeneralMapping}(\text{map}) \] (property)

is true if the underlying relation of the general mapping \( \text{map} \) knows its AsList (30.3.8) value, and false otherwise.

In the former case, \( \text{map} \) is allowed to use this list for calls to ImagesElm (32.4.3) etc.

#### 32.13.3 IsEndoGeneralMapping

\[ \text{IsEndoGeneralMapping}(\text{obj}) \] (property)

If a general mapping has this property then its source and range are equal.

### 32.14 Technical Matters Concerning General Mappings

Source (32.3.8) and Range (32.3.7) are basic operations for general mappings. UnderlyingRelation (32.3.9) is secondary, its default method sets up a domain that delegates tasks to the general mapping. (Note that this allows one to handle also infinite relations by generic methods if source or range of the general mapping is finite.)

The distinction between basic operations and secondary operations for general mappings may be a little bit complicated. Namely, each general mapping must be in one of the two categories IsNonSPGeneralMapping (32.14.1), IsSPGeneralMapping (32.14.1). (The category IsGeneralMapping (32.13.1) is defined as the disjoint union of these two.)

For general mappings of the first category, ImagesElm (32.4.3) and PreImagesElm (32.5.2) are basic operations. (Note that in principle it is possible to delegate from PreImagesElm (32.5.2) to ImagesElm (32.4.3).) Methods for the secondary operations ImageElm (32.4.5), PreImageElm (32.5.3), ImagesSet (32.4.4), PreImagesSet (32.5.5), ImagesRepresentative (32.4.2), and PreImagesRepresentative (32.5.4) may use ImagesElm (32.4.3) and PreImagesElm (32.5.2), respectively, and methods for ImagesElm (32.4.3), PreImagesElm (32.5.2) must not call the secondary operations. In particular, there are no generic methods for ImagesElm (32.4.3) and PreImagesElm (32.5.2).
Methods for ImagesSet (32.4.4) and PreImagesSet (32.5.5) must not use PreImagesRange (32.5.1) and ImagesSource (32.4.1), e.g., compute the intersection of the set in question with the preimage of the range resp. the image of the source.

For general mappings of the second category (which means structure preserving general mappings), the situation is different. The set of preimages under a group homomorphism, for example, is either empty or can be described as a coset of the (multiplicative) kernel. So it is reasonable to have ImagesRepresentative (32.4.2), PreImagesRepresentative (32.5.4), KernelOfMultiplicativeGeneralMapping (32.9.5), and CoKernelOfMultiplicativeGeneralMapping (32.9.6) as basic operations here, and to make ImagesElm (32.4.3) and PreImagesElm (32.5.2) secondary operations that may delegate to these.

In order to avoid infinite recursions, we must distinguish between the two different types of mappings.

(Note that the basic domain operations such as AsList (30.3.8) for the underlying relation of a general mapping may use either ImagesElm (32.4.3) or ImagesRepresentative (32.4.2) and the appropriate cokernel. Conversely, if AsList (30.3.8) for the underlying relation is known then ImagesElm (32.4.3) resp. ImagesRepresentative (32.4.2) may delegate to it, the general mapping gets the property IsConstantTimeAccessGeneralMapping (32.13.2) for this; note that this is not allowed if only an enumerator of the underlying relation is known.)

Secondary operations are IsInjective (32.3.4), IsSingleValued (32.3.2), IsSurjective (32.3.5), IsTotal (32.3.1); they may use the basic operations, and must not be used by them.

Methods for the operations ImagesElm (32.4.3), ImagesRepresentative (32.4.2), ImagesSet (32.4.4), ImageElm (32.4.5), PreImagesElm (32.5.2), PreImagesRepresentative (32.5.4), PreImagesSet (32.5.5), and PreImageElm (32.5.3) take two arguments, a general mapping map and an element or collection of elements elm. These methods must not check whether elm lies in the source or the range of map. In the case that elm does not, fail may be returned as well as any other GAP object, and even an error message is allowed. Checks of the arguments are done only by the functions Image (32.4.6), Images (32.4.7), PreImage (32.5.6), and PreImages (32.5.7), which then delegate to the operations listed above.

### 32.14.1 IsSPGeneralMapping

- IsSPGeneralMapping(map)  
- IsNonSPGeneralMapping(map)

### 32.14.2 IsGeneralMappingFamily

- IsGeneralMappingFamily(obj)

The family category of the category of general mappings.

### 32.14.3 FamilyRange

- FamilyRange(Fam)

is the elements family of the family of the range of each general mapping in the family Fam.
32.14.4 FamilySource

\[ \text{FamilySource}(\text{Fam}) \]

is the elements family of the family of the source of each general mapping in the family \( \text{Fam} \).

32.14.5 FamiliesOfGeneralMappingsAndRanges

\[ \text{FamiliesOfGeneralMappingsAndRanges}(\text{Fam}) \]

is a list that stores at the odd positions the families of general mappings with source in the family \( \text{Fam} \), at the even positions the families of ranges of the general mappings.

32.14.6 GeneralMappingsFamily

\[ \text{GeneralMappingsFamily}(\text{sourcefam}, \text{rangefam}) \]

All general mappings with same source family \( \text{FS} \) and same range family \( \text{FR} \) lie in the family \( \text{GeneralMappingsFamily}( \text{FS}, \text{FR} ) \).

32.14.7 TypeOfDefaultGeneralMapping

\[ \text{TypeOfDefaultGeneralMapping}(\text{source}, \text{range}, \text{filter}) \]

is the type of mappings with \( \text{IsDefaultGeneralMappingRep} \) with source \( \text{source} \) and range \( \text{range} \) and additional categories \( \text{filter} \).
Chapter 33

Relations

A binary relation $R$ on a set $X$ is a subset of $X \times X$. A binary relation can also be thought of as a (general) mapping from $X$ to itself or as a directed graph where each edge represents an element of $R$.

In GAP, a relation is conceptually represented as a general mapping from $X$ to itself. The category `IsBinaryRelation` (33.1.1) is a synonym for `IsEndoGeneralMapping` (32.13.3). Attributes and properties of relations in GAP are supported for relations, via considering relations as a subset of $X \times X$, or as a directed graph; examples include finding the strongly connected components of a relation, via `StronglyConnectedComponents` (33.4.5), or enumerating the tuples of the relation.

### 33.1 General Binary Relations

This section lists general constructors of relations.

#### 33.1.1 IsBinaryRelation

- `IsBinaryRelation(R)` (property)

  is exactly the same category as (i.e. a synonym for) `IsEndoGeneralMapping` (32.13.3).

#### 33.1.2 BinaryRelationByElements

- `BinaryRelationByElements(domain, elms)` (function)

  is the binary relation on `domain` and with underlying relation consisting of the tuples collection `elms`. This construction is similar to `GeneralMappingByElements` (32.2.1) where the source and range are the same set.

  Example

  ```
  gap> r := BinaryRelationByElements(Domain([1..3]), [Tuple([1,2]), Tuple([1,3])]);
  <general mapping: Domain([ 1 .. 3 ]) -> Domain([ 1 .. 3 ]) >
  ```

#### 33.1.3 IdentityBinaryRelation

- `IdentityBinaryRelation(degree)` (function)

- `IdentityBinaryRelation(domain)` (function)
is the binary relation which consists of diagonal pairs, i.e., pairs of the form \((x,x)\). In the first form if a positive integer \(\text{degree}\) is given then the domain is the set of the integers \(\{1,\ldots,\text{degree}\}\). In the second form, the objects \(x\) are from the domain \(\text{domain}\).

```
gap> IdentityBinaryRelation(5);  # Example
<equivalence relation on Domain([ 1 .. 5 ]) >
gap> s4:=SymmetricGroup(4);      # Example
Sym( [ 1 .. 4 ] )
gap> IdentityBinaryRelation(s4); # Example
IdentityMapping( Sym( [ 1 .. 4 ] ) )
```

### 33.1.4 EmptyBinaryRelation (for a degree)

\(\text{EmptyBinaryRelation}(\text{degree})\)

is the relation with \(R\) empty. In the first form of the command with \(\text{degree}\) an integer, the domain is the set of points \(\{1,\ldots,\text{degree}\}\). In the second form, the domain is that given by the argument \(\text{domain}\).

```
gap> EmptyBinaryRelation(3) = BinaryRelationOnPoints([ [null,null,null] ]); # Example
true
```

### 33.2 Properties and Attributes of Binary Relations

#### 33.2.1 IsReflexiveBinaryRelation

\(\text{IsReflexiveBinaryRelation}(R)\)

returns \(\text{true}\) if the binary relation \(R\) is reflexive, and \(\text{false}\) otherwise.

A binary relation \(R\) (as a set of pairs) on a set \(X\) is \textit{reflexive} if for all \(x \in X\), \((x,x) \in R\). Alternatively, \(R\) as a mapping is reflexive if for all \(x \in X\), \(x\) is an element of the image set \(R(x)\).

A reflexive binary relation is necessarily a total endomorphic mapping (tested via \text{IsTotal}(32.3.1)).

```
gap> IsReflexiveBinaryRelation(BinaryRelationOnPoints([[1,3],[2],[3]])); # Example
true
gap> IsReflexiveBinaryRelation(BinaryRelationOnPoints([[2],[2]]));        # Example
false
```

#### 33.2.2 IsSymmetricBinaryRelation

\(\text{IsSymmetricBinaryRelation}(R)\)

returns \(\text{true}\) if the binary relation \(R\) is symmetric, and \(\text{false}\) otherwise.

A binary relation \(R\) (as a set of pairs) on a set \(X\) is \textit{symmetric} if \((x,y) \in R\) then \((y,x) \in R\). Alternatively, \(R\) as a mapping is symmetric if for all \(x \in X\), the preimage set of \(x\) under \(R\) equals the image set \(R(x)\).
33.2.3 \textbf{IsTransitiveBinaryRelation}

\textbf{\texttt{IsTransitiveBinaryRelation}}(\texttt{R}) \hspace{1cm} \text{(property)}

returns \texttt{true} if the binary relation \texttt{R} is transitive, and \texttt{false} otherwise.

A binary relation \texttt{R} (as a set of pairs) on a set \texttt{X} is \textit{transitive} if \((x, y), (y, z) \in R\) implies \((x, z) \in R\). Alternatively, \texttt{R} as a mapping is transitive if for all \(x \in X\), the image set \(R(R(x))\) of the image set \(R(x)\) of \(x\) is a subset of \(R(x)\).

\begin{verbatim}
Example

gap> IsTransitiveBinaryRelation(BinaryRelationOnPoints([[2],[1]]));
true

gap> IsTransitiveBinaryRelation(BinaryRelationOnPoints([[2],[2]]));
false
\end{verbatim}

33.2.4 \textbf{IsAntisymmetricBinaryRelation}

\textbf{\texttt{IsAntisymmetricBinaryRelation}}(\texttt{rel}) \hspace{1cm} \text{(property)}

returns \texttt{true} if the binary relation \texttt{rel} is antisymmetric, and \texttt{false} otherwise.

A binary relation \texttt{R} (as a set of pairs) on a set \texttt{X} is \textit{antisymmetric} if \((x, y), (y, x) \in R\) implies \(x = y\). Alternatively, \texttt{R} as a mapping is antisymmetric if for all \(x \in X\), the intersection of the preimage set of \(x\) under \texttt{R} and the image set \(R(x)\) is \(\{x\}\).

\begin{verbatim}
Example

gap> IsAntisymmetricBinaryRelation(BinaryRelationOnPoints([[1,2,3],[2,3],[[]]]));
true

gap> IsAntisymmetricBinaryRelation(BinaryRelationOnPoints([[1,2],[2,3],[[]]]));
false
\end{verbatim}

33.2.5 \textbf{IsPreOrderBinaryRelation}

\textbf{\texttt{IsPreOrderBinaryRelation}}(\texttt{rel}) \hspace{1cm} \text{(property)}

returns \texttt{true} if the binary relation \texttt{rel} is a preorder, and \texttt{false} otherwise.

A \textit{preorder} is a binary relation that is both reflexive and transitive.

33.2.6 \textbf{IsPartialOrderBinaryRelation}

\textbf{\texttt{IsPartialOrderBinaryRelation}}(\texttt{rel}) \hspace{1cm} \text{(property)}

returns \texttt{true} if the binary relation \texttt{rel} is a partial order, and \texttt{false} otherwise.

A \textit{partial order} is a preorder which is also antisymmetric.

33.2.7 \textbf{IsHasseDiagram}

\textbf{\texttt{IsHasseDiagram}}(\texttt{rel}) \hspace{1cm} \text{(property)}
returns\texttt{true} if the binary relation \texttt{rel} is a Hasse Diagram of a partial order, i.e., was computed via\texttt{HasseDiagramBinaryRelation (33.4.4)}.

### 33.2.8 \texttt{IsEquivalenceRelation}

\begin{verbatim}
\texttt{IsEquivalenceRelation(R)}
\end{verbatim}

returns\texttt{true} if the binary relation \texttt{R} is an equivalence relation, and \texttt{false} otherwise.  
Recall, that a relation \texttt{R} is an \textit{equivalence relation} if it is symmetric, transitive, and reflexive.

### 33.2.9 \texttt{Successors}

\begin{verbatim}
\texttt{Successors(R)}
\end{verbatim}

returns the list of images of a binary relation \texttt{R}. If the underlying domain of the relation is not \{1, \ldots, n\}, for some positive integer \texttt{n}, then an error is signalled.

The returned value of \texttt{Successors} is a list of lists where the lists are ordered as the elements according to the sorted order of the underlying set of \texttt{R}. Each list consists of the images of the element whose index is the same as the list with the underlying set in sorted order.

The \texttt{Successors} of a relation is the adjacency list representation of the relation.

**Example**

gap> r1:=BinaryRelationOnPoints([[2],[3],[1]]);;
gap> Successors(r1);
\[[2],[3],[1]\]

### 33.2.10 \texttt{DegreeOfBinaryRelation}

\begin{verbatim}
\texttt{DegreeOfBinaryRelation(R)}
\end{verbatim}

returns the size of the underlying domain of the binary relation \texttt{R}. This is most natural when working with a binary relation on points.

**Example**

gap> DegreeOfBinaryRelation(r1);
3

### 33.2.11 \texttt{PartialOrderOfHasseDiagram}

\begin{verbatim}
\texttt{PartialOrderOfHasseDiagram(HD)}
\end{verbatim}

is the partial order associated with the Hasse Diagram \texttt{HD} i.e. the partial order generated by the reflexive and transitive closure of \texttt{HD}.

### 33.3 Binary Relations on Points

We have special construction methods when the underlying \texttt{X} of our relation is the set of integers \{1, \ldots, n\}. 

### 33.3.1 BinaryRelationOnPoints

- **BinaryRelationOnPoints(list)** (function)
- **BinaryRelationOnPointsNC(list)** (function)

Given a list of \( n \) lists, each containing elements from the set \( \{1, \ldots, n\} \), this function constructs a binary relation such that 1 is related to \( \text{list}[1] \), 2 to \( \text{list}[2] \) and so on. The first version checks whether the list supplied is valid. The the NC version skips this check.

```
Example
gap> R:=BinaryRelationOnPoints([[1,2],[2],[3]]);
Binary Relation on 3 points
```

### 33.3.2 RandomBinaryRelationOnPoints

- **RandomBinaryRelationOnPoints(degree)** (function)

creates a relation on points with degree \( \text{degree} \).

### 33.3.3 AsBinaryRelationOnPoints

- **AsBinaryRelationOnPoints(trans)** (function)
- **AsBinaryRelationOnPoints(perm)** (function)
- **AsBinaryRelationOnPoints(rel)** (function)

return the relation on points represented by general relation \( \text{rel} \), transformation \( \text{trans} \) or permutation \( \text{perm} \). If \( \text{rel} \) is already a binary relation on points then \( \text{rel} \) is returned.

Transformations and permutations are special general endomorphic mappings and have a natural representation as a binary relation on points.

In the last form, an isomorphic relation on points is constructed where the points are indices of the elements of the underlying domain in sorted order.

```
Example
gap> t:=Transformation([2,3,1]);
gap> r1:=AsBinaryRelationOnPoints(t);
Binary Relation on 3 points
gap> r2:=AsBinaryRelationOnPoints((1,2,3));
Binary Relation on 3 points
gap> r1=r2;
true
```

### 33.4 Closure Operations and Other Constructors

#### 33.4.1 ReflexiveClosureBinaryRelation

- **ReflexiveClosureBinaryRelation(R)** (operation)

is the smallest binary relation containing the binary relation \( R \) which is reflexive. This closure inherits the properties symmetric and transitive from \( R \). E.g., if \( R \) is symmetric then its reflexive closure is also.
33.4.2 SymmetricClosureBinaryRelation

\[ \text{SymmetricClosureBinaryRelation}(R) \]

is the smallest binary relation containing the binary relation \( R \) which is symmetric. This closure inherits the properties reflexive and transitive from \( R \). E.g., if \( R \) is reflexive then its symmetric closure is also.

33.4.3 TransitiveClosureBinaryRelation

\[ \text{TransitiveClosureBinaryRelation}(rel) \]

is the smallest binary relation containing the binary relation \( R \) which is transitive. This closure inherits the properties reflexive and symmetric from \( R \). E.g., if \( R \) is symmetric then its transitive closure is also.

The `TransitiveClosureBinaryRelation` is a modified version of the Floyd-Warshall method of solving the all-pairs shortest-paths problem on a directed graph. Its asymptotic runtime is \( O(n^3) \) where \( n \) is the size of the vertex set. It only assumes there is an arbitrary (but fixed) ordering of the vertex set.

33.4.4 HasseDiagramBinaryRelation

\[ \text{HasseDiagramBinaryRelation}(\text{partial-order}) \]

is the smallest relation contained in the partial order \( \text{partial-order} \) whose reflexive and transitive closure is equal to \( \text{partial-order} \).

33.4.5 StronglyConnectedComponents

\[ \text{StronglyConnectedComponents}(R) \]

returns an equivalence relation on the vertices of the binary relation \( R \).

33.4.6 PartialOrderByOrderingFunction

\[ \text{PartialOrderByOrderingFunction}(\text{dom}, \text{orderfunc}) \]

constructs a partial order whose elements are from the domain \( \text{dom} \) and are ordered using the ordering function \( \text{orderfunc} \). The ordering function must be a binary function returning a boolean value. If the ordering function does not describe a partial order then \( \text{fail} \) is returned.

33.5 Equivalence Relations

An equivalence relation \( E \) over the set \( X \) is a relation on \( X \) which is reflexive, symmetric, and transitive. A partition \( P \) is a set of subsets of \( X \) such that for all \( R,S \in P \), \( R \cap S \) is the empty set and \( \bigcup P = X \). An equivalence relation induces a partition such that if \( (x,y) \in E \) then \( x, y \) are in the same element of \( P \).

Like all binary relations in GAP, equivalence relations are regarded as general endomorphic mappings (and the operations, properties, and attributes of general mappings are available). However,
partitions provide an efficient way of representing equivalence relations. Moreover, only the non-
singleton classes or blocks are listed allowing for small equivalence relations to be represented on
infinite sets. Hence the main attribute of equivalence relations is 
\texttt{EquivalenceRelationPartition (33.6.1)} which provides the partition induced by the given equivalence.

### 33.5.1 EquivalenceRelationByPartition

\texttt{EquivalenceRelationByPartition(domain, list)} (function)

\texttt{EquivalenceRelationByPartitionNC(domain, list)} (function)

constructs the equivalence relation over the set \texttt{domain} which induces the partition represented by
\texttt{list}. This representation includes only the non-trivial blocks (or equivalent classes). \texttt{list} is a list
of lists, each of these lists contain elements of \texttt{domain} and are pairwise mutually exclusive.

The list of lists do not need to be in any order nor do the elements in the blocks (see 
\texttt{EquivalenceRelationPartition (33.6.1)}). a list of elements of \texttt{domain} The partition \texttt{list} is
a list of lists, each of these is a list of elements of \texttt{domain} that makes up a block (or equivalent class). The
\texttt{domain} is the domain over which the relation is defined, and \texttt{list} is a list of lists, each of these
is a list of elements of \texttt{domain} which are related to each other. \texttt{list} need only contain the nontrivial
blocks and singletons will be ignored. The \texttt{NC} version will not check to see if the lists are pairwise
mutually exclusive or that they contain only elements of the domain.

#### Example

\begin{verbatim}
gap> er:=EquivalenceRelationByPartition(Domain([1..10]),[[1,3,5,7,9],[2,4,6,8,10]]);
gap> IsEquivalenceRelation(er);
true
\end{verbatim}

### 33.5.2 EquivalenceRelationByRelation

\texttt{EquivalenceRelationByRelation(rel)} (function)

returns the smallest equivalence relation containing the binary relation \texttt{rel}.

### 33.5.3 EquivalenceRelationByPairs

\texttt{EquivalenceRelationByPairs(D, elms)} (function)

\texttt{EquivalenceRelationByPairsNC(D, elms)} (function)

return the smallest equivalence relation on the domain \texttt{D} such that every pair in \texttt{elms} is in the
relation.

In the \texttt{NC} form, it is not checked that \texttt{elms} are in the domain \texttt{D}.

### 33.5.4 EquivalenceRelationByProperty

\texttt{EquivalenceRelationByProperty(domain, property)} (function)

creates an equivalence relation on \texttt{domain} whose only defining datum is that of having the prop-
erty \texttt{property}. 
33.6 Attributes of and Operations on Equivalence Relations

33.6.1 EquivalenceRelationPartition

\[ \texttt{EquivalenceRelationPartition(equiv)} \]

returns a list of lists of elements of the underlying set of the equivalence relation \( \texttt{equiv} \). The lists are precisely the nonsingleton equivalence classes of the equivalence. This allows us to describe “small” equivalences on infinite sets.

33.6.2 GeneratorsOfEquivalenceRelationPartition

\[ \texttt{GeneratorsOfEquivalenceRelationPartition(equiv)} \]

is a set of generating pairs for the equivalence relation \( \texttt{equiv} \). This set is not unique. The equivalence \( \texttt{equiv} \) is the smallest equivalence relation over the underlying set which contains the generating pairs.

33.6.3 JoinEquivalenceRelations

\[ \texttt{JoinEquivalenceRelations(equiv1, equiv2)} \]
\[ \texttt{MeetEquivalenceRelations(equiv1, equiv2)} \]

\( \texttt{JoinEquivalenceRelations} \) returns the smallest equivalence relation containing both the equivalence relations \( \texttt{equiv1} \) and \( \texttt{equiv2} \).
\( \texttt{MeetEquivalenceRelations} \) returns the intersection of the two equivalence relations \( \texttt{equiv1} \) and \( \texttt{equiv2} \).

33.7 Equivalence Classes

33.7.1 IsEquivalenceClass

\[ \texttt{IsEquivalenceClass(obj)} \]

returns \texttt{true} if the object \( \texttt{obj} \) is an equivalence class, and \texttt{false} otherwise.

An equivalence class is a collection of elements which are mutually related to each other in the associated equivalence relation. Note, this is a special category of objects and not just a list of elements.

33.7.2 EquivalenceClassRelation

\[ \texttt{EquivalenceClassRelation(C)} \]

returns the equivalence relation of which \( \texttt{C} \) is a class.
33.7.3 EquivalenceClasses (attribute)

EquivalenceClasses(rel)

returns a list of all equivalence classes of the equivalence relation rel. Note that it is possible for different methods to yield the list in different orders, so that for two equivalence relations \( c_1 \) and \( c_2 \) we may have \( c_1 = c_2 \) without having EquivalenceClasses(c1) = EquivalenceClasses(c2).

Example

```
gap> er:=EquivalenceRelationByPartition(Domain([1..10]),[[1,3,5,7,9],[2,4,6,8,10]]);  
<equivalence relation on Domain([ 1 .. 10 ]) >
gap> classes := EquivalenceClasses(er);  
[ [ 1 ], [ 2 ] ]
```

33.7.4 EquivalenceClassOfElement

EquivalenceClassOfElement(rel, elt)

EquivalenceClassOfElementNC(rel, elt)

returns the equivalence class of \( elt \) in the binary relation \( rel \), where \( elt \) is an element (i.e. a pair) of the domain of \( rel \). In the NC form, it is not checked that \( elt \) is in the domain over which \( rel \) is defined.

Example

```
gap> EquivalenceClassOfElement(er,3);  
[ 3 ]
```
Chapter 34

Orderings

In GAP an ordering is a relation defined on a family, which is reflexive, anti-symmetric and transitive.

34.1 IsOrdering (Filter)

34.1.1 IsOrdering

\[ \text{IsOrdering}(obj) \]

(Category)

returns true if and only if the object ord is an ordering.

34.1.2 OrderingsFamily

\[ \text{OrderingsFamily}(fam) \]

(attribute)

for a family fam, returns the family of all orderings on elements of fam.

34.2 Building new orderings

34.2.1 OrderingByLessThanFunctionNC

\[ \text{OrderingByLessThanFunctionNC}(fam, lt[, l]) \]

(operation)

Called with two arguments, OrderingByLessThanFunctionNC returns the ordering on the elements of the elements of the family fam, according to the LessThanFunction (34.3.5) value given by lt, where lt is a function that takes two arguments in fam and returns true or false.

Called with three arguments, for a family fam, a function lt that takes two arguments in fam and returns true or false, and a list l of properties of orderings, OrderingByLessThanFunctionNC returns the ordering on the elements of fam with LessThanFunction (34.3.5) value given by lt and with the properties from l set to true.

34.2.2 OrderingByLessThanOrEqualFunctionNC

\[ \text{OrderingByLessThanOrEqualFunctionNC}(fam, lteq[, l]) \]

(operation)
Called with two arguments, OrderingByLessThanOrEqualFunctionNC returns the ordering on the elements of the elements of the family fam according to the LessThanOrEqualFunction (34.3.6) value given by lt eq, where lt eq is a function that takes two arguments in fam and returns true or false.

Called with three arguments, for a family fam, a function lt eq that takes two arguments in fam and returns true or false, and a list l of properties of orderings, OrderingByLessThanOrEqualFunctionNC returns the ordering on the elements of fam with LessThanOrEqualFunction (34.3.6) value given by lt eq and with the properties from l set to true.

Notice that these functions do not check whether fam and lt or lt eq are compatible, and whether the properties listed in l are indeed satisfied.

Example

```gap
gap> f := FreeSemigroup("a","b");;
gap> a := GeneratorsOfSemigroup(f)[1];;
gap> b := GeneratorsOfSemigroup(f)[2];;
gap> lt := function(x,y) return Length(x)<Length(y); end;
function( x, y ) ... end
gap> fam := FamilyObj(a);;
gap> ord := OrderingByLessThanFunctionNC(fam,lt);
Ordering
```

34.3 Properties and basic functionality

34.3.1 IsWellFoundedOrdering

▷ IsWellFoundedOrdering(ord) (property)

for an ordering ord, returns true if and only if the ordering is well founded. An ordering ord is well founded if it admits no infinite descending chains. Normally this property is set at the time of creation of the ordering and there is no general method to check whether a certain ordering is well founded.

34.3.2 IsTotalOrdering

▷ IsTotalOrdering(ord) (property)

for an ordering ord, returns true if and only if the ordering is total. An ordering ord is total if any two elements of the family are comparable under ord. Normally this property is set at the time of creation of the ordering and there is no general method to check whether a certain ordering is total.

34.3.3 IsIncomparableUnder

▷ IsIncomparableUnder(ord, el1, el2) (operation)

for an ordering ord on the elements of the family of el1 and el2, returns true if el1 ≠ el2 and IsLessThanUnder(ord,el1,el2), IsLessThanUnder(ord,el2,el1) are both false; and returns false otherwise.
34.3.4 FamilyForOrdering

FamilyForOrdering(ord) (attribute)

for an ordering ord, returns the family of elements that the ordering ord compares.

34.3.5 LessThanFunction

LessThanFunction(ord) (attribute)

for an ordering ord, returns a function f which takes two elements el1, el2 in FamilyForOrdering(ord) and returns true if el1 is strictly less than el2 (with respect to ord), and returns false otherwise.

34.3.6 LessThanOrEqualFunction

LessThanOrEqualFunction(ord) (attribute)

for an ordering ord, returns a function that takes two elements el1, el2 in FamilyForOrdering(ord) and returns true if el1 is less than or equal to el2 (with respect to ord), and returns false otherwise.

34.3.7 IsLessThanUnder

IsLessThanUnder(ord, el1, el2) (operation)

for an ordering ord on the elements of the family of el1 and el2, returns true if el1 is (strictly) less than el2 with respect to ord, and false otherwise.

34.3.8 IsLessThanOrEqualUnder

IsLessThanOrEqualUnder(ord, el1, el2) (operation)

for an ordering ord on the elements of the family of el1 and el2, returns true if el1 is less than or equal to el2 with respect to ord, and false otherwise.

Example

<table>
<thead>
<tr>
<th>Operation</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>IsLessThanUnder(ord, a, a*b)</td>
<td>true</td>
</tr>
<tr>
<td>IsLessThanOrEqualUnder(ord, a<em>b, a</em>b)</td>
<td>true</td>
</tr>
<tr>
<td>IsIncomparableUnder(ord, a, b)</td>
<td>true</td>
</tr>
<tr>
<td>FamilyForOrdering(ord) = FamilyObj(a)</td>
<td>true</td>
</tr>
</tbody>
</table>

34.4 Orderings on families of associative words

We now consider orderings on families of associative words.
Examples of families of associative words are the families of elements of a free semigroup or a free monoid; these are the two cases that we consider mostly. Associated with those families is an alphabet, which is the semigroup (resp. monoid) generating set of the correspondent free semigroup (resp. free monoid). For definitions of the orderings considered, see Sims [Sim94].

34.4.1 IsOrderingOnFamilyOfAssocWords

\[ \text{IsOrderingOnFamilyOfAssocWords(} \text{ord} \text{)} \]

for an ordering \( \text{ord} \), returns true if \( \text{ord} \) is an ordering over a family of associative words.

34.4.2 IsTranslationInvariantOrdering

\[ \text{IsTranslationInvariantOrdering(} \text{ord} \text{)} \]

for an ordering \( \text{ord} \) on a family of associative words, returns \text{true} if and only if the ordering is translation invariant.

This is a property of orderings on families of associative words. An ordering \( \text{ord} \) over a family \( F \), with alphabet \( X \) is translation invariant if \( \text{IsLessThanUnder(} \text{ord, u, v} \) \) implies that for any \( a, b \in X^* \), \( \text{IsLessThanUnder(} \text{ord, a} \ast u \ast b, a \ast v \ast b \) \).

34.4.3 IsReductionOrdering

\[ \text{IsReductionOrdering(} \text{ord} \text{)} \]

for an ordering \( \text{ord} \) on a family of associative words, returns \text{true} if and only if the ordering is a reduction ordering. An ordering \( \text{ord} \) is a reduction ordering if it is well founded and translation invariant.

34.4.4 OrderingOnGenerators

\[ \text{OrderingOnGenerators(} \text{ord} \text{)} \]

for an ordering \( \text{ord} \) on a family of associative words, returns a list in which the generators are considered. This could be indeed the ordering of the generators in the ordering, but, for example, if a weight is associated to each generator then this is not true anymore. See the example for \text{WeightLexOrdering} (34.4.8).

34.4.5 LexicographicOrdering

\[ \text{LexicographicOrdering(} \text{D[, gens]} \text{)} \]

Let \( D \) be a free semigroup, a free monoid, or the elements family of such a domain. Called with only argument \( D \), \text{LexicographicOrdering} returns the lexicographic ordering on the elements of \( D \).

The optional argument \( \text{gens} \) can be either the list of free generators of \( D \), in the desired order, or a list of the positions of these generators, in the desired order, and \text{LexicographicOrdering} returns the lexicographic ordering on the elements of \( D \) with the ordering on the generators as given.
Example

```gap
gap> f := FreeSemigroup(3);
<free semigroup on the generators [ s1, s2, s3 ]>
gap> lex := LexicographicOrdering(f,[2,3,1]);
Ordering
gap> IsLessThanUnder(lex,f.2*f.3,f.3);
true
gap> IsLessThanUnder(lex,f.3,f.2);
false
```

34.4.6 ShortLexOrdering

▷ ShortLexOrdering(D[, gens])

Let \( D \) be a free semigroup, a free monoid, or the elements family of such a domain. Called with only argument \( D \), ShortLexOrdering returns the shortlex ordering on the elements of \( D \).

The optional argument \( \text{gens} \) can be either the list of free generators of \( D \), in the desired order, or a list of the positions of these generators, in the desired order, and ShortLexOrdering returns the shortlex ordering on the elements of \( D \) with the ordering on the generators as given.

34.4.7 IsShortLexOrdering

▷ IsShortLexOrdering(ord)

for an ordering \( \text{ord} \) of a family of associative words, returns \text{true} if and only if \( \text{ord} \) is a shortlex ordering.

Example

```gap
gap> f := FreeSemigroup(3);
<free semigroup on the generators [ s1, s2, s3 ]>
gap> s1 := ShortLexOrdering(f,[2,3,1]);
Ordering
gap> IsLessThanUnder(s1,f.1,f.2);
false
gap> IsLessThanUnder(s1,f.3,f.2);
false
gap> IsLessThanUnder(s1,f.3,f.1);
true
```

34.4.8 WeightLexOrdering

▷ WeightLexOrdering(D, gens, wt)

Let \( D \) be a free semigroup, a free monoid, or the elements family of such a domain. \( \text{gens} \) can be either the list of free generators of \( D \), in the desired order, or a list of the positions of these generators, in the desired order. Let \( \text{wt} \) be a list of weights. WeightLexOrdering returns the weightlex ordering on the elements of \( D \) with the ordering on the generators and weights of the generators as given.
34.4.9  IsWeightLexOrdering

\[ \text{IsWeightLexOrdering}(\text{ord}) \]

for an ordering \( \text{ord} \) on a family of associative words, returns true if and only if \( \text{ord} \) is a weightlex ordering.

34.4.10  WeightOfGenerators

\[ \text{WeightOfGenerators}(\text{ord}) \]

for a weightlex ordering \( \text{ord} \), returns a list with length the size of the alphabet of the family. This list gives the weight of each of the letters of the alphabet which are used for weightlex orderings with respect to the ordering given by \text{OrderingOnGenerators} (34.4.4).

Example

\begin{verbatim}
gap> f := FreeSemigroup(3);
<free semigroup on the generators [ s1, s2, s3 ]>
gap> wtlex := WeightLexOrdering(f,[f.2,f.3,f.1],[3,2,1]);
Ordering
gap> IsLessThanUnder(wtlex,f.1,f.2);
true
gap> IsLessThanUnder(wtlex,f.3,f.2);
true
gap> IsLessThanUnder(wtlex,f.3,f.1);
false
gap> OrderingOnGenerators(wtlex);
[ s2, s3, s1 ]
gap> WeightOfGenerators(wtlex);
[ 3, 2, 1 ]
\end{verbatim}

34.4.11  BasicWreathProductOrdering

\[ \text{BasicWreathProductOrdering}(\text{D}[\text{gens}]) \]

Let \( D \) be a free semigroup, a free monoid, or the elements family of such a domain. Called with only argument \( D \), \text{BasicWreathProductOrdering} returns the basic wreath product ordering on the elements of \( D \).

The optional argument \( \text{gens} \) can be either the list of free generators of \( D \), in the desired order, or a list of the positions of these generators, in the desired order, and \text{BasicWreathProductOrdering} returns the lexicographic ordering on the elements of \( D \) with the ordering on the generators as given.

34.4.12  IsBasicWreathProductOrdering

\[ \text{IsBasicWreathProductOrdering}(\text{ord}) \]

Example

\begin{verbatim}
gap> f := FreeSemigroup(3);
<free semigroup on the generators [ s1, s2, s3 ]>
gap> basic := BasicWreathProductOrdering(f,[2,3,1]);
Ordering
\end{verbatim}
34.4.13 WreathProductOrdering

\[\text{WreathProductOrdering}(D[, \text{gens}], \text{levels})\]

Let \(D\) be a free semigroup, a free monoid, or the elements family of such a domain, let \(\text{gens}\) be either the list of free generators of \(D\), in the desired order, or a list of the positions of these generators, in the desired order, and let \(\text{levels}\) be a list of levels for the generators. If \(\text{gens}\) is omitted then the default ordering is taken. \(\text{WreathProductOrdering}\) returns the wreath product ordering on the elements of \(D\) with the ordering on the generators as given.

34.4.14 IsWreathProductOrdering

\[\text{IsWreathProductOrdering}(\text{ord})\]

specifies whether an ordering is a wreath product ordering (see \(\text{WreathProductOrdering}\) (34.4.13)).

34.4.15 LevelsOfGenerators

\[\text{LevelsOfGenerators}(\text{ord})\]

for a wreath product ordering \(\text{ord}\), returns the levels of the generators as given at creation (with respect to \(\text{OrderingOnGenerators}\) (34.4.4)).

Example

\[
\begin{align*}
gap> f := \text{FreeSemigroup}(3); \\
<\text{free semigroup on the generators } [ s1, s2, s3 ]> \\
gap> wrp := \text{WreathProductOrdering}(f,[1,2,3],[1,1,2]); \\
\text{Ordering} \\
gap> \text{IsLessThanUnder}(wgp,f.3,f.1); \\
false \\
gap> \text{IsLessThanUnder}(wgp,f.3,f.2); \\
false \\
gap> \text{IsLessThanUnder}(wgp,f.1,f.2); \\
true \\
gap> \text{LevelsOfGenerators}(wgp); \\
[ 1, 1, 2 ]
\end{align*}
\]
Chapter 35

Magmas

This chapter deals with domains (see 31) that are closed under multiplication *. Following [Bou70], we call them magmas in GAP. Together with the domains closed under addition + (see 55), they are the basic algebraic structures; every semigroup, monoid (see 51), group (see 39), ring (see 56), or field (see 58) is a magma. In the cases of a magma-with-one or magma-with-inverses, additional multiplicative structure is present, see 35.1. For functions to create free magmas, see 36.4.

35.1 Magma Categories

35.1.1 IsMagma

\[\text{IsMagma}(\text{obj})\]

A magma in GAP is a domain \(M\) with (not necessarily associative) multiplication \(*: M \times M \rightarrow M\).

35.1.2 IsMagmaWithOne

\[\text{IsMagmaWithOne}(\text{obj})\]

A magma-with-one in GAP is a magma \(M\) with an operation \(^0\) (or \(\text{One}(31.10.2)\)) that yields the identity of \(M\).

So a magma-with-one \(M\) does always contain a unique multiplicatively neutral element \(e\), i.e., \(e * m = m = m * e\) holds for all \(m \in M\) (see MultiplicativeNeutralElement (35.4.10)). This element \(e\) can be computed with the operation \(\text{One}(31.10.2)\) as \(\text{One}(M)\), and \(e\) is also equal to \(\text{One}(m)\) and to \(m^0\) for each element \(m \in M\).

Note that a magma may contain a multiplicatively neutral element but not an identity (see \(\text{One}(31.10.2)\)), and a magma containing an identity may not lie in the category IsMagmaWithOne (see Section 31.6).

35.1.3 IsMagmaWithInversesIfNonzero

\[\text{IsMagmaWithInversesIfNonzero}(\text{obj})\]

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An object in this GAP category is a magma-with-one \( M \) with an operation \(^{-1} : M \setminus Z \rightarrow M \setminus Z \) that maps each element \( m \) of \( M \setminus Z \) to its inverse \( m^{-1} \) (or \( \text{Inverse}(m) \), see \text{Inverse} (31.10.8)), where \( Z \) is either empty or consists exactly of one element of \( M \).

This category was introduced mainly to describe division rings, since the nonzero elements in a division ring form a group. So an object \( M \) in \text{IsMagmaWithInversesIfNonzero} will usually have both a multiplicative and an additive structure (see 55), and the set \( Z \), if it is nonempty, contains exactly the zero element (see \text{Zero} (31.10.3)) of \( M \).

35.1.4 \textbf{IsMagmaWithInverses}

\texttt{IsMagmaWithInverses(obj)} (Category)

A magma-with-inverses in GAP is a magma-with-one \( M \) with an operation \(^{-1} : M \rightarrow M \) that maps each element \( m \) of \( M \) to its inverse \( m^{-1} \) (or \( \text{Inverse}(m) \), see \text{Inverse} (31.10.8)).

Note that not every trivial magma is a magma-with-one, but every trivial magma-with-one is a magma-with-inverses. This holds also if the identity of the magma-with-one is a zero element. So a magma-with-inverses-if-nonzero can be a magma-with-inverses if either it contains no zero element or consists of a zero element that has itself as zero-th power.

35.2 \textbf{Magma Generation}

This section describes functions that create magmas from generators (see \text{Magma} (35.2.1), \text{MagmaWithOne} (35.2.2), \text{MagmaWithInverses} (35.2.3)), the underlying operations for which methods can be installed (see \text{MagmaByGenerators} (35.2.4), \text{MagmaWithOneByGenerators} (35.2.5), \text{MagmaWithInversesByGenerators} (35.2.6)), functions for forming submagmas (see \text{Submagma} (35.2.7), \text{SubmagmaWithOne} (35.2.8), \text{SubmagmaWithInverses} (35.2.9)), and functions that form a magma equal to a given collection (see \text{AsMagma} (35.2.10), \text{AsSubmagma} (35.2.11)).

InjectionZeroMagma (35.2.13) creates a new magma which is the original magma with a zero adjoined.

35.2.1 \textbf{Magma}

\texttt{Magma([Fam, ]gens)} (function)

returns the magma \( M \) that is generated by the elements in the list \( gens \), that is, the closure of \( gens \) under multiplication \( \ast \) (31.12.1). The family \( Fam \) of \( M \) can be entered as the first argument; this is obligatory if \( gens \) is empty (and hence also \( M \) is empty).

35.2.2 \textbf{MagmaWithOne}

\texttt{MagmaWithOne([Fam, ]gens)} (function)

returns the magma-with-one \( M \) that is generated by the elements in the list \( gens \), that is, the closure of \( gens \) under multiplication \( \ast \) (31.12.1) and \( \text{One} \) (31.10.2). The family \( Fam \) of \( M \) can be entered as first argument; this is obligatory if \( gens \) is empty (and hence \( M \) is trivial).
35.2.3 MagmaWithInverses

\[ \text{MagmaWithInverses}([\text{Fam}, \text{gens}]) \]

returns the magma-with-inverses \( M \) that is generated by the elements in the list \( \text{gens} \), that is, the closure of \( \text{gens} \) under multiplication \( \ast \) (31.12.1), \text{One} (31.10.2), and \text{Inverse} (31.10.8). The family \( \text{Fam} \) of \( M \) can be entered as first argument; this is obligatory if \( \text{gens} \) is empty (and hence \( M \) is trivial).

35.2.4 MagmaByGenerators

\[ \text{MagmaByGenerators}([\text{Fam}, \text{gens}]) \]

An underlying operation for \text{Magma} (35.2.1).

35.2.5 MagmaWithOneByGenerators

\[ \text{MagmaWithOneByGenerators}([\text{Fam}, \text{gens}]) \]

An underlying operation for \text{MagmaWithOne} (35.2.2).

35.2.6 MagmaWithInversesByGenerators

\[ \text{MagmaWithInversesByGenerators}([\text{Fam}, \text{gens}]) \]

An underlying operation for \text{MagmaWithInverses} (35.2.3).

35.2.7 Submagma

\[ \text{Submagma}(\text{D}, \text{gens}) \]
\[ \text{SubmagmaNC}(\text{D}, \text{gens}) \]

\text{Submagma} returns the magma generated by the elements in the list \( \text{gens} \), with parent the domain \( \text{D} \). \text{SubmagmaNC} does the same, except that it is not checked whether the elements of \( \text{gens} \) lie in \( \text{D} \).

35.2.8 SubmagmaWithOne

\[ \text{SubmagmaWithOne}(\text{D}, \text{gens}) \]
\[ \text{SubmagmaWithOneNC}(\text{D}, \text{gens}) \]

\text{SubmagmaWithOne} returns the magma-with-one generated by the elements in the list \( \text{gens} \), with parent the domain \( \text{D} \). \text{SubmagmaWithOneNC} does the same, except that it is not checked whether the elements of \( \text{gens} \) lie in \( \text{D} \).

35.2.9 SubmagmaWithInverses

\[ \text{SubmagmaWithInverses}(\text{D}, \text{gens}) \]
\[ \text{SubmagmaWithInversesNC}(\text{D}, \text{gens}) \]

\text{SubmagmaWithInverses} returns the magma-with-inverses generated by the elements in the list \( \text{gens} \), with parent the domain \( \text{D} \). \text{SubmagmaWithInversesNC} does the same, except that it is not checked whether the elements of \( \text{gens} \) lie in \( \text{D} \).
SubmagmaWithInverses returns the magma-with-inverses generated by the elements in the list gens, with parent the domain D. SubmagmaWithInversesNC does the same, except that it is not checked whether the elements of gens lie in D.

35.2.10 AsMagma

\[\text{AsMagma}(C)\]

For a collection C whose elements form a magma, AsMagma returns this magma. Otherwise fail is returned.

35.2.11 AsSubmagma

\[\text{AsSubmagma}(D, C)\]

Let D be a domain and C a collection. If C is a subset of D that forms a magma then AsSubmagma returns this magma, with parent D. Otherwise fail is returned.

35.2.12 IsMagmaWithZeroAdjoined

\[\text{IsMagmaWithZeroAdjoined}(M)\]

\text{Returns: true or false.}

IsMagmaWithZeroAdjoined returns true if the magma M was created using InjectionZeroMagma (35.2.13) or MagmaWithZeroAdjoined (35.2.13) and returns false if it was not.

Example

\[
\text{gap> S:=Semigroup(Transformation([1,1,1]), Transformation([1,3,2]));}\\
\text{gap> IsMagmaWithZeroAdjoined(S);}\\
\text{false}\\
\text{gap> M:=MagmaWithZeroAdjoined(S);}\\
\text{false}\\
\text{gap> IsMagmaWithZeroAdjoined(M);}\\
\text{true}
\]

35.2.13 InjectionZeroMagma

\[\text{InjectionZeroMagma}(M)\]

\[\text{MagmaWithZeroAdjoined}(M)\]

InjectionZeroMagma returns an embedding from the magma M into a new magma formed from N by adjoining a single new element which is the multiplicative zero of the resulting magma. The elements of the new magma form a family of elements in the category IsMultiplicativeElementWithZero (31.14.12) and the magma itself satisfies IsMagmaWithZeroAdjoined (35.2.12).

MagmaWithZeroAdjoined is just shorthand for Range(InjectionZeroMagma(M)).

If N is a magma with zero adjoined, then the embedding used to create N can be recovered using UnderlyingInjectionZeroMagma (35.2.14).
Example

```gap
gap> S:=Monoid(Transformation( [ 7, 7, 5, 3, 1, 3, 7 ] ), Transformation( [ 5, 1, 4, 1, 4, 4, 7 ] ));
gap> MultiplicativeZero(S);
Transformation( [ 7, 7, 7, 7, 7, 7, 7 ] )
gap> T:=MagmaWithZeroAdjoined(S);
<<transformation monoid of degree 7 with 2 generators>
with 0 adjoined>
gap> map:=UnderlyingInjectionZeroMagma(T);
gap> x:=Transformation( [ 7, 7, 7, 7, 3, 7, 7 ] );
gap> x^map;
<monoid with 0 adjoined elt: Transformation( [ 7, 7, 7, 7, 3, 7, 7 ] )>
gap> PreImage(map, x^map)=x;
true
```

35.2.14 UnderlyingInjectionZeroMagma

UnderlyingInjectionZeroMagma returns the embedding used to create the magma with zero adjoined \( M \).

Example

```gap
gap> S:=Monoid(Transformation( [ 8, 7, 5, 3, 1, 3, 8, 8 ] ), Transformation( [ 5, 1, 4, 1, 4, 4, 7, 8 ] ));
gap> MultiplicativeZero(S);
Transformation( [ 8, 8, 8, 8, 8, 8, 8, 8 ] )
gap> T:=MagmaWithZeroAdjoined(S);
<<transformation monoid of degree 8 with 2 generators>
with 0 adjoined>
gap> UnderlyingInjectionZeroMagma(T);
MappingByFunction( <transformation monoid of degree 8 with 2 generators>, <transformation monoid of degree 8 with 2 generators>
with 0 adjoined>, function( elt ) ... end, function( x ) ... end )
```

35.3 Magmas Defined by Multiplication Tables

The most elementary (but of course usually not recommended) way to implement a magma with only few elements is via a multiplication table.

35.3.1 MagmaByMultiplicationTable

MagmaByMultiplicationTable returns a magma \( M \) with multiplication \( \ast \) defined by \( A \). That is, \( M \) consists of the elements \( m_1, m_2, \ldots, m_n \), and \( m_i \ast m_j = m_k \), with \( k = A[i][j] \).

The ordering of elements is defined by \( m_1 < m_2 < \cdots < m_n \), so \( m_i \) can be accessed as MagmaElement( \( M \), \( i \) ), see MagmaElement (35.3.4).
35.3.2 MagmaWithOneByMultiplicationTable

\[ \text{Example} \]
\[
gap> \text{MagmaWithOneByMultiplicationTable}([[1,2,3],[2,3,1],[1,1,1]]); \\
<\text{magma with one with 3 generators}> \\
gap> \text{MagmaWithOneByMultiplicationTable}([[1,2,3],[2,3,1],[1,1,1]]); \\
\text{fail} \\
\]

35.3.3 MagmaWithInversesByMultiplicationTable

\[ \text{Example} \]
\[
gap> \text{MagmaWithInversesByMultiplicationTable}([[1,2,3],[2,3,1],[3,1,1]]); \\
<\text{magma-with-inverses with 3 generators}> \\
gap> \text{MagmaWithInversesByMultiplicationTable}([[1,2,3],[2,3,1],[1,1,1]]); \\
\text{fail} \\
\]

35.3.4 MagmaElement

\[ \text{Example} \]
\[
\text{Example} \\
\]

\[ \text{Example} \]
\[
\text{Example} \\
\]

35.3.5 MultiplicationTable

\[ \text{Example} \]
\[
\text{Example} \\
\]

\[ \text{Example} \]
\[
\text{Example} \\
\]

\[ \text{Example} \]
\[
\text{Example} \\
\]
Example

```gap
gap> l:= [ (), (1,2)(3,4), (1,3)(2,4), (1,4)(2,3) ];;
gap> a:= MultiplicationTable( l );
[ [ 1, 2, 3, 4 ], [ 2, 1, 4, 3 ], [ 3, 4, 1, 2 ], [ 4, 3, 2, 1 ] ]
gap> m:= MagmaByMultiplicationTable( a );
<magma with 4 generators>
gap> One( m );
m1
gap> elm:= MagmaElement( m, 2 ); One( elm ); elm^-2;
m2
m1
m1
gap> Inverse( elm );
m2
<group of size 4 with 2 generators>
gap> a:= [ [ 1, 2 ], [ 2, 2 ] ];
[ [ 1, 2 ], [ 2, 2 ] ]
gap> m:= MagmaByMultiplicationTable( a );
<magma with 2 generators>
gap> One( m ); Inverse( MagmaElement( m, 2 ) );
m1
fail
```

35.4 Attributes and Properties for Magmas

*Note* that IsAssociative (35.4.7) and IsCommutative (35.4.9) always refer to the multiplication of a domain. If a magma $M$ has also an *additive structure*, e.g., if $M$ is a ring (see 56), then the addition $+$ is always assumed to be associative and commutative, see 31.12.

35.4.1 GeneratorsOfMagma

▷ GeneratorsOfMagma($M$) (attribute)

is a list $gens$ of elements of the magma $M$ that generates $M$ as a magma, that is, the closure of $gens$ under multiplication $\times$ (31.12.1) is $M$.

For a free magma, each generator can also be accessed using the . operator (see GeneratorsOfDomain (31.9.2)).

35.4.2 GeneratorsOfMagmaWithOne

▷ GeneratorsOfMagmaWithOne($M$) (attribute)

is a list $gens$ of elements of the magma-with-one $M$ that generates $M$ as a magma-with-one, that is, the closure of $gens$ under multiplication $\times$ (31.12.1) and $\text{One}$ (31.10.2) is $M$.

For a free magma with one, each generator can also be accessed using the . operator (see GeneratorsOfDomain (31.9.2)).
35.4.3 GeneratorsOfMagmaWithInverses

GeneratorsOfMagmaWithInverses(M) (attribute)

is a list gens of elements of the magma-with-inverses M that generates M as a magma-with-inverses, that is, the closure of gens under multiplication \(* (31.12.1) and taking inverses (see Inverse (31.10.8)) is M.

35.4.4 Centralizer (for a magma and an element)

Centralizer(M, elm) (operation)
Centralizer(M, S) (operation)
Centralizer(class) (attribute)

For an element elm of the magma M this operation returns the centralizer of elm. This is the domain of those elements m ∈ M that commute with elm.

For a submagma S it returns the domain of those elements that commute with all elements s of S.

If class is a class of objects of a magma (this magma then is stored as the ActingDomain of class) such as given by ConjugacyClass (39.10.1), Centralizer returns the centralizer of Representative(class) (which is a slight abuse of the notation).

Example

```gap
gap> g:=Group((1,2,3,4),(1,2));;
gap> Centralizer(g,(1,2,3));
Group([ (1,2,3) ])
gap> Centralizer(g,Subgroup(g,[((1,2,3)]));
Group([ (1,2,3) ])
gap> Centralizer(g,Subgroup(g,[[1,2,3),(1,2)])�;
Group(()
```

35.4.5 Centre

Centre(M) (attribute)
Center(M) (attribute)

Centre returns the centre of the magma M, i.e., the domain of those elements m ∈ M that commute and associate with all elements of M. That is, the set \{m ∈ M; ∀a, b ∈ M : ma = am, (ma)b = m(ab), (am)b = a(mb), (ab)m = a(bm)\}.

Center is just a synonym for Centre.

For associative magmas we have that Centre(M) = Centralizer(M, M), see Centralizer (35.4.4).

The centre of a magma is always commutative (see IsCommutative (35.4.9)). (When one installs a new method for Centre, one should set the IsCommutative (35.4.9) value of the result to true, in order to make this information available.)

35.4.6 Idempotents

Idempotents(M) (attribute)

The set of elements of M which are their own squares.
35.4.7 IsAssociative
▷ IsAssociative(\( M \)) (property)

A magma \( M \) is *associative* if for all elements \( a, b, c \in M \) the equality \( (a \ast b) \ast c = a \ast (b \ast c) \) holds.

An associative magma is called a *semigroup* (see 51), an associative magma-with-one is called a *monoid* (see 51), and an associative magma-with-inverses is called a *group* (see 39).

35.4.8 IsCentral
▷ IsCentral(\( M, obj \)) (operation)

IsCentral returns true if the object \( obj \), which must either be an element or a magma, commutes with all elements in the magma \( M \).

35.4.9 IsCommutative
▷ IsCommutative(\( M \))
▷ IsAbelian(\( M \)) (property)

A magma \( M \) is *commutative* if for all elements \( a, b \in M \) the equality \( a \ast b = b \ast a \) holds. IsAbelian is a synonym of IsCommutative.

Note that the commutativity of the *addition \( \ast + \) (31.12.1)* in an additive structure can be tested with IsAdditivelyCommutative (55.3.1).

35.4.10 MultiplicativeNeutralElement
▷ MultiplicativeNeutralElement(\( M \)) (attribute)

returns the element \( e \) in the magma \( M \) with the property that \( e \ast m = m = m \ast e \) holds for all \( m \in M \), if such an element exists. Otherwise fail is returned.

A magma that is not a magma-with-one can have a multiplicative neutral element \( e \); in this case, \( e \) cannot be obtained as One(\( M \)), see One (31.10.2).

35.4.11 MultiplicativeZero
▷ MultiplicativeZero(\( M \)) (attribute)
▷ IsMultiplicativeZero(\( M, z \)) (operation)

MultiplicativeZero returns the multiplicative zero of the magma \( M \) which is the element \( z \) in \( M \) such that \( z \ast m = m = m \ast z = z \) for all \( m \) in \( M \).

IsMultiplicativeZero returns true if the element \( z \) of the magma \( M \) equals the multiplicative zero of \( M \).

Example

```gap
gap> S:=Semigroup( Transformation( [ 1, 1, 1 ] ),
                       Transformation( [ 2, 3, 1 ] ) );
<transformation semigroup of degree 3 with 2 generators>
gap> MultiplicativeZero(S);
```

fail

\begin{verbatim}
gap> S:=Semigroup( Transformation( [ 1, 1, 1 ] ),
> Transformation( [ 1, 3, 2 ] ) );
<transformation semigroup of degree 3 with 2 generators>
gap> MultiplicativeZero(S); Transformation( [ 1, 1, 1 ] )
\end{verbatim}

35.4.12 SquareRoots

\> SquareRoots\( (M, \textit{elm}) \) \hspace{10cm} (operation)

is the proper set of all elements \( r \) in the magma \( M \) such that \( r \ast r = \textit{elm} \) holds.

35.4.13 TrivialSubmagmaWithOne

\> TrivialSubmagmaWithOne\( (M) \) \hspace{10cm} (attribute)

is the magma-with-one that has the identity of the magma-with-one \( M \) as only element.
Chapter 36

Words

This chapter describes categories of words and nonassociative words, and operations for them. For information about associative words, which occur for example as elements in free groups, see Chapter 37.

36.1 Categories of Words and Nonassociative Words

36.1.1 IsWord

\[
\text{IsWord}(\text{obj}) \quad \text{(Category)}
\]

\[
\text{IsWordWithOne}(\text{obj}) \quad \text{(Category)}
\]

\[
\text{IsWordWithInverse}(\text{obj}) \quad \text{(Category)}
\]

Given a free multiplicative structure \( M \) that is freely generated by a subset \( X \), any expression of an element in \( M \) as an iterated product of elements in \( X \) is called a word over \( X \).

Interesting cases of free multiplicative structures are those of free semigroups, free monoids, and free groups, where the multiplication is associative (see \text{IsAssociative} (35.4.7)), which are described in Chapter 37, and also the case of free magmas, where the multiplication is nonassociative (see \text{IsNonassocWord} (36.1.3)).

Elements in free magmas (see \text{FreeMagma} (36.4.1)) lie in the category \text{IsWord}; similarly, elements in free magmas-with-one (see \text{FreeMagmaWithOne} (36.4.2)) lie in the category \text{IsWordWithOne}, and so on.

\text{IsWord} is mainly a “common roof” for the two disjoint categories \text{IsAssocWord} (37.1.1) and \text{IsNonassocWord} (36.1.3) of associative and nonassociative words. This means that associative words are not regarded as special cases of nonassociative words. The main reason for this setup is that we are interested in different external representations for associative and nonassociative words (see 36.5 and 37.7).

Note that elements in finitely presented groups and also elements in polycyclic groups in GAP are not in \text{IsWord} although they are usually called words, see Chapters 47 and 46.

Words are constants (see 12.6), that is, they are not copyable and not mutable.

The usual way to create words is to form them as products of known words, starting from generators of a free structure such as a free magma or a free group (see \text{FreeMagma} (36.4.1), \text{FreeGroup} (37.2.1)).
Words are also used to implement free algebras, in the same way as group elements are used to implement group algebras (see 62.3 and Chapter 65).

```
gap> m := FreeMagmaWithOne( 2 );; gens := GeneratorsOfMagmaWithOne( m );
[ x1, x2 ]
(x1*x2)*x1
(xi*(x2*x1))
gap> w1 = w2; IsAssociative( m );
false
false
gap> IsWord( w1 ); IsAssocWord( w1 ); IsNonassocWord( w1 );
true
false
true
```

```
gap> s := FreeMonoid( 2 );; gens := GeneratorsOfMagmaWithOne( s );
[ m1, m2 ]
m1*m2*m1
m1*m2*m1
```

```
gap> a := (1,2,3);; b := (1,2);
gap> w := a*b*a;; IsWord( w );
false
```

### 36.1.2 IsWordCollection

- **IsWordCollection**(obj) (Category)

IsWordCollection is the collections category (see CategoryCollections (30.2.4)) of IsWord (36.1.1).

```
gap> IsWordCollection( m ); IsWordCollection( s );
true
true
```

### 36.1.3 IsNonassocWord

- **IsNonassocWord**(obj) (Category)

```
gap> IsNonassocWordWithOne( obj )
```
A nonassociative word in GAP is an element in a free magma or a free magma-with-one (see 36.4).
The default methods for ViewObj (6.3.5) and PrintObj (6.3.5) show nonassociative words as products of letters, where the succession of multiplications is determined by round brackets.

In this sense each nonassociative word describes a “program” to form a product of generators. (Also associative words can be interpreted as such programs, except that the exact succession of multiplications is not prescribed due to the associativity.) The function MappedWord (36.3.1) implements a way to apply such a program. A more general way is provided by straight line programs (see 37.8).

Note that associative words (see Chapter 37) are not regarded as special cases of nonassociative words (see IsWord (36.1.1)).

36.1.4 IsNonassocWordCollection

\[\text{IsNonassocWordCollection}(\text{obj})\]

\[\text{IsNonassocWordWithOneCollection}(\text{obj})\]

IsNonassocWordCollection is the collections category (see CategoryCollections (30.2.4)) of IsNonassocWord (36.1.3), and IsNonassocWordWithOneCollection is the collections category of IsNonassocWordWithOne (36.1.3).

36.2 Comparison of Words

36.2.1 = (for nonassociative words)

\[\text{=} (w1, w2)\]

Two words are equal if and only if they are words over the same alphabet and with equal external representations (see 36.5 and 37.7). For nonassociative words, the latter means that the words arise from the letters of the alphabet by the same sequence of multiplications.

36.2.2 < (for nonassociative words)

\[\text{<} (w1, w2)\]

Words are ordered according to their external representation. More precisely, two words can be compared if they are words over the same alphabet, and the word with smaller external representation is smaller. For nonassociative words, the ordering is defined in 36.5; associative words are ordered by the shortlex ordering via < (see 37.7).

Note that the alphabet of a word is determined by its family (see 13.1), and that the result of each call to FreeMagma (36.4.1), FreeGroup (37.2.1) etc. consists of words over a new alphabet. In particular, there is no “universal” empty word, every families of words in IsWordWithOne (36.1.1) has its own empty word.

Example

```
gap> m:= FreeMagma( "a", "b" );
gap> x:= FreeMagma( "a", "b" );
gap> mgens:= GeneratorsOfMagma( m );
[ a, b ]
gap> xgens:= GeneratorsOfMagma( x );
[ a, b ]
```
gap> a := mgens[1];; b := mgens[2];;
gap> a = xgens[1];
false
gap> a*(a*a) = (a*a)*a; a*b = b*a; a*a = a*a;
false
false
true
gap> a < b; b < a; a < a*b;
true
false
true

36.3 Operations for Words

Two words can be multiplied via * only if they are words over the same alphabet (see 36.2).

36.3.1 MappedWord

\texttt{MappedWord}(\textit{w}, \textit{gens}, \textit{imgs})

\texttt{MappedWord} returns the object that is obtained by replacing each occurrence in the word \textit{w} of a generator in the list \textit{gens} by the corresponding object in the list \textit{imgs}. The lists \textit{gens} and \textit{imgs} must of course have the same length.

\texttt{MappedWord} needs to do some preprocessing to get internal generator numbers etc. When mapping many (several thousand) words, an explicit loop over the words syllables might be faster.

For example, if the elements in \textit{imgs} are all associative words (see Chapter 37) in the same family as the elements in \textit{gens}, and some of them are equal to the corresponding generators in \textit{gens}, then those may be omitted from \textit{gens} and \textit{imgs}. In this situation, the special case that the lists \textit{gens} and \textit{imgs} have only length 1 is handled more efficiently by \texttt{EliminatedWord} (37.4.6).

Example

\begin{verbatim}
gap> m := FreeMagma( "a", "b" );; gens := GeneratorsOfMagma( m );;
gap> a := gens[1]; b := gens[2];
a b
gap> w := (a*b)*((b*a)*a)*b;
(((a*b)*((b*a)*a))*b)
gap> MappedWord( w, gens, [ (1,2), (1,2,3,4) ] );
(2,4,3)
gap> a := (1,2);; b := (1,2,3,4);; (a*b)*((b*a)*a)*b;
(2,4,3)
gap> f := FreeGroup( "a", "b" );;
gap> a := GeneratorsOfGroup(f)[1]; b := GeneratorsOfGroup(f)[2];
gap> w := a^5*b*a^2*b^-4*a^4;a^5*b*a^2*b^-4*a^4;
(MappedWord( w, [ a, b ], [ (1,2), (1,2,3,4) ] );
(1,3,4,2)
gap> (1,2)^5*(1,2,3,4)*(1,2)^2/(1,2,3,4)^4*(1,2);
(1,3,4,2)
\end{verbatim}
36.4 Free Magmas

The easiest way to create a family of words is to construct the free object generated by these words. Each such free object defines a unique alphabet, and its generators are simply the words of length one over this alphabet; These generators can be accessed via GeneratorsOfMagma (35.4.1) in the case of a free magma, and via GeneratorsOfMagmaWithOne (35.4.2) in the case of a free magma-with-one.

36.4.1 FreeMagma

\begin{verbatim}
gap> MappedWord( w, [ a ], [ a^2 ] );
a^10*b*a^4*b^-4*a^2
\end{verbatim}

Called with a positive integer rank, FreeMagma returns a free magma on rank generators. If the optional argument name is given then the generators are printed as name1, name2 etc., that is, each name is the concatenation of the string name and an integer from 1 to range. The default for name is the string "m".

Called in the second form, FreeMagma returns a free magma on as many generators as arguments, printed as name1, name2 etc.

Called in the third form, FreeMagma returns a free magma on as many generators as the length of the list names, the i-th generator being printed as names[i].

Called in the fourth form, FreeMagma returns a free magma on infinitely many generators, where the first generators are printed by the names in the list init, and the other generators by name and an appended number.

36.4.2 FreeMagmaWithOne

\begin{verbatim}
\end{verbatim}

Called with a positive integer rank, FreeMagmaWithOne returns a free magma-with-one on rank generators. If the optional argument name is given then the generators are printed as name1, name2 etc., that is, each name is the concatenation of the string name and an integer from 1 to range. The default for name is the string "m".

Called in the second form, FreeMagmaWithOne returns a free magma-with-one on as many generators as arguments, printed as name1, name2 etc.

Called in the third form, FreeMagmaWithOne returns a free magma-with-one on as many generators as the length of the list names, the i-th generator being printed as names[i].
Called in the fourth form, FreeMagmaWithOne returns a free magma-with-one on infinitely many generators, where the first generators are printed by the names in the list init, and the other generators by name and an appended number.

Example

\begin{verbatim}
gap> FreeMagma( 3 );
<free magma on the generators [ x1, x2, x3 ]>
gap> FreeMagma( "a", "b" );
<free magma on the generators [ a, b ]>
gap> FreeMagma( infinity );
<free magma with infinity generators>
gap> FreeMagmaWithOne( 3 );
<free magma-with-one on the generators [ x1, x2, x3 ]>
gap> FreeMagmaWithOne( "a", "b" );
<free magma-with-one on the generators [ a, b ]>
gap> FreeMagmaWithOne( infinity );
<free magma-with-one with infinity generators>
\end{verbatim}

Remember that the names of generators used for printing do not necessarily distinguish letters of the alphabet; so it is possible to create arbitrarily weird situations by choosing strange letter names.

Example

\begin{verbatim}
gap> m:= FreeMagma( "x", "x" ); gens:= GeneratorsOfMagma( m );;
<free magma on the generators [ x, x ]>
gap> gens[1] = gens[2];
false
\end{verbatim}

36.5 External Representation for Nonassociative Words

The external representation of nonassociative words is defined as follows. The \(i\)-th generator of the family of elements in question has external representation \(i\), the identity (if exists) has external representation 0, the inverse of the \(i\)-th generator (if exists) has external representation \(-i\). If \(v\) and \(w\) are nonassociative words with external representations \(e_v\) and \(e_w\), respectively then the product \(v \ast w\) has external representation \([e_v, e_w]\). So the external representation of any nonassociative word is either an integer or a nested list of integers and lists, where each list has length two.

One can create a nonassociative word from a family of words and the external representation of a nonassociative word using ObjByExtRep (79.8.1).

Example

\begin{verbatim}
gap> m:= FreeMagma( 2 );; gens:= GeneratorsOfMagma( m );
[ x1, x2 ]
(x1*x2)*x1
gap> ExtRepOfObj( w );
[ [ 1, 2 ], 1 ]
gap> ExtRepOfObj( gens[1] );
1
\end{verbatim}
Chapter 37

Associative Words

37.1 Categories of Associative Words

Associative words are used to represent elements in free groups, semigroups and monoids in **GAP** (see 37.2). An associative word is just a sequence of letters, where each letter is an element of an alphabet (in the following called a **generator**) or its inverse. Associative words can be multiplied; in free monoids also the computation of an identity is permitted, in free groups also the computation of inverses (see 37.4).

Different alphabets correspond to different families of associative words. There is no relation whatsoever between words in different families.

```
gap> f:= FreeGroup( "a", "b", "c" );
<free group on the generators [ a, b, c ]>
gap> gens:= GeneratorsOfGroup(f);
[ a, b, c ]
gap> w:= gens[1]*gens[2]/gens[3]*gens[2]*gens[1]/gens[3]/gens[2];
a*b*c^-1*b*c*b^-1
gap> w^-1;
b*c^-1*b^-1*c*b^-1*a^-1
```

Words are displayed as products of letters. The letters are usually printed like \( f_1, f_2, \ldots \), but it is possible to give user defined names to them, which can be arbitrary strings. These names do not necessarily identify a unique letter (generator), it is possible to have several letters—even in the same family—that are displayed in the same way. Note also that **there is no relation between the names of letters and variable names**. In the example above, we might have typed

```
gap> a:= f.1;; b:= f.2;; c:= f.3;;
```

(*Interactively*, the function **AssignGeneratorVariables** (37.2.3) provides a shorthand for this.) This allows us to define \( w \) more conveniently:

```
gap> w := a*b/c*b*a/a*c/b;
a*b*c^-1*b*c*b^-1
```

Using homomorphisms it is possible to express elements of a group as words in terms of generators, see 39.5.
37.1.1 IsAssocWord

- IsAssocWord(obj)
- IsAssocWordWithOne(obj)
- IsAssocWordWithInverse(obj)

IsAssocWord is the category of associative words in free semigroups, IsAssocWordWithOne is the category of associative words in free monoids (which admit the operation One (31.10.2) to compute an identity), IsAssocWordWithInverse is the category of associative words in free groups (which have an inverse). See IsWord (36.1.1) for more general categories of words.

37.2 Free Groups, Monoids and Semigroups

Usually a family of associative words will be generated by constructing the free object generated by them. See FreeMonoid (51.2.9), FreeSemigroup (51.1.10) for details.

37.2.1 FreeGroup

- FreeGroup([wfilt, ]rank[, name])
- FreeGroup([wfilt, ]name1, name2, ...)
- FreeGroup([wfilt, ]names)
- FreeGroup([wfilt, ]infinity, name, init)

Called with a positive integer rank, FreeGroup returns a free group on rank generators. If the optional argument name is given then the generators are printed as name1, name2 etc., that is, each name is the concatenation of the string name and an integer from 1 to range. The default for name is the string "f".

Called in the second form, FreeGroup returns a free group on as many generators as arguments, printed as name1, name2 etc.

Called in the third form, FreeGroup returns a free group on as many generators as the length of the list names, the i-th generator being printed as names[i].

Called in the fourth form, FreeGroup returns a free group on infinitely many generators, where the first generators are printed by the names in the list init, and the other generators by name and an appended number.

If the extra argument wfilt is given, it must be either IsSyllableWordsFamily or IsLetterWordsFamily or IsWLetterWordsFamily or IsELetterWordsFamily. This filter then specifies the representation used for the elements of the free group (see 37.6). If no such filter is given, a letter representation is used.

(For interfacing to old code that omits the representation flag, use of the syllable representation is also triggered by setting the option FreeGroupFamilyType to the string "syllable".)

37.2.2 IsFreeGroup

- IsFreeGroup(obj)
Any group consisting of elements in `IsAssocWordWithInverse (37.1.1)` lies in the filter `IsFreeGroup`; this holds in particular for any group created with `FreeGroup (37.2.1)`, or any subgroup of such a group.

Also see Chapter 47.

### 37.2.3 AssignGeneratorVariables

> `AssignGeneratorVariables(G)`

If $G$ is a group, whose generators are represented by symbols (for example a free group, a finitely presented group or a pc group) this function assigns these generators to global variables with the same names.

The aim of this function is to make it easy in interactive use to work with (for example) a free group. It is a shorthand for a sequence of assignments of the form

```gap
var1:=GeneratorsOfGroup(G)[1];
var2:=GeneratorsOfGroup(G)[2];
...
varn:=GeneratorsOfGroup(G)[n];
```

However, since overwriting global variables can be very dangerous, **it is not permitted to use this function within a function.** (If –despite this warning– this is done, the result is undefined.)

If the assignment overwrites existing variables a warning is given, if any of the variables if write protected, or any of the generator names would not be a proper variable name, an error is raised.

### 37.3 Comparison of Associative Words

#### 37.3.1 `\=` (for associative words)

> `\=(w1, w2)`

Two associative words are equal if they are words over the same alphabet and if they are sequences of the same letters. This is equivalent to saying that the external representations of the words are equal, see 37.7 and 36.2.

There is no “universal” empty word, every alphabet (that is, every family of words) has its own empty word.

```gap
f:= FreeGroup( "a", "b", "b" );;
gens:= GeneratorsOfGroup(f);
[ a, b, b ]
gens[2] = gens[3];
false
x:= gens[1]*gens[2];
a*b
y:= gens[2]/gens[2]*gens[1]*gens[2];
a*b
x = y;
true
z:= gens[2]/gens[2]*gens[1]*gens[3];
```
37.3.2 \(<\) (for associative words)

\[
\begin{align*}
\text{\texttt{a*b}}
\text{\texttt{gap> x = z;}}
\text{\texttt{false}}
\end{align*}
\]

The ordering of associative words is defined by length and lexicography (this ordering is called \textit{short-lex} ordering), that is, shorter words are smaller than longer words, and words of the same length are compared w.r.t. the lexicographical ordering induced by the ordering of generators. Generators are sorted according to the order in which they were created. If the generators are invertible then each generator \(g\) is larger than its inverse \(g^{-1}\), and \(g^{-1}\) is larger than every generator that is smaller than \(g\).

Example

\[
\begin{align*}
\text{\texttt{gap> f:= FreeGroup( 2 );; gens:= GeneratorsOfGroup( f );;}} \\
\text{\texttt{gap> a:= gens[1];; b:= gens[2];;}} \\
\text{\texttt{gap> One(f) < a^-1; a^-1 < a; a < b^-1; b^-1 < b; b < a^2; a^2 < a*b;}} \\
\text{true} \\
\text{true} \\
\text{true} \\
\text{true} \\
\text{true} \\
\text{true}
\end{align*}
\]

37.3.3 \textbf{IsShortLexLessThanOrEqual}

\[
\begin{align*}
\text{\texttt{IsShortLexLessThanOrEqual(u, v)}}
\end{align*}
\]

returns \texttt{IsLessThanOrEqualUnder(ord, u, v)} where \(\text{ord}\) is the short less ordering for the family of \(u\) and \(v\). (This is here for compatibility with \texttt{GAP 4.2}.)

37.3.4 \textbf{IsBasicWreathLessThanOrEqual}

\[
\begin{align*}
\text{\texttt{IsBasicWreathLessThanOrEqual(u, v)}}
\end{align*}
\]

returns \texttt{IsLessThanOrEqualUnder(ord, u, v)} where \(\text{ord}\) is the basic wreath product ordering for the family of \(u\) and \(v\). (This is here for compatibility with \texttt{GAP 4.2}.)

37.4 Operations for Associative Words

The product of two given associative words is defined as the freely reduced concatenation of the words. Besides the multiplication \(\texttt{\*}(31.12.1)\), the arithmetical operators \texttt{One}(31.10.2) (if the word lies in a family with identity) and (if the generators are invertible) \texttt{Inverse}(31.10.8), \(\texttt{/}(31.12.1)\), \(\texttt{\^{}}(31.12.1)\), \texttt{Comm}(31.12.3), and \texttt{LeftQuotient}(31.12.2) are applicable to associative words, see 31.12.

See also \texttt{MappedWord}(36.3.1), an operation that is applicable to arbitrary words.
See Section 37.6 for a discussion of the internal representations of associative words that are supported by GAP. Note that operations to extract or act on parts of words (letter or syllables) can carry substantially different costs, depending on the representation the words are in.

### 37.4.1 Length (for a associative word)

#### Example

```gap
f := FreeGroup("a","b");; gens := GeneratorsOfGroup(f);;

a := gens[1];; b := gens[2];; w := a^5*b*a^2*b^-4*a;;

w; Length( w ); Length( a^17 ); Length( w^0 );
a^5*b*a^2*b^-4*a
13
17
0
```

### 37.4.2 ExponentSumWord

#### Example

```gap
w; ExponentSumWord( w, a ); ExponentSumWord( w, b );
a^5*b*a^2*b^-4*a
8
-3
ExponentSumWord( (a*b*a^-1)^3, a ); ExponentSumWord( w, b^-1 );
0
3
```

### 37.4.3 Subword

#### Example

```gap
w; Subword( w, 3, 7 );
a^5*b*a^2*b^-4*a
a^-3*b*a
```

### 37.4.4 PositionWord

#### Example
Let \( w \) and \( \text{sub} \) be associative words, and \( \text{from} \) a positive integer. \text{PositionWord} returns the position of the first occurrence of \( \text{sub} \) as a subword of \( w \), starting at position \( \text{from} \). If there is no such occurrence, \text{fail} is returned. Indexing is done with origin 1.

In other words, \text{PositionWord}( w, \text{sub}, \text{from} ) is the smallest integer \( i \) larger than or equal to \( \text{from} \) such that \( \text{Subword}( w, i, i+\text{Length}( \text{sub} )-1 ) = \text{sub} \), see \text{Subword} (37.4.3).

Example

\[
\text{gap> w; PositionWord( w, a/b, 1 );}
\]
\[
a^5*b*a^-2*b^-4*a
\]
\[
8
gap> \text{Subword}( w, 8, 9 );
\]
\[
a*b^-1
\]
\[
gap> \text{PositionWord( w, a^-2, 1 );}
\]
\[
1
\]
\[
gap> \text{PositionWord( w, a^-2, 2 );}
\]
\[
2
\]
\[
gap> \text{PositionWord( w, a^-2, 6 );}
\]
\[
7
\]
\[
gap> \text{PositionWord( w, a^-2, 8 ); fail}
\]

### 37.4.5 \text{SubstitutedWord}

\[\text{\triangleright SubstitutedWord}( w, \text{from}, \text{to}, \text{by} )\quad \text{(operation)}\]

\[\text{\triangleright SubstitutedWord}( w, \text{sub}, \text{from}, \text{by} )\quad \text{(operation)}\]

Let \( w \) be an associative word.

In the first form, \text{SubstitutedWord} returns the associative word obtained by replacing the subword of \( w \) that begins at position \( \text{from} \) and ends at position \( \text{to} \) by the associative word \( \text{by} \). \( \text{from} \) and \( \text{to} \) must be positive integers, indexing is done with origin 1. In other words, \text{SubstitutedWord}( w, \text{from}, \text{to}, \text{by} ) is the product of the three words \( \text{Subword}( w, 1, \text{from-1} ) \), \text{by}, and \( \text{Subword}( w, \text{to+1}, \text{Length}( w ) ) \), see \text{Subword} (37.4.3).

In the second form, \text{SubstitutedWord} returns the associative word obtained by replacing the first occurrence of the associative word \( \text{sub} \) of \( w \), starting at position \( \text{from} \), by the associative word \( \text{by} \); if there is no such occurrence, \text{fail} is returned.

Example

\[
\text{gap> w; SubstitutedWord( w, 3, 7, a^19 );}
\]
\[
a^5*b*a^-2*b^-4*a
\]
\[
a^22*b^-4*a
\]
\[
\text{gap> SubstitutedWord( w, a, 6, b^7 );}
\]
\[
a^5*b^-8*a*b^-4*a
\]
\[
\text{gap> SubstitutedWord( w, a*b, 6, b^7 ); fail}
\]

### 37.4.6 \text{EliminatedWord}

\[\text{\triangleright EliminatedWord}( w, \text{gen}, \text{by} )\quad \text{(operation)}\]

For an associative word \( w \), a generator \( \text{gen} \), and an associative word \( \text{by} \), \text{EliminatedWord} returns the associative word obtained by replacing each occurrence of \( \text{gen} \) in \( w \) by \( \text{by} \).
Example

```gap
gap> w; EliminatedWord( w, a, a^2 ); EliminatedWord( w, a, b^-1 );
a^5*b*a^2*b^-4*a
a^10*b*a^4*b^-4*a^2
b^-11
```

37.5 Operations for Associative Words by their Syllables

For an associative word \( w = x_1^{n_1} x_2^{n_2} \ldots x_k^{n_k} \) over an alphabet containing \( x_1, x_2, \ldots, x_k \), such that \( x_i \neq x_{i+1} \) for \( 1 \leq i \leq k - 1 \), the subwords \( x_i^{n_i} \) are uniquely determined; these powers of generators are called the syllables of \( w \).

37.5.1 NumberSyllables

\[ \text{NumberSyllables}(w) \]

NumberSyllables returns the number of syllables of the associative word \( w \).

37.5.2 ExponentSyllable

\[ \text{ExponentSyllable}(w, i) \]

ExponentSyllable returns the exponent of the \( i \)-th syllable of the associative word \( w \).

37.5.3 GeneratorSyllable

\[ \text{GeneratorSyllable}(w, i) \]

GeneratorSyllable returns the number of the generator that is involved in the \( i \)-th syllable of the associative word \( w \).

37.5.4 SubSyllables

\[ \text{SubSyllables}(w, \text{from}, \text{to}) \]

SubSyllables returns the subword of the associative word \( w \) that consists of the syllables from positions \( \text{from} \) to \( \text{to} \), where \( \text{from} \) and \( \text{to} \) must be positive integers, and indexing is done with origin 1.

```gap
gap> w; NumberSyllables( w );
a^5*b*a^2*b^-4*a
5
gap> ExponentSyllable( w, 3 );
2
gap> GeneratorSyllable( w, 3 );
1
gap> SubSyllables( w, 2, 3 );
b*a^2
```
37.6 Representations for Associative Words

GAP provides two different internal kinds of representations of associative words. The first one are “syllable representations” in which words are stored in syllable (i.e. generator,exponent) form. (Older versions of GAP only used this representation.) The second kind are “letter representations” in which each letter in a word is represented by its index number. Negative numbers are used for inverses. Unless the syllable representation is specified explicitly when creating the free group/monoid or semigroup, a letter representation is used by default.

Depending on the task in mind, either of these two representations will perform better in time or in memory use and algorithms that are syllable or letter based (for example GeneratorSyllable (37.5.3) and Subword (37.4.3)) perform substantially better in the corresponding representation. For example when creating pc groups (see 46), it is advantageous to use a syllable representation while calculations in free groups usually benefit from using a letter representation.

37.6.1 IsLetterAssocWordRep

A word in letter representation stores a list of generator/inverses numbers (as given by LetterRepAssocWord (37.6.8)). Letter access is fast, syllable access is slow for such words.

37.6.2 IsLetterWordsFamily

A letter word family stores words by default in letter form. Internally, there are letter representations that use integers (4 Byte) to represent a generator and letter representations that use single bytes to represent a character. The latter are more memory efficient, but can only be used if there are less than 128 generators (in which case they are used by default).

37.6.3 IsBLetterAssocWordRep

these two subrepresentations of IsLetterAssocWordRep (37.6.1) indicate whether the word is stored as a list of bytes (in a string) or as a list of integers).

37.6.4 IsBLetterWordsFamily

These two subcategories of IsLetterWordsFamily (37.6.2) specify the type of letter representation to be used.
37.6.5  IsSyllableAssocWordRep

\[ \text{IsSyllableAssocWordRep(obj)} \]

A word in syllable representation stores generator/exponents pairs (as given by ExtRepOfObj (79.8.1)). Syllable access is fast, letter access is slow for such words.

37.6.6  IsSyllableWordsFamily

\[ \text{IsSyllableWordsFamily}(obj) \]

A syllable word family stores words by default in syllable form. There are also different versions of syllable representations, which compress a generator exponent pair in 8, 16 or 32 bits or use a pair of integers. Internal mechanisms try to make this as memory efficient as possible.

37.6.7  Is16BitsFamily

\[ \text{Is16BitsFamily}(obj) \]

\[ \text{Is32BitsFamily}(obj) \]

\[ \text{IsInfBitsFamily}(obj) \]

Regardless of the internal representation used, it is possible to convert a word in a list of numbers in letter or syllable representation and vice versa.

37.6.8  LetterRepAssocWord

\[ \text{LetterRepAssocWord}(w[, gens]) \]

The letter representation of an associated word is as a list of integers, each entry corresponding to a group generator. Inverses of the generators are represented by negative numbers. The generator numbers are as associated to the family.

This operation returns the letter representation of the associative word \( w \).

In the call with two arguments, the generator numbers correspond to the generator order given in the list \( gens \).

(For words stored in syllable form the letter representation has to be computed.)

37.6.9  AssocWordByLetterRep

\[ \text{AssocWordByLetterRep}(\text{Fam}, \text{lrep}[, \text{gens}]) \]

takes a letter representation \( \text{lrep} \) (see LetterRepAssocWord (37.6.8)) and returns an associative word in family \( \text{fam} \) corresponding to this letter representation.

If \( \text{gens} \) is given, the numbers in the letter representation correspond to \( \text{gens} \).

\begin{verbatim}
Example

gap> w:=AssocWordByLetterRep(FamilyObj(a), [-1,2,1,-2,-2,-2,1,1,1,1]);
a^-1*b*a*b^-3*a^4
gap> LetterRepAssocWord( w^2 );
[ -1, 2, 1, -2, -2, -2, 1, 1, 1, 1, 2, 1, -2, -2, -2, 1, 1, 1, 1 ]
\end{verbatim}
The external representation (see section 37.7) can be used if a syllable representation is needed.

### 37.7 The External Representation for Associative Words

The external representation of the associative word \( w \) is defined as follows. If \( w = g_{i_1}^{e_1} * g_{i_2}^{e_2} * \cdots * g_{i_k}^{e_k} \) is a word over the alphabet \( g_1, g_2, \ldots \), i.e., \( g_i \) denotes the \( i \)-th generator of the family of \( w \), then \( w \) has external representation \([i_1, e_1, i_2, e_2, \ldots, i_k, e_k]\). The empty list describes the identity element (if exists) of the family. Exponents may be negative if the family allows inverses. The external representation of an associative word is guaranteed to be freely reduced; for example, \( g_1 * g_2 * g_2^{-1} * g_1 \) has the external representation \([1, 2]\).

Regardless of the family preference for letter or syllable representations (see 37.6), \texttt{ExtRepOfObj} and \texttt{ObjByExtRep} can be used and interface to this “syllable”-like representation.

```gap
gap> w := ObjByExtRep( FamilyObj(a), [1,5,2,-7,1,3,2,4,1,-2] );
a^5*b^-7*a^3*b^4*a^-2
gap> ExtRepOfObj( w^2 );
[ 1, 5, 2, -7, 1, 3, 2, 4, 1, 3, 2, -7, 1, 3, 2, 4, 1, -2 ]
```

### 37.8 Straight Line Programs

Straight line programs describe an efficient way for evaluating an abstract word at concrete generators, in a more efficient way than with \texttt{MappedWord} (36.3.1). For example, the associative word \( ababbab \) of length 7 can be computed from the generators \( a, b \) with only four multiplications, by first computing \( c = ab \), then \( d = cb \), and then \( cdc \); Alternatively, one can compute \( c = ab, e = bc \), and \( aee \). In each step of these computations, one forms words in terms of the words computed in the previous steps.

A straight line program in \texttt{GAP} is represented by an object in the category \texttt{IsStraightLineProgram} (37.8.1)) that stores a list of “lines” each of which has one of the following three forms.

1. a nonempty dense list \( l \) of integers,
2. a pair \([l, i]\) where \( l \) is a list of form 1. and \( i \) is a positive integer,
3. a list \([l_1, l_2, \ldots, l_k]\) where each \( l_i \) is a list of form 1.; this may occur only for the last line of the program.

The lists of integers that occur are interpreted as external representations of associative words (see Section 37.7); for example, the list \([1, 3, 2, -1]\) represents the word \( g_1^1 g_2^{-1} \), with \( g_1 \) and \( g_2 \) the first and second abstract generator, respectively.

For the meaning of the list of lines, see \texttt{ResultOfStraightLineProgram} (37.8.5).

Straight line programs can be constructed using \texttt{StraightLineProgram} (37.8.2).

Defining attributes for straight line programs are \texttt{NrInputsOfStraightLineProgram} (37.8.4) and \texttt{LinesOfStraightLineProgram} (37.8.3). Another operation for straight line programs is \texttt{ResultOfStraightLineProgram} (37.8.5).

Special methods applicable to straight line programs are installed for the operations \texttt{Display} (6.3.6), \texttt{IsInternallyConsistent} (12.8.4), \texttt{PrintObj} (6.3.5), and \texttt{ViewObj} (6.3.5).
For a straight line program \( prog \), the default \( \text{Display} \) (6.3.6) method prints the interpretation of \( prog \) as a sequence of assignments of associative words; a record with components \( \text{gensnames} \) (with value a list of strings) and \( \text{listname} \) (a string) may be entered as second argument of \( \text{Display} \) (6.3.6), in this case these names are used, the default for \( \text{gensnames} \) is \([ g_1, g_2, \ldots ]\), the default for \( \text{listname} \) is \( r \).

### 37.8.1 IsStraightLineProgram

\[
\text{IsStraightLineProgram}(\text{obj})
\]

Each straight line program in GAP lies in the category \( \text{IsStraightLineProgram} \).

### 37.8.2 StraightLineProgram (for a list of lines (and the number of generators))

\[
\text{StraightLineProgram}(\text{lines}[, nrgens]) \\
\text{StraightLineProgram}(\text{string}, \text{gens}) \\
\text{StraightLineProgramNC}(\text{lines}[, nrgens]) \\
\text{StraightLineProgramNC}(\text{string}, \text{gens})
\]

In the first form, \( \text{lines} \) must be a nonempty list of lists that defines a unique straight line program (see \( \text{IsStraightLineProgram} \) (37.8.1)); in this case \( \text{StraightLineProgram} \) returns this program, otherwise an error is signalled. The optional argument \( nrgens \) specifies the number of input generators of the program; if a line of form 1. (that is, a list of integers) occurs in \( \text{lines} \) except in the last position, this number is not determined by \( \text{lines} \) and therefore must be specified by the argument \( nrgens \); if not then \( \text{StraightLineProgram} \) returns \( \text{fail} \).

In the second form, \( \text{string} \) must be a nonempty string describing an arithmetic expression in terms of the strings in the list \( \text{gens} \), where multiplication is denoted by concatenation, powering is denoted by \( ^\cdot \), and round brackets \((, )\) may be used. Each entry in \( \text{gens} \) must consist only of uppercase or lowercase letters (i.e., letters in \( \text{IsAlphaChar} \) (27.5.4)) such that no entry is an initial part of another one. Called with this input, \( \text{StraightLineProgram} \) returns a straight line program that evaluates to the word corresponding to \( \text{string} \) when called with generators corresponding to \( \text{gens} \).

The \( \text{NC} \) variant does the same, except that the internal consistency of the program is not checked.

### 37.8.3 LinesOfStraightLineProgram

\[
\text{LinesOfStraightLineProgram}(\text{prog})
\]

For a straight line program \( \text{prog} \), \( \text{LinesOfStraightLineProgram} \) returns the list of program lines. There is no default method to compute these lines if they are not stored.

### 37.8.4 NrInputsOfStraightLineProgram

\[
\text{NrInputsOfStraightLineProgram}(\text{prog})
\]

For a straight line program \( \text{prog} \), \( \text{NrInputsOfStraightLineProgram} \) returns the number of generators that are needed as input.

If a line of form 1. (that is, a list of integers) occurs in the lines of \( \text{prog} \) except the last line then the number of generators is not determined by the lines, and must be set in the construction of the straight
line program (see StraightLineProgram (37.8.2)). So if \( \text{prog} \) contains a line of form 1. other than the last line and does not store the number of generators then \( \text{NrInputsOfStraightLineProgram} \) signals an error.

### 37.8.5 ResultOfStraightLineProgram

\[ \text{ResultOfStraightLineProgram} \] 

\( \text{ResultOfStraightLineProgram} \) evaluates the straight line program (see IsStraightLineProgram (37.8.1)) \( \text{prog} \) at the group elements in the list \( \text{gens} \).

The result of a straight line program with lines \( p_1, p_2, \ldots, p_k \) when applied to \( \text{gens} \) is defined as follows.

(a) First a list \( r \) of intermediate results is initialized with a shallow copy of \( \text{gens} \).

(b) For \( i < k \), before the \( i \)-th step, let \( r \) be of length \( n \). If \( p_i \) is the external representation of an associative word in the first \( n \) generators then the image of this word under the homomorphism that is given by mapping \( r \) to these first \( n \) generators is added to \( r \); if \( p_i \) is a pair \([l, j]\), for a list \( l \), then the same element is computed, but instead of being added to \( r \), it replaces the \( j \)-th entry of \( r \).

(c) For \( i = k \), if \( p_k \) is the external representation of an associative word then the element described in (b) is the result of the program, if \( p_k \) is a pair \([l, j]\), for a list \( l \), then the result is the element described by \( l \), and if \( p_k \) is a list \([l_1, l_2, \ldots, l_k]\) of lists then the result is a list of group elements, where each \( l_i \) is treated as in (b).

Example

```gap
f := FreeGroup( "x", "y" );;
gens := GeneratorsOfGroup( f );;
x := gens[1];;
y := gens[2];;
prg := StraightLineProgram( [ [] ] );
ResultOfStraightLineProgram( prg, [] );
[ ]
```

The above straight line program \( \text{prg} \) returns –for any list of input generators– an empty list.

Example

```gap
StraightLineProgram( [ [1, 2, 3], [3, -1] ] );
fail
prg := StraightLineProgram( [ [1, 2, 2, 3], [3, -1] ], 2 );
LinesOfStraightLineProgram( prg );
[ [ 1, 2, 2, 3 ], [ 3, -1 ] ]
prg := StraightLineProgram( "(a^2b^3)^-1", [ "a", "b" ] );
LinesOfStraightLineProgram( prg );
[ [ 1, 2, 2, 3 ], 3 ], [ 3, -1 ], 4 ]
res := ResultOfStraightLineProgram( prg, gens );
y^-3*x^-2
res = (x^-2 * y^-3)^-1;
true
NrInputsOfStraightLineProgram( prg );
```

2
gap> Print( prg, "\n" );
StraightLineProgram( [ [ [ 1, 2, 2, 3 ], 3 ], [ [ 3, -1 ], 4 ] ], 2 )
gap> Display( prg );
# input:
r := [ g1, g2 ];
# program:
r[4] := r[3]^(-1);
# return value:
r[4]
gap> IsInternallyConsistent( StraightLineProgramNC( [ [1,2] ] ) );
true
gap> IsInternallyConsistent( StraightLineProgramNC( [ [1,2,3] ] ) );
false
gap> prg1 := StraightLineProgram( [ [1,1,2,2], [3,3,1,1] ], 2 );;
gap> prg2 := StraightLineProgram( [ [1,1,2,2], [2,3,1,1] ] );;
gap> res1 := ResultOfStraightLineProgram( prg1, gens );
(x*y^2)^3*x
gap> res1 = (x*y^2)^3*x;
true
gap> res2 := ResultOfStraightLineProgram( prg2, gens );
(x*y^2)^3*x
gap> res2 = (x*y^2)^3*x;
true
gap> prg := StraightLineProgram( [ [2,3], [ [3,1,1,4], [1,2,3,1] ] ], 2 );;
gap> res := ResultOfStraightLineProgram( prg, gens );
[ y^3*x^4, x^2*y^3 ]

37.8.6 StringOfResultOfStraightLineProgram

StringOfResultOfStraightLineProgram returns a string that describes the result of
the straight line program (see IsStraightLineProgram (37.8.1)) prog as word(s) in terms of
the strings in the list gensnames. If the result of prog is a single element then
the return value of StringOfResultOfStraightLineProgram is a string consisting of
the entries of gensnames, opening and closing brackets ( and ), and
powering by integers via ". If the result of prog is a list of
elements then the return value of StringOfResultOfStraightLineProgram is a comma separated
concatenation of the strings of the single elements, enclosed in square brackets [ ].

Example
gap> prg := StraightLineProgram( [ [ 1, 2, 2, 3 ], [ 3, -1 ] ], 2 );;
gap> StringOfResultOfStraightLineProgram( prg, [ "a", "b" ] );
"(a^2b^-3)^-1"
gap> StringOfResultOfStraightLineProgram( prg, [ "a", "b" ], "LaTeX" );
"(a^{-2}b^{-3})^{-1}"
37.8.7 CompositionOfStraightLinePrograms

\( \text{CompositionOfStraightLinePrograms}( \text{prog2, prog1} ) \)

For two straight line programs \( \text{prog1} \) and \( \text{prog2} \), \text{CompositionOfStraightLinePrograms} returns a straight line program \( \text{prog} \) with the properties that \( \text{prog1} \) and \( \text{prog} \) have the same number of inputs, and the result of \( \text{prog} \) when applied to given generators \( \text{gens} \) equals the result of \( \text{prog2} \) when this is applied to the output of \( \text{prog1} \) applied to \( \text{gens} \).

(Of course the number of outputs of \( \text{prog1} \) must be the same as the number of inputs of \( \text{prog2} \).)

Example

```gap
gap> prg1:= StraightLineProgram( "a^2b", [ "a","b" ] );;
gap> prg2:= StraightLineProgram( "c^5", [ "c" ] );;
gap> comp:= CompositionOfStraightLinePrograms( prg2, prg1 );
<straight line program>
gap> StringOfResultOfStraightLineProgram( comp, [ "a", "b" ] );
"(a^2b)^5"
gap> prg:= StraightLineProgram( [ [2,3], [ [3,1,1,4], [1,2,3,1] ] ], 2 );;
gap> StringOfResultOfStraightLineProgram( prg, [ "a", "b" ] );
"[ b^3a^4, a^2b^-3 ]"
gap> comp:= CompositionOfStraightLinePrograms( prg, prg1 );
<straight line program>
gap> StringOfResultOfStraightLineProgram( comp, [ "a", "b" ] );
"[ (a^2b^-3)3(b^-3a^-4)4, (b^-3a^-4)2(a^2b^-3)^3 ]"
```

37.8.8 IntegratedStraightLineProgram

\( \text{IntegratedStraightLineProgram}( \text{listofprogs} ) \)

For a nonempty dense list \( \text{listofprogs} \) of straight line programs \( p_1, p_2, \ldots, p_m \), say, that have the same number \( n \), say, of inputs (see \text{NrInputsOfStraightLineProgram} (37.8.4)), \text{IntegratedStraightLineProgram} returns a straight line program \( \text{prog} \) with \( n \) inputs such that for each \( n \)-tuple \( \text{gens} \) of generators, \text{ResultOfStraightLineProgram}( \text{prog, gens} ) \) is the concatenation of the lists \( r_1, r_2, \ldots, r_m \), where \( r_i \) is equal to \text{ResultOfStraightLineProgram}( \text{p_i, gens} ) \) if this result is a list of elements, and otherwise \( r_i \) is equal to the list of length one that contains this result.

Example

```gap
gap> f:= FreeGroup( "x", "y" );;
gens:= GeneratorsOfGroup( f );;
gap> prg1:= StraightLineProgram([ [ 1, 2 ], 1 ], [ 1, 2, 2, -1 ]], 2 );;
gap> prg2:= StraightLineProgram([ [ 2, 2 ], 3 ], [ 1, 3, 3, 2 ]], 2 );;
gap> prg3:= StraightLineProgram([ [ 2, 2 ], [ 1, 3, 3, 2 ] ], 2 );;
gap> prg:= IntegratedStraightLineProgram( [ prg1, prg2, prg3 ] );
gap> ResultOfStraightLineProgram( prg, gens );
[ x^4*y^-1, x^3*y^-4, x^3*y^-4 ]
gap> prg:= IntegratedStraightLineProgram( [ prg2, prg3, prg1 ] );
gap> ResultOfStraightLineProgram( prg, gens );
[ x^3*y^-4, x^3*y^-4, x^4*y^-1 ]
gap> prg:= IntegratedStraightLineProgram( [ prg3, prg1, prg2 ] );
gap> ResultOfStraightLineProgram( prg, gens );
[ x^3*y^-4, x^4*y^-1, x^3*y^-4 ]
gap> prg:= IntegratedStraightLineProgram( [ prg, prg ] );
```
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37.8.9  RestrictOutputsOfSLP

\[ \text{RestrictOutputsOfSLP}(\text{slp}, k) \]

\( \text{slp} \) must be a straight line program returning a tuple of values. This function returns a new \( \text{slp} \) that calculates only those outputs specified by \( k \). The argument \( k \) may be an integer or a list of integers. If \( k \) is an integer, the resulting \( \text{slp} \) calculates only the result with that number in the original output tuple. If \( k \) is a list of integers, the resulting \( \text{slp} \) calculates those results with indices \( k \) in the original output tuple. In both cases the resulting \( \text{slp} \) does only what is necessary. Obviously, the \( \text{slp} \) must have a line with enough expressions (lists) for the supplied \( k \) as its last line. \( \text{slp} \) is either an \( \text{slp} \) or a pair where the first entry are the lines of the \( \text{slp} \) and the second is the number of inputs.

37.8.10  IntermediateResultOfSLP

\[ \text{IntermediateResultOfSLP}(\text{slp}, k) \]

Returns a new \( \text{slp} \) that calculates only the value of slot \( k \) at the end of \( \text{slp} \) doing only what is necessary. \( \text{slp} \) is either an \( \text{slp} \) or a pair where the first entry are the lines of the \( \text{slp} \) and the second is the number of inputs. Note that this assumes a general SLP with possible overwriting. If you know that your SLP does not overwrite slots, please use \( \text{IntermediateResultOfSLPWithoutOverwrite} \) (37.8.11), which is much faster in this case.

37.8.11  IntermediateResultOfSLPWithoutOverwrite

\[ \text{IntermediateResultOfSLPWithoutOverwrite}(\text{slp}, k) \]

Returns a new \( \text{slp} \) that calculates only the value of slot \( k \), which must be an integer. Note that \( \text{slp} \) must not overwrite slots but only append!!! Use \( \text{IntermediateResultOfSLP} \) (37.8.10) in the other case! \( \text{slp} \) is either an \( \text{slp} \) or a pair where the first entry is the lines of the \( \text{slp} \) and the second is the number of inputs.

37.8.12  IntermediateResultsOfSLPWithoutOverwrite

\[ \text{IntermediateResultsOfSLPWithoutOverwrite}(\text{slp}, k) \]

Returns a new \( \text{slp} \) that calculates only the value of slots contained in the list \( k \). Note that \( \text{slp} \) must not overwrite slots but only append!!! Use \( \text{IntermediateResultOfSLP} \) (37.8.10) in the other case! \( \text{slp} \) is either an \( \text{slp} \) or a pair where the first entry is the lines of the \( \text{slp} \) and the second is the number of inputs.

37.8.13  ProductOfStraightLinePrograms

\[ \text{ProductOfStraightLinePrograms}(\text{s1}, \text{s2}) \]

\[ \text{gap} \text{> ResultOfStraightLineProgram}(\text{prg}, \text{gens}); \]
\[ [ x^3*y^4, x^4*y^{-1}, x^3*y^4, x^3*y^4, x^4*y^{-1}, x^3*y^4 ] \]
\$s1\$ and \$s2\$ must be two slps that return a single element with the same number of inputs. This function constructs an slp that returns the product of the two results the slps \$s1\$ and \$s2\$ would produce with the same input.

### 37.8.14 SlotUsagePattern

\[ \triangledown \text{SlotUsagePattern}(s) \] (attribute)

Analyses the straight line program \$s\$ for more efficient evaluation. This means in particular two things, when this attribute is known: First of all, intermediate results which are not actually needed later on are not computed at all, and once an intermediate result is used for the last time in this SLP, it is discarded. The latter leads to the fact that the evaluation of the SLP needs less memory.

### 37.9 Straight Line Program Elements

When computing with very large (in terms of memory) elements, for example permutations of degree a few hundred thousands, it can be helpful (in terms of memory usage) to represent them via straight line programs in terms of an original generator set. (So every element takes only small extra storage for the straight line program.)

A straight line program element has a \$seed\$ (a list of group elements) and a straight line program on the same number of generators as the length of this seed, its value is the value of the evaluated straight line program.

At the moment, the entries of the straight line program have to be simple lists (i.e. of the first form).

Straight line program elements are in the same categories and families as the elements of the seed, so they should work together with existing algorithms.

Note however, that due to the different way of storage some normally very cheap operations (such as testing for element equality) can become more expensive when dealing with straight line program elements. This is essentially the tradeoff for using less memory.

See also Section 43.13.

### 37.9.1 IsStraightLineProgElm

\[ \triangledown \text{IsStraightLineProgElm}(obj) \] (Representation)

A straight line program element is a group element given (for memory reasons) as a straight line program. Straight line program elements are positional objects, the first component is a record with a component \$seeds\$, the second component the straight line program.

### 37.9.2 StraightLineProgElm

\[ \triangledown \text{StraightLineProgElm}(seed, prog) \] (function)

Creates a straight line program element for seed \$seed\$ and program \$prog\$. 
37.9.3 StraightLineProgGens

\[ \text{StraightLineProgGens}(\text{gens[], base}) \]

returns a set of straight line program elements corresponding to the generators in \text{gens}. If \text{gens} is a set of permutations then \text{base} can be given which must be a base for the group generated by \text{gens}. (Such a base will be used to speed up equality tests.)

37.9.4 EvalStraightLineProgElm

\[ \text{EvalStraightLineProgElm}(\text{slpel}) \]

evaluates a straight line program element \text{slpel} from its seeds.

37.9.5 StretchImportantSLPElement

\[ \text{StretchImportantSLPElement}(\text{elm}) \]

If \text{elm} is a straight line program element whose straight line representation is very long, this operation changes the representation of \text{elm} to a straight line program element, equal to \text{elm}, whose seed contains the evaluation of \text{elm} and whose straight line program has length 1.

For other objects nothing happens.

This operation permits to designate “important” elements within an algorithm (elements that will be referred to often), which will be represented by guaranteed short straight line program elements.

\begin{example}
\begin{verbatim}
gap> gens:=StraightLineProgGens([[1,2,3,4),(1,2)]);  
[ [ [ 2, 1 ] ](1,2,3,4), [ [ 1, 1 ] ](1,2) ]
gap> g:=Group(gens);,
[ [ 1, -1, 2, 3, 1, 1 ] ](1,2,4,3)
gap> Size(g);  
24
\end{verbatim}
\end{example}
Chapter 38

Rewriting Systems

Rewriting systems in GAP are a framework for dealing with the very general task of rewriting elements of a free (or term) algebra in some normal form. Although most rewriting systems currently in use are string rewriting systems (where the algebra has only one binary operation which is associative) the framework in GAP is general enough to encompass the task of rewriting algebras of any signature from groups to semirings.

Rewriting systems are already implemented in GAP for finitely presented semigroups and for pc groups. The use of these particular rewriting systems is described in the corresponding chapters. We describe here only the general framework of rewriting systems with a particular emphasis on material which would be helpful for a developer implementing a rewriting system.

We fix some definitions and terminology for the rest of this chapter. Let $T$ be a term algebra in some signature. A term rewriting system for $T$ is a set of ordered pairs of elements of $T$ of the form $(l, r)$. Viewed as a set of relations, the rewriting system determines a presentation for a quotient algebra $A$ of $T$.

When we take into account the fact that the relations are expressed as ordered pairs, we have a way of reducing the elements of $T$. Suppose an element $u$ of $T$ has a subword $l$ and $(l, r)$ is a rule of the rewriting system, then we can replace the subterm $l$ of $u$ by the term $r$ and obtain a new word $v$. We say that we have rewritten $u$ as $v$. Note that $u$ and $v$ represent the same element of $A$. If $u$ can not be rewritten using any rule of the rewriting system we sat that $u$ is reduced.

38.1 Operations on rewriting systems

38.1.1 IsRewritingSystem

\begin{verbatim}
>>> IsRewritingSystem(obj) \end{verbatim}

(Category)

This is the category in which all rewriting systems lie.

38.1.2 Rules

\begin{verbatim}
>>> Rules(rws) \end{verbatim}

(attribute)

The rules comprising the rewriting system. Note that these may change through the life of the rewriting system, however they will always be a set of defining relations of the algebra described by the rewriting system.

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38.1.3 OrderOfRewritingSystem

- OrderOfRewritingSystem(rws)
- OrderingOfRewritingSystem(rws)

return the ordering of the rewriting system rws.

38.1.4 ReducedForm

- ReducedForm(rws, u)

Given an element u in the free (or term) algebra T over which rws is defined, rewrite u by successive applications of the rules of rws until no further rewriting is possible, and return the resulting element of T.

38.1.5 IsConfluent

- IsConfluent(rws)
- IsConfluent(A)

For a rewriting system rws, IsConfluent returns true if and only if rws is confluent. A rewriting system is confluent if, for every two words u and v in the free algebra T which represent the same element of the algebra A defined by rws, ReducedForm(rws, u) = ReducedForm(rws, v) as words in the free algebra T. This element is the unique normal form of the element represented by u.

For an algebra A with a canonical rewriting system associated with it, IsConfluent checks whether that rewriting system is confluent.

Also see IsConfluent (46.4.7).

38.1.6 ConfluentRws

- ConfluentRws(rws)

Return a new rewriting system defining the same algebra as rws which is confluent.

38.1.7 IsReduced

- IsReduced(rws)

A rewriting system is reduced if for each rule (l, r), l and r are both reduced.

38.1.8 ReduceRules

- ReduceRules(rws)

Reduce rules and remove redundant rules to make rws reduced.
38.1.9 AddRule

AddRule\((\textit{rws}, \textit{rule})\)

Add rule to a rewriting system \(\textit{rws}\).

38.1.10 AddRuleReduced

AddRuleReduced\((\textit{rws}, \textit{rule})\)

Add rule to rewriting system \(\textit{rws}\). Performs a reduction operation on the resulting system, so that if \(\textit{rws}\) is reduced it will remain reduced.

38.1.11 MakeConfluent

MakeConfluent\((\textit{rws})\)

Add rules (and perhaps reduce) in order to make \(\textit{rws}\) confluent.

38.1.12 GeneratorsOfRws

GeneratorsOfRws\((\textit{rws})\)

Returns the list of generators of the rewriting system \(\textit{rws}\).

38.2 Operations on elements of the algebra

In this section let \(u\) denote an element of the term algebra \(T\) representing \([u]\) in the quotient algebra \(A\).

38.2.1 ReducedProduct

ReducedProduct\((\textit{rws}, \textit{u}, \textit{v})\)
ReducedSum\((\textit{rws}, \textit{left}, \textit{right})\)
ReducedOne\((\textit{rws})\)
ReducedAdditiveInverse\((\textit{rws}, \textit{obj})\)
ReducedComm\((\textit{rws}, \textit{left}, \textit{right})\)
ReducedConjugate\((\textit{rws}, \textit{left}, \textit{right})\)
ReducedDifference\((\textit{rws}, \textit{left}, \textit{right})\)
ReducedInverse\((\textit{rws}, \textit{obj})\)
ReducedLeftQuotient\((\textit{rws}, \textit{left}, \textit{right})\)
ReducedPower\((\textit{rws}, \textit{obj}, \textit{pow})\)
ReducedQuotient\((\textit{rws}, \textit{left}, \textit{right})\)
ReducedScalarProduct\((\textit{rws}, \textit{left}, \textit{right})\)
ReducedZero\((\textit{rws})\)

The result of \(\text{ReducedProduct}\) is \(w\) where \([w]\) equals \([u][v]\) in \(A\) and \(w\) is in reduced form.

The remaining operations are defined similarly when they are defined (as determined by the signature of the term algebra).
38.3 Properties of rewriting systems

38.3.1 IsBuiltFromAdditiveMagmaWithInverses

\[ \text{IsBuiltFromAdditiveMagmaWithInverses}(\text{obj}) \] (property)

These properties may be used to identify the type of term algebra over which the rewriting system is defined.

38.4 Rewriting in Groups and Monoids

One application of rewriting is to reduce words in finitely presented groups and monoids. The rewriting system still has to be built for a finitely presented monoid (using \( \text{IsomorphismFpMonoid} \) for conversion). Rewriting then can take place for words in the underlying free monoid. (These can be obtained from monoid elements with the command \( \text{UnderlyingElement} \).)

Example

```gap
gap> f:=FreeGroup(3);;
gap> rels:=[f.1*f.2^2/f.3,f.2*f.3^2/f.1,f.3*f.1^2/f.2];;
gap> g:=f/rels;;
gap> mhom:=IsomorphismFpMonoid(g);
MappingByFunction( <fp group on the generators [ f1, f2, f3 ]>, <fp monoid on the generators [ f1, f1^-1, f2, f2^-1, f3, f3^-1 ]>, function( x ) ... end, function( x ) ... end )
gap> mon:=Image(mhom);
<fp monoid on the generators [ f1, f1^-1, f2, f2^-1, f3, f3^-1 ]>
gap> k:=KnuthBendixRewritingSystem(mon);
Knuth Bendix Rewriting System for Monoid( [ f1, f1^-1, f2, f2^-1, f3, f3^-1 ] ) with rules
[ [ f1*f1^-1, <identity ...> ], [ f1^-1*f1, <identity ...> ],
  [ f2*f2^-1, <identity ...> ], [ f2^-1*f2, <identity ...> ],
  [ f3*f3^-1, <identity ...> ], [ f3^-1*f3, <identity ...> ],
  [ f1*f2^2*f3^-1, <identity ...> ], [ f2*f3^2*f1^-1, <identity ...> ],
  [ f3*f1^2*f2^-1, <identity ...> ] ]
gap> MakeConfluent(k);
gap> a:=Product(GeneratorsOfMonoid(mon));
f1*f1^-1*f2*f2^-1*f3*f3^-1
gap> ReducedForm(k,UnderlyingElement(a));
<identity ...>
```

To rewrite a word in the finitely presented group, one has to convert it to a word in the monoid first, rewrite in the underlying free monoid and convert back (by forming first again an element of the fp monoid) to the finitely presented group.
Example

```gap
gap> r:=PseudoRandom(g);;
gap> Length(r);
3704
gap> melm:=Image(mhom,r);;
gap> red:=ReducedForm(k,UnderlyingElement(melm));
f1^-1*3*f2^-1*f1^-2
gap> melm:=ElementOfFpMonoid(FamilyObj(One(mon)),red);
f1^-1*3*f2^-1*f1^-2
gap> gpelm:=PreImagesRepresentative(mhom,melm);
f1^-3*f2^-1*f1^-2
gap> r=gpelm;
true
gap> CategoriesOfObject(red);
[ "IsExtLElement", "IsExtRElement", "IsMultiplicativeElement",
  "IsMultiplicativeElementWithOne", "IsAssociativeElement", "IsWord" ]
gap> CategoriesOfObject(melm);
[ "IsExtLElement", "IsExtRElement", "IsMultiplicativeElement",
  "IsMultiplicativeElementWithOne", "IsAssociativeElement",
  "IsElementOfFpMonoid" ]
gap> CategoriesOfObject(gpelm);
[ "IsExtLElement", "IsExtRElement", "IsMultiplicativeElement",
  "IsMultiplicativeElementWithOne", "IsMultiplicativeElementWithInverse",
  "IsAssociativeElement", "IsElementOfFpGroup" ]
```

Note, that the elements red (free monoid) melm (fp monoid) and gpelm (group) differ, though they are displayed identically.

Under Unix, it is possible to use the kbmag package to replace the built-in rewriting by this packages efficient C implementation. You can do this (after loading the kbmag package) by assigning the variable KB_REW (52.5.2) to KBMAG_REW. Assignment to GAPKB_REW reverts to the built-in implementation.

```gap
gap> LoadPackage("kbmag");
true
gap> KB_REW:=KBMAG_REW;;
```

### 38.5 Developing rewriting systems

The key point to note about rewriting systems is that they have properties such as IsConfluent (38.1.5) and attributes such as Rules (38.1.2), however they are rarely stored, but rather computed afresh each time they are asked for, from data stored in the private members of the rewriting system object. This is because a rewriting system often evolves through a session, starting with some rules which define the algebra A as relations, and then adding more rules to make the system confluent. For example, in the case of Knuth-Bendix rewriting systems (see Chapter 52), the function CreateKnuthBendixRewritingSystem creating the rewriting system (in the file lib/kbsemi.gi) uses

```gap
kbwrs := Objectify(NewType(rwsfam,
  IsMutable and IsKnuthBendixRewritingSystem and
```
IsKnuthBendixRewritingSystemRep),
rec(family:= fam,
reduced:=false,
tzrules:=List(relwco,i->
    [LetterRepAssocWord(i[1]),LetterRepAssocWord(i[2])]),
pairs2check:=CantorList(Length(r)),
ordering:=wordord,
freefam:=freefam));

In particular, since we don't use the filter IsAttributeStoringRep in the Objectify (79.1.1),
whenever IsConfluent (38.1.5) is called, the appropriate method to determine confluence is called.
Chapter 39

Groups

This chapter explains how to create groups and defines operations for groups, that is operations whose definition does not depend on the representation used. However methods for these operations in most cases will make use of the representation.

If not otherwise specified, in all examples in this chapter the group \( g \) will be the symmetric group \( S_4 \) acting on the letters \{1,\ldots,4\}.

39.1 Group Elements

Groups in GAP are written multiplicatively. The elements from which a group can be generated must permit multiplication and multiplicative inversion (see 31.14).

\begin{verbatim}
gap> a:=(1,2,3);;b:=(2,3,4);;
gap> One(a);
()
gap> Inverse(b);
(2,4,3)
gap> a*b;
(1,3)(2,4)
gap> Order(a*b);
2
gap> Order( [ [ 1, 1 ], [ 0, 1 ] ] );
infinity
\end{verbatim}

The next example may run into an infinite loop because the given matrix in fact has infinite order.

\begin{verbatim}
gap> Order( [ [ 1, 1 ], [ 0, 1 ] ] * Indeterminate( Rationals ) );
#I Order: warning, order of <mat> might be infinite
\end{verbatim}

Since groups are domains, the recommended command to compute the order of a group is \texttt{Size} (30.4.6). For convenience, group orders can also be computed with \texttt{Order} (31.10.10).

The operation \texttt{Comm} (31.12.3) can be used to compute the commutator of two elements, the operation \texttt{LeftQuotient} (31.12.2) computes the product \( x^{-1}y \).
39.2 Creating Groups

When groups are created from generators, this means that the generators must be elements that can be multiplied and inverted (see also 31.3). For creating a free group on a set of symbols, see FreeGroup (37.2.1).

39.2.1 Group (for several generators)

\[
\text{Group(}\, \text{gen, ... } \text{)} \quad \text{(function)}
\]

\[
\text{Group(}\, \text{gens[, id]} \text{)} \quad \text{(function)}
\]

\[
\text{Group(}\, \text{gen, ... } \text{)} \text{ is the group generated by the arguments gen, ...}
\]

If the only argument gens is a list that is not a matrix then Group( gens ) is the group generated by the elements of that list.

If there are two arguments, a list gens and an element id, then Group( gens, id ) is the group generated by the elements of gens, with identity id.

Note that the value of the attribute GeneratorsOfGroup (39.2.4) need not be equal to the list gens of generators entered as argument. Use GroupWithGenerators (39.2.3) if you want to be sure that the argument gens is stored as value of GeneratorsOfGroup (39.2.4).

Example

\[
\text{gap> g := Group([}\,(1,2,3,4), (1,2)\,];}
\]

\[
\text{Group([}\,(1,2,3,4), (1,2)\,])}
\]

39.2.2 GroupByGenerators

\[
\text{GroupByGenerators(}\, \text{gens} \text{)} \quad \text{(operation)}
\]

\[
\text{GroupByGenerators(}\, \text{gens, id} \text{)} \quad \text{(operation)}
\]

GroupByGenerators returns the group G generated by the list gens. If a second argument id is present then this is stored as the identity element of the group.

The value of the attribute GeneratorsOfGroup (39.2.4) of G need not be equal to gens. GroupByGenerators is the underlying operation called by Group (39.2.1).

39.2.3 GroupWithGenerators

\[
\text{GroupWithGenerators(}\, \text{gens[, id]} \text{)} \quad \text{(operation)}
\]

GroupWithGenerators returns the group G generated by the list gens. If a second argument id is present then this is stored as the identity element of the group. The value of the attribute GeneratorsOfGroup (39.2.4) of G is equal to gens.

39.2.4 GeneratorsOfGroup

\[
\text{GeneratorsOfGroup(}\, \text{G} \text{)} \quad \text{(attribute)}
\]

returns a list of generators of the group G. If G has been created by the command GroupWithGenerators (39.2.3) with argument gens, then the list returned by GeneratorsOfGroup will be equal to gens. For such a group, each generator can also be accessed using the . operator.
(see `GeneratorsOfDomain` (31.9.2)): for a positive integer \( i \), \( G . i \) returns the \( i \)-th element of the list returned by `GeneratorsOfGroup`. Moreover, if \( G \) is a free group, and `name` is the name of a generator of \( G \) then \( G . \text{name} \) also returns this generator.

```gap
gap> g := GroupWithGenerators([(1,2,3,4), (1,2)]);
Group([ (1,2,3,4), (1,2) ])
gap> GeneratorsOfGroup(g);
[ (1,2,3,4), (1,2) ]
```

While in this example GAP displays the group via the generating set stored in the attribute `GeneratorsOfGroup`, the methods installed for `View` (6.3.3) will in general display only some information about the group which may even be just the fact that it is a group.

### 39.2.5 AsGroup

```
\textbf{\texttt{AsGroup}}(D)
```

If the elements of the collection \( D \) form a group the command returns this group, otherwise it returns `fail`.

```gap
gap> AsGroup([(1,2)]);
fail
gap> AsGroup([(),(1,2)]);
Group([ (1,2) ])
```

### 39.2.6 ConjugateGroup

```
\textbf{\texttt{ConjugateGroup}}(G, \text{obj})
```

returns the conjugate group of \( G \), obtained by applying the conjugating element \( \text{obj} \).

To form a conjugate (group) by any object acting via \( ^{\cdot} \), one can also use the infix operator \( ^{\cdot} \).

```gap
gap> ConjugateGroup(g,(1,5));
Group([ (2,3,4,5), (2,5) ])
```

### 39.2.7 IsGroup

```
\textbf{\texttt{IsGroup}}(\text{obj})
```

A group is a magma-with-inverses (see `IsMagmaWithInverses` (35.1.4)) and associative (see `IsAssociative` (35.4.7)) multiplication.

`IsGroup` tests whether the object \( \text{obj} \) fulfills these conditions, it does not test whether \( \text{obj} \) is a set of elements that forms a group under multiplication; use `AsGroup` (39.2.5) if you want to perform such a test. (See 13.3 for details about categories.)

```gap
gap> IsGroup(g);
true
```
39.2.8 InfoGroup

InfoGroup is the info class for the generic group theoretic functions (see 7.4).

39.3 Subgroups

For the general concept of parents and subdomains, see 31.7 and 31.8. More functions that construct certain subgroups can be found in the sections 39.11, 39.12, 39.13, and 39.14.

If a group \( U \) is created as a subgroup of another group \( G \), \( G \) becomes the parent of \( U \). There is no “universal” parent group, parent-child chains can be arbitrary long. GAP stores the result of some operations (such as Normalizer (39.11.1)) with the parent as an attribute.

39.3.1 Subgroup

\[ \text{Subgroup} \left( G, \text{gens} \right) \] (function)
\[ \text{SubgroupNC} \left( G, \text{gens} \right) \] (function)
\[ \text{Subgroup} \left( G \right) \] (function)

creates the subgroup \( U \) of \( G \) generated by \text{gens}. The \text{Parent} (31.7.1) value of \( U \) will be \( G \). The \text{NC} version does not check, whether the elements in \text{gens} actually lie in \( G \).

The unary version of \text{Subgroup} creates a (shell) subgroup that does not even know generators but can be used to collect information about a particular subgroup over time.

Example

\[
\text{gap> u:=Subgroup(g,[(1,2,3),(1,2)]);}
\text{Group([ (1,2,3), (1,2) ])}
\]

39.3.2 Index (GAP operation)

\[ \text{Index} \left( G, U \right) \] (operation)
\[ \text{IndexNC} \left( G, U \right) \] (operation)

For a subgroup \( U \) of the group \( G \), \text{Index} returns the index \([G : U] = |G|/|U|\) of \( U \) in \( G \). The \text{NC} version does not test whether \( U \) is contained in \( G \).

Example

\[
\text{gap> Index(g,u);} \quad 4
\]

39.3.3 IndexInWholeGroup

\[ \text{IndexInWholeGroup} \left( G \right) \] (attribute)

If the family of elements of \( G \) itself forms a group \( P \), this attribute returns the index of \( G \) in \( P \). It is used primarily for free groups or finitely presented groups.
39.3.4 AsSubgroup

\[ \text{AsSubgroup}(G, U) \]

creates a subgroup of \( G \) which contains the same elements as \( U \).

Example

\[
\text{gap> v} := \text{AsSubgroup}(g, \	ext{Group}((1,2,3),(1,4))); \\
\text{Group}([ (1,2,3), (1,4) ]); \\
\text{gap> Parent(v);} \\
\text{Group}([ (1,2,3,4), (1,2) ]); 
\]

39.3.5 IsSubgroup

\[ \text{IsSubgroup}(G, U) \]

IsSubgroup returns \texttt{true} if \( U \) is a group that is a subset of the domain \( G \). This is actually checked by calling \texttt{IsGroup( U )} and \texttt{IsSubset( G, U )}; note that special methods for \texttt{IsSubset(30.5.1)} are available that test only generators of \( U \) if \( G \) is closed under the group operations. So in most cases, for example whenever one knows already that \( U \) is a group, it is better to call only \texttt{IsSubset(30.5.1)}.

Example

\[
\text{gap> IsSubgroup(g,u);} \\
\text{true} \\
\text{gap> v} := \text{Group}((1,2,3),(1,2)); \\
\text{Group}([ (1,2,3), (1,2) ]); \\
\text{gap> u=v;} \\
\text{true} \\
\text{gap> IsSubgroup(g,v);} \\
\text{true} 
\]

39.3.6 IsNormal

\[ \text{IsNormal}(G, U) \]

returns \texttt{true} if the group \( G \) normalizes the group \( U \) and \texttt{false} otherwise.

A group \( G \) normalizes a group \( U \) if and only if for every \( g \in G \) and \( u \in U \) the element \( u^g \) is a member of \( U \). Note that \( U \) need not be a subgroup of \( G \).

Example

\[
\text{gap> IsNormal(g,u);} \\
\text{false} 
\]
39.3.7 IsCharacteristicSubgroup

\[\text{IsCharacteristicSubgroup}(G, N)\]

(tests whether \(N\) is invariant under all automorphisms of \(G\).

Example

\[
\text{gap> } \text{IsCharacteristicSubgroup}(g,u);
\]
false

39.3.8 ConjugateSubgroup

\[\text{ConjugateSubgroup}(G, g)\]

For a group \(G\) which has a parent group \(P\) (see \texttt{Parent}(31.7.1)), returns the subgroup of \(P\), obtained by conjugating \(G\) using the conjugating element \(g\).

If \(G\) has no parent group, it just delegates to the call to \texttt{ConjugateGroup}(39.2.6) with the same arguments.

To form a conjugate (subgroup) by any object acting via \(^\cdot\), one can also use the infix operator \(^\cdot\).

39.3.9 ConjugateSubgroups

\[\text{ConjugateSubgroups}(G, U)\]

returns a list of all images of the group \(U\) under conjugation action by \(G\).

39.3.10 IsSubnormal

\[\text{IsSubnormal}(G, U)\]

A subgroup \(U\) of the group \(G\) is subnormal if it is contained in a subnormal series of \(G\).

Example

\[
\text{gap> } \text{IsSubnormal}(g,\text{Group}([1,2,3]));
\]
false
\[
\text{gap> } \text{IsSubnormal}(g,\text{Group}([1,2,3]));
\]
true

39.3.11 SubgroupByProperty

\[\text{SubgroupByProperty}(G, prop)\]

creates a subgroup of \(G\) consisting of those elements fulfilling \(prop\) (which is a tester function).

No test is done whether the property actually defines a subgroup.

Note that currently very little functionality beyond an element test exists for groups created this way.
### 39.3.12 SubgroupShell

SubgroupShell(G) (function)

creates a subgroup of G which at this point is not yet specified further (but will be later, for example by assigning a generating set).

Example

```gap
gap> u:=SubgroupByProperty(g,i->3^i=3);
<subgrp of Group([ (1,2,3,4), (1,2) ]) by property>
gap> (1,3) in u; (1,4) in u; (1,5) in u;
false
true
false
gap> GeneratorsOfGroup(u);
[ (1,2), (1,4,2) ]
gap> u:=SubgroupShell(g);
<group>
```

### 39.4 Closures of (Sub)groups

#### 39.4.1 ClosureGroup

ClosureGroup(G, obj) (operation)

creates the group generated by the elements of G and obj. obj can be either an element or a collection of elements, in particular another group.

Example

```gap
g:=SmallGroup(24,12);; u:=Subgroup(g,[g.3,g.4]);
Group([ f3, f4 ])
gap> ClosureGroup(u,g.2);
Group([ f2, f3, f4 ])
gap> ClosureGroup(u,[g.1,g.2]);
Group([ f1, f2, f3, f4 ])
gap> ClosureGroup(u,Group(g.2*g.1));
Group([ f1*f2^2, f3, f4 ])
```

#### 39.4.2 ClosureGroupAddElm

ClosureGroupAddElm(G, elm) (function)

ClosureGroupCompare(G, elm) (function)

ClosureGroupIntest(G, elm) (function)

These three functions together with ClosureGroupDefault (39.4.3) implement the main methods for ClosureGroup (39.4.1). In the ordering given, they just add elm to the generators, remove duplicates and identity elements, and test whether elm is already contained in G.

#### 39.4.3 ClosureGroupDefault

ClosureGroupDefault(G, elm) (function)
This function returns the closure of the group $G$ with the element $elm$. If $G$ has the attribute \texttt{AsSSortedList (30.3.10)} then also the result has this attribute. This is used to implement the default method for \texttt{Enumerator (30.3.2)} and \texttt{EnumeratorSorted (30.3.3)}.

### 39.4.4 ClosureSubgroup

- \texttt{ClosureSubgroup($G$, obj)}
- \texttt{ClosureSubgroupNC($G$, obj)}

For a group $G$ that stores a parent group (see 31.7), \texttt{ClosureSubgroup} calls \texttt{ClosureGroup (39.4.1)} with the same arguments; if the result is a subgroup of the parent of $G$ then the parent of $G$ is set as parent of the result, otherwise an error is raised. The check whether the result is contained in the parent of $G$ is omitted by the \texttt{NC} version. As a wrong parent might imply wrong properties this version should be used with care.

### 39.5 Expressing Group Elements as Words in Generators

Using homomorphisms (see chapter 40) it is possible to express group elements as words in given generators: Create a free group (see \texttt{FreeGroup (37.2.1)}) on the correct number of generators and create a homomorphism from this free group onto the group $G$ in whose generators you want to factorize. Then the preimage of an element of $G$ is a word in the free generators, that will map on this element again.

### 39.5.1 EpimorphismFromFreeGroup

- \texttt{EpimorphismFromFreeGroup($G$)}

For a group $G$ with a known generating set, this attribute returns a homomorphism from a free group that maps the free generators to the groups generators.

The option \texttt{names} can be used to prescribe a (print) name for the free generators.

The following example shows how to decompose elements of $S_4$ in the generators $(1,2,3,4)$ and $(1,2)$:

```
Example

```

```gap
gap> g:=Group((1,2,3,4),(1,2));
Group([ (1,2,3,4), (1,2) ])
gap> hom:=EpimorphismFromFreeGroup(g:names:=["x","y"]);;
[ x, y ] -> [ (1,2,3,4), (1,2) ]
gap> PreImagesRepresentative(hom,(1,4));
y^-1*x^-1*(x^-1*y^-1)^2*x
```

The following example stems from a real request to the GAP Forum. In September 2000 a GAP user working with puzzles wanted to express the permutation $(1,2)$ as a word as short as possible in particular generators of the symmetric group $S_{16}$.

```
Example

```

```gap
gap> perms := [ (1,2,3,7,11,10,9,5), (2,3,4,8,12,11,10,6),
               (5,6,7,11,15,14,13,9), (6,7,8,12,16,15,14,10) ];;
> puzzle := Group( perms );;Size( puzzle );
20922789888000
```
gap> hom:=EpimorphismFromFreeGroup(puzzle:names:=\["a", "b", "c", "d"]);
gap> word := PreImagesRepresentative( hom, (1,2) );
a^-1*c*b*c^-1*a*b^-1*a^-2*c^-1*a*b^-1*c*b
gap> Length( word );
13

39.5.2 Factorization

\texttt{Factorization}(G, elm) (operation)

returns a factorization of \(elm\) as word in the generators of the group \(G\) given in the attribute \texttt{GeneratorsOfGroup} (39.2.4). The attribute \texttt{EpimorphismFromFreeGroup} (39.5.1) of \(G\) will contain a map from the group \(G\) to the free group in which the word is expressed. The attribute \texttt{MappingGeneratorsImages} (40.10.2) of this map gives a list of generators and corresponding letters.

The algorithm used forms all elements of the group to ensure a short word is found. Therefore this function should \textit{not} be used when the group \(G\) has more than a few million elements. Because of this, one should not call this function within algorithms, but use homomorphisms instead.

Example

```gap
gap> G:=SymmetricGroup( 6 );;
gap> r:=(3,4);; s:=(1,2,3,4,5,6);;
gap> # create subgroup to force the system to use the generators r and s:
gap> H:= Subgroup(G, \[ r, s \] );;
Group(\[ (3,4), (1,2,3,4,5,6) \])
gap> Factorization( H, (1,2,3) );
(x2*x1)^2*x2^-2
gap> s*r*s*r*s^-2;
(1,2,3)
 gap> MappingGeneratorsImages(EpimorphismFromFreeGroup(H));
[[ x1, x2 ], [ (3,4), (1,2,3,4,5,6) ]]
```

39.5.3 GrowthFunctionOfGroup

\texttt{GrowthFunctionOfGroup}(G) (attribute)

\texttt{GrowthFunctionOfGroup}(G, radius) (operation)

For a group \(G\) with a generating set given in \texttt{GeneratorsOfGroup} (39.2.4), this function calculates the number of elements whose shortest expression as words in the generating set is of a particular length. It returns a list \(L\), whose \(i+1\) entry counts the number of elements whose shortest word expression has length \(i\). If a maximal length \(radius\) is given, only words up to length \(radius\) are counted. Otherwise the group must be finite and all elements are enumerated.

Example

```gap
gap> GrowthFunctionOfGroup(MathieuGroup(12));
[ 1, 5, 19, 70, 255, 903, 3134, 9870, 25511, 38532, 16358, 382 ]
gap> GrowthFunctionOfGroup(MathieuGroup(12),2);
[ 1, 5, 19 ]

gap> GrowthFunctionOfGroup(MathieuGroup(12),99);
[ 1, 5, 19, 70, 255, 903, 3134, 9870, 25511, 38532, 16358, 382 ]

gap> free:=FreeGroup("a","b");
<free group on the generators [ a, b ]>
```
39.6 Structure Descriptions

39.6.1 StructureDescription

\[ \text{StructureDescription}(G) \]

The method for StructureDescription exhibits a structure of the given group \( G \) to some extent, using the strategy outlined below. The idea is to return a possibly short string which gives some insight in the structure of the considered group. It is intended primarily for small groups (order less than 100) or groups with few normal subgroups, in other cases, in particular large \( p \)-groups, it can be very costly. Furthermore, the string returned is – as the action on chief factors is not described – often not the most useful way to describe a group.

The string returned by StructureDescription is NOT an isomorphism invariant: non-isomorphic groups can have the same string value, and two isomorphic groups in different representations can produce different strings. The value returned by StructureDescription is a string of the following form:

\[
\text{StructureDescription}(<G>) ::= \\
\begin{align*}
1 &; \text{trivial group} \\
C<\text{size}> &; \text{finite cyclic group} \\
Z &; \text{infinite cyclic group} \\
A<\text{degree}> &; \text{alternating group} \\
S<\text{degree}> &; \text{symmetric group} \\
D<\text{size}> &; \text{dihedral group} \\
Q<\text{size}> &; \text{quaternion group} \\
QD<\text{size}> &; \text{quasidihedral group} \\
\text{PSL}(\langle n \rangle, \langle q \rangle) &; \text{projective special linear group} \\
\text{SL}(\langle n \rangle, \langle q \rangle) &; \text{special linear group} \\
\text{GL}(\langle n \rangle, \langle q \rangle) &; \text{general linear group} \\
\text{PSU}(\langle n \rangle, \langle q \rangle) &; \text{proj. special unitary group} \\
O(2n+1, \langle q \rangle) &; \text{orthogonal group, type } B \\
O+(2n, \langle q \rangle) &; \text{orthogonal group, type } D \\
O-(2n, \langle q \rangle) &; \text{orthogonal group, type } 2D \\
\text{PSp}(2n, \langle q \rangle) &; \text{proj. special symplectic group} \\
\text{Sz}(\langle q \rangle) &; \text{Suzuki group} \\
\text{Ree}(\langle q \rangle) &; \text{Ree group (type } 2F \text{ or } 2G) \\
\text{E}(6, \langle q \rangle) &; \text{Lie group of exceptional type} \\
\text{E}(7, \langle q \rangle) \text{ or } \text{E}(8, \langle q \rangle) &; \text{Lie group of exceptional type} \\
\text{2E}(6, \langle q \rangle) \text{ or } \text{F}(4, \langle q \rangle) \text{ or } \text{G}(2, \langle q \rangle) &; \text{Lie group of exceptional type} \\
\text{3D}(4, \langle q \rangle) &; \text{Steinberg triality group} \\
\text{M}_{11} \text{ or } \text{M}_{12} \text{ or } \text{M}_{22} \text{ or } \text{M}_{23} \text{ or } \text{M}_{24} &; \text{sporadic simple group} \\
\text{J}_1 \text{ or } \text{J}_2 \text{ or } \text{J}_3 \text{ or } \text{J}_4 \text{ or } \text{Co}_1 \text{ or } \text{Co}_2 &; \text{sporadic simple group} \\
\text{Co}_3 \text{ or } \text{Fi}_{22} \text{ or } \text{Fi}_{23} \text{ or } \text{Fi}_{24'} \text{ or } \text{Suz} &; \text{sporadic simple group} \\
\text{HS} \text{ or } \text{McL} \text{ or } \text{He} \text{ or } \text{HN} \text{ or } \text{Th} \text{ or } \text{B} &; \text{sporadic simple group} \\
M &; \text{sporadic simple group} \\
\text{ON} &; \text{sporadic simple group} \\
\text{Ly} &; \text{sporadic simple group} \\
\text{Ru} &; \text{sporadic simple group}
\end{align*}
\]
The strategy used to compute a StructureDescription is as follows:

1. Lookup in a precomputed list, if the order of $G$ is not larger than 100 and not equal to 64 or 96.
2. If $G$ is abelian, then decompose it into cyclic factors in "elementary divisors style". For example, "C2 x C3 x C3" is "C6 x C3". For infinite abelian groups, "Z" denotes the group of integers.
3. Recognize alternating groups, symmetric groups, dihedral groups, quasidihedral groups, quaternion groups, PSL’s, SL’s, GL’s and simple groups not listed so far as basic building blocks.
4. Decompose $G$ into a direct product of irreducible factors.
5. Recognize semidirect products $G=H$, where $N$ is normal. Select a pair $N, H$ with the following preferences:
   1. if $G$ is defined as a semidirect product of $N, H$ then select $N, H$.
   2. if $G$ is solvable, then select a solvable normal Hall subgroup $N$, if exists, and consider the semidirect decomposition of $N$ and $G/N$.
   3. find any nontrivial normal subgroup $N$ which has a complement $H$.

The option "nice" is recognized. If this option is set, then all semidirect products are computed in order to find a possibly nicer presentation. Note, that this may take a very long time if $G$ has many normal subgroups, e.g. if $G/G'$ has many cyclic factors. If the option "nice" is set, then GAP would select a pair $N, H$ with the following preferences:

1. $H$ is abelian
2. $N$ is abelian
2a. $N$ has many abelian invariants
3. $N$ is a direct product
3a. \( N \) has many direct factors.

4. \( \phi : H \to \text{Aut}(N), h \mapsto (n \mapsto n^h) \) is injective.

6. Fall back to non-splitting extensions: If the centre or the commutator factor group is non-trivial, write \( G \) as \( Z(G)G/Z(G) \) or \( G'/G' \), respectively. Otherwise if the Frattini subgroup is non-trivial, write \( G \) as \( \Phi(G)G/\Phi(G) \).

7. If no decomposition is found (maybe this is not the case for any finite group), try to identify \( G \) in the perfect groups library. If this fails also, then return a string describing this situation.

Note that \texttt{StructureDescription} is \textit{not} intended to be a research tool, but rather an educational tool. The reasons for this are as follows:

1. “Most” groups do not have “nice” decompositions. This is in some contrast to what is often taught in elementary courses on group theory, where it is sometimes suggested that basically every group can be written as iterated direct or semidirect product of cyclic groups and non-abelian simple groups.

2. In particular many \( p \)-groups have very “similar” structure, and \texttt{StructureDescription} can only exhibit a little of it. Changing this would likely make the output not essentially easier to read than a pc presentation.

**Example**

```gap
gap> l := AllSmallGroups(12);;
gap> List(l,StructureDescription);; l;
[ C3 : C4, C12, A4, D12, C6 x C2 ]
gap> List(AllSmallGroups(40),G->StructureDescription(G:short));
[ "5:8", "40", "5:8", "5:Q8", "4xD10", "D40", "2x(5:4)", "(10x2):2", "20x2", "5x8", "2x(5:4)", "2^2xD10", "10x2^2" ]
gap> List(AllTransitiveGroups(DegreeAction,6),
> G->StructureDescription(G:short));
[ "6", "S3", "D12", "A4", "3xS3", "2xA4", "S4", "S4", "S3xS3", 
gap> StructureDescription(SmallGroup(504,7));
"C7 : (C9 x Q8)"
gap> StructureDescription(SmallGroup(504,7):nice);
"(C7 : Q8) : C9"
gap> StructureDescription(AbelianGroup([0,2,3]));
"Z x C6"
gap> StructureDescription(AbelianGroup([0,0,2,3,6]):short);
"Z x 6^2"
gap> StructureDescription(PSL(4,2));
"A8"
```

### 39.7 Cosets

#### 39.7.1 RightCoset

`RightCoset(U, g)` (operation)
returns the right coset of \( U \) with representative \( g \), which is the set of all elements of the form \( u g \) for all \( u \in U \). \( g \) must be an element of a larger group \( \mathcal{G} \) which contains \( U \). For element operations such as in a right coset behaves like a set of group elements.

Right cosets are external orbits for the action of \( U \) which acts via \texttt{OnLeftInverse} (41.2.3). Of course the action of a larger group \( \mathcal{G} \) on right cosets is via \texttt{OnRight} (41.2.2).

```gap
Example

\begin{verbatim}
gap> u:=Group((1,2,3), (1,2));;
gap> c:=RightCoset(u,(2,3,4));
RightCoset(Group( 
[ (1,2,3), (1,2) ] ),(2,3,4))
gap> ActingDomain(c);
Group([ (1,2,3), (1,2) ])
gap> Representative(c);
(2,3,4)
gap> Size(c);
6
\end{verbatim}
```

### 39.7.2 RightCosets

\texttt{RightCosets(\mathcal{G}, U)} \hspace{1cm} \texttt{RightCosetsNC(\mathcal{G}, U)}

computes a duplicate free list of right cosets \( U g \) for \( g \in \mathcal{G} \). A set of representatives for the elements in this list forms a right transversal of \( U \) in \( \mathcal{G} \). (By inverting the representatives one obtains a list of representatives of the left cosets of \( U \).) The \texttt{NC} version does not check whether \( U \) is a subgroup of \( \mathcal{G} \).

```
Example

\begin{verbatim}
gap> RightCosets(g,u);
[ RightCoset(Group( 
[ (1,2,3), (1,2) ] ),()),
RightCoset(Group( 
[ (1,2,3), (1,2) ] ),(1,3)(2,4)),
RightCoset(Group( 
[ (1,2,3), (1,2) ] ),(1,3)(2,3)),
RightCoset(Group( 
[ (1,2,3), (1,2) ] ),(1,2)(3,4)) ]
\end{verbatim}
```

### 39.7.3 CanonicalRightCosetElement

\texttt{CanonicalRightCosetElement(\mathcal{U}, g)}

returns a “canonical” representative of the right coset \( \mathcal{U} g \) which is independent of the given representative \( g \). This can be used to compare cosets by comparing their canonical representatives.

The representative chosen to be the “canonical” one is representation dependent and only guaranteed to remain the same within one \texttt{GAP} session.

```
Example

\begin{verbatim}
gap> CanonicalRightCosetElement(u,(2,4,3));
(3,4)
\end{verbatim}
```
39.7.4 IsRightCoset

\[ \text{IsRightCoset}(\text{obj}) \]

(Category)

The category of right cosets. GAP does not provide left cosets as a separate data type, but as the left coset \( gU \) consists of exactly the inverses of the elements of the right coset \( Ug^{-1} \) calculations with left cosets can be emulated using right cosets by inverting the representatives.

39.7.5 IsBiCoset

\[ \text{IsBiCoset}(\text{C}) \]

(property)

A (right) coset \( Ug \) is considered a bicoset if its set of elements simultaneously forms a left coset for the same subgroup. This is the case if and only if the coset representative \( g \) normalizes the subgroup \( U \).

39.7.6 CosetDecomposition

\[ \text{CosetDecomposition}(\text{G}, \text{S}) \]

(function)

For a finite group \( G \) and a subgroup \( S \leq G \) this function returns a partition of the elements of \( G \) according to the (right) cosets of \( S \). The result is a list of lists, each sublist corresponding to one coset. The first sublist is the elements list of the subgroup, the other lists are arranged accordingly.

```
gap> CosetDecomposition(SymmetricGroup(4),SymmetricGroup(3));
[ [ (), (2,3), (1,2), (1,2,3), (1,3,2), (1,3) ],
  [ (1,4), (1,4)(2,3), (1,2,4), (1,2,3,4), (1,3,2,4), (1,3,4) ],
  [ (1,4,2), (1,4,2,3), (2,4), (2,3,4), (1,3) (2,4), (1,3,4,2) ],
  [ (1,4,3), (1,4,3,2), (1,2,4,3), (1,2)(3,4), (2,4,3), (3,4) ] ]
```

39.8 Transversals

39.8.1 RightTransversal

\[ \text{RightTransversal}(\text{G}, \text{U}) \]

(operation)

A right transversal \( t \) is a list of representatives for the set \( U \setminus G \) of right cosets (consisting of cosets \( Ug \)) of \( U \) in \( G \).

The object returned by RightTransversal is not a plain list, but an object that behaves like an immutable list of length \( |G : U| \), except if \( U \) is the trivial subgroup of \( G \) in which case RightTransversal may return the sorted plain list of coset representatives.

The operation PositionCanonical (21.16.3), called for a transversal \( t \) and an element \( g \) of \( G \), will return the position of the representative in \( t \) that lies in the same coset of \( U \) as the element \( g \) does. (In comparison, Position (21.16.1) will return fail if the element is not equal to the representative.) Functions that implement group actions such as Action (41.7.2) or Permutation (41.9.1) (see Chapter 41) use PositionCanonical (21.16.3), therefore it is possible to “act” on a right transversal to implement the action on the cosets. This is often much more efficient than acting on cosets.
Example

```gap
gap> g:=Group((1,2,3,4),(1,2));;
gap> u:=Subgroup(g,[[1,2,3),(1,2)]);;
gap> rt:=RightTransversal(g,u);
RightTransversal(Group([ (1,2,3,4), (1,2) ]),Group([ (1,2,3), (1,2) ]))
gap> Length(rt);
4
gap> Position(rt,(1,2,3));
fail
```

Note that the elements of a right transversal are not necessarily “canonical” in the sense of `CanonicalRightCosetElement (39.7.3)`, but we may compute a list of canonical coset representatives by calling that function. (See also `PositionCanonical (21.16.3)`.)

Example

```gap
gap> List(RightTransversal(g,u),i->CanonicalRightCosetElement(u,i));
[ (), (2,3,4), (1,2,3,4), (3,4) ]
gap> PositionCanonical(rt,(1,2,3));
1
gap> rt[1];
()  
```

39.9 Double Cosets

39.9.1 DoubleCoset

▷ `DoubleCoset(U,g,V)`

The groups $U$ and $V$ must be subgroups of a common supergroup $G$ of which $g$ is an element. This command constructs the double coset $UgV$ which is the set of all elements of the form $ugv$ for any $u \in U$, $v \in V$. For element operations such as in, a double coset behaves like a set of group elements. The double coset stores $U$ in the attribute `LeftActingGroup`, $g$ as `Representative (30.4.7)`, and $V$ as `RightActingGroup`.

39.9.2 RepresentativesContainedRightCosets

▷ `RepresentativesContainedRightCosets(D)`

A double coset $D = UgV$ can be considered as a union of right cosets $Uh_i$. (It is the union of the orbit of $Ug$ under right multiplication by $V$.) For a double coset $D$ this function returns a set of representatives $h_i$ such that $D = \bigcup_h Uh_i$. The representatives returned are canonical for $U$ (see `CanonicalRightCosetElement (39.7.3)`) and form a set.

Example

```gap
gap> u:=Subgroup(g,[[1,2,3),(1,2)]);;v:=Subgroup(g,[[3,4]]);;
gap> c:=DoubleCoset(u,(2,4),v);
DoubleCoset(Group( [ (1,2,3), (1,2) ] ),(2,4),Group( [ (3,4) ] ))
gap> (1,2,3) in c;
false
gap> (2,3,4) in c;
true
```
gap> LeftActingGroup(c);
Group([ (1,2,3), (1,2) ])
gap> RightActingGroup(c);
Group([ (3,4) ])
gap> RepresentativesContainedRightCosets(c);
[ (2,3,4) ]

39.9.3 DoubleCosets

▷ DoubleCosets(G, U, V)  (function)
▷ DoubleCosetsNC(G, U, V)  (operation)

computes a duplicate free list of all double cosets \( UgV \) for \( g \in G \). The groups \( U \) and \( V \) must be subgroups of the group \( G \). The NC version does not check whether \( U \) and \( V \) are subgroups of \( G \).

gap> dc:=DoubleCosets(g,u,v);
[ DoubleCoset(Group( [ (1,2,3), (1,2) ] ),(),Group( [ (3,4) ] )),
  DoubleCoset(Group( [ (1,2,3), (1,2) ] ),(1,3)(2,4),Group( [ (3,4) ] )),
  DoubleCoset(Group( [ (1,2,3), (1,2) ] ),(1,4)(2,3),Group( [ (3,4) ] )) ]
gap> List(dc,Representative);
[ (), (1,3)(2,4), (1,4)(2,3) ]

39.9.4 IsDoubleCoset (operation)

▷ IsDoubleCoset(obj)  (Category)

The category of double cosets.

39.9.5 DoubleCosetRepsAndSizes

▷ DoubleCosetRepsAndSizes(G, U, V)  (operation)

returns a list of double coset representatives and their sizes, the entries are lists of the form \([r,n]\) where \( r \) and \( n \) are an element of the double coset and the size of the coset, respectively. This operation is faster than DoubleCosetsNC (39.9.3) because no double coset objects have to be created.

gap> dc:=DoubleCosetRepsAndSizes(g,u,v);
[ [ () , 12 ] , [ (1,3)(2,4) , 6 ] , [ (1,4)(2,3) , 6 ] ]

39.9.6 InfoCoset

▷ InfoCoset  (info class)

The information function for coset and double coset operations is InfoCoset.
39.10 Conjugacy Classes

39.10.1 ConjugacyClass

\[ \text{ConjugacyClass}(G, g) \]

(operation)

creates the conjugacy class in \( G \) with representative \( g \). This class is an external set, so functions such as \text{Representative} (30.4.7) (which returns \( g \)), \text{ActingDomain} (41.12.3) (which returns \( G \)), \text{StabilizerOfExternalSet} (41.12.10) (which returns the centralizer of \( g \)) and \text{AsList} (30.3.8) work for it.

A conjugacy class is an external orbit (see \text{ExternalOrbit} (41.12.9)) of group elements with the group acting by conjugation on it. Thus element tests or operation representatives can be computed.

The attribute \text{Centralizer} (35.4.4) gives the centralizer of the representative (which is the same result as \text{StabilizerOfExternalSet} (41.12.10)). (This is a slight abuse of notation: This is not the centralizer of the class as a set which would be the standard behaviour of \text{Centralizer} (35.4.4).)

39.10.2 ConjugacyClasses (attribute)

\[ \text{ConjugacyClasses}(G) \]

(attribute)

returns the conjugacy classes of elements of \( G \) as a list of class objects of \( G \) (see \text{ConjugacyClass} (39.10.1) for details). It is guaranteed that the class of the identity is in the first position, the further arrangement depends on the method chosen (and might be different for equal but not identical groups).

For very small groups (of size up to 500) the classes will be computed by the conjugation action of \( G \) on itself (see \text{ConjugacyClassesByOrbits} (39.10.4)). This can be deliberately switched off using the “noaction” option shown below.

For solvable groups, the default method to compute the classes is by homomorphic lift (see section 45.17).

For other groups the method of [Hul00] is employed.

ConjugacyClasses supports the following options that can be used to modify this strategy:

- **random**
  The classes are computed by random search. See \text{ConjugacyClassesByRandomSearch} (39.10.3) below.

- **action**
  The classes are computed by action of \( G \) on itself. See \text{ConjugacyClassesByOrbits} (39.10.4) below.

- **noaction**
  Even for small groups \text{ConjugacyClassesByOrbits} (39.10.4) is not used as a default. This can be useful if the elements of the group use a lot of memory.

---

\[ \text{gap} \]

\text{g:=SymmetricGroup(4);} ;
\text{cl:=ConjugacyClasses(g);} ;
[ [ ()^G, (1,2)^G, (1,2)(3,4)^G, (1,2,3)^G, (1,2,3,4)^G ] ]
\text{Representative(cl[3]);Centralizer(cl[3]);}
(1,2)(3,4)
\text{Group([ (1,2), (1,3)(2,4), (3,4) ])}

---
In general, you will not need to have to influence the method, but simply call ConjugacyClasses -- GAP will try to select a suitable method on its own. The method specifications are provided here mainly for expert use.

### 39.10.3 ConjugacyClassesByRandomSearch

\[ \text{ConjugacyClassesByRandomSearch(} G \text{)} \]

computes the classes of the group \( G \) by random search. This works very efficiently for almost simple groups.

This function is also accessible via the option random to the function ConjugacyClass (39.10.1).

### 39.10.4 ConjugacyClassesByOrbits

\[ \text{ConjugacyClassesByOrbits(} G \text{)} \]

computes the classes of the group \( G \) as orbits of \( G \) on its elements. This can be quick but unsurprisingly may also take a lot of memory if \( G \) becomes larger. All the classes will store their element list and thus a membership test will be quick as well.

This function is also accessible via the option action to the function ConjugacyClass (39.10.1).

Typically, for small groups (roughly of order up to \( 10^3 \)) the computation of classes as orbits under the action is fastest; memory restrictions (and the increasing cost of eliminating duplicates) make this less efficient for larger groups.

Calculation by random search has the smallest memory requirement, but in generally performs worse, the more classes are there.

The following example shows the effect of this for a small group with many classes:

```
Example

\begin{verbatim}
gap> h := Group((4,5)(6,7,8),(1,2,3)(5,6,9));;
ConjugacyClasses(h:noaction);;time;
110
\end{verbatim}
\begin{verbatim}
gap> h := Group((4,5)(6,7,8),(1,2,3)(5,6,9));;
ConjugacyClasses(h:random);;time;
300
\end{verbatim}
\begin{verbatim}
gap> h := Group((4,5)(6,7,8),(1,2,3)(5,6,9));;
ConjugacyClasses(h:action);;time;
30
\end{verbatim}
```

### 39.10.5 NrConjugacyClasses

\[ \text{NrConjugacyClasses(} G \text{)} \]

returns the number of conjugacy classes of \( G \).

```
Example

\begin{verbatim}
gap> g := Group((1,2,3,4),(1,2));;
NrConjugacyClasses(g);
5
\end{verbatim}
```
39.10.6 RationalClass

\[ \text{RationalClass}(G, g) \] (operation)

creates the rational class in \( G \) with representative \( g \). A rational class consists of all elements that are conjugate to \( g \) or to an \( i \)-th power of \( g \) where \( i \) is coprime to the order of \( g \). Thus a rational class can be interpreted as a conjugacy class of cyclic subgroups. A rational class is an external set (IsExternalSet (41.12.1)) of group elements with the group acting by conjugation on it, but not an external orbit.

39.10.7 RationalClasses

\[ \text{RationalClasses}(G) \] (attribute)

returns a list of the rational classes of the group \( G \). (See RationalClass (39.10.6).)

Example

\[ \text{gap> RationalClasses(DerivedSubgroup(g));} \]
\[ [ \text{RationalClass( AlternatingGroup([1 .. 4]), () )}, \] \[ \text{RationalClass( AlternatingGroup([1 .. 4]), (1,2)(3,4) )}, \] \[ \text{RationalClass( AlternatingGroup([1 .. 4]), (1,2,3) )} ] \]

39.10.8 GaloisGroup (of rational class of a group)

\[ \text{GaloisGroup}(ractcl) \] (attribute)

Suppose that \( \text{ractcl} \) is a rational class of a group \( G \) with representative \( g \). The exponents \( i \) for which \( g^i \) lies already in the ordinary conjugacy class of \( g \), form a subgroup of the prime residue class group \( P_n \) (see PrimitiveRootMod (15.3.3)), the so-called Galois group of the rational class. The prime residue class group \( P_n \) is obtained in GAP as \( \text{Units} \left( \text{Integers mod } n \right) \), the unit group of a residue class ring. The Galois group of a rational class \( \text{ractcl} \) is stored in the attribute GaloisGroup as a subgroup of this group.

39.10.9 IsConjugate

\[ \text{IsConjugate}(G, x, y) \] (operation)
\[ \text{IsConjugate}(G, U, V) \] (operation)

tests whether the elements \( x \) and \( y \) or the subgroups \( U \) and \( V \) are conjugate under the action of \( G \). (They do not need to be contained in \( G \).) This command is only a shortcut to \( \text{RepresentativeAction} \) (41.6.1).

Example

\[ \text{gap> IsConjugate(g,Group((1,2,3,4),(1,3)),Group((1,3,2,4),(1,2)));} \]
\[ \text{true} \]

\( \text{RepresentativeAction} \) (41.6.1) can be used to obtain conjugating elements.

Example

\[ \text{gap> RepresentativeAction(g,(1,2),(3,4));} \]
\[ (1,3)(2,4) \]
39.10.10  NthRootsInGroup

Let \( e \) be an element in the group \( G \). This function returns a list of all those elements in \( G \) whose \( n \)-th power is \( e \).

```
gap> NthRootsInGroup(g,(1,2)(3,4),2);
[ (1,3,2,4), (1,4,2,3) ]
```

39.11  Normal Structure

For the operations Centralizer (35.4.4) and Centre (35.4.5), see Chapter 35.

39.11.1  Normalizer

\( \triangleright \) Normalizer\( (G, U) \) (operation)
\( \triangleright \) Normalizer\( (G, g) \) (operation)

For two groups \( G, U \), Normalizer computes the normalizer \( N_G(U) \), that is, the stabilizer of \( U \) under the conjugation action of \( G \).

For a group \( G \) and a group element \( g \), Normalizer computes \( N_G(\langle g \rangle) \).

```
gap> Normalizer(g,Subgroup(g,[[1,2,3]]));
Group([ (1,2,3), (2,3) ])
```

39.11.2  Core

\( \triangleright \) Core\( (S, U) \) (operation)

If \( S \) and \( U \) are groups of elements in the same family, this operation returns the core of \( U \) in \( S \), that is the intersection of all \( S \)-conjugates of \( U \).

```
gap> g:=Group((1,2,3,4),(1,2));;
gap> Core(g,Subgroup(g,[[1,2,3,4]]));
Group(())
```

39.11.3  PCore

\( \triangleright \) PCore\( (G, p) \) (operation)

The p-core of \( G \) is the largest normal p-subgroup of \( G \). It is the core of a Sylow p-subgroup of \( G \), see Core (39.11.2).

```
gap> g:=DicyclicGroup(12);;
gap> PCore(g,2);
Group([ y3 ])
```
39.11.4 NormalClosure

\[ \text{{NormalClosure}}(G, U) \]

The normal closure of \( U \) in \( G \) is the smallest normal subgroup of the closure of \( G \) and \( U \) which contains \( U \).

Example

\[
gap> \text{NormalClosure}(g, \text{Subgroup}(g, [(1,2,3)])) = \text{Group}([ (1,2,3), (2,3,4) ]);\]
true
\[
gap> \text{NormalClosure}(g, \text{Group}((3,4,5))) = \text{Group}([ (3,4,5), (1,5,4), (1,2,5) ]);\]
true

39.11.5 NormalIntersection

\[ \text{{NormalIntersection}}(G, U) \]

computes the intersection of \( G \) and \( U \), assuming that \( G \) is normalized by \( U \). This works faster than \text{Intersection}, but will not produce the intersection if \( G \) is not normalized by \( U \).

Example

\[
gap> \text{NormalIntersection}(\text{Group}((1,2)(3,4),(1,3)(2,4)), \text{Group}((1,2,3,4)));\]
\text{Group}([ (1,3)(2,4) ])

39.11.6 ComplementClassesRepresentatives

\[ \text{{ComplementClassesRepresentatives}}(G, N) \]

Let \( N \) be a normal subgroup of \( G \). This command returns a set of representatives for the conjugacy classes of complements of \( N \) in \( G \). Complements are subgroups of \( G \) which intersect trivially with \( N \) and together with \( N \) generate \( G \).

At the moment only methods for a solvable \( N \) are available.

Example

\[
gap> \text{ComplementClassesRepresentatives}(g, \text{Group}((1,2)(3,4),(1,3)(2,4)));\]
[ Group([ (3,4), (2,4,3) ])]
39.11.7 InfoComplement

Info class for the complement routines.

39.12 Specific and Parametrized Subgroups

The centre of a group (the subgroup of those elements that commute with all other elements of the group) can be computed by the operation Centre (35.4.5).

39.12.1 TrivialSubgroup

Example

gap> TrivialSubgroup(g);
Group(())

39.12.2 CommutatorSubgroup

Example

gap> CommutatorSubgroup(Group((1,2,3),(1,2)),Group((2,3,4),(3,4)));
Group([ (1,4)(2,3), (1,3,4) ])
gap> Size(last);
12

39.12.3 DerivedSubgroup

Example

gap> g:=Group((1,2,3,4),(1,2));;
gap> DerivedSubgroup(g) = Group([ (1,3,2), (2,4,3) ]);
true

39.12.4 CommutatorLength

Example

gap> CommutatorLength(g) = Group([ (1,3,2), (2,4,3) ]);
returns the minimal number \( n \) such that each element in the derived subgroup (see \texttt{DerivedSubgroup} (39.12.3)) of the group \( G \) can be written as a product of (at most) \( n \) commutators of elements in \( G \).

```
\texttt{gap> CommutatorLength( g );}
1
```

### 39.12.5 FittingSubgroup

\[\mathbb{FittingSubgroup}(G)\]

The Fitting subgroup of a group \( G \) is its largest nilpotent normal subgroup.

```
\texttt{gap> FittingSubgroup(g);
Group([ (1,2)(3,4), (1,4)(2,3) ])}
```

### 39.12.6 FrattiniSubgroup

\[\mathbb{FrattiniSubgroup}(G)\]

The Frattini subgroup of a group \( G \) is the intersection of all maximal subgroups of \( G \).

```
\texttt{gap> FrattiniSubgroup(g);
Group(())}
```

### 39.12.7 PrefrattiniSubgroup

\[\mathbb{PrefrattiniSubgroup}(G)\]

returns a Prefrattini subgroup of the finite solvable group \( G \).

A factor \( M/N \) of \( G \) is called a Frattini factor if \( M/N \) is contained in the Frattini subgroup of \( G/N \). A subgroup \( P \) is a Prefrattini subgroup of \( G \) if \( P \) covers each Frattini chief factor of \( G \), and if for each maximal subgroup of \( G \) there exists a conjugate maximal subgroup, which contains \( P \). In a finite solvable group \( G \) the Prefrattini subgroups form a characteristic conjugacy class of subgroups and the intersection of all these subgroups is the Frattini subgroup of \( G \).

```
\texttt{gap> G := SmallGroup( 60, 7 );}
\texttt{<pc group of size 60 with 4 generators>}
\texttt{gap> P := PrefrattiniSubgroup(G);
Group([ f2 ])}
\texttt{gap> Size(P);
2}
\texttt{gap> IsNilpotent(P);
true}
\texttt{gap> Core(G,P);
Group([ 1 ])}
\texttt{gap> FrattiniSubgroup(G);
Group([ 1 ])}
```
39.12.8 PerfectResiduum

▷ PerfectResiduum(G)

is the smallest normal subgroup of $G$ that has a solvable factor group.

```
gap> PerfectResiduum(Group([ (1,2,3,4,5), (1,2) ]));
Group([ (1,3,2), (1,4,3), (2,5,4) ])
```

39.12.9 RadicalGroup

▷ RadicalGroup(G)

is the radical of $G$, i.e., the largest solvable normal subgroup of $G$.

```
gap> RadicalGroup(SL(2,5));
<group of 2x2 matrices of size 2 over GF(5)>
gap> Size(last);
2
```

39.12.10 Socle

▷ Socle(G)

The socle of the group $G$ is the subgroup generated by all minimal normal subgroups.

```
gap> Socle(g);
Group([ (1,4)(2,3), (1,2)(3,4) ])
```

39.12.11 SupersolvableResiduum

▷ SupersolvableResiduum(G)

is the supersolvable residuum of the group $G$, that is, its smallest normal subgroup $N$ such that the factor group $G/N$ is supersolvable.

```
gap> SupersolvableResiduum(g) = Group([ (1,3)(2,4), (1,4)(2,3) ]);
true
```

39.12.12 PRump

▷ PRump(G, p)

For a prime $p$, the $p$-rump of a group $G$ is the subgroup $G'G^p$. Unless it equals $G$ itself (which is the e.g. the case if $G$ is perfect), it is equal to the second term of the $p$-central series of $G$, see PCentralSeries (39.17.13).
39.13 Sylow Subgroups and Hall Subgroups

With respect to the following GAP functions, please note that by theorems of P. Hall, a group $G$ is solvable if and only if one of the following conditions holds.

1. For each prime $p$ dividing the order of $G$, there exists a $p$-complement (see SylowComplement (39.13.2)).
2. For each set $P$ of primes dividing the order of $G$, there exists a $P$-Hall subgroup (see HallSubgroup (39.13.3)).
3. $G$ has a Sylow system (see SylowSystem (39.13.4)).
4. $G$ has a complement system (see ComplementSystem (39.13.5)).

39.13.1 SylowSubgroup

▷ SylowSubgroup($G$, $p$)  

returns a Sylow $p$-subgroup of the finite group $G$. This is a $p$-subgroup of $G$ whose index in $G$ is coprime to $p$. SylowSubgroup computes Sylow subgroups via the operation SylowSubgroupOp.

Example

```
gap> g:=SymmetricGroup(4);;
gap> SylowSubgroup(g,2);
Group([ (1,2), (3,4), (1,3)(2,4) ])
```

39.13.2 SylowComplement

▷ SylowComplement($G$, $p$)  

returns a Sylow $p$-complement of the finite group $G$. This is a subgroup $U$ of order coprime to $p$ such that the index $[G:U]$ is a $p$-power.

At the moment methods exist only if $G$ is solvable and GAP will issue an error if $G$ is not solvable.

Example

```
gap> SylowComplement(g,3);
Group([ (1,2), (3,4), (1,3)(2,4) ])
```
39.13.3 HallSubgroup

\begin{verbatim}
\textbf{HallSubgroup}(G, P)
\end{verbatim}

computes a \(P\)-Hall subgroup for a set \(P\) of primes. This is a subgroup the order of which is only divisible by primes in \(P\) and whose index is coprime to all primes in \(P\). Such a subgroup is unique up to conjugacy if \(G\) is solvable. The function computes Hall subgroups via the operation \texttt{HallSubgroupOp}.

If \(G\) is solvable this function always returns a subgroup. If \(G\) is not solvable this function might return a subgroup (if it is unique up to conjugacy), a list of subgroups (which are representatives of the conjugacy classes in case there are several such classes) or \texttt{fail} if no such subgroup exists.

\begin{verbatim}
gap> h:=SmallGroup(60,10);;
gap> u:=HallSubgroup(h,[2,3]);
Group([ f1, f2, f3 ])
gap> Size(u);
12

gap> h:=PSL(3,5);;
gap> HallSubgroup(h,[2,3]);
[ \text{permutation group of size 96 with 6 generators}, \text{permutation group of size 96 with 6 generators} ]
gap> u := HallSubgroup(h,[3,31]);;
gap> Size(u); StructureDescription(u);
93 "C31 : C3"
gap> HallSubgroup(h,[5,31]);
fail
\end{verbatim}

39.13.4 SylowSystem

\begin{verbatim}
\textbf{SylowSystem}(G)
\end{verbatim}

A Sylow system of a group \(G\) is a set of Sylow subgroups of \(G\) such that every pair of subgroups from this set commutes as subgroups. Sylow systems exist only for solvable groups. The operation returns \texttt{fail} if the group \(G\) is not solvable.

\begin{verbatim}
gap> h:=SmallGroup(60,10);;
gap> SylowSystem(h);
[ Group([ f1, f2 ]), Group([ f3 ]), Group([ f4 ]) ]
gap> List(last,Size);
[ 4, 3, 5 ]
\end{verbatim}

39.13.5 ComplementSystem

\begin{verbatim}
\textbf{ComplementSystem}(G)
\end{verbatim}

A complement system of a group \(G\) is a set of Hall \(p'\)-subgroups of \(G\), where \(p'\) runs through the subsets of prime factors of \(|G|\) that omit exactly one prime. Every pair of subgroups from this set commutes as subgroups. Complement systems exist only for solvable groups, therefore \texttt{ComplementSystem} returns \texttt{fail} if the group \(G\) is not solvable.
Example

```gap
gap> ComplementSystem(h);
[ Group([ f3, f4 ]), Group([ f1, f2, f4 ]), Group([ f1, f2, f3 ]) ]
gap> List(last,Size);
[ 15, 20, 12 ]
```

### 39.13.6 HallSystem

**HallSystem(G)**

( attribute )

returns a list containing one Hall $P$-subgroup for each set $P$ of prime divisors of the order of $G$. Hall systems exist only for solvable groups. The operation returns fail if the group $G$ is not solvable.

```gap
gap> HallSystem(h);
[ Group([ ]), Group([ f1, f2 ]), Group([ f1, f2, f3 ]),
  Group([ f1, f2, f3, f4 ]), Group([ f1, f2, f4 ]), Group([ f3 ]),
  Group([ f3, f4 ]), Group([ f4 ]) ]
gap> List(last,Size);
[ 1, 4, 12, 60, 20, 3, 15, 5 ]
```

### 39.14 Subgroups characterized by prime powers

#### 39.14.1 Omega

**Omega(G, p[, n])**

( operation )

For a $p$-group $G$, one defines $\Omega_n(G) = \{ g \in G \mid g^{p^n} = 1 \}$. The default value for $n$ is 1. @At the moment methods exist only for abelian $G$ and $n=1.@

```gap
gap> h:=SmallGroup(16,10);
<pc group of size 16 with 4 generators>
gap> Omega(h,2); Omega(h,2,2);
Group([ f4 ]) Group([ ])
```

#### 39.14.2 Agemo

**Agemo(G, p[, n])**

( function )

For a $p$-group $G$, one defines $\mathfrak{g}_n(G) = \langle g^{p^n} \mid g \in G \rangle$. The default value for $n$ is 1.

```gap
Agemo(h,2);Agemo(h,2,2);
Group([ f4 ])
Group([ ])
```

### 39.15 Group Properties

Some properties of groups can be defined not only for groups but also for other structures. For example, nilpotency and solvability make sense also for algebras. Note that these names refer to different
definitions for groups and algebras, contrary to the situation with finiteness or commutativity. In such cases, the name of the function for groups got a suffix `Group` to distinguish different meanings for different structures.

Some functions, such as `IsPSolvable (39.15.24)` and `IsNilpotent (39.15.25)`, although they are mathematical properties, are not properties in the sense of GAP (see 13.5 and 13.7), as they depend on a parameter.

### 39.15.1 IsCyclic

\[ \text{IsCyclic}(G) \]

A group is cyclic if it can be generated by one element. For a cyclic group, one can compute a generating set consisting of only one element using `MinimalGeneratingSet (39.22.3)`.

### 39.15.2 IsElementaryAbelian

\[ \text{IsElementaryAbelian}(G) \]

A group \( G \) is elementary abelian if it is commutative and if there is a prime \( p \) such that the order of each element in \( G \) divides \( p \).

### 39.15.3 IsNilpotentGroup

\[ \text{IsNilpotentGroup}(G) \]

A group is nilpotent if the lower central series (see `LowerCentralSeriesOfGroup (39.17.11)` for a definition) reaches the trivial subgroup in a finite number of steps.

### 39.15.4 NilpotencyClassOfGroup

\[ \text{NilpotencyClassOfGroup}(G) \]

The nilpotency class of a nilpotent group \( G \) is the number of steps in the lower central series of \( G \) (see `LowerCentralSeriesOfGroup (39.17.11)`);

If \( G \) is not nilpotent an error is issued.

### 39.15.5 IsPerfectGroup

\[ \text{IsPerfectGroup}(G) \]

A group is perfect if it equals its derived subgroup (see `DerivedSubgroup (39.12.3)`).

### 39.15.6 IsSolvableGroup

\[ \text{IsSolvableGroup}(G) \]

A group is solvable if the derived series (see `DerivedSeriesOfGroup (39.17.7)` for a definition) reaches the trivial subgroup in a finite number of steps.
For finite groups this is the same as being polycyclic (see IsPolycyclicGroup (39.15.7)), and each polycyclic group is solvable, but there are infinite solvable groups that are not polycyclic.

### 39.15.7 IsPolycyclicGroup

A group is polycyclic if it has a subnormal series with cyclic factors. For finite groups this is the same as if the group is solvable (see IsSolvableGroup (39.15.6)).

### 39.15.8 IsSupersolvableGroup

A finite group is *supersolvable* if it has a normal series with cyclic factors.

### 39.15.9 IsMonomialGroup

A finite group is *monomial* if every irreducible complex character is induced from a linear character of a subgroup.

### 39.15.10 IsSimpleGroup

A group is *simple* if it is nontrivial and has no nontrivial normal subgroups. A *nonabelian simple* group is simple and not abelian.

### 39.15.11 IsAlmostSimpleGroup

A group $G$ is *almost simple* if a nonabelian simple group $S$ exists such that $G$ is isomorphic to a subgroup of the automorphism group of $S$ that contains all inner automorphisms of $S$.

Equivalently, $G$ is almost simple if and only if it has a unique minimal normal subgroup $N$ and if $N$ is a nonabelian simple group.

Note that an almost simple group is *not* defined as an extension of a simple group by outer automorphisms, since we want to exclude extensions of groups of prime order. In particular, a *simple* group is *almost simple* if and only if it is nonabelian.

#### Example

```plaintext
gap> IsAlmostSimpleGroup( AlternatingGroup( 5 ) );
true
gap> IsAlmostSimpleGroup( SymmetricGroup( 5 ) );
true
gap> IsAlmostSimpleGroup( SymmetricGroup( 3 ) );
true
```
gap> IsAlmostSimpleGroup( SL( 2, 5 ) );
false

39.15.12 IsomorphismTypeInfoFiniteSimpleGroup

For a finite simple group $G$, IsomorphismTypeInfoFiniteSimpleGroup returns a record with the components name, shortname, series, and possibly parameter, describing the isomorphism type of $G$.

The values of the components name, shortname, and series are strings, name gives name(s) for $G$, shortname gives one name for $G$ that is compatible with the naming scheme used in the GAP packages CTblLib and AtlasRep (and in the Atlas of Finite Groups [CCN+85]), and series describes the following series.

(If different characterizations of $G$ are possible only one is given by series and parameter, while name may give several names.)

"A" Alternating groups, parameter gives the natural degree.

"L" Linear groups (Chevalley type A), parameter is a list $[n, q]$ that indicates $L(n,q)$.

"2A" Twisted Chevalley type $^2A$, parameter is a list $[n, q]$ that indicates $^2A(n,q)$.

"B" Chevalley type B, parameter is a list $[n, q]$ that indicates $B(n,q)$.

"2B" Twisted Chevalley type $^2B$, parameter is a value $q$ that indicates $^2B(2,q)$.

"C" Chevalley type C, parameter is a list $[n, q]$ that indicates $C(n,q)$.

"D" Chevalley type D, parameter is a list $[n, q]$ that indicates $D(n,q)$.

"2D" Twisted Chevalley type $^2D$, parameter is a list $[n, q]$ that indicates $^2D(n,q)$.

"3D" Twisted Chevalley type $^3D$, parameter is a value $q$ that indicates $^3D(4,q)$.

"E" Exceptional Chevalley type E, parameter is a list $[n, q]$ that indicates $E_n(q)$. The value of $n$ is 6, 7, or 8.

"2E" Twisted exceptional Chevalley type $^2E_6$, parameter is a value $q$ that indicates $^2E_6(q)$.

"F" Exceptional Chevalley type F, parameter is a value $q$ that indicates $F(4,q)$.

"2F" Twisted exceptional Chevalley type $^2F$ (Ree groups), parameter is a value $q$ that indicates $^2F(4,q)$.
"G" Exceptional Chevalley type $G$, parameter is a value $q$ that indicates $G(2,q)$.

"$2G$" Twisted exceptional Chevalley type $^2G$ (Ree groups), parameter is a value $q$ that indicates $^2G(2,q)$.

"Spor" Sporadic simple groups, name gives the name.

"Z" Cyclic groups of prime size, parameter gives the size.

An equal sign in the name denotes different naming schemes for the same group, a tilde sign abstract isomorphisms between groups constructed in a different way.

Example

\begin{verbatim}
gap> IsomorphismTypeInfoFiniteSimpleGroup( Group((4,5)(6,7),(1,2,4)(3,5,6)) );
rec( name := "A(1,7) = L(2,7) ~ B(1,7) = O(3,7) ~ C(1,7) = S(2,7) ~ 2A(1, 7) = U(2,7) ~ A(2,2) = L(3,2)",
    parameter := [ 2, 7 ],
    series := "L",
    shortname := "L3(2)" )
\end{verbatim}

For a positive integer $n$, IsomorphismTypeInfoFiniteSimpleGroup returns fail if $n$ is not the order of a finite simple group, and a record as described for the case of a group $G$ otherwise. If more than one simple group of order $n$ exists then the result record contains only the name component, a string that lists the two possible isomorphism types of simple groups of this order.

Example

\begin{verbatim}
gap> IsomorphismTypeInfoFiniteSimpleGroup( 5 );
rec( name := "Z(5)",
    parameter := 5,
    series := "Z",
    shortname := "C5" )

gap> IsomorphismTypeInfoFiniteSimpleGroup( 6 ); fail

gap> IsomorphismTypeInfoFiniteSimpleGroup( Size(SymplecticGroup(6,3))/2 );
rec( name := "cannot decide from size alone between B(3,3) = O(7,3) and C\(3,3) = S(6,3)"
    parameter := [ 3, 3 ] )
\end{verbatim}

39.15.13 SimpleGroup

\begin{verbatim}
\verb|\SimpleGroup(id[, param])|
\end{verbatim}

This function will construct AN instance of the specified nonabelian simple group. Groups are specified via their name in ATLAS style notation, with parameters added if necessary. The intelligence applied to parsing the name is limited, and at the moment no proper extensions can be constructed. For groups who do not have a permutation representation of small degree the ATLASREP package might need to be installed to construct these groups.

Example

\begin{verbatim}
gap> g:=SimpleGroup("M(23)")
g23

gap> Size(g);
10200960
\end{verbatim}
GAP> g:=SimpleGroup("PSL",3,5);
PSL(3,5)
GAP> Size(g);
372000
GAP> g:=SimpleGroup("PSp",6,2);
PSp(6,2)

39.15.14 SimpleGroupsIterator

This function returns an iterator that will run over all nonabelian simple groups, starting at order
\( \text{start} \) if specified, up to order \( 10^{18} \) (or – if specified – order \( \text{end} \)). If the option \( \text{NOPSL2} \) is given, groups of type \( PSL_2(q) \) are omitted.

Example

```gap
gap> it:=SimpleGroupsIterator(20000);
<iterator>
gap> List([1..8],x->NextIterator(it));
[ A8, PSL(3,4), PSL(2,37), PSp(4,3), Sz(8), PSL(2,32), PSL(2,41),
  PSL(2,43) ]
gap> it:=SimpleGroupsIterator(1,2000:);
<iterator>
gap> l:=[];;for i in it do Add(l,i);od;l;
[ A5, PSL(2,7), A6, PSL(2,8), PSL(2,11), PSL(2,13) ]
gap> it:=SimpleGroupsIterator(20000,100000:NOPSL2:);
<iterator>
gap> l:=[];;for i in it do Add(l,i);od;l;
[ A8, PSp(4,3), Sz(8), PSU(3,4), M12 ]
```

39.15.15 SmallSimpleGroup

\( \text{SmallSimpleGroup}(\text{order}, \text{i}) \)

Returns: The \( \text{i} \) th simple group of order \( \text{order} \) in the stored list, given in a small-degree permutation representation, or \( \text{fail} \) (20.2.1) if no such simple group exists.

If \( \text{i} \) is not given, it defaults to 1. Currently, all simple groups of order less than \( 10^6 \) are available via this function.

Example

```gap
gap> SmallSimpleGroup(60);
A5
gap> SmallSimpleGroup(20160,1);
A8
gap> SmallSimpleGroup(20160,2);
PSL(3,4)
```

39.15.16 AllSmallNonabelianSimpleGroups

\( \text{AllSmallNonabelianSimpleGroups}(\text{orders}) \)

Returns: A list of all nonabelian simple groups whose order lies in the range \( \text{orders} \).

The groups are given in small-degree permutation representations. The returned list is sorted by ascending group order. Currently, all simple groups of order less than \( 10^6 \) are available via this function.
Example

```gap
gap> List(AllSmallNonabelianSimpleGroups([1..1000000]), StructureDescription);
[ "A5", "PSL(3,2)", "A6", "PSL(2,8)", "PSL(2,11)", "PSL(2,13)",
  "PSL(2,17)", "A7", "PSL(2,19)", "PSL(2,16)", "PSL(3,3)",
  "PSU(3,3)", "PSL(2,23)", "PSL(2,25)", "M11", "PSL(2,27)",
  "PSL(2,29)", "PSL(2,31)", "A8", "PSL(3,4)", "PSL(2,37)", "O(5,3)",
  "Sz(8)", "PSL(2,32)", "PSL(2,41)", "PSL(2,43)", "PSL(2,47)",
  "PSL(2,49)", "PSU(3,4)", "PSL(2,53)", "M12", "PSL(2,59)",
  "PSL(2,61)", "PSU(3,5)", "PSL(2,67)", "J1", "PSL(2,71)", "A9",
  "PSL(2,73)", "PSL(2,79)", "PSL(2,64)", "PSL(2,81)", "PSL(2,83)",
  "PSL(2,89)", "PSL(3,5)", "M22", "PSL(2,97)", "PSL(2,101)",
  "PSL(2,103)", "HJ", "PSL(2,107)", "PSL(2,109)", "PSL(2,113)",
  "PSL(2,121)", "PSL(2,125)", "O(5,4)"
]
```

39.15.17  **IsFinitelyGeneratedGroup**

\[\textbf{IsFinitelyGeneratedGroup}(G)\]

Tests whether the group \(G\) can be generated by a finite number of generators. (This property is mainly used to obtain finiteness conditions.)

Note that this is a pure existence statement. Even if a group is known to be generated by a finite number of elements, it can be very hard or even impossible to obtain such a generating set if it is not known.

39.15.18  **IsSubsetLocallyFiniteGroup**

\[\textbf{IsSubsetLocallyFiniteGroup}(U)\]

A group is called locally finite if every finitely generated subgroup is finite. This property checks whether the group \(U\) is a subset of a locally finite group. This is used to check whether finite generation will imply finiteness, as it does for example for permutation groups.

39.15.19  **IsPGroup**

\[\textbf{IsPGroup}(G)\]

A \textit{p-group} is a group in which the order (see \texttt{Order (31.10.10)}) of every element is of the form \(p^n\) for a prime integer \(p\) and a nonnegative integer \(n\). \textbf{IsPGroup} returns \texttt{true} if \(G\) is a \textit{p-group}, and \texttt{false} otherwise.

Finite \textit{p}-groups are precisely those groups whose order (see \texttt{Size (30.4.6)}) is a prime power, and are always nilpotent.

Note that \textit{p}-groups can also be infinite, and in that case, need not be nilpotent.

39.15.20  **IsPowerfulPGroup**

\[\textbf{IsPowerfulPGroup}(G)\]
A finite $p$-group $G$ is said to be a powerful $p$-group if the commutator subgroup $[G, G]$ is contained in $G^p$ if the prime $p$ is odd, or if $[G, G]$ is contained in $G^4$ if $p = 2$. The subgroup $G^p$ is called the first Agemo subgroup, (see Agemo (39.14.2)). IsPowerfulPGroup returns true if $G$ is a powerful $p$-group, and false otherwise. Note: This function returns true if $G$ is the trivial group.

39.15.21 PrimePGroup

$\triangleright$ PrimePGroup($G$) (attribute)

If $G$ is a nontrivial $p$-group (see IsPGroup (39.15.19)), PrimePGroup returns the prime integer $p$; if $G$ is trivial then PrimePGroup returns fail. Otherwise an error is issued.

(One should avoid a common error of writing if IsPGroup($g$) then ... PrimePGroup($g$) ... where the code represented by dots assumes that PrimePGroup($g$) is an integer.)

39.15.22 PClassPGroup

$\triangleright$ PClassPGroup($G$) (attribute)

The $p$-class of a $p$-group $G$ (see IsPGroup (39.15.19)) is the length of the lower $p$-central series (see PCentralSeries (39.17.13)) of $G$. If $G$ is not a $p$-group then an error is issued.

39.15.23 RankPGroup

$\triangleright$ RankPGroup($G$) (attribute)

For a $p$-group $G$ (see IsPGroup (39.15.19)), RankPGroup returns the rank of $G$, which is defined as the minimal size of a generating system of $G$. If $G$ is not a $p$-group then an error is issued.

Example

```
gap> h:=Group((1,2,3,4),(1,3));;
gap> PClassPGroup(h);
2
gap> RankPGroup(h);
2
```

39.15.24 IsPSolvable

$\triangleright$ IsPSolvable($G$, $p$) (operation)

A finite group is $p$-solvable if every chief factor either has order not divisible by $p$, or is solvable.

39.15.25 IsPNilpotent

$\triangleright$ IsPNilpotent($G$, $p$) (operation)

A group is $p$-nilpotent if it possesses a normal $p$-complement.
39.16 Numerical Group Attributes

This section gives only some examples of numerical group attributes, so it should not serve as a collection of all numerical group attributes. The manual contains more such attributes documented in this manual, for example, NrConjugacyClasses (39.10.5), NilpotencyClassOfGroup (39.15.4) and others.

Note also that some functions, such as EulerianFunction (39.16.3), are mathematical attributes, but not GAP attributes (see 13.5) as they are depending on a parameter.

39.16.1 AbelianInvariants

\[ \text{AbelianInvariants}(G) \]

returns the abelian invariants (also sometimes called primary decomposition) of the commutator factor group of the group \( G \). These are given as a list of prime-powers or zeroes and describe the structure of \( G/G' \) as a direct product of cyclic groups of prime power (or infinite) order.

(See IndependentGeneratorsOfAbelianGroup (39.22.5) to obtain actual generators).

Example

\[
\begin{align*}
g &:= \text{Group}((1,2,3,4),(1,2),(5,6)); \\
g &:= \text{AbelianInvariants}(g); \\
[ &2, 2 ] \\
h &:= \text{FreeGroup}(2); h := h/[h.1^3]; \\
h &:= \text{AbelianInvariants}(h); \\
[ &0, 3 ]
\end{align*}
\]

39.16.2 Exponent

\[ \text{Exponent}(G) \]

The exponent \( e \) of a group \( G \) is the lcm of the orders of its elements, that is, \( e \) is the smallest integer such that \( g^e = 1 \) for all \( g \in G \).

Example

\[
\begin{align*}
g &:= \text{Exponent}(g); \\
12
\end{align*}
\]

39.16.3 EulerianFunction

\[ \text{EulerianFunction}(G, n) \]

returns the number of \( n \)-tuples \((g_1, g_2, \ldots, g_n)\) of elements of the group \( G \) that generate the whole group \( G \). The elements of such an \( n \)-tuple need not be different.

In [Hal36], the notation \( \phi_n(G) \) is used for the value returned by EulerianFunction, and the quotient of \( \phi_n(G) \) by the order of the automorphism group of \( G \) is called \( d_n(G) \). If \( G \) is a nonabelian simple group then \( d_n(G) \) is the greatest number \( d \) for which the direct product of \( d \) groups isomorphic with \( G \) can be generated by \( n \) elements.

If the Library of Tables of Marks (see Chapter 70) covers the group \( G \), you may also use EulerianFunctionByTom (70.9.9).
39.17 Subgroup Series

In group theory many subgroup series are considered, and GAP provides commands to compute them. In the following sections, there is always a series \( G = U_1 > U_2 > \cdots > U_m = \langle 1 \rangle \) of subgroups considered. A series also may stop without reaching \( G \) or \( \langle 1 \rangle \).

A series is called subnormal if every \( U_{i+1} \) is normal in \( U_i \).

A series is called normal if every \( U_i \) is normal in \( G \).

A series of normal subgroups is called central if \( U_i/U_{i+1} \) is central in \( G/U_{i+1} \).

We call a series refinable if intermediate subgroups can be added to the series without destroying the properties of the series.

Unless explicitly declared otherwise, all subgroup series are descending. That is they are stored in decreasing order.

39.17.1 ChiefSeries

\( \triangleright \) ChiefSeries\((G)\)  

is a series of normal subgroups of \( G \) which cannot be refined further. That is there is no normal subgroup \( N \) of \( G \) with \( U_i > N > U_{i+1} \). This attribute returns one chief series (of potentially many possibilities).

\( \triangleright \) ChiefSeriesThrough\((G, I)\)  

is a chief series of the group \( G \) going through the normal subgroups in the list \( I \), which must be a list of normal subgroups of \( G \) contained in each other, sorted by descending size. This attribute returns one chief series (of potentially many possibilities).

39.17.3 ChiefSeriesUnderAction

\( \triangleright \) ChiefSeriesUnderAction\((H, G)\)  

returns a series of normal subgroups of \( G \) which are invariant under \( H \) such that the series cannot be refined any further. \( G \) must be a subgroup of \( H \). This attribute returns one such series (of potentially many possibilities).
39.17.4 SubnormalSeries

\textbf{SubnormalSeries}(G, U) \hspace{1cm} (operation)

If \( U \) is a subgroup of \( G \) this operation returns a subnormal series that descends from \( G \) to a subnormal subgroup \( V \supseteq U \). If \( U \) is subnormal, \( V = U \).

\texttt{gap> s:=SubnormalSeries(g,Group([(1,2)(3,4)])) =}
\texttt{true}

39.17.5 CompositionSeries

\textbf{CompositionSeries}(G) \hspace{1cm} (attribute)

A composition series is a subnormal series which cannot be refined. This attribute returns one composition series (of potentially many possibilities).

39.17.6 DisplayCompositionSeries

\textbf{DisplayCompositionSeries}(G) \hspace{1cm} (function)

Displays a composition series of \( G \) in a nice way, identifying the simple factors.

\texttt{gap> CompositionSeries(g);}
\texttt{[ Group([ (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ]),}
\texttt{ Group([ (2,4,3), (1,4)(2,3), (1,3)(2,4) ]),}
\texttt{ Group([ (1,4)(2,3), (1,3)(2,4) ]), Group([ (1,3)(2,4) ]), Group(())]}
\texttt{gap> DisplayCompositionSeries(Group((1,2,3,4,5,6,7),(1,2)));}
\texttt{G (2 gens, size 5040)}
\texttt{| Z(2) |}
\texttt{S (5 gens, size 2520)}
\texttt{| A(7) |}
\texttt{1 (0 gens, size 1)}

39.17.7 DerivedSeriesOfGroup

\textbf{DerivedSeriesOfGroup}(G) \hspace{1cm} (attribute)

The derived series of a group is obtained by \( U_{i+1} = U_i' \). It stops if \( U_i \) is perfect.

39.17.8 DerivedLength

\textbf{DerivedLength}(G) \hspace{1cm} (attribute)

The derived length of a group is the number of steps in the derived series. (As there is always the group, it is the series length minus 1.)
returns a series of normal subgroups of \( G \) such that all factors are elementary abelian. If the group is not solvable (and thus no such series exists) it returns \textit{fail}.

The variant \texttt{ElementaryAbelianSeriesLargeSteps} tries to make the steps in this series large (by eliminating intermediate subgroups if possible) at a small additional cost.

In the third variant, an elementary abelian series through the given series of normal subgroups in the list \texttt{list} is constructed.

```gap
gap> List(ElementaryAbelianSeries(g),Size);
[ 24, 12, 4, 1 ]
```

### 39.17.10 InvariantElementaryAbelianSeries

\[ \texttt{InvariantElementaryAbelianSeries}(G, \text{morph}, N, \text{fine}] \]

For a (solvable) group \( G \) and a list of automorphisms \texttt{morph} of \( G \), this command finds a normal series of \( G \) with elementary abelian factors such that every group in this series is invariant under every automorphism in \texttt{morph}.

If a normal subgroup \( N \) of \( G \) which is invariant under \texttt{morph} is given, this series is chosen to contain \( N \). No tests are performed to check the validity of the arguments.

The series obtained will be constructed to prefer large steps unless \texttt{fine} is given as \texttt{true}.

```gap
gap> g:=Group((1,2,3,4),(1,3));
Group( [ (1,2,3,4), (1,3) ] )
gap> hom:=GroupHomomorphismByImages(g,g,GeneratorsOfGroup(g),
> [(1,2,3,4), (1,3)] -> [(1,4,3,2), (1,4)(2,3)];
Group([ (1,2,3,4), (1,3) ] -> [ (1,4,3,2), (1,4)(2,3) ]
gap> InvariantElementaryAbelianSeries(g,[hom]);
[ Group([ (1,2,3,4), (1,3) ]), Group([ (1,3)(2,4) ]), Group(()) ]
```

### 39.17.11 LowerCentralSeriesOfGroup

\[ \texttt{LowerCentralSeriesOfGroup}(G) \]

The lower central series of a group \( G \) is defined as \( U_{i+1} := [G, U_i] \). It is a central series of normal subgroups. The name derives from the fact that \( U_i \) is contained in the \( i \)-th step subgroup of any central series.
39.17.12 UpperCentralSeriesOfGroup

\[ \text{UpperCentralSeriesOfGroup}(G) \]

The upper central series of a group \( G \) is defined as an ending series \( U_i/U_{i+1} := Z(G/U_{i+1}) \). It is a central series of normal subgroups. The name derives from the fact that \( U_i \) contains every \( i \)-th step subgroup of a central series.

39.17.13 PCentralSeries

\[ \text{PCentralSeries}(G, p) \]

The \( p \)-central series of \( G \) is defined by \( U_1 := G, U_i := [G, U_{i-1}] U_{p-1}^p \).

Example

\[
\text{gap> g:=DicyclicGroup(12);}\\
\text{gap> PCentralSeries(g,2);}\\
\text{[ <pc group of size 12 with 3 generators>, Group([ y^3, y*y^3 ]), Group([ y*y^3 ]) ]}\\
\text{gap> g:=SymmetricGroup(4);}\\
\text{gap> PCentralSeries(g,2);}\\
\text{[ Sym( [ 1 .. 4 ] ), Group([ (1,2,3), (2,3,4) ]) ]}
\]

39.17.14 JenningsSeries

\[ \text{JenningsSeries}(G) \]

For a \( p \)-group \( G \), this function returns its Jennings series. This series is defined by setting \( G_1 = G \) and for \( i \geq 0, G_{i+1} = [G_i, G] G_j \), where \( j \) is the smallest integer \( > i/p \).

39.17.15 DimensionsLoewyFactors

\[ \text{DimensionsLoewyFactors}(G) \]

This operation computes the dimensions of the factors of the Loewy series of \( G \). (See [HB82, p. 157] for the slightly complicated definition of the Loewy Series.) The dimensions are computed via the JenningsSeries (39.17.14) without computing the Loewy series itself.

Example

\[
\text{gap> G:=SmallGroup( 3^6, 100 );}\\
\text{<pc group of size 729 with 6 generators>}\\
\text{gap> JenningsSeries( G );}\\
\text{[ <pc group of size 729 with 6 generators>, Group([ f3, f4, f5, f6 ]),}\\
\text{Group([ f4, f5, f6 ]), Group([ f5, f6 ]), Group([ f5, f6 ]),}\\
\text{Group([ f6 ]), Group([ f6 ]), Group([ f6 ]), Group([ f6 ]),}\\
\text{Group([ <identity> of ... ])]}\\
\text{gap> DimensionsLoewyFactors(G);}\\
\text{[ 1, 2, 4, 5, 7, 8, 10, 11, 13, 14, 16, 17, 19, 20, 22, 23, 25, 26,}\\
\text{27, 27, 27, 27, 27, 27, 27, 27, 27, 27, 26, 25, 23, 22, 20, 19, 17, 16,}\\
\text{14, 13, 11, 10, 8, 7, 5, 4, 2, 1 ]}
\]
39.17.16 AscendingChain

\[ \text{AscendingChain}(G, U) \] (function)

This function computes an ascending chain of subgroups from \( U \) to \( G \). This chain is given as a list whose first entry is \( U \) and the last entry is \( G \). The function tries to make the links in this chain small.

The option \texttt{refineIndex} can be used to give a bound for refinements of steps to avoid \texttt{GAP} trying to enforce too small steps. The option \texttt{cheap} (if set to \texttt{true}) will overall limit the amount of heuristic searches.

39.17.17 IntermediateGroup

\[ \text{IntermediateGroup}(G, U) \] (function)

This routine tries to find a subgroup \( E \) of \( G \), such that \( G > E > U \) holds. If \( U \) is maximal in \( G \), the function returns \texttt{fail}. This is done by finding minimal blocks for the operation of \( G \) on the right cosets of \( U \).

39.17.18 IntermediateSubgroups

\[ \text{IntermediateSubgroups}(G, U) \] (operation)

returns a list of all subgroups of \( G \) that properly contain \( U \); that is all subgroups between \( G \) and \( U \). It returns a record with a component \texttt{subgroups}, which is a list of these subgroups, as well as a component \texttt{inclusions}, which lists all maximality inclusions among these subgroups. A maximality inclusion is given as a list \([i, j]\) indicating that the subgroup number \( i \) is a maximal subgroup of the subgroup number \( j \), the numbers 0 and \( 1 + \text{Length}(\text{subgroups}) \) are used to denote \( U \) and \( G \), respectively.

39.18 Factor Groups

39.18.1 NaturalHomomorphismByNormalSubgroup

\[ \text{NaturalHomomorphismByNormalSubgroup}(G, N) \] (function)

\[ \text{NaturalHomomorphismByNormalSubgroupNC}(G, N) \] (function)

returns a homomorphism from \( G \) to another group whose kernel is \( N \). \texttt{GAP} will try to select the image group as to make computations in it as efficient as possible. As the factor group \( G/N \) can be identified with the image of \( G \) this permits efficient computations in the factor group. The homomorphism returned is not necessarily surjective, so \texttt{ImagesSource} (32.4.1) should be used instead of \texttt{Range} (32.3.7) to get a group isomorphic to the factor group. The \texttt{NC} variant does not check whether \( N \) is normal in \( G \).

39.18.2 FactorGroup

\[ \text{FactorGroup}(G, N) \] (function)

\[ \text{FactorGroupNC}(G, N) \] (operation)
returns the image of the \texttt{NaturalHomomorphismByNormalSubgroup}(G,N). The homomorphism will be returned by calling the function \texttt{NaturalHomomorphism} on the result. The \texttt{NC} version does not test whether \texttt{N} is normal in \texttt{G}.

\begin{verbatim}
gap> g:=Group((1,2,3,4),(1,2));;n:=Subgroup(g,[[(1,2)(3,4),(1,3)(2,4)]]);;
gap> hom:=NaturalHomomorphismByNormalSubgroup(g,n);
[ (1,2,3,4), (1,2) ] -> [ f1*f2, f1 ]
gap> Size(ImagesSource(hom));
6

gap> FactorGroup(g,n);

gap> StructureDescription(last);
"S3"
\end{verbatim}

\subsection{39.18.3 CommutatorFactorGroup}

\begin{verbatim}
\texttt{CommutatorFactorGroup}(G) (attribute)

computes the commutator factor group \( G/G' \) of the group \( G \).
\end{verbatim}

\begin{verbatim}
gap> CommutatorFactorGroup(g);
Group([ f1 ])
\end{verbatim}

\subsection{39.18.4 MaximalAbelianQuotient}

\begin{verbatim}
\texttt{MaximalAbelianQuotient}(G) (attribute)

returns an epimorphism from \( G \) onto the maximal abelian quotient of \( G \). The kernel of this epimorphism is the derived subgroup of \( G \), see \texttt{DerivedSubgroup} (39.12.3).
\end{verbatim}

\subsection{39.18.5 HasAbelianFactorGroup}

\begin{verbatim}
\texttt{HasAbelianFactorGroup}(G, N) (function)

tests whether \( G/N \) is abelian (without explicitly constructing the factor group and without testing whether \( N \) is in fact a normal subgroup).
\end{verbatim}

\begin{verbatim}
gap> HasAbelianFactorGroup(g,n);
false

gap> HasAbelianFactorGroup(DerivedSubgroup(g),n);
true
\end{verbatim}

\subsection{39.18.6 HasElementaryAbelianFactorGroup}

\begin{verbatim}
\texttt{HasElementaryAbelianFactorGroup}(G, N) (function)

tests whether \( G/N \) is elementary abelian (without explicitly constructing the factor group and without testing whether \( N \) is in fact a normal subgroup).
\end{verbatim}
39.18.7 CentralizerModulo

\[ \text{CentralizerModulo}(G, N, elm) \]

(operation)

Computes the full preimage of the centralizer \( C_G/N(\text{elm} \cdot N) \) in \( G \) (without necessarily constructing the factor group).

Example

```gap
gap> CentralizerModulo(g,n,(1,2));
group ([ (3,4), (1,3)(2,4), (1,4)(2,3) ])
```

39.19 Sets of Subgroups

39.19.1 ConjugacyClassSubgroups

\[ \text{ConjugacyClassSubgroups}(G, U) \]

(operation)

generates the conjugacy class of subgroups of \( G \) with representative \( U \). This class is an external set, so functions such as \text{Representative} (30.4.7), (which returns \( U \)), \text{ActingDomain} (41.12.3) (which returns \( G \)), \text{StabilizerOfExternalSet} (41.12.10) (which returns the normalizer of \( U \)), and \text{AsList} (30.3.8) work for it.

(The use of the [] list access to select elements of the class is considered obsolescent and will be removed in future versions. Use \text{ClassElementLattice} (39.20.2) instead.)

Example

```gap
g:=Group((1,2,3,4),(1,2));;IsNaturalSymmetricGroup(g);
gap> cl:=ConjugacyClassSubgroups(g,Subgroup(g,[[(1,2)]]));
gap> Size(cl);
6
gap> ClassElementLattice(cl,4);;
group ([ (2,3) ])
```

39.19.2 IsConjugacyClassSubgroupsRep

\[ \text{IsConjugacyClassSubgroupsRep}(\text{obj}) \]

(Representation)

\[ \text{IsConjugacyClassSubgroupsByStabilizerRep}(\text{obj}) \]

(Representation)

Is the representation GAP uses for conjugacy classes of subgroups. It can be used to check whether an object is a class of subgroups. The second representation \text{IsConjugacyClassSubgroupsByStabilizerRep} in addition is an external orbit by stabilizer and will compute its elements via a transversal of the stabilizer.

39.19.3 ConjugacyClassesSubgroups

\[ \text{ConjugacyClassesSubgroups}(G) \]

(attribute)

This attribute returns a list of all conjugacy classes of subgroups of the group \( G \). It also is applicable for lattices of subgroups (see \text{LatticeSubgroups} (39.20.1)). The order in which the classes are listed

```
depends on the method chosen by GAP. For each class of subgroups, a representative can be accessed using `Representative(30.4.7)`.

```gap
gap> ConjugacyClassesSubgroups(g);
[ Group( () )^G, Group( [ (1,3)(2,4) ] )^G, Group( [ (3,4) ] )^G,
  Group( [ (2,4,3) ] )^G, Group( [ (1,4)(2,3), (1,3)(2,4) ] )^G,
  Group( [ (3,4), (1,2)(3,4) ] )^G,
  Group( [ (1,3,2,4), (1,2)(3,4) ] )^G, Group( [ (3,4), (2,4,3) ] )^G,
  Group( [ (1,4)(2,3), (1,3)(2,4) ] )^G,
  Group( [ (2,4,3), (1,3)(2,4) ] )^G, Group( [ (3,4), (2,4,3) ] )^G,
  Group( [ (1,4)(2,3), (1,3)(2,4), (2,4,3) ] )^G,
  Group( [ (1,4)(2,3), (1,3)(2,4), (2,4,3), (3,4) ] )^G ]
```

### 39.19.4 ConjugacyClassesMaximalSubgroups

- ConjugacyClassesMaximalSubgroups(G)

  returns the conjugacy classes of maximal subgroups of G. Representatives of the classes can be computed directly by `MaximalSubgroupClassReps(39.19.5)`.

```gap
gap> ConjugacyClassesMaximalSubgroups(g);
[ Group( [ (2,4,3), (1,4)(2,3), (1,3)(2,4) ] )^G,
  Group( [ (3,4), (1,4)(2,3), (1,3)(2,4) ] )^G,
  Group( [ (3,4), (2,4,3) ] )^G ]
```

### 39.19.5 MaximalSubgroupClassReps

- MaximalSubgroupClassReps(G)

  returns a list of conjugacy representatives of the maximal subgroups of G.

```gap
gap> MaximalSubgroupClassReps(g);
[ Group([ (2,4,3), (1,4)(2,3), (1,3)(2,4) ]), Group([ (3,4), (1,4)
(2,3), (1,3)(2,4) ]), Group([ (3,4), (2,4,3) ]) ]
```

### 39.19.6 LowIndexSubgroups

- LowIndexSubgroups(G, index)

  The operation `LowIndexSubgroups` computes representatives of the conjugacy classes of subgroups of the group G that index less than or equal to index.

  For finitely presented groups this operation simply defaults to `LowIndexSubgroupsFpGroup(47.10.1)`. In other cases, it uses repeated calculation of maximal subgroups.

  The function `LowLayerSubgroups(39.20.6)` works similar but does not bound the index, but instead considers up to layer-th maximal subgroups.

```gap
gap> g:=TransitiveGroup(18,950);;
gap> l:=LowIndexSubgroups(g,20);;Collected(List(l,x->Index(g,x)));
[ [ 1, 1 ], [ 2, 1 ], [ 5, 1 ], [ 6, 1 ], [ 10, 2 ], [ 12, 3 ], [ 15, 1 ],
  [ 16, 2 ], [ 18, 1 ], [ 20, 9 ] ]
```
39.19.7 AllSubgroups

\[ \text{AllSubgroups}(G) \]  (function)

For a finite group \( G \) AllSubgroups returns a list of all subgroups of \( G \), intended primarily for use in class for small examples. This list will quickly get very long and in general use of ConjugacyClassesSubgroups (39.19.3) is recommended.

Example

\[
\text{gap> AllSubgroups(SymmetricGroup(3));}
\]
\[
[ \text{Group}(()), \text{Group}([ (2,3) ]), \text{Group}([ (1,2) ]), \text{Group}([ (1,3) ]),
\text{Group}([ (1,2,3) ]), \text{Group}([ (1,2,3), (2,3) ]) ]
\]

39.19.8 MaximalSubgroups

\[ \text{MaximalSubgroups}(G) \]  (attribute)

returns a list of all maximal subgroups of \( G \). This may take up much space, therefore the command should be avoided if possible. See ConjugacyClassesMaximalSubgroups (39.19.4).

Example

\[
\text{gap> MaximalSubgroups(Group((1,2,3),(1,2)));}
\]
\[
[ \text{Group}([ (1,2,3) ]), \text{Group}([ (2,3) ]), \text{Group}([ (1,2) ]), \text{Group}([ (1,3) ]) ]
\]

39.19.9 NormalSubgroups

\[ \text{NormalSubgroups}(G) \]  (attribute)

returns a list of all normal subgroups of \( G \).

Example

\[
\text{gap> g:=SymmetricGroup(4);; NormalSubgroups(g);}
\]
\[
[ \text{Sym( [ 1 .. 4 ] ), Alt( [ 1 .. 4 ] ), Group([ (1,4)(2,3), (1,3)(2,4) ]), Group(())]
\]
\[
\text{gap> g:=AbelianGroup([2,2]);; NormalSubgroups(g);}
\]
\[
[ \langle \text{pc group of size 4 with 2 generators\rangle}, \text{Group}([ f2 ]), \text{Group}([ f1*f2 ]), \text{Group}([ f1 ]), \text{Group([ ]])}
\]

The algorithm for the computation of normal subgroups is described in [Hul98].

39.19.10 MaximalNormalSubgroups

\[ \text{MaximalNormalSubgroups}(G) \]  (attribute)

is a list containing those proper normal subgroups of the group \( G \) that are maximal among the proper normal subgroups. Gives error if \( G/G' \) is infinite, yielding infinitely many maximal normal subgroups. Note, that the maximal normal subgroups of a group \( G \) can be computed more efficiently if the character table of \( G \) is known or if \( G \) is known to be abelian or solvable (even if infinite). So if the character table is needed, anyhow, or \( G \) is suspected to be abelian or solvable, then these should be computed before computing the maximal normal subgroups.
Example

```gap
g:=SymmetricGroup(4);; MaximalNormalSubgroups( g );
[ Alt( [ 1 .. 4 ] ) ]
f := FreeGroup("x", "y");; x := f.1;; y := f.2;;
List(MaximalNormalSubgroups(f/[x^2, y^2]), GeneratorsOfGroup);
[ x, y*x*y^-1 ], [ y, x*x*y^-1 ], [ y*x^-1 ]
```

### 39.19.11 MinimalNormalSubgroups

MinMaximalNormalSubgroups(G) (attribute)

is a list containing those nontrivial normal subgroups of the group G that are minimal among the nontrivial normal subgroups.

Example

```gap
g:=SymmetricGroup(4);; MinimalNormalSubgroups( g );
[ Group([ (1,4)(2,3), (1,3)(2,4) ] ) ]
```

### 39.19.12 CharacteristicSubgroups

CharacteristicSubgroups(G) (attribute)

returns a list of all characteristic subgroups of G, that is subgroups that are invariant under all automorphisms.

Example

```gap
g:=SymmetricGroup(4);; CharacteristicSubgroups(g);
[ Sym( [ 1 .. 4 ] ), Group([ (2,4,3), (1,4)(2,3), (1,3)(2,4) ]),
  Group([ (1,4)(2,3), (1,3)(2,4) ]), Group([ ]) ]
g:=AbelianGroup([2,2]);; CharacteristicSubgroups(g);
[ <pc group of size 4 with 2 generators>, Group([ ]) ]
```

### 39.20 Subgroup Lattice

#### 39.20.1 LatticeSubgroups

LatticeSubgroups(G) (attribute)

computes the lattice of subgroups of the group G. This lattice has the conjugacy classes of subgroups as attribute ConjugacyClassesSubgroups (39.19.3) and permits one to test maximality/minimality relations.

Example

```gap
g:=SymmetricGroup(4);;
g:=LatticeSubgroups(g);
<subgroup lattice of Sym( [ 1 .. 4 ] ), 11 classes, 30 subgroups>
g:=ConjugacyClassesSubgroups(1);
[ Group( () )^G, Group( [ (1,3)(2,4) ] )^G, Group( [ (3,4) ] )^G,
  Group( [ (2,4,3) ] )^G, Group( [ (1,4)(2,3), (1,3)(2,4) ] )^G,
  Group( [ (3,4), (1,2)(3,4) ] )^G,
  Group( [ (1,3,2,4), (1,2)(3,4) ] )^G, Group( [ (3,4), (2,4,3) ] )^G,
  Group( [ (1,4)(2,3), (1,3)(2,4), (3,4) ] )^G,
```
Group( [(1,4)(2,3), (1,3)(2,4), (2,4,3)]^G, 
Group( [(1,4)(2,3), (1,3)(2,4), (2,4,3), (3,4)]^G ]

39.20.2 ClassElementLattice

\( \text{ClassElementLattice}(C, n) \) (operation)

For a class \( C \) of subgroups, obtained by a lattice computation, this operation returns the \( n \)-th conjugate subgroup in the class.

*Because of other methods installed, calling\( \text{AsList}(30.3.8) \) with \( C \) can give a different arrangement of the class elements!*

The GAP package XGAP permits a graphical display of the lattice of subgroups in a nice way.

39.20.3 DotFileLatticeSubgroups

\( \text{DotFileLatticeSubgroups}(L, \text{file}) \) (function)

This function produces a graphical representation of the subgroup lattice \( L \) in file \( \text{file} \). The output is in .dot (also known as GraphViz format). For details on the format, and information about how to display or edit this format see \url{https://www.graphviz.org}. (On the Macintosh, the program OmniGraffle is also able to read this format.)

Subgroups are labelled in the form \( i-j \) where \( i \) is the number of the class of subgroups and \( j \) the number within this class. Normal subgroups are represented by a box.

\begin{verbatim}
Example

gap> DotFileLatticeSubgroups(1,"s4lat.dot")
\end{verbatim}

39.20.4 MaximalSubgroupsLattice

\( \text{MaximalSubgroupsLattice}(lat) \) (attribute)

For a lattice \( lat \) of subgroups this attribute contains the maximal subgroup relations among the subgroups of the lattice. It is a list corresponding to the \text{ConjugacyClassesSubgroups} (39.19.3) value of the lattice, each entry giving a list of the maximal subgroups of the representative of this class. Every maximal subgroup is indicated by a list of the form \([c,n]\) which means that the \( n \)-th subgroup in class number \( c \) is a maximal subgroup of the representative.

The number \( n \) corresponds to access via \text{ClassElementLattice} (39.20.2) and not necessarily the \text{AsList} (30.3.8) arrangement! See also \text{MinimalSupergroupsLattice} (39.20.5).

\begin{verbatim}
Example

gap> MaximalSubgroupsLattice(l);
[ [ ], [ [ 1, 1 ] ], [ [ 1, 1 ] ], [ [ 1, 1 ] ],
 [ [ 7, 1 ] ], [ [ 6, 1 ] ], [ [ 5, 1 ] ],
 [ [ 10, 1 ] ], [ [ 9, 1 ] ], [ [ 9, 2 ] ], [ [ 9, 3 ] ], [ [ 8, 1 ] ], [ [ 8, 2 ] ],

gap> last[6];
\end{verbatim}
gap> u1:=Representative(ConjugacyClassesSubgroups(l)[6]);
Group([ (3,4), (1,2)(3,4) ])
gap> u2:=ClassElementLattice(ConjugacyClassesSubgroups(l)[3],1);;
gap> u3:=ClassElementLattice(ConjugacyClassesSubgroups(l)[3],6);;
gap> u4:=ClassElementLattice(ConjugacyClassesSubgroups(l)[2],3);;
gap> IsSubgroup(u1,u2);IsSubgroup(u1,u3);IsSubgroup(u1,u4);
true
true
true

39.20.5 MinimalSupergroupsLattice

▷ MinimalSupergroupsLattice(lat)

(attribute)

For a lattice lat of subgroups this attribute contains the minimal supergroup relations among the
subgroups of the lattice. It is a list corresponding to the ConjugacyClassesSubgroups (39.19.3)
value of the lattice, each entry giving a list of the minimal supergroups of the representative of this
class. Every minimal supergroup is indicated by a list of the form \([c, n]\), which means that the \(n\)-th
subgroup in class number \(c\) is a minimal supergroup of the representative.

The number \(n\) corresponds to access via ClassElementLattice (39.20.2) and not necessarily the
AsList (30.3.8) arrangement! See also MaximalSubgroupsLattice (39.20.4).

Example

\begin{verbatim}
gap> MinimalSupergroupsLattice(l);
[ [ [ 2, 1 ], [ 2, 2 ], [ 2, 3 ], [ 3, 1 ], [ 3, 2 ], [ 3, 3 ],
  [ 3, 4 ], [ 3, 5 ], [ 3, 6 ], [ 4, 1 ], [ 4, 2 ], [ 4, 3 ],
  [ 4, 4 ], [ 5, 1 ], [ 6, 2 ], [ 7, 2 ] ],
[ [ 6, 1 ], [ 8, 1 ], [ 8, 3 ] ], [ [ 8, 1 ], [ 10, 1 ] ],
[ [ 9, 1 ], [ 9, 2 ], [ 9, 3 ], [ 10, 1 ] ], [ [ 9, 1 ] ],
[ [ 9, 1 ] ], [ [ 11, 1 ] ], [ [ 11, 1 ] ], [ ] ]
gap> last[3];
[ [ 6, 1 ], [ 8, 1 ], [ 8, 3 ] ]
gap> u5:=ClassElementLattice(ConjugacyClassesSubgroups(l)[8],1);
Group([ (3,4), (2,4,3) ])
gap> u6:=ClassElementLattice(ConjugacyClassesSubgroups(l)[8],3);
Group([ (1,3), (1,3,4) ])
gap> IsSubgroup(u5,u2);
true
\end{verbatim}

39.20.6 LowLayerSubgroups

▷ LowLayerSubgroups(act, G, lim, cond, dosub)

(function)

This function computes representatives of the conjugacy classes of subgroups of the finite group \(G\)
such that the subgroups can be obtained as \(\text{lim}\)-fold iterated maximal subgroups. If a function \(\text{cond}\)
is given, only subgroups for which this function returns true (also for their intermediate overgroups)
is returned. If also a function \(\text{dosub}\) is given, maximal subgroups are only attempted if this function
returns true (this is separated for performance reasons). In the example below, the result would be the same with leaving out the fourth function, but calculation this way is slightly faster.

### 39.20.7 ContainedConjugates

\[ \text{ContainedConjugates}(G, A, B) \]

For \( A, B \leq G \) this operation returns representatives of the \( A \) conjugacy classes of subgroups that are conjugate to \( B \) under \( G \). The function returns a list of pairs of subgroup and conjugating element.

**Example**

```gap
g:=SymmetricGroup(8);;
a:=TransitiveGroup(8,47);;b:=TransitiveGroup(8,7);;
ContainedConjugates(g,a,b);
```

\[ \left[ \left[ \text{Group}\left( \begin{array}{c} (1,4,2,5,3,6,8,7), (1,3)(2,8) \end{array} \right) \right], (2,4,5,3)(7,8) \right] \]

### 39.20.8 ContainingConjugates

\[ \text{ContainingConjugates}(G, A, B) \]

For \( A, B \leq G \) this operation returns all \( G \) conjugates of \( A \) that contain \( B \). The function returns a list of pairs of subgroup and conjugating element.

**Example**

```gap
g:=SymmetricGroup(8);;
a:=TransitiveGroup(8,47);;b:=TransitiveGroup(8,7);;
ContainingConjugates(g,a,b);
```

\[ \left[ \left[ \text{Group}\left( \begin{array}{c} (1,4,2,5,3,6,8,7), (1,3)(2,8) \end{array} \right) \right], (2,4,5,3)(7,8) \right] \]

### 39.20.9 MinimalFaithfulPermutationDegree

\[ \text{MinimalFaithfulPermutationDegree}(G) \]

For a finite group \( G \) this operation calculates the least positive integer \( n = \mu(G) \) such that \( G \) is isomorphic to a subgroup of the symmetric group of degree \( n \). This can require calculating the whole subgroup lattice.

**Example**

```gap
MinimalFaithfulPermutationDegree(SmallGroup(96,3));
```

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### 39.20.10 RepresentativesPerfectSubgroups

\[ \text{RepresentativesPerfectSubgroups}(G) \]

\[ \text{RepresentativesSimpleSubgroups}(G) \]

returns a list of conjugacy representatives of perfect (respectively simple) subgroups of \( G \). This uses the library of perfect groups (see \texttt{PerfectGroup} (50.6.2)), thus it will issue an error if the library is insufficient to determine all perfect subgroups.
```gap
gap> m11:=TransitiveGroup(11,6);
M(11)
gap> r:=RepresentativesPerfectSubgroups(m11);;
gap> List(r,Size);
[ 60, 60, 360, 660, 7920, 1 ]
gap> List(r,StructureDescription);
[ "A5", "A5", "A6", "PSL(2,11)", "M11", "1" ]
```

### 39.20.11 ConjugacyClassesPerfectSubgroups

returns a list of the conjugacy classes of perfect subgroups of \( G \). (see `RepresentativesPerfectSubgroups (39.20.10)`.)

```gap
gap> r := ConjugacyClassesPerfectSubgroups(m11);;
gap> List(r, x -> StructureDescription(Representative(x)));
[ "A5", "A5", "A6", "PSL(2,11)", "M11", "1" ]
gap> SortedList( List(r,Size) );
[ 1, 1, 11, 12, 66, 132 ]
```

### 39.20.12 Zuppos

returns a list of the Zuppos of \( G \). (The name “Zuppo” derives from the German abbreviation for “zyklische Untergruppen von Primzahlpotenzordnung”.) This attribute gives generators of all such subgroups of a group \( G \). That is all elements of \( G \) of prime power order up to the equivalence that they generate the same cyclic subgroup.

### 39.20.13 InfoLattice

is the information class used by the cyclic extension methods for subgroup lattice calculations.

### 39.21 Specific Methods for Subgroup Lattice Computations

#### 39.21.1 LatticeByCyclicExtension

computes the lattice of \( G \) using the cyclic extension algorithm. If the function \( \text{func} \) is given, the algorithm will discard all subgroups not fulfilling \( \text{func} \) (and will also not extend them), returning a partial lattice. This can be useful to compute only subgroups with certain properties. Note however that this will not necessarily yield all subgroups that fulfill \( \text{func} \), but the subgroups whose subgroups are used for the construction must also fulfill \( \text{func} \) as well. (In fact the filter \( \text{func} \) will simply
discard subgroups in the cyclic extension algorithm. Therefore the trivial subgroup will always be
included.) Also note, that for such a partial lattice maximality/minimality inclusion relations cannot
be computed. (If \texttt{func} is a list of length 2, its first entry is such a discarding function, the second a
function for discarding zuppos.)

The cyclic extension algorithm requires the perfect subgroups of \(G\). However \texttt{GAP}\ cannot analyze
the function \texttt{func} for its implication but can only apply it. If it is known that \texttt{func} implies solvability,
the computation of the perfect subgroups can be avoided by giving a third parameter \texttt{noperf} set to
true.

\begin{verbatim}
Example

gap> g:=WreathProduct(Group((1,2,3),(1,2)),Group((1,2,3,4)));
gap> l:=LatticeByCyclicExtension(g,function(G)
> return Size(G) in [1,2,3,6];end);
<subgroup lattice of <permutation group of size 5184 with
9 generators>, 47 classes,
2628 subgroups, restricted under further condition l!.func>

The total number of classes in this example is much bigger, as the following example shows:

Example

gap> LatticeSubgroups(g);
<subgroup lattice of <permutation group of size 5184 with
9 generators>, 566 classes, 27134 subgroups>
\end{verbatim}

##

39.21.2 InvariantSubgroupsElementaryAbelianGroup

\begin{verbatim}

Example

gap> g:=Group((1,2,3),(4,5,6),(7,8,9));
gap> hom:=GroupHomomorphismByImages(g,g,[[(1,2,3),(4,5,6),(7,8,9)]]);
> [ [ (1,2,3), (4,5,6), (7,8,9) ] ] -> [ (7,8,9), (1,2,3), (4,5,6) ]

Example

gap> u:=InvariantSubgroupsElementaryAbelianGroup(g,[hom]);
[ Group([ (1,2,3) ]), Group([ (1,2,3) ]), Group([ (4,5,6) ]),
  Group([ (7,8,9) ]), Group([ (7,8,9),(4,5,6) ]), Group([ (7,8,9),(1,2,3) ]) ]
\end{verbatim}

39.21.3 SubgroupsSolvableGroup

\begin{verbatim}

Example

\end{verbatim}
This function (implementing the algorithm published in [Hul99]) computes subgroups of a solvable group \( G \), using the homomorphism principle. It returns a list of representatives up to \( G \)-conjugacy.

The optional argument \( \text{opt} \) is a record, which may be used to suggest restrictions on the subgroups computed. The following record components of \( \text{opt} \) are recognized and have the following effects.

Note that all of the following restrictions to subgroups with particular properties are only used to speed up the calculation, but the result might still contain subgroups (that had to be computed in any case) that do not satisfy the properties. If this is not desired, the calculation must be followed by an explicit test for the desired properties (which is not done by default, as it would be a general slowdown). The function guarantees that representatives of all subgroups that satisfy the properties are found, i.e. there can be only false positives.

- **actions**
  - must be a list of automorphisms of \( G \). If given, only groups which are invariant under all these automorphisms are computed. The algorithm must know the normalizer in \( G \) of the group generated by \( \text{actions} \) (defined formally by embedding in the semidirect product of \( G \) with \( \text{actions} \)). This can be given in the component \( \text{funcnorm} \) and will be computed if this component is not given.

- **normal**
  - if set to \( \text{true} \) only normal subgroups are guaranteed to be returned (though some of the returned subgroups might still be not normal).

- **consider**
  - a function to restrict the groups computed. This must be a function of five parameters, \( C, A, N, B, M \), that are interpreted as follows: The arguments are subgroups of a factor \( F \) of \( G \) in the relation \( F \geq C > A > N > B > M \). \( N \) and \( M \) are normal subgroups. \( C \) is the full preimage of the normalizer of \( A/N \) in \( F/N \). When computing modulo \( M \) and looking for subgroups \( U \) such that \( U \cap N = B \) and \( \langle U, N \rangle = A \), this function is called. If it returns \( \text{false} \) then all potential groups \( U \) (and therefore all groups later arising from them) are disregarded. This can be used for example to compute only subgroups of certain sizes.

  \( \text{(This is just a restriction to speed up computations. The function may still return (invariant) subgroups which don't fulfill this condition!)} \) This parameter is used to permit calculations of some subgroups if the set of all subgroups would be too large to handle.

  The actual groups \( C, A, N \) and \( B \) which are passed to this function are not necessarily subgroups of \( G \) but might be subgroups of a proper factor group \( F = G/H \). Therefore the \( \text{consider} \) function may not relate the parameter groups to \( G \).

- **retnorm**
  - if set to \( \text{true} \) the function not only returns a list \( \text{subs} \) of subgroups but also a corresponding list \( \text{norms} \) of normalizers in the form \( [ \text{subs}, \text{norms} ] \).

- **series**
  - is an elementary abelian series of \( G \) which will be used for the computation.

- **groups**
  - is a list of groups to seed the calculation. Only subgroups of these groups are constructed.

\begin{example}
\begin{verbatim}
g:=Group([1,2,3],[1,2],[4,5,6],[4,5],[7,8,9],[7,8]);
Group([ [ 1, 2, 3 ], [ 1, 2 ], [ 4, 5, 6 ], [ 4, 5 ], [ 7, 8, 9 ], [ 7, 8 ] ])
\end{verbatim}
\end{example}
[248x762]576
[90x726]gap> hom:=GroupHomomorphismByImages(g,g,
> [(1,2,3),(1,2),(4,5,6),(4,5),(7,8,9),(7,8)],
> [(4,5,6),(4,5),(7,8,9),(7,8),(1,2,3),(1,2)]);
> [(1,2,3), (1,2), (4,5,6), (4,5), (7,8,9), (7,8)] ->
> [(4,5,6), (4,5), (7,8,9), (7,8), (1,2,3), (1,2)]
gap> l:=SubgroupsSolvableGroup(g,rec(actions:=[hom]));;
gap> List(l,Size);
gap> Length(ConjugacyClassesSubgroups(g)); # to compare
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39.21.4 SizeConsiderFunction

This function returns a function consider of four arguments that can be used in
SubgroupsSolvableGroup (39.21.3) for the option consider to compute subgroups whose sizes
are divisible by size.

Example

\begin{verbatim}
gap> l:=SubgroupsSolvableGroup(g,rec(actions:=[hom],
> consider:=SizeConsiderFunction(6));;
gap> List(l,Size);
[ 1, 3, 9, 27, 54, 6, 18, 108, 216 ]
\end{verbatim}

This example shows that in general the consider function does not provide a perfect filter. It is
guaranteed that all subgroups fulfilling the condition are returned, but not all subgroups returned
necessarily fulfill the condition.

39.21.5 ExactSizeConsiderFunction

This function returns a function consider of four arguments that can be used in
SubgroupsSolvableGroup (39.21.3) for the option consider to compute subgroups whose sizes
are exactly size.

Example

\begin{verbatim}
gap> l:=SubgroupsSolvableGroup(g,rec(actions:=[hom],
> consider:=ExactSizeConsiderFunction(6));;
gap> List(l,Size);
[ 1, 3, 9, 27, 54, 6, 108, 216 ]
\end{verbatim}

Again, the consider function does not provide a perfect filter. It is guaranteed that all subgroups
fulfilling the condition are returned, but not all subgroups returned necessarily fulfill the condition.

39.21.6 InfoPcSubgroup

Information function for the subgroup lattice functions using pcgs.
39.22 Special Generating Sets

39.22.1 GeneratorsSmallest

\textbf{GeneratorsSmallest}(G) \\
\text{(attribute)}

returns a “smallest” generating set for the group \( G \). This is the lexicographically (using GAP's order of group elements) smallest list \( l \) of elements of \( G \) such that \( G = \langle l \rangle \) and \( l_i \notin \langle l_1, \ldots, l_{i-1} \rangle \) (in particular \( l_1 \) is not the identity element of the group). The comparison of two groups via lexicographic comparison of their sorted element lists yields the same relation as lexicographic comparison of their smallest generating sets.

\texttt{gap> g:=SymmetricGroup(4);;}
\texttt{gap> GeneratorsSmallest(g);}
\texttt{[ (3,4), (2,3), (1,2) ]}

39.22.2 LargestElementGroup

\textbf{LargestElementGroup}(G) \\
\text{(attribute)}

returns the largest element of \( G \) with respect to the ordering \(<\) of the elements family.

39.22.3 MinimalGeneratingSet

\textbf{MinimalGeneratingSet}(G) \\
\text{(attribute)}

returns a generating set of \( G \) of minimal possible length.

Note that –apart from special cases– currently there are only efficient methods known to compute minimal generating sets of finite solvable groups and of finitely generated nilpotent groups. Hence so far these are the only cases for which methods are available. The former case is covered by a method implemented in the GAP library, while the second case requires the package Polycyclic.

If you do not really need a minimal generating set, but are satisfied with getting a reasonably small set of generators, you better use \texttt{SmallGeneratingSet} \texttt{(39.22.4)}.

Information about the minimal generating sets of the finite simple groups of order less than \( 10^6 \) can be found in \cite{MY79}. See also the package \texttt{AtlasRep}.

\texttt{gap> MinimalGeneratingSet(g);}
\texttt{[ (2,4,3), (1,4,2,3) ]}

39.22.4 SmallGeneratingSet

\textbf{SmallGeneratingSet}(G) \\
\text{(attribute)}

returns a generating set of \( G \) which has few elements. As neither irredundancy, nor minimal length is proven it runs much faster than \texttt{MinimalGeneratingSet} \texttt{(39.22.3)}. It can be used whenever a short generating set is desired which not necessarily needs to be optimal.

\texttt{gap> SmallGeneratingSet(g);}
\texttt{[ (1,2,3,4), (1,2) ]}
39.22.5 IndependentGeneratorsOfAbelianGroup

\( \text{IndependentGeneratorsOfAbelianGroup}(A) \) (attribute)

returns a list of generators \( a_1, a_2, \ldots \) of prime power order or infinite order of the abelian group \( A \) such that \( A \) is the direct product of the cyclic groups generated by the \( a_i \). The list of orders of the returned generators must match the result of AbelianInvariants (39.16.1) (taking into account that zero and infinity (18.2.1) are identified).

Example

\begin{verbatim}
gap> g := AbelianGroup(IsPermGroup, [15,14,22,78]);
gap> List(IndependentGeneratorsOfAbelianGroup(g), Order);
[ 2, 2, 2, 3, 3, 5, 7, 11, 13 ]
gap> AbelianInvariants(g);
[ 2, 2, 2, 3, 3, 5, 7, 11, 13 ]
\end{verbatim}

39.22.6 IndependentGeneratorExponents

\( \text{IndependentGeneratorExponents}(G, g) \) (operation)

For an abelian group \( G \), with \( \text{IndependentGeneratorsOfAbelianGroup} (39.22.5) \) value the list \( a_1, \ldots, a_n \), this operation returns the exponent vector \( e_1, \ldots, e_n \) to represent \( g = \prod a_i^{e_i} \).

Example

\begin{verbatim}
gap> g := AbelianGroup([16,9,625]);
gap> gens := IndependentGeneratorsOfAbelianGroup(g);
gap> List(gens, Order);
[ 9, 16, 625 ]
gap> AbelianInvariants(g);
[ 9, 16, 625 ]
gap> IndependentGeneratorExponents(g, r);
[ 4, 12, 128 ]
\end{verbatim}

39.23 1-Cohomology

Let \( G \) be a finite group and \( M \) an elementary abelian normal \( p \)-subgroup of \( G \). Then the group of 1-cocycles \( Z^1(G/M, M) \) is defined as

\[ Z^1(G/M, M) = \{ \gamma : G/M \to M \mid \forall g_1, g_2 \in G : \gamma(g_1M \cdot g_2M) = \gamma(g_1M)^{g_2} \cdot \gamma(g_2M) \} \]

and is a \( GF(p) \)-vector space.

The group of 1-coboundaries \( B^1(G/M, M) \) is defined as

\[ B^1(G/M, M) = \{ \gamma : G/M \to M \mid \exists m \in M \forall g \in G : \gamma(gM) = (m^{-1})^g \cdot m \} \]

It also is a \( GF(p) \)-vector space.

Let \( \alpha \) be the isomorphism of \( M \) into a row vector space \( \mathcal{W} \) and \( (g_1, \ldots, g_l) \) representatives for a generating set of \( G/M \). Then there exists a monomorphism \( \beta \) of \( Z^1(G/M, M) \) in the \( l \)-fold direct sum of \( \mathcal{W} \), such that \( \beta(\gamma) = (\alpha(\gamma(g_1M)), \ldots, \alpha(\gamma(g_lM))) \) for every \( \gamma \in Z^1(G/M, M) \).
39.23.1 OneCocycles

- \texttt{OneCocycles(}G, M\texttt{)}
- \texttt{OneCocycles(}G, mpcgs\texttt{)}
- \texttt{OneCocycles(}gens, M\texttt{)}
- \texttt{OneCocycles(}gens, mpcgs\texttt{)}

Computes the group of 1-cocycles \(Z^1(G/M, M)\). The normal subgroup \(M\) may be given by a (Modulo)Pcgs \(mpcgs\). In this case the whole calculation is performed modulo the normal subgroup defined by \texttt{DenominatorOfModuloPcgs(mpcgs)} (see 45.1). Similarly the group \(G\) may instead be specified by a set of elements \texttt{gens} that are representatives for a generating system for the factor group \(G/M\). If this is done the 1-cocycles are computed with respect to these generators (otherwise the routines try to select suitable generators themselves). The current version of the code assumes that \(G\) is a permutation group or a pc group.

39.23.2 OneCoboundaries

- \texttt{OneCoboundaries(}G, M\texttt{)}

computes the group of 1-coboundaries. Syntax of input and output otherwise is the same as with \texttt{OneCocycles (39.23.1)} except that entries that refer to cocycles are not computed.

The operations \texttt{OneCocycles (39.23.1)} and \texttt{OneCoboundaries} return a record with (at least) the components:

- \texttt{generators}
  Is a list of representatives for a generating set of \(G/M\). Cocycles are represented with respect to these generators.

- \texttt{oneCocycles}
  A space of row vectors over GF(\(p\)), representing \(Z^1\). The vectors are represented in dimension \(a \cdot b\) where \(a\) is the length of \texttt{generators} and \(p^b\) the size of \(M\).

- \texttt{oneCoboundaries}
  A space of row vectors that represents \(B^1\).

- \texttt{cocycleToList}
  is a function to convert a cocycle (a row vector in \texttt{oneCocycles}) to a corresponding list of elements of \(M\).

- \texttt{listToCocycle}
  is a function to convert a list of elements of \(M\) to a cocycle.

- \texttt{isSplitExtension}
  indicates whether \(G\) splits over \(M\). The following components are only bound if the extension splits. Note that if \(M\) is given by a modulo pcgs all subgroups are given as subgroups of \(G\) by generators corresponding to \texttt{generators} and thus may not contain the denominator of the modulo pcgs. In this case taking the closure with this denominator will give the full preimage of the complement in the factor group.
complement
One complement to \( M \) in \( G \).

cocycleToComplement( cyc )
is a function that takes a cocycle from oneCocycles and returns the corresponding complement to \( M \) in \( G \) (with respect to the fixed complement complement).

complementToCocycle( U )
is a function that takes a complement and returns the corresponding cocycle.

If the factor \( G/M \) is given by a (modulo) pcgs gens then special methods are used that compute a presentation for the factor implicitly from the pcgs.

Note that the groups of 1-cocycles and 1-coboundaries are not groups in the sense of Group (39.2.1) for GAP but vector spaces.

**Example**

```gap
g:=Group((1,2,3,4),(1,2));;
n:=Group((1,2)(3,4),(1,3)(2,4));;
oc:=OneCocycles(g,n);
rec( cocycleToComplement := function( c ) ... end,
cocycleToList := function( c ) ... end,
complement := Group([ (3,4), (2,4,3) ]),
complementGens := [ (3,4), (2,4,3) ],
complementToCocycle := function( K ) ... end,
factorGens := [ (3,4), (2,4,3) ], generators := [ (3,4), (2,4,3) ],
isSplitExtension := true, listToCocycle := function( L ) ... end,
oneCoboundaries := <vector space over GF(2), with 2 generators>,
oneCycles := <vector space over GF(2), with 2 generators>)
go.cocycleToList([0*Z(2), Z(2)^0, 0*Z(2), Z(2)^0]);
[ (1,2)(3,4), (1,2)(3,4) ]
go.cocycleToComplement([0*Z(2), 0*Z(2), Z(2)^0, 0*Z(2)]);
true
go.complementToCocycle([(),(1,3)(2,4)]) = Z(2) * [ 0, 0, 1, 0];
true
Group([ (3,4), (1,3,4) ])
go.complementToCocycle(Group((1,2,4),(1,4))) = Z(2) * [ 0, 1, 1, 1 ];
true
```

The factor group \( H^1(G/M,M) = Z^1(G/M,M)/B^1(G/M,M) \) is called the first cohomology group. Currently there is no function which explicitly computes this group. The easiest way to represent it is as a vector space complement to \( B^1 \) in \( Z^1 \).

If the only purpose of the calculation of \( H^1 \) is the determination of complements it might be desirable to stop calculations once it is known that the extension cannot split. This can be achieved via the more technical function OConOneCycles (39.23.3).

### 39.23.3 OConOneCycles

\( \text{OConOneCycles}(ocr, \text{onlySplit}) \)

is the more technical function to compute 1-cocycles. It takes a record \( ocr \) as first argument which must contain at least the components group for the group and modulePcgs for a (modulo) pcgs of the module. This record will also be returned with components as described under OneCocycles (39.23.1).
(with the exception of isSplitExtension which is indicated by the existence of a complement) but components such as oneCoboundaries will only be computed if not already present.

If onlySplit is true, UOneCocycles returns false as soon as possible if the extension does not split.

### 39.23.4 ComplementClassesRepresentativesEA

```
\[ \text{ComplementClassesRepresentativesEA}(G, N)(\text{function}) \]
```

computes complement classes to an elementary abelian normal subgroup \( N \) via 1-Cohomology. Normally, a user program should call ComplementClassesRepresentatives (39.11.6) instead, which also works for a solvable (not necessarily elementary abelian) \( N \).

### 39.23.5 InfoCoh

```
\[ \text{InfoCoh}(\text{info class}) \]
```

The info class for the cohomology calculations is InfoCoh.

### 39.24 Schur Covers and Multipliers

Additional attributes and properties of a group can be derived from computing its Schur cover. For example, if \( G \) is a finitely presented group, the derived subgroup of a Schur cover of \( G \) is invariant and isomorphic to the NonabelianExteriorSquare (39.24.5) value of \( G \), see [BJR87].

### 39.24.1 EpimorphismSchurCover

```
\[ \text{EpimorphismSchurCover}(G[, pl])(\text{attribute}) \]
```

returns an epimorphism \( epi \) from a group \( D \) onto \( G \). The group \( D \) is one (of possibly several) Schur covers of \( G \). The group \( D \) can be obtained as the Source (32.3.8) value of \( epi \). The kernel of \( epi \) is the Schur multiplier of \( G \). If \( pl \) is given as a list of primes, only the multiplier part for these primes is realized. At the moment, \( D \) is represented as a finitely presented group.

### 39.24.2 SchurCover

```
\[ \text{SchurCover}(G)(\text{attribute}) \]
```

returns one (of possibly several) Schur covers of the group \( G \).

At the moment this cover is represented as a finitely presented group and IsomorphismPermGroup (43.3.1) would be needed to convert it to a permutation group.

If also the relation to \( G \) is needed, EpimorphismSchurCover (39.24.1) should be used.

**Example**

```gap
g:=Group((1,2,3,4),(1,2));;
epi:=EpimorphismSchurCover(g);
[ F1, F2, F3 ] -> [ (1,2), (2,3), (3,4) ]
gap> Size(Source(epi));
48
```
If the group becomes bigger, Schur Cover calculations might become unfeasible.

There is another operation, AbelianInvariantsMultiplier (39.24.3), which only returns the structure of the Schur Multiplier, and which should work for larger groups as well.

39.24.3 AbelianInvariantsMultiplier

\[ \text{AbelianInvariantsMultiplier}(G) \]

returns a list of the abelian invariants of the Schur multiplier of \( G \).

At the moment, this operation will not give any information about how to extend the multiplier to a Schur Cover.

(Note that the last command from the example will take some time.)

The GAP 4.4.12 manual contained examples for larger groups e.g. \( M_{22} \). However, some issues that may very rarely (and not easily reproducibly) lead to wrong results were discovered in the code capable of handling larger groups, and in GAP 4.5 it was replaced by a more reliable basic method. To deal with larger groups, one can use the function SchurMultiplier (cohomolo: SchurMultiplier) from the cohomolo package. Also, additional methods for AbelianInvariantsMultiplier are installed in the Polycyclic package for pcp-groups.

39.24.4 Epicentre

\[ \text{Epicentre}(G) \]
\[ \text{ExteriorCentre}(G) \]

There are various ways of describing the epicentre of a group \( G \). It is the smallest normal subgroup \( N \) of \( G \) such that \( G/N \) is a central quotient of a group. It is also equal to the Exterior Center of \( G \), see [Ell98].
39.24.5 NonabelianExteriorSquare

\[
\text{NonabelianExteriorSquare}(G)
\]

(operation)

Computes the nonabelian exterior square \( G \wedge G \) of the group \( G \), which for a finitely presented group is the derived subgroup of any Schur cover of \( G \) (see [BJR87]).

39.24.6 EpimorphismNonabelianExteriorSquare

\[
\text{EpimorphismNonabelianExteriorSquare}(G)
\]

(operation)

Computes the mapping \( G \wedge G \to G \). The kernel of this mapping is equal to the Schur multiplier of \( G \).

39.24.7 IsCentralFactor

\[
\text{IsCentralFactor}(G)
\]

(property)

This function determines if there exists a group \( H \) such that \( G \) is isomorphic to the quotient \( H/Z(H) \). A group with this property is called in literature capable. A group being capable is equivalent to the epicentre of \( G \) being trivial, see [BFS79].

39.24.8 Covering groups of symmetric groups

The covering groups of symmetric groups were classified in [Sch11]; an inductive procedure to construct faithful, irreducible representations of minimal degree over all fields was presented in [Maa10]. Methods for EpimorphismSchurCover (39.24.1) are provided for natural symmetric groups which use these representations. For alternating groups, the restriction of these representations are provided, but they may not be irreducible. In the case of degree 6 and 7, they are not the full covering groups and so matrix representations are just stored explicitly for the six-fold covers.

Example

<table>
<thead>
<tr>
<th>Command</th>
<th>Output</th>
</tr>
</thead>
</table>
| gap> EpimorphismSchurCover(SymmetricGroup(15)); | \[
\text{< immutable compressed matrix 64x64 over GF(9) >},
\text{< immutable compressed matrix 64x64 over GF(9) >} \] ->
\[ (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15), (1,2) \]
| gap> EpimorphismSchurCover(AlternatingGroup(15)); | \[
\text{< immutable compressed matrix 64x64 over GF(9) >},
\text{< immutable compressed matrix 64x64 over GF(9) >} \] ->
\[ (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15), (13,14,15) \]
| gap> SchurCoverOfSymmetricGroup(12); | \[\text{<matrix group of size 968003200 with 2 generators}>\]
| gap> DoubleCoverOfAlternatingGroup(12); | \[\text{<matrix group of size 479001600 with 2 generators}>\]
| gap> BasicSpinRepresentationOfSymmetricGroup(10, 3, -1); | \[
\text{< immutable compressed matrix 16x16 over GF(9) >},
\text{< immutable compressed matrix 16x16 over GF(9) >},
\text{< immutable compressed matrix 16x16 over GF(9) >},
\text{< immutable compressed matrix 16x16 over GF(9) >},
\text{< immutable compressed matrix 16x16 over GF(9) >},
\text{< immutable compressed matrix 16x16 over GF(9) >},\]
39.24.9 BasicSpinRepresentationOfSymmetricGroup

\[ \text{BasicSpinRepresentationOfSymmetricGroup}(n, p, \text{sign}) \]

Constructs the image of the Coxeter generators in the basic spin (projective) representation of the symmetric group of degree \( n \) over a field of characteristic \( p \geq 0 \). There are two such representations and \( \text{sign} \) controls which is returned: +1 gives a group where the preimage of an adjacent transposition \((i, i+1)\) has order 4, -1 gives a group where the preimage of an adjacent transposition \((i, i+1)\) has order 2. If no \( \text{sign} \) is specified, +1 is used by default. If no \( p \) is specified, 3 is used by default. (Note that the convention of which cover is labelled as +1 is inconsistent in the literature.)

39.24.10 SchurCoverOfSymmetricGroup

\[ \text{SchurCoverOfSymmetricGroup}(n, p, \text{sign}) \]

Constructs a Schur cover of \( \text{SymmetricGroup}(n) \) as a faithful, irreducible matrix group in characteristic \( p (p \neq 2) \). For \( n \geq 4 \), there are two such covers, and \( \text{sign} \) determines which is returned: +1 gives a group where the preimage of an adjacent transposition \((i, i+1)\) has order 4, -1 gives a group where the preimage of an adjacent transposition \((i, i+1)\) has order 2. If no \( \text{sign} \) is specified, +1 is used by default. If no \( p \) is specified, 3 is used by default. (Note that the convention of which cover is labelled as +1 is inconsistent in the literature.) For \( n \leq 3 \), the symmetric group is its own Schur cover and \( \text{sign} \) is ignored. For \( p = 2 \), there is no faithful, irreducible representation of the Schur cover unless \( n = 1 \) or \( n = 3 \), so \text{fail} is returned if \( p = 2 \). For \( p = 3 \), \( n = 3 \), the representation is indecomposable, but reducible. The field of the matrix group is generally \( \text{GF}(p^2) \) if \( p > 0 \), and an abelian number field if \( p = 0 \).

39.24.11 DoubleCoverOfAlternatingGroup

\[ \text{DoubleCoverOfAlternatingGroup}(n, p) \]

Constructs a double cover of \( \text{AlternatingGroup}(n) \) as a faithful, completely reducible matrix group in characteristic \( p (p \neq 2) \) for \( n \geq 4 \). For \( n \leq 3 \), the alternating group is its own Schur cover, and \text{fail} is returned. For \( p = 2 \), there is no faithful, completely reducible representation of the double cover, so \text{fail} is returned. The field of the matrix group is generally \( \text{GF}(p^2) \) if \( p > 0 \), and an abelian number field if \( p = 0 \). If \( p \) is omitted, the default is 3.

39.25 2-Cohomology

39.25.1 TwoCohomologyGeneric

\[ \text{TwoCohomologyGeneric}(G, M) \]

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This function computes the second cohomology group for an arbitrary finite group \( G \). The generators of the module \( M \) must correspond to the generators of \( G \). It returns a record with components coboundaries, cocycles and cohomology which are lists of vectors that form a basis of the respective group. cohomology is chosen as a vector space complement to coboundaries in the cocycles. These vectors are representing tails in \( M \) with respect to the relators of the presentation presentation of \( G \). (Note that this presentation is on a generating set chosen by the routine, this generating system corresponds to the components group and module of the record returned. The extension corresponding to a cocyle \( c \) can be constructed as Extension(\( r, c \)) where \( r \) is the cohomology record. This is currently done as a finitely presented group.

```gap
gap> g:=Group((1,2,3,4,5),(1,2,3));;
gap> mats:=[[[2,0,0,1],[1,2,1,0],[2,1,1,1],[2,1,1,0]]*Z(3)^0;;
gap> mo:=GModuleByMats(mats,GF(3));;
gap> coh:=TwoCohomologyGeneric(g,mo,);
gap> coh.cocycles;
[ < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) > ]
gap> coh.coboundaries;
[ < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) >, < immutable compressed vector length 44 over GF(3) > ]
gap> coh.cohomology;
[ < immutable compressed vector length 44 over GF(3) > ]
gap> g1:=FpGroupCocycle(coh,coh.zero,true);
<fp group of size 4860 on the generators [ F1, F2, F3, m1, m2, m3, m4 ]>
gap> g2:=FpGroupCocycle(coh,coh.cohomology[1],true);
<fp group of size 4860 on the generators [ F1, F2, F3, m1, m2, m3, m4 ]>
gap> g1:=Image(IsomorphismPermGroup(g1));
<permutation group with 7 generators>
gap> Length(ComplementClassesRepresentatives(g1,RadicalGroup(g1))); 3
gap> g2:=Image(IsomorphismPermGroup(g2));
<permutation group with 7 generators>
gap> Length(ComplementClassesRepresentatives(g2,RadicalGroup(g2))); 0
```

### Example

39.25.2 FpGroupCocycle

\( \text{FpGroupCocycle}(r, c[, doperm]) \)
For a record \( r \) as returned by \TwoCohomologyGeneric (39.25.1) and a vector \( c \) in the space of two-cocycles, this operation returns a finitely presented group that is an extension corresponding to the cocycle \( c \). If the underlying module has dimension \( d \), the last \( d \) generators generate the normal subgroup. If the optional parameter \( doperm \) is given as \texttt{true}, a faithful permutation representation is computed and stored in the attribute \texttt{IsomorphismPermGroup} (43.3.1) of the computed group.

\begin{verbatim}
Example
\gap> g:=Group((2,15,8,16)(3,17,14,21)(4,23,20,6)(5,9,22,11)(7,13,19,25),
> (2,12,7,17)(3,18,13,23)(4,24,19,9)(5,10,25,15)(6,11,16,21));
\gap> StructureDescription(g);
"GL(2,5)"
\gap> mats:=[[[1,1,0,2],[2,0,0,0],[0,2,2,0],[0,1,0,0]],
> [[0,0,0,1],[1,1,2,0],[1,0,2,1],[1,0,1,0]]*Z(3)^0;;
\gap> mo:=GModuleByMats(mats,GF(3));;
\gap> coh:=TwoCohomologyGeneric(g,mo,);
\gap> coh.cohomology;
[ < immutable compressed vector length 116 over GF(3) > ]
\gap> p:=FpGroupCocycle(coh,coh.zero,true);
<fp group of size 38880 on the generators
[ F1, F2, F3, F4, F5, F6, m1, m2, m3, m4 ]>
\gap> g1:=Image(IsomorphismPermGroup(p));
<permutation group with 10 generators>
\gap> Collect\ed(List(MaximalSubgroupClassReps(g1),Size));
\gap> g2:=IsomorphismPermGroup(p);
<permutation group with 10 generators>
\gap> Collect\ed(List(MaximalSubgroupClassReps(g2),Size));
\end{verbatim}

Also see Section 46.8 for operations and methods specific for Pc groups.

\section{Tests for the Availability of Methods}

The following filters and operations indicate capabilities of GAP. They can be used in the method selection or algorithms to check whether it is feasible to compute certain operations for a given group. In general, they return \texttt{true} if good algorithms for the given arguments are available in \GAP. An answer \texttt{false} indicates that no method for this group may exist, or that the existing methods might run into problems.

Typical examples when this might happen is with finitely presented groups, for which many of the methods cannot be guaranteed to succeed in all situations.

The willingness of GAP to perform certain operations may change, depending on which further information is known about the arguments. Therefore the filters used are not implemented as properties but as “other filters” (see 13.7 and 13.8).

\section{CanEasilyTestMembership}

\begin{verbatim}
\gap> CanEasilyTestMembership(G)
\end{verbatim}
This filter indicates whether GAP can test membership of elements in the group $G$ (via the operation \texttt{\textbackslash{}in} (30.6.1)) in reasonable time. It is used by the method selection to decide whether an algorithm that relies on membership tests may be used.

\textbf{39.26.2 CanEasilyComputeWithIndependentGensAbelianGroup}

\texttt{CanEasilyComputeWithIndependentGensAbelianGroup(G)} \hspace{1cm} \text{(filter)}

This filter indicates whether GAP can in reasonable time compute independent abelian generators of the group $G$ (via \texttt{IndependentGeneratorsOfAbelianGroup} (39.22.5)) and then can decompose arbitrary group elements with respect to these generators using \texttt{IndependentGeneratorExponents} (39.22.6). It is used by the method selection to decide whether an algorithm that relies on these two operations may be used.

\textbf{39.26.3 CanComputeSize}

\texttt{CanComputeSize(dom)} \hspace{1cm} \text{(filter)}

This filter indicates that we know that the size of the domain $dom$ (which might be \texttt{infinity} (18.2.1)) can be computed reasonably easily. It doesn’t imply as quick a computation as \texttt{HasSize} would but its absence does not imply that the size cannot be computed.

\textbf{39.26.4 CanComputeSizeAnySubgroup}

\texttt{CanComputeSizeAnySubgroup(G)} \hspace{1cm} \text{(filter)}

This filter indicates whether GAP can easily compute the size of any subgroup of the group $G$. (This is for example advantageous if one can test that a stabilizer index equals the length of the orbit computed so far to stop early.)

\textbf{39.26.5 CanComputeIndex}

\texttt{CanComputeIndex(G, H)} \hspace{1cm} \text{(operation)}

This function indicates whether the index $[G:H]$ (which might be \texttt{infinity} (18.2.1)) can be computed. It assumes that $H \leq G$ (see \texttt{CanComputeIsSubset} (39.26.6)).

\textbf{39.26.6 CanComputeIsSubset}

\texttt{CanComputeIsSubset(A, B)} \hspace{1cm} \text{(operation)}

This filter indicates that GAP can test (via \texttt{IsSubset} (30.5.1)) whether $B$ is a subset of $A$.

\textbf{39.26.7 KnowsHowToDecompose}

\texttt{KnowsHowToDecompose(G[, gens])} \hspace{1cm} \text{(property)}
Tests whether the group \( G \) can decompose elements in the generators \( \text{gens} \). If \( \text{gens} \) is not given it tests, whether it can decompose in the generators given in the \texttt{GeneratorsOfGroup} (39.2.4) value of \( G \).

This property can be used for example to check whether a group homomorphism by images (see \texttt{GroupHomomorphismByImages} (40.1.1)) can be reasonably defined from this group.

### 39.27 Specific functions for Normalizer calculation

#### 39.27.1 NormalizerViaRadical

\( \triangleright \text{NormalizerViaRadical}(G, S) \)  

This function implements a particular approach, following the SolvableRadical paradigm, for calculating the normalizer of a subgroup \( S \) in \( G \). It is at the moment provided only as a separate function, and not as method for the operation \texttt{Normalizer}, as it can often be slower than other built-in routines. In certain hard cases (non-solvable groups with nontrivial radical), however its performance is substantially superior. The function thus is provided as a non-automated tool for advanced users.

```
\begin{verbatim}
gap> g:=TransitiveGroup(30,2030);;
gap> s:=SylowSubgroup(g,5);;
gap> Size(NormalizerViaRadical(g,s));
28800
\end{verbatim}
```

Note that this example only demonstrates usage, but that in this case in fact the ordinary \texttt{Normalizer} routine performs faster.
Chapter 40

Group Homomorphisms

A group homomorphism is a mapping from one group to another that respects multiplication and inverses. They are implemented as a special class of mappings, so in particular all operations for mappings, such as \texttt{Image (32.4.6)}, \texttt{PreImage (32.5.6)}, \texttt{PreImagesRepresentative (32.5.4)}, \texttt{KernelOfMultiplicativeGeneralMapping (32.9.5)}, \texttt{Source (32.3.8)}, \texttt{Range (32.3.7)}, \texttt{IsInjective (32.3.4)} and \texttt{IsSurjective (32.3.5)} (see chapter 32, in particular section 32.9) are applicable to them.

Homomorphisms can be used to transfer calculations into isomorphic groups in another representation, for which better algorithms are available. Section 40.5 explains a technique how to enforce this automatically.

Homomorphisms are also used to represent group automorphisms, and section 40.6 explains \texttt{GAP}'s facilities to work with automorphism groups.

Section 40.9 explains how to make \texttt{GAP} to search for all homomorphisms between two groups which fulfill certain specifications.

40.1 Creating Group Homomorphisms

The most important way of creating group homomorphisms is to give images for a set of group generators and to extend it to the group generated by them by the homomorphism property.

A second way to create homomorphisms is to give functions that compute image and preimage. (A similar case are homomorphisms that are induced by conjugation. Special constructors for such mappings are described in section 40.6).

The third class are epimorphisms from a group onto its factor group. Such homomorphisms can be constructed by \texttt{NaturalHomomorphismByNormalSubgroup (39.18.1)}.

The fourth class is homomorphisms in a permutation group that are induced by an action on a set. Such homomorphisms are described in the context of group actions, see chapter 41 and in particular \texttt{ActionHomomorphism (41.7.1)}.

40.1.1 GroupHomomorphismByImages

\begin{verbatim}
GroupHomomorphismByImages(G, H[, gens, imgs])
\end{verbatim}

\texttt{GroupHomomorphismByImages} returns the group homomorphism with source \(G\) and range \(H\) that is defined by mapping the list \texttt{gens} of generators of \(G\) to the list \texttt{imgs} of images in \(H\).
If omitted, the arguments `gens` and `imgs` default to the `GeneratorsOfGroup (39.2.4)` value of `G` and `H`, respectively. If `H` is not given the mapping is automatically considered as surjective.

If `gens` does not generate `G` or if the mapping of the generators does not extend to a homomorphism (i.e., if mapping the generators describes only a multi-valued mapping) then `fail` is returned.

This test can be quite expensive. If one is certain that the mapping of the generators extends to a homomorphism, one can avoid the checks by calling `GroupHomomorphismByImagesNC (40.1.2)`. (There also is the possibility to construct potentially multi-valued mappings with `GroupGeneralMappingByImages (40.1.3)` and to test with `IsMapping (32.3.3)` whether they are indeed homomorphisms.)

### 40.1.2 GroupHomomorphismByImagesNC

GroupHomomorphismByImagesNC creates a homomorphism as `GroupHomomorphismByImages (40.1.1)` does, however it does not test whether `gens` generates `G` and that the mapping of `gens` to `imgs` indeed defines a group homomorphism. Because these tests can be expensive it can be substantially faster than `GroupHomomorphismByImages (40.1.1)`. Results are unpredictable if the conditions do not hold.

If omitted, the arguments `gens` and `imgs` default to the `GeneratorsOfGroup (39.2.4)` value of `G` and `H`, respectively.

(For creating a possibly multi-valued mapping from `G` to `H` that respects multiplication and inverses, `GroupGeneralMappingByImages (40.1.3)` can be used.)

<table>
<thead>
<tr>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>gap&gt; gens:=[(1,2,3,4),(1,2)];</td>
</tr>
<tr>
<td>[ (1,2,3,4), (1,2) ]</td>
</tr>
<tr>
<td>gap&gt; g:=Group(gens);</td>
</tr>
<tr>
<td>Group([ (1,2,3,4), (1,2) ])</td>
</tr>
<tr>
<td>gap&gt; h:=Group((1,2,3),(1,2));</td>
</tr>
<tr>
<td>Group([ (1,2,3), (1,2) ])</td>
</tr>
<tr>
<td>gap&gt; hom:=GroupHomomorphismByImages(g,h,gens,[[(1,2),(1,3)]]);</td>
</tr>
<tr>
<td>[ (1,2,3,4), (1,2) ] -&gt; [ (1,2), (1,3) ]</td>
</tr>
<tr>
<td>gap&gt; Image(hom,(1,4));</td>
</tr>
<tr>
<td>(2,3)</td>
</tr>
<tr>
<td>gap&gt; map:=GroupHomomorphismByImagesNC(g,h,gens,[[(1,2),(1,3)]]);</td>
</tr>
<tr>
<td>fail</td>
</tr>
</tbody>
</table>

### 40.1.3 GroupGeneralMappingByImages

returns a general mapping defined by extending the mapping from `gens` to `imgs` homomorphically. If the range `H` is not given the mapping will be made automatically surjective. The NC version does not test whether `gens` are contained in `G` or `imgs` are contained in `H`. 
GroupHomomorphismByImages (40.1.1) creates a group general mapping by images and tests whether it is in IsMapping (32.3.3).

Example

```gap
gap> map:=GroupGeneralMappingByImages(g,h,gens,[[(1,2,3),(1,2)]];
[(1,2,3,4), (1,2)] -> [(1,2,3), (1,2)]
gap> IsMapping(map);
false
```

40.1.4 GroupHomomorphismByFunction

GroupHomomorphismByFunction returns a group homomorphism \( \text{hom} \) with source \( S \) and range \( R \), such that each element \( s \) of \( S \) is mapped to the element \( \text{fun}(s) \), where \( \text{fun} \) is a GAP function.

If the argument \( \text{invfun} \) is bound then \( \text{hom} \) is a bijection between \( S \) and \( R \), and the preimage of each element \( r \) of \( R \) is given by \( \text{invfun}(r) \), where \( \text{invfun} \) is a GAP function.

If five arguments are given and the fourth argument is false then the GAP function \( \text{prefun} \) can be used to compute a single preimage also if \( \text{hom} \) is not bijective.

No test is performed on whether the functions actually give an homomorphism between both groups because this would require testing the full multiplication table.

GroupHomomorphismByFunction creates a mapping which lies in IsSPGeneralMapping (32.14.1).

Example

```gap
gap> hom:=GroupHomomorphismByFunction(g,h,
> function(x) if SignPerm(x)=-1 then return (1,2); else return ();fi;end);
MappingByFunction( Group([ (1,2,3,4), (1,2) ]), Group(
[ (1,2,3), (1,2) ]), function( x ) ... end )
gap> ImagesSource(hom);
Group([ (1,2), (1,2) ])
gap> Image(hom,(1,2,3,4));
(1,2)
```

40.1.5 AsGroupGeneralMappingByImages

AsGroupGeneralMappingByImages (map)

If \( \text{map} \) is a mapping from one group to another this attribute returns a group general mapping that implements the same abstract mapping. (Some operations can be performed more effective in this representation, see also IsGroupGeneralMappingByAsGroupGeneralMappingByImages (40.10.3.).)

Example

```gap
AsGroupGeneralMappingByImages(hom);
[(1,2,3,4), (1,2)] -> [(1,2), (1,2)]
```
40.2 Operations for Group Homomorphisms

Group homomorphisms are mappings, so all the operations and properties for mappings described in chapter 32 are applicable to them. (However often much better methods, than for general mappings are available.)

Group homomorphisms will map groups to groups by just mapping the set of generators. KernelOfMultiplicativeGeneralMapping (32.9.5) can be used to compute the kernel of a group homomorphism.

Example

```gap
gap> hom:=GroupHomomorphismByImages(g,h,gens,[(1,2),(1,3)]);
_gap> Kernel(hom);
Group([ (1,4)(2,3), (1,2)(3,4) ])
```

Homomorphisms can map between groups in different representations and are also used to get isomorphic groups in a different representation.

Example

```gap
gap> m1:=[[0,-1],[1,0]]; m2:=[[0,-1],[1,1]];
gap> sl2z:=Group(m1,m2); # SL(2,Integers) as matrix group
gap> F:=FreeGroup(2);
gap> psl2z:=F/[F.1^2,F.2^3]; # PSL(2,2) as FP group
<fp group on the generators [ f1, f2 ]>
gap> phom:=GroupHomomorphismByImagesNC(sl2z,psl2z,[m1,m2],
GeneratorsOfGroup(psl2z)); # the non NC-version would be expensive
[ [ [ 0, -1 ], [ 1, 0 ] ], [ [ 0, -1 ], [ 1, 1 ] ] ] -> [ f1, f2 ]
gap> Kernel(phom); # the diagonal matrices
Group([ [ [ -1, 0 ], [ 0, -1 ] ], [ [ -1, 0 ], [ 0, -1 ] ] ])
gap> p1:=(1,2)(3,4); p2:=(2,4,5); a5:=Group(p1,p2);
gap> ahom:=GroupHomomorphismByImagesNC(psl2z,a5,
GeneratorsOfGroup(psl2z),[p1,p2]); # here homomorphism test is cheap.
[ f1, f2 ] -> [ (1,2)(3,4), (2,4,5) ]
gap> u:=PreImage(ahom,Group((1,2,3),(1,2)(4,5)));
Group(<fp, no generators known>)
gap> Index(psl2z,u);
10
```

For an automorphism \( \alpha \), Inverse (31.10.8) returns the inverse automorphism \( \alpha^{-1} \). However if \( \text{hom} \) is a bijective homomorphism between different groups, or if \( \text{hom} \) is injective and considered to be a bijection to its image, the operation InverseGeneralMapping (32.2.3) should be used instead. (See Inverse (31.10.8) for a further discussion of this problem.)

Example

```gap
gap> iso:=IsomorphismPcGroup(g);
Pcgs([ (3,4), (2,4,3), (1,4) (2,3), (1,3) (2,4) ]) -> [ f1, f2, f3, f4 ]
gap> Inverse(iso);
```
#I The mapping must be bijective and have source=range
#I You might want to use 'InverseGeneralMapping'
fail
gap> InverseGeneralMapping(iso);
[ f1, f2, f3, f4 ] -> Pcgs([ (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ])

40.3 Efficiency of Homomorphisms

GAP permits to create homomorphisms between arbitrary groups. This section considers the efficiency of the implementation and shows ways how to choose suitable representations. For permutation groups (see 43) or Pc groups (see 46) this is normally nothing to worry about, unless the groups get extremely large. For other groups however certain calculations might be expensive and some precaution might be needed to avoid unnecessarily expensive calculations.

In short, it is always worth to tell a mapping that it is a homomorphism (this can be done by calling SetIsMapping) (or to create it directly with GroupHomomorphismByImagesNC (40.1.2)).

The basic operations required are to compute image and preimage of elements and to test whether a mapping is a homomorphism. Their cost will differ depending on the type of the mapping.

40.3.1 Mappings given on generators

See GroupHomomorphismByImages (40.1.1) and GroupGeneralMappingByImages (40.1.3).

Computing images requires to express an element of the source as word in the generators. If it cannot be done effectively (this is determined by KnowsHowToDecompose (39.26.7) which returns true for example for arbitrary permutation groups, for Pc groups or for finitely presented groups with the images of the free generators) the span of the generators has to be computed elementwise which can be very expensive and memory consuming.

Computing preimages adheres to the same rules with swapped rôles of generators and their images.

The test whether a mapping is a homomorphism requires the computation of a presentation for the source and evaluation of its relators in the images of its generators. For larger groups this can be expensive and GroupHomomorphismByImagesNC (40.1.2) should be used if the mapping is known to be a homomorphism.

40.3.2 Action homomorphisms

See ActionHomomorphism (41.7.1).

The calculation of images is determined by the acting function used and –for large domains– is often dominated by the search for the position of an image in a list of the domain elements. This can be improved by sorting this list if an efficient method for \(<\) (31.11.1) to compare elements of the domain is available.

Once the images of a generating set are computed, computing preimages (which is done via AsGroupGeneralMappingByImages (40.1.5)) and computing the kernel behaves the same as for a homomorphism created with GroupHomomorphismByImages (40.1.1) from a permutation group.

GAP will always assume that the acting function provided implements a proper group action and thus that the mapping is indeed a homomorphism.
40.3.3 Mappings given by functions

See GroupHomomorphismByFunction (40.1.4).
Computing images is wholly determined by the function that performs the image calculation. If no function to compute preimages is given, computing preimages requires mapping every element of the source to find an element that maps to the requested image. This is time and memory consuming.

40.3.4 Other operations

To compute the kernel of a homomorphism (unless the mapping is known to be injective) requires the capability to compute a presentation of the image and to evaluate the relators of this presentation in preimages of the presentations generators.

The calculation of the Image (32.4.6) (respectively ImagesSource (32.4.1)) value requires to map a generating set of the source, testing surjectivity is a comparison for equality with the range.

Testing injectivity is a test for triviality of the kernel.

The comparison of mappings is based on a lexicographic comparison of a sorted element list of the source. For group homomorphisms, this can be simplified, using ImagesSmallestGenerators (40.3.5)

40.3.5 ImagesSmallestGenerators

▷ ImagesSmallestGenerators(map) (attribute)

returns the list of images of GeneratorsSmallest(Source(map)). This list can be used to compare group homomorphisms. (The standard comparison is to compare the image lists on the set of elements of the source. If however x and y have the same images under a and b, certainly all their products have. Therefore it is sufficient to test this on the images of the smallest generators.)

40.4 Homomorphism for very large groups

Some homomorphisms (notably particular actions) transfer known information about the source group (such as a stabilizer chain) to the image group if this is substantially cheaper than to compute the information in the image group anew. In most cases this is no problem and in fact speeds up further calculations notably.

For a huge source group, however this can be time consuming or take a large amount of extra memory for storage. In this case it can be helpful to avoid as much automatism as possible.

The following list of tricks might be useful in such a case. (However you will lose much automatic deduction. So please restrict the use of these to cases where the standard approach does not work.)

- Compute only images (or the PreImagesRepresentative (32.5.4)) of group elements. Do not compute the images of (sub)groups or the full preimage of a subgroup.

- Create action homomorphisms as “surjective” (see ActionHomomorphism (41.7.1)), otherwise the range is set to be the full symmetric group. However do not compute Range (32.3.7) or Image (32.4.6) values, but only the images of a generator set.

- If you suspect an action homomorphism to do too much internally, replace the action function with a function that does the same; i.e. replace OnPoints (41.2.1) by function( p, g )
return \( p^g \); end;

The action will be the same, but as the action function is not \texttt{OnPoints} (41.2.1), the extra processing for special cases is not triggered.

## 40.5 Nice Monomorphisms

\texttt{GAP} contains very efficient algorithms for some special representations of groups (for example pc groups or permutation groups) while for other representations only slow generic methods are available. In this case it can be worthwhile to do all calculations rather in an isomorphic image of the group, which is in a “better” representation. The way to achieve this in \texttt{GAP} is via \textit{nice monomorphisms}.

For this mechanism to work, of course there must be effective methods to evaluate the \texttt{NiceMonomorphism} (40.5.2) value on elements and to take preimages under it. As by definition no good algorithms exist for the source group, normally this can only be achieved by using the result of a call to \texttt{ActionHomomorphism} (41.7.1) or \texttt{GroupHomomorphismByFunction} (40.1.4) (see also section 40.3).

### 40.5.1 IsHandledByNiceMonomorphism

\[ \texttt{IsHandledByNiceMonomorphism(obj)} \]

If this property is \texttt{true}, high-valued methods that translate all calculations in \texttt{obj} in the image under the \texttt{NiceMonomorphism} (40.5.2) value of \texttt{obj} become available for \texttt{obj}.

### 40.5.2 NiceMonomorphism

\[ \texttt{NiceMonomorphism(obj)} \]

is a homomorphism that is defined (at least) on the whole of \texttt{obj} and whose restriction to \texttt{obj} is injective. The concrete morphism (and also the image group) will depend on the representation of \texttt{obj}.

### 40.5.3 NiceObject

\[ \texttt{NiceObject(obj)} \]

The \texttt{NiceObject} value of \texttt{obj} is the image of \texttt{obj} under the mapping stored as the value of \texttt{NiceMonomorphism} (40.5.2) for \texttt{obj}.

A typical example are finite matrix groups, which use a faithful action on vectors to translate all calculations in a permutation group.

```
gap> gl:=GL(3,2); SL(3,2)
gap> IsHandledByNiceMonomorphism(gl); true
gap> NiceObject(gl); Group([ (5,7)(6,8), (2,3,5)(4,7,6) ])
gap> Image(NiceMonomorphism(gl),Z(2)*[[1,0,0],[0,1,1],[1,0,1]]); (2,6)(3,4,7,8)
gap> g1:=GL(3,2); SL(3,2)
gap> IsHandledByNiceMonomorphism(g1); true
gap> NiceObject(g1); Group([ (5,7)(6,8), (2,3,5)(4,7,6) ])
gap> Image(NiceMonomorphism(g1),Z(2)*[[1,0,0],[0,1,1],[1,0,1]]); (2,6)(3,4,7,8)
```

Example
40.5.4  IsCanonicalNiceMonomorphism

\begin{verbatim}
▷ IsCanonicalNiceMonomorphism(nhom)

A nice monomorphism (see NiceMonomorphism (40.5.2)) \( nhom \) is canonical if the image set will only depend on the set of group elements but not on the generating set and \( \times \) (31.11.1) comparison of group elements translates through the nice monomorphism. This implies that equal objects will always have equal NiceObject (40.5.3) values. In some situations however this condition would be expensive to achieve, therefore it is not guaranteed for every nice monomorphism.
\end{verbatim}

40.6  Group Automorphisms

Group automorphisms are bijective homomorphism from a group onto itself. An important subclass are automorphisms which are induced by conjugation of the group itself or a supergroup.

40.6.1  ConjugatorIsomorphism

\begin{verbatim}
▷ ConjugatorIsomorphism(G, g)

Let \( G \) be a group, and \( g \) an element in the same family as the elements of \( G \). ConjugatorIsomorphism returns the isomorphism from \( G \) to \( G^g \) defined by \( h \mapsto h^g \) for all \( h \in G \). If \( g \) normalizes \( G \) then ConjugatorIsomorphism does the same as ConjugatorAutomorphismNC (40.6.2).
\end{verbatim}

40.6.2  ConjugatorAutomorphism

\begin{verbatim}
▷ ConjugatorAutomorphism(G, g)
▷ ConjugatorAutomorphismNC(G, g)

Let \( G \) be a group, and \( g \) an element in the same family as the elements of \( G \) such that \( g \) normalizes \( G \). ConjugatorAutomorphism returns the automorphism of \( G \) defined by \( h \mapsto h^g \) for all \( h \in G \). If conjugation by \( g \) does not leave \( G \) invariant, ConjugatorAutomorphism returns fail; in this case, the isomorphism from \( G \) to \( G^g \) induced by conjugation with \( g \) can be constructed with ConjugatorIsomorphism (40.6.1). ConjugatorAutomorphismNC does the same as ConjugatorAutomorphism, except that the check is omitted whether \( g \) normalizes \( G \) and it is assumed that \( g \) is chosen to be in \( G \) if possible.
\end{verbatim}

40.6.3  InnerAutomorphism

\begin{verbatim}
▷ InnerAutomorphism(G, g)
▷ InnerAutomorphismNC(G, g)

Let \( G \) be a group, and \( g \in G \). InnerAutomorphism returns the automorphism of \( G \) defined by \( h \mapsto h^g \) for all \( h \in G \). If \( g \) is not an element of \( G \), InnerAutomorphism returns fail; in this case, the isomorphism from \( G \) to \( G^g \) induced by conjugation with \( g \) can be constructed with ConjugatorIsomorphism (40.6.1) or with ConjugatorAutomorphism (40.6.2).
\end{verbatim}
InnerAutomorphismNC does the same as InnerAutomorphism, except that the check is omitted whether \( g \in G \).

### 40.6.4 IsConjugatorIsomorphism

- \( \triangleright \) IsConjugatorIsomorphism(\( \text{hom} \))  
  (property)
- \( \triangleright \) IsConjugatorAutomorphism(\( \text{hom} \))  
  (property)
- \( \triangleright \) IsInnerAutomorphism(\( \text{hom} \))  
  (property)

Let \( \text{hom} \) be a group general mapping (see IsGroupGeneralMapping (32.9.4)) with source \( G \), say. IsConjugatorIsomorphism returns true if \( \text{hom} \) is induced by conjugation of \( G \) by an element \( g \) that lies in \( G \) or in a group into which \( G \) is naturally embedded in the sense described below, and false otherwise.

Natural embeddings are dealt with in the case that \( G \) is a permutation group (see Chapter 43), a matrix group (see Chapter 44), a finitely presented group (see Chapter 47), or a group given w.r.t. a polycyclic presentation (see Chapter 46). In all other cases, IsConjugatorIsomorphism may return false if \( \text{hom} \) is induced by conjugation but is not an inner automorphism.

If IsConjugatorIsomorphism returns true for \( \text{hom} \) then an element \( g \) that induces \( \text{hom} \) can be accessed as value of the attribute ConjugatorOfConjugatorIsomorphism (40.6.5).

IsConjugatorAutomorphism returns true if \( \text{hom} \) is an automorphism (see IsEndoGeneralMapping (32.13.3)) that is regarded as a conjugator isomorphism by IsConjugatorIsomorphism, and false otherwise.

IsInnerAutomorphism returns true if \( \text{hom} \) is a conjugator automorphism such that an element \( g \) inducing \( \text{hom} \) can be chosen in \( G \), and false otherwise.

### 40.6.5 ConjugatorOfConjugatorIsomorphism

- \( \triangleright \) ConjugatorOfConjugatorIsomorphism(\( \text{hom} \))  
  (attribute)

For a conjugator isomorphism \( \text{hom} \) (see ConjugatorIsomorphism (40.6.1)), ConjugatorOfConjugatorIsomorphism returns an element \( g \) such that mapping under \( \text{hom} \) is induced by conjugation with \( g \).

To avoid problems with IsInnerAutomorphism (40.6.4), it is guaranteed that the conjugator is taken from the source of \( \text{hom} \) if possible.

**Example**

```gap
gap> hgens:=[(1,2,3),(1,2,4)];;h:=Group(hgens);;
gap> hom:=GroupHomomorphismByImages(h,h,hgens,[[(1,2,3),(2,3,4)]]);;
gap> IsInnerAutomorphism(hom); true
gap> ConjugatorOfConjugatorIsomorphism(hom); (1,2,3)
gap> hom:=GroupHomomorphismByImages(h,h,hgens,[[(1,3,2),(1,4,2)]];  
[ (1,2,3), (1,4,2) ] -> [ (1,3,2), (1,4,2) ]
gap> IsInnerAutomorphism(hom); false
gap> IsConjugatorAutomorphism(hom); true
gap> ConjugatorOfConjugatorIsomorphism(hom); (1,2)
```
40.7 Groups of Automorphisms

Group automorphism can be multiplied and inverted and thus it is possible to form groups of automorphisms.

40.7.1 AutomorphismGroup

\[
\text{AutomorphismGroup}(G)
\]

returns the full automorphism group of the group \(G\). The automorphisms act on \(G\) by the caret operator \(^\wedge\). The automorphism group often stores a \texttt{NiceMonomorphism (40.5.2)} value whose image is a permutation group, obtained by the action on a subset of \(G\).

Note that current methods for the calculation of the automorphism group of a group \(G\) require \(G\) to be a permutation group or a pc group to be efficient. For groups in other representations the calculation is likely very slow.

Also, the \texttt{AutPGrp} package installs enhanced methods for \texttt{AutomorphismGroup} for finite \(p\)-groups, and the \texttt{FGA} package - for finitely generated subgroups of free groups.

Methods may be installed for \texttt{AutomorphismGroup} for other domains, such as e.g. for linear codes in the \texttt{GUAVA} package, loops in the \texttt{loops} package and nilpotent Lie algebras in the \texttt{Sophus} package (see package manuals for their descriptions).

40.7.2 IsGroupOfAutomorphisms

\[
\text{IsGroupOfAutomorphisms}(G)
\]

indicates whether \(G\) consists of automorphisms of another group \(H\), say. The group \(H\) can be obtained from \(G\) via the attribute \texttt{AutomorphismDomain (40.7.3)}.

40.7.3 AutomorphismDomain

\[
\text{AutomorphismDomain}(G)
\]

If \(G\) consists of automorphisms of \(H\), this attribute returns \(H\).

40.7.4 IsAutomorphismGroup

\[
\text{IsAutomorphismGroup}(G)
\]

indicates whether \(G\) is the full automorphism group of another group \(H\), this group is given as \texttt{AutomorphismDomain (40.7.3)} value of \(G\).

```
Example

gap> g:=Group([(1,2,3,4),(1,3)]);
Group([ (1,2,3,4), (1,3) ])
gap> au:=AutomorphismGroup(g);
<group of size 8 with 3 generators>
gap> GeneratorsOfGroup(au);
[ Pcgs([ (2,4), (1,2,3,4), (1,3)(2,4) ]),
  Pcgs([ (2,4), (1,2,3,4), (1,3)(2,4) ]),
  Pcgs([ (2,4), (1,2,3,4), (1,3)(2,4) ]) ]
```
40.7.5 InnerAutomorphismsAutomorphismGroup

For an automorphism group `autgroup` of a group this attribute stores the subgroup of inner automorphisms (automorphisms induced by conjugation) of the original group.

```
gap> InnerAutomorphismsAutomorphismGroup(au);
<group with 2 generators>
```

40.7.6 InducedAutomorphism

Let `aut` be an automorphism of a group `G` and `epi` be a homomorphism from `G` to a group `H` such that the kernel of `epi` is fixed under `aut`. Let `U` be the image of `epi`. This command returns the automorphism of `U` induced by `aut` via `epi`, that is, the automorphism of `U` which maps `g^epi` to `(g^aut)^epi`, for `g ∈ G`.

```
gap> g:=Group((1,2,3,4),(1,2));
Group([ (1,2,3,4), (1,2) ])
gap> n:=Subgroup(g,[ (1,2)(3,4), (1,3)(2,4) ]);  
Group([ (1,2)(3,4), (1,3)(2,4) ])
gap> epi:=NaturalHomomorphismByNormalSubgroup(g,n);  
[ (1,2,3,4), (1,2) ] -> [ f1*f2, f1 ]
gap> aut:=InnerAutomorphism(g,(1,3));  
^f1
^f2
```

40.8 Calculating with Group Automorphisms

Usually the best way to calculate in a group of automorphisms is to translate all calculations to an isomorphic group in a representation, for which better algorithms are available, say a permutation group. This translation can be done automatically using `NiceMonomorphism` (40.5.2).

Once a group knows to be a group of automorphisms (this can be achieved by testing or setting the property `IsGroupOfAutomorphisms` (40.7.2)), GAP will try itself to find such a nice monomorphism once calculations in the automorphism group are done.

Note that nice homomorphisms inherit down to subgroups, but cannot necessarily be extended from a subgroup to the whole group. Thus when working with a group of automorphisms, it can be beneficial to enforce calculation of the nice monomorphism for the whole group (for example by
explicitly calling Random (30.7.1) and ignoring the result – it will be stored internally) at the start of
the calculation. Otherwise GAP might first calculate a nice monomorphism for the subgroup, only to
be forced to calculate a new nice monomorphism for the whole group later on.

If a good domain for a faithful permutation action is known already, a homomorphism for the
action on it can be created using NiceMonomorphismAutomGroup (40.8.2). It might be stored by
SetNiceMonomorphism (see NiceMonomorphism (40.5.2)).

Another nice way of representing automorphisms as permutations has been described in [Sim97].
It is not yet available in GAP, a description however can be found in section 87.3.

40.8.1 AssignNiceMonomorphismAutomorphismGroup

\[\text\textbf{AssignNiceMonomorphismAutomorphismGroup}(\text\text{autgrp, group})\]

computes a nice monomorphism for autgroup acting on group and stores it as
NiceMonomorphism (40.5.2) value of autgrp.

If the centre of AutomorphismDomain (40.7.3) of autgrp is trivial, the operation will first try to
represent all automorphisms by conjugation (in group or in a natural parent of group).
If this fails the operation tries to find a small subset of group on which the action will be faithful.
The operation sets the attribute NiceMonomorphism (40.5.2) and does not return a value.

40.8.2 NiceMonomorphismAutomGroup

\[\text\textbf{NiceMonomorphismAutomGroup}(\text\text{autgrp, elms, elmsgens})\]

This function creates a monomorphism for an automorphism group autgrp of a group by per-
muting the group elements in the list elms. This list must be chosen to yield a faithful representation.
elmsgens is a list of generators which are a subset of elms. (They can differ from the group’s original
generators.) It does not yet assign it as NiceMonomorphism (40.5.2) value.

40.9 Searching for Homomorphisms

40.9.1 IsomorphismGroups

\[\text\textbf{IsomorphismGroups}(\text\text{G, H})\]

computes an isomorphism between the groups G and H if they are isomorphic and returns fail
otherwise.

With the existing methods the amount of time needed grows with the size of a generating system
of G. (Thus in particular for p-groups calculations can be slow.) If you do only need to know whether
groups are isomorphic, you might want to consider IdGroup (smallgrp: IdGroup) or the random
isomorphism test (see RandomIsomorphismTest (46.10.1)).

\begin{verbatim}
gap> g:=Group((1,2,3,4),(1,3));;
gap> h:=Group((1,4,6,7)(2,3,5,8), (1,5)(2,6)(3,4)(7,8));;
gap> IsomorphismGroups(g,h);
[ (1,2,3,4), (1,3) ] -> [ (1,4,6,7)(2,3,5,8), (1,2) (3,7) (4,8)(5,6) ]
gap> IsomorphismGroups(g,Group((1,2,3,4),(1,2)));
fail
\end{verbatim}
40.9.2 AllHomomorphismClasses

▷ AllHomomorphismClasses(G, H) (function)

For two groups \( G \) and \( H \), this function returns representatives of all homomorphisms \( G \to H \) up to \( H \)-conjugacy.

```gap
gap> AllHomomorphismClasses(SymmetricGroup(4),SymmetricGroup(3));
[ [ (1,2,3), (2,4) ] -> [ (), () ],
  [ (1,2,3), (2,4) ] -> [ (), (1,2) ],
  [ (1,2,3), (2,4) ] -> [ (1,2,3), (1,2) ] ]
```

40.9.3 AllHomomorphisms

▷ AllHomomorphisms(G, H) (function)
▷ AllEndomorphisms(G) (function)
▷ AllAutomorphisms(G) (function)

For two groups \( G \) and \( H \), this function returns all homomorphisms \( G \to H \). Since this number will grow quickly, \texttt{AllHomomorphismClasses} (40.9.2) should be used in most cases. \texttt{AllEndomorphisms} returns all homomorphisms from \( G \) to itself, \texttt{AllAutomorphisms} returns all bijective endomorphisms.

```gap
gap> AllHomomorphisms(SymmetricGroup(3),SymmetricGroup(3));
[ [ (1,2,3), (1,2) ] -> [ (), () ],
  [ (1,2,3), (1,2) ] -> [ (), (1,2) ],
  [ (1,2,3), (1,2) ] -> [ (), (2,3) ],
  [ (1,2,3), (1,2) ] -> [ (), (1,3) ],
  [ (1,2,3), (1,2) ] -> [ (1,2,3), (1,2) ],
  [ (1,2,3), (1,2) ] -> [ (1,2,3), (2,3) ],
  [ (1,2,3), (1,2) ] -> [ (1,3,2), (1,2) ],
  [ (1,2,3), (1,2) ] -> [ (1,2,3), (1,3) ],
  [ (1,2,3), (1,2) ] -> [ (1,3,2), (1,3) ],
  [ (1,2,3), (1,2) ] -> [ (1,3,2), (2,3) ] ]
```

40.9.4 GQuotients

▷ GQuotients(F, G) (operation)

computes all epimorphisms from \( F \) onto \( G \) up to automorphisms of \( G \). This classifies all factor groups of \( F \) which are isomorphic to \( G \).

With the existing methods the amount of time needed grows with the size of a generating system of \( G \). (Thus in particular for \( p \)-groups calculations can be slow.)

If the \texttt{findall} option is set to \texttt{false}, the algorithm will stop once one homomorphism has been found (this can be faster and might be sufficient if not all homomorphisms are needed).

```gap
gap> g:=Group((1,2,3,4),(1,2));
Group([ (1,2,3,4), (1,2) ])
gap> h:=Group((1,2,3),(1,2));
```

```gap
```
Group([ (1,2,3), (1,2) ])

gap> quo:=GQuotients(g,h);
[ [ (1,2,3,4), (1,3,4) ] -> [ (2,3), (1,2,3) ] ]

40.9.5 IsomorphicSubgroups

\[ \text{IsomorphicSubgroups}(G, H) \] (operation)

computes all monomorphisms from \( H \) into \( G \) up to \( G \)-conjugacy of the image groups. This classifies all \( G \)-classes of subgroups of \( G \) which are isomorphic to \( H \).

With the existing methods, the amount of time needed grows with the size of a generating system of \( G \). (Thus in particular for \( p \)-groups calculations can be slow.) A main use of \text{IsomorphicSubgroups} therefore is to find nonsolvable subgroups (which often can be generated by 2 elements).

(To find \( p \)-subgroups it is often faster to compute the subgroup lattice of the Sylow subgroup and to use \text{IdGroup} (\texttt{smallgrp: IdGroup}) to identify the type of the subgroups.)

If the \texttt{findall} option is set to \texttt{false}, the algorithm will stop once one homomorphism has been found (this can be faster and might be sufficient if not all homomorphisms are needed).

Example

\[
\begin{align*}
\text{gap> g} & \text{:=Group((1,2,3,4),(1,2));} \\
\text{Group([ (1,2,3,4), (1,2) ])} \\
\text{gap> h} & \text{:=Group((3,4),(1,2));} \\
\text{gap> emb} & \text{:=IsomorphicSubgroups(g,h);} \\
& [ [ (3,4), (1,2) ] -> [ (1,2), (3,4) ], \\
& [ (3,4), (1,2) ] -> [ (1,3)(2,4), (1,2)(3,4) ] ]
\end{align*}
\]

40.9.6 MorClassLoop

\[ \text{MorClassLoop}(\text{range}, \text{classes}, \text{params}, \text{action}) \] (function)

This function loops over element tuples taken from \texttt{classes} and checks these for properties such as generating a given group, or fulfilling relations. This can be used to find small generating sets or all types of Morphisms. The element tuples are used only up to up to inner automorphisms as all images can be obtained easily from them by conjugation while running through all of them usually would take too long.

\texttt{range} is a group from which these elements are taken. The classes are given in a list \texttt{classes} which is a list of records with the following components.

\texttt{classes}

list of conjugacy classes

\texttt{representative}

One element in the union of these classes

\texttt{size}

The sum of the sizes of these classes

\texttt{params} is a record containing the following optional components.
gens
generators that are to be mapped (for testing morphisms). The length of this list determines the length of element tuples considered.

from
a preimage group (that contains gens)

to image group (which might be smaller than range)

free
free generators, a list of the same length than the generators gens.

rels
some relations that hold among the generators gens. They are given as a list \([\text{word}, \text{order}]\) where \text{word} is a word in the free generators free.

dom a set of elements on which automorphisms act faithfully (used to do element tests in partial automorphism groups).

aut Subgroup of already known automorphisms.

condition
A function that will be applied to the homomorphism and must return \text{true} for the homomorphism to be accepted.

action is a number whose bit-representation indicates the requirements which are enforced on the element tuples found, as follows.

1 homomorphism

2 injective

4 surjective

8 find all (otherwise stops after the first find)

If the search is for homomorphisms, the function returns homomorphisms obtained by mapping the given generators gens instead of element tuples.

The “Morpheus” algorithm used to find homomorphisms is described in [Hul96, Section V.5].

40.10 Representations for Group Homomorphisms

The different representations of group homomorphisms are used to indicate from what type of group to what type of group they map and thus determine which methods are used to compute images and preimages.

The information in this section is mainly relevant for implementing new methods and not for using homomorphisms.
40.10.1 **IsGroupGeneralMappingByImages**

\[\text{IsGroupGeneralMappingByImages(map)}\]

(Representation)

Representation for mappings from one group to another that are defined by extending a mapping of group generators homomorphically. Instead of record components, the attribute MappingGeneratorsImages (40.10.2) is used to store generators and their images.

40.10.2 **MappingGeneratorsImages**

\[\text{MappingGeneratorsImages(map)}\]

(attribute)

This attribute contains a list of length 2, the first entry being a list of generators of the source of \(map\) and the second entry a list of their images. This attribute is used, for example, by GroupHomomorphismByImages (40.1.1) to store generators and images.

40.10.3 **IsGroupGeneralMappingByAsGroupGeneralMappingByImages**

\[\text{IsGroupGeneralMappingByAsGroupGeneralMappingByImages(map)}\]

(Representation)

Representation for mappings that delegate work on a GroupHomomorphismByImages (40.1.1).

40.10.4 **IsPreimagesByAsGroupGeneralMappingByImages**

\[\text{IsPreimagesByAsGroupGeneralMappingByImages(map)}\]

(Representation)

Representation for mappings that delegate work for preimages to a mapping created with GroupHomomorphismByImages (40.1.1).

40.10.5 **IsPermGroupGeneralMapping**

\[\text{IsPermGroupGeneralMapping(map)}\]

\[\text{IsPermGroupGeneralMappingByImages(map)}\]

\[\text{IsPermGroupHomomorphism(map)}\]

\[\text{IsPermGroupHomomorphismByImages(map)}\]

(Representation)

are the representations for mappings that map from a perm group

40.10.6 **IsToPermGroupGeneralMappingByImages**

\[\text{IsToPermGroupGeneralMappingByImages(map)}\]

\[\text{IsToPermGroupHomomorphismByImages(map)}\]

(Representation)

is the representation for mappings that map to a perm group
40.10.7  IsGroupGeneralMappingByPcgs

▷ IsGroupGeneralMappingByPcgs(map)  (Representation)

is the representations for mappings that map a pcgs to images and thus may use exponents to decompose generators.

40.10.8  IsPcGroupGeneralMappingByImages

▷ IsPcGroupGeneralMappingByImages(map)  (Representation)
▷ IsPcGroupHomomorphismByImages(map)  (Representation)

is the representation for mappings from a pc group

40.10.9  IsToPcGroupGeneralMappingByImages

▷ IsToPcGroupGeneralMappingByImages(map)  (Representation)
▷ IsToPcGroupHomomorphismByImages(map)  (Representation)

is the representation for mappings to a pc group

40.10.10  IsFromFpGroupGeneralMappingByImages

▷ IsFromFpGroupGeneralMappingByImages(map)  (Representation)
▷ IsFromFpGroupHomomorphismByImages(map)  (Representation)

is the representation of mappings from an fp group.

40.10.11  IsFromFpGroupStdGensGeneralMappingByImages

▷ IsFromFpGroupStdGensGeneralMappingByImages(map)  (Representation)
▷ IsFromFpGroupStdGensHomomorphismByImages(map)  (Representation)

is the representation of total mappings from an fp group that give images of the standard generators.
Chapter 41

Group Actions

A group action is a triple \((G, \Omega, \mu)\), where \(G\) is a group, \(\Omega\) a set and \(\mu: \Omega \times G \to \Omega\) a function that is compatible with the group arithmetic. We call \(\Omega\) the domain of the action.

In GAP, \(\Omega\) can be a duplicate-free collection (an object that permits access to its elements via the \(\Omega[n]\) operation, for example a list), it does not need to be sorted (see IsSet (21.17.4)).

The acting function \(\mu\) is a binary GAP function that returns the image \(\mu(x, g)\) for a point \(x \in \Omega\) and a group element \(g \in G\).

In GAP, groups always act from the right, that is \(\mu(\mu(x, g), h) = \mu(x, gh)\).

GAP does not test whether the acting function \(\mu\) satisfies the conditions for a group operation but silently assumes that is does. (If it does not, results are unpredictable.)

The first section of this chapter, 41.1, describes the various ways how operations for group actions can be called.

Functions for several commonly used action are already built into GAP. These are listed in section 41.2.

The sections 41.7 and 41.8 describe homomorphisms and mappings associated to group actions as well as the permutation group image of an action.

The other sections then describe operations to compute orbits, stabilizers, as well as properties of actions.

Finally section 41.12 describes the concept of “external sets” which represent the concept of a \(G\)-set and underly the actions mechanism.

41.1 About Group Actions

The syntax which is used by the operations for group actions is quite flexible. For example we can call the operation OrbitsDomain (41.4.3) for the orbits of the group \(G\) on the domain \(\Omega\) in the following ways:

OrbitsDomain(G,\Omega,\mu])

The acting function \(\mu\) is optional. If it is not given, the built-in action OnPoints (41.2.1) (which defines an action via the caret operator ^) is used as a default.

OrbitsDomain(G,\Omega,gens,acts,\mu])

This second version of OrbitsDomain (41.4.3) permits one to implement an action induced by a homomorphism: If the group \(H\) acts on \(\Omega\) via \(\mu\) and \(\varphi: G \to H\) is a homomorphism, \(G\) acts on \(\Omega\) via the induced action \(\mu'(x, g) = \mu(x, g\varphi)\).
Here \( gens \) must be a set of generators of \( G \) and \( acts \) the images of \( gens \) under \( \varphi \). \( \mu \) is the acting function for \( H \). Again, the function \( \mu \) is optional and \texttt{OnPoints} (41.2.1) is used as a default.

The advantage of this notation is that \texttt{GAP} does not need to construct this homomorphism \( \varphi \) and the range group \( H \) as \texttt{GAP} objects. (If a small group \( G \) acts via complicated objects \( acts \) this otherwise could lead to performance problems.)

\texttt{GAP} does not test whether the mapping \( gens \mapsto acts \) actually induces a homomorphism and the results are unpredictable if this is not the case.

\texttt{OrbitsDomain(xset)}

A third variant is to call the operation with an external set, which then provides \( G \), \( \Omega \) and \( \mu \). You will find more about external sets in Section 41.12.

For operations like \texttt{Stabilizer} (41.5.2) of course the domain must be replaced by an element of the domain of the action.

### 41.2 Basic Actions

\texttt{GAP} already provides acting functions for the more common actions of a group. For built-in operations such as \texttt{Stabilizer} (41.5.2) special methods are available for many of these actions.

If one needs an action for which no acting function is provided by the library it can be implemented via a \texttt{GAP} function that conforms to the syntax

\[
\text{actfun} ( \omega, g )
\]

where \( \omega \) is an element of the action domain, \( g \) is an element of the acting group, and the return value is the image of \( \omega \) under \( g \).

For example one could define the following function that acts on pairs of polynomials via \texttt{OnIndeterminates} (41.2.13):

\begin{verbatim}
Example

OnIndeterminatesPairs:= function( polypair, g )
    return [ OnIndeterminates( polypair[1], g ),
              OnIndeterminates( polypair[2], g ) ];
end;

\end{verbatim}

Note that this function \textit{must} implement a group action from the \textit{right}. This is not verified by \texttt{GAP} and results are unpredictable otherwise.

#### 41.2.1 OnPoints

\begin{verbatim}
\texttt{OnPoints}(pnt, g)
\end{verbatim}

returns \( pnt \mapsto g \). This is for example the action of a permutation group on points, or the action of a group on its elements via conjugation. The action of a matrix group on vectors from the right is described by both \texttt{OnPoints} and \texttt{OnRight} (41.2.2).

#### 41.2.2 OnRight

\begin{verbatim}
\texttt{OnRight}(pnt, g)
\end{verbatim}
returns \( pnt \ast g \). This is for example the action of a group on its elements via right multiplication, or the action of a group on the cosets of a subgroup. The action of a matrix group on vectors from the right is described by both \( \text{OnPoints} \) (41.2.1) and \( \text{OnRight} \).

### 41.2.3 OnLeftInverse

\[ \text{OnLeftInverse}(\text{pnt}, g) \]

returns \( g^{-1} \ast pnt \). Forming the inverse is necessary to make this a proper action, as in GAP groups always act from the right.

\( \text{OnLeftInverse} \) is used for example in the representation of a right coset as an external set (see 41.12), that is, a right coset \( Ug \) is an external set for the group \( U \) acting on it via \( \text{OnLeftInverse} \).

### 41.2.4 OnSets

\[ \text{OnSets}(\text{set}, g) \]

Let \( \text{set} \) be a proper set (see 21.19). \( \text{OnSets} \) returns the proper set formed by the images of all points \( x \) of \( \text{set} \) via the action function \( \text{OnPoints} \) (41.2.1), applied to \( x \), and \( g \).

\( \text{OnSets} \) is for example used to compute the action of a permutation group on blocks.

(\( \text{OnTuples} \) (41.2.5) is an action on lists that preserves the ordering of entries.)

### 41.2.5 OnTuples

\[ \text{OnTuples}(\text{tup}, g) \]

Let \( \text{tup} \) be a list. \( \text{OnTuples} \) returns the list formed by the images of all points \( x \) of \( \text{tup} \) via the action function \( \text{OnPoints} \) (41.2.1), applied to \( x \) and \( g \).

(\( \text{OnSets} \) (41.2.4) is an action on lists that additionally sorts the entries of the result.)

### 41.2.6 OnPairs

\[ \text{OnPairs}(\text{tup}, g) \]

is a special case of \( \text{OnTuples} \) (41.2.5) for lists \( \text{tup} \) of length 2.

### 41.2.7 OnSetsSets

\[ \text{OnSetsSets}(\text{set}, g) \]

implements the action on sets of sets. For the special case that the sets are pairwise disjoint, it is possible to use \( \text{OnSetsDisjointSets} \) (41.2.8). \( \text{set} \) must be a sorted list whose entries are again sorted lists, otherwise an error is triggered (see 41.3).
41.2.8 OnSetsDisjointSets

\[\text{OnSetsDisjointSets}(\text{set}, \ g)\] (function)

implements the action on sets of pairwise disjoint sets (see also \texttt{OnSetsSets} (41.2.7)). \texttt{set} must be a sorted list whose entries are again sorted lists, otherwise an error is triggered (see 41.3).

41.2.9 OnSetsTuples

\[\text{OnSetsTuples}(\text{set}, \ g)\] (function)

implements the action on sets of tuples. \texttt{set} must be a sorted list, otherwise an error is triggered (see 41.3).

41.2.10 OnTuplesSets

\[\text{OnTuplesSets}(\text{set}, \ g)\] (function)

implements the action on tuples of sets. \texttt{set} must be a list whose entries are again sorted lists, otherwise an error is triggered (see 41.3).

41.2.11 OnTuplesTuples

\[\text{OnTuplesTuples}(\text{set}, \ g)\] (function)

implements the action on tuples of tuples.

Example

\begin{verbatim}
gap> g:=Group((1,2,3),(2,3,4));
gap> Orbit(g,1,OnPoints);
[ 1, 2, 3, 4 ]
gap> Orbit(g(),OnRight);
[ (), (1,2,3), (2,3,4), (1,3,2), (1,3)(2,4), (1,2)(3,4), (2,4,3),
  (1,4,2), (1,4,3), (1,3,4), (1,2,4), (1,4)(2,3) ]
gap> Orbit(g([1,2],OnPairs);
[ [ 1, 2 ], [ 2, 3 ], [ 1, 3 ], [ 3, 4 ], [ 2, 1 ],
  [ 1, 4 ], [ 4, 1 ], [ 4, 2 ], [ 3, 2 ], [ 2, 4 ], [ 4, 3 ] ]
gap> Orbit(g([1,2],OnSets);
[ [ 1, 2 ], [ 2, 3 ], [ 1, 3 ], [ 3, 4 ], [ 1, 4 ], [ 2, 4 ] ]
gap> Orbit(g([[1,2],[3,4]],OnSetsSets);
[ [ [ 1, 2 ], [ 3, 4 ] ], [ [ 1, 4 ], [ 2, 3 ] ],
  [ [ 1, 3 ], [ 2, 4 ] ] ]
gap> Orbit(g([[1,2],[3,4]],OnTuplesSets);
[ [ [ 1, 2 ], [ 3, 4 ] ], [ [ 2, 3 ], [ 1, 4 ] ],
  [ [ 1, 3 ], [ 2, 4 ] ], [ [ 3, 4 ], [ 1, 2 ] ],
  [ [ 1, 4 ], [ 2, 3 ] ], [ [ 2, 4 ], [ 1, 3 ] ] ]
gap> Orbit(g([[1,2],[3,4]],OnTuplesTuples);
[ [ [ 1, 2 ], [ 3, 4 ] ], [ [ 1, 4 ], [ 2, 3 ] ],
  [ [ 1, 3 ], [ 4, 2 ] ], [ [ 2, 4 ], [ 3, 1 ] ],
  [ [ 2, 1 ], [ 4, 3 ] ], [ [ 3, 2 ], [ 4, 1 ] ] ]
gap> Orbit(g([[1,2],[3,4]],OnTuplesTuples);
[ [ [ 1, 2 ], [ 3, 4 ] ], [ [ 2, 3 ], [ 1, 4 ] ],
  [ [ 1, 3 ], [ 4, 2 ] ], [ [ 2, 4 ], [ 3, 1 ] ],
  [ [ 2, 1 ], [ 4, 3 ] ], [ [ 3, 2 ], [ 4, 1 ] ] ]
\end{verbatim}
41.2.12 OnLines

\( \textbf{OnLines}(\text{vec}, g) \)

Let \text{vec} be a normed row vector, that is, its first nonzero entry is normed to the identity of the relevant field, see \texttt{NormedRowVector}\ (23.2.1). The function \texttt{OnLines} returns the row vector obtained from first multiplying \text{vec} from the right with \text{g} (via \texttt{OnRight}\ (41.2.2)) and then normalizing the resulting row vector by scalar multiplication from the left.

This action corresponds to the projective action of a matrix group on one-dimensional subspaces.

If \text{vec} is a zero vector or is not normed then an error is triggered (see 41.3).

\texttt{gap}\> gl:=GL(2,5);; v:=[1,0]*Z(5)^0; \\
\texttt{gap}\> h:=Action(gl,Orbit(gl,v,OnLines),OnLines); \\
\texttt{gap}\> Group([ (2,3,5,6), (1,2,4)(3,6,5) ]); \\

41.2.13 OnIndeterminates (as a permutation action)

\( \textbf{OnIndeterminates}(\text{poly}, \text{perm}) \)

A permutation \text{perm} acts on the multivariate polynomial \text{poly} by permuting the indeterminates as it permutes points.

\texttt{gap}\> x:=Indeterminate(Rationals,1);; y:=Indeterminate(Rationals,2);; \\
\texttt{gap}\> OnIndeterminates(x^7*y+x*y^4,(1,17)(2,28)); \\
x_17^7*x_28+x_17*x_28^4 \\
\texttt{gap}\> Stabilizer(Group((1,2,3,4),(1,2)),x*y,OnIndeterminates); \\
\texttt{gap}\> Group([ (1,2), (3,4) ]); \\

41.2.14Permuted (as a permutation action)

\( \textbf{Permuted}(\text{list}, \text{perm}) \)

The following example demonstrates \texttt{Permuted}\ (21.20.18) being used to implement a permutation action on a domain:

\texttt{gap}\> g:=Group((1,2,3),(1,2));; \\
\texttt{gap}\> dom:=[ "a", "b", "c" ];; \\
\texttt{gap}\> Orbit(g,dom,Permuted); \\
\[ [ "a", "b", "c" ], [ "c", "a", "b" ], [ "b", "a", "c" ], \\
[ "b", "c", "a" ], [ "a", "c", "b" ], [ "c", "b", "a" ] ]
41.2.15 OnSubspacesByCanonicalBasis

OnSubspacesByCanonicalBasis(bas, mat) (function)
OnSubspacesByCanonicalBasisConcatenations(basvec, mat) (function)

implements the operation of a matrix group on subspaces of a vector space. bas must be a list of
(linearly independent) vectors which forms a basis of the subspace in Hermite normal form. mat is
an element of the acting matrix group. The function returns a mutable matrix which gives the basis of
the image of the subspace in Hermite normal form. (In other words: it triangulizes the product of bas
with mat.)

bas must be given in Hermite normal form, otherwise an error is triggered (see 41.3).

41.3 Action on canonical representatives

A variety of action functions assumes that the objects on which it acts are given in a particular
form, for example canonical representatives. Affected actions are for example OnSetsSets (41.2.7),
OnSetsDisjointSets (41.2.8), OnSetsTuples (41.2.9), OnTuplesSets (41.2.10), OnLines
(41.2.12) and OnSubspacesByCanonicalBasis (41.2.15).

If orbit seeds or domain elements are not given in the required form GAP will issue an error
message:

gap> Orbit(SymmetricGroup(5),[[2,4],[1,3]],OnSetsSets);
Error, Action not well-defined. See the manual section
'Action on canonical representatives'.

In this case the affected domain elements have to be brought in canonical form, as documented for
the respective action function. For interactive use this is most easily done by acting with the identity
element of the group.

(A similar error could arise if a user-defined action function is used which actually does not im-
plement an action from the right.)

41.4 Orbits

If a group G acts on a set Ω, the set of all images of x ∈ Ω under elements of G is called the orbit of
x. The set of orbits of G is a partition of Ω.

41.4.1 Orbit

OnPoints (41.2.1) if no action function is given.

(Note that the arrangement of points in this list is not defined by the operation.)

The orbit of pnt will always contain one element that is equal to pnt, however for performance
reasons this element is not necessarily identical to pnt, in particular if pnt is mutable.
Example

```gap
g:=Group((1,3,2),(2,4,3));;
Orbit(g,1);;
Orbit(g,[1,2],OnSets);
```

(See Section 41.2 for information about specific actions.)

41.4.2 Orbits (operation)

\begin{verbatim}
\texttt{Orbits(}G, \texttt{seeds [, gens, acts][, act])}
\end{verbatim}

returns a duplicate-free list of the orbits of the elements in \texttt{seeds} under the action \texttt{act} of \texttt{G} or under \texttt{OnPoints (41.2.1)} if no action function is given.

For a permutation group \texttt{G}, one may also invoke this as \texttt{Orbits(G)}, which returns all the orbits of its natural action on the set of points moved by it. For example the group \langle (1,2,3),(4,5) \rangle has the orbits \{1,2,3\} and \{4,5\}.

(Note that the arrangement of orbits or of points within one orbit is not defined by the operation.)

41.4.3 OrbitsDomain

\begin{verbatim}
\texttt{OrbitsDomain(}G, \texttt{Omega [, gens, acts][, act])}
\end{verbatim}

returns a list of the orbits of \texttt{G} on the domain \texttt{Omega} (given as lists) under the action \texttt{act} or under \texttt{OnPoints (41.2.1)} if no action function is given.

This operation is often faster than \texttt{Orbits (41.4.2)}. The domain \texttt{Omega} must be closed under the action of \texttt{G}, otherwise an error can occur.

For a permutation group \texttt{G}, one may also invoke this as \texttt{OrbitsDomain(G)}, which returns all the orbits of its natural action on the set of points moved by it.

(Note that the arrangement of orbits or of points within one orbit is not defined by the operation.)
41.4.4 OrbitLength

\[ \text{OrbitLength}(G[, \Omega], \text{pnt}[, \text{gens}, \text{acts}][, \text{act}]) \] (operation)

computes the length of the orbit of \text{pnt} under the action function \text{act} or \text{OnPoints} (41.2.1) if no action function is given.

41.4.5 OrbitLengths

\[ \text{OrbitLengths}(G[, \text{seeds}[, \text{gens}, \text{acts}][, \text{act}])] \] (operation)
\[ \text{OrbitLengths}(G) \] (attribute)
\[ \text{OrbitLengths}(xset) \] (attribute)

computes the lengths of all the orbits of the elements in \text{seeds} under the action \text{act} of \text{G}.

For a permutation group \text{G}, one may also invoke this as \text{OrbitLengths}(\text{G}) which returns the lengths of all the orbits of its natural action on the set of points moved by it. For example the group \}\langle (1,2,3),(5,6)\rangle has the orbit lengths 2 and 3.

41.4.6 OrbitLengthsDomain

\[ \text{OrbitLengthsDomain}(G[, \Omega[, \text{gens}, \text{acts}][, \text{act}])] \] (operation)
\[ \text{OrbitLengthsDomain}(G) \] (attribute)
\[ \text{OrbitLengthsDomain}(xset) \] (attribute)

computes the lengths of all the orbits of \text{G} on \Omega.

This operation is often faster than \text{OrbitLengths} (41.4.5). The domain \Omega must be closed under the action of \text{G}, otherwise an error can occur.

For a permutation group \text{G}, one may also invoke this as \text{OrbitLengthsDomain}(\text{G}) which returns the length of all the orbits of its natural action on the set of points moved by it.

Example

\begin{verbatim}
gap> g:=Group((1,3,2),(2,4,3));;
gap> OrbitLength(g,[1,2,3,4],OnTuples);
12
gap> OrbitLengths(g,Arrangements([1..4],4),OnTuples);
[ 12, 12 ]
gap> g:=Group((1,2,3),(5,6,7));;
gap> OrbitLengthsDomain(g,[1,2,3]);
[ 3 ]
gap> OrbitLengthsDomain(g);
[ 3, 3 ]
\end{verbatim}
41.5 Stabilizers

The stabilizer of a point \( x \) under the action of a group \( G \) is the set of all those elements in \( G \) which fix \( x \).

41.5.1 OrbitStabilizer

\[ \texttt{OrbitStabilizer}(G[, Omega[, pnt[, gens, acts][, act]]]) \]

computes the orbit and the stabilizer of \( pnt \) simultaneously in a single orbit-stabilizer algorithm. The stabilizer will have \( G \) as its parent.

41.5.2 Stabilizer

\[ \texttt{Stabilizer}(G[, Omega[, pnt[, gens, acts][, act]]]) \]

computes the stabilizer in \( G \) of the point \( pnt \), that is the subgroup of those elements of \( G \) that fix \( pnt \). The stabilizer will have \( G \) as its parent.

Example

```gap
gap> g:=Group([(1,3,2),(2,4,3)]);
gap> stab:=Stabilizer(g,4);
Group([ (1,3,2) ])  
gap> Parent(stab);
Group([ (1,3,2), (2,4,3) ])
```

The stabilizer of a set or tuple of points can be computed by specifying an action of sets or tuples of points.

Example

```gap
gap> Stabilizer(g,[1,2],OnSets);
Group([ (1,2)(3,4) ])  
gap> Stabilizer(g,[1,2],OnTuples);
Group([()])  
gap> orbstab:=OrbitStabilizer(g,[1,2],OnSets);
rec(    orbit := [ [ 1, 2 ], [ 1, 3 ], [ 1, 4 ], [ 2, 3 ], [ 3, 4 ],    [ 2, 4 ] ], stabilizer := Group([ (1,2)(3,4) ]) )  
gap> Parent(orbstab.stabilizer);
Group([ (1,3,2), (2,4,3) ])  
```

(See Section 41.2 for information about specific actions.)

The standard methods for all these actions are an orbit-stabilizer algorithm. For permutation groups backtrack algorithms are used. For solvable groups an orbit-stabilizer algorithm for solvable groups, which uses the fact that the orbits of a normal subgroup form a block system (see [LNS84]) is used.

41.5.3 OrbitStabilizerAlgorithm

\[ \texttt{OrbitStabilizerAlgorithm}(G, Omega, blist, gens, acts, pntact) \]

operation
This operation should not be called by a user. It is documented however for purposes to extend or maintain the group actions package (the word “package” here refers to the GAP functionality for group actions, not to a GAP package).

OrbitStabilizerAlgorithm performs an orbit stabilizer algorithm for the group $G$ acting with the generators $gens$ via the generator images $gens$ and the group action $act$ on the element $pnt$. (For technical reasons $pnt$ and $act$ are put in one record with components $pnt$ and $act$ respectively.)

The $pntact$ record may carry a component $stabsub$. If given, this must be a subgroup stabilizing all points in the domain and can be used to abbreviate stabilizer calculations.

The $pntact$ component also may contain the boolean entry $onlystab$ set to true. In this case the orbit component may be omitted from the result.

The argument $Omega$ (which may be replaced by false to be ignored) is the set within which the orbit is computed (once the orbit is the full domain, the orbit calculation may stop). If $blist$ is given it must be a bit list corresponding to $Omega$ in which elements which have been found already will be “ticked off” with true. (In particular, the entries for the orbit of $pnt$ still must be all set to false). Again the remaining action domain (the bits set initially to false) can be used to stop if the orbit cannot grow any longer. Another use of the bit list is if $Omega$ is an enumerator which can determine PositionCanonical (21.16.3) values very quickly. In this situation it can be worth to search images not in the orbit found so far, but via their position in $Omega$ and use a the bit list to keep track whether the element is in the orbit found so far.

### 41.6 Elements with Prescribed Images

#### 41.6.1 RepresentativeAction

\[ RepresentativeAction(G[, Omega], d, e[, gens, acts][, act]) \] (function)

computes an element of $G$ that maps $d$ to $e$ under the given action and returns fail if no such element exists.

```
Example  gap> g:=Group((1,3,2),(2,4,3));;
gap> RepresentativeAction(g,1,3);
(1,3)(2,4)
gap> RepresentativeAction(g,1,3,OnPoints);
(1,3)(2,4)
gap> RepresentativeAction(g,(1,2,3),(2,4,3));
(1,2,4)
gap> RepresentativeAction(g,(1,2,3),(2,3,4));
fail
gap> RepresentativeAction(g,Group((1,2,3)),Group((2,3,4)));
(1,2,4)
gap> RepresentativeAction(g,[1,2,3],[1,2,4],OnSets);
(2,4,3)
gap> RepresentativeAction(g,[1,2,3],[1,2,4],OnTuples);
fail
```

(See Section 41.2 for information about specific actions.)

Again the standard method for RepresentativeAction is an orbit-stabilizer algorithm, for permutation groups and standard actions a backtrack algorithm is used.
41.7 The Permutation Image of an Action

When a group $G$ acts on a domain $\Omega$, an enumeration of $\Omega$ yields a homomorphism from $G$ into the symmetric group on $\{1, \ldots, |\Omega|\}$. In GAP, the enumeration of $\Omega$ is provided by the Enumerator (30.3.2) value of $\Omega$ which of course is $\Omega$ itself if it is a list.

For an action homomorphism, the operation UnderlyingExternalSet (41.12.16) will return the external set on $\Omega$ which affords the action.

41.7.1 ActionHomomorphism

\begin{verbatim}
<function>
ActionHomomorphism(G, Omega[, gens, acts][, act][, "surjective"])
</function>
\end{verbatim}

computes a homomorphism from $G$ into the symmetric group on $|\Omega|$ points that gives the permutation action of $G$ on $\Omega$. (In particular, this homomorphism is a permutation equivalence, that is the permutation image of a group element is given by the positions of points in $\Omega$.)

By default the homomorphism returned by ActionHomomorphism is not necessarily surjective (its Range (32.3.7) value is the full symmetric group) to avoid unnecessary computation of the image. If the optional string argument "surjective" is given, a surjective homomorphism is created.

The third version (which is supported only for GAP3 compatibility) returns the action homomorphism that belongs to the image obtained via Action (41.7.2). (See Section 41.2 for information about specific actions.)

Example

\begin{verbatim}
gap> g:=Group((1,2,3),(1,2));;
gap> hom:=ActionHomomorphism(g,Arrangements([1..4],3),OnTuples);
gap> Image(hom);
Group(
  [ (1,9,13)(2,10,14)(3,7,15)(4,8,16)(5,12,17)(6,11,18)(19,22,23)(20,21,24),
    (1,7)(2,8)(3,9)(4,10)(5,11)(6,12)(13,15)(14,16)(17,18)(19,
    21)(20,22)(23,24) ])
gap> Size(Range(hom));Size(Image(hom));
620448401733239439360000
6

gap> hom:=ActionHomomorphism(g,Arrangements([1..4],3),OnTuples,
> "surjective");;
gap> Size(Range(hom));
6
\end{verbatim}

When acting on a domain, the operation PositionCanonical (21.16.3) is used to determine the position of elements in the domain. This can be used to act on a domain given by a list of representatives for which PositionCanonical (21.16.3) is implemented, for example the return value of RightTransversal (39.8.1).

41.7.2 Action (for a group, an action domain, etc.)

\begin{verbatim}
<function>
Action(G, Omega[, gens, acts][, act])
</function>
\end{verbatim}

\begin{verbatim}
<function>
Action(xset)
</function>
\end{verbatim}
returns the image group of \texttt{ActionHomomorphism} (41.7.1) called with the same parameters.

Note that (for compatibility reasons to be able to get the action homomorphism) this image group internally stores the action homomorphism. If \( G \) or \( \Omega \) are extremely big, this can cause memory problems. In this case compute only generator images and form the image group yourself.

(See Section 41.2 for information about specific actions.)

The following code shows for example how to create the regular action of a group.

\begin{verbatim}
gap> g:=Group((1,2,3),(1,2));;
gap> Action(g,AsList(g),OnRight);
gap> Group([ (1,4,5)(2,3,6), (1,3)(2,4)(5,6) ])\end{verbatim}

### 41.7.3 SparseActionHomomorphism

\( \triangledown \) \texttt{SparseActionHomomorphism}(\( G, \text{start}[, \text{gens}, \text{acts}][, \text{act}] \)) \hspace{1cm} \text{(operation)}

\( \triangledown \) \texttt{SortedSparseActionHomomorphism}(\( G, \text{start}[, \text{gens}, \text{acts}][, \text{act}] \)) \hspace{1cm} \text{(operation)}

\texttt{SparseActionHomomorphism} computes the action homomorphism (see \texttt{ActionHomomorphism} (41.7.1)) with arguments \( G \), \( D \), and the optional arguments given, where \( D \) is the union of the \( G \)-orbits of all points in \text{start}. In the \texttt{Orbit} (41.4.1) calls that are used to create \( D \), again the optional arguments given are entered.

If \( G \) acts on a very large domain not surjectively this may yield a permutation image of substantially smaller degree than by action on the whole domain.

The operation \texttt{SparseActionHomomorphism} will only use \( \leq \) (31.11.1) comparisons of points in the orbit. Therefore it can be used even if no good \( < \) (31.11.1) comparison method for these points is available. However the image group will depend on the generators \texttt{gens} of \( G \).

The operation \texttt{SortedSparseActionHomomorphism} in contrast will sort the orbit and thus produce an image group which does not depend on these generators.

\begin{verbatim}
gap> h:=Group(Z(3)*[[[1,1],[0,1]]]);; Group([ [ Z(3), Z(3) ], [ 0*Z(3), Z(3) ] ]])
gap> hom:=ActionHomomorphism(h,GF(3)^2,OnRight);;
gap> Image(hom);
Group([ (2,3)(4,9,6,7,5,8) ])
gap> hom:=SparseActionHomomorphism(h,[Z(3)*[1,0]],OnRight);;
gap> Image(hom);
Group([ (1,2,3,4,5,6) ])
\end{verbatim}

### 41.8 Action of a group on itself

Of particular importance is the action of a group on its elements or cosets of a subgroup. These actions can be obtained by using \texttt{ActionHomomorphism} (41.7.1) for a suitable domain (for example a list of subgroups). For the following (frequently used) types of actions however special (often particularly efficient) functions are provided. A special case is the regular action on all elements.
### 41.8.1 FactorCosetAction

This command computes the action of the group $G$ on the right cosets of the subgroup $U$. If a normal subgroup $N$ of $G$ is given, it is stored as kernel of this action.

**Example**

```gap
g:=Group((1,2,3,4,5),(1,2));; u:=SylowSubgroup(g,2);; Index(g,u);
gap> FactorCosetAction(g,u);
<action epimorphism>
gap> StructureDescription(Range(last));
"S5"
```

### 41.8.2 RegularActionHomomorphism

This function returns an isomorphism from $G$ onto the regular permutation representation of $G$.

### 41.8.3 AbelianSubfactorAction

Let $G$ be a group and $M \geq N$ be subgroups of a common parent that are normal under $G$, such that the subfactor $M/N$ is elementary abelian. The operation AbelianSubfactorAction returns a list $[\phi, \alpha, \text{bas}]$ where $\text{bas}$ is a list of elements of $M$ which are representatives for a basis of $M/N$, $\alpha$ is a map from $M$ into a $n$-dimensional row space over $GF(p)$ where $[M:N] = p^n$ that is the natural homomorphism of $M$ by $N$ with the quotient represented as an additive group. Finally $\phi$ is a homomorphism from $G$ into $GL_n(p)$ that represents the action of $G$ on the factor $M/N$.

Note: If only matrices for the action are needed, LinearActionLayer (45.14.3) might be faster.

**Example**

```gap
g:=Group((1,8,10,7,3,5)(2,4,12,9,11,6),
  (1,9,5,6,3,10)(2,11,12,8,4,7));
c:=ChiefSeries(g);; List(c,Size);
[ 96, 48, 16, 4, 1 ]
gap> HasElementaryAbelianFactorGroup(c[3],c[4]);
true
gap> SetName(c[3],"my_group");
gap> a:=AbelianSubfactorAction(g,c[3],c[4]);
[ [ (1,8,10,7,3,5)(2,4,12,9,11,6), (1,9,5,6,3,10)(2,11,12,8,4,7) ] ->
  [ <an immutable 2x2 matrix over GF2>,
    <an immutable 2x2 matrix over GF2> ],
  MappingByFunction( my_group, GF(2)^2,
    2, function( e ) ... end, function( r ) ... end ),
  Pcgs([ (2,9,3,8)(4,11,6,10), (1,6,12,7)(4,10,5,11) ])
]
gap> mat:=Image(a[1],g);
Group([ [ <an immutable 2x2 matrix over GF2>,
    <an immutable 2x2 matrix over GF2> ]])
gap> Size(mat);
```
3

gap> e:=PreImagesRepresentative(a[2], [Z(2), 0*Z(2)]);
(2,9,3,8)(4,11,5,10)

gap> e in c[3]; e in c[4];
true
false

41.9 Permutations Induced by Elements and Cycles

If only the permutation image of a single element is needed, it might not be worth to create the action homomorphism, the following operations yield the permutation image and cycles of a single element.

41.9.1 Permutation

\[
\text{Permutation}(g, \text{Omega}[, \text{gens}, \text{acts}][, \text{act}])
\]

computes the permutation that corresponds to the action of \( g \) on the permutation domain \( \text{Omega} \) (a list of objects that are permuted). If an external set \( xset \) is given, the permutation domain is the \text{HomeEnumerator} (41.12.5) value of this external set (see Section 41.12). Note that the points of the returned permutation refer to the positions in \( \text{Omega} \), even if \( \text{Omega} \) itself consists of integers.

If \( g \) does not leave the domain invariant, or does not map the domain injectively then \text{fail} is returned.

41.9.2 PermutationCycle

\[
\text{PermutationCycle}(g, \text{Omega}, \text{pnt}[, \text{act}])
\]

computes the permutation that represents the cycle of \( \text{pnt} \) under the action of the element \( g \).

41.9.3 Cycle

\[
\text{Cycle}(g, \text{Omega}, \text{pnt}[, \text{act}])
\]

returns a list of the points in the cycle of \( \text{pnt} \) under the action of the element \( g \).

41.9.4 CycleLength

\[
\text{CycleLength}(g, \text{Omega}, \text{pnt}[, \text{act}])
\]

returns the length of the cycle of \( \text{pnt} \) under the action of the element \( g \).
41.9.5 Cycles

\[ \text{Cycles}(g, \Omega[, \text{act}]) \]  

returns a list of the cycles (as lists of points) of the action of the element \( g \).

41.9.6 CycleLengths

\[ \text{CycleLengths}(g, \Omega[, \text{act}]) \]  

returns the lengths of all the cycles under the action of the element \( g \) on \( \Omega \).

Example

\begin{verbatim}
gap> Cycle((1,2,3)(4,5)(6,7),[4..7],4); 
[ 4, 5 ]
gap> CycleLength((1,2,3)(4,5)(6,7),[4..7],4); 
2
gap> Cycles((1,2,3)(4,5)(6,7),[4..7]); 
[ [ 4, 5 ], [ 6, 7 ] ]
gap> CycleLengths((1,2,3)(4,5)(6,7),[4..7]); 
[ 2, 2 ]
\end{verbatim}

41.9.7 CycleIndex

\[ \text{CycleIndex}(g, \Omega[, \text{act}]) \]  

\[ \text{CycleIndex}(G, \Omega[, \text{act}]) \]  

The cycle index of a permutation \( g \) acting on \( \Omega \) is defined as

\[ z(g) = s_1^{c_1} s_2^{c_2} \cdots s_n^{c_n} \]

where \( c_k \) is the number of \( k \)-cycles in the cycle decomposition of \( g \) and the \( s_i \) are indeterminates.

The cycle index of a group \( G \) is defined as

\[ Z(G) = \left( \sum_{g \in G} z(g) \right) / |G|. \]

The indeterminates used by \text{CycleIndex} are the indeterminates \( 1 \) to \( n \) over the rationals (see \text{Indeterminate} (66.1.1)).

Example

\begin{verbatim}
gap> g:=TransitiveGroup(6,8); 
S_4(6c) = 1/2[2^3]S(3)
gap> CycleIndex(g); 
1/24*x_1^6+1/8*x_1^2*x_2^2+1/4*x_1^2*x_4+1/4*x_2^3+1/3*x_3^2
\end{verbatim}

41.10 Tests for Actions

41.10.1 IsTransitive

\[ \text{IsTransitive}(g, \Omega[, \text{gens, acts}][, \text{act}]) \]  

\[ \text{IsTransitive}(G) \]  

(operations)
IsTransitive(xset) (property)

returns true if the action implied by the arguments is transitive, or false otherwise.

We say that a group $G$ acts transitively on a domain $D$ if and only if for every pair of points $d, e \in D$ there is an element $g$ in $G$ such that $d^g = e$.

For a permutation group $G$, one may also invoke this as IsTransitive(G), which tests whether the group is transitive with respect to its natural action on the set of points moved by it. For example the group $\langle (2,3,4), (2,3) \rangle$ is transitive on the set $\{2,3,4\}$.

41.10.2 Transitivity

Transitivity(G, Omega[, gens, acts][, act]) (operation)
Transitivity(G) (attribute)
Transitivity(xset) (attribute)

returns the degree $k$ (a non-negative integer) of transitivity of the action implied by the arguments, i.e. the largest integer $k$ such that the action is $k$-transitive. If the action is not transitive 0 is returned.

An action is $k$-transitive if every $k$-tuple of points can be mapped simultaneously to every other $k$-tuple.

For a permutation group $G$, one may also invoke this as Transitivity(G), which returns the degree of transitivity of the group with respect to its natural action on the set of points moved by it. For example the group $\langle (2,3,4), (2,3) \rangle$ is 3-transitive on the set $\{2,3,4\}$.

Example

```gap
g := Group((1,3,2),(2,4,3));
IsTransitive(g,[1..5]);
false
Transitivity(g,[1..4]);
2
Transitivity(g);
2
```

41.10.3 RankAction

RankAction(G, Omega[, gens, acts][, act]) (operation)
RankAction(xset) (attribute)

returns the rank of a transitive action, i.e. the number of orbits of the point stabilizer.

Example

```gap
RankAction(g,Combinations([1..4],2),OnSets);
4
```

41.10.4 IsSemiRegular

IsSemiRegular(G, Omega[, gens, acts][, act]) (operation)
IsSemiRegular(G) (property)
IsSemiRegular(xset) (property)

returns true if the action implied by the arguments is semiregular, or false otherwise.
An action is *semiregular* if the stabilizer of each point is the identity.

For a permutation group $G$, one may also invoke this as $\text{IsSemiRegular}(G)$, which tests whether the group is semiregular with respect to its natural action on the set of points moved by it. For example the group $\langle (2,3,4)(5,6,7) \rangle$ is semiregular on the set $\{2,3,4,5,6,7\}$.

### 41.10.5 IsRegular

- $\text{IsRegular}(G, \Omega[, \text{gens}, \text{acts}][, \text{act}])$ (operation)
- $\text{IsRegular}(G)$ (property)
- $\text{IsRegular}(\text{xset})$ (property)

returns `true` if the action implied by the arguments is regular, or `false` otherwise.

An action is *regular* if it is both semiregular (see $\text{IsSemiRegular}$ (41.10.4)) and transitive (see $\text{IsTransitive}$ (41.10.1)). In this case every point $pnt$ of $\Omega$ defines a one-to-one correspondence between $G$ and $\Omega$.

For a permutation group $G$, one may also invoke this as $\text{IsRegular}(G)$, which tests whether the group is regular with respect to its natural action on the set of points moved by it. For example the group $\langle (2,3,4) \rangle$ is regular on the set $\{2,3,4\}$.

**Example**

```gap
gap> \text{IsSemiRegular}(g, \text{Arrangements([1..4],3)}, \text{OnTuples});
true
gap> \text{IsRegular}(g, \text{Arrangements([1..4],3)}, \text{OnTuples});
false
```

### 41.10.6 Earns

- $\text{Earns}(G, \Omega[, \text{gens}, \text{acts}][, \text{act}])$ (operation)
- $\text{Earns}(\text{xset})$ (attribute)

returns a list of the elementary abelian regular (when acting on $\Omega$) normal subgroups of $G$.

At the moment only methods for a primitive group $G$ are implemented.

### 41.10.7 IsPrimitive

- $\text{IsPrimitive}(G, \Omega[, \text{gens}, \text{acts}][, \text{act}])$ (operation)
- $\text{IsPrimitive}(G)$ (property)
- $\text{IsPrimitive}(\text{xset})$ (property)

returns `true` if the action implied by the arguments is primitive, or `false` otherwise.

An action is *primitive* if it is transitive and the action admits no nontrivial block systems. See 41.11 for the definition of block systems.

For a permutation group $G$, one may also invoke this as $\text{IsPrimitive}(G)$, which tests whether the group is primitive with respect to its natural action on the set of points moved by it. For example the group $\langle (2,3,4), (2,3) \rangle$ is primitive on the set $\{2,3,4\}$.

For an explanation of the meaning of all the inputs, please refer to 41.1.

**Note:** This operation does not tell whether a matrix group is primitive in the sense of preserving a direct sum of vector spaces. To do this use $\text{IsPrimitiveMatrixGroup}$ or $\text{IsPrimitive}$ from the package IRREDSOL.
41.11 Block Systems

A block system (system of imprimitivity) for the action of a group $G$ on an action domain $\Omega$ is a partition of $\Omega$ which –as a partition– remains invariant under the action of $G$.

41.11.1 Blocks

\[ \text{Blocks}(G, \Omega[, \text{seed}][, \text{gens}, \text{acts}][, \text{act}]) \]

\[ \text{Blocks}(xset[, \text{seed}]) \]

computes a block system for the action. If $\text{seed}$ is not given and the action is imprimitive, a minimal nontrivial block system will be found. If $\text{seed}$ is given, a block system in which $\text{seed}$ is the subset of one block is computed. The action must be transitive.

```
gap> g:=TransitiveGroup(8,3);
gap> Blocks(g,[1..8]);
gap> Blocks(g,[1..8],[1,4]);
```

(See Section 41.2 for information about specific actions.)

41.11.2 MaximalBlocks

\[ \text{MaximalBlocks}(G, \Omega[, \text{seed}][, \text{gens}, \text{acts}][, \text{act}]) \]

\[ \text{MaximalBlocks}(xset[, \text{seed}]) \]

returns a block system that is maximal (i.e., blocks are maximal with respect to inclusion) for the action of $G$ on $\Omega$. If $\text{seed}$ is given, a block system is computed in which $\text{seed}$ is a subset of one block.

```
gap> MaximalBlocks(g,[1..8]);
```

41.11.3 RepresentativesMinimalBlocks

\[ \text{RepresentativesMinimalBlocks}(G, \Omega[, \text{gens}, \text{acts}][, \text{act}]) \]

\[ \text{RepresentativesMinimalBlocks}(xset) \]

computes a list of block representatives for all minimal (i.e blocks are minimal with respect to inclusion) nontrivial block systems for the action.
Example

```
gap> RepresentativesMinimalBlocks(g,[1..8]);
[ [ 1, 2 ], [ 1, 3 ], [ 1, 4 ], [ 1, 5 ], [ 1, 6 ], [ 1, 7 ],
  [ 1, 8 ] ]
```

### 41.11.4 AllBlocks

\[ \text{AllBlocks}(G) \]

computes a list of representatives of all block systems for a permutation group \( G \) acting transitively on the points moved by the group.

Example

```
gap> AllBlocks(g);
[ [ 1, 8 ], [ 1, 2, 3, 8 ], [ 1, 4, 5, 8 ], [ 1, 6, 7, 8 ], [ 1, 3 ],
  [ 1, 3, 5, 7 ], [ 1, 3, 4, 6 ], [ 1, 5 ], [ 1, 2, 5, 6 ], [ 1, 2 ],
  [ 1, 2, 4, 7 ], [ 1, 4 ], [ 1, 7 ], [ 1, 6 ] ]
```

The stabilizer of a block can be computed via the action \( \text{OnSets} \) (41.2.4):

Example

```
gap> Stabilizer(g,[1,8],OnSets);
Group([ (1,8)(2,3)(4,5)(6,7) ])
```

If \( \mathcal{B} \) is a partition of the action domain, given as a set of sets, the stabilizer under the action \( \text{OnSetsDisjointSets} \) (41.2.8) returns the largest subgroup which preserves \( \mathcal{B} \) as a block system.

Example

```
gap> g:=Group((1,2,3,4,5,6,7,8),(1,2));;
gap> bs:=[[1,2,3,4],[5,6,7,8]];;
gap> Stabilizer(g,bs,OnSetsDisjointSets);
Group([ (6,7), (5,6), (5,8), (2,3), (3,4)(5,7), (1,4),
       (1,5,4,8)(2,6,3,7) ])
```

### 41.12 External Sets

When considering group actions, sometimes the concept of a \( G \)-set is used. This is a set \( \Omega \) endowed with an action of \( G \). The elements of the \( G \)-set are the same as those of \( \Omega \), however concepts like equality and equivalence of \( G \)-sets do not only consider the underlying domain \( \Omega \) but the group action as well.

This concept is implemented in GAP via external sets.

The constituents of an external set are stored in the attributes \( \text{ActingDomain} \) (41.12.3), \( \text{FunctionAction} \) (41.12.4) and \( \text{HomeEnumerator} \) (41.12.5).

Most operations for actions are applicable as an attribute for an external set.

The most prominent external subsets are orbits, see \( \text{ExternalOrbit} \) (41.12.9).

Many subsets of a group, such as conjugacy classes or cosets (see \( \text{ConjugacyClass} \) (39.10.1) and \( \text{RightCoset} \) (39.7.1)) are implemented as external orbits.

External sets also are implicitly underlying action homomorphisms, see \( \text{UnderlyingExternalSet} \) (41.12.16) and \( \text{SurjectiveActionHomomorphismAttr} \) (41.12.17).
41.12.1 IsExternalSet

\[ \text{IsExternalSet(obj)} \]

A set specifies a group action \( \mu : \Omega \times G \rightarrow \Omega \) of a group \( G \) on a domain \( \Omega \). The set knows the group, the domain and the actual acting function. Mathematically, an external set is the set \( \Omega \), which is endowed with the action of a group \( G \) via the group action \( \mu \). For this reason GAP treats an external set as a domain whose elements are the elements of \( \Omega \). An external set is always a union of orbits. Currently the domain \( \Omega \) must always be finite. If \( \Omega \) is not a list, an enumerator for \( \Omega \) is automatically chosen, see Enumerator (30.3.2).

41.12.2 ExternalSet

\[ \text{ExternalSet(G, Omega[, gens, acts][, act])} \]

creates the external set for the action \( \text{act} \) of \( G \) on \( \text{Omega} \). \( \text{Omega} \) can be either a proper set, or a domain which is represented as described in 12.4 and 30, or (to use less memory but with a slower performance) an enumerator (see Enumerator (30.3.2) ) of this domain.

```gap
gap> g:=Group((1,2,3),(2,3,4));;
gap> e:=ExternalSet(g,[1..4]);
gap> e:=ExternalSet(g,g,OnRight);
gap> Orbits(e);
[( (), (1,2)(3,4), (1,3)(2,4), (1,4)(2,3), (1,2,3), (1,3,4), (1,2,4),
  (1,3,2), (1,4,3), (1,2,4) ]
```

41.12.3 ActingDomain

\[ \text{ActingDomain(xset)} \]

This attribute returns the group with which the external set \( xset \) was defined.

41.12.4 FunctionAction

\[ \text{FunctionAction(xset)} \]

is the acting function with which the external set \( xset \) was defined.

41.12.5 HomeEnumerator

\[ \text{HomeEnumerator(xset)} \]

returns an enumerator of the action domain with which the external set \( xset \) was defined. For external subsets, this is in general different from the Enumerator (30.3.2) value of \( xset \), which enumerates only the subset.
41.12.6 IsExternalSubset

\[ \text{IsExternalSubset}(\text{obj}) \]

An external subset is the restriction of an external set to a subset of the domain (which must be invariant under the action). It is again an external set.

41.12.7 ExternalSubset

\[ \text{ExternalSubset}(\text{G}, \text{xset}, \text{start}[, \text{gens}, \text{acts}]), \text{act} \]

constructs the external subset of \( \text{xset} \) on the union of orbits of the points in \( \text{start} \).

41.12.8 IsExternalOrbit

\[ \text{IsExternalOrbit}(\text{obj}) \]

An external orbit is an external subset consisting of one orbit.

41.12.9 ExternalOrbit

\[ \text{ExternalOrbit}(\text{G}, \text{Omega}, \text{pnt}[, \text{gens}, \text{acts}]), \text{act} \]

constructs the external subset on the orbit of \( \text{pnt} \). The \text{Representative} (30.4.7) value of this external set is \( \text{pnt} \).

41.12.10 StabilizerOfExternalSet

\[ \text{StabilizerOfExternalSet}(\text{xset}) \]

computes the stabilizer of the \text{Representative} (30.4.7) value of the external set \( \text{xset} \). The stabilizer will have the acting group of \( \text{xset} \) as its parent.
41.12.11  ExternalOrbits

▷ ExternalOrbits\((G, \Omega, \text{gens}, \text{acts})\[, \text{act}\]\)
▷ ExternalOrbits\((\text{xset})\)

computes a list of external orbits that give the orbits of \(G\).

Example

\[
gap> \text{ExternalOrbits}(g, \text{AsList}(g));
[ (1)^G, (2,3,4)^G, (2,4,3)^G, (1,2)(3,4)^G ]
\]

41.12.12  ExternalOrbitsStabilizers

▷ ExternalOrbitsStabilizers\((G, \Omega, \text{gens}, \text{acts})\[, \text{act}\]\)
▷ ExternalOrbitsStabilizers\((\text{xset})\)

In addition to ExternalOrbits (41.12.11), this operation also computes the stabilizers of the representatives of the external orbits at the same time. (This can be quicker than computing the ExternalOrbits (41.12.11) value first and the stabilizers afterwards.)

Example

\[
gap> e := \text{ExternalOrbitsStabilizers}(g, \text{AsList}(g));
[ (1)^G, (2,3,4)^G, (2,4,3)^G, (1,2)(3,4)^G ]
gap> \text{HasStabilizerOfExternalSet}(e[3]);
true
gap> \text{StabilizerOfExternalSet}(e[3]);
\text{Group([ (2,4,3) ])}
\]

41.12.13  CanonicalRepresentativeOfExternalSet

▷ CanonicalRepresentativeOfExternalSet\((\text{xset})\)

The canonical representative of an external set \(\text{xset}\) may only depend on the defining attributes \(G, \Omega, \text{act}\) of \(\text{xset}\) and (in the case of external subsets) Enumerator\((\text{xset})\). It must not depend, e.g., on the representative of an external orbit. GAP does not know methods for arbitrary external sets to compute a canonical representative, see CanonicalRepresentativeDeterminatorOfExternalSet (41.12.14).

41.12.14  CanonicalRepresentativeDeterminatorOfExternalSet

▷ CanonicalRepresentativeDeterminatorOfExternalSet\((\text{xset})\)

returns a function that takes as its arguments the acting group and a point. This function returns a list of length 1 or 3, the first entry being the canonical representative and the other entries (if bound) being the stabilizer of the canonical representative and a conjugating element, respectively. An external set is only guaranteed to be able to compute a canonical representative if it has a CanonicalRepresentativeDeterminatorOfExternalSet.
41.12.15 ActorOfExternalSet

\[ \text{ActorOfExternalSet}(xset) \]

returns an element mapping \( \text{Representative}(xset) \) to \( \text{CanonicalRepresentativeOfExternalSet}(xset) \) under the given action.

\[
\text{Example}
\]

\begin{verbatim}
gap> u:=Subgroup(g,[(1,2,3)]);;
gap> e:=RightCoset(u,(1,2)(3,4));;
gap> CanonicalRepresentativeOfExternalSet(e);
(2,4,3)
gap> ActorOfExternalSet(e);
(1,3,2)
gap> FunctionAction(e)((1,2)(3,4),last);
(2,4,3)
\end{verbatim}

41.12.16 UnderlyingExternalSet

\[ \text{UnderlyingExternalSet}(\text{acthom}) \]

The underlying set of an action homomorphism \( \text{acthom} \) is the external set on which it was defined.

\[
\text{Example}
\]

\begin{verbatim}
gap> g:=Group((1,2,3),(1,2));;
gap> hom:=ActionHomomorphism(g,Arrangements([1..4],3),OnTuples);
gap> s:=UnderlyingExternalSet(hom);
<xset:|[1,2,3],[1,2,4],[1,3,2],[1,3,4],[1,4,2],[1,4,3],[2,1,3],[2,1,4],[2,3,1],[2,3,4],[2,4,1],[2,4,3],[3,1,2],[3,1,4],[3,2,1],...]>
gap> Print(s,"
);
[ [1,2,3],[1,2,4],[1,3,2],[1,3,4],[1,4,2],[1,4,3],[2,1,3],[2,1,4],[2,3,1],[2,3,4],[2,4,1],[2,4,3],[3,1,2],[3,1,4],[3,2,1],...]
\end{verbatim}

41.12.17 SurjectiveActionHomomorphismAttr

\[ \text{SurjectiveActionHomomorphismAttr}(xset) \]

returns an action homomorphism for the external set \( xset \) which is surjective. (As the \text{Image} (32.4.6) value of this homomorphism has to be computed to obtain the range, this may take substantially longer than \text{ActionHomomorphism} (41.7.1).)
Chapter 42
Permutations

GAP offers a data type *permutation* to describe the elements of permutation groups.

The points on which permutations in GAP act are the positive integers up to a certain architecture
dependent limit, and the image of a point \( i \) under a permutation \( p \) is written \( i^p \), which is expressed as \( i^p \) in GAP. (This action is also implemented by the function OnPoints (41.2.1).) If \( i^p \) is different
from \( i \), we say that \( i \) is *moved* by \( p \), otherwise it is *fixed*. Permutations in GAP are entered and
displayed in cycle notation, such as \((1,2,3)(4,5)\).

The preimage of the point \( i \) under the permutation \( p \) can be computed as \( i/p \), see PERM_INVERSE_THRESHOLD (42.1.4).

For arithmetic operations for permutations and their precedence, see 31.12.

In the names of the GAP functions that deal with permutations, the word “Permutation” is usually
abbreviated to “Perm”, to save typing. For example, the category test function for permutations is IsPerm (42.1.1).

42.1 IsPerm (Filter)

Internally, GAP stores a permutation as a list of the \( d \) images of the integers \( 1, \ldots, d \), where the
“internal degree” \( d \) is the largest integer moved by the permutation or bigger. When a permutation is
read in in cycle notation, \( d \) is always set to the largest moved integer, but a bigger \( d \) can result from
a multiplication of two permutations, because the product is not shortened if it fixes \( d \). The images
are stored all as 16-bit integers or all as 32-bit integers, depending on whether \( d \leq 65536 \) or not. For
example, if \( m \geq 65536 \), the permutation \((1,2,\ldots,m)\) has internal degree \( d = m \) and takes \( 4m \) bytes of
memory for storage. But — since the internal degree is not reduced — this means that the identity
permutation \( () \) calculated as \((1,2,\ldots,m) \ast (1,2,\ldots,m)^{-1} \) also takes \( 4m \) bytes of storage. It can take
even more because the internal list has sometimes room for more than \( d \) images.

On 32-bit systems, the limit on the degree of permutations is, for technical reasons, \( 2^{28} - 1 \). On
64-bit systems, it is \( 2^{32} - 1 \) because only a 32-bit integer is used to represent each image internally.
Error messages should be given if any command would require creating a permutation exceeding this
limit.

The operation RestrictedPerm (42.5.4) reduces the storage degree of its result and therefore can
be used to save memory if intermediate calculations in large degree result in a small degree result.

Permutations do not belong to a specific group. That means that one can work with permutations
without defining a permutation group that contains them.
Example

```
gap> (1,2,3);
(1,2,3)
gap> (1,2,3) * (2,3,4);
(1,3)(2,4)
gap> 17^(2,5,17,9,8);
9
gap> OnPoints(17,(2,5,17,9,8));
9
```

The operation `Permuted (21.20.18)` can be used to permute the entries of a list according to a permutation.

### 42.1.1 IsPerm

\[ \text{IsPerm}(\text{obj}) \] (Category)

Each permutation in GAP lies in the category `IsPerm`. Basic operations for permutations are `LargestMovedPoint (42.3.2)`, multiplication of two permutations via `*`, and exponentiation `^` with first argument a positive integer \( i \) and second argument a permutation \( \pi \), the result being the image \( i^\pi \) of the point \( i \) under \( \pi \).

### 42.1.2 IsPermCollection

\[ \text{IsPermCollection}(\text{obj}) \] (Category)
\[ \text{IsPermCollColl}(\text{obj}) \] (Category)

are the categories for collections of permutations and collections of collections of permutations, respectively.

### 42.1.3 PermutationsFamily

\[ \text{PermutationsFamily} \] (family)

is the family of all permutations.

### 42.1.4 PERM_INVERSE_THRESHOLD

\[ \text{PERM_INVERSE_THRESHOLD} \] (global variable)

For permutations of degree up to `PERM_INVERSE_THRESHOLD` whenever the inverse image of a point under a permutations is needed, the entire inverse is computed and stored. Otherwise, if the inverse is not stored, the point is traced around the cycle it is part of to find the inverse image. This takes time when it happens, and uses memory, but saves time on a variety of subsequent computations. This threshold can be adjusted by simply assigning to the variable. The default is 10000.
42.2 Comparison of Permutations

42.2.1 \( \leq \) (for permutations)

\( \leq (p_1, p_2) \) (method)
\( < (p_1, p_2) \) (method)

Two permutations are equal if they move the same points and all these points have the same images under both permutations.

The permutation \( p_1 \) is smaller than \( p_2 \) if \( p_1 \neq p_2 \) and \( i^{p_1} < i^{p_2} \), where \( i \) is the smallest point with \( i^{p_1} \neq i^{p_2} \). Therefore the identity permutation is the smallest permutation, see also Section 31.11.

Permutations can be compared with certain other GAP objects, see 4.12 for the details.

Example

\[
\begin{align*}
gap> & (1,2,3) = (2,3,1); \\
gap> & (1,2,3) \times (2,3,4) = (1,3)(2,4); \\
gap> & (1,2,3) < (1,3,2); \quad \# 1^-(1,2,3) = 2 < 3 = 1^-(1,3,2) \\
gap> & (1,3,2,4) < (1,3,4,2); \quad \# 2^-(1,3,2,4) = 4 > 1 = 2^-(1,3,4,2) \\
gap> & \text{false}
\end{align*}
\]

42.2.2 DistancePerms

\( \text{DistancePerms}(\text{perm1}, \text{perm2}) \) (operation)

returns the number of points for which \( \text{perm1} \) and \( \text{perm2} \) have different images. This should always produce the same result as \( \text{NrMovePoints}(\text{perm1} / \text{perm2}) \) but some methods may be much faster than this form, since no new permutation needs to be created.

42.2.3 SmallestGeneratorPerm

\( \text{SmallestGeneratorPerm}(\text{perm}) \) (attribute)

is the smallest permutation that generates the same cyclic group as the permutation \( \text{perm} \). This is very efficient, even when \( \text{perm} \) has large order.

Example

\[
\begin{align*}
gap> & \text{SmallestGeneratorPerm}( (1,4,3,2) ); \\
& (1,2,3,4)
\end{align*}
\]

42.3 Moved Points of Permutations

42.3.1 SmallestMovedPoint (for a permutation)

\( \text{SmallestMovedPoint}(\text{perm}) \) (attribute)
\( \text{SmallestMovedPoint}(\text{C}) \) (attribute)
is the smallest positive integer that is moved by \texttt{perm} if such an integer exists, and \texttt{infinity} (18.2.1) if \texttt{perm} is the identity. For \texttt{C} a collection or list of permutations, the smallest value of \texttt{SmallestMovedPoint} for the elements of \texttt{C} is returned (and \texttt{infinity} (18.2.1) if \texttt{C} is empty).

### 42.3.2 \texttt{LargestMovedPoint} (for a permutation)

\begin{verbatim}
\texttt{LargestMovedPoint(perm)} \quad (attribute)
\texttt{LargestMovedPoint(C)} \quad (attribute)
\end{verbatim}

For a permutation \texttt{perm}, this attribute contains the largest positive integer which is moved by \texttt{perm} if such an integer exists, and 0 if \texttt{perm} is the identity. For \texttt{C} a collection or list of permutations, the largest value of \texttt{LargestMovedPoint} for the elements of \texttt{C} is returned (and 0 if \texttt{C} is empty).

### 42.3.3 \texttt{MovedPoints} (for a permutation)

\begin{verbatim}
\texttt{MovedPoints(perm)} \quad (attribute)
\texttt{MovedPoints(C)} \quad (attribute)
\end{verbatim}

is the proper set of the positive integers moved by at least one permutation in the collection \texttt{C}, respectively by the permutation \texttt{perm}.

### 42.3.4 \texttt{NrMovedPoints} (for a permutation)

\begin{verbatim}
\texttt{NrMovedPoints(perm)} \quad (attribute)
\texttt{NrMovedPoints(C)} \quad (attribute)
\end{verbatim}

is the number of positive integers that are moved by \texttt{perm}, respectively by at least one element in the collection \texttt{C}. (The actual moved points are returned by \texttt{MovedPoints} (42.3.3).)

\begin{example}
\begin{verbatim}
gap> SmallestMovedPointPerm((4,5,6)(7,2,8));
gap> LargestMovedPointPerm((4,5,6)(7,2,8));
gap> NrMovedPointsPerm((4,5,6)(7,2,8));
gap> MovedPoints([(2,3,4),(7,6,3),(5,47)]);
gap> NrMovedPoints([(2,3,4),(7,6,3),(5,47)]);
gap> SmallestMovedPoint([(2,3,4),(7,6,3),(5,47)]);
gap> LargestMovedPoint([(2,3,4),(7,6,3),(5,47)]);
gap> LargestMovedPoint([]);
\end{verbatim}
\end{example}
42.4 Sign and Cycle Structure

42.4.1 SignPerm

▷ SignPerm(perm) (attribute)

The sign of a permutation perm is defined as \((-1)^k\) where \(k\) is the number of cycles of perm of even length.

The sign is a homomorphism from the symmetric group onto the multiplicative group \(\{+1,-1\}\), the kernel of which is the alternating group.

42.4.2 CycleStructurePerm

▷ CycleStructurePerm(perm) (attribute)

is the cycle structure (i.e. the numbers of cycles of different lengths) of the permutation perm. This is encoded in a list \(l\) in the following form: The \(i\)-th entry of \(l\) contains the number of cycles of perm of length \(i+1\). If perm contains no cycles of length \(i+1\) it is not bound. Cycles of length 1 are ignored.

Example

\[
\begin{align*}
gap> & \text{SignPerm}((1,2,3)(4,5)); \\
& \text{-1} \\
gap> & \text{CycleStructurePerm}((1,2,3)(4,5,9,7,8)); \\
& [ \ , \ 1\ , \ , \ 1 \ ]
\end{align*}
\]

42.5 Creating Permutations

42.5.1 ListPerm

▷ ListPerm(perm[, length]) (function)

is a list \(l\) that contains the images of the positive integers under the permutation perm. That means that \(l[i] = i^\text{perm}\), where \(i\) lies between 1 and the largest point moved by perm (see LargestMovedPoint (42.3.2)). An optional second argument specifies the length of the desired list.

42.5.2 PermList

▷ PermList(list) (function)

is the permutation \(\pi\) that moves points as described by the list list. That means that \(i^\pi = \text{list}[i]\) if \(i\) lies between 1 and the length of list, and \(i^\pi = i\) if \(i\) is larger than the length of the list list. PermList will return fail if list does not define a permutation, i.e., if list is not dense, or if list contains a positive integer twice, or if list contains an integer not in the range \([1..\ \text{Length}(\ list \ )\ ]\), or if list contains non-integer entries, etc.
42.5.3 MappingPermListList

Let \( src \) and \( dst \) be lists of positive integers of the same length, such that there is a permutation \( \pi \) such that \( \text{OnTuples}(src, \pi) = dst \). \text{MappingPermListList} returns the permutation \( p \) from the previous sentence, i.e. \( src[i]^p = dst[i] \). The permutation \( \pi \) fixes any point which is not in \( src \) or \( dst \). If there are several such permutations, it is not specified which of them \text{MappingPermListList} returns. If there is no such permutation, then \text{MappingPermListList} returns \text{fail}.

42.5.4 RestrictedPerm

\text{RestrictedPerm} returns the new permutation that acts on the points in the list \( list \) in the same way as the permutation \( perm \), and that fixes those points that are not in \( list \). The resulting permutation is stored internally of degree given by the maximal entry of \( list \). \( list \) must be a list of positive integers such that for each \( i \) in \( list \) the image \( i^perm \) is also in \( list \), i.e., \( list \) must be the union of cycles of \( perm \).

\text{RestrictedPermNC} does not check whether \( list \) is a union of cycles.

Example

\begin{verbatim}
gap> ListPerm((3,4,5)); [ 1, 2, 4, 5, 3 ]
gap> PermList([1,2,4,5,3]); (3,4,5)
gap> MappingPermListList([2,5,1,6],[7,12,8,2]); (1,8,5,12,6,2,7)
gap> RestrictedPerm((1,2)(3,4),[3..5]); (3,4)
\end{verbatim}

42.5.5 CycleFromList

\text{CycleFromList} returns the \( n \)-cycle \((a_1,a_2,...,a_n)\). For the empty list the trivial permutation () is returned.

If the given \( list \) contains duplicates or holes, return \text{fail}.

Example

\begin{verbatim}
gap> CycleFromList( [1,2,3,4] ); (1,2,3,4)
gap> CycleFromList( [3,2,6,4,5] ); (2,6,4,5,3)
gap> CycleFromList( [2,3,2] ); fail
\end{verbatim}
42.5.6 AsPermutation

\[\text{AsPermutation}(f)\] (attribute)

**Returns:** A permutation or fail.

Partial permutations and transformations which define permutations (mathematically) can be converted into GAP permutations using `AsPermutation`; see Chapters 53 and 54 for more details about transformations and partial permutations.

**for partial permutations**

If the partial permutation \( f \) is a permutation of its image, then `AsPermutation` returns this permutation. If \( f \) does not permute its image, then `fail` is returned.

**for transformations**

A transformation is a permutation if and only if its rank equals its degree. If a transformation in GAP is a permutation, then `AsPermutation` returns this permutation. If \( f \) is not a permutation, then `fail` is returned.

The function `Permutation` (41.9.1) can also be used to convert partial permutations and transformations into permutations where appropriate.

Example

```gap
gap> f:=PartialPerm([1, 2, 3, 4, 5, 6, 7, 8, 9, 10],
                  [2, 7, 9, 4, 1, 10, 5, 6, 3, 8]);
(1,2,7,5)(3,9)(6,10,8)
gap> AsPermutation(f);
(1,2,7,5)(3,9)(6,10,8)
gap> f:= PartialPerm([1, 2, 3, 4, 5, 7, 8], [5, 3, 8, 1, 9, 4, 10]);
[2,3,8,10][7,4,1,5,9]
gap> AsPermutation(f);
fail
gap> f:=Transformation([5, 8, 3, 5, 8, 6, 2, 2, 7, 8]);
gap> AsPermutation(f);
fail
gap> f:=Transformation([1, 3, 6, 6, 2, 10, 2, 3, 10, 5]);
gap> AsPermutation(f);
fail
gap> f:=Transformation([2, 7, 9, 4, 1, 10, 5, 6, 3, 8]);
Transformation([ 2, 7, 9, 4, 1, 10, 5, 6, 3, 8 ])
gap> AsPermutation(f);
(1,2,7,5)(3,9)(6,10,8)
```
Chapter 43

Permutation Groups

43.1 IsPermGroup (Filter)

43.1.1 IsPermGroup

\(\text{IsPermGroup}(\text{obj})\) (Category)

A permutation group is a group of permutations on a finite set \(\Omega\) of positive integers. \texttt{GAP} does not require the user to specify the operation domain \(\Omega\) when a permutation group is defined.

\begin{verbatim}
gap> g:=Group((1,2,3,4),(1,2)); Group([ (1,2,3,4), (1,2) ])
gap> MovedPoints( g ); NrMovedPoints( g ); [ 2, 3, 5, 6 ] 4
 gap> LargestMovedPoint( g ); SmallestMovedPoint( g ); 6 2
\end{verbatim}

Permutation groups are groups and therefore all operations for groups (see Chapter 39) can be applied to them. In many cases special methods are installed for permutation groups that make computations more effective.

43.2 The Natural Action

The functions \texttt{MovedPoints (42.3.3)}, \texttt{NrMovedPoints (42.3.4)}, \texttt{LargestMovedPoint (42.3.2)}, and \texttt{SmallestMovedPoint (42.3.1)} are defined for arbitrary collections of permutations (see 42.3), in particular they can be applied to permutation groups.

\begin{verbatim}
gap> g:= Group( (2,3,5,6), (2,3) );
gap> MovedPoints( g ); NrMovedPoints( g ); [ 2, 3, 5, 6 ] 4
 gap> LargestMovedPoint( g ); SmallestMovedPoint( g ); 6 2
\end{verbatim}

The action of a permutation group on the positive integers is a group action (via the acting function \texttt{OnPoints (41.2.1)}). Therefore all action functions can be applied (see the Chapter 41), for example \texttt{Orbit (41.4.1)}, \texttt{Stabilizer (41.5.2)}, \texttt{Blocks (41.11.1)}, \texttt{IsTransitive (41.10.1)}, \texttt{IsPrimitive (41.10.7)}. 636
If one has a list of group generators and is interested in the moved points (see above) or orbits, it may be useful to avoid the explicit construction of the group for efficiency reasons. For the special case of the action of permutations on positive integers via ^\ast, the functions OrbitPerms (43.2.1) and OrbitsPerms (43.2.2) are provided for this purpose.

Similarly, several functions concerning the natural action of permutation groups address stabilizer chains (see 43.6) rather than permutation groups themselves, for example BaseStabChain (43.10.1).

43.2.1 OrbitPerms

\>$ \texttt{OrbitPerms}(\text{perms}, \text{pnt})$ (function)

returns the orbit of the positive integer \text{pnt} under the group generated by the permutations in the list \text{perms}.

43.2.2 OrbitsPerms

\>$ \texttt{OrbitsPerms}(\text{perms}, \text{D})$ (function)

returns the list of orbits of the positive integers in the list \text{D} under the group generated by the permutations in the list \text{perms}.

**Example**

\[
gap> \text{OrbitPerms}([ (1,2,3)(4,5), (3,6) ], 1);
\]
\[
[ 1, 2, 3, 6 ]
\]
\[
gap> \text{OrbitsPerms}([ (1,2,3)(4,5), (3,6) ], [ 1 .. 6 ]); \\
\]
\[
[ [ 1, 2, 3, 6 ], [ 4, 5 ] ]
\]

43.3 Computing a Permutation Representation

43.3.1 IsomorphismPermGroup

\>$ \texttt{IsomorphismPermGroup}(\text{G})$ (attribute)

returns an isomorphism from the group \text{G} onto a permutation group which is isomorphic to \text{G}. The method will select a suitable permutation representation.

**Example**

\[
gap> \text{g:=SmallGroup(24,12)};
<\text{pc group of size 24 with 4 generators}>
\]
\[
gap> \text{iso:=IsomorphismPermGroup(g)};
<\text{action isomorphism}>
\]
\[
gap> \text{Image(iso,g.3*g.4)};
(1,12)(2,16)(3,19)(4,5)(6,22)(7,8)(9,23)(10,11)(13,24)(14,15)(17,18)(20,21)
\]

In many cases the permutation representation constructed by IsomorphismPermGroup is regular.
43.3.2 SmallerDegreePermutationRepresentation

\[ \text{SmallerDegreePermutationRepresentation}(G) \]

Let \( G \) be a permutation group that acts transitively on its moved points. \text{SmallerDegreePermutationRepresentation} tries to find a faithful permutation representation of smaller degree. The result is a group homomorphism onto a permutation group, in the worst case this is the identity mapping on \( G \).

If the cheap option is given, the function only tries to reduce to orbits or actions on blocks, otherwise also actions on cosets of random subgroups are tried.

Note that the result is not guaranteed to be a faithful permutation representation of smallest degree, or of smallest degree among the transitive permutation representations of \( G \). Using \text{GAP} interactively, one might be able to choose subgroups of small index for which the cores intersect trivially; in this case, the actions on the cosets of these subgroups give rise to an intransitive permutation representation the degree of which may be smaller than the original degree.

The methods used might involve the use of random elements and the permutation representation (or even the degree of the representation) is not guaranteed to be the same for different calls of \text{SmallerDegreePermutationRepresentation}.

If the option cheap is given less work is spent on trying to get a small degree representation, if the value of this option is set to the string "skip" the identity mapping is returned. (This is useful if a function called internally might try a degree reduction.)

Example

```gap
gap> image:= Image( iso );; NrMovedPoints( image ); 24
gap> small:= SmallerDegreePermutationRepresentation( image );;
Group([ (2,3), (2,3,4), (1,2)(3,4), (1,3)(2,4) ])
```

Example

```gap
gap> p:=Group((1,2,3,4,5,6),(1,2));;p:=Action(p,AsList(p),OnRight);;
gap> Length(MovedPoints(p)); 720
gap> q:=SmallerDegreePermutationRepresentation(p);;
gap> NrMovedPoints(Image(q)); 6
```

43.4 Symmetric and Alternating Groups

The commands \text{SymmetricGroup} (50.1.12) and \text{AlternatingGroup} (50.1.11) (see Section 50.1) construct symmetric and alternating permutation groups. \text{GAP} can also detect whether a given permutation group is a symmetric or alternating group on the set of its moved points; if so then the group is called a \textit{natural} symmetric or alternating group, respectively.

The functions \text{IsSymmetricGroup} (43.4.2) and \text{IsAlternatingGroup} (43.4.3) can be used to check whether a given group (not necessarily a permutation group) is isomorphic to a symmetric or alternating group.
43.4.1  IsNaturalSymmetricGroup

▷ IsNaturalSymmetricGroup(group)  (property)
▷ IsNaturalAlternatingGroup(group)  (property)

A group is a natural symmetric or alternating group if it is a permutation group acting as symmetric or alternating group, respectively, on its moved points.

For groups that are known to be natural symmetric or natural alternating groups, very efficient methods for computing membership, conjugacy classes, Sylow subgroups etc. are used.

Example

```gap
gap> g:=Group((1,5,7,8,99),(1,99,13,72));;
gap> IsNaturalSymmetricGroup(g);
true
gap> g;
Sym( [ 1, 5, 7, 8, 13, 72, 99 ] )
gap> IsNaturalSymmetricGroup( Group( (1,2)(4,5), (1,2,3)(4,5,6) ) );
false
```

43.4.2  IsSymmetricGroup

▷ IsSymmetricGroup(group)  (property)

is true if the group group is isomorphic to a symmetric group.

43.4.3  IsAlternatingGroup

▷ IsAlternatingGroup(group)  (property)

is true if the group group is isomorphic to a alternating group.

43.4.4  SymmetricParentGroup

▷ SymmetricParentGroup(grp)  (attribute)

For a permutation group grp this function returns the symmetric group that moves the same points as grp does.

Example

```gap
gap> SymmetricParentGroup( Group( (1,2), (4,5), (7,8,9) ) );
Sym( [ 1, 2, 4, 5, 7, 8, 9 ] )
```

43.5  Primitive Groups

43.5.1  ONanScottType

▷ ONanScottType(G)  (attribute)

returns the type of a primitive permutation group G, according to the O’Nan-Scott classification. The labelling of the different types is not consistent in the literature, we use the following identifications. The two-letter code given is the name of the type as used by Praeger.
1 Affine. (HA)
2 Almost simple. (AS)
3a Diagonal, Socle consists of two normal subgroups. (HS)
3b Diagonal, Socle is minimal normal. (SD)
4a Product action with the first factor primitive of type 3a. (HC)
4b Product action with the first factor primitive of type 3b. (CD)
4c Product action with the first factor primitive of type 2. (PA)
5 Twisted wreath product (TW)

See [EH01] for correspondence to other labellings used in the literature. As it can contain letters, the type is returned as a string.

If \( G \) is not a permutation group or does not act primitively on the points moved by it, the result is undefined.

43.5.2 SocleTypePrimitiveGroup

\[ \text{SocleTypePrimitiveGroup}(G) \]

returns the socle type of the primitive permutation group \( G \). The socle of a primitive group is the direct product of isomorphic simple groups, therefore the type is indicated by a record with components series, parameter (both as described under IsomorphismTypeInfoFiniteSimpleGroup (39.15.12)), and width for the number of direct factors.

If \( G \) does not have a faithful primitive action, the result is undefined.

Example

\[
\begin{align*}
\text{gap> } & \text{g:=AlternatingGroup(5);;} \\
\text{gap> } & \text{h:=DirectProduct(g,g);} \\
\text{gap> } & \text{p:=List([1,2],i->Projection(h,i));} \\
\text{gap> } & \text{ac:=Action(h,AsList(g),} \\
\text{> function(g,h) return Image(p[1],h)^-1*g*Image(p[2],h);end);} \\
\text{gap> } & \text{Size(ac);NrMovedPoints(ac);IsPrimitive(ac,[1..60]);} \\
& 3600 \\
& 60 \\
& \text{true} \\
\text{gap> } & \text{ONanScottType(ac);} \\
& "3a" \\
\text{gap> } & \text{SocleTypePrimitiveGroup(ac);} \\
\text{rec(} \\
& \text{ name := "A(5) ~ A(1,4) = L(2,4) ~ B(1,4) = O(3,4) ~ C(1,4) = S(2,4) \} \\
& \quad \text{ ~ 2A(1,4) = U(2,4) ~ A(1,5) = L(2,5) ~ B(1,5) = O(3,5) ~ C(1,5) = S(2,} \\
& \quad \text{ 5) ~ 2A(1,5) = U(2,5)"}, \text{ parameter := 5, series := "A", width := 2 })
\end{align*}
\]
43.6 Stabilizer Chains

Many of the algorithms for permutation groups use a stabilizer chain of the group. The concepts of stabilizer chains, bases, and strong generating sets were introduced by Charles Sims in [Sim70]. An extensive account of basic algorithms together with asymptotic runtime analysis can be found in reference [Ser03, Chapter 4]. A further discussion of base change is given in section 87.1.

Let $B = [b_1, \ldots, b_n]$ be a list of points, $G^{(1)} = G$ and $G^{(i+1)} = \text{Stab}_{G^{(i)}}(b_i)$, such that $G^{(n+1)} = \{\}$. Then the list $[b_1, \ldots, b_n]$ is called a base of $G$, the points $b_i$ are called base points. A set $S$ of generators for $G$ satisfying the condition $\langle S \cap G^{(i)} \rangle = G^{(i)}$ for each $1 \leq i \leq n$, is called a strong generating set (SGS) of $G$. (More precisely we ought to say that it is a SGS of $G$ relative to $B$). The chain of subgroups $G^{(i)}$ of $G$ itself is called the stabilizer chain of $G$ relative to $B$.

Since $[b_1, \ldots, b_n]$, where $n$ is the degree of $G$ and $b_i$ are the moved points of $G$, certainly is a base for $G$ there exists a base for each permutation group. The number of points in a base is called the length of the base. A base $B$ is called reduced if there exists no $i$ such that $G^{(i)} = G^{(i+1)}$. (This however does not imply that no subset of $B$ could also serve as a base.) Note that different reduced bases for one permutation group $G$ may have different lengths. For example, the irreducible degree 416 permutation representation of the Chevalley Group $G_2(4)$ possesses reduced bases of lengths 5 and 7.

Let $R^{(i)}$ be a right transversal of $G^{(i+1)}$ in $G^{(i)}$, i.e. a set of right coset representatives of the cosets of $G^{(i+1)}$ in $G^{(i)}$. Then each element $g$ of $G$ has a unique representation as a product of the form $g = r_n \ldots r_1$ with $r_i \in R^{(i)}$. The cosets of $G^{(i+1)}$ in $G^{(i)}$ are in bijective correspondence with the points in $O^{(i)} := b_i^{G^{(0)}}$. So we could represent a transversal as a list $T$ such that $T[p]$ is a representative of the coset corresponding to the point $p \in O^{(i)}$, i.e., an element of $G^{(i)}$ that takes $b_i$ to $p$. (Note that such a list has holes in all positions corresponding to points not contained in $O^{(i)}$.)

This approach however will store many different permutations as coset representatives which can be a problem if the degree $n$ gets bigger. Our goal therefore is to store as few different permutations as possible such that we can still reconstruct each representative in $R^{(i)}$, and from them the elements in $G$. A factorized inverse transversal $T$ is a list where $T[p]$ is a generator of $G^{(i)}$ such that $pT[p]$ is a point that lies earlier in $O^{(i)}$ than $p$ (note that we consider $O^{(i)}$ as a list, not as a set). If we assume inductively that we know an element $r \in G^{(i)}$ that takes $b_i$ to $pT[p]$, then $rT[p]^{-1}$ is an element in $G^{(i)}$ that takes $b_i$ to $p$. GAP uses such factorized inverse transversals.

Another name for a factorized inverse transversal is a Schreier tree. The vertices of the tree are the points in $O^{(i)}$, and the root of the tree is $b_i$. The edges are defined as the ordered pairs $(p, pT[p])$, for $p \in O^{(i)} \setminus \{b_i\}$. The edge $(p, pT[p])$ is labelled with the generator $T[p]$, and the product of edge labels along the unique path from $p$ to $b_i$ is the inverse of the transversal element carrying $b_i$ to $p$.

Before we describe the construction of stabilizer chains in 43.8, we explain in 43.7 the idea of using non-deterministic algorithms; this is necessary for understanding the options available for the construction of stabilizer chains. After that, in 43.9 it is explained how a stabilizer chain is stored in GAP, 43.10 lists operations for stabilizer chains, and 43.11 lists low level routines for manipulating stabilizer chains.

43.7 Randomized Methods for Permutation Groups

For most computations with permutation groups, it is crucial to construct stabilizer chains efficiently. Sims’s original construction in [Sim70] is deterministic, and is called the Schreier-Sims algorithm, because it is based on Schreier’s Lemma ([HJ59, p. 96]): given $K = \langle S \rangle$ and a transversal $T$ for $K$ mod
L, one can obtain $|S||T|$ generators for $L$. This lemma is applied recursively, with consecutive point stabilizers $G^{(i)}$ and $G^{(i+1)}$ playing the role of $K$ and $L$.

In permutation groups of large degree, the number of Schreier generators to be processed becomes too large, and the deterministic Schreier-Sims algorithm becomes impractical. Therefore, GAP uses randomized algorithms. The method selection process, which is quite different from Version 3, works the following way.

If a group acts on not more than a hundred points, Sims’s original deterministic algorithm is applied. In groups of degree greater than hundred, a heuristic algorithm based on ideas in [BCFS91] constructs a stabilizer chain. This construction is complemented by a verify-routine that either proves the correctness of the stabilizer chain or causes the extension of the chain to a correct one. The user can influence the verification process by setting the value of the record component random (cf. 43.8).

If the random value equals 1000 then a slight extension of an unpublished method of Sims is used. The outcome of this verification process is always correct. The user also can prescribe any integer $x$, $1 \leq x \leq 999$ as the value of random. In this case, a randomized verification process from [BCFS91] is applied, and the result of the stabilizer chain construction is guaranteed to be correct with probability at least $x/1000$. The practical performance of the algorithm is much better than the theoretical guarantee.

If the stabilizer chain is not correct then the elements in the product of transversals $R^{(m)}R^{(m-1)} \cdots R^{(1)}$ constitute a proper subset of the group $G$ in question. This means that a membership test with this stabilizer chain returns false for all elements that are not in $G$, but it may also return false for some elements of $G$; in other words, the result true of a membership test is always correct, whereas the result false may be incorrect.

The construction and verification phases are separated because there are situations where the verification step can be omitted; if one happens to know the order of the group in advance then the randomized construction of the stabilizer chain stops as soon as the product of the lengths of the basic orbits of the chain equals the group order, and the chain will be correct (see the size option of the StabChain (43.8.1) command).

Although the worst case running time is roughly quadratic for Sims’s verification and roughly linear for the randomized one, in most examples the running time of the stabilizer chain construction with random value 1000 (i.e., guaranteed correct output) is about the same as the running time of randomized verification with guarantee of at least 90 percent correctness. Therefore, we suggest to use the default value random = 1000. Possible uses of random values less than 1000 are when one has to run through a large collection of subgroups, and a low value of random is used to choose quickly a candidate for more thorough examination; another use is when the user suspects that the quadratic bottleneck of the guaranteed correct verification is hit.

We will give two examples to illustrate these ideas.

We created a permutation group on 400 points. First we compute a guaranteed correct stabilizer chain (see StabChain (43.8.1)).

```gap
gap> h:= SL(4,7);;
gap> o:= Orbit( h, [1,0,0,0]*Z(7)^0, OnLines );;
gap> op:= Action( h, o, OnLines );;
gap> NrMovedPoints( op );
400
```

Example

We created a permutation group on 400 points. First we compute a guaranteed correct stabilizer chain (see StabChain (43.8.1)).

```gap
gap> h:= Group( GeneratorsOfGroup( op ) );;
gap> StabChain( h );; time;
```
Now randomized verification will be used. We require that the result is guaranteed correct with probability 90 percent. This means that if we would do this calculation many times over, GAP would guarantee that in least 90 percent of all calculations the result is correct. In fact the results are much better than the guarantee, but we cannot promise that this will really happen. (For the meaning of the random component in the second argument of StabChain (43.8.1).)

First the group is created anew.

```
Example

gap> h:= Group( GeneratorsOfGroup( op ) );;
gap> StabChain( h, rec( random:= 900 ) );; time;
1410
gap> Size( h );
2317591180800
```

The result is still correct, and the running time is actually somewhat slower. If you give the algorithm additional information so that it can check its results, things become faster and the result is guaranteed to be correct.

```
Example

gap> h:=Group( GeneratorsOfGroup( op ) );;
gap> SetSize( h, 2317591180800 );
gap> StabChain( h );; time;
170
```

The second example gives a typical group when the verification with random value 1000 is slow. The problem is that the group has a stabilizer subgroup $G^{(i)}$ such that the fundamental orbit $O^{(i)}$ is split into a lot of orbits when we stabilize $b_i$ and one additional point of $O^{(i)}$.

```
Example

gap> p1:=PermList(Concatenation([401],[1..400]));;
gap> p2:=PermList(List([1..400],i->(i*20 mod 401)));;
gap> d:=DirectProduct(Group(p1,p2),SymmetricGroup(5));;
gap> h:=Group(GeneratorsOfGroup(d));;
gap> StabChain(h);;time;Size(h);
1030
192480

gap> h:=Group(GeneratorsOfGroup(d));;
gap> StabChain(h,rec(random:=900));;time;Size(h);
570
192480
```

When stabilizer chains of a group $G$ are created with random value less than 1000, this is noted in the group $G$, by setting of the record component random in the value of the attribute StabChainOptions (43.8.2) for $G$. As errors induced by the random methods might propagate, any group or homomorphism created from $G$ inherits a random component in its StabChainOptions (43.8.2) value from the corresponding component for $G$.

A lot of algorithms dealing with permutation groups use randomized methods; however, if the initial stabilizer chain construction for a group is correct, these further methods will provide guaranteed correct output.
43.8 Construction of Stabilizer Chains

43.8.1 StabChain (for a group (and a record))

These commands compute a stabilizer chain for the permutation group $G$; additionally, StabChainMutable is also an attribute for the group homomorphism $\text{permhomom}$ whose source is a permutation group.

(The mathematical background of stabilizer chains is sketched in 43.6, more information about the objects representing stabilizer chains in GAP can be found in 43.9.)

StabChainOp is an operation with two arguments $G$ and $\text{options}$, the latter being a record which controls some aspects of the computation of a stabilizer chain (see below); StabChainOp returns a mutable stabilizer chain. StabChainMutable is a mutable attribute for groups or homomorphisms, its default method for groups is to call StabChainOp with empty options record. StabChainImmutable is an attribute with immutable values; its default method dispatches to StabChainMutable.

StabChain is a function with first argument a permutation group $G$, and optionally a record $\text{options}$ as second argument. If the value of StabChainImmutable for $G$ is already known and if this stabilizer chain matches the requirements of $\text{options}$, StabChain simply returns this stored stabilizer chain. Otherwise StabChain calls StabChainOp and returns an immutable copy of the result; additionally, this chain is stored as StabChainImmutable value for $G$. If no $\text{options}$ argument is given, its components default to the global variable DefaultStabChainOptions (43.8.3). If $\text{base}$ is a list of positive integers, the version $\text{StabChain}(G, \text{base})$ defaults to $\text{StabChain}(G, \text{rec(\text{base}: = base)})$.

If given, $\text{options}$ is a record whose components specify properties of the desired stabilizer chain or which may help the algorithm. Default values for all of them can be given in the global variable DefaultStabChainOptions (43.8.3). The following options are supported.

**base** (default an empty list)

A list of points, through which the resulting stabilizer chain shall run. For the base $B$ of the resulting stabilizer chain $S$ this means the following. If the reduced component of $\text{options}$ is true then those points of $\text{base}$ with nontrivial basic orbits form the initial segment of $B$. If the reduced component is false then $\text{base}$ itself is the initial segment of $B$. Repeated occurrences of points in $\text{base}$ are ignored. If a stabilizer chain for $G$ is already known then the stabilizer chain is computed via a base change.

**knownBase** (no default value)

A list of points which is known to be a base for the group. Such a known base makes it easier to test whether a permutation given as a word in terms of a set of generators is the identity, since it suffices to map the known base with each factor consecutively, rather than multiplying the whole permutations (which would mean to map every point). This speeds up the Schreier-Sims algorithm which is used when a new stabilizer chain is constructed; it will not affect a base
change, however. The component knownBase bears no relation to the base component, you may specify a known base knownBase and a desired base base independently.

**reduced (default true)**
If this is true the resulting stabilizer chain $S$ is reduced, i.e., the case $G^i = G^{i+1}$ does not occur. Setting reduced to false makes sense only if the component base (see above) is also set; in this case all points of base will occur in the base $B$ of $S$, even if they have trivial basic orbits. Note that if base is just an initial segment of $B$, the basic orbits of the points in $B \setminus$ base are always nontrivial.

**tryPcgs (default true)**
If this is true and either the degree is at most 100 or the group is known to be solvable, GAP will first try to construct a pcgs (see Chapter 45) for $G$ which will succeed and implicitly construct a stabilizer chain if $G$ is solvable. If $G$ turns out non-solvable, one of the other methods will be used. This solvability check is comparatively fast, even if it fails, and it can save a lot of time if $G$ is solvable.

**random (default 1000)**
If the value is less than 1000, the resulting chain is correct with probability at least \(\frac{\text{random}}{1000}\). The random option is explained in more detail in 43.7.

**size (default Size(G) if this is known, i.e., if HasSize(G) is true)**
If this component is present, its value is assumed to be the order of the group $G$. This information can be used to prove that a non-deterministically constructed stabilizer chain is correct. In this case, GAP does a non-deterministic construction until the size is correct.

**limit (default Size(Parent(G)) or StabChainOptions(Parent(G)).limit if it is present)**
If this component is present, it must be greater than or equal to the order of $G$. The stabilizer chain construction stops if size limit is reached.

### 43.8.2 StabChainOptions

- **StabChainOptions(G)** (attribute)

  is a record that stores the options with which the stabilizer chain stored in StabChainImmutable (43.8.1) has been computed (see StabChain (43.8.1) for the options that are supported).

### 43.8.3 DefaultStabChainOptions

- **DefaultStabChainOptions** (global variable)

  are the options for StabChain (43.8.1) which are set as default.

### 43.8.4 StabChainBaseStrongGenerators

- **StabChainBaseStrongGenerators(base, sgs, one)** (function)

  Let base be a base for a permutation group $G$, and let sgs be a strong generating set for $G$ with respect to base; one must be the appropriate identity element of $G$ (see One (31.10.2), in most cases
this will be \((\))]. This function constructs a stabilizer chain without the need to find Schreier generators; so this is much faster than the other algorithms.

### 43.8.5 MinimalStabChain

\[ \texttt{MinimalStabChain} (G) \]

returns the reduced stabilizer chain corresponding to the base \([1,2,3,4,\ldots]\).

### 43.9 Stabilizer Chain Records

If a permutation group has a stabilizer chain, this is stored as a recursive structure. This structure is itself a record \(S\) and it has

1. components that provide information about one level \(G^{(i)}\) of the stabilizer chain (which we call the “current stabilizer”) and
2. a component \(\text{stabilizer}\) that holds another such record, namely the stabilizer chain of the next stabilizer \(G^{(i+1)}\).

This gives a recursive structure where the “outermost” record representing the “topmost” stabilizer is bound to the group record component \(\text{stabChain}\) and has the components explained below. Note: Since the structure is recursive, never print a stabilizer chain! (Unless you want to exercise the scrolling capabilities of your terminal.)

- **identity**
  - the identity element of the current stabilizer.

- **labels**
  - a list of permutations which contains labels for the Schreier tree of the current stabilizer, i.e., it contains elements for the factorized inverse transversal. The first entry in this list is always the identity. Note that \(\text{GAP}\) tries to arrange things so that the \(\text{labels}\) components are identical (i.e., the same \(\text{GAP}\) object) in every stabilizer of the chain; thus the \(\text{labels}\) of a stabilizer do not necessarily all lie in the this stabilizer (but see \(\text{genlabels}\) below).

- **genlabels**
  - a list of integers indexing some of the permutations in the \(\text{labels}\) component. The \(\text{labels}\) addressed in this way form a generating set for the current stabilizer. If the \(\text{genlabels}\) component is empty, the rest of the stabilizer chain represents the trivial subgroup, and can be ignored, e.g., when calculating the size.

- **generators**
  - a list of generators for the current stabilizer. Usually, it is \(\text{labels}\{ \text{genlabels} \}\).

- **orbit**
  - the vertices of the Schreier tree, which form the basic orbit \(b_i^{G_0}\), ordered in such a way that the base point \(b_i\) is in the first position in the orbit.
transversal
The factorized inverse transversal found during the orbit algorithm. The element \( g \) stored at \( \text{transversal}[i] \) will map \( i \) to another point \( j \) that in the Schreier tree is closer to the base point. By iterated application (\( \text{transversal}[j] \) and so on) eventually the base point is reached and an element that maps \( i \) to the base point found as product.

translabels
An index list such that \( \text{transversal}[j] = \text{labels}[\text{translabels}[j]] \). This list takes up comparatively little memory and is used to speed up base changes.

stabilizer
If the current stabilizer is not yet the trivial group, the stabilizer chain continues with the stabilizer of the current base point, which is again represented as a record with components labels, identity, genlabels, generators, orbit, translabels, transversal (and perhaps stabilizer). This record is bound to the stabilizer component of the current stabilizer. The last member of a stabilizer chain is recognized by the fact that it has no stabilizer component bound.

It is possible that different stabilizer chains share the same record as one of their iterated stabilizer components.

Example

```gap
gap> g:=Group((1,2,3,4),(1,2));;
<stabilizer chain record, Base [ 1, 2, 3 ], Orbit length 4, Size: 24>
gap> BaseOfGroup(g);
[ 1, 2, 3 ]
gap> StabChainOptions(g);
rec( random := 1000 )
gap> DefaultStabChainOptions;
rec( random := 1000, reduced := true, tryPcgs := true )
```

43.10 Operations for Stabilizer Chains

43.10.1 BaseStabChain

\begin{verbatim}
▷ BaseStabChain( S )
\end{verbatim}

returns the base belonging to the stabilizer chain \( S \).

43.10.2 BaseOfGroup

\begin{verbatim}
▷ BaseOfGroup( G )
\end{verbatim}

returns a base of the permutation group \( G \). There is no guarantee that a stabilizer chain stored in \( G \) corresponds to this base!
43.10.3 SizeStabChain

\[ \text{SizeStabChain}(S) \]

returns the product of the orbit lengths in the stabilizer chain \( S \), that is, the order of the group described by \( S \).

43.10.4 StrongGeneratorsStabChain

\[ \text{StrongGeneratorsStabChain}(S) \]

returns a strong generating set corresponding to the stabilizer chain \( S \).

43.10.5 GroupStabChain

\[ \text{GroupStabChain}(G, S) \]

constructs a permutation group with stabilizer chain \( S \), i.e., a group with generators \( \text{Generators}(S) \) to which \( S \) is assigned as component \text{stabChain}. If the optional argument \( G \) is given, the result will have the parent \( G \).

43.10.6 OrbitStabChain

\[ \text{OrbitStabChain}(S, \text{pnt}) \]

returns the orbit of \( \text{pnt} \) under the group described by the stabilizer chain \( S \).

43.10.7 IndicesStabChain

\[ \text{IndicesStabChain}(S) \]

returns a list of the indices of the stabilizers in the stabilizer chain \( S \).

43.10.8 ListStabChain

\[ \text{ListStabChain}(S) \]

returns a list that contains at position \( i \) the stabilizer of the first \( i - 1 \) base points in the stabilizer chain \( S \).

43.10.9 ElementsStabChain

\[ \text{ElementsStabChain}(S) \]

returns a list of all elements of the group described by the stabilizer chain \( S \).
43.10.10  IteratorStabChain

\[ \text{IteratorStabChain}(S) \] (function)

returns an iterator for the elements of the group described by the stabilizer chain \( S \). The elements of the group \( G \) are produced by iterating through all base images in turn, and in the ordering induced by the base. For more details see 43.6

43.10.11  InverseRepresentative

\[ \text{InverseRepresentative}(S, \text{pnt}) \] (function)

calculates the transversal element which maps \( \text{pnt} \) back to the base point of \( S \). It just runs back through the Schreier tree from \( \text{pnt} \) to the root and multiplies the labels along the way.

43.10.12  SiftedPermutation

\[ \text{SiftedPermutation}(S, g) \] (function)

sifts the permutation \( g \) through the stabilizer chain \( S \) and returns the result after the last step.

The element \( g \) is sifted as follows: \( g \) is replaced by \( g * \text{InverseRepresentative}(S, S.\text{orbit}[1]^g) \), then \( S \) is replaced by \( S.\text{stabilizer} \) and this process is repeated until \( S \) is trivial or \( S.\text{orbit}[1]^g \) is not in the basic orbit \( S.\text{orbit} \). The remainder \( g \) is returned, it is the identity permutation if and only if the original \( g \) is in the group \( G \) described by the original \( S \).

43.10.13  MinimalElementCosetStabChain

\[ \text{MinimalElementCosetStabChain}(S, g) \] (function)

Let \( G \) be the group described by the stabilizer chain \( S \). This function returns a permutation \( h \) such that \( Gg = Gh \) (that is, \( g/h \in G \)) and with the additional property that the list of images under \( h \) of the base belonging to \( S \) is minimal w.r.t. lexicographical ordering.

43.10.14  LargestElementStabChain

\[ \text{LargestElementStabChain}(S, \text{id}) \] (function)

Let \( G \) be the group described by the stabilizer chain \( S \). This function returns the element \( h \in G \) with the property that the list of images under \( h \) of the base belonging to \( S \) is maximal w.r.t. lexicographical ordering. The second argument must be an identity element (used to start the recursion).

43.10.15  ApproximateSuborbitsStabilizerPermGroup

\[ \text{ApproximateSuborbitsStabilizerPermGroup}(G, \text{pnt}) \] (function)

returns an approximation of the orbits of \( \text{Stabilizer}(G, \text{pnt}) \) on all points of the orbit \( \text{Orbit}(G, \text{pnt}) \), without computing the full point stabilizer; As not all Schreier generators are used, the result may represent the orbits of only a subgroup of the point stabilizer.
43.11 Low Level Routines to Modify and Create Stabilizer Chains

These operations modify a stabilizer chain or obtain new chains with specific properties. They are rather technical and should only be used if such low-level routines are deliberately required. (For all functions in this section the parameter $S$ is a stabilizer chain.)

43.11.1 CopyStabChain

$\triangleright$ CopyStabChain($S$) (function)

This function returns a mutable copy of the stabilizer chain $S$ that has no mutable object (list or record) in common with $S$. The labels components of the result are possibly shared by several levels, but superfluous labels are removed. (An entry in labels is superfluous if it does not occur among the genlabels or translabels on any of the levels which share that labels component.)

This is useful for stabiliser sub-chains that have been obtained as the (iterated) stabilizer component of a bigger chain.

43.11.2 CopyOptionsDefaults

$\triangleright$ CopyOptionsDefaults($G$, options) (function)

sets components in a stabilizer chain options record options according to what is known about the group $G$. This can be used to obtain a new stabilizer chain for $G$ quickly.

43.11.3 ChangeStabChain

$\triangleright$ ChangeStabChain($S$, base[, reduced]) (function)

changes or reduces a stabilizer chain $S$ to be adapted to the base base. The optional argument reduced is interpreted as follows.

reduced = false:
change the stabilizer chain, do not reduce it,
reduced = true:
change the stabilizer chain, reduce it.

43.11.4 ExtendStabChain

$\triangleright$ ExtendStabChain($S$, base) (function)

extends the stabilizer chain $S$ so that it corresponds to base base. The original base of $S$ must be a subset of base.

43.11.5 ReduceStabChain

$\triangleright$ ReduceStabChain($S$) (function)

changes the stabilizer chain $S$ to a reduced stabilizer chain by eliminating trivial steps.
43.11.6 RemoveStabChain

\( \texttt{RemoveStabChain}(S) \) (function)

\( S \) must be a stabilizer record in a stabilizer chain. This chain then is cut off at \( S \) by changing the entries in \( S \). This can be used to remove trailing trivial steps.

43.11.7 EmptyStabChain

\( \texttt{EmptyStabChain}(\text{labels}, \text{id}[, \text{pnt}]) \) (function)

constructs a stabilizer chain for the trivial group with identity value equal to \( \text{id} \) and labels = \{id\} \cup \text{labels} (but of course with \text{genlabels} and \text{generators} values an empty list). If the optional third argument \( \text{pnt} \) is present, the only stabilizer of the chain is initialized with the one-point basic orbit \([ \text{pnt} ]\) and with \text{translabels} and \text{transversal} components.

43.11.8 InsertTrivialStabilizer

\( \texttt{InsertTrivialStabilizer}(S, \text{pnt}) \) (function)

\text{InsertTrivialStabilizer} initializes the current stabilizer with \( \text{pnt} \) as \text{EmptyStabChain} (43.11.7) did, but assigns the original \( S \) to the new \( S.\text{stabilizer} \) component, such that a new level with trivial basic orbit (but identical labels and ShallowCopied \text{genlabels} and \text{generators}) is inserted. This function should be used only if \( \text{pnt} \) really is fixed by the generators of \( S \), because then new generators can be added and the orbit and transversal at the same time extended with \text{AddGeneratorsExtendSchreierTree} (43.11.10).

43.11.9 IsFixedStabilizer

\( \texttt{IsFixedStabilizer}(S, \text{pnt}) \) (function)

returns \text{true} if \( \text{pnt} \) is fixed by all generators of \( S \) and \text{false} otherwise.

43.11.10 AddGeneratorsExtendSchreierTree

\( \texttt{AddGeneratorsExtendSchreierTree}(S, \text{new}) \) (function)

adds the elements in \( \text{new} \) to the list of generators of \( S \) and at the same time extends the orbit and transversal. This is the only legal way to extend a Schreier tree (because this involves careful handling of the tree components).

43.12 Backtrack

A main use for stabilizer chains is in backtrack algorithms for permutation groups. \text{GAP} implements a partition-backtrack algorithm as described in [Leo91] and refined in [The97].
43.12.1 SubgroupProperty

\[\text{SubgroupProperty}(G, \text{Pr}[, L])\]

Pr must be a one-argument function that returns true or false for elements of the group G, and the subset of elements of G that fulfill Pr must be a subgroup. (If the latter is not true the result of this operation is unpredictable!) This command computes this subgroup. The optional argument L must be a subgroup of the set of all elements in G fulfilling Pr and can be given if known in order to speed up the calculation.

43.12.2 ElementProperty

\[\text{ElementProperty}(G, \text{Pr}[, L[, R]])\]

ElementProperty returns an element π of the permutation group G such that the one-argument function Pr returns true for π. It returns fail if no such element exists in G. The optional arguments L and R are subgroups of G such that the property Pr has the same value for all elements in the cosets L g and g R, respectively, with g ∈ G.

A typical example of using the optional subgroups L and R is the conjugacy test for elements a and b for which one can set L := CG(a) and R := CG(b).

Example

\[
\begin{align*}
gap> & \text{propfun} := \text{el} \rightarrow (1,2,3)^{\text{el}} \text{ in } [ (1,2,3), (1,3,2) ];; \\
gap> & \text{SubgroupProperty}( g, \text{propfun}, \text{Subgroup}( g, [ (1,2,3) ] )); \\
gap> & \text{ElementProperty}( g, \text{el} \rightarrow \text{Order}( \text{el} ) = 2 ); \\
& (2,4)
\end{align*}
\]

Chapter 42 describes special operations to construct permutations in the symmetric group without using backtrack constructions.

Backtrack routines are also called by the methods for permutation groups that compute centralizers, normalizers, intersections, conjugating elements as well as stabilizers for the operations of a permutation group via OnPoints (41.2.1), OnSets (41.2.4), OnTuples (41.2.5) and OnSetsSets (41.2.7). Some of these methods use more specific refinements than SubgroupProperty (43.12.1) or ElementProperty. For the definition of refinements, and how one can define refinements, see Section 87.2.

43.12.3 TwoClosure

\[\text{TwoClosure}(G)\]

The 2-closure of a transitive permutation group G on n points is the largest subgroup of the symmetric group S_n which has the same orbits on sets of ordered pairs of points as the group G has. It also can be interpreted as the stabilizer of the orbital graphs of G.

Example

\[
\begin{align*}
gap> & \text{TwoClosure}(\text{Group}([1,2,3),(2,3,4)])); \\
& \text{Sym}( [ 1 .. 4 ] )
\end{align*}
\]
43.12.4 InfoBckt

is the info class for the partition backtrack routines.

43.13 Working with large degree permutation groups

Permutation groups of large degree (usually at least a few 10000) can pose a challenge to the heuristics used in the algorithms for permutation groups. This section lists a few useful tricks that may speed up calculations with such large groups enormously.

The first aspect concerns solvable groups: A lot of calculations (including an initial stabilizer chain computation thanks to the algorithm from [Sim90]) are faster if a permutation group is known to be solvable. On the other hand, proving nonsolvability can be expensive for higher degrees. Therefore GAP will automatically test a permutation group for solvability, only if the degree is not exceeding 100. (See also the tryPcgs component of StabChainOptions (43.8.2).) It is therefore beneficial to tell a group of larger degree, which is known to be solvable, that it is, using SetIsSolvableGroup(G,true).

The second aspect concerns memory usage. A permutation on more than 65536 points requires 4 bytes per point for storing. So permutations on 256000 points require roughly 1MB of storage per permutation. Just storing the permutations required for a stabilizer chain might already go beyond the available memory, in particular if the base is not very short. In such a situation it can be useful, to replace the permutations by straight line program elements (see 37.9).

The following code gives an example of usage: We create a group of degree 231000. Using straight line program elements, one can compute a stabilizer chain in about 200 MB of memory.

Example
gap> Read("largeperms"); # read generators from file
gap> gens:=StraightLineProgGens(permutationlist,);;
gap> g:=Group(gens);
<permutation group with 5 generators>
gap> # use random algorithm (faster, but result is monte carlo)
gap> StabChainOptions(g).random:=1;;
gap> Size(g); # enforce computation of a stabilizer chain
3529698298145066075567232833758234188066080273649172207877011796336000

Without straight line program elements, the same calculation runs into memory problems after a while even with 512MB of workspace:

Example
gap> h:=Group(permutationlist);
<permutation group with 5 generators>
gap> StabChainOptions(h).random:=1;;
gap> Size(h);
exceeded the permitted memory (`-o' command line option) at
mlimit := 1; called from
SCRMakeStabStrong( S.stabilizer, [ g ], param, orbits, where, basesize,
base, correct, missing, false ); called from
SCRMakeStabStrong( S.stabilizer, [ g ], param, orbits, where, basesize,
...
The advantage in memory usage however is paid for in runtime: Comparisons of elements become much more expensive. One can avoid some of the related problems by registering a known base with the straight line program elements (see StraightLineProgGens (37.9.3)). In this case element comparison will only compare the images of the given base points. If we are planning to do extensive calculations with the group, it can even be worth to recreate it with straight line program elements knowing a previously computed base:

```
gap> # get the base we computed already
gap> bas:=BaseStabChain(StabChainMutable(g));
[ 1, 4, 7, 10, 13, 16, 19, 22, 25, 28, 31, 34, 37, 40, 43, 46, 49, 52, 55,
  ...2530, 2533, 2554, 2563, 2569 ]
gap> gens:=StraightLineProgGens(permutationlist,bas);;
gap> g:=Group(gens);;
gap> SetSize(g,
> 352969829814506075557232833758234188056080273649172207877011796336000);
gap> Random(g);; # enforce computation of a stabilizer chain
```

As we know already base and size, this second stabilizer chain calculation is much faster than the first one and takes less memory.
Chapter 44

Matrix Groups

Matrix groups are groups generated by invertible square matrices.

In the following example we temporarily increase the line length limit from its default value 80 to 83 in order to get a nicer output format.

Example

```
gap> m1 := [ [ Z(3)^0, Z(3)^0, Z(3) ],
        [ Z(3), 0*Z(3), Z(3) ],
        [ 0*Z(3), Z(3), 0*Z(3) ] ];
> m2 := [ [ Z(3), Z(3), Z(3)^0 ],
        [ Z(3), 0*Z(3), Z(3) ],
        [ Z(3)^0, 0*Z(3), Z(3) ] ];
> m := Group( m1, m2 );
Group( [ [ Z(3)^0, Z(3)^0, Z(3) ], [ Z(3), 0*Z(3), Z(3) ],
        [ 0*Z(3), Z(3), 0*Z(3) ] ],
      [ [ Z(3), Z(3), Z(3)^0 ], [ Z(3), 0*Z(3), Z(3) ],
        [ Z(3)^0, 0*Z(3), Z(3) ] ] )
```

44.1 IsMatrixGroup (Filter)

For most operations, GAP only provides methods for finite matrix groups. Many calculations in finite matrix groups are done via so-called “nice monomorphisms” (see Section 40.5) that represent a faithful action on vectors.

44.1.1 IsMatrixGroup

> IsMatrixGroup(grp) (Category)

The category of matrix groups.
44.2 Attributes and Properties for Matrix Groups

44.2.1 DimensionOfMatrixGroup

\[ \text{DimensionOfMatrixGroup}(\text{mat-grp}) \] (attribute)

The dimension of the matrix group.

44.2.2 DefaultFieldOfMatrixGroup

\[ \text{DefaultFieldOfMatrixGroup}(\text{mat-grp}) \] (attribute)

Is a field containing all the matrix entries. It is not guaranteed to be the smallest field with this property.

44.2.3 FieldOfMatrixGroup

\[ \text{FieldOfMatrixGroup}(	ext{matgrp}) \] (attribute)

The smallest field containing all the matrix entries of all elements of the matrix group \text{matgrp}. As the calculation of this can be hard, this should only be used if one really needs the smallest field, use \text{DefaultFieldOfMatrixGroup} (44.2.2) to get (for example) the characteristic.

```
gap> \text{DimensionOfMatrixGroup}(m); 
3

gap> \text{DefaultFieldOfMatrixGroup}(m); 
\text{GF}(3)
```

44.2.4 TransposedMatrixGroup

\[ \text{TransposedMatrixGroup}(\text{matgrp}) \] (attribute)

returns the transpose of the matrix group \text{matgrp}. The transpose of the transpose of \text{matgrp} is identical to \text{matgrp}.

```
gap> G := \text{Group}( \text{[[0,-1],[1,0]]});
Group([ [ 0, -1 ], [ 1, 0 ] ])

gap> T := \text{TransposedMatrixGroup}( G );
Group([ [ 0, 1 ], [ -1, 0 ] ])

gap> \text{IsIdenticalObj}( G, \text{TransposedMatrixGroup}( T ) );
true
```

44.2.5 IsFFEMatrixGroup

\[ \text{IsFFEMatrixGroup}(G) \] (Category)

tests whether all matrices in \text{G} have finite field element entries.
44.3 Actions of Matrix Groups

The basic operations for groups are described in Chapter 41, special actions for matrix groups mentioned there are OnLines (41.2.12), OnRight (41.2.2), and OnSubspacesByCanonicalBasis (41.2.15).

For subtleties concerning multiplication from the left or from the right, see 44.7.

44.3.1 ProjectiveActionOnFullSpace

\[ \text{ProjectiveActionOnFullSpace}(G, F, n) \]

Let \( G \) be a group of \( n \) by \( n \) matrices over a field contained in the finite field \( F \).

ProjectiveActionOnFullSpace returns the image of the projective action of \( G \) on the full row space \( F^n \).

44.3.2 ProjectiveActionHomomorphismMatrixGroup

\[ \text{ProjectiveActionHomomorphismMatrixGroup}(G) \]

returns an action homomorphism for a faithful projective action of \( G \) on the underlying vector space. (Note: The action is not necessarily on the full space, if a smaller subset can be found on which the action is faithful.)

44.3.3 BlowUpIsomorphism

\[ \text{BlowUpIsomorphism}( \text{matgrp}, B) \]

For a matrix group \( \text{matgrp} \) and a basis \( B \) of a field extension \( L/K \), say, such that the entries of all matrices in \( \text{matgrp} \) lie in \( L \), BlowUpIsomorphism returns the isomorphism with source \( \text{matgrp} \) that is defined by mapping the matrix \( A \) to \( \text{BlownUpMat}(A, B) \), see \( \text{BlownUpMat}(24.13.4) \).

Example

\begin{verbatim}
gap> g:= GL(2,4);;
gap> B:= CanonicalBasis( GF(4) );; BasisVectors( B );
[ Z(2)^0, Z(2^2) ]
gap> iso:= BlowUpIsomorphism( g, B );;
gap> Display( Image( iso, [ [ Z(4), Z(2) ], [ 0*Z(2), Z(4)^2 ] ] ) );
. 1 1 .
1 1 . 1
. . 1 1
. . 1 .
gap> img:= Image( iso, g );
gap> Index( GL(4,2), img );
112
\end{verbatim}

44.4 GL and SL

(See also section 50.2.)
44.4.1 IsGeneralLinearGroup

▷ IsGeneralLinearGroup(grp)  
▷ IsGL(grp)  

The General Linear group is the group of all invertible matrices over a ring. This property tests, whether a group is isomorphic to a General Linear group. (Note that currently only a few trivial methods are available for this operation. We hope to improve this in the future.)

44.4.2 IsNaturalGL

▷ IsNaturalGL(matgrp)  

This property tests, whether a matrix group is the General Linear group in the right dimension over the (smallest) ring which contains all entries of its elements. (Currently, only a trivial test that computes the order of the group is available.)

44.4.3 IsSpecialLinearGroup

▷ IsSpecialLinearGroup(grp)  
▷ IsSL(grp)  

The Special Linear group is the group of all invertible matrices over a ring, whose determinant is equal to 1. This property tests, whether a group is isomorphic to a Special Linear group. (Note that currently only a few trivial methods are available for this operation. We hope to improve this in the future.)

44.4.4 IsNaturalSL

▷ IsNaturalSL(matgrp)  

This property tests, whether a matrix group is the Special Linear group in the right dimension over the (smallest) ring which contains all entries of its elements. (Currently, only a trivial test that computes the order of the group is available.)

```
gap> IsNaturalGL(m);  
false
```

Example

44.4.5 IsSubgroupSL

▷ IsSubgroupSL(matgrp)  

This property tests, whether a matrix group is a subgroup of the Special Linear group in the right dimension over the (smallest) ring which contains all entries of its elements.
44.5 Invariant Forms

44.5.1 InvariantBilinearForm

\( \text{InvariantBilinearForm(matgrp)} \)

This attribute describes a bilinear form that is invariant under the matrix group \( \text{matgrp} \). The form is given by a record with the component \( \text{matrix} \) which is a matrix \( F \) such that for every generator \( g \) of \( \text{matgrp} \) the equation \( g \cdot F \cdot g^t = F \) holds.

44.5.2 IsFullSubgroupGLorSLRespectingBilinearForm

\( \text{IsFullSubgroupGLorSLRespectingBilinearForm(matgrp)} \)

This property tests, whether a matrix group \( \text{matgrp} \) is the full subgroup of GL or SL (the property \( \text{IsSubgroupSL(44.4.5)} \) determines which it is) respecting the form stored as the value of \( \text{InvariantBilinearForm(44.5.1)} \) for \( \text{matgrp} \).

44.5.3 InvariantSesquilinearForm

\( \text{InvariantSesquilinearForm(matgrp)} \)

This attribute describes a sesquilinear form that is invariant under the matrix group \( \text{matgrp} \) over the field \( F \) with \( q^2 \) elements, say. The form is given by a record with the component \( \text{matrix} \) which is a matrix \( M \) such that for every generator \( g \) of \( \text{matgrp} \) the equation \( g \cdot M \cdot (g^t)^f = M \) holds, where \( f \) is the automorphism of \( F \) that raises each element to its \( q \)-th power. (\( f \) can be obtained as a power of the FrobeniusAutomorphism (59.4.1) value of \( F \).)

44.5.4 IsFullSubgroupGLorSLRespectingSesquilinearForm

\( \text{IsFullSubgroupGLorSLRespectingSesquilinearForm(matgrp)} \)

This property tests, whether a matrix group \( \text{matgrp} \) is the full subgroup of GL or SL (the property \( \text{IsSubgroupSL(44.4.5)} \) determines which it is) respecting the form stored as the value of \( \text{InvariantSesquilinearForm(44.5.3)} \) for \( \text{matgrp} \).

44.5.5 InvariantQuadraticForm

\( \text{InvariantQuadraticForm(matgrp)} \)

For a matrix group \( \text{matgrp} \), \( \text{InvariantQuadraticForm} \) returns a record containing at least the component \( \text{matrix} \) whose value is a matrix \( Q \). The quadratic form \( q \) on the natural vector space \( V \) on which \( \text{matgrp} \) acts is given by \( q(v) = vQv^t \), and the invariance under \( \text{matgrp} \) is given by the equation \( q(v) = q(vM) \) for all \( v \in V \) and \( M \) in \( \text{matgrp} \). (Note that the invariance of \( q \) does not imply that the matrix \( Q \) is invariant under \( \text{matgrp} \).)

\( q \) is defined relative to an invariant symmetric bilinear form \( f \) (see \( \text{InvariantBilinearForm(44.5.1)} \)), via the equation \( q(\lambda x + \mu y) = \lambda^2 q(x) + \lambda \mu f(x,y) + \mu^2 q(y) \), see [CCN+85, Chapter 3.4]. If \( f \) is represented by the matrix \( F \) then this implies \( F = Q + Q^t \). In characteristic different from 2,
we have \( q(x) = f(x, x)/2 \), so \( Q \) can be chosen as the strictly upper triangular part of \( F \) plus half of the diagonal part of \( F \). In characteristic 2, \( F \) does not determine \( Q \) but still \( Q \) can be chosen as an upper (or lower) triangular matrix.

Whenever the InvariantQuadraticForm value is set in a matrix group then also the InvariantBilinearForm (44.5.1) value can be accessed, and the two values are compatible in the above sense.

### 44.5.6 IsFullSubgroupGLorSLRespectingQuadraticForm

\[ \text{IsFullSubgroupGLorSLRespectingQuadraticForm(matgrp)} \]

This property tests whether the matrix group \( \text{matgrp} \) is the full subgroup of GL or SL (the property \( \text{IsSubgroupSL (44.4.5)} \) determines which it is) respecting the InvariantQuadraticForm (44.5.5) value of \( \text{matgrp} \).

#### Example

```gap
gap> g:= Sp( 2, 3 );;
gap> m:= InvariantBilinearForm( g ).matrix;
[ [ 0*Z(3), Z(3)^0 ], [ z(3), 0*Z(3) ] ]
gap> [ 0, 1 ] * m * [ 1, -1 ]; # evaluate the bilinear form
Z(3)
gap> IsFullSubgroupGLorSLRespectingQuadraticForm( g );
true
gap> g:= SU( 2, 4 );;
gap> m:= InvariantSesquilinearForm( g ).matrix;
[ [ 0*Z(2), Z(2)^0 ], [ z(2)^0, 0*Z(2) ] ]
gap> [ 0, 1 ] * m * [ 1, 1 ]; # evaluate the bilinear form
Z(2)^0
gap> IsFullSubgroupGLorSLRespectingSesquilinearForm( g );
true
gap> g:= GO( 1, 2, 3 );;
gap> m:= InvariantBilinearForm( g ).matrix;
[ [ 0*Z(3), Z(3)^0 ], [ z(3)^0, 0*Z(3) ] ]
gap> [ 0, 1 ] * m * [ 1, 1 ]; # evaluate the bilinear form
Z(3)^0
gap> q:= InvariantQuadraticForm( g ).matrix;
[ [ 0*Z(3), Z(3)^0 ], [ 0*Z(3), 0*Z(3) ] ]
gap> [ 0, 1 ] * q * [ 0, 1 ]; # evaluate the quadratic form
0*Z(3)
gap> IsFullSubgroupGLorSLRespectingQuadraticForm( g );
true
```

### 44.6 Matrix Groups in Characteristic 0

Most of the functions described in this and the following section have implementations which use functions from the GAP package Carat. If Carat is not installed or not compiled, no suitable methods are available.
44.6.1 IsCyclotomicMatrixGroup

\[ \text{IsCyclotomicMatrixGroup}(G) \]

(Category)

tests whether all matrices in \( G \) have cyclotomic entries.

44.6.2 IsRationalMatrixGroup

\[ \text{IsRationalMatrixGroup}(G) \]

(property)

tests whether all matrices in \( G \) have rational entries.

44.6.3 IsIntegerMatrixGroup

\[ \text{IsIntegerMatrixGroup}(G) \]

(property)

tests whether all matrices in \( G \) have integer entries.

44.6.4 IsNaturalGLnZ

\[ \text{IsNaturalGLnZ}(G) \]

(property)

tests whether \( G \) is \( GL_n(\mathbb{Z}) \) in its natural representation by \( n \times n \) integer matrices. (The dimension \( n \) will be read off the generating matrices.)

Example

\[
\text{gap> IsNaturalGLnZ( GL( 2, Integers ) );}
\]

true

44.6.5 IsNaturalSLnZ

\[ \text{IsNaturalSLnZ}(G) \]

(property)

tests whether \( G \) is \( SL_n(\mathbb{Z}) \) in its natural representation by \( n \times n \) integer matrices. (The dimension \( n \) will be read off the generating matrices.)

Example

\[
\text{gap> IsNaturalSLnZ( SL( 2, Integers ) );}
\]

true

44.6.6 InvariantLattice

\[ \text{InvariantLattice}(G) \]

(attribute)

returns a matrix \( B \), whose rows form a basis of a \( \mathbb{Z} \)-lattice that is invariant under the rational matrix group \( G \) acting from the right. It returns \text{fail} if the group is not unimodular. The columns of the inverse of \( B \) span a \( \mathbb{Z} \)-lattice invariant under \( G \) acting from the left.
44.6.7 NormalizerInGLnZ

\[ \texttt{NormalizerInGLnZ}(G) \]  (attribute)

is an attribute used to store the normalizer of \( G \) in \( GL_n(\mathbb{Z}) \), where \( G \) is an integer matrix group of dimension \( n \). This attribute is used by \texttt{Normalizer( GL( n, Integers ), G )}.

44.6.8 CentralizerInGLnZ

\[ \texttt{CentralizerInGLnZ}(G) \]  (attribute)

is an attribute used to store the centralizer of \( G \) in \( GL_n(\mathbb{Z}) \), where \( G \) is an integer matrix group of dimension \( n \). This attribute is used by \texttt{Centralizer( GL( n, Integers ), G )}.

44.6.9 ZClassRepsQClass

\[ \texttt{ZClassRepsQClass}(G) \]  (attribute)

The conjugacy class in \( GL_n(\mathbb{Q}) \) of the finite integer matrix group \( G \) splits into finitely many conjugacy classes in \( GL_n(\mathbb{Z}) \). \texttt{ZClassRepsQClass( G )} returns representative groups for these.

44.6.10 IsBravaisGroup

\[ \texttt{IsBravaisGroup}(G) \]  (property)

test whether \( G \) coincides with its Bravais group (see \texttt{BravaisGroup (44.6.11)})

44.6.11 BravaisGroup

\[ \texttt{BravaisGroup}(G) \]  (attribute)

returns the Bravais group of a finite integer matrix group \( G \). If \( C \) is the cone of positive definite quadratic forms \( Q \) invariant under \( g \mapsto gQg^t \) for all \( g \in G \), then the Bravais group of \( G \) is the maximal subgroup of \( GL_n(\mathbb{Z}) \) leaving the forms in that same cone invariant. Alternatively, the Bravais group of \( G \) can also be defined with respect to the action \( g \mapsto g^tQg \) on positive definite quadratic forms \( Q \). This latter definition is appropriate for groups \( G \) acting from the right on row vectors, whereas the former definition is appropriate for groups acting from the left on column vectors. Both definitions yield the same Bravais group.

44.6.12 BravaisSubgroups

\[ \texttt{BravaisSubgroups}(G) \]  (attribute)

returns the subgroups of the Bravais group of \( G \), which are themselves Bravais groups.
44.6.13  BravaisSupergroups

\[ \text{BravaisSupergroups}(G) \] (attribute)

returns the subgroups of \( GL_n(\mathbb{Z}) \) that contain the Bravais group of \( G \) and are Bravais groups themselves.

44.6.14  NormalizerInGLnZBravaisGroup

\[ \text{NormalizerInGLnZBravaisGroup}(G) \] (attribute)

returns the normalizer of the Bravais group of \( G \) in the appropriate \( GL_n(\mathbb{Z}) \).

44.7  Acting OnRight and OnLeft

In GAP, matrices by convention act on row vectors from the right, whereas in crystallography the convention is to act on column vectors from the left. The definition of certain algebraic objects important in crystallography implicitly depends on which action is assumed. This holds true in particular for quadratic forms invariant under a matrix group. In a similar way, the representation of affine crystallographic groups, as they are provided by the GAP package CrystGap, depends on which action is assumed. Crystallographers are used to the action from the left, whereas the action from the right is the natural one for GAP. For this reason, a number of functions which are important in crystallography, and whose result depends on which action is assumed, are provided in two versions, one for the usual action from the right, and one for the crystallographic action from the left.

For every such function, this fact is explicitly mentioned. The naming scheme is as follows: If \text{SomeThing} is such a function, there will be functions \text{SomeThingOnRight} and \text{SomeThingOnLeft}, assuming action from the right and from the left, respectively. In addition, there is a generic function \text{SomeThing}, which returns either the result of \text{SomeThingOnRight} or \text{SomeThingOnLeft}, depending on the global variable \text{CrystGroupDefaultAction} (44.7.1).

44.7.1  CrystGroupDefaultAction

\[ \text{CrystGroupDefaultAction} \] (global variable)

can have either of the two values \text{RightAction} and \text{LeftAction}. The initial value is \text{RightAction}. For functions which have variants \text{OnRight} and \text{OnLeft}, this variable determines which variant is returned by the generic form. The value of \text{CrystGroupDefaultAction} can be changed with the function \text{SetCrystGroupDefaultAction} (44.7.2).

44.7.2  SetCrystGroupDefaultAction

\[ \text{SetCrystGroupDefaultAction}(\text{action}) \] (function)

allows one to set the value of the global variable \text{CrystGroupDefaultAction} (44.7.1). Only the arguments \text{RightAction} and \text{LeftAction} are allowed. Initially, the value of \text{CrystGroupDefaultAction} (44.7.1) is \text{RightAction}. 
Chapter 45

Polycyclic Groups

A group \( G \) is \textit{polycyclic} if there exists a subnormal series \( G = C_1 > C_2 > \ldots > C_n > C_{n+1} = \{1\} \) with cyclic factors. Such a series is called \textit{pc series} of \( G \).

Every polycyclic group is solvable and every finite solvable group is polycyclic. However, there are infinite solvable groups which are not polycyclic.

In \textsc{GAP} there exists a large number of methods for polycyclic groups which are based upon the polycyclic structure of these groups. These methods are usually very efficient, especially for groups which are given by a pc-presentation (see chapter 46), and can be applied to many types of groups. Hence \textsc{GAP} tries to use them whenever possible, for example, for permutation groups and matrix groups over finite fields that are known to be polycyclic (the only exception is the representation as finitely presented group for which the polycyclic methods cannot be used in general).

At the current state of implementations the \textsc{GAP} library contains methods to compute with finite polycyclic groups, while the \textsc{GAP} package \texttt{Polycyclic} by Bettina Eick and Werner Nickel allows also computations with infinite polycyclic groups which are given by a pc-presentation.

45.1 Polycyclic Generating Systems

Let \( G \) be a polycyclic group with a pc series as above. A \textit{polycyclic generating sequence} (pcgs for short) of \( G \) is a sequence \( P := (g_1, \ldots, g_n) \) of elements of \( G \) such that \( C_i = \langle C_{i+1}, g_i \rangle \) for \( 1 \leq i \leq n \). Note that each polycyclic group has a pcgs, but except for very small groups, a pcgs is not unique.

For each index \( i \) the subsequence of elements \( (g_i, \ldots, g_n) \) forms a pcgs of the subgroup \( C_i \). In particular, these \textit{tails} generate the subgroups of the pc series and hence we say that the pc series is determined by \( P \).

Let \( r_i \) be the index of \( C_{i+1} \) in \( C_i \), which is either a finite positive number or infinity. Then \( r_i \) is the order of \( g_i C_{i+1} \) and we call the resulting list of indices the \textit{relative orders} of the pcgs \( P \).

Moreover, with respect to a given pcgs \( (g_1, \ldots, g_n) \) each element \( g \) of \( G \) can be represented in a unique way as a product \( g = g_1^{e_1} \cdot g_2^{e_2} \cdots g_n^{e_n} \) with exponents \( e_i \in \{0, \ldots, r_i - 1\} \), if \( r_i \) is finite, and \( e_i \in \mathbb{Z} \) otherwise. Words of this form are called \textit{normal words} or \textit{words in normal form}. Then the integer vector \([e_1, \ldots, e_n]\) is called the \textit{exponent vector} of the element \( g \). Furthermore, the smallest index \( k \) such that \( e_k \neq 0 \) is called the \textit{depth} of \( g \) and \( e_k \) is the \textit{leading exponent} of \( g \).

For many applications we have to assume that each of the relative orders \( r_i \) is either a prime or infinity. This is equivalent to saying that there are no trivial factors in the pc series and the finite factors of the pc series are maximal refined. Then we obtain that \( r_i \) is the order of \( g C_{i+1} \) for all elements \( g \) in \( C_i \setminus C_{i+1} \) and we call \( r_i \) the \textit{relative order} of the element \( g \).
45.2 Computing a Pcgs

Suppose a group $G$ is given; for example, let $G$ be a permutation or matrix group. Then we can ask GAP to compute a pcgs of this group. If $G$ is not polycyclic, the result will be fail.

Note that these methods can only be applied if $G$ is not given as finitely presented group. For finitely presented groups one can try to compute a pcgs via the polycyclic quotient methods, see 47.14.

Note also that a pcgs behaves like a list.

45.2.1 Pcgs

\texttt{⊿Pcgs(G)(attribute)}

returns a pcgs for the group $G$. If $grp$ is not polycyclic it returns fail and this result is not stored as attribute value, in particular in this case the filter HasPcgs is not set for $G$!

45.2.2 IsPcgs

\texttt{⊿IsPcgs(obj)(Category)}

The category of pcgs.

Example

\begin{verbatim}
gap> G := Group([[(1,2,3,4),(1,2)];
gap> p := Pcgs(G);
Pcgs([ (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ])
gap> IsPcgs( p );
true
gap> p[1];
(3,4)
gap> G := Group([[(1,2,3,4,5),(1,2)];
gap> Pcgs(G);
fail
\end{verbatim}

45.2.3 CanEasilyComputePcgs

\texttt{⊿CanEasilyComputePcgs(grp)(filter)}

This filter indicates whether it is possible to compute a pcgs for $grp$ cheaply. Clearly, $grp$ must be polycyclic in this case. However, not for every polycyclic group there is a method to compute a pcgs at low costs. This filter is used in the method selection mainly. Note that this filter may change its value from false to true.

Example

\begin{verbatim}
gap> G := Group([ (1,2,3,4),(1,2) ]);
Group([ (1,2,3,4), (1,2) ])
gap> CanEasilyComputePcgs(G);
false
gap> Pcgs(G);
Pcgs([ (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ])
gap> CanEasilyComputePcgs(G);
true
\end{verbatim}
45.3 Defining a Pcgs Yourself

In a number of situations it might be useful to supply a pcgs to a group. Note that the elementary operations for such a pcgs might be rather inefficient, since GAP has to use generic methods in this case. It might be helpful to supply the relative orders of the self-defined pcgs as well by SetRelativeOrder. See also IsPrimeOrdersPcgs (45.4.3).

45.3.1 PcgsByPcSequence

\[ \text{PcgsByPcSequence}(fam, pcs) \] (operation)
\[ \text{PcgsByPcSequenceNC}(fam, pcs) \] (operation)

constructs a pcgs for the elements family \( fam \) from the elements in the list \( pcs \). The elements must lie in the family \( fam \). PcgsByPcSequence and its NC variant will always create a new pcgs which is not induced by any other pcgs (cf. InducedPcgsByPcSequence (45.7.2)).

**Example**

```gap
gap> fam := FamilyObj( (1,2) );; # the family of permutations
gap> p := PcgsByPcSequence( fam, [(1,2),(1,2,3)] );
Pcgs([ (1,2), (1,2,3) ])
gap> RelativeOrders(p);
[ 2, 3 ]
gap> ExponentsOfPcElement( p, (1,3,2) );
[ 0, 2 ]
```

45.4 Elementary Operations for a Pcgs

45.4.1 RelativeOrders

\[ \text{RelativeOrders}(pcgs) \] (attribute)

returns the list of relative orders of the pcgs \( pcgs \).

45.4.2 IsFiniteOrdersPcgs

\[ \text{IsFiniteOrdersPcgs}(pcgs) \] (property)

tests whether the relative orders of \( pcgs \) are all finite.

45.4.3 IsPrimeOrdersPcgs

\[ \text{IsPrimeOrdersPcgs}(pcgs) \] (property)

tests whether the relative orders of \( pcgs \) are prime numbers. Many algorithms require a pcgs to have this property. The operation IsomorphismRefinedPcGroup (46.4.8) can be of help here.
45.4.4 PcSeries

\( \text{PcSeries}(pcgs) \) (attribute)

returns the subnormal series determined by \( pcgs \).

45.4.5 GroupOfPcgs

\( \text{GroupOfPcgs}(pcgs) \) (attribute)

The group generated by \( pcgs \).

45.4.6 OneOfPcgs

\( \text{OneOfPcgs}(pcgs) \) (attribute)

The identity of the group generated by \( pcgs \).

Example

\[
\begin{align*}
gap> G := \text{Group}( (1,2,3,4),(1,2) );; \ p := \text{Pcgs}(G);;
gap> \text{RelativeOrders}(p); \\
[ 2, 3, 2, 2 ]
gap> \text{IsFiniteOrdersPcgs}(p); \\
true
gap> \text{IsPrimeOrdersPcgs}(p); \\
true
gap> \text{PcSeries}(p); \\
[ \text{Group}(\langle (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) \rangle), \\
\text{Group}(\langle (2,4,3), (1,4)(2,3), (1,3)(2,4) \rangle), \\
\text{Group}(\langle (1,4)(2,3), (1,3)(2,4) \rangle), \text{Group}(\langle (1,3)(2,4) \rangle), \text{Group}(()) ]
\end{align*}
\]

45.5 Elementary Operations for a Pcgs and an Element

45.5.1 RelativeOrderOfPcElement

\( \text{RelativeOrderOfPcElement}(pcgs, \ elm) \) (operation)

The relative order of \( \ elm \) with respect to the prime order \( pcgs \).

45.5.2 ExponentOfPcElement

\( \text{ExponentOfPcElement}(pcgs, \ elm, \ pos) \) (operation)

returns the \( pos \)-th exponent of \( \ elm \) with respect to \( pcgs \).

45.5.3 ExponentsOfPcElement

\( \text{ExponentsOfPcElement}(pcgs, \ elm[, \ posran]) \) (operation)
returns the exponents of $elm$ with respect to $pcgs$. The three argument version returns the exponents in the positions given in $posran$.

45.5.4 DepthOfPcElement

\[\text{DepthOfPcElement}(pcgs, elm)\]  
returns the depth of the element $elm$ with respect to $pcgs$.

45.5.5 LeadingExponentOfPcElement

\[\text{LeadingExponentOfPcElement}(pcgs, elm)\]  
returns the leading exponent of $elm$ with respect to $pcgs$.

45.5.6 PcElementByExponents

\[\text{PcElementByExponents}(pcgs, list)\]
\[\text{PcElementByExponentsNC}(pcgs[, basisind], list)\]  
returns the element corresponding to the exponent vector $list$ with respect to $pcgs$. The exponents in $list$ must be in the range of permissible exponents for $pcgs$. It is not guaranteed that $\text{PcElementByExponents}$ will reduce the exponents modulo the relative orders. (You should use the operation $\text{LinearCombinationPcgs}$ (45.5.7) for this purpose.) The $\text{NC}$ version does not check that the lengths of the lists fit together and does not check the exponent range.

The three argument version gives exponents only w.r.t. the generators in $pcgs$ indexed by $basisind$.

45.5.7 LinearCombinationPcgs

\[\text{LinearCombinationPcgs}(pcgs, list[, one])\]  
returns the product $\prod_i pcgs[i]^{|list[i]|}$. In contrast to $\text{PcElementByExponents}$ (45.5.6) this permits negative exponents. $pcgs$ might be a list of group elements. In this case, an appropriate identity element one must be given. $list$ can be empty.

\begin{verbatim}
gap> G := Group( (1,2,3,4),(1,2) );; P := Pcgs(G);;
gap> g := PcElementByExponents(P, [0,1,1,1]);
(1,2,3)
gap> ExponentsOfPcElement(P, g);
[ 0, 1, 1, 1 ]
\end{verbatim}

45.5.8 SiftedPcElement

\[\text{SiftedPcElement}(pcgs, elm)\]  
sifts $elm$ through $pcgs$, reducing it if the depth is the same as the depth of one of the generators in $pcgs$. Thus the identity is returned if $elm$ lies in the group generated by $pcgs$. $pcgs$ must be an induced $pcgs$ (see section 45.7) and $elm$ must lie in the span of the parent of $pcgs$. 
45.5.9 CanonicalPcElement

▶ CanonicalPcElement(ipcgs, elm)  

(reduction) reduces elm at the induces pcgs ipcgs such that the exponents of the reduced result r are zero at the depths for which there are generators in ipcgs. Elements, whose quotient lies in the group generated by ipcgs yield the same canonical element.

45.5.10 ReducedPcElement

▶ ReducedPcElement(pcgs, x, y)  

(reduction) reduces the element x by dividing off (from the left) a power of y such that the leading coefficient of the result with respect to pcgs becomes zero. The elements x and y therefore have to have the same depth.

45.5.11 CleanedTailPcElement

▶ CleanedTailPcElement(pcgs, elm, dep)  

returns an element in the span of pcgs whose exponents for indices 1 to dep − 1 with respect to pcgs are the same as those of elm, the remaining exponents are undefined. This can be used to obtain more “simple” elements if only representatives in a factor are required, see 45.9.

The difference to HeadPcElementByNumber (45.5.12) is that this function is guaranteed to zero out trailing coefficients while CleanedTailPcElement will only do this if it can be done cheaply.

45.5.12 HeadPcElementByNumber

▶ HeadPcElementByNumber(pcgs, elm, dep)  

returns an element in the span of pcgs whose exponents for indices 1 to dep − 1 with respect to pcgs are the same as those of elm, the remaining exponents are zero. This can be used to obtain more “simple” elements if only representatives in a factor are required.

45.6 Exponents of Special Products

There are certain products of elements whose exponents are used often within algorithms, and which might be obtained more easily than by computing the product first and to obtain its exponents afterwards. The operations in this section provide a way to obtain such exponent vectors directly.

(The circumstances under which these operations give a speedup depend very much on the pcgs and the representation of elements that is used. So the following operations are not guaranteed to give a speedup in every case, however the default methods are not slower than to compute the exponents of a product and thus these operations should always be used if applicable.)

The second class are exponents of products of the generators which make up the pcgs. If the pcgs used is a family pcgs (see FamilyPcgs (46.1.1)) then these exponents can be looked up and do not need to be computed.
45.6.1 ExponentsConjugateLayer

\begin{verbatim}
\textbf{ExponentsConjugateLayer}(mpcgs, elm, e)
\end{verbatim}

(\textit{operation})

Computes the exponents of \( elm^e \) with respect to \( mpcgs \); \( elm \) must be in the span of \( mpcgs \), \( e \) a \( \text{pc} \) element in the span of the parent \( \text{pcgs} \) of \( mpcgs \) and \( mpcgs \) must be the modulo \( \text{pcgs} \) for an abelian layer. (This is the usual case when acting on a chief factor). In this case if \( mpcgs \) is induced by the family \( \text{pcgs} \) (see section 45.7), the exponents can be computed directly by looking up exponents without having to compute in the group and having to collect a potential tail.

45.6.2 ExponentsOfRelativePower

\begin{verbatim}
\textbf{ExponentsOfRelativePower}(pcgs, i)
\end{verbatim}

(\textit{operation})

For \( p = pcgs[i] \) this function returns the exponent vector with respect to \( pcgs \) of the element \( p^e \) where \( e \) is the relative order of \( p \) in \( pcgs \). For the family \( \text{pcgs} \) or \( \text{pcgs} \) induced by it (see section 45.7), this might be faster than computing the element and computing its exponent vector.

45.6.3 ExponentsOfConjugate

\begin{verbatim}
\textbf{ExponentsOfConjugate}(pcgs, i, j)
\end{verbatim}

(\textit{operation})

returns the exponents of \( pcgs[i]^pcgs[j] \) with respect to \( pcgs \). For the family \( \text{pcgs} \) or \( \text{pcgs} \) induced by it (see section 45.7), this might be faster than computing the element and computing its exponent vector.

45.6.4 ExponentsOfCommutator

\begin{verbatim}
\textbf{ExponentsOfCommutator}(pcgs, i, j)
\end{verbatim}

(\textit{operation})

returns the exponents of the commutator \( \text{Comm}( pcgs[i], pcgs[j] ) \) with respect to \( pcgs \). For the family \( \text{pcgs} \) or \( \text{pcgs} \) induced by it, (see section 45.7), this might be faster than computing the element and computing its exponent vector.

45.7 Subgroups of Polycyclic Groups – Induced \text{pcgs}

Let \( U \) be a subgroup of \( G \) and let \( P \) be a \( \text{pcgs} \) of \( G \) as above such that \( P \) determines the subnormal series \( G = C_1 > \ldots > C_{n+1} = \{1\} \). Then the series of subgroups \( U \cap C_i \) is a subnormal series of \( U \) with cyclic or trivial factors. Hence, if we choose an element \( u_i \in (U \cap C_i) \setminus (U \cap C_{i+1}) \) whenever this factor is non-trivial, then we obtain a \( \text{pcgs} \) \( Q = (u_i, \ldots, u_m) \) of \( U \). We say that \( Q \) is an \textit{induced \text{pcgs}} with respect to \( P \). The \text{pcgs} \( P \) is the \textit{parent \text{pcgs}} to the induced \text{pcgs} \( Q \).

Note that the \text{pcgs} \( Q \) is induced with respect to \( P \) if and only if the matrix of exponent vectors of the elements \( u_i \) with respect to \( P \) is in upper triangular form. Thus \( Q \) is not unique in general.

In particular, the elements of an induced \text{pcgs} do not necessarily have leading coefficient 1 relative to the inducing \text{pcgs}. The attribute \textbf{LeadCoeffs}\text{\textsc{pcgs}} (45.7.7) holds the leading coefficients in case they have to be renormed in an algorithm.
Each induced pcgs is a pcgs and hence allows all elementary operations for pcgs. On the other hand each pcgs could be transformed into an induced pcgs for the group defined by the pcgs, but note that an arbitrary pcgs is in general not an induced pcgs for technical reasons.

An induced pcgs is "compatible" with its parent, see ParentPcgs (45.7.3).

In [LNS84] a "non-commutative Gauss" algorithm is described to compute an induced pcgs of a subgroup $U$ from a generating set of $U$. For calling this in GAP, see 45.7.4 to 45.7.8.

To create a subgroup generated by an induced pcgs such that the induced pcgs gets stored automatically, use SubgroupByPcgs (45.7.9).

45.7.1 IsInducedPcgs

\texttt{IsInducedPcgs}(<\text{pcgs}>)

The category of induced pcgs. This a subcategory of pcgs.

45.7.2 InducedPcgsByPcSequence

\texttt{InducedPcgsByPcSequence}(<\text{pcgs}, \text{pcs}>)
\texttt{InducedPcgsByPcSequenceNC}(<\text{pcgs}, \text{pcs}[, \text{depths}]>)

If \text{pcs} is a list of elements that form an induced pcgs with respect to \text{pcgs} this operation returns an induced pcgs with these elements.

In the third version, the depths of \text{pcs} with respect to \text{pcgs} can be given (they are computed anew otherwise).

45.7.3 ParentPcgs

\texttt{ParentPcgs}(<\text{pcgs}>)

returns the pcgs by which \text{pcgs} was induced. If \text{pcgs} was not induced, it simply returns \text{pcgs}.

\begin{verbatim}
gap> G := Group( (1,2,3,4),(1,2) );;
gap> P := Pcgs(G);;
gap> K := InducedPcgsByPcSequence( P, [(1,2,3,4),(1,3)(2,4)] );
Pcgs([ (1,2,3,4), (1,3)(2,4) ])
gap> ParentPcgs( K );
Pcgs([ (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ])
gap> IsInducedPcgs( K );
true
\end{verbatim}

45.7.4 InducedPcgs

\texttt{InducedPcgs}(<\text{pcgs}, \text{grp}>)

computes a pcgs for \text{grp} which is induced by \text{pcgs}. If \text{pcgs} has a parent pcgs, then the result is induced with respect to this parent pcgs.

\texttt{InducedPcgs} is a wrapper function only. Therefore, methods for computing computing an induced pcgs should be installed for the operation \texttt{InducedPcgsOp}.
45.7.5 InducedPcgsByGenerators

\texttt{InducedPcgsByGenerators}(\textit{pcgs}, \textit{gens}) \hspace{1cm} \text{(operation)}

\texttt{InducedPcgsByGeneratorsNC}(\textit{pcgs}, \textit{gens}) \hspace{1cm} \text{(operation)}

returns an induced pcgs with respect to \text{pcgs} for the subgroup generated by \textit{gens}.

45.7.6 InducedPcgsByPcSequenceAndGenerators

\texttt{InducedPcgsByPcSequenceAndGenerators}(\textit{pcgs}, \textit{ind}, \textit{gens}) \hspace{1cm} \text{(operation)}

returns an induced pcgs with respect to \textit{pcgs} of the subgroup generated by \textit{ind} and \textit{gens}. Here \textit{ind} must be an induced pcgs with respect to \textit{pcgs} (or a list of group elements that form such an igs) and it will be used as initial sequence for the computation.

Example

\begin{verbatim}
gap> G := Group( (1,2,3,4),(1,2) );; P := Pcgs(G);
gap> I := InducedPcgsByGenerators( P, [(1,2,3,4)] );
Pcgs([ (1,2,3,4), (1,3)(2,4) ])
gap> J := InducedPcgsByPcSequenceAndGenerators( P, I, [(1,2)] );
Pcgs([ (1,2,3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ])
\end{verbatim}

45.7.7 LeadCoeffsIGS

\texttt{LeadCoeffsIGS}(\textit{igs}) \hspace{1cm} \text{(attribute)}

This attribute is used to store leading coefficients with respect to the parent pcgs. the \textit{i}-th entry \textit{--}if bound\textit{--} is the leading exponent of the element of \textit{igs} that has depth \textit{i} in the parent. (It cannot be assigned to a component in the object created by \texttt{InducedPcgsByPcSequenceNC} (45.7.2) as the permutation group methods call it from within the postprocessing, before this postprocessing however no coefficients may be computed.)

45.7.8 ExtendedPcgs

\texttt{ExtendedPcgs}(\textit{N}, \textit{gens}) \hspace{1cm} \text{(operation)}

extends the pcgs \textit{N} (induced w.r.t. \text{home}) to a new induced pcgs by prepending \textit{gens}. No checks are performed that this really yields an induced pcgs.

45.7.9 SubgroupByPcgs

\texttt{SubgroupByPcgs}(\textit{G}, \textit{pcgs}) \hspace{1cm} \text{(operation)}

returns a subgroup of \textit{G} generated by the elements of \textit{pcgs}.

45.8 Subgroups of Polycyclic Groups – Canonical Pcgs

The induced pcgs \textit{Q} of \textit{U} is called canonical if the matrix of exponent vectors contains normed vectors only and above each leading entry in the matrix there are 0's only. The canonical pcgs of \textit{U} with
respect to $P$ is unique and hence such pcgs can be used to compare subgroups.

45.8.1 IsCanonicalPcgs

▷ IsCanonicalPcgs(pcg$) (property)

An induced pcgs is canonical if the matrix of the exponent vectors of the elements of pcgs with respect to the ParentPcgs (45.7.3) value of pcgs is in Hermite normal form (see [LNS84]). While a subgroup can have various induced pcgs with respect to a parent pcgs a canonical pcgs is unique.

45.8.2 CanonicalPcgs

▷ CanonicalPcgs(pcg$) (attribute)

returns the canonical pcgs corresponding to the induced pcgs pcgs.

Example

```gap
gap> G := Group([ (1,2,3,4), (5,6,7) ]); Group([ (1,2,3,4), (5,6,7) ])
gap> P := Pcgs(G); Pcgs([ (5,6,7), (1,2,3,4), (1,3)(2,4) ])
gap> I := InducedPcgsByPcSequence(P, [(5,6,7)*(1,3)(2,4), (1,3)(2,4)] );
Pcgs([ (1,3)(2,4)(5,6,7), (1,3)(2,4) ])
gap> CanonicalPcgs(I); Pcgs([ (5,6,7), (1,3)(2,4) ])
```

45.9 Factor Groups of Polycyclic Groups – Modulo Pcgs

Let $N$ be a normal subgroup of $G$ such that $G/N$ is polycyclic with pcgs $(h_1N, \ldots, h_rN)$. Then we call the sequence of preimages $(h_1, \ldots, h_r)$ a modulo pcgs of $G/N$. $G$ is called the numerator of the modulo pcgs and $N$ is the denominator of the modulo pcgs.

Modulo pcgs are often used to facilitate efficient computations with factor groups, since they allow computations with factor groups without formally defining the factor group at all.

All elementary operations of pcgs, see Sections 45.4 and 45.5, apply to modulo pcgs as well. However, it is in general not possible to compute induced pcgs with respect to a modulo pcgs.

Two more elementary operations for modulo pcgs are NumeratorOfModuloPcgs (45.9.3) and DenominatorOfModuloPcgs (45.9.4).

45.9.1 ModuloPcgs

▷ ModuloPcgs($G$, $N$) (operation)

returns a modulo pcgs for the factor $G/N$ which must be solvable, while $N$ may be non-solvable. ModuloPcgs will return a pcgs for the factor, there is no guarantee that it will be “compatible” with any other pcgs. If this is required, the mod operator must be used on induced pcgs, see \mod (45.9.5).
45.9.2 IsModuloPcgs

\[ \text{IsModuloPcgs}(obj) \]  (Category)

The category of modulo pcgs. Note that each pcgs is a modulo pcgs for the trivial subgroup.

45.9.3 NumeratorOfModuloPcgs

\[ \text{NumeratorOfModuloPcgs}(pcgs) \]  (attribute)

returns a generating set for the numerator of the modulo pcgs \( pcgs \).

45.9.4 DenominatorOfModuloPcgs

\[ \text{DenominatorOfModuloPcgs}(pcgs) \]  (attribute)

returns a generating set for the denominator of the modulo pcgs \( pcgs \).

Example

\begin{verbatim}
gap> G := Group( (1,2,3,4,5), (1,2) );
Group([ (1,2,3,4,5), (1,2) ])
gap> P := ModuloPcgs(G, DerivedSubgroup(G) );
Pcgs([ (4,5) ])
gap> NumeratorOfModuloPcgs(P);
[ (1,2,3,4,5), (1,2) ]
gap> DenominatorOfModuloPcgs(P);
[ (1,3,2), (1,4,3), (2,5,4) ]
gap> RelativeOrders(P);
[ 2 ]
gap> ExponentsOfPcElement( P, (1,2,3,4,5) );
[ 0 ]
gap> ExponentsOfPcElement( P, (4,5) );
[ 1 ]
\end{verbatim}

45.9.5 \mod \text{ (for two pcgs)}

\[ \text{\mod}(P, I) \]  (method)

Modulo Pcgs can also be built from compatible induced pcgs. Let \( G \) be a group with pcgs \( P \) and let \( I \) be an induced pcgs of a normal subgroup \( N \) of \( G \). (Respectively: \( P \) and \( I \) are both induced with respect to the same Pcgs.) Then we can compute a modulo pcgs of \( G \mod N \) by \( P \mod I \).

Note that in this case we obtain the advantage that the values of NumeratorOfModuloPcgs (45.9.3) and DenominatorOfModuloPcgs (45.9.4) are just \( P \) and \( I \), respectively, and hence are unique.

The resulting modulo pcgs will consist of a subset of \( P \) and will be “compatible” with \( P \) (or its parent).

Example

\begin{verbatim}
gap> G := Group([(1,2,3,4)]);;
gap> P := Pcgs(G);
\end{verbatim}
Pcgs([[1,2,3,4], (1,3)(2,4)])
gap> I := InducedPcgsByGenerators(P, [(1,3)(2,4)]);
Pcgs([[1,3)(2,4)])
gap> M := P mod I;
[ (1,2,3,4) ]
gap> NumeratorOfModuloPcgs(M);
Pcgs([[1,2,3,4], (1,3)(2,4)])
gap> DenominatorOfModuloPcgs(M);
Pcgs([[1,3)(2,4)])

45.9.6 CorrespondingGeneratorsByModuloPcgs

Let mpcgs be a modulo pcgs for a factor of a group G and let U be a subgroup of G generated by imgs such that U covers the factor for the modulo pcgs. Then this function computes elements in U corresponding to the generators of the modulo pcgs.

Note that the computation of induced generating sets is not possible for some modulo pcgs.

45.9.7 CanonicalPcgsByGeneratorsWithImages

computes a canonical, pcgs-induced pcgs for the span of gens and simultaneously does the same transformations on imgs, preserving thus a correspondence between gens and imgs. This operation is used to represent homomorphisms from a pc group.

45.10 Factor Groups of Polycyclic Groups in their Own Representation

If substantial calculations are done in a factor it might be worth still to construct the factor group in its own representation (for example by calling PcGroupWithPcgs (46.5.1) on a modulo pcgs.

The following functions are intended for working with factor groups obtained by factoring out the tail of a pcgs. They provide a way to map elements or induced pcgs quickly in the factor (respectively to take preimages) without the need to construct a homomorphism.

The setup is always a pcgs pcgs of G and a pcgs fpcgs of a factor group \( H = G/N \) which corresponds to a head of pcgs.

No tests for validity of the input are performed.

45.10.1 ProjectedPcElement

returns the image in H of an element elm of G.

45.10.2 ProjectedInducedPcgs


\texttt{ipcgs} must be an induced pcgs with respect to \texttt{pcgs}. This operation returns an induced pcgs with respect to \texttt{fpcgs} consisting of the nontrivial images of \texttt{ipcgs}.

\subsection*{45.10.3 \texttt{LiftedPcElement}}

\begin{verbatim}
\> LiftedPcElement(pcgs, fpcgs, elm)
\end{verbatim}

returns a preimage in \(G\) of an element \(elm\) of \(H\).

\subsection*{45.10.4 \texttt{LiftedInducedPcgs}}

\begin{verbatim}
\> LiftedInducedPcgs(pcgs, fpcgs, ipcgs, ker)
\end{verbatim}

\texttt{ipcgs} must be an induced pcgs with respect to \texttt{fpcgs}. This operation returns an induced pcgs with respect to \texttt{pcgs} consisting of the preimages of \texttt{ipcgs}, appended by the elements in \texttt{ker} (assuming there is a bijection of \texttt{pcgs} mod \texttt{ker} to \texttt{fpcgs}). \texttt{ker} might be a simple element list.

\section*{45.11 Pcgs and Normal Series}

By definition, a pcgs determines a pc series of its underlying group. However, in many applications it will be necessary that this pc series refines a normal series with certain properties; for example, a normal series with abelian factors.

There are functions in GAP to compute a pcgs through a normal series with elementary abelian factors, a central series or the lower p-central series. See also Section 45.13 for a more explicit possibility.

\subsection*{45.11.1 \texttt{IsPcgsElementaryAbelianSeries}}

\begin{verbatim}
\> IsPcgsElementaryAbelianSeries(pcgs)
\end{verbatim}

returns \texttt{true} if the pcgs \texttt{pcgs} refines an elementary abelian series. \texttt{IndicesEANormalSteps} (45.11.3) then gives the indices in the Pcgs, at which the subgroups of this series start.

\subsection*{45.11.2 \texttt{PcgsElementaryAbelianSeries} (for a group)}

\begin{verbatim}
\> PcgsElementaryAbelianSeries(G)
\> PcgsElementaryAbelianSeries(list)
\end{verbatim}

computes a pcgs for \(G\) that refines an elementary abelian series. \texttt{IndicesEANormalSteps} (45.11.3) gives the indices in the pcgs, at which the normal subgroups of this series start. The second variant returns a pcgs that runs through the normal subgroups in the list \texttt{list}.

\subsection*{45.11.3 \texttt{IndicesEANormalSteps}}

\begin{verbatim}
\> IndicesEANormalSteps(pcgs)
\> IndicesEANormalStepsBounded(pcgs, bound)
\end{verbatim}
Let \textit{pcgs} be a pcgs obtained as corresponding to a series of normal subgroups with elementary abelian factors (for example from calling \texttt{PcgElementaryAbelianSeries (45.11.2)}). Then \texttt{IndicesEANormalSteps} returns a sorted list of integers, indicating the tails of \textit{pcgs} which generate these normal subgroup of \textit{G}. If \(i\) is an element of this list, \((g_i, \ldots, g_n)\) is a normal subgroup of \(G\). The list always starts with 1 and ends with \(n + 1\). (These indices form \textit{one} series with elementary abelian subfactors, not necessarily the most refined one.)

The attribute \texttt{EANormalSeriesByPcgs (45.11.4)} returns the actual series of subgroups.

For arbitrary pcgs not obtained as belonging to a special series such a set of indices not necessarily exists, and \texttt{IndicesEANormalSteps} is not guaranteed to work in this situation.

Typically, \texttt{IndicesEANormalSteps} is set by \texttt{PcgElementaryAbelianSeries (45.11.2)}.

The variant \texttt{IndicesEANormalStepsBounded} will aim to ensure that no factor will be larger than the given bound.

45.11.4  EANormalSeriesByPcgs

\texttt{EANormalSeriesByPcgs} \((\textit{pcgs})\) (attribute)

Let \textit{pcgs} be a pcgs obtained as corresponding to a series of normal subgroups with elementary abelian factors (for example from calling \texttt{PcgElementaryAbelianSeries (45.11.2)}). This attribute returns the actual series of normal subgroups, corresponding to \texttt{IndicesEANormalSteps (45.11.3)}.

45.11.5  IsPcgsCentralSeries

\texttt{IsPcgsCentralSeries} \((\textit{pcgs})\) (property)

returns \texttt{true} if the pcgs \textit{pcgs} refines an central elementary abelian series. \texttt{IndicesCentralNormalSteps (45.11.7)} then gives the indices in the pcgs, at which the subgroups of this series start.

45.11.6  PcgsCentralSeries

\texttt{PcgCentralSeries} \((\textit{G})\) (attribute)

computes a pcgs for \(G\) that refines a central elementary abelian series. \texttt{IndicesCentralNormalSteps (45.11.7)} gives the indices in the pcgs, at which the normal subgroups of this series start.

45.11.7  IndicesCentralNormalSteps

\texttt{IndicesCentralNormalSteps} \((\textit{pcgs})\) (attribute)

Let \textit{pcgs} be a pcgs obtained as corresponding to a series of normal subgroups with central elementary abelian factors (for example from calling \texttt{PcgCentralSeries (45.11.6)}). Then \texttt{IndicesCentralNormalSteps} returns a sorted list of integers, indicating the tails of \textit{pcgs} which generate these normal subgroups of \(G\). If \(i\) is an element of this list, \((g_i, \ldots, g_n)\) is a normal subgroup of \(G\). The list always starts with 1 and ends with \(n + 1\). (These indices form \textit{one} series with central elementary abelian subfactors, not necessarily the most refined one.)
The attribute CentralNormalSeriesByPcgs (45.11.8) returns the actual series of subgroups. 
For arbitrary pcgs not obtained as belonging to a special series such a set of indices not necessarily 
exists, and IndicesCentralNormalSteps is not guaranteed to work in this situation. 
Typically, IndicesCentralNormalSteps is set by PcgsCentralSeries (45.11.6).

45.11.8 CentralNormalSeriesByPcgs

\[ \text{CentralNormalSeriesByPcgs}(pcgs) \]

Let \( pcgs \) be a pcgs obtained as corresponding to a series of normal subgroups with central elementary abelian factors (for example from calling PcgsCentralSeries (45.11.6)). This attribute returns the actual series of normal subgroups, corresponding to IndicesCentralNormalSteps (45.11.7).

45.11.9 IsPcgsPCentralSeriesPGroup

\[ \text{IsPcgsPCentralSeriesPGroup}(pcgs) \]

returns true if the pcgs \( pcgs \) refines a \( p \)-central elementary abelian series for a \( p \)-group. IndicesPCentralNormalStepsPGroup (45.11.11) then gives the indices in the pcgs, at which the subgroups of this series start.

45.11.10 PcgsPCentralSeriesPGroup

\[ \text{PcgsPCentralSeriesPGroup}(G) \]

computes a pcgs for the \( p \)-group \( G \) that refines a \( p \)-central elementary abelian series. IndicesPCentralNormalStepsPGroup (45.11.11) gives the indices in the pcgs, at which the normal subgroups of this series start.

45.11.11 IndicesPCentralNormalStepsPGroup

\[ \text{IndicesPCentralNormalStepsPGroup}(pcgs) \]

Let \( pcgs \) be a pcgs obtained as corresponding to a series of normal subgroups with \( p \)-central elementary abelian factors (for example from calling PcgsPCentralSeriesPGroup (45.11.10)). Then IndicesPCentralNormalStepsPGroup returns a sorted list of integers, indicating the tails of \( pcgs \) which generate these normal subgroups of \( G \). If \( i \) is an element of this list, \( (g_i, \ldots, g_n) \) is a normal subgroup of \( G \). The list always starts with 1 and ends with \( n+1 \). (These indices form one series with central elementary abelian subfactors, not necessarily the most refined one.)

The attribute PCentralNormalSeriesByPcgsPGroup (45.11.12) returns the actual series of subgroups.

For arbitrary pcgs not obtained as belonging to a special series such a set of indices not necessarily exists, and IndicesPCentralNormalStepsPGroup is not guaranteed to work in this situation.

Typically, IndicesPCentralNormalStepsPGroup is set by PcgsPCentralSeriesPGroup (45.11.10).
45.11.12  PCentralNormalSeriesByPcgsPGroup

Let \( pcgs \) be a pcgs obtained as corresponding to a series of normal subgroups with\( p \)-central elementary abelian factors (for example from calling \( \text{PcgsPCentralSeriesPGroup} \) (45.11.10)). This attribute returns the actual series of normal subgroups, corresponding to \( \text{IndicesPCentralNormalStepsPGroup} \) (45.11.11).

45.11.13  IsPcgsChiefSeries

returns true if the pcgs \( pcgs \) refines a chief series. \( \text{IndicesChiefNormalSteps} \) (45.11.15) then gives the indices in the pcgs, at which the subgroups of this series start.

45.11.14  PcgsChiefSeries

computes a pcgs for \( G \) that refines a chief series. \( \text{IndicesChiefNormalSteps} \) (45.11.15) gives the indices in the pcgs, at which the normal subgroups of this series start.

45.11.15  IndicesChiefNormalSteps

Let \( pcgs \) be a pcgs obtained as corresponding to a chief series for example from calling \( \text{PcgsChiefSeries} \) (45.11.14)). Then \( \text{IndicesChiefNormalSteps} \) returns a sorted list of integers, indicating the tails of \( pcgs \) which generate these normal subgroups of \( G \). If \( i \) is an element of this list, \( (g_i,\ldots,g_n) \) is a normal subgroup of \( G \). The list always starts with 1 and ends with \( n+1 \). (These indices form one series with elementary abelian subfactors, not necessarily the most refined one.) The attribute \( \text{ChiefNormalSeriesByPcgs} \) (45.11.16) returns the actual series of subgroups.

For arbitrary pcgs not obtained as belonging to a special series such a set of indices not necessarily exists, and \( \text{IndicesChiefNormalSteps} \) is not guaranteed to work in this situation.

Typically, \( \text{IndicesChiefNormalSteps} \) is set by \( \text{PcgsChiefSeries} \) (45.11.14).

45.11.16  ChiefNormalSeriesByPcgs

Let \( pcgs \) be a pcgs obtained as corresponding to a chief series (for example from calling \( \text{PcgsChiefSeries} \) (45.11.14)). This attribute returns the actual series of normal subgroups, corresponding to \( \text{IndicesChiefNormalSteps} \) (45.11.15).

Example

\[
gap> g:=\text{Group}((1,2,3,4),(1,2));;
gap> p:=\text{PcgsElementaryAbelianSeries}(g);
gap> \text{Pcgs}([ (3,4), (2,4,3), (1,4) (2,3), (1,3)(2,4) ])
gap> \text{IndicesEANormalSteps}(p);
\]
\begin{verbatim}
[ 1, 2, 3, 5 ]
gap> g:=Group((1,2,3,4),(1,5)(2,6)(3,7)(4,8));;
gap> p:=PcgsCentralSeries(g);
Pcgs([ (1,5)(2,6)(3,7)(4,8), (5,6,7,8), (5,7)(6,8),
    (1,4,3,2)(5,6,7,8), (1,3)(2,4)(5,7)(6,8) ])  
gap> IndicesCentralNormalSteps(p);
[ 1, 2, 4, 5, 6 ]
gap> q:=PcgsPCentralSeriesPGroup(g);
Pcgs([ (1,5)(2,6)(3,7)(4,8), (5,6,7,8), (5,7)(6,8),
    (1,4,3,2)(5,6,7,8), (1,3)(2,4)(5,7)(6,8) ])  
gap> IndicesPCentralNormalStepsPGroup(q);
[ 1, 3, 5, 6 ]
\end{verbatim}

45.11.17  IndicesNormalSteps

\texttt{IndicesNormalSteps\hspace{1em}(\texttt{pcgs})}  

returns the indices of all steps in the pc series, which are normal in the group defined by the pcgs.  
(In general, this function yields a slower performance than the more specialized index functions  
for elementary abelian series etc.)

45.11.18  NormalSeriesByPcgs

\texttt{NormalSeriesByPcgs\hspace{1em}(\texttt{pcgs})}  

returns the subgroups the pc series, which are normal in the group defined by the pcgs.  
(In general, this function yields a slower performance than the more specialized index functions  
for elementary abelian series etc.)

45.12  Sum and Intersection of Pcs

45.12.1  SumFactorizationFunctionPcs

\texttt{SumFactorizationFunctionPcs\hspace{1em}(\texttt{parentpcgs, n, u, kerpcgs})}  

computes the sum and intersection of the lists \texttt{n} and \texttt{u} whose elements form modulo pcgs induced by \texttt{parentpcgs} for two subgroups modulo a kernel given by \texttt{kerpcgs}. If \texttt{kerpcgs} is a tail if the \texttt{parent-pcgs} it is sufficient to give the starting depth, this can be more efficient than to construct an explicit pcgs. The factor group modulo \texttt{kerpcgs} generated by \texttt{n} must be elementary abelian and normal under \texttt{u}.

The function returns a record with components

\texttt{sum}  
elements that form a modulo pcgs for the span of both subgroups.

\texttt{intersection}  
elements that form a modulo pcgs for the intersection of both subgroups.
factorization

function that returns for an element \( x \) in the span of \( \sum \) a record with components \( u \) and \( n \) that give its decomposition.

The record components \( \sum \) and \( \text{intersection} \) are not pcgs but only lists of pc elements (to avoid unnecessary creation of induced pcgs).

45.13 Special Pcgs

In short, a special pcgs is a pcgs which has particularly nice properties, for example it always refines an elementary abelian series, for \( p \)-groups it even refines a central series. These nice properties permit particularly efficient algorithms.

Let \( G \) be a finite polycyclic group. A special pcgs of \( G \) is a pcgs which is closely related to a Hall system and the maximal subgroups of \( G \). These pcgs have been introduced by C. R. Leedham-Green who also gave an algorithm to compute them. Improvements to this algorithm are due to Bettina Eick. For a more detailed account of their definition the reader is referred to \([\text{Eic97}]\).

To introduce the definition of special pcgs we first need to define the LG-series and head complements of a finite polycyclic group \( G \). Let \( G = G_1 > G_2 > \ldots > G_m > G_{m+1} = \{1\} \) be the lower nilpotent series of \( G \); that is, \( G_i \) is the smallest normal subgroup of \( G_{i-1} \) with nilpotent factor. To obtain the LG-series of \( G \) we need to refine this series. Thus consider a factor \( F_i := G_i / G_{i+1} \). Since \( F_i \) is finite nilpotent, it is a direct product of its Sylow subgroups, say \( F_i = P_{i,1} \cdots P_{i,r_i} \). For each Sylow \( p_j \)-subgroup \( P_{i,j} \) we can consider its lower \( p_j \)-central series. To obtain a characteristic central series with elementary abelian factors of \( F_i \) we loop over its Sylow subgroups. Each time we consider \( P_{i,j} \) in this process we take the next step of its lower \( p_j \)-central series into the series of \( F_i \). If there is no next step, then we just skip the consideration of \( P_{i,j} \). Note that the second term of the lower \( p \)-central series of a \( p \)-group is in fact its Frattini subgroup. Thus the Frattini subgroup of \( F_i \) is contained in the computed series of this group. We denote the Frattini subgroup of \( F_i \) as \( \text{Frattini subgroups of } F_i \).

The factors \( G_i / G_i^* \) are called the heads of \( G \), while the (possibly trivial) factors \( G_i^* / G_{i+1} \) are the tails of \( G \). A head complement of \( G \) is a subgroup \( U \) of \( G \) such that \( U / G_i \) is a complement to the head \( G_i / G_i^* \) in \( G / G_i^* \) for some \( i \).

Now we are able to define a special pcgs of \( G \). It is a pcgs of \( G \) with three additional properties. First, the pc series determined by the pcgs refines the LG-series of \( G \). Second, a special pcgs exhibits a Hall system of the group \( G \); that is, for each set of primes \( \pi \) the elements of the pcgs with relative order in \( \pi \) form a pcgs of a Hall \( \pi \)-subgroup in a Hall system of \( G \). Third, a special pcgs exhibits a head complement for each head of \( G \).

To record information about the LG-series with the special pcgs we define the LGWeights of the special pcgs. These weights are a list which contains a weight \( w \) for each elements \( g \) of the special pcgs. Such a weight \( w \) represents the smallest subgroup of the LG-series containing \( g \).

Since the LG-series is defined in terms of the lower nilpotent series, Sylow subgroups of the factors and lower \( p \)-central series of the Sylow subgroup, the weight \( w \) is a triple. More precisely, \( g \) is contained in the \( w(1) \)th term \( U \) of the lower nilpotent series of \( G \), but not in the next smaller one \( V \). Then \( w(3) \) is a prime such that \( gV \) is contained in the Sylow \( w(3) \)-subgroup \( P/V \) of \( U/V \). Moreover, \( gV \) is contained in the \( w(2) \)th term of the lower \( p \)-central series of \( P/V \).

There are two more attributes of a special pcgs containing information about the LG-series: the list LGLayers and the list LGFirst. The list of layers corresponds to the elements of the special pcgs and denotes the layer of the LG-series in which an element lies. The list LGFirst corresponds to the LG-series and gives the number of the first element in the special pcgs of the corresponding subgroup.
45.13.1 IsSpecialPcgs

▷ IsSpecialPcgs(obj) (property)

tests whether obj is a special pcgs.

45.13.2 SpecialPcgs

▷ SpecialPcgs(pcgs) (attribute)
▷ SpecialPcgs(G) (attribute)

computes a special pcgs for the group defined by pcgs or for G.

45.13.3 LGWeights

▷ LGWeights(pcgs) (attribute)

returns the LGWeights of the special pcgs pcgs.

45.13.4 LGLayers

▷ LGLayers(pcgs) (attribute)

returns the layers of the special pcgs pcgs.

45.13.5 LGFirst

▷ LGFirst(pcgs) (attribute)

returns the first indices for each layer of the special pcgs pcgs.

45.13.6 LGLength

▷ LGLength(G) (attribute)

returns the length of the LG-series of the group G, if G is solvable, and fail otherwise.

Example

```gap
gap> G := SmallGroup( 96, 220 );
gap> spec := SpecialPcgs( G );
<pcgs([ f1, f2, f3, f4, f5, f6 ])
gap> LGWeights(spec);
[ [ 1, 1, 2 ], [ 1, 1, 2 ], [ 1, 1, 2 ], [ 1, 1, 2 ], [ 1, 1, 3 ],
  [ 1, 2, 2 ] ]
gap> LGLayers(spec);
[ 1, 1, 1, 1, 2, 3 ]
gap> LGFirst(spec);
[ 1, 5, 6, 7 ]
gap> LGLength( G );
3
```
Thus the first group, SmallGroup(96, 220), has a lower nilpotent series of length 1; that is, the group is nilpotent. It is a direct product of its Sylow subgroups. Moreover the Sylow 2-subgroup is generated by the elements \( f_1, f_2, f_3, f_4, f_6 \), and the Sylow 3-subgroup is generated by \( f_5 \). The lower 2-central series of the Sylow 2-subgroup has length 2 and the second subgroup in this series is generated by \( f_6 \).

The second group, SmallGroup(96, 120), has a lower nilpotent series of length 2 and hence is not nilpotent. The second subgroup in this series is just the Sylow 3-subgroup and it is generated by \( f_6 \). The subgroup generated by \( f_1, \ldots, f_5 \) is a Sylow 2-subgroup of the group and also a head complement to the second head of the group. Its lower 2-central series has length 2.

In this example the FamilyPcgs (46.1.1) value of the groups used was a special pcgs, but this is not necessarily the case. For performance reasons it can be worth to enforce this, see IsomorphismSpecialPcGroup (46.5.3).

45.13.7 IsInducedPcgsWrtSpecialPcgs

\[ \text{IsInducedPcgsWrtSpecialPcgs}(pcgs) \]

tests whether \( pcgs \) is induced with respect to a special pcgs.

45.13.8 InducedPcgsWrtSpecialPcgs

\[ \text{InducedPcgsWrtSpecialPcgs}(G) \]

computes an induced pcgs with respect to the special pcgs of the parent of \( G \).

InducedPcgsWrtSpecialPcgs will return a pcgs induced by a special pcgs (which might differ from the one you had in mind). If you need an induced pcgs compatible with a given special pcgs use InducedPcgs (45.7.4) for this special pcgs.

45.14 Action on Subfactors Defined by a Pcgs

When working with a polycyclic group, one often needs to compute matrix operations of the group on a factor of the group. For this purpose there are the functions described in 45.14.1 to 45.14.3.

In certain situations, for example within the computation of conjugacy classes of finite soluble groups as described in [MN89], affine actions of groups are required. For this purpose we introduce the functions AffineAction (45.14.4) and AffineActionLayer (45.14.5).

45.14.1 VectorSpaceByPcgsOfElementaryAbelianGroup

\[ \text{VectorSpaceByPcgsOfElementaryAbelianGroup}(mpcgs, fld) \]

returns the vector space over \( fld \) corresponding to the modulo pcgs \( mpcgs \). Note that \( mpcgs \) has to define an elementary abelian \( p \)-group where \( p \) is the characteristic of \( fld \).
45.14.2 LinearAction

\[ \text{LinearAction}(\text{gens, basisvectors, linear}) \quad \text{(operation)} \]
\[ \text{LinearOperation}(\text{gens, basisvectors, linear}) \quad \text{(operation)} \]

returns a list of matrices, one for each element of \textit{gens}, which corresponds to the matrix action of the elements in \textit{gens} on the basis \textit{basisvectors} via \textit{linear}.

45.14.3 LinearActionLayer

\[ \text{LinearActionLayer}(G, \text{gens, pcgs}) \quad \text{(function)} \]
\[ \text{LinearOperationLayer}(G, \text{gens, pcgs}) \quad \text{(function)} \]

returns a list of matrices, one for each element of \textit{gens}, which corresponds to the matrix action of \textit{G} on the vector space corresponding to the modulo pcgs \textit{pcgs}.

45.14.4 AffineAction

\[ \text{AffineAction}(\text{gens, basisvectors, linear, transl}) \quad \text{(operation)} \]

return a list of matrices, one for each element of \textit{gens}, which corresponds to the affine action of the elements in \textit{gens} on the basis \textit{basisvectors} via \textit{linear} with translation \textit{transl}.

45.14.5 AffineActionLayer

\[ \text{AffineActionLayer}(G, \text{gens, pcgs, transl}) \quad \text{(function)} \]

returns a list of matrices, one for each element of \textit{gens}, which corresponds to the affine action of \textit{G} on the vector space corresponding to the modulo pcgs \textit{pcgs} with translation \textit{transl}.

Example

```gap
gap> G := SmallGroup( 96, 51 );
<pc group of size 96 with 6 generators>
gap> spec := SpecialPcgs( G );
Pcgs([ f1, f2, f3, f4, f5, f6 ])
gap> LGWeights( spec );
[ [ 1, 1, 2 ], [ 1, 1, 2 ], [ 1, 1, 3 ], [ 1, 2, 2 ], [ 1, 2, 2 ],
   [ 1, 3, 2 ] ]
gap> mpcgs := InducedPcgsByPcSequence( spec, spec{|4,5,6|} );
Pcgs([ f4, f5, f6 ])
gap> npcgs := InducedPcgsByPcSequence( spec, spec{|6|} );
Pcgs([ f6 ])
gap> modu := mpcgs mod npcgs;
[ f4, f5 ]
gap> mat := LinearActionLayer( G, spec{|1,2,3|}, modu );
[ an immutable 2x2 matrix over GF2>,
  <an immutable 2x2 matrix over GF2>
  <an immutable 2x2 matrix over GF2> ]
gap> Print( mat, '\n');
[ [ Z(2)^0, 0*Z(2) ], [ 0*Z(2), Z(2)^0 ] ]
```
45.15 Orbit Stabilizer Methods for Polycyclic Groups

If a pcgs `pcgs` is known for a group `G`, then orbits and stabilizers can be computed by a special method which is particularly efficient. Note that within this function only the elements in `pcgs` and the relative orders of `pcgs` are needed. Hence this function works effectively even if the elementary operations for `pcgs` are slow.

### 45.15.1 StabilizerPcgs

`StabilizerPcgs(pcgs, pnt[, acts][, act])` (function)

computes the stabilizer in the group generated by `pcgs` of the point `pnt`. If given, `acts` are elements by which `pcgs` acts, `act` is the acting function. This function returns a pcgs for the stabilizer which is induced by the `ParentPcgs` of `pcgs`, that is it is compatible with `pcgs`.

### 45.15.2 Pcgs_OrbitStabilizer

`Pcgs_OrbitStabilizer(pcgs, domain, pnt, oprs, opr)` (function)

runs a solvable group orbit-stabilizer algorithm on `pnt` with `pcgs` acting via the images `oprs` and the operation function `opr`. The domain `domain` can be used to speed up search, if it is not known, `false` can be given instead. The function returns a record with components `orbit`, `stabpcgs` and `lengths`, the latter indicating the lengths of the orbit whenever it got extended. This can be used to recompute transversal elements. This function should be used only inside algorithms when speed is essential.

45.16 Operations which have Special Methods for Groups with Pcgs

For the following operations there are special methods for groups with pcgs installed:

- `IsNilpotentGroup (39.15.3)`
- `IsSupersolvableGroup (39.15.8)`
- `Size (30.4.6)`
- `CompositionSeries (39.17.5)`
- `ConjugacyClasses (39.10.2)`
- `Centralizer (35.4.4)`
- `PrattiniSubgroup (39.12.6)`
- `PrefrattiniSubgroup (39.12.7)`
- `MaximalSubgroups (39.19.8)`
- `HallSystem (39.13.6)`
- `MinimalGeneratingSet (39.22.3)`
- `Centre (35.4.5)`
- `Intersection (30.5.2)`
- `AutomorphismGroup (40.7.1)`
- `IrreducibleModules (71.15.1)`

45.17 Conjugacy Classes in Solvable Groups

There are a variety of algorithms to compute conjugacy classes and centralizers in solvable groups via epimorphic images ([FN79], [MN89], [The93]). Usually these are only invoked as methods, but it is possible to access the algorithm directly.
45.17.1 ClassesSolvableGroup

\texttt{ClassesSolvableGroup}(\texttt{G, mode[, opt]}) \hspace{1cm} \text{(function)}

computes conjugacy classes and centralizers in solvable groups. \texttt{G} is the acting group. \texttt{mode} indicates the type of the calculation:

0 Conjugacy classes
4 Conjugacy test for the two elements in \texttt{opt.candidates}

In mode 0 the function returns a list of records containing components \texttt{representative} and \texttt{centralizer}. In mode 4 it returns a conjugating element.

The optional record \texttt{opt} may contain the following components that will affect the algorithm’s behaviour:

\texttt{pcgs}

is a pcgs that will be used for the calculation. The attribute \texttt{EANormalSeriesByPcgs (45.11.4)} must return an appropriate series of normal subgroups with elementary abelian factors among them. The algorithm will step down this series. In the case of the calculation of rational classes, it must be a pcgs refining a central series.

\texttt{candidates}

is a list of elements for which canonical representatives are to be computed or for which a conjugacy test is performed. Both elements must lie in \texttt{G}, but this is not tested. In mode 4 these elements must be given. In mode 0 a list of classes corresponding to \texttt{candidates} is returned (which may contain duplicates). The \texttt{representatives} chosen are canonical with respect to \texttt{pcgs}. The records returned also contain components \texttt{operator} such that \texttt{candidate} ^ \texttt{operator} = \texttt{representative}.

\texttt{consider}

is a function \texttt{consider( fhome, rep, cenp, K, L )}. Here \texttt{fhome} is a home pcgs for the factor group \texttt{F} in which the calculation currently takes place, \texttt{rep} is an element of the factor and \texttt{cenp} is a pcgs for the centralizer of \texttt{rep} modulo \texttt{K}. In mode 0, when lifting from \texttt{F/K} to \texttt{F/L} (note: for efficiency reasons, \texttt{F} can be different from \texttt{G} or \texttt{L} might be not trivial) this function is called before performing the actual lifting and only those representatives for which it returns \texttt{true} are passed to the next level. This permits for example the calculation of only those classes with small centralizers or classes of restricted orders.

45.17.2 CentralizerSizeLimitConsiderFunction

\texttt{CentralizerSizeLimitConsiderFunction(sz)} \hspace{1cm} \text{(function)}

returns a function (with arguments \texttt{fhome, rep, cen, K, L}) that can be used in \texttt{ClassesSolvableGroup (45.17.1)} as the \texttt{consider} component of the options record. It will restrict the lifting to those classes, for which the size of the centralizer (in the factor) is at most \texttt{sz}.

See also \texttt{SubgroupsSolvableGroup (39.21.3)}. 
Chapter 46

Pc Groups

Pc groups are polycyclic groups that use the polycyclic presentation for element arithmetic. This presentation gives them a “natural” pcgs, the FamilyPcgs (46.1.1) with respect to which pcgs operations as described in chapter 45 are particularly efficient.

Let $G$ be a polycyclic group with pcgs $P = \langle g_1, \ldots, g_n \rangle$ and corresponding relative orders $\langle r_1, \ldots, r_n \rangle$. Recall that the $r_i$ are positive integers or infinity and let $I$ be the set of indices $i$ with $r_i$ a positive integer. Then $G$ has a finite presentation on the generators $g_1, \ldots, g_n$ with relations of the following form.

$$g_i^{r_i} = g_{i+1}^{a(i,i+1)} \cdots g_n^{a(i,n)}$$

for $1 \leq i \leq n$ and $i \in I$

$$g_i^{-1} g_j g_i = g_{i+1}^{a(i,j+1)} \cdots g_n^{a(i,n)}$$

for $1 \leq i < j \leq n$

For infinite groups we need additionally

$$g_i^{-1} g_j^{-1} g_i = g_{i+1}^{b(i,j+1)} \cdots g_n^{b(i,n)}$$

for $1 \leq i < j \leq n$ and $j \notin I$

$$g_i g_j g_i^{-1} = g_{i+1}^{c(i,j+1)} \cdots g_n^{c(i,n)}$$

for $1 \leq i < j \leq n$ and $i \notin I$

$$g_i g_j^{-1} g_i^{-1} = g_{i+1}^{d(i,j+1)} \cdots g_n^{d(i,n)}$$

for $1 \leq i < j \leq n$ and $i, j \notin I$

Here the right hand sides are assumed to be words in normal form; that is, for $k \in I$ we have for all exponents $0 \leq a(i,j,k), b(i,j,k), c(i,j,k), d(i,j,k) < r_k$.

A finite presentation of this type is called a power-conjugate presentation and a pc group is a polycyclic group defined by a power-conjugate presentation. Instead of conjugates we could just as well work with commutators and then the presentation would be called a power-commutator presentation. Both types of presentation are abbreviated as pc presentation. Note that a pc presentation is a rewriting system.

Clearly, whenever a group $G$ with pcgs $P$ is given, then we can write down the corresponding pc presentation. On the other hand, one may just write down a presentation on $n$ abstract generators $g_1, \ldots, g_n$ with relations of the above form and define a group $H$ by this. Then the subgroups $C_i = \langle g_i, \ldots, g_n \rangle$ of $H$ form a subnormal series whose factors are cyclic or trivial. In the case that all factors are non-trivial, we say that the pc presentation of $H$ is confluent. Note that GAP 4 can only work correctly with pc groups defined by a confluent pc presentation.
At the current state of implementations the GAP library contains methods to compute with finite polycyclic groups, while the GAP package Polycyclic by Bettina Eick and Werner Nickel allows also computations with infinite polycyclic groups which are given by a pc-presentation.

Algorithms for pc groups use the methods for polycyclic groups described in chapter 45.

46.1 The Family Pcs

Clearly, the generators of a power-conjugate presentation of a pc group $G$ form a pcs of the pc group. This pcs is called the family pcs.

46.1.1 FamilyPcs

\[ \text{FamilyPcs}(\text{grp}) \] 

returns a “natural” pcs of a pc group $\text{grp}$ (with respect to which pcs operations as described in Chapter 45 are particularly efficient).

46.1.2 IsFamilyPcs

\[ \text{IsFamilyPcs}(\text{pcs}) \] 

specifies whether the pcs is a FamilyPcs (46.1.1) of a pc group.

46.1.3 InducedPcsWrtFamilyPcs

\[ \text{InducedPcsWrtFamilyPcs}(\text{grp}) \] 

returns the pcs which induced with respect to a family pcs (see IsParentPcsFamilyPcs (46.1.4) for further details).

46.1.4 IsParentPcsFamilyPcs

\[ \text{IsParentPcsFamilyPcs}(\text{pcs}) \] 

This property indicates that the pcs pcs is induced with respect to a family pcs.

This property is needed to distinguish between different independent polycyclic generating sequences which a pc group may have, since the elementary operations for a non-family pcs may not be as efficient as the elementary operations for the family pcs.

This can have a significant influence on the performance of algorithms for polycyclic groups. Many algorithms require a pcs that corresponds to an elementary abelian series (see PcgsElementaryAbelianSeries (45.11.2)) or even a special pcs (see 45.13). If the family pcs has the required properties, it will be used for these purposes, if not GAP has to work with respect to a new pcs which is not the family pcs and thus takes longer for elementary calculations like ExponentsOfPcElement (45.5.3).

Therefore, if the family pcs chosen for arithmetic is not of importance it might be worth to change to another, nicer, pcs to speed up calculations. This can be achieved, for example, by using the Range (32.3.7) value of the isomorphism obtained by IsomorphismSpecialPcGroup (46.5.3).
46.2 Elements of Pc Groups

46.2.1 Comparison of elements of pc groups

\[ \langle pcword1, pcword2 \rangle \] (method)

\[ \langle pcword1, pcword2 \rangle \] (method)

The elements of a pc group \( G \) are always represented as words in normal form with respect to the family pcgs of \( G \). Thus it is straightforward to compare elements of a pc group, since this boils down to a mere comparison of exponent vectors with respect to the family pcgs. In particular, the word problem is efficiently solvable in pc groups.

46.2.2 Arithmetic operations for elements of pc groups

\[ \langle pcword1, pcword2 \rangle \] (method)

Inverse(pcword) (attribute)

However, multiplication and inversion of elements in pc groups is not as straightforward as in arbitrary finitely presented groups where a simple concatenation or reversion of the corresponding words is sufficient (but one cannot solve the word problem).

To multiply two elements in a pc group, we first concatenate the corresponding words and then use an algorithm called collection to transform the new word into a word in normal form.

Example

```
gap> g := FamilyPcgs( SmallGroup( 24, 12 ) );
Pcgs([ f1, f2, f3, f4 ])
gap> g[4] * g[1];
f1*f3
gap> (g[2] * g[3])^-1;
f2^2*f3*f4
```

46.3 Pc Groups versus Fp Groups

In theory pc groups are finitely presented groups. In practice the arithmetic in pc groups is different from the arithmetic in fp groups. Thus for technical reasons the pc groups in GAP do not form a subcategory of the fp groups and hence the methods for fp groups cannot be applied to pc groups in general.

46.3.1 IsPcGroup

\[ \text{IsPcGroup}(G) \] (Category)

tests whether \( G \) is a pc group.

Example

```
gap> G := SmallGroup( 24, 12 );
<pc group of size 24 with 4 generators>
gap> IsPcGroup( G );
true
gap> IsFpGroup( G );
false
```
46.3.2 IsomorphismFpGroupByPcgs

It is possible to convert a pc group to a fp group in GAP. The function `IsomorphismFpGroupByPcgs` computes the power-commutator presentation defined by `pcgs`. The string `str` can be used to give a name to the generators of the fp group.

Example

```gap
gap> p := FamilyPcgs( SmallGroup( 24, 12 ) );
Pcgs([ f1, f2, f3, f4 ])
gap> iso := IsomorphismFpGroupByPcgs( p, "g" );
[ f1, f2, f3, f4 ] -> [ g1, g2, g3, g4 ]
gap> F := Image( iso );
<fp group of size 24 on the generators [ g1, g2, g3, g4 ]>
gap> RelatorsOfFpGroup( F );
[ g1^2, g2^-1*g1^-1*g2*g1*g2^-1, g3^-1*g1^-1*g3*g1*g4^-1*g3^-1,
g4^-1*g1^-1*g4*g1*g4^-1*g3^-1, g2^3, g3^-1*g2^-1*g3*g2*g4^-1*g3^-1,
g4^-1*g2^-1*g4*g2*g3^-1, g3^2, g4^-1*g3^-1*g4*g3, g4^2 ]
```

46.4 Constructing Pc Groups

If necessary, you can supply GAP with a pc presentation by hand. (Although this is the most tedious way to input a pc group.) Note that the pc presentation has to be confluent in order to work with the pc group in GAP.

(If you have already a suitable pcgs in another representation, use `PcGroupWithPcgs` (46.5.1), see below.)

One way is to define a finitely presented group with a pc presentation in GAP and then convert this presentation into a pc group, see `PcGroupFpGroup` (46.4.1). Note that this does not work for arbitrary presentations of polycyclic groups, see Chapter 47.14 for further information.

Another way is to create and manipulate a collector of a pc group by hand and to use it to define a pc group. GAP provides different collectors for different collecting strategies; at the moment, there are two collectors to choose from: the single collector for finite pc groups (see `SingleCollector` (46.4.2)) and the combinatorial collector for finite \( p \)-groups. See [Sim94] for further information on collecting strategies.

A collector is initialized with an underlying free group and the relative orders of the pc series. Then one adds the right hand sides of the power and the commutator or conjugate relations one by one. Note that omitted relators are assumed to be trivial.

For performance reasons it is beneficial to enforce a “syllable” representation in the free group (see 37.6).

Note that in the end, the collector has to be converted to a group, see `GroupByRws` (46.4.6).

With these methods a pc group with arbitrary defining pcgs can be constructed. However, for almost all applications within GAP we need to have a pc group whose defining pcgs is a prime order pcgs, see `IsomorphismRefinedPcGroup` (46.4.8) and `RefinedPcGroup` (46.4.9).

46.4.1 PcGroupFpGroup

```gap
\> PcGroupFpGroup( G )
```

(function)
creates a pc group \( P \) from an fp group (see Chapter 47) \( G \) whose presentation is polycyclic. The resulting group \( P \) has generators corresponding to the generators of \( G \). They are printed in the same way as generators of \( G \), but they lie in a different family. If the pc presentation of \( G \) is not confluent, an error message occurs.

```
Example
gap> F := FreeGroup(IsSyllableWordsFamily,"a","b","c","d");;
gap> a := F.1;; b := F.2;; c := F.3;; d := F.4;;
gap> rels := [a^2, b^3, c^2, d^2, Comm(b,a)/b, Comm(c,a)/d, Comm(d,a),
          Comm(c,b)/(c*d), Comm(d,b)/c, Comm(d,c)];
[ a^2, b^3, c^2, d^2, b^-1*a^-1*b*a*b^-1, c^-1*a^-1*c*a*d^-1,
  d^-1*a^-1*d*a, c^-1*b^-1*c*b*d^-1*c^-1, d^-1*b^-1*d*b*c^-1,
  d^-1*c^-1*d*c ]
gap> G := F / rels;
<fp group on the generators [ a, b, c, d ]>
 gap> H := PcGroupFpGroup( G );
<pc group of size 24 with 4 generators>
```

46.4.2 SingleCollector

▷ SingleCollector(fgrp, relorders) (operation)
▷ CombinatorialCollector(fgrp, relorders) (operation)

initializes a single collector or a combinatorial collector, where \( fgrp \) must be a free group and \( \text{relorders} \) must be a list of the relative orders of the pc series.

A combinatorial collector can only be set up for a finite \( p \)-group. Here, the relative orders \( \text{relorders} \) must all be equal and a prime.

46.4.3 SetConjugate

▷ SetConjugate(coll, j, i, w) (operation)

Let \( f_1, \ldots, f_n \) be the generators of the underlying free group of the collector \( \text{coll} \).

For \( i < j \), \text{SetConjugate} sets the conjugate \( f_j^i \) to equal \( w \), which is assumed to be a word in \( f_{i+1}, \ldots, f_n \).

46.4.4 SetCommutator

▷ SetCommutator(coll, j, i, w) (operation)

Let \( f_1, \ldots, f_n \) be the generators of the underlying free group of the collector \( \text{coll} \).

For \( i < j \), \text{SetCommutator} sets the commutator of \( f_j \) and \( f_i \) to equal \( w \), which is assumed to be a word in \( f_{i+1}, \ldots, f_n \).

46.4.5 SetPower

▷ SetPower(coll, i, w) (operation)
Let $f_1, \ldots, f_n$ be the generators of the underlying free group of the collector \texttt{coll1}, and let $r_i$ be the corresponding relative orders.

\texttt{SetPower} sets the power $f_i^{r_i}$ to equal $w$, which is assumed to be a word in $f_{i+1}, \ldots, f_n$.

### 46.4.6 GroupByRws

\begin{align*}
\texttt{GroupByRws}(\texttt{coll1}) \quad & \text{(operation)} \\
\texttt{GroupByRwsNC}(\texttt{coll1}) \quad & \text{(operation)}
\end{align*}

creates a group from a rewriting system. In the first version it is checked whether the rewriting system is confluent, in the second version this is assumed to be true.

### 46.4.7 IsConfluent (for pc groups)

\begin{align*}
\texttt{IsConfluent}(\text{G}) \quad & \text{(property)}
\end{align*}

checks whether the pc group $G$ has been built from a collector with a confluent power-commutator presentation.

```
\textbf{Example}
\begin{verbatim}
gap> F := FreeGroup(IsSyllableWordsFamily, 2 );;
gap> coll1 := SingleCollector( F, [2,3] );
<<single collector, 8 Bits>>
gap> SetConjugate( coll1, 2, 1, F.2 );
gap> SetPower( coll1, 1, F.2 );
gap> G1 := GroupByRws( coll1 );
<pc group of size 6 with 2 generators>
gap> IsConfluent(G1);  \text{true}
gap> IsAbelian(G1);
true
\end{verbatim}
```

### 46.4.8 IsomorphismRefinedPcGroup

\begin{align*}
\texttt{IsomorphismRefinedPcGroup}(\text{G}) \quad & \text{(attribute)}
\end{align*}

returns an isomorphism from $G$ onto an isomorphic pc group whose family $\text{pcgs}$ is a prime order.

### 46.4.9 RefinedPcGroup

\begin{align*}
\texttt{RefinedPcGroup}(\text{G}) \quad & \text{(attribute)}
\end{align*}

returns the range of the \texttt{IsomorphismRefinedPcGroup} (46.4.8) value of $G$. 
46.5 Computing Pc Groups

Another possibility to get a pc group in GAP is to convert a polycyclic group given by some other representation to a pc group. For finitely presented groups there are various quotient methods available. For all other types of groups one can use the following functions.

46.5.1 PcGroupWithPcgs

\[ \text{PcGroupWithPcgs}(\text{mpcgs}) \]
creates a new pc group \( G \) whose family pcgs is isomorphic to the (modulo) pcgs \( \text{mpcgs} \).

**Example**

```gap
gap> G := Group( (1,2,3), (3,4,1) );;
gap> PcGroupWithPcgs( Pcgs(G) );
<pc group of size 12 with 3 generators>
```

If a pcgs is only given by a list of pc elements, \text{PcgsByPcSequence} (45.3.1) can be used:

**Example**

```gap
gap> G := Group((1,2,3,4),(1,2));;
gap> p := PcgsByPcSequence(FamilyObj(One(G)),
> [ (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ]);
Pcgs([ (3,4), (2,4,3), (1,4)(2,3), (1,3)(2,4) ])
gap> PcGroupWithPcgs(p);
<pc group of size 24 with 4 generators>
```

46.5.2 IsomorphismPcGroup

\[ \text{IsomorphismPcGroup}(G) \]
returns an isomorphism from \( G \) onto an isomorphic pc group. The series chosen for this pc representation depends on the method chosen. \( G \) must be a polycyclic group of any kind, for example a solvable permutation group.

**Example**

```gap
gap> G := Group( (1,2,3), (3,4,1) );;
gap> iso := IsomorphismPcGroup( G );
Pcgs([ (2,4,3), (1,2)(3,4), (1,3)(2,4) ]) -> [ f1, f2, f3 ]
gap> H := Image( iso );
Group([ f1, f2, f3 ])
```
46.5.3 IsomorphismSpecialPcGroup

\verb|IsomorphismSpecialPcGroup(G)| (attribute)

returns an isomorphism from \( G \) onto an isomorphic pc group whose family pcgs is a special pcgs. (This can be beneficial to the runtime of calculations.) \( G \) may be a polycyclic group of any kind, for example a solvable permutation group.

46.6 Saving a Pc Group

As printing a polycyclic group does not display the presentation, one cannot simply print a pc group to a file to save it. For this purpose we need the following function.

46.6.1 GapInputPcGroup

\verb|GapInputPcGroup(grp, string)| (function)

Example

```gap
gap> G := SmallGroup( 24, 12 );
<pc group of size 24 with 4 generators>
gap> PrintTo( "save", GapInputPcGroup( G, "H" ) );
gap> Read( "save" );
#I A group of order 24 has been defined.
#I It is called H
gap> H = G;
false
gap> IdSmallGroup( H ) = IdSmallGroup( G );
true
gap> RemoveFile( "save" );;
```

46.7 Operations for Pc Groups

All the operations described in Chapters 39 and 45 apply to a pc group. Nearly all methods for pc groups are methods for groups with pcgs as described in Chapter 45. The only method with is special for pc groups is a method to compute intersections of subgroups, since here a pcgs of a parent group is needed and this can only by guaranteed within pc groups. Section 39.25 describes operations and methods for arbitrary finite groups.

46.8 2-Cohomology and Extensions

One of the most interesting applications of pc groups is the possibility to compute with extensions of these groups by elementary abelian groups; that is, \( H \) is an extension of \( G \) by \( M \), if there exists a normal subgroup \( N \) in \( H \) which is isomorphic to \( M \) such that \( H/N \) is isomorphic to \( G \).

PC groups are particularly suited for such applications, since the 2-cohomology can be computed efficiently for such groups and, moreover, extensions of pc groups by elementary abelian groups can be represented as pc groups again.
To define the elementary abelian group \( M \) together with an action of \( G \) on \( M \) we consider \( M \) as a MeatAxe module for \( G \) over a finite field (section \textit{IrreducibleModules} (71.15.1) describes functions that can be used to obtain certain modules). For further information on meataxe modules see Chapter 69. Note that the matrices defining the module must correspond to the pcgs of the group \( G \).

There exists an action of the subgroup of \textit{compatible pairs} in \( \text{Aut}(G) \times \text{Aut}(M) \) which acts on the second cohomology group, see \textit{CompatiblePairs} (46.8.8). 2-cocycles which lie in the same orbit under this action define isomorphic extensions of \( G \). However, there may be isomorphic extensions of \( G \) corresponding to cocycles in different orbits.

See also the \textbf{GAP} package \textbf{GrpConst} by Hans Ulrich Besche and Bettina Eick that contains methods to construct up to isomorphism the groups of a given order.

Finally we note that for the computation of split extensions it is not necessary that \( M \) must correspond to an elementary abelian group. Here it is possible to construct split extensions of arbitrary pc groups, see \textit{SplitExtension} (46.8.6).

### 46.8.1 TwoCoboundaries

\[
\triangleright \text{TwoCoboundaries}(G, M)
\]

returns the group of 2-coboundaries of a pc group \( G \) by the \( G \)-module \( M \). The generators of \( M \) must correspond to the \textit{Pcgs} (45.2.1) value of \( G \). The group of coboundaries is given as vector space over the field underlying \( M \).

### 46.8.2 TwoCocycles

\[
\triangleright \text{TwoCocycles}(G, M)
\]

returns the 2-cocycles of a pc group \( G \) by the \( G \)-module \( M \). The generators of \( M \) must correspond to the \textit{Pcgs} (45.2.1) value of \( G \). The operation returns a list of vectors over the field underlying \( M \) and the additive group generated by these vectors is the group of 2-cocycles.

### 46.8.3 TwoCohomology

\[
\triangleright \text{TwoCohomology}(G, M)
\]

This operation computes the second cohomology group for the special case of a Pc Group. It returns a record defining the second cohomology group as factor space of the space of cocycles by the space of coboundaries. \( G \) must be a pc group and the generators of \( M \) must correspond to the pcgs of \( G \).

\begin{verbatim}
    gap> G := SmallGroup( 4, 2 );   # Example
    <pc group of size 4 with 2 generators>
    gap> mats := List( Pcgs( G ), x -> IdentityMat( 1, GF(2) ) );
    [ [ <a GF2 vector of length 1> ], [ <a GF2 vector of length 1> ] ]
    gap> M := GModuleByMats( mats, GF(2) );
    rec( IsOverFiniteField := true, dimension := 1, field := GF(2),
        generators := [ <an immutable 1x1 matrix over GF2>,
                        <an immutable 1x1 matrix over GF2> ], isMTXModule := true )
    gap> TwoCoboundaries( G, M );
    [ ]
\end{verbatim}
46.8.4 Extensions

\begin{itemize}
\item \textbf{Extensions}(\textit{G}, \textit{M}) \quad \text{(operation)}
\end{itemize}

returns all extensions of \textit{G} by the \textit{G}-module \textit{M} up to equivalence as pc groups.

46.8.5 Extension

\begin{itemize}
\item \textbf{Extension}(\textit{G}, \textit{M}, \textit{c}) \quad \text{(operation)}
\item \textbf{ExtensionNC}(\textit{G}, \textit{M}, \textit{c}) \quad \text{(operation)}
\end{itemize}

returns the extension of \textit{G} by the \textit{G}-module \textit{M} via the cocycle \textit{c} as pc groups. The \textit{NC} version does not check the resulting group for consistence.

46.8.6 SplitExtension

\begin{itemize}
\item \textbf{SplitExtension}(\textit{G}, \textit{M}) \quad \text{(operation)}
\end{itemize}

returns the split extension of \textit{G} by the \textit{G}-module \textit{M}. See also SplitExtension (46.8.10) for its 3-argument version.

46.8.7 ModuleOfExtension

\begin{itemize}
\item \textbf{ModuleOfExtension}(\textit{E}) \quad \text{(attribute)}
\end{itemize}

returns the module of an extension \textit{E} of \textit{G} by \textit{M}. This is the normal subgroup of \textit{E} which corresponds to \textit{M}.

---

Example

\begin{verbatim}
gap> G := SmallGroup(4, 2);;
gap> mats := List(Pcgs(G), x -> IdentityMat(1, GF(2)));;
gap> M := GModuleByMats(mats, GF(2));;
gap> co := TwoCocycles(G, M);;
gap> cc := TwoCohomology(G, M);;
gap> cc.cohom;
<linear mapping by matrix, <vector space of dimension 3 over GF(2)> -> (GF(2)^3)>;
gap> Extension(G, M, co[2]);
<pc group of size 8 with 3 generators>
gap> SplitExtension(G, M);
<pc group of size 8 with 3 generators>
gap> Extensions(G, M);
[ <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators> ];
\end{verbatim}
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<pc group of size 8 with 3 generators>,
<pc group of size 8 with 3 generators>,
<pc group of size 8 with 3 generators>,
<pc group of size 8 with 3 generators> ]
gap> List(last, IdSmallGroup);
[ [ 8, 5 ], [ 8, 2 ], [ 8, 3 ], [ 8, 3 ], [ 8, 2 ], [ 8, 2 ],
  [ 8, 3 ], [ 8, 4 ] ]

Note that the extensions returned by Extensions (46.8.4) are computed up to equivalence, but not up to isomorphism.

46.8.8 CompatiblePairs

\[ \text{CompatiblePairs}(G, M[, D]) \]

returns the group of compatible pairs of the group \( G \) with the \( G \)-module \( M \) as subgroup of the direct product \( \text{Aut}(G) \times \text{Aut}(M) \). Here \( \text{Aut}(M) \) is considered as subgroup of a general linear group. The optional argument \( D \) should be a subgroup of \( \text{Aut}(G) \times \text{Aut}(M) \). If it is given, then only the compatible pairs in \( D \) are computed.

46.8.9 ExtensionRepresentatives

\[ \text{ExtensionRepresentatives}(G, M, P) \]

returns all extensions of \( G \) by the \( G \)-module \( M \) up to equivalence under action of \( P \) where \( P \) has to be a subgroup of the group of compatible pairs of \( G \) with \( M \).

\begin{verbatim}
gap> G := SmallGroup( 4, 2 );;
gap> mats := List( Pcgs( G ), x -> IdentityMat( 1, GF(2) ) );;
gap> M := GModuleByMats( mats, GF(2) );;
gap> A := AutomorphismGroup( G );;
gap> B := GL( 1, 2 );;
gap> D := DirectProduct( A, B );; Size(D); 6

gap> P := CompatiblePairs( G, M, D );
<group of size 6 with 2 generators>
gap> ExtensionRepresentatives( G, M, P );
[ <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators> ]
gap> Extensions( G, M );
[ <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators> ]
\end{verbatim}

Example
## 46.8.10 SplitExtension (with specified homomorphism)

\[ \text{SplitExtension}(G, \text{aut}, N) \]

returns the split extensions of the pc group \( G \) by the pc group \( N \). \text{aut} should be a homomorphism from \( G \) into \( \text{Aut}(N) \).

In the following example we construct the holomorph of \( Q_8 \) as split extension of \( Q_8 \) by \( S_4 \).

```gap
gap> N := SmallGroup( 8, 4 );
<pc group of size 8 with 3 generators>
gap> IsAbelian( N );
false
gap> A := AutomorphismGroup( N );
<group of size 24 with 4 generators>
gap> iso := IsomorphismPcGroup( A );
CompositionMapping( Pcgs([ (2,6,5,3), (1,3,5)(2,4,6), (2,5)(3,6), (1,4)(3,6) ] -> [ f1, f2, f3, f4 ], <action isomorphism> )
gap> H := Image( iso );
Group([ f1, f2, f3, f4 ])
gap> G := Subgroup( H, Pcgs(H){[1,2]} );
Group([ f1, f2 ])
gap> inv := InverseGeneralMapping( iso );
[ f1*f2, f2^-2*f3, f4, f3 ] ->
[ Pcgs([ f1, f2, f3 ]) -> [ f1*f2, f2, f3 ],
Pcgs([ f1, f2, f3 ]) -> [ f2, f1*f2, f3 ],
Pcgs([ f1, f2, f3 ]) -> [ f1*f3, f2, f3 ],
Pcgs([ f1, f2, f3 ]) -> [ f1, f2*f3, f3 ]]
gap> K := SplitExtension( G, inv, N );
<pc group of size 192 with 7 generators>
```

## 46.9 Coding a Pc Presentation

If one wants to store a large number of pc groups, then it can be useful to store them in a compressed format, since pc presentations can be space consuming. Here we introduce a method to code and decode pc presentations by integers. To decode a given code the size of the underlying pc group is needed as well. For the full definition and the coding and decoding procedures see [BE99]. This method is used with the small groups library (see (smallgrp: The Small Groups Library).

### 46.9.1 CodePcgs

\[ \text{CodePcgs}(pcgs) \]

returns the code corresponding to \( pcgs \).

```gap
gap> G := CyclicGroup(612);;
gap> p := Pcgs( G );;
gap> CodePcgs( p );
16289658718739690298008613020159
```
46.9.2 CodePcGroup

\[ \text{CodePcGroup}(G) \]  (function)

returns the code for a pcgs of \( G \).

Example

\[
\text{gap> G := DihedralGroup(512);;}
\text{gap> CodePcGroup( G );}
\text{2940208627577393070560341803949986912431725641726}
\]

46.9.3 PcGroupCode

\[ \text{PcGroupCode}(code, size) \]  (function)

returns a pc group of size \( size \) corresponding to \( code \). The argument \( code \) must be a valid code for a pcgs, otherwise anything may happen. Valid codes are usually obtained by one of the functions CodePcgs (46.9.1) or CodePcGroup (46.9.2).

Example

\[
\text{gap> G := SmallGroup( 24, 12 );;}
\text{gap> p := Pcgs( G );;}
\text{gap> code := CodePcgs( p );}
\text{5790338948}
\text{gap> H := PcGroupCode( code, 24 );}
\text{<pc group of size 24 with 4 generators>}
\text{gap> map := GroupHomomorphismByImages( G, H, p, FamilyPcgs(H));}
\text{Pcgs([ f1, f2, f3, f4 ])} -> \text{Pcgs([ f1, f2, f3, f4 ])}
\text{gap> IsBijective(map);}
\text{true}
\]

46.10 Random Isomorphism Testing

The generic isomorphism test for groups may be applied to pc groups as well. However, this test is often quite time consuming. Here we describe another method to test isomorphism by a probabilistic approach.

46.10.1 RandomIsomorphismTest

\[ \text{RandomIsomorphismTest}(coderecs, n) \]  (function)

The first argument is a list \( coderecs \) containing records describing groups, and the second argument is a non-negative integer \( n \).

The test returns a sublist of \( coderecs \) where isomorphic copies detected by the probabilistic test have been removed.

The list \( coderecs \) should contain records with two components, \text{code} and \text{order}, describing a group via \text{PcGroupCode( code, order )} (see \text{PcGroupCode (46.9.3)}).

The integer \( n \) gives a certain amount of control over the probability to detect all isomorphisms. If it is 0, then nothing will be done at all. The larger \( n \) is, the larger is the probability of finding all isomorphisms. However, due to the underlying method we can not guarantee that the algorithm finds all isomorphisms, no matter how large \( n \) is.
Chapter 47

Finitely Presented Groups

A finitely presented group (in short: FpGroup) is a group generated by a finite set of abstract generators subject to a finite set of relations that these generators satisfy. Every finite group can be represented as a finitely presented group, though in almost all cases it is computationally much more efficient to work in another representation (even the regular permutation representation).

Finitely presented groups are obtained by factoring a free group by a set of relators. Their elements know about this presentation and compare accordingly.

So to create a finitely presented group you first have to generate a free group (see FreeGroup (37.2.1) for details). There are two ways to specify a quotient of the free group: either by giving a list of relators or by giving a list of equations. Relators are just words in the generators of the free group. Equations are represented as pairs of words in the generators of the free group. In either case the generators of the quotient are the images of the free generators under the canonical homomorphism from the free group onto the quotient. So for example to create the group

\[ \langle a, b \mid a^2, b^3, (ab)^5 \rangle \]

you can use the following commands:

```gap
Example
\begin{verbatim}
gap> f := FreeGroup( "a", "b" );;
gap> g := f / [ f.1^2, f.2^3, (f.1*f.2)^5 ];
<fp group on the generators [ a, b ]>
gap> h := f / [ [f.1^2, f.1^0], [f.2^3, f.1^0], [(f.1*f.2)^4, f.2^-1*f.1^-1] ];
<fp group on the generators [ a, b ]>
\end{verbatim}

Note that you cannot call the generators by their names. These names are not variables, but just display figures. So, if you want to access the generators by their names, you first have to introduce the respective variables and to assign the generators to them.

```gap
Example
\begin{verbatim}
gap> Unbind(a);
gap> GeneratorsOfGroup( g );
[ a, b ]
gap> a;
Error, Variable: 'a' must have a value
gap> a := g.1;; b := g.2;; # assign variables
gap> GeneratorsOfGroup( g );
[ a, b ]
gap> a in f;
\end{verbatim}
```
To relieve you of the tedium of typing the above assignments, *when working interactively*, there is the function `AssignGeneratorVariables` (37.2.3).

Note that the generators of the free group are different from the generators of the FpGroup (even though they are displayed by the same names). That means that words in the generators of the free group are not elements of the finitely presented group. Vice versa elements of the FpGroup are not words.

```gap
gap> a*b = b*a;
fake
gap> (b^2*a*b)^2 = a^0;
true
```

Such calculations comparing elements of an FpGroup may run into problems: There exist finitely presented groups for which no algorithm exists (it is known that no such algorithm can exist) that will tell for two arbitrary words in the generators whether the corresponding elements in the FpGroup are equal.

Therefore the methods used by GAP to compute in finitely presented groups may run into warning errors, run out of memory or run forever. If the FpGroup is (by theory) known to be finite the algorithms are guaranteed to terminate (if there is sufficient memory available), but the time needed for the calculation cannot be bounded a priori. See 47.6 and 47.16.

```gap
gap> (b^2*a*b)^2;
(b^2*a*b)^2
gap> a^0;
<identity ...>
```

A consequence of our convention is that elements of finitely presented groups are not printed in a unique way. See also `SetReducedMultiplication` (47.3.4).

### 47.1 IsSubgroupFpGroup and IsFpGroup

#### 47.1.1 IsSubgroupFpGroup

```plaintext`
IsSubgroupFpGroup( H )
```

(Category)

returns `true` if `H` is a finitely presented group or a subgroup of a finitely presented group.

#### 47.1.2 IsFpGroup

```plaintext`
IsFpGroup( G )
```

(filter)

is a synonym for `IsSubgroupFpGroup(G)` and `IsGroupOfFamily(G)`.

Free groups are a special case of finitely presented groups, namely finitely presented groups with no relators.
Another special case are groups given by polycyclic presentations. GAP uses a special representation for these groups which is created in a different way. See chapter 46 for details.

Example

```gap
g:=FreeGroup(2);
<free group on the generators [ f1, f2 ]>
g:=IsFpGroup(g);
true
h:=CyclicGroup(2);
<pc group of size 2 with 1 generators>
g:=IsFpGroup(h);
false
```

47.1.3 InfoFpGroup

The info class for functions dealing with finitely presented groups is InfoFpGroup.

47.2 Creating Finitely Presented Groups

47.2.1 \( \langle \text{free group and a list of elements} \rangle \)

```gap
\( \langle F, \text{rels} \rangle \)
\( \langle F, \text{eqns} \rangle \)
```

creates a finitely presented group given by the presentation \( \langle \text{gens} | \text{rels} \rangle \) or \( \langle \text{gens} | \text{eqns} \rangle \), respectively where \text{gens} are the free generators of the free group \( F \). Relations can be entered either as words or as pairs of words in the generators of \( F \). In the former case we refer to the words given as relators, in the latter we refer to the pairs of words as equations. The two methods can currently not be mixed.

The same result is obtained with the infix operator \( / \), i.e., as \( F / \text{rels} \).

Example

```gap
f := FreeGroup(3);
f / [ [ f.1^4, f.2^3, f.3^5, f.1*f.2*f.3 ]];
<fp group on the generators [ f1, f2, f3 ]>
f / [ [ f.1^4, f.1^0 ], [ f.2^3, f.1^0 ], [ f.1, f.2^-1*f.3^-1 ] ];
<fp group on the generators [ f1, f2, f3 ]>
```

47.2.2 FactorGroupFpGroupByRel

```gap
FactorGroupFpGroupByRel(G, elts)
```

returns the factor group \( G/N \) of \( G \) by the normal closure \( N \) of \( elts \) where \( elts \) is expected to be a list of elements of \( G \).

47.2.3 ParseRelators

```gap
ParseRelators(gens, rels)
```
Will translate a list of relations as given in print, e.g. $xy^2 = (xy^3x)^2xy = yzx$ into relators. \texttt{gens} must be a list of generators of a free group, each being displayed by a single letter. \texttt{rels} is a string that lists a sequence of equalities. These must be written in the letters which are the names of the generators in \texttt{gens}. Change of upper/lower case is interpreted to indicate inverses.

\begin{verbatim}
gap> f:=FreeGroup("x","y","z");;
gap> AssignGeneratorVariables(f);
#I Assigned the global variables [ x, y, z ]
gap> r:=ParseRelators([x,y,z],
> "x^2 = y^5 = z^3 = (xyxyxyy^4)^2 = (xz)^2 = (y^2z)^2 = 1");
[ x^2, y^5, z^3, (x*z)^2, (y^2*z)^2, ((x*y)^3*y^3)^2 ]
gap> g:=f/r;
<fp group on the generators [ x, y, z ]>
\end{verbatim}

47.2.4 \texttt{StringFactorizationWord}

\begin{verbatim}
\texttt{StringFactorizationWord(w)}
\end{verbatim}

returns a string that expresses a given word \texttt{w} in compact form written as a string. Inverses are expressed by changing the upper/lower case of the generators, recurring expressions are written as products.

\begin{verbatim}
gap> StringFactorizationWord(z^-1*x*y*y*y*x*x*y*y*y*x*y^-1*x);
"Z(xy3x)2Yx"
\end{verbatim}

47.3 Comparison of Elements of Finitely Presented Groups

47.3.1 \texttt{=} (for two elements in a f.p. group)

\begin{verbatim}
\texttt{=}\texttt{(a, b)}
\end{verbatim}

Two elements of a finitely presented group are equal if they are equal in this group. Nevertheless they may be represented as different words in the generators. Because of the fundamental problems mentioned in the introduction to this chapter such a test may take very long and cannot be guaranteed to finish.

The method employed by \texttt{GAP} for such an equality test use the underlying finitely presented group. First (unless this group is known to be infinite) \texttt{GAP} tries to find a faithful permutation representation by a bounded Todd-Coxeter. If this fails, a Knuth-Bendix (see 52.5) is attempted and the words are compared via their normal form.

If only elements in a subgroup are to be tested for equality it thus can be useful to translate the problem in a new finitely presented group by rewriting (see \texttt{IsomorphismFpGroup} (47.11.1));

The equality test of elements underlies many “basic” calculations, such as the order of an element, and the same type of problems can arise there. In some cases, working with rewriting systems can still help to solve the problem. The \texttt{kbmag} package provides such functionality, see the package manual for further details.
47.3.2 \(<\) (for two elements in a f.p. group)

\[ \langle a, b \rangle \]

Compared with equality testing, problems get even worse when trying to compute a total ordering on the elements of a finitely presented group. As any ordering that is guaranteed to be reproducible in different runs of GAP or even with different groups given by syntactically equal presentations would be prohibitively expensive to implement, the ordering of elements is depending on a method chosen by GAP and not guaranteed to stay the same when repeating the construction of an FpGroup. The only guarantee given for the \(<\) ordering for such elements is that it will stay the same for one family during its lifetime. The attribute FpElmComparisonMethod (47.3.3) is used to obtain a comparison function for a family of FpGroup elements.

47.3.3 FpElmComparisonMethod

\[ \text{FpElmComparisonMethod}(\text{fam}) \]

If \textit{fam} is the elements family of a finitely presented group this attribute returns a function \texttt{smaller(left, right)} that will be used to compare elements in \textit{fam}.

47.3.4 SetReducedMultiplication

\[ \text{SetReducedMultiplication}(\text{obj}) \]

For an FpGroup \textit{obj}, an element \textit{obj} of it or the family \textit{obj} of its elements, this function will force immediate reduction when multiplying, keeping words short at extra cost per multiplication.

47.4 Preimages in the Free Group

47.4.1 FreeGroupOfFpGroup

\[ \text{FreeGroupOfFpGroup}(\mathcal{G}) \]

returns the underlying free group for the finitely presented group \mathcal{G}. This is the group generated by the free generators provided by the FreeGeneratorsOfFpGroup (47.4.2) value of \mathcal{G}.

47.4.2 FreeGeneratorsOfFpGroup

\[ \text{FreeGeneratorsOfFpGroup}(\mathcal{G}) \]

\[ \text{FreeGeneratorsOfWholeGroup}(\mathcal{U}) \]

FreeGeneratorsOfFpGroup returns the underlying free generators corresponding to the generators of the finitely presented group \mathcal{G} which must be a full FpGroup.

FreeGeneratorsOfWholeGroup also works for subgroups of an FpGroup and returns the free generators of the full group that defines the family.
47.4.3 RelatorsOfFpGroup

\[ \text{RelatorsOfFpGroup}(G) \]

returns the relators of the finitely presented group \( G \) as words in the free generators provided by the \text{FreeGeneratorsOfFpGroup} (47.4.2) value of \( G \).

Example

\[
\begin{verbatim}
gap> f := FreeGroup( "a", "b" );;
gap> g := f / [ f.1^5, f.2^2, f.1*f.2*f.1 ];
<fp group on the generators [ a, b ]>
gap> Size( g );
10
gap> FreeGroupOfFpGroup( g ) = f;
true
gap> FreeGeneratorsOfFpGroup( g );
[ a, b ]
gap> RelatorsOfFpGroup( g );
[ a^5, b^-2, b^-1*a*b*a ]
\end{verbatim}
\]

Note that these attributes are only available for the full finitely presented group. It is possible (for example by using \text{Subgroup} (39.3.1)) to construct a subgroup of index 1 which is not identical to the whole group. The latter one can be obtained in this situation via \text{Parent} (31.7.1).

Elements of a finitely presented group are not words, but are represented using a word from the free group as representative. The following two commands obtain this representative, respectively create an element in the finitely presented group.

47.4.4 UnderlyingElement (fp group elements)

\[ \text{UnderlyingElement}(elm) \]

Let \( elm \) be an element of a group whose elements are represented as words with further properties. Then \text{UnderlyingElement} returns the word from the free group that is used as a representative for \( elm \).

Example

\[
\begin{verbatim}
gap> w := g.1*g.2;
a*b
gap> IsWord( w );
false
gap> ue := UnderlyingElement( w );
a*b
gap> IsWord( ue );
true
\end{verbatim}
\]

47.4.5 ElementOfFpGroup

\[ \text{ElementOfFpGroup}(fam, \text{word}) \]

If \( fam \) is the elements family of a finitely presented group and \( \text{word} \) is a word in the free generators underlying this finitely presented group, this operation creates the element with the representative \( \text{word} \) in the free group.
Example

```gap
ge := ElementOfFpGroup( FamilyObj( g.1 ), f.1*f.2 );
a*b
ge in f;
false
ge in g;
true
```

### 47.5 Operations for Finitely Presented Groups

Finitely presented groups are groups and so all operations for groups should be applicable to them (though not necessarily efficient methods are available). Most methods for finitely presented groups rely on coset enumeration. See 47.6 for details.

The command `IsomorphismPermGroup` (43.3.1) can be used to obtain a faithful permutation representation, if such a representation of small degree exists. (Otherwise it might run very long or fail.)

```gap
f := FreeGroup( "a", "b" );
<free group on the generators [ a, b ]>
g := f / [ f.1^-2, f.2^-3, (f.1*f.2)^5 ];
<fp group on the generators [ a, b ]>
h := IsomorphismPermGroup( g );
[ a, b ] -> [ (1,2)(3,5), (2,3,4) ]
```

Example

```gap
u:=Subgroup(g,[g.1*g.2]);;
rt:=RightTransversal(g,u);
RightTransversal(<fp group of size 60 on the generators [ a, b ]>,Group([ a*b ]));
```

### 47.5.1 PseudoRandom (for finitely presented groups)

```gap
PseudoRandom(F: radius := 1)
```

The default algorithm for `PseudoRandom` (30.7.2) makes little sense for finitely presented or free groups, as it produces words that are extremely long.

By specifying the option `radius`, instead elements are taken as words in the generators of `F` in the ball of radius 1 with equal distribution in the free group.

```gap
PseudoRandom(g:radius:=20);
a^-3*b^-2*a^-2*b^-1*a*b^-4*a*b^-1*a*b^-4
```

### 47.6 Coset Tables and Coset Enumeration

Coset enumeration (see [Neu82] for an explanation) is one of the fundamental tools for the examination of finitely presented groups. This section describes GAP functions that can be used to invoke a coset enumeration.
Note that in addition to the built-in coset enumerator there is the GAP package ACE. Moreover, GAP provides an interactive Todd-Coxeter in the GAP package ITC which is based on the XGAP package.

47.6.1 CosetTable

\[\text{CosetTable}(G, H)\]

(operation)

returns the coset table of the finitely presented group \(G\) on the cosets of the subgroup \(H\).

Basically a coset table is the permutation representation of the finitely presented group on the cosets of a subgroup (which need not be faithful if the subgroup has a nontrivial core). Most of the set theoretic and group functions use the regular representation of \(G\), i.e., the coset table of \(G\) over the trivial subgroup.

The coset table is returned as a list of lists. For each generator of \(G\) and its inverse the table contains a generator list. A generator list is simply a list of integers. If \(l\) is the generator list for the generator \(g\) and if \(l[i] = j\) then generator \(g\) takes the coset \(i\) to the coset \(j\) by multiplication from the right. Thus the permutation representation of \(G\) on the cosets of \(H\) is obtained by applying \texttt{PermList} (42.5.2) to each generator list.

The coset table is standard (see below).

For finitely presented groups, a coset table is computed by a Todd-Coxeter coset enumeration. Note that you may influence the performance of that enumeration by changing the values of the global variables \texttt{CosetTableDefaultLimit} (47.6.7) and \texttt{CosetTableDefaultMaxLimit} (47.6.6) described below and that the options described under \texttt{CosetTableFromGensAndRel} (47.6.5) are recognized.

\texttt{Example}

\begin{verbatim}
gap> tab := CosetTable(g, Subgroup(g, [ g.1, g.2*g.1*g.2*g.1*g.2^-1 ]));
[ [ 1, 4, 5, 2, 3 ], [ 1, 4, 5, 2, 3 ], [ 2, 3, 1, 4, 5 ],
 [ 3, 1, 2, 4, 5 ] ]
gap> List( last, PermList );
[ (2,4)(3,5), (2,4)(3,5), (1,2,3), (1,3,2) ]
gap> PrintArray( TransposedMat( tab ) );
[ [ 1, 1, 2, 3 ],
 [ 4, 4, 3, 1 ],
 [ 5, 5, 1, 2 ],
 [ 2, 2, 4, 4 ],
 [ 3, 3, 5, 5 ] ]
\end{verbatim}

The last printout in the preceding example provides the coset table in the form in which it is usually used in hand calculations: The rows correspond to the cosets, the columns correspond to the generators and their inverses in the ordering \(g_1, g_1^{-1}, g_2, g_2^{-1}\). (See section 47.7 for a description on the way the numbers are assigned.)

47.6.2 TracedCosetFpGroup

\[\text{TracedCosetFpGroup}(\text{tab}, \text{word}, \text{pt})\]

(function)

Traces the coset number \(pt\) under the word \text{word} through the coset table \text{tab}. (Note: \text{word} must be in the free group, use \texttt{UnderlyingElement} (47.4.4) if in doubt.)
**47.6.3 FactorCosetAction (for fp groups)**

\[ \text{FactorCosetAction}(G, H) \]

returns the action of \( G \) on the cosets of its subgroup \( H \).  

\[
gap> \text{u := Subgroup}( g, [ g.1, g.1^g.2 ] ); \text{Group([ a, b^-1*a*b ])}; 
gap> \text{FactorCosetAction}( g, u ); 
\[
[ a, b ] \rightarrow [ (2,4)(5,6), (1,2,3)(4,5,6) ]
\]

**47.6.4 CosetTableBySubgroup**

\[ \text{CosetTableBySubgroup}(G, H) \]

returns a coset table for the action of \( G \) on the cosets of \( H \). The columns of the table correspond to the \text{GeneratorsOfGroup} (39.2.4) value of \( G \).

**47.6.5 CosetTableFromGensAndRelss**

\[ \text{CosetTableFromGensAndRelss}(fgens, grels, fsgens) \]

is an internal function which is called by the functions \text{CosetTable} (47.6.1), \text{CosetTableInWholeGroup} (47.8.1) and others. It is, in fact, the proper working horse that performs a Todd-Coxeter coset enumeration. \( fgens \) must be a set of free generators and \( grels \) a set of relators in these generators. \( fsgens \) are subgroup generators expressed as words in these generators. The function returns a coset table with respect to \( fgens \).

\text{CosetTableFromGensAndRelss} will call TCENUM.CosetTableFromGensAndRelss. This makes it possible to replace the built-in coset enumerator with another one by assigning TCENUM to another record.

The library version which is used by default performs a standard Felsch strategy coset enumeration. You can call this function explicitly as GAPTCEMUCosetTableFromGensAndRelss even if other coset enumerators are installed.

The expected parameters are

- \( fgens \)
  - generators of the free group \( F \)
- \( grels \)
  - relators as words in \( F \)
- \( fsgens \)
  - subgroup generators as words in \( F \).

\text{CosetTableFromGensAndRelss} processes two options (see chapter 8):
max  The limit of the number of cosets to be defined. If the enumeration does not finish with this number of cosets, an error is raised and the user is asked whether she wants to continue. The default value is the value given in the variable CosetTableDefaultMaxLimit. (Due to the algorithm the actual limit used can be a bit higher than the number given.)

silent
If set to true the algorithm will not raise the error mentioned under option max but silently return fail. This can be useful if an enumeration is only wanted unless it becomes too big.

47.6.6 CosetTableDefaultMaxLimit

CosetTableDefaultMaxLimit (global variable)

is the default limit for the number of cosets allowed in a coset enumeration.

A coset enumeration will not finish if the subgroup does not have finite index, and even if it has it may take many more intermediate cosets than the actual index of the subgroup is. To avoid a coset enumeration “running away” therefore GAP has a “safety stop” built in. This is controlled by the global variable CosetTableDefaultMaxLimit.

If this number of cosets is reached, GAP will issue an error message and prompt the user to either continue the calculation or to stop it. The default value is 4096000.

See also the description of the options to CosetTableFromGensAndRels (47.6.5).

Example

gap> f := FreeGroup( "a", "b" );;
gap> u := Subgroup( f, [ f.2 ] );
Group([ b ])
gap> Index( f, u );
Error, the coset enumeration has defined more than 4096000 cosets
called from
TCENUM.CosetTableFromGensAndRelss( fgens, grels, fsgens ) called from
CosetTableFromGensAndRelss( fgens, grels, fsgens ) called from
TryCosetTableInWholeGroup( H ) called from
CosetTableInWholeGroup( H ) called from
IndexInWholeGroup( H ) called from
... Entering break read-eval-print loop ...
type ’return;’ if you want to continue with a new limit of 8192000 cosets,
type ’quit;’ if you want to quit the coset enumeration,
type ’maxlimit := 0; return;’ in order to continue without a limit
brk> quit;

At this point, a break-loop (see Section 6.4) has been entered. The line beginning Error tells you why this occurred. The next seven lines occur if OnBreak (6.4.3) has its default value Where (6.4.5). They explain, in this case, how GAP came to be doing a coset enumeration. Then you are given a number of options of how to escape the break-loop: you can either continue the calculation with a larger number of permitted cosets, stop the calculation if you don’t expect the enumeration to finish (like in the example above), or continue without a limit on the number of cosets. (Choosing the first option will, of course, land you back in a break-loop. Try it!)

Setting CosetTableDefaultMaxLimit (or the max option value, for any function that invokes a coset enumeration) to infinity (18.2.1) (or to 0) will force all coset enumerations to continue until
they either get a result or exhaust the whole available space. For example, each of the following two inputs

```gap
gap> CosetTableDefaultMaxLimit := 0;;
gap> Index( f, u );
```

or

```gap
gap> Index( f, u : max := 0 );
```

have essentially the same effect as choosing the third option (typing: `maxlimit := 0; return;`) at the `brk>` prompt above (instead of `quit;`).

### 47.6.7 CosetTableDefaultLimit

**▷ CosetTableDefaultLimit**

is the default number of cosets with which any coset table is initialized before doing a coset enumeration.

The function performing this coset enumeration will automatically extend the table whenever necessary (as long as the number of cosets does not exceed the value of `CosetTableDefaultMaxLimit` (47.6.6)), but this is an expensive operation. Thus, if you change the value of `CosetTableDefaultLimit`, you should set it to a number of cosets that you expect to be sufficient for your subsequent coset enumerations. On the other hand, if you make it too large, your job will unnecessarily waste a lot of space.

The default value of `CosetTableDefaultLimit` is 1000.

### 47.6.8 MostFrequentGeneratorFpGroup

**▷ MostFrequentGeneratorFpGroup**

is an internal function which is used in some applications of coset table methods. It returns the first of those generators of the given finitely presented group \( G \) which occur most frequently in the relators.

### 47.6.9 IndicesInvolutaryGenerators

**▷ IndicesInvolutaryGenerators**

returns the indices of those generators of the finitely presented group \( G \) which are known to be involutions. This knowledge is used by internal functions to improve the performance of coset enumerations.

### 47.7 Standardization of coset tables

For any two coset numbers \( i \) and \( j \) with \( i < j \) the first occurrence of \( i \) in a coset table precedes the first occurrence of \( j \) with respect to the usual row-wise ordering of the table entries. Following the notation
of Charles Sims’ book on computation with finitely presented groups [Sim94] we call such a table a **standard coset table**.

The table entries which contain the first occurrences of the coset numbers \( i > 1 \) recursively provide for each \( i \) a representative of the corresponding coset in form of a unique word \( w_i \) in the generators and inverse generators of \( G \). The first coset (which is \( H \) itself) can be represented by the empty word \( w_1 \). A coset table is standard if and only if the words \( w_1, w_2, \ldots \) are length-plus-lexicographic ordered (as defined in [Sim94]), for short: **lenlex**.

This standardization of coset tables is different from that used in GAP versions 4.2 and earlier. Before that, we ignored the columns that correspond to inverse generators and hence only considered words in the generators of \( G \). We call this older ordering the **semilenlex** standard as it also applies to the case of semigroups where no inverses of the generators are known.

We changed our default from the semilenlex standard to the lenlex standard to be consistent with [Sim94]. However, the semilenlex standardisation remains available and the convention used for all implicit standardisations can be selected by setting the value of the global variable `CosetTableStandard` (47.7.1) to either "lenlex" or "semilenlex". Independent of the current value of `CosetTableStandard` (47.7.1) you can standardize (or restandardize) a coset table at any time using `StandardizeTable` (47.7.2).

### 47.7.1 `CosetTableStandard`

**`CosetTableStandard`**

(specification)

specifies the definition of a **standard coset table**. It is used whenever coset tables or augmented coset tables are created. Its value may be "lenlex" or "semilenlex". If it is "lenlex" coset tables will be standardized using all their columns as defined in Charles Sims’ book (this is the new default standard of GAP). If it is "semilenlex" they will be standardized using only their generator columns (this was the original GAP standard). The default value of `CosetTableStandard` is "lenlex".

### 47.7.2 `StandardizeTable`

**`StandardizeTable(table, standard)`**

standardizes the given coset table `table`. The second argument is optional. It defines the standard to be used, its values may be "lenlex" or "semilenlex" specifying the new or the old convention, respectively. If no value for the parameter `standard` is provided the function will use the global variable `CosetTableStandard` (47.7.1) instead. Note that the function alters the given table, it does not create a copy.

```gap
gap> StandardizeTable( tab, "semilenlex" );
gap> PrintArray( TransposedMat( tab ) );
```

```
[ [ 1, 1, 2, 4 ],
 [ 3, 3, 4, 1 ],
 [ 2, 2, 3, 3 ],
 [ 5, 5, 1, 2 ],
 [ 4, 4, 5, 5 ] ]
```
47.8 Coset tables for subgroups in the whole group

47.8.1 CosetTableInWholeGroup

\[ \text{CosetTableInWholeGroup}(H) \] (attribute)

\[ \text{TryCosetTableInWholeGroup}(H) \] (operation)

is equivalent to \( \text{CosetTable}(G,H) \) where \( G \) is the (unique) finitely presented group such that \( H \) is a subgroup of \( G \). It overrides a silent option (see \( \text{CosetTableFromGensAndRels} \) (47.6.5)) with false.

The variant \( \text{TryCosetTableInWholeGroup} \) does not override the silent option with false in case a coset table is only wanted if not too expensive. It will store a result that is not fail in the attribute \( \text{CosetTableInWholeGroup} \).

47.8.2 SubgroupOfWholeGroupByCosetTable

\[ \text{SubgroupOfWholeGroupByCosetTable}(\text{fpfam}, \text{tab}) \] (function)

takes a family \( \text{fpfam} \) of an FpGroup and a standardized coset table \( \text{tab} \) and returns the subgroup of \( \text{fpfam}!.\text{wholeGroup} \) defined by this coset table. The function will not check whether the coset table is standardized. See also \( \text{CosetTableBySubgroup} \) (47.6.4).

47.9 Augmented Coset Tables and Rewriting

47.9.1 AugmentedCosetTableInWholeGroup

\[ \text{AugmentedCosetTableInWholeGroup}(H[, \text{gens}]) \] (function)

For a subgroup \( H \) of a finitely presented group, this function returns an augmented coset table. If a generator set \( \text{gens} \) is given, it is guaranteed that \( \text{gens} \) will be a subset of the primary and secondary subgroup generators of this coset table.

It is mutable so we are permitted to add further entries. However existing entries may not be changed. Any entries added however should correspond to the subgroup only and not to a homomorphism.

47.9.2 AugmentedCosetTableMtc

\[ \text{AugmentedCosetTableMtc}(G, H, \text{type}, \text{string}) \] (function)

is an internal function used by the subgroup presentation functions described in 48.2. It applies a Modified Todd-Coxeter coset representative enumeration to construct an augmented coset table (see 48.2) for the given subgroup \( H \) of \( G \). The subgroup generators will be named \( \text{string}\_1, \text{string}\_2, \ldots \).

The function accepts the options \( \text{max} \) and \( \text{silent} \) as described for the function \( \text{CosetTableFromGensAndRels} \) (47.6.5).
47.9.3 AugmentedCosetTableRrs

AugmentedCosetTableRrs(G, table, type, string)

is an internal function used by the subgroup presentation functions described in 48.2. It applies
the Reduced Reidemeister-Schreier method to construct an augmented coset table for the subgroup
of G which is defined by the given coset table table. The new subgroup generators will be named
string1, string2, ... .

47.9.4 RewriteWord

RewriteWord(aug, word)

RewriteWord rewrites word (which must be a word in the underlying free group with respect to
which the augmented coset table aug is given) in the subgroup generators given by the augmented
coset table aug. It returns a Tietze-type word (i.e. a list of integers), referring to the primary and
secondary generators of aug.

If word is not contained in the subgroup, fail is returned.

47.10 Low Index Subgroups

47.10.1 LowIndexSubgroupsFpGroupIterator

LowIndexSubgroupsFpGroupIterator(G[, H], index[, excluded])

These functions compute representatives of the conjugacy classes of subgroups of the finitely
presented group G that contain the subgroup H of G and that have index less than or equal to index.

LowIndexSubgroupsFpGroupIterator returns an iterator (see 30.8) that can be used to run
over these subgroups, and LowIndexSubgroupsFpGroup returns the list of these subgroups. If one is
interested only in one or a few subgroups up to a given index then preferably the iterator should be
used.

If the optional argument excluded has been specified, then it is expected to be a list of words in
the free generators of the underlying free group of G, and LowIndexSubgroupsFpGroup returns only
those subgroups of index at most index that contain H, but do not contain any conjugate of any of the
group elements defined by these words.

If not given, H defaults to the trivial subgroup.

The algorithm used finds the requested subgroups by systematically running through a tree of all
potential coset tables of G of length at most index (where it skips all branches of that tree for which
it knows in advance that they cannot provide new classes of such subgroups). The time required to
do this depends, of course, on the presentation of G, but in general it will grow exponentially with the
value of index. So you should be careful with the choice of index.

Example

```gap
gap> li:=LowIndexSubgroupsFpGroup( g, TrivialSubgroup( g ), 10 );
[ Group(<fp, no generators known>), Group(<fp, no generators known>),
  Group(<fp, no generators known>), Group(<fp, no generators known>) ]
```
By default, the algorithm computes no generating sets for the subgroups. This can be enforced with \texttt{GeneratorsOfGroup} (39.2.4):

```
gap> GeneratorsOfGroup(li[2]);
[ a, b*a*b^-1 ]
```

If we are interested just in one (proper) subgroup of index at most 10, we can use the function that returns an iterator. The first subgroup found is the group itself, except if a list of excluded elements is entered (see below), so we look at the second subgroup.

```
gap> iter:= LowIndexSubgroupsFpGroupIterator( g, 10 );;
gap> s1:= NextIterator( iter );; Index( g, s1 );
1

gap> IsDoneIterator( iter );
false

gap> s2:= NextIterator( iter );; s2 = li[2];
true
```

As an example for an application of the optional parameter \texttt{excluded}, we compute all conjugacy classes of torsion free subgroups of index at most 24 in the group $G = \langle x, y, z \mid x^2, y^4, z^3, (xy)^3, (yz)^2, (xz)^3 \rangle$. It is know from theory that each torsion element of this group is conjugate to a power of $x, y, z, xy, xz, or yz$. (Note that this includes conjugates of $y^2$.)

```
gap> F := FreeGroup( "x", "y", "z" );;
gap> x := F.1;; y := F.2;; z := F.3;;
gap> G := F / [ x^2, y^4, z^3, (x*y)^3, (y*z)^2, (x*z)^3 ];;
gap> torsion := [ x, y, y^2, z, x*y, x*z, y*z ];;
gap> lis := LowIndexSubgroupsFpGroup(G, TrivialSubgroup(G), 24, torsion);
#I LowIndexSubgroupsFpGroup called
#I class 1 of index 24 and length 8
#I class 2 of index 24 and length 24
#I class 3 of index 24 and length 24
#I class 4 of index 24 and length 24
#I class 5 of index 24 and length 24
#I LowIndexSubgroupsFpGroup done. Found 5 classes

gap> SetInfoLevel( InfoFpGroup, 0 );
```

If a particular image group is desired, the operation \texttt{GQuotients} (40.9.4) (see 47.14) can be useful as well.

### 47.11 Converting Groups to Finitely Presented Groups

#### 47.11.1 IsomorphismFpGroup

\texttt{IsomorphismFpGroup} ($G$) (attribute)

returns an isomorphism from the given finite group $G$ to a finitely presented group isomorphic to $G$. The function first \textit{chooses a set of generators of $G$} and then computes a presentation in terms of these generators.
Example

```gap
gap> g := Group( (2,3,4,5), (1,2,5) );
[ (1,2,5), (2,3,4,5) ]
go := IsomorphismFpGroup( g );
[ F1, F2 ]
gap> fp := Image( go );
<fp group of size 120 on the generators [ F1, F2 ]>
gap> RelatorsOfFpGroup( fp );
[ F1^2, F2^2, (F1*F2)^3, (F1*F3)^2, (F1*F4)^2, (F2*F3)^2, (F2*F4)^3 ]
```

### Example

```gap
gap> SetInfoLevel( InfoFpGroup, 1 );
go := IsomorphismFpGroupByGenerators( g, [ (1,2), (1,2,3,4,5) ] );
#I the image group has 2 gens and 5 rels of total length 39
[ (1,2,3,4,5) ] -> [ F1, F2 ]
gap> fp := Image( go );
<fp group of size 120 on the generators [ F1, F2 ]>
gap> RelatorsOfFpGroup( fp );
[ F1^2, F2^5, (F2^-1*F1)^4, (F1*F2*F1*F2)^3, (F2*F1*F2^-2*F1*F2)^2 ]
```

### 47.11.2 IsomorphismFpGroupByGenerators

- `IsomorphismFpGroupByGenerators(G, gens[, string])` (function)
- `IsomorphismFpGroupByGeneratorsNC(G, gens, string)` (operation)

returns an isomorphism from a finite group $G$ to a finitely presented group $F$ isomorphic to $G$. The generators of $F$ correspond to the generators of $G$ given in the list $gens$. If $string$ is given it is used to name the generators of the finitely presented group.

The NC version will avoid testing whether the elements in $gens$ generate $G$.

The main task of the function `IsomorphismFpGroupByGenerators` is to find a presentation of $G$ in the provided generators $gens$. In the case of a permutation group $G$ it does this by first constructing a stabilizer chain of $G$ and then it works through that chain from the bottom to the top, recursively computing a presentation for each of the involved stabilizers. The method used is essentially an implementation of John Cannon's multi-stage relations-finding algorithm as described in [Neu82] (see also [Can73] for a more graph theoretical description). Moreover, it makes heavy use of Tietze transformations in each stage to avoid an explosion of the total length of the relators.

Note that because of the random methods involved in the construction of the stabilizer chain the resulting presentations of $G$ will in general be different for repeated calls with the same arguments.
Also in the case of a permutation group \( G \), the function \texttt{IsomorphismFpGroupByGenerators} supports the option \texttt{method} that can be used to modify the strategy. The option \texttt{method} may take the following values.

\texttt{method := \"regular\"}

This may be specified for groups of small size, up to \( 10^5 \) say. It implies that the function first constructs a regular representation \( R \) of \( G \) and then a presentation of \( R \). In general, this presentation will be much more concise than the default one, but the price is the time needed for the construction of \( R \).

\texttt{method := \[ \texttt{\"regular\"}, \texttt{bound} \]}

This is a refinement of the previous possibility. In this case, \texttt{bound} should be an integer, and if so the method \texttt{\"regular\"} as described above is applied to the largest stabilizer in the stabilizer chain of \( G \) whose size does not exceed the given bound and then the multi-stage algorithm is used to work through the chain from that subgroup to the top.

\texttt{method := \"fast\"}

This chooses an alternative method which essentially is a kind of multi-stage algorithm for a stabilizer chain of \( G \) but does not make any attempt to reduce the number of relators as it is done in Cannon’s algorithm or to reduce their total length. Hence it is often much faster than the default method, but the total length of the resulting presentation may be huge.

\texttt{method := \"default\"}

This simply means that the default method shall be used, which is the case if the option \texttt{method} is not given a value.

\begin{verbatim}
Example
gap> iso := IsomorphismFpGroupByGenerators( M12, gens : >     method := \"regular\" );;
#I the image group has 3 gens and 11 rels of total length 92
gap> iso := IsomorphismFpGroupByGenerators( M12, gens :
>     method := \"fast\" );;
#I the image group has 3 gens and 135 rels of total length 2938
\end{verbatim}

Though the option \texttt{method := \"regular\"} is only checked in the case of a permutation group it also affects the performance and the results of the function \texttt{IsomorphismFpGroupByGenerators} for other groups, e.g. for matrix groups. This happens because, for these groups, the function first calls the function \texttt{NiceMonomorphism (40.5.2)} to get a bijective action homomorphism from \( G \) to a suitable permutation group, \( P \) say, and then, recursively, calls itself for the group \( P \) so that now the option becomes relevant.

\begin{verbatim}
Example
gap> G := ImfMatrixGroup( 5, 1, 3 );
ImfMatrixGroup(5,1,3)
gap> gens := GeneratorsOfGroup( G );
[ [ [ -1, 0, 0, 0, 0 ], [ 0, 1, 0, 0, 0 ], [ 0, 0, 1, 0, 0 ],
  [ -1, -1, -1, -1, 2 ], [ -1, 0, 0, 0, 1 ] ],
  [ 0, 1, 0, 0, 0 ], [ 0, 0, 1, 0, 0 ], [ 0, 0, 1, 0, 0 ],
  [ 1, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 1 ] ] ]
gap> iso := IsomorphismFpGroupByGenerators( G, gens );;
#I the image group has 2 gens and 10 rels of total length 118
\end{verbatim}

gap> iso := IsomorphismFpGroupByGenerators( G, gens : > method := "regular");;
#I the image group has 2 gens and 6 rels of total length 56
gap> SetInfoLevel( InfoFpGroup, 0 );

gap> iso;
<composed isomorphism:
[ [ -1, 0, 0, 0, 0 ], [ 0, 1, 0, 0, 0 ], [ 0, 0, 1, 0, 0 ], [ -1, -1, -1, -1, 2 ],
  [ -1, 0, 0, 1, 0 ], [ 0, 1, 0, 0, 1 ] ],
[ 0, 0, 0, 1, 0 ] ] -> [ F1, F2 ]>

gap> ConstituentsCompositionMapping(iso);
[ <action isomorphism>,
[ (2,3,4)(5,6)(8,9,10), (1,2,3,5)(6,7,8,9) ] -> [ F1, F2 ] ]

Since GAP cannot decompose elements of a matrix group into generators, the resulting isomorphism is stored as a composition of a (faithful) permutation action on vectors and a homomorphism from the permutation image to the finitely presented group. In such a situation the constituent mappings can be obtained via ConstituentsCompositionMapping (32.2.8) as separate GAP objects.

47.12 New Presentations and Presentations for Subgroups

IsomorphismFpGroup (47.11.1) is also used to compute a new finitely presented group that is isomorphic to the given subgroup of a finitely presented group. (This is typically the only method to compute with subgroups of a finitely presented group.)

Example

```gap
gap> f:=FreeGroup(2);;
gap> g:=f/[f.1^2,f.2^3,(f.1*f.2)^5];
<fp group on the generators [ f1, f2 ]>
gap> u:=Subgroup(g,[g.1*g.2]);
Group([ f1*f2 ])
gap> hom:=IsomorphismFpGroup(u);
gap> new:=Range(hom);
<fp group on the generators [ F1 ]>
gap> List(GeneratorsOfGroup(new),i->PreImagesRepresentative(hom,i));
[ [ [ 1, 1 ] ] | f2^-1*f1^-1 ] ]
```

When working with such homomorphisms, some subgroup elements are expressed as extremely long words in the group generators. Therefore the underlying words of subgroup generators stored in the isomorphism (as obtained by MappingGeneratorsImages (40.10.2) and displayed when View (6.3.3)ing the homomorphism) as well as preimages under the homomorphism are stored in the form of straight line program elements (see 37.9). These will behave like ordinary words and no extra treatment should be necessary.

Example

```gap
gap> r:=Range(hom).1^10;
F1^10
gap> p:=PreImagesRepresentative(hom,r);
[ [ 1, 10 ] ] | (f2^-1*f1^-1)^10
```
If desired, it also is possible to convert these underlying words using `EvalStraightLineProgElm` (37.9.4):

```gap
Example

gap> r:=EvalStraightLineProgElm(UnderlyingElement(p));
(f2^-1*f1^-1)^10
gap> p:=ElementOfFpGroup(FamilyObj(p),r);
(f2^-1*f1^-1)^10
```

(If you are only interested in a finitely presented group isomorphic to the given subgroup but not in the isomorphism, you may also use the functions `PresentationViaCosetTable` (48.1.5) and `FpGroupPresentation` (48.1.4) (see 48.1.).

Homomorphisms can also be used to obtain an isomorphic finitely presented group with a (hopefully) simpler presentation.

### 47.12.1 IsomorphismSimplifiedFpGroup

**applies Tietze transformations to a copy of the presentation of the given finitely presented group \( G \) in order to reduce it with respect to the number of generators, the number of relators, and the relator lengths.**

The operation returns an isomorphism with source \( G \), range a group \( H \) isomorphic to \( G \), so that the presentation of \( H \) has been simplified using Tietze transformations.

```gap
Example

gap> f:=FreeGroup(3);;
gap> g:=f/[f.1^2,f.2^3,(f.1*f.2)^5,f.1/f.3];
<fp group on the generators [ f1, f2, f3 ]>
gap> hom:=IsomorphismSimplifiedFpGroup(g);
[ f1, f2, f3 ] -> [ f1, f2, f1 ]
gap> Range(hom);
<fp group on the generators [ f1, f2 ]>
gap> RelatorsOfFpGroup(Range(hom));
[ f1^-2, f2^-3, (f1*f2)^5 ]
```

`IsomorphismSimplifiedFpGroup` uses Tietze transformations to simplify the presentation, see 48.1.6.

### 47.13 Preimages under Homomorphisms from an FpGroup

For some subgroups of a finitely presented group the number of subgroup generators increases with the index of the subgroup. However often these generators are not needed at all for further calculations, but what is needed is the action of the cosets of the subgroup. This gives the image of the subgroup in a finite quotient and this finite quotient can be used to calculate normalizers, closures, intersections and so forth [Hul01].

The same applies for subgroups that are obtained as preimages under homomorphisms.
47.13.1 SubgroupOfWholeGroupByQuotientSubgroup

\texttt{SubgroupOfWholeGroupByQuotientSubgroup(fpfam, Q, U)}

(takes a FpGroup family \textit{fpfam}, a finitely generated group \textit{Q} such that the fp generators of \textit{fpfam} can be mapped by an epimorphism \textit{phi} onto the \texttt{GeneratorsOfGroup} (39.2.4) value of \textit{Q}, and a subgroup \textit{U} of \textit{Q}. It returns the subgroup of \textit{fpfam!wholeGroup} which is the full preimage of \textit{U} under \textit{phi}.

47.13.2 IsSubgroupOfWholeGroupByQuotientRep

\texttt{IsSubgroupOfWholeGroupByQuotientRep(G)}

(is the representation for subgroups of an FpGroup, given by a quotient subgroup. The components \textit{G!.quot} and \textit{G!.sub} hold quotient, respectively subgroup.

47.13.3 AsSubgroupOfWholeGroupByQuotient

\texttt{AsSubgroupOfWholeGroupByQuotient(U)}

returns the same subgroup in the representation \texttt{AsSubgroupOfWholeGroupByQuotient}. See also \texttt{SubgroupOfWholeGroupByCosetTable} (47.8.2) and \texttt{CosetTableBySubgroup} (47.6.4).

This technique is used by \texttt{GAP} for example to represent the derived subgroup, which is obtained from the quotient \textit{G/G'}.

\begin{example}
\begin{verbatim}
gap> f:=FreeGroup(2);;g:=f/[f.1^6,f.2^6,(f.1*f.2)^6];;
gap> d:=DerivedSubgroup(g);
group(<fp, no generators known>)
gap> Index(g,d);
36
\end{verbatim}
\end{example}

47.13.4 DefiningQuotientHomomorphism

\texttt{DefiningQuotientHomomorphism(U)}

if \textit{U} is a subgroup in quotient representation (\textit{IsSubgroupOfWholeGroupByQuotientRep} (47.13.2)), this function returns the defining homomorphism from the whole group to \textit{U!.quot}.

47.14 Quotient Methods

An important class of algorithms for finitely presented groups are the \textit{quotient algorithms} which compute quotient groups of a given finitely presented group. There are algorithms for epimorphisms onto abelian groups, \textit{p}-groups and solvable groups. (The “low index” algorithm \texttt{LowIndexSubgroupsFpGroup} (47.10.1)– can be considered as well as an algorithm that produces permutation group quotients.)

\texttt{MaximalAbelianQuotient} (39.18.4), as defined for general groups, returns the largest abelian quotient of the given group.
Example

```gap
gap> f:=FreeGroup(2);;
<fp group on the generators [ f1, f2 ]>
gap> hom:=MaximalAbelianQuotient(fp);
[ f1, f2 ] -> [ f1, f3 ]
gap> Size(Image(hom));
36
```

### 47.14.1 PQuotient

\[ \text{PQuotient}(F, p[, c[, logord[, ctype]]]) \]

computes a factor \( p \)-group of a finitely presented group \( F \) in form of a quotient system. The quotient system can be converted into an epimorphism from \( F \) onto the \( p \)-group computed by the function \text{EpimorphismQuotientSystem} (47.14.2).

For a group \( G \) define the exponent-\( p \) central series of \( G \) inductively by \( P_1(G) = G \) and \( P_{i+1}(G) = [P_i(G), G]P_i(G)^p \). The factor groups modulo the terms of the lower exponent-\( p \) central series are \( p \)-groups. The group \( G \) has \( p \)-class \( c \) if \( P_c(G) \neq P_{c+1}(G) = 1 \).

The algorithm computes successive quotients modulo the terms of the exponent-\( p \) central series of \( F \). If the parameter \( c \) is present, then the factor group modulo the \((c+1)\)-th term of the exponent-\( p \) central series of \( F \) is returned. If \( c \) is not present, then the algorithm attempts to compute the largest \( p \)-group of \( F \). In case \( F \) does not have a largest \( p \)-group, the algorithm will not terminate.

By default the algorithm computes only with factor groups of order at most \( p^{56} \). If the parameter \( logord \) is present, it will compute with factor groups of order at most \( p^{\logord} \). If this parameter is specified, then the parameter \( c \) must also be given. The present implementation produces an error message if the order of a \( p \)-quotient exceeds \( p^{56} \) or \( p^{\logord} \), respectively. Note that the order of intermediate \( p \)-groups may be larger than the final order of a \( p \)-quotient.

The parameter \( ctype \) determines the type of collector that is used for computations within the factor \( p \)-group. \( ctype \) must either be "single" in which case a simple collector from the left is used or "combinatorial" in which case a combinatorial collector from the left is used.

### 47.14.2 EpimorphismQuotientSystem

\[ \text{EpimorphismQuotientSystem}(\text{quotsys}) \]

For a quotient system \text{quotsys} obtained from the function \text{PQuotient} (47.14.1), this operation returns an epimorphism \( F \rightarrow P \) where \( F \) is the finitely presented group of which \text{quotsys} is a quotient system and \( P \) is a \( p \)-group isomorphic to the quotient of \( F \) determined by \text{quotsys}.

Different calls to this operation will create different groups \( P \), each with its own family.

Example

```gap
gap> PQuotient( FreeGroup(2), 5, 10, 1024, "combinatorial" );
<5-quotient system of 5-class 10 with 520 generators>
gap> phi := EpimorphismQuotientSystem( last );
[ f1, f2 ] -> [ a1, a2 ]
gap> Collected( Factors( Size( Image(phi) ) ) );
[ [ 5, 520 ] ]
```
47.14.3 EpimorphismPGroup

EpimorphismPGroup(fpgrp, p[, cl]) (operation)

computes an epimorphism from the finitely presented group \( fpgrp \) to the largest \( p \)-group of \( p \)-class \( cl \) which is a quotient of \( fpgrp \). If \( cl \) is omitted, the largest finite \( p \)-group quotient (of \( p \)-class up to 1000) is determined.

Example

\[
\begin{align*}
\text{gap> hom := EpimorphismPGroup(fp, 2);} \\
&[ f1, f2 ] -> [ a1, a2 ] \\
\text{gap> Size(Image(hom));} \\
&8 \\
\text{gap> hom := EpimorphismPGroup(fp, 3, 7);} \\
&[ f1, f2 ] -> [ a1, a2 ] \\
\text{gap> Size(Image(hom));} \\
&6561
\end{align*}
\]

47.14.4 EpimorphismNilpotentQuotient

EpimorphismNilpotentQuotient(fpgrp[, n]) (function)

returns an epimorphism on the class \( n \) finite nilpotent quotient of the finitely presented group \( fpgrp \). If \( n \) is omitted, the largest finite nilpotent quotient (of \( p \)-class up to 1000) is taken.

Example

\[
\begin{align*}
\text{gap> hom := EpimorphismNilpotentQuotient(fp, 7);} \\
&[ f1, f2 ] -> [ f1*f4, f2*f5 ] \\
\text{gap> Size(Image(hom));} \\
&52488
\end{align*}
\]

A related operation which is also applicable to finitely presented groups is GQuotients (40.9.4), which computes all epimorphisms from a (finitely presented) group \( F \) onto a given (finite) group \( G \).

Example

\[
\begin{align*}
\text{gap> GQuotients(fp, Group((1,2,3),(1,2)));} \\
&[ [ f1, f2 ] -> [(1,2), (2,3)], [ f1, f2 ] -> [(2,3), (1,2,3)], [ f1, f2 ] -> [(1,2,3), (2,3)] ]
\end{align*}
\]

47.14.5 SolvableQuotient (for a f.p. group and a size)

SolvableQuotient(F, size) (function)

SolvableQuotient(F, primes) (function)

SolvableQuotient(F, tuples) (function)

SQ(F, ...) (function)

This routine calls the solvable quotient algorithm for a finitely presented group \( F \). The quotient to be found can be specified in the following ways: Specifying an integer \( size \) finds a quotient of size up to \( size \) (if such large quotients exist). Specifying a list of primes in \( primes \) finds the largest quotient involving the given primes. Finally \( tuples \) can be used to prescribe a chief series.

\( SQ \) can be used as a synonym for \( \text{SolvableQuotient} \).
47.14.6 EpimorphismSolvableQuotient

\textbf{EpimorphismSolvableQuotient}(F, \texttt{param})

computes an epimorphism from the finitely presented group \texttt{fpgrp} to the largest solvable quotient given by \texttt{param} (specified as in \texttt{SolvableQuotient}(47.14.5)).

\textbf{Example}

\begin{verbatim}
gap> f := FreeGroup( "a", "b", "c", "d" );;
gap> fp := f / \[ f.1^2, f.2^2, f.3^2, f.4^2, f.1*f.2*f.1*f.2*f.1*f.2, 
            > f.2*f.3*f.2*f.3*f.2*f.3, f.3*f.4*f.3*f.4*f.3*f.4, 
            > f.1^-1*f.3^-1*f.1*f.3, f.1^-1*f.4^-1*f.1*f.4, 
            > f.2^-1*f.4^-1*f.2*f.4 \];;
gap> hom:=EpimorphismSolvableQuotient(fp,300);Size(Image(hom));
[ a, b, c, d ] -> [ f1*f2, f1*f2, f2*f3, f2 ]
12

gap> hom:=EpimorphismSolvableQuotient(fp,[2,3]);Size(Image(hom));
[ a, b, c, d ] -> [ f1*f2*f4, f1*f2*f6*f8, f2*f3, f2 ]
1152
\end{verbatim}

47.14.7 LargerQuotientBySubgroupAbelianization

\textbf{LargerQuotientBySubgroupAbelianization}(\texttt{hom}, \texttt{U})

Let \texttt{hom} a homomorphism from a finitely presented group \texttt{G} to a finite group \texttt{H} and \texttt{U} ≤ \texttt{H}. This function will – if it exists – return a subgroup \texttt{S} ≤ \texttt{G}, such that the core of \texttt{S} is properly contained in the kernel of \texttt{hom} as well as in \texttt{V′}, where \texttt{V} is the pre-image of \texttt{U} under \texttt{hom}. Thus \texttt{S} exposes a larger quotient of \texttt{G}. If no such subgroup exists, fail is returned.

\textbf{Example}

\begin{verbatim}
gap> f:=FreeGroup("x","y","z");
gap> g:=f / ParseRelators(f,"x^3=y^3=z^5=(xyx^2y^2)^2=(xz)^2=(yz^3)^2=1");
<fp group on the generators [ x, y, z ]>
gap> 1:=LowIndexSubgroupsFpGroup(g,6);
gap> List(1,IndexInWholeGroup);
[ 1, 5, 5, 5, 5, 6, 6, 6, 6, 6, 6 ]
gap> q:=DefiningQuotientHomomorphism(1[6]);p:=Image(q);Size(p);
Group([ (4,5,6), (1,2,3)(4,6,5), (2,4,6,3,5) ])
360

gap> s:=LargerQuotientBySubgroupAbelianization(q,SylowSubgroup(p,3));
Group( [ f1, no generators known ] )
gap> Size(Image(DefiningQuotientHomomorphism(s)));
193273528320
\end{verbatim}

47.15 Abelian Invariants for Subgroups

Using variations of coset enumeration it is possible to compute the abelian invariants of a subgroup of a finitely presented group without computing a complete presentation for the subgroup in the first place. Typically, the operation \texttt{AbelianInvariants (39.16.1)} when called for subgroups should automatically take care of this, but in case you want to have further control about the methods used, the following operations might be of use.
47.15.1 AbelianInvariantsSubgroupFpGroup

\[ \text{AbelianInvariantsSubgroupFpGroup}(G, H) \quad \text{(function)} \]

AbelianInvariantsSubgroupFpGroup is a synonym for AbelianInvariantsSubgroupFpGroupRrs (47.15.3).

47.15.2 AbelianInvariantsSubgroupFpGroupMtc

\[ \text{AbelianInvariantsSubgroupFpGroupMtc}(G, H) \quad \text{(function)} \]

uses the Modified Todd-Coxeter method to compute the abelian invariants of a subgroup \( H \) of a finitely presented group \( G \).

47.15.3 AbelianInvariantsSubgroupFpGroupRrs

\[ \text{AbelianInvariantsSubgroupFpGroupRrs}(G, H) \quad \text{(function)} \]

\[ \text{AbelianInvariantsSubgroupFpGroupRrs}(G, \text{table}) \quad \text{(function)} \]

uses the Reduced Reidemeister-Schreier method to compute the abelian invariants of a subgroup \( H \) of a finitely presented group \( G \).

Alternatively to the subgroup \( H \), its coset table \( \text{table} \) in \( G \) may be given as second argument.

47.15.4 AbelianInvariantsNormalClosureFpGroup

\[ \text{AbelianInvariantsNormalClosureFpGroup}(G, H) \quad \text{(function)} \]

AbelianInvariantsNormalClosureFpGroup is a synonym for AbelianInvariantsNormalClosureFpGroupRrs (47.15.5).

47.15.5 AbelianInvariantsNormalClosureFpGroupRrs

\[ \text{AbelianInvariantsNormalClosureFpGroupRrs}(G, H) \quad \text{(function)} \]

uses the Reduced Reidemeister-Schreier method to compute the abelian invariants of the normal closure of a subgroup \( H \) of a finitely presented group \( G \). See 48.2 for details on the different strategies.

The following example shows a calculation for the Coxeter group \( B_1 \). This calculation and a similar one for \( B_0 \) have been used to prove that \( B_1' / B_1'' \cong \mathbb{Z}_2^9 \times \mathbb{Z}_3^3 \) and \( B_0' / B_0'' \cong \mathbb{Z}_2^{11} \times \mathbb{Z}_3^3 \) as stated in [FJNT95, Proposition 5].

Example

\[
\text{gap> } \# \text{ Define the Coxeter group } E_1. \\
\text{gap> } \text{F := FreeGroup( "x1", "x2", "x3", "x4", "x5" );} \\
\langle \text{free group on the generators } [ \text{x1, x2, x3, x4, x5} ] \rangle \\
\text{gap> x1 := F.1;; x2 := F.2;; x3 := F.3;; x4 := F.4;; x5 := F.5;;} \\
\text{gap> rels := [ x1^2, x2^2, x3^2, x4^2, x5^2,} \\
\quad \text{ (x1 * x3)^2, (x2 * x4)^2, (x1 * x2)^3, (x2 * x3)^3, (x3 * x4)^3,} \\
\quad \text{ (x4 * x1)^3, (x1 * x5)^3, (x2 * x5)^2, (x3 * x5)^3, (x4 * x5)^2,} \\
\quad \text{ (x1 * x2 * x3 * x4 * x5)^2 ];}; \\
\text{gap> E1 := F / rels;}
\]
47.16 Testing Finiteness of Finitely Presented Groups

As a consequence of the algorithmic insolvabilities mentioned in the introduction to this chapter, there cannot be a general method that will test whether a given finitely presented group is actually finite.

Therefore testing the finiteness of a finitely presented group can be problematic. What GAP actually does upon a call of IsFinite (30.4.2) (or if it is –probably implicitly– asked for a faithful permutation representation) is to test whether it can find (via coset enumeration) a cyclic subgroup of finite index. If it can, it rewrites the presentation to this subgroup. Since the subgroup is cyclic, its size can be checked easily from the resulting presentation, the size of the whole group is the product of the index and the subgroup size. Since however no bound for the index of such a subgroup (if any exist) is known, such a test might continue unsuccessfully until memory is exhausted.

On the other hand, a couple of methods exist, that might prove that a group is infinite. Again, none is guaranteed to work in every case:

The first method is to find (for example via the low index algorithm, see LowIndexSubgroupsFpGroup (47.10.1)) a subgroup $U$ such that $[U : U']$ is infinite. If $U$ has finite index, this can be checked by IsInfiniteAbelianizationGroup (47.16.1).

Note that this test has been done traditionally by checking the AbelianInvariants (39.16.1) (see section 47.15) of $U$, IsInfiniteAbelianizationGroup (47.16.1) does a similar calculation but stops as soon as it is known whether 0 is an invariant without computing the actual values. This can be notably faster.
Another method is based on $p$-group quotients, see $\text{NewmanInfinityCriterion}$ (47.16.2).

### 47.16.1 $\text{IsInfiniteAbelianizationGroup}$

\[ \text{IsInfiniteAbelianizationGroup}(G) \]

returns true if the commutator factor group $G / G'$ is infinite. This might be done without computing the full structure of the commutator factor group.

### 47.16.2 $\text{NewmanInfinityCriterion}$

\[ \text{NewmanInfinityCriterion}(G, p) \]

Let $G$ be a finitely presented group and $p$ a prime that divides the order of the commutator factor group of $G$. This function applies an infinity criterion due to M. F. Newman [New90] to $G$. (See [Joh97, chapter 16] for a more explicit description.) It returns true if the criterion succeeds in proving that $G$ is infinite and fail otherwise.

Note that the criterion uses the number of generators and relations in the presentation of $G$. Reduction of the presentation via Tietze transformations ($\text{IsomorphismSimplifiedFpGroup}$ (47.12.1)) therefore might produce an isomorphic group, for which the criterion will work better.

```gap
gap> g:=FibonacciGroup(2,9);
<fp group on the generators [ f1, f2, f3, f4, f5, f6, f7, f8, f9 ]>
gap> hom:=EpimorphismNilpotentQuotient(g,2);;
gap> k:=Kernel(hom);;
gap> Index(g,k);
152
gap> AbelianInvariants(k);
[ 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5 ]
gap> NewmanInfinityCriterion(Kernel(hom),5);  
true
```

This proves that the subgroup $k$ (and thus the whole group $g$) is infinite. (This is the original example from [New90].)
Chapter 48

Presentations and Tietze Transformations

A finite presentation describes a group, but usually there is a multitude of presentations that describe isomorphic groups. Therefore a presentation in GAP is different from a finitely presented group though there are ways to translate between both.

An important feature of presentations is that they can be modified (see sections 48.5 to 48.8).

If you only want to get new presentations for subgroups of a finitely presented group (and do not want to manipulate presentations yourself), chances are that the operation IsomorphismFpGroup (47.11.1) already does what you want (see 47.12).

48.1 Creating Presentations

Most of the functions creating presentations and all functions performing Tietze transformations on them sort the relators by increasing lengths. The function PresentationFpGroup (48.1.1) is an exception because it is intended to reflect the relators that were used to define the involved f. p. group. You may use the command TzSort (48.1.2) to sort the presentation.

48.1.1 PresentationFpGroup

\[ \text{PresentationFpGroup(} G[, \text{printlevel}]) \]

creates a presentation, i.e., a Tietze object, for the given finitely presented group \( G \). This presentation will be exactly as the presentation of \( G \) and no initial Tietze transformations are applied to it.

The optional \text{printlevel} parameter can be used to restrict or to extend the amount of output provided by Tietze transformation commands when being applied to the created presentation. The default value 1 is designed for interactive use and implies explicit messages to be displayed by most of these commands. A \text{printlevel} value of 0 will suppress these messages, whereas a \text{printlevel} value of 2 will enforce some additional output.

Example

\begin{verbatim}
gap> f := FreeGroup( "a", "b" );
<free group on the generators [ a, b ]>
gap> g := f / [ f.1^3, f.2^2, (f.1*f.2)^3 ];
<fp group on the generators [ a, b ]>
gap> p := PresentationFpGroup( g );
<presentation with 2 gens and 3 rels of total length 11>
\end{verbatim}
48.1.2 TzSort

\[ \text{TzSort}(P) \] (function)

sorts the relators of the given presentation \( P \) by increasing lengths. There is no particular ordering defined for the relators of equal length. Note that \text{TzSort} does not return a new object. It changes the given presentation.

48.1.3 GeneratorsOfPresentation

\[ \text{GeneratorsOfPresentation}(P) \] (function)

returns a list of free generators that is a shallow copy (see \text{ShallowCopy} (12.7.1)) of the current generators of the presentation \( P \).

48.1.4 FpGroupPresentation

\[ \text{FpGroupPresentation}(P[, \text{nam}]) \] (function)

constructs an f.p. group as defined by the given Tietze presentation \( P \).

Example

\begin{verbatim}
gap> h := FpGroupPresentation( p );
<fp group on the generators [ a, b ]>
gap> h = g;
false
\end{verbatim}

48.1.5 PresentationViaCosetTable

\[ \text{PresentationViaCosetTable}(G[, F, \text{words}]) \] (function)

constructs a presentation for a given concrete finite group. It applies the relations finding algorithm which has been described in [Can73] and [Neu82]. It automatically applies Tietze transformations to the presentation found.

If only a group \( G \) has been specified, the single stage algorithm is applied.

The operation \text{IsomorphismFpGroup} (47.11.1) in contrast uses a multiple-stage algorithm using a chief series and stabilizer chains. It usually should be used rather than \text{PresentationViaCosetTable}. (It does not apply Tietze transformations automatically.)

If the two stage algorithm is to be used, \text{PresentationViaCosetTable} expects a subgroup \( H \) of \( G \) to be provided in form of two additional arguments \( F \) and \( \text{words} \), where \( F \) is a free group with the same number of generators as \( G \), and \( \text{words} \) is a list of words in the generators of \( F \) which supply a list of generators of \( H \) if they are evaluated as words in the corresponding generators of \( G \).

Example

\begin{verbatim}
gap> G := GeneralLinearGroup( 2, 7 );
GL(2,7)
gap> GeneratorsOfGroup( G );
[ [ [ Z(7), 0*Z(7) ], [ 0*Z(7), Z(7)^0 ] ],
  [ [ Z(7)^3, Z(7)^0 ], [ Z(7)^3, 0*Z(7) ] ] ]
gap> Size( G );
2016
\end{verbatim}
The two stage algorithm saves an essential amount of space by constructing two coset tables of lengths $|H|$ and $|G|/|H|$ instead of just one coset table of length $|G|$. The next example shows an application of this option in the case of a subgroup of size 7920 and index 12 in a permutation group of size 95040.

Before it is returned, the resulting presentation is being simplified by appropriate calls of the function SimplifyPresentation (48.6.2) (see 48.6), but without allowing any eliminations of generators. This restriction guarantees that we get a bijection between the list of generators of $G$ and the list of generators in the presentation. Hence, if the generators of $G$ are redundant and if you don't care for the bijection, you may get a shorter presentation by calling the function SimplifyPresentation (48.6.2), now without this restriction, once more yourself.

If you apply the function FpGroupPresentation (48.1.4) to the resulting presentation you will get a finitely presented group isomorphic to $G$. Note, however, that the function IsomorphismFpGroup (47.11.1) is recommended for this purpose.
48.1.6 SimplifiedFpGroup

applies Tietze transformations to a copy of the presentation of the given finitely presented group \( G \) in order to reduce it with respect to the number of generators, the number of relators, and the relator lengths.

SimplifiedFpGroup returns a group isomorphic to the given one with a presentation which has been tried to simplify via Tietze transformations.

If the connection to the original group is important, then the operation IsomorphismSimplifiedFpGroup (47.12.1) should be used instead.

Example

\[
gap> F6 := FreeGroup( 6, "G" );;
gap> H := SimplifiedFpGroup( G );;
<fp group on the generators [ G1, G3 ]>
gap> RelatorsOfFpGroup( H );
[ G1^2, (G1*G3^-1)^2, G3^4 ]
\]

In fact, the command

\[
H := \text{SimplifiedFpGroup}( G );
\]

is an abbreviation of the command sequence

\[
P := \text{PresentationFpGroup}( G, 0 );;
\text{SimplifyPresentation}( P );
H := \text{FpGroupPresentation}( P );
\]

which applies a rather simple-minded strategy of Tietze transformations to the intermediate presentation \( P \). If, for some concrete group, the resulting presentation is unsatisfying, then you should try a more sophisticated, interactive use of the available Tietze transformation commands (see 48.6).

48.2 Subgroup Presentations

48.2.1 PresentationSubgroup

PresentationSubgroup is a synonym for PresentationSubgroupRrs (48.2.2).

48.2.2 PresentationSubgroupRrs
uses the Reduced Reidemeister-Schreier method to compute a presentation \( P \), say, for a subgroup \( H \) of a finitely presented group \( G \). The generators in the resulting presentation will be named \texttt{string1}, \texttt{string2}, ..., the default string is \"\texttt{x}\". You may access the \( i \)-th of these generators by \( P[i] \).

Alternatively, to the subgroup \( H \), its coset table \texttt{table} in \( G \) may be given as the second argument.

Example

\begin{verbatim}
gap> f := FreeGroup( "a", "b" );
gap> g := f / [ f.1^2, f.2^3, (f.1*f.2)^5 ];
<fp group on the generators [ a, b ]>
gap> g1 := Size( g );
60
gap> u := Subgroup( g, [ g.1, g.1^g.2 ] );
Group([ a, b^-1*a*b ])
gap> p := PresentationSubgroup( g, u, "g" );
<presentation with 3 gens and 4 rels of total length 12>
gap> gens := GeneratorsOfPresentation( p );
[ g1, g2, g3 ]
gap> TzPrintRelators( p );
#I 1. g1^2
#I 2. g2^2
#I 3. g3*g2*g1
#I 4. g3^5
\end{verbatim}

Note that you cannot call the generators by their names. These names are not variables, but just display figures. So, if you want to access the generators by their names, you first will have to introduce the respective variables and to assign the generators to them.

Example

\begin{verbatim}
gap> gens[1] = g1;
false
gap> g1;
60
gap> g1 := gens[1];; g2 := gens[2];; g3 := gens[3];;
gap> g1;
\end{verbatim}

The Reduced Reidemeister-Schreier algorithm is a modification of the Reidemeister-Schreier algorithm of George Havas [Hav74]. It was proposed by Joachim Neubüser and first implemented in 1986 by Andrea Lucchini and Volkmar Felsch in the SPAS system [SPA89]. Like the Reidemeister-Schreier algorithm of George Havas, it needs only the presentation of \( G \) and a coset table of \( H \) in \( G \) to construct a presentation of \( H \).

Whenever you call the command \texttt{PresentationSubgroupRrs}, it first obtains a coset table of \( H \) in \( G \) if not given. Next, a set of generators of \( H \) is determined by reconstructing the coset table and introducing in that process as many Schreier generators of \( H \) in \( G \) as are needed to do a Felsch strategy coset enumeration without any coincidences. (In general, though containing redundant generators, this set will be much smaller than the set of all Schreier generators. That is why we call the method the \texttt{Reduced} Reidemeister-Schreier.)

After having constructed this set of \textit{primary subgroup generators}, say, the coset table is extended to an \textit{augmented coset table} which describes the action of the group generators on coset representatives, i.e., on elements instead of cosets. For this purpose, suitable words in the (primary) subgroup generators have to be associated to the coset table entries. In order to keep the lengths of these words
short, additional *secondary subgroup generators* are introduced as abbreviations of subwords. Their number may be large.

Finally, a Reidemeister rewriting process is used to get defining relators for $H$ from the relators of $G$. As the resulting presentation of $H$ is a presentation on primary and secondary generators, in general you will have to simplify it by appropriate Tietze transformations (see 48.6) or by the command `DecodeTree` (48.10.1) before you can use it. Therefore it is returned in the form of a presentation, $P$ say.

Compared with the Modified Todd-Coxeter method described below, the Reduced Reidemeister-Schreier method (as well as Havas’ original Reidemeister-Schreier program) has the advantage that it does not require generators of $H$ to be given if a coset table of $H$ in $G$ is known. This provides a possibility to compute a presentation of the normal closure of a given subgroup (see `PresentationNormalClosureRrs` (48.2.5)).

For certain applications you may be interested in getting not only just a presentation for $H$, but also a relation between the involved generators of $H$ and the generators of $G$. The subgroup generators in the presentation are sorted such that the primary generators precede the secondary ones. Moreover, for each secondary subgroup generator there is a relator in the presentation which expresses this generator as a word in preceding ones. Hence, all we need in addition is a list of words in the generators of $G$ which express the primary subgroup generators. In fact, such a list is provided in the attribute `PrimaryGeneratorWords` (48.2.3) of the resulting presentation.

### 48.2.3 PrimaryGeneratorWords

```
▷ PrimaryGeneratorWords(P) (attribute)
```

is an attribute of the presentation $P$ which holds a list of words in the associated group generators (of the underlying free group) which express the primary subgroup generators of $P$.

```
gap> PrimaryGeneratorWords( p );
[ a, b^-1*a*b ]
```

### 48.2.4 PresentationSubgroupMtc

```
▷ PresentationSubgroupMtc(G, H[, string][, print, level]) (function)
```

uses the Modified Todd-Coxeter coset representative enumeration method to compute a presentation $P$, say, for a subgroup $H$ of a finitely presented group $G$. The presentation returned is in generators corresponding to the generators of $H$. The generators in the resulting presentation will be named `string1`, `string2`, ..., the default string is "-_x". You may access the $i$-th of these generators by $P!i$.

The default print level is 1. If the print level is set to 0, then the printout of the implicitly called function `DecodeTree` (48.10.1) will be suppressed.

```
gap> p := PresentationSubgroupMtc( g, u );
<presentation with 2 gens and 3 rels of total length 14>
```

The so called Modified Todd-Coxeter method was proposed, in slightly different forms, by Nathan S. Mendelsohn and William O. J. Moser in 1966. Moser’s method was proved in [BC76]. It has been generalized to cover a broad spectrum of different versions (see the survey [Neu82]).
The Modified Todd-Coxeter method performs an enumeration of coset representatives. It proceeds like an ordinary coset enumeration (see 47.6), but as the product of a coset representative by a group generator or its inverse need not be a coset representative itself, the Modified Todd-Coxeter has to store a kind of correction element for each coset table entry. Hence it builds up a so called augmented coset table of $H$ in $G$ consisting of the ordinary coset table and a second table in parallel which contains the associated subgroup elements.

Theoretically, these subgroup elements could be expressed as words in the given generators of $H$, but in general these words tend to become unmanageable because of their enormous lengths. Therefore, a highly redundant list of subgroup generators is built up starting from the given ("primary") generators of $H$ and adding additional ("secondary") generators which are defined as abbreviations of suitable words of length two in the preceding generators such that each of the subgroup elements in the augmented coset table can be expressed as a word of length at most one in the resulting (primary and secondary) subgroup generators.

Then a rewriting process (which is essentially a kind of Reidemeister rewriting process) is used to get relators for $H$ from the defining relators of $G$.

The resulting presentation involves all the primary, but not all the secondary generators of $H$. In fact, it contains only those secondary generators which explicitly occur in the augmented coset table. If we extended this presentation by those secondary generators which are not yet contained in it as additional generators, and by the definitions of all secondary generators as additional relators, we would get a presentation of $H$, but, in general, we would end up with a large number of generators and relators.

On the other hand, if we avoid this extension, the current presentation will not necessarily define $H$ although we have used the same rewriting process which in the case of the \texttt{PresentationSubgroupRrs} (48.2.2) command computes a defining set of relators for $H$ from an augmented coset table and defining relators of $G$. The different behaviour here is caused by the fact that coincidences may have occurred in the Modified Todd-Coxeter coset enumeration.

To overcome this problem without extending the presentation by all secondary generators, the \texttt{PresentationSubgroupMtc} command applies the so called decoding tree algorithm which provides a more economical approach. The reader is strongly recommended to carefully read section 48.10 where this algorithm is described in more detail. Here we will only mention that this procedure may add a lot of intermediate generators and relators (and even change the isomorphism type) in a process which in fact eliminates all secondary generators from the presentation and hence finally provides a presentation of $H$ on the primary, i.e., the originally given, generators of $H$. This is a remarkable advantage of the command \texttt{PresentationSubgroupMtc} compared to the command \texttt{PresentationSubgroupRrs} (48.2.2). But note that, for some particular subgroup $H$, the Reduced Reidemeister-Schreier method might quite well produce a more concise presentation.

The resulting presentation is returned in the form of a presentation, $P$ say.

As the function \texttt{PresentationSubgroupRrs} (48.2.2) described above (see there for details), the function \texttt{PresentationSubgroupMtc} returns a list of the primary subgroup generators of $H$ in the attribute \texttt{PrimaryGeneratorWords} (48.2.3) of $P$. In fact, this list is not very exciting here because it is just a shallow copy of the value of \texttt{GeneratorsOfPresentation} (48.1.3) of $H$, however it is needed to guarantee a certain consistency between the results of the different functions for computing subgroup presentations.

Though the decoding tree routine already involves a lot of Tietze transformations, we recommend that you try to further simplify the resulting presentation by appropriate Tietze transformations (see 48.6).
48.2.5 PresentationNormalClosureRrs

\[ \text{PresentationNormalClosureRrs}(G, H[, \text{string}]) \]

uses the Reduced Reidemeister-Schreier method to compute a presentation \( P \), say, for the normal closure of a subgroup \( H \) of a finitely presented group \( G \). The generators in the resulting presentation will be named \text{string1}, \text{string2}, ..., the default string is "\_x". You may access the \( i \)-th of these generators by \( P!i \).

48.2.6 PresentationNormalClosure

\[ \text{PresentationNormalClosure}(G, H[, \text{string}]) \]

PresentationNormalClosure is a synonym for PresentationNormalClosureRrs (48.2.5).

48.3 Relators in a Presentation

In order to speed up the Tietze transformation routines, each relator in a presentation is internally represented by a list of positive or negative generator numbers, i.e., each factor of the proper GAP word is represented by the position number of the corresponding generator with respect to the current list of generators, or by the respective negative number, if the factor is the inverse of a generator. Note that the numbering of the generators in Tietze words is always relative to a generator list and bears no relation to the internal numbering of generators in a family of associative words.

48.3.1 TietzeWordAbstractWord

\[ \text{TietzeWordAbstractWord}(\text{word}, \text{fgens}) \]

assumes \text{fgens} to be a list of free group generators and \text{word} to be an abstract word in these generators. It converts \text{word} into a Tietze word, i.e., a list of positive or negative generator numbers.

This function simply calls LetterRepAssocWord (37.6.8).

48.3.2 AbstractWordTietzeWord

\[ \text{AbstractWordTietzeWord}(\text{word}, \text{fgens}) \]

assumes \text{fgens} to be a list of free group generators and \text{word} to be a Tietze word in these generators, i.e., a list of positive or negative generator numbers. It converts \text{word} to an abstract word.

This function simply calls AssocWordByLetterRep (37.6.9).

Example

\begin{verbatim}
gap> F := FreeGroup( "a", "b", "c", "d");
<free group on the generators [ a, b, c, d ]>
gap> tzword := TietzeWordAbstractWord( Comm(F.4,F.2) * (F.3^2 * F.2)^-1, GeneratorsOfGroup( F ){[2,3,4]} );
\[ -3, -1, 3, -2, -2 \]
gap> AbstractWordTietzeWord( tzword, GeneratorsOfGroup( F ){[2,3,4]} );
d^-1*b^-1*d*c^-2
\end{verbatim}
48.4 Printing Presentations

Whenever you create a presentation \( P \), say, or assign it to a variable, GAP will respond by printing \( P \). However, as \( P \) may contain a lot of generators and many relators of large length, it would be annoying if the standard print facilities displayed all this information in detail. So they restrict the printout to just one line of text containing the number of generators, the number of relators, and the total length of all relators of \( P \). As compensation, GAP offers some special print commands which display various details of a presentation. Note that there is also a function \texttt{TzPrintOptions (48.11.2)}.

It is described in Section 48.11.

48.4.1 TzPrintGenerators

\[ \texttt{TzPrintGenerators(P[, list])} \]

prints the generators of the given Tietze presentation \( P \) together with the number of their occurrences in the relators. The optional second argument can be used to specify the numbers of the generators to be printed. Default: all generators are printed.

Example

\[
\begin{array}{ll}
\texttt{gap> G := Group( [ (1,2,3,4,5), (2,3,5,4), (1,6)(3,4) ], () );}
\texttt{Group([ (1,2,3,4,5), (2,3,5,4), (1,6)(3,4) ])}
\texttt{gap> P := PresentationViaCosetTable( G );}
\texttt{<presentation with 3 gens and 6 rels of total length 28>}
\texttt{gap> TzPrintGenerators( P );}
\text{1. f1 11 occurrences} \\
\text{2. f2 10 occurrences} \\
\text{3. f3 7 occurrences involution}
\end{array}
\]

48.4.2 TzPrintRelators

\[ \texttt{TzPrintRelators(P[, list])} \]

prints the relators of the given Tietze presentation \( P \). The optional second argument \( \text{list} \) can be used to specify the numbers of the relators to be printed. Default: all relators are printed.

Example

\[
\begin{array}{ll}
\texttt{gap> TzPrintRelators( P );} \\
\text{1. f3^2} \\
\text{2. f2^4} \\
\text{3. (f2^-1*f3)^2} \\
\text{4. f1^5} \\
\text{5. f1^-1*f2*f1*f2^-1} \\
\text{6. f1^-1*f3*f1*f3*f1^-1*f2^2*f3}
\end{array}
\]

48.4.3 TzPrintLengths

\[ \texttt{TzPrintLengths(P)} \]

prints just a list of all relator lengths of the given presentation \( P \).

Example

\[
\begin{array}{ll}
\texttt{gap> TzPrintLengths( P );} \\
\text{[ 2, 4, 5, 5, 8 ]}
\end{array}
\]
48.4.4 TzPrintStatus

\[\text{TzPrintStatus}(P[, \text{norepeat}])\] (function)

is an internal function which is used by the Tietze transformation routines to print the number of
generators, the number of relators, and the total length of all relators in the given Tietze presentation
\(P\). If \text{norepeat} is specified as true, the printing is suppressed if none of the three values has changed
since the last call.

Example

\[
gap> \text{TzPrintStatus}(P); \\
\#I \text{ there are 3 generators and 6 relators of total length 28}
\]

48.4.5 TzPrintPresentation

\[\text{TzPrintPresentation}(P)\] (function)

prints the generators and the relators of a Tietze presentation. In fact, it is an abbreviation for the
successive call of the three commands TzPrintGenerators (48.4.1), TzPrintRelators (48.4.2),
and TzPrintStatus (48.4.4), each with the presentation \(P\) as only argument.

48.4.6 TzPrint

\[\text{TzPrint}(P[, \text{list}])\] (function)

prints the current generators of the given presentation \(P\), and prints the relators of \(P\) as Tietze
words (without converting them back to abstract words as the functions TzPrintRelators (48.4.2)
and TzPrintPresentation (48.4.5) do). The optional second argument can be used to specify the
numbers of the relators to be printed. Default: all relators are printed.

Example

\[
gap> \text{TzPrint}(P); \\
\#I \text{ generators: } [ f1, f2, f3 ] \\
\#I \text{ relators:} \\
\#I 1. 2 [ 3, 3 ] \\
\#I 2. 4 [ 2, 2, 2, 2 ] \\
\#I 3. 4 [ -2, 3, -2, 3 ] \\
\#I 4. 5 [ 1, 1, 1, 1, 1 ] \\
\#I 5. 5 [ 1, 1, 2, 1, -2 ] \\
\#I 6. 8 [ -1, 3, 1, 3, -1, 2, 2, 3 ]
\]

48.4.7 TzPrintPairs

\[\text{TzPrintPairs}(P[, n])\] (function)

prints the \(n\) most often occurring relator subwords of the form \(ab\), where \(a\) and \(b\) are different
generators or inverses of generators, together with the number of their occurrences. The default value
of \(n\) is 10. A value \(n = 0\) is interpreted as infinity (18.2.1).

The function TzPrintPairs is useful in the context of Tietze transformations which introduce
new generators by substituting words in the current generators (see 48.8). It gives some evidence for
an appropriate choice of a word of length 2 to be substituted.
48.5 Changing Presentations

The functions described in this section may be used to change a presentation. Note, however, that in general they do not perform Tietze transformations because they change or may change the isomorphism type of the group defined by the presentation.

48.5.1 AddGenerator

\[ \text{AddGenerator}(P) \]

extends the presentation \( P \) by a new generator.

Let \( i \) be the smallest positive integer which has not yet been used as a generator number in the given presentation. \text{AddGenerator} defines a new abstract generator \( x_i \) with the name "\( \_x^i \)" and adds it to the list of generators of \( P \).

You may access the generator \( x_i \) by typing \( P!.i \). However, this is only practicable if you are running an interactive job because you have to know the value of \( i \). Hence the proper way to access the new generator is to write \( \text{GeneratorsOfPresentation}(P)[\text{Length}(\text{GeneratorsOfPresentation}(P))] \).

\[ \text{Example} \]

\begin{verbatim}
gap> TzPrintPairs( P, 3 );
#I 1. 3 occurrences of f2 * f3
#I 2. 2 occurrences of f2^(-1) * f3
#I 3. 2 occurrences of f1 * f3
\end{verbatim}

48.5.2 TzNewGenerator

\[ \text{TzNewGenerator}(P) \]

is an internal function which defines a new abstract generator and adds it to the presentation \( P \). It is called by \text{AddGenerator} (48.5.1) and by several Tietze transformation commands. As it does not know which global lists have to be kept consistent, you should not call it. Instead, you should call the function \text{AddGenerator} (48.5.1), if needed.

\[ \text{Example} \]

\begin{verbatim}
gap> G := PerfectGroup( 120 );;
gap> H := Subgroup( G, [ G.1^G.2, G.3 ] );;
gap> P := PresentationSubgroup( G, H );
<presentation with 4 gens and 7 rels of total length 21>
gap> AddGenerator( P );
#I now the presentation has 5 generators, the new generator is \_x7

gap> gens := GeneratorsOfPresentation( P );
[ \_x1, \_x2, \_x4, \_x5, \_x7 ]
gap> gen := gens[Length( gens )];
\_x7
gap> gen = P!.7;
true
\end{verbatim}
48.5.3 AddRelator

\[ \text{AddRelator}(P, \text{word}) \]

adds the relator \text{word} to the presentation \( P \), probably changing the group defined by \( P \). \text{word} must be an abstract word in the generators of \( P \).

48.5.4 RemoveRelator

\[ \text{RemoveRelator}(P, n) \]

removes the \( n \)-th relator from the presentation \( P \), probably changing the group defined by \( P \).

48.6 Tietze Transformations

The commands in this section can be used to modify a presentation by Tietze transformations.

In general, the aim of such modifications will be to simplify the given presentation, i.e., to reduce the number of generators and the number of relators without increasing too much the sum of all relator lengths which we will call the total length of the presentation. Depending on the concrete presentation under investigation one may end up with a nice, short presentation or with a very huge one.

Unfortunately there is no algorithm which could be applied to find the shortest presentation which can be obtained by Tietze transformations from a given one. Therefore, what GAP offers are some lower-level Tietze transformation commands and, in addition, some higher-level commands which apply the lower-level ones in a kind of default strategy which of course cannot be the optimal choice for all presentations.

The design of these commands follows closely the concept of the ANU Tietze transformation program [Hav69] and its later revisions (see [HKRR84], [Rob88]).

48.6.1 TzGo

\[ \text{TzGo}(P[, \text{silent}]) \]

automatically performs suitable Tietze transformations of the given presentation \( P \). It is perhaps the most convenient one among the interactive Tietze transformation commands. It offers a kind of default strategy which, in general, saves you from explicitly calling the lower-level commands it involves.

If \text{silent} is specified as \text{true}, the printing of the status line by TzGo is suppressed if the Tietze option printLevel (see 48.11) has a value less than 2.

48.6.2 SimplifyPresentation

\[ \text{SimplifyPresentation}(P) \]

SimplifyPresentation is a synonym for TzGo (48.6.1).

Example

\[
\begin{align*}
gap> F2 := \text{FreeGroup}( \text{"a"}, \text{"b"} );; \\
gap> G := F2 / [ F2.1^9, F2.2^2, (F2.1*F2.2)^4, (F2.1^2*F2.2)^3 ];; \\
gap> a := G.1;; b := G.2;;
\end{align*}
\]
GAP> H := Subgroup( G, [ (a*b)^2, (a^-1*b)^2 ] );
GAP> Index( G, H );
408
GAP> P := PresentationSubgroup( G, H );
<presentation with 8 gens and 36 rels of total length 111>
GAP> PrimaryGeneratorWords( P );
[ b, a*b*a ]
GAP> TzOptions( P ).protected := 2;
2
GAP> TzOptions( P ).printLevel := 2;
2
GAP> SimplifyPresentation( P );
#I eliminating _x7 = _x5^-1
#I eliminating _x5 = _x4
#I eliminating _x18 = _x3
#I eliminating _x8 = _x3
#I there are 4 generators and 8 relators of total length 21
#I there are 4 generators and 7 relators of total length 18
#I eliminating _x4 = _x3^-1*_x2^-1
#I eliminating _x3 = _x2*_x1^-1
#I there are 2 generators and 4 relators of total length 14
#I there are 2 generators and 4 relators of total length 13
#I there are 2 generators and 3 relators of total length 9
GAP> TzPrintRelators( P );
#I 1. _x1^2
#I 2. _x2^3
#I 3. (_x2*_x1)^2

Roughly speaking, TzGo (48.6.1) consists of a loop over a procedure which involves two phases:
In the search phase it calls TzSearch (48.7.2) and TzSearchEqual (48.7.3) described below which try to reduce the relator lengths by substituting common subwords of relators, in the elimination phase it calls the command TzEliminate (48.7.1) described below (or, more precisely, a subroutine of TzEliminate (48.7.1) in order to save some administrative overhead) which tries to eliminate generators that can be expressed as words in the remaining generators.

If TzGo (48.6.1) succeeds in reducing the number of generators, the number of relators, or the total length of all relators, it displays the new status before returning (provided that you did not set the print level to zero). However, it does not provide any output if all these three values have remained unchanged, even if the command TzSearchEqual (48.7.3) involved has changed the presentation such that another call of TzGo (48.6.1) might provide further progress. Hence, in such a case it makes sense to repeat the call of the command for several times (or to call the command TzGoGo (48.6.3) instead).

48.6.3 TzGoGo

\texttt{TzGoGo}(P) \\
\text{(function)}

calls the command TzGo (48.6.1) again and again until it does not reduce the presentation any more.

The result of the Tietze transformations can be affected substantially by the options parameters (see 48.11). To demonstrate the effect of the eliminationLimit parameter, we will give an example in which we handle a subgroup of index 240 in a group of order 40320 given by a presentation due
to B. H. Neumann. First we construct a presentation of the subgroup, and then we apply to it the command \texttt{TzGoGo} for different values of the parameter \texttt{eliminationsLimit} (including the default value 100). In fact, we also alter the \texttt{printLevel} parameter, but this is only done in order to suppress most of the output. In all cases the resulting presentations cannot be improved any more by applying the command \texttt{TzGoGo} again, i.e., they are the best results which we can get without substituting new generators.

\begin{verbatim}
Example

gap> F3 := FreeGroup( "a", "b", "c" );;
gap> G := F3 / [ F3.1^3, F3.2^3, F3.3^3, (F3.1*F3.2)^5, 
> (F3.1^-1*F3.2)^5, (F3.1*F3.3)^4, (F3.1*F3.3^-1)^4, 
> (F3.1*F3.2^-1*F3.1*F3.2*F3.3^-1*F3.1*F3.3*F3.1*F3.3^-1, 
> (F3.2*F3.3)^3, (F3.2^-1*F3.3)^4 ];;
gap> a := G.1;; b := G.2;; c := G.3;;
gap> H := Subgroup( G, [ a, c ] );;
gap> for i in [ 61, 62, 63, 90, 97 ] do
> Pi := PresentationSubgroup( G, H );
> TzOptions( Pi ).eliminationsLimit := i;
> Print("#I eliminationsLimit set to ",i,"\n");
> TzOptions( Pi ).printLevel := 0;
> TzGoGo( Pi );
> TzPrintStatus( Pi );
> od;
#I eliminationsLimit set to 61
#I there are 2 generators and 104 relators of total length 7012
#I eliminationsLimit set to 62
#I there are 2 generators and 7 relators of total length 56
#I eliminationsLimit set to 63
#I there are 3 generators and 97 relators of total length 5998
#I eliminationsLimit set to 90
#I there are 3 generators and 11 relators of total length 68
#I eliminationsLimit set to 97
#I there are 4 generators and 109 relators of total length 3813

Similarly, we demonstrate the influence of the \texttt{saveLimit} parameter by just continuing the preceding example for some different values of the \texttt{saveLimit} parameter (including its default value 10), but without changing the \texttt{eliminationsLimit} parameter which keeps its default value 100.

\begin{verbatim}
Example

gap> for i in [ 7 .. 11 ] do
> Pi := PresentationSubgroup( G, H );
> TzOptions( Pi ).saveLimit := i;
> Print( "#I saveLimit set to ", i, "\n" );
> TzOptions( Pi ).printLevel := 0;
> TzGoGo( Pi );
> TzPrintStatus( Pi );
> od;
#I saveLimit set to 7
#I there are 3 generators and 99 relators of total length 2713
#I saveLimit set to 8
#I there are 2 generators and 103 relators of total length 11982
#I saveLimit set to 9
#I there are 2 generators and 6 relators of total length 41
\end{verbatim}
48.7 Elementary Tietze Transformations

48.7.1 TzEliminate

\( \text{TzEliminate}(P[, \text{gen}]) \) \( \text{(function)} \)
\( \text{TzEliminate}(P[, n]) \) \( \text{(function)} \)

tries to eliminate a generator from a presentation \( P \) via Tietze transformations.

Any relator which contains some generator just once can be used to substitute that generator by a word in the remaining generators. If such generators and relators exist, then TzEliminate chooses a generator for which the product of its number of occurrences and the length of the substituting word is minimal, and then it eliminates this generator from the presentation, provided that the resulting total length of the relators does not exceed the associated Tietze option parameter spaceLimit (see 48.11). The default value of that parameter is infinity (18.2.1), but you may alter it appropriately.

If a generator \( \text{gen} \) has been specified, TzEliminate eliminates it if possible, i.e. if there is a relator in which \( \text{gen} \) occurs just once. If no second argument has been specified, TzEliminate eliminates some appropriate generator if possible and if the resulting total length of the relators will not exceed the Tietze options parameter lengthLimit.

If an integer \( n \) has been specified, TzEliminate tries to eliminate up to \( n \) generators. Note that the calls TzEliminate\((P)\) and TzEliminate\((P,1)\) are equivalent.

48.7.2 TzSearch

\( \text{TzSearch}(P) \) \( \text{(function)} \)

searches for relator subwords which, in some relator, have a complement of shorter length and which occur in other relators, too, and uses them to reduce these other relators.

The idea is to find pairs of relators \( r_1 \) and \( r_2 \) of length \( l_1 \) and \( l_2 \), respectively, such that \( l_1 \leq l_2 \) and \( r_1 \) and \( r_2 \) coincide (possibly after inverting or conjugating one of them) in some maximal subword \( w \), say, of length greater than \( l_1/2 \), and then to substitute each copy of \( w \) in \( r_2 \) by the inverse complement of \( w \) in \( r_1 \).

Two of the Tietze option parameters which are listed in section 48.11 may strongly influence the performance and the results of the command TzSearch. These are the parameters saveLimit and searchSimultaneous. The first of them has the following effect:

When TzSearch has finished its main loop over all relators, then, in general, there are relators which have changed and hence should be handled again in another run through the whole procedure. However, experience shows that it really does not pay to continue this way until no more relators change. Therefore, TzSearch starts a new loop only if the loop just finished has reduced the total length of the relators by at least saveLimit per cent.

The default value of saveLimit is 10 per cent.

To understand the effect of the option searchSimultaneous, we have to look in more detail at how TzSearch proceeds:
First, it sorts the list of relators by increasing lengths. Then it performs a loop over this list. In each step of this loop, the current relator is treated as short relator $r_1$, and a subroutine is called which loops over the succeeding relators, treating them as long relators $r_2$ and performing the respective comparisons and substitutions.

As this subroutine performs a very expensive process, it has been implemented as a C routine in the GAP kernel. For the given relator $r_1$ of length $l_1$, say, it first determines the minimal match length $l$ which is $l_1/2 + 1$, if $l_1$ is even, or $(l_1 + 1)/2$, otherwise. Then it builds up a hash list for all subwords of length $l$ occurring in the conjugates of $r_1$ or $r_1^{-1}$, and finally it loops over all long relators $r_2$ and compares the hash values of their subwords of length $l$ against this list. A comparison of subwords which is much more expensive is only done if a hash match has been found.

To improve the efficiency of this process we allow the subroutine to handle several short relators simultaneously provided that they have the same minimal match length. If, for example, it handles $n$ short relators simultaneously, then you save $n - 1$ loops over the long relators $r_2$, but you pay for it by additional fruitless subword comparisons. In general, you will not get the best performance by always choosing the maximal possible number of short relators to be handled simultaneously. In fact, the optimal choice of the number will depend on the concrete presentation under investigation. You can use the parameter $\text{searchSimultaneous}$ to prescribe an upper bound for the number of short relators to be handled simultaneously.

The default value of $\text{searchSimultaneous}$ is 20.

### 48.7.3 TzSearchEqual

$\text{TzSearchEqual}(P)$

searches for Tietze relator subwords which, in some relator, have a complement of equal length and which occur in other relators, too, and uses them to modify these other relators.

The idea is to find pairs of relators $r_1$ and $r_2$ of length $l_1$ and $l_2$, respectively, such that $l_1$ is even, $l_1 \leq l_2$, and $r_1$ and $r_2$ coincide (possibly after inverting or conjugating one of them) in some maximal subword $w$, say, of length at least $l_1/2$. Let $l$ be the length of $w$. Then, if $l > l_1/2$, the pair is handled as in TzSearch (48.7.2). Otherwise, if $l = l_1/2$, then TzSearchEqual substitutes each copy of $w$ in $r_2$ by the inverse complement of $w$ in $r_1$.

The Tietze option parameter $\text{searchSimultaneous}$ is used by TzSearchEqual in the same way as described for TzSearch (48.7.2). However, TzSearchEqual does not use the parameter $\text{saveLimit}$: The loop over the relators is executed exactly once.

### 48.7.4 TzFindCyclicJoins

$\text{TzFindCyclicJoins}(P)$

searches for power and commutator relators in order to find pairs of generators which generate a common cyclic subgroup. It uses these pairs to introduce new relators, but it does not introduce any new generators as is done by TzSubstituteCyclicJoins (48.8.2).

More precisely: TzFindCyclicJoins searches for pairs of generators $a$ and $b$ such that (possibly after inverting or conjugating some relators) the set of relators contains the commutator $[a, b]$, a power $a^n$, and a product of the form $a^sb^t$ with $s$ prime to $n$. For each such pair, TzFindCyclicJoins uses the Euclidean algorithm to express $a$ as a power of $b$, and then it eliminates $a$. 
48.8 Tietze Transformations that introduce new Generators

Some of the Tietze transformation commands listed so far may eliminate generators and hence change the given presentation to a presentation on a subset of the given set of generators, but they all do not introduce new generators. However, sometimes there will be the need to substitute certain words as new generators in order to improve a presentation. Therefore GAP offers the two commands TzSubstitute (48.8.1) and TzSubstituteCyclicJoins (48.8.2) which introduce new generators.

48.8.1 TzSubstitute

\[ \text{TzSubstitute}(P, \text{word}) \]  
\[ \text{TzSubstitute}(P[, n[, \text{eliminate}]])) \]

In the first form TzSubstitute expects \( P \) to be a presentation and \( \text{word} \) to be either an abstract word or a Tietze word in the generators of \( P \). It substitutes the given word as a new generator of \( P \). This is done as follows: First, TzSubstitute creates a new abstract generator, \( g \) say, and adds it to the presentation, then it adds a new relator \( g^{-1} \cdot \text{word} \).

In its second form, TzSubstitute substitutes a squarefree word of length 2 as a new generator and then eliminates a generator from the extended generator list. We will describe this process in more detail below.

The parameters \( n \) and \( \text{eliminate} \) are optional. If you specify arguments for them, then \( n \) is expected to be a positive integer, and \( \text{eliminate} \) is expected to be 0, 1, or 2. The default values are \( n = 1 \) and \( \text{eliminate} = 0 \).

TzSubstitute first determines the \( n \) most frequently occurring relator subwords of the form \( g_1 g_2 \), where \( g_1 \) and \( g_2 \) are different generators or their inverses, and sorts them by decreasing numbers of occurrences.

Let \( ab \) be the last word in that list, and let \( i \) be the smallest positive integer which has not yet been used as a generator number in the presentation \( P \) so far. TzSubstitute defines a new abstract generator \( x_i \) named "x_i" and adds it to \( P \) (see AddGenerator (48.5.1)). Then it adds the word \( x_i^{-1} ab \) as a new relator to \( P \) and replaces all occurrences of \( ab \) in the relators by \( x_i \). Finally, it eliminates some suitable generator from \( P \).

The choice of the generator to be eliminated depends on the actual value of the parameter \( \text{eliminate} \):

If \( \text{eliminate} \) is zero, TzSubstitute just calls the function TzEliminate (48.7.1). So it may happen that it is the just introduced generator \( x_i \) which now is deleted again so that you don’t get any remarkable progress in simplifying your presentation. On the first glance this does not look reasonable, but it is a consequence of the request that a call of TzSubstitute with \( \text{eliminate} = 0 \) must not increase the total length of the relators.

Otherwise, if \( \text{eliminate} \) is 1 or 2, TzSubstitute eliminates the respective factor of the substituted word \( ab \), i.e., it eliminates \( a \) if \( \text{eliminate} = 1 \) or \( b \) if \( \text{eliminate} = 2 \). In this case, it may happen that the total length of the relators increases, but sometimes such an intermediate extension is the only way to finally reduce a given presentation.

There is still another property of the command TzSubstitute which should be mentioned. If, for instance, \( \text{word} \) is an abstract word, a call

\[ \text{TzSubstitute}(P, \text{word}); \]

Example
is more or less equivalent to

```
Example
AddGenerator( P );
g := GeneratorsOfPresentation(P)[Length(GeneratorsOfPresentation(P))];
AddRelator( P, g^-1 * word );
```

However, there is a difference: If you are tracing generator images and preimages of \( P \) through the Tietze transformations applied to \( P \) (see 48.9), then \texttt{TzSubstitute}, as a Tietze transformation of \( P \), will update and save the respective lists, whereas a call of the function \texttt{AddGenerator} (48.5.1) (which does not perform a Tietze transformation) will delete these lists and hence terminate the tracing.

```
Example
gap> G := PerfectGroup( IsSubgroupFpGroup, 960, 1 );
A5 2^-4
gap> P := PresentationFpGroup( G );
<presentation with 6 gens and 21 rels of total length 84>
gap> GeneratorsOfPresentation( P );
[ a, b, s, t, u, v ]
gap> TzGoGo( P );
#I there are 3 generators and 10 relators of total length 81
#I there are 3 generators and 10 relators of total length 80
gap> TzPrintGenerators( P );
#I 1. a 31 occurrences involution
#I 2. b 26 occurrences
#I 3. t 23 occurrences involution
gap> a := GeneratorsOfPresentation( P )[1];;
gap> b := GeneratorsOfPresentation( P )[2];;
gap> TzSubstitute( P, a*b );
#I now the presentation has 4 generators, the new generator is _x7
#I substituting new generator _x7 defined by a*b
#I there are 4 generators and 11 relators of total length 83
gap> TzGo( P );
#I there are 3 generators and 10 relators of total length 74
```

As an example of an application of the command \texttt{TzSubstitute} in its second form we handle a subgroup of index 266 in the Janko group \( J_1 \).

```
Example
gap> F2 := FreeGroup( "a", "b" );;
gap> J1 := F2 / [ F2.1^2, F2.2^3, (F2.1*F2.2)^7, 
                Comm(F2.1,F2.2)^10, Comm(F2.1,F2.2^-1*(F2.1*F2.2)^2)^6 ];;
gap> a := J1.1;; b := J1.2;;
gap> H := Subgroup( J1, [ a, b^(a*b*(a*b^-1)^2) ] );;
gap> P := PresentationSubgroup( J1, H );
<presentation with 23 gens and 82 rels of total length 530>
gap> TzGoGo( P );
#I there are 3 generators and 47 relators of total length 1368
#I there are 2 generators and 46 relators of total length 3773
#I there are 2 generators and 46 relators of total length 2570
```
Here we do not get any more progress without substituting a new generator.

Example

GAP cannot substitute a new generator without extending the total length, so we have to explicitly ask for it by using the second form of the command TzSubstitute. Our problem is to choose appropriate values for the arguments \( n \) and eliminate. For this purpose it may be helpful to print out a list of the most frequently occurring squarefree relator subwords of length 2.

Example

If we save a copy of the current presentation, then later we will be able to restart the computation from the current state.
Example

\begin{verbatim}
gap> P1 := ShallowCopy( P );;  
<presentation with 2 gens and 10 rels of total length 101>
\end{verbatim}

Just for demonstration we make an inconvenient choice:

\begin{verbatim}
gap> TzSubstitute( P, 3, 1 );
#I substituting new generator _x31 defined by _x23*_x30
#I eliminating _x23 = _x31*_x30^-1
#I there are 2 generators and 10 relators of total length 122

gap> TzGoGo( P );
#I there are 2 generators and 9 relators of total length 105
\end{verbatim}

This presentation is worse than the one we have saved, so we restart from that presentation again.

\begin{verbatim}
gap> P := ShallowCopy( P1 );
<presentation with 2 gens and 10 rels of total length 101>

gap> TzSubstitute( P, 2, 1);
#I substituting new generator _x31 defined by _x23^-1*_x30
#I eliminating _x23 = _x30*_x31^-1
#I there are 2 generators and 10 relators of total length 107

gap> TzGoGo( P );
#I there are 2 generators and 9 relators of total length 84
#I there are 2 generators and 8 relators of total length 75

gap> TzSubstitute( P, 2, 1);
#I substituting new generator _x32 defined by _x30^-1*_x31
#I eliminating _x30 = _x31*_x32^-1
#I there are 2 generators and 8 relators of total length 71

gap> TzGoGo( P );
#I there are 2 generators and 7 relators of total length 56
#I there are 2 generators and 5 relators of total length 36
\end{verbatim}

48.8.2 TzSubstituteCyclicJoins

\begin{verbatim}
\& TzSubstituteCyclicJoins(P)
\end{verbatim}

tries to find pairs of commuting generators \(a\) and \(b\), say, such that the exponent of \(a\) (i.e., the least currently known positive integer \(n\) such that \(a^n\) is a relator in \(P\)) is prime to the exponent of \(b\). For each such pair, their product \(ab\) is substituted as a new generator, and \(a\) and \(b\) are eliminated.

48.9 Tracing generator images through Tietze transformations

Any sequence of Tietze transformations applied to a presentation, starting from some presentation \(P_1\) and ending up with some presentation \(P_2\), defines an isomorphism, \(\varphi\) say, between the groups defined
by $P_1$ and $P_2$, respectively. Sometimes it is desirable to know the images of the (old) generators of $P_1$ or the preimages of the (new) generators of $P_2$ under $\varphi$. The GAP Tietze transformation functions are able to trace these images. This is not automatically done because the involved words may grow to tremendous length, but it will be done if you explicitly request for it by calling the function $\text{TzInitGeneratorImages}$ (48.9.1).

### 48.9.1 $\text{TzInitGeneratorImages}$

\[ \text{TzInitGeneratorImages}(P) \]

expects $P$ to be a presentation. It defines the current generators to be the “old generators” of $P$ and initializes the (pre)image tracing. See $\text{TzImagesOldGens}$ (48.9.3) and $\text{TzPreImagesNewGens}$ (48.9.4) for details.

You can reinitialize the tracing of the generator images at any later state by just calling the function $\text{TzInitGeneratorImages}$ again.

Note: A subsequent call of the function $\text{DecodeTree}$ (48.10.1) will imply that the images and preimages are deleted and reinitialized after decoding the tree.

Moreover, if you introduce a new generator by calling the function $\text{AddGenerator}$ (48.5.1) described in Section 48.5, this new generator cannot be traced in the old generators. Therefore $\text{AddGenerator}$ (48.5.1) will terminate the tracing of the generator images and preimages and delete the respective lists whenever it is called.

### 48.9.2 $\text{OldGeneratorsOfPresentation}$

\[ \text{OldGeneratorsOfPresentation}(P) \]

assumes that $P$ is a presentation for which the generator images and preimages are being traced under Tietze transformations. It returns the list of old generators of $P$.

### 48.9.3 $\text{TzImagesOldGens}$

\[ \text{TzImagesOldGens}(P) \]

assumes that $P$ is a presentation for which the generator images and preimages are being traced under Tietze transformations. It returns a list $l$ of words in the (current) $\text{GeneratorsOfPresentation}$ (48.1.3) value of $P$ such that the $i$-th word $l[i]$ represents the $i$-th old generator of $P$, i.e., the $i$-th entry of the $\text{OldGeneratorsOfPresentation}$ (48.9.2) value of $P$.

### 48.9.4 $\text{TzPreImagesNewGens}$

\[ \text{TzPreImagesNewGens}(P) \]

assumes that $P$ is a presentation for which the generator images and preimages are being traced under Tietze transformations. It returns a list $l$ of words in the old generators of $P$ (the $\text{OldGeneratorsOfPresentation}$ (48.9.2) value of $P$) such that the $i$-th entry of $l$ represents the $i$-th (current) generator of $P$ (the $\text{GeneratorsOfPresentation}$ (48.1.3) value of $P$).
48.9.5 TzPrintGeneratorImages

\[ \text{TzPrintGeneratorImages}(P) \]

assumes that \( P \) is a presentation for which the generator images and preimages are being traced under Tietze transformations. It displays the preimages of the current generators as Tietze words in the old generators, and the images of the old generators as Tietze words in the current generators.

```
gap> G := PerfectGroup( IsSubgroupFpGroup, 960, 1 );
A5 2^-4
gap> P := PresentationFpGroup( G );
<presentation with 6 gens and 21 rels of total length 84>
gap> TzInitGeneratorImages( P );
gap> TzGo( P );
#I there are 3 generators and 11 relators of total length 96
#I there are 3 generators and 10 relators of total length 81
gap> TzPrintGeneratorImages( P );
#I preimages of current generators as Tietze words in the old ones:
#I 1. [ 1 ]
#I 2. [ 2 ]
#I 3. [ 4 ]
#I images of old generators as Tietze words in the current ones:
#I 1. [ 1 ]
#I 2. [ 2 ]
#I 3. [ 1, -2, 1, 3, 1, 2, 1 ]
#I 4. [ 3 ]
#I 5. [ -2, 1, 3, 1, 2 ]
#I 6. [ 1, 3, 1 ]
gap> gens := GeneratorsOfPresentation( P );
[ a, b, t ]
gap> oldgens := OldGeneratorsOfPresentation( P );
[ a, b, s, t, u, v ]
gap> TzImagesOldGens( P );
[ a, b, a*b^-1*a*t*a*b*a, t, b^-1*a*t*a*b, a*t*a ]
gap> for i in [ 1 .. Length( oldgens ) ] do
  > Print( oldgens[i], " = ", TzImagesOldGens( P )[i], "\n" );
  > od;
a = a
b = b
s = a*b^-1*a*t*a*b*a
t = t
u = b^-1*a*t*a*b
v = a*t*a
```

48.10 The Decoding Tree Procedure

48.10.1 DecodeTree

\[ \text{DecodeTree}(P) \]

Example

```
assumes that \( P \) is a subgroup presentation provided by the Reduced Reidemeister-Schreier or by the Modified Todd-Coxeter method (see `PresentationSubgroupRrs` (48.2.2), `PresentationNormalClosureRrs` (48.2.5), `PresentationSubgroupMtc` (48.2.4)). It eliminates the secondary generators of \( P \) (see Section 48.2) by applying the so called “decoding tree” procedure.

`DecodeTree` is called automatically by the command `PresentationSubgroupMtc` (48.2.4) where it reduces \( P \) to a presentation on the given (primary) subgroup generators.

In order to explain the effect of this command we need to insert a few remarks on the subgroup presentation commands described in section 48.2. All these commands have the common property that in the process of constructing a presentation for a given subgroup \( H \) of a finitely presented group \( G \) they first build up a highly redundant list of generators of \( H \) which consists of an (in general small) list of “primary” generators, followed by an (in general large) list of “secondary” generators, and then construct a presentation \( P_0 \), say, on a sublist of these generators by rewriting the defining relators of \( G \). This sublist contains all primary, but, at least in general, by far not all secondary generators.

The role of the primary generators depends on the concrete choice of the subgroup presentation command. If the Modified Todd-Coxeter method is used, they are just the given generators of \( H \), whereas in the case of the Reduced Reidemeister-Schreier algorithm they are constructed by the program.

Each of the secondary generators is defined by a word of length two in the preceding generators and their inverses. By historical reasons, the list of these definitions is called the subgroup generators tree though in fact it is not a tree but rather a kind of bush.

Now we have to distinguish two cases. If \( P_0 \) has been constructed by the Reduced Reidemeister-Schreier routines, it is a presentation of \( H \). However, if the Modified Todd-Coxeter routines have been used instead, then the relators in \( P_0 \) are valid relators of \( H \), but they do not necessarily define \( H \). We handle these cases in turn, starting with the latter one.

In fact, we could easily receive a presentation of \( H \) also in this case if we extended \( P_0 \) by adding to it all the secondary generators which are not yet contained in it and all the definitions from the generators tree as additional generators and relators. Then we could recursively eliminate all secondary generators by Tietze transformations using the new relators. However, this procedure turns out to be too inefficient to be of interest.

Instead, we use the so called decoding tree procedure (see [AMW82], [AR84]). It proceeds as follows.

Starting from \( P = P_0 \), it runs through a number of steps in each of which it eliminates the current “last” generator (with respect to the list of all primary and secondary generators). If the last generator \( g \), say, is a primary generator, then the procedure terminates. Otherwise it checks whether there is a relator in the current presentation which can be used to substitute \( g \) by a Tietze transformation. If so, this is done. Otherwise, and only then, the tree definition of \( g \) is added to \( P \) as a new relator, and the generators involved are added as new generators if they have not yet been contained in \( P \). Subsequently, \( g \) is eliminated.

Note that the extension of \( P \) by one or two new generators is not a Tietze transformation. In general, it will change the isomorphism type of the group defined by \( P \). However, it is a remarkable property of this procedure, that at the end, i.e., as soon as all secondary generators have been eliminated, it provides a presentation \( P = P_1 \), say, which defines a group isomorphic to \( H \). In fact, it is this presentation which is returned by the command `DecodeTree` and hence by the command `PresentationSubgroupMtc` (48.2.4).

If, in the other case, the presentation \( P_0 \) has been constructed by the Reduced Reidemeister-Schreier algorithm, then \( P_0 \) itself is a presentation of \( H \), and the corresponding subgroup presentation
command (PresentationSubgroupRrs (48.2.2) or PresentationNormalClosureRrs (48.2.5)) just returns $P_0$.

As mentioned in section 48.2, we recommend to further simplify this presentation before you use it. The standard way to do this is to start from $P_0$ and to apply suitable Tietze transformations, e. g., by calling the commands TzGo (48.6.1) or TzGoGo (48.6.3). This is probably the most efficient approach, but you will end up with a presentation on some unpredictable set of generators. As an alternative, GAP offers you the DecodeTree command which you can use to eliminate all secondary generators (provided that there are no space or time problems). For this purpose, the subgroup presentation commands do not only return the resulting presentation, but also the tree (together with some associated lists) as a kind of side result in a component $P!.tree$ of the resulting presentation $P$.

Note, however, that the decoding tree routines will not work correctly any more on a presentation from which generators have already been eliminated by Tietze transformations. Therefore, to prevent you from getting wrong results by calling DecodeTree in such a situation, GAP will automatically remove the subgroup generators tree from a presentation as soon as one of the generators is substituted by a Tietze transformation.

Nevertheless, a certain misuse of the command is still possible, and we want to explicitly warn you from this. The reason is that the Tietze option parameters described in Section 48.11 apply to DecodeTree as well. Hence, in case of inadequate values of these parameters, it may happen that DecodeTree stops before all the secondary generators have vanished. In this case GAP will display an appropriate warning. Then you should change the respective parameters and continue the process by calling DecodeTree again. Otherwise, if you would apply Tietze transformations, it might happen because of the convention described above that the tree is removed and that you end up with a wrong presentation.

After a successful run of DecodeTree it is convenient to further simplify the resulting presentation by suitable Tietze transformations.

As an example of an explicit call of DecodeTree we compute two presentations of a subgroup of order 384 in a group of order 6912. In both cases we use the Reduced Reidemeister-Schreier algorithm, but in the first run we just apply the Tietze transformations offered by the TzGoGo (48.6.3) command with its default parameters, whereas in the second run we call the DecodeTree command before.

```
Example

```gap
F2 := FreeGroup( "a", "b" );;
gap> G := F2 / [ F2.1*F2.2^2*F2.1^-1*F2.2^-1*F2.1^3*F2.2^-1, 
  F2.2*F2.1^2*F2.2^-1*F2.1^-1*F2.2^3*F2.1^-1 ];;
gap> a := G.1;; b := G.2;;
gap> H := Subgroup( G, [ Comm(a^-1,b^-1), Comm(a^-1,b), Comm(a,b) ] );;
```gap

We use the Reduced Reidemeister Schreier method and default Tietze transformations to get a presentation for $H$.

```
Example

```gap
P := PresentationSubgroupRrs( G, H );
<presentation with 18 gens and 35 rels of total length 169>
gap> TzGoGo( P );
#I there are 3 generators and 20 relators of total length 488
#I there are 3 generators and 20 relators of total length 466
```gap

We end up with 20 relators of total length 466. Now we repeat the procedure, but we call the decoding tree algorithm before doing the Tietze transformations.
Example

```gap
gap> P := PresentationSubgroupRrs( G, H );
<presentation with 18 gens and 35 rels of total length 169>
gap> DecodeTree( P );
#I there are 9 generators and 26 relators of total length 185
#I there are 6 generators and 23 relators of total length 213
#I there are 3 generators and 20 relators of total length 262
#I there are 3 generators and 20 relators of total length 244

gap> TzGoGo( P );
#I there are 3 generators and 19 relators of total length 168
#I there are 3 generators and 17 relators of total length 138
#I there are 3 generators and 15 relators of total length 114
#I there are 3 generators and 13 relators of total length 96
#I there are 3 generators and 12 relators of total length 84
```

This time we end up with a shorter presentation.

### 48.11 Tietze Options

Several of the Tietze transformation commands described above are controlled by certain parameters, the Tietze options, which often have a tremendous influence on their performance and results. However, in each application of the commands, an appropriate choice of these option parameters will depend on the concrete presentation under investigation. Therefore we have implemented the Tietze options in such a way that they are associated to the presentation: Each presentation keeps its own set of Tietze option parameters as an attribute.

#### 48.11.1 TzOptions

```gap
d> TzOptions(P) (attribute)
```

is a record whose components direct the heuristics applied by the Tietze transformation functions. You may alter the value of any of these Tietze options by just assigning a new value to the respective record component.

The following Tietze options are recognized by GAP:

protected:
The first protected generators in a presentation \( P \) are protected from being eliminated by the Tietze transformations functions. There are only two exceptions: The option protected is ignored by the functions TzEliminate (48.7.1) and TzSubstitute (48.8.1) because they explicitly specify the generator to be eliminated. The default value of protected is 0.

eliminationsLimit:
Whenever the elimination phase of the TzGo (48.6.1) command is entered for a presentation \( P \), then it will eliminate at most eliminationsLimit generators (except for further ones which have turned out to be trivial). Hence you may use the eliminationsLimit parameter as a break criterion for the TzGo (48.6.1) command. Note, however, that it is ignored by the TzEliminate (48.7.1) command. The default value of eliminationsLimit is 100.
expandLimit:
Whenever the routine for eliminating more than 1 generators is called for a presentation \( P \) by the \texttt{TzEliminate} (48.7.1) command or the elimination phase of the \texttt{TzGo} (48.6.1) command, then it saves the given total length of the relators, and subsequently it checks the current total length against its value before each elimination. If the total length has increased to more than \( \text{expandLimit} \) per cent of its original value, then the routine returns instead of eliminating another generator. Hence you may use the \( \text{expandLimit} \) parameter as a break criterion for the \texttt{TzGo} (48.6.1) command. The default value of \( \text{expandLimit} \) is 150.

generatorsLimit:
Whenever the elimination phase of the \texttt{TzGo} (48.6.1) command is entered for a presentation \( P \) with \( n \) generators, then it will eliminate at most \( n - \text{generatorsLimit} \) generators (except for generators which turn out to be trivial). Hence you may use the \( \text{generatorsLimit} \) parameter as a break criterion for the \texttt{TzGo} (48.6.1) command. The default value of \( \text{generatorsLimit} \) is 0.

lengthLimit:
The Tietze transformation commands will never eliminate a generator of a presentation \( P \), if they cannot exclude the possibility that the resulting total length of the relators exceeds the maximal \texttt{GAP} list length of \( 2^{31} - 1 \) or the value of the option \( \text{lengthLimit} \). The default value of \( \text{lengthLimit} \) is \( 2^{31} - 1 \).

loopLimit:
Whenever the \texttt{TzGo} (48.6.1) command is called for a presentation \( P \), then it will loop over at most \( \text{loopLimit} \) of its basic steps. Hence you may use the \( \text{loopLimit} \) parameter as a break criterion for the \texttt{TzGo} (48.6.1) command. The default value of \( \text{loopLimit} \) is \textit{infinity} (18.2.1).

printLevel:
Whenever Tietze transformation commands are called for a presentation \( P \) with \( \text{printLevel} = 0 \), they will not provide any output except for error messages. If \( \text{printLevel} = 1 \), they will display some reasonable amount of output which allows you to watch the progress of the computation and to decide about your next commands. In the case \( \text{printLevel} = 2 \), you will get a much more generous amount of output. Finally, if \( \text{printLevel} = 3 \), various messages on internal details will be added. The default value of \( \text{printLevel} \) is 1.

saveLimit:
Whenever the \texttt{TzSearch} (48.7.2) command has finished its main loop over all relators of a presentation \( P \), then it checks whether during this loop the total length of the relators has been reduced by at least \( \text{saveLimit} \) per cent. If this is the case, then \texttt{TzSearch} (48.7.2) repeats its procedure instead of returning. Hence you may use the \( \text{saveLimit} \) parameter as a break criterion for the \texttt{TzSearch} (48.7.2) command and, in particular, for the search phase of the \texttt{TzGo} (48.6.1) command. The default value of \( \text{saveLimit} \) is 10.

searchSimultaneous:
Whenever the \texttt{TzSearch} (48.7.2) or the \texttt{TzSearchEqual} (48.7.3) command is called for a presentation \( P \), then it is allowed to handle up to \( \text{searchSimultaneous} \) short relators simultaneously (see the description of the \texttt{TzSearch} (48.7.2) command for more details). The choice of this parameter may heavily influence the performance as well as the result of the \texttt{TzSearch} command.
and the TzSearchEqual commands and hence also of the search phase of the TzGo command. The default value of searchSimultaneous is 20.

48.11.2 TzPrintOptions

\texttt{TzPrintOptions(P)}

prints the current values of the Tietze options of the presentation \(P\).

\begin{verbatim}
gap> TzPrintOptions(P); #I protected = 0 #I eliminationLimit = 100 #I expandLimit = 150 #I generatorsLimit = 0 #I lengthLimit = 2147483647 #I loopLimit = infinity #I printLevel = 1 #I saveLimit = 10 #I searchSimultaneous = 20
\end{verbatim}
Chapter 49

Group Products

This chapter describes the various group product constructions that are possible in GAP.

At the moment for some of the products methods are available only if both factors are given in the same representation or only for certain types of groups such as permutation groups and pc groups when the product can be naturally represented as a group of the same kind.

GAP does not guarantee that a product of two groups will be in a particular representation. (Exceptions are WreathProductImprimitiveAction (49.4.2) and WreathProductProductAction (49.4.3) which are construction that makes sense only for permutation groups, see WreathProduct (49.4.1)).

GAP however will try to choose an efficient representation, so products of permutation groups or pc groups often will be represented as a group of the same kind again.

Therefore the only guaranteed way to relate a product to its factors is via the embedding and projection homomorphisms, see 49.6.

49.1 Direct Products

The direct product of groups is the cartesian product of the groups (considered as element sets) with component-wise multiplication.

49.1.1 DirectProduct

▷ DirectProduct(G[, H, ...])
▷ DirectProductOp(list, expl)

These functions construct the direct product of the groups given as arguments. DirectProduct takes an arbitrary positive number of arguments and calls the operation DirectProductOp, which takes exactly two arguments, namely a nonempty list list of groups and one of these groups, expl. (This somewhat strange syntax allows the method selection to choose a reasonable method for special cases, e.g., if all groups are permutation groups or pc groups.)

GAP will try to choose an efficient representation for the direct product. For example the direct product of permutation groups will be a permutation group again and the direct product of pc groups will be a pc group.

If the groups are in different representations a generic direct product will be formed which may not be particularly efficient for many calculations. Instead it may be worth to convert all factors to a
common representation first, before forming the product.

For a direct product \( P \), calling \texttt{Embedding (32.2.11)} with \( P \) and \( n \) yields the homomorphism embedding the \( n \)-th factor into \( P \); calling \texttt{Projection (32.2.12)} with \( P \) and \( n \) yields the projection of \( P \) onto the \( n \)-th factor, see 49.6.

```gap
gap> g:=Group((1,2,3),(1,2));;
gap> d:=DirectProduct(g,g,g);
Group([ (1,2,3), (1,2), (4,5,6), (4,5), (7,8,9), (7,8) ])
gap> Size(d);
216
gap> e:=Embedding(d,2);
2nd embedding into Group([ (1,2,3), (1,2), (4,5,6), (4,5), (7,8,9),
(7,8) ])
gap> Image(e,(1,2));
(4,5)
gap> Image(Projection(d,2),(1,2,3)(4,5)(8,9));
(1,2)
gap> f:=FreeGroup("a","b");;
gap> g:=f/ParseRelators(f,"a2,b3,(ab)5");
<fp group on the generators [ a, b ]>
gap> f2:=FreeGroup("x","y");;
gap> h:=f2/ParseRelators(f2,"x2,y4,xy=Yx");
<fp group on the generators [ x, y ]>
gap> d:=DirectProduct(g,h);
<fp group on the generators [ a, b, x, y ]>
```

### 49.2 Semidirect Products

The semidirect product of a group \( N \) with a group \( G \) acting on \( N \) via a homomorphism \( \alpha \) from \( G \) into the automorphism group of \( N \) is the cartesian product \( G \times N \) with the multiplication \((g,n) \cdot (h,m) = (gh,n^{h_{\alpha}}m)\).

#### 49.2.1 SemidirectProduct

- \texttt{SemidirectProduct(G, alpha, N)} (operation)
- \texttt{SemidirectProduct(autgp, N)} (operation)

constructs the semidirect product of \( N \) with \( G \) acting via \( \alpha \), which must be a homomorphism from \( G \) into a group of automorphisms of \( N \).

If \( N \) is a group, \( \alpha \) must be a homomorphism from \( G \) into a group of automorphisms of \( N \).

If \( N \) is a full row space over a field \( F \), \( \alpha \) must be a homomorphism from \( G \) into a matrix group of the right dimension over a subfield of \( F \), or into a permutation group (in this case permutation matrices are taken).

In the second variant, \( \texttt{autgp} \) must be a group of automorphism of \( N \), it is a shorthand for \texttt{SemidirectProduct(autgp,IdentityMapping(autgp),N)}. Note that (unless \( \texttt{autgp} \) has been obtained by the operation \texttt{AutomorphismGroup (40.7.1)}) you have to test \texttt{IsGroupOfAutomorphisms (40.7.2)} for \( \texttt{autgp} \) to ensure that GAP knows that \( \texttt{autgp} \) consists of group automorphisms.
Example

```gap
gap> n:=AbelianGroup(IsPcGroup,[5,5]);
<pc group of size 25 with 2 generators>
gap> au:=DerivedSubgroup(AutomorphismGroup(n));;
gap> Size(au);
120
gap> p:=SemidirectProduct(au,n);
gap> Size(p);
3000
gap> n:=Group((1,2),(3,4));;
gap> au:=AutomorphismGroup(n);
gap> au:=First(AsSet(au),i->Order(i)=3);
gap> au:=Group(au);
<group with 1 generators>
gap> IsGroupOfAutomorphisms(au);
true
gap> SemidirectProduct(au,n);
<pc group with 3 generators>
gap> n:=AbelianGroup(IsPcGroup,[2,2]);
<pc group of size 4 with 2 generators>
gap> au:=AutomorphismGroup(n);
gap> apc:=IsomorphismPcGroup(au);
gap> g:=Image(apc);
Group([ f1, f2 ])
gap> apci:=InverseGeneralMapping(apc);
gap> IsGroupHomomorphism(apci);
true
gap> p:=SemidirectProduct(g,apci,n);
<pc group of size 24 with 4 generators>
gap> IsomorphismGroups(p,Group((1,2,3,4),(1,2))) <> fail;
true
gap> SemidirectProduct(SU(3,3),GF(9)^3);
<matrix group of size 4408992 with 3 generators>
gap> SemidirectProduct(Group((1,2,3),(2,3,4)),GF(5)^4);
<matrix group of size 7500 with 3 generators>
gap> g:=Group((3,4,5),(1,2,3));;
gap> mats:=
[[Z(2^2),0*Z(2)],[0*Z(2),Z(2^2)^2]],
> [[Z(2)^0,Z(2)^0],[Z(2)^0,0*Z(2)]]];
gap> hom:=GroupHomomorphismByImages(g,Group(mats),[g.1,g.2],mats);
gap> SemidirectProduct(g,hom,GF(4)^2);
<matrix group of size 960 with 3 generators>
gap> SemidirectProduct(g,hom,GF(16)^2);
<matrix group of size 15360 with 4 generators>
```

For a semidirect product $P$ of $G$ with $N$, calling `Embedding` (32.2.11) with $P$ and 1 yields the embedding of $G$, calling `Embedding` (32.2.11) with $P$ and 2 yields the embedding of $N$; calling `Projection` (32.2.12) with $P$ yields the projection of $P$ onto $G$, see 49.6.

Example

```gap
gap> Size(Image(Embedding(p,1)));  
6
gap> Embedding(p,2);
[ f1, f2 ] -> [ f3, f4 ]
```
49.3 Subdirect Products

The subdirect product of the groups $G$ and $H$ with respect to the epimorphisms $\varphi: G \rightarrow A$ and $\psi: H \rightarrow A$ (for a common group $A$) is the subgroup of the direct product $G \times H$ consisting of the elements $(g, h)$ for which $g^\varphi = h^\psi$. It is the pull-back of the following diagram.

\[
\begin{array}{ccc}
G & \xrightarrow{\varphi} & A \\
\downarrow & & \\
H & \xrightarrow{\psi} & A \\
\end{array}
\]

49.3.1 SubdirectProduct

`SubdirectProduct(G, H, Ghom, Hhom)` constructs the subdirect product of $G$ and $H$ with respect to the epimorphisms $Ghom$ from $G$ onto a group $A$ and $Hhom$ from $H$ onto the same group $A$.

For a subdirect product $P$, calling `Projection` (32.2.12) with $P$ and $n$ yields the projection on the $n$-th factor. (In general the factors do not embed into a subdirect product.)

```gap
gap> g:=Group((1,2,3),(1,2));
Group([ (1,2,3), (1,2) ])
gap> hom:=GroupHomomorphismByImagesNC(g,g,[[(1,2,3),(1,2)],[()],(1,2)]);
[ (1,2,3), (1,2) ] -> [ (), (1,2) ]
gap> s:=SubdirectProduct(g,g,hom,hom);
Group([ (1,2,3), (1,2)(4,5), (4,5,6) ])
gap> Size(s);
18
gap> p:=Projection(s,2);
2nd projection of Group([ (1,2,3), (1,2)(4,5), (4,5,6) ])
gap> Image(p,(1,3,2)(4,5,6));
(1,2,3)
```

49.3.2 SubdirectProducts

`SubdirectProducts(G, H)` computes all subdirect products of $G$ and $H$ up to conjugacy in the direct product of `Parent(G)` and `Parent(H)`. The subdirect products are returned as subgroups of this direct product.

49.4 Wreath Products

The wreath product of a group $G$ with a permutation group $P$ acting on $n$ points is the semidirect product of the normal subgroup $G^n$ with the group $P$ which acts on $G^n$ by permuting the components.
Note that GAP always considers the domain of a permutation group to be the points moved by elements of the group as returned by `MovedPoints (42.3.3)`, i.e. it is not possible to have a domain to include fixed points, i.e. $P = \langle (1,2,3) \rangle$ and $P = \langle (1,3,5) \rangle$ result in isomorphic wreath products. (If fixed points are desired the wreath product $G \wr T$ has to be formed with a transitive overgroup $T$ of $P$ and then the pre-image of $P$ under the projection $G \wr T \to T$ has to be taken.)

### 49.4.1 WreathProduct

- `WreathProduct(G, H[, hom])` (operation)
- `StandardWreathProduct(G, H)` (operation)

WreathProduct constructs the wreath product of the group $G$ with the group $H$, acting as a permutation group.

If a third argument `hom` is given, it must be a homomorphism from $H$ into a permutation group, and the action of this group on its moved points is considered.

If only two arguments are given, $H$ must be a permutation group.

`StandardWreathProduct` returns the wreath product for the (right regular) permutation action of $H$ on its elements.

For a wreath product $W$ of $G$ with a permutation group $P$ of degree $n$ and $1 \leq i \leq n$ calling `Embedding (32.2.11)` with $W$ and $i$ yields the embedding of $G$ in the $i$-th component of the direct product of the base group $G^n$ of $W$. For $i = n + 1$, `Embedding (32.2.11)` yields the embedding of $P$ into $W$. Calling `Projection (32.2.12)` with $W$ yields the projection onto the acting group $P$, see 49.6.

```gap
g:=Group((1,2,3),(1,2));  
group:=Group([(1,2,3),(1,2)]);
p:=Group((1,2,3));
p:=Group([(1,2,3)]);
w:=WreathProduct(g,p);
w:=Group([(1,2,3),(1,2),(4,5,6),(4,5),(7,8,9),(7,8),(1,4,7)(2,5,8)(3,6,9)]);
Size(w);  
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Embedding(w,1);  
1st embedding into Group( [ (1,2,3), (1,2), (4,5,6), (4,5), (7,8,9), (7,8), (1,4,7)(2,5,8)(3,6,9) ] )

Image(Embedding(w,3));  
Group([ (7,8,9),(7,8) ])

Image(Embedding(w,4));  
Group([ (1,4,7)(2,5,8)(3,6,9) ])

Image(Projection(w),(1,4,8,2,6,7,3,5,9));  
(1,2,3)
```

### 49.4.2 WreathProductImprimitiveAction

- `WreathProductImprimitiveAction(G, H)` (function)

For two permutation groups $G$ and $H$, this function constructs the wreath product of $G$ and $H$ in the imprimitive action. If $G$ acts on $l$ points and $H$ on $m$ points this action will be on $l \cdot m$ points, it will be imprimitive with $m$ blocks of size $l$ each.
The operations Embedding (32.2.11) and Projection (32.2.12) operate on this product as described for general wreath products.

Example

```gap
gap> w:=WreathProductImprimitiveAction(g,p);
gap> LargestMovedPoint(w);
gap> 9
```

### 49.4.3 WreathProductProductAction

**WreathProductProductAction**

For two permutation groups \( G \) and \( H \), this function constructs the wreath product in product action. If \( G \) acts on \( l \) points and \( H \) on \( m \) points this action will be on \( lm \) points.

The operations Embedding (32.2.11) and Projection (32.2.12) operate on this product as described for general wreath products.

Example

```gap
gap> w:=WreathProductProductAction(g,p);
gap> LargestMovedPoint(w);
gap> 27
```

### 49.4.4 KuKGenerators

**KuKGenerators**

If \( \beta \) is a homomorphism from \( G \) into a transitive permutation group, \( U \) the full preimage of the point stabilizer and \( \alpha \) a homomorphism defined on (a superset) of \( U \), this function returns images of the generators of \( G \) when mapping to the wreath product \((U\alpha) \wr (G\beta)\). (This is the Krasner-Kaloujnine embedding theorem.)

Example

```gap
gap> g:=Group((1,2,3,4),(1,2));;
gap> hom:=GroupHomomorphismByImages(g,Group((1,2)),
> GeneratorsOfGroup(g),[(1,2),(1,2)]);
gap> u:=PreImage(hom,Stabilizer(Image(hom),1));
gap> hom2:=GroupHomomorphismByImages(u,Group((1,2,3)),
> GeneratorsOfGroup(u),[(1,2,3),(1,2,3)]);
gap> KuKGenerators(g,hom,hom2);
[ (1,4)(2,5)(3,6), (1,6)(2,4)(3,5) ]
```

### 49.5 Free Products

Let \( G \) and \( H \) be groups with presentations \( \langle X \mid R \rangle \) and \( \langle Y \mid S \rangle \), respectively. Then the free product \( G \ast H \) is the group with presentation \( \langle X \cup Y \mid R \cup S \rangle \). This construction can be generalized to an arbitrary number of groups.
49.5.1 FreeProduct

\[ \text{FreeProduct}(G[, H, \ldots]) \]
\[ \text{FreeProduct}(\text{list}) \]

constructs a finitely presented group which is the free product of the groups given as arguments. If the group arguments are not finitely presented groups, then \texttt{IsomorphismFpGroup (47.11.1)} must be defined for them.

The operation \texttt{Embedding (32.2.11)} operates on this product.

\begin{verbatim}
gap> g := DihedralGroup(8);;  
gap> h := CyclicGroup(5);;  
gap> fp := FreeProduct(g,h,h);  
<fp group on the generators [ f1, f2, f3, f4, f5 ]>  
gap> fp := FreeProduct([g,h,h]);  
<fp group on the generators [ f1, f2, f3, f4, f5 ]>  
gap> Embedding(fp,2);  
[ f1 ] -> [ f4 ]
\end{verbatim}

49.6 Embeddings and Projections for Group Products

The relation between a group product and its factors is provided via homomorphisms, the embeddings in the product and the projections from the product. Depending on the kind of product only some of these are defined.

49.6.1 Embedding (for group products)

\[ \text{Embedding}(P, \text{nr}) \]

returns the \( \text{nr} \)-th embedding in the group product \( P \). The actual meaning of this embedding is described in the manual section for the appropriate product.

49.6.2 Projection (for group products)

\[ \text{Projection}(P, \text{nr}) \]

returns the (\text{nr} -th) projection of the group product \( P \). The actual meaning of the projection returned is described in the manual section for the appropriate product.
Chapter 50

Group Libraries

When you start GAP, it already knows several groups. Currently GAP initially knows the following groups:

- some basic groups, such as cyclic groups or symmetric groups (see 50.1),
- Classical matrix groups (see 50.2),
- the transitive permutation groups of degree at most 30, provided by the TransGrp package (see (transgrp: Transitive Permutation Groups)),
- a library of groups of small order (see (smallgrp: The Small Groups Library)),
- the finite perfect groups of size at most $10^6$ (excluding 11 sizes) (see 50.6).
- the primitive permutation groups of degree $< 4096$, provided by the PrimGrp package (see (primgrp: Primitive Permutation Groups)),
- the irreducible solvable subgroups of $GL(n, p)$ for $n > 1$ and $p^n < 256$, provided by the PrimGrp package (see (primgrp: Irreducible Solvable Matrix Groups)),
- the irreducible maximal finite integral matrix groups of dimension at most 31 (see 50.7),
- the crystallographic groups of dimension at most 4

There is usually no relation between the groups in the different libraries and a group may occur in different libraries in different incarnations.

Note that a system administrator may choose to install all, or only a few, or even none of the libraries. So some of the libraries mentioned below may not be available on your installation.

GAP might use data libraries that are available to speed up calculations, for example in using a classification to determine that groups must be isomorphic, based on agreement of properties; or to determine maximal subgroups or subgroup maximality. This will be indicated by an info message of level 2 in the info class InfoPerformance. If the calculation is to be independent of such data library use, for example if it is used to verify the data library, functions can be called with the option NoPrecomputedData, to turn these features off. Doing so might cause significantly longer calculations, or even failure of certain calculations.
50.1 Basic Groups

There are several infinite families of groups which are parametrized by numbers. GAP provides various functions to construct these groups. The functions always permit (but do not require) one to indicate a filter (see 13.2), for example IsPermGroup (43.1.1), IsMatrixGroup (44.1.1) or IsPcGroup (46.3.1), in which the group shall be constructed. There always is a default filter corresponding to a “natural” way to describe the group in question. Note that not every group can be constructed in every filter, there may be theoretical restrictions (IsPcGroup (46.3.1) only works for solvable groups) or methods may be available only for a few filters.

Certain filters may admit additional hints. For example, groups constructed in IsMatrixGroup (44.1.1) may be constructed over a specified field, which can be given as second argument of the function that constructs the group; The default field is Rationals (17.1.1).

50.1.1 TrivialGroup

\texttt{TrivialGroup([filter])} (function)

constructs a trivial group in the category given by the filter \texttt{filter}. If \texttt{filter} is not given it defaults to IsPcGroup (46.3.1). For more information on possible values of \texttt{filt} see section (50.1).

Example
\begin{verbatim}
gap> TrivialGroup();
<pc group of size 1 with 0 generators>
gap> TrivialGroup( IsPermGroup );
Group(())
\end{verbatim}

50.1.2 CyclicGroup

\texttt{CyclicGroup([filt, ]n)} (function)

constructs the cyclic group of size \texttt{n} in the category given by the filter \texttt{filt}. If \texttt{filt} is not given it defaults to IsPcGroup (46.3.1), unless \texttt{n} equals infinity (18.2.1), in which case the default filter is switched to IsFpGroup (47.1.2). For more information on possible values of \texttt{filt} see section (50.1).

Example
\begin{verbatim}
gap> CyclicGroup(12);
<pc group of size 12 with 3 generators>
gap> CyclicGroup(infinity);
<free group on the generators [ a ]>
gap> CyclicGroup(IsPermGroup,12);
Group([ (1,2,3,4,5,6,7,8,9,10,11,12) ])
gap> matgrp1:= CyclicGroup( IsMatrixGroup, 12 );
<matrix group of size 12 with 1 generators>
gap> FieldOfMatrixGroup( matgrp1 );
Rationals
gap> matgrp2:= CyclicGroup( IsMatrixGroup, GF(2), 12 );
<matrix group of size 12 with 1 generators>
gap> FieldOfMatrixGroup( matgrp2 );
GF(2)
\end{verbatim}
50.1.3 AbelianGroup

\[ \text{AbelianGroup}([\text{filt}, \text{ints}]) \]

constructs an abelian group in the category given by the filter \( \text{filt} \) which is of isomorphism type \( \mathbb{C}_{\text{ints}[1]} \times \mathbb{C}_{\text{ints}[2]} \times \cdots \times \mathbb{C}_{\text{ints}[n]} \), where \( \text{ints} \) must be a list of non-negative integers or infinity (18.2.1); for the latter value or 0, \( \mathbb{C}_{\text{ints}[i]} \) is taken as an infinite cyclic group, otherwise as a cyclic group of order \( \text{ints}[i] \). If \( \text{filt} \) is not given it defaults to \text{IsPcGroup} (46.3.1), unless any 0 or infinity is contained in \( \text{ints} \), in which the default filter is switched to \text{IsFpGroup} (47.1.2). The generators of the group returned are the elements corresponding to the factors \( \mathbb{C}_{\text{ints}[i]} \) and hence the integers in \( \text{ints} \). For more information on possible values of \( \text{filt} \) see section (50.1).

Example

```gap
gap> AbelianGroup([1,2,3]);
<pc group of size 6 with 3 generators>
```

```gap
gap> G:=AbelianGroup([0,3]);
<fp group of size infinity on the generators [ f1, f2 ]>
```

50.1.4 ElementaryAbelianGroup

\[ \text{ElementaryAbelianGroup}([\text{filt}, \text{n}]) \]

constructs the elementary abelian group of size \( n \) in the category given by the filter \( \text{filt} \). If \( \text{filt} \) is not given it defaults to \text{IsPcGroup} (46.3.1). For more information on possible values of \( \text{filt} \) see section (50.1).

Example

```gap
gap> ElementaryAbelianGroup(8192);
<pc group of size 8192 with 13 generators>
```

50.1.5 FreeAbelianGroup

\[ \text{FreeAbelianGroup}([\text{filt}, \text{rank}]) \]

constructs the free abelian group of rank \( n \) in the category given by the filter \( \text{filt} \). If \( \text{filt} \) is not given it defaults to \text{IsFpGroup} (47.1.2). For more information on possible values of \( \text{filt} \) see section (50.1).

Example

```gap
gap> FreeAbelianGroup(4);
<fp group of size infinity on the generators [ f1, f2, f3, f4 ]>
```

50.1.6 DihedralGroup

\[ \text{DihedralGroup}([\text{filt}, \text{n}]) \]

constructs the dihedral group of size \( n \) in the category given by the filter \( \text{filt} \). If \( \text{filt} \) is not given it defaults to \text{IsPcGroup} (46.3.1), unless \( n \) equals infinity (18.2.1), in which case the default
filter is switched to \texttt{IsFpGroup} (47.1.2). For more information on possible values of \texttt{filt} see section (50.1).

\begin{verbatim}
GAP> DihedralGroup(8);
<pc group of size 8 with 3 generators>
GAP> DihedralGroup( IsPermGroup, 8 );
Group([ (1,2,3,4), (2,4) ])
GAP> DihedralGroup(infinity);
<fp group of size infinity on the generators [ r, s ]>
\end{verbatim}

50.1.7 \textbf{IsDihedralGroup}

\begin{itemize}
\item \texttt{IsDihedralGroup(}G\texttt{)}
\item \texttt{DihedralGenerators(}G\texttt{)}
\end{itemize}

\texttt{IsDihedralGroup} indicates whether the group \texttt{G} is a dihedral group. If it is, methods may set the attribute \texttt{DihedralGenerators} to \texttt{[t, s]}, where \texttt{t} and \texttt{s} are two elements such that \texttt{G} = \langle \texttt{t}, \texttt{s} | t^2 = s^n = 1, t^-1 = \texttt{s} \rangle.

50.1.8 \textbf{DicyclicGroup}

\begin{itemize}
\item \texttt{DicyclicGroup([filt[, field, ]]n)}
\item \texttt{QuaternionGroup([filt[, field, ]]n)}
\end{itemize}

\texttt{DicyclicGroup} constructs the dicyclic group of size \texttt{n} in the category given by the filter \texttt{filt}. Here, \texttt{n} must be a multiple of 4. The synonym \texttt{QuaternionGroup} for \texttt{DicyclicGroup} is provided for backward compatibility, but will print a warning if \texttt{n} is not a power of 2. If \texttt{filt} is not given it defaults to \texttt{IsPcGroup} (46.3.1). For more information on possible values of \texttt{filt} see section (50.1). Methods are also available for permutation and matrix groups (of minimal degree and minimal dimension in coprime characteristic).

\begin{verbatim}
GAP> DicyclicGroup(24);
<pc group of size 24 with 4 generators>
GAP> g:=QuaternionGroup(IsMatrixGroup,CF(16),32);
Group([ [ [ 0, 1 ], [ -1, 0 ] ], [ [ E(16), 0 ], [ 0, -E(16)^7 ] ] ])
\end{verbatim}

50.1.9 \textbf{IsGeneralisedQuaternionGroup}

\begin{itemize}
\item \texttt{IsGeneralisedQuaternionGroup(}G\texttt{)}
\item \texttt{QuaternionGroup(}G\texttt{)}
\item \texttt{GeneralisedQuaternionGenerators(}G\texttt{)}
\item \texttt{QuaternionGenerators(}G\texttt{)}
\end{itemize}

\texttt{IsGeneralisedQuaternionGroup} indicates whether the group \texttt{G} is a generalized quaternion group of size \texttt{N} = 2^k(k + 1), \texttt{k} \geq 2. If it is, methods may set the attribute \texttt{GeneralisedQuaternionGenerators} to \texttt{[t, s]}, where \texttt{t} and \texttt{s} are two elements such that \texttt{G} = \langle \texttt{t}, \texttt{s} | t^{2^k} = 1, t^2 = s^{2^k-1}, t^{-1} = \texttt{s} \rangle. \texttt{IsQuaternionGroup} and \texttt{QuaternionGenerators} are provided for backwards compatibility with existing code.
50.1.10 ExtraspecialGroup

\[ \text{ExtraspecialGroup( } \text{filt, order, exp} \text{)} \] (function)

Let \( \text{order} \) be of the form \( p^{2n+1} \), for a prime integer \( p \) and a positive integer \( n \). \text{ExtraspecialGroup} returns the extraspecial group of order \( \text{order} \) that is determined by \( \text{exp} \), in the category given by the filter \( \text{filt} \).

If \( p \) is odd then admissible values of \( \text{exp} \) are the exponent of the group (either \( p \) or \( p^2 \)) or one of \( '+' \), \( '+' \), \( '-' \), \( '-' \). For \( p = 2 \), only the above plus or minus signs are admissible.

If \( \text{filt} \) is not given it defaults to \text{IsPcGroup} (46.3.1). For more information on possible values of \( \text{filt} \) see section (50.1).

Example

\begin{verbatim}
gap> ExtraspecialGroup( 27, 3 );
<pc group of size 27 with 3 generators>
gap> ExtraspecialGroup( 27, '+' );
<pc group of size 27 with 3 generators>
gap> ExtraspecialGroup( 8, '-' );
<pc group of size 8 with 3 generators>
\end{verbatim}

50.1.11 AlternatingGroup

\[ \text{AlternatingGroup( } \text{filt, deg} \text{)} \] (function)
\[ \text{AlternatingGroup( } \text{filt, dom} \text{)} \] (function)

constructs the alternating group of degree \( \text{deg} \) in the category given by the filter \( \text{filt} \). If \( \text{filt} \) is not given it defaults to \text{IsPermGroup} (43.1.1). For more information on possible values of \( \text{filt} \) see section (50.1). In the second version, the function constructs the alternating group on the points given in the set \( \text{dom} \) which must be a set of positive integers.

Example

\begin{verbatim}
gap> AlternatingGroup(5);
Alt( [ 1 .. 5 ] )
\end{verbatim}

50.1.12 SymmetricGroup

\[ \text{SymmetricGroup( } \text{filt, deg} \text{)} \] (function)
\[ \text{SymmetricGroup( } \text{filt, dom} \text{)} \] (function)

constructs the symmetric group of degree \( \text{deg} \) in the category given by the filter \( \text{filt} \). If \( \text{filt} \) is not given it defaults to \text{IsPermGroup} (43.1.1). For more information on possible values of \( \text{filt} \) see section (50.1). In the second version, the function constructs the symmetric group on the points given in the set \( \text{dom} \) which must be a set of positive integers.

Example

\begin{verbatim}
gap> SymmetricGroup(10);
Sym( [ 1 .. 10 ] )
\end{verbatim}

Note that permutation groups provide special treatment of symmetric and alternating groups, see 43.4.
50.1.13 MathieuGroup

\texttt{MathieuGroup([filt, } \textit{degree})} \\
\texttt{(function)}

constructs the Mathieu group of degree \textit{degree} in the category given by the filter \textit{filt},
where \textit{degree} must be in the set \{9, 10, 11, 12, 21, 22, 23, 24\}. If \textit{filt} is not given it defaults to \texttt{IsPermGroup (43.1.1)}. For more information on possible values of \textit{filt} see section (50.1).

\textbf{Example}
\begin{verbatim}
gap> MathieuGroup( 11 ); Group([ (1,2,3,4,5,6,7,8,9,10,11), (3,7,11,8)(4,10,5,6) ]) \end{verbatim}

50.1.14 SuzukiGroup

\texttt{SuzukiGroup([filt, } \textit{q})} \\
\texttt{(function)}

\texttt{Sz([filt, } \textit{q})} \\
\texttt{(function)}

Constructs a group isomorphic to the Suzuki group $Sz( q )$ over the field with $q$ elements, where
$q$ is a non-square power of 2.

If \textit{filt} is not given it defaults to \texttt{IsMatrixGroup (44.1.1)}, and the returned group is the Suzuki
group itself. For more information on possible values of \textit{filt} see section (50.1).

\textbf{Example}
\begin{verbatim}
gap> SuzukiGroup( 32 ); Sz(32) \end{verbatim}

50.1.15 ReeGroup

\texttt{ReeGroup([filt, } \textit{q})} \\
\texttt{(function)}

\texttt{Ree([filt, } \textit{q})} \\
\texttt{(function)}

Constructs a group isomorphic to the Ree group $^2G_2(q)$ where $q = 3^{1+2m}$ for $m$ a non-negative
integer.

If \textit{filt} is not given it defaults to \texttt{IsMatrixGroup (44.1.1)} and the generating matrices are based
on \texttt{[KLM01]}. (No particular choice of a generating set is guaranteed.) For more information on
possible values of \textit{filt} see section (50.1).

\textbf{Example}
\begin{verbatim}
gap> ReeGroup( 27 ); Ree(27) \end{verbatim}

50.2 Classical Groups

The following functions return classical groups.

For the linear, symplectic, and unitary groups (the latter in dimension at least 3), the generators are
taken from \texttt{[Tay87]}. For the unitary groups in dimension 2, the isomorphism of $SU(2, q)$ and $SL(2, q)$
is used, see for example \texttt{[Hup67]}.

The generators of the general and special orthogonal groups are taken from \texttt{[IE94]} and \texttt{[KL90]},
except that the generators of the groups in odd dimension in even characteristic are constructed via the
isomorphism to a symplectic group, see for example \texttt{[Car72]}.
The generators of the groups $\Omega^\epsilon(d, q)$ are taken from [RT98], except that in odd dimension and even characteristic, the generators of $\text{SO}(d, q)$ are taken for $\Omega(d, q)$. Note that the generators claimed in [RT98, Section 4.5 and 4.6] do not describe orthogonal groups, one would have to transpose these matrices in order to get groups that respect the required forms. The matrices from [RT98] generate groups of the right isomorphism types but not orthogonal groups, except in the case $(d, q) = (5, 2)$, where the matrices from [RT98] generate the simple group $S_4(2)'$ and not the group $S_4(2)$.

The generators for the semilinear groups are constructed from the generators of the corresponding linear groups plus one additional generator that describes the action of the group of field automorphisms; for prime integers $p$ and positive integers $f$, this yields the matrix groups $\Gamma L(d, p^f)$ and $\Sigma L(d, p^f)$ as groups of $df \times df$ matrices over the field with $p$ elements.

For symplectic and orthogonal matrix groups returned by the functions described below, the invariant bilinear form is stored as the value of the attribute `InvariantBilinearForm` (44.5.1). Analogously, the invariant sesquilinear form defining the unitary groups is stored as the value of the attribute `InvariantSesquilinearForm` (44.5.3). The defining quadratic form of orthogonal groups is stored as the value of the attribute `InvariantQuadraticForm` (44.5.5).

Note that due to the different sources for the generators, the invariant forms for the groups $\Omega(e, d, q)$ are in general different from the forms for $\text{SO}(e, d, q)$ and $\text{GO}(e, d, q)$.

### 50.2.1 GeneralLinearGroup

- `GeneralLinearGroup([-filt, ], d, R)` (function)
- `GL([-filt, ], d, R)` (function)
- `GeneralLinearGroup([-filt, ], d, q)` (function)
- `GL([-filt, ], d, q)` (function)

The first two forms construct a group isomorphic to the general linear group $\text{GL}(d, R)$ of all $d \times d$ matrices that are invertible over the ring $R$, in the category given by the filter `filt`.

The third and the fourth form construct the general linear group over the finite field with $q$ elements.

If `filt` is not given it defaults to `IsMatrixGroup` (44.1.1), and the returned group is the general linear group as a matrix group in its natural action (see also `IsNaturalGL` (44.4.2), `IsNaturalGLnZ` (44.6.4)).

Currently supported rings $R$ are finite fields, the ring $\mathbb{Z}$ (14), and residue class rings $\mathbb{Z}/m\mathbb{Z}$, see 14.5.

```gap
gap> GL(4,3);
GL(4,3)
gap> GL(2,Integers);
GL(2,Integers)
gap> GL(3,Integers mod 12);
GL(3,Z/12Z)
```

Using the `OnLines` (41.2.12) operation it is possible to obtain the corresponding projective groups in a permutation action:

```gap
gap> g:=GL(4,3);;Size(g);
24261120
gap> pgl:=Action(g,Orbit(g,Z(3)^0*[1,0,0,0],OnLines),OnLines);
```

---

Example
If you are interested only in the projective group as a permutation group and not in the correspondence between its moved points and the points in the projective space, you can also use `PGL`.

### 50.2.2 SpecialLinearGroup

\[
\text{SpecialLinearGroup}(\text{filt}, d, R)
\]

\[
\text{SL}(\text{filt}, d, R)
\]

\[
\text{SpecialLinearGroup}(\text{filt}, d, q)
\]

\[
\text{SL}(\text{filt}, d, q)
\]

The first two forms construct a group isomorphic to the special linear group \(\text{SL}(d, R)\) of all those \(d \times d\) matrices over the ring \(R\) whose determinant is the identity of \(R\), in the category given by the filter \(\text{filt}\).

The third and the fourth form construct the special linear group over the finite field with \(q\) elements.

If \(\text{filt}\) is not given it defaults to \(\text{IsMatrixGroup}(44.1.1)\), and the returned group is the special linear group as a matrix group in its natural action (see also \(\text{IsNaturalSL}(44.4.4)\), \(\text{IsNaturalSLnZ}(44.6.5)\)).

Currently supported rings \(R\) are finite fields, the ring \(\text{Integers}(14)\), and residue class rings \(\text{Integers mod m}\), see 14.5.

#### Example

```gap
gap> SpecialLinearGroup(2,2);
SL(2,2)
gap> SL(3,Integers);
SL(3,Integers)
gap> SL(4,Integers mod 4);
SL(4,Z/4Z)
```

### 50.2.3 GeneralUnitaryGroup

\[
\text{GeneralUnitaryGroup}(\text{filt}, d, q)
\]

\[
\text{GU}(\text{filt}, d, q)
\]

constructs a group isomorphic to the general unitary group \(\text{GU}(d, q)\) of those \(d \times d\) matrices over the field with \(q^2\) elements that respect a fixed nondegenerate sesquilinear form, in the category given by the filter \(\text{filt}\).

If \(\text{filt}\) is not given it defaults to \(\text{IsMatrixGroup}(44.1.1)\), and the returned group is the general unitary group itself.

#### Example

```gap
gap> GeneralUnitaryGroup( 3, 5 );
GU(3,5)
```
50.2.4 SpecialUnitaryGroup

\[ \text{SpecialUnitaryGroup}(\text{filt, } d, q) \]
\[ \text{SU}(\text{filt, } d, q) \]

constructs a group isomorphic to the special unitary group GU\((d, q)\) of those \(d \times d\) matrices over the field with \(q^2\) elements whose determinant is the identity of the field and that respect a fixed nondegenerate sesquilinear form, in the category given by the filter \(\text{filt}\).

If \(\text{filt}\) is not given it defaults to \(\text{IsMatrixGroup}(44.1.1)\), and the returned group is the special unitary group itself.

Example

\[
\text{gap> SpecialUnitaryGroup( 3, 5 );}
\]
\[
\text{SU(3,5)}
\]

50.2.5 SymplecticGroup

\[ \text{SymplecticGroup}(\text{filt, } d, q) \]
\[ \text{Sp}(\text{filt, } d, q) \]
\[ \text{SP}(\text{filt, } d, q) \]

constructs a group isomorphic to the symplectic group \(\text{Sp}(d, q)\) of those \(d \times d\) matrices over the field with \(q\) elements that respect a fixed nondegenerate symplectic form, in the category given by the filter \(\text{filt}\).

If \(\text{filt}\) is not given it defaults to \(\text{IsMatrixGroup}(44.1.1)\), and the returned group is the symplectic group itself.

At the moment finite fields or residue class rings \(\text{Integers mod } q\), with \(q\) an odd prime power are supported.

Example

\[
\text{gap> SymplecticGroup( 4, 2 );}
\]
\[
\text{Sp(4,2)}
\]
\[
\text{gap> g:=SymplecticGroup(6,Integers mod 9);}
\]
\[
\text{Sp(6,Z/9Z)}
\]
\[
\text{gap> Size(g);}
\]
\[
95928796266538862080
\]

50.2.6 GeneralOrthogonalGroup

\[ \text{GeneralOrthogonalGroup}(\text{filt, } \text{filte, } d, q) \]
\[ \text{GO}(\text{filt, } \text{filte, } d, q) \]

constructs a group isomorphic to the general orthogonal group \(\text{GO}(e, d, q)\) of those \(d \times d\) matrices over the field with \(q\) elements that respect a non-singular quadratic form (see \(\text{InvariantQuadraticForm}(44.5.5)\)) specified by \(e\), in the category given by the filter \(\text{filt}\).
The value of $e$ must be $0$ for odd $d$ (and can optionally be omitted in this case), respectively one of $1$ or $-1$ for even $d$. If \texttt{filt} is not given it defaults to \texttt{IsMatrixGroup (44.1.1)}, and the returned group is the general orthogonal group itself.

Note that in [KL90], GO is defined as the stabilizer $\Delta(V,F,\kappa)$ of the quadratic form, up to scalars, whereas our GO is called $I(V,F,\kappa)$ there.

### 50.2.7 SpecialOrthogonalGroup

**SpecialOrthogonalGroup**

\[ \textbf{\texttt{SpecialOrthogonalGroup([filt, ]}[e, ]\texttt{d, q})} \]

\[ \textbf{\texttt{SO([filt, ]}[e, ]texttt{d, q})} \]

\texttt{SpecialOrthogonalGroup} returns a group isomorphic to the special orthogonal group $SO(e, d, q)$, which is the subgroup of all those matrices in the general orthogonal group (see \texttt{GeneralOrthogonalGroup (50.2.6)}) that have determinant one, in the category given by the filter \texttt{filt}. (The index of $SO(e, d, q)$ in $GO(e, d, q)$ is $2$ if $q$ is odd, and $1$ if $q$ is even.) Also interesting is the group $\Omega(e, d, q)$, see \texttt{Omega (50.2.8)}, which is always of index $2$ in $SO(e, d, q)$.

If \texttt{filt} is not given it defaults to \texttt{IsMatrixGroup (44.1.1)}, and the returned group is the special orthogonal group itself.

**Example**

\begin{verbatim}
gap> GeneralOrthogonalGroup( 3, 7 );
GO(0,3,7)
gap> GeneralOrthogonalGroup( -1, 4, 3 );
GO(-1,4,3)
gap> SpecialOrthogonalGroup( 1, 4, 4 );
GO(+1,4,4)
\end{verbatim}

### 50.2.8 Omega (construct an orthogonal group)

**Omega**

\[ \textbf{\texttt{Omega([filt, ]}[e, ]\texttt{d, q})} \]

\texttt{Omega} constructs a group isomorphic to the group $\Omega(e, d, q)$ of those $d \times d$ matrices over the field with $q$ elements that respect a non-singular quadratic form (see \texttt{InvariantQuadraticForm (44.5.5)}) specified by $e$, and that have square spinor norm in odd characteristic or Dickson invariant $0$ in even characteristic, respectively, in the category given by the filter \texttt{filt}. For odd $q$, this group has always index two in the corresponding special orthogonal group, which will be conjugate in $GL(d,q)$ to the group returned by $SO(e, d, q)$, see \texttt{SpecialOrthogonalGroup (50.2.7)}, but may fix a different form (see 50.2).

The value of $e$ must be $0$ for odd $d$ (and can optionally be omitted in this case), respectively one of $1$ or $-1$ for even $d$. If \texttt{filt} is not given it defaults to \texttt{IsMatrixGroup (44.1.1)}, and the returned group is the group $\Omega(e, d, q)$ itself.

**Example**

\begin{verbatim}
gap> g:= Omega( 3, 5 );  StructureDescription( g );
"A5"
gap> g:= Omega( 1, 4, 4 );  StructureDescription( g );
"A5 x A5"
\end{verbatim}
50.2.9 GeneralSemilinearGroup

▶ GeneralSemilinearGroup([filt, d, q])  (function)
▶ GammaL([filt, d, q])  (function)

GeneralSemilinearGroup returns a group isomorphic to the general semilinear group \( \Gamma L(d, q) \) of semilinear mappings of the vector space \( GF(q)^d \).

If \( \text{filt} \) is not given it defaults to IsMatrixGroup (44.1.1), and the returned group consists of matrices of dimension \( df \) over the field with \( p \) elements, where \( q = p^f \), for a prime integer \( p \).

50.2.10 SpecialSemilinearGroup

▶ SpecialSemilinearGroup([filt, d, q])  (function)
▶ SigmaL([filt, d, q])  (function)

SpecialSemilinearGroup returns a group isomorphic to the special semilinear group \( \Sigma L(d, q) \) of those semilinear mappings of the vector space \( GF(q)^d \) (see GeneralSemilinearGroup (50.2.9)) whose linear part has determinant one.

If \( \text{filt} \) is not given it defaults to IsMatrixGroup (44.1.1), and the returned group consists of matrices of dimension \( df \) over the field with \( p \) elements, where \( q = p^f \), for a prime integer \( p \).

50.2.11 ProjectiveGeneralLinearGroup

▶ ProjectiveGeneralLinearGroup([filt, d, q])  (function)
▶ PGL([filt, d, q])  (function)

constructs a group isomorphic to the projective general linear group \( PGL(d, q) \) of those \( d \times d \) matrices over the field with \( q \) elements, modulo the centre, in the category given by the filter \( \text{filt} \).

If \( \text{filt} \) is not given it defaults to IsPermGroup (43.1.1), and the returned group is the action on lines of the underlying vector space.

50.2.12 ProjectiveSpecialLinearGroup

▶ ProjectiveSpecialLinearGroup([filt, d, q])  (function)
▶ PSL([filt, d, q])  (function)

constructs a group isomorphic to the projective special linear group \( PSL(d, q) \) of those \( d \times d \) matrices over the field with \( q \) elements whose determinant is the identity of the field, modulo the centre, in the category given by the filter \( \text{filt} \).

If \( \text{filt} \) is not given it defaults to IsPermGroup (43.1.1), and the returned group is the action on lines of the underlying vector space.
PROJECTIVEUNITARYGROUP

constructs a group isomorphic to the projective general unitary group PGU(d, q) of those $d \times d$ matrices over the field with $q^2$ elements that respect a fixed nondegenerate sesquilinear form, modulo the centre, in the category given by the filter filt.

If filt is not given it defaults to IsPermGroup (43.1.1), and the returned group is the action on lines of the underlying vector space.

PROJECTIVESPECIALUNITARYGROUP

constructs a group isomorphic to the projective special unitary group PSU(d, q) of those $d \times d$ matrices over the field with $q^2$ elements that respect a fixed nondegenerate sesquilinear form and have determinant 1, modulo the centre, in the category given by the filter filt.

If filt is not given it defaults to IsPermGroup (43.1.1), and the returned group is the action on lines of the underlying vector space.

PROJECTIVESYMPLECTICGROUP

constructs a group isomorphic to the projective symplectic group PSp(d, q) of those $d \times d$ matrices over the field with $q$ elements that respect a fixed nondegenerate symplectic form, modulo the centre, in the category given by the filter filt.

If filt is not given it defaults to IsPermGroup (43.1.1), and the returned group is the action on lines of the underlying vector space.

PROJECTIVEOMEGA

constructs a group isomorphic to the projective group PΩ(e, d, q) of Ω(e, d, q), modulo the centre (see Omega (50.2.8)), in the category given by the filter filt.

If filt is not given it defaults to IsPermGroup (43.1.1), and the returned group is the action on lines of the underlying vector space.
50.3 Conjugacy Classes in Classical Groups

For general and special linear groups (see GeneralLinearGroup (50.2.1) and SpecialLinearGroup (50.2.2)) GAP has an efficient method to generate representatives of the conjugacy classes. This uses results from linear algebra on normal forms of matrices. If you know how to do this for other types of classical groups, please, tell us.

Example

```gap
gap> g := SL(4,9);
SL(4,9)
gap> NrConjugacyClasses(g);
861
gap> cl := ConjugacyClasses(g);

Example

50.3.1 NrConjugacyClassesGL

The first of these functions compute for given positive integer \( n \) and prime power \( q \) the number of conjugacy classes in the classical groups \( GL(n, q) \), \( GU(n, q) \), \( SL(n, q) \), \( SU(n, q) \), \( PGL(n, q) \), \( PGU(n, q) \), \( PSL(n, q) \), \( PSU(n, q) \), respectively. (See also ConjugacyClasses (39.10.2) and Section 50.2.)

For each divisor \( f \) of \( n \) there is a group of Lie type with the same order as \( SL(n, q) \), such that its derived subgroup modulo its center is isomorphic to \( PSL(n, q) \). The various such groups with fixed \( n \) and \( q \) are called isogeneous. (Depending on congruence conditions on \( q \) and \( n \) several of these groups may actually be isomorphic.) The function \( \text{NrConjugacyClassesSLIsogeneous} \) computes the number of conjugacy classes in this group. The extreme cases \( f = 1 \) and \( f = n \) lead to the groups \( \text{SL}(n, q) \) and \( \text{PGL}(n, q) \), respectively.

The function \( \text{NrConjugacyClassesSUIsogeneous} \) is the analogous one for the corresponding unitary groups.

The formulae for the number of conjugacy classes are taken from [Mac81].

Example
50.4 Constructors for Basic Groups

All functions described in the previous sections call constructor operations to do the work. The names of the constructors are obtained from the names of the functions by appending "Cons", so for example CyclicGroup (50.1.2) calls the constructor

\[
\text{CyclicGroupCons( cat, n )}
\]

The first argument \(\text{cat}\) for each method of this constructor must be the category for which the method is installed. For example the method for constructing a cyclic permutation group is installed as follows (see InstallMethod (78.3.1) for the meaning of the arguments).

```gap
Example
InstallMethod( CyclicGroupCons,
"regular perm group",
true,
[ IsPermGroup and IsRegularProp and IsFinite, IsInt and IsPosRat ], 0,
function( filter, n )
...
end );
```

50.5 Selection Functions

AllLibraryGroups( \(\text{fun1, val1, ... }\) )

For a number of the group libraries two selection functions are provided. Each AllLibraryGroups selection function permits one to select all groups from the library Library that have a given set of properties. Currently, the library selection functions provided, of this type, are AllSmallGroups (smallgrp: AllSmallGroups), AllIrreducibleSolvableGroups (primgrp: AllIrreducibleSolvableGroups), AllTransitiveGroups (transgrp: AllTransitiveGroups), and AllPrimitiveGroups (primgrp: AllPrimitiveGroups). Corresponding to each of these there is a OneLibraryGroup function (see below) which returns at most one group.

These functions take an arbitrary number of pairs (but at least one pair) of arguments. The first argument in such a pair is a function that can be applied to the groups in the library, and the second argument is either a single value that this function must return in order to have this group included in the selection, or a list of such values. For the function AllSmallGroups (smallgrp: AllSmallGroups) the first such function must be Size (30.4.6), and, unlike the other library selection functions, it supports an alternative syntax where Size (30.4.6) is omitted (see AllSmallGroups (smallgrp: AllSmallGroups)). Also, see AllIrreducibleSolvableGroups (primgrp: AllIrreducibleSolvableGroups), for details pertaining to this function.

For an example, let us consider the selection function for the library of transitive groups (also see (transgrp: Transitive Permutation Groups)). The command

```gap
Example
gap> AllTransitiveGroups(NrMovedPoints,[10..15],
> Size, [1..100],
> IsAbelian, false );
```

returns a list of all transitive groups with degree between 10 and 15 and size less than 100 that are not abelian.
Thus `AllTransitiveGroups` behaves as if it was implemented by a function similar to the one defined below, where `TransitiveGroupsList` is a list of all transitive groups. (Note that in the definition below we assume for simplicity that `AllTransitiveGroups` accepts exactly 4 arguments. It is of course obvious how to change this definition so that the function would accept a variable number of arguments.)

```gap
Example

AllTransitiveGroups := function( fun1, val1, fun2, val2 )
local groups, g, i;
groups := [];
for i in [ 1 .. Length( TransitiveGroupsList ) ] do
  g := TransitiveGroupsList[i];
  if fun1(g) = val1 or IsList(val1) and fun1(g) in val1
     and fun2(g) = val2 or IsList(val2) and fun2(g) in val2
  then
    Add( groups, g );
  fi;
od;
return groups;
end;
```

Note that the real selection functions are considerably more difficult, to improve the efficiency. Most important, each recognizes a certain set of properties which are precomputed for the library without having to compute them anew for each group. This will substantially speed up the selection process. In the description of each library we will list the properties that are stored for this library.

For each `AllLibraryGroups` function (see above) there is a corresponding function `OneLibraryGroup` on exactly the same arguments, i.e., there are `OneSmallGroup` (smallgrp: `OneSmallGroup`), `OneIrreducibleSolvableGroup` (primgrp: `OneIrreducibleSolvableGroup`), `OneTransitiveGroup` (transgrp: `OneTransitiveGroup`), and `OnePrimitiveGroup` (primgrp: `OnePrimitiveGroup`). Each function simply returns one group in the library that has the prescribed properties, instead of all such groups. It returns `fail` if no such group exists in the library.

### 50.6 Finite Perfect Groups

The GAP library of finite perfect groups provides, up to isomorphism, a list of all perfect groups whose sizes are less than $10^6$ excluding the following sizes:

- For $n = 61440, 122880, 172032, 245760, 344064, 491520, 688128, 983040$, the perfect groups of size $n$ have not completely been determined yet. The library neither provides the number of these groups nor the groups themselves.

- For $n = 86016, 368640, 737280$, the library does not yet contain the perfect groups of size $n$, it only provides their numbers which are 52, 46, and 54, respectively.

Except for these eleven sizes, the list of altogether 1097 perfect groups in the library is complete. It relies on results of Derek F. Holt and Wilhelm Plesken which are published in their book “Perfect Groups” [HP89]. Moreover, they have supplied us with files with presentations of 488 of the groups. In terms of these, the remaining 607 nontrivial groups in the library can be described as 276 direct
products, 107 central products, and 224 subdirect products. They are computed automatically by suitable GAP functions whenever they are needed. Two additional groups omitted from the book “Perfect Groups” have also been included.

We are grateful to Derek Holt and Wilhelm Plesken for making their groups available to the GAP community by contributing their files. It should be noted that their book contains a lot of further information for many of the library groups. So we would like to recommend it to any GAP user who is interested in the groups.

The library has been brought into GAP format by Volkmar Felsch.

As all groups are stored by presentations, a permutation representation is obtained by coset enumeration. Note that some of the library groups do not have a faithful permutation representation of small degree. Computations in these groups may be rather time consuming.

50.6.1 SizesPerfectGroups

\[ \text{SizesPerfectGroups()} \]

This is the ordered list of all numbers up to \(10^6\) that occur as sizes of perfect groups. One can iterate over the perfect groups library with:

Example

\[
\text{gap> for n in SizesPerfectGroups() do } \\
\> \text{ for k in [1..NrPerfectLibraryGroups(n)] do } \\
\> \text{ pg := PerfectGroup(n,k); } \\
\> \text{ od; } \\
\> \text{ od; }
\]

50.6.2 PerfectGroup

\[ \text{PerfectGroup([filt, ]size[, n])} \]
\[ \text{PerfectGroup([filt, ]sizenumberpair)} \]

returns a group which is isomorphic to the library group specified by the size number \([\text{size}, \text{n}]\) or by the two separate arguments \text{size} and \text{n}, assuming a default value of \text{n} = 1. The optional argument \text{filt} defines the filter in which the group is returned. Possible filters so far are \text{IsPermGroup (43.1.1)} and \text{IsSubgroupFpGroup (47.1.1)}. In the latter case, the generators and relators used coincide with those given in [HP89]. The default filter is \text{IsSubgroupFpGroup (47.1.1)}.

Example

\[
\text{gap> G := PerfectGroup(IsPermGroup,6048,1); } \\
U3(3) \\
\text{gap> G:=PerfectGroup(IsPermGroup,823080,2); } \\
A5 2^1 19^2 C 19^1 \\
\text{gap> NrMovedPoints(G); } \\
6889
\]

50.6.3 PerfectIdentification

\[ \text{PerfectIdentification(G)} \]

This attribute is set for all groups obtained from the perfect groups library and has the value \([\text{size},\text{nr}]\) if the group is obtained with these parameters from the library.
50.6.4 NumberPerfectGroups

\[ \text{NumberPerfectGroups(size)} \]

returns the number of non-isomorphic perfect groups of size \( \text{size} \) for each positive integer \( \text{size} \) up to 10\(^6\) except for the eight sizes listed at the beginning of this section for which the number is not yet known. For these values as well as for any argument out of range it returns fail.

50.6.5 NumberPerfectLibraryGroups

\[ \text{NumberPerfectLibraryGroups(size)} \]

returns the number of perfect groups of size \( \text{size} \) which are available in the library of finite perfect groups. (The purpose of the function is to provide a simple way to formulate a loop over all library groups of a given size.)

50.6.6 SizeNumbersPerfectGroups

\[ \text{SizeNumbersPerfectGroups(factor1, factor2, ...)} \]

\( \text{SizeNumbersPerfectGroups} \) returns a list of pairs, each entry consisting of a group order and the number of those groups in the library of perfect groups that contain the specified factors \( \text{factor1}, \text{factor2}, \ldots \) among their composition factors.

Each argument must either be the name of a nonabelian simple group or an integer which stands for the product of the sizes of one or more cyclic factors. (In fact, the function replaces all integers among the arguments by their product.)

The following text strings are accepted as simple group names.

- \( \text{An} \) or \( \text{A(n)} \) for the alternating groups \( A_n, 5 \leq n \leq 9 \), for example \( A_5 \) or \( A(6) \).
- \( \text{Ln}(q) \) or \( \text{L(n,q)} \) for \( \text{PSL}(n,q) \), where \( n \in \{2,3\} \) and \( q \) a prime power, ranging
  - for \( n = 2 \) from 4 to 125
  - for \( n = 3 \) from 2 to 5
- \( \text{Un}(q) \) or \( \text{U(n,q)} \) for \( \text{PSU}(n,q) \), where \( n \in \{3,4\} \) and \( q \) a prime power, ranging
  - for \( n = 3 \) from 3 to 5
  - for \( n = 4 \) from 2 to 2
- \( \text{Sp4}(4) \) or \( \text{S(4,4)} \) for the symplectic group \( \text{Sp}(4,4) \).
- \( \text{Sz}(8) \) for the Suzuki group \( \text{Sz}(8) \).
- \( \text{Mn} \) or \( \text{M(n)} \) for the Mathieu groups \( M_{11}, M_{12}, \) and \( M_{22} \), and
- \( \text{Jn} \) or \( \text{J(n)} \) for the Janko groups \( J_1 \) and \( J_2 \).
Note that, for most of the groups, the preceding list offers two different names in order to be consistent with the notation used in [HP89] as well as with the notation used in the DisplayCompositionSeries (39.17.6) command of GAP. However, as the names are compared as text strings, you are restricted to the above choice. Even expressions like \( \text{L2}(2^5) \) are not accepted.

As the use of the term \( \text{PSU}(n,q) \) is not unique in the literature, we mention that in this library it denotes the factor group of \( \text{SU}(n,q) \) by its centre, where \( \text{SU}(n,q) \) is the group of all \( n \times n \) unitary matrices with entries in \( GF(q^2) \) and determinant \( 1 \).

The purpose of the function is to provide a simple way to formulate a loop over all library groups which contain certain composition factors.

### 50.6.7 DisplayInformationPerfectGroups

\[
\begin{array}{l}
\text{DisplayInformationPerfectGroups} \quad (\text{function}) \\
\text{DisplayInformationPerfectGroups}\quad (\text{function})
\end{array}
\]

DisplayInformationPerfectGroups displays some invariants of the \( n \)-th group of order \( \text{size} \) from the perfect groups library.

If no value of \( n \) has been specified, the invariants will be displayed for all groups of size \( \text{size} \) available in the library.

Alternatively, also a list of length two may be entered as the only argument, with entries \( \text{size} \) and \( n \).

The information provided for \( G \) includes the following items:

- a headline containing the size number \([ \text{size}, n ]\) of \( G \) in the form \( \text{size} \cdot n \) (the suffix \( .n \) will be suppressed if, up to isomorphism, \( G \) is the only perfect group of order \( \text{size} \)),
- a message if \( G \) is simple or quasisimple, i.e., if the factor group of \( G \) by its centre is simple,
- the “description” of the structure of \( G \) as it is given by Holt and Plesken in [HP89] (see below),
- the size of the centre of \( G \) (suppressed, if \( G \) is simple),
- the prime decomposition of the size of \( G \),
- orbit sizes for a faithful permutation representation of \( G \) which is provided by the library (see below),
- a reference to each occurrence of \( G \) in the tables of section 5.3 of [HP89]. Each of these references consists of a class number and an internal number \((i,j)\) under which \( G \) is listed in that class. For some groups, there is more than one reference because these groups belong to more than one of the classes in the book.

**Example**

```
gap> DisplayInformationPerfectGroups( 30720, 3 );
#I Perfect group 30720: A5 ( 2^4 E N 2^1 E 2^4 ) A
#I size = 2^11*3*5 orbit size = 240
#I Holt-Plesken class 1 (9,3)
gap> DisplayInformationPerfectGroups( 30720, 6 );
#I Perfect group 30720: A5 ( 2^4 x 2^4 ) C N 2^1
#I centre = 2. size = 2^11*3*5 orbit size = 384
#I Holt-Plesken class 1 (9,6)
```
For any library group $G$, the library files do not only provide a presentation, but, in addition, a list of one or more subgroups $S_1, \ldots, S_r$ of $G$ such that there is a faithful permutation representation of $G$ of degree $\sum_{i=1}^{r} [G : S_i]$ on the set $\{S_ig \mid 1 \leq i \leq r, g \in G\}$ of the cosets of the $S_i$. This allows one to construct the groups as permutation groups. The function \texttt{DisplayInformationPerfectGroups} (50.6.7) displays only the available degree. The message
\begin{verbatim}
orbit size = 8
\end{verbatim}
in the above example means that the available permutation representation is transitive and of degree 8, whereas the message
\begin{verbatim}
orbit sizes = 5 + 16
\end{verbatim}
means that a nontransitive permutation representation is available which acts on two orbits of size 5 and 16 respectively.

The notation used in the “description” of a group is explained in section 5.1.2 of [HP89]. We quote the respective page from there:

Within a class $Q#p$, an isomorphism type of groups will be denoted by an ordered pair of integers $(r,n)$, where $r \geq 0$ and $n > 0$. More precisely, the isomorphism types in $Q#p$ of order $p^{r}[Q]$ will be denoted by $(r,1),(r,2),(r,3),\ldots$. Thus $Q$ will always get the size number $(0,1)$.

In addition to the symbol $(r,n)$, the groups in $Q#p$ will also be given a more descriptive name. The purpose of this is to provide a very rough idea of the structure of the group. The names are derived in the following manner. First of all, the isomorphism classes of irreducible $F_p Q$-modules $M$ with $|Q| |M| \leq 10^6$, where $F_p$ is the field of order $p$, are assigned symbols. These will either be simply $p^x$, where $x$ is the dimension of the module, or, if there is more than one isomorphism class of irreducible modules having the same dimension, they will be denoted by $p^x, p^x', \ldots$. The one-dimensional module with trivial $Q$-action will therefore be denoted by $p^1$. These symbols will be listed under the description of $Q$. The group name consists essentially of a list of the composition factors working from the top of the group downwards; hence it always starts with the name of $Q$ itself. (This convention is the most convenient in our context, but it is different from that adopted in
the ATLAS [CCN+85], for example, where composition factors are listed in the reverse order. For example, we denote a group isomorphic to $SL(2,5)$ by $A_52^1$ rather than $2.A_5$.

Some other symbols are used in the name, in order to give some idea of the relationship between these composition factors, and splitting properties. We shall now list these additional symbols.

- $\times$ between two factors denotes a direct product of $F_pQ$-modules or groups.
- $C$ (for “commutator”) between two factors means that the second lies in the commutator subgroup of the first. Similarly, a segment of the form $(f_1 \times f_2)Cf_3$ would mean that the factors $f_1$ and $f_2$ commute modulo $f_3$ and $f_3$ lies in $[f_1, f_2]$.
- $A$ (for “abelian”) between two factors indicates that the second is in the $p$th power (but not the commutator subgroup) of the first. “A” may also follow the factors, if bracketed.
- $E$ (for “elementary abelian”) between two factors indicates that together they generate an elementary abelian group (modulo subsequent factors), but that the resulting $F_pQ$-module extension does not split.
- $N$ (for “nonsplit”) before a factor indicates that $Q$ (or possibly its covering group) splits down as far at this factor but not over the factor itself. So “$Qf_1Nf_2$” means that the normal subgroup $f_1f_2$ of the group has no complement but, modulo $f_2$, $f_1$, does have a complement.

Brackets have their obvious meaning. Summarizing, we have:

- $\times =$ direct product;
- $C =$ commutator subgroup;
- $A =$ abelian;
- $E =$ elementary abelian; and
- $N =$ nonsplit.

Here are some examples.

(i) $A_5(2^4E2^1E2^4)A$ means that the pairs $2^4E2^1$ and $2^1E2^4$ are both elementary abelian of exponent 4.

(ii) $A_5(2^4E2^1A)C2^1$ means that $O_2(G)$ is of symplectic type $2^{1+5}$, with Frattini factor group of type $2^4E2^1$. The “A” after the $2^1$ indicates that $G$ has a central cyclic subgroup $2^1A2^1$ of order 4.

(iii) $L_3(2)((2^1E) \times (N2^3E2^3A)C)2^3$ means that the $2^3$ factor at the bottom lies in the commutator subgroup of the pair $2^3E2^3A$ in the middle, but the lower pair $2^3A2^3$ is abelian of exponent 4. There is also a submodule $2^1E2^1$, and the covering group $L_3(2)2^1$ of $L_3(2)$ does not split over the $2^3$ factor. (Since $G$ is perfect, it goes without saying that the extension $L_3(2)2^1$ cannot split itself.)

We must stress that this notation does not always succeed in being precise or even unambiguous, and the reader is free to ignore it if it does not seem helpful.

If such a group description has been given in the book for $G$ (and, in fact, this is the case for most of the library groups), it is displayed by DisplayInformationPerfectGroups (50.6.7). Otherwise the function provides a less explicit description of the (in these cases unique) Holt-Plesken class to which $G$ belongs, together with a serial number if this is necessary to make it unique.
50.7 Irreducible Maximal Finite Integral Matrix Groups

A library of irreducible maximal finite integral matrix groups is provided with GAP. It contains \( \mathbb{Q} \)-class representatives for all of these groups of dimension at most 31, and \( \mathbb{Z} \)-class representatives for those of dimension at most 11 or of dimension 13, 17, 19, or 23.

The groups provided in this library have been determined by Wilhelm Plesken, partially as joint work with Michael Pohst, or by members of his institute (Lehrstuhl B für Mathematik, RWTH Aachen). In particular, the data for the groups of dimensions 2 to 9 have been taken from the output of computer calculations which they performed in 1979 (see [PP77], [PP80]). The \( \mathbb{Z} \)-class representatives of the groups of dimension 10 have been determined and computed by Bernd Souvignier ([Sou94]), and those of dimensions 11, 13, and 17 have been recomputed for this library from the circulant Gram matrices given in [Ple85], using the stand-alone programs for the computation of short vectors and Bravais groups which have been developed in Plesken’s institute. The \( \mathbb{Z} \)-class representatives of the groups of dimensions 19 and 23 had already been determined in [Ple85]. Gabriele Nebe has recomputed them for us. Her main contribution to this library, however, is that she has determined and computed the \( \mathbb{Q} \)-class representatives of the groups of non-prime dimensions between 12 and 24 and the groups of dimensions 25 to 31 (see [PN95], [NP95b], [Neb95], [Neb96]).

The library has been brought into GAP format by Volkmar Felsch. He has applied several GAP routines to check certain consistency of the data. However, the credit and responsibility for the lists remain with the authors. We are grateful to Wilhelm Plesken, Gabriele Nebe, and Bernd Souvignier for supplying their results to GAP.

In the preceding acknowledgement, we used some notations that will also be needed in the sequel. We first define these.

Any integral matrix group \( G \) of dimension \( n \) is a subgroup of \( GL_n(\mathbb{Z}) \) as well as of \( GL_n(\mathbb{Q}) \) and hence lies in some conjugacy class of integral matrix groups under \( GL_n(\mathbb{Z}) \) and also in some conjugacy class of rational matrix groups under \( GL_n(\mathbb{Q}) \). As usual, we call these classes the \( \mathbb{Z} \)-class and the \( \mathbb{Q} \)-class of \( G \), respectively. Note that any conjugacy class of subgroups of \( GL_n(\mathbb{Q}) \) contains at least one \( \mathbb{Z} \)-class of subgroups of \( GL_n(\mathbb{Z}) \) and hence can be considered as the \( \mathbb{Q} \)-class of some integral matrix group.

In the context of this library we are only concerned with \( \mathbb{Z} \)-classes and \( \mathbb{Q} \)-classes of subgroups of \( GL_n(\mathbb{Z}) \) which are irreducible and maximal finite in \( GL_n(\mathbb{Z}) \) (we will call them i.m.f. subgroups of \( GL_n(\mathbb{Z}) \)). We can distinguish two types of these groups:

First, there are those i.m.f. subgroups of \( GL_n(\mathbb{Z}) \) which are also maximal finite subgroups of \( GL_n(\mathbb{Q}) \). Let us denote the set of their \( \mathbb{Q} \)-classes by \( Q_1(n) \). It is clear from the above remark that \( Q_1(n) \) just consists of the \( \mathbb{Q} \)-classes of i.m.f. subgroups of \( GL_n(\mathbb{Q}) \).

Secondly, there is the set \( Q_2(n) \) of the \( \mathbb{Q} \)-classes of the remaining i.m.f. subgroups of \( GL_n(\mathbb{Z}) \), i.e., of those which are not maximal finite subgroups of \( GL_n(\mathbb{Q}) \). For any such group \( G \), say, there is at least one class \( C \in Q_1(n) \) such that \( G \) is conjugate under \( \mathbb{Q} \) to a proper subgroup of some group \( H \in C \). In fact, the class \( C \) is uniquely determined for any group \( G \) occurring in the library (though there seems to be no reason to assume that this property should hold in general). Hence we may call \( C \) the rational i.m.f. class of \( G \). Finally, we will denote the number of classes in \( Q_1(n) \) and \( Q_2(n) \) by \( q_1(n) \) and \( q_2(n) \), respectively.

As an example, let us consider the case \( n = 4 \). There are 6 \( \mathbb{Z} \)-classes of i.m.f. subgroups of \( GL_4(\mathbb{Z}) \) with representative subgroups \( G_1, \ldots, G_6 \) of isomorphism types \( G_1 \cong W(F_4) \), \( G_2 \cong D_{12} \! : \! C_2 \), \( G_3 \cong G_4 \cong C_2 \times S_5 \), \( G_5 \cong W(B_4) \), and \( G_6 \cong (D_{12} \! : \! D_{12}) \! : \! C_2 \). The corresponding \( \mathbb{Q} \)-classes, \( R_1, \ldots, R_6 \), say, are pairwise different except that \( R_3 \) coincides with \( R_4 \). The groups \( G_1, G_2, \) and \( G_3 \) are i.m.f. subgroups of \( GL_4(\mathbb{Q}) \), but \( G_5 \) and \( G_6 \) are not because they are conjugate under \( GL_4(\mathbb{Q}) \) to proper subgroups of \( G_1 \)
and $G_2$, respectively. So we have $Q_1(4) = \{R_1, R_2, R_3\}$, $Q_2(4) = \{R_5, R_6\}$, $q_1(4) = 3$, and $q_2(4) = 2$.

The $q_1(n)$ $Q$-classes of i.m.f. subgroups of $GL_n(\mathbb{Q})$ have been determined for each dimension $n \leq 31$. The current GAP library provides integral representative groups for all these classes. Moreover, all $\mathbb{Z}$-classes of i.m.f. subgroups of $GL_n(\mathbb{Z})$ are known for $n \leq 11$ and for $n \in \{13, 17, 19, 23\}$. For these dimensions, the library offers integral representative groups for all $\mathbb{Q}$-classes in $Q_1(n)$ and $Q_2(n)$ as well as for all $\mathbb{Z}$-classes of i.m.f. subgroups of $GL_n(\mathbb{Z})$.

Any group $G$ of dimension $n$ given in the library is represented as the automorphism group $G = \text{Aut}(F, L) = \{g \in GL_n(\mathbb{Z}) \mid Lg = L, gFg^t = F\}$ of a positive definite symmetric $n \times n$ matrix $F \in \mathbb{Z}^{n \times n}$ on an $n$-dimensional lattice $L \cong \mathbb{Z}^n$ (for details see e.g. [PN95]). GAP provides for $G$ a list of matrix generators and the Gram matrix $F$.

The positive definite quadratic form defined by $F$ defines a norm $vFv^t$ for each vector $v \in L$, and there is only a finite set of vectors of minimal norm. These vectors are often simply called the short vectors. Their set splits into orbits under $G$, and $G$ being irreducible acts faithfully on each of these orbits by multiplication from the right. GAP provides for each of these orbits the orbit size and a representative vector.

Like most of the other GAP libraries, the library of i.m.f. integral matrix groups supplies an extraction function, $\text{ImfMatrixGroup}$. However, as the library involves only 525 different groups, there is no need for a selection or an example function. Instead, there are two functions, $\text{ImfInvariants}(50.7.3)$ and $\text{DisplayInvariants}(50.7.2)$, which provide some $\mathbb{Z}$-class invariants that can be extracted from the library without actually constructing the representative groups themselves. The difference between these two functions is that the latter one displays the resulting data in some easily readable format, whereas the first one returns them as record components so that you can properly access them.

We shall give an individual description of each of the library functions, but first we would like to insert a short remark concerning their names: Any self-explaining name of a function handling irreducible maximal finite integral matrix groups would have to include this term in full length and hence would grow extremely long. Therefore we have decided to use the abbreviation Imf instead in order to restrict the names to some reasonable length.

The first three functions can be used to formulate loops over the classes.

### 50.7.1 $\text{ImfNumberQQClasses}$

- $\text{ImfNumberQQClasses}(\text{dim})$ (function)
- $\text{ImfNumberQQClasses}(\text{dim})$ (function)
- $\text{ImfNumberQQClasses}(\text{dim, q})$ (function)

$\text{ImfNumberQQClasses}$ returns the number $q_1(\text{dim})$ of $Q$-classes of i.m.f. rational matrix groups of dimension $\text{dim}$. Valid values of $\text{dim}$ are all positive integers up to 31.

Note: In order to enable you to loop just over the classes belonging to $Q_1(\text{dim})$, we have arranged the list of $\mathbb{Q}$-classes of dimension $\text{dim}$ for any dimension $\text{dim}$ in the library such that, whenever the classes of $Q_2(\text{dim})$ are known, too, i.e., in the cases $\text{dim} \leq 11$ or $\text{dim} \in \{13, 17, 19, 23\}$, the classes of $Q_1(\text{dim})$ precede those of $Q_2(\text{dim})$ and hence are numbered from 1 to $q_1(\text{dim})$.

$\text{ImfNumberQQClasses}$ returns the number of $Q$-classes of groups of dimension $\text{dim}$ which are available in the library. If $\text{dim} \leq 11$ or $\text{dim} \in \{13, 17, 19, 23\}$, this is the number $q_1(\text{dim}) + q_2(\text{dim})$ of $Q$-classes of i.m.f. subgroups of $GL_{\text{dim}}(\mathbb{Z})$. Otherwise, it is just the number $q_1(\text{dim})$ of $Q$-classes of i.m.f. subgroups of $GL_{\text{dim}}(\mathbb{Q})$. Valid values of $\text{dim}$ are all positive integers up to 31.
ImfNumberZClasses returns the number of \( \mathbb{Z} \)-classes in the \( q \)-th \( \mathbb{Q} \)-class of i.m.f. integral matrix groups of dimension \( \dim \). Valid values of \( \dim \) are all positive integers up to 11 and all primes up to 23.

### 50.7.2 DisplayImfInvariants

\[
\text{DisplayImfInvariants}(\dim, q[, z])
\]

DisplayImfInvariants displays the following \( \mathbb{Z} \)-class invariants of the groups in the \( z \)-th \( \mathbb{Z} \)-class in the \( q \)-th \( \mathbb{Q} \)-class of i.m.f. integral matrix groups of dimension \( \dim \):

- its \( \mathbb{Z} \)-class number in the form \( \dim.q.z \), if \( \dim \) is at most 11 or a prime at most 23, or its \( \mathbb{Q} \)-class number in the form \( \dim.q \), else,
- a message if the group is solvable,
- the size of the group,
- the isomorphism type of the group,
- the elementary divisors of the associated quadratic form,
- the sizes of the orbits of short vectors (these sizes are the degrees of the faithful permutation representations which you may construct using the functions IsomorphismPermGroup (50.7.5) or IsomorphismPermGroupImfGroup (50.7.6) below),
- the norm of the associated short vectors,
- only in case that the group is not an i.m.f. group in \( \text{GL}_n(\mathbb{Q}) \): an appropriate message, including the \( \mathbb{Q} \)-class number of the corresponding rational i.m.f. class.

If you specify the value 0 for any of the parameters \( \dim \), \( q \), or \( z \), the command will loop over all available dimensions, \( \mathbb{Q} \)-classes of given dimension, or \( \mathbb{Z} \)-classes within the given \( \mathbb{Q} \)-class, respectively. Otherwise, the values of the arguments must be in range. A value \( z \neq 1 \) must not be specified if the \( \mathbb{Z} \)-classes are not known for the given dimension, i.e., if \( \dim > 11 \) and \( \dim \not\in \{13, 17, 19, 23\} \). The default value of \( z \) is 1. This value of \( z \) will be accepted even if the \( \mathbb{Z} \)-classes are not known. Then it specifies the only representative group which is available for the \( q \)-th \( \mathbb{Q} \)-class. The greatest legal value of \( \dim \) is 31.

#### Example

```
gap> DisplayImfInvariants( 3, 1, 0 );
#I Z-class 3.1.1: Solvable, size = 2^4*3
#I  isomorphism type = C2 wr S3 = C2 x S4 = W(B3)
#I  elementary divisors = 1^3
#I  orbit size = 6, minimal norm = 1
#I Z-class 3.1.2: Solvable, size = 2^4*3
#I  isomorphism type = C2 wr S3 = C2 x S4 = C2 x W(A3)
#I  elementary divisors = 1*4^2
#I  orbit size = 8, minimal norm = 3
#I Z-class 3.1.3: Solvable, size = 2^4*3
#I  isomorphism type = C2 wr S3 = C2 x S4 = C2 x W(A3)
#I  elementary divisors = 1^2*4
```
Note that the function `DisplayImfInvariants` uses a kind of shorthand to display the elementary divisors. E.g., the expression `1*3^3*9^3*27` in the preceding example stands for the elementary divisors `1`, `3`, `3`, `3`, `9`, `9`, `9`, `27`. (See also the next example which shows that the function `ImfInvariants(50.7.3)` provides the elementary divisors in form of an ordinary GAP list.)

In the description of the isomorphism types the following notations are used:

- `A x B` denotes a direct product of a group `A` by a group `B`,
- `A subd B` denotes a subdirect product of `A` by `B`,
- `A Y B` denotes a central product of `A` by `B`,
- `A wr B` denotes a wreath product of `A` by `B`,
- `A:B` denotes a split extension of `A` by `B`,
- `A . B` denotes just an extension of `A` by `B` (split or nonsplit).

The groups involved are

- the cyclic groups `C_n`, dihedral groups `D_n`, and generalized quaternion groups `Q_n` of order `n`, denoted by `C_n`, `D_n`, and `Q_n`, respectively,
- the alternating groups `A_n` and symmetric groups `S_n` of degree `n`, denoted by `A_n` and `S_n`, respectively,
- the linear groups `GL_n(q)`, `PGL_n(q)`, `SL_n(q)`, and `PSL_n(q)`, denoted by `GL(n,q)`, `PGL(n,q)`, `SL(n,q)`, and `PSL(n,q)`, respectively,
- the unitary groups `SU_n(q)` and `PSU_n(q)`, denoted by `SU(n,q)` and `PSU(n,q)`, respectively,
- the symplectic groups `Sp(n,q)` and `PSp(n,q)`, denoted by `Sp(n,q)` and `PSp(n,q)`, respectively,
- the orthogonal groups `O^+_8(2)` and `PO^+_8(2)`, denoted by `O^+(8,2)` and `PO^+(8,2)`, respectively,
• the extraspecial groups $2_+^{1+8}$, $3_+^{1+2}$, $3_+^{1+4}$, and $5_+^{1+2}$, denoted by $2^+(1+8)$, $3^+(1+2)$, $3^+(1+4)$, and $5^+(1+2)$, respectively,
• the Chevalley group $G_2(3)$, denoted by $G_2(3)$,
• the twisted Chevalley group $^3D_4(2)$, denoted by $^3D_4(2)$,
• the Suzuki group $Sz(8)$, denoted by $Sz(8)$,
• the Weyl groups $W(A_n)$, $W(B_n)$, $W(D_n)$, and $W(E_n)$, denoted by $W(A_n)$, $W(B_n)$, $W(D_n)$, $W(E_n)$, and $W(F_4)$, respectively,
• the sporadic simple groups $Co_1$, $Co_2$, $Co_3$, $HS$, $J_2$, $M_{12}$, $M_{22}$, $M_{23}$, $M_{24}$, and $Mc$, denoted by $Co_1$, $Co_2$, $Co_3$, $HS$, $J_2$, $M_{12}$, $M_{22}$, $M_{23}$, $M_{24}$, and $Mc$, respectively,
• a point stabilizer of index 11 in $M_{11}$, denoted by $M_{10}$.

As mentioned above, the data assembled by the function DisplayImfInvariants are “cheap data” in the sense that they can be provided by the library without loading any of its large matrix files or performing any matrix calculations. The following function allows you to get proper access to these cheap data instead of just displaying them.

50.7.3 ImfInvariants

ImfInvariants returns a record which provides some $\mathbb{Z}$-class invariants of the groups in the $z$-th $\mathbb{Z}$-class in the $q$-th $\mathbb{Q}$-class of i.m.f. integral matrix groups of dimension $\text{dim}$. A value $z \neq 1$ must not be specified if the $\mathbb{Z}$-classes are not known for the given dimension, i.e., if $\text{dim} > 11$ and $\text{dim} \not\in \{13, 17, 19, 23\}$. The default value of $z$ is 1. This value of $z$ will be accepted even if the $\mathbb{Z}$-classes are not known. Then it specifies the only representative group which is available for the $q$-th $\mathbb{Q}$-class.

The greatest legal value of $\text{dim}$ is 31.

The resulting record contains six or seven components:

size the size of any representative group $G$,

isSolvable true if $G$ is solvable,

isomorphismType a text string describing the isomorphism type of $G$ (in the same notation as used by the function DisplayImfInvariants above),

elementaryDivisors the elementary divisors of the associated Gram matrix $F$ (in the same format as the result of the function ElementaryDivisorsMat (24.9.1),

minimalNorm the norm of the associated short vectors,
sizesOrbitsShortVectors
the sizes of the orbits of short vectors under \( F \).

maximalQClass
the \( \mathbb{Q} \)-class number of an i.m.f. group in \( GL_n(\mathbb{Q}) \) that contains \( G \) as a subgroup (only in case that not \( G \) itself is an i.m.f. subgroup of \( GL_n(\mathbb{Q}) \)).

Note that four of these data, namely the group size, the solvability, the isomorphism type, and the corresponding rational i.m.f. class, are not only \( \mathbb{Z} \)-class invariants, but also \( \mathbb{Q} \)-class invariants.

Note further that, though the isomorphism type is a \( \mathbb{Q} \)-class invariant, you will sometimes get different descriptions for different \( \mathbb{Z} \)-classes of the same \( \mathbb{Q} \)-class (as, e.g., for the classes 3.1.1 and 3.1.2 in the last example above). The purpose of this behaviour is to provide some more information about the underlying lattices.

```
Example

gap> ImfInvariants( 8, 15, 1 );
rec( elementaryDivisors := [ 1, 3, 3, 9, 9, 9, 9, 27 ],
    isSolvable := true, isomorphismType := "C2 x (S3 wr S3)",
    maximalQClass := 5, minimalNorm := 8, size := 2692,
    sizesOrbitsShortVectors := [ 54 ] )
gap> ImfInvariants( 24, 1 ).size;
1040939685273332453861621760000

gap> ImfInvariants( 23, 5, 2 ).sizesOrbitsShortVectors;
[ 552, 53130 ]
gap> for i in [ 1 .. ImfNumberQClasses( 22 ) ] do
   Print( ImfInvariants( 22, i ).isomorphismType, "\n" ); od;
C2 wr S22 = W(B22)
(C2 x PSL(2,23)).S3
(C2 x S3) wr S11 = (C2 x W(A2)) wr S11
(C2 x S12) wr C2 = (C2 x W(A11)) wr C2
C2 x S3 x S12 = C2 x W(A2) x W(A11)
(C2 x HS).C2
(C2 x M2).C2
C2 x S23 = C2 x W(A22)
C2 x PSL(2,23)
C2 x PSL(2,23)
C2 x PGL(2,23)
C2 x PGL(2,23)
```

50.7.4 ImfMatrixGroup

\[ \text{ImfMatrixGroup}(\text{dim}, q[ , z]) \]

`ImfMatrixGroup` is the essential extraction function of this library (note that its name has been changed from `ImfMatGroup` in GAP 3 to `ImfMatrixGroup` in GAP 4). It returns a representative group, \( G \) say, of the \( z \)-th \( \mathbb{Z} \)-class in the \( q \)-th \( \mathbb{Q} \)-class of i.m.f. integral matrix groups of dimension \( \text{dim} \). A value \( z \neq 1 \) must not be specified if the \( \mathbb{Z} \)-classes are not known for the given dimension, i.e., if \( \text{dim} > 11 \) and \( \text{dim} \notin \{13, 17, 19, 23\} \). The default value of \( z \) is 1. This value of \( z \) will be accepted even if the \( \mathbb{Z} \)-classes are not known. Then it specifies the only representative group which is available for the \( q \)-th \( \mathbb{Q} \)-class. The greatest legal value of \( \text{dim} \) is 31.
Example

```gap
gap> G := ImfMatrixGroup( 5, 1, 3 );
ImfMatrixGroup(5,1,3)
gap> for m in GeneratorsOfGroup( G ) do PrintArray( m ); od;
[ [ -1, 0, 0, 0, 0 ],
  [ 0, 1, 0, 0, 0 ],
  [ 0, 0, 0, 1, 0 ],
  [ -1, -1, -1, -1, 2 ],
  [ -1, 0, 0, 0, 1 ] ]
[ [ 0, 1, 0, 0, 0 ],
  [ 0, 0, 1, 0, 0 ],
  [ 0, 0, 0, 1, 0 ],
  [ 1, 0, 0, 0, 0 ],
  [ 0, 0, 0, 0, 1 ] ]
```

The attributes Size (30.4.6) and IsSolvable will be properly set in the resulting matrix group \( G \). In addition, it has two attributes IsImfMatrixGroup and ImfRecord where the first one is just a logical flag set to true and the latter one is a record. Except for the group size and the solvability flag, this record contains the same components as the resulting record of the function ImfInvariants (50.7.3) described above, namely the components isomorphismType, elementaryDivisors, minimalNorm, and sizesOrbitsShortVectors and, if \( G \) is not a rational i.m.f. group, maximalQClass. Moreover, it has the two components

- **form**
  - the associated Gram matrix \( F \), and
- **repsOrbitsShortVectors**
  - representatives of the orbits of short vectors under \( F \).

The last one of these components will be required by the function IsomorphismPermGroup (50.7.5) below.

```gap
gap> Size( G );
3840
gap> imf := ImfRecord( G );;
gap> imf.isomorphismType;
"C2 wr S5 = C2 x W(D5)"
gap> PrintArray( imf.form );
[ [ 4, 0, 0, 0, 2 ],
  [ 0, 4, 0, 0, 2 ],
  [ 0, 0, 4, 0, 2 ],
  [ 0, 0, 0, 4, 2 ],
  [ 2, 2, 2, 2, 5 ] ]
gap> imf.elementaryDivisors;
[ 4, 4, 4, 4 ]
gap> imf.minimalNorm;
4
```

If you want to perform calculations in such a matrix group \( G \) you should be aware of the fact that the permutation group routines of GAP are much more efficient than the matrix group
routines. Hence we recommend that you do your computations, whenever possible, in the isomorphic permutation group which is induced by the action of \( G \) on one of the orbits of the associated short vectors. You may call one of the following functions \texttt{IsomorphismPermGroup (50.7.5)} or \texttt{IsomorphismPermGroupImfGroup (50.7.6)} to get an isomorphism to such a permutation group (note that these \texttt{GAP 4} functions have replaced the \texttt{GAP 3} functions \texttt{PermGroup} and \texttt{PermGroupImfGroup}).

### 50.7.5 \texttt{IsomorphismPermGroup} (for Imf matrix groups)

\begin{verbatim}
\texttt{IsomorphismPermGroup\((G)\)}
\end{verbatim}

returns an isomorphism, \( \varphi \) say, from the given i.m.f. integral matrix group \( G \) to a permutation group \( P := \varphi(G) \) acting on a minimal orbit, \( S \) say, of short vectors of \( G \) such that each matrix \( m \in G \) is mapped to the permutation induced by its action on \( S \).

Note that in case of a large orbit the construction of \( \varphi \) may be space and time consuming. Fortunately, there are only six \( \mathbb{Q} \)-classes in the library for which the smallest orbit of short vectors is of size greater than 20000, the worst case being the orbit of size 196560 for the Leech lattice (\( \dim = 24, q = 3 \)).

The inverse isomorphism \( \varphi^{-1} \) from \( P \) to \( G \) is constructed by determining a \( \mathbb{Q} \)-base \( B \subset S \) of \( \mathbb{Q}^{\dim} \times \dim \) in \( S \) and, in addition, the associated base change matrix \( M \) which transforms \( B \) into the standard base of \( \mathbb{Z}^{\dim} \). This allows a simple computation of the preimage \( \varphi^{-1}(p) \) of any permutation \( p \in P \), as follows. If, for \( 1 \leq i \leq \dim \), \( b_i \) is the position number in \( S \) of the \( i \)-th base vector in \( B \), it suffices to look up the vector whose position number in \( S \) is the image of \( b_i \) under \( p \) and to multiply this vector by \( M \) to get the \( i \)-th row of \( \varphi^{-1}(p) \).

You may use the functions \texttt{Image (32.4.6)} and \texttt{PreImage (32.5.6)} to switch from \( G \) to \( P \) and back from \( P \) to \( G \).

As an example, let us continue the preceding example and compute the solvable residuum of the group \( G \).

\begin{verbatim}
gap> # Perform the computations in an isomorphic permutation group.
gap> phi := IsomorphismPermGroup( G );;
gap> P := Image( phi );
Group([ (1,7,6)(2,9)(4,5,10), (2,3,4,5)(6,9,8,7) ])
gap> D := DerivedSubgroup( P );;
gap> Size( D );
960
gap> IsPerfectGroup( D );
true

gap> # We have found the solvable residuum of P,
gap> # now move the results back to the matrix group G.
gap> R := PreImage( phi, D );;
gap> StructureDescription(R);
"(C2 x C2 x C2 x C2) : A5"

gap> IdGroup(D)=IdGroup(R);
true
\end{verbatim}
50.7.6 IsomorphismPermGroupImfGroup

\> IsomorphismPermGroupImfGroup(G, n) \hspace{1cm} (function)

IsomorphismPermGroupImfGroup returns an isomorphism, \( \varphi \) say, from the given i.m.f. integral matrix group \( G \) to a permutation group \( P \) acting on the \( n \)-th orbit, \( S \) say, of short vectors of \( G \) such that each matrix \( m \in G \) is mapped to the permutation induced by its action on \( S \).

The only difference to the above function IsomorphismPermGroup (50.7.5) is that you can specify the orbit to be used. In fact, as the orbits of short vectors are sorted by increasing sizes, the function IsomorphismPermGroup\( (G) \) has been implemented such that it is equivalent to IsomorphismPermGroupImfGroup\( (G, 1) \).

Example

\begin{verbatim}
    gap> ImfInvariants( 12, 9 ).sizesOrbitsShortVectors;
    [ 120, 300 ]
    gap> G := ImfMatrixGroup( 12, 9 );
    ImfMatrixGroup(12,9)
    gap> phi1 := IsomorphismPermGroupImfGroup( G, 1 );;
    gap> P1 := Image( phi1 );
    <permutation group of size 2400 with 2 generators>
    gap> LargestMovedPoint( P1 );
    120
    gap> phi2 := IsomorphismPermGroupImfGroup( G, 2 );;
    gap> P2 := Image( phi2 );
    <permutation group of size 2400 with 2 generators>
    gap> LargestMovedPoint( P2 );
    300
\end{verbatim}
Chapter 51

Semigroups and Monoids

This chapter describes functions for creating semigroups and monoids and determining information about them.

51.1 Semigroups

51.1.1 IsSemigroup

\[
\text{IsSemigroup}(D) \quad \text{(Synonym)}
\]

returns true if the object \( D \) is a semigroup. A semigroup is a magma (see 35) with associative multiplication.

51.1.2 Semigroup

\[
\text{Semigroup}(\text{gen1, gen2, ...}) \quad \text{(function)}
\]

\[
\text{Semigroup}(\text{gens}) \quad \text{(function)}
\]

In the first form, \text{Semigroup} returns the semigroup generated by the arguments \text{gen1, gen2, ...}, that is, the closure of these elements under multiplication. In the second form, \text{Semigroup} returns the semigroup generated by the elements in the homogeneous list \text{gens}; a square matrix as only argument is treated as one generator, not as a list of generators.

It is not checked whether the underlying multiplication is associative, use \text{Magma} (35.2.1) and \text{IsAssociative} (35.4.7) if you want to check whether a magma is in fact a semigroup.

\begin{verbatim}
gap> a:= Transformation( [ 2, 3, 4, 1 ] );
Transformation( [ 2, 3, 4, 1 ] )
gap> b:= Transformation( [ 2, 2, 3, 4 ] );
Transformation( [ 2, 2, 3, 4 ] )
gap> s:= Semigroup(a, b);
<transformation semigroup of degree 4 with 2 generators>
\end{verbatim}

51.1.3 Subsemigroup

\[
\text{Subsemigroup}(S, \text{gens}) \quad \text{(function)}
\]

\[
\text{SubsemigroupNC}(S, \text{gens}) \quad \text{(function)}
\]
are just synonyms of Submagma (35.2.7) and SubmagmaNC (35.2.7), respectively.

Example

```gap
gap> a:=GeneratorsOfSemigroup(s)[1];
Transformation( [ 2, 3, 4, 1 ] )
gap> t:=Submagma(s,[a]);
<commutative transformation semigroup of degree 4 with 1 generator>
```

51.1.4 IsSubsemigroup

\[ \text{IsSubsemigroup}(S, T) \]

Returns: true or false.

This operation returns true if the semigroup \( T \) is a subsemigroup of the semigroup \( S \) and false if it is not.

Example

```gap
gap> f := Transformation([5, 6, 7, 1, 4, 3, 2, 7]);
Transformation( [ 5, 6, 7, 1, 4, 3, 2, 7 ] )
gap> T := Semigroup(f);
true
```  

51.1.5 SemigroupByGenerators

\[ \text{SemigroupByGenerators}(\text{gens}) \]

is the underlying operation of Semigroup (51.1.2).

51.1.6 AsSemigroup

\[ \text{AsSemigroup}(C) \]

If \( C \) is a collection whose elements form a semigroup (see IsSemigroup (51.1.1)) then AsSemigroup returns this semigroup. Otherwise fail is returned.

51.1.7 AsSubsemigroup

\[ \text{AsSubsemigroup}(D, C) \]

Let \( D \) be a domain and \( C \) a collection. If \( C \) is a subset of \( D \) that forms a semigroup then AsSubsemigroup returns this semigroup, with parent \( D \). Otherwise fail is returned.
51.1.8 GeneratorsOfSemigroup

GeneratorsOfSemigroup($S$) (attribute)

Semigroup generators of a semigroup $S$ are the same as magma generators, see GeneratorsOfMagma (35.4.1).

Example

```
gap> GeneratorsOfSemigroup(s);
[ Transformation([2, 3, 4, 1]), Transformation([2, 2]) ]
gap> GeneratorsOfSemigroup(t);
[ Transformation([2, 3, 4, 1]) ]
```

51.1.9 IsGeneratorsOfSemigroup

IsGeneratorsOfSemigroup($C$) (property)

This property reflects whether the list or collection $C$ generates a semigroup. IsAssociativeElementCollection (31.15.1) implies IsGeneratorsOfSemigroup, but is not used directly in semigroup code, because of conflicts with matrices.

Example

```
gap> IsGeneratorsOfSemigroup([Transformation([2,3,1])]);
true
```

51.1.10 FreeSemigroup

FreeSemigroup([$wfilter$, $rank$], $name$) (function)
FreeSemigroup([$wfilter$, $name1$, $name2$, ...]) (function)
FreeSemigroup([$wfilter$, $names$]) (function)
FreeSemigroup([$wfilter$, $infinity$, $name$, $init$]) (function)

Called with a positive integer $rank$, FreeSemigroup returns a free semigroup on $rank$ generators. If the optional argument $name$ is given then the generators are printed as $name1$, $name2$ etc., that is, each name is the concatenation of the string $name$ and an integer from 1 to $range$. The default for $name$ is the string "s".

Called in the second form, FreeSemigroup returns a free semigroup on as many generators as arguments, printed as $name1$, $name2$ etc.

Called in the third form, FreeSemigroup returns a free semigroup on as many generators as the length of the list $names$, the $i$-th generator being printed as $names[i]$.

Called in the fourth form, FreeSemigroup returns a free semigroup on infinitely many generators, where the first generators are printed by the names in the list $init$, and the other generators by $name$ and an appended number.

If the extra argument $wfilter$ is given, it must be either IsSyllableWordsFamily (37.6.6) or IsLetterWordsFamily (37.6.2) or IsWLetterWordsFamily (37.6.4) or IsBLetterWordsFamily (37.6.4). This filter then specifies the representation used for the elements of the free semigroup (see 37.6). If no such filter is given, a letter representation is used.

Example

```
gap> f1 := FreeSemigroup(3);
<free semigroup on the generators [ s1, s2, s3 ]>
```
For more on associative words see Chapter 37.

Each free object defines a unique alphabet (and a unique family of words). Its generators are the letters of this alphabet, thus words of length one.

Example

```gap
gap> FreeGroup( 5 );
<free group on the generators [ f1, f2, f3, f4, f5 ]>
gap> FreeGroup( "a", "b" );
<free group on the generators [ a, b ]>
gap> FreeGroup( infinity );
<free group with infinity generators>
gap> FreeSemigroup( "x", "y" );
<free semigroup on the generators [ x, y ]>
gap> FreeMonoid( ? );
<free monoid on the generators [ m1, m2, m3, m4, m5, m6, m7 ]>
```

Remember that names are just a help for printing and do not necessarily distinguish letters. It is possible to create arbitrarily weird situations by choosing strange names for the letters.

Example

```gap
gap> f:= FreeGroup( "x", "x" ); gens:= GeneratorsOfGroup( f );;
<free group on the generators [ x, x ]>
gap> gens[1] = gens[2];
false
gap> f:= FreeGroup( "f1*f2", "f2^-1", "Group( [ f1, f2 ] )" );
<free group on the generators [ f1*f2, f2^-1, Group( [ f1, f2 ] ) ]>
gap> gens:= GeneratorsOfGroup( f );;
gap> gens[1]*gens[2];
f1*f2*f2^-1
gap> gens[1]/gens[3];
f1*f2*Group( [ f1, f2 ] )*f2^-1*f2^-1^-1
```

51.1.11 SemigroupByMultiplicationTable

returns the semigroup whose multiplication is defined by the square matrix A (see MagmaByMultiplicationTable (35.3.1)) if such a semigroup exists. Otherwise fail is returned.

Example

```gap
gap> SemigroupByMultiplicationTable([[1,2,3],[2,3,1],[3,1,2]]);
<semigroup of size 3, with 3 generators>
```
51.2 Monoids

51.2.1 IsMonoid

▷ IsMonoid(D)

(Synonym)

A monoid is a magma-with-one (see 35) with associative multiplication.

51.2.2 Monoid

▷ Monoid(gen1, gen2, ...)

(function)

▷ Monoid(gens[, id])

(function)

In the first form, Monoid returns the monoid generated by the arguments gen1, gen2, ..., that is, the closure of these elements under multiplication and taking the 0-th power. In the second form, Monoid returns the monoid generated by the elements in the homogeneous list gens; a square matrix as only argument is treated as one generator, not as a list of generators. In the second form, the identity element id may be given as the second argument.

It is not checked whether the underlying multiplication is associative, use MagmaWithOne (35.2.2) and IsAssociative (35.4.7) if you want to check whether a magma-with-one is in fact a monoid.

51.2.3 Submonoid

▷ Submonoid(M, gens)

(function)

▷ SubmonoidNC(M, gens)

(function)

are just synonyms of SubmagmaWithOne (35.2.8) and SubmagmaWithOneNC (35.2.8), respectively.

51.2.4 MonoidByGenerators

▷ MonoidByGenerators(gens[, one])

(operation)

is the underlying operation of Monoid (51.2.2).

51.2.5 AsMonoid

▷ AsMonoid(C)

(operation)

If C is a collection whose elements form a monoid, then AsMonoid returns this monoid. Otherwise fail is returned.
51.2.6 AsSubmonoid

\[ \text{AsSubmonoid}(D, C) \]

Let \( D \) be a domain and \( C \) a collection. If \( C \) is a subset of \( D \) that forms a monoid then \text{AsSubmonoid} returns this monoid, with parent \( D \). Otherwise \text{fail} is returned.

51.2.7 GeneratorsOfMonoid

\[ \text{GeneratorsOfMonoid}(M) \]

Monoid generators of a monoid \( M \) are the same as magma-with-one generators (see \text{GeneratorsOfMagmaWithOne} (35.4.2)).

51.2.8 TrivialSubmonoid

\[ \text{TrivialSubmonoid}(M) \]

is just a synonym for \text{TrivialSubmagmaWithOne} (35.4.13).

51.2.9 FreeMonoid

\[ \text{FreeMonoid}([\text{wfilt}, \text{rank}], \text{name}) \]
\[ \text{FreeMonoid}([\text{wfilt}, \text{name1}, \text{name2}, \ldots]) \]
\[ \text{FreeMonoid}([\text{wfilt}, \text{names}]) \]
\[ \text{FreeMonoid}([\text{wfilt}, \text{infinity}, \text{name}, \text{init}]) \]

Called with a positive integer \text{rank}, \text{FreeMonoid} returns a free monoid on \text{rank} generators. If the optional argument \text{name} is given then the generators are printed as \text{name1}, \text{name2} etc., that is, each name is the concatenation of the string \text{name} and an integer from 1 to \text{range}. The default for \text{name} is the string "m".

Called in the second form, \text{FreeMonoid} returns a free monoid on as many generators as arguments, printed as \text{name1}, \text{name2} etc.

Called in the third form, \text{FreeMonoid} returns a free monoid on as many generators as the length of the list \text{names}, the \( i \)-th generator being printed as \text{names} [\( i \)].

Called in the fourth form, \text{FreeMonoid} returns a free monoid on infinitely many generators, where the first generators are printed by the names in the list \text{init}, and the other generators by \text{name} and an appended number.

If the extra argument \text{wfilt} is given, it must be either \text{IsSyllableWordsFamily} (37.6.6) or \text{IsLetterWordsFamily} (37.6.2) or \text{IsWLetterWordsFamily} (37.6.4) or \text{IsBLetterWordsFamily} (37.6.4). This filter then specifies the representation used for the elements of the free monoid (see 37.6). If no such filter is given, a letter representation is used.

For more on associative words see Chapter 37.

51.2.10 MonoidByMultiplicationTable

\[ \text{MonoidByMultiplicationTable}(A) \]
returns the monoid whose multiplication is defined by the square matrix \( A \) (see \texttt{MagmaByMultiplicationTable (35.3.1)}) if such a monoid exists. Otherwise \texttt{fail} is returned.

Example

\begin{verbatim}
gap> MonoidByMultiplicationTable([[1,2,3],[2,3,1],[3,1,2]]);
<monoid of size 3, with 3 generators>
gap> MonoidByMultiplicationTable([[1,2,3],[2,3,1],[1,3,2]]);
fail
\end{verbatim}

## 51.3 Inverse semigroups and monoids

### 51.3.1 InverseSemigroup

\begin{verbatim}
\textbf{InverseSemigroup}(obj1, obj2, ...)
\end{verbatim}

\textbf{Returns:} An inverse semigroup.

If \texttt{obj1}, \texttt{obj2}, ... are (any combination) of associative elements with unique semigroup inverses, semigroups of such elements, or collections of such elements, then \texttt{InverseSemigroup} returns the inverse semigroup generated by the union of \texttt{obj1}, \texttt{obj2}, ... This equals the semigroup generated by the union of \texttt{obj1}, \texttt{obj2}, ... and their inverses.

For example if \texttt{S} and \texttt{T} are inverse semigroups, then \texttt{InverseSemigroup(S, f, Idempotents(T))} is the inverse semigroup generated by \texttt{Union(GeneratorsOfInverseSemigroup(S), [f], Idempotents(T)))}.

As present, the only associative elements with unique semigroup inverses, which do not always generate a group, are partial permutations; see Chapter 54.

Example

\begin{verbatim}
gap> S := InverseSemigroup(
gap>   PartialPerm( [ 1, 2, 3, 6, 8, 10 ], [ 2, 6, 7, 9, 1, 5 ] ));
gap> f := PartialPerm( [ 1, 2, 3, 4, 5, 8, 10 ],
gap>   [ 7, 1, 4, 3, 2, 6, 5 ] );;
gap> S := InverseSemigroup(S, f, Idempotents(SymmetricInverseSemigroup(5)));
<inverse partial perm semigroup of rank 10 with 34 generators>
gap> Size(S);
1233
\end{verbatim}

### 51.3.2 InverseMonoid

\begin{verbatim}
\textbf{InverseMonoid}(obj1, obj2, ...)
\end{verbatim}

\textbf{Returns:} An inverse monoid.

If \texttt{obj1}, \texttt{obj2}, ... are (any combination) of associative elements with unique semigroup inverses, semigroups of such elements, or collections of such elements, then \texttt{InverseMonoid} returns the inverse monoid generated by the union of \texttt{obj1}, \texttt{obj2}, ... This equals the monoid generated by the union of \texttt{obj1}, \texttt{obj2}, ... and their inverses.

As present, the only associative elements with unique semigroup inverses are partial permutations; see Chapter 54.

For example if \texttt{S} and \texttt{T} are inverse monoids, then \texttt{InverseMonoid(S, f, Idempotents(T))} is the inverse monoid generated by \texttt{Union(GeneratorsOfInverseMonoid(S), [f], Idempotents(T)))}. 
Example

```gap
S := InverseMonoid(
  PartialPerm( [ 1, 2, 3, 6, 8, 10 ], [ 2, 6, 7, 9, 1, 5 ] ));;
S := InverseMonoid(S, f, Idempotents(SymmetricInverseSemigroup(5)));;
Size(S);
1243
```

51.3.3 GeneratorsOfInverseSemigroup

▷ GeneratorsOfInverseSemigroup(S)

Returns: The generators of an inverse semigroup.

If S is an inverse semigroup, then GeneratorsOfInverseSemigroup returns the generators used to define S, i.e. an inverse semigroup generating set for S.

The value of GeneratorsOfSemigroup(S), for an inverse semigroup S, is the union of inverse semigroup generator and their inverses. So, S is the semigroup, as opposed to inverse semigroup, generated by the elements of GeneratorsOfInverseSemigroup(S) and their inverses.

If S is an inverse monoid, then GeneratorsOfInverseSemigroup returns the generators used to define S, as described above, and the identity of S.

Example

```gap
S := InverseMonoid(
  PartialPerm( [ 1, 2 ], [ 1, 4 ] ),
  PartialPerm( [ 1, 2, 4 ], [ 3, 4, 1 ] ));;
S := InverseMonoid(S);
GeneratorsOfSemigroup(S);
GeneratorsOfInverseSemigroup(S);
GeneratorsOfMonoid(S);
GeneratorsOfMonoid(S);
```

51.3.4 GeneratorsOfInverseMonoid

▷ GeneratorsOfInverseMonoid(S)

Returns: The generators of an inverse monoid.

If S is an inverse monoid, then GeneratorsOfInverseMonoid returns the generators used to define S, i.e. an inverse monoid generating set for S.

There are four different possible generating sets which define an inverse monoid. More precisely, an inverse monoid can be generated as an inverse monoid, inverse semigroup, monoid, or semigroup. The different generating sets in each case can be obtained using GeneratorsOfInverseMonoid, GeneratorsOfInverseSemigroup (51.3.3), GeneratorsOfMonoid (51.2.7), and GeneratorsOfSemigroup (51.1.8), respectively.

Example

```gap
S := InverseMonoid(
  PartialPerm( [ 1, 2 ], [ 1, 4 ] ),
  PartialPerm( [ 1, 2, 4 ], [ 3, 4, 1 ] ));;
```
51.3.5 IsInverseSubsemigroup

\[ \text{IsInverseSubsemigroup}(S, T) \]  
\textbf{Returns:} \ true \ or \ false.  
If the semigroup \( T \) is an inverse subsemigroup of the semigroup \( S \), then this operation returns \true\.

\begin{verbatim}
gap> T:=InverseSemigroup(RandomPartialPerm(4));;
gap> IsInverseSubsemigroup(SymmetricInverseSemigroup(4), T);  
true
\end{verbatim}

51.4 Properties of Semigroups

The following functions determine information about semigroups.

51.4.1 IsRegularSemigroup

\[ \text{IsRegularSemigroup}(S) \]  
\textbf{returns} \ true \ if \( S \) is regular, i.e., if every \( \mathcal{D} \)-class of \( S \) is regular.

51.4.2 IsRegularSemigroupElement

\[ \text{IsRegularSemigroupElement}(S, x) \]  
\textbf{returns} \ true \ if \( x \) has a general inverse in \( S \), i.e., there is an element \( y \in S \) such that \( xyx=x \) and \( yxy=y \).

51.4.3 InversesOfSemigroupElement

\[ \text{InversesOfSemigroupElement}(S, x) \]  
\textbf{Returns:} \ A list of the inverses of an element of a semigroup.  
\text{InversesOfSemigroupElement} returns a list of the inverses of the element \( x \) in the semigroup \( S \).  
An element \( y \) in \( S \) is an inverse of \( x \) if \( x*y*x=x \) and \( y*x*y=y \). The element \( x \) has an inverse if and only if \( x \) is a regular element of \( S \).

\begin{verbatim}
gap> S := Semigroup([  > Transformation([3, 1, 4, 2, 5, 2, 1, 6, 1]),  > Transformation([5, 7, 8, 8, 7, 5, 9, 1, 9]),  
\end{verbatim}
> Transformation([7, 6, 2, 8, 4, 7, 5, 8, 3]));
<transformation semigroup of degree 9 with 3 generators>
gap> x := Transformation([3, 1, 4, 2, 5, 2, 1, 6, 1]);;
gap> InversesOfSemigroupElement(S, x);
[ ]
gap> IsRegularSemigroupElement(S, x);
false

gap> x := Transformation([1, 9, 7, 5, 5, 1, 9, 5, 1]);;
gap> Set(InversesOfSemigroupElement(S, x));
[ Transformation( [ 1, 2, 3, 5, 5, 1, 3, 5, 2 ] ),
  Transformation( [ 1, 5, 1, 1, 5, 1, 3, 1, 2 ] ),
  Transformation( [ 1, 5, 1, 2, 5, 1, 3, 2, 2 ] ) ]
gap> IsRegularSemigroupElement(S, x);
true

gap> S := ReesZeroMatrixSemigroup(Group((1,2,3)),
> [[(), ()], [(1,2,3)], [(), 0], [(1,2,3)]]);
gap> x := ReesZeroMatrixSemigroupElement(S, (1,2,3), 3);
gap> InversesOfSemigroupElement(S, x);
[ (1,(1,2,3),3), (1,(1,3,2),1), (2,(),3), (2,(1,2,3),1) ]

51.4.4 IsSimpleSemigroup

▷ IsSimpleSemigroup(S) (property)

is true if and only if the semigroup S has no proper ideals.

51.4.5 IsZeroSimpleSemigroup

▷ IsZeroSimpleSemigroup(S) (property)

is true if and only if the semigroup has no proper ideals except for 0, where S is a semigroup with zero. If the semigroup does not find its zero, then a break-loop is entered.

51.4.6 IsZeroGroup

▷ IsZeroGroup(S) (property)

is true if and only if the semigroup S is a group with zero adjoined.

51.4.7 IsReesCongruenceSemigroup

▷ IsReesCongruenceSemigroup(S) (property)

returns true if S is a Rees Congruence semigroup, that is, if all congruences of S are Rees Congruences.
51.4.8 IsInverseSemigroup

\begin{verbatim}
PROPERTY IsInverseSemigroup(S)

RETURNS: true or false.

A semigroup S is an inverse semigroup if every element x in S has a unique semigroup inverse, that is, a unique element y in S such that x*y*x = x and y*x*y = y.

A monoid that happens to be an inverse semigroup is called an inverse monoid; see IsMonoid (51.2.1).
\end{verbatim}

Example

\begin{verbatim}
gap> S := Semigroup([ Transformation([1, 2, 4, 5, 6, 3, 7, 8]),
  Transformation([3, 3, 4, 5, 6, 2, 7, 8]),
  Transformation([1, 2, 5, 3, 6, 8, 4, 4])]);

gap> IsInverseSemigroup(S);
true
\end{verbatim}

51.5 Ideals of semigroups

Ideals of semigroups are the same as ideals of the semigroup when considered as a magma. For documentation on ideals for magmas, see Magma (35.2.1).

51.5.1 SemigroupIdealByGenerators

\begin{verbatim}
OPERATION SemigroupIdealByGenerators(S, gens)

S is a semigroup, gens is a list of elements of S. Returns the two-sided ideal of S generated by gens.
\end{verbatim}

51.5.2 ReesCongruenceOfSemigroupIdeal

\begin{verbatim}
ATTRIBUTE ReesCongruenceOfSemigroupIdeal(I)

A two sided ideal I of a semigroup S defines a congruence on S given by \( \Delta \cup I \times I \).
\end{verbatim}

51.5.3 IsLeftSemigroupIdeal

\begin{verbatim}
PROPERTY IsLeftSemigroupIdeal(I)

PROPERTY IsRightSemigroupIdeal(I)

PROPERTY IsSemigroupIdeal(I)

Categories of semigroup ideals.
\end{verbatim}

51.6 Congruences on semigroups

An equivalence or a congruence on a semigroup is the equivalence or congruence on the semigroup considered as a magma. So, to deal with equivalences and congruences on semigroups, magma functions are used. For documentation on equivalences and congruences on magmas, see Magma (35.2.1).
51.6.1 IsSemigroupCongruence

\[ \text{IsSemigroupCongruence}(c) \]  

a magma congruence \( c \) on a semigroup.

51.6.2 IsReesCongruence

\[ \text{IsReesCongruence}(c) \]  

returns \true\ if and only if the congruence \( c \) has at most one nonsingleton congruence class.

51.7 Quotients

Given a semigroup and a congruence on the semigroup, one can construct a new semigroup: the quotient semigroup. The following functions deal with quotient semigroups in GAP. For a semigroup \( S \), elements of a quotient semigroup are equivalence classes of elements of the \text{QuotientSemigroupPreimage} (51.7.3) value under the congruence given by the value of \text{QuotientSemigroupCongruence} (51.7.3).

It is probably most useful for calculating the elements of the equivalence classes by using \text{Elements} (30.3.11) or by looking at the images of elements of \text{QuotientSemigroupPreimage} (51.7.3) under the map returned by \text{QuotientSemigroupHomomorphism} (51.7.3), which maps the \text{QuotientSemigroupPreimage} (51.7.3) value to \( S \).

For intensive computations in a quotient semigroup, it is probably worthwhile finding another representation as the equality test could involve enumeration of the elements of the congruence classes being compared.

51.7.1 IsQuotientSemigroup

\[ \text{IsQuotientSemigroup}(S) \]  

is the category of semigroups constructed from another semigroup and a congruence on it.

51.7.2 HomomorphismQuotientSemigroup

\[ \text{HomomorphismQuotientSemigroup}(\text{cong}) \]  

for a congruence \( \text{cong} \) and a semigroup \( S \). Returns the homomorphism from \( S \) to the quotient of \( S \) by \( \text{cong} \).

51.7.3 QuotientSemigroupPreimage

\[ \text{QuotientSemigroupPreimage}(S) \]  
\[ \text{QuotientSemigroupCongruence}(S) \]  
\[ \text{QuotientSemigroupHomomorphism}(S) \]  

for a quotient semigroup \( S \).
51.8 Green’s Relations

Green’s equivalence relations play a very important role in semigroup theory. In this section we describe how they can be used in GAP.

The five Green’s relations are $R$, $L$, $J$, $H$, $D$: two elements $x, y$ from a semigroup $S$ are $R$-related if and only if $xS^1 = yS^1$, $L$-related if and only if $S^1x = S^1y$ and $J$-related if and only if $S^1xS^1 = S^1yS^1$; finally, $H = R \land L$, and $D = R \circ L$.

Recall that relations $R$, $L$ and $J$ induce a partial order among the elements of the semigroup $S$: for two elements $x, y$ from $S$, we say that $x$ is less than or equal to $y$ in the order on $R$ if $xS^1 \subseteq yS^1$; similarly, $x$ is less than or equal to $y$ under $L$ if $S^1x \subseteq S^1y$; finally $x$ is less than or equal to $y$ under $J$ if $S^1xS^1 \subseteq S^1yS^1$. We extend this preorder to a partial order on equivalence classes in the natural way.

51.8.1 GreensRRelation

- GreensRRelation(semigroup) (attribute)
- GreensLRelation(semigroup) (attribute)
- GreensJRelation(semigroup) (attribute)
- GreensDRelation(semigroup) (attribute)
- GreensHRelation(semigroup) (attribute)

The Green’s relations (which are equivalence relations) are attributes of the semigroup semigroup.

51.8.2 IsGreensRelation

- IsGreensRelation(bin-relation) (filter)
- IsGreensRRelation(equiv-relation) (filter)
- IsGreensLRelation(equiv-relation) (filter)
- IsGreensJRelation(equiv-relation) (filter)
- IsGreensHRelation(equiv-relation) (filter)
- IsGreensDRelation(equiv-relation) (filter)

Categories for the Green’s relations.

51.8.3 IsGreensClass

- IsGreensClass(equiv-class) (filter)
- IsGreensRClass(equiv-class) (filter)
- IsGreensLClass(equiv-class) (filter)
- IsGreensJClass(equiv-class) (filter)
- IsGreensHClass(equiv-class) (filter)
- IsGreensDClass(equiv-class) (filter)

return true if the equivalence class equiv-class is a Green’s class of any type, or of $R, L, J, H, D$ type, respectively, or false otherwise.
51.8.4  IsGreensLessThanOrEqual

\[ \text{IsGreensLessThanOrEqual}(C1, C2) \text{ (operation)} \]

returns true if the Green’s class $C1$ is less than or equal to $C2$ under the respective ordering (as defined above), and false otherwise.

Only defined for $R$, $L$ and $J$ classes.

51.8.5  RClassOfHClass

\[ \text{RClassOfHClass}(H) \text{ (attribute)} \]
\[ \text{LClassOfHClass}(H) \text{ (attribute)} \]

are attributes reflecting the natural ordering over the various Green’s classes. $\text{RClassOfHClass}$ and $\text{LClassOfHClass}$ return the $R$ and $L$ classes, respectively, in which an $H$ class is contained.

51.8.6  EggBoxOfDClass

\[ \text{EggBoxOfDClass}(Dclass) \text{ (attribute)} \]

returns for a Green’s $D$ class $Dclass$ a matrix whose rows represent $R$ classes and columns represent $L$ classes. The entries are the $H$ classes.

51.8.7  DisplayEggBoxOfDClass

\[ \text{DisplayEggBoxOfDClass}(Dclass) \text{ (function)} \]

displays a “picture” of the $D$ class $Dclass$, as an array of 1s and 0s. A 1 represents a group $H$ class.

51.8.8  GreensRClassOfElement

\[ \text{GreensRClassOfElement}(S, a) \text{ (operation)} \]
\[ \text{GreensLClassOfElement}(S, a) \text{ (operation)} \]
\[ \text{GreensDClassOfElement}(S, a) \text{ (operation)} \]
\[ \text{GreensJClassOfElement}(S, a) \text{ (operation)} \]
\[ \text{GreensHClassOfElement}(S, a) \text{ (operation)} \]

Creates the $X$ class of the element $a$ in the semigroup $S$ where $X$ is one of $L$, $R$, $D$, $J$, or $H$.

51.8.9  GreensRClasses

\[ \text{GreensRClasses}(S) \text{ (attribute)} \]
\[ \text{GreensLClasses}(S) \text{ (attribute)} \]
\[ \text{GreensHClasses}(S) \text{ (attribute)} \]
\[ \text{GreensJClasses}(S) \text{ (attribute)} \]
\[ \text{GreensDClasses}(S) \text{ (attribute)} \]
If $S$ is a semigroup, then these attributes return the Green’s $R$, $L$, $H$, $J$, or $D$-classes, respectively for the semigroup $S$.

Additionally, if $S$ is a Green’s $D$-class of a semigroup, then $\text{GreensRClasses}$ and $\text{GreensLClasses}$ return the Green’s $R$- or $L$-classes of the semigroup, respectively, contained in the $D$-class $S$; if $S$ is a Green’s $D$, $R$, or $L$-class of a semigroup, then $\text{GreensHClasses}$ returns the Green’s $H$-classes of the semigroup contained in the Green’s class $S$.

EquivalenceClasses (33.7.3) for a Green’s relation lead to one of these functions.

51.8.10 GroupHClassOfGreensDClass

\[ \text{GroupHClassOfGreensDClass(Dclass)} \] (attribute)

for a $D$ class $Dclass$ of a semigroup, returns a group $H$ class of the $D$ class, or fail if there is no group $H$ class.

51.8.11 IsGroupHClass

\[ \text{IsGroupHClass(Hclass)} \] (property)

returns true if the Green’s $H$ class $Hclass$ is a group, which in turn is true if and only if $Hclass^2$ intersects $Hclass$.

51.8.12 IsRegularDClass

\[ \text{IsRegularDClass(Dclass)} \] (property)

returns true if the Greens $D$ class $Dclass$ is regular. A $D$ class is regular if and only if each of its elements is regular, which in turn is true if and only if any one element of $Dclass$ is regular. Idempotents are regular since $eee = e$ so it follows that a Green’s $D$ class containing an idempotent is regular. Conversely, it is true that a regular $D$ class must contain at least one idempotent. (See [How76, Prop. 3.2].)

51.8.13 DisplaySemigroup

\[ \text{DisplaySemigroup(S)} \] (operation)

Produces a convenient display of a transformation semigroup’s $D$-Class structure. Let $S$ be a transformation semigroup of degree $n$. Then for each $r \leq n$, we show all $D$-classes of rank $r$.

A regular $D$-class with a single $H$-class of size 120 appears as

Example

```
* [H size = 120, 1 L-class, 1 R-class]
```

(the * denoting regularity).
51.9 Rees Matrix Semigroups

In this section, we describe the functions in GAP for Rees matrix and 0-matrix semigroups and their subsemigroups. The importance of these semigroups lies in the fact that Rees matrix semigroups over groups are exactly the completely simple semigroups, and Rees 0-matrix semigroups over groups are the completely 0-simple semigroups.

Let \( I \) and \( J \) be sets, let \( S \) be a semigroup, and let \( P = (p_{jk})_{j \in J, k \in I} \) be a \(|J| \times |I|\) matrix with entries in \( S \). Then the Rees matrix semigroup with underlying semigroup \( S \) and matrix \( P \) is just the direct product \( I \times S \times J \) with multiplication defined by

\[
(i, s, j)(k, t, l) = (i, s \cdot p_{jk} \cdot t, l).
\]

Rees 0-matrix semigroups are defined as follows. If \( I, J, S, \) and \( P \) are as above and 0 denotes a new element, then the Rees 0-matrix semigroup with underlying semigroup \( S \) and matrix \( P \) is \((I \times S \times J) \cup \{0\}\) with multiplication defined by

\[
(i, s, j)(k, t, l) = (i, s \cdot p_{jk} \cdot t, l)
\]

when \( p_{jk} \neq 0 \) and 0 if \( p_{jk} = 0 \).

If \( R \) is a Rees matrix or 0-matrix semigroup, then the rows of \( R \) is the index set \( I \), the columns of \( R \) is the index set \( J \), the semigroup \( S \) is the underlying semigroup of \( R \), and the matrix \( P \) is the matrix of \( S \).

Throughout this section, wherever the distinction is unimportant, we will refer to Rees matrix or 0-matrix semigroups collectively as Rees matrix semigroups.

Multiplication of elements of a Rees matrix semigroup obviously depends on the matrix used to create the semigroup. Hence elements of a Rees matrix semigroup can only be created with reference to the semigroup to which they belong. More specifically, every collection or semigroup of Rees matrix semigroup elements is created from a specific Rees matrix semigroup, which contains the whole family of its elements. So, it is not possible to multiply or compare elements belonging to distinct Rees matrix semigroups, since they belong to different families. This situation is similar to, say, free groups, and different to, say, permutations, which belong to a single family, and where arbitrary permutations can be compared and multiplied without reference to any group containing them.

A subsemigroup of a Rees matrix semigroup is not necessarily a Rees matrix semigroup. Every semigroup consisting of elements of a Rees matrix semigroup satisfies the property \( \text{IsReesMatrixSubsemigroup} \) (51.9.6) and every semigroup of Rees 0-matrix semigroup elements satisfies \( \text{IsReesZeroMatrixSubsemigroup} \) (51.9.6).

Rees matrix and 0-matrix semigroups can be created using the operations \( \text{ReesMatrixSemigroup} \) (51.9.1) and \( \text{ReesZeroMatrixSemigroup} \) (51.9.1), respectively, from an underlying semigroup and a matrix. Rees matrix semigroups created in this way contain the whole family of their elements. Every element of a Rees matrix semigroup belongs to a unique semigroup created in this way; every subsemigroup of a Rees matrix semigroup is a subsemigroup of a unique semigroup created in this way.

Subsemigroups of Rees matrix semigroups can also be created by specifying generators. A subsemigroup of a Rees matrix semigroup \( I \times U \times J \) satisfies \( \text{IsReesMatrixSubsemigroup} \) (51.9.7) if and only if it is equal to \( I' \times U' \times J' \) where \( I' \subseteq I, J' \subseteq J, \) and \( U' \) is a subsemigroup of \( U \). The analogous statements holds for Rees 0-matrix semigroups.
It is not necessarily the case that a simple subsemigroups of Rees matrix semigroups satisfies \texttt{IsReesMatrixSemigroup} (51.9.7). A Rees matrix semigroup is simple if and only if its underlying semigroup is simple. A finite semigroup is simple if and only if it is isomorphic to a Rees matrix semigroup over a group; this isomorphism can be obtained explicitly using \texttt{IsomorphismReesMatrixSemigroup} (51.9.3).

Similarly, 0-simple subsemigroups of Rees 0-matrix semigroups do not have to satisfy \texttt{IsReesZeroMatrixSemigroup} (51.9.7). A Rees 0-matrix semigroup with more than 2 elements is 0-simple if and only if every row and every column of its matrix contains a non-zero entry, and its underlying semigroup is simple. A finite semigroup is 0-simple if and only if it is isomorphic to a Rees 0-matrix semigroup over a group; again this isomorphism can be found by using \texttt{IsomorphismReesZeroMatrixSemigroup} (51.9.3).

Elements of a Rees matrix or 0-matrix semigroup belong to the categories \texttt{IsReesMatrixSemigroupElement} (51.9.4) and \texttt{IsReesZeroMatrixSemigroupElement} (51.9.4), respectively. Such elements can be created directly using the functions \texttt{ReesMatrixSemigroupElement} and \texttt{ReesZeroMatrixSemigroupElement}. A semigroup in \texttt{GAP} can either satisfies \texttt{IsReesMatrixSemigroup} (51.9.7) or \texttt{IsReesZeroMatrixSemigroup} (51.9.7) but not both.

### 51.9.1 ReesMatrixSemigroup

\begin{verbatim}
▷ ReesMatrixSemigroup(S, mat)  (operation)
▷ ReesZeroMatrixSemigroup(S, mat)  (operation)

Returns: A Rees matrix or 0-matrix semigroup.

When \textit{S} is a semigroup and \textit{mat} is an \textit{m} by \textit{n} matrix with entries in \textit{S}, the function \texttt{ReesMatrixSemigroup} returns the \textit{n} by \textit{m} Rees matrix semigroup over \textit{S} with multiplication defined by \textit{mat}.

The arguments of \texttt{ReesZeroMatrixSemigroup} should be a semigroup \textit{S} and an \textit{m} by \textit{n} matrix \textit{mat} with entries in \textit{S} or equal to the integer 0. \texttt{ReesZeroMatrixSemigroup} returns the \textit{n} by \textit{m} Rees 0-matrix semigroup over \textit{S} with multiplication defined by \textit{mat}. In \texttt{GAP} a Rees 0-matrix semigroup always contains a multiplicative zero element, regardless of whether there are any entries in \textit{mat} which are equal to 0.

Example

```gap
G:=Random(AllGroups(Size, 32));;
mat:=List([1..5], x-> List([1..3], y-> Random(G)));;
S:=ReesMatrixSemigroup(G, mat);
<Rees matrix semigroup 3x5 over <pc group of size 32 with 5 generators>>
mat:=[[(), 0, 0, 0], [0, 0, 0, 0], [0, 0, 0, 0]];
S:=ReesZeroMatrixSemigroup(DihedralGroup(IsPermGroup, 8), mat);
<Rees 0-matrix semigroup 4x2 over Group([ (1,2,3,4), (2,4 ) ])
```
\end{verbatim}

### 51.9.2 ReesMatrixSubsemigroup

\begin{verbatim}
▷ ReesMatrixSubsemigroup(R, I, U, J)  (operation)
▷ ReesZeroMatrixSubsemigroup(R, I, U, J)  (operation)

Returns: A Rees matrix or 0-matrix subsemigroup.

The arguments of \texttt{ReesMatrixSubsemigroup} should be a Rees matrix semigroup \textit{R}, subsets \textit{I} and \textit{J} of the rows and columns of \textit{R}, respectively, and a subsemigroup \textit{S} of the underlying semigroup.
of \( R \). \text{ReesMatrixSubsemigroup} returns the subsemigroup of \( R \) generated by the direct product of \( I \), \( U \), and \( J \).

The usage and returned value of \text{ReesZeroMatrixSubsemigroup} is analogous when \( R \) is a Rees 0-matrix semigroup.

Example

```gap
gap> G:=CyclicGroup(IsPermGroup, 1007);;
gap> mat:=[[(), 0, 0], [0, (), 0], [0, 0, ()], [(), (), ()], [0, 0, ()]];
gap> R:=ReesZeroMatrixSemigroup(G, mat);
<Rees 0-matrix semigroup 3x5 over <permutation group of size 1007 with 1 generators>>
gap> ReesZeroMatrixSubsemigroup(R, [1,3], G, [1..5]);
<Rees 0-matrix semigroup 2x5 over <permutation group of size 1007 with 1 generators>>
```

51.9.3 \textbf{IsomorphismReesMatrixSemigroup}

\textbf{Returns:} An isomorphism.

Every finite simple semigroup is isomorphic to a Rees matrix semigroup over a group, and every finite 0-simple semigroup is isomorphic to a Rees 0-matrix semigroup over a group.

If the argument \( S \) is a simple semigroup, then \text{IsomorphismReesMatrixSemigroup} returns an isomorphism to a Rees matrix semigroup over a group. If \( S \) is not simple, then \text{IsomorphismReesMatrixSemigroup} returns an error.

If the argument \( S \) is a 0-simple semigroup, then \text{IsomorphismReesMatrixSemigroup} returns an isomorphism to a Rees 0-matrix semigroup over a group. If \( S \) is not 0-simple, then \text{IsomorphismReesMatrixSemigroup} returns an error.

See \text{IsSimpleSemigroup} (51.4.4) and \text{IsZeroSimpleSemigroup} (51.4.5).

Example

```gap
gap> S := Semigroup(Transformation([2, 1, 1, 2, 1]),
> Transformation([3, 4, 3, 4, 4]),
> Transformation([3, 4, 3, 4, 3]),
> Transformation([4, 3, 3, 4, 4]));;
gap> IsSimpleSemigroup(S);
true
gap> Range(IsomorphismReesMatrixSemigroup(S));
<Rees matrix semigroup 4x2 over Group([ (1,2) ])> 
gap> mat := [[(), 0, 0], [0, (), 0], [0, 0, ()]];
gap> R := ReesZeroMatrixSemigroup(Group([1,2,4,5,6]), mat);
<Rees 0-matrix semigroup 3x3 over Group([1,2,4,5,6])>
gap> U := ReesZeroMatrixSubsemigroup(R, [1, 2], Group(()), [2, 3]);
<subsemigroup of 3x3 Rees 0-matrix semigroup with 4 generators>
gap> IsZeroSimpleSemigroup(U); 
false
gap> U := ReesZeroMatrixSubsemigroup(R, [2, 3], Group(()), [2, 3]);
<subsemigroup of 3x3 Rees 0-matrix semigroup with 3 generators>
gap> IsZeroSimpleSemigroup(U);
```
true
gap> Rows(U); Columns(U);
[ 2, 3 ]
[ 2, 3 ]
gap> V := Range(IsomorphismReesZeroMatrixSemigroup(U));
<Rees 0-matrix semigroup 2x2 over Group(())>
gap> Rows(V); Columns(V);
[ 1, 2 ]
[ 1, 2 ]

51.9.4 IsReesMatrixSemigroupElement

▷ IsReesMatrixSemigroupElement(elt) (Category)
▷ IsReesZeroMatrixSemigroupElement(elt) (Category)

Returns: true or false.

Every element of a Rees matrix semigroup belongs to the category IsReesMatrixSemigroupElement, and every element of a Rees 0-matrix semigroup belongs to the category IsReesZeroMatrixSemigroupElement.

Example

gap> G:=Group((1,2,3));;
gap> mat:=[ [ (), (1,3,2) ], [ (1,3,2), () ] ];;
gap> R:=ReesMatrixSemigroup(G, mat);
<Rees matrix semigroup 2x2 over Group([ (1,2,3) ])>
gap> GeneratorsOfSemigroup(R);
[ (1,(1,2,3),1), (2,(),2) ]
gap> IsReesMatrixSemigroupElement(last[1]);
true
gap> IsReesZeroMatrixSemigroupElement(last[2]);
false

51.9.5 ReesMatrixSemigroupElement

▷ ReesMatrixSemigroupElement(R, i, x, j) (function)
▷ ReesZeroMatrixSemigroupElement(R, i, x, j) (function)

Returns: An element of a Rees matrix or 0-matrix semigroup.

The arguments of ReesMatrixSemigroupElement should be a Rees matrix subsemigroup R, elements i and j of the the rows and columns of R, respectively, and an element x of the underlying semigroup of R. ReesMatrixSemigroupElement returns the element of R with row index i, underlying element x in the underlying semigroup of R, and column index j, if such an element exist, if such an element exists.

The usage of ReesZeroMatrixSemigroupElement is analogous to that of ReesMatrixSemigroupElement, when R is a Rees 0-matrix semigroup.

The row i, underlying element x, and column j of an element y of a Rees matrix (or 0-matrix) semigroup can be recovered from y using y[1], y[2], and y[3], respectively.

Example

gap> G:=Group((1,2,3));;
gap> mat:=[ [ 0, () ], [ (1,3,2), (1,3,2) ] ];;
gap> R:=ReesZeroMatrixSemigroup(G, mat);
<Rees 0-matrix semigroup 2x2 over Group([ (1,2,3) ])>

 gap> ReesZeroMatrixSemigroupElement(R, 1, (1,2,3), 2); 
(1,(1,2,3),2) 
gap> MultiplicativeZero(R); 
0 

51.9.6  IsReesMatrixSubsemigroup

▷ IsReesMatrixSubsemigroup(R)  
▷ IsReesZeroMatrixSubsemigroup(R)  

defined at 51.9.6.  

Properties:  
Returns: true or false.

Every semigroup consisting of elements of a Rees matrix semigroup satisfies the property  
IsReesMatrixSubsemigroup and every semigroup of Rees 0-matrix semigroup elements satisfies  
IsReesZeroMatrixSubsemigroup.

Note that a subsemigroup of a Rees matrix semigroup is not necessarily a Rees matrix semigroup.

Example

\[
\begin{align*}
gap> & G:=DihedralGroup(32);; 
gap> & mat:=List([1..2], x-> List([1..10], x-> Random(G)));; 
gap> & R:=ReesMatrixSemigroup(G, mat); <Rees matrix semigroup 10x2 over <pc group of size 32 with 
5 generators>> 
gap> & S:=Semigroup(GeneratorsOfSemigroup(R)); <subsemigroup of 10x2 Rees matrix semigroup with 14 generators> 
gap> & IsReesMatrixSubsemigroup(S); true 
\end{align*}
\]

51.9.7  IsReesMatrixSemigroup

▷ IsReesMatrixSemigroup(R)  
▷ IsReesZeroMatrixSemigroup(R)  

defined at 51.9.7.  

Properties:  
Returns: true or false.

A subsemigroup of a Rees matrix semigroup \( I \times U \times J \) satisfies IsReesMatrixSemigroup if and only if it is equal to \( I' \times U' \times J' \) where \( I' \subseteq I, J' \subseteq J \), and \( U' \) is a subsemigroup of \( U \). It can be costly to check that a subsemigroup defined by generators satisfies IsReesMatrixSemigroup. The analogous statements holds for Rees 0-matrix semigroups.

It is not necessarily the case that a simple subsemigroups of Rees matrix semigroups satisfies IsReesMatrixSemigroup. A Rees matrix semigroup is simple if and only if its underlying semigroup is simple. A finite semigroup is simple if and only if it is isomorphic to a Rees matrix semigroup over a group; this isomorphism can be obtained explicitly using IsomorphismReesMatrixSemigroup (51.9.3).

Similarly, 0-simple subsemigroups of Rees 0-matrix semigroups do not have to satisfy IsReesZeroMatrixSemigroup. A Rees 0-matrix semigroup with more than 2 elements is 0-simple if and only if every row and every column of its matrix contains a non-zero entry, and its underlying semigroup is simple. A finite semigroup is 0-simple if and only if it is isomor-
phic to a Rees 0-matrix semigroup over a group; again this isomorphism can be found by using \texttt{IsomorphismReesMatrixSemigroup} (51.9.3).

\begin{verbatim}
Example

gap> G:=PSL(2,5);
gap> mat:=
> [ [ 0, ((), (), 0, (2,6,3,5,4) ]],
> [ ((), 0, ((), 0, (0, 0, 0) ) ] ];

gap> R:=ReesZeroMatrixSemigroup(G, mat);
<Rees 0-matrix semigroup 4x3 over Group([ (3,5)(4,6), (1,2,5)
(3,4,6) ])

gap> IsReesZeroMatrixSemigroup(R);
true

gap> U:=ReesZeroMatrixSubsemigroup(R, [1..3], Group(()), [1..2]);
<subsemigroup of 4x3 Rees 0-matrix semigroup with 4 generators>

gap> IsReesZeroMatrixSemigroup(U);
true

gap> V:=Semigroup(GeneratorsOfSemigroup(U));
<subsemigroup of 4x3 Rees 0-matrix semigroup with 4 generators>

gap> IsReesZeroMatrixSemigroup(V);
true

gap> S:=Semigroup(Transformation([1,1]), Transformation([1,2]));
<commutative transformation monoid of degree 2 with 1 generator>

gap> IsSimpleSemigroup(S);
false

gap> mat:=[[0, One(S), 0, One(S)],
> [One(S), 0, One(S), 0],
> [0, 0, One(S)],
> [One(S), 0, One(S)] ];

gap> R:=ReesZeroMatrixSemigroup(S, mat);

gap> U:=ReesZeroMatrixSubsemigroup(R, [1..3],
> Semigroup(Transformation([1,1])), [1..2]);
<subsemigroup of 4x3 Rees 0-matrix semigroup with 6 generators>

gap> V:=Semigroup(GeneratorsOfSemigroup(U));
<subsemigroup of 4x3 Rees 0-matrix semigroup with 6 generators>

gap> IsReesZeroMatrixSemigroup(V);
true

gap> T:=Semigroup(
> ReesZeroMatrixSemigroupElement(R, 3, Transformation([1,1]), 3),
> ReesZeroMatrixSemigroupElement(R, 2, Transformation([1,1]), 2));
<subsemigroup of 4x3 Rees 0-matrix semigroup with 2 generators>

gap> IsReesZeroMatrixSemigroup(T);
false
\end{verbatim}

\section{51.9.8 Matrix}

\textbf{\texttt{Matrix(R)}}

\textbf{Returns:} A matrix.

If \texttt{R} is a Rees matrix or 0-matrix semigroup, then \texttt{Matrix} returns the matrix used to define multiplication in \texttt{R}.

More specifically, if \texttt{R} is a Rees matrix or 0-matrix semigroup, which is a proper subsemigroup of another such semigroup, then \texttt{Matrix} returns the matrix used to define the Rees matrix (or 0-matrix) semigroup consisting of the whole family to which the elements of \texttt{R} belong. Thus, for example, a 1 by 1 Rees matrix semigroup can have a 65 by 15 matrix.
Arbitrary subsemigroups of Rees matrix or 0-matrix semigroups do not have a matrix. Such a subsemigroup $R$ has a matrix if and only if it satisfies \texttt{IsReesMatrixSemigroup} (51.9.7) or \texttt{IsReesZeroMatrixSemigroup} (51.9.7).

Example

\begin{verbatim}
gap> G:=AlternatingGroup(5);;
gap> mat:=[[(),(),()], [(),(),()]];;
gap> R:=ReesMatrixSemigroup(G, mat);
<Rees matrix semigroup 3x2 over Alt( [ 1 .. 5 ] )>
gap> Matrix(R);
[ [ (), (), () ], [ (), (), () ] ]
gap> R:=ReesMatrixSubsemigroup(R, [1,2], Group(()), [2]);
<subsemigroup of 3x2 Rees matrix semigroup with 2 generators>
gap> Matrix(R);
[ [ (), (), () ], [ (), (), () ] ]
\end{verbatim}

51.9.9 Rows and columns

\begin{verbatim}
\begin{verbatim}
\textbf{Returns:} The rows or columns of $R$.
\end{verbatim}
\end{verbatim}

\texttt{Rows} returns the rows of the Rees matrix or 0-matrix semigroup $R$. Note that the rows of the semigroup correspond to the columns of the matrix used to define multiplication in $R$.

\texttt{Columns} returns the columns of the Rees matrix or 0-matrix semigroup $R$. Note that the columns of the semigroup correspond to the rows of the matrix used to define multiplication in $R$.

Arbitrary subsemigroups of Rees matrix or 0-matrix semigroups do not have rows or columns. Such a subsemigroup $R$ has rows and columns if and only if it satisfies \texttt{IsReesMatrixSemigroup} (51.9.7) or \texttt{IsReesZeroMatrixSemigroup} (51.9.7).

Example

\begin{verbatim}
gap> G:=Group((1,2,3));;
gap> mat:=List([1..100], x-> List([1..200], x->Random(G)));;
gap> R:=ReesZeroMatrixSemigroup(G, mat);
<Rees 0-matrix semigroup 200x100 over Group([ (1,2,3) ] )>
gap> Rows(R);
[ 1 .. 100 ]
gap> Columns(R);
[ 1 .. 100 ]
\end{verbatim}

51.9.10 UnderlyingSemigroup (for a Rees matrix semigroup)

\begin{verbatim}
\begin{verbatim}
\textbf{Returns:} A semigroup.
\end{verbatim}
\end{verbatim}

Arbitrary subsemigroups of Rees matrix or 0-matrix semigroups do not have an underlying semigroup. Such a subsemigroup $R$ has an underlying semigroup if and only if it satisfies \texttt{IsReesMatrixSemigroup} (51.9.7) or \texttt{IsReesZeroMatrixSemigroup} (51.9.7).
Example

```gap
gap> S:=Semigroup(Transformation([2, 1, 1, 2, 1]),
              Transformation([3, 4, 3, 4, 4]), Transformation([3, 4, 3, 4, 3]),
              Transformation([4, 3, 3, 4, 4]));;
gap> R:=Range(IsomorphismReesMatrixSemigroup(S));
<Rees matrix semigroup 4x2 over Group([ (1,2) ])
gap> UnderlyingSemigroup(R);
Group([ (1,2) ])
```

### 51.9.11  AssociatedReesMatrixSemigroupOfDClass

**AssociatedReesMatrixSemigroupOfDClass**

- **Returns:** A Rees matrix or 0-matrix semigroup.

If \( D \) is a regular \( \mathcal{D} \)-class of a finite semigroup \( S \), then there is a standard way of associating a Rees matrix semigroup to \( D \). If \( D \) is a subsemigroup of \( S \), then \( D \) is simple and hence is isomorphic to a Rees matrix semigroup. In this case, the associated Rees matrix semigroup of \( D \) is just the Rees matrix semigroup isomorphic to \( D \).

If \( D \) is not a subsemigroup of \( S \), then we define a semigroup with elements \( D \) and a new element 0 with multiplication of \( x, y \in D \) defined by:

\[
xy = \begin{cases} 
  x \ast y \text{ (in } S) & \text{if } x \ast y \in D \\
  0 & \text{if } xy \not\in D.
\end{cases}
\]

The semigroup thus defined is 0-simple and hence is isomorphic to a Rees 0-matrix semigroup. This semigroup can also be described as the Rees quotient of the ideal generated by \( D \) by its maximal subideal. The associated Rees matrix semigroup of \( D \) is just the Rees 0-matrix semigroup isomorphic to the semigroup defined above.

Example

```gap
gap> S:=FullTransformationSemigroup(5);;
gap> D:=GreensDClasses(S)[3];
{Transformation([1, 1, 1, 2, 3])}
gap> AssociatedReesMatrixSemigroupOfDClass(D);
<Rees 0-matrix semigroup 25x10 over Group([ (1,2)(3,5)(4,6), (1,3)
   (2,4)(5,6) ])
```
Chapter 52

Finitely Presented Semigroups and Monoids

A finitely presented semigroup (resp. finitely presented monoid) is a quotient of a free semigroup (resp. free monoid) on a finite number of generators over a finitely generated congruence on the free semigroup (resp. free monoid).

Finitely presented semigroups are obtained by factoring a free semigroup by a set of relations (a generating set for the congruence), i.e., a set of pairs of words in the free semigroup.

Example

```gap
gap> f := FreeSemigroup( "a", "b" );;
gap> x := GeneratorsOfSemigroup( f );;
gap> GeneratorsOfSemigroup( s );
[ a, b ]
gap> RelationsOfFpSemigroup( s );
[ [ a*b, b*a ] ]
```

Finitely presented monoids are obtained by factoring a free monoid by a set of relations, i.e. a set of pairs of words in the free monoid.

Example

```gap
gap> f := FreeMonoid( "a", "b" );;
gap> x := GeneratorsOfMonoid( f );
[ a, b ]
gap> e := Identity( f );
<identity ...>
gap> m := f / [ [ x[1] * x[2], e ] ];
gap> RelationsOfFpMonoid( m );
[ [ a*b, <identity ...> ] ]
```

Notice that for GAP a finitely presented monoid is not a finitely presented semigroup.

Example

```gap
gap> IsFpSemigroup( m );
false
```
However, one can build a finitely presented semigroup isomorphic to that finitely presented monoid (see IsomorphismFpSemigroup (52.2.3)).

Also note that it is not possible to refer to the generators by their names. These names are not variables, but just display figures. So, if one wants to access the generators by their names, one first has to introduce the respective variables and to assign the generators to them.

```
gap> Unbind( a );
gap> f := FreeSemigroup( "a", "b" );;
gap> s := f / [ [ f.1 * f.2, f.2 * f.1 ] ];;
gap> a;
Error, Variable: 'a' must have a value

gap> a := s.1;
a

gap> a in f;
false

gap> a in s;
true
```

The generators of the free semigroup (resp. free monoid) are different from the generators of the finitely presented semigroup (resp. finitely presented monoid) (even though they are displayed by the same names). This means that words in the generators of the free semigroup (resp. free monoid) are not elements of the finitely presented semigroup (resp. finitely presented monoid). Conversely, elements of the finitely presented semigroup (resp. finitely presented monoid) are not words of the free semigroup (resp. free monoid).

Calculations comparing elements of a finitely presented semigroup may run into problems: there are finitely presented semigroups for which no algorithm exists (it is known that no such algorithm can exist) that will tell for two arbitrary words in the generators whether the corresponding elements in the finitely presented semigroup are equal. Therefore the methods used by GAP to compute in finitely presented semigroups may run into warning errors, run out of memory or run forever. If the finitely presented semigroup is (by theory) known to be finite the algorithms are guaranteed to terminate (if there is sufficient memory available), but the time needed for the calculation cannot be bounded a priori. The same can be said for monoids. (See 52.5.)

```
gap> b := s.2;;
gap> a^b = a^5;
false

gap> a^5 * b^2 * a = a^6 * b^2;
true
```

Note that elements of a finitely presented semigroup (or monoid) are not printed in a unique way:

```
gap> a^5 * b^2 * a;
a^5*b^2*a

gap> a^6 * b^2;
a^6*b^2
```
52.1 IsSubsemigroupFpSemigroup (Filter)

52.1.1 IsSubsemigroupFpSemigroup

\[ \text{IsSubsemigroupFpSemigroup}(t) \] (filter)
\[ \text{IsSubmonoidFpMonoid}(t) \] (filter)

The first function returns true if \( t \) is a finitely presented semigroup or a subsemigroup of a finitely presented semigroup. The second function does the equivalent thing for monoids. (Generally speaking, such a subsemigroup or monoid can be constructed with \texttt{Semigroup(gens)} or \texttt{Monoid(gens)}, where \texttt{gens} is a list of elements of a finitely presented semigroup or monoid.)

A submonoid of a monoid has the same identity as the monoid.

52.1.2 IsFpSemigroup

\[ \text{IsFpSemigroup}(s) \] (filter)
\[ \text{IsFpMonoid}(m) \] (filter)

The first function is a synonym for \texttt{IsSubsemigroupFpSemigroup(s)} and \texttt{IsWholeFamily(s)} (this is because a subsemigroup of a finitely presented semigroup is not necessarily finitely presented).

Similarly, the second function is a synonym for \texttt{IsSubmonoidFpMonoid(m)} and \texttt{IsWholeFamily(m)}.

52.1.3 IsElementOfFpSemigroup

\[ \text{IsElementOfFpSemigroup}(elm) \] (Category)
\[ \text{IsElementOfFpMonoid}(elm) \] (Category)

returns true if \( elm \) is an element of a finitely presented semigroup or monoid.

Example

```
gap> f := FreeSemigroup( "a", "b" );;
gap> IsFpSemigroup( f );
false
gap> s := f / [ [ f.1^2, f.2^2 ] ];;
gap> IsFpSemigroup( s );
true
gap> t := Semigroup( [ s.1^2 ] );
<commutative semigroup with 1 generator>
gap> IsSubsemigroupFpSemigroup( t );
true
gap> IsSubsemigroupFpSemigroup( s );
true
gap> IsSubsemigroupFpSemigroup( f );
false
gap> IsElementOfFpSemigroup( t.1^3 );
true
```
52.1.4 FpGrpMonSmgOfFpGrpMonSmgElement

\( \text{FpGrpMonSmgOfFpGrpMonSmgElement}(\text{elm}) \) (operation)

returns the finitely presented group, monoid or semigroup to which \text{elm} belongs.

```
Example

gap> s = FpGrpMonSmgOfFpGrpMonSmgElement( s.1 );
true
gap> s = FpGrpMonSmgOfFpGrpMonSmgElement( t.1 );
true
```

52.2 Creating Finitely Presented Semigroups and Monoids

52.2.1 \( / \) (for a free semigroup or monoid and a list of pairs of elements)

\( \text{F, rels} \) (method)

creates a finitely presented semigroup or monoid given by the presentation \( \langle \text{gens} \mid \text{rels} \rangle \) where \text{gens} are the generators of the free semigroup or free monoid \( F \), and the relations \text{rels} are entered as pairs of words in the generators of the free semigroup or free monoid.

The same result is obtained with the infix operator \( / \), i.e. as \( F / \text{rels} \).

```
Example

gap> fs := FreeSemigroup( 3 );;
gap> x := GeneratorsOfSemigroup( fs );;
<fp semigroup on the generators [ s1, s2, s3 ]>
```

52.2.2 FactorFreeSemigroupByRelations

\( \text{FactorFreeSemigroupByRelations}(f, \text{rels}) \) (function)

\( \text{FactorFreeMonoidByRelations}(f, \text{rels}) \) (function)

for a free semigroup or free monoid \( f \) and a list \text{rels} of pairs of elements of \( f \). Returns the finitely presented semigroup or monoid which is the quotient of \( f \) by the least congruence on \( f \) generated by the pairs in \text{rels}.

Users should be aware that much of the code described in this chapter is in need of substantial revision. In particular, the two functions described here are not called by the operation \( / \) of the previous subsection, and so are liable to be removed in due course.

```
Example

gap> fm := FreeMonoid( 3 );;
gap> y := GeneratorsOfMonoid( fm );;
<fp monoid on the generators [ m1, m2, m3 ]>
```
52.2.3 IsomorphismFpSemigroup

\[ \text{IsomorphismFpSemigroup}(m) \] (attribute)

\[ \text{IsomorphismFpMonoid}(g) \] (attribute)

for a finitely presented monoid \( m \) or a finitely presented group \( g \). Returns an isomorphism from \( m \) or \( g \) to a finitely presented semigroup or monoid.

Example

\begin{verbatim}
gap> phis := IsomorphismFpSemigroup( m );
MappingByFunction( <fp monoid on the generators [ m1, m2, m3 ]>, <fp semigroup on the generators [ <identity ...>, m1, m2, m3 ]>, function( x ) ... end, function( x ) ... end )
gap> fg := FreeGroup( 2 );;
gap> g := fg / [ fg.1^4, fg.2^5 ];
<fp group on the generators [ f1, f2 ]>
gap> phim := IsomorphismFpMonoid( g );
MappingByFunction( <fp group on the generators [ f1, f2 ]>, <fp monoid on the generators [ f1, f1^-1, f2, f2^-1 ]>, function( x ) ... end, function( x ) ... end )
\end{verbatim}

52.3 Comparison of Elements of Finitely Presented Semigroups

52.3.1 \( \backslash = \) (for two elements in a f.p. semigroup)

\[ \backslash = (a, b) \] (method)

Two elements \( a, b \) of a finitely presented semigroup are equal if they are equal in the semigroup. Nevertheless they may be represented as different words in the generators. Because of the fundamental problems mentioned in the introduction to this chapter such a test may take a very long time and cannot be guaranteed to finish (see 52.5).

52.4 Preimages in the Free Semigroup or Monoid

Elements of a finitely presented semigroup or monoid are not words, but are represented using a word from the free semigroup or free monoid as representative.

52.4.1 UnderlyingElement (of an element in a fp semigroup or monoid)

\[ \text{UnderlyingElement}(elm) \] (operation)

for an element \( elm \) of a finitely presented semigroup or monoid. Returns the word from the free semigroup or free monoid that is used as a representative for \( elm \).
```gap
gap> ue := UnderlyingElement( e );
4
gap> IsWord( ue );
true
```

### 52.4.2 ElementOfFpSemigroup

- **ElementOfFpSemigroup**(fam, word) (operation)
- **ElementOfFpMonoid**(fam, word) (operation)

For a family *fam* of elements of a finitely presented semigroup or monoid and a word *word* in the free generators underlying this finitely presented semigroup or monoid. Returns the element of the finitely presented semigroup or monoid with the representative *word* in the free semigroup or free monoid. These operations are inverse to UnderlyingElement.

```gap
gap> fam := FamilyObj( genm[1] );;
m1^3*m2^4*m3^5
gap> ew := ElementOfFpMonoid( fam, w );
m1^3*m2^4*m3^5
gap> ew in fm;
false
gap> ew in m;
true
gap> w = UnderlyingElement( ew );
true
```

### 52.4.3 FreeSemigroupOfFpSemigroup

- **FreeSemigroupOfFpSemigroup**(s) (attribute)
- **FreeSemigroupOfFpMonoid**(m) (attribute)

Returns the underlying free semigroup or free monoid for the finitely presented semigroup *s* or monoid *m*, i.e. the free semigroup or free monoid over which *s* or *m* is defined as a quotient. (This is the free semigroup or free monoid generated by the free generators provided by FreeGeneratorsOfFpSemigroup(s) or FreeGeneratorsOfFpMonoid(m)).

### 52.4.4 FreeGeneratorsOfFpSemigroup

- **FreeGeneratorsOfFpSemigroup**(s) (attribute)
- **FreeGeneratorsOfFpMonoid**(m) (attribute)

Returns the underlying free generators corresponding to the generators of the finitely presented semigroup *s* or monoid *m*.

### 52.4.5 RelationsOfFpSemigroup

- **RelationsOfFpSemigroup**(s) (attribute)
- **RelationsOfFpMonoid**(m) (attribute)
returns the relations of the finitely presented semigroup \( s \) or monoid \( m \) as pairs of words in the free generators provided by \( \text{FreeGeneratorsOfFpSemigroup}(s) \) or \( \text{FreeGeneratorsOfFpMonoid}(m) \).

\[
\begin{align*}
gap> & \text{fs = FreeSemigroupOfFpSemigroup( s );} \\
& \text{true} \\
& \text{gap> FreeGeneratorsOfFpMonoid( m );} \\
& [ m1, m2, m3 ] \\
& \text{gap> RelationsOfFpSemigroup( s );} \\
& [ [ s1*s2*s1, s1 ], [ s2^4, s1 ] ]
\end{align*}
\]

52.5 Rewriting Systems and the Knuth-Bendix Procedure

If a finitely presented semigroup (or monoid) has a confluent rewriting system then it has a solvable word problem, that is, there is an algorithm to decide when two words in the free underlying semigroup represent the same element of the finitely presented semigroup. Indeed, once we have a confluent rewriting system, it is possible to successfully test that two words represent the same element in the semigroup, by reducing both words using the rewriting system rules. This is, at the moment, the method that GAP uses to check equality in finitely presented semigroups and monoids.

52.5.1 ReducedConfluentRewritingSystem

\[\text{\$\text{\$}\$}\text{ReducedConfluentRewritingSystem}(S[, ordering])\]

returns a reduced confluent rewriting system of the finitely presented semigroup or monoid \( S \) with respect to the reduction ordering \( ordering \) (see 34).

The default for \( ordering \) is the length plus lexicographic ordering on words, also called the shortlex ordering; for the definition see for example [Sim94].

Notice that this might not terminate. In particular, if the semigroup or monoid \( S \) does not have a solvable word problem then it this will certainly never end. Also, in this case, the object returned is an immutable rewriting system, because once we have a confluent rewriting system for a finitely presented semigroup or monoid we do not want to allow it to change (as it was most probably very time consuming to get it in the first place). Furthermore, this is also an attribute storing object (see 13.4).

\[
\begin{align*}
gap> & f := \text{FreeSemigroup( "a", "b" );} \\
& a := f.1; \quad b := f.2; \\
& s := f / [ [ a*b*a, b ], [ b*a*b, a ] ]; \\
& \text{rws := ReducedConfluentRewritingSystem( s );} \\
& \text{Rewriting System for Semigroup( [ a, b ] ) with rules} \\
& [ [ a*b*a, b ], [ b*a*b, a ], [ b*a^2, a^2*b ], [ b^2, a^2 ], [ a^3*b, b*a ], \\
& [ a^5, a ] ] \\
& c := s.1; \quad d := s.2; \\
& e := (c*d^2)^3; \\
& (a*b^2)^3 \\
& \text{## ReducedForm( rws, e ); gives an error!} \\
& \text{w := UnderlyingElement( e );} \\
& (a*b^2)^3
\end{align*}
\]
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```
gap> ReducedForm( rws, w );
a
```

The creation of a reduced confluent rewriting system for a semigroup or for a monoid, in GAP, uses the Knuth-Bendix procedure for strings, which manipulates a rewriting system of the semigroup or monoid and attempts to make it confluent, (see Chapter 38 and also Sims [Sim94]). (Since the word problem for semigroups/monoids is not solvable in general, the Knuth-Bendix procedure cannot always terminate).

In order to apply this procedure we will build a rewriting system for the semigroup or monoid, which we will call a Knuth-Bendix Rewriting System (we need to define this because we need the rewriting system to store some information needed for the implementation of the Knuth-Bendix procedure).

Actually, Knuth-Bendix Rewriting Systems do not only serve this purpose. Indeed these are objects which are mutable and which can be manipulated (see 38).

Note that the implemented version of the Knuth-Bendix procedure, in GAP returns, if it terminates, a confluent rewriting system which is reduced. Also, a reduction ordering has to be specified when building a rewriting system. If none is specified, the shortlex ordering is assumed (note that the procedure may terminate with a certain ordering and not with another one).

On Unix systems it is possible to replace the built-in Knuth-Bendix by other routines, for example the package kbmag offers such a possibility.

### 52.5.2 KB_REW

- KB_REW
- GAPKB_REW (global variable)

KB_REW is a global record variable whose components contain functions used for Knuth-Bendix. By default KB_REW is assigned to GAPKB_REW, which contains the KB functions provided by the GAP library.

### 52.5.3 KnuthBendixRewritingSystem

- KnuthBendixRewritingSystem(s, wordord) (operation)
- KnuthBendixRewritingSystem(m, wordord) (operation)

in the first form, for a semigroup s and a reduction ordering for the underlying free semigroup, it returns the Knuth-Bendix rewriting system of the finitely presented semigroup s using the reduction ordering wordord. In the second form, for a monoid m and a reduction ordering for the underlying free monoid, it returns the Knuth-Bendix rewriting system of the finitely presented monoid m using the reduction ordering wordord.

### 52.5.4 SemigroupOfRewritingSystem

- SemigroupOfRewritingSystem(rws) (attribute)
- MonoidOfRewritingSystem(rws) (attribute)

returns the semigroup or monoid over which rws is a rewriting system.
52.5.5 FreeSemigroupOfRewritingSystem

-
FreeSemigroupOfRewritingSystem(rws) (attribute)
-
FreeMonoidOfRewritingSystem(rws) (attribute)

returns the free semigroup or monoid over which rws is a rewriting system.

Example

```gap
gap> f1 := FreeSemigroupOfRewritingSystem( rws );
<free semigroup on the generators [ a, b ]>
gap> f1 = f;
true
gap> s1 := SemigroupOfRewritingSystem( rws );
<fp semigroup on the generators [ a, b ]>
gap> s1 = s;
true
```

As mentioned before, having a confluent rewriting system, one can decide whether two words represent the same element of a finitely presented semigroup (or finitely presented monoid).

Example

```gap
gap> d^6 = c^2;
true
gap> ReducedForm( rws, UnderlyingElement( d^6 ) );
a^2
gap> ReducedForm( rws, UnderlyingElement( c^2 ) );
a^2
```

52.6 Todd-Coxeter Procedure

This procedure gives a standard way of finding a transformation representation of a finitely presented semigroup. Usually one does not explicitly call this procedure but uses IsomorphismTransformationSemigroup (53.7.5).

52.6.1 CosetTableOfFpSemigroup

-
CosetTableOfFpSemigroup(r) (attribute)

r is a right congruence of an fp-semigroup S. This attribute is the coset table of FP semigroup S on a right congruence r. Given a right congruence r we represent S as a set of transformations of the congruence classes of r.

The images of the cosets under the generators are compiled in a list table such that table[i][s] contains the image of coset s under generator i.
Chapter 53

Transformations

This chapter describes the functions in GAP for transformations.

A transformation in GAP is simply a function from the positive integers to the positive integers. Transformations are to semigroup theory what permutations are to group theory, in the sense that every semigroup can be realised as a semigroup of transformations. In GAP transformation semigroups are always finite, and so only finite semigroups can be realised in this way.

A transformation in GAP acts on the positive integers (up to some architecture dependent limit) on the right. The image of a point $i$ under a transformation $f$ is expressed as $i \circ f$ in GAP. This action is also implemented by the function OnPoints (41.2.1). If $i \circ f$ is different from $i$, then $i$ is moved by $f$ and otherwise it is fixed by $f$. Transformations in GAP are created using the operations described in Section 53.2.

The degree of a transformation $f$ is usually defined as the largest positive integer where $f$ is defined. In previous versions of GAP, transformations were only defined on positive integers less than their degree, it was only possible to multiply transformations of equal degree, and a transformation did not act on any point exceeding its degree. Starting with version 4.7 of GAP, transformations behave more like permutations, in that they fix unspecified points and it is possible to multiply arbitrary transformations; see Chapter 42. The definition of the degree of a transformation $f$ in the current version of GAP is the largest value $n$ such that $n \circ f \neq n$ or $i \circ f = n$ for some $i \neq n$. Equivalently, the degree of a transformation is the least value $n$ such that $\{ n + 1, n + 2, \ldots \}$ is fixed pointwise by $f$.

The transformations of a given degree belong to the full transformation semigroup of that degree; see FullTransformationSemigroup (53.7.3). Transformation semigroups are hence subsemigroups of the full transformation semigroup.

It is possible to use transformations in GAP without reference to the degree, much as it is possible to use permutations in this way. However, for backwards compatibility, and because it is sometimes useful, it is possible to access the degree of a transformation using DegreeOfTransformation (53.5.1). Certain attributes of transformations are also calculated with respect to the degree, such as the rank, image set, or kernel (these values can also be calculated with respect to any positive integer). So, it is possible to ignore the degree of a transformation if you prefer to think of transformations as acting on the positive integers in a similar way to permutations. For example, this approach is used in the FR package. It is also possible to think of transformations as only acting on the positive integers not exceeding their degree. For example, this was the approach formerly used in GAP and it is also useful in the Semigroups package.

Transformations are displayed, by default, using the list $[ 1 \circ f \ldots n \circ f ]$ where $n$ is the
degree of \( f \). This behaviour differs from that of versions of GAP earlier than 4.7. See Section 53.6 for more information.

The rank of a transformation on the positive integers up to \( n \) is the number of distinct points in \([ 1 \, \ldots \, n ]\). The kernel of a transformation \( f \) on \([ 1 \, \ldots \, n ]\) is the equivalence relation on \([ 1 \, \ldots \, n ]\) consisting of those pairs \((i, j)\) of positive integers such that \( i ^ f = j ^ f \). The kernel of a transformation is represented in two ways: as a partition of \([ 1 \, \ldots \, n ]\) or as the image list of a transformation \( g \) such that the kernel of \( g \) on \([ 1 \, \ldots \, n ]\) equals the kernel of \( f \) and \( j ^ g = i \) for all \( j \) in ith class. The latter is referred to as the flat kernel of \( f \). For any given transformation \( f \) and value \( n \), there is a unique transformation \( g \) with this property.

A functional digraph is a directed graph where every vertex has out-degree 1. A transformation \( f \) can be thought of as a functional digraph with vertices the positive integers and edges from \( i \) to \( i ^ f \) for every \( i \). A component of a transformation is defined as a component of the corresponding functional digraph. More specifically, \( i \) and \( j \) are in the same component if and only if there are \( i = v_0, v_1, \ldots, v_n = j \) such that either \( v_{k+1} = v_k^f \) or \( v_k = v_{k+1}^f \) for all \( k \). A cycle of a transformation is defined as a cycle (or strongly connected component) of the corresponding functional digraph. More specifically, \( i \) belongs to a cycle of \( f \) if there are \( i = v_0, v_1, \ldots, v_n = i \) such that either \( v_{k+1} = v_k^f \) or \( v_k = v_{k+1}^f \) for all \( k \).

Internally, GAP stores a transformation \( f \) as a list consisting of the images \( i ^ f \) for all values of \( i \) less than a value which is at least the degree of \( f \) and which is determined at the time of the creation of \( f \). When the degree of a transformation \( f \) is at most 65536, the images of points under \( f \) are stored as 16-bit integers, the kernel and image set are subobjects of \( f \) which are plain lists of GAP integers. When the degree of \( f \) is greater than 65536, the images of points under \( f \) are stored as 32-bit integers; the kernel and image set are stored in the same way as before. A transformation belongs to \texttt{IsTrans2Rep} if it is stored using 16-bit integers and to \texttt{IsTrans4Rep} if it is stored using 32-bit integers.

### 53.1 The family and categories of transformations

#### 53.1.1 \texttt{IsTransformation}

\begin{verbatim}
\texttt{> IsTransformation(obj)} (Category)
\end{verbatim}

Every transformation in GAP belongs to the category \texttt{IsTransformation}. Basic operations for transformations are \texttt{ImageListOfTransformation} (53.5.2), \texttt{ImageSetOfTransformation} (53.5.3), \texttt{KernelOfTransformation} (53.5.12), \texttt{FlatKernelOfTransformation} (53.5.11), \texttt{RankOfTransformation} (53.5.4), \texttt{DegreeOfTransformation} (53.5.1), multiplication of two transformations via \texttt{*}, and exponentiation with the first argument a positive integer \( i \) and second argument a transformation \( f \) where the result is the image \( i ^ f \) of the point \( i \) under \( f \).

#### 53.1.2 \texttt{IsTransformationCollection}

\begin{verbatim}
\texttt{> IsTransformationCollection(obj)} (Category)
\end{verbatim}

Every collection of transformations belongs to the category \texttt{IsTransformationCollection}. For example, transformation semigroups belong to \texttt{IsTransformationCollection}.
53.1.3 TransformationFamily

The family of all transformations is TransformationFamily.

53.2 Creating transformations

There are several ways of creating transformations in GAP, which are described in this section.

53.2.1 Transformation (for an image list)

Syntax:

- Transformation(list)
- Transformation(list, func)
- TransformationList(list)

Returns: A transformation.

TransformationList returns the transformation \( f \) such that \( i ^ f = list[i] \) if \( i \) is between 1 and the length of \( list \) and \( i ^ f = i \) if \( i \) is larger than the length of \( list \). An error will occur in TransformationList if \( list \) is not dense, if \( list \) contains an element which is not a positive integer, or if \( list \) contains an integer not in \([1 .. \text{Length}(list)]\).

TransformationList is the analogue in the context of transformations of PermList (42.5.2). Transformation is a synonym of TransformationList when the argument is a list.

When the arguments are a list of positive integers \( list \) and a function \( func \), Transformation returns the transformation \( f \) such that \( list[i] ^ f = func(list[i]) \) if \( i \) is in the range \([1 .. \text{Length}(list)]\) and \( f \) fixes all other points.

Example:

```gap
gap> SetUserPreference( "NotationForTransformations", "input" );
gap> f := Transformation( [ 11, 10, 2, 11, 4, 4, 7, 6, 9, 10, 1, 11 ] );
Transformation( [ 11, 10, 2, 11, 4, 4, 7, 6, 9, 10, 1, 11 ] )
gap> f := TransformationList( [ 2, 3, 3, 1 ] );
TransformationList( [ 2, 3, 3, 1 ] )
gap> SetUserPreference( "NotationForTransformations", "fr" );
gap> f := Transformation( [ 10, 11 ], x -> x ^ 2 );
<transformation: 1,2,3,4,5,6,7,8,9,100,121>
gap> SetUserPreference( "NotationForTransformations", "input" );
```

53.2.2 Transformation (for a source and destination)

Syntax:

- Transformation(src, dst)
- TransformationListList(src, dst)

Returns: A transformation.

If \( src \) and \( dst \) are lists of positive integers of the same length, such that \( src \) contains no element twice, then TransformationListList(\( src, dst \)) returns a transformation \( f \) such that \( src[i] ^ f = dst[i] \). The transformation \( f \) fixes all points larger than the maximum of the entries in \( src \) and \( dst \).

TransformationListList is the analogue in the context of transformations of MappingPermListList (42.5.3). Transformation is a synonym of TransformationListList when its arguments are two lists of positive integers.
Example

```gap
gap> Transformation([ 10, 11 ], [ 11, 12 ]);
Transformation( [ 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 12 ] )
gap> TransformationListList([ 1, 2, 3 ], [ 4, 5, 6 ]); Transformation( [ 4, 5, 6, 4, 5, 6 ] )
```

53.2.3 TransformationByImageAndKernel (for an image and kernel)

▷ TransformationByImageAndKernel(\im, \ker)

Returns: A transformation or fail.

This operation returns the transformation \( f \) where \( i ^ f = \im[\ker[i]] \) for \( i \) in the range \([1..\Length(\ker)]\). This transformation has flat kernel equal to \( \ker \) and image set equal to \( \Set(\im) \).

The argument \( \im \) should be a duplicate free list of positive integers and \( \ker \) should be the flat kernel of a transformation with rank equal to the length of \( \im \). If the arguments do not fulfill these conditions, then fail is returned.

Example

```gap
gap> TransformationByImageAndKernel([ 8, 1, 3, 4 ], [ 1, 2, 3, 1, 2, 1, 2, 4 ]); Transformation( [ 8, 1, 3, 8, 1, 8, 1, 4 ] )
gap> TransformationByImageAndKernel([ 1, 3, 8, 4 ], [ 1, 2, 3, 1, 2, 1, 2, 4 ]); Transformation( [ 1, 3, 8, 1, 3, 1, 3, 4 ] )
```

53.2.4 Idempotent

▷ Idempotent(\im, \ker)

Returns: A transformation or fail.

Idempotent returns the idempotent transformation with image set \( \im \) and flat kernel \( \ker \) if such a transformation exists and fail if it does not. More specifically, a transformation is returned when the argument \( \im \) is a set of positive integers and \( \ker \) is the flat kernel of a transformation with rank equal to the length of \( \im \) and where \( \im \) has one element in every class of the kernel corresponding to \( \ker \).

Note that this function does not always return the same transformation as TransformationByImageAndKernel with the same arguments.

Example

```gap
gap> Idempotent([ 2, 4, 6, 7, 8, 10, 11 ], [ 1, 2, 1, 3, 3, 4, 5, 1, 6, 6, 7, 5 ]); Transformation( [ 8, 2, 8, 4, 4, 6, 7, 8, 10, 10, 11, 7 ] )
gap> TransformationByImageAndKernel([ 2, 4, 6, 7, 8, 10, 11 ], [ 1, 2, 1, 3, 3, 4, 5, 1, 6, 6, 7, 5 ]); Transformation( [ 2, 4, 2, 6, 6, 7, 8, 2, 10, 10, 11, 8 ] )
```

53.2.5 TransformationOp

▷ TransformationOp(obj, list[, func])

▷ TransformationOpNC(obj, list[, func])

Returns: A transformation or fail.
TransformationOp returns the transformation that corresponds to the action of the object \texttt{obj} on the domain or list \texttt{list} via the function \texttt{func}. If the optional third argument \texttt{func} is not specified, then the action \texttt{OnPoints} (41.2.1) is used by default. Note that the returned transformation refers to the positions in \texttt{list} even if \texttt{list} itself consists of integers.

This function is the analogue in the context of transformations of \texttt{Permutation} (41.9.1).

If \texttt{obj} does not map elements of \texttt{list} into \texttt{list}, then \texttt{fail} is returned.

TransformationOpNC does not check that \texttt{obj} maps elements of \texttt{list} to elements of \texttt{list} or that a transformation is defined by the action of \texttt{obj} on \texttt{list} via \texttt{func}. This function should be used only with caution, and in situations where it is guaranteed that the arguments have the required properties.

Example

\begin{verbatim}
gap> f := Transformation([ 10, 2, 3, 10, 5, 10, 7, 2, 5, 6 ]);;
gap> TransformationOp( f, [ 2, 3 ] );
IdentityTransformation

fail

gap> S := SemigroupByMultiplicationTable( [ [ 1, 1, 1 ],
                                      [ 1, 1, 1 ],
                                      [ 1, 1, 2 ] ] );

Transformation([ 1, 1, 1 ])

TransformationOp( Elements( S )[1], S, OnRight );
Transformation([ 1, 1, 1 ])

TransformationOp( Elements( S )[3], S, OnRight );
Transformation([ 1, 1, 2 ])
\end{verbatim}

53.2.6 TransformationNumber

\begin{verbatim}
\texttt{TransformationNumber(m, n)} (operation)
\texttt{NumberTransformation(f[, n])} (operation)

Returns: A transformation or a number.

These functions implement a bijection from the transformations with degree at most \texttt{n} to the numbers \([ 1 \ldots n ^ {n} ]\).

More precisely, if \texttt{m} and \texttt{n} are positive integers such that \texttt{m} is at most \texttt{n} \texttt{^} \texttt{n}, then \texttt{TransformationNumber} returns the \texttt{m}th transformation with degree at most \texttt{n}.

If \texttt{f} is a transformation and \texttt{n} is a positive integer, which is greater than or equal to the degree of \texttt{f}, then \texttt{NumberTransformation} returns the number in \([ 1 \ldots n ^ {n} ]\) that corresponds to \texttt{f}. If the optional second argument \texttt{n} is not specified, then the degree of \texttt{f} is used by default.

Example

\begin{verbatim}
gap> f := Transformation([ 3, 3, 5, 3, 3 ]);;
gap> NumberTransformation( f, 5 );
1613

NumberTransformation( f, 10 );
2242256790

TransformationNumber( 2242256790, 10 );
Transformation([ 3, 3, 5, 3, 3 ])

TransformationNumber( 1613, 5 );
Transformation([ 3, 3, 5, 3, 3 ])\end{verbatim}
53.2.7 RandomTransformation

\texttt{RandomTransformation}(n) \hspace{1cm} \text{(operation)}

\textbf{Returns:} A random transformation.

If \( n \) is a positive integer, then \texttt{RandomTransformation} returns a random transformation with degree at most \( n \).

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
gap> RandomTransformation( 6 );
Transformation( [ 2, 1, 2, 1, 1, 2 ] )
\end{verbatim}

53.2.8 IdentityTransformation

\texttt{IdentityTransformation} \hspace{1cm} \text{(global variable)}

\textbf{Returns:} The identity transformation.

Returns the identity transformation, which has degree 0.

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
gap> IdentityTransformation;
IdentityTransformation
\end{verbatim}

53.2.9 ConstantTransformation

\texttt{ConstantTransformation}(m, n) \hspace{1cm} \text{(operation)}

\textbf{Returns:} A transformation.

This function returns a constant transformation \( f \) such that \( i \circ f = n \) for all \( i \) less than or equal to \( m \), when \( n \) and \( m \) are positive integers.

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
gap> ConstantTransformation( 5, 1 );
Transformation( [ 1, 1, 1, 1 ] )
gap> ConstantTransformation( 6, 4 );
Transformation( [ 4, 4, 4, 4, 4, 4 ] )
\end{verbatim}

53.3 Changing the representation of a transformation

It is possible that a transformation in GAP can be represented as another type of object, or that another type of GAP object can be represented as a transformation.

The operations \texttt{AsPermutation} \hspace{1cm} (42.5.6) and \texttt{AsPartialPerm} \hspace{1cm} (54.4.2) can be used to convert transformations into permutations or partial permutations, where appropriate. In this section we describe functions for converting other types of objects into transformations.

53.3.1 AsTransformation

\texttt{AsTransformation}(f[, n]) \hspace{1cm} \text{(attribute)}

\textbf{Returns:} A transformation.

\texttt{AsTransformation} returns the permutation, transformation, partial permutation or binary relation \( f \) as a transformation.
for permutations

If \( f \) is a permutation and \( n \) is a non-negative integer, then \( \text{AsTransformation}( f, n ) \) returns the transformation \( g \) such that \( i \circ g = i \circ f \) for all \( i \) in the range \([1..n]\).

If no non-negative integer \( n \) is specified, then the largest moved point of \( f \) is used as the value for \( n \); see \texttt{LargestMovedPoint(42.3.2)}.

for transformations

If \( f \) is a transformation and \( n \) is a non-negative integer less than the degree of \( f \) such that \( f \) is a transformation of \([1..n]\), then \( \text{AsTransformation}( f, n ) \) returns the restriction of \( f \) to \([1..n]\).

If \( f \) is a transformation and \( n \) is not specified or is greater than or equal to the degree of \( f \), then \( f \) is returned.

for partial permutations

A partial permutation \( f \) can be converted into a transformation \( g \) as follows. The degree \( m \) of \( g \) is equal to the maximum of \( n \), the largest moved point of \( f \) plus 1, and the largest image of a moved point plus 1. The transformation \( g \) agrees with \( f \) on the domain of \( f \) and maps the points in \([1..m]\), which are not in the domain of \( f \) to \( n \), i.e. \( i \circ g = i \circ f \) for all \( i \) in the domain of \( f \), \( i \circ g = n \) for all \( i \) in \([1..n]\), and \( i \circ g = i \) for all \( i \) greater than \( n \). \( \text{AsTransformation}( f ) \) returns the transformation \( g \) defined in the previous sentences.

If the optional argument \( n \) is not present, then the default value of the maximum of the largest moved point and the largest image of a moved point of \( f \) plus 1 is used.

for binary relations

In the case that \( f \) is a binary relation, which defines a transformation, \( \text{AsTransformation}( f ) \) returns that transformation.

Example

```gap
gap> f := Transformation([ 3, 5, 3, 4, 1, 2 ]);;
gap> AsTransformation( f, 5 );
Transformation([ 3, 5, 3, 4, 1 ])
gap> AsTransformation( f, 10 );
Transformation([ 3, 5, 3, 4, 1, 2 ])
gap> AsTransformation( ( 1, 3 )( 2, 4 ) );
Transformation([ 3, 5, 3, 4, 1, 2 ])
gap> AsPartialPerm( [ 1, 2, 3, 4, 5, 6 ], [ 6, 7, 1, 4, 3, 2 ] );
gap> AsPartialPerm( last, DomainOfPartialPerm( f ) );
[5,3,1,6,2,7](4)
gap> AsTransformation( f, 11 );
Transformation([ 6, 7, 1, 4, 3, 2, 11, 11, 11, 11, 11 ])
gap> AsPartialPerm( last, DomainOfPartialPerm( f ) );
[5,3,1,6,2,7](4)
gap> AsTransformation( f, 14 );
Transformation([ 6, 7, 1, 4, 3, 2, 14, 14, 14, 14, 14, 14, 14, 14 ])
gap> AsPartialPerm( last, DomainOfPartialPerm( f ) );
[5,3,1,6,2,7](4)
gap> AsTransformation( f );
Transformation([ 6, 7, 1, 4, 3, 2, 8, 8 ])
gap> AsTransformation( Transformation([ 1, 1, 2 ] ), 0 );
IdentityTransformation
```
53.3.2 RestrictedTransformation

\( \text{ restricted transformation } \) \( f \), \( \ell \)

Returns: A transformation.

RestrictedTransformation returns the new transformation \( g \) such that \( i \circ g = i \circ f \) for all \( i \) in \( \ell \) and such that \( i \circ g = i \) for all \( i \) not in \( \ell \).

Example

\[
\begin{align*}
\text{gap> } & f := \text{Transformation}( [2, 10, 5, 9, 10, 9, 6, 3, 8, 4, 6, 5] ); \\
\text{gap> } & \text{RestrictedTransformation}( f, [1, 2, 3, 10, 11, 12] ); \\
& \text{Transformation}( [2, 10, 5, 4, 5, 6, 7, 8, 9, 4, 6, 5] )
\end{align*}
\]

53.3.3 PermutationOfImage

\( \text{ permutation of image } \) \( f \)

Returns: A permutation or \( \text{fail} \).

If the transformation \( f \) is a permutation of the points in its image, then \( \text{PermutationOfImage} \) returns this permutation. If \( f \) does not permute its image, then \( \text{fail} \) is returned.

If \( f \) happens to be a permutation, then \( \text{PermutationOfImage} \) with argument \( f \) returns the same value as \( \text{AsPermutation} \) with argument \( f \).

Example

\[
\begin{align*}
\text{gap> } & f := \text{Transformation}( [5, 8, 3, 5, 8, 6, 2, 2, 7, 8] ); \\
\text{gap> } & \text{PermutationOfImage}( f ); \\
& \text{fail} \\
\text{gap> } & f := \text{Transformation}( [8, 2, 10, 2, 4, 4, 7, 6, 9, 10] ); \\
\text{gap> } & \text{PermutationOfImage}( f ); \\
& \text{fail} \\
\text{gap> } & f := \text{Transformation}( [1, 3, 6, 6, 2, 10, 2, 3, 10, 5] ); \\
\text{gap> } & \text{PermutationOfImage}( f ); \\
&(2,3,6,10,5) \\
\text{gap> } & f := \text{Transformation}( [5, 2, 8, 4, 1, 8, 10, 3, 5, 7] ); \\
\text{gap> } & \text{PermutationOfImage}( f ); \\
&(1,5)(3,8)(7,10)
\end{align*}
\]

53.4 Operators for transformations

\( i \circ f \)

returns the image of the positive integer \( i \) under the transformation \( f \).

\( f \circ g \)

returns \( g \circ -1 \circ f \circ -1 \) when \( f \) is a transformation and \( g \) is a permutation \( \text{\circ} \) (31.12.1). This operation requires essentially the same number of steps as multiplying a transformation by a permutation, which is approximately one third of the number required to first invert \( g \), take the product with \( f \), and then the product with \( g \).

\( f \circ g \)

returns the composition of \( f \) and \( g \) when \( f \) and \( g \) are transformations or permutations. The product of a permutation and a transformation is returned as a transformation.
\[ f / g \]
returns \( f * g^{-1} \) when \( f \) is a transformation and \( g \) is a permutation. This operation requires essentially the same number of steps as multiplying a transformation by a permutation, which is approximately half the number required to first invert \( g \) and then take the product with \( f \).

\[ \text{LQUO}(g, f) \]
returns \( g^{-1} * f \) when \( f \) is a transformation and \( g \) is a permutation. This operation uses essentially the same number of steps as multiplying a transformation by a permutation, which is approximately half the number required to first invert \( g \) and then take the product with \( f \).

\[ f < g \]
returns \text{true} if the image list of \( f \) is lexicographically less than the image list of \( g \) and \text{false} if it is not.

\[ f = g \]
returns \text{true} if the transformation \( f \) equals the transformation \( g \) and returns \text{false} if it does not.

**53.4.1 PermLeftQuoTransformation**

\[ \text{PermLeftQuoTransformation}(f, g) \]
\[ \text{PermLeftQuoTransformationNC}(f, g) \]

**Returns:** A permutation.

Returns the permutation on the image set of \( f \) induced by \( f^{-1} * g \) when the transformations \( f \) and \( g \) have equal kernel and image set.

\text{PermLeftQuoTransformation} verifies that \( f \) and \( g \) have equal kernels and image sets, and returns an error if they do not. \text{PermLeftQuoTransformationNC} does no checks.

**Example**

\[
gap> f := \text{Transformation}( \{ 5, 6, 7, 1, 4, 3, 2, 7 \} );;
gap> g := \text{Transformation}( \{ 5, 7, 1, 6, 4, 3, 2, 1 \} );;
gap> \text{PermLeftQuoTransformation}( f, g );
\( (1,6,7) \)
gap> \text{PermLeftQuoTransformation}( g, f );
\( (1,7,6) \)
\]

**53.4.2 IsInjectiveListTrans**

\[ \text{IsInjectiveListTrans}(\text{list}, \text{obj}) \]

**Returns:** true or false.

The argument \( \text{obj} \) should be a transformation or the list of images of a transformation and \( \text{list} \) should be a list of positive integers. \text{IsInjectiveListTrans} checks if \( \text{obj} \) is injective on \( \text{list} \).

More precisely, if \( \text{obj} \) is a transformation, then we define \( f := \text{obj} \) and if \( \text{obj} \) is the image list of a transformation we define \( f := \text{Transformation}( \text{obj} ) \). \text{IsInjectiveListTrans} returns true if \( f \) is injective on \( \text{list} \) and \text{false} if it is not. If \( \text{list} \) is not duplicate free, then \text{false} is returned.

**Example**

\[
gap> f := \text{Transformation}( \{ 2, 6, 7, 2, 6, 9, 9, 1, 1, 5 \} );;
gap> \text{IsInjectiveListTrans}( \{ 1, 5 \}, f );
\text{true}
gap> \text{IsInjectiveListTrans}( \{ 5, 1 \}, f );
\]
true
gap> IsInjectiveListTrans([ 5, 1, 5, 1, 1 ], f );
false
gap> IsInjectiveListTrans([ 5, 1, 2, 3 ], [ 1, 2, 3, 4, 5 ]);
true

### 53.4.3 ComponentTransformationInt

**ComponentTransformationInt(\( f, n \))**

**Returns:** A list of positive integers.

If \( f \) is a transformation and \( n \) is a positive integer, then ComponentTransformationInt returns those elements \( i \) such that \( n^f \cdot j = i \) for some positive integer \( j \), i.e. the elements of the component of \( f \) containing \( n \) that can be obtained by applying powers of \( f \) to \( n \).

**Example**

```gap
gap> f := Transformation([ 6, 2, 8, 4, 7, 5, 8, 3, 5, 8 ]);;
gap> ComponentTransformationInt( f, 1 );
[ 1, 6, 5, 7, 8, 3 ]
gap> ComponentTransformationInt( f, 12 );
[ 12 ]
gap> ComponentTransformationInt( f, 5 );
[ 5, 7, 8, 3 ]
```

### 53.4.4 PreImagesOfTransformation

**PreImagesOfTransformation(\( f, n \))**

**Returns:** A set of positive integers.

Returns the preimages of the positive integer \( n \) under the transformation \( f \), i.e. the positive integers \( i \) such that \( i^f = n \).

**Example**

```gap
gap> f := Transformation([ 2, 6, 7, 2, 6, 9, 9, 1, 1, 5 ]);;
gap> PreImagesOfTransformation( f, 1 );
[ 8, 9 ]
gap> PreImagesOfTransformation( f, 3 );
[ ]
gap> PreImagesOfTransformation( f, 100 );
[ 100 ]
```

### 53.5 Attributes for transformations

In this section we describe the functions available in GAP for finding various properties and attributes of transformations.

#### 53.5.1 DegreeOfTransformation

**DegreeOfTransformation(\( f \))**

**Returns:** A positive integer.
The degree of a transformation \( f \) is the largest value such that \( n \uparrow f \neq n \) or \( i \uparrow f = n \) for some \( i \neq n \). Equivalently, the degree of a transformation is the least value \( n \) such that \([ n + 1, n + 2, \ldots ]\) is fixed pointwise by \( f \).

The degree of a collection of transformations \( \text{coll} \) is the maximum degree of any transformation in \( \text{coll} \).

Example

```gap
gap> DegreeOfTransformation( IdentityTransformation );
0
gap> DegreeOfTransformationCollection(  
> [ Transformation( [ 1, 3, 4, 1 ] ),  
> Transformation( [ 3, 1, 1, 3, 4 ] ),  
> Transformation( [ 2, 4, 1, 2 ] ) ] );
5
```

### 53.5.2 ImageListOfTransformation

- **ImageListOfTransformation** \((f[, n])\)
  - **ListTransformation** \((f[, n])\)
    - **Returns:** The list of images of a transformation.

Returns the list of images of \([ 1 \ldots n ]\) under the transformation \( f \), which is \([ 1 \uparrow f \ldots n \uparrow f ]\). If the optional second argument \( n \) is not present, then the degree of \( f \) is used by default.

This is the analogue for transformations of \(\text{ListPerm}(42.5.1)\) for permutations.

Example

```gap
f := Transformation( [ 2, 3, 4, 2, 4 ] );;
gap> ImageListOfTransformation( f );
[ 2, 3, 4, 2, 4 ]
gap> ImageListOfTransformation( f, 10 );
[ 2, 3, 4, 2, 4, 6, 7, 8, 9, 10 ]
```

### 53.5.3 ImageSetOfTransformation

- **ImageSetOfTransformation** \((f[, n])\)
  - **Returns:** The set of images of the transformation.

Returns the set of points in the list of images of \([ 1 \ldots n ]\) under \( f \), i.e. the sorted list of images with duplicates removed. If the optional second argument \( n \) is not given, then the degree of \( f \) is used.

Example

```gap
f := Transformation( [ 5, 6, 7, 1, 4, 3, 2, 7 ] );;
gap> ImageSetOfTransformation( f );
[ 1, 2, 3, 4, 5, 6, 7 ]
gap> ImageSetOfTransformation( f, 10 );
[ 1, 2, 3, 4, 5, 6, 7, 9, 10 ]
```

### 53.5.4 RankOfTransformation (for a transformation and a positive integer)

- **RankOfTransformation** \((f[, n])\)
  - **Returns:** The rank of a transformation.
When the arguments are a transformation \( f \) and a positive integer \( n \), \texttt{RankOfTransformation} returns the size of the set of images of the transformation \( f \) in the range \([1 \ldots n]\). If the optional second argument \( n \) is not specified, then the degree of \( f \) is used.

When the arguments are a transformation \( f \) and a list \texttt{list} of positive integers, this function returns the size of the set of images of the transformation \( f \) on \texttt{list}.

```gap
Example
gap> f := Transformation( [ 8, 5, 8, 2, 2, 8, 4, 7, 3, 1 ] );;
gap> ImageSetOfTransformation( f );
[ 1, 2, 3, 4, 5, 7, 8 ]
gap> RankOfTransformation( f );
7
gap> RankOfTransformation( f, 100 );
97
gap> RankOfTransformation( f, [ 2, 5, 8 ] );
3
```

### 53.5.5 MovedPoints (for a transformation)

\[ 
\texttt{MovedPoints(} \ f \texttt{)} \]
\[ 
\texttt{MovedPoints(} \ \texttt{coll} \texttt{)} \]

**Returns:** A set of positive integers.

When the argument is a transformation, \texttt{MovedPoints} returns the set of positive integers \( i \) such that \( i ^ f \neq i \).

\texttt{MovedPoints} returns the set of points moved by some element of the collection of transformations \texttt{coll}.

```gap
Example
gap> f := Transformation( [ 6, 10, 1, 4, 6, 5, 1, 2, 3, 3 ] );;
gap> MovedPoints( f );
[ 1, 2, 3, 5, 6, 7, 8, 9, 10 ]
gap> f := IdentityTransformation;
IdentityTransformation
gap> MovedPoints( f );
[ ]
```

### 53.5.6 NrMovedPoints (for a transformation)

\[ 
\texttt{NrMovedPoints(} \ f \texttt{)} \]
\[ 
\texttt{NrMovedPoints(} \ \texttt{coll} \texttt{)} \]

**Returns:** A positive integer.

When the argument is a transformation, \texttt{NrMovedPoints} returns the number of positive integers \( i \) such that \( i ^ f \neq i \).

\texttt{MovedPoints} returns the number of points which are moved by at least one element of the collection of transformations \texttt{coll}.

```gap
Example
gap> f := Transformation( [ 7, 1, 4, 3, 2, 7, 7, 6, 6, 5 ] );;
gap> NrMovedPoints( f );
9
gap> NrMovedPoints( IdentityTransformation );
0
```
53.5.7 SmallestMovedPoint (for a transformation)

\[ \text{SmallestMovedPoint}(f) \] (attribute)
\[ \text{SmallestMovedPoint}(\text{coll}) \] (method)

**Returns:** A positive integer or infinity.

SmallestMovedPoint returns the smallest positive integer \( i \) such that \( i \, ^{f} \neq i \) if such an \( i \) exists. If \( f \) is the identity transformation, then infinity is returned.

If the argument is a collection of transformations \( \text{coll} \), then the smallest point which is moved by at least one element of \( \text{coll} \) is returned, if such a point exists. If \( \text{coll} \) only contains identity transformations, then SmallestMovedPoint returns infinity.

**Example**
\[
\text{gap} \> S := \text{FullTransformationSemigroup}(5); \\
<\text{full transformation monoid of degree 5}> \\
\text{gap} \> \text{SmallestMovedPoint}(S); \\
1 \\
\text{gap} \> S := \text{Semigroup}(\text{IdentityTransformation}); \\
<\text{trivial transformation group of degree 0 with 1 generator}> \\
\text{gap} \> \text{SmallestMovedPoint}(S); \\
\infty \\
\text{gap} \> f := \text{Transformation}(\left[1, 2, 3, 6, 6, 6\right]);; \\
\text{gap} \> \text{SmallestMovedPoint}(f); \\
4
\]

53.5.8 LargestMovedPoint (for a transformation)

\[ \text{LargestMovedPoint}(f) \] (attribute)
\[ \text{LargestMovedPoint}(\text{coll}) \] (method)

**Returns:** A positive integer.

LargestMovedPoint returns the largest positive integers \( i \) such that \( i \, ^{f} \neq i \) if such an \( i \) exists. If \( f \) is the identity transformation, then 0 is returned.

If the argument is a collection of transformations \( \text{coll} \), then the largest point which is moved by at least one element of \( \text{coll} \) is returned, if such a point exists. If \( \text{coll} \) only contains identity transformations, then LargestMovedPoint returns 0.

**Example**
\[
\text{gap} \> S := \text{FullTransformationSemigroup}(5); \\
<\text{full transformation monoid of degree 5}> \\
\text{gap} \> \text{LargestMovedPoint}(S); \\
5 \\
\text{gap} \> S := \text{Semigroup}(\text{IdentityTransformation}); \\
<\text{trivial transformation group of degree 0 with 1 generator}> \\
\text{gap} \> \text{LargestMovedPoint}(S); \\
0 \\
\text{gap} \> f := \text{Transformation}(\left[1, 2, 3, 6, 6, 6\right]);; \\
\text{gap} \> \text{LargestMovedPoint}(f); \\
5
\]

53.5.9 SmallestImageOfMovedPoint (for a transformation)

\[ \text{SmallestImageOfMovedPoint}(f) \] (attribute)
\[ \text{SmallestImageOfMovedPoint}(\text{coll}) \] (method)
**Returns:** A positive integer or infinity.

SmallestImageOfMovedPoint returns the smallest positive integer $i^f$ such that $i^f \not< i$ if such an $i$ exists. If $f$ is the identity transformation, then infinity is returned.

If the argument is a collection of transformations $coll$, then the smallest integer which is the image a point moved by at least one element of $coll$ is returned, if such a point exists. If $coll$ only contains identity transformations, then SmallestImageOfMovedPoint returns infinity.

Example

```gap
gap> S := FullTransformationSemigroup( 5 );
<full transformation monoid of degree 5>
gap> SmallestImageOfMovedPoint( S );
1
gap> S := Semigroup( IdentityTransformation );
<trivial transformation group of degree 0 with 1 generator>
gap> SmallestImageOfMovedPoint( S );
infinity
gap> f := Transformation( [ 1, 2, 3, 6, 6, 6 ] );;
gap> SmallestImageOfMovedPoint( f );
6
```

---

53.5.10 LargestImageOfMovedPoint (for a transformation)

**Returns:** A positive integer.

LargestImageOfMovedPoint returns the largest positive integer $i^f$ such that $i^f \not< i$ if such an $i$ exists. If $f$ is the identity transformation, then 0 is returned.

If the argument is a collection of transformations $coll$, then the largest integer which is the image a point moved by at least one element of $coll$ is returned, if such a point exists. If $coll$ only contains identity transformations, then LargestImageOfMovedPoint returns 0.

Example

```gap
gap> S := FullTransformationSemigroup( 5 );
<full transformation monoid of degree 5>
gap> LargestImageOfMovedPoint( S );
5
gap> S := Semigroup( IdentityTransformation );
<trivial transformation group of degree 0 with 1 generator>
gap> LargestImageOfMovedPoint( S );
0
gap> f := Transformation( [ 1, 2, 3, 6, 6, 6 ] );;
gap> LargestImageOfMovedPoint( f );
6
```

---

53.5.11 FlatKernelOfTransformation

**Returns:** The flat kernel of a transformation.

If the kernel classes of the transformation $f$ on $[1..n]$ are $K_1,\ldots,K_r$, then FlatKernelOfTransformation returns a list $L$ such that $L[i] = j$ for all $i$ in $K_j$. For a given transformation and positive integer $n$, there is a unique such list.

If the optional second argument $n$ is not present, then the degree of $f$ is used by default.
53.5.12 KernelOfTransformation

KernelOfTransformation returns the kernel of a transformation on \([1 .. n]\) as a set of sets of positive integers. If the argument \(bool\) is false, then only the non-singleton classes are returned.

Example

```gap
gap> f := Transformation( [ 10, 3, 7, 10, 1, 5, 9, 2, 6, 10 ] );;
gap> KernelOfTransformation( f, 10 );
[ [ 1, 2, 3, 1, 4, 5, 6, 7, 8, 1 ] ]
```

53.5.13 InverseOfTransformation

InverseOfTransformation returns a semigroup inverse of the transformation \(f\) in the full transformation semigroup. An inverse of \(f\) is any transformation \(g\) such that \(f \cdot g \cdot f = f\) and \(g \cdot f \cdot g = g\). Every transformation has at least one inverse.

Example

```gap
gap> f := Transformation( [ 2, 6, 7, 2, 6, 9, 9, 1, 1, 5 ] );;
gap> g := InverseOfTransformation( f ) ;
Transformation( [ 8, 1, 1, 1, 10, 2, 3, 1, 6, 1 ] )
gap> g * f * g ;
Transformation( [ 2, 6, 7, 2, 6, 9, 9, 1, 1, 5 ] )
gap> f * g * f ;
Transformation( [ 8, 1, 1, 1, 10, 2, 3, 1, 6, 1 ] )
```

53.5.14 Inverse (for a transformation)

Example

```gap
gap> f := Transformation( [ 2, 6, 7, 2, 6, 9, 9, 1, 1, 5 ] );;
gap> g := Inverse( f ) ;
Transformation( [ 8, 1, 1, 1, 10, 2, 3, 1, 6, 1 ] )```
If the transformation $f$ is a bijection, then $\text{Inverse}$ or $f^{-1}$ returns the inverse of $f$. If $f$ is not a bijection, then $\text{fail}$ is returned.

```gap
gap> Transformation([3, 8, 12, 1, 11, 9, 9, 4, 10, 5, 10, 6]) ^ -1;
fail
gap> Transformation([2, 3, 1]) ^ -1;
Transformation([3, 1, 2])
```

53.5.15 \textbf{IndexPeriodOfTransformation}

\textbf{IndexPeriodOfTransformation($f$)} \hspace{1cm} (function)

\textbf{Returns:} A pair of positive integers.

Returns the least positive integers $m$ and $r$ such that $f \ ^{(m + r)} = f \ ^{m}$, which are known as the \textit{index} and \textit{period} of the transformation $f$.

```gap
gap> f := Transformation([3, 4, 4, 6, 1, 3, 3, 7, 1]);;
gap> IndexPeriodOfTransformation( f );
[2, 3]
gap> f ^ 2 = f ^ 5;
true
gap> IndexPeriodOfTransformation( IdentityTransformation );
[1, 1]
gap> IndexPeriodOfTransformation( Transformation([1, 2, 1]));
[1, 1]
gap> IndexPeriodOfTransformation( Transformation([1, 2, 3]));
[1, 1]
gap> IndexPeriodOfTransformation( Transformation([1, 3, 2]));
[1, 2]
```

53.5.16 \textbf{SmallestIdempotentPower (for a transformation)}

\textbf{SmallestIdempotentPower($f$)} \hspace{1cm} (attribute)

\textbf{Returns:} A positive integer.

This function returns the least positive integer $n$ such that the transformation $f \ ^{n}$ is an idempotent. The smallest idempotent power of $f$ is the least multiple of the period of $f$ that is greater than or equal to the index of $f$; see \texttt{IndexPeriodOfTransformation} (53.5.15).

```gap
gap> f := Transformation([6, 7, 4, 1, 7, 4, 6, 1, 3, 4]);;
gap> SmallestIdempotentPower( f );
3
gap> f := Transformation([6, 6, 6, 2, 7, 1, 5, 3, 10, 6]);;
gap> SmallestIdempotentPower( f );
2
```

53.5.17 \textbf{ComponentsOfTransformation}

\textbf{ComponentsOfTransformation($f$)} \hspace{1cm} (attribute)

\textbf{Returns:} A list of lists of positive integers.
ComponentsOfTransformation returns a list of the components of the transformation \( f \). Each component is a subset of \([ 1 .. \text{DegreeOfTransformation}( f ) \] \), and the union of the components is \([ 1 .. \text{DegreeOfTransformation}( f ) \].

Example

```gap
gap> f := Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] );
Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] )
gap> ComponentsOfTransformation( f );
[ [ 1, 6, 4, 9 ], [ 2, 12, 3, 11, 5, 7, 10 ], [ 8 ] ]
gap> f := AsTransformation( (1,8,2,4,11,5,10)(3,7)(9,12) );
Transformation( [ 8, 4, 7, 11, 10, 6, 3, 2, 12, 1, 5, 9 ] )
gap> ComponentsOfTransformation( f );
[ [ 1, 8, 2, 4, 11, 5, 10 ], [ 3, 7 ], [ 6 ], [ 9, 12 ] ]
```

53.5.18 NrComponentsOfTransformation

▷ NrComponentsOfTransformation\( (f) \)

Returns: A positive integer.

NrComponentsOfTransformation returns the number of components of the transformation \( f \) on the range \([ 1 .. \text{DegreeOfTransformation}( f ) \].

Example

```gap
gap> f := Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] );
Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] )
gap> NrComponentsOfTransformation( f );
3
gap> f := AsTransformation( (1,8,2,4,11,5,10)(3,7)(9,12) );
Transformation( [ 8, 4, 7, 11, 10, 6, 3, 2, 12, 1, 5, 9 ] )
gap> NrComponentsOfTransformation( f );
4
```

53.5.19 ComponentRepsOfTransformation

▷ ComponentRepsOfTransformation\( (f) \)

Returns: A list of lists of positive integers.

ComponentRepsOfTransformation returns the representatives, in the following sense, of the components of the transformation \( f \). For every \( i \) in \([ 1 .. \text{DegreeOfTransformation}( f ) \] there exists a representative \( j \) and a positive integer \( k \) such that \( i ^ { (f \circ k)} = j \). The representatives returned by ComponentRepsOfTransformation are partitioned according to the component they belong to. ComponentRepsOfTransformation returns the least number of representatives.

Example

```gap
gap> f := Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] );
Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] )
gap> ComponentRepsOfTransformation( f );
[ [ 3, 10 ], [ 9 ], [ 8 ] ]
gap> f := AsTransformation( (1,8,2,4,11,5,10)(3,7)(9,12) );
Transformation( [ 8, 4, 7, 11, 10, 6, 3, 2, 12, 1, 5, 9 ] )
gap> ComponentRepsOfTransformation( f );
[ [ 1 ], [ 3 ], [ 6 ], [ 9 ] ]
```
53.5.20 CyclesOfTransformation

\[ \text{CyclesOfTransformation}(f[, \text{list}]) \]

\textbf{Returns:} A list of lists of positive integers.

When the arguments of this function are a transformation \( f \) and a list \( \text{list} \), it returns a list of the cycles of the components of \( f \) containing any element of \( \text{list} \).

If the optional second argument is not present, then the range \([ 1 .. \text{DegreeOfTransformation}( f ) ]\) is used as the default value for \( \text{list} \).

\textbf{Example}

\begin{verbatim}
gap> f := Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] ); Transformation( [ 6, 12, 11, 1, 7, 6, 2, 8, 4, 7, 5, 12 ] )
gap> CyclesOfTransformation( f ); [[ 6 ], [ 12 ], [ 8 ]]
gap> CyclesOfTransformation( f, [ 1, 2, 4 ] ); [[ 6 ], [ 12 ]]
gap> CyclesOfTransformation( f, [ 1 .. 17 ] ); [[ 6 ], [ 12 ], [ 8 ], [ 13 ], [ 14 ], [ 15 ], [ 16 ], [ 17 ]]
\end{verbatim}

53.5.21 CycleTransformationInt

\[ \text{CycleTransformationInt}(f, n) \]

\textbf{Returns:} A list of positive integers.

If \( f \) is a transformation and \( n \) is a positive integer, then \( \text{CycleTransformationInt} \) returns the cycle of the component of \( f \) containing \( n \).

\textbf{Example}

\begin{verbatim}
gap> f := Transformation( [ 6, 2, 8, 4, 7, 5, 8, 3, 5, 8 ] );;
gap> CycleTransformationInt( f, 1 ); [ 8, 3 ]
gap> CycleTransformationInt( f, 12 ); [ 12 ]
gap> CycleTransformationInt( f, 5 ); [ 8, 3 ]
\end{verbatim}

53.5.22 LeftOne (for a transformation)

\[ \text{LeftOne}(f) \]

\[ \text{RightOne}(f) \]

\textbf{Returns:} A transformation.

\textbf{Example}

\begin{verbatim}
gap> f := Transformation( [ 11, 10, 2, 11, 4, 4, 7, 6, 9, 10, 1, 11 ] );;
gap> e := RightOne( f ); Transformation( [ 1, 2, 2, 4, 4, 6, 7, 7, 9, 10, 11, 11 ] )
gap> IsIdempotent( e );
true
\end{verbatim}
gap> e := LeftOne( f );
Transformation( [ 1, 2, 3, 1, 5, 5, 7, 8, 9, 2, 11, 1 ] )
gap> e * f = f;
true
gap> IsIdempotent( e );
true

53.5.23 TrimTransformation

\[ \text{TrimTransformation}( f[, n]) \]

\textbf{Returns:} Nothing.

It can happen that the internal representation of a transformation uses more memory than necessary. For example, this can happen when composing transformations where it is possible that the resulting transformation \( f \) belongs to IsTrans4Rep and stores its images as 32-bit integers, while none of its moved points exceeds 65536. The purpose of \text{TrimTransformation} is to change the internal representation of such an \( f \) to remove the trailing fixed points in the internal representation of \( f \).

If the optional second argument \( n \) is provided, then the internal representation of \( f \) is reduced to the images of the first \( n \) positive integers. Please note that it must be the case that \( i \cdot f \leq n \) for all \( i \) in the range \([ 1 .. n ]\) otherwise the resulting object will not define a transformation.

If the optional second argument is not included, then the degree of \( f \) is used by default. The transformation \( f \) is changed in-place, and nothing is returned by this function.

\begin{verbatim}
gap> f := Transformation( [ 1 .. 2^16 ], x -> x + 1 );
<transformation on 65537 pts with rank 65536>
gap> g := Transformation( [ 1 .. 2^16 + 1 ],
> function( x )
> if x = 1 or x = 65537 then
> return x;
> else
> return x - 1;
> fi;
> end );
<transformation on 65536 pts with rank 65535>
gap> h := g * f;
Transformation( [ 2, 2 ] )
gap> DegreeOfTransformation( h ); IsTrans4Rep( h ); MemoryUsage( h );
65537 true 262188
gap> TrimTransformation( h ); h;
Transformation( [ 2, 2 ] )
gap> DegreeOfTransformation( h ); IsTrans4Rep( h ); MemoryUsage( h );
2 false 44
\end{verbatim}
53.6 Displaying transformations

It is possible to change the way that GAP displays transformations using the user preferences TransformationDisplayLimit and NotationForTransformations: see Section UserPreference (3.2.3) for more information about user preferences.

If \( f \) is a transformation where the degree \( n \) of \( f \) exceeds the value of the user preference TransformationDisplayLimit, then \( f \) is displayed as:

\[
\text{Example} \quad \langle \text{transformation on \( n \) pts with rank \( r \) } \rangle
\]

where \( r \) is the rank of \( f \) relative to \( n \). The idea is to abbreviate the display of transformations defined on many points. The default value for the TransformationDisplayLimit is 100.

If the degree of \( f \) does not exceed the value of TransformationDisplayLimit, then how \( f \) is displayed depends on the value of the user preference NotationForTransformations.

There are two possible values for NotationForTransformations:

**input**

With this option a transformation \( f \) is displayed in as: Transformation( ImageListOfTransformation( \( f \), \( n \)) ) where \( n \) is the degree of \( f \). The only exception is the identity transformation, which is displayed as: IdentityTransformation.

**fr**

With this option a transformation \( f \) is displayed in as: \langle transformation: ImageListOfTransformation( \( f \), \( n \)) \rangle where \( n \) is the largest moved point of \( f \). The only exception is the identity transformation, which is displayed as: \langle identity transformation \rangle.

\[
\text{Example} \quad \text{gap> SetUserPreference( "TransformationDisplayLimit", 12 );}
\]
\[
\text{gap> f := Transformation( [ 3, 8, 12, 1, 11, 9, 9, 4, 10, 5, 10, 6 ] );}
\]
\[
\text{gap> SetUserPreference( "TransformationDisplayLimit", 100 );}
\]
\[
\text{gap> f;}
\]
\[
\text{Transformation( [ 3, 8, 12, 1, 11, 9, 9, 4, 10, 5, 10, 6 ] )}
\]
\[
\text{gap> SetUserPreference( "NotationForTransformations", "fr" );}
\]
\[
\text{gap> f;}
\]
\[
\text{<transformation: 3,8,12,1,11,9,9,4,10,5,10,6>}
\]

53.7 Semigroups of transformations

As mentioned at the start of the chapter, every semigroup is isomorphic to a semigroup of transformations, and in this section we describe the functions in GAP specific to transformation semigroups. For more information about semigroups in general see Chapter 51.

The Semigroups package contains many additional functions and methods for computing with semigroups of transformations. In particular, Semigroups contains more efficient methods than those available in the GAP library (and in many cases more efficient than any other software) for creating semigroups of transformations, calculating their Green's classes, size, elements, group of units, minimal ideal, small generating sets, testing membership, finding the inverses of a regular element, factorizing elements over the generators, and more. Since a transformation semigroup is also a transformation collection, there are special methods for MovedPoints
(53.5.5), NrMovedPoints (53.5.6), LargestMovedPoint (53.5.8), SmallestMovedPoint (53.5.7), LargestImageOfMovedPoint (53.5.10), and SmallestImageOfMovedPoint (53.5.9), when applied to a transformation semigroup.

### 53.7.1 IsTransformationSemigroup

\[ IsTransformationSemigroup(obj) \] (Synonym)
\[ IsTransformationMonoid(obj) \] (Synonym)

**Returns:** true or false.

A **transformation semigroup** is simply a semigroup consisting of transformations. An object obj is a transformation semigroup in GAP if it satisfies IsSemigroup (51.1.1) and IsTransformationCollection (53.1.2).

A **transformation monoid** is a monoid consisting of transformations. An object obj is a transformation monoid in GAP if it satisfies IsMonoid (51.2.1) and IsTransformationCollection (53.1.2).

Note that it is possible for a transformation semigroup to have a multiplicative neutral element (i.e., an identity element) but not to satisfy IsTransformationMonoid. For example,

```gap
gap> f := Transformation( [ 2, 6, 7, 2, 6, 9, 9, 1, 1, 5 ] );;
gap> S := Semigroup( f, One( f ) );
<commutative transformation monoid of degree 10 with 1 generator>
gap> IsMonoid( S );
true
gap> IsTransformationMonoid( S );
true
gap> S := Semigroup(  
  Transformation( [ 3, 8, 1, 4, 5, 6, 7, 1, 10, 10 ] ),  
  Transformation( [ 1, 2, 3, 4, 5, 6, 7, 8, 10, 10 ] ) );  
<transformation semigroup of degree 10 with 2 generators>
gap> One( S );
fail
gap> MultiplicativeNeutralElement( S );
Transformation( [ 1, 2, 3, 4, 5, 6, 7, 8, 10, 10 ] )
gap> IsMonoid( S );
false
```

In this example S cannot be converted into a monoid using AsMonoid (51.2.5) since the One (31.10.2) of any element in S differs from the multiplicative neutral element.

For more details see IsMagmaWithOne (35.1.2).

### 53.7.2 DegreeOfTransformationSemigroup

\[ DegreeOfTransformationSemigroup(S) \] (attribute)

**Returns:** A non-negative integer.

The **degree** of a transformation semigroup S is just the maximum of the degrees of the elements of S.

```gap
gap> S := Semigroup(  
  Transformation( [ 3, 8, 1, 4, 5, 6, 7, 1, 10, 10 ] ),  
  Transformation( [ 1, 2, 3, 4, 5, 6, 7, 8, 1, 11 ] ) );
```

53.7.3 FullTransformationSemigroup

\[ \text{FullTransformationSemigroup}(n) \]

\[ \text{FullTransformationMonoid}(n) \]

**Returns:** The full transformation semigroup of degree \( n \).

If \( n \) is a positive integer, then FullTransformationSemigroup returns the monoid consisting of all transformations with degree at most \( n \), called the full transformation semigroup.

The full transformation semigroup is regular, has \( n^n \) elements, and is generated by any set containing transformations that generate the symmetric group on \( n \) points and any transformation of rank \( n - 1 \).

FullTransformationMonoid is a synonym for FullTransformationSemigroup.

**Example**

```
gap> FullTransformationSemigroup( 1234 );
<full transformation monoid of degree 1234>
```

53.7.4 IsFullTransformationSemigroup

\[ \text{IsFullTransformationSemigroup}(S) \]

\[ \text{IsFullTransformationMonoid}(S) \]

**Returns:** true or false.

If the transformation semigroup \( S \) of degree \( n \) contains every transformation of degree at most \( n \), then IsFullTransformationSemigroup returns true and otherwise it returns false.

IsFullTransformationMonoid is a synonym of IsFullTransformationSemigroup. It is common in the literature for the full transformation monoid to be referred to as the full transformation semigroup.

**Example**

```
gap> S := Semigroup( AsTransformation( (1,3,4,2), 5 ),
> AsTransformation( (1,3,5), 5 ),
> Transformation( [ 1, 1, 2, 3, 4 ] ) );
<transformation semigroup of degree 5 with 3 generators>
gap> IsFullTransformationSemigroup( S );
true
<full transformation monoid of degree 5>
gap> IsFullTransformationMonoid( S );
true
```

53.7.5 IsomorphismTransformationSemigroup

\[ \text{IsomorphismTransformationSemigroup}(S) \]

\[ \text{IsomorphismTransformationMonoid}(S) \]

**Returns:** An isomorphism to a transformation semigroup or monoid.
Returns an isomorphism from the finite semigroup \( S \) to a transformation semigroup. For most types of objects in GAP the degree of this transformation semigroup will be equal to the size of \( S \) plus 1.

Let \( S \uparrow 1 \) denote the monoid obtained from \( S \) by adjoining an identity element. Then \( S \) acts faithfully on \( S \uparrow 1 \) by right multiplication, i.e. every element of \( S \) describes a transformation on \( 1, \ldots, |S| + 1 \). The isomorphism from \( S \) to the transformation semigroup described in this way is called the right regular representation of \( S \). In most cases, \texttt{IsomorphismTransformationSemigroup} will return the right regular representation of \( S \).

As exceptions, if \( S \) is a permutation group or a partial perm semigroup, then the elements of \( S \) act naturally and faithfully by transformations on the values from 1 to the largest moved point of \( S \).

If \( S \) is a finitely presented semigroup, then the Todd-Coxeter approach will be attempted.

\texttt{IsomorphismTransformationMonoid} differs from \texttt{IsomorphismTransformationSemigroup} only in that its range is a transformation monoid, and not only a semigroup, when the semigroup \( S \) is a monoid.

\begin{verbatim}
Example

\definput{example.gap}
\end{verbatim}

53.7.6 \texttt{AntiIsomorphismTransformationSemigroup}

\texttt{AntiIsomorphismTransformationSemigroup(S)}

\textbf{Returns:} An anti-isomorphism.

If \( S \) is a semigroup, then \texttt{AntiIsomorphismTransformationSemigroup} returns an anti-isomorphism from \( S \) to a transformation semigroup. At present, the degree of the resulting transformation semigroup equals the size of \( S \) plus 1, and, consequently, this function is of limited use.

\begin{verbatim}
Example

\definput{example.gap}
\end{verbatim}
with 2 generators>, <transformation semigroup of degree 173 with 2
generators>, function( x ) ... end, function( x ) ... end )
Chapter 54

Partial permutations

This chapter describes the functions in GAP for partial permutations.

A partial permutation in GAP is simply an injective function from any finite set of positive integers to any other finite set of positive integers. The largest point on which a partial permutation can be defined, and the largest value that the image of such a point can have, are defined by certain architecture dependent limits.

Every inverse semigroup is isomorphic to an inverse semigroup of partial permutations and, as such, partial permutations are to inverse semigroup theory what permutations are to group theory and transformations are to semigroup theory. In this way, partial permutations are the elements of inverse partial permutation semigroups.

A partial permutation in GAP acts on a finite set of positive integers on the right. The image of a point \(i\) under a partial permutation \(f\) is expressed as \(i^f\) in GAP. This action is also implemented by the function OnPoints (41.2.1). The preimage of a point \(i\) under the partial permutation \(f\) can be computed using \(i/f\) without constructing the inverse of \(f\). Partial permutations in GAP are created using the operations described in Section 54.2. Partial permutations are, by default, displayed in component notation, which is described in Section 54.6.

The fundamental attributes of a partial permutation are:

**Domain**

The domain of a partial permutation is just the set of positive integers where it is defined; see DomainOfPartialPerm (54.3.4). We will denote the domain of a partial permutation \(f\) by \(\text{dom}(f)\).

**Degree**

The degree of a partial permutation \(f\) is just the largest positive integer where \(f\) is defined. In other words, the degree of \(f\) is the largest element in the domain of \(f\); see DegreeOfPartialPerm (54.3.1).

**Image list**

The image list of a partial permutation \(f\) is the list \([i_1^f, i_2^f, \ldots, i_n^f]\) where the domain of \(f\) is \([i_1, i_2, \ldots, i_n]\) see ImageListOfPartialPerm (54.3.6). For example, the partial perm sending 1 to 5 and 2 to 4 has image list \([5, 4]\).

**Image set**

The image set of a partial permutation \(f\) is just the set of points in the image list (i.e. the image
list after it has been sorted into increasing order); see \texttt{ImageSetOfPartialPerm} (54.3.7). We will denote the image set of a partial permutation $f$ by $\text{im}(f)$.

**Codegree**

The \textit{codegree} of a partial permutation $f$ is just the largest positive integer of the form $i^f$ for any $i$ in the domain of $f$. In other words, the codegree of $f$ is the largest element in the image of $f$; see \texttt{CodegreeOfPartialPerm} (54.3.2).

**Rank**

The \textit{rank} of a partial permutation $f$ is the size of its domain, or equivalently the size of its image set or image list; see \texttt{RankOfPartialPerm} (54.3.3).

A \textit{functional digraph} is a directed graph where every vertex has out-degree 1. A partial permutation $f$ can be thought of as a functional digraph with vertices $[1..\text{DegreeOfPartialPerm}(f)]$ and edges from $i$ to $i^f$ for every $i$. A \textit{component} of a partial permutation is defined as a component of the corresponding functional digraph. More specifically, $i$ and $j$ are in the same component if and only if there are $i = v_0, v_1, \ldots, v_n = j$ such that either $v_{k+1} = v_k^f$ or $v_k = v_{k+1}^f$ for all $k$.

If $S$ is a semigroup and $s$ is an element of $S$, then an element $t$ in $S$ is a \textit{semigroup inverse} for $s$ if $s*t*s=s$ and $t*s*t=t$; see, for example, \texttt{InverseOfTransformation} (53.5.13). A semigroup in which every element has a unique semigroup inverse is called an \textit{inverse semigroup}.

Every partial permutation belongs to a symmetric inverse monoid; see \texttt{SymmetricInverseSemigroup} (54.7.3). Inverse semigroups of partial permutations are hence inverse subsemigroups of the symmetric inverse monoids.

The inverse $f^{-1}$ of a partial permutation $f$ is simply the partial permutation that maps $i^f$ to $i$ for all $i$ in the image of $f$. It follows that the domain of $f^{-1}$ equals the image of $f$ and that the image of $f^{-1}$ equals the domain of $f$. The inverse $f^{-1}$ is the unique partial permutation with the property that $f*f^{-1}*f*f^{-1}=f^{-1}$. In other words, $f^{-1}$ is the unique semigroup inverse of $f$ in the symmetric inverse monoid.

If $f$ and $g$ are partial permutations, then the domain and image of the product are:

$$\text{dom}(fg) = (\text{im}(f) \cap \text{dom}(g))f^{-1} \text{ and } \text{im}(fg) = (\text{im}(f) \cap \text{dom}(g))g$$

A partial permutation is an idempotent if and only if it is the identity function on its domain. The products $f*f^{-1}$ and $f^{-1}*f$ are just the identity functions on the domain and image of $f$, respectively. It follows that $f*f^{-1}$ is a left identity for $f$ and $f^{-1}*f$ is a right identity. These products will be referred to here as the \textit{left one} and \textit{right one} of the partial permutation $f$; see \texttt{LeftOne} (54.3.21). The \textit{one} of a partial permutation is just the identity on the union of its domain and its image, and the \textit{zero} of a partial permutation is just the empty partial permutation; see \texttt{One} (54.3.22) and \texttt{MultiplicativeZero} (54.3.23).

If $S$ is an arbitrary inverse semigroup, the \textit{natural partial order} on $S$ is defined as follows: for elements $x$ and $y$ of $S$ we say $x \leq y$ if there exists an idempotent element $e$ in $S$ such that $x=ey$. In the context of the symmetric inverse monoid, a partial permutation $f$ is less than or equal to a partial permutation $g$ in the natural partial order if and only if $f$ is a restriction of $g$. The natural partial order is a meet semilattice, in other words, every pair of elements has a greatest lower bound; see \texttt{MeetOfPartialPerms} (54.2.5).

Note that unlike permutations, partial permutations do not fix unspecified points but are simply undefined on such points; see Chapter 42. Similar to permutations, and unlike transformations, it is possible to multiply any two partial permutations in \texttt{GAP}. 
Internally, GAP stores a partial permutation $f$ as a list consisting of the codegree of $f$ and the images $i^f$ of the points $i$ that are less than or equal to the degree of $f$; the value 0 is stored where $i^f$ is undefined. The domain and image set of $f$ are also stored after either of these values is computed. When the codegree of a partial permutation $f$ is less than 65536, the codegree and images $i^f$ are stored as 16-bit integers, the domain and image set are subobjects of $f$ which are immutable plain lists of GAP integers. When the codegree of $f$ is greater than or equal to 65536, the codegree and images are stored as 32-bit integers; the domain and image set are stored in the same way as before. A partial permutation belongs to IsPPerm2Rep if it is stored using 16-bit integers and to IsPPerm4Rep otherwise.

In the names of the GAP functions that deal with partial permutations, the word “Permutation” is usually abbreviated to “Perm”, to save typing. For example, the category test function for partial permutations is IsPartialPerm (54.1.1).

## 54.1 The family and categories of partial permutations

### 54.1.1 IsPartialPerm

**IsPartialPerm(obj)**

*(Category)*

Returns: true or false.

Every partial permutation in GAP belongs to the category IsPartialPerm. Basic operations for partial permutations are DomainOfPartialPerm (54.3.4), ImageListOfPartialPerm (54.3.6), ImageSetOfPartialPerm (54.3.7), RankOfPartialPerm (54.3.3), DegreeOfPartialPerm (54.3.1), multiplication of two partial permutations is via *, and exponentiation with the first argument a positive integer $i$ and second argument a partial permutation $f$ where the result is the image $i^f$ of the point $i$ under $f$. The inverse of a partial permutation $f$ can be obtained using $f^{-1}$.

### 54.1.2 IsPartialPermCollection

**IsPartialPermCollection(obj)**

*(Category)*

Every collection of partial permutations belongs to the category IsPartialPermCollection. For example, a semigroup of partial permutations belongs in IsPartialPermCollection.

### 54.1.3 PartialPermFamily

**PartialPermFamily**

*(family)*

The family of all partial permutations is PartialPermFamily.

## 54.2 Creating partial permutations

There are several ways of creating partial permutations in GAP, which are described in this section.

### 54.2.1 PartialPerm (for a domain and image)

**PartialPerm(dom, img)**

*(function)*

**PartialPerm(list)**

*(function)*
**Returns:** A partial permutation.

Partial permutations can be created in two ways: by giving the domain and the image, or the dense image list.

**Domain and image**

The partial permutation defined by a domain \( \text{dom} \) and image \( \text{img} \), where \( \text{dom} \) is a set of positive integers and \( \text{img} \) is a duplicate free list of positive integers, maps \( \text{dom}[i] \) to \( \text{img}[i] \). For example, the partial permutation mapping 1 and 5 to 20 and 2 can be created using:

```
PartialPerm([1,5],[20,2]);
```

In this setting, `PartialPerm` is the analogue in the context of partial permutations of `MappingPermListList` (42.5.3).

**Dense image list**

The partial permutation defined by a dense image list \( \text{list} \), maps the positive integer \( i \) to \( \text{list}[i] \) if \( \text{list}[i]<>0 \) and is undefined at \( i \) if \( \text{list}[i]=0 \). For example, the partial permutation mapping 1 and 5 to 20 and 2 can be created using:

```
PartialPerm([20,0,0,0,2]);
```

In this setting, `PartialPerm` is the analogue in the context of partial permutations of `PermList` (42.5.2).

Regardless of which of these two methods are used to create a partial permutation in GAP the internal representation is the same.

If the largest point in the domain is larger than the rank of the partial permutation, then using the dense image list to define the partial permutation will require less typing; otherwise using the domain and the image will require less typing. For example, the partial permutation mapping 10000 to 1 can be defined using:

```
PartialPerm([10000], [1]);
```

but using the dense image list would require a list with 9999 entries equal to 0 and the final entry equal to 1. On the other hand, the identity on \([1,2,3,4,6]\) can be defined using:

```
PartialPerm([1,2,3,4,0,6]);
```

Please note that a partial permutation in GAP is never a permutation nor is a permutation ever a partial permutation. For example, the permutation \((1,4,2)\) fixes 3 but the partial permutation

```
PartialPerm([4,1,0,2]);
```

is not defined on 3.

### 54.2.2 PartialPermOp

\[
\begin{align*}
\triangleright & \text{PartialPermOp(obj, list[, func])} \\
\triangleright & \text{PartialPermOpNC(obj, list[, func])}
\end{align*}
\]

**Returns:** A partial permutation or fail.

`PartialPermOp` returns the partial permutation that corresponds to the action of the object \( \text{obj} \) on the domain or list \( \text{list} \) via the function \( \text{func} \). If the optional third argument \( \text{func} \) is not specified,
then the action OnPoints (41.2.1) is used by default. Note that the returned partial permutation refers to the positions in list even if list itself consists of integers.

This function is the analogue in the context of partial permutations of Permutation (41.9.1) or TransformationOp (53.2.5).

If obj does not map the elements of list injectively, then fail is returned.

PartialPermOpNC does not check that obj maps elements of list injectively or that a partial permutation is defined by the action of obj on list via func. This function should be used only with caution, in situations where it is guaranteed that the arguments have the required properties.

Example

\begin{verbatim}
gap> f:=Transformation([ 9, 10, 4, 2, 10, 5, 9, 10, 9, 6 ]);;
gap> PartialPermOp(f, [ 6 .. 8 ], OnPoints);
[1,4][2,5][3,6]
\end{verbatim}

54.2.3 RestrictedPartialPerm

\begin{verbatim}
▷ RestrictedPartialPerm(f, set)
\end{verbatim}

\textbf{Returns}: A partial permutation.

RestrictedPartialPerm returns a new partial permutation that acts on the points in the set of positive integers set in the same way as the partial permutation f, and that is undefined on those points that are not in set.

Example

\begin{verbatim}
gap> f:=PartialPerm([ 1, 3, 4, 7, 8, 9 ], [ 9, 4, 1, 6, 2, 8 ]);;
gap> RestrictedPartialPerm(f, [ 2, 3, 6, 10 ]);
[3,4]
\end{verbatim}

54.2.4 JoinOfPartialPerms

\begin{verbatim}
▷ JoinOfPartialPerms(arg)
▷ JoinOfIdempotentPartialPermsNC(arg)
\end{verbatim}

\textbf{Returns}: A partial permutation or fail.

The join of partial permutations f and g is just the join, or supremum, of f and g under the natural partial ordering of partial permutations.

JoinOfPartialPerms returns the union of the partial permutations in its argument if this defines a partial permutation, and fail if it is not. The argument arg can be a partial permutation collection or a number of partial permutations.

The function JoinOfIdempotentPartialPermsNC returns the join of its argument which is assumed to be a collection of idempotent partial permutations or a number of idempotent partial permutations. It is not checked that the arguments are idempotents. The performance of this function is higher than JoinOfPartialPerms when it is known a priori that the argument consists of idempotents.

The union of f and g is a partial permutation if and only if f and g agree on the intersection \( \text{dom}(f) \cap \text{dom}(g) \) of their domains and the images of \( \text{dom}(f) \setminus \text{dom}(g) \) and \( \text{dom}(g) \setminus \text{dom}(f) \) under f and g, respectively, are disjoint.

Example

\begin{verbatim}
gap> f:=PartialPerm([ 1, 2, 3, 6, 8, 10 ], [ 2, 6, 7, 9, 1, 5 ]);;
gap> g:=PartialPerm([ 11, 12, 14, 16, 18, 19 ],
> [ 17, 20, 11, 19, 14, 12 ] );
\end{verbatim}
gap> JoinOfPartialPerms(f, g);
[3,7][8,1,2,6,9][10,5][16,19,12,20][18,14,11,17]
gap> f:=PartialPerm( [ 1, 4, 5, 6, 7 ], [ 5, 7, 3, 1, 4 ] );
[6,1,5,3](4,7)
gap> g:=PartialPerm( [ 100 ], [ 1 ] );
[100,1]
gap> JoinOfPartialPerms(f, g);
fail
gap> f:=PartialPerm( [ 1, 3, 4 ], [ 3, 2, 4 ] );
[1,3,2](4)
gap> g:=PartialPerm( [ 1, 2, 4 ], [ 2, 3, 4 ] );
[1,2,3](4)
gap> JoinOfPartialPerms(f, g);
fail
gap> f:=PartialPerm( [ 1 ], [ 2 ] );
[1,2]
gap> JoinOfPartialPerms(f, f^-1);
(1,2)

54.2.5 MeetOfPartialPerms

MeetOfPartialPerms(arg)  (function)

Returns: A partial permutation.

The meet of partial permutations \( f \) and \( g \) is just the meet, or infimum, of \( f \) and \( g \) under the natural partial ordering of partial permutations. In other words, the meet is the greatest partial permutation which is a restriction of both \( f \) and \( g \).

Note that unlike the join of partial permutations, the meet always exists.

\( \text{MeetOfPartialPerms} \) returns the meet of the partial permutations in its argument. The argument \( \text{arg} \) can be a partial permutation collection or a number of partial permutations.

Example

\begin{verbatim}
gap> f:=PartialPerm( [ 1, 2, 3, 6, 100000 ], [ 2, 6, 7, 1, 5 ] );
[3,7][100000,5](1,2,6)
gap> g:=PartialPerm( [ 1, 2, 3, 4, 6 ], [ 2, 4, 6, 1, 5 ] );
[3,6,5](1,2,4)
gap> MeetOfPartialPerms(f, g);
[1,2]
gap> g:=PartialPerm( [ 1, 2, 3, 5, 6, 7, 9, 10 ],
> [ 4, 10, 5, 6, 7, 1, 3, 2 ] );
[9,3,5;6,7,1,4](2,10)
gap> MeetOfPartialPerms(f, g);
<empty partial perm>
\end{verbatim}

54.2.6 EmptyPartialPerm

EmptyPartialPerm()  (function)

Returns: The empty partial permutation.

The empty partial permutation is returned by this function when it is called with no arguments. This is just short hand for \( \text{PartialPerm}([\ ]); \)
54.2.7 RandomPartialPerm

RandomPartialPerm(n)  
RandomPartialPerm(set)  
RandomPartialPerm(dom, img)

Returns: A random partial permutation.

In its first form, RandomPartialPerm returns a randomly chosen partial permutation where points in the domain and image are bounded above by the positive integer n.

Example  
```gap
gap> RandomPartialPerm(10);  
[2,9][4,1,6,5][7,3]()[8]
```

In its second form, RandomPartialPerm returns a randomly chosen partial permutation with points in the domain and image contained in the set of positive integers set.

Example  
```gap
gap> RandomPartialPerm([1,2,3,1000]);  
[2,3,1000]()
```

In its third form, RandomPartialPerm creates a randomly chosen partial permutation with domain contained in the set of positive integers dom and image contained in the set of positive integers img. The arguments dom and img do not have to have equal length.

Note that it is not guaranteed in either of these cases that partial permutations are chosen with a uniform distribution.

54.3 Attributes for partial permutations

In this section we describe the functions available in GAP for finding various attributes of partial permutations.

54.3.1 DegreeOfPartialPerm

DegreeOfPartialPerm(f)  
DegreeOfPartialPermCollection(coll)

Returns: A non-negative integer.

The degree of a partial permutation f is the largest positive integer where it is defined, i.e. the maximum element in the domain of f.

The degree a collection of partial permutations coll is the largest degree of any partial permutation in coll.

Example  
```gap
gap> f:=PartialPerm([1,2,3,6,8,10],[2,6,7,9,1,5]);  
[3,7][8,1,2,6,9][10,5]
gap> DegreeOfPartialPerm(f);  
10
```
54.3.2 CodegreeOfPartialPerm

- **CodegreeOfPartialPerm**
  - **Function**
  - **CodegreeOfPartialPermCollection**
    - **Attribute**
    - **Returns**: A non-negative integer.
      - The codegree of a partial permutation \( f \) is the largest positive integer in its image.
      - The codegree of a collection of partial permutations \( coll \) is the largest codegree of any partial permutation in \( coll \).

```
Example

gap> f:=PartialPerm([1, 2, 3, 4, 5, 8, 10], [7, 1, 4, 3, 2, 6, 5]);
[8,6][10,5,2,1,7](3,4)
gap> CodegreeOfPartialPerm(f);
7
```

54.3.3 RankOfPartialPerm

- **RankOfPartialPerm**
  - **Function**
  - **RankOfPartialPermCollection**
    - **Attribute**
    - **Returns**: A non-negative integer.
      - The rank of a partial permutation \( f \) is the size of its domain, or equivalently the size of its image set or image list.
      - The rank of a partial permutation collection \( coll \) is the size of the union of the domains of the elements of \( coll \), or equivalently, the total number of points on which the elements of \( coll \) act. Note that this value may not be the same as the size of the union of the images of the elements in \( coll \).

```
Example

gap> f:=PartialPerm([1, 2, 4, 6, 8, 9], [7, 10, 1, 9, 4, 2]);
[6,9,2,10][8,4,1,7]
gap> RankOfPartialPerm(f);
6
```

54.3.4 DomainOfPartialPerm

- **DomainOfPartialPerm**
  - **Function**
  - **DomainOfPartialPermCollection**
    - **Attribute**
    - **Returns**: A set of positive integers (maybe empty).
      - The domain of a partial permutation \( f \) is the set of positive integers where \( f \) is defined.
      - The domain of a partial permutation collection \( coll \) is the union of the domains of its elements.

```
Example

gap> f:=PartialPerm([1, 2, 3, 6, 8, 10], [2, 6, 7, 9, 1, 5]);
[3,7][8,1,2,6,9][10,5]
gap> DomainOfPartialPerm(f);
[1, 2, 3, 6, 8, 10]
```

54.3.5 ImageOfPartialPermCollection

- **ImageOfPartialPermCollection**
  - **Function**
  - **ImageOfPartialPermCollection**
    - **Attribute**
    - **Returns**: A set of positive integers (maybe empty).
      - The image of a partial permutation collection \( coll \) is the union of the images of its elements.
Example

```gap
gap> S := SymmetricInverseSemigroup(5);
<symmetric inverse monoid of degree 5>
gap> ImageOfPartialPermCollection(GeneratorsOfInverseSemigroup(S));
[ 1 .. 5 ]
```

### 54.3.6 ImageListOfPartialPerm

**ImageListOfPartialPerm**

**Returns:** The list of images of a partial permutation.

The *image list* of a partial permutation \( f \) is the list of images of the elements of the domain \( f \) where \( \text{ImageListOfPartialPerm}(f)[i] = \text{DomainOfPartialPerm}(f)[i]^f \) for any \( i \) in the range from 1 to the rank of \( f \).

```gap
gap> f:=PartialPerm( [1, 2, 3, 4, 5, 8, 10 ], [ 7, 1, 4, 3, 2, 6, 5 ] );
[8,6][10,5,2,1,7](3,4)
gap> ImageListOfPartialPerm(f);
[ 7, 1, 4, 3, 2, 6, 5 ]
```

### 54.3.7 ImageSetOfPartialPerm

**ImageSetOfPartialPerm**

**Returns:** The image set of a partial permutation.

The *image set* of a partial permutation \( f \) is just the set of points in the image list (i.e. the image list after it has been sorted into increasing order).

```gap
gap> f:=PartialPerm( [1, 2, 3, 5, 7, 10 ], [ 10, 2, 3, 5, 7, 6 ] );
[1,10,6](2)(3)(5)(7)
gap> ImageSetOfPartialPerm(f);
[ 2, 3, 5, 6, 7, 10 ]
```

### 54.3.8 FixedPointsOfPartialPerm (for a partial perm)

**FixedPointsOfPartialPerm**

**Returns:** A set of positive integers.

**FixedPointsOfPartialPerm** returns the set of points \( i \) in the domain of the partial permutation \( f \) such that \( i^f = i \).

When the argument is a collection of partial permutations \( \text{coll} \), **FixedPointsOfPartialPerm** returns the set of points fixed by every element of the collection of partial permutations \( \text{coll} \).

```gap
gap> f := PartialPerm( [1, 2, 3, 6, 7], [1, 3, 4, 7, 5] );
[2,3,4][6,7,5](1)
gap> FixedPointsOfPartialPerm(f);
[ 1 ]
gap> f := PartialPerm([1 .. 10]);;
gap> FixedPointsOfPartialPerm(f);
[ 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ]
```
54.3.9 MovedPoints (for a partial perm)

\[ \text{MovedPoints}(f) \] (attribute)
\[ \text{MovedPoints}(\text{coll}) \] (method)

**Returns:** A set of positive integers.

\text{MovedPoints} returns the set of points \( i \) in the domain of the partial permutation \( f \) such that \( i^f \neq i \).

When the argument is a collection of partial permutations \( \text{coll} \), \text{MovedPoints} returns the set of points moved by some element of the collection of partial permutations \( \text{coll} \).

Example:

\begin{verbatim}
gap> f := PartialPerm( [ 1, 2, 3, 4 ], [ 5, 7, 1, 6 ] );
[2,7][3,1,5][4,6]
gap> MovedPoints(f);
[ 1, 2, 3, 4 ]
gap> FixedPointsOfPartialPerm(f);
[ ]
gap> FixedPointsOfPartialPerm(PartialPerm([1 .. 4]));
[ 1, 2, 3, 4 ]
\end{verbatim}

54.3.10 NrFixedPoints (for a partial perm)

\[ \text{NrFixedPoints}(f) \] (attribute)
\[ \text{NrFixedPoints}(\text{coll}) \] (method)

**Returns:** A positive integer.

\text{NrFixedPoints} returns the number of points \( i \) in the domain of the partial permutation \( f \) such that \( i^f = i \).

When the argument is a collection of partial permutations \( \text{coll} \), \text{NrFixedPoints} returns the number of points fixed by every element of the collection of partial permutations \( \text{coll} \).

Example:

\begin{verbatim}
gap> f := PartialPerm( [ 1, 2, 3, 4, 5 ], [ 3, 2, 4, 6, 1 ] );
[5,1,3,4,6](2)
gap> NrFixedPoints(f);
1
gap> NrFixedPoints(PartialPerm([1 .. 10]));
10
\end{verbatim}

54.3.11 NrMovedPoints (for a partial perm)

\[ \text{NrMovedPoints}(f) \] (attribute)
\[ \text{NrMovedPoints}(\text{coll}) \] (method)

**Returns:** A positive integer.

\text{NrMovedPoints} returns the number of points \( i \) in the domain of the partial permutation \( f \) such that \( i^f \neq i \).

When the argument is a collection of partial permutations \( \text{coll} \), \text{NrMovedPoints} returns the number of points moved by some element of the collection of partial permutations \( \text{coll} \).

Example:

\begin{verbatim}
gap> f := PartialPerm( [ 1, 2, 3, 4, 5, 7, 8 ], [ 4, 5, 6, 7, 1, 3, 2 ] );
[8,2,5,1,4,7,3,6]
gap> NrMovedPoints(f);
\end{verbatim}
54.3.12 SmallestMovedPoint (for a partial perm)

\[\text{SmallestMovedPoint}(f)\]
\[\text{SmallestMovedPoint}(\text{coll})\]

**Returns:** A positive integer or infinity.

SmallestMovedPoint returns the smallest positive integer \(i\) such that \(i^f \neq i\) if such an \(i\) exists. If \(f\) is an identity partial permutation, then infinity is returned.

If the argument is a collection of partial permutations \(\text{coll}\), then the smallest point which is moved by at least one element of \(\text{coll}\) is returned, if such a point exists. If \(\text{coll}\) only contains identity partial permutations, then SmallestMovedPoint returns infinity.

**Example**

\[
gap> f := \text{PartialPerm}([1,3],[4,3]);
\]
\[
\text{[3,1,4]}(3)
\]
\[
\text{gap> SmallestMovedPoint}\;(f);
\]
\[
1
\]
\[
\text{gap> SmallestMovedPoint}\;(\text{PartialPerm}([1..10]));
\]
\[
infinity
\]

54.3.13 LargestMovedPoint (for a partial perm)

\[\text{LargestMovedPoint}(f)\]
\[\text{LargestMovedPoint}(\text{coll})\]

**Returns:** A positive integer or infinity.

LargestMovedPoint returns the largest positive integers \(i\) such that \(i^f \neq i\) if such an \(i\) exists. If \(f\) is the identity partial permutation, then 0 is returned.

If the argument is a collection of partial permutations \(\text{coll}\), then the largest point which is moved by at least one element of \(\text{coll}\) is returned, if such a point exists. If \(\text{coll}\) only contains identity partial permutations, then LargestMovedPoint returns 0.

**Example**

\[
gap> f := \text{PartialPerm}([1,3,4,5],[5,1,6,4]);
\]
\[
\text{[3,1,5,4,6]}
\]
\[
\text{gap> LargestMovedPoint}\;(f);
\]
\[
5
\]
\[
\text{gap> LargestMovedPoint}\;(\text{PartialPerm}([1..10]));
\]
\[
0
\]

54.3.14 SmallestImageOfMovedPoint (for a partial permutation)

\[\text{SmallestImageOfMovedPoint}(f)\]
\[\text{SmallestImageOfMovedPoint}(\text{coll})\]

**Returns:** A positive integer or infinity.

SmallestImageOfMovedPoint returns the smallest positive integer \(i\) such that \(i^f \neq i\) if such an \(i\) exists. If \(f\) is the identity partial permutation, then infinity is returned.
If the argument is a collection of partial permutations `coll`, then the smallest integer which is the image a point moved by at least one element of `coll` is returned, if such a point exists. If `coll` only contains identity partial permutations, then `SmallestImageOfMovedPoint` returns `infinity`.

Example

```gap
gap> S := SymmetricInverseSemigroup(5);
<symmetric inverse monoid of degree 5>
gap> SmallestImageOfMovedPoint(S);
1
gap> S := Semigroup(PartialPerm([10 .. 100], [10 .. 100]));;
gap> SmallestImageOfMovedPoint(S);
infinity
gap> f := PartialPerm( [ 1, 2, 3, 6 ] );
[4,6](1)(2)(3)
gap> SmallestImageOfMovedPoint(f);
6
```

54.3.15 LargestImageOfMovedPoint (for a partial permutation)

- `LargestImageOfMovedPoint(f)` (attribute)
- `LargestImageOfMovedPoint(coll)` (method)

Returns: A positive integer.

`LargestImageOfMovedPoint` returns the largest positive integer \(i^f\) such that \(i^f \neq i\) if such an \(i\) exists. If \(f\) is an identity partial permutation, then \(0\) is returned.

If the argument is a collection of partial permutations `coll`, then the largest integer which is the image of a point moved by at least one element of `coll` is returned, if such a point exists. If `coll` only contains identity partial permutations, then `LargestImageOfMovedPoint` returns `0`.

Example

```gap
gap> S := SymmetricInverseSemigroup(5);
<symmetric inverse monoid of degree 5>
gap> LargestImageOfMovedPoint(S);
5
gap> S := Semigroup(PartialPerm([10 .. 100], [10 .. 100]));;
gap> LargestImageOfMovedPoint(S);
0
gap> f := PartialPerm( [ 1, 2, 3, 6 ] );
[4,6](1)(2)(3)
gap> LargestImageOfMovedPoint(f);
6
```

54.3.16 IndexPeriodOfPartialPerm

- `IndexPeriodOfPartialPerm(f)` (attribute)

Returns: A pair of positive integers.

Returns the least positive integers \(m, r\) such that \(f^m = f^{m+r}\), which are known as the index and period of the partial permutation \(f\).

Example

```gap
gap> f:=PartialPerm( [ 1, 2, 3, 5, 6, 7, 8, 11, 12, 16, 19 ],
> [ 9, 18, 20, 11, 5, 16, 8, 19, 14, 13, 1 ] );
[2,18][3,20][6,8,11,19,1,9][7,16,13][12,14](8)
gap> IndexPeriodOfPartialPerm(f);
[ 6, 1 ]
```
54.3.17 SmallestIdempotentPower (for a partial perm)

\textbf{SmallestIdempotentPower}(f) \hspace{1cm} \text{(attribute)}

\textbf{Returns:} A positive integer.

This function returns the least positive integer \( n \) such that the partial permutation \( f^n \) is an idempotent. The smallest idempotent power of \( f \) is the least multiple of the period of \( f \) that is greater than or equal to the index of \( f \); see \texttt{IndexPeriodOfPartialPerm} (54.3.16).

Example
\begin{verbatim}
gap> f:=PartialPerm( [ 1, 2, 3, 4, 5, 7, 8, 10, 11, 13, 18, 19, 20 ],
> [5, 1, 7, 3, 10, 2, 12, 14, 11, 16, 6, 9, 15] );
[4,3,7,2,5,10,14][8,12][13,16][18,6][19,9][20,15](11)
gap> SmallestIdempotentPower(f);
8
gap> f^8;
<identity partial perm on [ 11 ]>
\end{verbatim}

54.3.18 ComponentsOfPartialPerm

\textbf{ComponentsOfPartialPerm}(f) \hspace{1cm} \text{(attribute)}

\textbf{Returns:} A list of lists of positive integer.

\texttt{ComponentsOfPartialPerm} returns a list of the components of the partial permutation \( f \). Each component is a subset of the domain of \( f \), and the union of the components equals the domain.

Example
\begin{verbatim}
gap> f:=PartialPerm( [ 1, 2, 3, 4, 5, 7, 8, 10, 11, 12, 13, 19 ],
> [20, 4, 6, 19, 9, 14, 3, 12, 17, 5, 15, 13] );
[1,20][2,4,19,13,15][7,14][8,3,6][10,12,5,9][11,17]
gap> ComponentsOfPartialPerm(f);
[ [ 1, 20 ], [ 2, 4, 19, 13, 15 ], [ 7, 14 ], [ 8, 3, 6 ],
[ 10, 12, 5, 9 ], [ 11, 17 ] ]
\end{verbatim}

54.3.19 NrComponentsOfPartialPerm

\textbf{NrComponentsOfPartialPerm}(f) \hspace{1cm} \text{(attribute)}

\textbf{Returns:} A positive integer.

\texttt{NrComponentsOfPartialPerm} returns the number of components of the partial permutation \( f \) on its domain.

Example
\begin{verbatim}
gap> f:=PartialPerm( [ 1, 2, 3, 4, 5, 7, 8, 10, 11, 12, 13, 19 ],
> [20, 4, 6, 19, 9, 14, 3, 12, 17, 5, 15, 13] );
[1,20][2,4,19,13,15][7,14][8,3,6][10,12,5,9][11,17]
gap> NrComponentsOfPartialPerm(f);
6
\end{verbatim}
54.3.20 ComponentRepsOfPartialPerm

**ComponentRepsOfPartialPerm**

- **Returns:** A list of positive integers.

ComponentRepsOfPartialPerm returns the representatives, in the following sense, of the components of the partial permutation \( f \). Every component of \( f \) contains a unique element in the domain but not the image of \( f \); this element is called the *representative* of the component. If \( i \) is a representative of a component of \( f \), then for every \( j \neq i \) in the component of \( i \), there exists a positive integer \( k \) such that \( i \cdot (f \circ k) = j \). Unlike transformations, there is exactly one representative for every component of \( f \). ComponentRepsOfPartialPerm returns the least number of representatives.

**Example**

```gap
gap> f:=PartialPerm([1,2,3,4,5,7,8,10,11,12,13,19], [20,4,6,19,9,14,3,12,17,5,15,13]);
gap> ComponentRepsOfPartialPerm(f);
gap> [1,2,7,8,10,11]
```

54.3.21 LeftOne (for a partial perm)

- **LeftOne**
- **RightOne**

**Returns:** A partial permutation.

LeftOne returns the identity partial permutation \( e \) such that the domain and image of \( e \) equal the domain of the partial permutation \( f \) and such that \( e \cdot f = f \).

RightOne returns the identity partial permutation \( e \) such that the domain and image of \( e \) equal the image of \( f \) and such that \( f \cdot e = f \).

**Example**

```gap
gap> f:=PartialPerm([1,2,4,5,6,7], [10,1,6,5,8,7,]);
gap> RightOne(f);
<identity partial perm on [1,5,6,7,8,10]>
gap> LeftOne(f);
<identity partial perm on [1,2,4,5,6,7]>
```

54.3.22 One (for a partial perm)

- **One**

**Returns:** A partial permutation.

As described in OneImmutable (31.10.2), One returns the multiplicative neutral element of the partial permutation \( f \), which is the identity partial permutation on the union of the domain and image of \( f \). Equivalently, the one of \( f \) is the join of the right one and left one of \( f \).

**Example**

```gap
gap> f:=PartialPerm([1,2,3,4,5,7,10], [3,7,9,6,1,10,2]);
gap> One(f);
<identity partial perm on [1,2,3,4,5,6,7,9,10]>
```
### 54.3.23 MultiplicativeZero (for a partial perm)

**Returns:** The empty partial permutation.

As described in MultiplicativeZero (35.4.11), Zero returns the multiplicative zero element of the partial permutation $f$, which is the empty partial permutation.

#### Example

```gap
gap> f := PartialPerm([ 1, 2, 3, 4, 5, 7, 10 ], [ 3, 7, 9, 6, 1, 10, 2 ]);;
gap> MultiplicativeZero(f);
<empty partial perm>
```

### 54.4 Changing the representation of a partial permutation

It is possible that a partial permutation in GAP can be represented by other types of objects, or that other types of GAP objects can be represented by partial permutations. Partial permutations which are mathematically permutations can be converted into permutations in GAP using the function `AsPermutation` (42.5.6). Similarly, a partial permutation can be converted into a transformation using `AsTransformation` (53.3.1).

In this section we describe functions for converting other types of objects in GAP into partial permutations.

### 54.4.1 AsPartialPerm (for a permutation and a set of positive integers)

**Returns:** A partial permutation.

A permutation $f$ defines a partial permutation when it is restricted to any finite set of positive integers. `AsPartialPerm` can be used to obtain this partial permutation.

There are several possible arguments for `AsPartialPerm`:

**for a permutation and set of positive integers**

`AsPartialPerm` returns the partial permutation that equals $f$ on the set of positive integers set and that is undefined on every other positive integer.

Note that as explained in PartialPerm (54.2.1) a permutation is never a partial permutation in GAP, please keep this in mind when using `AsPartialPerm`.

**for a permutation**

`AsPartialPerm` returns the partial permutation that agrees with $f$ on $[1..\text{LargestMovedPoint}(f)]$ and that is not defined on any other positive integer.

**for a permutation and a positive integer**

`AsPartialPerm` returns the partial permutation that agrees with $f$ on $[1..n]$, when $n$ is a positive integer, and that is not defined on any other positive integer.

The operation `PartialPermOp` (54.2.2) can also be used to convert permutations into partial permutations.
Example

```
gap> f:=(2,8,19,9,14,10,20,17,4,13,12,3,5,7,18,16);;
gap> AsPartialPerm(f);
(1)(2,8,19,9,14,10,20,17,4,13,12,3,5,7,18,16)(6)(11)(15)
gap> AsPartialPerm(f, [ 1, 2, 3 ] );
[2,8][3,5](1)
```

54.4.2 AsPartialPerm (for a transformation and a set of positive integer)

\[
\text{\textgreater \ AsPartialPerm}(f, \text{set}) \quad \text{(operation)}
\]
\[
\text{\textgreater \ AsPartialPerm}(f, n) \quad \text{(method)}
\]

**Returns:** A partial permutation or fail.

A transformation \( f \) defines a partial permutation when it is restricted to a set of positive integers where it is injective. AsPartialPerm can be used to obtain this partial permutation.

There are several possible arguments for AsPartialPerm:

**for a transformation and set of positive integers**

AsPartialPerm returns the partial permutation obtained by restricting \( f \) to the set of positive integers \( \text{set} \) when:

- \( \text{set} \) contains no elements exceeding the degree of \( f \);
- \( f \) is injective on \( \text{set} \).

**for a transformation and a positive integer**

AsPartialPerm returns the partial permutation that agrees with \( f \) on \([1..n]\) when \( n \) is a positive integer and this set satisfies the conditions given above.

The operation PartialPermOp (54.2.2) can also be used to convert transformations into partial permutations.

Example

```
gap> f:=Transformation( [ 8, 3, 5, 9, 6, 2, 9, 7, 9 ] );;
gap> AsPartialPerm(f, [1, 2, 3, 5, 8]);
[1,8,7][2,3,5,6]
gap> AsPartialPerm(f, 3);
[1,8][2,3,5]
gap> AsPartialPerm(f, [ 2 .. 4 ] );
[2,3,5][4,9]
```

54.5 Operators and operations for partial permutations

\( f ^ -1 \)

returns the inverse of the partial permutation \( f \).

\( i ^ f \)

returns the image of the positive integer \( i \) under the partial permutation \( f \) if it is defined and 0 if it is not.

\( i / f \)

returns the preimage of the positive integer \( i \) under the partial permutation \( f \) if it is defined and 0 if it is not. Note that the inverse of \( f \) is not calculated to find the preimage of \( i \).
\( f^g \) returns \( g^{-1}f^g \) when \( f \) is a partial permutation and \( g \) is a permutation or partial permutation; see \( \sim \) (31.12.1). This operation requires essentially the same number of steps as multiplying partial permutations, which is around one third as many as inverting and multiplying twice.

\( f \ast g \) returns the composition of \( f \) and \( g \) when \( f \) and \( g \) are partial permutations or permutations. The product of a permutation and a partial permutation is returned as a partial permutation.

\( f / g \) returns \( f \ast g^{-1} \) when \( f \) is a partial permutation and \( g \) is a permutation or partial permutation. This operation requires essentially the same number of steps as multiplying partial permutations, which is approximately half that required to first invert \( g \) and then take the product with \( f \).

\( \text{LQUO}(g, f) \) returns \( g^{-1} \ast f \) when \( f \) is a partial permutation and \( g \) is a permutation or partial permutation. This operation requires essentially the same number of steps as multiplying partial permutations, which is approximately half that required to first invert \( g \) and then take the product with \( f \).

\( f < g \) returns true if the image of \( f \) on the range from 1 to the degree of \( f \) is lexicographically less than the corresponding image for \( g \) and false if it is not. See \( \text{NaturalLeqPartialPerm} \) (54.5.4) and \( \text{ShortLexLeqPartialPerm} \) (54.5.5) for additional orders for partial permutations.

\( f = g \) returns true if the partial permutation \( f \) equals the partial permutation \( g \) and returns false if it does not.

54.5.1 PermLeftQuoPartialPerm

\( \text{PermLeftQuoPartialPerm}(f, g) \) (operation)
\( \text{PermLeftQuoPartialPermNC}(f, g) \) (operation)

Returns: A permutation.

Returns the permutation on the image set of \( f \) induced by \( f^g^{-1} \) when the partial permutations \( f \) and \( g \) have equal domain and image set.

\text{PermLeftQuoPartialPerm} verifies that \( f \) and \( g \) have equal domains and image sets, and returns an error if they do not. \text{PermLeftQuoPartialPermNC} does no checks.

Example:
\begin{verbatim}
gap> f:=PartialPerm([1, 2, 3, 4, 5, 7], [7, 9, 10, 4, 2, 5]);
[1,7,5,2,9][3,10](4)
gap> g:=PartialPerm([1, 2, 3, 4, 5, 7], [7, 4, 9, 2, 5, 10]);
[1,7,10][3,9](2,4)(5)
gap> PermLeftQuoPartialPerm(f, g);
(2,5,10,9,4)
\end{verbatim}

54.5.2 PreImagePartialPerm

\( \text{PreImagePartialPerm}(f, i) \) (operation)

Returns: A positive integer or fail.
PreImagePartialPerm returns the preimage of the positive integer \( i \) under the partial permutation \( f \) if \( i \) belongs to the image of \( f \). If \( i \) does not belong to the image of \( f \), then \texttt{fail} is returned. The same result can be obtained by using \( i/f \) as described in Section 54.5.

\begin{verbatim}
> f := PartialPerm([1, 2, 3, 5, 9, 10], [5, 10, 7, 8, 9, 1]);
[2,10,1,5,8][3,7](9)
> PreImagePartialPerm(f, 8);
5
> PreImagePartialPerm(f, 5);
1
> PreImagePartialPerm(f, 1);
10
> PreImagePartialPerm(f, 10);
2
> PreImagePartialPerm(f, 2);
fail
\end{verbatim}

### 54.5.3 ComponentPartialPermInt

\texttt{ComponentPartialPermInt} \( f, i \)

\textbf{Returns:} A set of positive integers.

\texttt{ComponentPartialPermInt} returns the elements of the component of \( f \) containing \( i \) that can be obtained by repeatedly applying \( f \) to \( i \).

\begin{verbatim}
> f := PartialPerm([1, 2, 4, 5, 6, 7, 8, 10, 14, 15, 16, 17, 18],
> [11, 4, 14, 16, 15, 3, 20, 8, 17, 19, 1, 6, 12]);
> ComponentPartialPermInt(f, 4);
[4, 14, 17, 6, 15, 19]
> ComponentPartialPermInt(f, 3);
[]
> ComponentPartialPermInt(f, 10);
[10, 8, 20]
> ComponentPartialPermInt(f, 100);
[]
\end{verbatim}

### 54.5.4 NaturalLeqPartialPerm

\texttt{NaturalLeqPartialPerm} \( f, g \)

\textbf{Returns:} \texttt{true} or \texttt{false}.

The natural partial order \( \leq \) on an inverse semigroup \( S \) is defined by \( s \leq t \) if there exists an idempotent \( e \) in \( S \) such that \( s = et \). Hence if \( f \) and \( g \) are partial permutations, then \( f \leq g \) if and only if \( f \) is a restriction of \( g \); see \texttt{RestrictedPartialPerm} (54.2.3).

\texttt{NaturalLeqPartialPerm} returns \texttt{true} if \( f \) is a restriction of \( g \) and \texttt{false} if it is not. Note that since this is a partial order and not a total order, it is possible that \( f \) and \( g \) are incomparable with respect to the natural partial order.

\begin{verbatim}
> f := PartialPerm([1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 16, 17, 18, 19],
> [3, 12, 14, 4, 11, 18, 17, 2, 9, 5, 15, 8, 20, 10, 19]);
\end{verbatim}
gap> g:=RestrictedPartialPerm(f, [ 1, 2, 3, 9, 13, 20 ] );
[1,3,14][2,12]
gap> NaturalLeqPartialPerm(g,f);
true
gap> NaturalLeqPartialPerm(f,g);
false
gap> g:=PartialPerm( [ 1, 2, 3, 4, 5, 8, 10 ],
> [ 7, 1, 4, 3, 2, 6, 5 ] );;
gap> NaturalLeqPartialPerm(f, g);
false
gap> NaturalLeqPartialPerm(g, f);
false

54.5.5  ShortLexLeqPartialPerm

▷ ShortLexLeqPartialPerm(f, g)  
Returns: true or false.

ShortLexLeqPartialPerm returns true if the concatenation of the domain and image list of f
is short-lex less than the corresponding concatenation for g and false otherwise.

Note that this is not the natural partial order on partial permutation or the same as comparing f
and g using \.<

gap> f:=PartialPerm( [ 1, 2, 3, 4, 6, 7, 8, 10 ],
> [ 3, 8, 1, 9, 4, 10, 5, 6 ] );
[2,8,5][7,10,6,4,9](1,3)
gap> g:=PartialPerm( [ 1, 2, 3, 4, 5, 8, 10 ],
> [ 7, 1, 4, 3, 2, 6, 5 ] );;
[8,6][10,5,2,1,7](3,4)
gap> f<g;
true
gap> g<f;
false
gap> ShortLexLeqPartialPerm(f, g);
false
gap> ShortLexLeqPartialPerm(g, f);
true
gap> NaturalLeqPartialPerm(f, g);
false
gap> NaturalLeqPartialPerm(g, f);
false

54.5.6  TrimPartialPerm

▷ TrimPartialPerm(f)  
Returns: Nothing.

It can happen that the internal representation of a partial permutation uses more memory than nec-
essary. For example, by composing a partial permutation with codegree less than 65536 with a partial
permutation with codegree greater than 65535. It is possible that the resulting partial permutation f
has its codegree and images stored as 32-bit integers, while none of its image points exceeds 65536.
The purpose of this function is to change the internal representation of such a \( f \) from using 32-bit to using 16-bit integers.

Note that the partial permutation \( f \) is changed in-place, and nothing is returned by this function.

Example

```gap
gap> f:=PartialPerm( [ 1, 2 ], [ 3, 4 ] );
[1,3]
> *PartialPerm( [ 3, 5 ], [ 3, 100000 ] );
gap> IsPPerm4Rep(f);
true
gap> TrimPartialPerm(f); f;
[1,3]
> IsPPerm4Rep(f);
false
```

### 54.6 Displaying partial permutations

It is possible to change the way that \texttt{GAP} displays partial permutations using the user preferences \texttt{PartialPermDisplayLimit} and \texttt{NotationForPartialPerms}; see Section \texttt{UserPreference} (3.2.3) for more information about user preferences.

If \( f \) is a partial permutation of rank \( r \) exceeding the value of the user preference \texttt{PartialPermDisplayLimit}, then \( f \) is displayed as:

Example

\(<\text{partial perm on } r \text{ pts with degree } m, \text{ codegree } n>\>

where the degree and codegree are \( m \) and \( n \), respectively. The idea is to abbreviate the display of partial permutations defined on many points. The default value for the \texttt{PartialPermDisplayLimit} is 100.

If the rank of \( f \) does not exceed the value of \texttt{PartialPermDisplayLimit}, then how \( f \) is displayed depends on the value of the user preference \texttt{NotationForPartialPerms} except in the case that \( f \) is the empty partial permutation or an identity partial permutation.

There are three possible values for \texttt{NotationForPartialPerms} user preference, which are described below.

**component**

Similar to permutations, and unlike transformations, partial permutations can be expressed as products of disjoint permutations and chains. A \texttt{chain} is a list \( c \) of some length \( n \) such that:

- \( c[1] \) is an element of the domain of \( f \) but not the image
- \( c[i]^f = c[i+1] \) for all \( i \) in the range from 1 to \( n-1 \).
- \( c[n] \) is in the image of \( f \) but not the domain.

In the display, permutations are displayed as they usually are in \texttt{GAP}, except that fixed points are displayed enclosed in round brackets, and chains are displayed enclosed in square brackets.

Example

```gap
gap> f := PartialPerm([ 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 16, 17, 18, 19 ],
> [ 3, 12, 14, 4, 11, 18, 17, 2, 9, 5, 15, 8, 20, 10, 19 ]);
[1,3,14][16,8,2,12,15](4)(5,11)[6,18,10,9][7,17,20](19)
```

This option is the most compact way to display a partial permutation and is the default value of the user preference \texttt{NotationForPartialPerms}. 

```
domainimage

With this option a partial permutation \( f \) is displayed in the format:
\[
\text{DomainOfPartialPerm}(f) \rightarrow \text{ImageListOfPartialPerm}(f).
\]

Example

\[
gap> f:=\text{PartialPerm}( [ 1, 2, 4, 5, 6, 7 ], [ 10, 1, 6, 5, 8, 7 ]); \\
[ 1, 2, 4, 5, 6, 7 ] \rightarrow [ 10, 1, 6, 5, 8, 7 ]
\]

input

With this option a partial permutation \( f \) is displayed as:
\[
\text{PartialPerm(DomainOfPartialPerm}(f), \text{ImageListOfPartialPerm}(f))
\]
which corresponds to the input (of the first type described in \text{PartialPerm}(54.2.1)).

Example

\[
gap> f:=\text{PartialPerm}( [ 1, 2, 3, 5, 6, 9, 10 ], \> [ 4, 7, 3, 8, 2, 1, 6 ] ); \\
\text{PartialPerm}( [ 1, 2, 3, 5, 6, 9, 10 ], [ 4, 7, 3, 8, 2, 1, 6 ])
\]

54.7 Semigroups and inverse semigroups of partial permutations

As mentioned at the start of the chapter, every inverse semigroup is isomorphic to a semigroup of partial permutations, and in this section we describe the functions in \text{GAP} specific to partial permutation semigroups. For more information about semigroups and inverse semigroups see Chapter 51.

The \text{Semigroups} package contains many additional functions and methods for computing with semigroups of partial permutations. In particular, \text{Semigroups} contains more efficient methods than those available in the \text{GAP} library (and in many cases more efficient than any other software) for creating semigroups of transformations, calculating their Green’s classes, size, elements, group of units,
minimal ideal, small generating sets, testing membership, finding the inverses of a regular element, factorizing elements over the generators, and more.

Since a partial permutation semigroup is also a partial permutation collection, there are special methods for \texttt{DomainOfPartialPermCollection (54.3.4)}, \texttt{ImageOfPartialPermCollection (54.3.5)}, \texttt{FixedPointsOfPartialPerm (54.3.8)}, \texttt{MovedPoints (54.3.9)}, \texttt{NrFixedPoints (54.3.10)}, \texttt{NrMovedPoints (54.3.11)}, \texttt{LargestMovedPoint (54.3.13)}, and \texttt{SmallestMovedPoint (54.3.12)} when applied to a partial permutation semigroup.

### 54.7.1 IsPartialPermSemigroup

\[
\text{\texttt{IsPartialPermSemigroup(obj)}}
\]

\[
\text{\texttt{IsPartialPermMonoid(obj)}}
\]

**Returns:** true or false.

A partial perm semigroup is simply a semigroup consisting of partial permutations, which may or may not be an inverse semigroup. An object \(\text{obj}\) in GAP is a partial perm semigroup if and only if it satisfies \texttt{IsSemigroup (51.1.1)} and \texttt{IsPartialPermCollection (54.1.2)}.

A partial perm monoid is a monoid consisting of partial permutations. An object in GAP is a partial perm monoid if it satisfies \texttt{IsMonoid (51.2.1)} and \texttt{IsPartialPermCollection (54.1.2)}.

Note that it is possible for a partial perm semigroup to have a multiplicative neutral element (i.e. an identity element) but not to satisfy \texttt{IsPartialPermMonoid}. For example,

\[
\begin{verbatim}
gap> f := PartialPerm([1, 2, 3, 6, 8, 10], [2, 6, 7, 9, 1, 5]);;
gap> S := Semigroup(f, One(f));
<commutative partial perm monoid of rank 9 with 1 generator>
gap> IsMonoid(S);
true
gap> IsPartialPermMonoid(S);
true
\end{verbatim}
\]

Note that unlike transformation semigroups, the \texttt{One (31.10.2)} of a partial permutation semigroup must coincide with the multiplicative neutral element, if either exists.

For more details see \texttt{IsMagmaWithOne (35.1.2)}.

### 54.7.2 DegreeOfPartialPermSemigroup

\[
\text{\texttt{DegreeOfPartialPermSemigroup(S)}}
\]

\[
\text{\texttt{CodegreeOfPartialPermSemigroup(S)}}
\]

\[
\text{\texttt{RankOfPartialPermSemigroup(S)}}
\]

**Returns:** A non-negative integer.

The degree of a partial permutation semigroup \(S\) is the largest degree of any partial permutation in \(S\).

The codegree of a partial permutation semigroup \(S\) is the largest positive integer in its image.

The rank of a partial permutation semigroup \(S\) is the number of points on which it acts.

\[
\begin{verbatim}
gap> S := Semigroup(PartialPerm([1, 5], [10000, 3]));
<commutative partial perm semigroup of rank 2 with 1 generator>
gap> DegreeOfPartialPermSemigroup(S);
5
gap> CodegreeOfPartialPermSemigroup(S);
\end{verbatim}
\]
54.7.3 SymmetricInverseSemigroup

▷ SymmetricInverseSemigroup(\(n\))
▷ SymmetricInverseMonoid(\(n\))

**Returns:** The symmetric inverse semigroup of degree \(n\).

If \(n\) is a non-negative integer, then SymmetricInverseSemigroup returns the inverse semigroup consisting of all partial permutations with degree and codegree at most \(n\). Note that \(n\) must be non-negative, but in particular, can equal 0.

The symmetric inverse semigroup has \(\sum_{r=0}^{n} \binom{n}{r}^2 \cdot r!\) elements and is generated by any set that of partial permutations that generate the symmetric group on \(n\) points and any partial permutation of rank \(n-1\).

SymmetricInverseMonoid is a synonym for SymmetricInverseSemigroup.

Example

```
gap> S := SymmetricInverseSemigroup(5);
<symmetric inverse monoid of degree 5>
gap> Size(S);
1546
gap> GeneratorsOfInverseMonoid(S);
[ (1,2,3,4,5), (1,2)(3)(4)(5), [5,4,3,2,1] ]
```

54.7.4 IsSymmetricInverseSemigroup

▷ IsSymmetricInverseSemigroup(\(S\))
▷ IsSymmetricInverseMonoid(\(S\))

**Returns:** true or false.

If the partial perm semigroup \(S\) of degree and codegree \(n\) equals the symmetric inverse semigroup on \(n\) points, then IsSymmetricInverseSemigroup return true and otherwise it returns false.

IsSymmetricInverseMonoid is a synonym of IsSymmetricInverseSemigroup. It is common in the literature for the symmetric inverse monoid to be referred to as the symmetric inverse semigroup.

Example

```
gap> S := Semigroup(AsPartialPerm((1, 3, 4, 2), 5), AsPartialPerm((1, 3, 5), 5),
> PartialPerm([1, 2, 3, 4]));
<partial perm semigroup of rank 5 with 3 generators>
gap> IsSymmetricInverseSemigroup(S);
true
gap> S;
<symmetric inverse monoid of degree 5>
```

54.7.5 NaturalPartialOrder

▷ NaturalPartialOrder(\(S\))
▷ ReverseNaturalPartialOrder(\(S\))

**Returns:** The natural partial order on an inverse semigroup.
The natural partial order \( \leq \) on an inverse semigroup \( S \) is defined by \( s \leq t \) if there exists an idempotent \( e \) in \( S \) such that \( s = et \). Hence if \( f \) and \( g \) are partial permutations, then \( f \leq g \) if and only if \( f \) is a restriction of \( g \); see RestrictedPartialPerm (54.2.3).

NaturalPartialOrder returns the natural partial order on the inverse semigroup of partial permutations \( S \) as a list of sets of positive integers where entry \( i \) in \( \text{NaturalPartialOrder}(S) \) is the set of positions in \( \text{Elements}(S) \) of elements which are less than \( \text{Elements}(S)[i] \). See also NaturalLeqPartialPerm (54.5.4).

ReverseNaturalPartialOrder returns the reverse of the natural partial order on the inverse semigroup of partial permutations \( S \) as a list of sets of positive integers where entry \( i \) in \( \text{ReverseNaturalPartialOrder}(S) \) is the set of positions in \( \text{Elements}(S) \) of elements which are greater than \( \text{Elements}(S)[i] \). See also NaturalLeqPartialPerm (54.5.4).

Example

\[
\text{gap> } S := \text{InverseSemigroup([ PartialPerm([ 1, 3 ], [ 1, 3 ]),} \\
\text{ PartialPerm([ 1, 2 ], [ 3, 2 ] ) ] });} \\
\text{<inverse partial perm semigroup of rank 3 with 2 generators>} \\
\text{gap> Size(S);} \\
11 \\
\text{gap> NaturalPartialOrder(S);} \\
[ [ 1 ], [ 1 ], [ 1 ], [ 1 ], [ 1, 2, 4 ], [ 1, 3, 4 ], [ 1 ], [ 1 ],} \\
[ 1, 4, 7 ], [ 1, 4, 8 ], [ 1, 2, 8 ] ] \\
\text{gap> NaturalLeqPartialPerm(Elements(S)[4], Elements(S)[10]);} \\
true \\
\text{gap> NaturalLeqPartialPerm(Elements(S)[4], Elements(S)[1]};} \\
false
\]

54.7.6 IsomorphismPartialPermSemigroup

▷ IsomorphismPartialPermSemigroup(S) \hspace{1cm} \text{(attribute)}
▷ IsomorphismPartialPermMonoid(S) \hspace{1cm} \text{(attribute)}

Returns: An isomorphism.

IsomorphismPartialPermSemigroup(S) returns an isomorphism from the inverse semigroup \( S \) to an inverse semigroup of partial permutations.

IsomorphismPartialPermMonoid(S) returns an isomorphism from the inverse semigroup \( S \) to an inverse monoid of partial permutations, if possible.

We only describe IsomorphismPartialPermMonoid, the corresponding statements for IsomorphismPartialPermSemigroup also hold.

Partial permutation semigroups

If \( S \) is a partial permutation semigroup that does not satisfy IsMonoid (51.2.1) but where MultiplicativeNeutralElement(S)<>fail, then IsomorphismPartialPermMonoid(S) returns an isomorphism from \( S \) to an inverse monoid of partial permutations.

Permutation groups

If \( S \) is a permutation group, then IsomorphismPartialPermMonoid returns an isomorphism from \( S \) to an inverse monoid of partial permutations on the set MovedPoints(S) obtained using AsPartialPerm (54.4.1). The inverse of this isomorphism is obtained using AsPermutation (42.5.6).
Transformation semigroups

If $S$ is a transformation semigroup which is mathematically a monoid but which does not necessarily belong to the category IsMonoid (51.2.1), then IsomorphismPartialPermMonoid returns an isomorphism from $S$ to an inverse monoid of partial permutations.

Example

```gap
gap> S := InverseSemigroup(
  > PartialPerm( [ 1, 2, 3, 4, 5 ], [ 4, 2, 3, 1, 5 ] ),
  > PartialPerm( [ 1, 2, 4, 5 ], [ 3, 1, 4, 2 ] ));
  
gap> IsMonoid(S);
false

gap> iso := IsomorphismPartialPermMonoid(S);
MappingByFunction( <inverse partial perm semigroup of size 508,
  rank 5 with 2 generators>, <inverse partial perm monoid of size 508,
  rank 5 with 2 generators>, function( object ) ... end, function( object ) ... end )

gap> Size(S);
508

gap> Size(Range(iso));
508

gap> G := Group((1,2)(3,8)(4,6)(5,7), (1,3,4,7)(2,5,6,8), (1,4)(2,6)(3,7)(5,8));

gap> IsomorphismPartialPermSemigroup(G);
MappingByFunction( Group([ (1,2)(3,8)(4,6)(5,7), (1,3,4,7)(2,5,6,8), (1,4)(2,6)(3,7)(5,8) ]), <partial perm group of rank 8 with 3 generators>, function( p ) ... end, <Attribute "AsPermutation"> )

gap> S := Semigroup(Transformation( [ 2, 5, 1, 7, 3, 7, 7 ] ),
  > Transformation( [ 3, 6, 5, 7, 2, 1, 7 ] ));

gap> iso := IsomorphismPartialPermMonoid(S);

gap> MultiplicativeNeutralElement(S) ^ iso;
<identity partial perm on [ 1, 2, 3, 4, 5, 6 ]>

gap> One(Range(iso));
<identity partial perm on [ 1, 2, 3, 4, 5, 6 ]>

gap> MovedPoints(Range(iso));
[ 1 .. 5 ]
```
Chapter 55

Additive Magmas

This chapter deals with domains that are closed under addition $+$, which are called near-additive magmas in GAP. Together with the domains closed under multiplication $\ast$ (see 35), they are the basic algebraic structures. In many cases, the addition is commutative (see IsAdditivelyCommutative (55.3.1)), the domain is called an additive magma then. Every module (see 57), vector space (see 61), ring (see 56), or field (see 58) is an additive magma. In the cases of all (near-)additive magma-with-zero or (near-)additive magma-with-inverses, additional additive structure is present (see 55.1).

55.1 (Near-)Additive Magma Categories

55.1.1 IsNearAdditiveMagma

$\triangleright$ IsNearAdditiveMagma(obj) (Category)

A near-additive magma in GAP is a domain $A$ with an associative but not necessarily commutative addition $+: A \times A \to A$.

55.1.2 IsNearAdditiveMagmaWithZero

$\triangleright$ IsNearAdditiveMagmaWithZero(obj) (Category)

A near-additive magma-with-zero in GAP is a near-additive magma $A$ with an operation $0 \ast$ (or Zero (31.10.3)) that yields the zero element of $A$.

So a near-additive magma-with-zero $A$ does always contain a unique additively neutral element $z$, i.e., $z + a = a = a + z$ holds for all $a \in A$ (see AdditiveNeutralElement (55.3.5)). This zero element $z$ can be computed with the operation Zero (31.10.3), by applying this function to $A$ or to any element $a$ in $A$. The zero element can be computed also as $0 \ast a$, for any $a$ in $A$.

Note that it may happen that a near-additive magma containing a zero does not lie in the category IsNearAdditiveMagmaWithZero (see 31.6).

55.1.3 IsNearAdditiveGroup

$\triangleright$ IsNearAdditiveGroup(obj) (Category)

$\triangleright$ IsNearAdditiveMagmaWithInverses(obj) (Category)
A near-additive group in GAP is a near-additive magma-with-zero $A$ with an operation $-1*: A \to A$ that maps each element $a$ of $A$ to its additive inverse $-1*a$ (or `AdditiveInverse( a )`), see `AdditiveInverse (31.10.9)`.

The addition $+$ of $A$ is assumed to be associative, so a near-additive group is not more than a near-additive magma-with-inverses. `IsNearAdditiveMagmaWithInverses` is just a synonym for `IsNearAdditiveGroup`, and can be used alternatively in all function names involving the string "NearAdditiveGroup".

Note that not every trivial near-additive magma is a near-additive magma-with-zero, but every trivial near-additive magma-with-zero is a near-additive group.

### 55.1.4 IsAdditiveMagma

\[ \text{IsAdditiveMagma}(\text{obj}) \]

\text{(Category)}

An additive magma in GAP is a domain $A$ with an associative and commutative addition $*: A \times A \to A$, see `IsNearAdditiveMagma (55.1.1)` and `IsAdditivelyCommutative (55.3.1)`.

### 55.1.5 IsAdditiveMagmaWithZero

\[ \text{IsAdditiveMagmaWithZero}(\text{obj}) \]

\text{(Category)}

An additive magma-with-zero in GAP is an additive magma $A$ (see `IsAdditiveMagma (55.1.4)`) with an operation $0*$ (or `Zero (31.10.3)`) that yields the zero of $A$.

So an additive magma-with-zero $A$ does always contain a unique additively neutral element $z$, i.e., $z + a = a = a + z$ holds for all $a \in A$ (see `AdditiveNeutralElement (55.3.5)`). This element $z$ can be computed with the operation `Zero (31.10.3)` as `Zero( A )`, and $z$ is also equal to `Zero( a )` and to $0*a$ for each element $a$ in $A$.

Note that it may happen that an additive magma containing a zero does not lie in the category `IsAdditiveMagmaWithZero` (see 31.6).

### 55.1.6 IsAdditiveGroup

\[ \text{IsAdditiveGroup}(\text{obj}) \]

\[ \text{IsAdditiveMagmaWithInverses}(\text{obj}) \]

\text{(Category)}

An additive group in GAP is an additive magma-with-zero $A$ with an operation $-1*: A \to A$ that maps each element $a$ of $A$ to its additive inverse $-1*a$ (or `AdditiveInverse( a )`), see `AdditiveInverse (31.10.9)`.

The addition $+$ of $A$ is assumed to be commutative and associative, so an additive group is not more than an additive magma-with-inverses. `IsAdditiveMagmaWithInverses` is just a synonym for `IsAdditiveGroup`, and can be used alternatively in all function names involving the string "AdditiveGroup".

Note that not every trivial additive magma is an additive magma-with-zero, but every trivial additive magma-with-zero is an additive group.
55.2 (Near-)Additive Magma Generation

This section describes functions that create additive magmas from generators (see NearAdditiveMagma (55.2.1), NearAdditiveMagmaWithZero (55.2.2), NearAdditiveGroup (55.2.3)), the underlying operations for which methods can be installed (see NearAdditiveMagmaByGenerators (55.2.4), NearAdditiveMagmaWithZeroByGenerators (55.2.5), NearAdditiveGroupByGenerators (55.2.6)) and functions for forming additive sub-magmas (see SubnearAdditiveMagma (55.2.7), SubnearAdditiveMagmaWithZero (55.2.8), SubnearAdditiveGroup (55.2.9)).

55.2.1 NearAdditiveMagma

```
MQQNearAdditiveMagma([Fam, ]gens) (function)
```

returns the (near-)additive magma A that is generated by the elements in the list gens, that is, the closure of gens under addition +. The family Fam of A can be entered as first argument; this is obligatory if gens is empty (and hence also A is empty).

55.2.2 NearAdditiveMagmaWithZero

```
MQQNearAdditiveMagmaWithZero([Fam, ]gens) (function)
```

returns the (near-)additive magma-with-zero A that is generated by the elements in the list gens, that is, the closure of gens under addition + and Zero (31.10.3). The family Fam of A can be entered as first argument; this is obligatory if gens is empty (and hence A is trivial).

55.2.3 NearAdditiveGroup

```
MQQNearAdditiveGroup([Fam, ]gens) (function)
```

returns the (near-)additive group A that is generated by the elements in the list gens, that is, the closure of gens under addition +, Zero (31.10.3), and AdditiveInverse (31.10.9). The family Fam of A can be entered as first argument; this is obligatory if gens is empty (and hence A is trivial).

55.2.4 NearAdditiveMagmaByGenerators

```
MQQNearAdditiveMagmaByGenerators([Fam, ]gens) (operation)
```

An underlying operation for NearAdditiveMagma (55.2.1).

55.2.5 NearAdditiveMagmaWithZeroByGenerators

```
MQQNearAdditiveMagmaWithZeroByGenerators([Fam, ]gens) (operation)
```

An underlying operation for NearAdditiveMagmaWithZero (55.2.2).
55.2.6 NearAdditiveGroupByGenerators

`NearAdditiveGroupByGenerators([Fam, ]gens)` (operation)

An underlying operation for NearAdditiveGroup (55.2.3).

55.2.7 SubnearAdditiveMagma

`SubnearAdditiveMagma(D, gens)` (function)
`SubadditiveMagma(D, gens)` (function)
`SubnearAdditiveMagmaNC(D, gens)` (function)
`SubadditiveMagmaNC(D, gens)` (function)

`SubnearAdditiveMagma` returns the near-additive magma generated by the elements in the list `gens`, with parent the domain `D`. `SubnearAdditiveMagmaNC` does the same, except that it does not check whether the elements of `gens` lie in `D`.

`SubadditiveMagma` and `SubadditiveMagmaNC` are just synonyms of these functions.

55.2.8 SubnearAdditiveMagmaWithZero

`SubnearAdditiveMagmaWithZero(D, gens)` (function)
`SubadditiveMagmaWithZero(D, gens)` (function)
`SubnearAdditiveMagmaWithZeroNC(D, gens)` (function)
`SubadditiveMagmaWithZeroNC(D, gens)` (function)

`SubnearAdditiveMagmaWithZero` returns the near-additive magma-with-zero generated by the elements in the list `gens`, with parent the domain `D`. `SubnearAdditiveMagmaWithZeroNC` does the same, except that it does not check whether the elements of `gens` lie in `D`.

`SubadditiveMagmaWithZero` and `SubadditiveMagmaWithZeroNC` are just synonyms of these functions.

55.2.9 SubnearAdditiveGroup

`SubnearAdditiveGroup(D, gens)` (function)
`SubadditiveGroup(D, gens)` (function)
`SubnearAdditiveGroupNC(D, gens)` (function)
`SubadditiveGroupNC(D, gens)` (function)

`SubnearAdditiveGroup` returns the near-additive group generated by the elements in the list `gens`, with parent the domain `D`. `SubadditiveGroupNC` does the same, except that it does not check whether the elements of `gens` lie in `D`.

`SubadditiveGroup` and `SubadditiveGroupNC` are just synonyms of these functions.
55.3 Attributes and Properties for (Near-)Additive Magmas

55.3.1 IsAdditivelyCommutative

\[ \text{IsAdditivelyCommutative}(A) \]

A near-additive magma \( A \) in GAP is \textit{additively commutative} if for all elements \( a, b \in A \) the equality \( a + b = b + a \) holds.

Note that the commutativity of the multiplication \( * \) in a multiplicative structure can be tested with \text{IsCommutative} (35.4.9).

55.3.2 GeneratorsOfNearAdditiveMagma

\[ \text{GeneratorsOfNearAdditiveMagma}(A) \]
\[ \text{GeneratorsOfAdditiveMagma}(A) \]

is a list of elements of the near-additive magma \( A \) that generates \( A \) as a near-additive magma, that is, the closure of this list under addition is \( A \).

55.3.3 GeneratorsOfNearAdditiveMagmaWithZero

\[ \text{GeneratorsOfNearAdditiveMagmaWithZero}(A) \]
\[ \text{GeneratorsOfAdditiveMagmaWithZero}(A) \]

is a list of elements of the near-additive magma-with-zero \( A \) that generates \( A \) as a near-additive magma-with-zero, that is, the closure of this list under addition and \text{Zero} (31.10.3) is \( A \).

55.3.4 GeneratorsOfNearAdditiveGroup

\[ \text{GeneratorsOfNearAdditiveGroup}(A) \]
\[ \text{GeneratorsOfAdditiveGroup}(A) \]

is a list of elements of the near-additive group \( A \) that generates \( A \) as a near-additive group, that is, the closure of this list under addition, taking the zero element, and taking additive inverses (see \text{AdditiveInverse} (31.10.9)) is \( A \).

55.3.5 AdditiveNeutralElement

\[ \text{AdditiveNeutralElement}(A) \]

returns the element \( z \) in the near-additive magma \( A \) with the property that \( z + a = a = a + z \) holds for all \( a \in A \), if such an element exists. Otherwise \text{fail} is returned.

A near-additive magma that is not a near-additive magma-with-zero can have an additive neutral element \( z \); in this case, \( z \) \textit{cannot} be obtained as \text{Zero}( \( A \) ) or as \( 0 * a \) for an element \( a \) in \( A \), see \text{Zero} (31.10.3).
55.3.6 TrivialSubnearAdditiveMagmaWithZero

\[ \text{TrivialSubnearAdditiveMagmaWithZero}(A) \]

is the additive magma-with-zero that has the zero of the near-additive magma-with-zero \( A \) as its only element.

55.4 Operations for (Near-)Additive Magmas

55.4.1 ClosureNearAdditiveGroup

\[ \text{ClosureNearAdditiveGroup}(A, a) \]
\[ \text{ClosureNearAdditiveGroup}(A, B) \]

returns the closure of the near-additive magma \( A \) with the element \( a \) or with the near-additive magma \( B \), w.r.t. addition, taking the zero element, and taking additive inverses.

55.4.2 ShowAdditionTable

\[ \text{ShowAdditionTable}(R) \]
\[ \text{ShowMultiplicationTable}(M) \]

For a structure \( R \) with an addition given by +, respectively a structure \( M \) with a multiplication given by *, this command displays the addition (multiplication) table of the structure in a pretty way.

```
gap> ShowAdditionTable(GF(4));
+
<table>
<thead>
<tr>
<th></th>
<th>0*Z(2)</th>
<th>Z(2)^0</th>
<th>Z(2^2)</th>
<th>Z(2^2)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0*Z(2)</td>
<td>0*Z(2)</td>
<td>Z(2)^0</td>
<td>Z(2^2)</td>
<td>Z(2^2)^2</td>
</tr>
<tr>
<td>Z(2)^0</td>
<td>Z(2)^0</td>
<td>0*Z(2)</td>
<td>Z(2^2)^2</td>
<td>Z(2^2)</td>
</tr>
<tr>
<td>Z(2^2)</td>
<td>Z(2^2)</td>
<td>0*Z(2)</td>
<td>Z(2^2)^2</td>
<td>Z(2)^0</td>
</tr>
<tr>
<td>Z(2^2)^2</td>
<td>Z(2^2)^2</td>
<td>Z(2)^0</td>
<td>0*Z(2)</td>
<td>Z(2^2)</td>
</tr>
</tbody>
</table>
```

```
gap> ShowMultiplicationTable(GF(4));
*
<table>
<thead>
<tr>
<th></th>
<th>0*Z(2)</th>
<th>Z(2)^0</th>
<th>Z(2^2)</th>
<th>Z(2^2)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0*Z(2)</td>
<td>0*Z(2)</td>
<td>0*Z(2)</td>
<td>0*Z(2)</td>
<td>0*Z(2)</td>
</tr>
<tr>
<td>Z(2)^0</td>
<td>0*Z(2)</td>
<td>Z(2)^0</td>
<td>Z(2^2)^2</td>
<td>Z(2^2)</td>
</tr>
<tr>
<td>Z(2^2)</td>
<td>0*Z(2)</td>
<td>Z(2^2)</td>
<td>Z(2^2)^2</td>
<td>Z(2)^0</td>
</tr>
<tr>
<td>Z(2^2)^2</td>
<td>0*Z(2)</td>
<td>Z(2^2)^2</td>
<td>Z(2)^0</td>
<td>Z(2^2)</td>
</tr>
</tbody>
</table>
```
Chapter 56

Rings

This chapter deals with domains that are additive groups (see IsAdditiveGroup (55.1.6) closed under multiplication \(*\). Such a domain, if \(*\) and + are distributive, is called a ring in GAP. Each division ring, field (see 58), or algebra (see 62) is a ring. Important examples of rings are the integers (see 14) and matrix rings.

In the case of a ring-with-one, additional multiplicative structure is present, see IsRingWithOne (56.3.1). There is a little support in GAP for rings that have no additional structure: it is possible to perform some computations for small finite rings; infinite rings are handled by GAP in an acceptable way in the case that they are algebras.

Also, the SONATA package provides support for near-rings, and a related functionality for multiplicative semigroups of near-rings is available in the Smallsemi package.

Several functions for ring elements, such as IsPrime (56.5.8) and Factors (56.5.9), are defined only relative to a ring \(R\), which can be entered as an optional argument; if \(R\) is omitted then a default ring is formed from the ring elements given as arguments, see DefaultRing (56.1.3).

56.1 Generating Rings

56.1.1 IsRing

\[\text{IsRing}(R)\] (filter)

A ring in GAP is an additive group (see IsAdditiveGroup (55.1.6)) that is also a magma (see IsMagma (35.1.1)), such that addition + and multiplication * are distributive, see IsDistributive (56.4.5).

The multiplication need not be associative (see IsAssociative (35.4.7)). For example, a Lie algebra (see 64) is regarded as a ring in GAP.

56.1.2 Ring

\[\text{Ring}(r, s, \ldots)\] (function)
\[\text{Ring}(\text{coll})\] (function)

In the first form \text{Ring} returns the smallest ring that contains all the elements \(r, s, \ldots\). In the second form \text{Ring} returns the smallest ring that contains all the elements in the collection \text{coll}. If any element is not an element of a ring or if the elements lie in no common ring an error is raised.
Ring differs from DefaultRing (56.1.3) in that it returns the smallest ring in which the elements lie, while DefaultRing (56.1.3) may return a larger ring if that makes sense.

```
gap> Ring( 2, E(4) );
<ring with 2 generators>
```

### 56.1.3 DefaultRing

- DefaultRing(r, s, ...)
- DefaultRing(coll)

In the first form DefaultRing returns a ring that contains all the elements r, s, ... etc. In the second form DefaultRing returns a ring that contains all the elements in the collection coll. If any element is not an element of a ring or if the elements lie in no common ring an error is raised.

The ring returned by DefaultRing need not be the smallest ring in which the elements lie. For example for elements from cyclotomic fields, DefaultRing may return the ring of integers of the smallest cyclotomic field in which the elements lie, which need not be the smallest ring overall, because the elements may in fact lie in a smaller number field which is itself not a cyclotomic field.

(For the exact definition of the default ring of a certain type of elements, look at the corresponding method installation.)

DefaultRing is used by ring functions such as Quotient (56.1.9), IsPrime (56.5.8), Factors (56.5.9), or Gcd (56.7.1) if no explicit ring is given.

```
gap> DefaultRing( 2, E(4) );
GaussianIntegers
```

### 56.1.4 RingByGenerators

- RingByGenerators(C)

RingByGenerators returns the ring generated by the elements in the collection C, i.e., the closure of C under addition, multiplication, and taking additive inverses.

```
gap> RingByGenerators([ 2, E(4) ]);  # Example
<ring with 2 generators>
```

### 56.1.5 DefaultRingByGenerators

- DefaultRingByGenerators(coll)

For a collection coll, returns a default ring in which coll is contained.

```
gap> DefaultRingByGenerators([ 2, E(4) ]);  # Example
GaussianIntegers
```
56.1.6 GeneratorsOfRing

GeneratorsOfRing returns a list of elements such that the ring \( R \) is the closure of these elements under addition, multiplication, and taking additive inverses.

```
gap> R := Ring( 2, 1/2 );
<ring with 2 generators>
gap> GeneratorsOfRing( R );
[ 2, 1/2 ]
```

56.1.7 Subring

returns the ring with parent \( R \) generated by the elements in \( gens \). When the second form, SubringNC is used, it is not checked whether all elements in \( gens \) lie in \( R \).

```
gap> R := Integers;
Integers
gap> S := Subring( R, [ 4, 6 ] );
<ring with 1 generators>
gap> Parent( S );
Integers
```

56.1.8 ClosureRing

For a ring \( R \) and either an element \( r \) of its elements family or a ring \( S \), ClosureRing returns the ring generated by both arguments.

```
gap> ClosureRing( Integers, E(4) );
<ring-with-one, with 2 generators>
```

56.1.9 Quotient

Quotient returns a (right) quotient of the two ring elements \( r \) and \( s \) in the ring \( R \), if given, and otherwise in their default ring (see DefaultRing (56.1.3)). More specifically, it returns a ring element \( q \) such that \( r = q * s \) holds, or fail if no such elements exists in the respective ring.

The result may not be unique if the ring contains zero divisors.

(To perform the division in the quotient field of a ring, use the quotient operator /.)

56.2  Ideals of Rings

A left ideal in a ring $R$ is a subring of $R$ that is closed under multiplication with elements of $R$ from the left.

A right ideal in a ring $R$ is a subring of $R$ that is closed under multiplication with elements of $R$ from the right.

A two-sided ideal or simply ideal in a ring $R$ is both a left ideal and a right ideal in $R$.

So being a (left/right/two-sided) ideal is not a property of a domain but refers to the acting ring(s). Hence we must ask, e.g., `IsIdeal( R, I )` if we want to know whether the ring $I$ is an ideal in the ring $R$. The property `IsTwoSidedIdealInParent (56.2.3)` can be used to store whether a ring is an ideal in its parent.

(Whenever the term "Ideal" occurs in an identifier without a specifying prefix "Left" or "Right", this means the same as "TwoSidedIdeal". Conversely, any occurrence of "TwoSidedIdeal" can be substituted by "Ideal".)

For any of the above kinds of ideals, there is a notion of generators, namely `GeneratorsOfLeftIdeal (56.2.8)`, `GeneratorsOfRightIdeal (56.2.9)`, and `GeneratorsOfTwoSidedIdeal (56.2.7)`. The acting rings can be accessed as `LeftActingRingOfIdeal (56.2.10)` and `RightActingRingOfIdeal (56.2.10)`, respectively. Note that ideals are detected from known values of these attributes, especially it is assumed that whenever a domain has both a left and a right acting ring then these two are equal.

Note that we cannot use `LeftActingDomain (57.1.11)` and `RightActingDomain` here, since ideals in algebras are themselves vector spaces, and such a space can of course also be a module for an action from the right. In order to make the usual vector space functionality automatically available for ideals, we have to distinguish the left and right module structure from the additional closure properties of the ideal.

Further note that the attributes denoting ideal generators and acting ring are used to create ideals if this is explicitly wanted, but the ideal relation in the sense of `IsTwoSidedIdeal (56.2.3)` is of course independent of the presence of the attribute values.

Ideals are constructed with `LeftIdeal (56.2.1)`, `RightIdeal (56.2.1)`, `TwoSidedIdeal (56.2.1)`. Principal ideals of the form $x \cdot R$, $R \cdot x$, $R \cdot x \cdot R$ can also be constructed with a simple multiplication.

Currently many methods for dealing with ideals need linear algebra to work, so they are mainly applicable to ideals in algebras.

### 56.2.1 TwoSidedIdeal

- `TwoSidedIdeal(R, gens [, "basis"] )` (function)
- `Ideal(R, gens [, "basis"] )` (function)
- `LeftIdeal(R, gens [, "basis"] )` (function)
- `RightIdeal(R, gens [, "basis"] )` (function)
Let $R$ be a ring, and $\text{gens}$ a list of collection of elements in $R$. \text{TwoSidedIdeal}, \text{LeftIdeal}, and \text{RightIdeal} return the two-sided, left, or right ideal, respectively, $I$ in $R$ that is generated by $\text{gens}$. The ring $R$ can be accessed as \text{LeftActingRingOfIdeal} (56.2.10) or \text{RightActingRingOfIdeal} (56.2.10) (or both) of $I$.

If $R$ is a left $F$-module then also $I$ is a left $F$-module, in particular the \text{LeftActingDomain} (57.1.11) values of $R$ and $I$ are equal.

If the optional argument "basis" is given then $\text{gens}$ are assumed to be a list of basis vectors of $I$ viewed as a free $F$-module. (This is mainly applicable to ideals in algebras.) In this case, it is not checked whether $\text{gens}$ really is linearly independent and whether $\text{gens}$ is a subset of $R$.

\text{Ideal} is simply a synonym of \text{TwoSidedIdeal}.

\begin{verbatim}
gap> R := Integers;;
gap> I := Ideal( R, [ 2 ] );
<two-sided ideal in Integers, (1 generators)>
\end{verbatim}

56.2.2 \textbf{TwoSidedIdealNC}

- \text{TwoSidedIdealNC($R$, $\text{gens}$[, "basis"])}
- \text{IdealNC($R$, $\text{gens}$[, "basis"])}
- \text{LeftIdealNC($R$, $\text{gens}$[, "basis"])}
- \text{RightIdealNC($R$, $\text{gens}$[, "basis"])}

The effects of \text{TwoSidedIdealNC}, \text{LeftIdealNC}, and \text{RightIdealNC} are the same as \text{TwoSidedIdeal} (56.2.1), \text{LeftIdeal} (56.2.1), and \text{RightIdeal} (56.2.1), respectively, but they do not check whether all entries of $\text{gens}$ lie in $R$.

56.2.3 \textbf{IsTwoSidedIdeal}

- \text{IsTwoSidedIdeal($R$, $I$)}
- \text{IsLeftIdeal($R$, $I$)}
- \text{IsRightIdeal($R$, $I$)}
- \text{IsTwoSidedIdealInParent($I$)}
- \text{IsLeftIdealInParent($I$)}
- \text{IsRightIdealInParent($I$)}

The properties \text{IsTwoSidedIdealInParent} etc., are attributes of the ideal, and once known they are stored in the ideal.

\begin{verbatim}
gap> A := FullMatrixAlgebra( Rationals, 3 );
( Rationals^[ 3, 3 ] )
gap> I := Ideal( A, [ Random( A ) ] );
<two-sided ideal in ( Rationals^[ 3, 3 ] ), (1 generators)>
gap> IsTwoSidedIdeal( A, I );
true
\end{verbatim}
56.2.4 TwoSidedIdealByGenerators

\[ \text{TwoSidedIdealByGenerators}(\text{R, gens}) \] (operation)
\[ \text{IdealByGenerators}(\text{R, gens}) \] (operation)

TwoSidedIdealByGenerators returns the ring that is generated by the elements of the collection gens under addition, multiplication, and multiplication with elements of the ring R from the left and from the right.

R can be accessed by \text{LeftActingRingOfIdeal} (56.2.10) or \text{RightActingRingOfIdeal} (56.2.10), gens can be accessed by \text{GeneratorsOfTwoSidedIdeal} (56.2.7).

56.2.5 LeftIdealBy Generators

\[ \text{LeftIdealByGenerators}(\text{R, gens}) \] (operation)

LeftIdealByGenerators returns the ring that is generated by the elements of the collection gens under addition, multiplication, and multiplication with elements of the ring R from the left.

R can be accessed by \text{LeftActingRingOfIdeal} (56.2.10), gens can be accessed by \text{GeneratorsOfLeftIdeal} (56.2.8).

56.2.6 RightIdealByGenerators

\[ \text{RightIdealByGenerators}(\text{R, gens}) \] (operation)

RightIdealByGenerators returns the ring that is generated by the elements of the collection gens under addition, multiplication, and multiplication with elements of the ring R from the right.

R can be accessed by \text{RightActingRingOfIdeal} (56.2.10), gens can be accessed by \text{GeneratorsOfRightIdeal} (56.2.9).

56.2.7 GeneratorsOfTwo Sided Ideal

\[ \text{GeneratorsOfTwoSidedIdeal}(\text{I}) \] (attribute)
\[ \text{GeneratorsOfIdeal}(\text{I}) \] (attribute)

is a list of generators for the ideal I, with respect to the action of the rings that are stored as the values of \text{LeftActingRingOfIdeal} (56.2.10) and \text{RightActingRingOfIdeal} (56.2.10), from the left and from the right, respectively.

Example
\begin{verbatim}
gap> A:= FullMatrixAlgebra( Rationals, 3 );;
gap> I:= Ideal( A, [ One( A ) ] );;
gap> GeneratorsOfIdeal( I );
[ [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ] ]
\end{verbatim}

56.2.8 GeneratorsOfLeftIdeal

\[ \text{GeneratorsOfLeftIdeal}(\text{I}) \] (attribute)
is a list of generators for the left ideal $I$, with respect to the action from the left of the ring that is stored as the value of $\text{LeftActingRingOfIdeal}$ (56.2.10).

### 56.2.9 GeneratorsOfRightIdeal

$$\text{GeneratorsOfRightIdeal}(I)$$

is a list of generators for the right ideal $I$, with respect to the action from the right of the ring that is stored as the value of $\text{RightActingRingOfIdeal}$ (56.2.10).

### 56.2.10 LeftActingRingOfIdeal

$$\text{LeftActingRingOfIdeal}(I)$$

$$\text{RightActingRingOfIdeal}(I)$$

returns the left (resp. right) acting ring of an ideal $I$.

### 56.2.11 AsLeftIdeal

$$\text{AsLeftIdeal}(R, S)$$

$$\text{AsRightIdeal}(R, S)$$

$$\text{AsTwoSidedIdeal}(R, S)$$

Let $S$ be a subring of the ring $R$.
If $S$ is a left ideal in $R$ then $\text{AsLeftIdeal}$ returns this left ideal, otherwise $\text{fail}$ is returned.
If $S$ is a right ideal in $R$ then $\text{AsRightIdeal}$ returns this right ideal, otherwise $\text{fail}$ is returned.
If $S$ is a two-sided ideal in $R$ then $\text{AsTwoSidedIdeal}$ returns this two-sided ideal, otherwise $\text{fail}$ is returned.

#### Example

```gap
gap> A:= FullMatrixAlgebra( Rationals, 3 );;
gap> B:= DirectSumOfAlgebras( A, A );
<algebra over Rationals, with 6 generators>
gap> C:= Subalgebra( B, Basis( B ){[1..9]} );
<algebra over Rationals, with 9 generators>
gap> I:= AsTwoSidedIdeal( B, C );
<two-sided ideal in <algebra of dimension 18 over Rationals>,
(9 generators>)
```

### 56.3 Rings With One

#### 56.3.1 IsRingWithOne

$$\text{IsRingWithOne}(R)$$

A ring-with-one in $\text{GAP}$ is a ring (see $\text{IsRing}$ (56.1.1)) that is also a magma-with-one (see $\text{IsMagmaWithOne}$ (35.1.2)).

Note that the identity and the zero of a ring-with-one need not be distinct. This means that a ring that consists only of its zero element can be regarded as a ring-with-one.
This is especially useful in the case of finitely presented rings, in the sense that each factor of a ring-with-one is again a ring-with-one.

### 56.3.2 RingWithOne

- **RingWithOne(r, s, ...)**  
  (function)
- **RingWithOne(coll)**  
  (function)

In the first form `RingWithOne` returns the smallest ring with one that contains all the elements `r, s, ...` In the second form `RingWithOne` returns the smallest ring with one that contains all the elements in the collection `coll`. If any element is not an element of a ring or if the elements lie in no common ring an error is raised.

```
gap> RingWithOne( [ 4, 6 ] );
Integers
```

### 56.3.3 RingWithOneByGenerators

- **RingWithOneByGenerators(coll)**  
  (operation)

`RingWithOneByGenerators` returns the ring-with-one generated by the elements in the collection `coll`, i.e., the closure of `coll` under addition, multiplication, taking additive inverses, and taking the identity of an element.

### 56.3.4 GeneratorsOfRingWithOne

- **GeneratorsOfRingWithOne(R)**  
  (attribute)

`GeneratorsOfRingWithOne` returns a list of elements such that the ring `R` is the closure of these elements under addition, multiplication, taking additive inverses, and taking the identity element `One(R)`.

```
gap> R:= RingWithOne( [ 4, 6 ] );
Integers
gap> GeneratorsOfRingWithOne( R );
[ 1 ]
```

### 56.3.5 SubringWithOne

- **SubringWithOne(R, gens)**  
  (function)
- **SubringWithOneNC(R, gens)**  
  (function)

returns the ring with one with parent `R` generated by the elements in `gens`. When the second form, `SubringWithOneNC` is used, it is *not* checked whether all elements in `gens` lie in `R`. 
56.4 Properties of Rings

56.4.1 IsIntegralRing

A ring-with-one $R$ is integral if it is commutative, contains no nontrivial zero divisors, and if its identity is distinct from its zero.

Example

```gap
gap> R := SubringWithOne( Integers, [ 4, 6 ] );
Integers
gap> Parent( R );
Integers
```

56.4.2 IsUniqueFactorizationRing

A ring $R$ is called a unique factorization ring if it is an integral ring (see IsIntegralRing (56.4.1)), and every nonzero element has a unique factorization into irreducible elements, i.e., a unique representation as product of irreducibles (see IsIrreducibleRingElement (56.5.7)). Unique in this context means unique up to permutations of the factors and up to multiplication of the factors by units (see Units (56.5.2)).

Mathematically, a field should therefore also be a unique factorization ring, since every nonzero element is a unit. In GAP, however, at least at present fields do not lie in the filter IsUniqueFactorizationRing, since operations such as Factors (56.5.9), Gcd (56.7.1), StandardAssociate (56.5.5) and so on do not apply to fields (the results would be trivial, and not especially useful) and methods which require their arguments to lie in IsUniqueFactorizationRing expect these operations to work.

(No replacement that we cannot install a subset maintained method for this filter since the factorization of an element needs not exist in a subring. As an example, consider the subring $4\mathbb{N} + 1$ of the ring $4\mathbb{Z} + 1$; in the subring, the element $3 \cdot 3 \cdot 11 \cdot 7$ has the two factorizations $33 \cdot 21 = 9 \cdot 77$, but in the large ring there is the unique factorization $(-3) \cdot (-3) \cdot (-11) \cdot (-7)$, and it is easy to see that every element in $4\mathbb{Z} + 1$ has a unique factorization.)

Example

```gap
gap> IsUniqueFactorizationRing( PolynomialRing( Rationals, 1 ) );
true
```

56.4.3 IsLDistributive

A ring $R$ is left distributive if it is commutative, contains no zero divisors, and if its identity is distinct from its zero.

Example

```gap
gap> IsLdistributive( [ 4, 6 ] );
```
is true if the relation \( a \ast (b + c) = (a \ast b) + (a \ast c) \) holds for all elements \( a, b, c \) in the collection \( C \), and false otherwise.

### 56.4.4 IsRDistributive

\[\text{IsRDistributive}(C)\]  

is true if the relation \( (a + b) \ast c = (a \ast c) + (b \ast c) \) holds for all elements \( a, b, c \) in the collection \( C \), and false otherwise.

### 56.4.5 IsDistributive

\[\text{IsDistributive}(C)\]  

is true if the collection \( C \) is both left and right distributive (see \text{IsLDistributive} (56.4.3), \text{IsRDistributive} (56.4.4)), and false otherwise.

#### Example

\[\text{gap> IsDistributive( Integers );}\]  
\[\text{true}\]

### 56.4.6 IsAnticommutative

\[\text{IsAnticommutative}(R)\]  

is true if the relation \( a \ast b = -b \ast a \) holds for all elements \( a, b \) in the ring \( R \), and false otherwise.

### 56.4.7 IsZeroSquaredRing

\[\text{IsZeroSquaredRing}(R)\]  

is true if \( a \ast a \) is the zero element of the ring \( R \) for all \( a \) in \( R \), and false otherwise.

### 56.4.8 IsJacobianRing

\[\text{IsJacobianRing}(R)\]  

is true if the Jacobi identity holds in the ring \( R \), and false otherwise. The Jacobi identity means that \( x \ast (y \ast z) + z \ast (x \ast y) + y \ast (z \ast x) \) is the zero element of \( R \), for all elements \( x, y, z \) in \( R \).

#### Example

\[\text{gap> L:= FullMatrixLieAlgebra( GF( 5 ), 7 );}\]  
\[<\text{Lie algebra over GF(5), with 13 generators}>\]  
\[\text{gap> IsJacobianRing( L );}\]  
\[\text{true}\]
56.5 Units and Factorizations

56.5.1 IsUnit

\( \text{IsUnit}( [R, \]r) \) (operation)

IsUnit returns true if \( r \) is a unit in the ring \( R \), if given, and otherwise in its default ring (see DefaultRing (56.1.3)). If \( r \) is not a unit then false is returned.

An element \( r \) is called a unit in a ring \( R \), if \( r \) has an inverse in \( R \). IsUnit may call Quotient (56.1.9).

56.5.2 Units

\( \text{Units}( R ) \) (attribute)

Units returns the group of units of the ring \( R \). This may either be returned as a list or as a group.

An element \( r \) is called a unit of a ring \( R \) if \( r \) has an inverse in \( R \). It is easy to see that the set of units forms a multiplicative group.

Example

\begin{verbatim}
gap> Units( GaussianIntegers );
[ -1, 1, -E(4), E(4) ]
gap> Units( GF( 16 ) );
<group of size 15 with 1 generators>
\end{verbatim}

56.5.3 IsAssociated

\( \text{IsAssociated}( [R, \]r, s) \) (operation)

IsAssociated returns true if the two ring elements \( r \) and \( s \) are associated in the ring \( R \), if given, and otherwise in their default ring (see DefaultRing (56.1.3)). If the two elements are not associated then false is returned.

Two elements \( r \) and \( s \) of a ring \( R \) are called associated if there is a unit \( u \) of \( R \) such that \( r \ u = s \).

56.5.4 Associates

\( \text{Associates}( [R, \]r) \) (operation)

Associates returns the set of associates of \( r \) in the ring \( R \), if given, and otherwise in its default ring (see DefaultRing (56.1.3)).

Two elements \( r \) and \( s \) of a ring \( R \) are called associated if there is a unit \( u \) of \( R \) such that \( r \ u = s \).

Example

\begin{verbatim}
gap> Associates( Integers, 2 );
[ -2, 2 ]
gap> Associates( GaussianIntegers, 2 );
[ -2, 2, -2*E(4), 2*E(4) ]
\end{verbatim}
56.5.5 StandardAssociate

\[
\text{StandardAssociate}([R, ]r) \quad \text{(operation)}
\]

StandardAssociate returns the standard associate of the ring element \( r \) in the ring \( R \), if given, and otherwise in its default ring (see DefaultRing (56.1.3)).

The standard associate of a ring element \( r \) of \( R \) is an associated element of \( r \) which is, in a ring dependent way, distinguished among the set of associates of \( r \). For example, in the ring of integers the standard associate is the absolute value.

\[\begin{align*}
gap &> \ x:= \text{Indeterminate}( \text{Rationals}, \text{"x"});; \\
gap &> \ \text{StandardAssociate}( -x^2-x+1 ); \\
&> x^2+x-1
\end{align*}\]

56.5.6 StandardAssociateUnit

\[
\text{StandardAssociateUnit}([R, ]r) \quad \text{(operation)}
\]

StandardAssociateUnit returns a unit in the ring \( R \) such that the ring element \( r \) times this unit equals the standard associate of \( r \) in \( R \).

If \( R \) is not given, the default ring of \( r \) is used instead. (see DefaultRing (56.1.3)).

\[\begin{align*}
gap &> \ y:= \text{Indeterminate}( \text{Rationals}, \text{"y"});; \\
gap &> \ r:= -y^2-y+1; \\
&> -y^2-y+1 \\
gap &> \ \text{StandardAssociateUnit}( \ r ); \\
&> -1 \\
gap &> \ \text{StandardAssociateUnit}( \ r \ ) \ast r = \text{StandardAssociate}( \ r \ ); \\
&> \text{true}
\end{align*}\]

56.5.7 IsIrreducibleRingElement

\[
\text{IsIrreducibleRingElement}([R, ]r) \quad \text{(operation)}
\]

IsIrreducibleRingElement returns true if the ring element \( r \) is irreducible in the ring \( R \), if given, and otherwise in its default ring (see DefaultRing (56.1.3)). If \( r \) is not irreducible then false is returned.

An element \( r \) of a ring \( R \) is called irreducible if \( r \) is not a unit in \( R \) and if there is no nontrivial factorization of \( r \) in \( R \), i.e., if there is no representation of \( r \) as product \( st \) such that neither \( s \) nor \( t \) is a unit (see IsUnit (56.5.1)). Each prime element (see IsPrime (56.5.8)) is irreducible.

\[\begin{align*}
gap &> \ \text{IsIrreducibleRingElement}( \ \text{Integers}, \ 2 ); \\
&> \text{true}
\end{align*}\]

56.5.8 IsPrime

\[
\text{IsPrime}([R, ]r) \quad \text{(operation)}
\]
IsPrime returns true if the ring element \( r \) is a prime in the ring \( R \), if given, and otherwise in its default ring (see DefaultRing (56.1.3)). If \( r \) is not a prime then false is returned.

An element \( r \) of a ring \( R \) is called prime if for each pair \( s \) and \( t \) such that \( r \) divides \( st \) the element \( r \) divides either \( s \) or \( t \). Note that there are rings where not every irreducible element (see IsIrreducibleRingElement (56.5.7)) is a prime.

56.5.9 Factors

\[ \text{Factors}( [R, ]r) \]

Factors returns the factorization of the ring element \( r \) in the ring \( R \), if given, and otherwise in its default ring (see DefaultRing (56.1.3)). The factorization is returned as a list of primes (see IsPrime (56.5.8)). Each element in the list is a standard associate (see StandardAssociate (56.5.5)) except the first one, which is multiplied by a unit as necessary to have \( \text{Product}( \text{Factors}( R, r )) = r \). This list is usually also sorted, thus smallest prime factors come first. If \( r \) is a unit or zero, \( \text{Factors}( R, r ) = [ r ] \).

Example

\[
gap> x:=\text{Indeterminate}( \text{GF}(2), "x" );
gap> \text{pol}: = x^2+x+1;
x^2+x+Z(2)^0
gap> \text{Factors}( \text{pol} );
[ x^2+x+Z(2)^0 ]
gap> \text{Factors}( \text{PolynomialRing}( \text{GF}(4) ), \text{pol} );
[ x+Z(2^2), x+Z(2^2)^2 ]
\]

56.5.10 PadicValuation

\[ \text{PadicValuation}( r, p ) \]

PadicValuation is the operation to compute the \( p \)-adic valuation of a ring element \( r \).

56.6 Euclidean Rings

56.6.1 IsEuclideanRing

\[ \text{IsEuclideanRing}( R ) \]

A ring \( R \) is called a Euclidean ring if it is an integral ring and there exists a function \( \delta \), called the Euclidean degree, from \( R - \{0_R\} \) into a well-ordered set (such as the the nonnegative integers), such that for every pair \( r \in R \) and \( s \in R - \{0_R\} \) there exists an element \( q \) such that either \( r - qs = 0_R \) or \( \delta(r - qs) < \delta(s) \). In GAP the Euclidean degree \( \delta \) is implicitly built into a ring and cannot be changed. The existence of this division with remainder implies that the Euclidean algorithm can be applied to compute a greatest common divisor of two elements, which in turn implies that \( R \) is a unique factorization ring.

Example

\[
gap> \text{IsEuclideanRing}( \text{GaussianIntegers} ) ;
true
\]
56.6.2 EuclideanDegree

\[ \text{EuclideanDegree}( \text{[R, Jr]} ) \] (operation)

EuclideanDegree returns the Euclidean degree of the ring element \( r \) in the ring \( R \), if given, and otherwise in its default ring (see DefaultRing (56.1.3)).

The ring \( R \) must be a Euclidean ring (see IsEuclideanRing (56.6.1)).

Example

\[ \text{gap> EuclideanDegree( GaussianIntegers, 3 );} \]
\[ 9 \]

56.6.3 EuclideanQuotient

\[ \text{EuclideanQuotient}( \text{[R, Jr, m]} ) \] (operation)

EuclideanQuotient returns the Euclidean quotient of the ring elements \( r \) and \( m \) in the ring \( R \), if given, and otherwise in their default ring (see DefaultRing (56.1.3)).

The ring \( R \) must be a Euclidean ring (see IsEuclideanRing (56.6.1)), otherwise an error is signalled.

Example

\[ \text{gap> EuclideanQuotient( 8, 3 );} \]
\[ 2 \]

56.6.4 EuclideanRemainder

\[ \text{EuclideanRemainder}( \text{[R, Jr, m]} ) \] (operation)

EuclideanRemainder returns the Euclidean remainder of the ring element \( r \) modulo the ring element \( m \) in the ring \( R \), if given, and otherwise in their default ring (see DefaultRing (56.1.3)).

The ring \( R \) must be a Euclidean ring (see IsEuclideanRing (56.6.1)), otherwise an error is signalled.

Example

\[ \text{gap> EuclideanRemainder( 8, 3 );} \]
\[ 2 \]

56.6.5 QuotientRemainder

\[ \text{QuotientRemainder}( \text{[R, Jr, m]} ) \] (operation)

QuotientRemainder returns the Euclidean quotient and the Euclidean remainder of the ring elements \( r \) and \( m \) in the ring \( R \), if given, and otherwise in their default ring (see DefaultRing (56.1.3)). The result is a pair of ring elements.

The ring \( R \) must be a Euclidean ring (see IsEuclideanRing (56.6.1)), otherwise an error is signalled.

Example

\[ \text{gap> QuotientRemainder( GaussianIntegers, 8, 3 );} \]
\[ [ 3, -1 ] \]
56.7  Gcd and Lcm

56.7.1  Gcd

\[ \text{Gcd}( [R, ]r_1, r_2, \ldots) \]  
\[ \text{Gcd}( [R, ]\text{list}) \]

Gcd returns the greatest common divisor of the ring elements \( r_1, r_2, \ldots \) resp. of the ring elements in the list \( \text{list} \) in the ring \( R \), if given, and otherwise in their default ring, see DefaultRing (56.1.3).

Gcd returns the standard associate (see StandardAssociate (56.5.5)) of the greatest common divisors.

A divisor of an element \( r \) in the ring \( R \) is an element \( d \in R \) such that \( r \) is a multiple of \( d \). A common divisor of the elements \( r_1, r_2, \ldots \) in the ring \( R \) is an element \( d \in R \) which is a divisor of each \( r_1, r_2, \ldots \). A greatest common divisor \( d \) in addition has the property that every other common divisor of \( r_1, r_2, \ldots \) is a divisor of \( d \).

Note that this in particular implies the following: For the zero element \( z \) of \( R \), we have \( \text{Gcd}( r, z ) = \text{Gcd}( z, r ) = \text{StandardAssociate}( r ) \) and \( \text{Gcd}( z, z ) = z \).

\[
\begin{verbatim}
gap> \text{Gcd}( \text{Integers}, [ 10, 15 ] );
5
\end{verbatim}
\]

56.7.2  GcdOp

\[ \text{GcdOp}( [R, ]r, s) \]

GcdOp is the operation to compute the greatest common divisor of two ring elements \( r, s \) in the ring \( R \) or in their default ring.

56.7.3  GcdRepresentation

\[ \text{GcdRepresentation}( [R, ]r_1, r_2, \ldots) \]  
\[ \text{GcdRepresentation}( [R, ]\text{list}) \]

GcdRepresentation returns a representation of the greatest common divisor of the ring elements \( r_1, r_2, \ldots \) resp. of the ring elements in the list \( \text{list} \) in the Euclidean ring \( R \), if given, and otherwise in their default ring, see DefaultRing (56.1.3).

A representation of the gcd \( g \) of the elements \( r_1, r_2, \ldots \) of a ring \( R \) is a list of ring elements \( s_1, s_2, \ldots \) of \( R \), such that \( g = s_1 r_1 + s_2 r_2 + \ldots \). Such representations do not exist in all rings, but they do exist in Euclidean rings (see IsEuclideanRing (56.6.1)), which can be shown using the Euclidean algorithm, which in fact can compute those coefficients.

\[
\begin{verbatim}
gap> a := \text{Indeterminate}( \text{Rationals}, "a" );
gap> \text{GcdRepresentation}( a^2+1, a^3+1 );
[ -1/2*a^2-1/2*a+1/2, 1/2*a+1/2 ]
\end{verbatim}
\]

Gcdex (14.3.5) provides similar functionality over the integers.
56.7.4 GcdRepresentationOp

GcdRepresentationOp is the operation to compute the representation of the greatest common divisor of two ring elements \( r, s \) in the Euclidean ring \( R \) or in their default ring, respectively.

56.7.5 ShowGcd

This function takes two elements \( a \) and \( b \) of an Euclidean ring and returns their greatest common divisor. It will print out the steps performed by the Euclidean algorithm, as well as the rearrangement of these steps to express the gcd as a ring combination of \( a \) and \( b \).

```gap
gap> ShowGcd(192,42);
192 = 4 * 42 + 24
42 = 1 * 24 + 18
24 = 1 * 18 + 6
18 = 3 * 6 + 0
The Gcd is 6
  = 1 * 24 - 1 * 18
  = -1 * 42 + 2 * 24
  = 2 * 192 - 9 * 42
6
```

56.7.6 Lcm

Lcm returns the least common multiple of the ring elements \( r_1, r_2, \ldots \) resp. of the ring elements in the list \( list \) in the ring \( R \), if given, and otherwise in their default ring, see DefaultRing (56.1.3).

Lcm returns the standard associate (see StandardAssociate (56.5.5)) of the least common multiples.

A least common multiple of the elements \( r_1, r_2, \ldots \) of the ring \( R \) is an element \( m \) that is a multiple of \( r_1, r_2, \ldots \), and every other multiple of these elements is a multiple of \( m \).

Note that this in particular implies the following: For the zero element \( z \) of \( R \), we have \( \text{Lcm}(r, z) = \text{StandardAssociate}(r) \) and \( \text{Lcm}(z, z) = z \).

56.7.7 LcmOp

LcmOp is the operation to compute the least common multiple of two ring elements \( r, s \) in the ring \( R \) or in their default ring, respectively.

The default methods for this uses the equality \( \text{lcm}(m,n) = m \ast n / \text{gcd}(m,n) \) (see GcdOp (56.7.2)).
56.7.8 QuotientMod

\texttt{QuotientMod([R, ]r, s, m)}

(\text{operation})

QuotientMod returns a quotient of the ring elements $r$ and $s$ modulo the ring element $m$ in the ring $R$, if given, and otherwise in their default ring, see \texttt{DefaultRing (56.1.3)}.

$R$ must be a Euclidean ring (see \texttt{IsEuclideanRing (56.6.1)}) so that \texttt{EuclideanRemainder (56.6.4)} can be applied. If no modular quotient exists, \texttt{fail} is returned.

A quotient $q$ of $r$ and $s$ modulo $m$ is an element of $R$ such that $qs = r$ modulo $m$, i.e., such that $qs - r$ is divisible by $m$ in $R$ and that $q$ is either zero (if $r$ is divisible by $m$) or the Euclidean degree of $q$ is strictly smaller than the Euclidean degree of $m$.

\begin{verbatim}
gap> QuotientMod( 7, 2, 3 ); 2
\end{verbatim}

56.7.9 PowerMod

\texttt{PowerMod([R, ]r, e, m)}

(\text{operation})

PowerMod returns the $e$-th power of the ring element $r$ modulo the ring element $m$ in the ring $R$, if given, and otherwise in their default ring, see \texttt{DefaultRing (56.1.3)}. $e$ must be an integer.

$R$ must be a Euclidean ring (see \texttt{IsEuclideanRing (56.6.1)}) so that \texttt{EuclideanRemainder (56.6.4)} can be applied to its elements.

If $e$ is positive the result is $r^e$ modulo $m$. If $e$ is negative then PowerMod first tries to find the inverse of $r$ modulo $m$, i.e., $i$ such that $ir = 1$ modulo $m$. If the inverse does not exist an error is signalled. If the inverse does exist PowerMod returns \texttt{PowerMod( R, i, -e, m )}.

PowerMod reduces the intermediate values modulo $m$, improving performance drastically when $e$ is large and $m$ small.

\begin{verbatim}
gap> PowerMod( 12, 100000, 7 ); 2
\end{verbatim}

56.7.10 InterpolatedPolynomial

\texttt{InterpolatedPolynomial(R, x, y)}

(\text{operation})

InterpolatedPolynomial returns, for given lists $x, y$ of elements in a ring $R$ of the same length $n$, say, the unique polynomial of degree less than $n$ which has value $y[i]$ at $x[i]$, for all $i \in \{1, \ldots, n\}$. Note that the elements in $x$ must be distinct.

\begin{verbatim}
gap> InterpolatedPolynomial( Integers, [ 1, 2, 3 ], [ 5, 7, 0 ] ); -9/2*x^2+31/2*x-6
\end{verbatim}

56.8 Homomorphisms of Rings

A ring homomorphism is a mapping between two rings that respects addition and multiplication.
Currently GAP supports ring homomorphisms between finite rings (using straightforward methods) and ring homomorphisms with additional structures, where source and range are in fact algebras and where also the linear structure is respected, see 62.10.

56.8.1 RingGeneralMappingByImages

\texttt{RingGeneralMappingByImages(R, S, gens, imgs)}

is a general mapping from the ring \( A \) to the ring \( S \). This general mapping is defined by mapping the entries in the list \( gens \) (elements of \( R \)) to the entries in the list \( imgs \) (elements of \( S \)), and taking the additive and multiplicative closure.

\( gens \) need not generate \( R \) as a ring, and if the specification does not define an additive and multiplicative mapping then the result will be multivalued. Hence, in general it is not a mapping.

56.8.2 RingHomomorphismByImages

\texttt{RingHomomorphismByImages(R, S, gens, imgs)}

\texttt{RingHomomorphismByImages} returns the ring homomorphism with source \( R \) and range \( S \) that is defined by mapping the list \( gens \) of generators of \( R \) to the list \( imgs \) of images in \( S \).

If \( gens \) does not generate \( R \) or if the homomorphism does not exist (i.e., if mapping the generators describes only a multi-valued mapping) then \texttt{fail} is returned.

One can avoid the checks by calling \texttt{RingHomomorphismByImagesNC} (56.8.3), and one can construct multi-valued mappings with \texttt{RingGeneralMappingByImages} (56.8.1).

56.8.3 RingHomomorphismByImagesNC

\texttt{RingHomomorphismByImagesNC(R, S, gens, imgs)}

\texttt{RingHomomorphismByImagesNC} is the operation that is called by the function \texttt{RingHomomorphismByImages} (56.8.2). Its methods may assume that \( gens \) generates \( R \) as a ring and that the mapping of \( gens \) to \( imgs \) defines a ring homomorphism. Results are unpredictable if these conditions do not hold.

For creating a possibly multi-valued mapping from \( R \) to \( S \) that respects addition and multiplication, \texttt{RingGeneralMappingByImages} (56.8.1) can be used.

56.8.4 NaturalHomomorphismByIdeal

\texttt{NaturalHomomorphismByIdeal(R, I)}

is the homomorphism of rings provided by the natural projection map of \( R \) onto the quotient ring \( R/I \). This map can be used to take pre-images in the original ring from elements in the quotient.

56.9 Small Rings

GAP contains a library of small (order up to 15) rings.
56.9.1 SmallRing

\texttt{SmallRing}(s, n) \hspace{1cm} \text{(function)}

returns the $n$-th ring of order $s$ from a library of rings of small order (up to isomorphism).

\begin{verbatim}
gap> R := SmallRing(8, 37);
<ring with 3 generators>
gap> ShowMultiplicationTable(R);
* | 0*a c b b+c a a+c a+b a+b+c
---+----------------------------------
0*a | 0*a 0*a 0*a 0*a 0*a 0*a 0*a 0*a 
c | 0*a 0*a 0*a 0*a 0*a 0*a 0*a 0*a 
b | 0*a 0*a 0*a 0*a b b b b 
b+c | 0*a 0*a 0*a 0*a b b b b 
a | 0*a c b b+c a+b a+b+c a a+c 
a+c | 0*a c b b+c a+b a+b+c a a+c 
a+b | 0*a c b b+c a a+c a+b a+b+c 
a+b+c | 0*a c b b+c a a+c a+b a+b+c
\end{verbatim}

56.9.2 NumberSmallRings

\texttt{NumberSmallRings}(s) \hspace{1cm} \text{(function)}

returns the number of (nonisomorphic) rings of order $s$ stored in the library of small rings.

\begin{verbatim}
gap> List([1..15], NumberSmallRings);
[ 1, 2, 2, 11, 2, 4, 2, 52, 11, 4, 2, 22, 2, 4, 4 ]
\end{verbatim}

56.9.3 Subrings

\texttt{Subrings}(R) \hspace{1cm} \text{(attribute)}

for a finite ring $R$ this function returns a list of all subrings of $R$.

\begin{verbatim}
gap> Subrings(SmallRing(8, 37));
[ <ring with 1 generators>, <ring with 1 generators>,
  <ring with 1 generators>, <ring with 1 generators>,
  <ring with 1 generators>, <ring with 1 generators>,
  <ring with 2 generators>, <ring with 2 generators>,
  <ring with 2 generators>, <ring with 2 generators>,
  <ring with 3 generators> ]
\end{verbatim}

56.9.4 Ideals

\texttt{Ideals}(R) \hspace{1cm} \text{(attribute)}

for a finite ring $R$ this function returns a list of all ideals of $R$. 

\begin{verbatim}

\end{verbatim}
Example

\begin{verbatim}
gap> Ideals(SmallRing(8,37));
[ <ring with 1 generators>, <ring with 1 generators>,
  <ring with 1 generators>, <ring with 2 generators>,
  <ring with 3 generators> ]
\end{verbatim}

56.9.5 DirectSum

\begin{verbatim}
gap> DirectSum(SmallRing(5,1),SmallRing(5,1));
<ring with 2 generators>
\end{verbatim}

56.9.6 RingByStructureConstants

\begin{verbatim}
gap> RingByStructureConstants(SmallRing(5,1),SmallRing(5,1));
<ring with 2 generators>
\end{verbatim}
Chapter 57

Modules

57.1 Generating modules

57.1.1 IsLeftOperatorAdditiveGroup

\[ \text{IsLeftOperatorAdditiveGroup}(D) \] (Category)

A domain \( D \) lies in \text{IsLeftOperatorAdditiveGroup} if it is an additive group that is closed under scalar multiplication from the left, and such that \( \lambda \cdot (x+y) = \lambda \cdot x + \lambda \cdot y \) for all scalars \( \lambda \) and elements \( x, y \in D \) (here and below by scalars we mean elements of a domain acting on \( D \) from left or right as appropriate).

57.1.2 IsLeftModule

\[ \text{IsLeftModule}(M) \] (Category)

A domain \( M \) lies in \text{IsLeftModule} if it lies in \text{IsLeftOperatorAdditiveGroup}, and the set of scalars forms a ring, and \( (\lambda + \mu) \cdot x = \lambda \cdot x + \mu \cdot x \) for scalars \( \lambda, \mu \) and \( x \in M \), and scalar multiplication satisfies \( \lambda \cdot (\mu \cdot x) = (\lambda \cdot \mu) \cdot x \) for scalars \( \lambda, \mu \) and \( x \in M \).

Example

\begin{verbatim}
gap> V := FullRowSpace( Rationals, 3 );
( Rationals^3 )
gap> IsLeftModule( V );
true
\end{verbatim}

57.1.3 GeneratorsOfLeftOperatorAdditiveGroup

\[ \text{GeneratorsOfLeftOperatorAdditiveGroup}(D) \] (attribute)

returns a list of elements of \( D \) that generates \( D \) as a left operator additive group.

57.1.4 GeneratorsOfLeftModule

\[ \text{GeneratorsOfLeftModule}(M) \] (attribute)

returns a list of elements of \( M \) that generate \( M \) as a left module.

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57.1.5 AsLeftModule

▷ AsLeftModule(\textit{R}, \textit{D}) \hspace{1cm} \text{(operation)}

if the domain \textit{D} forms an additive group and is closed under left multiplication by the elements of \textit{R}, then \textit{AsLeftModule( R, D )} returns the domain \textit{D} viewed as a left module.

Example

\begin{verbatim}
gap> V:= FullRowSpace( Rationals, 3 );;
gap> GeneratorsOfLeftModule( V );
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ]
\end{verbatim}

57.1.6 IsRightOperatorAdditiveGroup

▷ IsRightOperatorAdditiveGroup\textit{(D)} \hspace{1cm} \text{(Category)}

A domain \textit{D} lies in \textit{IsRightOperatorAdditiveGroup} if it is an additive group that is closed under scalar multiplication from the right, and such that \((x+y) * \lambda = x * \lambda + y * \lambda\) for all scalars \(\lambda\) and elements \(x,y \in D\).

57.1.7 IsRightModule

▷ IsRightModule\textit{(M)} \hspace{1cm} \text{(Category)}

A domain \textit{M} lies in \textit{IsRightModule} if it lies in \textit{IsRightOperatorAdditiveGroup}, and the set of scalars forms a ring, and \(x * (\lambda + \mu) = x * \lambda + x * \mu\) for scalars \(\lambda, \mu\) and \(x \in M\), and scalar multiplication satisfies \((x * \mu) * \lambda = x * (\mu * \lambda)\) for scalars \(\lambda, \mu\) and \(x \in M\).

57.1.8 GeneratorsOfRightOperatorAdditiveGroup

▷ GeneratorsOfRightOperatorAdditiveGroup\textit{(D)} \hspace{1cm} \text{(attribute)}

returns a list of elements of \(D\) that generates \(D\) as a right operator additive group.

57.1.9 GeneratorsOfRightModule

▷ GeneratorsOfRightModule\textit{(M)} \hspace{1cm} \text{(attribute)}

returns a list of elements of \(M\) that generate \(M\) as a left module.
57.1.10 LeftModuleByGenerators

returns the left module over \( R \) generated by \( gens \).

Example

```gap
gap> coll := [ [Z(2),0*Z(2)], [0*Z(2),Z(2)], [Z(2),Z(2)] ];;
gap> V := LeftModuleByGenerators( GF(16), coll );;
<vector space over GF(2^4), with 3 generators>
```

57.1.11 LeftActingDomain

Let \( D \) be an external left set, that is, \( D \) is closed under the action of a domain \( L \) by multiplication from the left. Then \( L \) can be accessed as value of \texttt{LeftActingDomain} for \( D \).

57.2 Submodules

57.2.1 Submodule

is the left module generated by the collection \( gens \), with parent module \( M \). If the string "basis" is entered as the third argument then the submodule of \( M \) is created for which the list \( gens \) is known to be a list of basis vectors; in this case, it is not checked whether \( gens \) really is linearly independent and whether all in \( gens \) lie in \( M \).

Example

```gap
gap> coll := [ [Z(2),0*Z(2)], [0*Z(2),Z(2)], [Z(2),Z(2)] ];;
gap> V := LeftModuleByGenerators( GF(16), coll );;
gap> W := Submodule( V, [ coll[1], coll[2] ] );
<vector space over GF(2^4), with 2 generators>
gap> Parent( W ) = V;
true
```

57.2.2 SubmoduleNC

SubmoduleNC does the same as \texttt{Submodule} (57.2.1), except that it does not check whether all in \( gens \) lie in \( M \).

57.2.3 ClosureLeftModule

is the left module generated by the left module generators of \( M \) and the element \( m \).
Example

\begin{verbatim}
gap> V := LeftModuleByGenerators(Rationals, [[1, 0, 0], [0, 1, 0]]);
<vector space over Rationals, with 2 generators>
gap> ClosureLeftModule(V, [1, 1, 1]);
<vector space over Rationals, with 3 generators>
\end{verbatim}

57.2.4 TrivialSubmodule

\begin{verbatim}
\texttt{TrivialSubmodule(M)}
\end{verbatim}

returns the zero submodule of \( M \).

Example

\begin{verbatim}
gap> V := LeftModuleByGenerators(Rationals, [[1, 0, 0], [0, 1, 0]]);
gap> TrivialSubmodule(V);
<vector space of dimension 0 over Rationals>
\end{verbatim}

57.3 Free Modules

57.3.1 IsFreeLeftModule

\begin{verbatim}
\texttt{IsFreeLeftModule(M)}
\end{verbatim}

A left module is free as module if it is isomorphic to a direct sum of copies of its left acting domain.

Free left modules can have bases.

The characteristic (see \texttt{Characteristic (31.10.1)}) of a free left module is defined as the characteristic of its left acting domain (see \texttt{LeftActingDomain (57.1.11)}).

57.3.2 FreeLeftModule

\begin{verbatim}
\texttt{FreeLeftModule(R, gens[, zero[, "basis"]])}
\end{verbatim}

\texttt{FreeLeftModule(R, gens)} is the free left module over the ring \( R \), generated by the vectors in the collection \( \text{gens} \).

If there are three arguments, a ring \( R \) and a collection \( \text{gens} \) and an element \( \text{zero} \), then \texttt{FreeLeftModule(R, gens, zero)} is the \( R \)-free left module generated by \( \text{gens} \), with zero element \( \text{zero} \).

If the last argument is the string "basis" then the vectors in \( \text{gens} \) are known to form a basis of the free module.

It should be noted that the generators \( \text{gens} \) must be vectors, that is, they must support an addition and a scalar action of \( R \) via left multiplication. (See also Section 31.3 for the general meaning of “generators” in GAP.) In particular, \texttt{FreeLeftModule} is not an equivalent of commands such as \texttt{FreeGroup (37.2.1)} in the sense of a constructor of a free group on abstract generators. Such a construction seems to be unnecessary for vector spaces, for that one can use for example row spaces (see \texttt{FullRowSpace (61.9.4)}) in the finite dimensional case and polynomial rings (see \texttt{PolynomialRing (66.15.1)}) in the infinite dimensional case. Moreover, the definition of a “natural” addition for elements of a given magma (for example a permutation group) is possible via the construction of magma rings (see Chapter 65).
57.3.3 Dimension

\[ \text{Dimension}(M) \] (attribute)

A free left module has dimension \( n \) if it is isomorphic to a direct sum of \( n \) copies of its left acting domain.

(We do not mark \text{Dimension} as invariant under isomorphisms since we want to call \text{UseIsomorphismRelation} (31.13.3) also for free left modules over different left acting domains.)

Example

```gap
gap> V := FreeLeftModule(Rationals, [[1, 0, 0], [0, 1, 0]], "basis");
<vector space of dimension 2 over Rationals>
```

57.3.4 IsFiniteDimensional

\[ \text{IsFiniteDimensional}(M) \] (property)

is \textbf{true} if \( M \) is a free left module that is finite dimensional over its left acting domain, and \textbf{false} otherwise.

Example

```gap
gap> V := FreeLeftModule(Rationals, [[1, 0], [0, 1], [1, 1]]);
gap> IsFiniteDimensional(V);
true
```

57.3.5 UseBasis

\[ \text{UseBasis}(V, gens) \] (operation)

The vectors in the list \( gens \) are known to form a basis of the free left module \( V \). \text{UseBasis} stores information in \( V \) that can be derived from this fact, namely

- \( gens \) are stored as left module generators if no such generators were bound (this is useful especially if \( V \) is an algebra),
- the dimension of \( V \) is stored.

Example

```gap
gap> V := FreeLeftModule(Rationals, [[1, 0], [0, 1], [1, 1]]);
gap> UseBasis(V, [[1, 0], [1, 1]]);
V; # now V knows its dimension
<vector space of dimension 2 over Rationals>
```

57.3.6 IsRowModule

\[ \text{IsRowModule}(V) \] (property)

A \textit{row module} is a free left module whose elements are row vectors.
57.3.7 IsMatrixModule

▷ IsMatrixModule(V) (property)

A matrix module is a free left module whose elements are matrices.

57.3.8 IsFullRowModule

▷ IsFullRowModule(M) (property)

A full row module is a module $R^n$, for a ring $R$ and a nonnegative integer $n$.

More precisely, a full row module is a free left module over a ring $R$ such that the elements are row vectors of the same length $n$ and with entries in $R$ and such that the dimension is equal to $n$.

Several functions delegate their tasks to full row modules, for example Iterator (30.8.1) and Enumerator (30.3.2).

57.3.9 FullRowModule

▷ FullRowModule(R, n) (function)

is the row module $R^n$, for a ring $R$ and a nonnegative integer $n$.

Example

```
gap> V := FullRowModule( Integers, 5 );
( Integers^5 )
```

57.3.10 IsFullMatrixModule

▷ IsFullMatrixModule(M) (property)

A full matrix module is a module $R^{[m,n]}$, for a ring $R$ and two nonnegative integers $m$, $n$.

More precisely, a full matrix module is a free left module over a ring $R$ such that the elements are $m$ by $n$ matrices with entries in $R$ and such that the dimension is equal to $mn$.

57.3.11 FullMatrixModule

▷ FullMatrixModule(R, m, n) (function)

is the matrix module $R^{[m,n]}$, for a ring $R$ and nonnegative integers $m$ and $n$.

Example

```
gap> FullMatrixModule( GaussianIntegers, 3, 6 );
( GaussianIntegers^[ 3, 6 ] )
```
Chapter 58

Fields and Division Rings

A division ring is a ring (see Chapter 56) in which every non-zero element has an inverse. The most important class of division rings are the commutative ones, which are called fields.

GAP supports finite fields (see Chapter 59) and abelian number fields (see Chapter 60), in particular the field of rationals (see Chapter 17).

This chapter describes the general GAP functions for fields and division rings.

If a field \( F \) is a subfield of a commutative ring \( C \), \( C \) can be considered as a vector space over the (left) acting domain \( F \) (see Chapter 61). In this situation, we call \( F \) the field of definition of \( C \).

Each field in GAP is represented as a vector space over a subfield (see IsField (58.1.2)), thus each field is in fact a field extension in a natural way, which is used by functions such as Norm (58.3.4) and Trace (58.3.5) (see 58.3).

58.1 Generating Fields

58.1.1 IsDivisionRing

\[
\text{IsDivisionRing}(D)
\]

A division ring in GAP is a nontrivial associative algebra \( D \) with a multiplicative inverse for each nonzero element. In GAP every division ring is a vector space over a division ring (possibly over itself). Note that being a division ring is thus not a property that a ring can get, because a ring is usually not represented as a vector space.

The field of coefficients is stored as the value of the attribute LeftActingDomain (57.1.11) of \( D \).

58.1.2 IsField

\[
\text{IsField}(D)
\]

A field is a commutative division ring (see IsDivisionRing (58.1.1) and IsCommutative (35.4.9)).

\[
\begin{array}{l}
gap> \text{IsField( GaloisField(16) );} \\
true \\
\text{# the field with 16 elements} \\
\end{array}
\]

\[
\begin{array}{l}
gap> \text{IsField( Rationals );} \\
true \\
\text{# the field of rationals} \\
\end{array}
\]

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58.1.3 Field (for several generators)

Field returns the smallest field \( K \) that contains all the elements \( z, \ldots \), or the smallest field \( K \) that contains all elements in the list \( \text{list} \). If no subfield \( F \) is given, \( K \) is constructed as a field over itself, i.e. the left acting domain of \( K \) is \( K \). Called with a field \( F \) and a list \( \text{list} \), Field constructs the field generated by \( F \) and the elements in \( \text{list} \), as a vector space over \( F \).

58.1.4 DefaultField (for several generators)

DefaultField returns a field \( K \) that contains all the elements \( z, \ldots \), or a field \( K \) that contains all elements in the list \( \text{list} \).

This field need not be the smallest field in which the elements lie, cf. Field (58.1.3). For example, for elements from cyclotomic fields DefaultField returns the smallest cyclotomic field in which the elements lie, but the elements may lie in a smaller number field which is not a cyclotomic field.

Example

58.1.5 DefaultFieldByGenerators

returns the default field containing the elements \( z, \ldots \). This field may be bigger than the smallest field containing these elements.
58.1.6 GeneratorsOfDivisionRing

\[ \text{GeneratorsOfDivisionRing}(D) \] (attribute)

generators with respect to addition, multiplication, and taking inverses (the identity cannot be omitted ...)

58.1.7 GeneratorsOfField

\[ \text{GeneratorsOfField}(F) \] (attribute)

generators with respect to addition, multiplication, and taking inverses. This attribute is the same as \text{GeneratorsOfDivisionRing} (58.1.6).

58.1.8 DivisionRingByGenerators

\[ \text{DivisionRingByGenerators}([F, \text{gens}]) \] (operation)
\[ \text{FieldByGenerators}([F, \text{gens}]) \] (operation)

Called with a field \( F \) and a list \( \text{gens} \) of scalars, \text{DivisionRingByGenerators} returns the division ring over \( F \) generated by \( \text{gens} \). The unary version returns the division ring as vector space over \text{FieldOverItselfByGenerators} (\( \text{gens} \)).

\text{FieldByGenerators} is just a synonym for \text{DivisionRingByGenerators}.

58.1.9 AsDivisionRing

\[ \text{AsDivisionRing}([F, \text{C}]) \] (operation)
\[ \text{AsField}([F, \text{C}]) \] (operation)

If the collection \( \text{C} \) can be regarded as a division ring then \text{AsDivisionRing} (\( \text{C} \)) is the division ring that consists of the elements of \( \text{C} \), viewed as a vector space over its prime field; otherwise \text{fail} is returned.

In the second form, if \( F \) is a division ring contained in \( \text{C} \) then the returned division ring is viewed as a vector space over \( F \).

\text{AsField} is just a synonym for \text{AsDivisionRing}.

58.2 Subfields of Fields

58.2.1 Subfield

\[ \text{Subfield}(F, \text{gens}) \] (function)
\[ \text{SubfieldNC}(F, \text{gens}) \] (function)

Constructs the subfield of \( F \) generated by \( \text{gens} \).
58.2.2 FieldOverItselfByGenerators

FieldOverItselfByGenerators([z, ...])

This operation is needed for the call of Field (58.1.3) or FieldByGenerators (58.1.8) without explicitly given subfield, in order to construct a left acting domain for such a field.

58.2.3 PrimitiveElement

PrimitiveElement(D)

is an element of $D$ that generates $D$ as a division ring together with the left acting domain.

58.2.4 PrimeField

PrimeField(D)

The prime field of a division ring $D$ is the smallest field which is contained in $D$. For example, the prime field of any field in characteristic zero is isomorphic to the field of rational numbers.

58.2.5 IsPrimeField

IsPrimeField(D)

A division ring is a prime field if it is equal to its prime field (see PrimeField (58.2.4)).

58.2.6 DegreeOverPrimeField

DegreeOverPrimeField(F)

is the degree of the field $F$ over its prime field (see PrimeField (58.2.4)).

58.2.7 DefiningPolynomial

DefiningPolynomial(F)

is the defining polynomial of the field $F$ as a field extension over the left acting domain of $F$. A root of the defining polynomial can be computed with RootOfDefiningPolynomial (58.2.8).

58.2.8 RootOfDefiningPolynomial

RootOfDefiningPolynomial(F)

is a root in the field $F$ of its defining polynomial as a field extension over the left acting domain of $F$. The defining polynomial can be computed with DefiningPolynomial (58.2.7).
58.2.9 FieldExtension

▷ FieldExtension(F, poly) (operation)

is the field obtained on adjoining a root of the irreducible polynomial poly to the field F.

FieldExtension (operation)

58.2.10 Subfields

▷ Subfields(F) (attribute)

is the set of all subfields of the field F.

Subfields (attribute)

58.3 Galois Action

Let $L > K$ be a field extension of finite degree. Then to each element $\alpha \in L$, we can associate a $K$-linear mapping $\varphi_\alpha$ on $L$, and for a fixed $K$-basis of $L$, we can associate to $\alpha$ the matrix $M_\alpha$ (over $K$) of this mapping.

The norm of $\alpha$ is defined as the determinant of $M_\alpha$, the trace of $\alpha$ is defined as the trace of $M_\alpha$, the minimal polynomial $\mu_\alpha$ and the trace polynomial $\chi_\alpha$ of $\alpha$ are defined as the minimal polynomial (see 66.8.1) and the characteristic polynomial (see CharacteristicPolynomial (24.13.1) and TracePolynomial (58.3.3)) of $M_\alpha$. (Note that $\mu_\alpha$ depends only on $K$ whereas $\chi_\alpha$ depends on both $L$ and $K$.)

Thus norm and trace of $\alpha$ are elements of $K$, and $\mu_\alpha$ and $\chi_\alpha$ are polynomials over $K$, $\chi_\alpha$ being a power of $\mu_\alpha$, and the degree of $\chi_\alpha$ equals the degree of the field extension $L > K$.

The conjugates of $\alpha$ in $L$ are those roots of $\chi_\alpha$ (with multiplicity) that lie in $L$; note that if only $L$ is given, there is in general no way to access the roots outside $L$.

Analogously, the Galois group of the extension $L > K$ is defined as the group of all those field automorphisms of $L$ that fix $K$ pointwise.

If $L > K$ is a Galois extension then the conjugates of $\alpha$ are all roots of $\chi_\alpha$ (with multiplicity), the set of conjugates equals the roots of $\mu_\alpha$, the norm of $\alpha$ equals the product and the trace of $\alpha$ equals the sum of the conjugates of $\alpha$, and the Galois group in the sense of the above definition equals the usual Galois group.

Note that MinimalPolynomial (66.8.1) solves a system of linear equations, TracePolynomial (58.3.3) computes the appropriate power of the minimal polynomial, Norm (58.3.4) and Trace (58.3.5) values are obtained as coefficients of the characteristic polynomial, and Conjugates (58.3.6) uses the factorization of the characteristic polynomial.

For elements in finite fields and cyclotomic fields, one wants to do the computations in a different way since the field extensions in question are Galois extensions, and the Galois groups are well-known in these cases. More general, if a field is in the category IsFieldControlledByGaloisGroup then the default methods are the following. Conjugates (58.3.6) returns the sorted list of images (with multiplicity) of the element under the Galois group, Norm (58.3.4) computes the product of the conjugates, Trace (58.3.5) computes the sum of the conjugates, TracePolynomial (58.3.3) and MinimalPolynomial (66.8.1) compute the product of linear factors $x - c$ with $c$ ranging over the conjugates and the set of conjugates, respectively.
58.3.1 GaloisGroup (of field)

The Galois group of a field \( F \) is the group of all field automorphisms of \( F \) that fix the subfield \( K = \text{LeftActingDomain}(F) \) pointwise.

Note that the field extension \( F > K \) need not be a Galois extension.

```
Example
gap> g := GaloisGroup( AsField( GF(2^2), GF(2^12) ) );;
gap> Size( g ); IsCyclic( g );
6  true

gap> h := GaloisGroup( CF(60) );;
gap> Size( h ); IsAbelian( h );
16  true
```

58.3.2 MinimalPolynomial (over a field)

```
Example
gap> MinimalPolynomial( Rationals, E(8) );
x_1^4+1

gap> MinimalPolynomial( CF(4), E(8) );
x_1^2+(-E(4))

gap> MinimalPolynomial( CF(8), E(8) );
x_1+(-E(8))
```

58.3.3 TracePolynomial

```
Example
gap> TracePolynomial( CF(8), Rationals, E(8) );
x_1^4+1

gap> TracePolynomial( CF(16), Rationals, E(8) );
x_1^8+2*x_1^4+1
```
58.3.4 Norm

\[ \text{Norm}(\mathbb{L}, K, z) (\text{attribute}) \]

\text{Norm} returns the norm of the field element \( z \). If two fields \( L \) and \( K \) are given then the norm is computed w.r.t. the field extension \( L > K \), if only one field \( L \) is given then \text{LeftActingDomain}(L) \) is taken as default for the subfield \( K \), and if no field is given then \text{DefaultField}(z) \) is taken as default for \( L \).

58.3.5 Traces of field elements and matrices

\[ \text{Trace}(\mathbb{L}, K, z) (\text{attribute}) \]
\[ \text{Trace(mat)} (\text{attribute}) \]

\text{Trace} returns the trace of the field element \( z \). If two fields \( L \) and \( K \) are given then the trace is computed w.r.t. the field extension \( L > K \), if only one field \( L \) is given then \text{LeftActingDomain}(L) \) is taken as default for the subfield \( K \), and if no field is given then \text{DefaultField}(z) \) is taken as default for \( L \).

The trace of a matrix is the sum of its diagonal entries. Note that this is not compatible with the definition of \text{Trace} for field elements, so the one-argument version is not suitable when matrices shall be regarded as field elements.

58.3.6 Conjugates

\[ \text{Conjugates}(\mathbb{L}, K, z) (\text{attribute}) \]

\text{Conjugates} returns the list of conjugates of the field element \( z \). If two fields \( L \) and \( K \) are given then the conjugates are computed w.r.t. the field extension \( L > K \), if only one field \( L \) is given then \text{LeftActingDomain}(L) \) is taken as default for the subfield \( K \), and if no field is given then \text{DefaultField}(z) \) is taken as default for \( L \).

The result list will contain duplicates if \( z \) lies in a proper subfield of \( L \), or of the default field of \( z \), respectively. The result list need not be sorted.

```
gap> Norm( E(8) ); Norm( CF(8), E(8) );
1
1

gap> Norm( CF(8), CF(4), E(8) );
-E(4)

gap> Norm( AsField( CF(4), CF(8) ), E(8) );
-E(4)

gap> Trace( E(8) ); Trace( CF(8), CF(8), E(8) );
0
E(8)

gap> Conjugates( CF(8), E(8) );
[ E(8), E(8)^3, -E(8), -E(8)^3 ]

gap> Conjugates( CF(8), CF(4), E(8) );
[ E(8), -E(8) ]

gap> Conjugates( CF(16), E(8) );
[ E(8), E(8)^3, -E(8), -E(8)^3, E(8)^3, -E(8), -E(8)^3 ]
```
58.3.7 NormalBase

▷ NormalBase(F[, elm])

Let $F$ be a field that is a Galois extension of its subfield LeftActingDomain($F$). Then NormalBase returns a list of elements in $F$ that form a normal basis of $F$, that is, a vector space basis that is closed under the action of the Galois group (see GaloisGroup (58.3.1)) of $F$.

If a second argument $elm$ is given, it is used as a hint for the algorithm to find a normal basis with the algorithm described in [Art73].

```
gap> NormalBase( CF(5) );
gap> NormalBase( CF(4) );
[ 1/2-1/2*E(4), 1/2+1/2*E(4) ]
gap> NormalBase( GF(3^6) );
[ Z(3^6)^2, Z(3^6)^6, Z(3^6)^18, Z(3^6)^54, Z(3^6)^162, Z(3^6)^486 ]
gap> NormalBase( GF( GF(8), 2 ) );
[ Z(2^6), Z(2^6)^8 ]
```
Chapter 59

Finite Fields

This chapter describes the special functionality which exists in GAP for finite fields and their elements. Of course the general functionality for fields (see Chapter 58) also applies to finite fields.

In the following, the term *finite field element* is used to denote GAP objects in the category IsFFE (59.1.1), and *finite field* means a field consisting of such elements. Note that in principle we must distinguish these fields from (abstract) finite fields. For example, the image of the embedding of a finite field into a field of rational functions in the same characteristic is of course a finite field but its elements are not in IsFFE (59.1.1), and in fact GAP does currently not support such fields.

Special representations exist for row vectors and matrices over small finite fields (see sections 23.3 and 24.14).

59.1 Finite Field Elements

59.1.1 IsFFE

Objects in the category IsFFE are used to implement elements of finite fields. In this manual, the term *finite field element* always means an object in IsFFE. All finite field elements of the same characteristic form a family in GAP (see 13.1). Any collection of finite field elements (see IsCollection (30.1.1)) lies in IsFFECollection, and a collection of such collections (e.g., a matrix of finite field elements) lies in IsFFECollColl.

59.1.2 Z (for field size)

For creating elements of a finite field, the function Z can be used. The call Z(p^d) (alternatively Z(p, d)) returns the designated generator of the multiplicative group of the finite field with p^d elements. p must be a prime integer.
GAP can represent elements of all finite fields \( GF(p^d) \) such that either (1) \( p^d \leq 65536 \) (in which case an extremely efficient internal representation is used); (2) \( d = 1 \), (in which case, for large \( p \), the field is represented using the machinery of residue class rings (see section 14.5) or (3) if the Conway polynomial of degree \( d \) over the field with \( p \) elements is known, or can be computed (see \texttt{ConwayPolynomial} (59.5.1)).

If you attempt to construct an element of \( GF(p^d) \) for which \( d > 1 \) and the relevant Conway polynomial is not known, and not necessarily easy to find (see \texttt{IsCheapConwayPolynomial} (59.5.2)), then GAP will stop with an error and enter the break loop. If you leave this break loop by entering \texttt{return}; GAP will attempt to compute the Conway polynomial, which may take a very long time.

The root returned by \( Z \) is a generator of the multiplicative group of the finite field with \( p^d \) elements, which is cyclic. The order of the element is of course \( p^d - 1 \). The \( p^d - 1 \) different powers of the root are exactly the nonzero elements of the finite field.

Thus all nonzero elements of the finite field with \( p^d \) elements can be entered as \( Z(p^d)^i \). Note that this is also the form that GAP uses to output those elements when they are stored in the internal representation. In larger fields, it is more convenient to enter and print elements as linear combinations of powers of the primitive element, see section 59.6.

The additive neutral element is \( 0 \ast Z(p) \). It is different from the integer 0 in subtle ways. First \texttt{IsInt( 0 \ast Z(p) )} (see \texttt{IsInt} (14.2.1)) is false and \texttt{IsFFE( 0 \ast Z(p) )} (see \texttt{IsFFE} (59.1.1)) is true, whereas it is just the other way around for the integer 0.

The multiplicative neutral element is \( Z(p)^0 \). It is different from the integer 1 in subtle ways. First \texttt{IsInt( Z(p)^0 )} (see \texttt{IsInt} (14.2.1)) is false and \texttt{IsFFE( Z(p)^0 )} (see \texttt{IsFFE} (59.1.1)) is true, whereas it is just the other way around for the integer 1. Also \( 1 + 1 = 2 \), whereas, e.g., \( Z(2)^0 + Z(2)^0 = 0 \ast Z(2) \).

The various roots returned by \( Z \) for finite fields of the same characteristic are compatible in the following sense. If the field \( GF(p,n) \) is a subfield of the field \( GF(p,m) \), i.e., \( n \) divides \( m \), then \( Z(p^n) = Z(p^m)^{p^m - 1}/(p^n - 1) \). Note that this is the simplest relation that may hold between a generator of \( GF(p,n) \) and \( GF(p,m) \), since \( Z(p^n) \) is an element of order \( p^m - 1 \) and \( Z(p^m) \) is an element of order \( p^n - 1 \). This is achieved by choosing \( Z(p) \) as the smallest primitive root modulo \( p \) and \( Z(p^n) \) as a root of the \( n \)-th Conway polynomial (see \texttt{ConwayPolynomial} (59.5.1)) of characteristic \( p \). Those polynomials were defined by J. H. Conway, and many of them were computed by R. A. Parker.

```
Example

gap> a := Z(32);
Z(2^5)
gap> a+a;
0*Z(2)
gap> a*a;
Z(2^5)^2
gap> b := Z(3,12);
z
gap> b*b;
z2
gap> b+b;
z

gap> Print(b^100,"\n");
Z(3)^0+Z(3,12)^5+Z(3,12)^6+2*Z(3,12)^8+Z(3,12)^10+Z(3,12)^11

Example

gap> Z(11,40);
Error, Conway Polynomial 11^40 will need to computed and might be slow
Elements of finite fields can be compared using the operators = and <. The call \( a = b \) returns \( \text{true} \) if and only if the finite field elements \( a \) and \( b \) are equal. Furthermore \( a < b \) tests whether \( a \) is smaller than \( b \). The exact behaviour of this comparison depends on which of two categories the field elements belong to:

Finite field elements are ordered in **GAP** (by \( \langle \) (31.11.1)) first by characteristic and then by their degree (i.e. the sizes of the smallest fields containing them). Amongst irreducible elements of a given field, the ordering depends on which of these categories the elements of the field belong to (all irreducible elements of a given field should belong to the same one).

Elements in **IsLexOrderedFFE** are ordered lexicographically by their coefficients with respect to the canonical basis of the field.

Elements in **IsLogOrderedFFE** are ordered according to their discrete logarithms with respect to the **PrimitiveElement** (58.2.3) attribute of the field. For the comparison of finite field elements with other **GAP** objects, see 4.12.

**Example**

```
gap> Z( 16 )^10 = Z( 4 )^2; # illustrates embedding of GF(4) in GF(16)
true
gap> 0 < 0*Z(101);
true
gap> Z(256) > Z(101);
false
gap> Z(2,20) < Z(2,20)^2; # this illustrates the lexicographic ordering
false
```

### 59.2 Operations for Finite Field Elements

Since finite field elements are scalars, the operations **Characteristic** (31.10.1), **One** (31.10.2), **Zero** (31.10.3), **Inverse** (31.10.8), **AdditiveInverse** (31.10.9), and **Order** (31.10.10) can be applied to them (see 31.10). Contrary to the situation with other scalars, **Order** (31.10.10) is defined also for the zero element in a finite field, with value 0.

**Example**

```
gap> Characteristic( Z( 16 )^10 ); Characteristic( Z( 9 )^2 );
2
3
gap> Characteristic( [ Z(4), Z(8) ] );
2
```
59.2.1 DegreeFFE (for a FFE)

\[ \text{DegreeFFE}(z) \] (attribute)
\[ \text{DegreeFFE}(\mathtt{vec}) \] (method)
\[ \text{DegreeFFE}(\mathtt{mat}) \] (method)

DegreeFFE returns the degree of the smallest finite field \( F \) containing the element \( z \), respectively all elements of the row vector \( \mathtt{vec} \) over a finite field (see 23), or the matrix \( \mathtt{mat} \) over a finite field (see 24).

Example

\[
\begin{align*}
\text{gap} & > \text{DegreeFFE}(\text{Z(16)}^{10}); \\
& 2 \\
\text{gap} & > \text{DegreeFFE}(\text{Z(16)}^{11}); \\
& 4 \\
\text{gap} & > \text{DegreeFFE}(\left[ \text{Z(2^{13}), Z(2^{10})} \right]); \\
& 130
\end{align*}
\]

59.2.2 LogFFE

\[ \text{LogFFE}(z, r) \] (operation)

LogFFE returns the discrete logarithm of the element \( z \) in a finite field with respect to the root \( r \). An error is signalled if \( z \) is zero. \texttt{fail} is returned if \( z \) is not a power of \( r \).

The discrete logarithm of the element \( z \) with respect to the root \( r \) is the smallest nonnegative integer \( i \) such that \( r^i = z \) holds.

Example

\[
\begin{align*}
\text{gap} & > \text{LogFFE}(\text{Z(409)}^{116}, \text{Z(409)}); \\
& 116 \\
\text{gap} & > \text{LogFFE}(\text{Z(409)}^{116}, \text{Z(409)}^{2}); \\
& 58
\end{align*}
\]

59.2.3 IntFFE

\[ \text{IntFFE}(z) \] (attribute)
\[ \text{Int}(z) \] (method)

IntFFE returns the integer corresponding to the element \( z \), which must lie in a finite prime field. That is, IntFFE returns the smallest nonnegative integer \( i \) such that \( i \cdot \text{One}(z) = z \).
The correspondence between elements from a finite prime field of characteristic \( p \) (for \( p < 2^{16} \)) and the integers between 0 and \( p - 1 \) is defined by choosing \( \mathbb{Z}(p) \) the element corresponding to the smallest primitive root mod \( p \) (see \texttt{PrimitiveRootMod (15.3.3)}).

\texttt{IntFFE} is installed as a method for the operation \texttt{Int (14.2.3)} with argument a finite field element.

\begin{verbatim}
gap> IntFFE( Z(13) );  PrimitiveRootMod( 13 );
2
2
gap> IntFFE( Z(409) );
21
gap> IntFFE( Z(409)^116 );  21^116 mod 409;
311
311
\end{verbatim}

See also \texttt{IntFFESymm (59.2.4)}.

\subsection{59.2.4 \texttt{IntFFESymm} (for a FFE)}

\begin{verbatim}
\triangleright \texttt{IntFFESymm(z)} \hspace{1cm} \texttt{(attribute)}
\triangleright \texttt{IntFFESymm(vec)} \hspace{1cm} \texttt{(attribute)}
\end{verbatim}

For a finite prime field element \( z \), \texttt{IntFFESymm} returns the corresponding integer of smallest absolute value. That is, \texttt{IntFFESymm} returns the integer \( i \) of smallest absolute value such that \( i \times \texttt{One( z )} = z \) holds.

For a vector \( \texttt{vec} \) of FFEs, the operation returns the result of applying \texttt{IntFFESymm} to every entry of the vector.

The correspondence between elements from a finite prime field of characteristic \( p \) (for \( p < 2^{16} \)) and the integers between \(-p/2\) and \( p/2 \) is defined by choosing \( \mathbb{Z}(p) \) the element corresponding to the smallest positive primitive root mod \( p \) (see \texttt{PrimitiveRootMod (15.3.3)}) and reducing results to the \(-p/2..p/2\) range.

\begin{verbatim}
gap> IntFFE(Z(13)^2);IntFFE(Z(13)^3);
4
8
gap> IntFFESymm(Z(13)^2);IntFFESymm(Z(13)^3);
4
-5
\end{verbatim}

See also \texttt{IntFFE (59.2.3)}

\subsection{59.2.5 \texttt{IntVecFFE}}

\begin{verbatim}
\triangleright \texttt{IntVecFFE(vecffe)} \hspace{1cm} \texttt{(operation)}
\end{verbatim}

is the list of integers corresponding to the vector \texttt{vecffe} of finite field elements in a prime field (see \texttt{IntFFE (59.2.3)}).
59.2.6 AsInternalFFE

\[ \text{AsInternalFFE}(ffe) \]

\[ \begin{align*} \text{return an internal FFE equal to } ffe & \text{ if one exists, otherwise fail} \end{align*} \]

59.3 Creating Finite Fields

59.3.1 DefaultField (for finite field elements)

\[ \begin{align*} \text{DefaultField}(\text{list}) \quad \text{(function)} \\
\text{DefaultRing}(\text{list}) \quad \text{(function)} \\
\end{align*} \]

DefaultField and DefaultRing for finite field elements are defined to return the smallest field containing the given elements.

```
gap> \text{DefaultField( [ Z(4), Z(4)^2 ] ); DefaultField( [ Z(4), Z(8) ] );}
GF(2^2)
GF(2^6)
```

59.3.2 GaloisField (for field size)

\[ \begin{align*} \text{GaloisField}(p^d) \quad \text{(function)} \\
\text{GF}(p^d) \quad \text{(function)} \\
\text{GaloisField}(p, d) \quad \text{(function)} \\
\text{GF}(p, d) \quad \text{(function)} \\
\text{GaloisField}(\text{subfield}, d) \quad \text{(function)} \\
\text{GF}(\text{subfield}, d) \quad \text{(function)} \\
\text{GaloisField}(p, \text{pol}) \quad \text{(function)} \\
\text{GF}(p, \text{pol}) \quad \text{(function)} \\
\text{GaloisField}(\text{subfield}, \text{pol}) \quad \text{(function)} \\
\text{GF}(\text{subfield}, \text{pol}) \quad \text{(function)} \\
\end{align*} \]

GaloisField returns a finite field. It takes two arguments. The form \text{GaloisField}(p, d), where \text{p}, \text{d} are integers, can also be given as \text{GaloisField}(p^d). GF is an abbreviation for GaloisField.

The first argument specifies the subfield \( S \) over which the new field is to be taken. It can be a prime integer or a finite field. If it is a prime \text{p}, the subfield is the prime field of this characteristic.

The second argument specifies the extension. It can be an integer or an irreducible polynomial over the field \( S \). If it is an integer \text{d}, the new field is constructed as the polynomial extension w.r.t. the Conway polynomial (see \text{ConwayPolynomial} (59.5.1)) of degree \text{d} over \( S \). If it is an irreducible polynomial \text{pol} over \( S \), the new field is constructed as polynomial extension of \( S \) with this polynomial; in this case, \text{pol} is accessible as the value of \text{DefiningPolynomial} (59.2.7) for the new field, and a root of \text{pol} in the new field is accessible as the value of \text{RootOfDefiningPolynomial} (58.2.8).

Note that the subfield over which a field was constructed determines over which field the Galois group, conjugates, norm, trace, minimal polynomial, and trace polynomial are
computed (see GaloisGroup (58.3.1), Conjugates (58.3.6), Norm (58.3.4), Trace (58.3.5), MinimalPolynomial (58.3.2), TracePolynomial (58.3.3)).

The field is regarded as a vector space (see 61) over the given subfield, so this determines the dimension and the canonical basis of the field.

\begin{verbatim}
gap> f1:= GF( 2^4 );
GF(2^4)
gap> Size( GaloisGroup( f1 ) );
4
gap> BasisVectors( Basis( f1 ) );
[ Z(2)^0, Z(2^4), Z(2^4)^2, Z(2^4)^3 ]
gap> f2:= GF( GF(4), 2 );
AsField( GF(2^2), GF(2^4) )
gap> Size( GaloisGroup( f2 ) );
2
gap> BasisVectors( Basis( f2 ) );
[ Z(2)^0, Z(2^4) ]
\end{verbatim}

\section{59.3 PrimitiveRoot}
\\(\triangleright\) PrimitiveRoot\((F)\)\hspace{1cm}\hspace{1cm}\hspace{1cm} (attribute)

A primitive root of a finite field is a generator of its multiplicative group. A primitive root is always a primitive element (see PrimitiveElement (58.2.3)), the converse is in general not true.

\begin{verbatim}
gap> f:= GF( 3^5 );
GF(3^5)
gap> PrimitiveRoot( f );
Z(3^5)
\end{verbatim}

\section{59.4 Frobenius Automorphisms}

\subsection{59.4.1 FrobeniusAutomorphism}
\\(\triangleleft\) FrobeniusAutomorphism\((F)\)\hspace{1cm}\hspace{1cm}\hspace{1cm} (attribute)

returns the Frobenius automorphism of the finite field \(F\) as a field homomorphism (see 32.12).

The Frobenius automorphism \(f\) of a finite field \(F\) of characteristic \(p\) is the function that takes each element \(z\) of \(F\) to its \(p\)-th power. Each field automorphism of \(F\) is a power of \(f\). Thus \(f\) is a generator for the Galois group of \(F\) relative to the prime field of \(F\), and an appropriate power of \(f\) is a generator of the Galois group of \(F\) over a subfield (see GaloisGroup (58.3.1)).

\begin{verbatim}
gap> f := GF(16);
GF(2^4)
gap> x := FrobeniusAutomorphism( f );
FrobeniusAutomorphism( GF(2^4) )
gap> Z(16) ^ x;
Z(2^4)^2
\end{verbatim}
gap> x^2;
FrobeniusAutomorphism( GF(2^4) )^2

The image of an element \( z \) under the \( i \)-th power of \( f \) is computed as the \( p^i \)-th power of \( z \). The product of the \( i \)-th power and the \( j \)-th power of \( f \) is the \( k \)-th power of \( f \), where \( k \equiv ij \mod \text{Size}(F) - 1 \). The zeroth power of \( f \) is \( \text{IdentityMapping}(F) \).

### 59.5 Conway Polynomials

#### 59.5.1 ConwayPolynomial

\[ \text{ConwayPolynomial}(p, n) \]

is the Conway polynomial of the finite field \( GF(p^n) \) as polynomial over the prime field in characteristic \( p \).

The Conway polynomial \( \Phi_{n,p} \) of \( GF(p^n) \) is defined by the following properties.

First define an ordering of polynomials of degree \( n \) over \( GF(p) \), as follows. \( f = \sum_{i=0}^{n} (-1)^i f_i x^i \) is smaller than \( g = \sum_{i=0}^{n} (-1)^i g_i x^i \) if and only if there is an index \( m \leq n \) such that \( f_i = g_i \) for all \( i > m \), and \( f_m < g_m \), where \( \tilde{c} \) denotes the integer value in \( \{0, 1, \ldots, p-1\} \) that is mapped to \( c \in GF(p) \) under the canonical epimorphism that maps the integers onto \( GF(p) \).

\( \Phi_{n,p} \) is primitive over \( GF(p) \) (see \( \text{IsPrimitivePolynomial}(66.4.12) \)). That is, \( \Phi_{n,p} \) is irreducible, monic, and is the minimal polynomial of a primitive root of \( GF(p^n) \).

For all divisors \( d \) of \( n \) the compatibility condition \( \Phi_{d,p}(x^{p^n-1}) \equiv 0 \pmod{\Phi_{n,p}(x)} \) holds. (That is, the appropriate power of a zero of \( \Phi_{n,p} \) is a zero of the Conway polynomial \( \Phi_{d,p} \).)

With respect to the ordering defined above, \( \Phi_{n,p} \) shall be minimal.

The computation of Conway polynomials can be time consuming. Therefore, GAP comes with a list of precomputed polynomials. If a requested polynomial is not stored then GAP prints a warning and computes it by checking all polynomials in the order defined above for the defining conditions. If \( n \) is not a prime this is probably a very long computation. (Some previously known polynomials with prime \( n \) are not stored in GAP because they are quickly recomputed.) Use the function \( \text{IsCheapConwayPolynomial}(59.5.2) \) to check in advance if \( \text{ConwayPolynomial} \) will give a result after a short time.

Note that primitivity of a polynomial can only be checked if GAP can factorize \( p^n - 1 \). A sufficiently new version of the \texttt{FactInt} package contains many precomputed factors of such numbers from various factorization projects.

See [Lüb03] for further information on known Conway polynomials.

An interactive overview of the Conway polynomials known to GAP is provided by the function \( \text{BrowseConwayPolynomials} \) from the GAP package Browse, see \texttt{BrowseGapData} (Browse: \texttt{BrowseGapData}).

If \( \text{pol} \) is a result returned by \texttt{ConwayPolynomial} the command \( \text{Print( InfoText( \text{pol} ) )} \); will print some info on the origin of that particular polynomial.

For some purposes it may be enough to have any primitive polynomial for an extension of a finite field instead of the Conway polynomial, see \texttt{RandomPrimitivePolynomial} (59.5.3) below.

\texttt{gap> ConwayPolynomial( 2, 5 ); ConwayPolynomial( 3, 7 );}
\begin{verbatim}
x_1^5+x_1^2+Z(2)^0
x_1^7-x_1^2+Z(3)^0
\end{verbatim}
59.5.2 IsCheapConwayPolynomial

\[ \text{IsCheapConwayPolynomial}(p, n) \]

Returns true if ConwayPolynomial(\( p, n \)) will give a result in reasonable time. This is either the case when this polynomial is pre-computed, or if \( n \) is a not too big prime.

59.5.3 RandomPrimitivePolynomial

\[ \text{RandomPrimitivePolynomial}(F, n[, i]) \]

For a finite field \( F \) and a positive integer \( n \) this function returns a primitive polynomial of degree \( n \) over \( F \), that is a zero of this polynomial has maximal multiplicative order \( |F|^n - 1 \). If \( i \) is given then the polynomial is written in variable number \( i \) over \( F \) (see Indeterminate (66.1.1)), the default for \( i \) is 1.

Alternatively, \( F \) can be a prime power \( q \), then \( F = GF(q) \) is assumed. And \( i \) can be a univariate polynomial over \( F \), then the result is a polynomial in the same variable.

This function can work for much larger fields than those for which Conway polynomials are available, of course GAP must be able to factorize \( |F|^n - 1 \).

59.6 Printing, Viewing and Displaying Finite Field Elements

59.6.1 ViewObj (for a ffe)

\[ \text{ViewObj}(z) \]
\[ \text{PrintObj}(z) \]
\[ \text{Display}(z) \]

Internal finite field elements are viewed, printed and displayed (see section 6.3 for the distinctions between these operations) as powers of the primitive root (except for the zero element, which is displayed as 0 times the primitive root). Thus:

\begin{verbatim}
Example

gap> Z(2);  
Z(2)^0
gap> Z(5)+Z(5);  
Z(5)^2
gap> Z(256);  
Z(2)^8
gap> Zero(Z(125));  
0*Z(5)
\end{verbatim}

Note also that each element is displayed as an element of the field it generates, and that the size of the field is printed as a power of the characteristic.

Elements of larger fields are printed as GAP expressions which represent them as sums of low powers of the primitive root:

\begin{verbatim}
Example

gap> Print( Z(3,20)^100, "\n" );  
2*Z(3,20)^2+Z(3,20)^4+Z(3,20)^6+Z(3,20)^7+2*Z(3,20)^9+2*Z(3,20)^10+2*Z
\end{verbatim}
Note from the second example above, that these elements are not always written over the smallest possible field before being output.

The ViewObj and Display methods for these large finite field elements use a slightly more compact, but mathematically equivalent representation. The primitive root is represented by \( z \); its \( i \)-th power by \( z^i \) and \( k \) times this power by \( k z^i \).

Example
\[
gap> Z(5,20)^100; \\
z2+z4+4z5+2z6+z8+3z9+4z10+3z12+z13+2z14+4z16+3z17+2z18+2z19
\]

This output format is always used for Display. For ViewObj it is used only if its length would not exceed the number of lines specified in the user preference ViewLength (see SetUserPreference (3.2.3)). Longer output is replaced by \(<\text{an element of GF}(p, d)>\>\).

Example
\[
gap> Z(2,409)^100000; \\
<<\text{an element of GF}(2, 409)>>
\]

Finally note that elements of large prime fields are stored and displayed as residue class objects. So

Example
\[
gap> Z(65537); \\
ZmodpZObj( 3, 65537 )
\]
Chapter 60

Abelian Number Fields

An abelian number field is a field in characteristic zero that is a finite dimensional normal extension of its prime field such that the Galois group is abelian. In GAP, one implementation of abelian number fields is given by fields of cyclotomic numbers (see Chapter 18). Note that abelian number fields can also be constructed with the more general AlgebraicExtension (67.1.1), a discussion of advantages and disadvantages can be found in 18.6. The functions described in this chapter have been developed for fields whose elements are in the filter IsCyclotomic (18.1.3), they may or may not work well for abelian number fields consisting of other kinds of elements.

Throughout this chapter, \( \mathbb{Q}_n \) will denote the cyclotomic field generated by the field \( \mathbb{Q} \) of rationals together with \( n \)-th roots of unity.

In 60.1, constructors for abelian number fields are described, 60.2 introduces operations for abelian number fields, 60.3 deals with the vector space structure of abelian number fields, and 60.4 describes field automorphisms of abelian number fields.

60.1 Construction of Abelian Number Fields

Besides the usual construction using Field (58.1.3) or DefaultField (18.1.16) (see DefaultField (18.1.16)), abelian number fields consisting of cyclotomics can be created with CyclotomicField (60.1.1) and AbelianNumberField (60.1.2).

60.1.1 CyclotomicField (for (subfield and) conductor)

\[
\begin{align*}
\text{CyclotomicField}([\text{subfield}, \, n]) & \quad \text{(function)} \\
\text{CyclotomicField}([\text{subfield}, \, \text{gens}]) & \quad \text{(function)} \\
\text{CF}([\text{subfield}, \, n]) & \quad \text{(function)} \\
\text{CF}([\text{subfield}, \, \text{gens}]) & \quad \text{(function)}
\end{align*}
\]

The first version creates the \( n \)-th cyclotomic field \( \mathbb{Q}_n \). The second version creates the smallest cyclotomic field containing the elements in the list \( \text{gens} \). In both cases the field can be generated as an extension of a designated subfield \( \text{subfield} \) (cf. 60.3).

CyclotomicField can be abbreviated to CF, this form is used also when GAP prints cyclotomic fields.

Fields constructed with the one argument version of CF are stored in the global list CYCLOTOMIC_FIELDS, so repeated calls of CF just fetch these field objects after they have been created.
once.

```gap
gap> CyclotomicField( 5 ); CyclotomicField( [ Sqrt(3) ] );
CF(5)
CF(12)
gap> CF( CF(3), 12 ); CF( CF(4), [ Sqrt(7) ] );
AsField( CF(3), CF(12) )
AsField( GaussianRationals, CF(28) )
```

### 60.1.2 AbelianNumberField

For a positive integer $n$ and a list `stab` of prime residues modulo $n$, `AbelianNumberField` returns the fixed field of the group described by `stab` (cf. `GaloisStabilizer` (60.2.5)), in the $n$-th cyclotomic field. `AbelianNumberField` is mainly thought for internal use and for printing fields in a standard way; `Field` (58.1.3) (cf. also 60.2) is probably more suitable if one knows generators of the field in question.

`AbelianNumberField` can be abbreviated to `NF`, this form is used also when `GAP` prints abelian number fields.

Fields constructed with `NF` are stored in the global list `ABELIAN_NUMBER_FIELDS`, so repeated calls of `NF` just fetch these field objects after they have been created once.

```gap
gap> NF( 7, [ 1 ] );
CF(7)
gap> f:= NF( 7, [ 1, 2 ] ); Sqrt(-7); Sqrt(-7) in f;
NF(7,[ 1, 2, 4 ])
E(7)+E(7)^2-E(7)^3+E(7)^4-E(7)^5-E(7)^6
true
```

### 60.1.3 GaussianRationals

`GaussianRationals` is the field $\mathbb{Q}_4 = \mathbb{Q}(\sqrt{-1})$ of Gaussian rationals, as a set of cyclotomic numbers, see Chapter 18 for basic operations. This field can also be obtained as $\text{CF}(4)$ (see `CyclotomicField` (60.1.1)).

The filter `IsGaussianRationals` returns `true` for the `GAP` object `GaussianRationals`, and `false` for all other `GAP` objects.

(For details about the field of rationals, see Chapter `Rationals` (17.1.1)).

```gap
gap> CF(4) = GaussianRationals;
true
gap> Sqrt(-1) in GaussianRationals;
true
```
60.2 Operations for Abelian Number Fields

For operations for elements of abelian number fields, e.g., `Conductor (18.1.7)` or `ComplexConjugate (18.5.2)`, see Chapter 18.

60.2.1 Factors (for polynomials over abelian number fields)

▷ `Factors(F)`

Factoring of polynomials over abelian number fields consisting of cyclotomics works in principle but is not very efficient if the degree of the field extension is large.

```
gap> x := Indeterminate( CF(5) );
  x_1
gap> Factors( PolynomialRing( Rationals ), x^5-1 );
  [ x_1-1, x_1^4+x_1^3+x_1^2+x_1+1 ]
gap> Factors( PolynomialRing( CF(5) ), x^5-1 );
  [ x_1-1, x_1+(-E(5)), x_1+(-E(5)^2), x_1+(-E(5)^3), x_1+(-E(5)^4) ]
```

60.2.2 IsNumberField

▷ `IsNumberField(F)`

returns `true` if the field `F` is a finite dimensional extension of a prime field in characteristic zero, and `false` otherwise.

60.2.3 IsAbelianNumberField

▷ `IsAbelianNumberField(F)`

returns `true` if the field `F` is a number field (see `IsNumberField (60.2.2)`) that is a Galois extension of the prime field, with abelian Galois group (see `GaloisGroup (58.3.1)`).

60.2.4 IsCyclotomicField

▷ `IsCyclotomicField(F)`

returns `true` if the field `F` is a cyclotomic field, i.e., an abelian number field (see `IsAbelianNumberField (60.2.3)`) that can be generated by roots of unity.

```
gap> IsNumberField( CF(9) ); IsAbelianNumberField( Field( [ ER(3) ] ) );
  true
  true
gap> IsNumberField( GF(2) );
  false
gap> IsCyclotomicField( CF(9) );
  true
gap> IsCyclotomicField( Field( [ Sqrt(-3) ] ) );
  true
```
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gap> IsCyclotomicField( Field( [ Sqrt(3) ] ) );
false

60.2.5 GaloisStabilizer

\texttt{GaloisStabilizer(} \texttt{F}) \quad \text{(attribute)}

Let \( F \) be an abelian number field (see \texttt{IsAbelianNumberField (60.2.3)}) with conductor \( n \), say. (This means that the \( n \)-th cyclotomic field is the smallest cyclotomic field containing \( F \), see \texttt{Conductor (18.1.7)}.) \texttt{GaloisStabilizer} returns the set of all those integers \( k \) in the range \([1..n]\) such that the field automorphism induced by raising \( n \)-th roots of unity to the \( k \)-th power acts trivially on \( F \).

Example

\begin{verbatim}
gap> r5:= Sqrt(5);;  # a cycl. field over the rationals
gap> GaloisCyc( r5, 4 ) = r5;  GaloisCyc( r5, 2 ) = r5;
true false
gap> GaloisStabilizer( Field( [ r5 ] ) );
[ 1, 4 ]
\end{verbatim}

60.3 Integral Bases of Abelian Number Fields

Each abelian number field is naturally a vector space over \( \mathbb{Q} \). Moreover, if the abelian number field \( F \) contains the \( n \)-th cyclotomic field \( \mathbb{Q}_n \) then \( F \) is a vector space over \( \mathbb{Q}_n \). In \texttt{GAP}, each field object represents a vector space object over a certain subfield \( S \), which depends on the way \( F \) was constructed. The subfield \( S \) can be accessed as the value of the attribute \texttt{LeftActingDomain (57.1.11)}.

The return values of \texttt{NF (60.1.2)} and of the one argument versions of \texttt{CF (60.1.1)} represent vector spaces over \( \mathbb{Q} \), and the return values of the two argument version of \texttt{CF (60.1.1)} represent vector spaces over the field that is given as the first argument. For an abelian number field \( F \) and a subfield \( S \) of \( F \), a \texttt{GAP} object representing \( F \) as a vector space over \( S \) can be constructed using \texttt{AsField (58.1.9)}.

Let \( F \) be the cyclotomic field \( \mathbb{Q}_n \), represented as a vector space over the subfield \( S \). If \( S \) is the cyclotomic field \( \mathbb{Q}_m \), with \( m \) a divisor of \( n \), then \texttt{CanonicalBasis(} \texttt{F}) \texttt{returns the Zumbroich basis of } \delta \texttt{relative to } S, \texttt{which consists of the roots of unity } E(n)^i \texttt{where } i \texttt{is an element of the list } ZumbroichBase( n, m ) \texttt{(see } ZumbroichBase (60.3.1)) \texttt{. If } S \texttt{is an abelian number field that is not a cyclotomic field then } CanonicalBasis( F ) \texttt{returns the Lenstra basis of } F \texttt{relative to } S, \texttt{that consists of the sums of roots of unity described by } LenstraBase( n, stab, stab, m ) \texttt{(see LenstraBase (60.3.2)). If } S \texttt{is an abelian number field that is not a cyclotomic field then } CanonicalBasis( F ) \texttt{returns a normal } S \texttt{-basis of } F.

Example

\begin{verbatim}
gap> f:= CF(8);;  # a cycl. field over the rationals
gap> b:= CanonicalBasis( f );;  BasisVectors( b );
[ 1, E(8), E(4), E(8)^3 ]
gap> Coefficients( b, Sqrt(-2) );
\end{verbatim}
gap> f:= AsField( CF(4), CF(8) );; # a cycl. field over a cycl. field
gap> b:= CanonicalBasis( f );; BasisVectors( b );
[ 1, E(8) ]
gap> Coefficients( b, Sqrt(-2) );
[ 0, 1+E(4) ]
gap> f:= AsField( Field( [ Sqrt(-2) ] ), CF(8) );;
# a cycl. field over a non-cycl. field
gap> b:= CanonicalBasis( f );; BasisVectors( b );
[ 1/2+1/2*E(8)-1/2*E(8)^2-1/2*E(8)^3,
 1/2-1/2*E(8)+1/2*E(8)^2+1/2*E(8)^3 ]
gap> Coefficients( b, Sqrt(-2) );
[ E(8)+E(8)^3, E(8)+E(8)^3 ]
gap> f:= Field( [ Sqrt(-2) ] ); # a non-cycl. field over the rationals
NF(8,[ 1, 3 ])
gap> b:= CanonicalBasis( f );; BasisVectors( b );
[ 1, E(8)+E(8)^3 ]
gap> Coefficients( b, Sqrt(-2) );
[ 0, 1 ]

60.3.1 ZumbroichBase

\[ \text{ZumbroichBase}(n, m) \]

Let \( n \) and \( m \) be positive integers, such that \( m \) divides \( n \). \text{ZumbroichBase} returns the set of exponents \( i \) for which \( E(n)^i \) belongs to the (generalized) Zumbroich basis of the cyclotomic field \( \mathbb{Q}_n \), viewed as a vector space over \( \mathbb{Q}_m \).

This basis is defined as follows. Let \( P \) denote the set of prime divisors of \( n \), \( n = \prod_{p \in P} p^{\nu_p} \), and \( m = \prod_{p \in P} p^{\mu_p} \) with \( \mu_p \leq \nu_p \). Let \( e_l = E(l) \) for any positive integer \( l \), and \( \{ e_{n_1}^j \}_{j \in J} \otimes \{ e_{n_2}^k \}_{k \in K} = \{ e_{n_1}^j \cdot e_{n_2}^k \}_{j \in J, k \in K} \).

Then the basis is

\[ B_{n,m} = \bigotimes_{p \in P} \bigotimes_{k=\mu_p}^{\nu_p-1} \{ e_{p^k}^j \}_{j \in J_{k,p}} \]

where \( J_{k,p} = \)

\[
\begin{align*}
\{0\} & \quad ; \quad k = 0, p = 2 \\
\{0, 1\} & \quad ; \quad k > 0, p = 2 \\
\{1, \ldots, p-1\} & \quad ; \quad k = 0, p \neq 2 \\
\{-(p-1)/2, \ldots, (p-1)/2\} & \quad ; \quad k > 0, p \neq 2
\end{align*}
\]

\( B_{n,1} \) is equal to the basis of \( \mathbb{Q}_n \) over the rationals which is introduced in [Zum89]. Also the conversion of arbitrary sums of roots of unity into its basis representation, and the reduction to the minimal cyclotomic field are described in this thesis. (Note that the notation here is slightly different from that there.)

\( B_{n,m} \) consists of roots of unity, it is an integral basis (that is, exactly the integral elements in \( \mathbb{Q}_n \) have integral coefficients w.r.t. \( B_{n,m} \), cf. \text{IsIntegralCyclotomic} (18.1.4)), it is a normal basis for squarefree \( n \) and closed under complex conjugation for odd \( n \).
Note: For \( n \equiv 2 \pmod{4} \), we have \( \text{ZumbroichBase}(n, 1) = 2 \times \text{ZumbroichBase}(n/2, 1) \) and \( \text{List}( \text{ZumbroichBase}(n, 1), x \rightarrow E(n)^{x} ) = \text{List}( \text{ZumbroichBase}(n/2, 1), x \rightarrow E(n/2)^{x} ) \).

Example

```gap
gap> ZumbroichBase( 15, 1 ); ZumbroichBase( 12, 3 );
[ 1, 2, 4, 7, 8, 11, 13, 14 ]
[ 0, 3 ]
gap> ZumbroichBase( 10, 2 ); ZumbroichBase( 32, 4 );
[ 2, 4, 6, 8 ]
[ 0, 1, 2, 3, 4, 5, 6, 7 ]
```

60.3.2 LenstraBase

\texttt{LenstraBase}(n, \texttt{stabilizer}, \texttt{super}, m)

Let \( n \) and \( m \) be positive integers such that \( m \) divides \( n \), \( \text{stabilizer} \) be a list of prime residues modulo \( n \), which describes a subfield of the \( n \)-th cyclotomic field (see \texttt{GaloisStabilizer} (60.2.5)), and \( \text{super} \) be a list representing a supergroup of the group given by \( \text{stabilizer} \).

\text{LenstraBase} returns a list \([b_1, b_2, \ldots, b_k]\) of lists, each \( b_i \) consisting of integers such that the elements \( \sum_{j \in b_i} E(n)^j \) form a basis of the abelian number field \( \text{NF}(n, \text{stabilizer}) \), as a vector space over the \( m \)-th cyclotomic field (see \texttt{AbelianNumberField} (60.1.2)).

This basis is an integral basis, that is, exactly the integral elements in \( \text{NF}(n, \text{stabilizer}) \) have integral coefficients. (For details about this basis, see [Bre97].)

If possible then the result is chosen such that the group described by \( \text{super} \) acts on it, consistently with the action of \( \text{stabilizer} \), i.e., each orbit of \( \text{super} \) is a union of orbits of \( \text{stabilizer} \). (A usual case is \( \text{super} = \text{stabilizer} \), so there is no additional condition.

Note: The \( b_i \) are in general not sets, since for \( \text{stabilizer} = \text{super} \), the first entry is always an element of \( \text{ZumbroichBase}(n, m) \); this property is used by \( \text{NF} \) (60.1.2) and \texttt{Coefficients} (61.6.3) (see 60.3).

\( \text{stabilizer} \) must not contain the stabilizer of a proper cyclotomic subfield of the \( n \)-th cyclotomic field, i.e., the result must describe a basis for a field with conductor \( n \).

Example

```gap
gap> LenstraBase( 24, [ 1, 19 ], [ 1, 19 ], 1 );
[ [ 1, 19 ], [ 8 ], [ 11, 17 ], [ 16 ] ]
gap> LenstraBase( 24, [ 1, 19 ], [ 1, 5, 19, 23 ], 1 );
[ [ 1, 19 ], [ 5, 23 ], [ 8 ], [ 16 ] ]
gap> LenstraBase( 15, [ 1, 4 ], 
PrimeResidues( 15 ), 1 );
[ [ 1, 4 ], [ 2, 8 ], [ 7, 13 ], [ 11, 14 ] ]
```

The first two results describe two bases of the field \( \mathbb{Q}_3(\sqrt{6}) \), the third result describes a normal basis of \( \mathbb{Q}_3(\sqrt{5}) \).

60.4 Galois Groups of Abelian Number Fields

The field automorphisms of the cyclotomic field \( \mathbb{Q}_n \) (see Chapter 18) are given by the linear maps *k on \( \mathbb{Q}_n \) that are defined by \( E(n)^k = E(n)^k \), where \( 1 \leq k < n \) and \( \text{Gcd}(n, k) = 1 \) hold (see \texttt{GaloisCyc}...
Note that this action is not equal to exponentiation of cyclotomics, i.e., for general cyclotomics \( z, z^k \) is different from \( z^k \).

(In GAP, the image of a cyclotomic \( z \) under \( \ast k \) can be computed as \texttt{GaloisCyc( } z,k \texttt{ ).})

\begin{verbatim}
gap> ( E(5) + E(5)^4 )^2; GaloisCyc( E(5) + E(5)^4, 2 );
-2*E(5)-E(5)^2-E(5)^3-2*E(5)^4
E(5)^2+E(5)^3
\end{verbatim}

For \( \gcd(n,k) \neq 1 \), the map \( E(n) \mapsto E(n)^k \) does not define a field automorphism of \( \mathbb{Q}_n \) but only a \( \mathbb{Q} \)-linear map.

\begin{verbatim}
Example

\texttt{gap> GaloisCyc( E(5)+E(5)^4, 5 ); GaloisCyc( ( E(5)+E(5)^4 )^2, 5 );
2 -6}
\end{verbatim}

\section{GaloisGroup (for abelian number fields)}

\texttt{\textgreater \ GaloisGroup( } F \texttt{ )}

The Galois group \( \text{Gal}(\mathbb{Q}_n, \mathbb{Q}) \) of the field extension \( \mathbb{Q}_n/\mathbb{Q} \) is isomorphic to the group \( (\mathbb{Z}/n\mathbb{Z})^* \) of prime residues modulo \( n \), via the isomorphism \( (\mathbb{Z}/n\mathbb{Z})^* \rightarrow \text{Gal}(\mathbb{Q}_n, \mathbb{Q}) \) that is defined by \( k+n\mathbb{Z} \mapsto (z \mapsto z^k) \).

The Galois group of the field extension \( \mathbb{Q}_n/L \) with any abelian number field \( L \subseteq \mathbb{Q}_n \) is simply the factor group of \( \text{Gal}(\mathbb{Q}_n, \mathbb{Q}) \) modulo the stabilizer of \( L \), and the Galois group of \( L'/L' \), with \( L' \) an abelian number field contained in \( L \), is the subgroup in this group that stabilizes \( L' \). These groups are easily described in terms of \( (\mathbb{Z}/n\mathbb{Z})^* \). Generators of \( (\mathbb{Z}/n\mathbb{Z})^* \) can be computed using \texttt{GeneratorsPrimeResidues (15.2.4)}.

In GAP, a field extension \( L/L' \) is given by the field object \( L \) with \texttt{LeftActingDomain (57.1.11)} value \( L' \) (see 60.3).

\begin{verbatim}
Example

\texttt{gap> f:= CF(15);
CF(15)
\texttt{gap> g:= GaloisGroup( f );
<group with 2 generators>
\texttt{gap> Size( g ); IsCyclic( g ); IsAbelian( g );
8 false true
\texttt{gap> Action( g, NormalBase( f ), OnPoints );
Group([ (1,6)(2,4)(3,8)(5,7), (1,4,3,7)(2,8,5,6) ])
\end{verbatim}

The following example shows Galois groups of a cyclotomic field and of a proper subfield that is not a cyclotomic field.

\begin{verbatim}
Example

\texttt{gap> gens1:= GeneratorsOfGroup( GaloisGroup( CF(5) ) );
[ ANFAutomorphism( CF(5), 2 ) ]
\texttt{gap> gens2:= GeneratorsOfGroup( GaloisGroup( Field( Sqrt(5) ) ) );
[ ANFAutomorphism( NF(5,[ 1, 4 ]), 2 ) ]}
\end{verbatim}
The following example shows the Galois group of a cyclotomic field over a non-cyclotomic field.

```gap
gap> g:= GaloisGroup( AsField( Field( [ Sqrt(5) ] ), CF(5) ) );
<group of size 2 with 1 generators>
gap> gens:= GeneratorsOfGroup( g );
[ ANFAutomorphism( AsField( NF(5,[ 1, 4 ]), CF(5) ), 4 ) ]
gap> x:= last[1];; x^2;
IdentityMapping( AsField( NF(5,[ 1, 4 ]), CF(5) ) )
```

### ANFAutomorphism

**Example**

Let $F$ be an abelian number field and $k$ be an integer that is coprime to the conductor (see `Conductor (18.1.7)`) of $F$. Then `ANFAutomorphism` returns the automorphism of $F$ that is defined as the linear extension of the map that raises each root of unity in $F$ to its $k$-th power.

```gap
gap> f:= CF(25);
CF(25)
gap> alpha:= ANFAutomorphism( f, 2 );
ANFAutomorphism( CF(25), 2 )
gap> alpha^2;
ANFAutomorphism( CF(25), 4 )
gap> Order( alpha );
20
gap> E(5)^alpha;
E(5)^2
```

### Gaussians

#### GaussianIntegers

**Example**

GaussianIntegers is the ring $\mathbb{Z}[\sqrt{-1}]$ of Gaussian integers. This is a subring of the cyclotomic field GaussianRationals (60.1.3).

#### IsGaussianIntegers

is the defining category for the domain GaussianIntegers (60.5.1).
Chapter 61

Vector Spaces

61.1 IsLeftVectorSpace (Filter)

61.1.1 IsLeftVectorSpace

\[ \text{IsLeftVectorSpace}(V) \quad \text{(Category)} \]
\[ \text{IsVectorSpace}(V) \quad \text{(Category)} \]

A vector space in GAP is a free left module (see IsFreeLeftModule (57.3.1)) over a division ring (see Chapter 58).

Whenever we talk about an \( F \)-vector space \( V \) then \( V \) is an additive group (see IsAdditiveGroup (55.1.6)) on which the division ring \( F \) acts via multiplication from the left such that this action and the addition in \( V \) are left and right distributive. The division ring \( F \) can be accessed as value of the attribute LeftActingDomain (57.1.11).

Vector spaces in GAP are always left vector spaces, IsLeftVectorSpace and IsVectorSpace are synonyms.

61.2 Constructing Vector Spaces

61.2.1 VectorSpace

\[ \text{VectorSpace}(F, \text{gens}[, \text{zero}] [, \text{"basis"]}) \quad \text{(function)} \]

For a field \( F \) and a collection \( \text{gens} \) of vectors, VectorSpace returns the \( F \)-vector space spanned by the elements in \( \text{gens} \).

The optional argument \( \text{zero} \) can be used to specify the zero element of the space; \( \text{zero} \) must be given if \( \text{gens} \) is empty. The optional string "basis" indicates that \( \text{gens} \) is known to be linearly independent over \( F \), in particular the dimension of the vector space is immediately set; note that Basis (61.5.2) need not return the basis formed by \( \text{gens} \) if the string "basis" is given as an argument.

Example

\[ \text{gap}\> V := \text{VectorSpace} (\text{Rationals}, \{ [1, 2, 3], [1, 1, 1] \}); \]
\[<\text{vector space over Rationals, with 2 generators}>\]
61.2.2 Subspace

- Subspace\((V, \text{gens}[, \text{"basis"}])\) (function)
- SubspaceNC\((V, \text{gens}[, \text{"basis"}])\) (function)

For an \(F\)-vector space \(V\) and a list or collection \(\text{gens}\) that is a subset of \(V\), Subspace returns the \(F\)-vector space spanned by \(\text{gens}\); if \(\text{gens}\) is empty then the trivial subspace (see TrivialSubspace (61.3.2)) of \(V\) is returned. The parent (see 31.7) of the returned vector space is set to \(V\).

SubspaceNC does the same as Subspace, except that it omits the check whether \(\text{gens}\) is a subset of \(V\).

The optional string \"basis\" indicates that \(\text{gens}\) is known to be linearly independent over \(F\). In this case the dimension of the subspace is immediately set, and both Subspace and SubspaceNC do not check whether \(\text{gens}\) really is linearly independent and whether \(\text{gens}\) is a subset of \(V\).

Example

\[
gap> V := \text{VectorSpace}(\text{Rationals}, \left[ \begin{array}{c} 1, 2, 3 \end{array} \right], \left[ \begin{array}{c} 1, 1, 1 \end{array} \right]);;
gap> W := \text{Subspace}(V, \left[ \begin{array}{c} 0, 1, 2 \end{array} \right]);
\text{<vector space over Rationals, with 1 generators>}
\]

61.2.3 AsVectorSpace

- AsVectorSpace\((F, D)\) (operation)

Let \(F\) be a division ring and \(D\) a domain. If the elements in \(D\) form an \(F\)-vector space then AsVectorSpace returns this \(F\)-vector space, otherwise fail is returned.

AsVectorSpace can be used for example to view a given vector space as a vector space over a smaller or larger division ring.

Example

\[
gap> V := \text{FullRowSpace}(\text{GF}(27), 3);
\text{( GF(3^3)^3 )}
gap> \text{Dimension}(V); \text{LeftActingDomain}(V);
3 \text{GF(3^3)}
gap> W := \text{AsVectorSpace}(\text{GF}(3), V);
\text{<vector space over GF(3), with 9 generators>}
gap> \text{Dimension}(W); \text{LeftActingDomain}(W);
9 \text{GF(3)}
gap> \text{AsVectorSpace}(\text{GF}(9), V);
\text{fail}
\]

61.2.4 AsSubspace

- AsSubspace\((V, U)\) (operation)

Let \(V\) be an \(F\)-vector space, and \(U\) a collection. If \(U\) is a subset of \(V\) such that the elements of \(U\) form an \(F\)-vector space then AsSubspace returns this vector space, with parent set to \(V\) (see AsVectorSpace (61.2.3)). Otherwise fail is returned.
Example

```gap
gap> V := VectorSpace( Rationals, [[ 1, 2, 3 ], [ 1, 1, 1 ]] );;
gap> W := VectorSpace( Rationals, [[ 1/2, 1/2, 1/2 ]] );;
gap> U := AsSubspace( V, W );
<vector space over Rationals, with 1 generators>
gap> Parent( U ) = V;
true
gap> AsSubspace( V, [[ 1, 1, 1 ]] );
fail
```

### 61.3 Operations and Attributes for Vector Spaces

#### 61.3.1 GeneratorsOfLeftVectorSpace

- **GeneratorsOfLeftVectorSpace**
  - **GeneratorsOfLeftVectorSpace** \((V)\) (attribute)
  - **GeneratorsOfVectorSpace** \((V)\) (attribute)

  For an \(F\)-vector space \(V\), \texttt{GeneratorsOfLeftVectorSpace} returns a list of vectors in \(V\) that generate \(V\) as an \(F\)-vector space.

  **Example**

  ```gap
gap> GeneratorsOfVectorSpace( FullRowSpace( Rationals, 3 ) );
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ]
```

#### 61.3.2 TrivialSubspace

- **TrivialSubspace**
  - **TrivialSubspace** \((V)\) (attribute)

  For a vector space \(V\), \texttt{TrivialSubspace} returns the subspace of \(V\) that consists of the zero vector in \(V\).

  **Example**

  ```gap
gap> V := GF(3)^3;;
gap> triv := TrivialSubspace( V );
<vector space of dimension 0 over GF(3)>
gap> AsSet( triv );
[ [ 0*Z(3), 0*Z(3), 0*Z(3) ] ]
```

### 61.4 Domains of Subspaces of Vector Spaces

#### 61.4.1 Subspaces

- **Subspaces** \((V[I, k])\) (attribute)

  Called with a finite vector space \(V\), \texttt{Subspaces} returns the domain of all subspaces of \(V\).
  Called with \(V\) and a nonnegative integer \(k\), \texttt{Subspaces} returns the domain of all \(k\)-dimensional subspaces of \(V\).

  Special \texttt{Size} (30.4.6) and \texttt{Iterator} (30.8.1) methods are provided for these domains.
61.4.2 IsSubspacesVectorSpace

The domain of all subspaces of a (finite) vector space or of all subspaces of fixed dimension, as returned by Subspaces (61.4.1) (see Subspaces (61.4.1)) lies in the category IsSubspacesVectorSpace.

Example

```gap
gap> D:= Subspaces( GF(3)^3 );
Subspaces( ( GF(3)^3 ) )
gap> Size( D );
28
gap> iter:= Iterator( D );;
gap> NextIterator( iter );
<vector space of dimension 0 over GF(3)>
gap> NextIterator( iter );
<vector space of dimension 1 over GF(3)>
gap> IsSubspacesVectorSpace( D );
true
```

61.5 Bases of Vector Spaces

In GAP, a basis of a free left F-module V is a list of vectors \( B = [v_1, v_2, \ldots, v_n] \) in V such that V is generated as a left F-module by these vectors and such that \( B \) is linearly independent over F. The integer \( n \) is the dimension of V (see Dimension (57.3.3)). In particular, as each basis is a list (see Chapter 21), it has a length (see Length (21.17.5)), and the \( i \)-th vector of \( B \) can be accessed as \( B[i] \).

Example

```gap
gap> V:= Rationals^3;
( Rationals^3 )
gap> B:= Basis( V );
CanonicalBasis( ( Rationals^3 ) )
gap> Length( B );
3
gap> B[1];
[ 1, 0, 0 ]
```

The operations described below make sense only for bases of finite dimensional vector spaces. (In practice this means that the vector spaces must be low dimensional, that is, the dimension should not exceed a few hundred.)

Besides the basic operations for lists (see 21.2), the basic operations for bases are BasisVectors (61.6.1), Coefficients (61.6.3), LinearCombination (61.6.4), and UnderlyingLeftModule (61.6.2). These and other operations for arbitrary bases are described in 61.6. For special kinds of bases, further operations are defined (see 61.7).

GAP supports the following three kinds of bases.

Relative bases delegate the work to other bases of the same free left module, via basechange matrices (see RelativeBasis (61.5.4)).

Bases handled by nice bases delegate the work to bases of isomorphic left modules over the same left acting domain (see 61.11).

Finally, of course there must be bases in GAP that really do the work.
For example, in the case of a Gaussian row or matrix space $V$ (see 61.9), $\text{Basis}(V)$ is a semi-echelonized basis (see $\text{IsSemiEchelonized}$ (61.9.7)) that uses Gaussian elimination; such a basis is of the third kind. $\text{Basis}(V, \text{vectors})$ is either semi-echelonized or a relative basis. Other examples of bases of the third kind are canonical bases of finite fields and of abelian number fields.

Bases handled by nice bases are described in 61.11. Examples are non-Gaussian row and matrix spaces, and subspaces of finite fields and abelian number fields that are themselves not fields.

### 61.5.1 IsBasis

\[ \text{IsBasis}( \text{obj} ) \]

(Category)

In GAP, a basis of a free left module is an object that knows how to compute coefficients w.r.t. its basis vectors (see Coefficients (61.6.3)). Bases are constructed by $\text{Basis}$ (61.5.2). Each basis is an immutable list, the $i$-th entry being the $i$-th basis vector.

(See 61.8 for mutable bases.)

---

Example

\[
gap> V := \text{GF}(2)^2; \\
gap> B := \text{Basis}( V ); \\
gap> \text{IsBasis}( B ); \\
true \\
gap> \text{IsBasis}( [ [ 1, 0 ], [ 0, 1 ] ] ); \\
false \\
gap> \text{IsBasis}( \text{Basis}( \text{Rationals}^2, [ [ 1, 0 ], [ 0, 1 ] ] ) ); \\
true
\]

---

### 61.5.2 Basis

\[ \text{Basis}(V[, \text{vectors}]) \]

\[ \text{BasisNC}(V, \text{vectors}) \]

Called with a free left $F$-module $V$ as the only argument, $\text{Basis}$ returns an $F$-basis of $V$ whose vectors are not further specified.

If additionally a list $\text{vectors}$ of vectors in $V$ is given that forms an $F$-basis of $V$ then $\text{Basis}$ returns this basis; if $\text{vectors}$ is not linearly independent over $F$ or does not generate $V$ as a free left $F$-module then fail is returned.

$\text{BasisNC}$ does the same as the two argument version of $\text{Basis}$, except that it does not check whether $\text{vectors}$ form a basis.

If no basis vectors are prescribed then $\text{Basis}$ need not compute basis vectors; in this case, the vectors are computed in the first call to $\text{BasisVectors}$ (61.6.1).

---

Example

\[
gap> V := \text{VectorSpace}( \text{Rationals}, [ [ 1, 2, 7 ], [ 1/2, 1/3, 5 ] ] );; \\
gap> B := \text{Basis}( V ); \\
\text{SemiEchelonBasis}( \text{<vector space over Rationals, with 2 generators>, ... } ) \\
gap> \text{BasisVectors}( B ); \\
[ [ 1, 2, 7 ], [ 0, 1, -9/4 ] ] \\
gap> B := \text{Basis}( V, [ [ 1, 2, 7 ], [ 3, 2, 30 ] ] ); \\
\text{Basis}( \text{<vector space over Rationals, with 2 generators>, [ [ 1, 2, 7 ], [ 3, 2, 30 ] ] } )
\]
61.5.3 CanonicalBasis

If the vector space $V$ supports a *canonical basis* then CanonicalBasis returns this basis, otherwise fail is returned.

The defining property of a canonical basis is that its vectors are uniquely determined by the vector space. If canonical bases exist for two vector spaces over the same left acting domain (see LeftActingDomain (57.1.11)) then the equality of these vector spaces can be decided by comparing the canonical bases.

The exact meaning of a canonical basis depends on the type of $V$. Canonical bases are defined for example for Gaussian row and matrix spaces (see 61.9).

If one designs a new kind of vector spaces (see 61.12) and defines a canonical basis for these spaces then the CanonicalBasis method one installs (see InstallMethod (78.3.1)) must *not* call Basis (61.5.2). On the other hand, one probably should install a Basis method that simply calls CanonicalBasis, the value of the method (see 78.3 and 78.4) being CANONICAL_BASIS_FLAGS.

Example

```gap
gap> vecs:= [ [ 1, 2, 3 ], [ 1, 1, 1 ], [ 1, 1, 1 ] ];;
gap> V:= VectorSpace( Rationals, vecs );;
gap> B:= CanonicalBasis( V );
CanonicalBasis( <vector space over Rationals, with 3 generators> )
gap> BasisVectors( B );
[ [ 1, 0, -1 ], [ 0, 1, 2 ] ]
```

61.5.4 RelativeBasis

A relative basis is a basis of the free left module $V$ that delegates the computation of coefficients etc. to another basis of $V$ via a basechange matrix.

Let $B$ be a basis of the free left module $V$, and $vectors$ a list of vectors in $V$.

RelativeBasis checks whether vectors form a basis of $V$, and in this case a basis is returned in which vectors are the basis vectors; otherwise fail is returned.

RelativeBasisNC does the same, except that it omits the check.

61.6 Operations for Vector Space Bases

61.6.1 BasisVectors

Example

```gap
gap> vecs:= [ [ 1, 2, 3 ], [ 1, 1, 1 ], [ 1, 1, 1 ] ];;
gap> V:= VectorSpace( Rationals, vecs );;
gap> B:= CanonicalBasis( V );
CanonicalBasis( <vector space over Rationals, with 3 generators> )
gap> BasisVectors( B );
[ [ 1, 0, -1 ], [ 0, 1, 2 ] ]
```
For a vector space basis \( B \), \texttt{BasisVectors} returns the list of basis vectors of \( B \). The lists \( B \) and \texttt{BasisVectors( \( B \))} are equal; the main purpose of \texttt{BasisVectors} is to provide access to a list of vectors that does \textit{not} know about an underlying vector space.

**Example**

```gap
gap> V:= VectorSpace( Rationals, [ [ 1, 2, 7 ], [ 1/2, 1/3, 5 ] ] );;
gap> B:= Basis( V, [ [ 1, 2, 7 ], [ 0, 1, -9/4 ] ] );;
gap> BasisVectors( B );
[ [ 1, 2, 7 ], [ 0, 1, -9/4 ] ]
```

### 61.6.2 UnderlyingLeftModule

\( \triangleright \texttt{UnderlyingLeftModule(} \( B \texttt{)} \) (attribute)

For a basis \( B \) of a free left module \( V \), say, \texttt{UnderlyingLeftModule} returns \( V \).

The reason why a basis stores a free left module is that otherwise one would have to store the basis vectors and the coefficient domain separately. Storing the module allows one for example to deal with bases whose basis vectors have not yet been computed yet (see \texttt{Basis (61.5.2)}); furthermore, in some cases it is convenient to test membership of a vector in the module before computing coefficients w.r.t. a basis.

**Example**

```gap
gap> B:= Basis( GF(2)^6 );
gap> UnderlyingLeftModule( B );
( GF(2)^6 )
```

### 61.6.3 Coefficients

\( \triangleright \texttt{Coefficients(} \( B, v \texttt{)} \) (operation)

Let \( V \) be the underlying left module of the basis \( B \), and \( v \) a vector such that the family of \( v \) is the elements family of the family of \( V \). Then \texttt{Coefficients( \( B, v \))} is the list of coefficients of \( v \) w.r.t. \( B \) if \( v \) lies in \( V \), and \textit{fail} otherwise.

**Example**

```gap
gap> V:= VectorSpace( Rationals, [ [ 1, 2, 7 ], [ 1/2, 1/3, 5 ] ] );;
gap> B:= Basis( V, [ [ 1, 2, 7 ], [ 0, 1, -9/4 ] ] );;
gap> Coefficients( B, [ 1/2, 1/3, 5 ] );
[ 1/2, -2/3 ]
gap> Coefficients( B, [ 1, 0, 0 ] );
fail
```

### 61.6.4 LinearCombination

\( \triangleright \texttt{LinearCombination(} \( B, \texttt{coeff} \texttt{)} \) (operation)

If \( B \) is a basis object (see \texttt{IsBasis (61.5.1)}) or a homogeneous list of length \( n \), say, and \texttt{coeff} is a row vector of the same length, \texttt{LinearCombination} returns the vector \( \sum_{i=1}^{n} \texttt{coeff[i]} \ast \texttt{B[i]} \).

Perhaps the most important usage is the case where \( B \) forms a basis.

**Example**

```gap
gap> V:= VectorSpace( Rationals, [ [ 1, 2, 7 ], [ 1/2, 1/3, 5 ] ] );;
gap> B:= Basis( V, [ [ 1, 2, 7 ], [ 0, 1, -9/4 ] ] );;
gap> LinearCombination( B, [ 1/2, -2/3 ] );
[ 1/2, 1/3, 5 ]
```
61.6.5 EnumeratorByBasis

\[ \text{EnumeratorByBasis}(B) \] (attribute)

For a basis \( B \) of the free left \( F \)-module \( V \) of dimension \( n \), say, \( \text{EnumeratorByBasis} \) returns an enumerator that loops over the elements of \( V \) as linear combinations of the vectors of \( B \) with coefficients the row vectors in the full row space (see FullRowSpace (61.9.4)) of dimension \( n \) over \( F \), in the succession given by the default enumerator of this row space.

Example

\begin{verbatim}
gap> V:= GF(2)^3;;
gap> enum:= EnumeratorByBasis( CanonicalBasis( V ) );;
gap> Print( enum{ [ 1 .. 4 ] }, "\n" );
[ [ 0*Z(2), 0*Z(2), 0*Z(2) ], [ 0*Z(2), 0*Z(2), Z(2)^0 ],
  [ 0*Z(2), Z(2)^0, 0*Z(2) ], [ 0*Z(2), Z(2)^0, Z(2)^0 ] ]
gap> B:= Basis( V, [ [ 1, 1, 1 ], [ 1, 1, 0 ], [ 1, 0, 0 ] ] * Z(2) );;
gap> enum:= EnumeratorByBasis( B );;
gap> Print( enum{ [ 1 .. 4 ] }, "\n" );
[ [ 0*Z(2), 0*Z(2), 0*Z(2) ], [ Z(2)^0, 0*Z(2), 0*Z(2) ],
  [ Z(2)^0, Z(2)^0, 0*Z(2) ], [ 0*Z(2), Z(2)^0, 0*Z(2) ] ]
\end{verbatim}

61.6.6 IteratorByBasis

\[ \text{IteratorByBasis}(B) \] (operation)

For a basis \( B \) of the free left \( F \)-module \( V \) of dimension \( n \), say, \( \text{IteratorByBasis} \) returns an iterator that loops over the elements of \( V \) as linear combinations of the vectors of \( B \) with coefficients the row vectors in the full row space (see FullRowSpace (61.9.4)) of dimension \( n \) over \( F \), in the succession given by the default enumerator of this row space.

Example

\begin{verbatim}
gap> V:= GF(2)^3;;
gap> iter:= IteratorByBasis( CanonicalBasis( V ) );;
gap> for i in [ 1 .. 4 ] do Print( NextIterator( iter ), "\n" ); od;
[ 0*Z(2), 0*Z(2), 0*Z(2) ]
[ 0*Z(2), 0*Z(2), Z(2)^0 ]
[ 0*Z(2), Z(2)^0, 0*Z(2) ]
[ 0*Z(2), Z(2)^0, Z(2)^0 ]
gap> B:= Basis( V, [ [ 1, 1, 1 ], [ 1, 1, 0 ], [ 1, 0, 0 ] ] * Z(2) );;
gap> iter:= IteratorByBasis( B );;
gap> for i in [ 1 .. 4 ] do Print( NextIterator( iter ), "\n" ); od;
[ 0*Z(2), 0*Z(2), 0*Z(2) ]
[ Z(2)^0, 0*Z(2), 0*Z(2) ]
[ Z(2)^0, Z(2)^0, 0*Z(2) ]
[ 0*Z(2), Z(2)^0, 0*Z(2) ]
\end{verbatim}

61.7 Operations for Special Kinds of Bases

61.7.1 IsCanonicalBasis

\[ \text{IsCanonicalBasis}(B) \] (property)
If the underlying free left module \( V \) of the basis \( B \) supports a canonical basis (see \texttt{CanonicalBasis} (61.5.3)) then \texttt{IsCanonicalBasis} returns \texttt{true} if \( B \) is equal to the canonical basis of \( V \), and \texttt{false} otherwise.

### 61.7.2 IsIntegralBasis

\[ \texttt{IsIntegralBasis}(B) \] (property)

Let \( B \) be an \( S \)-basis of a field \( F \), say, for a subfield \( S \) of \( F \), and let \( R \) and \( M \) be the rings of algebraic integers in \( S \) and \( F \), respectively. \texttt{IsIntegralBasis} returns \texttt{true} if \( B \) is also an \( R \)-basis of \( M \), and \texttt{false} otherwise.

### 61.7.3 IsNormalBasis

\[ \texttt{IsNormalBasis}(B) \] (property)

Let \( B \) be an \( S \)-basis of a field \( F \), say, for a subfield \( S \) of \( F \). \texttt{IsNormalBasis} returns \texttt{true} if \( B \) is invariant under the Galois group (see \texttt{GaloisGroup} (58.3.1)) of the field extension \( F/S \), and \texttt{false} otherwise.

**Example**

```gap
gap> B:= CanonicalBasis( GaussianRationals );
CanonicalBasis( GaussianRationals )
gap> IsIntegralBasis( B ); IsNormalBasis( B );
true false
```

### 61.8 Mutable Bases

It is useful to have a mutable basis of a free module when successively closures with new vectors are formed, since one does not want to create a new module and a corresponding basis for each step.

Note that the situation here is different from the situation with stabilizer chains, which are (mutable or immutable) records that do not need to know about the groups they describe, whereas each (immutable) basis stores the underlying left module (see \texttt{UnderlyingLeftModule} (61.6.2)).

So immutable bases and mutable bases are different categories of objects. The only thing they have in common is that one can ask both for their basis vectors and for the coefficients of a given vector.

Since \texttt{Immutable} produces an immutable copy of any \texttt{GAP} object, it would in principle be possible to construct a mutable basis that is in fact immutable. In the sequel, we will deal only with mutable bases that are in fact mutable \texttt{GAP} objects, hence these objects are unable to store attribute values.

Basic operations for immutable bases are \texttt{NrBasisVectors} (61.8.3), \texttt{IsContainedInSpan} (61.8.5), \texttt{CloseMutableBasis} (61.8.6), \texttt{ImmutableBasis} (61.8.4), \texttt{Coefficients} (61.6.3), and \texttt{BasisVectors} (61.6.1). \texttt{ShallowCopy} (12.7.1) for a mutable basis returns a mutable plain list containing the current basis vectors.

Since mutable bases do not admit arbitrary changes of their lists of basis vectors, a mutable basis is not a list. It is, however, a collection, more precisely its family (see 13.1) equals the family of its collection of basis vectors.

Mutable bases can be constructed with \texttt{MutableBasis}.
Similar to the situation with bases (cf. 61.5), GAP supports the following three kinds of mutable bases.

The generic method of `MutableBasis` returns a mutable basis that simply stores an immutable basis; clearly one wants to avoid this whenever possible with reasonable effort.

There are mutable bases that store a mutable basis for a nicer module. Note that this is meaningful only if the mechanism of computing nice and ugly vectors (see 61.11) is invariant under closures of the basis; this is the case for example if the vectors are matrices, Lie objects, or elements of structure constants algebras.

There are mutable bases that use special information to perform their tasks; examples are mutable bases of Gaussian row and matrix spaces.

### 61.8.1 IsMutableBasis

`IsMutableBasis( MB )` (Category)

Every mutable basis lies in the category `IsMutableBasis`.

### 61.8.2 MutableBasis

`MutableBasis( R, vectors [, zero] )` (operation)

`MutableBasis` returns a mutable basis for the $R$-free module generated by the vectors in the list `vectors`. The optional argument `zero` is the zero vector of the module; it must be given if `vectors` is empty.

Note that `vectors` will in general not be the basis vectors of the mutable basis!

Example

```gap
gap> MB:= MutableBasis( Rationals, [ [ 1, 2, 3 ], [ 0, 1, 0 ] ] );
<mutable basis over Rationals, 2 vectors>
```

### 61.8.3 NrBasisVectors

`NrBasisVectors( MB )` (operation)

For a mutable basis `MB`, `NrBasisVectors` returns the current number of basis vectors of `MB`. Note that this operation is not an attribute, as it makes no sense to store the value. `NrBasisVectors` is used mainly as an equivalent of `Dimension` for the underlying left module in the case of immutable bases.

Example

```gap
gap> MB:= MutableBasis( Rationals, [ [ 1, 1 ], [ 2, 2 ] ] );
gap> NrBasisVectors( MB );
1
```

### 61.8.4 ImmutableBasis

`ImmutableBasis( MB [, V] )` (operation)

`ImmutableBasis` returns the immutable basis $B$, say, with the same basis vectors as in the mutable basis `MB`. 
If the second argument \( V \) is present then \( V \) is the value of `UnderlyingLeftModule (61.6.2)` for \( B \). The second variant is used mainly for the case that one knows the module for the desired basis in advance, and if it has a nicer structure than the module known to \( MB \), for example if it is an algebra.

Example

```gap
gap> MB := MutableBasis( Rationals, [[1, 1], [2, 2]] );;
gap> B := ImmutableBasis( MB );
SemiEchelonBasis( <vector space of dimension 1 over Rationals>,
[ [ 1, 1 ] ] )
gap> UnderlyingLeftModule( B );
<vector space of dimension 1 over Rationals>
```

### 61.8.5 IsContainedInSpan

\( \triangledown \) IsContainedInSpan(\( MB \), \( v \)) (operation)

For a mutable basis \( MB \) over the coefficient ring \( R \), say, and a vector \( v \), `IsContainedInSpan` returns \( \text{true} \) if \( v \) lies in the \( R \)-span of the current basis vectors of \( MB \), and \( \text{false} \) otherwise.

### 61.8.6 CloseMutableBasis

\( \triangledown \) CloseMutableBasis(\( MB \), \( v \)) (operation)

For a mutable basis \( MB \) over the coefficient ring \( R \), say, and a vector \( v \), `CloseMutableBasis` changes \( MB \) such that afterwards it describes the \( R \)-span of the former basis vectors together with \( v \).

*Note* that if \( v \) enlarges the dimension then this does in general *not* mean that \( v \) is simply added to the basis vectors of \( MB \). Usually a linear combination of \( v \) and the other basis vectors is added, and also the old basis vectors may be modified, for example in order to keep the list of basis vectors echelonized (see `IsSemiEchelonized (61.9.7)`).

`CloseMutableBasis` returns \( \text{false} \) if \( v \) was already in the \( R \)-span described by \( MB \), and \( \text{true} \) if \( MB \) got extended.

Example

```gap
gap> MB := MutableBasis( Rationals, [[1, 1, 3], [2, 2, 1]] );;
<mutable basis over Rationals, 2 vectors>
gap> IsContainedInSpan( MB, [1, 0, 0] );
false
gap> CloseMutableBasis( MB, [1, 0, 0] );
true
gap> MB;
<mutable basis over Rationals, 3 vectors>
gap> IsContainedInSpan( MB, [1, 0, 0] );
true
gap> CloseMutableBasis( MB, [1, 0, 0] );
false
```
61.9 Row and Matrix Spaces

61.9.1 IsRowSpace

\[ \text{IsRowSpace}(V) \] 
(filter)

A row space in GAP is a vector space that consists of row vectors (see Chapter 23).

61.9.2 IsMatrixSpace

\[ \text{IsMatrixSpace}(V) \] 
(filter)

A matrix space in GAP is a vector space that consists of matrices (see Chapter 24).

61.9.3 IsGaussianSpace

\[ \text{IsGaussianSpace}(V) \] 
(filter)

The filter \text{IsGaussianSpace} (see 13.2) for the row space (see \text{IsRowSpace} (61.9.1)) or matrix space (see \text{IsMatrixSpace} (61.9.2)) \( V \) over the field \( F \), say, indicates that the entries of all row vectors or matrices in \( V \), respectively, are all contained in \( F \). In this case, \( V \) is called a Gaussian vector space. Bases for Gaussian spaces can be computed using Gaussian elimination for a given list of vector space generators.

\begin{verbatim}
gap> mats:= [ [[1,1],[2,2]], [[3,4],[0,1]] ];;
gap> V:= VectorSpace( Rationals, mats );;
gap> IsGaussianSpace( V );
true
gap> mats[1][1][1]:= E(4);; # an element in an extension field
gap> V:= VectorSpace( Rationals, mats );;
gap> IsGaussianSpace( V );
false
gap> V:= VectorSpace( Field( Rationals, [ E(4) ] ), mats );;
gap> IsGaussianSpace( V );
true
\end{verbatim}

61.9.4 FullRowSpace

\[ \text{FullRowSpace}(F, n) \] 
(function)

\[ F^n \] 
(method)

For a field \( F \) and a nonnegative integer \( n \), \text{FullRowSpace} returns the \( F \)-vector space that consists of all row vectors (see \text{IsRowVector} (23.1.1)) of length \( n \) with entries in \( F \).

An alternative to construct this vector space is via \( F^n \).

\begin{verbatim}
gap> FullRowSpace( GF( 9 ), 3 );
( GF(3^2)^3 )
gap> GF(9)^3; # the same as above
( GF(3^2)^3 )
\end{verbatim}
61.9.5 FullMatrixSpace

\[ \text{FullMatrixSpace}(F, m, n) \] (function)
\[ ^{(F, \text{dims})} \] (method)

For a field \( F \) and two positive integers \( m \) and \( n \), \text{FullMatrixSpace} returns the \( F \)-vector space that consists of all \( m \) by \( n \) matrices (see \text{IsMatrix} (24.2.1)) with entries in \( F \).
If \( m = n \) then the result is in fact an algebra (see \text{FullMatrixAlgebra} (62.5.4)).
An alternative to construct this vector space is via \( F^{[m,n]} \).

\begin{verbatim}
gap> FullMatrixSpace( GF(2), 4, 5 );
( GF(2)^[ 4, 5 ] )
gap> GF(2)^[ 4, 5 ]; # the same as above
( GF(2)^[ 4, 5 ] )
\end{verbatim}

Example

61.9.6 DimensionOfVectors

\[ \text{DimensionOfVectors}(M) \] (attribute)

For a left module \( M \) that consists of row vectors (see \text{IsRowModule} (57.3.6)), \text{DimensionOfVectors} returns the common length of all row vectors in \( M \). For a left module \( M \) that consists of matrices (see \text{IsMatrixModule} (57.3.7)), \text{DimensionOfVectors} returns the common matrix dimensions (see \text{DimensionsMat} (24.4.1)) of all matrices in \( M \).

\begin{verbatim}
gap> DimensionOfVectors( GF(2)^5 );
5
gap> DimensionOfVectors( GF(2)^[2,3] );
[ 2, 3 ]
\end{verbatim}

Example

61.9.7 IsSemiEchelonized

\[ \text{IsSemiEchelonized}(B) \] (property)

Let \( B \) be a basis of a Gaussian row or matrix space \( V \), say (see \text{IsGaussianSpace} (61.9.3)) over the field \( F \).
If \( V \) is a row space then \( B \) is semi-echelonized if the matrix formed by its basis vectors has the property that the first nonzero element in each row is the identity of \( F \), and all values exactly below these pivot elements are the zero of \( F \) (cf. \text{SemiEchelonMat} (24.10.1)).
If \( V \) is a matrix space then \( B \) is semi-echelonized if the matrix obtained by replacing each basis vector by the concatenation of its rows is semi-echelonized (see above, cf. \text{SemiEchelonMats} (24.10.4)).

\begin{verbatim}
gap> V:= GF(2)^2;;
gap> B1:= Basis( V, [ [ 0, 1 ], [ 1, 0 ] ] * Z(2) );;
gap> IsSemiEchelonized( B1 );
true
gap> B2:= Basis( V, [ [ 0, 1 ], [ 1, 1 ] ] * Z(2) );;
gap> IsSemiEchelonized( B2 );
false
\end{verbatim}

Example
61.9.8 SemiEchelonBasis

D SemiEchelonBasis(V[, vectors])  
D SemiEchelonBasisNC(V, vectors)  

Let $V$ be a Gaussian row or matrix vector space over the field $F$ (see IsGaussianSpace (61.9.3), IsRowSpace (61.9.1), IsMatrixSpace (61.9.2)).

Called with $V$ as the only argument, SemiEchelonBasis returns a basis of $V$ that has the property IsSemiEchelonized (61.9.7).

If additionally a list $vectors$ of vectors in $V$ is given that forms a semi-echelonized basis of $V$ then SemiEchelonBasis returns this basis; if $vectors$ do not form a basis of $V$ then fail is returned.

SemiEchelonBasisNC does the same as the two argument version of SemiEchelonBasis, except that it is not checked whether $vectors$ form a semi-echelonized basis.

Example

```gap
gap> V := GF(2)^2;;
gap> B := SemiEchelonBasis( V );
SemiEchelonBasis( ( GF(2)^2 ), ... )
gap> Print( BasisVectors( B ), "\n" );
[ [ Z(2)^0, 0*Z(2) ], [ 0*Z(2), Z(2)^0 ] ]
gap> B := SemiEchelonBasisNC( V, [ [ 1, 1 ], [ 0, 1 ] ] * Z(2) );
SemiEchelonBasisNC( ( GF(2)^2 ), <an immutable 2x2 matrix over GF2> )
gap> Print( BasisVectors( B ), "\n" );
[ [ Z(2)^0, Z(2)^0 ], [ 0*Z(2), Z(2)^0 ] ]
gap> Coefficients( B, [ 0, 1 ] * Z(2) );
[ 0*Z(2), Z(2)^0 ]
gap> Coefficients( B, [ 1, 0 ] * Z(2) );
[ Z(2)^0, Z(2)^0 ]
gap> SemiEchelonBasisNC( V, [ [ 0, 1 ], [ 1, 1 ] ] * Z(2) );
fail
```

61.9.9 Is CanonicalBasisFullRowModule

D IsCanonicalBasisFullRowModule(B)  

IsCanonicalBasisFullRowModule returns true if $B$ is the canonical basis (see IsCanonicalBasis (61.7.1)) of a full row module (see IsFullRowModule (57.3.8)), and false otherwise.

The canonical basis of a Gaussian row space is defined as the unique semi-echelonized (see IsSemiEchelonized (61.9.7)) basis with the additional property that for $j > i$ the position of the pivot of row $j$ is bigger than the position of the pivot of row $i$, and that each pivot column contains exactly one nonzero entry.

61.9.10 Is CanonicalBasisFullMatrixModule

D IsCanonicalBasisFullMatrixModule(B)  

IsCanonicalBasisFullMatrixModule returns true if $B$ is the canonical basis (see IsCanonicalBasis (61.7.1)) of a full matrix module (see IsFullMatrixModule (57.3.10)), and false otherwise.
The **canonical basis** of a Gaussian matrix space is defined as the unique semi-echelonized (see IsSemiEchelonized (61.9.7)) basis for which the list of concatenations of the basis vectors forms the canonical basis of the corresponding Gaussian row space.

### 61.9.11 NormedRowVectors

**NormedRowVectors(V)** (attribute)

For a finite Gaussian row space V (see IsRowSpace (61.9.1), IsGaussianSpace (61.9.3)), NormedRowVectors returns a list of those nonzero vectors in V that have a one in the first nonzero component. The result list can be used as action domain for the action of a matrix group via OnLines (41.2.12), which yields the natural action on one-dimensional subspaces of V (see also Subspaces (61.4.1)).

```gap
gap> vecs:= NormedRowVectors( GF(3)^2 );
gap> Action( GL(2,3), vecs, OnLines );
group([ (3,4), (1,2,4) ])
```

### 61.9.12 SiftedVector

**SiftedVector(B, v)** (operation)

Let B be a semi-echelonized basis (see IsSemiEchelonized (61.9.7)) of a Gaussian row or matrix space V (see IsGaussianSpace (61.9.3)), and v a row vector or matrix, respectively, of the same dimension as the elements in V. SiftedVector returns the residuum of v with respect to B, which is obtained by successively cleaning the pivot positions in v by subtracting multiples of the basis vectors in B. So the result is the zero vector in V if and only if v lies in V.

B may also be a mutable basis (see 61.8) of a Gaussian row or matrix space.

```gap
gap> V:= VectorSpace( Rationals, [ [ 1, 2, 7 ], [ 1/2, 1/3, 5 ] ] );;
gap> B:= Basis( V );;
gap> SiftedVector( B, [ 1, 2, 8 ] );
gap> SiftedVector( B, [ 0, 0, 1 ] )
```

### 61.10 Vector Space Homomorphisms

**Vector space homomorphisms** (or **linear mappings**) are defined in Section 32.11. GAP provides special functions to construct a particular linear mapping from images of given elements in the source, from a matrix of coefficients, or as a natural epimorphism.

F-linear mappings with same source and same range can be added, so one can form vector spaces of linear mappings.

#### 61.10.1 LeftModuleGeneralMappingByImages

**LeftModuleGeneralMappingByImages(V, W, gens, imgs)** (operation)
Let $V$ and $W$ be two left modules over the same left acting domain $R$, say, and $\text{gens}$ and $\text{imgs}$ lists (of the same length) of elements in $V$ and $W$, respectively. \text{LeftModuleGeneralMappingByImages} returns the general mapping with source $V$ and range $W$ that is defined by mapping the elements in $\text{gens}$ to the corresponding elements in $\text{imgs}$, and taking the $R$-linear closure.

$\text{gens}$ need not generate $V$ as a left $R$-module, and if the specification does not define a linear mapping then the result will be multi-valued; hence in general it is not a mapping (see \text{IsMapping} (32.3.3)).

Example

```gap
gap> V:= Rationals^2;;
gap> W:= VectorSpace( Rationals, [ [1,2,3], [1,0,1] ] );;
gap> f:= LeftModuleGeneralMappingByImages( V, W, 
> [ [1,0],[2,0] ], [ [1,0,1],[1,0,1] ] );
gap> IsMapping( f );
false
```

61.10.2 LeftModuleHomomorphismByImages

\text{LeftModuleHomomorphismByImages}(V, W, \text{gens}, \text{imgs})

\text{LeftModuleHomomorphismByImagesNC}(V, W, \text{gens}, \text{imgs})

Let $V$ and $W$ be two left modules over the same left acting domain $R$, say, and $\text{gens}$ and $\text{imgs}$ lists (of the same length) of elements in $V$ and $W$, respectively. \text{LeftModuleHomomorphismByImages} returns the left $R$-module homomorphism with source $V$ and range $W$ that is defined by mapping the elements in $\text{gens}$ to the corresponding elements in $\text{imgs}$.

If $\text{gens}$ does not generate $V$ or if the homomorphism does not exist (i.e., if mapping the generators describes only a multi-valued mapping) then $\text{fail}$ is returned. For creating a possibly multi-valued mapping from $V$ to $W$ that respects addition, multiplication, and scalar multiplication, \text{LeftModuleGeneralMappingByImages} (61.10.1) can be used.

\text{LeftModuleHomomorphismByImagesNC} does the same as \text{LeftModuleHomomorphismByImages}, except that it omits all checks.

Example

```gap
gap> V:=Rationals^2;;
gap> W:=VectorSpace( Rationals, [ [1,0,1], [1,2,3] ] );;
gap> f:=LeftModuleHomomorphismByImages( V, W, 
> [ [1,0],[0,1] ], [ [1,0,1],[1,2,3] ] );
gap> f[ [1,0],[0,1] ] -> F[ [1,0,1],[1,2,3] ]
gap> Image( f, [1,1] );
[ 2, 2, 4 ]
```

61.10.3 LeftModuleHomomorphismByMatrix

\text{LeftModuleHomomorphismByMatrix}(\text{BS}, \text{matrix}, \text{BR})

Let $\text{BS}$ and $\text{BR}$ be bases of the left $R$-modules $V$ and $W$, respectively. \text{LeftModuleHomomorphismByMatrix} returns the $R$-linear mapping from $V$ to $W$ that is defined by the matrix $\text{matrix}$, as follows. The image of the $i$-th basis vector of $\text{BS}$ is the linear combination of the basis vectors of $\text{BR}$ with coefficients the $i$-th row of $\text{matrix}$. 
Example

```
gap> V := Rationals^2;;
gap> W := VectorSpace( Rationals, [ [ 1, 0, 1 ], [ 1, 2, 3 ] ] );;
gap> f := LeftModuleHomomorphismByMatrix( Basis( V ),
  > [ [ 1, 2 ], [ 3, 1 ] ], Basis( W ) );
<linear mapping by matrix, ( Rationals^2 ) -> <vector space over Rationals, with 2 generators>>
```

### 61.10.4 NaturalHomomorphismBySubspace

\[ \text{NaturalHomomorphismBySubspace}(V, W) \]

For an \( R \)-vector space \( V \) and a subspace \( W \) of \( V \), \text{NaturalHomomorphismBySubspace} returns the \( R \)-linear mapping that is the natural projection of \( V \) onto the factor space \( V / W \).

Example

```
gap> V := Rationals^3;;
gap> W := VectorSpace( Rationals, [ [ 1, 1, 1 ] ] );;
gap> f := NaturalHomomorphismBySubspace( V, W );
<linear mapping by matrix, ( Rationals^3 ) -> ( Rationals^2 )>
```

### 61.10.5 Hom

\[ \text{Hom}(F, V, W) \]

For a field \( F \) and two vector spaces \( V \) and \( W \) that can be regarded as \( F \)-modules (see \text{AsLeftModule} (57.1.5)), \text{Hom} returns the \( F \)-vector space of all \( F \)-linear mappings from \( V \) to \( W \).

Example

```
gap> V := Rationals^2;;
gap> W := VectorSpace( Rationals, [ [ 1, 1, 1 ] ] );;
gap> H := Hom( Rationals, V, W );
Hom( Rationals, ( Rationals^2 ), <vector space over Rationals, with 2 generators> )
gap> Dimension( H );
4
```

### 61.10.6 End

\[ \text{End}(F, V) \]

For a field \( F \) and a vector space \( V \) that can be regarded as an \( F \)-module (see \text{AsLeftModule} (57.1.5)), \text{End} returns the \( F \)-algebra of all \( F \)-linear mappings from \( V \) to \( V \).

Example

```
gap> A := End( Rationals, Rationals^2 );
End( Rationals, ( Rationals^2 ) )
gap> Dimension( A );
4
```
61.10.7  IsFullHomModule

▷ IsFullHomModule(M)  (property)

A full hom module is a module of all $R$-linear mappings between two left $R$-modules. The function \texttt{Hom} (61.10.5) can be used to construct a full hom module.

**Example**

```gap
gap> V := Rationals^2;;
gap> W := VectorSpace( Rationals, [ [ 1, 0, 1 ], [ 1, 2, 3 ] ] );;
gap> H := Hom( Rationals, V, W );;
gap> IsFullHomModule( H );
true
```

61.10.8  IsPseudoCanonicalBasisFullHomModule

▷ IsPseudoCanonicalBasisFullHomModule(B)  (property)

A basis of a full hom module is called pseudo canonical basis if the matrices of its basis vectors w.r.t. the stored bases of source and range contain exactly one identity entry and otherwise zeros.

Note that this is not a canonical basis (see \texttt{CanonicalBasis} (61.5.3)) because it depends on the stored bases of source and range.

**Example**

```gap
gap> IsPseudoCanonicalBasisFullHomModule( Basis( H ) );
true
```

61.10.9  IsLinearMappingsModule

▷ IsLinearMappingsModule(V)  (filter)

If an $F$-vector space $V$ is in the filter \texttt{IsLinearMappingsModule} then this expresses that $V$ consists of linear mappings, and that $V$ is handled via the mechanism of nice bases (see 61.11), in the following way. Let $S$ and $R$ be the source and the range, respectively, of each mapping in $V$. Then the \texttt{NiceFreeLeftModuleInfo} (61.11.3) value of $V$ is a record with the components \texttt{basissource} (a basis $B_S$ of $S$) and \texttt{basisrange} (a basis $B_R$ of $R$), and the \texttt{NiceVector} (61.11.2) value of $v \in V$ is defined as the matrix of the $F$-linear mapping $v$ w.r.t. the bases $B_S$ and $B_R$.

61.11  Vector Spaces Handled By Nice Bases

There are kinds of free $R$-modules for which efficient computations are possible because the elements are “nice”, for example subspaces of full row modules or of full matrix modules. In other cases, a “nice” canonical basis is known that allows one to do the necessary computations in the corresponding row module, for example algebras given by structure constants.

In many other situations, one knows at least an isomorphism from the given module $V$ to a “nicer” free left module $W$, in the sense that for each vector in $V$, the image in $W$ can easily be computed, and analogously for each vector in $W$, one can compute the preimage in $V$.

This allows one to delegate computations w.r.t. a basis $B$, say, of $V$ to the corresponding basis $C$, say, of $W$. We call $W$ the \textit{nice free left module} of $V$, and $C$ the \textit{nice basis} of $B$. (Note that it may happen
that also C delegates questions to a “nicer” basis.) The basis B indicates the intended behaviour by the filter IsBasisByNiceBasis (61.11.5), and stores C as value of the attribute NiceBasis (61.11.4). V indicates the intended behaviour by the filter IsHandledByNiceBasis (61.11.6), and stores W as value of the attribute NiceFreeLeftModule (61.11.1).

The bijection between V and W is implemented by the functions NiceVector (61.11.2) and UglyVector (61.11.2); additional data needed to compute images and preimages can be stored as value of NiceFreeLeftModuleInfo (61.11.3).

61.11.1 NiceFreeLeftModule

\[ \text{NiceFreeLeftModule}(V) \]

For a free left module V that is handled via the mechanism of nice bases, this attribute stores the associated free left module to which the tasks are delegated.

61.11.2 NiceVector

\[ \text{NiceVector}(V, v) \]
\[ \text{UglyVector}(V, r) \]

NiceVector and UglyVector provide the linear bijection between the free left module V and \( W := \text{NiceFreeLeftModule}(V) \).

If v lies in the elements family of the family of V then NiceVector( v ) is either fail or an element in the elements family of the family of W.

If r lies in the elements family of the family of W then UglyVector( r ) is either fail or an element in the elements family of the family of V.

If v lies in V (which usually cannot be checked without using W) then UglyVector( V, NiceVector( V, v ) ) = v. If r lies in W (which usually can be checked) then NiceVector( V, UglyVector( V, r ) ) = r.

(This allows one to implement for example a membership test for V using the membership test in W.)

61.11.3 NiceFreeLeftModuleInfo

\[ \text{NiceFreeLeftModuleInfo}(V) \]

For a free left module V that is handled via the mechanism of nice bases, this operation has to provide the necessary information (if any) for calls of NiceVector (61.11.2) and UglyVector (61.11.2).

61.11.4 NiceBasis

\[ \text{NiceBasis}(B) \]

Let B be a basis of a free left module V that is handled via nice bases. If B has no basis vectors stored at the time of the first call to NiceBasis then NiceBasis( B ) is obtained as Basis( NiceFreeLeftModule( V ) ). If basis vectors are stored then NiceBasis( B ) is the result of the
call of Basis with arguments NiceFreeLeftModule(V) and the NiceVector values of the basis vectors of B.

Note that the result is fail if and only if the “basis vectors” stored in B are in fact not basis vectors.

The attributes GeneratorsOfLeftModule of the underlying left modules of B and the result of NiceBasis correspond via NiceVector (61.11.2) and UglyVector (61.11.2).

61.11.5 IsBasisByNiceBasis

▷ IsBasisByNiceBasis(B) (Category)

This filter indicates that the basis B delegates tasks such as the computation of coefficients (see Coefficients (61.6.3)) to a basis of an isomorphic “nicer” free left module.

61.11.6 IsHandledByNiceBasis

▷ IsHandledByNiceBasis(M) (Category)

For a free left module M in this category, essentially all operations are performed using a “nicer” free left module, which is usually a row module.

61.12 How to Implement New Kinds of Vector Spaces

61.12.1 DeclareHandlingByNiceBasis

▷ DeclareHandlingByNiceBasis(name, info) (function)
▷ InstallHandlingByNiceBasis(name, record) (function)

These functions are used to implement a new kind of free left modules that shall be handled via the mechanism of nice bases (see 61.11).

name must be a string, a filter f with this name is created, and a logical implication from f to IsHandledByNiceBasis (61.11.6) is installed.

record must be a record with the following components.

detect
a function of four arguments R, l, V, and z, where V is a free left module over the ring R with generators the list or collection l, and z is either the zero element of V or false (then l is nonempty); the function returns true if V shall lie in the filter f, and false otherwise; the return value may also be fail, which indicates that V is not to be handled via the mechanism of nice bases at all,

NiceFreeLeftModuleInfo
the NiceFreeLeftModuleInfo method for left modules in f,

NiceVector
the NiceVector method for left modules V in f; called with V and a vector v ∈ V, this function returns the nice vector r associated with v, and
the **UglyVector** \((61.11.2)\) method for left modules \(V\) in \(f\); called with \(V\) and a vector \(r\) in the \(\text{NiceFreeLeftModule}\) value of \(V\), this function returns the vector \(v \in V\) to which \(r\) is associated.

The idea is that all one has to do for implementing a new kind of free left modules handled by the mechanism of nice bases is to call `DeclareHandlingByNiceBasis` and `InstallHandlingByNiceBasis`, which causes the installation of the necessary methods and adds the pair \([f, \text{record}.\text{detect}]\) to the global list `NiceBasisFiltersInfo`. The `LeftModuleByGenerators` \((57.1.10)\) methods call `CheckForHandlingByNiceBasis` \((61.12.3)\), which sets the appropriate filter for the desired left module if applicable.

### 61.12.2 NiceBasisFiltersInfo

#### ▶ NiceBasisFiltersInfo

(global variable)

An overview of all kinds of vector spaces that are currently handled by nice bases is given by the global list `NiceBasisFiltersInfo`. Examples of such vector spaces are vector spaces of field elements (but not the fields themselves) and non-Gaussian row and matrix spaces (see `IsGaussianSpace` \((61.9.3)\)).

### 61.12.3 CheckForHandlingByNiceBasis

#### ▶ CheckForHandlingByNiceBasis\((R, gens, M, zero)\)

(function)

Whenever a free left module is constructed for which the filter `IsHandledByNiceBasis` may be useful, `CheckForHandlingByNiceBasis` should be called. (This is done in the methods for `VectorSpaceByGenerators`, `AlgebraByGenerators`, `IdealByGenerators` etc. in the GAP library.)

The arguments of this function are the coefficient ring \(R\), the list `gens` of generators, the constructed module \(M\) itself, and the zero element `zero` of \(M\); if `gens` is nonempty then the `zero` value may also be `false`. 
Chapter 62

Algebras

An algebra is a vector space equipped with a bilinear map (multiplication). This chapter describes the functions in GAP that deal with general algebras and associative algebras.

Algebras in GAP are vector spaces in a natural way. So all the functionality for vector spaces (see Chapter 61) is also applicable to algebras.

62.1 InfoAlgebra (Info Class)

62.1.1 InfoAlgebra

▷ InfoAlgebra (info class)

is the info class for the functions dealing with algebras (see 7.4).

62.2 Constructing Algebras by Generators

62.2.1 Algebra

▷ Algebra(F, gens[, zero][, "basis"])

Algebra( F, gens ) is the algebra over the division ring F, generated by the vectors in the list gens.

If there are three arguments, a division ring F and a list gens and an element zero, then Algebra( F, gens, zero ) is the F-algebra generated by gens, with zero element zero.

If the last argument is the string "basis" then the vectors in gens are known to form a basis of the algebra (as an F-vector space).

Example

```
gap> m:= [[ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ]];;
gap> A:= Algebra( Rationals, [ m ] );
<algebra over Rationals, with 1 generators>
gap> Dimension( A );
2
```
62.2.2 AlgebraWithOne

\texttt{AlgebraWithOne( F, gens [, zero] [, "basis"] )}

\texttt{AlgebraWithOne( F, gens )} is an algebra-with-one over the division ring \texttt{F}, generated by the vectors in the list \texttt{gens}.

If there are three arguments, a division ring \texttt{F} and a list \texttt{gens} and an element \texttt{zero}, then \texttt{AlgebraWithOne( F, gens, zero )} is the \texttt{F}-algebra-with-one generated by \texttt{gens}, with zero element \texttt{zero}.

If the last argument is the string "basis" then the vectors in \texttt{gens} are known to form a basis of the algebra (as an \texttt{F}-vector space).

\begin{verbatim}
gap> m:= [[0, 1, 2], [0, 0, 3], [0, 0, 0]];;
gap> A:= AlgebraWithOne( Rationals, [m] );
<algebra-with-one over Rationals, with 1 generators>
gap> Dimension( A );
3
gap> One(A);
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ]
\end{verbatim}

62.3 Constructing Algebras as Free Algebras

62.3.1 FreeAlgebra (for ring, rank (and name))

\texttt{FreeAlgebra(R, rank[, name])}

is a free (nonassociative) algebra of rank \texttt{rank} over the division ring \texttt{R}. Here \texttt{name}, and \texttt{name1}, \texttt{name2}, ... are optional strings that can be used to provide names for the generators.

\begin{verbatim}
gap> A:= FreeAlgebra( Rationals, "a", "b" );<algebra over Rationals, with 2 generators>
gap> g:= GeneratorsOfAlgebra( A );
[ (1)*a, (1)*b ]
gap> (g[1]*g[2])*((g[2]*g[1])*g[1]);
(1)*((a*b)*((b*a)*a))
\end{verbatim}

62.3.2 FreeAlgebraWithOne (for ring, rank (and name))

\texttt{FreeAlgebraWithOne(R, rank[, name])}

is a free (nonassociative) algebra-with-one of rank \texttt{rank} over the division ring \texttt{R}. Here \texttt{name}, and \texttt{name1}, \texttt{name2}, ... are optional strings that can be used to provide names for the generators.

\begin{verbatim}
gap> A:= FreeAlgebraWithOne( Rationals, 4, "q" );<algebra-with-one over Rationals, with 4 generators>
gap> GeneratorsOfAlgebra( A );
[ (1)*<identity ...>, (1)*q.1, (1)*q.2, (1)*q.3, (1)*q.4 ]
\end{verbatim}
62.3.3 FreeAssociativeAlgebra (for ring, rank (and name))

\[ \text{FreeAssociativeAlgebra}(R, \text{rank}[, \text{name}]) \]

\[ \text{FreeAssociativeAlgebra}(R, \text{name1}, \text{name2}, \ldots) \]

is a free associative algebra of rank \( \text{rank} \) over the division ring \( R \). Here \( \text{name} \), and \( \text{name1}, \text{name2}, \ldots \) are optional strings that can be used to provide names for the generators.

Example:

```gap
gap> A:= FreeAssociativeAlgebra( GF( 5 ), 4, "a" );
<algebra over GF(5), with 4 generators>
```

62.3.4 FreeAssociativeAlgebraWithOne (for ring, rank (and name))

\[ \text{FreeAssociativeAlgebraWithOne}(R, \text{rank}[, \text{name}]) \]

\[ \text{FreeAssociativeAlgebraWithOne}(R, \text{name1}, \text{name2}, \ldots) \]

is a free associative algebra-with-one of rank \( \text{rank} \) over the division ring \( R \). Here \( \text{name} \), and \( \text{name1}, \text{name2}, \ldots \) are optional strings that can be used to provide names for the generators.

Example:

```gap
gap> A:= FreeAssociativeAlgebraWithOne( Rationals, "a", "b", "c" );
<algebra-with-one over Rationals, with 3 generators>
```

62.4 Constructing Algebras by Structure Constants

For an introduction into structure constants and how they are handled by GAP, we refer to Section (Tutorial: Algebras) of the user’s tutorial.

62.4.1 AlgebraByStructureConstants

\[ \text{AlgebraByStructureConstants}(R, \text{sctable}[, \text{nameinfo}]) \]

returns a free left module \( A \) over the division ring \( R \), with multiplication defined by the structure constants table \( \text{sctable} \). The optional argument \( \text{nameinfo} \) can be used to prescribe names for the elements of the canonical basis of \( A \); it can be either a string \( \text{name} \) (then \( \text{name1}, \text{name2} \) etc. are chosen) or a list of strings which are then chosen. The vectors of the canonical basis of \( A \) correspond to the vectors of the basis given by \( \text{sctable} \).

It is not checked whether the coefficients in \( \text{sctable} \) are really elements in \( R \).

Example:

```gap
gap> T:= EmptySCTable( 2, 0 );;
gap> SetEntrySCTable( T, 1, 1, [ 1/2, 1, 2/3, 2 ] );
```
gap> A := AlgebraByStructureConstants( Rationals, T );
<algebra of dimension 2 over Rationals>
gap> b := BasisVectors( Basis( A ) );;

gap> b[1]^2;
(1/2)*v.1+(2/3)*v.2

gap> b[1]*b[2];
0*v.1

62.4.2 StructureConstantsTable

\textbf{StructureConstantsTable}(B) \hspace{1cm} (attribute)

Let $B$ be a basis of a free left module $R$, say, that is also a ring. In this case \textbf{StructureConstantsTable} returns a structure constants table $T$ in sparse representation, as used for structure constants algebras (see Section (\textit{Tutorial: Algebras}) of the GAP User’s Tutorial).

If $B$ has length $n$ then $T$ is a list of length $n+2$. The first $n$ entries of $T$ are lists of length $n$. $T[n+1]$ is one of $1$, $-1$, or $0$; in the case of $1$ the table is known to be symmetric, in the case of $-1$ it is known to be antisymmetric, and $0$ occurs in all other cases. $T[n+2]$ is the zero element of the coefficient domain.

The coefficients w.r.t. $B$ of the product of the $i$-th and $j$-th basis vector of $B$ are stored in $T[i][j]$ as a list of length 2; its first entry is the list of positions of nonzero coefficients, the second entry is the list of these coefficients themselves.

The multiplication in an algebra $A$ with vector space basis $B$ with basis vectors $[v_1,\ldots,v_n]$ is determined by the so-called structure matrices $M_k = [m_{ijk}], 1 \leq k \leq n$. The $M_k$ are defined by $v_i v_j = \sum_k m_{ijk} v_k$. Let $a = [a_1,\ldots,a_n]$ and $b = [b_1,\ldots,b_n]$. Then

$$\left( \sum_i a_i v_i \right) \left( \sum_j b_j v_j \right) = \sum_{i,j} a_i b_j (v_i v_j) = \sum_k \left( \sum_j \left( \sum_i a_i m_{ijk} \right) b_j \right) v_k = \sum_k (a M_k b^T) v_k.$$

Example

| \textbf{gap} > A := QuaternionAlgebra( Rationals );;
| \textbf{gap} > StructureConstantsTable( Basis( A ) );;

```
[ [ [ 1 ], [ 1 ] ], [ [ 2 ], [ 1 ] ], [ [ 3 ], [ 1 ] ],
  [ [ 4 ], [ 1 ] ]],
[ [ [ 2 ], [ 1 ] ], [ [ 1 ], [ -1 ] ], [ [ 4 ], [ 1 ] ],
  [ [ 3 ], [ -1 ] ]],
[ [ [ 3 ], [ 1 ] ], [ [ 4 ], [ -1 ] ], [ [ 1 ], [ -1 ] ],
  [ [ 2 ], [ 1 ] ]],
[ [ [ 4 ], [ 1 ] ], [ [ 3 ], [ 1 ] ], [ [ 2 ], [ -1 ] ],
  [ [ 1 ], [ -1 ] ]],
0, 0 ]
```

62.4.3 EmptySCTable

\textbf{EmptySCTable}(dim, zero[, flag]) \hspace{1cm} (function)

\textbf{EmptySCTable} returns a structure constants table for an algebra of dimension $dim$, describing trivial multiplication. $zero$ must be the zero of the coefficients domain. If the multiplication is known to be (anti)commutative then this can be indicated by the optional third argument $flag$, which must be one of the strings "symmetric", "antisymmetric".
For filling up the structure constants table, see SetEntrySCTable (62.4.4).

Example

```gap
gap> EmptySCTable( 2, Zero( GF(5) ), "antisymmetric" );
[ [ [ [ ], [ ] ], [ [ ], [ ] ] ],
  [ [ [ ], [ ] ], [ [ ], [ ] ] ], -1, 0*Z(5) ]
```

### 62.4.4 SetEntrySCTable

- **SetEntrySCTable(T, i, j, list)** (function)

  sets the entry of the structure constants table \( T \) that describes the product of the \( i \)-th basis element with the \( j \)-th basis element to the value given by the list \( \text{list} \).

  If \( T \) is known to be antisymmetric or symmetric then also the value \( T[j][i] \) is set.

  \( \text{list} \) must be of the form \([c_{k_1}^{i_j}, k_1, c_{k_2}^{i_j}, k_2, ...]\).

  The entries at the odd positions of \( \text{list} \) must be compatible with the zero element stored in \( T \).

  For convenience, these entries may also be rational numbers that are automatically replaced by the corresponding elements in the appropriate prime field in finite characteristic if necessary.

Example

```gap
gap> T:= EmptySCTable( 2, 0 );;
gap> SetEntrySCTable( T, 1, 1, [ 1/2, 1, 2/3, 2 ] );
gap> T;
[ [ [ 1, 2 ], [ 1/2, 2/3 ] ], [ [ ], [ ] ] ],
  [ [ [ ], [ ] ], [ [ ], [ ] ] ], 0, 0 ]
```

### 62.4.5 GapInputSCTable

- **GapInputSCTable(T, varname)** (function)

  is a string that describes the structure constants table \( T \) in terms of EmptySCTable (62.4.3) and SetEntrySCTable (62.4.4). The assignments are made to the variable \( \text{varname} \).

Example

```gap
gap> T:= EmptySCTable( 2, 0 );;
gap> SetEntrySCTable( T, 1, 2, [ 1, 2 ] );
gap> SetEntrySCTable( T, 2, 1, [ 1, 2 ] );
gap> GapInputSCTable( T, "T" );
"T:= EmptySCTable( 2, 0 );\nSetEntrySCTable( T, 1, 2, [1,2]);\nSetEntrySCTable( T, 2, 1, [1,2]);\n"n"n"
```

### 62.4.6 TestJacobi

- **TestJacobi(T)** (function)

  tests whether the structure constants table \( T \) satisfies the Jacobi identity \( v_i \ast (v_j \ast v_k) + v_j \ast (v_k \ast v_i) + v_k \ast (v_i \ast v_j) = 0 \) for all basis vectors \( v_i \) of the underlying algebra, where \( i \leq j \leq k \). (Thus antisymmetry is assumed.)

  The function returns \texttt{true} if the Jacobi identity is satisfied, and a failing triple \([i, j, k]\) otherwise.
62.4.7 IdentityFromSCTable

\hspace{1.6em} \texttt{IdentityFromSCTable(} \texttt{T} \texttt{)} (function)

Let \( T \) be a structure constants table of an algebra \( A \) of dimension \( n \). \texttt{IdentityFromSCTable(} \texttt{T} \texttt{)} is either \texttt{fail} or the vector of length \( n \) that contains the coefficients of the multiplicative identity of \( A \) with respect to the basis that belongs to \( T \).

\begin{verbatim}
gap> T:= EmptySCTable( 2, 0 );;
gap> SetEntrySCTable( T, 1, 1, [ 1, 1 ] );;
gap> SetEntrySCTable( T, 2, 1, [ 1, 2 ] );;
gap> IdentityFromSCTable( T );
[ 1, 0 ]
\end{verbatim}

62.4.8 QuotientFromSCTable

\hspace{1.6em} \texttt{QuotientFromSCTable(} \texttt{T, num, den} \texttt{)} (function)

Let \( T \) be a structure constants table of an algebra \( A \) of dimension \( n \). \texttt{QuotientFromSCTable(} \texttt{T, num, den} \texttt{)} is either \texttt{fail} or the vector of length \( n \) that contains the coefficients of the quotient of \( \texttt{num} \) and \( \texttt{den} \) with respect to the basis that belongs to \( T \).

We solve the equation system \( \texttt{num} = x \ast \texttt{den} \). If no solution exists, \texttt{fail} is returned.

In terms of the basis \( B \) with vectors \( b_1, \ldots, b_n \) this means for \( \texttt{num} = \sum_{i=1}^{n} a_i b_i \), \( \texttt{den} = \sum_{i=1}^{n} c_i b_i \), \( x = \sum_{i=1}^{n} x_i b_i \) that \( a_k = \sum_{i,j} c_{ij} x_i c_{jk} \) for all \( k \). Here \( c_{ijk} \) denotes the structure constants with respect to \( B \). This means that (as a vector) \( a = x M \) with \( M_{jk} = \sum_{i=1}^{n} c_{ijk} c_{i} \).

\begin{verbatim}
gap> T:= EmptySCTable( 2, 0 );;
gap> SetEntrySCTable( T, 1, 1, [ 1, 1 ] );;
gap> SetEntrySCTable( T, 2, 1, [ 1, 2 ] );;
gap> QuotientFromSCTable( T, [0,1], [1,0] );
[ 0, 1 ]
\end{verbatim}

62.5 Some Special Algebras

62.5.1 QuaternionAlgebra

\hspace{1.6em} \texttt{QuaternionAlgebra(} \texttt{F[, a, b]} \texttt{)} (function)

\textbf{Returns:} a quaternion algebra over \( F \), with parameters \( a \) and \( b \).

Let \( F \) be a field or a list of field elements, let \( F \) be the field generated by \( F \), and let \( a \) and \( b \) two elements in \( F \). \texttt{QuaternionAlgebra} returns a quaternion algebra over \( F \), with parameters \( a \) and \( b \).
i.e., a four-dimensional associative $F$-algebra with basis $(e, i, j, k)$ and multiplication defined by $ee = e$, $ei = ie = i$, $ej = je = j$, $ek = ke = k$, $ii = a e$, $ij = -ji = a j$, $jj = b e$, $jk = -kj = bi$, $kk = -a b e$. The default value for both $a$ and $b$ is $-1 \in F$.

The `GeneratorsOfAlgebra` (62.9.1) and `CanonicalBasis` (61.5.3) value of an algebra constructed with `QuaternionAlgebra` is the list $[e, i, j, k]$.

Two quaternion algebras with the same parameters $a, b$ lie in the same family, so it makes sense to consider their intersection or to ask whether they are contained in each other. (This is due to the fact that the results of `QuaternionAlgebra` are cached, in the global variable `QuaternionAlgebraData`.)

The embedding of the field `GaussianRationals` (60.1.3) into a quaternion algebra $A$ over `Rationals` (17.1.1) is not uniquely determined. One can specify one embedding as a vector space homomorphism that maps $1$ to the first algebra generator of $A$, and $E(4)$ to one of the others.

Example

```gap
QuaternionAlgebra( Rationals );
```

For a vector:

```
ComplexificationQuat( vector )
```

Let $A = eF \oplus iF \oplus jF \oplus kF$ be a quaternion algebra over the field $F$ of cyclotomics, with basis $(e, i, j, k)$.

If $v = v_1 + v_2 j$ is a row vector over $A$ with $v_1 = e w_1 + i w_2$ and $v_2 = e w_3 + i w_4$ then `ComplexificationQuat` called with argument $v$ returns the concatenation of $w_1 + E(4) w_2$ and $w_3 + E(4) w_4$.

If $M = M_1 + M_2 j$ is a matrix over $A$ with $M_1 = e N_1 + i N_2$ and $M_2 = e N_3 + i N_4$ then `ComplexificationQuat` called with argument $M$ returns the block matrix $A$ over $eF \oplus iF$ such that $A(1, 1) = N_1 + E(4) N_2$, $A(2, 2) = N_1 - E(4) N_2$, $A(1, 2) = N_3 + E(4) N_4$, and $A(2, 1) = -N_3 + E(4) N_4$.

Then `ComplexificationQuat(v) * ComplexificationQuat(M)` = `ComplexificationQuat(v * M)`, since

$vM = v_1 M_1 + v_2 j M_1 + v_1 M_2 j + v_2 j M_2 j = (v_1 M_1 - v_2 M_2) + (v_1 M_2 + v_2 M_1) j$.

**62.5.3 OctaveAlgebra**

```
OctaveAlgebra(F)
```

The algebra of octonions over $F$.

Example

```gap
OctaveAlgebra( Rationals );
```

**62.5.4 FullMatrixAlgebra**

```
FullMatrixAlgebra(R, n)
MatrixAlgebra(R, n)
```

The algebra of $n \times n$ matrices over $R$. 
MatAlgebra\((R, n)\)

is the full matrix algebra of \(n \times n\) matrices over the ring \(R\), for a nonnegative integer \(n\).

```
gap> A:=FullMatrixAlgebra( Rationals, 20 );
( Rationals^[ 20, 20 ] )
gap> Dimension( A );
400
```

62.5.5 NullAlgebra

NullAlgebra\((R)\)

The zero-dimensional algebra over \(R\).

```
gap> A:= NullAlgebra( Rationals );
<algebra of dimension 0 over Rationals>
gap> Dimension( A );
0
```

62.6 Subalgebras

62.6.1 Subalgebra

Subalgebra\((A, gens[, "basis"]\))

is the \(F\)-algebra generated by \(gens\), with parent algebra \(A\), where \(F\) is the left acting domain of \(A\).

*Note* that being a subalgebra of \(A\) means to be an algebra, to be contained in \(A\), and to have the same left acting domain as \(A\).

An optional argument "basis" may be added if it is known that the generators already form a basis of the algebra. Then it is *not* checked whether \(gens\) really are linearly independent and whether all elements in \(gens\) lie in \(A\).

```
gap> m:= [ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ];;
gap> A:= Algebra( Rationals, [ m ] );
gap> B:= Subalgebra( A, [ m^2 ] );
```

62.6.2 SubalgebraNC

SubalgebraNC\((A, gens[, "basis"]\))

SubalgebraNC does the same as Subalgebra (62.6.1), except that it does not check whether all elements in \(gens\) lie in \(A\).

```
gap> m:= RandomMat( 3, 3 );;
gap> A:= Algebra( Rationals, [ m ] );
```
62.6.3 SubalgebraWithOne

\[ \text{SubalgebraWithOne}(A, \ gens[, \ "basis"] ) \]

is the algebra-with-one generated by \( \gens \), with parent algebra \( A \).

The optional third argument, the string "basis", may be added if it is known that the elements from \( \gens \) are linearly independent. Then it is \textit{not} checked whether \( \gens \) really are linearly independent and whether all elements in \( \gens \) lie in \( A \).

Example

\begin{verbatim}
gap> m:= [ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ];;
gap> A:= AlgebraWithOne( Rationals, [ m ] );;
<algebra-with-one over Rationals, with 1 generators>
gap> B1:= SubalgebraWithOne( A, [ m ] );;
gap> B2:= Subalgebra( A, [ m ] );;
gap> Dimension( B1 );
3
gap> Dimension( B2 );
2
\end{verbatim}

62.6.4 SubalgebraWithOneNC

\[ \text{SubalgebraWithOneNC}(A, \ gens[, \ "basis"] ) \]

SubalgebraWithOneNC does the same as SubalgebraWithOne (62.6.3), except that it does not check whether all elements in \( \gens \) lie in \( A \).

Example

\begin{verbatim}
gap> m:= RandomMat( 3, 3 );; A:= Algebra( Rationals, [ m ] );;
gap> SubalgebraWithOneNC( A, [ m ] );
<algebra-with-one over Rationals, with 1 generators>
\end{verbatim}

62.6.5 TrivialSubalgebra

\[ \text{TrivialSubalgebra}(A) \]

The zero dimensional subalgebra of the algebra \( A \).

Example

\begin{verbatim}
gap> A:= QuaternionAlgebra( Rationals );;
gap> B:= TrivialSubalgebra( A );
<algebra of dimension 0 over Rationals>
gap> Dimension( B );
0
\end{verbatim}
62.7 Ideals of Algebras

For constructing and working with ideals in algebras the same functions are available as for ideals in rings. So for the precise description of these functions we refer to Chapter 56. Here we give examples demonstrating the use of ideals in algebras. For an introduction into the construction of quotient algebras we refer to Chapter (Tutorial: Algebras) of the user’s tutorial.

Example

```
gap> m:= [ [ 0, 2, 3 ], [ 0, 0, 4 ], [ 0, 0, 0 ] ];;
gap> A:= AlgebraWithOne( Rationals, [ m ] );;
gap> I:= Ideal( A, [ m ] ); # the two-sided ideal of `A' generated by `m'
<two-sided ideal in <algebra-with-one of dimension 3 over Rationals>,
(1 generators)>
gap> Dimension( I );
2

gap> GeneratorsOfIdeal( I );
[ [ [ 0, 2, 3 ], [ 0, 0, 4 ], [ 0, 0, 0 ] ] ]
gap> BasisVectors( Basis( I ) );
[ [ [ 0, 1, 3/2 ], [ 0, 0, 2 ], [ 0, 0, 0 ] ],
  [ [ 0, 0, 1 ], [ 0, 0, 0 ], [ 0, 0, 0 ] ] ]
gap> A:= FullMatrixAlgebra( Rationals, 4 );
gap> m:= NullMat( 4, 4 );; m[1][4]:=1;;
gap> I:= LeftIdeal( A, [ m ] );
<left ideal in ( Rationals^[ 4, 4 ] ), (1 generators)>
gap> Dimension( I );
4

gap> GeneratorsOfLeftIdeal( I );
[ [ [ 0, 0, 0, 0 ], [ 0, 0, 0, 1 ], [ 0, 0, 0, 0 ], [ 0, 0, 0, 0 ], [ 0, 0, 0, 0 ] ] ]
gap> mats:= [ [1,0],[0,0] ], [ [0,1],[0,0] ], [ [0,0],[1,0] ] ];;
gap> A:= Algebra( Rationals, mats );;
gap> # Form the two-sided ideal for which `mats[2]' is known to be
  # the unique basis element.
  
gap> I:= Ideal( A, [ mats[2] ], "basis" );
<two-sided ideal in <algebra of dimension 3 over Rationals>,
(dimensions 1)>
```

62.8 Categories and Properties of Algebras

62.8.1 IsFLMLOR

```
> IsFLMLOR( obj )

A FLMLOR (“free left module left operator ring”) in GAP is a ring that is also a free left module. Note that this means that being a FLMLOR is not a property a ring can get, since a ring is usually not represented as an external left set. Examples are magma rings (e.g. over the integers) or algebras.
```

Example

```
gap> A:= FullMatrixAlgebra( Rationals, 2 );;
gap> IsFLMLOR( A );
true
```
62.8.2 IsFLMLORWithOne

A FLMLOR-with-one in GAP is a ring-with-one that is also a free left module. Note that this means that being a FLMLOR-with-one is not a property a ring-with-one can get, since a ring-with-one is usually not represented as an external left set. Examples are magma rings-with-one or algebras-with-one (but also over the integers).

Example

\begin{verbatim}
gap> A := FullMatrixAlgebra( Rationals, 2 );;
gap> IsFLMLORWithOne( A );
true
\end{verbatim}

62.8.3 IsAlgebra

An algebra in GAP is a ring that is also a left vector space. Note that this means that being an algebra is not a property a ring can get, since a ring is usually not represented as an external left set.

Example

\begin{verbatim}
gap> A := MatAlgebra( Rationals, 3 );;
gap> IsAlgebra( A );
true
\end{verbatim}

62.8.4 IsAlgebraWithOne

An algebra-with-one in GAP is a ring-with-one that is also a left vector space. Note that this means that being an algebra-with-one is not a property a ring-with-one can get, since a ring-with-one is usually not represented as an external left set.

Example

\begin{verbatim}
gap> A := MatAlgebra( Rationals, 3 );;
gap> IsAlgebraWithOne( A );
true
\end{verbatim}

62.8.5 IsLieAlgebra

An algebra \( A \) is called Lie algebra if \( a \ast a = 0 \) for all \( a \in A \) and \( (a \ast (b \ast c)) + (b \ast (c \ast a)) + (c \ast (a \ast b)) = 0 \) for all \( a, b, c \in A \) (Jacobi identity).

Example

\begin{verbatim}
gap> A := FullMatrixLieAlgebra( Rationals, 3 );;
gap> IsLieAlgebra( A );
true
\end{verbatim}
62.8.6 IsSimpleAlgebra

▷ IsSimpleAlgebra(A) (property)

is true if the algebra A is simple, and false otherwise. This function is only implemented for the cases where A is an associative or a Lie algebra. And for Lie algebras it is only implemented for the case where the ground field is of characteristic zero.

Example

```gap
gap> A := FullMatrixLieAlgebra( Rationals, 3 );;
gap> IsSimpleAlgebra( A );
false
gap> A := MatAlgebra( Rationals, 3 );;
gap> IsSimpleAlgebra( A );
true
```

62.8.7 IsFiniteDimensional (for matrix algebras)

▷ IsFiniteDimensional(matalg) (method)

returns true (always) for a matrix algebra matalg, since matrix algebras are always finite dimensional.

Example

```gap
gap> A := MatAlgebra( Rationals, 3 );;
gap> IsFiniteDimensional( A );
true
```

62.8.8 IsQuaternion

▷ IsQuaternion(obj) (Category)
▷ IsQuaternionCollection(obj) (Category)
▷ IsQuaternionCollColl(obj) (Category)

IsQuaternion is the category of elements in an algebra constructed by QuaternionAlgebra (62.5.1). A collection of quaternions lies in the category IsQuaternionCollection. Finally, a collection of quaternion collections (e.g., a matrix of quaternions) lies in the category IsQuaternionCollColl.

Example

```gap
gap> A := QuaternionAlgebra( Rationals );;
gap> b := BasisVectors( Basis( A ) );
[ e, i, j, k ]
gap> IsQuaternion( b[1] );
true
true
```
62.9 Attributes and Operations for Algebras

62.9.1 GeneratorsOfAlgebra

\[ \text{GeneratorsOfAlgebra}(A) \]

returns a list of elements that generate \( A \) as an algebra.

For a free algebra, each generator can also be accessed using the \( \cdot \) operator (see GeneratorsOfDomain (31.9.2)).

Example

\[
\begin{align*}
gap &> m := [ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ];; \\
gap &> A := \text{AlgebraWithOne}( \text{Rationals}, [ m ] ); \\
&\langle\text{algebra-with-one over Rationals, with 1 generators}\rangle \\
gap &> \text{GeneratorsOfAlgebra}( A );\ \\
&\{ [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ], \\
&[ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ] \}
\end{align*}
\]

62.9.2 GeneratorsOfAlgebraWithOne

\[ \text{GeneratorsOfAlgebraWithOne}(A) \]

returns a list of elements of \( A \) that generate \( A \) as an algebra with one.

For a free algebra with one, each generator can also be accessed using the \( \cdot \) operator (see GeneratorsOfDomain (31.9.2)).

Example

\[
\begin{align*}
gap &> m := [ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ];; \\
gap &> A := \text{AlgebraWithOne}( \text{Rationals}, [ m ] ); \\
&\langle\text{algebra-with-one over Rationals, with 1 generators}\rangle \\
gap &> \text{GeneratorsOfAlgebraWithOne}( A );\ \\
&\{ [ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ] \}
\end{align*}
\]

62.9.3 ProductSpace

\[ \text{ProductSpace}(U, V) \]

is the vector space \( \langle u \cdot v; u \in U, v \in V \rangle \), where \( U \) and \( V \) are subspaces of the same algebra.

If \( U = V \) is known to be an algebra then the product space is also an algebra, moreover it is an ideal in \( U \). If \( U \) and \( V \) are known to be ideals in an algebra \( A \) then the product space is known to be an algebra and an ideal in \( A \).

Example

\[
\begin{align*}
gap &> A := \text{QuaternionAlgebra}( \text{Rationals} );; \\
gap &> b := \text{BasisVectors}( \text{Basis}( A ) );; \\
gap &> B := \text{Subalgebra}( A, [ b[4] ] ); \\
&\langle\text{algebra over Rationals, with 1 generators}\rangle \\
gap &> \text{ProductSpace}( A, B );\ \\
&\langle\text{vector space of dimension 4 over Rationals}\rangle
\end{align*}
\]
62.9.4 PowerSubalgebraSeries

\[ \text{PowerSubalgebraSeries}(A) \]

returns a list of subalgebras of \( A \), the first term of which is \( A \); and every next term is the product space of the previous term with itself.

```gap
gap> A:= QuaternionAlgebra( Rationals );
<algebra-with-one of dimension 4 over Rationals>
gap> PowerSubalgebraSeries( A );
[ <algebra-with-one of dimension 4 over Rationals> ]
```

62.9.5 AdjointBasis

\[ \text{AdjointBasis}(B) \]

The adjoint map \( \text{ad}(x) \) of an element \( x \) in an \( F \)-algebra \( A \), say, is the left multiplication by \( x \). This map is \( F \)-linear and thus, w.r.t. the given basis \( B = (x_1, x_2, \ldots, x_n) \) of \( A \), \( \text{ad}(x) \) can be represented by a matrix over \( F \). Let \( V \) denote the \( F \)-vector space of the matrices corresponding to \( \text{ad}(x) \), for \( x \in A \). Then \( \text{AdjointBasis} \) returns the basis of \( V \) that consists of the matrices for \( \text{ad}(x_1), \ldots, \text{ad}(x_n) \).

```gap
gap> A:= QuaternionAlgebra( Rationals );;
gap> AdjointBasis( Basis( A ) );
Basis( <vector space over Rationals, with 4 generators>,
[ [ 1, 0, 0, 0 ], [ 0, 1, 0, 0 ], [ 0, 0, 1, 0 ], [ 0, 0, 0, 1 ] ],
[ [ 0, -1, 0, 0 ], [ 1, 0, 0, 0 ], [ 0, 0, 0, -1 ], [ 0, 0, 1, 0 ] ],
[ [ 0, 0, -1, 0 ], [ 0, 0, 0, 1 ], [ 1, 0, 0, 0 ], [ 0, -1, 0, 0 ] ],
[ [ 0, 0, 0, -1 ], [ 0, 0, -1, 0 ], [ 0, 1, 0, 0 ], [ 1, 0, 0, 0 ] ] )
```

62.9.6 IndicesOfAdjointBasis

\[ \text{IndicesOfAdjointBasis}(B) \]

Let \( A \) be an algebra and let \( B \) be the basis that is output by \( \text{AdjointBasis}( \text{Basis}( A ) ) \). This function returns a list of indices. If \( i \) is an index belonging to this list, then \( \text{ad}x_i \) is a basis vector of the matrix space spanned by \( \text{ad}A \), where \( x_i \) is the \( i \)-th basis vector of the basis \( B \).

```gap
gap> L:= FullMatrixLieAlgebra( Rationals, 3 );;
gap> B:= AdjointBasis( Basis( L ) );;
gap> IndicesOfAdjointBasis( B );
[ 1, 2, 3, 4, 5, 6, 7, 8 ]
```

62.9.7 AsAlgebra

\[ \text{AsAlgebra}(F, A) \]

Returns the algebra over \( F \) generated by \( A \).
Example

```
gap> V := VectorSpace( Rationals, [ IdentityMat( 2 ) ] );
<algebra of dimension 1 over Rationals>
```

### 62.9.8 AsAlgebraWithOne

*AsAlgebraWithOne*(F, A)

(operation)

If the algebra A has an identity, then it can be viewed as an algebra with one over F. This function returns this algebra with one.

Example

```
gap> V := VectorSpace( Rationals, [ IdentityMat( 2 ) ] );
gap> A := AsAlgebra( Rationals, V );
gap> AsAlgebraWithOne( Rationals, A );
<algebra-with-one over Rationals, with 1 generators>
```

### 62.9.9 AsSubalgebra

*AsSubalgebra*(A, B)

(operation)

If all elements of the algebra B happen to be contained in the algebra A, then B can be viewed as a subalgebra of A. This function returns this subalgebra.

Example

```
gap> A := FullMatrixAlgebra( Rationals, 2 );
gap> V := VectorSpace( Rationals, [ IdentityMat( 2 ) ] );
gap> B := AsAlgebra( Rationals, V );
gap> BA := AsSubalgebra( A, B );
<algebra of dimension 1 over Rationals>
```

### 62.9.10 AsSubalgebraWithOne

*AsSubalgebraWithOne*(A, B)

(operation)

If B is an algebra with one, all elements of which happen to be contained in the algebra with one A, then B can be viewed as a subalgebra with one of A. This function returns this subalgebra with one.

Example

```
gap> A := FullMatrixAlgebra( Rationals, 2 );
gap> V := VectorSpace( Rationals, [ IdentityMat( 2 ) ] );
gap> B := AsAlgebra( Rationals, V );
gap> C := AsAlgebraWithOne( Rationals, B );
gap> AC := AsSubalgebraWithOne( A, C );
<algebra-with-one over Rationals, with 1 generators>
```

### 62.9.11 MutableBasisOfClosureUnderAction

*MutableBasisOfClosureUnderAction*(F, Agens, from, init, opr, zero, maxdim)

(function)
Let $F$ be a ring, $\text{Agens}$ a list of generators for an $F$-algebra $A$, and from one of "left", "right", "both"; this means that elements of $A$ act via multiplication from the respective side(s). init must be a list of initial generating vectors, and opr the operation (a function of two arguments).

$\text{MutableBasisOfClosureUnderAction}$ returns a mutable basis of the $F$-free left module generated by the vectors in init and their images under the action of $\text{Agens}$ from the respective side(s).

zero is the zero element of the desired module. maxdim is an upper bound for the dimension of the closure; if no such upper bound is known then the value of maxdim must be infinity (18.2.1).

$\text{MutableBasisOfClosureUnderAction}$ can be used to compute a basis of an associative algebra generated by the elements in $\text{Agens}$. In this case from may be "left" or "right", opr is the multiplication $\ast$, and init is a list containing either the identity of the algebra or a list of algebra generators. (Note that if the algebra has an identity then it is in general not sufficient to take algebra-with-one generators as init, whereas of course $\text{Agens}$ need not contain the identity.)

(Note that bases of not necessarily associative algebras can be computed using $\text{MutableBasisOfNonassociativeAlgebra}$ (62.9.12).)

Other applications of $\text{MutableBasisOfClosureUnderAction}$ are the computations of bases for (left/ right/ two-sided) ideals $I$ in an associative algebra $A$ from ideal generators of $I$; in these cases $\text{Agens}$ is a list of algebra generators of $A$, from denotes the appropriate side(s), init is a list of ideal generators of $I$, and opr is again $\ast$.

(Note that bases of ideals in not necessarily associative algebras can be computed using $\text{MutableBasisOfIdealInNonassociativeAlgebra}$ (62.9.13).)

Finally, bases of right $A$-modules also can be computed using $\text{MutableBasisOfClosureUnderAction}$. The only difference to the ideal case is that init is now a list of right module generators, and opr is the operation of the module.

```gap
gap> A:= QuaternionAlgebra( Rationals );;
gap> g:= GeneratorsOfAlgebra( A );;
gap> B:= MutableBasisOfClosureUnderAction( Rationals, g, "left", [ g[1] ], \*, Zero(A), 4 );
<mutable basis over Rationals, 4 vectors>
gap> BasisVectors( B );
[ e, i, j, k ]
```

### 62.9.12 $\text{MutableBasisOfNonassociativeAlgebra}$

$\text{MutableBasisOfNonassociativeAlgebra}(F, \text{Agens}, \text{zero}, \text{maxdim})$ is a mutable basis of the (not necessarily associative) $F$-algebra that is generated by $\text{Agens}$, has zero element $\text{zero}$, and has dimension at most $\text{maxdim}$. If no finite bound for the dimension is known then infinity (18.2.1) must be the value of maxdim.

The difference to $\text{MutableBasisOfClosureUnderAction}$ (62.9.11) is that in general it is not sufficient to multiply just with algebra generators. (For special cases of nonassociative algebras, especially for Lie algebras, multiplying with algebra generators suffices.)

```gap
gap> L:= FullMatrixLieAlgebra( Rationals, 4 );;
gap> m1:= Random( L );;
gap> m2:= Random( L );;
gap> MutableBasisOfNonassociativeAlgebra( Rationals, [ m1, m2 ],
```

---

Example

```gap
gap> A:= QuaternionAlgebra( Rationals );;
gap> g:= GeneratorsOfAlgebra( A );;
gap> B:= MutableBasisOfClosureUnderAction( Rationals, g, "left", [ g[1] ], \*, Zero(A), 4 );
<mutable basis over Rationals, 4 vectors>
gap> BasisVectors( B );
[ e, i, j, k ]
```

### 62.9.12 $\text{MutableBasisOfNonassociativeAlgebra}$

> $\text{MutableBasisOfNonassociativeAlgebra}(F, \text{Agens}, \text{zero}, \text{maxdim})$ (function)

is a mutable basis of the (not necessarily associative) $F$-algebra that is generated by $\text{Agens}$, has zero element $\text{zero}$, and has dimension at most $\text{maxdim}$. If no finite bound for the dimension is known then infinity (18.2.1) must be the value of maxdim.

The difference to $\text{MutableBasisOfClosureUnderAction}$ (62.9.11) is that in general it is not sufficient to multiply just with algebra generators. (For special cases of nonassociative algebras, especially for Lie algebras, multiplying with algebra generators suffices.)

```gap
gap> L:= FullMatrixLieAlgebra( Rationals, 4 );;
gap> m1:= Random( L );;
gap> m2:= Random( L );;
gap> MutableBasisOfNonassociativeAlgebra( Rationals, [ m1, m2 ],
```

---

Example

```gap
gap> A:= QuaternionAlgebra( Rationals );;
gap> g:= GeneratorsOfAlgebra( A );;
gap> B:= MutableBasisOfClosureUnderAction( Rationals, g, "left", [ g[1] ], \*, Zero(A), 4 );
<mutable basis over Rationals, 4 vectors>
gap> BasisVectors( B );
[ e, i, j, k ]
```
62.9.13 MutableBasisOfIdealInNonassociativeAlgebra

is a mutable basis of the ideal generated by \( Igens \) under the action of the (not necessarily associative) \( F \)-algebra with vector space generators \( Vgens \). The zero element of the ideal is \( zero \), \( from \) is one of "left", "right", "both" (with the same meaning as in \( \text{MutableBasisOfClosureUnderAction} \) (62.9.11)), and \( \text{maxdim} \) is a known upper bound on the dimension of the ideal; if no finite bound for the dimension is known then \( \text{infinity} \) (18.2.1) must be the value of \( \text{maxdim} \).

The difference to \( \text{MutableBasisOfClosureUnderAction} \) (62.9.11) is that in general it is not sufficient to multiply just with algebra generators. (For special cases of nonassociative algebras, especially for Lie algebras, multiplying with algebra generators suffices.)

Example

```
gap> mats:= [ [ [ 1, 0 ], [ 0, -1 ] ], [[0,1],[0,0]] ];;
gap> A:= Algebra( Rationals, mats );;
gap> basA:= BasisVectors( Basis( A ) );;
gap> B:= MutableBasisOfIdealInNonassociativeAlgebra( Rationals, basA,>
> mats[2], 0*mats[1], "both", infinity );
<mutable basis over Rationals, 1 vectors>
gap> BasisVectors( B );
[ [ [ 0, 1 ], [ 0, 0 ] ] ]
```

62.9.14 DirectSumOfAlgebras (for two algebras)

is the direct sum of the two algebras \( A1 \) and \( A2 \) respectively of the algebras in the list \( list \).

If all involved algebras are associative algebras then the result is also known to be associative. If all involved algebras are Lie algebras then the result is also known to be a Lie algebra.

All involved algebras must have the same left acting domain.

The default case is that the result is a structure constants algebra. If all involved algebras are matrix algebras, and either both are Lie algebras or both are associative then the result is again a matrix algebra of the appropriate type.

Example

```
gap> A:= QuaternionAlgebra( Rationals );;
gap> DirectSumOfAlgebras( [A, A, A] );
<algebra of dimension 12 over Rationals>
```

62.9.15 FullMatrixAlgebraCentralizer

is a structure constants algebra if all involved algebras are matrix algebras, and either both are Lie algebras or both are associative then the result is again a matrix algebra of the appropriate type.

Example

```
gap> A:= QuaternionAlgebra( Rationals );;
gap> DirectSumOfAlgebras( [A, A, A] );
<algebra of dimension 12 over Rationals>
```
Let list be a nonempty list of square matrices of the same dimension \( n \), say, with entries in the field \( F \). `FullMatrixAlgebraCentralizer` returns the (pointwise) centralizer of all matrices in list, inside the full matrix algebra of \( n \times n \) matrices over \( F \).

```gap
gap> A := QuaternionAlgebra( Rationals );;
gap> b := Basis( A );;
gap> mats := List( BasisVectors( b ), x -> AdjointMatrix( b, x ) );;
gap> FullMatrixAlgebraCentralizer( Rationals, mats );
<algebra-with-one of dimension 4 over Rationals>
```

### 62.9.16 RadicalOfAlgebra

\[ \triangleleft \text{RadicalOfAlgebra}(A) \] (attribute)

is the maximal nilpotent ideal of \( A \), where \( A \) is an associative algebra.

```gap
gap> m := [ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ];;
gap> A := AlgebraWithOneByGenerators( Rationals, [ m ] );
<algebra-with-one over Rationals, with 1 generators>
gap> RadicalOfAlgebra( A );
<algebra of dimension 2 over Rationals>
```

### 62.9.17 CentralIdempotentsOfAlgebra

\[ \triangleleft \text{CentralIdempotentsOfAlgebra}(A) \] (attribute)

For an associative algebra \( A \), this function returns a list of central primitive idempotents such that their sum is the identity element of \( A \). Therefore \( A \) is required to have an identity.

(This is a synonym of `CentralIdempotentsOfSemiring`.)

```gap
gap> A := QuaternionAlgebra( Rationals );;
gap> B := DirectSumOfAlgebras( [A, A, A] );
<algebra of dimension 12 over Rationals>
gap> CentralIdempotentsOfAlgebra( B );
[ v.9, v.5, v.1 ]
```

### 62.9.18 DirectSumDecomposition (for Lie algebras)

\[ \triangleleft \text{DirectSumDecomposition}(L) \] (attribute)

This function calculates a list of ideals of the algebra \( L \) such that \( L \) is equal to their direct sum. Currently this is only implemented for semisimple associative algebras, and for Lie algebras (semisimple or not).

```gap
gap> G := SymmetricGroup( 4 );;
gap> A := GroupRing( Rationals, G );
<algebra-with-one over Rationals, with 2 generators>
gap> dd := DirectSumDecomposition( A );
[ <two-sided ideal in
```

---

**Here is a table format for the examples:**

<table>
<thead>
<tr>
<th>Example</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>A := QuaternionAlgebra( Rationals );</code></td>
<td>Defines a quaternion algebra over the rationals</td>
</tr>
<tr>
<td><code>b := Basis( A );</code></td>
<td>Defines the basis of the quaternion algebra</td>
</tr>
<tr>
<td><code>mats := List( BasisVectors( b ), x -&gt; AdjointMatrix( b, x ) );</code></td>
<td>Generates a list of matrices</td>
</tr>
<tr>
<td><code>FullMatrixAlgebraCentralizer( Rationals, mats );</code></td>
<td>Returns the centralizer of the matrices</td>
</tr>
<tr>
<td><code>m := [ [ 0, 1, 2 ], [ 0, 0, 3 ], [ 0, 0, 0 ] ];</code></td>
<td>Defines a matrix</td>
</tr>
<tr>
<td><code>A := AlgebraWithOneByGenerators( Rationals, [ m ] );</code></td>
<td>Defines an algebra with one generator</td>
</tr>
<tr>
<td><code>RadicalOfAlgebra( A );</code></td>
<td>Returns the radical of the algebra</td>
</tr>
<tr>
<td><code>CentralIdempotentsOfAlgebra( B );</code></td>
<td>Returns central idempotents of the algebra</td>
</tr>
<tr>
<td><code>G := SymmetricGroup( 4 );</code></td>
<td>Defines a symmetric group</td>
</tr>
<tr>
<td><code>A := GroupRing( Rationals, G );</code></td>
<td>Defines a group ring</td>
</tr>
<tr>
<td><code>dd := DirectSumDecomposition( A );</code></td>
<td>Calculates a direct sum decomposition</td>
</tr>
</tbody>
</table>

---

**Here is the LaTeX representation:**

Let list be a nonempty list of square matrices of the same dimension \( n \), say, with entries in the field \( F \). `FullMatrixAlgebraCentralizer` returns the (pointwise) centralizer of all matrices in list, inside the full matrix algebra of \( n \times n \) matrices over \( F \).
<algebra-with-one of dimension 24 over Rationals>,
(1 generators)>
<two-sided ideal in
<algebra-with-one of dimension 24 over Rationals>,
(1 generators)>,
<two-sided ideal in
<algebra-with-one of dimension 24 over Rationals>,
(1 generators)>
<two-sided ideal in
<algebra-with-one of dimension 24 over Rationals>,
(1 generators)> ]
gap> List( dd, Dimension );
[ 1, 1, 4, 9, 9 ]

62.9.19 LeviMalcevDecomposition (for Lie algebras)

A Levi-Malcev subalgebra of the algebra \( L \) is a semisimple subalgebra complementary to the radical of \( L \). This function returns a list with two components. The first component is a Levi-Malcev subalgebra, the second the radical. This function is implemented for associative and Lie algebras.

Example

\[
gap> m:= \begin{bmatrix} 1 & 2 & 0 \\ 0 & 1 & 3 \\ 0 & 0 & 1 \end{bmatrix};;
gap> A:= Algebra( Rationals, \{ m \} );;
gap> LeviMalcevDecomposition( A );
[ <algebra of dimension 1 over Rationals>,
<algebra of dimension 2 over Rationals> ]
\]

62.9.20 Grading

\[
gap> L:= FullMatrixLieAlgebra( Rationals, 5 );;;
gap> LeviMalcevDecomposition( L );
[ <two-sided ideal in <Lie algebra of dimension 24 over Rationals>,
(dimension 1)>, (dimension 1)>,
<two-sided ideal in <Lie algebra of dimension 25 over Rationals>,
(dimension 24)>, (dimension 24)> ]
\]

Example

\[
gap> L:= FullMatrixLieAlgebra( Rationals, 5 );;;
gap> LeviMalcevDecomposition( L );
[ <Lie algebra of dimension 24 over Rationals>,
<two-sided ideal in <Lie algebra of dimension 25 over Rationals>,
(dimension 1)>, (dimension 1)>,
<two-sided ideal in <Lie algebra of dimension 25 over Rationals>,
(dimension 24)>, (dimension 24)> ]
\]

Example

\[
gap> L:= FullMatrixLieAlgebra( Rationals, 5 );;;
gap> LeviMalcevDecomposition( L );
[ <Lie algebra of dimension 24 over Rationals>,
<two-sided ideal in <Lie algebra of dimension 25 over Rationals>,
(dimension 1)>, (dimension 1)>,
<two-sided ideal in <Lie algebra of dimension 25 over Rationals>,
(dimension 24)>, (dimension 24)> ]
\]

Example

\[
gap> L:= FullMatrixLieAlgebra( Rationals, 5 );;;
gap> LeviMalcevDecomposition( L );
[ <Lie algebra of dimension 24 over Rationals>,
<two-sided ideal in <Lie algebra of dimension 25 over Rationals>,
(dimension 1)>, (dimension 1)>,
<two-sided ideal in <Lie algebra of dimension 25 over Rationals>,
(dimension 24)>, (dimension 24)> ]
\]

Example
Let $G$ be an Abelian group and $A$ an algebra. Then $A$ is said to be graded over $G$ if for every $g \in G$ there is a subspace $A_g$ of $A$ such that $A_g \cdot A_h \subset A_{g+h}$ for $g, h \in G$. In GAP 4 a grading of an algebra is a record containing the following components.

**source**
- the Abelian group over which the algebra is graded.

**hom_components**
- a function assigning to each element from the source a subspace of the algebra.

**min_degree**
- in the case where the algebra is graded over the integers this is the minimum number for which `hom_components` returns a nonzero subspace.

**max_degree**
- is analogous to `min_degree`.

We note that there are no methods to compute a grading of an arbitrary algebra; however some algebras get a natural grading when they are constructed (see `JenningsLieAlgebra` (64.8.4), `NilpotentQuotientOfFpLieAlgebra` (64.11.2)).

We note also that these components may be not enough to handle the grading efficiently, and another record component may be needed. For instance in a Lie algebra $L$ constructed by `JenningsLieAlgebra` (64.8.4), the length of the of the range $[\text{Grading}(L)!.\text{min\_degree} .. \text{Grading}(L)!.\text{max\_degree}]$ may be non-polynomial in the dimension of $L$. To handle efficiently this situation, an optional component can be used:

**non_zero_hom_components**
- the subset of `source` for which `hom_components` returns a nonzero subspace.

Example

```
gap> G := SmallGroup(3^6, 100 );
<pc group of size 729 with 6 generators>
gap> L := JenningsLieAlgebra( G );
<Lie algebra of dimension 6 over GF(3)>
gap> g := Grading( L );
g := Grading( L );
rec( hom_components := function( d ) ... end, max_degree := 9,
  min_degree := 1, source := Integers )
g.hom_components( 3 );
<vector space over GF(3), with 1 generators>
g.hom_components( 14 );
<vector space of dimension 0 over GF(3)>
```

### 62.10 Homomorphisms of Algebras

Algebra homomorphisms are vector space homomorphisms that preserve the multiplication. So the default methods for vector space homomorphisms work, and in fact there is not much use of the fact that source and range are algebras, except that preimages and images are algebras (or even ideals) in certain cases.
62.10.1 AlgebraGeneralMappingByImages

\[ \text{AlgebraGeneralMappingByImages}(A, B, \text{gens}, \text{imgs}) \]

is a general mapping from the \( F \)-algebra \( A \) to the \( F \)-algebra \( B \). This general mapping is defined by mapping the entries in the list \( \text{gens} \) (elements of \( A \)) to the entries in the list \( \text{imgs} \) (elements of \( B \)), and taking the \( F \)-linear and multiplicative closure.

\( \text{gens} \) need not generate \( A \) as an \( F \)-algebra, and if the specification does not define a linear and multiplicative mapping then the result will be multivalued. Hence, in general it is not a mapping. For constructing a linear map that is not necessarily multiplicative, we refer to \text{LeftModuleHomomorphismByImages} (61.10.2).

Example

```gap
gap> A:= QuaternionAlgebra( Rationals );;
gap> B:= FullMatrixAlgebra( Rationals, 2 );;
gap> bA:= BasisVectors( Basis( A ) );; bB:= BasisVectors( Basis( B ) );;
gap> f:= AlgebraGeneralMappingByImages( A, B, bA, bB );
[ e, i, j, k ] -> [ [ [ 1, 0 ], [ 0, 0 ] ], [ [ 0, 1 ], [ 0, 0 ] ],
[ [ 0, 0 ], [ 1, 0 ] ], [ [ 0, 0 ], [ 0, 1 ] ] ]
gap> Images( f, bA[1] );
<add. coset of <algebra over Rationals, with 16 generators>>
```

62.10.2 AlgebraHomomorphismByImages

\[ \text{AlgebraHomomorphismByImages}(A, B, \text{gens}, \text{imgs}) \]

\text{AlgebraHomomorphismByImages} returns the algebra homomorphism with source \( A \) and range \( B \) that is defined by mapping the list \( \text{gens} \) of generators of \( A \) to the list \( \text{imgs} \) of images in \( B \).

If \( \text{gens} \) does not generate \( A \) or if the homomorphism does not exist (i.e., if mapping the generators describes only a multi-valued mapping) then \text{fail} is returned.

One can avoid the checks by calling \text{AlgebraHomomorphismByImagesNC} (62.10.3), and one can construct multi-valued mappings with \text{AlgebraGeneralMappingByImages} (61.10.1).

Example

```gap
gap> T:= EmptySCTable( 2, 0 );;
gap> SetEntrySCTable( T, 1, 1, [1,1] ); SetEntrySCTable( T, 2, 2, [1,2] );
gap> A:= AlgebraByStructureConstants( Rationals, T );;
gap> m1:= NullMat( 2, 2 );; m1[1][1]:= 1;;
gap> m2:= NullMat( 2, 2 );; m2[2][2]:= 1;;
gap> B:= AlgebraByGenerators( Rationals, [ m1, m2 ] );
gap> bA:= BasisVectors( Basis( A ) );; bB:= BasisVectors( Basis( B ) );;
gap> f:= AlgebraHomomorphismByImagesImag( A, B, bA, bB );
[ v.1, v.2 ] -> [ [ 1, 0 ], [ 0, 0 ] ], [ [ 0, 0 ], [ 0, 1 ] ]
[ [ 1, 0 ], [ 0, 1 ] ]
```

62.10.3 AlgebraHomomorphismByImagesNC

\[ \text{AlgebraHomomorphismByImagesNC}(A, B, \text{gens}, \text{imgs}) \]

\text{AlgebraHomomorphismByImagesNC} returns the algebra homomorphism with source \( A \) and range \( B \) that is defined by mapping the list \( \text{gens} \) of generators of \( A \) to the list \( \text{imgs} \) of images in \( B \).

If \( \text{gens} \) does not generate \( A \) or if the homomorphism does not exist (i.e., if mapping the generators describes only a multi-valued mapping) then \text{fail} is returned.

One can avoid the checks by calling \text{AlgebraHomomorphismByImagesNC} (62.10.3), and one can construct multi-valued mappings with \text{AlgebraGeneralMappingByImages} (61.10.1).
AlgebraHomomorphismByImagesNC is the operation that is called by the function AlgebraHomomorphismByImages (62.10.2). Its methods may assume that gens generates A and that the mapping of gens to imgs defines an algebra homomorphism. Results are unpredictable if these conditions do not hold.

For creating a possibly multi-valued mapping from A to B that respects addition, multiplication, and scalar multiplication, AlgebraGeneralMappingByImages (62.10.1) can be used.

For the definitions of the algebras A and B in the next example we refer to the previous example.

Example

\[
gap> f:= \text{AlgebraHomomorphismByImagesNC}( A, B, bA, bB );
[ v.1, v.2 ] \rightarrow [ [ [ 1, 0 ], [ 0, 0 ] ], [ [ 0, 0 ], [ 0, 1 ] ] ]
\]

62.10.4 AlgebraWithOneGeneralMappingByImages

\[ \text{AlgebraWithOneGeneralMappingByImages}( A, B, \text{gens}, \text{imgs}) \]

This function is analogous to AlgebraGeneralMappingByImages (62.10.1); the only difference being that the identity of A is automatically mapped to the identity of B.

Example

\[
gap> A:= \text{QuaternionAlgebra}( \text{Rationals} );
gap> B:= \text{FullMatrixAlgebra}( \text{Rationals}, 2 );
gap> bA:= \text{BasisVectors}( \text{Basis}( A ) );; bB:= \text{BasisVectors}( \text{Basis}( B ) );;
gap> f:= \text{AlgebraWithOneGeneralMappingByImages}( A, B, bA[{2,3,4}], bB[{1,2,3}]);;
[ i, j, k, e ] \rightarrow [ [ [ 1, 0 ], [ 0, 0 ] ], [ [ 0, 1 ], [ 0, 0 ] ],
[ [ 0, 0 ], [ 1, 0 ] ], [ [ 1, 0 ], [ 0, 1 ] ] ]
\]

62.10.5 AlgebraWithOneHomomorphismByImages

\[ \text{AlgebraWithOneHomomorphismByImages}( A, B, \text{gens}, \text{imgs}) \]

AlgebraWithOneHomomorphismByImages returns the algebra-with-one homomorphism with source A and range B that is defined by mapping the list gens of generators of A to the list imgs of images in B.

The difference between an algebra homomorphism and an algebra-with-one homomorphism is that in the latter case, it is assumed that the identity of A is mapped to the identity of B, and therefore gens needs to generate A only as an algebra-with-one.

If gens does not generate A or if the homomorphism does not exist (i.e., if mapping the generators describes only a multi-valued mapping) then fail is returned.

One can avoid the checks by calling AlgebraWithOneHomomorphismByImagesNC (62.10.6), and one can construct multi-valued mappings with AlgebraWithOneGeneralMappingByImages (62.10.4).

Example

\[
gap> m1:= \text{NullMat}( 2, 2 );; m1[1][1]:=1;;
gap> m2:= \text{NullMat}( 2, 2 );; m2[2][2]:=1;;
gap> A:= \text{AlgebraByGenerators}( \text{Rationals}, [m1,m2] );;
gap> T:= \text{EmptySCTable}( 2, 0 );;
gap> \text{SetEntrySCTable}( T, 1, 1, [1,1] );
gap> \text{SetEntrySCTable}( T, 2, 2, [1,2] );
gap> B:= \text{AlgebraByStructureConstants}(\text{Rationals}, T);;
\]
gap> bA:= BasisVectors( Basis( A ) );; bB:= BasisVectors( Basis( B ) );;
gap> f:= AlgebraWithOneHomomorphismByImages( A, B, bA{[1]}, bB{[1]} );;
[ [ [ 1, 0 ], [ 0, 0 ] ], [ [ 1, 0 ], [ 0, 1 ] ] ] -> [ v.1, v.1+v.2 ]

62.10.6  AlgebraWithOneHomomorphismByImagesNC

\[ \text{AlgebraWithOneHomomorphismByImagesNC}(A, B, \text{gens, imgs}) \]

AlgebraWithOneHomomorphismByImagesNC is the operation that is called by the function
AlgebraWithOneHomomorphismByImages (62.10.5). Its methods may assume that gens generates
A and that the mapping of gens to imgs defines an algebra-with-one homomorphism. Results are
unpredictable if these conditions do not hold.

For creating a possibly multi-valued mapping from A to B that respects addition, multiplication,
identity, and scalar multiplication, AlgebraWithOneGeneralMappingByImages (62.10.4) can
be used.

Example

\[
gap> m1:= \text{NullMat}( 2, 2 );; m1[1][1]:=1;;
gap> m2:= \text{NullMat}( 2, 2 );; m2[2][2]:=1;;
gap> A:= \text{AlgebraByGenerators}( \text{Rationals}, [m1,m2] );;
gap> T:= \text{EmptySCTable}( 2, 0 );;
gap> \text{SetEntrySCTable}( T, 1, 1, [1,1] );
gap> \text{SetEntrySCTable}( T, 2, 2, [1,2] );
gap> B:= \text{AlgebraByStructureConstants}( \text{Rationals}, T );;
gap> bA:= \text{BasisVectors}( \text{Basis}( A ) );; bB:= \text{BasisVectors}( \text{Basis}( B ) );;
gap> f:= \text{AlgebraWithOneHomomorphismByImagesNC}( A, B, bA{[1]}, bB{[1]} );;
[ [ [ 1, 0 ], [ 0, 0 ] ], [ [ 1, 0 ], [ 0, 1 ] ] ] -> [ v.1, v.1+v.2 ]
\]

62.10.7  NaturalHomomorphismByIdeal (for an algebra and an ideal)

\[ \text{NaturalHomomorphismByIdeal}(A, I) \]

For an algebra A and an ideal I in A, the return value of NaturalHomomorphismByIdeal (56.8.4)
is a homomorphism of algebras, in particular the range of this mapping is also an algebra.

Example

\[
gap> L:= \text{FullMatrixLieAlgebra}( \text{Rationals}, 3 );;
gap> C:= \text{LieCentre}( L );
<\text{two-sided ideal in } <\text{Lie algebra of dimension 9 over Rationals}>,
\text{(dimension 1)}>
gap> \text{hom:= NaturalHomomorphismByIdeal}( L, C );
<\text{linear mapping by matrix, } <\text{Lie algebra of dimension 9 over Rationals}> \to <\text{Lie algebra of dimension 8 over Rationals}>>
gap> ImagesSource( hom );
<\text{Lie algebra of dimension 8 over Rationals}>
\]

62.10.8  OperationAlgebraHomomorphism (action w.r.t. a basis of the module)

\[ \text{OperationAlgebraHomomorphism}(A, B[, opr]) \]

\[ \text{OperationAlgebraHomomorphism}(A, V[, opr]) \]
OperationAlgebraHomomorphism returns an algebra homomorphism from the \( F \)-algebra \( A \) into a matrix algebra over \( F \) that describes the \( F \)-linear action of \( A \) on the basis \( B \) of a free left module respectively on the free left module \( V \) (in which case some basis of \( V \) is chosen), via the operation \( \text{opr} \).

The homomorphism need not be surjective. The default value for \( \text{opr} \) is OnRight (41.2.2).

If \( A \) is an algebra-with-one then the operation homomorphism is an algebra-with-one homomorphism because the identity of \( A \) must act as the identity.

Example

```gap
gap> m1:= NullMat( 2, 2 );; m1[1][1]:= 1;;
gap> m2:= NullMat( 2, 2 );; m2[2][2]:= 1;;
gap> B:= AlgebraByGenerators( Rationals, [ m1, m2 ] );;
gap> V:= FullRowSpace( Rationals, 2 );
( Rationals^2 )
gap> f:= OperationAlgebraHomomorphism( B, Basis( V ), OnRight );
<op. hom. Algebra( Rationals, 
[ [ [ 1, 0 ], [ 0, 0 ] ], [ [ 0, 0 ], [ 0, 1 ] ] ] ) -> matrices of dim. 2>
gap> Image( f, m1 );
[ [ 1, 0 ], [ 0, 0 ] ]
```

62.10.9 NiceAlgebraMonomorphism

\( \triangleright \) NiceAlgebraMonomorphism(\( A \))

(\( \text{attribute} \))

If \( A \) is an associative algebra with one, returns an isomorphism from \( A \) onto a matrix algebra (see IsomorphismMatrixAlgebra (62.10.11) for an example). If \( A \) is a finitely presented Lie algebra, returns an isomorphism from \( A \) onto a Lie algebra defined by a structure constants table (see 64.11 for an example).

62.10.10 IsomorphismFpAlgebra

\( \triangleright \) IsomorphismFpAlgebra(\( A \))

(\( \text{attribute} \))

isomorphism from the algebra \( A \) onto a finitely presented algebra. Currently this is only implemented for associative algebras with one.

Example

```gap
gap> A:= QuaternionAlgebra( Rationals );
<algebra-with-one of dimension 4 over Rationals>
gap> f:= IsomorphismFpAlgebra( A );
[ e, i, j, k, e ] -> [ [1]*x.1], [1]*x.2], [1]*x.3], [1]*x.4],
[(1)*<identity ...>] ]
```

62.10.11 IsomorphismMatrixAlgebra

\( \triangleright \) IsomorphismMatrixAlgebra(\( A \))

(\( \text{attribute} \))

isomorphism from the algebra \( A \) onto a matrix algebra. Currently this is only implemented for associative algebras with one.
Example

```gap
gap> T:= EmptySCTable( 2, 0 );;
gap> SetEntrySCTable( T, 1, 1, [1,1] ); SetEntrySCTable( T, 2, 2, [1,2] );
gap> A:= AlgebraByStructureConstants( Rationals, T );;
gap> A:= AsAlgebraWithOne( Rationals, A );;
gap> f:= IsomorphismMatrixAlgebra( A );
<op. hom. AlgebraWithOne( Rationals, ... ) -> matrices of dim. 2>
gap> Image( f, BasisVectors( Basis( A ) )[1] );
[ [ 1, 0 ], [ 0, 0 ] ]
```

62.10.12 IsomorphismSCAlgebra (w.r.t. a given basis)

- IsomorphismSCAlgebra(B) (attribute)
- IsomorphismSCAlgebra(A) (attribute)

For a basis \( B \) of an algebra \( A \), say, IsomorphismSCAlgebra returns an algebra isomorphism from \( A \) to an algebra \( S \) given by structure constants (see 62.4), such that the canonical basis of \( S \) is the image of \( B \).

For an algebra \( A \), IsomorphismSCAlgebra chooses a basis of \( A \) and returns the IsomorphismSCAlgebra value for that basis.

```gap
gap> IsomorphismSCAlgebra( GF(8) );
CanonicalBasis( GF(2^3) ) -> CanonicalBasis( <algebra of dimension 3 over GF(2)> )
gap> IsomorphismSCAlgebra( GF(2)^[2,2] );
CanonicalBasis( ( GF(2)^ [ 2, 2 ] ) ) -> CanonicalBasis( <algebra of dimension 4 over GF(2)> )
```

62.10.13 RepresentativeLinearOperation

- RepresentativeLinearOperation(A, v, w, opr) (operation)

is an element of the algebra \( A \) that maps the vector \( v \) to the vector \( w \) under the linear operation described by the function \( opr \). If no such element exists then fail is returned.

```gap
gap> m1:= NullMat( 2, 2 );; m1[1][1]:= 1;;
gap> m2:= NullMat( 2, 2 );; m2[2][2]:= 1;;
gap> B:= AlgebraByGenerators( Rationals, [ m1, m2 ] );;
gap> RepresentativeLinearOperation( B, [1,0], [1,0], OnRight );
[ [ 1, 0 ], [ 0, 0 ] ]
gap> RepresentativeLinearOperation( B, [1,0], [0,1], OnRight );
fail
```

62.11 Representations of Algebras

An algebra module is a vector space together with an action of an algebra. So a module over an algebra is constructed by giving generators of a vector space, and a function for calculating the action...
of algebra elements on elements of the vector space. When creating an algebra module, the genera-
tors of the vector space are wrapped up and given the category IsLeftAlgebraModuleElement or
IsRightModuleElement if the algebra acts from the left, or right respectively. (So in the case of a
bi-module the elements get both categories.) Most linear algebra computations are delegated to the
original vector space.

The transition between the original vector space and the corresponding algebra module is handled
by ExtRepOfObj and ObjByExtRep. For an element \( v \) of the algebra module, ExtRepOfObj(\( v \))
returns the underlying element of the original vector space. Furthermore, if \( \vec{e} \)c is an element of
the original vector space, and \( \text{fam} \) the elements family of the corresponding algebra module, then
ObjByExtRep(\( \text{fam}, \vec{e}c \)) returns the corresponding element of the algebra module. Below is an
example of this.

The action of the algebra on elements of the algebra module is constructed by using the operator
\(^\wedge\). If \( x \) is an element of an algebra \( A \), and \( v \) an element of a left \( A \)-module, then \( x^v \) calculates the
result of the action of \( x \) on \( v \). Similarly, if \( v \) is an element of a right \( A \)-module, then \( v^x \) calculates the
action of \( x \) on \( v \).

62.11.1 LeftAlgebraModuleByGenerators

\[
\text{LeftAlgebraModuleByGenerators}(A, op, gens)
\]

(declaration)

Constructs the left algebra module over \( A \) generated by the list of vectors \( gens \). The action of
\( A \) is described by the function \( op \). This must be a function of two arguments; the first argument is
the algebra element, and the second argument is a vector; it outputs the result of applying the algebra
element to the vector.

62.11.2 RightAlgebraModuleByGenerators

\[
\text{RightAlgebraModuleByGenerators}(A, op, gens)
\]

(declaration)

Constructs the right algebra module over \( A \) generated by the list of vectors \( gens \). The action of
\( A \) is described by the function \( op \). This must be a function of two arguments; the first argument is a
vector, and the second argument is the algebra element; it outputs the result of applying the algebra
element to the vector.

62.11.3 BiAlgebraModuleByGenerators

\[
\text{BiAlgebraModuleByGenerators}(A, B, opl, opr, gens)
\]

(declaration)

Constructs the algebra bi-module over \( A \) and \( B \) generated by the list of vectors \( gens \). The left
action of \( A \) is described by the function \( opl \), and the right action of \( B \) by the function \( opr \). \( opl \) must
be a function of two arguments; the first argument is the algebra element, and the second argument is a vector; it outputs the result of applying the algebra element on the left to the vector. \( opr \) must
be a function of two arguments; the first argument is a vector, and the second argument is the algebra
element; it outputs the result of applying the algebra element on the right to the vector.

Example

\[
gap> A:=\text{Rationals}^[3,3];
( \text{Rationals}^[3,3] )
\]
\[
gap> V:=\text{LeftAlgebraModuleByGenerators}(A,\text{\_*},[[1,0,0]]);
\]
In the above examples, the modules $V$, $W$, and $M$ are 3-dimensional vector spaces over the rationals. The algebra $A$ acts from the left on $V$, from the right on $W$, and from the left and from the right on $M$.

### 62.11.4 LeftAlgebraModule

\[ \text{LeftAlgebraModule}(A, \text{op}, V) \]

Constructs the left algebra module over $A$ with underlying space $V$. The action of $A$ is described by the function $\text{op}$. This must be a function of two arguments; the first argument is the algebra element, and the second argument is a vector from $V$; it outputs the result of applying the algebra element to the vector.

### 62.11.5 RightAlgebraModule

\[ \text{RightAlgebraModule}(A, \text{op}, V) \]

Constructs the right algebra module over $A$ with underlying space $V$. The action of $A$ is described by the function $\text{op}$. This must be a function of two arguments; the first argument is a vector from $V$ and the second argument is the algebra element; it outputs the result of applying the algebra element to the vector.

### 62.11.6 BiAlgebraModule

\[ \text{BiAlgebraModule}(A, B, \text{opl}, \text{opr}, V) \]

Constructs the algebra bi-module over $A$ and $B$ with underlying space $V$. The left action of $A$ is described by the function $\text{opl}$, and the right action of $B$ by the function $\text{opr}$. $\text{opl}$ must be a function of two arguments; the first argument is the algebra element, and the second argument is a vector from $V$; it outputs the result of applying the algebra element on the left to the vector. $\text{opr}$ must be a function of two arguments; the first argument is a vector from $V$, and the second argument is the algebra element; it outputs the result of applying the algebra element on the right to the vector.
62.11.7 GeneratorsOfAlgebraModule

\texttt{GeneratorsOfAlgebraModule}(M)  \quad \text{(attribute)}

A list of elements of \( M \) that generate \( M \) as an algebra module.

\begin{verbatim}
gap> A := Rationals^[3,3];;
gap> V := LeftAlgebraModuleByGenerators( A, \*, [ [ 1, 0, 0 ] ] );;
gap> GeneratorsOfAlgebraModule( V );
[ [ 1, 0, 0 ] ]
\end{verbatim}

62.11.8 IsAlgebraModuleElement

\begin{verbatim}
\texttt{IsAlgebraModuleElement}(\textit{obj}) \quad \text{(Category)}
\texttt{IsAlgebraModuleElementCollection}(\textit{obj}) \quad \text{(Category)}
\texttt{IsAlgebraModuleElementFamily}(\textit{fam}) \quad \text{(Category)}
\end{verbatim}

Category of algebra module elements. If an object has \texttt{IsAlgebraModuleElementCollection}, then it is an algebra module. If a family has \texttt{IsAlgebraModuleElementFamily}, then it is a family of algebra module elements (every algebra module has its own elements family).

62.11.9 IsLeftAlgebraModuleElement

\begin{verbatim}
\texttt{IsLeftAlgebraModuleElement}(\textit{obj}) \quad \text{(Category)}
\texttt{IsLeftAlgebraModuleElementCollection}(\textit{obj}) \quad \text{(Category)}
\end{verbatim}

Category of left algebra module elements. If an object has \texttt{IsLeftAlgebraModuleElementCollection}, then it is a left-algebra module.

62.11.10 IsRightAlgebraModuleElement

\begin{verbatim}
\texttt{IsRightAlgebraModuleElement}(\textit{obj}) \quad \text{(Category)}
\texttt{IsRightAlgebraModuleElementCollection}(\textit{obj}) \quad \text{(Category)}
\end{verbatim}

Category of right algebra module elements. If an object has \texttt{IsRightAlgebraModuleElementCollection}, then it is a right-algebra module.

\begin{verbatim}
gap> A := Rationals^[3,3];
( Rationals^[ 3, 3 ] )
gap> M := BiAlgebraModuleByGenerators( A, A, \*, \*, [ [ 1, 0, 0 ] ] ) ;
<bi-module over ( Rationals^[ 3, 3 ] ) (left) and ( Rationals^[ 3, 3 ] ) (right)>
gap> vv := BasisVectors( Basis( M ) );
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ]
gap> IsLeftAlgebraModuleElement( vv[1] );
true
gap> IsRightAlgebraModuleElement( vv[1] );
true
gap> vv[1] = [ 1, 0, 0 ];
false
\end{verbatim}
gap> ExtRepOfObj( vv[1] ) = [ 1, 0, 0 ];
true
gap> ObjByExtRep( ElementsFamily( FamilyObj( M ) ), [ 1, 0, 0 ] ) in M;
true
gap> xx:= BasisVectors( Basis( A ) );;
gap> xx[4]^vv[1]; # left action
[ 0, 1, 0 ]
gap> vv[1]^xx[2]; # right action
[ 0, 1, 0 ]

62.11.11 LeftActingAlgebra

▷ LeftActingAlgebra(V) (attribute)

Here V is a left-algebra module; this function returns the algebra that acts from the left on V.

62.11.12 RightActingAlgebra

▷ RightActingAlgebra(V) (attribute)

Here V is a right-algebra module; this function returns the algebra that acts from the right on V.

62.11.13 ActingAlgebra

▷ ActingAlgebra(V) (operation)

Here V is an algebra module; this function returns the algebra that acts on V (this is the same as LeftActingAlgebra(V) if V is a left module, and RightActingAlgebra(V) if V is a right module; it will signal an error if V is a bi-module).

Example

\begin{verbatim}
gap> A:= Rationals^[3,3];;
gap> M:= BiAlgebraModuleByGenerators( A, A, \*, \*, [ [ 1, 0, 0 ] ] );;
gap> LeftActingAlgebra( M );
( Rationals^[ 3, 3 ] )
gap> RightActingAlgebra( M );
( Rationals^[ 3, 3 ] )
gap> V:= RightAlgebraModuleByGenerators( A, \*, [ [ 1, 0, 0 ] ] );;
gap> ActingAlgebra( V );
( Rationals^[ 3, 3 ] )
\end{verbatim}

62.11.14 IsBasisOfAlgebraModuleElementSpace

▷ IsBasisOfAlgebraModuleElementSpace(B) (Category)

If a basis B lies in the category IsBasisOfAlgebraModuleElementSpace, then B is a basis of a subspace of an algebra module. This means that B has the record field B!.delegateBasis set. This last object is a basis of the corresponding subspace of the vector space underlying the algebra module (i.e., the vector space spanned by all ExtRepOfObj( v ) for v in the algebra module).
Example

```gap
gap> A:= Rationals^[3,3];;
gap> M:= BiAlgebraModuleByGenerators( A, A, \*, \*, [ [ 1, 0, 0 ] ] );;
gap> B:= Basis( M );;
Basis( <3-dimensional bi-module over ( Rationals^ [ 3, 3 ] ) (left) and ( Rationals^[ 3, 3 ] ) (right)>,
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ] )
gap> IsBasisOfAlgebraModuleElementSpace( B );
true
gap> B!.delegateBasis;
SemiEchelonBasis( <vector space of dimension 3 over Rationals>,
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ] )
```

62.11.15 MatrixOfAction

> MatrixOfAction( B, x[ , side] ) (operation)

Here \( B \) is a basis of an algebra module and \( x \) is an element of the algebra that acts on this module. This function returns the matrix of the action of \( x \) with respect to \( B \). If \( x \) acts from the left, then the coefficients of the images of the basis elements of \( B \) (under the action of \( x \)) are the columns of the output. If \( x \) acts from the right, then they are the rows of the output.

If the module is a bi-module, then the third parameter \( \text{side} \) must be specified. This is the string "left", or "right" depending whether \( x \) acts from the left or the right.

Example

```gap
gap> M:= LeftAlgebraModuleByGenerators( A, \*, [ [ 1, 0, 0 ] ] );;
gap> x:= Basis(A)[3];
[ [ 0, 0, 1 ], [ 0, 0, 0 ], [ 0, 0, 0 ] ]
gap> MatrixOfAction( Basis( M ), x );
[ [ 0, 0, 1 ], [ 0, 0, 0 ], [ 0, 0, 0 ] ]
```

62.11.16 SubAlgebraModule

> SubAlgebraModule( M, gens[, "basis"] ) (operation)

is the sub-module of the algebra module \( M \), generated by the vectors in \( \text{gens} \). If as an optional argument the string \( \text{basis} \) is added, then it is assumed that the vectors in \( \text{gens} \) form a basis of the submodule.

Example

```gap
gap> m1:= NullMat( 2, 2 );; m1[1][1]:= 1;;
gap> m2:= NullMat( 2, 2 );; m2[2][2]:= 1;;
gap> A:= Algebra( Rationals, [ m1, m2 ] );;
gap> M:= LeftAlgebraModuleByGenerators( A, \*, [ [ 1, 0 ], [ 0, 1 ] ] );
<left-module over <algebra over Rationals, with 2 generators>>
gap> bb:= BasisVectors( Basis( M ) );
[ [ 1, 0 ], [ 0, 1 ] ]
gap> V:= SubAlgebraModule( M, [ bb[1] ] );
<left-module over <algebra over Rationals, with 2 generators>>
gap> Dimension( V );
1
```
62.11.17  LeftModuleByHomomorphismToMatAlg

- **LeftModuleByHomomorphismToMatAlg** 
  *operation*

  Here \( A \) is an algebra and \( \hom \) a homomorphism from \( A \) into a matrix algebra. This function returns the left \( A \)-module defined by the homomorphism \( \hom \).

62.11.18  RightModuleByHomomorphismToMatAlg

- **RightModuleByHomomorphismToMatAlg** 
  *operation*

  Here \( A \) is an algebra and \( \hom \) a homomorphism from \( A \) into a matrix algebra. This function returns the right \( A \)-module defined by the homomorphism \( \hom \).

  First we produce a structure constants algebra with basis elements \( x, y, z \) such that \( x^2 = x \), \( y^2 = y \), \( xz = z \), \( yz = z \) and all other products are zero.

  **Example**

  ```
  gap> T:= EmptySCTable( 3, 0 );;
  gap> SetEntrySCTable( T, 1, 1, [ 1, 1 ] );
  gap> SetEntrySCTable( T, 2, 2, [ 1, 2 ] );
  gap> SetEntrySCTable( T, 1, 3, [ 1, 3 ] );
  gap> SetEntrySCTable( T, 3, 2, [ 1, 3 ] );
  gap> A:= AlgebraByStructureConstants( Rationals, T );
  <algebra of dimension 3 over Rationals>
  ```

  Now we construct an isomorphic matrix algebra.

  **Example**

  ```
  gap> m1:= NullMat( 2, 2 );; m1[1][1]:= 1;;
  gap> m2:= NullMat( 2, 2 );; m2[2][2]:= 1;;
  gap> m3:= NullMat( 2, 2 );; m3[1][2]:= 1;;
  gap> B:= Algebra( Rationals, [ m1, m2, m3 ] );
  <algebra over Rationals, with 3 generators>
  ```

  Finally we construct the homomorphism and the corresponding right module.

  **Example**

  ```
  gap> f:= AlgebraHomomorphismByImages( A, B, Basis(A), [ m1, m2, m3 ] );;
  gap> RightModuleByHomomorphismToMatAlg( A, f );
  <right-module over <algebra of dimension 3 over Rationals>>
  ```

62.11.19  AdjointModule

- **AdjointModule** 
  *attribute*

  returns the \( A \)-module defined by the left action of \( A \) on itself.

  **Example**

  ```
  gap> m1:= NullMat( 2, 2 );; m1[1][1]:= 1;;
  gap> m2:= NullMat( 2, 2 );; m2[2][2]:= 1;;
  gap> m3:= NullMat( 2, 2 );; m3[1][2]:= 1;;
  gap> A:= Algebra( Rationals, [ m1, m2, m3 ] );
  <algebra over Rationals, with 3 generators>
  ```
GAP> V:= AdjointModule( A );
<3-dimensional left-module over <algebra of dimension
3 over Rationals>>
GAP> v:= Basis( V )[3];
[ [ 0, 1 ], [ 0, 0 ] ]
GAP> W:= SubAlgebraModule( V, [ v ] );
<left-module over <algebra of dimension 3 over Rationals>>
GAP> Dimension( W );
1

62.11.20 FaithfulModule (for Lie algebras)

FaithfulModule(A) (attribute)

returns a faithful finite-dimensional left-module over the algebra $A$. This is only implemented for
associative algebras, and for Lie algebras of characteristic 0. (It may also work for certain Lie algebras of characteristic $p > 0$.)

Example
gap> T:= EmptySCTable( 2, 0 );;
gap> A:= AlgebraByStructureConstants( Rationals, T );
<algebra of dimension 2 over Rationals>
Example
gap> T:= EmptySCTable( 3, 0, "antisymmetric" );;
gap> SetEntrySCTable( T, 1, 2, [ 1, 3 ]);
gap> L:= LieAlgebraByStructureConstants( Rationals, T );
<Lie algebra of dimension 3 over Rationals>
gap> V:= FaithfulModule( L );
<left-module over <Lie algebra of dimension 3 over Rationals>>
gap> vv:= BasisVectors( Basis( V ) );
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ]
gap> x:= Basis( L )[3];

A is a 2-dimensional algebra where all products are zero.

Example
gap> V:= FaithfulModule( A );
<left-module over <algebra of dimension 2 over Rationals>>
gap> vv:= BasisVectors( Basis( V ) );
[ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ]
gap> xx:= BasisVectors( Basis( A ) );
[ v.1, v.2 ]
gap> xx[1]*vv[3];
[ 1, 0, 0 ]

62.11.21 ModuleByRestriction

ModuleByRestriction(V, sub1[, sub2]) (operation)
Here \( V \) is an algebra module and \( \text{sub1} \) is a subalgebra of the acting algebra of \( V \). This function returns the module that is the restriction of \( V \) to \( \text{sub1} \). So it has the same underlying vector space as \( V \), but the acting algebra is \( \text{sub} \). If two subalgebras \( \text{sub1}, \text{sub2} \) are given then \( V \) is assumed to be a bi-module, and \( \text{sub1} \) a subalgebra of the algebra acting on the left, and \( \text{sub2} \) a subalgebra of the algebra acting on the right.

Example

```
gap> A:= Rationals^[3,3];;
gap> V:= LeftAlgebraModuleByGenerators( A, \*, [ [ 1, 0, 0 ] ] );;
gap> B:= Subalgebra( A, [ Basis(A)[1] ] );;
<algebra over Rationals, with 1 generators>
gap> W:= ModuleByRestriction( V, B );
<left-module over <algebra over Rationals, with 1 generators>>
```

### 62.11.22 NaturalHomomorphismBySubAlgebraModule

\( \text{NaturalHomomorphismBySubAlgebraModule}(V, W) \)

This function returns the projection from \( V \) onto \( V/W \). It is a linear map, that is also a module homomorphism. As usual images can be formed with \( \text{Image}(f, v) \) and pre-images with \( \text{PreImagesRepresentative}(f, u) \).

The quotient module can also be formed by entering \( V/W \).

Example

```
gap> A:= Rationals^[3,3];;
gap> B:= DirectSumOfAlgebras( A, A );
<algebra over Rationals, with 6 generators>
gap> T:= StructureConstantsTable( Basis( B ) );;
gap> C:= AlgebraByStructureConstants( Rationals, T );
<algebra of dimension 18 over Rationals>
gap> V:= AdjointModule( C );
<left-module over <algebra of dimension 18 over Rationals>>
gap> W:= SubAlgebraModule( V, [ Basis(V)[1] ] );
<left-module over <algebra of dimension 18 over Rationals>>
gap> f:= NaturalHomomorphismBySubAlgebraModule( V, W );
<linear mapping by matrix, <18-dimensional left-module over <algebra of dimension 18 over Rationals>> -> <9-dimensional left-module over <algebra of dimension 18 over Rationals>>>
gap> quo:= ImagesSource( f ); # i.e., the quotient module
<9-dimensional left-module over <algebra of dimension 18 over Rationals>>
gap> v:= Basis( quo )[1];
[ 1, 0, 0, 0, 0, 0, 0, 0, 0 ]
gap> PreImagesRepresentative( f, v );
v.4
gap> Basis( C )[4]^v;
[ 1, 0, 0, 0, 0, 0, 0, 0, 0 ]
```
### 62.11.23 DirectSumOfAlgebraModules (for a list of Lie algebra modules)

- **DirectSumOfAlgebraModules(list)**
- **DirectSumOfAlgebraModules(V, W)**

Here `list` must be a list of algebra modules. This function returns the direct sum of the elements in the list (as an algebra module). The modules must be defined over the same algebras.

In the second form is short for `DirectSumOfAlgebraModules([V, W])`.

**Example**

```gap
gap> A:= FullMatrixAlgebra( Rationals, 3 );;
gap> V:= BiAlgebraModuleByGenerators( A, A, 
\* , \*, [ [1,0,0] ] );;
grupoid> W:= DirectSumOfAlgebraModules( V, V );
groupoid> <6-dimensional left-module over ( Rationals^[ 3, 3 ] )>
gap> BasisVectors( Basis( W ) );
[ ( [ 1, 0, 0 ] )(+)( [ 0, 0, 0 ] ), ( [ 0, 1, 0 ] )(+)( [ 0, 0, 0 ] )
, ( [ 0, 0, 1 ] )(+)( [ 0, 0, 0 ] ), ( [ 0, 0, 0 ] )(+)( [ 1, 0, 0 ] )
, ( [ 0, 0, 0 ] )(+)( [ 0, 1, 0 ] )
]```

### 62.11.24 TranslatorSubalgebra

- **TranslatorSubalgebra(M, U, W)**

Here `M` is an algebra module, and `U` and `W` are two subspaces of `M`. Let `A` be the algebra acting on `M`. This function returns the subspace of elements of `A` that map `U` into `W`. If `W` is a sub-algebra-module (i.e., closed under the action of `A`), then this space is a subalgebra of `A`.

This function works for left, or right modules over a finite-dimensional algebra. We stress that it is not checked whether `U` and `W` are indeed subspaces of `M`. If this is not the case nothing is guaranteed about the behaviour of the function.

**Example**

```gap
gap> A:= FullMatrixAlgebra( Rationals, 3 );
( Rationals^[ 3, 3 ] )
gap> V:= Rationals^[3,2];
( Rationals^[ 3, 2 ] )
gap> M:= LeftAlgebraModule( A, \*, V );
<left-module over ( Rationals^[ 3, 3 ] )>
gap> bm:= Basis(M);;
grupoid> U:= SubAlgebraModule( M, [ bm[1] ] );
<left-module over ( Rationals^[ 3, 3 ] )>
```
gap> TranslatorSubalgebra( M, U, M );
<algebra of dimension 9 over Rationals>
gap> W:= SubAlgebraModule( M, [ bm[4] ] );
<left-module over ( Rationals^[ 3, 3 ] )>
gap> T:= TranslatorSubalgebra( M, U, W );
<algebra of dimension 0 over Rationals>
Chapter 63

Finitely Presented Algebras

Currently the GAP library contains only few functions dealing with general finitely presented algebras, so this chapter is merely a placeholder.

The special case of finitely presented Lie algebras is described in 64.11, and there is also a GAP package fplsa for computing structure constants of finitely presented Lie (super)algebras.
Chapter 64

Lie Algebras

A Lie algebra $L$ is an algebra such that $xx = 0$ and $x(yz) + y(zx) + z(xy) = 0$ for all $x, y, z \in L$. A common way of creating a Lie algebra is by taking an associative algebra together with the commutator as product. Therefore the product of two elements $x, y$ of a Lie algebra is usually denoted by $[x, y]$, but in GAP this denotes the list of the elements $x$ and $y$; hence the product of elements is made by the usual $\ast$. This gives no problems when dealing with Lie algebras given by a table of structure constants. However, for matrix Lie algebras the situation is not so easy as $\ast$ denotes the ordinary (associative) matrix multiplication. In GAP this problem is solved by wrapping elements of a matrix Lie algebra up as LieObjects, and then define the $\ast$ for LieObjects to be the commutator (see 64.1).

64.1 Lie Objects

Let $x$ be a ring element, then LieObject $(x)$ (see LieObject (64.1.1)) wraps $x$ up into an object that contains the same data (namely $x$). The multiplication $\ast$ for Lie objects is formed by taking the commutator. More exactly, if $l_1$ and $l_2$ are the Lie objects corresponding to the ring elements $r_1$ and $r_2$, then $l_1 \ast l_2$ is equal to the Lie object corresponding to $r_1 \ast r_2 - r_2 \ast r_1$. Two rules for Lie objects are worth noting:

- An element is not equal to its Lie element.

- If we take the Lie object of an ordinary (associative) matrix then this is again a matrix; it is therefore a collection (of its rows) and a list. But it is not a collection of collections of its entries, and its family is not a collections family.

Given a family $F$ of ring elements, we can form its Lie family $L$. The elements of $F$ and $L$ are in bijection, only the multiplications via $\ast$ differ for both families. More exactly, if $l_1$ and $l_2$ are the Lie elements corresponding to the elements $f_1$ and $f_2$ in $F$, we have $l_1 \ast l_2$ equal to the Lie element corresponding to $f_1 \ast f_2 - f_2 \ast f_1$. Furthermore, the product of Lie elements $l_1$, $l_2$ and $l_3$ is left-normed, that is $l_1 \ast l_2 \ast l_3$ is equal to $(l_1 \ast l_2) \ast l_3$.

The main reason to distinguish elements and Lie elements on the family level is that this helps to avoid forming domains that contain elements of both types. For example, if we could form vector spaces of matrices then at first glance it would be no problem to have both ordinary and Lie matrices in it, but as soon as we find out that the space is in fact an algebra (e.g., because its dimension is that of the full matrix algebra), we would run into strange problems.

Note that the family situation with Lie families may be not familiar.
• We have to be careful when installing methods for certain types of domains that may involve Lie elements. For example, the zero element of a matrix space is either an ordinary matrix or its Lie element, depending on the space. So either the method must be aware of both cases, or the method selection must distinguish the two cases. In the latter situation, only one method may be applicable to each case; this means that it is not sufficient to treat the Lie case with the additional requirement `IsLieObjectCollection` but that we must explicitly require non-Lie elements for the non-Lie case.

• Being a full matrix space is a property that may hold for a space of ordinary matrices or a space of Lie matrices. So methods for full matrix spaces must also be aware of Lie matrices.

64.1.1 LieObject

\[ \text{LieObject}(\text{obj}) \] (attribute)

Let \( \text{obj} \) be a ring element. Then \( \text{LieObject}(\text{obj}) \) is the corresponding Lie object. If \( \text{obj} \) lies in the family \( F \), then \( \text{LieObject}(\text{obj}) \) lies in the family \( \text{LieFamily}(F) \) (see `LieFamily` (64.1.3)).

Example

```
gap> m := [ [ 1, 0 ], [ 0, 1 ] ];;
gap> lo := LieObject( m );
LieObject( [ [ 1, 0 ], [ 0, 1 ] ] )
gap> m*m;
[ [ 1, 0 ], [ 0, 1 ] ]
gap> lo*lo;
LieObject( [ [ 0, 0 ], [ 0, 0 ] ] )
```

64.1.2 IsLieObject

\[ \text{IsLieObject}(\text{obj}) \] (Category)
\[ \text{IsLieObjectCollection}(\text{obj}) \] (Category)
\[ \text{IsRestrictedLieObject}(\text{obj}) \] (Category)
\[ \text{IsRestrictedLieObjectCollection}(\text{obj}) \] (Category)

An object lies in \( \text{IsLieObject} \) if and only if it lies in a family constructed by `LieFamily` (64.1.3).

Example

```
gap> m := [ [ 1, 0 ], [ 0, 1 ] ];;
gap> lo := LieObject( m );
LieObject( [ [ 1, 0 ], [ 0, 1 ] ] )
gap> IsLieObject( m );
false
gap> IsLieObject( lo );
true
```

64.1.3 LieFamily

\[ \text{LieFamily}(\text{Fam}) \] (attribute)
is a family $F$ in bijection with the family $\text{Fam}$, but with the Lie bracket as infix multiplication. That is, for $x, y$ in $\text{Fam}$, the product of the images in $F$ will be the image of $x \ast y - y \ast x$.

The standard type of objects in a Lie family $F$ is $F!\text{.packedType}$.

The bijection from $\text{Fam}$ to $F$ is given by $\text{Embedding}(\text{Fam}, F)$ (see $\text{Embedding}$ (32.2.11)); this bijection respects addition and additive inverses.

### 64.1.4 UnderlyingFamily

$\triangleright$ UnderlyingFamily($\text{Fam}$)

(attribute)

If $\text{Fam}$ is a Lie family then $\text{UnderlyingFamily}(\text{Fam})$ is a family $F$ such that $\text{Fam} = \text{LieFamily}(F)$.

### 64.1.5 UnderlyingRingElement

$\triangleright$ UnderlyingRingElement($\text{obj}$)

(attribute)

Let $\text{obj}$ be a Lie object constructed from a ring element $r$ by calling $\text{LieObject}(r)$. Then $\text{UnderlyingRingElement}(\text{obj})$ returns the ring element $r$ used to construct $\text{obj}$. If $r$ lies in the family $F$, then $\text{obj}$ lies in the family $\text{LieFamily}(F)$ (see $\text{LieFamily}$ (64.1.3)).

**Example**

```gap
gap> lo:=\text{LieObject}(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix});
\text{LieObject}(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix})
gap> m:=\text{UnderlyingRingElement}(lo);
\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
gap> l0:=\text{LieObject}(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix});
\text{LieObject}(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix})
gap> l0\ast m;
\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
gap> m\ast m;
\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
```

### 64.2 Constructing Lie algebras

In this section we describe functions that create Lie algebras. Creating and working with subalgebras goes exactly in the same way as for general algebras; so for that we refer to Chapter 62.

### 64.2.1 LieAlgebraByStructureConstants

$\triangleright$ LieAlgebraByStructureConstants($R$, $sct$, $nameinfo$)

(function)

$\text{LieAlgebraByStructureConstants}$ does the same as $\text{AlgebraByStructureConstants}$ (62.4.1), and has the same meaning of arguments, except that the result is assumed to be a Lie algebra. Note that the function does not check whether $sct$ satisfies the Jacobi identity. (So if one creates a Lie algebra this way with a table that does not satisfy the Jacobi identity, errors may occur later on.)

**Example**

```gap
gap> T:=\text{EmptySCTable}(2,0,\text{"antisymmetric"});;
gap> \text{SetEntrySCTable}(T,1,2,\begin{bmatrix} 1/2 & 1 \end{bmatrix});
```
gap> L := LieAlgebraByStructureConstants( Rationals, T );
<Lie algebra of dimension 2 over Rationals>

64.2.2 RestrictedLieAlgebraByStructureConstants

\texttt{RestrictedLieAlgebraByStructureConstants(R, sct[, nameinfo[, pmapping]])} (function)

\texttt{RestrictedLieAlgebraByStructureConstants} does the same as \texttt{LieAlgebraByStructureConstants} (64.2.1), and has the same meaning of all arguments, except that the result is assumed to be a restricted Lie algebra (see 64.8) with the $p$-map given by the additional argument \texttt{pmapping}. This last argument is a list of the length equal to the dimension of the algebra; its $i$-th entry specifies the $p$-th power of the $i$-th basis vector in the same format $[\text{coeff1, position1, coeff2, position2, ...}]$ as \texttt{SetEntrySCTable} (62.4.4) uses to specify entries of the structure constants table.

Note that the function does not check whether \texttt{sct} satisfies the Jacobi identity, of whether \texttt{pmapping} specifies a legitimate $p$-mapping.

The following example creates a commutative restricted Lie algebra of dimension 3, in which the $p$-th power of the $i$-th basis element is the $i + 1$-th basis element (except for the 3rd basis element which goes to zero).

\texttt{gap> T:= EmptySCTable( 3, Zero(GF(5)), "antisymmetric" );;}
\texttt{gap> L:= RestrictedLieAlgebraByStructureConstants( GF(5), T, [[1,2],[1,3],[3]] );}
\texttt{<Lie algebra of dimension 3 over GF(5)>}
\texttt{gap> List(Basis(L),PthPowerImage);}
\texttt{[ v.2, v.3, 0*v.1 ]}
\texttt{gap> PthPowerImage(L.1+L.2);}
\texttt{v.2+v.3}

64.2.3 LieAlgebra (for an associative algebra)

\texttt{LieAlgebra(L)} (function)
\texttt{LieAlgebra(F, gens[, zero][, "basis"])} (function)

For an associative algebra $L$, \texttt{LieAlgebra( L )} is the Lie algebra isomorphic to $L$ as a vector space but with the Lie bracket as product.

\texttt{LieAlgebra( F, gens )} is the Lie algebra over the division ring $F$, generated as Lie algebra by the Lie objects corresponding to the vectors in the list \texttt{gens}.

\texttt{Note} that the algebra returned by \texttt{LieAlgebra} does not contain the vectors in \texttt{gens}. The elements in \texttt{gens} are wrapped up as Lie objects (see 64.1). This allows one to create Lie algebras from ring elements with respect to the Lie bracket as product. But of course the product in the Lie algebra is the usual $\ast$.

If there are three arguments, a division ring $F$ and a list \texttt{gens} and an element \texttt{zero}, then \texttt{LieAlgebra( F, gens, zero )} is the corresponding $F$-Lie algebra with zero element the Lie object corresponding to \texttt{zero}.
If the last argument is the string "basis" then the vectors in gens are known to form a basis of the algebra (as an \( F \)-vector space).

Note that even if each element in gens is already a Lie element, i.e., is of the form \( \text{LieElement}( \, \text{elm} \, ) \) for an object \( \text{elm} \), the elements of the result lie in the Lie family of the family that contains gens as a subset.

Example

\[
\text{gap> A:= FullMatrixAlgebra( GF(7), 4 );;}
\]
\[
\text{gap> L:= LieAlgebra( A );;}
\]
\[
\text{<Lie algebra of dimension 16 over GF(7)>}
\]
\[
\text{gap> mats:= [ [ [ 1, 0 ], [ 0, -1 ] ], [ [ 0, 1 ], [ 0, 0 ] ],}
\]
\[
\text{[ [ 0, 0 ], [ 1, 0 ] ] ];;}
\]
\[
\text{gap> L:= LieAlgebra( Rationals, mats );;}
\]
\[
\text{<Lie algebra over Rationals, with 3 generators>}
\]

### 64.2.4 FreeLieAlgebra (for ring, rank (and name))

\[
\text{FreeLieAlgebra(R, rank [, name])}
\]

Returns a free Lie algebra of rank rank over the ring \( R \). FreeLieAlgebra( \( R \), name1, name2, ... ) returns a free Lie algebra over \( R \) with generators named name1, name2, and so on. The elements of a free Lie algebra are written on the Hall-Lyndon basis.

Example

\[
\text{gap> L:= FreeLieAlgebra( Rationals, "x", "y", "z" );}
\]
\[
\text{<Lie algebra over Rationals, with 3 generators>}
\]

### 64.2.5 FullMatrixLieAlgebra

\[
\text{FullMatrixLieAlgebra( R, n )}
\]

is the full matrix Lie algebra of \( n \times n \) matrices over the ring \( R \), for a nonnegative integer \( n \).

Example

\[
\text{gap> FullMatrixLieAlgebra( GF(9), 10 );}
\]
\[
\text{<Lie algebra over GF(3^2), with 19 generators>}
\]

### 64.2.6 RightDerivations

\[
\text{RightDerivations( B )}
\]

\[
\text{LeftDerivations( B )}
\]

\[
\text{Derivations( B )}
\]

These functions all return the matrix Lie algebra of derivations of the algebra \( A \) with basis \( B \).
RightDerivations( B ) returns the algebra of derivations represented by their right action on the algebra A. This means that with respect to the basis B of A, the derivation D is described by the matrix \([d_{ij}]\) which means that \(D\) maps the \(i\)-th basis element \(b_i\) to \(\sum_{j=1}^{n} d_{ij}b_j\).

LeftDerivations( B ) returns the Lie algebra of derivations represented by their left action on the algebra A. So the matrices contained in the algebra output by LeftDerivations( B ) are the transposes of the matrices contained in the output of RightDerivations( B ).

Derivations is just a synonym for RightDerivations.

Example

```gap
gap> A := OctaveAlgebra( Rationals );
<algebra of dimension 8 over Rationals>
gap> L := Derivations( Basis( A ) );
<Lie algebra of dimension 14 over Rationals>
```

64.2.7 SimpleLieAlgebra

\[\text{SimpleLieAlgebra}(\text{type}, n, F)\]

This function constructs the simple Lie algebra of type given by the string \(\text{type}\) and rank \(n\) over the field \(F\). The string \(\text{type}\) must be one of "A", "B", "C", "D", "E", "F", "G", "H", "K", "S", "W" or "M". For the types A to G, \(n\) must be a positive integer. The last five types only exist over fields of characteristic \(p > 0\). If the type is H, then \(n\) must be a list of positive integers of even length. If the type is K, then \(n\) must be a list of positive integers of odd length. For the types S and W, \(n\) must be a list of positive integers of any length. If the type is M, then the Melikyan algebra is constructed. In this case \(n\) must be a list of two positive integers. This Lie algebra only exists over fields of characteristic 5. This Lie algebra is \(\mathbb{Z} \times \mathbb{Z}\) graded; and the grading can be accessed via the attribute Grading(L) (see Grading (62.9.20)). In some cases the Lie algebra returned by this function is not simple. Examples are the Lie algebras of type \(A_n\) over a field of characteristic \(p > 0\) where \(p\) divides \(n + 1\), and the Lie algebras of type \(K_n\) where \(n\) is a list of length 1.

If \(\text{type}\) is one of A, B, C, D, E, F, G, and \(F\) is a field of characteristic zero, then the basis of the returned Lie algebra is a Chevalley basis.

Example

```gap
gap> SimpleLieAlgebra( "E", 6, Rationals );
<Lie algebra of dimension 78 over Rationals>
gap> SimpleLieAlgebra( "A", 6, GF(5) );
<Lie algebra of dimension 14 over GF(5)>
gap> SimpleLieAlgebra( "W", [1,2], GF(5) );
<Lie algebra of dimension 250 over GF(5)>
gap> SimpleLieAlgebra( "H", [1,2], GF(5) );
<Lie algebra of dimension 123 over GF(5)>
gap> L := SimpleLieAlgebra( "M", [1,1], GF(5) );
<Lie algebra of dimension 125 over GF(5)>
```

64.3 Distinguished Subalgebras

Here we describe functions that calculate well-known subalgebras and ideals of a Lie algebra (such as the centre, the centralizer of a subalgebra, etc.).
64.3.1 LieCentre

\[ \text{LieCentre}(L) \quad \text{(attribute)} \]
\[ \text{LieCenter}(L) \quad \text{(attribute)} \]

The Lie centre of the Lie algebra \( L \) is the kernel of the adjoint mapping, that is, the set \( \{ a \in L : \forall x \in L : ax = 0 \} \).

In characteristic 2 this may differ from the usual centre (that is the set of all \( a \in L \) such that \( ax = xa \) for all \( x \in L \)). Therefore, this operation is named \text{LieCentre} and not \text{Centre} (35.4.5).

Example

\begin{verbatim}
gap> L:= FullMatrixLieAlgebra( GF(3), 3 ); 
<Lie algebra over GF(3), with 5 generators>
gap> LieCentre( L ); 
<two-sided ideal in <Lie algebra of dimension 9 over GF(3)>, (dimension 1)>
\end{verbatim}

64.3.2 LieCentralizer

\[ \text{LieCentralizer}(L, S) \quad \text{(operation)} \]

is the annihilator of \( S \) in the Lie algebra \( L \), that is, the set \( \{ a \in L : \forall s \in S : a * s = 0 \} \). Here \( S \) may be a subspace or a subalgebra of \( L \).

Example

\begin{verbatim}
gap> L:= SimpleLieAlgebra( "G", 2, Rationals ); 
<Lie algebra of dimension 14 over Rationals>
gap> b:= BasisVectors( Basis( L ) );;
gap> LieCentralizer( L, Subalgebra( L, [ b[1], b[2] ] ) ); 
<Lie algebra of dimension 1 over Rationals>
\end{verbatim}

64.3.3 LieNormalizer

\[ \text{LieNormalizer}(L, U) \quad \text{(operation)} \]

is the normalizer of the subspace \( U \) in the Lie algebra \( L \), that is, the set \( N_L(U) = \{ x \in L : [x, U] \subseteq U \} \).

Example

\begin{verbatim}
gap> L:= SimpleLieAlgebra( "G", 2, Rationals ); 
<Lie algebra of dimension 14 over Rationals>
gap> b:= BasisVectors( Basis( L ) );;
gap> LieNormalizer( L, Subalgebra( L, [ b[1], b[2] ] ) ); 
<Lie algebra of dimension 8 over Rationals>
\end{verbatim}

64.3.4 LieDerivedSubalgebra

\[ \text{LieDerivedSubalgebra}(L) \quad \text{(attribute)} \]

is the (Lie) derived subalgebra of the Lie algebra \( L \).
Example

```gap
gap> L := FullMatrixLieAlgebra( GF(3), 3 );
<Lie algebra over GF(3), with 5 generators>
gap> LieDerivedSubalgebra( L );
<Lie algebra of dimension 8 over GF(3)>
```

64.3.5 LieNilRadical

\[ \texttt{LieNilRadical(L)} \]

This function calculates the (Lie) nil radical of the Lie algebra \( L \).

Example

```gap
gap> mats := [ [1,0],[0,0] ], [ [0,1],[0,0] ], [ [0,0],[0,1] ];;
gap> L := LieAlgebra( Rationals, mats );;
gap> LieNilRadical( L );
<two-sided ideal in <Lie algebra of dimension 3 over Rationals>,
(dimension 2)>
```

64.3.6 LieSolvableRadical

\[ \texttt{LieSolvableRadical(L)} \]

Returns the (Lie) solvable radical of the Lie algebra \( L \).

Example

```gap
gap> L := FullMatrixLieAlgebra( Rationals, 3 );;
gap> LieSolvableRadical( L );
<two-sided ideal in <Lie algebra of dimension 9 over Rationals>,
(dimension 1)>
```

64.3.7 CartanSubalgebra

\[ \texttt{CartanSubalgebra(L)} \]

A Cartan subalgebra of a Lie algebra \( L \) is defined as a nilpotent subalgebra of \( L \) equal to its own Lie normalizer in \( L \).

Example

```gap
gap> L := SimpleLieAlgebra( "G", 2, Rationals );;
gap> CartanSubalgebra( L );
<Lie algebra of dimension 2 over Rationals>
```

64.4 Series of Ideals

64.4.1 LieDerivedSeries

\[ \texttt{LieDerivedSeries(L)} \]

is the (Lie) derived series of the Lie algebra \( L \).
Example

```gap
gap> mats := [ [[1,0], [0,0]], [[0,1], [0,0]], [[0,0], [0,1]] ];;
gap> L := LieAlgebra( Rationals, mats );;
[ <Lie algebra of dimension 3 over Rationals>,
  <Lie algebra of dimension 1 over Rationals>,
  <Lie algebra of dimension 0 over Rationals> ]
```

### 64.4.2 LieLowerCentralSeries

`LieLowerCentralSeries(L)` (attribute)

is the (Lie) lower central series of the Lie algebra `L`.

**Example**

```gap
gap> mats := [ [[1,0], [0,0]], [[0,1], [0,0]], [[0,0], [0,1]] ];;
gap> L := LieAlgebra( Rationals, mats );;
gap> LieLowerCentralSeries( L );
[ <Lie algebra of dimension 3 over Rationals>,
  <Lie algebra of dimension 1 over Rationals> ]
```

### 64.4.3 LieUpperCentralSeries

`LieUpperCentralSeries(L)` (attribute)

is the (Lie) upper central series of the Lie algebra `L`.

**Example**

```gap
gap> mats := [ [[1,0], [0,0]], [[0,1], [0,0]], [[0,0], [0,1]] ];;
gap> L := LieAlgebra( Rationals, mats );;
gap> LieUpperCentralSeries( L );
[ <two-sided ideal in <Lie algebra of dimension 3 over Rationals>,
  (dimension 1)>, <Lie algebra of dimension 0 over Rationals> ]
```

### 64.5 Properties of a Lie Algebra

#### 64.5.1 IsLieAbelian

`IsLieAbelian(L)` (property)

returns `true` if `L` is a Lie algebra such that each product of elements in `L` is zero, and `false` otherwise.

**Example**

```gap
gap> T := EmptySCTable( 5, 0, "antisymmetric" );;
gap> L := LieAlgebraByStructureConstants( Rationals, T );
<Lie algebra of dimension 5 over Rationals>
gap> IsLieAbelian( L );
true
```
64.5.2 IsLieNilpotent

A Lie algebra $L$ is defined to be (Lie) nilpotent when its (Lie) lower central series reaches the trivial subalgebra.

Example

```gap
T:= EmptySCTable( 5, 0, "antisymmetric" );;
L:= LieAlgebraByStructureConstants( Rationals, T );
<Lie algebra of dimension 5 over Rationals>
IsLieNilpotent( L );
true
```

64.5.3 IsLieSolvable

A Lie algebra $L$ is defined to be (Lie) solvable when its (Lie) derived series reaches the trivial subalgebra.

Example

```gap
T:= EmptySCTable( 5, 0, "antisymmetric" );;
L:= LieAlgebraByStructureConstants( Rationals, T );
<Lie algebra of dimension 5 over Rationals>
IsLieSolvable( L );
true
```

64.6 Semisimple Lie Algebras and Root Systems

This section contains some functions for dealing with semisimple Lie algebras and their root systems.

64.6.1 SemiSimpleType

Let $L$ be a semisimple Lie algebra, i.e., a direct sum of simple Lie algebras. Then SemiSimpleType returns the type of $L$, i.e., a string containing the types of the simple summands of $L$.

Example

```gap
L:= SimpleLieAlgebra( "B", 8, Rationals );;
b:= BasisVectors( Basis( L ) );;
<Lie algebra of dimension 102 over Rationals>
lev:= LeviMalcevDecomposition(K);;
SemiSimpleType( lev[1] );
"B3 A1"
```
64.6.2 ChevalleyBasis

▷ ChevalleyBasis(L)  (attribute)

Here L must be a semisimple Lie algebra with a split Cartan subalgebra. Then ChevalleyBasis(L) returns a list consisting of three sublists. Together these sublists form a Chevalley basis of L. The first list contains the positive root vectors, the second list contains the negative root vectors, and the third list the Cartan elements of the Chevalley basis.

Example

```
gap> L := SimpleLieAlgebra( "G", 2, Rationals );
<Lie algebra of dimension 14 over Rationals>
gap> ChevalleyBasis( L );
[ [ v.1, v.2, v.3, v.4, v.5, v.6 ],
```

64.6.3 IsRootSystem

▷ IsRootSystem(obj)  (Category)

Category of root systems.

64.6.4 IsRootSystemFromLieAlgebra

▷ IsRootSystemFromLieAlgebra(obj)  (Category)

Category of root systems that come from (semisimple) Lie algebras. They often have special attributes such as UnderlyingLieAlgebra (64.6.6), PositiveRootVectors (64.6.9), NegativeRootVectors (64.6.10), CanonicalGenerators (64.6.14).

64.6.5 RootSystem

▷ RootSystem(L)  (attribute)

RootSystem calculates the root system of the semisimple Lie algebra L with a split Cartan subalgebra.

Example

```
gap> L := SimpleLieAlgebra( "G", 2, Rationals );
<Lie algebra of dimension 14 over Rationals>
gap> R := RootSystem( L );
<root system of rank 2>
gap> IsRootSystem( R );
true
gap> IsRootSystemFromLieAlgebra( R );
true
```

64.6.6 UnderlyingLieAlgebra

▷ UnderlyingLieAlgebra(R)  (attribute)

For a root system R coming from a semisimple Lie algebra L, returns the Lie algebra L.
64.6.7 PositiveRoots

\[ \text{PositiveRoots}(R) \]

The list of positive roots of the root system \( R \).

64.6.8 NegativeRoots

\[ \text{NegativeRoots}(R) \]

The list of negative roots of the root system \( R \).

64.6.9 PositiveRootVectors

\[ \text{PositiveRootVectors}(R) \]

A list of positive root vectors of the root system \( R \) that comes from a Lie algebra \( L \). This is a list in bijection with the list \( \text{PositiveRoots}(L) \) (see \( \text{PositiveRoots} \) (64.6.7)). The root vector is a non-zero element of the root space (in \( L \)) of the corresponding root.

64.6.10 NegativeRootVectors

\[ \text{NegativeRootVectors}(R) \]

A list of negative root vectors of the root system \( R \) that comes from a Lie algebra \( L \). This is a list in bijection with the list \( \text{NegativeRoots}(L) \) (see \( \text{NegativeRoots} \) (64.6.8)). The root vector is a non-zero element of the root space (in \( L \)) of the corresponding root.

64.6.11 SimpleSystem

\[ \text{SimpleSystem}(R) \]

A list of simple roots of the root system \( R \).

64.6.12 CartanMatrix

\[ \text{CartanMatrix}(R) \]

The Cartan matrix of the root system \( R \), relative to the simple roots in \( \text{SimpleSystem}(R) \) (see \( \text{SimpleSystem} \) (64.6.11)).

64.6.13 BilinearFormMat

\[ \text{BilinearFormMat}(R) \]

The matrix of the bilinear form of the root system \( R \). If we denote this matrix by \( B \), then we have \( B(i,j) = (\alpha_i, \alpha_j) \), where the \( \alpha_i \) are the simple roots of \( R \).
### 64.6.14 CanonicalGenerators

**CanonicalGenerators(R)**

Here \( R \) must be a root system coming from a semisimple Lie algebra \( L \). This function returns \( 3l \) generators of \( L \), \( x_1, \ldots, x_l, y_1, \ldots, y_l, h_1, \ldots, h_l \), where \( x_i \) lies in the root space corresponding to the \( i \)-th simple root of the root system of \( L \), \( y_i \) lies in the root space corresponding to \( -i \)-th simple root, and the \( h_i \) are elements of the Cartan subalgebra. These elements satisfy the relations

\[
h_i \cdot h_j = 0, \quad x_i \cdot y_j = \delta_{ij}, \quad h_j \cdot x_i = c_{ij} x_i, \quad h_j \cdot y_i = -c_{ij} y_i,
\]

where \( c_{ij} \) is the entry of the Cartan matrix on position \( ij \).

Also if \( a \) is a root of the root system \( R \) (so \( a \) is a list of numbers), then we have the relation

\[
h_i \cdot x = a[i] x,
\]

where \( x \) is a root vector corresponding to \( a \).

#### Example

```gap
gap> L:= SimpleLieAlgebra( "G", 2, Rationals );;
gap> R:= RootSystem( L );;
gap> UnderlyingLieAlgebra( R );
<Lie algebra of dimension 14 over Rationals>
gap> PositiveRoots( R );
[ [ 2, -1 ], [ -3, 2 ], [ -1, 1 ], [ 1, 0 ], [ 3, -1 ], [ 0, 1 ] ]
gap> x:= PositiveRootVectors( R );
gap> g:= CanonicalGenerators( R );
[ [ v.1, v.2 ], [ v.7, v.8 ], [ v.13, v.14 ] ]
gap> g[3][1]*x[1];
(2)*v.1
gap> g[3][2]*x[1];
(-1)*v.1
gap> # i.e., x[1] is the root vector belonging to the root [ 2, -1 ]
gap> BilinearFormMat( R );
[ [ 1/12, -1/8 ], [ -1/8, 1/4 ] ]
```

### 64.7 Semisimple Lie Algebras and Weyl Groups of Root Systems

This section deals with the Weyl group of a root system. A Weyl group is represented by its action on the weight lattice. A **weight** is by definition a linear function \( \lambda : H \to F \) (where \( F \) is the ground field), such that the values \( \lambda(h_i) \) are all integers (where the \( h_i \) are the Cartan elements of the CanonicalGenerators (64.6.14)). On the other hand each weight is determined by these values. Therefore we represent a weight by a vector of integers; the \( i \)-th entry of this vector is the value \( \lambda(h_i) \).

Now the elements of the Weyl group are represented by matrices, and if \( g \) is an element of a Weyl group and \( w \) a weight, then \( w \cdot g \) gives the result of applying \( g \) to \( w \). Another way of applying the \( i \)-th simple reflection to a weight is by using the function ApplySimpleReflection (64.7.4).

A Weyl group is generated by the simple reflections. So GeneratorsOfGroup (39.2.4) for a Weyl group \( W \) gives a list of matrices and the \( i \)-th entry of this list is the simple reflection corresponding to the \( i \)-th simple root of the corresponding root system.

#### 64.7.1 IsWeylGroup

**IsWeylGroup(G)**

* (property)
A Weyl group is a group generated by reflections, with the attribute `SparseCartanMatrix` (64.7.2) set.

### 64.7.2 SparseCartanMatrix

**SparseCartanMatrix(W)**

This is a sparse form of the Cartan matrix of the corresponding root system. If we denote the Cartan matrix by \( C \), then the sparse Cartan matrix of \( W \) is a list (of length equal to the length of the Cartan matrix), where the \( i \)-th entry is a list consisting of elements \([ j, C[i][j] \]) where \( j \) is such that \( C[i][j] \) is non-zero.

### 64.7.3 WeylGroup

**WeylGroup(R)**

The Weyl group of the root system \( R \). It is generated by the simple reflections. A simple reflection is represented by a matrix, and the result of letting a simple reflection \( m \) act on a weight \( w \) is obtained by \( w \cdot m \).

```gap
gap> L := SimpleLieAlgebra( "F", 4, Rationals );;
gap> R := RootSystem( L );;
gap> W := WeylGroup( R );;
<matrix group with 4 generators>
gap> IsWeylGroup( W );
true
gap> SparseCartanMatrix( W );
[[ [ 1, 2 ], [ 3, -1 ] ], [ [ 2, 2 ], [ 4, -1 ] ],
  [ [ 1, -1 ], [ 3, 2 ], [ 4, -1 ] ],
  [ [ 2, -1 ], [ 3, -2 ], [ 4, 2 ] ]]
gap> g := GeneratorsOfGroup( W );;
gap> [ 1, 1, 1, 1 ]*g[2];
[ 1, -1, 1, 2 ]
```

### 64.7.4 ApplySimpleReflection

**ApplySimpleReflection(SC, i, wt)**

Here \( SC \) is the sparse Cartan matrix of a Weyl group. This function applies the \( i \)-th simple reflection to the weight \( wt \), thus changing \( wt \).

```gap
gap> L := SimpleLieAlgebra( "F", 4, Rationals );;
gap> W := WeylGroup( RootSystem( L ) );;
gap> C := SparseCartanMatrix( W );;
gap> w := [ 1, 1, 1, 1 ];;
gap> ApplySimpleReflection( C, 2, w );
gap> w;
[ 1, -1, 1, 2 ]
```
64.7.5 LongestWeylWordPerm

Let \( g_0 \) be the longest element in the Weyl group \( W \), and let \( \{ \alpha_1, \ldots, \alpha_l \} \) be a simple system of the corresponding root system. Then \( g_0 \) maps \( \alpha_i \) to \( -\alpha_{\sigma(i)} \), where \( \sigma \) is a permutation of \( \{1, \ldots, l\} \). This function returns that permutation.

Example

```gap
gap> L := SimpleLieAlgebra( "E", 6, Rationals );;
gap> W := WeylGroup( RootSystem( L ) );;
gap> LongestWeylWordPerm( W );
(1,6)(3,5)
```

64.7.6 ConjugateDominantWeight

Here \( W \) is a Weyl group and \( \mathbf{wt} \) a weight (i.e., a list of integers). `ConjugateDominantWeight` returns the unique dominant weight conjugate to \( \mathbf{wt} \) under \( W \).

`ConjugateDominantWeightWithWord` returns a list of two elements. The first of these is the dominant weight conjugate to \( \mathbf{wt} \). The second element is a list of indices of simple reflections that have to be applied to \( \mathbf{wt} \) in order to get the dominant weight conjugate to it.

Example

```gap
gap> L := SimpleLieAlgebra( "E", 6, Rationals );;
gap> W := WeylGroup( RootSystem( L ) );;
gap> C := SparseCartanMatrix( W );;
gap> w := [ 1, -1, 2, -2, 3, -3 ];;
gap> ConjugateDominantWeight( W, w );
[ 2, 1, 0, 0, 0, 0 ]
gap> c:= ConjugateDominantWeightWithWord( W, w );
[ [ 2, 1, 0, 0, 0, 0 ], [ 2, 4, 2, 3, 6, 5, 4, 2, 3, 1 ] ]
gap> for i in [1..Length(c[2])] do
  > ApplySimpleReflection( C, c[2][i], w );
  > od;
gap> w;
[ 2, 1, 0, 0, 0, 0 ]
```

64.7.7 WeylOrbitIterator

Returns an iterator for the orbit of the weight \( \mathbf{wt} \) under the action of the Weyl group \( W \).

Example

```gap
gap> L := SimpleLieAlgebra( "E", 6, Rationals );;
gap> W := WeylGroup( RootSystem( L ) );;
gap> orb:= WeylOrbitIterator( W, [ 1, 1, 1, 1, 1, 1 ] );
<iterator>
gap> NextIterator( orb );
[ 1, 1, 1, 1, 1, 1 ]
```
64.8 Restricted Lie algebras

A Lie algebra $L$ over a field of characteristic $p > 0$ is called restricted if there is a map $x \mapsto x^p$ from $L$ into $L$ (called a $p$-map) such that $\text{ad} x^p = (\text{ad} x)^p$, $(\alpha x)^p = \alpha^p x^p$ and $(x + y)^p = x^p + y^p + \sum_{i=1}^{p-1} s_i(x, y)$, where $s_i : L \times L \to L$ are certain Lie polynomials in two variables. Using these relations we can calculate $y^p$ for all $y \in L$, once we know $x^p$ for $x$ in a basis of $L$. Therefore a $p$-map is represented in GAP by a list containing the images of the basis vectors of a basis $B$ of $L$. For this reason this list is an attribute of the basis $B$.

64.8.1 IsRestrictedLieAlgebra

\[ IsRestrictedLieAlgebra(L) \]

Test whether $L$ is restricted.

\begin{verbatim}
gap> L := SimpleLieAlgebra( "W", [2], GF(5));
<Lie algebra of dimension 25 over GF(5)>
gap> IsRestrictedLieAlgebra( L );
false
gap> L := SimpleLieAlgebra( "W", [1], GF(5));
<Lie algebra of dimension 5 over GF(5)>
gap> IsRestrictedLieAlgebra( L );
true
\end{verbatim}

64.8.2 PthPowerImages

\[ PthPowerImages(B) \]

Here $B$ is a basis of a restricted Lie algebra. This function returns the list of the images of the basis vectors of $B$ under the $p$-map.

\begin{verbatim}
gap> L := SimpleLieAlgebra( "W", [1], GF(11) );
<Lie algebra of dimension 11 over GF(11)>
gap> B := Basis( L );
CanonicalBasis( <Lie algebra of dimension 11 over GF(11)> )
gap> PthPowerImages( B );
\end{verbatim}
64.8.3 PthPowerImage (for basis and element)

This function computes the image of an element \( x \) of a restricted Lie algebra under its \( p \)-map.

In the first form, a basis of the Lie algebra is provided; this basis stores the \( p \)th powers of its elements. It is the traditional form, provided for backwards compatibility.

In its second form, only the element \( x \) is provided. It is the only form for elements of Lie algebras with no predetermined basis, such as those constructed by \texttt{LieObject} (64.1.1).

In its third form, an extra non-negative integer \( n \) is specified; the \( p \)-mapping is iterated \( n \) times on the element \( x \).

```
gap> L:= SimpleLieAlgebra( "W", [1], GF(11) );;
gap> B:= Basis( L );;
v.1+v.11
gap> PthPowerImage( B, x );
v.1+v.11
gap> PthPowerImage( x, 2 );
v.1+v.11
```

64.8.4 JenningsLieAlgebra

Let \( G \) be a nontrivial \( p \)-group, and let \( G = G_1 \triangleright G_2 \triangleright \cdots \triangleright G_m = 1 \) be its Jennings series (see JenningsSeries (39.17.14)). Then the quotients \( G_i/G_{i+1} \) are elementary abelian \( p \)-groups, i.e., they can be viewed as vector spaces over \( \text{GF}(p) \). Now the Jennings-Lie algebra \( L \) of \( G \) is the direct sum of those vector spaces. The Lie bracket on \( L \) is induced by the commutator in \( G \). Furthermore, the map \( g \mapsto g^p \) in \( G \) induces a \( p \)-map in \( L \) making \( L \) into a restricted Lie algebra. In the canonical basis of \( L \) this \( p \)-map is added as an attribute. A Lie algebra created by JenningsLieAlgebra is naturally graded. The attribute \texttt{Grading} (62.9.20) is set.

64.8.5 PCentralLieAlgebra

```
gap> f := FreeAssociativeAlgebra(GF(2),"x","y");
<algebra over GF(2), with 2 generators>
gap> x := LieObject(f.1);;
y := LieObject(f.2);
```

```
gap> PthPowerImage(x);
```

```
LieObject( (Z(2)^0)*x*y+(Z(2)^0)*y*x )
```

```
LieObject( <zero> of ... )
```

```
LieObject( (Z(2)^0)*x^2 )
```
Here $G$ is a nontrivial $p$-group. \texttt{PCentralLieAlgebra( G )} does the same as \texttt{JenningsLieAlgebra (64.8.4)} except that the $p$-central series is used instead of the Jennings series (see \texttt{PCentralSeries (39.17.13)}). This function also returns a graded Lie algebra. However, it is not necessarily restricted.

\begin{verbatim}
 gap> G:= SmallGroup( 3^6, 123 );
 <pc group of size 729 with 6 generators>
 gap> L:= JenningsLieAlgebra( G );
 <Lie algebra of dimension 6 over GF(3)>
 gap> HasPthPowerImages( Basis( L ) );
 true
 gap> PthPowerImages( Basis( L ) );
 [ v.6, 0*v.1, 0*v.1, 0*v.1, 0*v.1, 0*v.1 ]
 gap> g:= Grading( L );
 rec( hom_components := function( d ) ... end, max_degree := 3,
     min_degree := 1, source := Integers )
 gap> List( [1,2,3], g.hom_components );
 [ <vector space over GF(3), with 3 generators>,
   <vector space over GF(3), with 2 generators>,
   <vector space over GF(3), with 1 generators> ]
\end{verbatim}

\subsection{64.8.6 NaturalHomomorphismOfLieAlgebraFromNilpotentGroup}

\texttt{NaturalHomomorphismOfLieAlgebraFromNilpotentGroup(L)}

This is an attribute of Lie algebras created by \texttt{JenningsLieAlgebra (64.8.4)} or \texttt{PCentralLieAlgebra (64.8.5)}. Then $L$ is the direct sum of quotients of successive terms of the Jennings, or $p$-central series of a $p$-group $G$. Let $G_i$ be the $i$-th term in this series, and let $f = \texttt{NaturalHomomorphismOfLieAlgebraFromNilpotentGroup( L )}$, then for $g$ in $G_i$, $f( g, i )$ returns the element of $L$ (lying in the $i$-th homogeneous component) corresponding to $g$.

\subsection{64.9 The Adjoint Representation}

In this section we show functions for calculating with the adjoint representation of a Lie algebra (and the corresponding trace form, called the Killing form) (see also \texttt{AdjointBasis (62.9.5)} and \texttt{IndicesOfAdjointBasis (62.9.6)}).

\subsection{64.9.1 AdjointMatrix}

\texttt{AdjointMatrix( B, x )}

is the matrix of the adjoint representation of the element $x$ w.r.t. the basis $B$. The adjoint map is the left multiplication by $x$. The $i$-th column of the resulting matrix represents the image of the $i$-th basis vector of $B$ under left multiplication by $x$.

\begin{verbatim}
 gap> L:= SimpleLieAlgebra( "A", 1, Rationals );;
 gap> AdjointMatrix( Basis( L ), Basis( L )[1] );
 [ [ 0, 0, -2 ], [ 0, 0, 0 ], [ 0, 1, 0 ] ]
\end{verbatim}
64.9.2 AdjointAssociativeAlgebra

\[ \text{AdjointAssociativeAlgebra}(L, K) \]

is the associative matrix algebra (with 1) generated by the matrices of the adjoint representation of the subalgebra \( K \) on the Lie algebra \( L \).

Example

\begin{verbatim}
gap> L := SimpleLieAlgebra( "A", 1, Rationals );;
gap> AdjointAssociativeAlgebra( L, L );
<algebra of dimension 9 over Rationals>
gap> AdjointAssociativeAlgebra( L, CartanSubalgebra( L ) );
<algebra of dimension 3 over Rationals>
\end{verbatim}

64.9.3 KillingMatrix

\[ \text{KillingMatrix}(B) \]

is the matrix of the Killing form \( \kappa \) with respect to the basis \( B \), i.e., the matrix \( (\kappa(b_i, b_j)) \) where \( b_1, b_2, \ldots \) are the basis vectors of \( B \).

Example

\begin{verbatim}
gap> L := SimpleLieAlgebra( "A", 1, Rationals );;
gap> KillingMatrix( Basis( L ) );
\begin{bmatrix}
0 & 4 & 0 \\
4 & 0 & 0 \\
0 & 0 & 8
\end{bmatrix}
\end{verbatim}

64.9.4 KappaPerp

\[ \text{KappaPerp}(L, U) \]

is the orthogonal complement of the subspace \( U \) of the Lie algebra \( L \) with respect to the Killing form \( \kappa \), that is, the set \( U^\perp = \{ x \in L; \kappa(x, y) = 0 \text{ for all } y \in L \} \).

\( U^\perp \) is a subspace of \( L \), and if \( U \) is an ideal of \( L \) then \( U^\perp \) is a subalgebra of \( L \).

Example

\begin{verbatim}
gap> L := SimpleLieAlgebra( "A", 1, Rationals );;
gap> b := BasisVectors( Basis( L ) );;
gap> V := VectorSpace( Rationals, [b[1],b[2]] );;
gap> KappaPerp( L, V );
<vector space of dimension 1 over Rationals>
\end{verbatim}

64.9.5 IsNilpotentElement

\[ \text{IsNilpotentElement}(L, x) \]

\( x \) is nilpotent in \( L \) if its adjoint matrix is a nilpotent matrix.

Example

\begin{verbatim}
gap> L := SimpleLieAlgebra( "A", 1, Rationals );;
gap> IsNilpotentElement( L, Basis( L )[1] );
true
\end{verbatim}
64.9.6 NonNilpotentElement

\texttt{NonNilpotentElement(L)} \hspace{1cm} \text{(attribute)}

A non-nilpotent element of a Lie algebra \( L \) is an element \( x \) such that \( \text{ad}_x \) is not nilpotent. If \( L \) is not nilpotent, then by Engel’s theorem non-nilpotent elements exist in \( L \). In this case this function returns a non-nilpotent element of \( L \), otherwise (if \( L \) is nilpotent) \texttt{fail} is returned.

\texttt{gap> L:= SimpleLieAlgebra( "G", 2, Rationals );;}
\texttt{gap> NonNilpotentElement( L );}
\texttt{v.13}
\texttt{gap> IsNilpotentElement( L, last );}
\texttt{false}

64.9.7 FindSl2

\texttt{FindSl2(L, x)} \hspace{1cm} \text{(function)}

This function tries to find a subalgebra \( S \) of the Lie algebra \( L \) with \( S \) isomorphic to \( \mathfrak{sl}_2 \) and such that the nilpotent element \( x \) of \( L \) is contained in \( S \). If such an algebra exists then it is returned, otherwise \texttt{fail} is returned.

\texttt{gap> L:= SimpleLieAlgebra( "G", 2, Rationals );;}
\texttt{gap> b:= BasisVectors( Basis( L ) );;}
\texttt{gap> IsNilpotentElement( L, b[1] );}
\texttt{true}
\texttt{gap> FindSl2( L, b[1] );}
\texttt{<Lie algebra of dimension 3 over Rationals>}

64.10 Universal Enveloping Algebras

64.10.1 UniversalEnvelopingAlgebra

\texttt{UniversalEnvelopingAlgebra(L[, B])} \hspace{1cm} \text{(attribute)}

Returns the universal enveloping algebra of the Lie algebra \( L \). The elements of this algebra are written on a Poincare-Birkhoff-Witt basis.

If a second argument \( B \) is given, it must be a basis of \( L \), and an isomorphic copy of the universal enveloping algebra is returned, generated by the images (in the universal enveloping algebra) of the elements of \( B \).

\texttt{gap> L:= SimpleLieAlgebra( "A", 1, Rationals );;}
\texttt{gap> UL:= UniversalEnvelopingAlgebra( L );}
\texttt{<algebra-with-one of dimension infinity over Rationals>}
\texttt{gap> g:= GeneratorsOfAlgebraWithOne( UL );}
\texttt{[ [1]*x.1, [1]*x.2, [1]*x.3 ]}
\texttt{gap> g[3]*g[2]^2*g[1]^2;}
\texttt{[(-4)*x.1*x.2*x.3^3+(1)*x.1^2*x.2^2*x.3^2+(2)*x.3^3+(2)*x.3^4]}
64.11 Finitely Presented Lie Algebras

Finitely presented Lie algebras can be constructed from free Lie algebras by using the / constructor, i.e., \( \mathcal{F}/[r_1, \ldots, r_k] \) is the quotient of the free Lie algebra \( \mathcal{F} \) by the ideal generated by the elements \( r_1, \ldots, r_k \) of \( \mathcal{F} \). If the finitely presented Lie algebra \( \mathcal{K} \) happens to be finite dimensional then an isomorphic structure constants Lie algebra can be constructed by \text{NiceAlgebraMonomorphism}(\mathcal{K}) \) (see \text{NiceAlgebraMonomorphism} (62.10.9)), which returns a surjective homomorphism. The structure constants Lie algebra can then be accessed by calling \text{Range} (32.3.7) for this map. Also limited computations with elements of the finitely presented Lie algebra are possible.

\begin{verbatim}
gap> L:= FreeLieAlgebra( Rationals, "s", "t" );
<Lie algebra over Rationals, with 2 generators>
gap> gL:= GeneratorsOfAlgebra( L );
[ s, t ]
gap> s:= gL[1];
s
gap> t:= gL[2];
t
gap> K:= L/[ s*(s*t), t*(t*(s*t)), s*(t*(s*t))-t*(s*t) ];
<Lie algebra over Rationals, with 2 generators>

gap> h:= NiceAlgebraMonomorphism( K );
[ [ (1)*s ], [ (1)*t ] ] -> [ v.1, v.2 ]

gap> U:= Range( h );
<Lie algebra of dimension 3 over Rationals>

gap> IsLieNilpotent( U );
true

gap> gK:= GeneratorsOfAlgebra( K );
[ [ (1)*s ], [ (1)*t ] ]

gap> gK[1]*(gK[2]*gK[1]) = Zero( K );
true
\end{verbatim}

64.11.1 FpLieAlgebraByCartanMatrix

\( \text{FpLieAlgebraByCartanMatrix}(\mathcal{C}) \)

Here \( \mathcal{C} \) must be a Cartan matrix. The function returns the finitely-presented Lie algebra over the field of rational numbers defined by this Cartan matrix. By Serre’s theorem, this Lie algebra is a semisimple Lie algebra, and its root system has Cartan matrix \( \mathcal{C} \).

\begin{verbatim}
gap> C:= [ [ 2, -1 ], [ -3, 2 ] ];
gap> K:= FpLieAlgebraByCartanMatrix( C );
<Lie algebra over Rationals, with 6 generators>

gap> h:= NiceAlgebraMonomorphism( K );
[ [ (1)*x1 ], [ (1)*x2 ], [ (1)*x3 ], [ (1)*x4 ], [ (1)*x5 ], [ (1)*x6 ] ] ->

gap> SemiSimpleType( Range( h ) );
"G2"
\end{verbatim}

64.11.2 NilpotentQuotientOfFpLieAlgebra

\( \text{NilpotentQuotientOfFpLieAlgebra}(\mathcal{FpL}, \max[, \mathit{weights}]) \)

Here \( \mathcal{FpL} \) is a finitely presented Lie algebra. Let \( K \) be the quotient of \( \mathcal{FpL} \) by the \( \max+1 \)-th term of its lower central series. This function calculates a surjective homomorphism from \( \mathcal{FpL} \) onto \( K \). When
called with the third argument \texttt{weights}, the \( k \)-th generator of \( FpL \) gets assigned the \( k \)-th element of the list \( \texttt{weights} \). In that case a quotient is calculated of \( FpL \) by the ideal generated by all elements of weight \( \texttt{max+1} \). If the list \( \texttt{weights} \) only consists of 1’s then the two calls are equivalent. The default value of \( \texttt{weights} \) is a list (of length equal to the number of generators of \( FpL \)) consisting of 1’s.

If the relators of \( FpL \) are homogeneous, then the resulting algebra is naturally graded.

\begin{verbatim}
gap> L:= FreeLieAlgebra( Rationals, "x", "y" );;
gap> g:= GeneratorsOfAlgebra(L);; x:= g[1]; y:= g[2];
(1)*x
(1)*y
gap> rr:= [ ((y*x)*x)*x-6*(y*x)*y, 3*(((y*x)*x)*x)*x-20*(((y*x)*x)*x)*y ];
[ (-1)*(x*(x*(x*y)))+(6)*((x*y)*y),
  (-3)*(x*(x*(x*(x*(x*y)))))+20*(x*(x*(x*y)))+(x*(x*y))*y ]
gap> K:= L/rr;
<Lie algebra over Rationals, with 2 generators>
gap> h:= NilpotentQuotientOfFpLieAlgebra(K, 50, [1,2] );
[ [ (1)*x ], [ (1)*y ] ] -> [ v.1, v.2 ]
gap> L:= Range( h );
<Lie algebra of dimension 50 over Rationals>
gap> Grading( L );
rec( hom_components := function( d ) ... end, max_degree := 50,
  min_degree := 1, source := Integers )
\end{verbatim}

\section{64.12 Modules over Lie Algebras and Their Cohomology}

Representations of Lie algebras are dealt with in the same way as representations of ordinary algebras (see \ref{sec:modules}). In this section we mainly deal with modules over general Lie algebras and their cohomology. The next section is devoted to modules over semisimple Lie algebras. An \( s \)-cochain of a module \( V \) over a Lie algebra \( L \) is an \( s \)-linear map

\[ c : L \times \cdots \times L \to V, \]

with \( s \) factors \( L \), that is skew-symmetric (meaning that if any of the arguments are interchanged, \( c \) changes to \(-c\)).

Let \((x_1,\ldots,x_n)\) be a basis of \( L \). Then any \( s \)-cochain is determined by the values \( c(x_{i_1},\ldots,x_{i_s}) \), where \( 1 \leq i_1 < i_2 < \cdots < i_s \leq \dim L \). Now this value again is a linear combination of basis elements of \( V \): \( c(x_{i_1},\ldots,x_{i_s}) = \sum \lambda_{i_1,\ldots,i_s}^{k} v_k \). Denote the dimension of \( V \) by \( r \). Then we represent an \( s \)-cocycle by a list of \( r \) lists. The \( j \)-th of those lists consists of entries of the form

\[ [i_1,i_2,\ldots,i_s,\lambda_{i_1,\ldots,i_s}^{j}], \]

where the coefficient on the second position is non-zero. (We only store those entries for which this coefficient is non-zero.) It follows that every \( s \)-tuple \((i_1,\ldots,i_s)\) gives rise to \( r \) basis elements.

So the zero cochain is represented by a list of the form \([ [ ] , [ ] , \ldots, [ ] ] \). Furthermore, if \( V \) is, e.g., 4-dimensional, then the 2-cocycle represented by

\begin{verbatim}
[ [ [ [1,2], 2 ] ], [ ], [ [ [1,2], 1/2 ] ], [ ] ]
\end{verbatim}
maps the pair \((x_1, x_2)\) to \(2v_1 + 1/2v_3\) (where \(v_1\) is the first basis element of \(V\), and \(v_3\) the third), and all other pairs to zero.

By definition, 0-cochains are constant maps \(c(x) = v_c \in V\) for all \(x \in L\). So 0-cochains have a different representation: they are just represented by the list \([ v_c ]\).

Cochains are constructed using the function \texttt{Cochain}\ (64.12.2), if \(c\) is a cochain, then its corresponding list is returned by \texttt{ExtRepOfObj(} \(c\) \texttt{)}.

### 64.12.1 IsCochain

\[\texttt{IsCochain(obj)}\]

\[\texttt{IsCochainCollection(obj)}\]

Categories of cochains and of collections of cochains.

### 64.12.2 Cochain

\[\texttt{Cochain(V, s, obj)}\]

Constructs a \(s\)-cochain given by the data in \(\text{obj}\), with respect to the Lie algebra module \(V\). If \(s\) is non-zero, then \(\text{obj}\) must be a list.

Example

\begin{verbatim}
gap> L:= SimpleLieAlgebra( "A", 1, Rationals );;
gap> V:= AdjointModule( L );;
<3-dimensional left-module over <Lie algebra of dimension 3 over Rationals>>
gap> c1:= Cochain( V, 2,
>      [[ [[ [ 1, 3 ], -1 ] ], [ ], [ [ [ 2, 3 ], 1/2 ] ] ] ]);;
<2-cochain>
gap> ExtRepOfObj( c1 );
[ [ [ [ 1, 3 ], -1 ] ], [ ], [ [ [ 2, 3 ], 1/2 ] ] ]
gap> c2:= Cochain( V, 0, Basis( V )[1] );
<0-cochain>
gap> ExtRepOfObj( c2 );
v.1
gap> IsCochain( c2 );
true
\end{verbatim}

### 64.12.3 CochainSpace

\[\texttt{CochainSpace(V, s)}\]

Returns the space of all \(s\)-cochains with respect to \(V\).

Example

\begin{verbatim}
gap> L:= SimpleLieAlgebra( "A", 1, Rationals );;
gap> V:= AdjointModule( L );;
gap> C:=CochainSpace( V, 2 );
<vector space of dimension 9 over Rationals>
gap> BasisVectors( Basis( C ) );;
[ <2-cochain>, <2-cochain>, <2-cochain>, <2-cochain>, <2-cochain>,
  <2-cochain>, <2-cochain>, <2-cochain>, <2-cochain> ]
\end{verbatim}
64.12.4 ValueCochain

\texttt{ValueCochain(c, y1, y2, ..., ys)} (function)

Here \( c \) is an \( s \)-cochain. This function returns the value of \( c \) when applied to the \( s \) elements \( y_1 \) to \( y_s \) (that lie in the Lie algebra acting on the module corresponding to \( c \)). It is also possible to call this function with two arguments: first \( c \) and then the list containing \( y_1, \ldots, y_s \).

\texttt{Example}

\begin{verbatim}
gap> L:= SimpleLieAlgebra( "A", 1, Rationals );;
gap> V:= AdjointModule( L );;
gap> C:= CochainSpace( V, 2 );;
gap> c:= Basis( C )[1];
<2-cochain>
gap> ValueCochain( c, Basis(L)[2], Basis(L)[1] );
(-1)*v.1
\end{verbatim}

64.12.5 LieCoboundaryOperator

\texttt{LieCoboundaryOperator(c)} (function)

This is a function that takes an \( s \)-cochain \( c \), and returns an \( s+1 \)-cochain. The coboundary operator is applied.

\texttt{Example}

\begin{verbatim}
gap> L:= SimpleLieAlgebra( "A", 1, Rationals );;
gap> V:= AdjointModule( L );;
gap> C:= CochainSpace( V, 2 );;
gap> c:= Basis( C )[1];
<2-cochain>
gap> c1:= LieCoboundaryOperator( c );
<3-cochain>
gap> c2:= LieCoboundaryOperator( c1 );
<4-cochain>
\end{verbatim}

64.12.6 Cocycles (for Lie algebra module)

\texttt{Cocycles(V, s)} (operation)

is the space of all \( s \)-cocycles with respect to the Lie algebra module \( V \). That is the kernel of the coboundary operator when restricted to the space of \( s \)-cochains.

64.12.7 Coboundaries

\texttt{Coboundaries(V, s)} (operation)

is the space of all \( s \)-coboundaries with respect to the Lie algebra module \( V \). That is the image of the coboundary operator, when applied to the space of \( s-1 \)-cochains. By definition the space of all 0-coboundaries is zero.
64.13 Modules over Semisimple Lie Algebras

This section contains functions for calculating information on representations of semisimple Lie algebras. First we have some functions for calculating some combinatorial data (set of dominant weights, the dominant character, the decomposition of a tensor product, the dimension of a highest-weight module). Then there is a function for creating an admissible lattice in the universal enveloping algebra of a semisimple Lie algebra. Finally we have a function for constructing a highest-weight module over a semisimple Lie algebra.

64.13.1 DominantWeights

\[
\text{DominantWeights}(R, \text{maxw})
\]

Returns a list consisting of two lists. The first of these contains the dominant weights (written on the basis of fundamental weights) of the irreducible highest-weight module, with highest weight \(\text{maxw}\), over the Lie algebra with the root system \(R\). The \(i\)-th element of the second list is the level of the \(i\)-th dominant weight. (Where the level is defined as follows. For a weight \(\mu\) we write \(\mu = \lambda - \sum k_i \alpha_i\), where the \(\alpha_i\) are the simple roots, and \(\lambda\) the highest weight. Then the level of \(\mu\) is \(\sum k_i\).)

64.13.2 DominantCharacter (for a semisimple Lie algebra and a highest weight)

\[
\text{DominantCharacter}(L, \text{maxw}) \quad \text{DominantCharacter}(R, \text{maxw})
\]

For a highest weight \(\text{maxw}\) and a semisimple Lie algebra \(L\), this returns the dominant weights of the highest-weight module over \(L\), with highest weight \(\text{maxw}\). The output is a list of two lists, the first list contains the dominant weights; the second list contains their multiplicities.

The first argument can also be a root system, in which case the dominant character of the highest-weight module over the corresponding semisimple Lie algebra is returned.

64.13.3 DecomposeTensorProduct

\[
\text{DecomposeTensorProduct}(L, w1, w2)
\]

Example

\begin{verbatim}
gap> T := EmptySCTable( 3, 0, "antisymmetric" );;
gap> SetEntrySCTable( T, 1, 2, [ 1, 3 ] );
gap> L := LieAlgebraByStructureConstants( Rationals, T );;
gap> V := FaithfulModule( L );
gap> Cocycles( V, 2 );
gap> Coboundaries( V, 2 );
gap> Dimension( last );
5
\end{verbatim}
Here \( L \) is a semisimple Lie algebra and \( w_1, w_2 \) are dominant weights. Let \( V_i \) be the irreducible highest-weight module over \( L \) with highest weight \( w_i \) for \( i = 1, 2 \). Let \( W = V_1 \otimes V_2 \). Then in general \( W \) is a reducible \( L \)-module. Now this function returns a list of two lists. The first of these is the list of highest weights of the irreducible modules occurring in the decomposition of \( W \) as a direct sum of irreducible modules. The second list contains the multiplicities of these weights (i.e., the number of copies of the irreducible module with the corresponding highest weight that occur in \( W \)). The algorithm uses Klimyk’s formula (see [Kli68] or [Kli66] for the original Russian version).

### 64.13.4 DimensionOfHighestWeightModule

\[ \text{DimensionOfHighestWeightModule}(L, w) \]

Here \( L \) is a semisimple Lie algebra, and \( w \) a dominant weight. This function returns the dimension of the highest-weight module over \( L \) with highest weight \( w \). The algorithm uses Weyl’s dimension formula.

Example

\[
\text{gap> L:= SimpleLieAlgebra( "F", 4, Rationals );;}
\text{gap> R:= RootSystem( L );;}
\text{gap> DominantWeights( R, [ 1, 1, 0, 0 ] );}
\text{gap> DominantCharacter( L, [ 1, 1, 0, 0 ] );}
\text{gap> DecomposeTensorProduct( L, [ 1, 0, 0, 0 ], [ 0, 0, 1, 0 ];}
\text{gap> DimensionOfHighestWeightModule( L, [ 1, 2, 3, 4 ];}
\]

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### 64.14 Admissible Lattices in UEA

Let \( L \) be a semisimple Lie algebra over a field of characteristic 0, and let \( R \) be its root system. For a positive root \( \alpha \) we let \( x_\alpha \) and \( y_\alpha \) be positive and negative root vectors, respectively, both from a fixed Chevalley basis of \( L \). Furthermore, \( h_1, \ldots, h_l \) are the Cartan elements from the same Chevalley basis. Also we set

\[ x_\alpha^{(n)} = \frac{x_\alpha^n}{n!}, \quad y_\alpha^{(n)} = \frac{y_\alpha^n}{n!}. \]

Furthermore, let \( \alpha_1, \ldots, \alpha_s \) denote the positive roots of \( R \). For multi-indices \( N = (n_1, \ldots, n_s) \), \( M = (m_1, \ldots, m_s) \) and \( K = (k_1, \ldots, k_s) \) (where \( n_i, m_i, k_i \geq 0 \)) set

\[ x^N = x_{\alpha_1}^{(n_1)} \cdots x_{\alpha_s}^{(n_s)}, \quad y^M = y_{\alpha_1}^{(m_1)} \cdots y_{\alpha_s}^{(m_s)}, \]

\[ h^K = (h_1^{k_1}) \cdots (h_l^{k_l}). \]

Then by a theorem of Kostant, the \( x_\alpha^{(n)} \) and \( y_\alpha^{(n)} \) generate a subring of the universal enveloping algebra \( U(L) \) spanned (as a free \( Z \)-module) by the elements

\[ y^M h^K x^N. \]
(see, e.g., [Hum72] or [Hum78, Section 26]) So by the Poincare-Birkhoff-Witt theorem this subring is a lattice in $U(L)$. Furthermore, this lattice is invariant under the $x^{(n)}_\alpha$ and $y^{(n)}_\alpha$. Therefore, it is called an admissible lattice in $U(L)$.

The next functions enable us to construct the generators of such an admissible lattice.

### 64.14.1 IsUEALatticeElement

- `IsUEALatticeElement(obj)`
- `IsUEALatticeElementCollection(obj)`
- `IsUEALatticeElementFamily(fam)`

is the category of elements of an admissible lattice in the universal enveloping algebra of a semisimple Lie algebra $L$.

### 64.14.2 LatticeGeneratorsInUEA

- `LatticeGeneratorsInUEA(L)`

Here $L$ must be a semisimple Lie algebra of characteristic 0. This function returns a list of generators of an admissible lattice in the universal enveloping algebra of $L$, relative to the Chevalley basis contained in `ChevalleyBasis(L)` (see `ChevalleyBasis(64.6.2)`). First are listed the negative root vectors (denoted by $y_1, \ldots, y_s$), then the positive root vectors (denoted by $x_1, \ldots, x_s$). At the end of the list there are the Cartan elements. They are printed as $(hi/1)$, which means

$$\begin{pmatrix} h_i \\ 1 \end{pmatrix}.$$  

In general the printed form $(hi/k)$ means

$$\begin{pmatrix} h_i \\ k \end{pmatrix}.$$  

Also $y_i^{(m)}$ is printed as $y_i^\sim(m)$, which means that entering $y_i^\sim m$ at the `GAP` prompt results in the output $m!*y_i^\sim(m)$.

Products of lattice generators are collected using the following order: first come the $y_i^{(m)}$ (in the same order as the positive roots), then the $(h_i/k)$, and then the $x_i^{(n)}$ (in the same order as the positive roots).

### 64.14.3 ObjByExtRep (for creating a UEALattice element)

- `ObjByExtRep(F, descr)`

An UEALattice element is represented by a list of the form $[m_1, c_1, m_2, c_2, \ldots]$, where the $c_1, c_2$ etc. are coefficients, and the $m_1, m_2$ etc. are monomials. A monomial is a list of the form $[\text{ind1, e1, ind2, e2, \ldots}]$ where $\text{ind1, ind2}$ are indices, and $e1, e2$ etc. are exponents. Let $N$ be the number of positive roots of the underlying Lie algebra $L$. The indices lie between 1 and $dim(L)$. If an index lies between 1 and $N$, then it represents a negative root vector (corresponding to the root $\text{NegativeRoots(R)[ind]}$, where $R$ is the root system of $L$; see `NegativeRoots(64.6.8)`). This
leads to a factor $y_{\text{ind}1}^{e_{\text{ind}1}}$ in the printed form of the monomial (which equals $z^{e_1/e_1!}$, where $z$ is a basis element of $L$). If an index lies between $N+1$ and $2N$, then it represents a positive root vector. Finally, if ind lies between $2N+1$ and $2N+\text{rank}$, then it represents an element of the Cartan subalgebra. This is printed as $(h_1/e_1)$, meaning $(h_{i_1})$, where $h_{i_1},...,h_{\text{rank}}$ are the canonical Cartan generators.

The zero element is represented by the empty list, the identity element by the list $[[],1]$.

```gap
gap> L := SimpleLieAlgebra( "G", 2, Rationals );;
gap> g := LatticeGeneratorsInUEA( L );
[ y1, y2, y3, y4, y5, y6, x1, x2, x3, x4, x5, x6, ( h13/1 ),
  ( h14/1 ) ]
gap> IsUEALatticeElement( g[1] );
true
gap> g[1]^3;
6*y1^(3)
gap> q := g[7]*g[1]^2;
-2*y1+2*y1*( h13/1 )+2*y1^(2)*x1
gap> ExtRepOfObj( q );
[ [ 1, 1 ], -2, [ 1, 1, 13, 1 ], 2, [ 1, 2, 7, 1 ], 2 ]
```

### 64.14.4 IsWeightRepElement

- **IsWeightRepElement**

  Is a category of vectors, that is used to construct elements of highest-weight modules (by `HighestWeightModule(64.14.5)`).

  WeightRepElements are represented by a list of the form $[v_1, c_1, v_2, c_2, ..., ]$, where the $v_i$ are basis vectors, and the $c_i$ are coefficients. Furthermore a basis vector $v$ is a weight vector. It is represented by a list of the form $[k, \text{mon}, \text{wt}]$, where $k$ is an integer (the basis vectors are numbered from 1 to dim $V$, where $V$ is the highest weight module), mon is an UELatticeElement (which means that the result of applying mon to a highest weight vector is $v$; see IsUEALatticeElement (64.14.1)) and wt is the weight of $v$. A WeightRepElement is printed as mon * $v_0$, where $v_0$ denotes a fixed highest weight vector.

  If $v$ is a WeightRepElement, then ExtRepOfObj( $v$ ) returns the corresponding list, and if list is such a list and fam a WeightRepElementFamily, then ObjByExtRep( list, fam ) returns the corresponding WeightRepElement.

### 64.14.5 HighestWeightModule

- **HighestWeightModule**

  returns the highest weight module with highest weight $\text{wt}$ of the semisimple Lie algebra $L$ of characteristic 0.

  Note that the elements of such a module lie in the category IsLeftAlgebraModuleElement (62.11.9) (and in particular they do not lie in the category IsWeightRepElement (64.14.4)). However, if $v$ is an element of such a module, then ExtRepOfObj( $v$ ) is a WeightRepElement.
Note that for the following examples of this chapter we increase the line length limit from its default value 80 to 81 in order to make some long output expressions fit into the lines.

```
Example

gap> K1:= SimpleLieAlgebra( "G", 2, Rationals );;
gap> K2:= SimpleLieAlgebra( "B", 2, Rationals );;
gap> L:= DirectSumOfAlgebras( K1, K2 );
<Lie algebra of dimension 24 over Rationals>
gap> V:= HighestWeightModule( L, [ 0, 1, 1, 1 ] );
<224-dimensional left-module over <Lie algebra of dimension
24 over Rationals>>
gap> vv:= GeneratorsOfLeftModule( V );;
gap> vv[100];
y5*y7*y10*v0

gap> e:= ExtRepOfObj( vv[100] );
y5*y7*y10*v0

gap> ExtRepOfObj( e );
[ [ 100, y5*y7*y10, [ -3, 2, -1, 1 ] ], 1 ]
gap> Basis(L)[17]^vv[100];
-1*y5*y7*y8*v0-1*y5*y9*v0
```

## 64.15 Tensor Products and Exterior and Symmetric Powers

### 64.15.1 TensorProductOfAlgebraModules (for a list of algebra modules)

- `TensorProductOfAlgebraModules(list)` (operation)
- `TensorProductOfAlgebraModules(V, W)` (operation)

Here the elements of `list` must be algebra modules. The tensor product is returned as an algebra module. The two-argument version works in the same way and returns the tensor product of its arguments.

```
Example

gap> L:= SimpleLieAlgebra("G",2,Rationals);;
gap> V:= HighestWeightModule( L, [ 1, 0 ] );;
gap> W:= TensorProductOfAlgebraModules( [ V, V, V ] );
<343-dimensional left-module over <Lie algebra of dimension
14 over Rationals>>
gap> w:= Basis(W)[1];
1*(1*v0<x>1*v0<x>1*v0)
gap> Basis(L)[1]^w;
<0-tensor>
gap> Basis(L)[7]^w;
1*(1*v0<x>1*v0<x>y1*v0)+1*(1*v0<x>y1*v0<x>1*v0)+1*(y
1*v0<x>1*v0<x>1*v0)
```

### 64.15.2 ExteriorPowerOfAlgebraModule

- `ExteriorPowerOfAlgebraModule(V, k)` (operation)

Here `V` must be an algebra module, defined over a Lie algebra. This function returns the `k`-th exterior power of `V` as an algebra module.
Example

```gap
gap> L := SimpleLieAlgebra("G",2,Rationals);;
gap> V := HighestWeightModule( L, [ 1, 0 ] );;
gap> W := ExteriorPowerOfAlgebraModule( V, 3 );
<35-dimensional left-module over <Lie algebra of dimension
14 over Rationals>>
gap> w := Basis(W)[1];
1*(1*v0\y1*v0\y3*v0)
gap> Basis(L)[10]^w;
1*(1*v0\y1*v0\y6*v0)+1*(1*v0\y3*v0\y5*v0)+1*(y1*v0\y3*v0\y4*v0)
```

64.15.3 SymmetricPowerOfAlgebraModule

\[ \text{SymmetricPowerOfAlgebraModule}(V, k) \]

Here \( V \) must be an algebra module. This function returns the \( k \)-th symmetric power of \( V \) (as an algebra module).

Example

```gap
gap> L := SimpleLieAlgebra("G",2,Rationals);;
gap> V := HighestWeightModule( L, [ 1, 0 ] );;
gap> W := SymmetricPowerOfAlgebraModule( V, 3 );
<84-dimensional left-module over <Lie algebra of dimension
14 over Rationals>>
gap> w := Basis(W)[1];
1*(1*v0.1*v0.1*v0)
gap> Basis(L)[2]^w;
<0-symmetric element>
gap> Basis(L)[7]^w;
3*(1*v0.1*v0.1*v0)
```
Chapter 65

Magma Rings

Given a magma \( M \) then the **free magma ring** (or **magma ring** for short) \( RM \) of \( M \) over a ring-with-one \( R \) is the set of finite sums \( \sum_{i \in I} r_i m_i \) with \( r_i \in R \) and \( m_i \in M \). With the obvious addition and \( R \)-action from the left, \( RM \) is a free \( R \)-module with \( R \)-basis \( M \), and with the usual convolution product, \( RM \) is a ring.

Typical examples of free magma rings are

- (multivariate) polynomial rings (see 66.15), where the magma is a free abelian monoid generated by the indeterminates,
- group rings (see \texttt{IsGroupRing} (65.1.5)), where the magma is a group,
- Laurent polynomial rings, which are group rings of the free abelian groups generated by the indeterminates,
- free algebras and free associative algebras, with or without one, where the magma is a free magma or a free semigroup, or a free magma-with-one or a free monoid, respectively.

Note that formally, polynomial rings in \texttt{GAP} are not constructed as free magma rings.

Furthermore, a free Lie algebra is **not** a magma ring, because of the additional relations given by the Jacobi identity; see 65.4 for a generalization of magma rings that covers such structures.

The coefficient ring \( R \) and the magma \( M \) cannot be regarded as subsets of \( RM \), hence the natural embeddings of \( R \) and \( M \) into \( RM \) must be handled via explicit embedding maps (see 65.3). Note that in a magma ring, the addition of elements is in general different from an addition that may be defined already for the elements of the magma; for example, the addition in the group ring of a matrix group does in general **not** coincide with the addition of matrices.

```gap
gap> a:= Algebra( GF(2), [ [ Z(2) ] ] );; Size( a );
2
gap> rm:= FreeMagmaRing( GF(2), a );;
gap> emb:= Embedding( a, rm );;
gap> z:= Zero( a );; o:= One( a );;
gap> imz:= z ^ emb; IsZero( imz );
(Z(2)^0)*[ [ 0*Z(2) ] ]
false
gap> im1:= ( z + o ) ^ emb;
(Z(2)^0)*[ [ Z(2)^0 ] ]
gap> true
```

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GAP> im2:= z ^ emb + o ^ emb;
(Z(2)^0)*[ [ 0*Z(2) ] ]+(Z(2)^0)*[ [ Z(2)^0 ] ]
GAP> im1 = im2;
false

65.1 Free Magma Rings

65.1.1 FreeMagmaRing

▷ FreeMagmaRing( R, M )

(function)

is a free magma ring over the ring R, free on the magma M.

65.1.2 GroupRing

▷ GroupRing( R, G )

(function)

is the group ring of the group G, over the ring R.

65.1.3 IsFreeMagmaRing

▷ IsFreeMagmaRing( D )

(Category)

A domain lies in the category IsFreeMagmaRing if it has been constructed as a free magma ring. In particular, if D lies in this category then the operations LeftActingDomain (57.1.11) and UnderlyingMagma (65.1.6) are applicable to D, and yield the ring R and the magma M such that D is the magma ring RM.

So being a magma ring in GAP includes the knowledge of the ring and the magma. Note that a magma ring RM may abstractly be generated as a magma ring by a magma different from the underlying magma M. For example, the group ring of the dihedral group of order 8 over the field with 3 elements is also spanned by a quaternion group of order 8 over the same field.

Example

```gap
gap> d8:= DihedralGroup( 8 );
<pc group of size 8 with 3 generators>
gap> rm:= FreeMagmaRing( GF(3), d8 );
<algebra-with-one over GF(3), with 3 generators>
gap> emb:= Embedding( d8, rm );;
gap> gens:= List( GeneratorsOfGroup( d8 ), x -> x^emb );;
gap> x1:= gens[1] + gens[2];;
gap> g1:= x1 - x2 + x3;;
gap> g2:= x1 + x2;;
gap> q8:= Group( g1, g2 );;
gap> Size( q8 );
8
gap> ForAny( [ d8, q8 ], IsAbelian );
false
gap> List( [ d8, q8 ], g -> Number( AsList( g ), x -> Order( x ) = 2 ) );
```
65.1.4 IsFreeMagmaRingWithOne

\[ \text{IsFreeMagmaRingWithOne}(\text{obj}) \]

IsFreeMagmaRingWithOne is just a synonym for the meet of IsFreeMagmaRing (65.1.3) and IsMagmaWithOne (35.1.2).

65.1.5 IsGroupRing

\[ \text{IsGroupRing}(\text{obj}) \]

A group ring is a magma ring where the underlying magma is a group.

65.1.6 UnderlyingMagma

\[ \text{UnderlyingMagma}(\text{RM}) \]

stores the underlying magma of a free magma ring.

65.1.7 AugmentationIdeal

\[ \text{AugmentationIdeal}(\text{RG}) \]

is the augmentation ideal of the group ring \( RG \), i.e., the kernel of the trivial representation of \( RG \).

65.2 Elements of Free Magma Rings

In order to treat elements of free magma rings uniformly, also without an external representation, the attributes CoefficientsAndMagmaElements (65.2.4) and ZeroCoefficient (65.2.5) were introduced that allow one to “take an element of an arbitrary magma ring into pieces”.

Conversely, for constructing magma ring elements from coefficients and magma elements, ElementOfMagmaRing (65.2.6) can be used. (Of course one can also embed each magma element into the magma ring, see 65.3, and then form the linear combination, but many unnecessary intermediate elements are created this way.)

65.2.1 IsMagmaRingObjDefaultRep

\[ \text{IsMagmaRingObjDefaultRep}(\text{obj}) \]

The default representation of a magma ring element is a list of length 2, at first position the zero coefficient, at second position a list with the coefficients at the even positions, and the magma elements at the odd positions, with the ordering as defined for the magma elements.

It is assumed that arithmetic operations on magma rings produce only normalized elements.
65.2.2 IsElementOfFreeMagmaRing

▷ IsElementOfFreeMagmaRing(obj) (Category)
▷ IsElementOfFreeMagmaRingCollection(obj) (Category)

The category of elements of a free magma ring (See IsFreeMagmaRing (65.1.3)).

65.2.3 IsElementOfFreeMagmaRingFamily

▷ IsElementOfFreeMagmaRingFamily(Fam) (Category)

Elements of families in this category have trivial normalisation, i.e., efficient methods for \( \leq \) and \( \prec \).

65.2.4 CoefficientsAndMagmaElements

▷ CoefficientsAndMagmaElements(elm) (attribute)

is a list that contains at the odd positions the magma elements, and at the even positions their coefficients in the element \( elm \).

65.2.5 ZeroCoefficient

▷ ZeroCoefficient(elm) (attribute)

For an element \( elm \) of a magma ring (modulo relations) \( RM \), ZeroCoefficient returns the zero element of the coefficient ring \( R \).

65.2.6 ElementOfMagmaRing

▷ ElementOfMagmaRing(Fam, zerocoeff, coeffs, mgmelms) (operation)

ElementOfMagmaRing returns the element \( \sum_{i=1}^{n} c_{i} m_{i}' \), where \( coeffs = [c_{1}, c_{2}, \ldots, c_{n}] \) is a list of coefficients, \( mgmelms = [m_{1}, m_{2}, \ldots, m_{n}] \) is a list of magma elements, and \( m_{i}' \) is the image of \( m_{i} \) under an embedding of a magma containing \( m_{i} \) into a magma ring whose elements lie in the family \( Fam \). \( zerocoeff \) must be the zero of the coefficient ring containing the \( c_{i} \).

65.3 Natural Embeddings related to Magma Rings

Neither the coefficient ring \( R \) nor the magma \( M \) are regarded as subsets of the magma ring \( RM \), so one has to use embeddings (see Embedding (32.2.11)) explicitly whenever one needs for example the magma ring element corresponding to a given magma element.

```
Example

gap> f:= Rationals;; g:= SymmetricGroup( 3 );;
gap> fg:= FreeMagmaRing( f, g );
<algebra-with-one over Rationals, with 2 generators>
gap> Dimension( fg );
6
```
65.4 Magma Rings modulo Relations

A more general construction than that of free magma rings allows one to create rings that are not free \( R \)-modules on a given magma \( M \) but arise from the magma ring \( RM \) by factoring out certain identities. Examples for such structures are finitely presented (associative) algebras and free Lie algebras (see FreeLieAlgebra (64.2.4)).

In GAP, the use of magma rings modulo relations is limited to situations where a normal form of the elements is known and where one wants to guarantee that all elements actually constructed are in normal form. (In particular, the computation of the normal form must be cheap.) This is because the methods for comparing elements in magma rings modulo relations via \( \neq \) and \( \prec \) just compare the involved coefficients and magma elements, and also the vector space functions regard those monomials as linearly independent over the coefficients ring that actually occur in the representation of an element of a magma ring modulo relations.

Thus only very special finitely presented algebras will be represented as magma rings modulo relations, in general finitely presented algebras are dealt with via the mechanism described in Chapter 63.

65.4.1 IsElementOfMagmaRingModuloRelations

\[
\text{IsElementOfMagmaRingModuloRelations}(\text{obj}) \quad \text{(Category)}
\]
\[
\text{IsElementOfMagmaRingModuloRelationsCollection}(\text{obj}) \quad \text{(Category)}
\]

This category is used, e.g., for elements of free Lie algebras.

65.4.2 IsElementOfMagmaRingModuloRelationsFamily

\[
\text{IsElementOfMagmaRingModuloRelationsFamily}(\text{Fam}) \quad \text{(Category)}
\]

The family category for the category IsElementOfMagmaRingModuloRelations (65.4.1).
65.4.3 NormalizedElementOfMagmaRingModuloRelations

\[ \text{NormalizedElementOfMagmaRingModuloRelations}(F, \text{descr}) \]

Let \( F \) be a family of magma ring elements modulo relations, and \( \text{descr} \) the description of an element in a magma ring modulo relations. \( \text{NormalizedElementOfMagmaRingModuloRelations} \) returns a description of the same element, but normalized w.r.t. the relations. So two elements are equal if and only if the result of \( \text{NormalizedElementOfMagmaRingModuloRelations} \) is equal for their internal data, that is, \( \text{CoefficientsAndMagmaElements}(65.2.4) \) will return the same for the corresponding two elements.

\( \text{NormalizedElementOfMagmaRingModuloRelations} \) is allowed to return \( \text{descr} \) itself, it need not make a copy. This is the case for example in the case of free magma rings.

65.4.4 IsMagmaRingModuloRelations

\[ \text{IsMagmaRingModuloRelations}(\text{obj}) \]

A GAP object lies in the category \( \text{IsMagmaRingModuloRelations} \) if it has been constructed as a magma ring modulo relations. Each element of such a ring has a unique normal form, so \( \text{CoefficientsAndMagmaElements}(65.2.4) \) is well-defined for it.

This category is not inherited to factor structures, which are in general best described as finitely presented algebras, see Chapter 63.

65.5 Magma Rings modulo the Span of a Zero Element

65.5.1 IsElementOfMagmaRingModuloSpanOfZeroFamily

\[ \text{IsElementOfMagmaRingModuloSpanOfZeroFamily}(\text{Fam}) \]

We need this for the normalization method, which takes a family as first argument.

65.5.2 IsMagmaRingModuloSpanOfZero

\[ \text{IsMagmaRingModuloSpanOfZero}(\text{RM}) \]

The category of magma rings modulo the span of a zero element.

65.5.3 MagmaRingModuloSpanOfZero

\[ \text{MagmaRingModuloSpanOfZero}(\text{R, M, z}) \]

Let \( R \) be a ring, \( M \) a magma, and \( z \) an element of \( M \) with the property that \( z \cdot m = z \) holds for all \( m \in M \). The element \( z \) could be called a “zero element” of \( M \), but note that in general \( z \) cannot be obtained as \( \text{Zero}(m) \) for each \( m \in M \), so this situation does not match the definition of \( \text{Zero}(31.10.3) \).

\( \text{MagmaRingModuloSpanOfZero} \) returns the magma ring \( RM \) modulo the relation given by the identification of \( z \) with zero. This is an example of a magma ring modulo relations, see 65.4.
65.6 Technical Details about the Implementation of Magma Rings

The family containing elements in the magma ring $RM$ in fact contains all elements with coefficients in the family of elements of $R$ and magma elements in the family of elements of $M$. So arithmetic operations with coefficients outside $R$ or with magma elements outside $M$ might create elements outside $RM$.

It should be mentioned that each call of FreeMagmaRing (65.1.1) creates a new family of elements, so for example the elements of two group rings of permutation groups over the same ring lie in different families and therefore are regarded as different.

Example

```gap
gap> g:= SymmetricGroup( 3 );;
gap> h:= AlternatingGroup( 3 );;
gap> IsSubset( g, h );
true

gap> f:= GF(2);;
gap> fg:= GroupRing( f, g );
<algebra-with-one over GF(2), with 2 generators>
gap> fh:= GroupRing( f, h );
<algebra-with-one over GF(2), with 1 generators>
gap> IsSubset( fg, fh );
false

gap> o1:= One( fh );
o2:= One( fg );
o1 = o2;
(Z(2)^0)*()
(Z(2)^0)*()
false

gap> emb:= Embedding( g, fg );;

gap> im:= Image( emb, h );
<group of size 3 with 1 generators>

gap> IsSubset( fg, im );
true
```

There is no generic external representation for elements in an arbitrary free magma ring. For example, polynomials are elements of a free magma ring, and they have an external representation relying on the special form of the underlying monomials. On the other hand, elements in a group ring of a permutation group do not admit such an external representation.

For convenience, magma rings constructed with FreeAlgebra (62.3.1), FreeAssociativeAlgebra (62.3.3), FreeAlgebraWithOne (62.3.2), and FreeAssociativeAlgebraWithOne (62.3.4) support an external representation of their elements, which is defined as a list of length 2, the first entry being the zero coefficient, the second being a list with the external representations of the magma elements at the odd positions and the corresponding coefficients at the even positions.

As the above examples show, there are several possible representations of magma ring elements, the representations used for polynomials (see Chapter 66) as well as the default representation IsMagmaRingObjDefaultRep (65.2.1) of magma ring elements. The latter simply stores the zero coefficient and a list containing the coefficients of the element at the even positions and the corresponding magma elements at the odd positions, where the succession is compatible with the ordering of magma elements via \<.
Chapter 66

Polynomials and Rational Functions

Let $R$ be a commutative ring-with-one. We call a free associative algebra $A$ over $R$ a polynomial ring over $R$. The free generators of $A$ are called indeterminates (to avoid naming conflicts with the word variables which will be used to denote GAP variables only), they are usually denoted by $x_1, x_2, \ldots$. The number of indeterminates is called the rank of $A$. The elements of $A$ are called polynomials. Products of indeterminates are called monomials, every polynomial can be expressed as a finite sum of products of monomials with ring elements in a form like $r_{1,0}x_1 + r_{1,1}x_1x_2 + r_{0,1}x_2 + \cdots$ with $r_{i,j} \in R$.

A polynomial ring of rank 1 is called an univariate polynomial ring, its elements are univariate polynomials. Polynomial rings of smaller rank naturally embed in rings of higher rank; if $S$ is a subring of $R$ then a polynomial ring over $S$ naturally embeds in a polynomial ring over $R$ of the same rank. Note however that GAP does not consider $R$ as a subset of a polynomial ring over $R$; for example the zero of $R$ ($0_R$) and the zero of the polynomial ring (0) are different objects.

Internally, indeterminates are represented by positive integers, but it is possible to give names to them to have them printed in a nicer way. Beware, however that there is not necessarily any relation between the way an indeterminate is called and the way it is printed. See section 66.1 for details.

If $R$ is an integral domain, the polynomial ring $A$ over $R$ is an integral domain as well and one can therefore form its quotient field $Q$. This field is called a field of rational functions. Again $A$ embeds naturally into $Q$ and GAP will perform this embedding implicitly. (In fact it implements the ring of rational functions over $R$.) To avoid problems with leading coefficients, however, $R$ must be a unique factorization domain.

66.1 Indeterminates

Internally, indeterminates are created for a family of objects (for example all elements of finite fields in characteristic 3 are in one family). Thus a variable “x” over the rationals is also an “x” over the integers, while an “x” over $GF(3)$ is different.

Within one family, every indeterminate has a number $nr$ and as long as no other names have been assigned, this indeterminate will be displayed as “x$\_nr$”. Indeterminate numbers can be arbitrary nonnegative integers.

It is possible to assign names to indeterminates; these names are strings and only provide a means for printing the indeterminates in a nice way. Indeterminates that have not been assigned a name will be printed as “x$\_nr$”.

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(Because of this printing convention, the name \(x_{nr}\) is interpreted specially to always denote the variable with internal number \(nr\).)

The indeterminate names have not necessarily any relations to variable names: this means that an indeterminate whose name is, say, “\(x\)” cannot be accessed using the variable \(x\), unless \(x\) was defined to be that indeterminate.

When asking for indeterminates with certain names, GAP usually will take the first (with respect to the internal numbering) indeterminates that are not yet named, name these accordingly and return them. Thus when asking for named indeterminates, no relation between names and indeterminate numbers can be guaranteed. The attribute \(\text{IndeterminateNumberOfLaurentPolynomial(indet)}\) will return the number of the indeterminate \(indet\).

When asked to create an indeterminate with a name that exists already for the family, GAP will by default return this existing indeterminate. If you explicitly want a new indeterminate, distinct from the already existing one with the same name, you can add the new option to the function call. (This is in most cases not a good idea.)

```
Example

gap> R:=PolynomialRing(GF(3),["x","y","z"]);
GF(3)[x,y,z]
gap> List(IndeterminatesOfPolynomialRing(R),
    IndeterminateNumberOfLaurentPolynomial);
[ 1, 2, 3 ]
gap> R:=PolynomialRing(GF(3),["z"]);
GF(3)[z]
gap> List(IndeterminatesOfPolynomialRing(R),
    IndeterminateNumberOfLaurentPolynomial);
[ 3 ]
gap> R:=PolynomialRing(GF(3),["x","y","z"]:new);
GF(3)[x,y,z]
gap> List(IndeterminatesOfPolynomialRing(R),
    IndeterminateNumberOfLaurentPolynomial);
[ 4, 5, 6 ]
gap> R:=PolynomialRing(GF(3),["z"]);
GF(3)[z]
gap> List(IndeterminatesOfPolynomialRing(R),
    IndeterminateNumberOfLaurentPolynomial);
[ 3 ]
```

### 66.1.1 Indeterminate

\[ \text{Indeterminate}(R[, nr]) \]
\[ \text{Indeterminate}(R[, name[, avoid]]) \]
\[ \text{X}(R[, nr]) \]
\[ \text{X}(R[, name[, avoid]]) \]
\[ \text{X}(fam, nr) \]

returns the indeterminate number \(nr\) over the ring \(R\). If \(nr\) is not given it defaults to 1. If the number is not specified a list \(avoid\) of indeterminates may be given. The function will return an indeterminate that is guaranteed to be different from all the indeterminates in the list \(avoid\). The third usage returns an indeterminate called \(name\) (also avoiding the indeterminates in \(avoid\) if given).
X is simply a synonym for Indeterminate.

```
gap> x := Indeterminate(GF(3), "x");
  x
  gap> y := X(GF(3), "y"); z := X(GF(3), "X");
  y
  x
  gap> X(GF(3), 2);
  y
  x
  gap> X(GF(3), "x_3");
  x
  x
```

### 66.1.2 IndeterminateNumberOfUnivariateRationalFunction

\[\text{IndeterminateNumberOfUnivariateRationalFunction}(rfun)\]

returns the number of the indeterminate in which the univariate rational function \(rfun\) is expressed. (This also provides a way to obtain the number of a given indeterminate.)

A constant rational function might not possess an indeterminate number. In this case \(\text{IndeterminateNumberOfUnivariateRationalFunction}\) will default to a value of 1. Therefore two univariate polynomials may be considered to be in the same univariate polynomial ring if their indeterminates have the same number or one if of them is constant. (see also \(\text{CIUnivPols}\) (66.1.5) and \(\text{IsLaurentPolynomialDefaultRep}\) (66.21.7)).

### 66.1.3 IndeterminateOfUnivariateRationalFunction

\[\text{IndeterminateOfUnivariateRationalFunction}(rfun)\]

returns the indeterminate in which the univariate rational function \(rfun\) is expressed. (cf. \(\text{IndeterminateNumberOfUnivariateRationalFunction}\) (66.1.2).)

```
gap> IndeterminateNumberOfUnivariateRationalFunction(z);
  3
  gap> IndeterminateOfUnivariateRationalFunction(z^5+z);
  x
```

### 66.1.4 IndeterminateName

\[\text{IndeterminateName}(fam, nr)\] (operation)
\[\text{HasIndeterminateName}(fam, nr)\] (operation)
\[\text{SetIndeterminateName}(fam, nr, name)\] (operation)

SetIndeterminateName assigns the name \(name\) to indeterminate \(nr\) in the rational functions family \(fam\). It issues an error if the indeterminate was already named.

IndeterminateName returns the name of the \(nr\)-th indeterminate (and returns fail if no name has been assigned).

HasIndeterminateName tests whether indeterminate \(nr\) has already been assigned a name.
As a convenience there is a special method installed for `SetName` that will assign a name to an indeterminate.

Example

\[
gap> \text{IndeterminateName(FamilyObj(x),2);}
\]
"y"
\[
gap> \text{HasIndeterminateName(FamilyObj(x),4);}
false
\]
\[
gap> \text{SetIndeterminateName(FamilyObj(x),10,"bla");}
\]
\[
gap> \text{Indeterminate(GF(3),10);}
bla
\]

66.1.5 CIUnivPols

\texttt{CIUnivPols(upol1, upol2)}

This function (whose name stands for “common indeterminate of univariate polynomials”) takes two univariate polynomials as arguments. If both polynomials are given in the same indeterminate number \texttt{indnum} (in this case they are “compatible” as univariate polynomials) it returns \texttt{indnum}. In all other cases it returns \texttt{fail}. \texttt{CIUnivPols} also accepts if either polynomial is constant but formally expressed in another indeterminate, in this situation the indeterminate of the other polynomial is selected.

66.2 Operations for Rational Functions

The rational functions form a field, therefore all arithmetic operations are applicable to rational functions.

\[
f + g
\]
\[
f - g
\]
\[
f * g
\]
\[
f / g
\]

Example

\[
gap> x:=\text{Indeterminate(Rationals,1)};;y:=\text{Indeterminate(Rationals,2)};;
\]
\[
gap> f:=3+x*y*x^5;;g:=5+x^2*y+x*y^2;;
\]
\[
gap> a:=g/f;
\]
\[
(x_1^2*x_2+x_1*x_2^2+5)/(x_1^5+x_1*x_2+3)
\]

Note that the quotient \( f/g \) of two polynomials might be represented as a rational function again. If \( g \) is known to divide \( f \) the call \texttt{Quotient(f,g)} (see \texttt{Quotient (56.1.9)}) should be used instead.

\[
f \mod g
\]

For two Laurent polynomials \( f \) and \( g \), \( f \mod g \) is the Euclidean remainder (see \texttt{EuclideanRemainder (56.6.4)}) of \( f \) modulo \( g \).
As calculating a multivariate Gcd can be expensive, it is not guaranteed that rational functions will always be represented as a quotient of coprime polynomials. In certain unfortunate situations this might lead to a degree explosion. To ensure cancellation you can use \texttt{Gcd\ (56.7.1)} on the \texttt{NumeratorOfRationalFunction (66.4.2)} and \texttt{DenominatorOfRationalFunction (66.4.3)} values of a given rational function.

All polynomials as well as all the univariate polynomials in the same indeterminate form subrings of this field. If two rational functions are known to be in the same subring, the result will be expressed as element in this subring.

### 66.3 Comparison of Rational Functions

**f = g**

Two rational functions \( f \) and \( g \) are equal if the product \( \text{Numerator}(f) \times \text{Denominator}(g) \) equals \( \text{Numerator}(g) \times \text{Denominator}(f) \).

```gap
gap> x:=Indeterminate(Rationals,"x");;y:=Indeterminate(Rationals,"y");;
gap> f:=3+x*y+x^5;;g:=5+x^2*y+x*y^2;;
gap> a:=g/f;
(x^2*y+x*y^2+5)/(x^5+x*y+3)
gap> b:=(g*f)/(f^2);
(x^7*y+x^6*y^2+5*x^5+x^3*y^2+x^2*y^3+3*x*y+3*x*y^2+6*x*y+9)/(x^10+2\*x^6*y+6*x^5+x^2*y^2+6*x*y+9)
gap> a=b;
true
```

**f < g**

The ordering of rational functions is defined in several steps. Monomials (products of indeterminates) are sorted first by degree, then lexicographically (with \( x_1 > x_2 \)) (see \texttt{MonomialGrlexOrdering (66.17.8)})). Products of monomials with ring elements (“terms”) are compared first by their monomials and then by their coefficients.

```gap
gap> x>y;
true
gap> x^2*y<x*y^2;
false
gap> x*y<x^2*y;
true
gap> x^2*y < 5* y*x^2;
true
```

Polynomials are compared by comparing the largest terms in turn until they differ.

```gap
gap> x+y<y;
false
gap> x<x+1;
true
```
Rational functions are compared by comparing the polynomial $\text{Numerator}(f) \times \text{Denominator}(g)$ with the polynomial $\text{Numerator}(g) \times \text{Denominator}(f)$. (As the ordering of monomials used by GAP is invariant under multiplication this is independent of common factors in numerator and denominator.)

```
gap> f/g<g/f;  
false  
gap> f/g<(g*g)/(f*g);  
false
```

For univariate polynomials this reduces to an ordering first by total degree and then lexicographically on the coefficients.

### 66.4 Properties and Attributes of Rational Functions

All these tests are applicable to every rational function. Depending on the internal representation of the rational function, however some of these tests (in particular, univariateness) might be expensive in some cases.

For reasons of performance within algorithms it can be useful to use other attributes, which give a slightly more technical representation. See section 66.20 for details.

#### 66.4.1 IsPolynomialFunction

A rational function is an element of the quotient field of a polynomial ring over an UFD. It is represented as a quotient of two polynomials, its numerator (see NumeratorOfRationalFunction (66.4.2)) and its denominator (see DenominatorOfRationalFunction (66.4.3)).

A polynomial function is an element of a polynomial ring (not necessarily an UFD), or a rational function.

GAP considers IsRationalFunction as a subcategory of IsPolynomialFunction.

#### 66.4.2 NumeratorOfRationalFunction

returns the numerator of the rational function `ratfun`.

As no proper multivariate gcd has been implemented yet, numerators and denominators are not guaranteed to be reduced!

#### 66.4.3 DenominatorOfRationalFunction

returns the denominator of the rational function `ratfun`.

As no proper multivariate gcd has been implemented yet, numerators and denominators are not guaranteed to be reduced!
66.4.4 \textbf{IsPolynomial}

\begin{verbatim}
\texttt{gap> } \text{IsPolynomial}((x*y+x^2*y^3)/y);
\texttt{true}
\texttt{gap> } \text{IsPolynomial}((x*y+x^2)/y);
\texttt{false}
\end{verbatim}

66.4.5 \textbf{AsPolynomial}

\begin{verbatim}
\texttt{gap> } \text{AsPolynomial}((x*y+x^2*y^3)/y);
x^2*y^2+x
\end{verbatim}

66.4.6 \textbf{IsUnivariateRationalFunction}

\begin{verbatim}
\texttt{gap> } \text{IndeterminateNumberOfUnivariateRationalFunction}((x*y+x^2*y^3)/y);
2
\end{verbatim}

66.4.7 \textbf{CoefficientsOfUnivariateRationalFunction}

\begin{verbatim}
\texttt{gap> } \text{CoefficientsOfUnivariateRationalFunction}((x*y+x^2*y^3)/y);
[ [ 1, 2, 3 ], [ 1, -2, -3 ], 1 ]
\end{verbatim}
66.4.8  **IsUnivariatePolynomial**

\[ \text{IsUnivariatePolynomial(ratfun)} \]  

(property)

A univariate polynomial is a polynomial in only one indeterminate.

66.4.9  **CoefficientsOfUnivariatePolynomial**

\[ \text{CoefficientsOfUnivariatePolynomial(pol)} \]  

(attribute)

CoefficientsOfUnivariatePolynomial returns the coefficient list of the polynomial pol, sorted in ascending order. (It returns the empty list if pol is 0.)

66.4.10  **IsLaurentPolynomial**

\[ \text{IsLaurentPolynomial(ratfun)} \]  

(property)

A Laurent polynomial is a univariate rational function whose denominator is a monomial. Therefore every univariate polynomial is a Laurent polynomial.

The attribute CoefficientsOfLaurentPolynomial (66.13.2) gives a compact representation as Laurent polynomial.

66.4.11  **IsConstantRationalFunction**

\[ \text{IsConstantRationalFunction(ratfun)} \]  

(property)

A constant rational function is a function whose numerator and denominator are polynomials of degree 0.

66.4.12  **IsPrimitivePolynomial**

\[ \text{IsPrimitivePolynomial(F, pol)} \]  

(operation)

For a univariate polynomial pol of degree d in the indeterminate X, with coefficients in a finite field F with q elements, say, IsPrimitivePolynomial returns true if

1. pol divides \( X^{q^d - 1} - 1 \), and
2. for each prime divisor \( p \) of \( q^d - 1 \), pol does not divide \( X^{(q^d-1)/p - 1} \),

and false otherwise.

66.4.13  **SplittingField**

\[ \text{SplittingField(f)} \]  

(attribute)

returns the smallest field which contains the coefficients of f and the roots of f.
66.5 Univariate Polynomials

Some of the operations are actually defined on the larger domain of Laurent polynomials (see 66.13). For this section you can simply ignore the word “Laurent” if it occurs in a description.

66.5.1 UnivariatePolynomial

\[ \text{UnivariatePolynomial}(\text{ring, coefs[, ind]}) \]

(operation)

constructs an univariate polynomial over the ring \text{ring} in the indeterminate \text{ind} with the coefficients given by \text{coefs}.

66.5.2 UnivariatePolynomialByCoefficients

\[ \text{UnivariatePolynomialByCoefficients}(\text{fam, coefs, ind}) \]

(operation)

constructs an univariate polynomial over the coefficients family \text{fam} and in the indeterminate \text{ind} with the coefficients given by \text{coefs}. This function should be used in algorithms to create polynomials as it avoids overhead associated with \text{UnivariatePolynomial} (66.5.1).

66.5.3 DegreeOfLaurentPolynomial

\[ \text{DegreeOfLaurentPolynomial}(\text{pol}) \]

(attribute)

The degree of a univariate (Laurent) polynomial \text{pol} is the largest exponent \( n \) of a monomial \( x^n \) of \text{pol}. The degree of a zero polynomial is defined to be \(-\infty\).

\begin{verbatim}
gap> p:=UnivariatePolynomial(Rationals,[1,2,3,4],1);
4*x^3+3*x^2+2*x+1
gap> UnivariatePolynomialByCoefficients(FamilyObj(1),[9,2,3,4],73);
4*x_73^3+3*x_73^2+2*x_73+9
gap> CoefficientsOfUnivariatePolynomial(p);
[ 1, 2, 3, 4 ]
gap> DegreeOfLaurentPolynomial(p);
3
gap> DegreeOfLaurentPolynomial(Zero(p));
-infinity
gap> IndeterminateNumberOfLaurentPolynomial(p);
1
\end{verbatim}

66.5.4 RootsOfPolynomial

\[ \text{RootsOfPolynomial}(\text{[R, ]p}) \]

(function)

For a univariate polynomial \text{p}, this function returns all roots of \text{p} over the ring \text{R}. If the ring is not specified, it defaults to the ring specified by the coefficients of \text{p} via \text{DefaultRing} (56.1.3).
Example

```gap
gap> x:=X(Rationals,"x");;
p:=x^4-1;
gap> RootsOfPolynomial(p);
[ 1, -1 ]
gap> RootsOfPolynomial(CF(4),p);
[ 1, -1, E(4), -E(4) ]
```

66.5.5 RootsOfUPol

\texttt{RootsOfUPol([field, ]upol)}

This function returns a list of all roots of the univariate polynomial \texttt{upol} in its default domain. If the optional argument \texttt{field} is a field then the roots in this field are computed. If \texttt{field} is the string "split" then the splitting field of the polynomial is taken.

Example

```gap
gap> RootsOfUPol(50-45*x-6*x^2+x^3);
[ 10, 1, -5 ]
```

66.5.6 QuotRemLaurpols

\texttt{QuotRemLaurpols(left, right, mode)}

This internal function for euclidean division of polynomials takes two polynomials \texttt{left} and \texttt{right} and computes their quotient. No test is performed whether the arguments indeed are polynomials. Depending on the integer variable \texttt{mode}, which may take values in a range from 1 to 4, it returns respectively:

1. the quotient (there might be some remainder),
2. the remainder,
3. a list \texttt{[q,r]} of quotient and remainder,
4. the quotient if there is no remainder and \texttt{fail} otherwise.

66.5.7 UnivariatenessTestRationalFunction

\texttt{UnivariatenessTestRationalFunction(f)}

This function takes a rational function \texttt{f} and tests whether it is univariate rational function (or even a Laurent polynomial). It returns a list \texttt{[isunivariate, indet, islaurent, cofs]}.

If \texttt{f} is a univariate rational function then \texttt{isunivariate} is \texttt{true} and \texttt{indet} is the number of the appropriate indeterminate.

Furthermore, if \texttt{f} is a Laurent polynomial, then \texttt{islaurent} is also \texttt{true}. In this case the fourth entry, \texttt{cofs}, is the value of the attribute \texttt{CoefficientsOfLaurentPolynomial (66.13.2)} for \texttt{f}.

If \texttt{isunivariate} is \texttt{true} but \texttt{islaurent} is \texttt{false}, then \texttt{cofs} is the value of the attribute \texttt{CoefficientsOfUnivariateRationalFunction (66.4.7)} for \texttt{f}.

Otherwise, each entry of the returned list is equal to \texttt{fail}. As there is no proper multivariate gcd, this may also happen for the rational function which may be reduced to univariate (see example).
Example

\begin{verbatim}
gap> UnivariatenessTestRationalFunction( 50-45*x-6*x^2+x^3 );
[ true, 1, true, [ [ 50, -45, -6, 1 ], 0 ] ]
gap> UnivariatenessTestRationalFunction( (-6*y^2+y^3) / (y+1) );
[ true, 2, false, [ [ -6, 1 ], [ 1, 1 ], 2 ] ]
gap> UnivariatenessTestRationalFunction( (-6*y^2+y^3) / (x+1));
[ false, fail, false, fail ]
gap> UnivariatenessTestRationalFunction( ((y+2)*(x+1)) / ((y-1)*(x+1)) );
[ fail, fail, fail, fail ]
\end{verbatim}

66.5.8 InfoPoly

\begin{verbatim}
Gap> p:=UnivariatePolynomial(Rationals,[1,2,3,4],1);
4*x^3+3*x^2+2*x+1
Gap> Value(p,Z(5));
Z(5)^2
Gap> LeadingCoefficient(p);
4
Gap> Derivative(p);
12*x^2+6*x+2
\end{verbatim}

66.6 Polynomials as Univariate Polynomials in one Indeterminate

66.6.1 DegreeIndeterminate

\begin{verbatim}
Gap> f:=x^5+3*x*y+9*y^7+4*y^5*x+3*y+2;
9*y^7+4*x*y^5+5+3*x*y+3*y+2
Gap> DegreeIndeterminate(f,1);
5
Gap> DegreeIndeterminate(f,y);
7
\end{verbatim}

66.6.2 PolynomialCoefficientsOfPolynomial

\begin{verbatim}
\end{verbatim}
PolynomialCoefficientsOfPolynomial returns the coefficient list (whose entries are polynomials not involving the indeterminate \textit{ind}) describing the polynomial \textit{pol} viewed as a polynomial in \textit{ind}. Instead of the indeterminate, \textit{ind} can also be an indeterminate number.

\begin{verbatim}
gap> PolynomialCoefficientsOfPolynomial(f,2);
[ x^5+2, 3*x+3, 0, 0, 0, 4*x, 0, 9 ]
\end{verbatim}

66.6.3 LeadingCoefficient

\texttt{LeadingCoefficient(\textit{pol})} (operation)

returns the leading coefficient (that is the coefficient of the leading monomial, see \texttt{LeadingMonomial (66.6.4)}) of the polynomial \textit{pol}.

66.6.4 LeadingMonomial

\texttt{LeadingMonomial(\textit{pol})} (operation)

returns the leading monomial (with respect to the ordering given by \texttt{MonomialExtGrlexLess (66.17.14)}) of the polynomial \textit{pol} as a list containing indeterminate numbers and exponents.

\begin{verbatim}
gap> LeadingCoefficient(f,1);
1
gap> LeadingCoefficient(f,2);
9
gap> LeadingMonomial(f);
[ 2, 7 ]
\end{verbatim}

66.6.5 Derivative

\texttt{Derivative(\textit{ratfun}[, \textit{ind}])} (attribute)

If \textit{ratfun} is a univariate rational function then \texttt{Derivative} returns the derivative of \textit{ufun} by its indeterminate. For a rational function \textit{ratfun}, the derivative by the indeterminate \textit{ind} is returned, regarding \textit{ratfun} as univariate in \textit{ind}. Instead of the desired indeterminate, also the number of this indeterminate can be given as \textit{ind}.

\begin{verbatim}
gap> Derivative(f,2);
63*y^6+20*x*y^4+3*x+3
\end{verbatim}

66.6.6 Discriminant

\texttt{Discriminant(\textit{pol}[, \textit{ind}])} (operation)

If \textit{pol} is a univariate polynomial then \texttt{Discriminant} returns the discriminant of \textit{pol} by its indeterminate. The two-argument form returns the discriminant of a polynomial \textit{pol} by the indeterminate.
number \textit{ind}, regarding \textit{pol} as univariate in this indeterminate. Instead of the indeterminate number, the indeterminate itself can also be given as \textit{ind}.

\begin{verbatim}
gap> Discriminant(f,1);
20603125*y^28+262144*y^25+27337500*y^22+19208040*y^21+1474560*y^17+
68750*y^16+18225000*y^15+6075000*y^14+1105920*y^13+3037500*y^10+
67500*y^9+300000*y^8+50000
true
\end{verbatim}

Example

66.6.7 Resultant

\textbf{Resultant}(\textit{pol1}, \textit{pol2}, \textit{ind})

\[(\text{operation})\]

computes the resultant of the polynomials \textit{pol1} and \textit{pol2} with respect to the indeterminate \textit{ind}, or indeterminate number \textit{ind}. The resultant considers \textit{pol1} and \textit{pol2} as univariate in \textit{ind} and returns an element of the corresponding base ring (which might be a polynomial ring).

\begin{verbatim}
gap> Resultant(x^4+y,y^4+x,1);
y^16+y
\end{verbatim}

Example

66.7 Multivariate Polynomials

66.7.1 Value

\textbf{Value}(\textit{ratfun}, \textit{indets}, \textit{vals}[, \textit{one}])

\[(\text{operation})\]

\textbf{Value}(\textit{upol}, \textit{value}[, \textit{one}])

\[(\text{operation})\]

The first variant takes a rational function \textit{ratfun} and specializes the indeterminates given in \textit{indets} to the values given in \textit{vals}, replacing the \textit{i}-th entry in \textit{indets} by the \textit{i}-th entry in \textit{vals}. If this specialization results in a constant polynomial, an element of the coefficient ring is returned. If the specialization would specialize the denominator of \textit{ratfun} to zero, an error is raised.

A variation is the evaluation at elements of another ring \textit{R}, for which a multiplication with elements of the coefficient ring of \textit{ratfun} are defined. In this situation the identity element of \textit{R} may be given by a further argument \textit{one} which will be used for \textit{x}^0 for any specialized indeterminate \textit{x}.

The second version takes an univariate rational function and specializes the value of its indeterminate to \textit{val}. Again, an optional argument \textit{one} may be given.

Example

\begin{verbatim}
gap> Value(x*y+y+x^7,[x,y],[5,7]);
78167
\end{verbatim}

Note that the default values for \textit{one} can lead to different results than one would expect: For example for a matrix \textit{M}, the values \textit{M} + \textit{M}^0 and \textit{M} + 1 are \textit{different}. As \texttt{Value} defaults to the one of the coefficient ring, when evaluating matrices in polynomials always the correct \textit{one} should be given!
66.8  Minimal Polynomials

66.8.1  MinimalPolynomial

\[ \text{MinimalPolynomial}(R, \text{elm}[, \text{ind}]) \]

(operation)

returns the minimal polynomial of \( \text{elm} \) over the ring \( R \), expressed in the indeterminate number \( \text{ind} \). If \( \text{ind} \) is not given, it defaults to 1.

The minimal polynomial is the monic polynomial of smallest degree with coefficients in \( R \) that has value zero at \( \text{elm} \).

\[
\text{gap}\> \text{MinimalPolynomial}(\text{Rationals},[[2,0],[0,2]]);
\]
\[
x-2
\]

66.9  Cyclotomic Polynomials

66.9.1  CyclotomicPolynomial

\[ \text{CyclotomicPolynomial}(F, n) \]

(function)

is the \( n \)-th cyclotomic polynomial over the ring \( F \).

\[
\text{gap}\> \text{CyclotomicPolynomial}(\text{Rationals},5);
\]
\[
x^4+x^3+x^2+x+1
\]

66.10  Polynomial Factorization

At the moment GAP provides only methods to factorize polynomials over finite fields (see Chapter 59), over subfields of cyclotomic fields (see Chapter 60), and over algebraic extensions of these (see Chapter 67).

66.10.1  Factors (of polynomial)

\[ \text{Factors}(R, \text{poly}[, \text{opt}]) \]

(method)

returns a list of the irreducible factors of the polynomial \( \text{poly} \) in the polynomial ring \( R \). (That is factors over the \text{CoefficientsRing} (66.15.3) value of \( R \).)

For univariate factorizations, it is possible to pass a record \( \text{opt} \) as a third argument. This record can contain the following components:

\text{onlydegs }

is a set of positive integers. The factorization assumes that all irreducible factors have a degree in this set.

\text{stopdegs }

is a set of positive integers. The factorization will stop once a factor of degree in \text{stopdegs} has been found and will return the factorization found so far.
Example

```gap
gap> f:= CyclotomicPolynomial( GF(2), 7 );
x_1^6+x_1^5+x_1^4+x_1^3+x_1^2+x_1+Z(2)^0
gap> Factors( f );
[ x_1^3+x_1+Z(2)^0, x_1^3+x_1^2+Z(2)^0 ]
gap> Factors( PolynomialRing( GF(8) ), f );
[ x_1+Z(2^3), x_1+Z(2^3)^2, x_1+Z(2^3)^3, x_1+Z(2^3)^4, x_1+Z(2^3)^5,
x_1+Z(2^3)^6 ]
gap> f:= MinimalPolynomial( Rationals, E(4) );
x^2+1
gap> Factors( f );
[ x^2+1 ]
gap> Factors( PolynomialRing( Rationals ), f );
[ x^2+1 ]
gap> Factors( PolynomialRing( CF(4) ), f );
[ x+E(4), x+(-E(4)) ]
```

66.10.2 FactorsSquarefree

\[ \text{FactorsSquarefree(pring, upol, opt)} \]

returns a factorization of the squarefree, monic, univariate polynomial \( \text{upol} \) in the polynomial ring \( \text{pring} \); \( \text{opt} \) must be a (possibly empty) record of options. \( \text{upol} \) must not have zero as a root. This function is used by the factoring algorithms.

The current method for multivariate factorization reduces to univariate factorization by use of a reduction homomorphism of the form \[ f(x_1,x_2,x_3) \mapsto f(x,x^p,x^{p^2}). \] It can be very time intensive for larger degrees.

Example

```gap
gap> Factors(x^10-y^10);
[ x-y, x+y, x^4-x^3*y+x^2*y^2-x*y^3+y^4, x^4+x^3*y+x^2*y^2+x*y^3+y^4 ]
```

66.11 Polynomials over the Rationals

The following functions are only available to polynomials with rational coefficients:

66.11.1 PrimitivePolynomial

\[ \text{PrimitivePolynomial(f)} \]

takes a polynomial \( f \) with rational coefficients and computes a new polynomial with integral coefficients, obtained by multiplying with the Lcm of the denominators of the coefficients and casting out the content (the Gcd of the coefficients). The operation returns a list \([\text{newpol}, \text{coeff}] \) with rational \( \text{coeff} \) such that \( \text{coeff} \ast \text{newpol} = f \).

66.11.2 PolynomialModP

\[ \text{PolynomialModP(pol, p)} \]


for a rational polynomial $p\mathcal{O}$ this function returns a polynomial over the field with $p$ elements, obtained by reducing the coefficients modulo $p$.

### 66.11.3 GaloisType

**GaloisType($f$)**

Let $f$ be an irreducible polynomial with rational coefficients. This function returns the type of $\text{Gal}(f)$ (considered as a transitive permutation group of the roots of $f$). It returns a number $i$ if $\text{Gal}(f)$ is permutation isomorphic to $\text{TransitiveGroup}(n, i)$ where $n$ is the degree of $f$.

Identification is performed by factoring appropriate Galois resolvents as proposed in [SM85]. This function is provided for rational polynomials of degree up to 15. However, in some cases the required calculations become unfeasibly large.

For a few polynomials of degree 14, a complete discrimination is not yet possible, as it would require computations, that are not feasible with current factoring methods.

This function requires the transitive groups library to be installed (see (transgrp: Transitive Permutation Groups)).

### 66.11.4 ProbabilityShapes

**ProbabilityShapes($f$)**

Let $f$ be an irreducible polynomial with rational coefficients. This function returns a list of the most likely type(s) of $\text{Gal}(f)$ (see GaloisType (66.11.3)), based on factorization modulo a set of primes. It is very fast, but the result is only probabilistic.

This function requires the transitive groups library to be installed (see (transgrp: Transitive Permutation Groups)).

**Example**

```gap
gap> f:=x^9-9*x^7+27*x^5-39*x^3+36*x-8;;
gap> GaloisType(f);
25
gap> TransitiveGroup(9,25);
[1/2.S(3)^3]

gap> ProbabilityShapes(f);
[ 25 ]
```

### 66.12 Factorization of Polynomials over the Rationals

The following operations are used by GAP inside the factorization algorithm but might be of interest also in other contexts.

### 66.12.1 BombieriNorm

**BombieriNorm($p\mathcal{O}$)**

computes weighted Norm $[p\mathcal{O}]_2$ of $p\mathcal{O}$ which is a good measure for factor coefficients (see [BTW93]).
66.12.2 MinimizedBombieriNorm

MinimizedBombieriNorm\((f)\)

This function applies linear Tschirnhaus transformations \((x \mapsto x + i)\) to the polynomial \(f\), trying to get the Bombieri norm of \(f\) small. It returns a list \([\text{new\_polynomial}, \text{i\_of\_transformation}]\).

66.12.3 HenselBound

HenselBound\((\text{pol}[, \text{minpol}, \text{den}])\)

returns the Hensel bound of the polynomial \(\text{pol}\). If the computation takes place over an algebraic extension, then the minimal polynomial \(\text{minpol}\) and denominator \(\text{den}\) must be given.

66.12.4 OneFactorBound

OneFactorBound\((\text{pol})\)

returns the coefficient bound for a single factor of the rational polynomial \(\text{pol}\).

66.13 Laurent Polynomials

A univariate polynomial can be written in the form \(r_0 + r_1x + \cdots + r_nx^n\), with \(r_i \in R\). Formally, there is no reason to start with 0, if \(m\) is an integer, we can consider objects of the form \(r_mx^m + r_{m+1}x^{m+1} + \cdots + r_nx^n\). We call these Laurent polynomials. Laurent polynomials also can be considered as quotients of a univariate polynomial by a power of the indeterminate. The addition and multiplication of univariate polynomials extends to Laurent polynomials (though it might be impossible to interpret a Laurent polynomial as a function) and many functions for univariate polynomials extend to Laurent polynomials (or extended versions for Laurent polynomials exist).

66.13.1 LaurentPolynomialByCoefficients

LaurentPolynomialByCoefficients\((\text{fam}, \text{cofs}, \text{val}[, \text{ind}])\)

constructs a Laurent polynomial over the coefficients family \(\text{fam}\) and in the indeterminate \(\text{ind}\) (defaulting to 1) with the coefficients given by \(\text{cofs}\) and valuation \(\text{val}\).

66.13.2 CoefficientsOfLaurentPolynomial

CoefficientsOfLaurentPolynomial\((\text{laurent})\)

For a Laurent polynomial \(\text{laurent}\), this function returns a pair \([\text{cof}, \text{val}]\), consisting of the coefficient list (in ascending order) \(\text{cof}\) and the valuation \(\text{val}\) of \(\text{laurent}\).

Example

```
gap> p:=LaurentPolynomialByCoefficients(FamilyObj(1),
> [1,2,3,4,5],-2);
5*x^2+4*x+3+2*x^(-1)+x^(-2)
gap> NumeratorOfRationalFunction(p);DenominatorOfRationalFunction(p);
```
5*x^4+4*x^3+3*x^2+2*x+1
x^2
gap> CoefficientsOfLaurentPolynomial(p*p);
[ [ 1, 4, 10, 20, 35, 44, 46, 40, 25 ], -4 ]

66.13.3 IndeterminateNumberOfLaurentPolynomial

\[ \text{IndeterminateNumberOfLaurentPolynomial}(\text{pol}) \]

Is a synonym for \text{IndeterminateNumberOfUnivariateRationalFunction} (66.1.2).

66.14 Univariate Rational Functions

66.14.1 UnivariateRationalFunctionByCoefficients

\[ \text{UnivariateRationalFunctionByCoefficients}(\text{fam}, \text{ncof}, \text{dcof}, \text{val}[, \text{ind}]) \]

constructs a univariate rational function over the coefficients family \text{fam} and in the indeterminate \text{ind} (defaulting to 1) with numerator and denominator coefficients given by \text{ncof} and \text{dcof} and valuation \text{val}.

66.15 Polynomial Rings and Function Fields

While polynomials depend only on the family of the coefficients, polynomial rings \( A \) are defined over a base ring \( R \). A polynomial is an element of \( A \) if and only if all its coefficients are contained in \( R \). Besides providing domains and an easy way to create polynomials, polynomial rings can affect the behavior of operations like factorization into irreducibles.

If you need to work with a polynomial ring and its indeterminates the following two approaches will produce a ring that contains given variables (see section 66.1 for details about the internal numbering): Either, first create the ring and then get the indeterminates with \text{IndeterminatesOfPolynomialRing} (66.15.2).

Example

\begin{verbatim}
gap> r := PolynomialRing(Rationals,\"a\",\"b\");;
gap> indets := IndeterminatesOfPolynomialRing(r);;
gap> a := indets[1]; a := indets[2];
a b
\end{verbatim}

Alternatively, first create the indeterminates and then create the ring including these indeterminates.

Example

\begin{verbatim}
gap> a:=Indeterminate(Rationals,"a":old);;
gap> b:=Indeterminate(Rationals,"b":old);;
gap> PolynomialRing(Rationals,[a,b]);;
\end{verbatim}

As a convenient shortcut, intended mainly for interactive working, the \text{i-}th indeterminate of a polynomial ring \( R \) can be accessed as \( R.i \), which corresponds exactly to
IndeterminatesOfPolynomialRing(R)[i] or, if it has the name nam, as R.nam. Note that the number i is in general not the indeterminate number, but simply an index into the indeterminates list of R.

Example

```gap
gap> r := PolynomialRing(Rationals, ["a", "b":old ]);;
gap> r.1; r.2; r.a; r.b;
a b a b
gap> IndeterminateNumberOfLaurentPolynomial(r.1);
3
```

Polynomials as GAP objects can exist without a polynomial ring being defined and polynomials cannot be associated to a particular polynomial ring. (For example dividing a polynomial which is in a polynomial ring over the integers by another integer will result in a polynomial over the rationals, not in a rational function over the integers.)

### 66.15.1 PolynomialRing

- **PolynomialRing(R, rank [, avoid])**  
  - (operation)
- **PolynomialRing(R, names [, avoid])**  
  - (operation)
- **PolynomialRing(R, indets)**  
  - (operation)
- **PolynomialRing(R, indetnums)**  
  - (operation)

creates a polynomial ring over the ring R. If a positive integer rank is given, this creates the polynomial ring in rank indeterminates. These indeterminates will have the internal index numbers 1 to rank. The second usage takes a list names of strings and returns a polynomial ring in indeterminates labelled by names. These indeterminates have “new” internal index numbers as if they had been created by calls to Indeterminate (66.1.1). (If the argument avoid is given it contains indeterminates that should be avoided, in this case internal index numbers are incremented to skip these variables.) In the third version, a list of indeterminates indets is given. This creates the polynomial ring in the indeterminates indets. Finally, the fourth version specifies indeterminates by their index numbers.

To get the indeterminates of a polynomial ring use IndeterminatesOfPolynomialRing (66.15.2). (Indeterminates created independently with Indeterminate (66.1.1) will usually differ, though they might be given the same name and display identically, see Section 66.1.)

### 66.15.2 IndeterminatesOfPolynomialRing

- **IndeterminatesOfPolynomialRing(pring)**  
  - (attribute)
- **IndeterminatesOfFunctionField(ffield)**  
  - (attribute)

returns a list of the indeterminates of the polynomial ring pring, respectively the function field ffield.

### 66.15.3 CoefficientsRing

- **CoefficientsRing(pring)**  
  - (attribute)
returns the ring of coefficients of the polynomial ring \texttt{pring}, that is the ring over which \texttt{pring} was defined.

```
gap> r:=PolynomialRing(GF(7));  
GF(7)[x_1]
gap> r:=PolynomialRing(GF(7),3);  
GF(7)[x_1,x_2,x_3]
gap> IndeterminatesOfPolynomialRing(r);  
[ x_1, x_2, x_3 ]
gap> r2:=PolynomialRing(GF(7),[5,7,12]);  
GF(7)[x_5,x_7,x_12]
gap> CoefficientsRing(r);  
GF(7)
gap> r:=PolynomialRing(GF(7),3);  
GF(7)[x_1,x_2,x_3]
gap> r2:=PolynomialRing(GF(7),3,IndeterminatesOfPolynomialRing(r));  
GF(7)[x_4,x_5,x_6]
gap> r:=PolynomialRing(GF(7),["x","y","z","z2"]);  
GF(7)[x,y,z,z2]
```

### 66.15.4 \texttt{IsPolynomialRing}

\begin{itemize}
\item \texttt{IsPolynomialRing(pring)}
\end{itemize}

is the category of polynomial rings

### 66.15.5 \texttt{IsFiniteFieldPolynomialRing}

\begin{itemize}
\item \texttt{IsFiniteFieldPolynomialRing(pring)}
\end{itemize}

is the category of polynomial rings over a finite field (see Chapter 59).

### 66.15.6 \texttt{IsAbelianNumberFieldPolynomialRing}

\begin{itemize}
\item \texttt{IsAbelianNumberFieldPolynomialRing(pring)}
\end{itemize}

is the category of polynomial rings over a field of cyclotomics (see the chapters 18 and 60).

### 66.15.7 \texttt{IsRationalsPolynomialRing}

\begin{itemize}
\item \texttt{IsRationalsPolynomialRing(pring)}
\end{itemize}

is the category of polynomial rings over the rationals (see Chapter 17).
66.15.8 FunctionField

\[ \text{FunctionField}(R, \text{rank} [, \text{avoid}]) \]
\[ \text{FunctionField}(R, \text{names} [, \text{avoid}]) \]
\[ \text{FunctionField}(R, \text{indets}) \]
\[ \text{FunctionField}(R, \text{indetnums}) \]

creates a function field over the integral ring \( R \). If a positive integer \( \text{rank} \) is given, this creates the function field in \( \text{rank} \) indeterminates. These indeterminates will have the internal index numbers 1 to \( \text{rank} \). The second usage takes a list \text{names} of strings and returns a function field in indeterminates labelled by \text{names}. These indeterminates have “new” internal index numbers as if they had been created by calls to \text{Indeterminate} (66.1.1). (If the argument \text{avoid} is given it contains indeterminates that should be avoided, in this case internal index numbers are incremented to skip these variables.)

In the third version, a list of indeterminates \text{indets} is given. This creates the function field in the indeterminates \text{indets}. Finally, the fourth version specifies indeterminates by their index number.

To get the indeterminates of a function field use \text{IndeterminatesOfFunctionField} (66.15.2). (Indeterminates created independently with \text{Indeterminate} (66.1.1) will usually differ, though they might be given the same name and display identically, see Section 66.1.)

66.15.9 IsFunctionField

\[ \text{IsFunctionField}(\text{ffield}) \]

is the category of function fields

66.16 Univariate Polynomial Rings

66.16.1 UnivariatePolynomialRing

\[ \text{UnivariatePolynomialRing}(R [, \text{nr}]) \]
\[ \text{UnivariatePolynomialRing}(R [, \text{name}] [, \text{avoid}]) \]

returns a univariate polynomial ring in the indeterminate \( \text{nr} \) over the base ring \( R \). If \( \text{nr} \) is not given it defaults to 1.

If the number is not specified a list \text{avoid} of indeterminates may be given. Then the function will return a ring in an indeterminate that is guaranteed to be different from all the indeterminates in \text{avoid}.

Also a string \text{name} can be prescribed as the name of the indeterminate chosen (also avoiding the indeterminates in the list \text{avoid} if given).

66.16.2 IsUnivariatePolynomialRing

\[ \text{IsUnivariatePolynomialRing}(\text{pring}) \]

is the category of polynomial rings with one indeterminate.

Example

\[
gap> r:=\text{UnivariatePolynomialRing(Rationals,}"p")\text{);}
\]
\[
\text{Rationals}[p]
\]
It is often desirable to consider the monomials within a polynomial to be arranged with respect to a certain ordering. Such an ordering is called a monomial ordering if it is total, invariant under multiplication with other monomials and admits no infinite descending chains. For details on monomial orderings see [CLO97].

In GAP, monomial orderings are represented by objects that provide a way to compare monomials (as polynomials as well as –for efficiency purposes within algorithms– in the internal representation as lists).

Normally the ordering chosen should be admissible, i.e. it must be compatible with products: If \( a < b \) then \( ca < cb \) for all monomials \( a, b \) and \( c \).

Each monomial ordering provides the two functions MonomialComparisonFunction (66.17.5) and MonomialExtrepComparisonFunction (66.17.6) to compare monomials. These functions work as “is less than”, i.e. they return `true` if and only if the left argument is smaller.

### 66.17.1 IsMonomialOrdering

**IsMonomialOrdering**(obj)  

A monomial ordering is an object representing a monomial ordering. Its attributes MonomialComparisonFunction (66.17.5) and MonomialExtrepComparisonFunction (66.17.6) are actual comparison functions.

### 66.17.2 LeadingMonomialOfPolynomial

**LeadingMonomialOfPolynomial**(pol, ord)  

returns the leading monomial (with respect to the ordering \( \text{ord} \)) of the polynomial \( \text{pol} \).

Example

```gap
gap> x:=Indeterminate(Rationals,"x");;
gap> y:=Indeterminate(Rationals,"y");;
gap> z:=Indeterminate(Rationals,"z");;
gap> lexord:=MonomialLexOrdering();grlexord:=MonomialGrlexOrdering();
MonomialLexOrdering()
MonomialGrlexOrdering()
gap> f:=2*x+3*y+4*z+5*x^2-6*z^2+7*y^3;
7*y^3+5*x^2-6*z^2+2*x+3*y+4*z
gap> LeadingMonomialOfPolynomial(f,lexord);
x^2
gap> LeadingMonomialOfPolynomial(f,grlexord);
y^3
```
66.17.3 LeadingTermOfPolynomial

\( \text{LeadingTermOfPolynomial}(\text{pol}, \text{ord}) \)

returns the leading term (with respect to the ordering \text{ord}) of the polynomial \text{pol}, i.e. the product of leading coefficient and leading monomial.

66.17.4 LeadingCoefficientOfPolynomial

\( \text{LeadingCoefficientOfPolynomial}(\text{pol}, \text{ord}) \)

returns the leading coefficient (that is the coefficient of the leading monomial, see \text{LeadingMonomialOfPolynomial} (66.17.2)) of the polynomial \text{pol}.

Example

\[
\text{gap> LeadingTermOfPolynomial(f,lem\text{ord});}
\]
\[
5\times x^2
\]
\[
\text{gap> LeadingTermOfPolynomial(f,gr\text{lexord});}
\]
\[
7\times y^3
\]
\[
\text{gap> LeadingCoefficientOfPolynomial(f,lem\text{ord});}
\]
\[
5
\]

66.17.5 MonomialComparisonFunction

\( \text{MonomialComparisonFunction}(\text{O}) \)

If \text{O} is an object representing a monomial ordering, this attribute returns a \text{function} that can be used to compare or sort monomials (and polynomials which will be compared by their monomials in decreasing order) in this order.

Example

\[
\text{gap> MonomialComparisonFunction(lem\text{ord});}
\]
\[
\text{function( a, b ) ... end}
\]
\[
\text{gap> l:=[f,Derivative(f,x),Derivative(f,y),Derivative(f,z)];}
\]
\[
\text{gap> Sort(l,MonomialComparisonFunction(lem\text{ord}));l;}
\]
\[
[ -12\times z+4, 21\times y^2+2+3, 10\times x+2, 7\times y^3+5\times x^2-6\times z^2+2+2\times x+3\times y+4\times z ]
\]

66.17.6 MonomialExtrepComparisonFunction

\( \text{MonomialExtrepComparisonFunction}(\text{O}) \)

If \text{O} is an object representing a monomial ordering, this attribute returns a \text{function} that can be used to compare or sort monomials in their external representation (as lists). This comparison variant is used inside algorithms that manipulate the external representation.

66.17.7 MonomialLexOrdering

\( \text{MonomialLexOrdering}([\text{vari}]) \)

This function creates a lexicographic ordering for monomials. Monomials are compared first by the exponents of the largest variable, then the exponents of the second largest variable and so on.
The variables are ordered according to their (internal) index, i.e., $x_1$ is larger than $x_2$ and so on. If \texttt{vari} is given, and is a list of variables or variable indices, instead this arrangement of variables (in descending order; i.e. the first variable is larger than the second) is used as the underlying order of variables.

\texttt{Example}

\begin{verbatim}
gap> 1:=List(Tuples([1..3],3),i->[i[1]-1]*y^(i[2]-1)*z^(i[3]-1));
[ 1, z, z^2, y, y*z, y^2, y^2*z, x, x*z, x*z^2, x*y, x*y*z, x*y^2, x*y^2*z, x*y^2*z^2, x^2, x^2*z, x^2*z^2, x^2*y, x^2*y*z, x^2*y*z^2, x^2*y^2, x^2*y^2*z, x^2*y^2*z^2, x^2*z, x^2*z^2, x^2*y*z, x^2*y^2*z, x^2*y^2*z^2, x^2*z^2, x^2*y^2*z^2 ]
gap> Sort(1,MonomialComparisonFunction(MonomialLexOrdering()));l;
[ 1, z, z^2, y, y*z, y^2, y^2*z, x, x*z, x*z^2, x*y, x*y*z, x*y^2, x*y^2*z, x*y^2*z^2, x^2, x^2*z, x^2*z^2, x^2*y, x^2*y*z, x^2*y*z^2, x^2*y^2, x^2*y^2*z, x^2*y^2*z^2 ]
gap> Sort(1,MonomialComparisonFunction(MonomialLexOrdering([y,z,x])));l;
[ 1, y, y^2, x, x*y, x*y^2, x^2, x^2*y, x^2*y^2, z, y*z, y^2*z, x*z, x*y*z, x*y^2*z, x^2*z, x^2*y*z, x^2*y^2*z, x^2*y^2*z^2, x^2*z^2, x^2*y^2*z^2, x^2*y^2*z^2 ]
\end{verbatim}

\newpage

66.17.8 MonomialGrlexOrdering

\begin{verbatim}
\# MonomialGrlexOrdering([vari])
\end{verbatim}

This function creates a degree/lexicographic ordering. In this ordering monomials are compared first by their total degree, then lexicographically (see MonomialLexOrdering (66.17.7)).

The variables are ordered according to their (internal) index, i.e., $x_1$ is larger than $x_2$ and so on. If \texttt{vari} is given, and is a list of variables or variable indices, instead this arrangement of variables (in descending order; i.e. the first variable is larger than the second) is used as the underlying order of variables.

66.17.9 MonomialGrevlexOrdering

\begin{verbatim}
\# MonomialGrevlexOrdering([vari])
\end{verbatim}

This function creates a “grevlex” ordering. In this ordering monomials are compared first by total degree and then backwards lexicographically. (This is different than “grlex” ordering with variables reversed.)

The variables are ordered according to their (internal) index, i.e., $x_1$ is larger than $x_2$ and so on. If \texttt{vari} is given, and is a list of variables or variable indices, instead this arrangement of variables (in descending order; i.e. the first variable is larger than the second) is used as the underlying order of variables.

\texttt{Example}

\begin{verbatim}
gap> Sort(1,MonomialComparisonFunction(MonomialGrevlexOrdering()));l;
[ 1, z, z^2, y, y*z, y^2, y^2*z, x, x*z, x*z^2, x*y, x*y*z, x*y^2, x*y^2*z, x*y^2*z^2, x^2, x^2*z, x^2*z^2, x^2*y, x^2*y*z, x^2*y*z^2, x^2*y^2, x^2*y^2*z, x^2*y^2*z^2 ]
gap> Sort(1,MonomialComparisonFunction(MonomialGrevlexOrdering([y,z,x])));l;
[ 1, y, y^2, z, z^2, x, x*z, x*z^2, x*y, x*y*z, x*y^2, x*y^2*z, x*y^2*z^2, x^2, x^2*z, x^2*z^2, x^2*y, x^2*y*z, x^2*y^2, x^2*y^2*z, x^2*y^2*z^2 ]
\end{verbatim}
\[ 1, z, y, x, z^2, y*z, x*z, y^2, x*y, x^2, y*z^2, x*z^2, y^2*z, x*y*z, x^2*z, x*y^2, x^2*y, y^2*z^2, x*y*z^2, x^2*z^2, x*y^2*z, x^2*y*z, x^2*y^2, x*y^2*z^2, x^2*y^2*z, x^2*y^2*z^2 \]

\[ \text{gap> Sort(1,MonomialComparisonFunction(MonomialGrlexOrdering([z,y,x])));1;} \]

\[ 1, x, y, z, x^2, x*y, y^2, x*z, y*z, z^2, x^2*y, x*y^2, x^2*z, x*y*z, y^2*z, x*z^2, y*z^2, x^2*y^2, x^2*y*z, x*y^2*z, x^2*z^2, x*y^2*z^2, x^2*y^2*z^2 \]

### 66.17.10 EliminationOrdering

\[ \text{& EliminationOrdering(elim[, rest])} \]

This function creates an elimination ordering for eliminating the variables in `elim`. Two monomials are compared first by the exponent vectors for the variables listed in `elim` (a lexicographic comparison with respect to the ordering indicated in `elim`). If these submonomials are equal, the submonomials given by the other variables are compared by a graded lexicographic ordering (with respect to the variable order given in `rest`, if called with two parameters).

Both `elim` and `rest` may be a list of variables or a list of variable indices.

### 66.17.11 PolynomialReduction

\[ \text{& PolynomialReduction(poly, gens, order)} \]

reduces the polynomial `poly` by the ideal generated by the polynomials in `gens`, using the order `order` of monomials. Unless `gens` is a Gröbner basis the result is not guaranteed to be unique.

The operation returns a list of length two, the first entry is the remainder after the reduction. The second entry is a list of quotients corresponding to `gens`.

Note that the strategy used by `PolynomialReduction` differs from the standard textbook reduction algorithm, which is provided by `PolynomialDivisionAlgorithm` (66.17.13).

### 66.17.12 PolynomialReducedRemainder

\[ \text{& PolynomialReducedRemainder(poly, gens, order)} \]

this operation does the same way as `PolynomialReduction` (66.17.11) but does not keep track of the actual quotients and returns only the remainder (it is therefore slightly faster).

### 66.17.13 PolynomialDivisionAlgorithm

\[ \text{& PolynomialDivisionAlgorithm(poly, gens, order)} \]

This function implements the division algorithm for multivariate polynomials as given in [CLO97, Theorem 3 in Chapter 2]. (It might be slower than `PolynomialReduction` (66.17.11) but the remainders are guaranteed to agree with the textbook.)

The operation returns a list of length two, the first entry is the remainder after the reduction. The second entry is a list of quotients corresponding to `gens`. 
Example

```
gap> bas:=\{x^3*y*z,x*y^2*z,z*y*z^3+x\};;
gap> pol:=x^7*z*bas[1]+y^5*bas[3]+x*z;;
gap> PolynomialReduction(pol,bas,MonomialLexOrdering());
[ -y*z^5, \{ x^7*z, 0, y^5+z \} ]
gap> PolynomialReducedRemainder(pol,bas,MonomialLexOrdering());
-y*z^5
```  

66.17.14 MonomialExtGrlexLess

\[ \text{MonomialExtGrlexLess}(a, b) \]

implements comparison of monomial in their external representation by a “grlex” order with \( x_1 > x_2 \) (This is exactly the same as the ordering by MonomialGrlexOrdering (66.17.8), see 66.17). The function takes two monomials \( a \) and \( b \) in expanded form and returns whether the first is smaller than the second. (This ordering is also used by GAP internally for representing polynomials as a linear combination of monomials.)

See section 66.21 for details on the expanded form of monomials.

66.18 Groebner Bases

A Groebner Basis of an ideal \( I \), in a polynomial ring \( R \), with respect to a monomial ordering, is a set of ideal generators \( G \) such that the ideal generated by the leading monomials of all polynomials in \( G \) is equal to the ideal generated by the leading monomials of all polynomials in \( I \).

For more details on Groebner bases see [CLO97].

66.18.1 GroebnerBasis

\[ \text{GroebnerBasis}(L, O) \]

Let \( O \) be a monomial ordering and \( L \) be a list of polynomials that generate an ideal \( I \). This operation returns a Groebner basis of \( I \) with respect to the ordering \( O \).

GroebnerBasisNC works like GroebnerBasis with the only distinction that the first argument has to be a list of polynomials and that no test is performed to check whether the ordering is defined for all occurring variables.

Note that GAP at the moment only includes a naïve implementation of Buchberger’s algorithm (which is mainly intended as a teaching tool). It might not be sufficient for serious problems.

Example

```
gap> 1:=[x^2*y^2+z^2-1,x^2+z^2-y,x-y];;
gap> GroebnerBasis(1,MonomialLexOrdering());
[ x^2*y^2+z^2-1, x^2+z^2-y, x-y, -y^2+y+1, -1/2*z^4+2*y^2-1/2 ]
gap> GroebnerBasisNC(1,MonomialLexOrdering([z,x,y]));
[ x^2*y^2+z^2-1, x^2+z^2-y, x-y, -y^2+y+1 ]
```
66.18.2 ReducedGroebnerBasis

- ReducedGroebnerBasis(L, O) (operation)
- ReducedGroebnerBasis(I, O) (operation)

A Groebner basis $B$ (see GroebnerBasis (66.18.1)) is reduced if no monomial in a polynomial in $B$ is divisible by the leading monomial of another polynomial in $B$. This operation computes a Groebner basis with respect to the monomial ordering $O$ and then reduces it.

Example

```gap
gap> ReducedGroebnerBasis(l,MonomialGrlexOrdering());
[ x-y, z^2-2*y+1, y^2+y-1 ]
gap> ReducedGroebnerBasis(l,MonomialLexOrdering());
[ z^4+4*z^2-1, -1/2*z^2+y-1/2, -1/2*z^2+x-1/2 ]
gap> ReducedGroebnerBasis(l,MonomialLexOrdering([y,z,x]));
[ x^2+x-1, z^2-2*x+1, -x+y ]
```

For performance reasons it can be advantageous to define monomial orderings once and then to reuse them:

Example

```gap
gap> ord:=MonomialGrlexOrdering();;
gap> GroebnerBasis(l,ord);
[ x^2+y^2+z^2-1, x^2+z^2-y, x-y, -y^2-y+1, -z^2+2*y-1 ]
gap> ReducedGroebnerBasis(l,ord);
[ x-y, z^2-2*y+1, y^2+y-1 ]
```

66.18.3 StoredGroebnerBasis

- StoredGroebnerBasis(I) (attribute)

For an ideal $I$ in a polynomial ring, this attribute holds a list $[B, O]$ where $B$ is a Groebner basis for the monomial ordering $O$. this can be used to test membership or canonical coset representatives.

66.18.4 InfoGroebner

- InfoGroebner (info class)

This info class gives information about Groebner basis calculations.

66.19 Rational Function Families

All rational functions defined over a ring lie in the same family, the rational functions family over this ring.

In GAP therefore the family of a polynomial depends only on the family of the coefficients, all polynomials whose coefficients lie in the same family are "compatible".
66.19.1 RationalFunctionsFamily

▶ RationalFunctionsFamily(fam) (attribute)

creates a family containing rational functions with coefficients in fam. All elements of the RationalFunctionsFamily are rational functions (see IsRationalFunction (66.4.1)).

66.19.2 IsPolynomialFunctionsFamily

▶ IsPolynomialFunctionsFamily(obj) (Category)
▶ IsRationalFunctionsFamily(obj) (Category)

IsPolynomialFunctionsFamily is the category of a family of polynomials. For families over an UFD, the category becomes IsRationalFunctionsFamily (as rational functions and quotients are only provided for families over an UFD.)

```
Example

gap> fam:=RationalFunctionsFamily(FamilyObj(1));
NewFamily( "RationalFunctionsFamily(...)", [ 618, 620 ],
[ 82, 85, 89, 93, 97, 100, 103, 107, 111, 618, 620 ] )
```

66.19.3 CoefficientsFamily

▶ CoefficientsFamily(rffam) (attribute)

If rffam has been created as RationalFunctionsFamily(cfam) this attribute holds the coefficients family cfam.

GAP does not embed the base ring in the polynomial ring. While multiplication and addition of base ring elements to rational functions return the expected results, polynomials and rational functions are not equal.

```
Example

gap> 1=Indeterminate(Rationals)^0;
false
```

66.20 The Representations of Rational Functions

GAP uses four representations of rational functions: Rational functions given by numerator and denominator, polynomials, univariate rational functions (given by coefficient lists for numerator and denominator and valuation) and Laurent polynomials (given by coefficient list and valuation).

These representations do not necessarily reflect mathematical properties: While an object in the Laurent polynomials representation must be a Laurent polynomial it might turn out that a rational function given by numerator and denominator is actually a Laurent polynomial and the property tests in section 66.4 will find this out.

Each representation is associated one or several “defining attributes” that give an “external” representation (see 66.21) of the representation in the form of lists and are the defining information that tells a rational function what it is.

GAP also implements methods to compute these attributes for rational functions in other representations, provided it would be possible to express an mathematically equal rational function in the
representation associated with the attribute. (That is one can always get a numerator/denominator representation of a polynomial while an arbitrary function of course can compute a polynomial representation only if it is a polynomial.)

Therefore these attributes can be thought of as “conceptual” representations that allow us—as far as possible—to consider an object as a rational function, a polynomial or a Laurent polynomial, regardless of the way it is represented in the computer.

Functions thus usually do not need to care about the representation of a rational function. Depending on its (known in the context or determined) properties, they can access the attribute representing the rational function in the desired way.

Consequentially, methods for rational functions are installed for properties and not for representations.

When creating new rational functions however they must be created in one of the three representations. In most cases this will be the representation for which the “conceptual” representation in which the calculation was done is the defining attribute.

Iterated operations (like forming the product over a list) therefore will tend to stay in the most suitable representation and the calculation of another conceptual representation (which may be comparatively expensive in certain circumstances) is not necessary.

66.21 The Defining Attributes of Rational Functions

In general, rational functions are given in terms of monomials. They are represented by lists, using numbers (see 66.1) for the indeterminates.

A monomial is a product of powers of indeterminates. A monomial is stored as a list (we call this the \textit{expanded form} of the monomial) of the form \([\text{inum}, \text{exp}, \text{inum}, \text{exp}, \ldots]\) where each \text{inum} is the number of an indeterminate and \text{exp} the corresponding exponent. The list must be sorted according to the numbers of the indeterminates. Thus for example, if \(x, y\) and \(z\) are the first three indeterminates, the expanded form of the monomial \(x^5 z^8 = z^8 x^5\) is \([1, 5, 3, 8]\). The representation of a polynomials is a list of the form \([\text{mon}, \text{coeff}, \text{mon}, \text{coeff}, \ldots]\) where \text{mon} is a monomial in expanded form (that is given as list) and \text{coeff} its coefficient. The monomials must be sorted according to the total degree/lexicographic order (This is the same as given by the “grlex” monomial ordering, see \texttt{MonomialGrlexOrdering} (66.17.8)). We call this the \textit{external representation} of a polynomial. (The reason for ordering is that addition of polynomials becomes linear in the number of monomials instead of quadratic; the reason for the particular ordering chose is that it is compatible with multiplication and thus gives acceptable performance for quotient calculations.)

The attributes that give a representation of a a rational function as a Laurent polynomial are \texttt{CoefficientsOfLaurentPolynomial} (66.13.2) and \texttt{IndeterminateNumberOfUnivariateRationalFunction} (66.1.2).

Algorithms should use only the attributes \texttt{ExtRepNumeratorRatFun} (66.21.2), \texttt{ExtRepDenominatorRatFun} (66.21.3), \texttt{ExtRepPolynomialRatFun} (66.21.6), \texttt{CoefficientsOfLaurentPolynomial} (66.13.2) and—if the univariate function is not constant—\texttt{IndeterminateNumberOfUnivariateRationalFunction} (66.1.2) as the low-level interface to work with a polynomial. They should not refer to the actual representation used.
66.21.1 IsRationalFunctionDefaultRep

\[\text{IsRationalFunctionDefaultRep}(\text{obj})\]

is the default representation of rational functions. A rational function in this representation is defined by the attributes \text{ExtRepNumeratorRatFun} (66.21.2) and \text{ExtRepDenominatorRatFun} (66.21.3), the values of which are external representations of polynomials.

66.21.2 ExtRepNumeratorRatFun

\[\text{ExtRepNumeratorRatFun}(\text{ratfun})\]

returns the external representation of the numerator polynomial of the rational function \text{ratfun}. Numerator and denominator are not guaranteed to be cancelled against each other.

66.21.3 ExtRepDenominatorRatFun

\[\text{ExtRepDenominatorRatFun}(\text{ratfun})\]

returns the external representation of the denominator polynomial of the rational function \text{ratfun}. Numerator and denominator are not guaranteed to be cancelled against each other.

66.21.4 ZeroCoefficientRatFun

\[\text{ZeroCoefficientRatFun}(\text{ratfun})\]

returns the zero of the coefficient ring. This might be needed to represent the zero polynomial for which the external representation of the numerator is the empty list.

66.21.5 IsPolynomialDefaultRep

\[\text{IsPolynomialDefaultRep}(\text{obj})\]

is the default representation of polynomials. A polynomial in this representation is defined by the components and \text{ExtRepNumeratorRatFun} (66.21.2) where \text{ExtRepNumeratorRatFun} (66.21.2) is the external representation of the polynomial.

66.21.6 ExtRepPolynomialRatFun

\[\text{ExtRepPolynomialRatFun}(\text{polynomial})\]

returns the external representation of a polynomial. The difference to \text{ExtRepNumeratorRatFun} (66.21.2) is that rational functions might know to be a polynomial but can still have a non-vanishing denominator. In this case \text{ExtRepPolynomialRatFun} has to call a quotient routine.
66.21.7 IsLaurentPolynomialDefaultRep

\[ \text{IsLaurentPolynomialDefaultRep}(\text{obj}) \]

(Representation)

This representation is used for Laurent polynomials and univariate polynomials. It represents a Laurent polynomial via the attributes CoefficientsOfLaurentPolynomial (66.13.2) and IndeterminateNumberOfLaurentPolynomial (66.13.3).

66.22 Creation of Rational Functions

The operations \text{LaurentPolynomialByCoefficients} (66.13.1), \text{PolynomialByExtRep} (66.22.2) and \text{RationalFunctionByExtRep} (66.22.1) are used to construct objects in the three basic representations for rational functions.

66.22.1 RationalFunctionByExtRep

\[ \text{RationalFunctionByExtRep}(\text{rfam}, \text{num}, \text{den}) \]

(Representation)

\[ \text{RationalFunctionByExtRepNC}(\text{rfam}, \text{num}, \text{den}) \]

(Representation)

constructs a rational function (in the representation \text{IsRationalFunctionDefaultRep} (66.21.1)) in the rational function family \text{rfam}, the rational function itself is given by the external representations \text{num} and \text{den} for numerator and denominator. No cancellation takes place.

The variant \text{RationalFunctionByExtRepNC} does not perform any test of the arguments and thus potentially can create illegal objects. It only should be used if speed is required and the arguments are known to be in correct form.

66.22.2 PolynomialByExtRep

\[ \text{PolynomialByExtRep}(\text{rfam}, \text{extrep}) \]

(Representation)

\[ \text{PolynomialByExtRepNC}(\text{rfam}, \text{extrep}) \]

(Representation)

constructs a polynomial (in the representation \text{IsPolynomialDefaultRep} (66.21.5)) in the rational function family \text{rfam}, the polynomial itself is given by the external representation \text{extrep}.

The variant \text{PolynomialByExtRepNC} does not perform any test of the arguments and thus potentially can create invalid objects. It only should be used if speed is required and the arguments are known to be in correct form.

Example

\[ \text{gap> fam:=RationalFunctionsFamily(FamilyObj(1));} \]
\[ \text{gap> p:=PolynomialByExtRep(fam,[[[1,2],1,[2,1,15,7],3]);} \]
\[ 3*y*x_{15}^7+x^2 \]
\[ \text{gap> q:=p}/(p+1); \]
\[ (3*y*x_{15}^7+x^2)/(3*y*x_{15}^7+x^2+1) \]
\[ \text{gap> ExtRepNumeratorRatFun(q)}; \]
\[ [ [ 1, 2 ], 1, [ 2, 1, 15, 7 ], 3 ] \]
\[ \text{gap> ExtRepDenominatorRatFun(q)}; \]
\[ [ [ ], 1, [ 1, 2 ], 1, [ 2, 1, 15, 7 ], 3 ] \]
66.22.3 LaurentPolynomialByExtRep

- **LaurentPolynomialByExtRep**
  - function
  - **LaurentPolynomialByExtRep**(fam, cofs, val, ind)

  creates a Laurent polynomial in the family fam with [cofs, val] as value of CoefficientsOfLaurentPolynomial (66.13.2). No coefficient shifting is performed. This is the lowest level function to create a Laurent polynomial but will rely on the coefficients being shifted properly and will not perform any tests. Unless this is guaranteed for the parameters, LaurentPolynomialByCoefficients (66.13.1) should be used.

66.23 Arithmetic for External Representations of Polynomials

The following operations are used internally to perform the arithmetic for polynomials in their “external” representation (see 66.21) as lists.

Functions to perform arithmetic with the coefficient lists of Laurent polynomials are described in Section 23.4.

66.23.1 ZippedSum

- **ZippedSum**(z1, z2, czero, funcs)

  computes the sum of two external representations of polynomials z1 and z2. czero is the appropriate coefficient zero and funcs a list [monomial_less, coefficient_sum] containing a monomial comparison and a coefficient addition function. This list can be found in the component fam!.zippedSum of the rational functions family.

  Note that coefficient_sum must be a proper “summation” function, not a function computing differences.

66.23.2 ZippedProduct

- **ZippedProduct**(z1, z2, czero, funcs)

  computes the product of two external representations of polynomials z1 and z2. czero is the appropriate coefficient zero and funcs a list [monomial_prod, monomial_less, coefficient_sum, coefficient_prod] containing functions to multiply and compare monomials, to add and to multiply coefficients. This list can be found in the component fam!.zippedProduct of the rational functions family.

66.23.3 QuotientPolynomialsExtRep

- **QuotientPolynomialsExtRep**(fam, a, b)

  Let a and b the external representations of two polynomials in the rational functions family fam. This function computes the external representation of the quotient of both polynomials, it returns fail if the polynomial described by b does not divide the polynomial described by a.
66.24  Cancellation Tests for Rational Functions

The operation Gcd (56.7.1) can be used to test for common factors of two polynomials. This however would be too expensive to be done in the arithmetic, thus uses the following operations internally to try to keep the denominators as small as possible.

66.24.1  RationalFunctionByExtRepWithCancellation

\[ \text{RationalFunctionByExtRepWithCancellation}(\text{rfam, num, den}) \]

constructs a rational function as RationalFunctionByExtRep (66.22.1) does but tries to cancel out common factors of numerator and denominator, calling TryGcdCancelExtRepPolynomials (66.24.2).

66.24.2  TryGcdCancelExtRepPolynomials

\[ \text{TryGcdCancelExtRepPolynomials}(\text{fam, a, b}) \]

Let a and b be the external representations of two polynomials. This function tries to cancel common factors between the corresponding polynomials and returns a list \([a', b']\) of external representations of cancelled polynomials. As there is no proper multivariate GCD cancellation is not guaranteed to be optimal.

66.24.3  HeuristicCancelPolynomialsExtRep

\[ \text{HeuristicCancelPolynomialsExtRep}(\text{fam, ext1, ext2}) \]

is called by TryGcdCancelExtRepPolynomials (66.24.2) to perform the actual work. It will return either fail or a new list of of external representations of cancelled polynomials. The cancellation performed is not necessarily optimal.
Chapter 67

Algebraic extensions of fields

If we adjoin a root \( \alpha \) of an irreducible polynomial \( f \in K[x] \) to the field \( K \) we get an algebraic extension \( K(\alpha) \), which is again a field. We call \( K \) the base field of \( K(\alpha) \).

By Kronecker’s construction, we may identify \( K(\alpha) \) with the factor ring \( K[x]/(f) \), an identification that also provides a method for computing in these extension fields.

It is important to note that different extensions of the same field are entirely different (and its elements lie in different families), even if mathematically one could be embedded in the other one.

Currently GAP only allows extension fields of fields \( K \), when \( K \) itself is not an extension field.

67.1 Creation of Algebraic Extensions

67.1.1 AlgebraicExtension

\[
\text{AlgebraicExtension}(K, f[, nam]) \quad \text{(operation)}
\]

\[
\text{AlgebraicExtensionNC}(K, f[, nam]) \quad \text{(operation)}
\]

constructs an extension \( L \) of the field \( K \) by one root of the irreducible polynomial \( f \), using Kronecker’s construction. \( L \) is a field whose \text{LeftActingDomain} (57.1.11) value is \( K \). The polynomial \( f \) is the \text{DefiningPolynomial} (58.2.7) value of \( L \) and the attribute \text{RootOfDefiningPolynomial} (58.2.8) of \( L \) holds a root of \( f \) in \( L \). By default this root is printed as \( a \), this string can be overwritten with the optional argument \text{nam}.

The first version of the command checks that the polynomial \( f \) is an irreducible polynomial over \( K \). This check is skipped with the \text{NC} variant.

\begin{verbatim}
Example
\end{verbatim}
### 67.1.2 IsAlgebraicExtension

> **IsAlgebraicExtension**

**(obj)**

is the category of algebraic extensions of fields.

**Example**

```gap
gap> IsAlgebraicExtension(e);
true
gap> IsAlgebraicExtension(Rationals);
false
```

### 67.2 Elements in Algebraic Extensions

According to Kronecker’s construction, the elements of an algebraic extension are considered to be polynomials in the primitive element. The elements of the base field are represented as polynomials of degree zero. **GAP** therefore displays elements of an algebraic extension as polynomials in an indeterminate “a”, which is a root of the defining polynomial of the extension. Polynomials of degree zero are displayed with a leading exclamation mark to indicate that they are different from elements of the base field.

The usual field operations are applicable to algebraic elements.

**Example**

```gap
gap> a^3/(a^2+a+1);
-1/2*a^3+1/2*a^2-1/2*a
gap> a*(1/a);
!1
```

The external representation of algebraic extension elements are the polynomial coefficients in the primitive element a, the operations ExtRep0fObj (79.8.1) and ObjByExtRep (79.8.1) can be used for conversion.

**Example**

```gap
gap> ExtRep0fObj(One(a));
[ 1, 0, 0, 0 ]
gap> ExtRep0fObj(a^3+2*a-9);
[ -9, 2, 0, 1 ]
gap> ObjByExtRep(FamilyObj(a),[3,19,-27,433]);
433*a^3-27*a^2+19*a+3
```

**GAP** does not embed the base field in its algebraic extensions and therefore lists which contain elements of the base field and of the extension are not homogeneous and thus cannot be used as polynomial coefficients or to form matrices. The remedy is to multiply the list(s) with the value of the attribute One (31.10.2) of the extension which will embed all entries in the extension.

**Example**

```gap
gap> m:=[[1,a],[0,1]];
[ [ 1, a ], [ 0, 1 ] ]
gap> IsMatrix(m);
false
gap> m:=m*One(e);
[ [ !1, a ], [ !0, !1 ] ]
```
67.2.1 IsAlgebraicElement

\( \text{IsAlgebraicElement}(\text{obj}) \)

is the category for elements of an algebraic extension.

67.3 Finding Subfields

67.3.1 IdealDecompositionsOfPolynomial

\( \text{IdealDecompositionsOfPolynomial}(\text{pol}) \)

Let \( f \) be a univariate, rational, irreducible, polynomial. A pair \( g, h \) of polynomials of degree strictly smaller than that of \( f \), such that \( f(x)|g(h(x)) \) is called an ideal decomposition. In the context of field extensions, if \( \alpha \) is a root of \( f \) in a suitable extension and \( Q \) the field of rational numbers. Such decompositions correspond to (proper) subfields \( Q < Q(\beta) < Q(\alpha) \). where \( g \) is the minimal polynomial of \( \beta \). This function determines such decompositions up to equality of the subfields \( Q(\beta) \), thus determining subfields of a given algebraic extension. It returns a list of pairs \([g,h]\) (and an empty list if no such decomposition exists). If the option onlyone is given it returns at most one such decomposition (and performs faster).

Example

```gap
gap> x:=X(Rationals,"x");;pol:=x^8-24*x^6+144*x^4-288*x^2+144;;
gap> l:=IdealDecompositionsOfPolynomial(pol);
[ [ x^2+72*x+144, x^6-20*x^4+60*x^2-36 ],
  [ x^2-48*x+144, x^6-21*x^4+84*x^2-48 ],
  [ x^2+288*x+17280, x^6-24*x^4+132*x^2-288 ],
  [ x^4-24*x^3+144*x^2-288*x+144, x^2 ] ]
```

```gap
gap> List(l,x->Value(x[1],x[2])/pol);
[ x^4-16*x^2-8, x^4-18*x^2+33, x^4-24*x^2+120, 1 ]
```

```gap
gap> IdealDecompositionsOfPolynomial(pol:onlyone);
[ [ x^2+72*x+144, x^6-20*x^4+60*x^2-36 ] ]
```

In this example the given polynomial is regular with Galois group \( Q_8 \), as expected we get four proper subfields.
In this chapter \( p \) is always a (fixed) prime integer.

The \( p \)-adic numbers \( \mathbb{Q}_p \) are the completion of the rational numbers with respect to the valuation \( v_p(p^v \cdot a/b) = v \) if \( p \) divides neither \( a \) nor \( b \). They form a field of characteristic 0 which nevertheless shows some behaviour of the finite field with \( p \) elements.

A \( p \)-adic numbers can be represented by a “\( p \)-adic expansion” which is similar to the decimal expansion used for the reals (but written from left to right). So for example if \( p = 2 \), the numbers 1, 2, 3, 4, 1/2, and 4/5 are represented as 1(2), 0.1(2), 1.1(2), 0.01(2), 10(2), and the infinite periodic expansion 0.010110011001100...(2). \( p \)-adic numbers can be approximated by ignoring higher powers of \( p \), so for example with only 2 digits accuracy 4/5 would be approximated as 0.01(2). This is different from the decimal approximation of real numbers in that \( p \)-adic approximation is a ring homomorphism on the subrings of \( p \)-adic numbers whose valuation is bounded from below so that rounding errors do not increase with repeated calculations.

In GAP, \( p \)-adic numbers are always represented by such approximations. A family of approximated \( p \)-adic numbers consists of \( p \)-adic numbers with a fixed prime \( p \) and a certain precision, and arithmetic with these numbers is done with this precision.

### 68.1 Pure \( p \)-adic Numbers

Pure \( p \)-adic numbers are the \( p \)-adic numbers described so far.

#### 68.1.1 PurePadicNumberFamily

\[ \text{PurePadicNumberFamily}(p, \text{precision}) \]

returns the family of pure \( p \)-adic numbers over the prime \( p \) with \text{precision} “digits”. That is to say, the approximate value will differ from the correct value by a multiple of \( p^{\text{digits}} \).

#### 68.1.2 PadicNumber (for pure padics)

\[ \text{PadicNumber}(\text{fam}, \text{rat}) \]

returns the element of the \( p \)-adic number family \( \text{fam} \) that approximates the rational number \( \text{rat} \). \( p \)-adic numbers allow the usual operations for fields.
Example

```gap
gap> fam:=PurePadicNumberFamily(2,20);;
gap> a:=PadicNumber(fam,4/5);
0.010110011001100110011(2)
gap> fam:=PurePadicNumberFamily(2,3);;
gap> a:=PadicNumber(fam,4/5);
0.0101(2)

gap> 3*a;
0.0111(2)
gap> a/2;
0.101(2)
gap> a*10;
0.001(2)
```

See `PadicNumber (68.2.2)` for other methods for `PadicNumber`.

68.1.3 Valuation

\[ \text{Valuation(obj)} \]

(operation)

The valuation is the \( p \)-part of the \( p \)-adic number. See also `PValuation (15.7.1)`.

68.1.4 ShiftedPadicNumber

\[ \text{ShiftedPadicNumber(padic, int)} \]

(operation)

`ShiftedPadicNumber` takes a \( p \)-adic number `padic` and an integer `shift` and returns the \( p \)-adic number \( c \), that is \( padic \times p^\text{shift} \).

68.1.5 IsPurePadicNumber

\[ \text{IsPurePadicNumber(obj)} \]

(Category)

The category of pure \( p \)-adic numbers.

68.1.6 IsPurePadicNumberFamily

\[ \text{IsPurePadicNumberFamily(fam)} \]

(Category)

The family of pure \( p \)-adic numbers.

68.2 Extensions of the \( p \)-adic Numbers

The usual Kronecker construction with an irreducible polynomial can be used to construct extensions of the \( p \)-adic numbers. Let \( L \) be such an extension. Then there is a subfield \( K < L \) such that \( K \) is an unramified extension of the \( p \)-adic numbers and \( L/K \) is purely ramified.

(For an explanation of “ramification” see for example [Neu92, Section II.7], or another book on algebraic number theory. Essentially, an extension \( L \) of the \( p \)-adic numbers generated by a rational
polynomial \( f \) is unramified if \( f \) remains squarefree modulo \( p \) and is completely ramified if modulo \( p \) the polynomial \( f \) is a power of a linear factor while remaining irreducible over the \( p \)-adic numbers.)

The representation of extensions of \( p \)-adic numbers in GAP uses the subfield \( K \).

### 68.2.1 PadicExtensionNumberFamily

\[ \text{PadicExtensionNumberFamily}(p, \text{precision}, \text{unram}, \text{ram}) \]

An extended \( p \)-adic field \( L \) is given by two polynomials \( h \) and \( g \) with coefficient lists \( \text{unram} \) (for the unramified part) and \( \text{ram} \) (for the ramified part). Then \( L \) is isomorphic to \( \mathbb{Q}_p[x,y]/(h(x),g(y)) \).

This function takes the prime number \( p \) and the two coefficient lists \( \text{unram} \) and \( \text{ram} \) for the two polynomials. The polynomial given by the coefficients in \( \text{unram} \) must be a cyclotomic polynomial and the polynomial given by \( \text{ram} \) must be either an Eisenstein polynomial or \( 1 + x \). This is not checked by GAP.

Every number in \( L \) is represented as a coefficient list w. r. t. the basis \( \{ 1, x, x^2, \ldots, y, xy, x^2y, \ldots \} \) of \( L \). The integer \( \text{precision} \) is the number of “digits” that all the coefficients have.

A general comment:

The polynomials with which \( \text{PadicExtensionNumberFamily} \) is called define an extension of \( \mathbb{Q}_p \). It must be ensured that both polynomials are really irreducible over \( \mathbb{Q}_p \). For example \( x^2 + x + 1 \) is not irreducible over \( \mathbb{Q}_p \). Therefore the “extension” \( \text{PadicExtensionNumberFamily}(3, 4, [1,1,1], [1,1]) \) contains non-invertible “pseudo-p-adic numbers”. Conversely, if an “extension” contains noninvertible elements then one of the defining polynomials was not irreducible.

### 68.2.2 PadicNumber (for a \( p \)-adic extension family and a rational)

\[ \text{PadicNumber}(\text{fam}, \text{rat}) \]

\[ \text{PadicNumber}(\text{purefam}, \text{list}) \]

\[ \text{PadicNumber}(\text{extfam}, \text{list}) \]

(see also \( \text{PadicNumber} \) (68.1.2)).

\( \text{PadicNumber} \) creates a \( p \)-adic number in the \( p \)-adic numbers family \( \text{fam} \). The first form returns the \( p \)-adic number corresponding to the rational \( \text{rat} \).

The second form takes a pure \( p \)-adic numbers family \( \text{purefam} \) and a list \( \text{list} \) of length two, and returns the number \( p^\text{\text{list}[1]} \ast \text{\text{list}[2]} \). It must be guaranteed that no entry of \( \text{list}[2] \) is divisible by the prime \( p \). (Otherwise precision will get lost.)

The third form creates a number in the family \( \text{extfam} \) of a \( p \)-adic extension. The second argument must be a list \( \text{list} \) of length two such that \( \text{list}[2] \) is the list of coefficients w.r.t. the basis \( \{ 1, \ldots, x^{f-1}, y^{e-1} \} \) of the extended \( p \)-adic field and \( \text{\text{list}[1]} \) is a common \( p \)-part of all these coefficients.

\( p \)-adic numbers admit the usual field operations.

Example

\[
\text{gap> efam:=PadicExtensionNumberFamily(3, 5, [1,1,1], [1,1]);;}
\text{gap> PadicNumber(efam,7/9);} \]

\[
\text{padic(120(3),0(3))}
\]

A word of warning:

Depending on the actual representation of quotients, precision may seem to “vanish”. For example in \( \text{PadicExtensionNumberFamily}(3, 5, [1,1,1], [1,1]) \) the number \( (1.2000, 0.1210)(3) \)
can be represented as \([ 0, [ 1.2000, 0.1210 ] ]\) or as \([-1, [ 12.000, 1.2100 ] ]\) (here the coefficients have to be multiplied by \(p^{-1}\)).

So there may be a number \((1.2, 2.2)(3)\) which seems to have only two digits of precision instead of the declared 5. But internally the number is stored as \([-3, [ 0.0012, 0.0022 ] ]\) and so has in fact maximum precision.

### 68.2.3 IsPadicExtensionNumber

\[\textbf{IsPadicExtensionNumber}(\textbf{obj})\]

The category of elements of the extended \(p\)-adic field.

```gap
gap> efam:=PadicExtensionNumberFamily(3, 5, [1,1,1], [1,1]);;
gap> IsPadicExtensionNumber(PadicNumber(efam,7/9));
true
```

### 68.2.4 IsPadicExtensionNumberFamily

\[\textbf{IsPadicExtensionNumberFamily}(\textbf{fam})\]

Family of elements of the extended \(p\)-adic field.

```gap
gap> efam:=PadicExtensionNumberFamily(3, 5, [1,1,1], [1,1]);;
gap> IsPadicExtensionNumberFamily(efam);
true
```
Chapter 69

The MeatAxe

The MeatAxe [Par84] is a tool for the examination of submodules of a group algebra. It is a basic tool for the examination of group actions on finite-dimensional modules.

GAP uses the improved MeatAxe of Derek Holt and Sarah Rees, and also incorporates further improvements of Ivanyos and Lux.

Please note that, consistently with the convention for group actions, the action of the GAP MeatAxe is always that of matrices on row vectors by multiplication on the right. If you want to investigate left modules you will have to transpose the matrices.

69.1 MeatAxe Modules

69.1.1 GModuleByMats

\[ \text{GModuleByMats}(\text{gens, field}) \]
\[ \text{GModuleByMats}(\text{emptygens, dim, field}) \]

creates a MeatAxe module over field from a list of invertible matrices gens which reflect a group’s action. If the list of generators is empty, the dimension must be given as second argument.

MeatAxe routines are on a level with Gaussian elimination. Therefore they do not deal with GAP modules but essentially with lists of matrices. For the MeatAxe, a module is a record with components

generators
A list of matrices which represent a group operation on a finite dimensional row vector space.

dimension
The dimension of the vector space (this is the common length of the row vectors (see DimensionOfVectors (61.9.6))).

field
The field over which the vector space is defined.

Once a module has been created its entries may not be changed. A MeatAxe may create a new component NameOfMeatAxe in which it can store private information. By a MeatAxe “submodule” or “factor module” we denote actually the induced action on the submodule, respectively factor module. Therefore the submodules or factor modules are again MeatAxe modules. The arrangement of
generators is guaranteed to be the same for the induced modules, but to obtain the complete relation to the original module, the bases used are needed as well.

### 69.2 Module Constructions

#### 69.2.1 PermutationGModule

```
PermutationGModule(G, F)
```

Called with a permutation group \(G\) and a field \(F\) (\(F\) may be infinite), \(\text{PermutationGModule}\) returns the natural permutation module \(M\) over \(F\) for the group of permutation matrices that acts on the canonical basis of \(M\) in the same way as \(G\) acts on the points up to its largest moved point (see \(\text{LargestMovedPoint}\) (42.3.2)).

#### 69.2.2 TensorProductGModule

```
TensorProductGModule(m1, m2)
```

\(\text{TensorProductGModule}\) calculates the tensor product of the modules \(m1\) and \(m2\). They are assumed to be modules over the same algebra so, in particular, they should have the same number of generators.

#### 69.2.3 WedgeGModule

```
WedgeGModule(module)
```

\(\text{WedgeGModule}\) calculates the wedge product of a \(G\)-module. That is the action on antisymmetric tensors.

### 69.3 Selecting a Different MeatAxe

#### 69.3.1 MTX

```
MTX
```

All MeatAxe routines are accessed via the global variable \(\text{MTX}\), which is a record whose components hold the various functions. It is possible to have several implementations of a MeatAxe available. Each MeatAxe represents its routines in an own global variable and assigning \(\text{MTX}\) to this variable selects the corresponding MeatAxe.

### 69.4 Accessing a Module

Even though a MeatAxe module is a record, its components should never be accessed outside of MeatAxe functions. Instead the following operations should be used:
69.4.1 MTX.Generators

\[ \text{MTX.Generators}(\text{module}) \]

returns a list of matrix generators of module.

69.4.2 MTX.Dimension

\[ \text{MTX.Dimension}(\text{module}) \]

returns the dimension in which the matrices act.

69.4.3 MTX.Field

\[ \text{MTX.Field}(\text{module}) \]

returns the field over which module is defined.

69.5 Irreducibility Tests

69.5.1 MTX.IsIrreducible

\[ \text{MTX.IsIrreducible}(\text{module}) \]

tests whether the module module is irreducible (i.e. contains no proper submodules.)

69.5.2 MTX.IsAbsolutelyIrreducible

\[ \text{MTX.IsAbsolutelyIrreducible}(\text{module}) \]

A module is absolutely irreducible if it remains irreducible over the algebraic closure of the field.

(Formally: If the tensor product \( L \otimes_K M \) is irreducible where \( M \) is the module defined over \( K \) and \( L \) is the algebraic closure of \( K \).)

69.5.3 MTX.DegreeSplittingField

\[ \text{MTX.DegreeSplittingField}(\text{module}) \]

returns the degree of the splitting field as extension of the prime field.

69.6 Decomposition of modules

A module is decomposable if it can be written as the direct sum of two proper submodules (and indecomposable if not). Obviously every finite dimensional module is a direct sum of its indecomposable parts. The homogeneous components of a module are the direct sums of isomorphic indecomposable components. They are uniquely determined.
69.6.1 MTX.IsIndecomposable
\> MTX.IsIndecomposable(module)  (function)

returns whether module is indecomposable.

69.6.2 MTX.Indecomposition
\> MTX.Indecomposition(module)  (function)

returns a decomposition of module as a direct sum of indecomposable modules. It returns a list, each entry is a list of form \([B, ind]\) where \(B\) is a list of basis vectors for the indecomposable component and \(ind\) the induced module action on this component. (Such a decomposition is not unique.)

69.6.3 MTX.HomogeneousComponents
\> MTX.HomogeneousComponents(module)  (function)

computes the homogeneous components of module given as sums of indecomposable components. The function returns a list, each entry of which is a record corresponding to one isomorphism type of indecomposable components. The record has the following components.

indices
the index numbers of the indecomposable components, as given by MTX.Indecomposition (69.6.2), that are in the homogeneous component,

component
one of the indecomposable components,

images
a list of the remaining indecomposable components, each given as a record with the components component (the component itself) and isomorphism (an isomorphism from the defining component to this one).

69.7 Finding Submodules

69.7.1 MTX.SubmoduleGModule
\> MTX.SubmoduleGModule(module, subspace)  (function)
\> MTX.SubGModule(module, subspace)  (function)

subspace should be a subspace of (or a vector in) the underlying vector space of module i.e. the full row space of the same dimension and over the same field as module. A normalized basis of the submodule of module generated by subspace is returned.
69.7.2 MTX.ProperSubmoduleBasis
MTX.ProperSubmoduleBasis(module)
returns the basis of a proper submodule of module and fail if no proper submodule exists.

69.7.3 MTX.BasesSubmodules
MTX.BasesSubmodules(module)
returns a list containing a basis for every submodule.

69.7.4 MTX.BasesMinimalSubmodules
MTX.BasesMinimalSubmodules(module)
returns a list of bases of all minimal submodules.

69.7.5 MTX.BasesMaximalSubmodules
MTX.BasesMaximalSubmodules(module)
returns a list of bases of all maximal submodules.

69.7.6 MTX.BasisRadical
MTX.BasisRadical(module)
returns a basis of the radical of module.

69.7.7 MTX.BasisSocle
MTX.BasisSocle(module)
returns a basis of the socle of module.

69.7.8 MTX.BasesMinimalSupermodules
MTX.BasesMinimalSupermodules(module, sub)
returns a list of bases of all minimal supermodules of the submodule given by the basis sub.

69.7.9 MTX.BasesCompositionSeries
MTX.BasesCompositionSeries(module)
returns a list of bases of submodules in a composition series in ascending order.
69.7.10 **MTX.CompositionFactors**

\[\text{MTX.CompositionFactors(module)}\]

returns a list of composition factors of \texttt{module} in ascending order.

69.7.11 **MTX.CollectedFactors**

\[\text{MTX.CollectedFactors(module)}\]

returns a list giving all irreducible composition factors with their frequencies.

69.8 **Induced Actions**

69.8.1 **MTX.NormedBasisAndBaseChange**

\[\text{MTX.NormedBasisAndBaseChange(sub)}\]

returns a list \([\texttt{bas}, \texttt{change}]\) where \texttt{bas} is a normed basis (i.e. in echelon form with pivots normed to 1) for \texttt{sub} and \texttt{change} is the base change from \texttt{bas} to \texttt{sub} (the basis vectors of \texttt{bas} expressed in coefficients for \texttt{sub}).

69.8.2 **MTX.InducedActionSubmodule**

\[\text{MTX.InducedActionSubmodule(module, sub)}\]
\[\text{MTX.InducedActionSubmoduleNB(module, sub)}\]

creates a new module corresponding to the action of \texttt{module} on the non-trivial submodule \texttt{sub}. In the \texttt{NB} version the basis \texttt{sub} must be normed. (That is it must be in echelon form with pivots normed to 1, see \texttt{MTX.NormedBasisAndBaseChange (69.8.1)}.)

69.8.3 **MTX.InducedActionFactorModule**

\[\text{MTX.InducedActionFactorModule(module, sub[, compl])}\]

creates a new module corresponding to the action of \texttt{module} on the factor of the proper submodule \texttt{sub}. If \texttt{compl} is given, it has to be a basis of a (vector space-)complement of \texttt{sub}. The action then will correspond to \texttt{compl}.

The basis \texttt{sub} has to be given in normed form. (That is it must be in echelon form with pivots normed to 1, see \texttt{MTX.NormedBasisAndBaseChange (69.8.1)}.)

69.8.4 **MTX.InducedActionSubMatrix**

\[\text{MTX.InducedActionSubMatrix(mat, sub)}\]
\[\text{MTX.InducedActionSubMatrixNB(mat, sub)}\]
\[\text{MTX.InducedActionFactorMatrix(mat, sub[, compl])}\]

work the same way as the above functions for modules, but take as input only a single matrix.
69.8.5 MTX.InducedAction

\[ \text{MTX.InducedAction}(\text{module}, \text{sub}[, \text{type}]) \] (function)

Computes induced actions on submodules or factor modules and also returns the corresponding bases. The action taken is binary encoded in type: 1 stands for subspace action, 2 for factor action, and 4 for action of the full module on a subspace adapted basis. The routine returns the computed results in a list in sequence (sub, quot, both, basis) where basis is a basis for the whole space, extending sub. (Actions which are not computed are omitted, so the returned list may be shorter.) If no type is given, it is assumed to be 7. The basis given in sub must be normed!

All these routines return fail if sub is not a proper subspace.

69.9 Module Homomorphisms

69.9.1 MTX.BasisModuleHomomorphisms

\[ \text{MTX.BasisModuleHomomorphisms}(\text{module1}, \text{module2}) \] (function)

returns a basis of all module homomorphisms from module1 to module2. Homomorphisms are by matrices, whose rows give the images of the standard basis vectors of module1 in the standard basis of module2.

69.9.2 MTX.BasisModuleEndomorphisms

\[ \text{MTX.BasisModuleEndomorphisms}(\text{module}) \] (function)

returns a basis of all module homomorphisms from module to module.

69.9.3 MTX.IsomorphismModules

\[ \text{MTX.IsomorphismModules}(\text{module1}, \text{module2}) \] (function)

If module1 and module2 are isomorphic modules, this function returns an isomorphism from module1 to module2 in form of a matrix. It returns fail if the modules are not isomorphic.

69.9.4 MTX.ModuleAutomorphisms

\[ \text{MTX.ModuleAutomorphisms}(\text{module}) \] (function)

returns the module automorphisms of module (the set of all isomorphisms from module to itself) as a matrix group.

69.10 Module Homomorphisms for irreducible modules

The following are lower-level functions that provide homomorphism functionality for irreducible modules. Generic code should use the functions in Section 69.9 instead.
69.10.1 MTX.IsEquivalent

\[ \text{MTX.IsEquivalent(module1, module2)} \]

Tests two irreducible modules for equivalence.

69.10.2 MTX.IsomorphismIrred

\[ \text{MTX.IsomorphismIrred(module1, module2)} \]

Returns an isomorphism from module1 to module2 (if one exists), and fail otherwise. It requires that one of the modules is known to be irreducible. It implicitly assumes that the same group is acting, otherwise the results are unpredictable. The isomorphism is given by a matrix \( M \), whose rows give the images of the standard basis vectors of module1 in the standard basis of module2. That is, conjugation of the generators of module2 with \( M \) yields the generators of module1.

69.10.3 MTX.Homomorphism

\[ \text{MTX.Homomorphism(module1, module2, mat)} \]

Mat should be a \( \text{dim1} \times \text{dim2} \) matrix defining a homomorphism from module1 to module2. This function verifies that mat really does define a module homomorphism, and then returns the corresponding homomorphism between the underlying row spaces of the modules. This can be used for computing kernels, images and pre-images.

69.10.4 MTX.Homomorphisms

\[ \text{MTX.Homomorphisms(module1, module2)} \]

Returns a basis of the space of all homomorphisms from the irreducible module module1 to module2.

69.10.5 MTX.Distinguish

\[ \text{MTX.Distinguish(cf, nr)} \]

Let cf be the output of MTX.CollectedFactors (69.7.11). This routine tries to find a group algebra element that has nullity zero on all composition factors except number nr.

69.11 MeatAxe Functionality for Invariant Forms

The functions in this section can only be applied to an absolutely irreducible MeatAxe module.

69.11.1 MTX.InvariantBilinearForm

\[ \text{MTX.InvariantBilinearForm(module)} \]
returns an invariant bilinear form, which may be symmetric or anti-symmetric, of \texttt{module}, or \texttt{fail} if no such form exists.

69.11.2 \texttt{MTX.InvariantSesquilinearForm}

\texttt{MTX.InvariantSesquilinearForm(module)} \hspace{1cm} \text{(function)}

returns an invariant hermitian (= self-adjoint) sesquilinear form of \texttt{module}, which must be defined over a finite field whose order is a square, or \texttt{fail} if no such form exists.

69.11.3 \texttt{MTX.InvariantQuadraticForm}

\texttt{MTX.InvariantQuadraticForm(module)} \hspace{1cm} \text{(function)}

returns an invariant quadratic form of \texttt{module}, or \texttt{fail} if no such form exists. If the characteristic of the field over which \texttt{module} is defined is not 2, then the invariant bilinear form (if any) divided by two will be returned. In characteristic 2, the form returned will be lower triangular.

69.11.4 \texttt{MTX.BasisInOrbit}

\texttt{MTX.BasisInOrbit(module)} \hspace{1cm} \text{(function)}

returns a basis of the underlying vector space of \texttt{module} which is contained in an orbit of the action of the generators of \texttt{module} on that space. This is used by \texttt{MTX.InvariantQuadraticForm (69.11.3)} in characteristic 2.

69.11.5 \texttt{MTX.OrthogonalSign}

\texttt{MTX.OrthogonalSign(module)} \hspace{1cm} \text{(function)}

for an even dimensional module, returns 1 or -1, according as \texttt{MTX.InvariantQuadraticForm(module)} is of + or - type. For an odd dimensional module, returns 0. For a module with no invariant quadratic form, returns \texttt{fail}. This calculation uses an algorithm due to Jon Thackray.

69.12 The Smash MeatAxe

The standard MeatAxe provided in the \texttt{GAP} library is based on the MeatAxe in the \texttt{GAP 3} package \texttt{Smash}, originally written by Derek Holt and Sarah Rees [HR94]. It is accessible via the variable \texttt{SMTX} to which \texttt{MTX (69.3.1)} is assigned by default. For the sake of completeness the remaining sections document more technical functions of this MeatAxe.

69.12.1 \texttt{SMTX.RandomIrreducibleSubGModule}

\texttt{SMTX.RandomIrreducibleSubGModule(module)} \hspace{1cm} \text{(function)}

returns the module action on a random irreducible submodule.
69.12.2 SMTX.GoodElementGModule

SMTX.GoodElementGModule(module)

finds an element with minimal possible nullspace dimension if module is known to be irreducible.

69.12.3 SMTX.SortHomGModule

SMTX.SortHomGModule(module1, module2, homs)

Function to sort the output of Homomorphisms.

69.12.4 SMTX.MinimalSubGModules

SMTX.MinimalSubGModules(module1, module2[, max])

returns (at most max) bases of submodules of module2 which are isomorphic to the irreducible module module1.

69.12.5 SMTX.Setter

SMTX.Setter(string)

returns a setter function for the component smashMeataxe.(string).

69.12.6 SMTX.Getter

SMTX.Getter(string)

returns a getter function for the component smashMeataxe.(string).

69.12.7 SMTX.IrreducibilityTest

SMTX.IrreducibilityTest(module)

Tests for irreducibility and sets a subbasis if reducible. It neither sets an irreducibility flag, nor tests it. Thus the routine also can simply be called to obtain a random submodule.

69.12.8 SMTX.AbsoluteIrreducibilityTest

SMTX.AbsoluteIrreducibilityTest(module)

Tests for absolute irreducibility and sets splitting field degree. It neither sets an absolute irreducibility flag, nor tests it.
69.12.9 SMTX.MinimalSubGModule

\( \text{SMTX.MinimalSubGModule}(\text{module}, \text{cf}, \text{nr}) \) (function)

returns the basis of a minimal submodule of \text{module} containing the indicated composition factor. It assumes \text{Distinguish} has been called already.

69.12.10 SMTX.MatrixSum

\( \text{SMTX.MatrixSum}(\text{matrices1}, \text{matrices2}) \) (function)

creates the direct sum of two matrix lists.

69.12.11 SMTX.CompleteBasis

\( \text{SMTX.CompleteBasis}(\text{module}, \text{pbasis}) \) (function)

extends the partial basis \text{pbasis} to a basis of the full space by action of \text{module}. It returns whether it succeeded.

69.13 Smash MeatAxe Flags

The following getter routines access internal flags. For each routine, the appropriate setter’s name is prefixed with \text{Set}.

69.13.1 SMTX.Subbasis

\( \text{SMTX.Subbasis}(\text{module}) \) (function)

Basis of a submodule.

69.13.2 SMTX.AlgEl

\( \text{SMTX.AlgEl}(\text{module}) \) (function)

list \([\text{newgens}, \text{coefflist}]\) giving an algebra element used for chopping.

69.13.3 SMTX.AlgElMat

\( \text{SMTX.AlgElMat}(\text{module}) \) (function)

matrix of \text{SMTX.AlgEl} (69.13.2).

69.13.4 SMTX.AlgElCharPol

\( \text{SMTX.AlgElCharPol}(\text{module}) \) (function)

minimal polynomial of \text{SMTX.AlgEl} (69.13.2).
69.13.5 SMTX.AlgElCharPolFac
▶ SMTX.AlgElCharPolFac(module) (function)

uses factor of SMTX.AlgEl (69.13.2).

69.13.6 SMTX.AlgElNullspaceVec
▶ SMTX.AlgElNullspaceVec(module) (function)

nullspace of the matrix evaluated under this factor.

69.13.7 SMTX.AlgElNullspaceDimension
▶ SMTX.AlgElNullspaceDimension(module) (function)

dimension of the nullspace.

69.13.8 SMTX.CentMat
▶ SMTX.CentMat(module) (function)

matrix centralising all generators which is computed as a byproduct of SMTX.AbsoluteIrreducibilityTest (69.12.8).

69.13.9 SMTX.CentMatMinPoly
▶ SMTX.CentMatMinPoly(module) (function)

minimal polynomial of SMTX.CentMat (69.13.8).
Chapter 70

Tables of Marks

The concept of a *table of marks* was introduced by W. Burnside in his book “Theory of Groups of Finite Order”, see [Bur55]. Therefore a table of marks is sometimes called a *Burnside matrix*.

The table of marks of a finite group $G$ is a matrix whose rows and columns are labelled by the conjugacy classes of subgroups of $G$ and where for two subgroups $A$ and $B$ the $(A,B)$-entry is the number of fixed points of $B$ in the transitive action of $G$ on the cosets of $A$ in $G$. So the table of marks characterizes the set of all permutation representations of $G$.

Moreover, the table of marks gives a compact description of the subgroup lattice of $G$, since from the numbers of fixed points the numbers of conjugates of a subgroup $B$ contained in a subgroup $A$ can be derived.

A table of marks of a given group $G$ can be constructed from the subgroup lattice of $G$ (see 70.3). For several groups, the table of marks can be restored from the GAP library of tables of marks (see 70.13).

Given the table of marks of $G$, one can display it (see 70.4) and derive information about $G$ and its Burnside ring from it (see 70.7, 70.8, 70.9). Moreover, tables of marks in GAP provide an easy access to the classes of subgroups of their underlying groups (see 70.10).

70.1 More about Tables of Marks

Let $G$ be a finite group with $n$ conjugacy classes of subgroups $C_1, C_2, \ldots, C_n$ and representatives $H_i \in C_i$, $1 \leq i \leq n$. The *table of marks* of $G$ is defined to be the $n \times n$ matrix $M = (m_{ij})$ where the mark $m_{ij}$ is the number of fixed points of the subgroup $H_j$ in the action of $G$ on the right cosets of $H_i$ in $G$.

Since $H_j$ can only have fixed points if it is contained in a point stabilizer the matrix $M$ is lower triangular if the classes $C_i$ are sorted according to the condition that if $H_i$ is contained in a conjugate of $H_j$ then $i \leq j$.

Moreover, the diagonal entries $m_{ii}$ are nonzero since $m_{ii}$ equals the index of $H_i$ in its normalizer in $G$. Hence $M$ is invertible. Since any transitive action of $G$ is equivalent to an action on the cosets of a subgroup of $G$, one sees that the table of marks completely characterizes the set of all permutation representations of $G$.

The marks $m_{ij}$ have further meanings. If $H_1$ is the trivial subgroup of $G$ then each mark $m_{1j}$ in the first column of $M$ is equal to the index of $H_j$ in $G$ since the trivial subgroup fixes all cosets of $H_j$. If $H_n = G$ then each $m_{nj}$ in the last row of $M$ is equal to 1 since there is only one coset of $G$ in $G$.

In general, $m_{ij}$ equals the number of conjugates of $H_i$ containing $H_j$, multiplied by the index of $H_j$ in its normalizer in $G$. Moreover, the number $c_{ij}$ of conjugates of $H_j$ which are contained in $H_i$ can be
derived from the marks $m_{ij}$ via the formula
\[ c_{ij} = \frac{(m_{ij}m_{1j})}{(m_{i1}m_{jj})} \]

Both the marks $m_{ij}$ and the numbers of subgroups $c_{ij}$ are needed for the functions described in this chapter.

A brief survey of properties of tables of marks and a description of algorithms for the interactive construction of tables of marks using GAP can be found in [Pfe97].

### 70.2 Table of Marks Objects in GAP

A table of marks of a group $G$ in GAP is represented by an immutable (see 12.6) object `tom` in the category `IsTableOfMarks (70.6.2)`, with defining attributes `SubsTom (70.7.1)` and `MarksTom (70.7.1)`. These two attributes encode the matrix of marks in a compressed form. The `SubsTom (70.7.1)` value of `tom` is a list where for each conjugacy class of subgroups the class numbers of its subgroups are stored. These are exactly the positions in the corresponding row of the matrix of marks which have nonzero entries. The marks themselves are stored via the `MarksTom (70.7.1)` value of `tom`, which is a list that contains for each entry in `SubsTom (tom)` the corresponding nonzero value of the table of marks.

It is possible to create table of marks objects that do not store a group, moreover one can create a table of marks object from a matrix of marks (see `TableOfMarks (70.3.1)`). So it may happen that a table of marks object in GAP is in fact not the table of marks of a group. To some extent, the consistency of a table of marks object can be checked (see 70.9), but GAP knows no general way to prove or disprove that a given matrix of nonnegative integers is the matrix of marks for a group. Many functions for tables of marks work well without access to the group –this is one of the arguments why tables of marks are so useful–, but for example normalizers (see `NormalizerTom (70.9.4)`) and derived subgroups (see `DerivedSubgroupTom (70.9.2)`) of subgroups are in general not uniquely determined by the matrix of marks.

GAP tables of marks are assumed to be in lower triangular form, that is, if a subgroup from the conjugacy class corresponding to the $i$-th row is contained in a subgroup from the class corresponding to the $j$-th row then $i \leq j$.

The `MarksTom (70.7.1)` information can be computed from the values of the attributes `NrSubsTom (70.7.2)`, `LengthsTom (70.7.3)`, `OrdersTom (70.7.2)`, and `SubsTom (70.7.1)`. `NrSubsTom (70.7.2)` stores a list containing for each entry in the `SubsTom (70.7.1)` value the corresponding number of conjugates that are contained in a subgroup, `LengthsTom (70.7.3)` a list containing for each conjugacy class of subgroups its length, and `OrdersTom (70.7.2)` a list containing for each class of subgroups their order. So the `MarksTom (70.7.1)` value of `tom` may be missing provided that the values of `NrSubsTom (70.7.2)`, `LengthsTom (70.7.3)`, and `OrdersTom (70.7.2)` are stored in `tom`.

Additional information about a table of marks is needed by some functions. The class numbers of normalizers in $G$ and the number of the derived subgroup of $G$ can be stored via appropriate attributes (see `NormalizersTom (70.9.4)` and `DerivedSubgroupTom (70.9.2)`).

If `tom` stores its group $G$ and a bijection from the rows and columns of the matrix of marks of `tom` to the classes of subgroups of $G$ then clearly normalizers, derived subgroup etc. can be computed from this information. But in general a table of marks need not have access to $G$, for example `tom` might have been constructed from a generic table of marks (see 70.12), or as table of marks of a factor group from a given table of marks (see `FactorGroupTom (70.9.11)`). Access to the group $G$ is provided by
the attribute UnderlyingGroup (70.7.7) if this value is set. Access to the relevant information about
conjugacy classes of subgroups of $G$ – compatible with the ordering of rows and columns of the marks
in tom – is signalled by the filter IsTableOfMarksWithGens (70.10.3).

Several examples in this chapter require the GAP package TomLib (the GAP Library of Tables of
Marks) to be available. If it is not yet loaded then we load it now.

```
gap> LoadPackage( "tomlib" );
true
```

70.3 Constructing Tables of Marks

70.3.1 TableOfMarks (for a group)

```
> TableOfMarks( G )
> TableOfMarks( string )
> TableOfMarks( matrix )
```

In the first form, $G$ must be a finite group, and TableOfMarks constructs the table of
marks of $G$. This computation requires the knowledge of the complete subgroup lattice of $G$
(see LatticeSubgroups (39.20.1)). If the lattice is not yet stored then it will be constructed. This
may take a while if $G$ is large. The result has the IsTableOfMarksWithGens (70.10.3) value true.

In the second form, string must be a string, and TableOfMarks gets the table of marks with
name string from the GAP library (see 70.13). If no table of marks with this name is contained in
the library then fail is returned.

In the third form, matrix must be a matrix or a list of rows describing a lower triangular matrix
where the part above the diagonal is omitted. For such an argument matrix, TableOfMarks returns a
table of marks object (see 70.2) for which matrix is the matrix of marks. Note that not every matrix
(containing only nonnegative integers and having lower triangular shape) describes a table of marks of
a group. Necessary conditions are checked with IsInternallyConsistent (70.9.1) (see 70.9), and
fail is returned if matrix is proved not to describe a matrix of marks; but if TableOfMarks returns
a table of marks object created from a matrix then it may still happen that this object does not describe
the table of marks of a group.

For an overview of operations for table of marks objects, see the introduction to Chapter 70.

```
gap> tom:= TableOfMarks( AlternatingGroup( 5 ) );
TableOfMarks( Alt( [ 1 .. 5 ] ) )
gap> TableOfMarks( "J5" );
fail
gap> a5:= TableOfMarks( "A5" );
TableOfMarks( "A5" )
gap> mat:=
> [ [ 60, 0, 0, 0, 0, 0, 0, 0, 0 ], [ 30, 2, 0, 0, 0, 0, 0, 0, 0 ]],
> [ 20, 0, 2, 0, 0, 0, 0, 0, 0 ], [ 15, 3, 0, 3, 0, 0, 0, 0, 0 ]],
> [ 12, 0, 0, 0, 2, 0, 0, 0, 0 ], [ 10, 2, 1, 0, 0, 1, 0, 0, 0 ]],
> [ 6, 2, 0, 0, 1, 0, 1, 0, 0 ], [ 5, 1, 2, 1, 0, 0, 1, 0, 0 ]],
> [ 1, 1, 1, 1, 1, 1, 1, 1, 1 ] ];
gap> TableOfMarks( mat );
TableOfMarks( <9 classes> )
```
The following `TableOfMarks` methods for a group are installed.

- If the group is known to be cyclic then `TableOfMarks` constructs the table of marks essentially without the group, instead the knowledge about the structure of cyclic groups is used.

- If the lattice of subgroups is already stored in the group then `TableOfMarks` computes the table of marks from the lattice (see `TableOfMarksByLattice (70.3.2)`).

- If the group is known to be solvable then `TableOfMarks` takes the lattice of subgroups (see `LatticeSubgroups (39.20.1)`) of the group –which means that the lattice is computed if it is not yet stored– and then computes the table of marks from it. This method is also accessible via the global function `TableOfMarksByLattice (70.3.2)`.

- If the group doesn’t know its lattice of subgroups or its conjugacy classes of subgroups then the table of marks and the conjugacy classes of subgroups are computed at the same time by the cyclic extension method. Only the table of marks is stored because the conjugacy classes of subgroups or the lattice of subgroups can be easily read off (see `LatticeSubgroupsByTom (70.3.3)`).

Conversely, the lattice of subgroups of a group with known table of marks can be computed using the table of marks, via the function `LatticeSubgroupsByTom (70.3.3)`. This is also installed as a method for `LatticeSubgroups (39.20.1)`.

### 70.3.2 TableOfMarksByLattice

`TableOfMarksByLattice (function)`

This function attempts to compute the table of marks of the group $G$ from the lattice of subgroups of $G$. If the lattice is not yet stored in $G$, it is computed via `LatticeSubgroups (39.20.1)`. This method is installed as a method for `TableOfMarks (70.3.1)` for solvable groups and groups with stored subgroup lattice, and is available as a global variable only in order to provide explicit access to this method.

### 70.3.3 LatticeSubgroupsByTom

`LatticeSubgroupsByTom (function)`

This function computes the lattice of subgroups of $G$ from the table of marks of $G$, using `RepresentativeTom (70.10.4)`.

### 70.4 Printing Tables of Marks

#### 70.4.1 ViewObj (for a table of marks)

This method prints the string "TableOfMarks", followed by –if known– the identifier (see `Identifier (70.7.9)`) or the group of the table of marks enclosed in brackets; if neither group nor identifier are known then just the number of conjugacy classes of subgroups is printed instead.
70.4.2 PrintObj (for a table of marks)

\[ \text{PrintObj}(\text{tom}) \]

The default PrintObj (6.3.5) method for tables of marks does the same as ViewObj (6.3.5), except that PrintObj (6.3.5) is used for the group instead of ViewObj (6.3.5).

70.4.3 Display (for a table of marks)

\[ \text{Display}(\text{tom}[, \text{arec}]) \]

The default Display (6.3.6) method for a table of marks \text{tom} produces a formatted output of the marks in \text{tom}. Each line of output begins with the number of the corresponding class of subgroups. This number is repeated if the output spreads over several pages. The number of columns printed at one time depends on the actual line length, which can be accessed and changed by the function SizeScreen (6.12.1).

An interactive variant of Display (6.3.6) is the \text{Browse} (Browse: Browse) method for tables of marks that is provided by the GAP package \text{Browse}, see Browse (Browse: Browse for tables of marks).

The optional second argument \text{arec} of Display (6.3.6) can be used to change the default style for displaying a table of marks. \text{arec} must be a record, its relevant components are the following.

\begin{description}
  \item[classes] a list of class numbers to select only the rows and columns of the matrix that correspond to this list for printing.
  \item[form] one of the strings "subgroups", "supergroups": in the former case, at position \((i, j)\) of the matrix the number of conjugates of \(H_j\) contained in \(H_i\) is printed, and in the latter case, at position \((i, j)\) the number of conjugates of \(H_i\) which contain \(H_j\) is printed.
\end{description}

\begin{Verbatim}
\texttt{gap> tom} := \texttt{TableOfMarks( "A5" )};
\texttt{gap> Display( tom );}
1:  60
2:  30  2
3:  20 .  2
4:  15  3 .  3
5:  12 . .  2
6:  10  2  1 . .  1
7:   6  2 . .  1 .  1
8:  5  1  2  1 . . .  1
9:  1  1  1  1  1  1  1  1  1  1

\texttt{gap> Display( tom, rec( classes:= [ 1, 2, 3, 4, 8 ] ) );}
1:  60
2:  30  2
3:  20 .  2
4:  15  3 .  3
8:  5  1  2  1  1
\end{Verbatim}
gap> Display( tom, rec( form:= "subgroups" ) );
1: 1
2: 1 1
3: 1 . 1
4: 1 3 . 1
5: 1 . . 1
6: 1 3 1 . 1
7: 1 5 . . 1 .
8: 1 3 4 1 . . 1
9: 1 15 10 5 6 10 6 5 1

gap> Display( tom, rec( form:= "supergroups" ) );
1: 1
2: 15 1
3: 10 . 1
4: 5 1 . 1
5: 6 . . . 1
6: 10 2 1 . . 1
7: 6 2 . . 1 . 1
8: 5 1 2 1 . . . 1
9: 1 1 1 1 1 1 1 1 1

70.5 Sorting Tables of Marks

70.5.1 SortedTom

▷ SortedTom(tom, perm)

SortedTom returns a table of marks where the rows and columns of the table of marks $tom$ are reordered according to the permutation $perm$.

*Note* that in each table of marks in GAP, the matrix of marks is assumed to have lower triangular shape (see 70.2). If the permutation $perm$ does not have this property then the functions for tables of marks might return wrong results when applied to the output of SortedTom.

The returned table of marks has only those attribute values stored that are known for $tom$ and listed in TableOfMarksComponents (70.6.4).

Example

```gap
gap> tom:= TableOfMarksCyclic( 6 );; Display( tom );
1: 6
2: 3 3
3: 2 . 2
4: 1 1 1 1

gap> sorted:= SortedTom( tom, (2,3) );; Display( sorted );
1: 6
2: 2 2
3: 3 . 3
4: 1 1 1 1

gap> wrong:= SortedTom( tom, (1,2) );; Display( wrong );
```
70.5.2 PermutationTom

\[ \texttt{PermutationTom}(\text{tom}) \]

(\text{attribute})

For the table of marks \texttt{tom} of the group \( G \) stored as \texttt{UnderlyingGroup} (70.7.7) value of \texttt{tom}, \texttt{PermutationTom} is a permutation \( \pi \) such that the \( i \)-th conjugacy class of subgroups of \( G \) belongs to the \( \pi^i \)-th column and row of marks in \texttt{tom}.

This attribute value is bound only if \texttt{tom} was obtained from another table of marks by permuting with \texttt{SortedTom} (70.5.1), and there is no default method to compute its value.

The attribute is necessary because the original and the sorted table of marks have the same identifier and the same group, and information computed from the group may depend on the ordering of marks, for example the fusion from the ordinary character table of \( G \) into \texttt{tom}.

\begin{verbatim}
gap> MarksTom( tom )[2];
[ 3, 3 ]
gap> MarksTom( sorted )[2];
[ 2, 2 ]
gap> HasPermutationTom( sorted );
true
gap> PermutationTom( sorted );
(2,3)
\end{verbatim}

70.6 Technical Details about Tables of Marks

70.6.1 InfoTom

\[ \texttt{InfoTom} \]

(info class)

is the info class for computations concerning tables of marks.

70.6.2 IsTableOfMarks

\[ \texttt{IsTableOfMarks}(\text{obj}) \]

(Category)

Each table of marks belongs to this category.

70.6.3 TableOfMarksFamily

\[ \texttt{TableOfMarksFamily} \]

(family)

Each table of marks belongs to this family.
70.6.4 TableOfMarksComponents

▷ TableOfMarksComponents (global variable)

The list `TableOfMarksComponents` is used when a table of marks object is created from a record via `ConvertToTableOfMarks (70.6.5)`. `TableOfMarksComponents` contains at position $2i - 1$ a name of an attribute and at position $2i$ the corresponding attribute getter function.

70.6.5 ConvertToTableOfMarks

▷ `ConvertToTableOfMarks(record)` (function)

`ConvertToTableOfMarks` converts a record with components from `TableOfMarksComponents (70.6.4)` into a table of marks object with the corresponding attributes.

Example

```gap
gap> record:= rec( MarksTom:= [ [ 4 ], [ 2, 2 ], [ 1, 1, 1 ] ],
    > SubsTom:= [ [ 1 ], [ 1, 2 ], [ 1, 2, 3 ] ] );;
gap> ConvertToTableOfMarks( record );;
gap> record;
```

TableOfMarks( <3 classes> )

70.7 Attributes of Tables of Marks

70.7.1 MarksTom

▷ `MarksTom(tom)` (attribute)
▷ `SubsTom(tom)` (attribute)

The matrix of marks (see 70.1) of the table of marks `tom` is stored in a compressed form where zeros are omitted, using the attributes `MarksTom` and `SubsTom`. If $M$ is the square matrix of marks of `tom` (see `MatTom (70.7.10)`) then the `SubsTom` value of `tom` is a list that contains at position $i$ the list of all positions of nonzero entries of the $i$-th row of $M$, and the `MarksTom` value of `tom` is a list that contains at position $i$ the list of the corresponding marks.

`MarksTom` and `SubsTom` are defining attributes of tables of marks (see 70.2). There is no default method for computing the `SubsTom` value, and the default `MarksTom` method needs the values of `NrSubsTom (70.7.2)` and `OrdersTom (70.7.2).

Example

```gap
gap> a5:= TableOfMarks( "A5" );
TableOfMarks( "A5" )
gap> MarksTom( a5 );
[ [ 60 ], [ 30, 2 ], [ 20, 2 ], [ 15, 3, 3 ], [ 12, 2 ],
  [ 10, 2, 1, 1 ], [ 6, 2, 1, 1 ], [ 5, 1, 2, 1, 1 ],
  [ 1, 1, 1, 1, 1, 1, 1, 1, 1 ] ]
gap> SubsTom( a5 );
[ [ 1 ], [ 1, 2 ], [ 1, 3 ], [ 1, 2, 4 ], [ 1, 5 ], [ 1, 2, 3, 6 ],
  [ 1, 2, 5, 7 ], [ 1, 2, 3, 4, 8 ], [ 1, 2, 3, 4, 5, 6, 7, 8, 9 ] ]
```
70.7.2 NrSubsTom

\texttt{NrSubsTom(tom)} \hspace{1cm} (attribute)
\texttt{OrdersTom(tom)} \hspace{1cm} (attribute)

Instead of storing the marks (see \texttt{MarksTom (70.7.1)}) of the table of marks \texttt{tom} one can use a matrix which contains at position \((i, j)\) the number of subgroups of conjugacy class \(j\) that are contained in one member of the conjugacy class \(i\). These values are stored in the \texttt{NrSubsTom} value in the same way as the marks in the \texttt{MarksTom (70.7.1)} value.

\texttt{OrdersTom} returns a list that contains at position \(i\) the order of a representative of the \(i\)-th conjugacy class of subgroups of \(tom\).

One can compute the \texttt{NrSubsTom} and \texttt{OrdersTom} values from the \texttt{MarksTom (70.7.1)} value of \(tom\) and vice versa.

\begin{verbatim}
gap> NrSubsTom( a5 );
[ [ 1 ], [ 1, 1 ], [ 1, 1 ], [ 1, 3, 1 ], [ 1, 1 ], [ 1, 3, 1, 1 ],
  [ 1, 5, 1, 1 ], [ 1, 3, 4, 1, 1 ], [ 1, 15, 10, 5, 6, 10, 6, 5, 1 ]

gap> OrdersTom( a5 );
[ 1, 2, 3, 4, 5, 6, 10, 12, 60 ]
\end{verbatim}

70.7.3 LengthsTom

\texttt{LengthsTom(tom)} \hspace{1cm} (attribute)

For a table of marks \texttt{tom}, \texttt{LengthsTom} returns a list of the lengths of the conjugacy classes of subgroups.

\begin{verbatim}
gap> LengthsTom( a5 );
[ 1, 15, 10, 5, 6, 10, 6, 5, 1 ]
\end{verbatim}

70.7.4 ClassTypesTom

\texttt{ClassTypesTom(tom)} \hspace{1cm} (attribute)

\texttt{ClassTypesTom} distinguishes isomorphism types of the classes of subgroups of the table of marks \texttt{tom} as far as this is possible from the \texttt{SubsTom (70.7.1)} and \texttt{MarksTom (70.7.1)} values of \texttt{tom}.

Two subgroups are clearly not isomorphic if they have different orders. Moreover, isomorphic subgroups must contain the same number of subgroups of each type.

Each type is represented by a positive integer. \texttt{ClassTypesTom} returns the list which contains for each class of subgroups its corresponding type.

\begin{verbatim}
gap> a6:= TableOfMarks( "A6" );;
gap> ClassTypesTom( a6 );
[ 1, 2, 3, 3, 4, 5, 6, 6, 7, 7, 8, 9, 10, 11, 11, 12, 13, 13, 14, 15,
  15, 16 ]
\end{verbatim}
70.7.5 ClassNamesTom

ClassNamesTom constructs generic names for the conjugacy classes of subgroups of the table of marks \texttt{tom}. In general, the generic name of a class of non-cyclic subgroups consists of three parts and has the form "(o)_(t)l", where o indicates the order of the subgroup, t is a number that distinguishes different types of subgroups of the same order, and l is a letter that distinguishes classes of subgroups of the same type and order. The type of a subgroup is determined by the numbers of its subgroups of other types (see \texttt{ClassTypesTom (70.7.4)}). This is slightly weaker than isomorphism.

The letter is omitted if there is only one class of subgroups of that order and type, and the type is omitted if there is only one class of that order. Moreover, the braces \{\} around the type are omitted if the type number has only one digit.

For classes of cyclic subgroups, the parentheses round the order and the type are omitted. Hence the most general form of their generic names is "o, l". Again, the letter is omitted if there is only one class of cyclic subgroups of that order.

**Example**

```gap
gap> ClassNamesTom( a6 );
[ "1", "2", "3a", "3b", "5", "4", "(4)_2a", "(4)_2b", "(6)a", "(6)b", "(8)", "(9)", "(10)", "(12)a", "(12)b", "(18)", "(24)a", "(24)b", "(36)", "(60)a", "(60)b", "(360)" ]
```

70.7.6 FusionsTom

FusionsTom is a list of fusions into other tables of marks. Each fusion is a list of length two, the first entry being the \texttt{Identifier (70.7.9)} value of the image table, the second entry being the list of images of the class positions of \texttt{tom} in the image table.

This attribute is mainly used for tables of marks in the \texttt{GAP} library (see 70.13).

**Example**

```gap
gap> fus:= FusionsTom( a6 );
gap> fus[1];
[ "L3(4)",
  [ 1, 2, 3, 3, 14, 5, 9, 7, 15, 15, 24, 26, 27, 32, 33, 52, 57, 55, 63, 73, 77, 90 ] ]
```

70.7.7 UnderlyingGroup (for tables of marks)

UnderlyingGroup is used to access an underlying group that is stored on the table of marks \texttt{tom}. There is no default method to compute an underlying group if it is not stored.

**Example**

```gap
gap> UnderlyingGroup( a6 );
Group([ (1,2)(3,4), (1,2,4,5)(3,6) ])
```
70.7.8 IdempotentsTom

\[ \text{IdempotentsTom}(\text{tom}) \]  
\[ \text{IdempotentsTomInfo}(\text{tom}) \]

IdempotentsTom encodes the idempotents of the integral Burnside ring described by the table of marks \( \text{tom} \). The return value is a list \( l \) of positive integers such that each row vector describing a primitive idempotent has value 1 at all positions with the same entry in \( l \), and 0 at all other positions.

According to A. Dress [Dre69] (see also [Pfe97]), these idempotents correspond to the classes of perfect subgroups, and each such idempotent is the characteristic function of all those subgroups that arise by cyclic extension from the corresponding perfect subgroup (see CyclicExtensionsTom (70.9.7)).

IdempotentsTomInfo returns a record with components fixpointvectors and primidems, both bound to lists. The \( i \)-th entry of the fixpointvectors list is the \( 0-1 \)-vector describing the \( i \)-th primitive idempotent, and the \( i \)-th entry of primidems is the decomposition of this idempotent in the rows of \( \text{tom} \).

Example

```gap
gap> IdempotentsTom( a5 );
[ 1, 1, 1, 1, 1, 1, 1, 1, 9 ]
gap> IdempotentsTomInfo( a5 );
rec(
    fixpointvectors := [ [ 1, 1, 1, 1, 1, 1, 1, 1, 0 ],
                        [ 0, 0, 0, 0, 0, 0, 0, 0, 1 ] ],
    primidems := [ [ 1, -2, -1, 0, 0, 1, 1, 1 ],
                    [ -1, 2, 1, 0, -1, -1, -1, 1 ] ] )
```

70.7.9 Identifier (for tables of marks)

\[ \text{Identifier}(\text{tom}) \]

The identifier of a table of marks \( \text{tom} \) is a string. It is used for printing the table of marks (see 70.4) and in fusions between tables of marks (see FusionTom (70.7.6)).

If \( \text{tom} \) is a table of marks from the GAP library of tables of marks (see 70.13) then it has an identifier, and if \( \text{tom} \) was constructed from a group with Name (12.8.2) then this name is chosen as Identifier value. There is no default method to compute an identifier in all other cases.

Example

```gap
gap> Identifier( a5 );
"A5"
```

70.7.10 MatTom

\[ \text{MatTom}(\text{tom}) \]

MatTom returns the square matrix of marks (see 70.1) of the table of marks \( \text{tom} \) which is stored in a compressed form using the attributes MarksTom (70.7.1) and SubsTom (70.7.1). This may need substantially more space than the values of MarksTom (70.7.1) and SubsTom (70.7.1).
Example

```
gap> MatTom( a5 );
[ [ 60, 0, 0, 0, 0, 0, 0, 0, 0 ], [ 30, 2, 0, 0, 0, 0, 0, 0, 0 ],
  [ 20, 2, 0, 0, 0, 0, 0, 0, 0 ], [ 15, 3, 0, 3, 0, 0, 0, 0, 0 ],
  [ 12, 0, 0, 0, 0, 0, 0, 0, 0 ], [ 10, 2, 1, 0, 0, 1, 0, 0, 0 ],
  [ 6, 2, 0, 0, 1, 0, 1, 0, 0 ], [ 5, 1, 2, 1, 0, 0, 1, 0, 0 ],
  [ 1, 1, 1, 1, 1, 1, 1, 1, 1 ] ]
```

70.7.11 MoebiusTom

\texttt{MoebiusTom(tom)}

MoebiusTom computes the Möbius values both of the subgroup lattice of the group \( G \) with table of marks \( tom \) and of the poset of conjugacy classes of subgroups of \( G \). It returns a record where the component \texttt{mu} contains the Möbius values of the subgroup lattice, and the component \texttt{nu} contains the Möbius values of the poset.

Moreover, according to an observation of Isaacs et al. (see [HIÖ89], [Pah93]), the values on the subgroup lattice often can be derived from those of the poset of conjugacy classes. These “expected values” are returned in the component \texttt{ex}, and the list of numbers of those subgroups where the expected value does not coincide with the actual value are returned in the component \texttt{hyp}. For the computation of these values, the position of the derived subgroup of \( G \) is needed (see \texttt{DerivedSubgroupTom (70.7.7)}). If it is not uniquely determined then the result does not have the components \texttt{ex} and \texttt{hyp}.

Example

```
gap> MoebiusTom( a5 );
rec( ex := [ -60, 4, 2,,, -1, -1, -1, 1 ],
    mu := [ -60, 4, 2,,, -1, -1, -1, 1 ],
    nu := [ -1, 2, 1,,, -1, -1, -1, 1 ] )
```

70.7.12 WeightsTom

\texttt{WeightsTom(tom)}

WeightsTom extracts the \textit{weights} from the table of marks \( tom \), i.e., the diagonal entries of the matrix of marks (see \texttt{MarksTom (70.7.7)}), indicating the index of a subgroup in its normalizer.

Example

```
gap> wt:= WeightsTom( a5 );
[ 60, 2, 2, 3, 2, 1, 1, 1 ]
```

This information may be used to obtain the numbers of conjugate supergroups from the marks.
Example

```gap
gap> marks:= MarksTom( a5 );;
gap> List( [ 1 .. 9 ], x -> marks[x] / wt[x] );
[ [ 1 ], [ 15, 1 ], [ 10, 1 ], [ 5, 1, 1 ], [ 6, 1 ], [ 10, 2, 1, 1 ],
  [ 6, 2, 1, 1 ], [ 5, 1, 2, 1, 1 ], [ 1, 1, 1, 1, 1, 1, 1, 1, 1 ] ]
```

### 70.8 Properties of Tables of Marks

For a table of marks \( \text{tom} \) of a group \( G \), the following properties have the same meaning as the corresponding properties for \( G \). Additionally, if a positive integer \( \text{sub} \) is given as the second argument then the value of the corresponding property for the \( \text{sub} \)-th class of subgroups of \( \text{tom} \) is returned.

#### 70.8.1 IsAbelianTom

\[
\text{IsAbelianTom}(\text{tom}[\text{sub}])
\]

\[
\text{IsCyclicTom}(\text{tom}[\text{sub}])
\]

\[
\text{IsNilpotentTom}(\text{tom}[\text{sub}])
\]

\[
\text{IsPerfectTom}(\text{tom}[\text{sub}])
\]

\[
\text{IsSolvableTom}(\text{tom}[\text{sub}])
\]

Example

```gap
gap> tom:= TableOfMarks( "A5" );;
gap> IsAbelianTom( tom ); IsPerfectTom( tom );
false  true
gap> IsAbelianTom( tom, 3 ); IsNilpotentTom( tom, 7 );
true  false
gap> IsPerfectTom( tom, 7 ); IsSolvableTom( tom, 7 );
false  true
gap> for i in [ 1 .. 6 ] do
> Print( i, " : ", IsCyclicTom( a5, i ), " ");
> od;
1: true 2: true 3: true 4: false 5: true 6: false
```

### 70.9 Other Operations for Tables of Marks

#### 70.9.1 IsInternallyConsistent (for tables of marks)

\[
\text{IsInternallyConsistent}(\text{tom})
\]

For a table of marks \( \text{tom} \). \( \text{IsInternallyConsistent} \) decomposes all tensor products of rows of \( \text{tom} \). It returns \text{true} if all decomposition numbers are nonnegative integers, and \text{false} otherwise. This provides a strong consistency check for a table of marks.
70.9.2 DerivedSubgroupTom

DerivedSubgroupTom(tom, sub)

For a table of marks tom and a positive integer sub, DerivedSubgroupTom returns either a positive integer i or a list l of positive integers. In the former case, the result means that the derived subgroups of the subgroups in the sub-th class of tom lie in the i-th class. In the latter case, the class of the derived subgroups could not be uniquely determined, and the position of the class of derived subgroups is an entry of l.

Values computed with DerivedSubgroupTom are stored using the attribute DerivedSubgroupsTomPossible (70.9.3).

DerivedSubgroupsTom is just the list of DerivedSubgroupTom values for all values of sub.

70.9.3 DerivedSubgroupsTomPossible

DerivedSubgroupsTomPossible(tom)

Let tom be a table of marks. The value of the attribute DerivedSubgroupsTomPossible is a list in which the value at position i— if bound— is a positive integer or a list; the meaning of the entry is the same as in DerivedSubgroupTom (70.9.2).

If the value of the attribute DerivedSubgroupsTomUnique is known for tom then it is a list of positive integers, the value at position i being the position of the class of derived subgroups of the i-th class of subgroups in tom.

The derived subgroups are in general not uniquely determined by the table of marks if no UnderlyingGroup (70.7.7) value is stored, so there is no default method for DerivedSubgroupsTomUnique. But in some cases the derived subgroups are explicitly set when the table of marks is constructed. In this case, DerivedSubgroupTom (70.9.2) does not set values in the DerivedSubgroupsTomPossible list.

The DerivedSubgroupsTomUnique value is automatically set when the last missing unique value is entered in the DerivedSubgroupsTomPossible list by DerivedSubgroupTom (70.9.2).

70.9.4 NormalizerTom

NormalizerTom(tom, sub)

Let tom be the table of marks of a group G, say. NormalizerTom tries to find the conjugacy class of the normalizer N in G of a subgroup U in the sub-th class of tom. The return value is either the list of class numbers of those subgroups that have the right size and contain the subgroup and all subgroups that clearly contain it as a normal subgroup, or the class number of the normalizer if it is uniquely determined by these conditions. If tom knows the subgroup lattice of G (see IsTableOfMarksWithGens (70.10.3)) then all normalizers are uniquely determined. NormalizerTom should never return an empty list.

NormalizersTom returns the list of positions of the classes of normalizers of subgroups in tom. In addition to the criteria for a single class of subgroup used by NormalizerTom, the approximations of
normalizers for several classes are used and thus \texttt{NormalizersTom} may return better approximations than \texttt{NormalizerTom}.

\begin{verbatim}
gap> NormalizerTom( a5, 4 );
8
gap> NormalizersTom( a5 );
[ 9, 4, 6, 8, 7, 6, 7, 8, 9 ]
\end{verbatim}

The example shows that a subgroup with class number 4 in \texttt{A5} (which is a Kleinian four group) is normalized by a subgroup in class 8. This class contains the subgroups of \texttt{A5} which are isomorphic to \texttt{A4}.

**70.9.5 ContainedTom**

\[
\text{ContainedTom}(\text{tom}, \text{sub1}, \text{sub2})
\]

\texttt{ContainedTom} returns the number of subgroups in class \texttt{sub1} of the table of marks \texttt{tom} that are contained in one fixed member of the class \texttt{sub2}.

\begin{verbatim}
gap> ContainedTom( a5, 3, 5 ); ContainedTom( a5, 3, 8 );
0 4
\end{verbatim}

**70.9.6 ContainingTom**

\[
\text{ContainingTom}(\text{tom}, \text{sub1}, \text{sub2})
\]

\texttt{ContainingTom} returns the number of subgroups in class \texttt{sub2} of the table of marks \texttt{tom} that contain one fixed member of the class \texttt{sub1}.

\begin{verbatim}
gap> ContainingTom( a5, 3, 5 ); ContainingTom( a5, 3, 8 );
0 2
\end{verbatim}

**70.9.7 CyclicExtensionsTom (for a prime)**

\[
\text{CyclicExtensionsTom}(\text{tom}, \text{p})
\]

\texttt{CyclicExtensionsTom} (\texttt{tom}[, \texttt{list}]) returns the classes of this equivalence relation.

According to A. Dress [Dre69], two columns of the table of marks \texttt{tom} are equal modulo the prime \texttt{p} if and only if the corresponding subgroups are connected by a chain of normal extensions of order \texttt{p}.

Called with \texttt{tom} and \texttt{p}, \texttt{CyclicExtensionsTom} returns the classes of this equivalence relation.

In the second form, \texttt{list} must be a list of primes, and the return value is the list of classes of the relation obtained by considering chains of normal extensions of prime order where all primes are in \texttt{list}. The default value for \texttt{list} is the set of prime divisors of the order of the group of \texttt{tom}.

(This information is not used by \texttt{NormalizerTom} (70.9.4) although it might give additional restrictions in the search of normalizers.)
70.9.8  DecomposedFixedPointVector

\[ \text{DecomposedFixedPointVector}(\text{tom}, \text{fix}) \]

Let \( \text{tom} \) be the table of marks of the group \( G \), say, and let \( \text{fix} \) be a vector of fixed point numbers w.r.t. an action of \( G \), i.e., a vector which contains for each class of subgroups the number of fixed points under the given action. \text{DecomposedFixedPointVector} returns the decomposition of \( \text{fix} \) into rows of the table of marks. This decomposition corresponds to a decomposition of the action into transitive constituents. Trailing zeros in \( \text{fix} \) may be omitted.

\[ \text{Example} \]

\text{gap> DecomposedFixedPointVector(a5, [16, 4, 1, 0, 1, 1, 1]);}
\[ [0, 0, 0, 0, 0, 1, 1] \]

The vector \( \text{fix} \) may be any vector of integers. The resulting decomposition, however, will not be integral, in general.

\[ \text{Example} \]

\text{gap> DecomposedFixedPointVector(a5, [0, 0, 0, 0, 1, 1]);}
\[ [2/5, -1, -1/2, 0, 1/2, 1] \]

70.9.9  EulerianFunctionByTom

\[ \text{EulerianFunctionByTom}(\text{tom}, n[, \text{sub}]) \]

Called with two arguments, \text{EulerianFunctionByTom} computes the Eulerian function (see \text{EulerianFunction} (39.16.3)) of the underlying group \( G \) of the table of marks \( \text{tom} \), that is, the number of \( n \)-tuples of elements in \( G \) that generate \( G \). If the optional argument \( \text{sub} \) is given then \text{EulerianFunctionByTom} computes the Eulerian function of each subgroup in the \( \text{sub} \)-th class of subgroups of \( \text{tom} \).

For a group \( G \) whose table of marks is known, \text{EulerianFunctionByTom} is installed as a method for \text{EulerianFunction} (39.16.3).

\[ \text{Example} \]

\text{gap> EulerianFunctionByTom(a5, 2);}
\[ 2280 \]
\text{gap> EulerianFunctionByTom(a5, 3);}
\[ 200160 \]
\text{gap> EulerianFunctionByTom(a5, 2, 3);}
\[ 8 \]

70.9.10  IntersectionsTom

\[ \text{IntersectionsTom}(\text{tom}, \text{sub1}, \text{sub2}) \]

\[ \text{Example} \]

\text{CyclicExtensionsTom(a5, 2);}
The intersections of the groups in the \texttt{sub1}-th conjugacy class of subgroups of the table of marks \texttt{tom} with the groups in the \texttt{sub2}-th conjugacy classes of subgroups of \texttt{tom} are determined up to conjugacy by the decomposition of the tensor product of their rows of marks. \texttt{IntersectionsTom} returns a list \( l \) that describes this decomposition. The \( i \)-th entry in \( l \) is the multiplicity of groups in the \( i \)-th conjugacy class as an intersection.

\begin{verbatim}
gap> IntersectionsTom( a5, 8, 8 ); [ 0, 0, 1, 0, 0, 0, 0, 1 ]
\end{verbatim}

Any two subgroups of class number 8 (\( A_4 \)) of \( A_5 \) are either equal and their intersection has again class number 8, or their intersection has class number 3, and is a cyclic subgroup of order 3.

### 70.9.11 FactorGroupTom

\begin{verbatim}
\triangleright \texttt{FactorGroupTom(\,tom,\,n)} \hspace{1cm} \text{(operation)}
\end{verbatim}

For a table of marks \texttt{tom} of the group \( G \), say, and the normal subgroup \( N \) of \( G \) corresponding to the \( n \)-th class of subgroups of \texttt{tom}, \texttt{FactorGroupTom} returns the table of marks of the factor group \( G/N \).

\begin{verbatim}
gap> s4:= TableOfMarks( SymmetricGroup( 4 ) );
TableOfMarks( Sym( [ 1 .. 4 ] ) )
gap> LengthsTom( s4 );
[ 1, 3, 6, 4, 1, 3, 3, 4, 3, 1, 1 ]
gap> OrdersTom( s4 );
[ 1, 2, 2, 3, 4, 4, 4, 6, 8, 12, 24 ]
gap> s3:= FactorGroupTom( s4, 5 );
TableOfMarks( Group([ f1, f2 ]) )
gap> Display( s3 );
1: 6
2: 3 1
3: 2 . 2
4: 1 1 1 1
\end{verbatim}

### 70.9.12 MaximalSubgroupsTom

\begin{verbatim}
\triangleright \texttt{MaximalSubgroupsTom(\,tom[,\,sub]\,)} \hspace{1cm} \text{(attribute)}
\end{verbatim}

Called with a table of marks \texttt{tom}, \texttt{MaximalSubgroupsTom} returns a list of length two, the first entry being the list of positions of the classes of maximal subgroups of the whole group of \texttt{tom}, the second entry being the list of class lengths of these groups.

Called with a table of marks \texttt{tom} and a position \texttt{sub}, the same information for the \texttt{sub}-th class of subgroups is returned.

\begin{verbatim}
gap> MaximalSubgroupsTom( a5 );
[ [ 10, 9, 8 ], [ 1, 3, 4 ] ]
gap> MaximalSubgroupsTom( a5, 10 );
[ [ 5, 4 ], [ 1, 4 ] ]
\end{verbatim}
70.9.13 MinimalSupergroupsTom

\texttt{MinimalSupergroupsTom(tom, sub)}

For a table of marks \texttt{tom}, \texttt{MinimalSupergroupsTom} returns a list of length two, the first entry being the list of positions of the classes containing the minimal supergroups of the groups in the \texttt{sub}-th class of subgroups of \texttt{tom}, the second entry being the list of class lengths of these groups.

\textbf{Example}

\begin{verbatim}
gap> MinimalSupergroupsTom( s4, 5 );
[ [ 9, 10 ], [ 3, 1 ] ]
\end{verbatim}

70.10 Accessing Subgroups via Tables of Marks

Let \texttt{tom} be the table of marks of the group \( G \), and assume that \texttt{tom} has access to \( G \) via the \texttt{UnderlyingGroup (70.7.7)} value. Then it makes sense to use \texttt{tom} and its ordering of conjugacy classes of subgroups of \( G \) for storing information for constructing representatives of these classes. The group \( G \) is in general not sufficient for this, \texttt{tom} needs more information; this is available if and only if the \texttt{IsTableOfMarksWithGens (70.10.3)} value of \texttt{tom} is true. In this case, \texttt{RepresentativeTom (70.10.4)} can be used to get a subgroup of the \( i \)-th class, for all \( i \).

\textsc{GAP} provides two different possibilities to store generators of the representatives of classes of subgroups. The first is implemented by the attribute \texttt{GeneratorsSubgroupsTom (70.10.1)}, which uses explicit generators of the subgroups. The second, more general, possibility is implemented by the attribute \texttt{StraightLineProgramsTom (70.10.2)}, which encodes the generators as straight line programs (see 37.8) that evaluate to the generators in question when applied to \textit{standard generators} of \( G \). This means that on the one hand, standard generators of \( G \) must be known in order to use \texttt{StraightLineProgramsTom (70.10.2)}. On the other hand, the straight line programs allow one to compute easily generators not only of a subgroup \( U \) of \( G \) but also generators of the image of \( U \) in any representation of \( G \), provided that one knows standard generators of the image of \( G \) under this representation. See the manual of the package \texttt{TomLib} for details and an example.

70.10.1 GeneratorsSubgroupsTom

\texttt{GeneratorsSubgroupsTom(tom)}

Let \texttt{tom} be a table of marks with \texttt{IsTableOfMarksWithGens (70.10.3)} value \texttt{true}. Then \texttt{GeneratorsSubgroupsTom} returns a list of length two, the first entry being a list \( l \) of elements of the group stored as \texttt{UnderlyingGroup (70.7.7)} value of \texttt{tom}, the second entry being a list that contains at position \( i \) a list of positions in \( l \) of generators of a representative of a subgroup in class \( i \).

The \texttt{GeneratorsSubgroupsTom} value is known for all tables of marks that have been computed with \texttt{TableOfMarks (70.3.1)} from a group, and there is a method to compute the value for a table of marks that admits \texttt{RepresentativeTom (70.10.4)}.

70.10.2 StraightLineProgramsTom

\texttt{StraightLineProgramsTom(tom)}

\textsc{GAP} provides two different possibilities to store generators of the representatives of classes of subgroups. The first is implemented by the attribute \texttt{GeneratorsSubgroupsTom (70.10.1)}, which uses explicit generators of the subgroups. The second, more general, possibility is implemented by the attribute \texttt{StraightLineProgramsTom (70.10.2)}, which encodes the generators as straight line programs (see 37.8) that evaluate to the generators in question when applied to \textit{standard generators} of \( G \). This means that on the one hand, standard generators of \( G \) must be known in order to use \texttt{StraightLineProgramsTom (70.10.2)}. On the other hand, the straight line programs allow one to compute easily generators not only of a subgroup \( U \) of \( G \) but also generators of the image of \( U \) in any representation of \( G \), provided that one knows standard generators of the image of \( G \) under this representation. See the manual of the package \texttt{TomLib} for details and an example.
For a table of marks \( \text{tom} \) with \text{IsTableOfMarksWithGens} \ (70.10.3) \ value \text{true}, \text{StraightLineProgramsTom} \ returns a list that contains at position \( i \) either a list of straight line programs or a straight line program (see 37.8), encoding the generators of a representative of the \( i \)-th conjugacy class of subgroups of \text{UnderlyingGroup( \text{tom})}; in the former case, each straight line program returns a generator, in the latter case, the program returns the list of generators.

There is no default method to compute the \text{StraightLineProgramsTom} \ value of a table of marks if they are not yet stored. The value is known for all tables of marks that belong to the GAP library of tables of marks (see 70.13).

### 70.10.3 \text{IsTableOfMarksWithGens}

\[ \text{IsTableOfMarksWithGens(\text{tom})} \]

This filter shall express the union of the filters \text{IsTableOfMarks} and \text{HasStraightLineProgramsTom} and \text{IsTableOfMarks} and \text{HasGeneratorsSubgroupsTom}.

If a table of marks \( \text{tom} \) has this filter set then \( \text{tom} \) can be asked to compute information that is in general not uniquely determined by a table of marks, for example the positions of derived subgroups or normalizers of subgroups (see \text{DerivedSubgroupTom} \ (70.9.2), \text{NormalizerTom} \ (70.9.4)).

```gap
Example

gap> a5:= TableOfMarks( "A5" );; IsTableOfMarksWithGens( a5 );
true

\text{HasGeneratorsSubgroupsTom( a5 ); HasStraightLineProgramsTom( a5 );}
false

\text{true}

\text{IsTableOfMarksWithGens( alt5 );}
true
false

\text{HasGeneratorsSubgroupsTom(al55); HasStraightLineProgramsTom(al55);}
true
false

\text{progs:= StraightLineProgramsTom( a5 );}
\text{OrdersTom( a5 );}
\text{[ 1, 2, 3, 4, 5, 6, 10, 12, 60 ]}

\text{IsCyclicTom( a5, 4 );}
false

\text{Length( progs[4] );}
2

\text{progs[4][1];}
<\text{straight line program}>

\text{# first generator of an el. ab group of order 4:}
\text{Display( progs[4][1] );}
\text{# input:}
r:= [ g1, g2 ];
\text{# program:}
r[3]:= r[2]*r[1];
r[4]:= r[3]*r[2]^(-1)*r[1]*r[3]*r[2]^(-1)*r[1]*r[2];
\text{# return value:}
r[4]

\text{gap} x:= [ [ Z(2)^0, 0*Z(2) ], [ Z(2)^2, Z(2)^0 ] ];
\text{gap} y:= [ [ Z(2)^2, Z(2)^0 ], [ 0*Z(2), Z(2)^2^2 ] ];
\text{gap} resi:= ResultOfStraightLineProgram( progs[4][1], [ x, y ] );
```
\textbf{70.10.4 RepresentativeTom}

\texttt{RepresentativeTom}(tom, sub) \hspace{1cm} (operation)
\texttt{RepresentativeTomByGenerators}(tom, sub, gens) \hspace{1cm} (operation)
\texttt{RepresentativeTomByGeneratorsNC}(tom, sub, gens) \hspace{1cm} (operation)

Let \texttt{tom} be a table of marks with \texttt{IsTableOfMarksWithGens (70.10.3)} value \texttt{true}, and \texttt{sub} a positive integer. \texttt{RepresentativeTom} returns a representative of the \texttt{sub}-th conjugacy class of subgroups of \texttt{tom}.

If the attribute \texttt{StraightLineProgramsTom (70.10.2)} is set in \texttt{tom} then methods for the operations \texttt{RepresentativeTomByGenerators} and \texttt{RepresentativeTomByGeneratorsNC} are available, which return a representative of the \texttt{sub}-th conjugacy class of subgroups of \texttt{tom}, as a subgroup of the group generated by \texttt{gens}. This means that the standard generators of \texttt{tom} are replaced by \texttt{gens}.

\texttt{RepresentativeTomByGenerators} checks whether mapping the standard generators of \texttt{tom} to \texttt{gens} extends to a group isomorphism, and returns \texttt{fail} if not. \texttt{RepresentativeTomByGeneratorsNC} omits all checks. So \texttt{RepresentativeTomByGenerators} is thought mainly for debugging purposes; note that when several representatives are constructed, it is cheaper to construct (and check) the isomorphism once, and to map the groups returned by \texttt{RepresentativeTom} under this isomorphism. The idea behind \texttt{RepresentativeTomByGeneratorsNC}, however, is to avoid the overhead of using isomorphisms when \texttt{gens} are known to be standard generators. In order to proceed like this, the attribute \texttt{StraightLineProgramsTom (70.10.2)} is needed.

Example
\begin{verbatim}
> RepresentativeTom( a5, 4 );
Group([ (2,3)(4,5), (2,4)(3,5) ])
\end{verbatim}

\textbf{70.11 The Interface between Tables of Marks and Character Tables}

The following examples require the GAP Character Table Library to be available. If it is not yet loaded then we load it now.

Example
\begin{verbatim}
> LoadPackage( "ctbllib" );
true
\end{verbatim}
70.11.1 FusionCharTableTom

\begin{verbatim}
▷ FusionCharTableTom(tbl, tom)  (operation)
▷ PossibleFusionsCharTableTom(tbl, tom[, options])  (operation)
\end{verbatim}

Let tbl be the ordinary character table of the group \( G \), say, and tom the table of marks of \( G \). FusionCharTableTom determines the fusion of the classes of elements from tbl to the classes of cyclic subgroups on tom, that is, a list that contains at position \( i \) the position of the class of cyclic subgroups in tom that are generated by elements in the \( i \)-th conjugacy class of elements in tbl.

Three cases are handled differently.

1. The fusion is explicitly stored on tbl. Then nothing has to be done. This happens only if both tbl and tom are tables from the GAP library (see 70.13 and the manual of the GAP Character Table Library).

2. The UnderlyingGroup (70.7.7) values of tbl and tom are known and equal. Then the group is used to compute the fusion.

3. There is neither fusion nor group information available. In this case only necessary conditions can be checked, and if they are not sufficient to determine the fusion uniquely then fail is returned by FusionCharTableTom.

PossibleFusionsCharTableTom computes the list of possible fusions from tbl to tom, according to the criteria that have been checked. So if FusionCharTableTom returns a unique fusion then the list returned by PossibleFusionsCharTableTom for the same arguments contains exactly this fusion, and if FusionCharTableTom returns fail then the length of this list is different from 1.

The optional argument options must be a record that may have the following components.

\begin{itemize}
  \item fusionmap
    a parametrized map which is an approximation of the desired map,
  \item quick
    a Boolean; if true then as soon as only one possibility remains this possibility is returned immediately; the default value is false.
\end{itemize}

Example

\begin{verbatim}
gap> a5c := CharacterTable( "A5" );;
gap> fus:= FusionCharTableTom( a5c, a5 );
[ 1, 2, 3, 5, 5 ]
\end{verbatim}

70.11.2 PermCharsTom (via fusion map)

\begin{verbatim}
▷ PermCharsTom(fus, tom)  (operation)
▷ PermCharsTom(tbl, tom)  (operation)
\end{verbatim}

PermCharsTom returns the list of transitive permutation characters from the table of marks tom. In the first form, fus must be the fusion map from the ordinary character table of the group of tom to tom (see FusionCharTableTom (70.11.1)). In the second form, tbl must be the character table of the group of which tom is the table of marks. If the fusion map is not uniquely determined (see FusionCharTableTom (70.11.1)) then fail is returned.
If the fusion map $f_{\text{us}}$ is given as first argument then each transitive permutation character is represented by its values list. If the character table $\text{tbl}$ is given then the permutation characters are class function objects (see Chapter 72).

```gap
gap> PermCharsTom( a5c, a5 );
[ Character( CharacterTable( "A5" ), [ 60, 0, 0, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 30, 2, 0, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 20, 0, 2, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 15, 3, 0, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 12, 0, 0, 2, 2 ] ),
  Character( CharacterTable( "A5" ), [ 10, 2, 1, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 6, 2, 0, 1, 1 ] ),
  Character( CharacterTable( "A5" ), [ 5, 1, 2, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ) ]
gap> PermCharsTom( fus, a5 )[1];
[ 60, 0, 0, 0, 0 ]
```

### 70.12 Generic Construction of Tables of Marks

The following three operations construct a table of marks only from the data given, i.e., without underlying group.

#### 70.12.1 TableOfMarksCyclic

`TableOfMarksCyclic(n)`

`TableOfMarksCyclic` returns the table of marks of the cyclic group of order $n$.

A cyclic group of order $n$ has as its subgroups for each divisor $d$ of $n$ a cyclic subgroup of order $d$.

```gap
gap> Display( TableOfMarksCyclic( 6 ) );
1: 6
2: 3 3
3: 2 . 2
4: 1 1 1 1
```

#### 70.12.2 TableOfMarksDihedral

`TableOfMarksDihedral(n)`

`TableOfMarksDihedral` returns the table of marks of the dihedral group of order $m$.

For each divisor $d$ of $m$, a dihedral group of order $m = 2n$ contains subgroups of order $d$ according to the following rule. If $d$ is odd and divides $n$ then there is only one cyclic subgroup of order $d$. If $d$ is even and divides $n$ then there are a cyclic subgroup of order $d$ and two classes of dihedral subgroups of order $d$ (which are cyclic, too, in the case $d = 2$, see the example below). Otherwise (i.e., if $d$ does not divide $n$) there is just one class of dihedral subgroups of order $d$. 

```gap
gap> Display( TableOfMarksDihedral( 6 ) );
1: 6
2: 3 3
3: 2 . 2
4: 1 1 1 1
```
Example

gap> Display( TableOfMarksDihedral( 12 ) );
1: 12
2: 6 6
3: 6 . 2
4: 6 . . 2
5: 4 . . . 4
6: 3 3 1 1 . 1
7: 2 2 . 2 . 2
8: 2 . 2 . 2 . 2
9: 2 . 2 2 . . 2
10: 1 1 1 1 1 1 1 1

70.12.3 TableOfMarksFrobenius

\texttt{TableOfMarksFrobenius}(p, q)

\textit{(operation)}

TableOfMarksFrobenius computes the table of marks of a Frobenius group of order $pq$, where $p$ is a prime and $q$ divides $p - 1$.

Example

gap> Display( TableOfMarksFrobenius( 5, 4 ) );
1: 20
2: 10 2
3: 5 1 1
4: 4 . . 4
5: 2 2 . 2
6: 1 1 1 1 1

70.13 The Library of Tables of Marks

The GAP package \texttt{TomLib} provides access to several hundred tables of marks of almost simple groups and their maximal subgroups. If this package is installed then the tables from this database can be accessed via \texttt{TableOfMarks(70.3.1)} with argument a string. If also the GAP Character Table Library is installed and contains the ordinary character table of the group for which one wants to fetch the table of marks then one can also call \texttt{TableOfMarks(70.3.1)} with argument the character table.

A list of all names of tables of marks that are provided by the \texttt{TomLib} package can be obtained via \texttt{AllLibTomNames} (\texttt{TomLib: AllLibTomNames}).

Example

gap> names:= AllLibTomNames();
gap> "A5" in names;
true
Chapter 71

Character Tables

This chapter describes operations for character tables of finite groups. Operations for characters (or, more general, class functions) are described in Chapter 72.

For a description of the GAP Library of Character Tables, see the separate manual for the GAP package CTblLib.

Several examples in this chapter require the GAP Character Table Library to be available. If it is not yet loaded then we load it now.

```
Example

gap> LoadPackage( "ctbllib" );
true
```

71.1 Some Remarks about Character Theory in GAP

It seems to be necessary to state some basic facts --and maybe warnings-- at the beginning of the character theory package. This holds for people who are familiar with character theory because there is no global reference on computational character theory, although there are many papers on this topic, such as [NPP84] or [LP91]. It holds, however, also for people who are familiar with GAP because the general concept of domains (see Chapter 12.4) plays no important role here --we will justify this later in this section.

Intuitively, characters (or more generally, class functions) of a finite group \( G \) can be thought of as certain mappings defined on \( G \), with values in the complex number field; the set of all characters of \( G \) forms a semiring, with both addition and multiplication defined pointwise, which is naturally embedded into the ring of generalized (or virtual) characters in the natural way. A \( \mathbb{Z} \)-basis of this ring, and also a vector space basis of the complex vector space of class functions of \( G \), is given by the irreducible characters of \( G \).

At this stage one could ask where there is a problem, since all these algebraic structures are supported by GAP. But in practice, these structures are of minor importance, compared to individual characters and the character tables themselves (which are not domains in the sense of GAP).

For computations with characters of a finite group \( G \) with \( n \) conjugacy classes, say, we fix an ordering of the classes, and then identify each class with its position according to this ordering. Each character of \( G \) can be represented by a list of length \( n \) in which the character value for elements of the \( i \)-th class is stored at the \( i \)-th position. Note that we need not know the conjugacy classes of \( G \) physically, even our knowledge of \( G \) may be implicit in the sense that, e.g., we know how many classes of involutions \( G \) has, and which length these classes have, but we never have seen an element
of $G$, or a presentation or representation of $G$. This allows us to work with the character tables of very large groups, e.g., of the so-called monster, where GAP has (currently) no chance to deal with the group.

As a consequence, also other information involving characters is given implicitly. For example, we can talk about the kernel of a character not as a group but as a list of classes (more exactly: a list of their positions according to the chosen ordering of classes) forming this kernel; we can deduce the group order, the contained cyclic subgroups and so on, but we do not get the group itself.

So typical calculations with characters involve loops over lists of character values. For example, the scalar product of two characters $\chi$, $\psi$ of $G$ given by

$$[\chi, \psi] = \left( \sum_{g \in G} \chi(g) \psi(g^{-1}) \right) / |G|$$

can be written as

```gap
Sum( [ 1 .. n ], i -> SizesConjugacyClasses( t )[i] * chi[i] * ComplexConjugate( psi[i] ) ) / Size( t );
```

where $t$ is the character table of $G$, and $\text{chi}$, $\text{psi}$ are the lists of values of $\chi$, $\psi$, respectively.

It is one of the advantages of character theory that after one has translated a problem concerning groups into a problem concerning only characters, the necessary calculations are mostly simple. For example, one can often prove that a group is a Galois group over the rationals using calculations with structure constants that can be computed from the character table, and information about (the character tables of) maximal subgroups. When one deals with such questions, the translation back to groups is just an interpretation by the user, it does not take place in GAP.

GAP uses character tables to store information such as class lengths, element orders, the irreducible characters of $G$ etc. in a consistent way; in the example above, we have seen that $\text{SizesConjugacyClasses}(71.9.3)$ returns the list of class lengths of its argument. Note that the values of these attributes rely on the chosen ordering of conjugacy classes, a character table is not determined by something similar to generators of groups or rings in GAP where knowledge could in principle be recovered from the generators but is stored mainly for the sake of efficiency.

Note that the character table of a group $G$ in GAP must not be mixed up with the list of complex irreducible characters of $G$. The irreducible characters are stored in a character table via the attribute $\text{Irr}(71.8.2)$.

Two further important instances of information that depends on the ordering of conjugacy classes are power maps and fusion maps. Both are represented as lists of integers in GAP. The $k$-th power map maps each class to the class of $k$-th powers of its elements, the corresponding list contains at each position the position of the image. A class fusion map between the classes of a subgroup $H$ of $G$ and the classes of $G$ maps each class $c$ of $H$ to that class of $G$ that contains $c$, the corresponding list contains again the positions of image classes; if we know only the character tables of $H$ and $G$ but not the groups themselves, this means with respect to a fixed embedding of $H$ into $G$. More about power maps and fusion maps can be found in Chapter 73.

So class functions, power maps, and fusion maps are represented by lists in GAP. If they are plain lists then they are regarded as class functions etc. of an appropriate character table when they are passed to GAP functions that expect class functions etc. For example, a list with all entries equal to 1 is regarded as the trivial character if it is passed to a function that expects a character. Note that this approach requires the character table as an argument for such a function.
One can construct class function objects that store their underlying character table and other attribute values (see Chapter 72). This allows one to omit the character table argument in many functions, and it allows one to use infix operations for tensoring or inducing class functions.

### 71.2 History of Character Theory Stuff in GAP

GAP provides functions for dealing with group characters since the version GAP 3.1, which was released in March 1992. The reason for adding this branch of mathematics to the topics of GAP was (apart from the usefulness of character theoretic computations in general) the insight that GAP provides an ideal environment for developing the algorithms needed. In particular, it had been decided at Lehrstuhl D für Mathematik that the CAS system (a standalone Fortran program together with a database of character tables, see [NPP84]) should not be developed further and the functionality of CAS should be made available in GAP. The background was that extending CAS (by new Fortran code) had turned out to be much less flexible than writing analogous GAP library code.

For integrating the existing character theory algorithms, GAP’s memory management and long integer arithmetic were useful as well as the list handling—it is an important feature of character theoretic methods that questions about groups are translated into manipulations of lists; on the other hand, the datatype of cyclotomics (see Chapter Cyclotomics (18.1.2)) was added to the GAP kernel because of the character theory algorithms. For developing further code, also other areas of GAP’s library became interesting, such as permutation groups, finite fields, and polynomials.

The development of character theory code for GAP has been supported by several DFG grants, in particular the project “Representation Theory of Finite Groups and Finite Dimensional Algebras” (until 1991), and the Schwerpunkt “Algorithmische Zahlentheorie und Algebra” (from 1991 until 1997). Besides that, several Diploma theses at Lehrstuhl D were concerned with the development and/or implementation of algorithms dealing with characters in GAP.

The major contributions can be listed as follows.

- The arithmetic for the cyclotomics data type, following [Zum89], was first implemented by Marco van Meegen; an alternative approach was studied in the diploma thesis of Michael Scherner (see [Sch92]) but was not efficient enough; later Martin Schönert replaced the implementation by a better one.

- The basic routines for characters and character tables were written by Thomas Breuer and Götz Pfeiffer.

- The lattice related functions, such as LLL (72.10.4), OrthogonalEmbeddings (25.6.1), and DnLattice (72.10.8), were implemented by Ansgar Kaup (see [Kau92]).

- Functions for computing possible class fusions, possible power maps, and table automorphisms were written by Thomas Breuer (see [Bre91]).

- Functions for computing possible permutation characters were written by Thomas Breuer (see [Bre91]) and Götz Pfeiffer (see [Pfe91]).

- Functions for computing character tables from groups were written by Alexander Hulpke (Dixon-Schneider algorithm, see [Hul93]) and Hans Ulrich Besche (Baum algorithm and Conlon algorithm, see [Bes92]).

- Functions for dealing with Clifford matrices were written by Ute Schiffer (see [Sch94]).
Functions for monomiality questions were written by Thomas Breuer and Erzsébet Horváth. Since then, the code has been maintained and extended further by Alexander Hulpke (code related to his implementation of the Dixon-Schneider algorithm) and Thomas Breuer.

Currently GAP does not provide special functionality for computing Brauer character tables, but there is an interface to the MOC system (see [HJLP]), and the GAP Character Table Library contains many known Brauer character tables.

### 71.3 Creating Character Tables

There are in general five different ways to get a character table in GAP. You can

1. compute the table from a group,
2. read a file that contains the table data,
3. construct the table using generic formulae,
4. derive it from known character tables, or
5. combine partial information about conjugacy classes, power maps of the group in question, and about (character tables of) some subgroups and supergroups.

In 1., the computation of the irreducible characters is the hardest part; the different algorithms available for this are described in 71.14. Possibility 2. is used for the character tables in the GAP Character Table Library, see the manual of this library. Generic character tables—as addressed by 3.—are described in (CTblLib: Generic Character Tables). Several occurrences of 4. are described in 71.20. The last of the above possibilities is currently not supported and will be described in a chapter of its own when it becomes available.

The operation `CharacterTable` can be used for the cases 1. to 3.

#### 71.3.1 CharacterTable

- `CharacterTable(G[, p])` (operation)
- `CharacterTable(ordtbl, p)` (operation)
- `CharacterTable(name[, param])` (operation)

Called with a group $G$, `CharacterTable` calls the attribute `OrdinaryCharacterTable` (71.8.4). Called with first argument a group $G$ or an ordinary character table `ordtbl`, and second argument a prime $p$, `CharacterTable` calls the operation `BrauerTable` (71.3.2).

Called with a string `name` and perhaps optional parameters `param`, `CharacterTable` tries to access a character table from the GAP Character Table Library. See the manual of the GAP package CTblLib for an overview of admissible arguments. An error is signalled if this GAP package is not loaded in this case.

Probably the most interesting information about the character table is its list of irreducibles, which can be accessed as the value of the attribute `Irr` (71.8.2). If the argument of `CharacterTable` is a string `name` then the irreducibles are just read from the library file, therefore the returned table stores them already. However, if `CharacterTable` is called with a group $G$ or with an ordinary
character table `ordtbl`, the irreducible characters are not computed by `CharacterTable`. They are only computed when the `Irr` (71.8.2) value is accessed for the first time, for example when `Display` (6.3.6) is called for the table (see 71.13). This means for example that `CharacterTable` returns its result very quickly, and the first call of `Display` (6.3.6) for this table may take some time because the irreducible characters must be computed at that time before they can be displayed together with other information stored on the character table. The value of the filter `HasIrr` indicates whether the irreducible characters have been computed already.

The reason why `CharacterTable` does not compute the irreducible characters is that there are situations where one only needs the “table head”, that is, the information about class lengths, power maps etc., but not the irreducibles. For example, if one wants to inspect permutation characters of a group then all one has to do is to induce the trivial characters of subgroups one is interested in; for that, only class lengths and the class fusion are needed. Or if one wants to compute the Molien series (see `MolienSeries` (72.12.1)) for a given complex matrix group, the irreducible characters of this group are in general of no interest.

For details about different algorithms to compute the irreducible characters, see 71.14.

If the group \( G \) is given as an argument, `CharacterTable` accesses the conjugacy classes of \( G \) and therefore causes that these classes are computed if they were not yet stored (see 71.6).

### 71.3.2 BrauerTable

\[
\begin{align*}
\triangleright \text{BrauerTable}(\text{ordtbl}, p) & \quad \text{(operation)} \\
\triangleright \text{BrauerTable}(G, p) & \quad \text{(operation)} \\
\triangleright \text{BrauerTableOp}(\text{ordtbl}, p) & \quad \text{(operation)} \\
\triangleright \text{ComputedBrauerTables}(\text{ordtbl}) & \quad \text{(attribute)}
\end{align*}
\]

Called with an ordinary character table `ordtbl` or a group \( G \), `BrauerTable` returns its \( p \)-modular character table if `GAP` can compute this table, and `fail` otherwise.

The \( p \)-modular table can be computed in the following cases.

- The group is \( p \)-solvable (see `IsPSolvable` (39.15.24), apply the Fong-Swan Theorem);
- the Sylow \( p \)-subgroup of \( G \) is cyclic, and all \( p \)-modular Brauer characters of \( G \) lift to ordinary characters (note that this situation can be detected from the ordinary character table of \( G \));
- the table `ordtbl` stores information how it was constructed from other tables (as a direct product or as an isoclinic variant, for example), and the Brauer tables of the source tables can be computed;
- `ordtbl` is a table from the `GAP` character table library for which also the \( p \)-modular table is contained in the table library.

The default method for a group and a prime delegates to `BrauerTable` for the ordinary character table of this group. The default method for `ordtbl` uses the attribute `ComputedBrauerTables` for storing the computed Brauer table at position \( p \), and calls the operation `BrauerTableOp` for computing values that are not yet known.

So if one wants to install a new method for computing Brauer tables then it is sufficient to install it for `BrauerTableOp`.

The \texttt{mod} operator for a character table and a prime (see 71.7) delegates to `BrauerTable`. 
71.3.3 CharacterTableRegular

\textbf{CharacterTableRegular}(tbl, p)

For an ordinary character table \( tbl \) and a prime integer \( p \), \textbf{CharacterTableRegular} returns the “table head” of the \( p \)-modular Brauer character table of \( tbl \). This is the restriction of \( tbl \) to its \( p \)-regular classes, like the return value of \textbf{BrauerTable} (71.3.2), but without the irreducible Brauer characters. (In general, these characters are hard to compute, and \textbf{BrauerTable} (71.3.2) may return \texttt{fail} for the given arguments, for example if \( tbl \) is a table from the GAP character table library.)

The returned table head can be used to create \( p \)-modular Brauer characters, by restricting ordinary characters, for example when one is interested in approximations of the (unknown) irreducible Brauer characters.

\begin{verbatim}
gap> g := SymmetricGroup( 4 );
Sym( [ 1 .. 4 ] )
gap> tbl := CharacterTable( g ); HasIrr( tbl );
false
gap> tblmod2 := CharacterTable( tbl, 2 );
BrauerTable( Sym( [ 1 .. 4 ] ), 2 )
gap> tblmod2 = CharacterTable( tbl, 2 );
true
gap> tblmod2 = BrauerTable( tbl, 2 );
true
gap> tblmod2 = BrauerTable( g, 2 );
true
gap> libtbl := CharacterTable( "M" );
CharacterTable( "M" )
gap> CharacterTableRegular( libtbl, 2 );
BrauerTable( "M", 2 )
gap> BrauerTable( libtbl, 2 );
fail
gap> CharacterTable( "Symmetric", 4 );
CharacterTable( "Sym(4)" )
gap> ComputedBrauerTables( tbl );
[ , BrauerTable( Sym( [ 1 .. 4 ] ), 2 ) ]
\end{verbatim}

71.3.4 SupportedCharacterTableInfo

\textbf{SupportedCharacterTableInfo}

SupportedCharacterTableInfo is a list that contains at position \( 3i - 2 \) an attribute getter function, at position \( 3i - 1 \) the name of this attribute, and at position \( 3i \) a list containing a subset of [ "character", "class", "mutable" ], depending on whether the attribute value relies on the ordering of characters or classes, or whether the attribute value is a mutable list or record.

When (ordinary or Brauer) character table objects are created from records, using \textbf{ConvertToCharacterTable} (71.3.5), \textbf{SupportedCharacterTableInfo} specifies those record components that shall be used as attribute values; other record components are not be regarded as attribute values in the conversion process.

New attributes and properties can be notified to \textbf{SupportedCharacterTableInfo} by creating them with \textbf{DeclareAttributeSuppCT} and \textbf{DeclarePropertySuppCT} instead of
DeclareAttribute (13.5.4) and DeclareProperty (13.7.5).

71.3.5 ConvertToCharacterTable

\begin{itemize}
\item ConvertToCharacterTable \textit{(record)} \hspace{1cm} \text{(function)}
\item ConvertToCharacterTableNC \textit{(record)} \hspace{1cm} \text{(function)}
\end{itemize}

Let \textit{record} be a record. \texttt{ConvertToCharacterTable} converts \textit{record} into a component object (see 79.2) representing a character table. The values of those components of \textit{record} whose names occur in \texttt{SupportedCharacterTableInfo} (71.3.4) correspond to attribute values of the returned character table. All other components of the record simply become components of the character table object.

If inconsistencies in \textit{record} are detected, \texttt{fail} is returned. \textit{record} must have the component \texttt{UnderlyingCharacteristic} bound (cf. \texttt{UnderlyingCharacteristic} (71.9.5)), since this decides about whether the returned character table lies in \texttt{IsOrdinaryTable} (71.4.1) or in \texttt{IsBrauerTable} (71.4.1).

\texttt{ConvertToCharacterTableNC} does the same except that all checks of \textit{record} are omitted.

An example of a conversion from a record to a character table object can be found in Section PrintCharacterTable (71.13.5).

71.4 Character Table Categories

71.4.1 IsNearlyCharacterTable

\begin{itemize}
\item IsNearlyCharacterTable \textit{(obj)} \hspace{1cm} \text{(Category)}
\item IsCharacterTable \textit{(obj)} \hspace{1cm} \text{(Category)}
\item IsOrdinaryTable \textit{(obj)} \hspace{1cm} \text{(Category)}
\item IsBrauerTable \textit{(obj)} \hspace{1cm} \text{(Category)}
\item IsCharacterTableInProgress \textit{(obj)} \hspace{1cm} \text{(Category)}
\end{itemize}

Every “character table like object” in \texttt{GAP} lies in the category \texttt{IsNearlyCharacterTable}. There are four important subcategories, namely the ordinary tables in \texttt{IsOrdinaryTable}, the Brauer tables in \texttt{IsBrauerTable}, the union of these two in \texttt{IsCharacterTable}, and the incomplete ordinary tables in \texttt{IsCharacterTableInProgress}.

We want to distinguish ordinary and Brauer tables because a Brauer table may delegate tasks to the ordinary table of the same group, for example the computation of power maps. A Brauer table is constructed from an ordinary table and stores this table upon construction (see \texttt{OrdinaryCharacterTable} (71.8.4)).

Furthermore, \texttt{IsOrdinaryTable} and \texttt{IsBrauerTable} denote character tables that provide enough information to compute all power maps and irreducible characters (and in the case of Brauer tables to get the ordinary table), for example because the underlying group (see \texttt{UnderlyingGroup} (71.6.1)) is known or because the table is a library table (see the manual of the \texttt{GAP} Character Table Library). We want to distinguish these tables from partially known ordinary tables that cannot be asked for all power maps or all irreducible characters.

The character table objects in \texttt{IsCharacterTable} are always immutable (see 12.6). This means mainly that the ordering of conjugacy classes used for the various attributes of the character table cannot be changed; see 71.21 for how to compute a character table with a different ordering of classes.
The GAP objects in `IsCharacterTableInProgress` represent incomplete ordinary character tables. This means that not all irreducible characters, not all power maps are known, and perhaps even the number of classes and the centralizer orders are known. Such tables occur when the character table of a group $G$ is constructed using character tables of related groups and information about $G$ but for example without explicitly computing the conjugacy classes of $G$. An object in `IsCharacterTableInProgress` is first of all mutable, so nothing is stored automatically on such a table, since otherwise one has no control of side-effects when a hypothesis is changed. Operations for such tables may return more general values than for other tables, for example class functions may contain unknowns (see Chapter 74) or lists of possible values in certain positions, the same may happen also for power maps and class fusions (see 73.5). Incomplete tables in this sense are currently not supported and will be described in a chapter of their own when they become available. Note that the term “incomplete table” shall express that GAP cannot compute certain values such as irreducible characters or power maps. A table with access to its group is therefore always complete, also if its irreducible characters are not yet stored.

Example

```gap
gap> g:= SymmetricGroup( 4 );;
gap> tbl:= CharacterTable( g );
CharacterTable( Sym( [ 1 .. 4 ] ) )
gap> modtbl:= tbl mod 2;
BrauerTable( Sym( [ 1 .. 4 ] ), 2 )

gap> IsCharacterTable( tbl );
true

gap> IsCharacterTable( modtbl );
true

gap> IsBrauerTable( modtbl );
true

gap> IsOrdinaryTable( tbl );
false

gap> IsOrdinaryTable( modtbl );
false

gap> IsCharacterTable( g );
false

gap> IsCharacterTable( Irr( g ) );
false
```

71.4.2 InfoCharacterTable

`InfoCharacterTable` (info class)

is the info class (see 7.4) for computations with character tables.

71.4.3 NearlyCharacterTablesFamily

`NearlyCharacterTablesFamily` (family)

Every character table like object lies in this family (see 13.1).

71.5 Conventions for Character Tables

The following few conventions should be noted.
• The class of the *identity element* is expected to be the first one; thus the degree of a character is the character value at position 1.

• The *trivial character* of a character table need not be the first in the list of irreducibles.

• Most functions that take a character table as an argument and work with characters expect these characters as an argument, too. For some functions, the list of irreducible characters serves as the default, i.e., the value of the attribute \( \text{Irr} \) (71.8.2); in these cases, the \( \text{Irr} \) (71.8.2) value is automatically computed if it was not yet known.

• For a stored class fusion, the image table is denoted by its *Identifier* (71.9.8) value; each library table has a unique identifier by which it can be accessed (see (CTbLib: Accessing a Character Table from the Library) in the manual for the GAP Character Table Library), tables constructed from groups get an identifier that is unique in the current GAP session.

### 71.6 The Interface between Character Tables and Groups

For a character table with underlying group (see UnderlyingGroup (71.6.1)), the interface between table and group consists of three attribute values, namely the group, the conjugacy classes stored in the table (see ConjugacyClasses (71.6.2) below) and the *identification* of the conjugacy classes of table and group (see IdentificationOfConjugacyClasses (71.6.3) below).

Character tables constructed from groups know these values upon construction, and for character tables constructed without groups, these values are usually not known and cannot be computed from the table.

However, given a group \( G \) and a character table of a group isomorphic to \( G \) (for example a character table from the GAP table library), one can tell GAP to compute a new instance of the given table and to use it as the character table of \( G \) (see CharacterTableWithStoredGroup (71.6.4)).

Tasks may be delegated from a group to its character table or vice versa only if these three attribute values are stored in the character table.

#### 71.6.1 UnderlyingGroup (for character tables)

```gap
\begin{verbatim}
\triangleright \text{UnderlyingGroup(}\text{ordtbl}\text{)} (attribute)
\end{verbatim}
```

For an ordinary character table \( \text{ordtbl} \) of a finite group, the group can be stored as value of UnderlyingGroup.

Brauer tables do not store the underlying group, they access it via the ordinary table (see OrdinaryCharacterTable (71.8.4)).

#### 71.6.2 ConjugacyClasses (for character tables)

```gap
\begin{verbatim}
\triangleright \text{ConjugacyClasses(}\text{tbl}\text{)} (attribute)
\end{verbatim}
```

For a character table \( \text{tbl} \) with known underlying group \( G \), the \text{ConjugacyClasses} value of \( \text{tbl} \) is a list of conjugacy classes of \( G \). All those lists stored in the table that are related to the ordering of conjugacy classes (such as sizes of centralizers and conjugacy classes, orders of representatives, power maps, and all class functions) refer to the ordering of this list.
This ordering need not coincide with the ordering of conjugacy classes as stored in the underlying group of the table (see 71.21). One reason for this is that otherwise we would not be allowed to use a library table as the character table of a group for which the conjugacy classes are stored already. (Another, less important reason is that we can use the same group as underlying group of character tables that differ only w.r.t. the ordering of classes.)

The class of the identity element must be the first class (see 71.5).

If \( \text{tbl} \) was constructed from \( G \) then the conjugacy classes have been stored at the same time when \( G \) was stored. If \( G \) and \( \text{tbl} \) have been connected later than in the construction of \( \text{tbl} \), the recommended way to do this is via \texttt{CharacterTableWithStoredGroup} (71.6.4). So there is no method for \texttt{ConjugacyClasses} that computes the value for \( \text{tbl} \) if it is not yet stored.

Brauer tables do not store the \((p\text{-regular})\) conjugacy classes, they access them via the ordinary table (see \texttt{OrdinaryCharacterTable} (71.8.4)) if necessary.

### 71.6.3 IdentificationOfConjugacyClasses

\texttt{IdentificationOfConjugacyClasses(tbl)} (attribute)

For an ordinary character table \( \text{tbl} \) with known underlying group \( G \), \texttt{IdentificationOfConjugacyClasses} returns a list of positive integers that contains at position \( i \) the position of the \( i \)-th conjugacy class of \( \text{tbl} \) in the \texttt{ConjugacyClasses} (71.6.2) value of \( G \).

```gap
gap> g:= SymmetricGroup( 4 );;
gap> repres:= [ (1,2), (1,2,3), (1,2,3,4), (1,2)(3,4), () ];;
gap> ccl:= List( repres, x -> ConjugacyClass( g, x ) );;
gap> SetConjugacyClasses( g, ccl );
gap> tbl:= CharacterTable( g );; # the table stores already the values
gap> HasConjugacyClasses( tbl ); HasUnderlyingGroup( tbl );
true
true
gap> UnderlyingGroup( tbl ) = g;
true
gap> HasIdentificationOfConjugacyClasses( tbl );
true
gap> IdentificationOfConjugacyClasses( tbl );
[ 5, 1, 2, 3, 4 ]
```

### 71.6.4 CharacterTableWithStoredGroup

\texttt{CharacterTableWithStoredGroup(G, tbl[, info])} (function)

Let \( G \) be a group and \( \text{tbl} \) a character table of (a group isomorphic to) \( G \), such that \( G \) does not store its \texttt{OrdinaryCharacterTable} (71.8.4) value. \texttt{CharacterTableWithStoredGroup} calls \texttt{CompatibleConjugacyClasses} (71.6.5), trying to identify the classes of \( G \) with the columns of \( \text{tbl} \).

If this identification is unique up to automorphisms of \( \text{tbl} \) (see \texttt{AutomorphismsOfTable} (71.9.4)) then \( \text{tbl} \) is stored as \texttt{CharacterTable} (71.3.1) value of \( G \), and a new character table is returned that is equivalent to \( \text{tbl} \), is sorted in the same way as \( \text{tbl} \), and has the values of \texttt{UnderlyingGroup} (71.6.1), \texttt{ConjugacyClasses} (71.6.2), and \texttt{IdentificationOfConjugacyClasses} (71.6.3) set.
Otherwise, i.e., if GAP cannot identify the classes of \( G \) up to automorphisms of \( \text{tbl} \), \text{fail} is returned.

If a record is present as the third argument \( \text{info} \), its meaning is the same as the optional argument \( \text{arec} \) for \text{CompatibleConjugacyClasses} (71.6.5).

If a list is entered as third argument \( \text{info} \) it is used as value of \text{IdentificationOfConjugacyClasses} (71.6.3), relative to the \text{ConjugacyClasses} (71.6.2) value of \( G \), without further checking, and the corresponding character table is returned.

### 71.6.5 CompatibleConjugacyClasses

\[
\text{CompatibleConjugacyClasses}([G, ccl, ]\text{tbl}[, \text{arec}])
\]

If the arguments \( G \) and \( ccl \) are present then \( ccl \) must be a list of the conjugacy classes of the group \( G \), and \( \text{tbl} \) the ordinary character table of \( G \). Then \text{CompatibleConjugacyClasses} returns a list \( l \) of positive integers that describes an identification of the columns of \( \text{tbl} \) with the conjugacy classes \( ccl \) in the sense that \( l[i] \) is the position in \( ccl \) of the class corresponding to the \( i \)-th column of \( \text{tbl} \). If this identification is unique up to automorphisms of \( \text{tbl} \) (see \text{AutomorphismsOfTable} (71.9.4)); if GAP cannot identify the classes, \text{fail} is returned.

If \( \text{tbl} \) is the first argument then it must be an ordinary character table, and \text{CompatibleConjugacyClasses} checks whether the columns of \( \text{tbl} \) can be identified with the conjugacy classes of a group isomorphic to that for which \( \text{tbl} \) is the character table; the return value is a list of all those sets of class positions for which the columns of \( \text{tbl} \) cannot be distinguished with the invariants used, up to automorphisms of \( \text{tbl} \). So the identification is unique if and only if the returned list is empty.

The usual approach is that one first calls \text{CompatibleConjugacyClasses} in the second form for checking quickly whether the first form will be successful, and only if this is the case the more time consuming calculations with both group and character table are done.

The following invariants are used.

1. element orders (see \text{OrdersClassRepresentatives} (71.9.1)),
2. class lengths (see \text{SizesConjugacyClasses} (71.9.3)),
3. power maps (see \text{PowerMap} (73.1.1), \text{ComputedPowerMaps} (73.1.1)),
4. symmetries of the table (see \text{AutomorphismsOfTable} (71.9.4)).

If the optional argument \( \text{arec} \) is present then it must be a record whose components describe additional information for the class identification. The following components are supported.

- **natchar**
  
  if \( G \) is a permutation group or matrix group then the value of this component is regarded as the list of values of the natural character (see \text{NaturalCharacter} (72.7.2)) of \( G \), w.r.t. the ordering of classes in \( \text{tbl} \).

- **bijection**
  
  a list describing a partial bijection; the \( i \)-th entry, if bound, is the position of the \( i \)-th conjugacy class of \( \text{tbl} \) in the list \( ccl \).
Example

```gap
gap> g := AlternatingGroup( 5 );
Alt( [ 1 .. 5 ] )
gap> tbl := CharacterTable( "A5" );
CharacterTable( "A5" )
gap> HasUnderlyingGroup( tbl ); HasOrdinaryCharacterTable( g );
false false
gap> CompatibleConjugacyClasses( tbl ); # unique identification
[ ]
gap> new := CharacterTableWithStoredGroup( g, tbl );
CharacterTable( Alt( [ 1 .. 5 ] ) )
gap> Irr( new ) = Irr( tbl );
true
gap> HasConjugacyClasses( new ); HasUnderlyingGroup( new );
true true
gap> IdentificationOfConjugacyClasses( new );
[ 1, 2, 3, 4, 5 ]
gap> # Here is an example where the identification is not unique.
gap> CompatibleConjugacyClasses( CharacterTable( "J2" ) );
[ [ 17, 18 ], [ 9, 10 ] ]
```

71.7 Operators for Character Tables

The following infix operators are defined for character tables.

- `tbl1 * tbl2`
  - the direct product of two character tables (see `CharacterTableDirectProduct` (71.20.1)),

- `tbl / list`
  - the table of the factor group modulo the normal subgroup spanned by the classes in the list `list` (see `CharacterTableFactorGroup` (71.20.3)),

- `tbl mod p`
  - the \( p \)-modular Brauer character table corresponding to the ordinary character table `tbl` (see `BrauerTable` (71.3.2)),

- `tbl . name`
  - the position of the class with name `name` in `tbl` (see `ClassNames` (71.9.6)).

71.8 Attributes and Properties for Groups and Character Tables

Several attributes for groups are valid also for character tables.

These are first those that have the same meaning for both the group and its character table, and whose values can be read off or computed, respectively, from the character table, such as `Size` (71.8.5), `IsAbelian` (71.8.5), or `IsSolvable` (71.8.5).

Second, there are attributes whose meaning for character tables is different from the meaning for groups, such as `ConjugacyClasses` (71.6.2).
71.8.1 CharacterDegrees

\textbf{CharacterDegrees}(G[, p]) \hspace{1cm} \text{(attribute)}
\textbf{CharacterDegrees}(tbl) \hspace{1cm} \text{(attribute)}

In the first form, \textbf{CharacterDegrees} returns a collected list of the degrees of the absolutely irreducible characters of the group \(G\); the optional second argument \(p\) must be either zero or a prime integer denoting the characteristic, the default value is zero. In the second form, \(tbl\) must be an (ordinary or Brauer) character table, and \textbf{CharacterDegrees} returns a collected list of the degrees of the absolutely irreducible characters of \(tbl\).

(The default method for the call with only argument a group is to call the operation with second argument 0.)

For solvable groups, the default method is based on [Con90b].

\begin{verbatim}
Example
gap> CharacterDegrees( SymmetricGroup( 4 ) );
[ [ 1, 2 ], [ 2, 1 ], [ 3, 2 ] ]
gap> CharacterDegrees( SymmetricGroup( 4 ), 2 );
[ [ 1, 1 ], [ 2, 1 ] ]
gap> CharacterDegrees( CharacterTable( "A5" ) );
[ [ 1, 1 ], [ 3, 2 ], [ 4, 1 ], [ 5, 1 ] ]
gap> CharacterDegrees( CharacterTable( "A5" ) mod 2 );
[ [ 1, 1 ], [ 2, 2 ], [ 4, 1 ] ]
\end{verbatim}

71.8.2 \textbf{Irr}

\textbf{Irr}(G[, p]) \hspace{1cm} \text{(attribute)}
\textbf{Irr}(tbl) \hspace{1cm} \text{(attribute)}

Called with a group \(G\), \textbf{Irr} returns the irreducible characters of the ordinary character table of \(G\). Called with a group \(G\) and a prime integer \(p\), \textbf{Irr} returns the irreducible characters of the \(p\)-modular Brauer table of \(G\). Called with an (ordinary or Brauer) character table \(tbl\), \textbf{Irr} returns the list of all complex absolutely irreducible characters of \(tbl\).

For a character table \(tbl\) with underlying group, \textbf{Irr} may delegate to the group. For a group \(G\), \textbf{Irr} may delegate to its character table only if the irreducibles are already stored there.

(If \(G\) is \(p\)-solvable (see \textbf{IsPSolvable} (39.15.24)) then the \(p\)-modular irreducible characters can be computed by the Fong-Swan Theorem; in all other cases, there may be no method.)

Note that the ordering of columns in the \textbf{Irr} matrix of the group \(G\) refers to the ordering of conjugacy classes in the \textbf{CharacterTable} (71.3.1) value of \(G\), which may differ from the ordering of conjugacy classes in \(G\) (see 71.6). As an extreme example, for a character table obtained from sorting the classes of the \textbf{CharacterTable} (71.3.1) value of \(G\), the ordering of columns in the \textbf{Irr} matrix respects the sorting of classes (see 71.21), so the irreducibles of such a table will in general not coincide with the irreducibles stored as the \textbf{Irr} value of \(G\) although also the sorted table stores the group \(G\).

The ordering of the entries in the attribute \textbf{Irr} of a group need not coincide with the ordering of its \textbf{IrreducibleRepresentations} (71.14.4) value.

\begin{verbatim}
Example
gap> Irr( SymmetricGroup( 4 ) );
[ Character( CharacterTable( Sym( [ 1 .. 4 ] ) ), [ 1, -1, 1, -1
\end{verbatim}
LinearCharacters returns the linear (i.e., degree 1) characters in the Irr (71.8.2) list of the group \( G \) or the character table \( tbl \), respectively. In the second form, LinearCharacters returns the \( p \)-modular linear characters of the group \( G \).

For a character table \( tbl \) with underlying group, LinearCharacters may delegate to the group. For a group \( G \), LinearCharacters may delegate to its character table only if the irreducibles are already stored there.

The ordering of linear characters in \( tbl \) need not coincide with the ordering of linear characters in the irreducibles of \( tbl \) (see Irr (71.8.2)).

Example

\[
\text{gap> LinearCharacters( SymmetricGroup( 4 ) );}
\[
[ \text{Character( CharacterTable( Sym( [ 1 .. 4 ] ) ), [ 1, 1, 1, 1 ] ),}
  \text{Character( CharacterTable( Sym( [ 1 .. 4 ] ) ), [ 1, -1, 1, -1 ] )} ]
\]

OrdinaryCharacterTable

OrdinaryCharacterTable returns the ordinary irreducible characters of a group or the ordinary characters of a character table.

Example

\[
\text{gap> OrdinaryCharacterTable( SymmetricGroup( 4 ) );}
\[
[ \text{Character( CharacterTable( Sym( [ 1 .. 4 ] ) ), [ 1, 1, 1, 1 ] )} ]
\]
OrdinaryCharacterTable returns the ordinary character table of the group $G$ or the Brauer character table `modtbl`, respectively.

Since Brauer character tables are constructed from ordinary tables, the attribute value for `modtbl` is already stored (cf. 71.4).

```
gap> OrdinaryCharacterTable( SymmetricGroup( 4 ) );
CharacterTable( Sym( [ 1 .. 4 ] ) )
gap> tbl:= CharacterTable( "A5" );;
Gap> modtbl:= tbl mod 2;
BrauerTable( "A5", 2 )
gap> OrdinaryCharacterTable( modtbl ) = tbl;
true
```

### 71.8.5 Group Operations Applicable to Character Tables

- `AbelianInvariants(tbl)` (attribute)
- `CommutatorLength(tbl)` (attribute)
- `Exponent(tbl)` (attribute)
- `IsAbelian(tbl)` (property)
- `IsAlmostSimple(tbl)` (property)
- `IsCyclic(tbl)` (property)
- `IsElementaryAbelian(tbl)` (property)
- `IsFinite(tbl)` (property)
- `IsMonomial(tbl)` (property)
- `IsNilpotent(tbl)` (property)
- `IsPerfect(tbl)` (property)
- `IsSimple(tbl)` (property)
- `IsSolvable(tbl)` (property)
- `IsSporadicSimple(tbl)` (property)
- `IsSupersolvable(tbl)` (property)
- `IsomorphismTypeInfoFiniteSimpleGroup(tbl)` (attribute)
- `NrConjugacyClasses(tbl)` (attribute)
- `Size(tbl)` (attribute)

These operations for groups are applicable to character tables and mean the same for a character table as for its underlying group; see Chapter 39 for the definitions. The operations are mainly useful for selecting character tables with certain properties, also for character tables without access to a group.

```
gap> tables:= [ CharacterTable( CyclicGroup( 3 ) ),
              CharacterTable( SymmetricGroup( 4 ) ),
              CharacterTable( AlternatingGroup( 5 ) ) ];;
gap> List( tables, AbelianInvariants );
[ [ 3 ], [ 2 ], [ ] ]
gap> List( tables, CommutatorLength );
[ 1, 1, 1 ]
gap> List( tables, Exponent );
[ 3, 12, 30 ]
gap> List( tables, IsAbelian );
```

Example
[ true, false, false ]
gap> List( tables, IsAlmostSimple );
[ false, false, true ]
gap> List( tables, IsCyclic );
[ true, false, false ]
gap> List( tables, IsFinite );
[ true, true, true ]
gap> List( tables, IsMonomial );
[ true, true, false ]
gap> List( tables, IsNilpotent );
[ true, false, false ]
gap> List( tables, IsPerfect );
[ true, false, true ]
gap> List( tables, IsSimple );
[ false, false, true ]
gap> List( tables, IsSolvable );
[ true, true, false ]
gap> List( tables, IsSupersolvable );
[ false, false, false ]
gap> List( tables, NrConjugacyClasses );
[ 3, 5, 5 ]
gap> List( tables, Size );
[ 3, 24, 60 ]
gap> IsomorphismTypeInfoFiniteSimpleGroup( CharacterTable( "C5" ) );
rec( name := "Z(5)", parameter := 5, series := "Z", shortname := "C5"
 )
gap> IsomorphismTypeInfoFiniteSimpleGroup( CharacterTable( "S3" ) );
fail
gap> IsomorphismTypeInfoFiniteSimpleGroup( CharacterTable( "S6(3)" ) );
rec( name := "C(3,3) = S(6,3)", parameter := [ 3, 3 ], series := "C",
    shortname := "S6(3)"
 )
gap> IsomorphismTypeInfoFiniteSimpleGroup( CharacterTable( "O7(3)" ) );
rec( name := "B(3,3) = O(7,3)", parameter := [ 3, 3 ], series := "B",
    shortname := "O7(3)"
 )
gap> IsomorphismTypeInfoFiniteSimpleGroup( CharacterTable( "A8" ) );
rec( name := "A(8) ~ A(3,2) = L(4,2) ~ D(3,2) = O+(6,2)",
    parameter := 8, series := "A", shortname := "A8"
 )
gap> IsomorphismTypeInfoFiniteSimpleGroup( CharacterTable( "L3(4)" ) );
rec( name := "A(2,4) = L(3,4)", parameter := [ 3, 4 ], series := "L",
    shortname := "L3(4)"
 )

71.9 Attributes and Properties only for Character Tables

The following three attributes for character tables – OrdersClassRepresentatives (71.9.1), SizesCentralizers (71.9.2), and SizesConjugacyClasses (71.9.3) – would make sense also for groups but are in fact not used for groups. This is because the values depend on the ordering of conjugacy classes stored as the value of ConjugacyClasses (71.6.2), and this value may differ for a group and its character table (see 71.6). Note that for character tables, the consistency of attribute values must be guaranteed, whereas for groups, there is no need to impose such a consistency rule.

The other attributes introduced in this section apply only to character tables, not to groups.
71.9.1 OrdersClassRepresentatives

OrdersClassRepresentatives(tbl)

is a list of orders of representatives of conjugacy classes of the character table tbl, in the same ordering as the conjugacy classes of tbl.

Example

```
gap> tbl:= CharacterTable( "A5" );;
gap> OrdersClassRepresentatives( tbl );
[ 1, 2, 3, 5, 5 ]
```

71.9.2 SizesCentralizers

SizesCentralizers(tbl)

SizesCentralisers(tbl)

is a list that stores at position $i$ the size of the centralizer of any element in the $i$-th conjugacy class of the character table tbl.

Example

```
gap> tbl:= CharacterTable( "A5" );;
gap> SizesCentralizers( tbl );
[ 60, 4, 3, 5, 5 ]
```

71.9.3 SizesConjugacyClasses

SizesConjugacyClasses(tbl)

is a list that stores at position $i$ the size of the $i$-th conjugacy class of the character table tbl.

Example

```
gap> tbl:= CharacterTable( "A5" );;
gap> SizesConjugacyClasses( tbl );
[ 1, 15, 20, 12, 12 ]
```

71.9.4 AutomorphismsOfTable

AutomorphismsOfTable(tbl)

is the permutation group of all column permutations of the character table tbl that leave the set of irreducibles and each power map of tbl invariant (see also TableAutomorphisms (71.22.2)).

Example

```
gap> tbl:= CharacterTable( "Dihedral", 8 );;
gap> AutomorphismsOfTable( tbl );
Group([ (4,5) ]) 
gap> OrdersClassRepresentatives( tbl );
[ 1, 4, 2, 2, 2 ]
gap> SizesConjugacyClasses( tbl );
[ 1, 2, 1, 2, 2 ]
```
### 71.9.5 UnderlyingCharacteristic

- `UnderlyingCharacteristic(tbl)` (attribute)
- `UnderlyingCharacteristic(psi)` (attribute)

For an ordinary character table `tbl`, the result is 0, for a $p$-modular Brauer table `tbl`, it is $p$. The underlying characteristic of a class function `psi` is equal to that of its underlying character table.

The underlying characteristic must be stored when the table is constructed, there is no method to compute it.

We cannot use the attribute `Characteristic (31.10.1)` to denote this, since of course each Brauer character is an element of characteristic zero in the sense of GAP (see Chapter 72).

```gap
gap> tbl:= CharacterTable( "A5" );;
gap> UnderlyingCharacteristic( tbl );
0
gap> UnderlyingCharacteristic( tbl mod 17 );
17
```

### 71.9.6 Class Names and Character Names

- `ClassNames(tbl [, "ATLAS"])` (attribute)
- `CharacterNames(tbl)` (attribute)

`ClassNames` and `CharacterNames` return lists of strings, one for each conjugacy class or irreducible character, respectively, of the character table `tbl`. These names are used when `tbl` is displayed.

The default method for `ClassNames` computes class names consisting of the order of an element in the class and at least one distinguishing letter.

The default method for `CharacterNames` returns the list `[ "X.1", "X.2", ... ]`, whose length is the number of irreducible characters of `tbl`.

The position of the class with name `name` in `tbl` can be accessed as `tbl.name`.

When `ClassNames` is called with two arguments, the second being the string "ATLAS", the class names returned obey the convention used in the Atlas of Finite Groups [CCN+85, Chapter 7, Section 5]. If one is interested in “relative” class names of almost simple Atlas groups, one can use the function `AtlasClassNames (AtlasRep: AtlasClassNames)`.

```gap
gap> tbl:= CharacterTable( "A5" );;
gap> ClassNames( tbl );
[ "1a", "2a", "3a", "5a", "5b" ]
gap> tbl.2a;
2
```

### 71.9.7 Class Parameters and Character Parameters

- `ClassParameters(tbl)` (attribute)
- `CharacterParameters(tbl)` (attribute)
The values of these attributes are lists containing a parameter for each conjugacy class or irreducible character, respectively, of the character table \( tbl \).

It depends on \( tbl \) what these parameters are, so there is no default to compute class and character parameters.

For example, the classes of symmetric groups can be parametrized by partitions, corresponding to the cycle structures of permutations. Character tables constructed from generic character tables (see the manual of the GAP Character Table Library) usually have class and character parameters stored.

If \( tbl \) is a \( p \)-modular Brauer table such that class parameters are stored in the underlying ordinary table (see \texttt{OrdinaryCharacterTable (71.8.4)}) of \( tbl \) then \texttt{ClassParameters} returns the sublist of class parameters of the ordinary table, for \( p \)-regular classes.

### 71.9.8 Identifier (for character tables)

\[ \texttt{Identifier(tbl)} \]

is a string that identifies the character table \( tbl \) in the current GAP session. It is used mainly for class fusions into \( tbl \) that are stored on other character tables. For character tables without group, the identifier is also used to print the table; this is the case for library tables, but also for tables that are constructed as direct products, factors etc. involving tables that may or may not store their groups.

The default method for ordinary tables constructs strings of the form "CT\( n \)" where \( n \) is a positive integer. \texttt{LARGEST\_IDENTIFIER\_NUMBER} is a list containing the largest integer \( n \) used in the current GAP session.

The default method for Brauer tables returns the concatenation of the identifier of the ordinary table, the string "\( \text{mod} \)", and the (string of the) underlying characteristic.

#### Example

\[
\text{gap> } \text{Identifier( CharacterTable( "A5" ) )};
\]

"A5"

\[
\text{gap> tbl:= CharacterTable( Group( () ) )};
\]

\[
\text{gap> Identifier( tbl );} \quad \text{Identifier( tbl mod 2 );}
\]

"CT8"

"CT8mod2"

### 71.9.9 InfoText (for character tables)

\[ \texttt{InfoText(tbl)} \]

is a mutable string with information about the character table \( tbl \). There is no default method to create an info text.

This attribute is used mainly for library tables (see the manual of the GAP Character Table Library). Usual parts of the information are the origin of the table, tests it has passed (\texttt{1.o.r.} for the test of orthogonality, \texttt{pow[p]} for the construction of the \( p \)-th power map, \texttt{DEC} for the decomposition of ordinary into Brauer characters, \texttt{TENS} for the decomposition of tensor products of irreducibles), and choices made without loss of generality.

#### Example

\[
\text{gap> Print( InfoText( CharacterTable( "A5" ) ), "\n" );}
\]

origin: ATLAS of finite groups, tests: 1.o.r., pow[2,3,6]
71.9.10 InverseClasses

\[ \text{InverseClasses}(\text{tbl}) \]

For a character table \( \text{tbl} \), \text{InverseClasses} returns the list mapping each conjugacy class to its inverse class. This list can be regarded as \((-1)^{-1}\) power map of \( \text{tbl} \) (see \text{PowerMap} (73.1.1)).

\[
gap \text{InverseClasses( CharacterTable( "A5" ) );}
\[ [1, 2, 3, 4, 5] \]
\[
gap \text{InverseClasses( CharacterTable( "Cyclic", 3 ) );}
\[ [1, 3, 2] \]

71.9.11 RealClasses

\[ \text{RealClasses}(\text{tbl}) \]

For a character table \( \text{tbl} \), \text{RealClasses} returns the strictly sorted list of positions of classes in \( \text{tbl} \) that consist of real elements.

An element \( x \) is real iff it is conjugate to its inverse \( x^{-1} = x^{\langle x \rangle^{-1}} \).

\[
gap \text{RealClasses( CharacterTable( "A5" ) );}
\[ [1, 2, 3, 4, 5] \]
\[
gap \text{RealClasses( CharacterTable( "Cyclic", 3 ) );}
\[ [1] \]

71.9.12 ClassOrbit

\[ \text{ClassOrbit}(\text{tbl}, \text{cc}) \]

is the list of positions of those conjugacy classes of the character table \( \text{tbl} \) that are Galois conjugate to the \( \text{cc} \)-th class. That is, exactly the classes at positions given by the list returned by \text{ClassOrbit} contain generators of the cyclic group generated by an element in the \( \text{cc} \)-th class.

This information is computed from the power maps of \( \text{tbl} \).

\[
gap \text{ClassOrbit( CharacterTable( "A5" ), 4 );}
\[ [4, 5] \]

71.9.13 ClassRoots

\[ \text{ClassRoots}(\text{tbl}) \]

For a character table \( \text{tbl} \), \text{ClassRoots} returns a list containing at position \( i \) the list of positions of the classes of all nontrivial \( p \)-th roots, where \( p \) runs over the prime divisors of the \text{Size} (71.8.5) value of \( \text{tbl} \).

This information is computed from the power maps of \( \text{tbl} \).
71.10 Normal Subgroups Represented by Lists of Class Positions

The following attributes for a character table \( \text{tbl} \) correspond to attributes for the group \( G \) of \( \text{tbl} \). But instead of a normal subgroup (or a list of normal subgroups) of \( G \), they return a strictly sorted list of positive integers (or a list of such lists) which are the positions –relative to the \texttt{ConjugacyClasses(71.6.2)} value of \( \text{tbl} \)– of those classes forming the normal subgroup in question.

71.10.1 ClassPositionsOfNormalSubgroups

\[
\texttt{ClassPositionsOfNormalSubgroups}(\text{ordtbl})
\]

\[
\texttt{ClassPositionsOfMaximalNormalSubgroups}(\text{ordtbl})
\]

\[
\texttt{ClassPositionsOfMinimalNormalSubgroups}(\text{ordtbl})
\]

These correspond to \texttt{NormalSubgroups (39.19.9)}, \texttt{MaximalNormalSubgroups (39.19.10)}, \texttt{MinimalNormalSubgroups (39.19.11)} for the group of the ordinary character table \( \text{ordtbl} \).

The entries of the result lists are sorted according to increasing length. (So this total order respects the partial order of normal subgroups given by inclusion.)

\[
\texttt{Gap> tbls4:= CharacterTable( "Symmetric", 4 );;}
\texttt{Gap> ClassPositionsOfNormalSubgroups( tbls4 );}
\[
\texttt{[ [ 1 ], [ 1, 3 ], [ 1, 3, 4 ], [ 1 .. 5 ] ]}
\]

71.10.2 ClassPositionsOfAgemo

\[
\texttt{ClassPositionsOfAgemo}(\text{ordtbl}, p)
\]

This corresponds to \texttt{Agemo (39.14.2)} for the group of the ordinary character table \( \text{ordtbl} \).

\[
\texttt{Gap> tbls4:= CharacterTable( "Symmetric", 4 );;}
\texttt{Gap> ClassPositionsOfAgemo( tbls4, 2 );}
\[
\texttt{[ 1, 3, 4 ]}
\]

71.10.3 ClassPositionsOfCentre (for a character table)

\[
\texttt{ClassPositionsOfCentre}(\text{ordtbl})
\]

This corresponds to \texttt{Centre (35.4.5)} for the group of the ordinary character table \( \text{ordtbl} \).
71.10.4 ClassPositionsOfDirectProductDecompositions

\[ \text{ClassPositionsOfDirectProductDecompositions}(\text{tbl}[\text{, nclasses}]) \]

Let \( \text{tbl} \) be the ordinary character table of the group \( G \), say. Called with the only argument \( \text{tbl} \), \text{ClassPositionsOfDirectProductDecompositions} returns the list of all those pairs \([l_1, l_2]\) where \( l_1 \) and \( l_2 \) are lists of class positions of normal subgroups \( N_1, N_2 \) of \( G \) such that \( G \) is their direct product and \(|N_1| \leq |N_2|\) holds. Called with second argument a list \( \text{nclasses} \) of class positions of a normal subgroup \( N \) of \( G \), \text{ClassPositionsOfDirectProductDecompositions} returns the list of pairs describing the decomposition of \( N \) as a direct product of two normal subgroups of \( G \).

71.10.5 ClassPositionsOfDerivedSubgroup

\[ \text{ClassPositionsOfDerivedSubgroup}(\text{ordtbl}) \]

corresponds to \text{DerivedSubgroup} (39.12.3) for the group of the ordinary character table \( \text{ordtbl} \).

Example

```gap
gap> tbld8:= CharacterTable( "Dihedral", 8 );;
gap> ClassPositionsOfDerivedSubgroup( tbld8 );
[ 1, 3 ]
```

71.10.6 ClassPositionsOfElementaryAbelianSeries

\[ \text{ClassPositionsOfElementaryAbelianSeries}(\text{ordtbl}) \]

corresponds to \text{ElementaryAbelianSeries} (39.17.9) for the group of the ordinary character table \( \text{ordtbl} \).

Example

```gap
gap> tbls4:= CharacterTable( "Symmetric", 4 );;
gap> tbla5:= CharacterTable( "A5" );;
gap> ClassPositionsOfElementaryAbelianSeries( tbls4 );
[ [ 1 .. 5 ], [ 1, 3, 4 ], [ 1, 3 ], [ 1 ] ]
gap> ClassPositionsOfElementaryAbelianSeries( tbla5 );
fail
```

71.10.7 ClassPositionsOfFittingSubgroup

\[ \text{ClassPositionsOfFittingSubgroup}(\text{ordtbl}) \]

corresponds to \text{FittingSubgroup} (39.12.5) for the group of the ordinary character table \( \text{ordtbl} \).

Example

```gap
gap> tbls4:= CharacterTable( "Symmetric", 4 );;
gap> ClassPositionsOfFittingSubgroup( tbls4 );
[ 1, 3 ]
```
71.10.8 ClassPositionsOfLowerCentralSeries

\[ \text{ClassPositionsOfLowerCentralSeries} \]

\[ \text{corresponds to LowerCentralSeriesOfGroup (39.17.11) for the group of the ordinary character table ordtbl.} \]

\[ \text{Example} \]

\[ \text{gap> tbls4:= CharacterTable("Symmetric", 4);} \]
\[ \text{gap> tbld8:= CharacterTable("Dihedral", 8);} \]
\[ \text{gap> ClassPositionsOfLowerCentralSeries( tbls4 );} \]
\[ \text{[ [ 1 .. 5 ], [ 1, 3, 4 ] ]} \]
\[ \text{gap> ClassPositionsOfLowerCentralSeries( tbld8 );} \]
\[ \text{[ [ 1 .. 5 ], [ 1, 3 ], [ 1 ] ]} \]

71.10.9 ClassPositionsOfUpperCentralSeries

\[ \text{ClassPositionsOfUpperCentralSeries} \]

\[ \text{corresponds to UpperCentralSeriesOfGroup (39.17.12) for the group of the ordinary character table ordtbl.} \]

\[ \text{Example} \]

\[ \text{gap> tbls4:= CharacterTable("Symmetric", 4);} \]
\[ \text{gap> tbld8:= CharacterTable("Dihedral", 8);} \]
\[ \text{gap> ClassPositionsOfUpperCentralSeries( tbls4 );} \]
\[ \text{[ [ 1 ] ]} \]
\[ \text{gap> ClassPositionsOfUpperCentralSeries( tbld8 );} \]
\[ \text{[ [ 1, 3 ], [ 1, 2, 3, 4, 5 ] ]} \]

71.10.10 ClassPositionsOfSolvableRadical

\[ \text{ClassPositionsOfSolvableRadical} \]

\[ \text{corresponds to RadicalGroup (39.12.9) for the group of the ordinary character table ordtbl.} \]

\[ \text{Example} \]

\[ \text{gap> ClassPositionsOfSolvableRadical( CharacterTable("2.A5") );} \]
\[ \text{[ [ 1, 2 ] ]} \]

71.10.11 ClassPositionsOfSupersolvableResiduum

\[ \text{ClassPositionsOfSupersolvableResiduum} \]

\[ \text{corresponds to SupersolvableResiduum (39.12.11) for the group of the ordinary character table ordtbl.} \]

\[ \text{Example} \]

\[ \text{gap> tbls4:= CharacterTable("Symmetric", 4);} \]
\[ \text{gap> ClassPositionsOfSupersolvableResiduum( tbls4 );} \]
\[ \text{[ [ 1, 3 ] ]} \]
71.10.12 ClassPositionsOfPCore

\[ \text{ClassPositionsOfPCore}(\text{ordtbl}, p) \] (operation)

Corresponds to \text{PCore} (39.11.3) for the group of the ordinary character table \text{ordtbl}.

Example

\[
\text{gap> tbls4:= CharacterTable( "Symmetric", 4 );;}
\text{gap> ClassPositionsOfPCore( tbls4, 2 );}
\text{[ 1, 3 ]}
\text{gap> ClassPositionsOfPCore( tbls4, 3 );}
\text{[ 1 ]}
\]

71.10.13 ClassPositionsOfNormalClosure

\[ \text{ClassPositionsOfNormalClosure}(\text{ordtbl}, \text{classes}) \] (operation)

Is the sorted list of the positions of all conjugacy classes of the ordinary character table \text{ordtbl} that form the normal closure (see \text{NormalClosure} (39.11.4)) of the conjugacy classes at positions in the list \text{classes}.

Example

\[
\text{gap> tbls4:= CharacterTable( "Symmetric", 4 );;}
\text{gap> ClassPositionsOfNormalClosure( tbls4, [ 1, 4 ] );}
\text{[ 1, 3, 4 ]}
\]

71.11 Operations Concerning Blocks

71.11.1 PrimeBlocks

\[ \text{PrimeBlocks}(\text{ordtbl}, p) \] (operation)
\[ \text{PrimeBlocksOp}(\text{ordtbl}, p) \] (operation)
\[ \text{ComputedPrimeBlockss}(\text{tbl}) \] (attribute)

For an ordinary character table \text{ordtbl} and a prime integer \( p \), \text{PrimeBlocks} returns a record with the following components.

- **block**
  - A list, the value \( j \) at position \( i \) means that the \( i \)-th irreducible character of \text{ordtbl} lies in the \( j \)-th \( p \)-block of \text{ordtbl},

- **defect**
  - A list containing at position \( i \) the defect of the \( i \)-th block,

- **height**
  - A list containing at position \( i \) the height of the \( i \)-th irreducible character of \text{ordtbl} in its block,

- **relevant**
  - A list of class positions such that only the restriction to these classes need be checked for deciding whether two characters lie in the same block, and
central character

a list containing at position $i$ a list whose values at the positions stored in the component relevant are the values of a central character in the $i$-th block.

The components relevant and central characters are used by SameBlock (71.11.2).

If InfoCharacterTable (71.4.2) has level at least 2, the defects of the blocks and the heights of the characters are printed.

The default method uses the attribute ComputedPrimeBlocks for storing the computed value at position $p$, and calls the operation PrimeBlocksOp for computing values that are not yet known.

Two ordinary irreducible characters $\chi$, $\psi$ of a group $G$ are said to lie in the same $p$-block if the images of their central characters $\omega_\chi, \omega_\psi$ (see CentralCharacter (72.8.17)) under the natural ring epimorphism $R \to R/M$ are equal, where $R$ denotes the ring of algebraic integers in the complex number field, and $M$ is a maximal ideal in $R$ with $pR \subseteq M$. (The distribution to $p$-blocks is in fact independent of the choice of $M$, see [Isa76].)

For $|G| = p^a m$ where $p$ does not divide $m$, the defect of a block is the integer $d$ such that $p^{a-d}$ is the largest power of $p$ that divides the degrees of all characters in the block.

The height of a character $\chi$ in the block is defined as the largest exponent $h$ for which $p^h$ divides $\chi(1)/p^{a-d}$.

Example

```gap
gap> tbl:= CharacterTable( "L3(2)" );;
gap> pbl:= PrimeBlocks( tbl, 2 );
rec( block := [ 1, 1, 1, 1, 1, 2 ],
    centralcharacter := [ [,, 56,, 24 ], [,, -7,, 3 ] ],
    defect := [ 3, 0 ],
    height := [ 0, 0, 0, 1, 0, 0 ],
    relevant := [ 3, 5 ] )
```

71.11.2 SameBlock

▷ SameBlock($p$, omega1, omega2, relevant) (function)

Let $p$ be a prime integer, $\omega_1$ and $\omega_2$ be two central characters (or their values lists) of a character table, and relevant be a list of positions as is stored in the component relevant of a record returned by PrimeBlocks (71.11.1).

SameBlock returns true if $\omega_1$ and $\omega_2$ are equal modulo any maximal ideal in the ring of complex algebraic integers containing the ideal spanned by $p$, and false otherwise.

Example

```gap
gap> omega:= List( Irr( tbl ), CentralCharacter );;
gap> SameBlock( 2, omega[1], omega[2], pbl.relevant );
true
gap> SameBlock( 2, omega[1], omega[6], pbl.relevant );
false
```

71.11.3 BlocksInfo

▷ BlocksInfo(modtbl) (attribute)

For a Brauer character table modtbl, the value of BlocksInfo is a list of (mutable) records, the $i$-th entry containing information about the $i$-th block. Each record has the following components.
defect
  the defect of the block,

ordchars
  the list of positions of the ordinary characters that belong to the block, relative to \( \text{Irr}(\text{OrdinaryCharacterTable}(\text{modtbl})) \),

modchars
  the list of positions of the Brauer characters that belong to the block, relative to \( \text{IBr}(\text{modtbl}) \).

Optional components are

basicset
  a list of positions of ordinary characters in the block whose restriction to \text{modtbl} is maximally linearly independent, relative to \( \text{Irr}(\text{OrdinaryCharacterTable}(\text{modtbl})) \),

decmat
  the decomposition matrix of the block, it is stored automatically when \text{DecompositionMatrix} (71.11.4) is called for the block,

decinv
  inverse of the decomposition matrix of the block, restricted to the ordinary characters described by basicset,

brauertree
  a list that describes the Brauer tree of the block, in the case that the block is of defect 1.

Example

```
gap> BlocksInfo( CharacterTable( "L3(2)" ) mod 2 );
[ rec( basicset := [ 1, 2, 3 ],
  decinv := [ [ 1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, 1 ] ],
  defect := 3, modchars := [ 1, 2, 3 ],
  ordchars := [ 1, 2, 3, 4, 5 ] ),
  rec( basicset := [ 6 ], decinv := [ [ 1 ] ], defect := 0,
    modchars := [ 4 ], ordchars := [ 6 ] ) ]
```

71.11.4 DecompositionMatrix

\text{DecompositionMatrix} (\text{modtbl}[, \text{blocknr}])  \hspace{1em} (\text{operation})

Let \text{modtbl} be a Brauer character table.

Called with one argument, \text{DecompositionMatrix} returns the decomposition matrix of \text{modtbl}, where the rows and columns are indexed by the irreducible characters of the ordinary character table of \text{modtbl} and the irreducible characters of \text{modtbl}, respectively.

Called with two arguments, \text{DecompositionMatrix} returns the decomposition matrix of the block of \text{modtbl} with number \text{blocknr}; the matrix is stored as value of the \text{decmat} component of the \text{blocknr}-th entry of the \text{BlocksInfo} (71.11.3) list of \text{modtbl}.

An ordinary irreducible character is in block \( i \) if and only if all characters before the first character of the same block lie in \( i - 1 \) different blocks. An irreducible Brauer character is in block \( i \) if it has nonzero scalar product with an ordinary irreducible character in block \( i \).

\text{DecompositionMatrix} is based on the more general function \text{Decomposition} (25.4.1).
Example

```gap
modtbl:= CharacterTable( "L3(2)" ) mod 2;
BrauerTable( "L3(2)" , 2 );
DecompositionMatrix( modtbl );
DecompositionMatrix( modtbl, 1 );
DecompositionMatrix( modtbl, 2 );
```

71.11.5 \LaTeXStringDecompositionMatrix

\[ \text{LaTeXStringDecompositionMatrix( modtbl[, blocknr][, options])} \]

is a string that contains \LaTeX code to print a decomposition matrix (see \text{DecompositionMatrix (71.11.4)}) nicely.

The optional argument \text{options}, if present, must be a record with components \text{phi}, \text{chi} (strings used in each label for columns and rows), \text{collabels}, \text{rowlabels} (subscripts for the labels). The defaults for \text{phi} and \text{chi} are "\{\tt Y\}" and "\{\tt X\}", the defaults for \text{collabels} and \text{rowlabels} are the lists of positions of the Brauer characters and ordinary characters in the respective lists of irreducibles in the character tables.

The optional components \text{nrows} and \text{ncols} denote the maximal number of rows and columns per array; if they are present then each portion of \text{nrows} rows and \text{ncols} columns forms an array of its own which is enclosed in \[\].

If the component \text{decmat} is bound in \text{options} then it must be the decomposition matrix in question, in this case the matrix is not computed from the information in \text{modtbl}.

For those character tables from the GAP table library that belong to the Atlas of Finite Groups \cite{Atlas}, \text{AtlasLabelsOfIrreducibles (CTblLib: AtlasLabelsOfIrreducibles)} constructs character labels that are compatible with those used in the Atlas (see \text{(CTblLib: Atlas Tables)} in the manual of the GAP Character Table Library).

```gap
modtbl:= CharacterTable( "L3(2)" ) mod 2;
Print( LaTeXStringDecompositionMatrix( modtbl, 1 ) );
```

```
Example
```

```gap
options:= rec( phi:= "\varphi", chi:= "\chi" );
```
\begin{verbatim}
\gap> Print( LaTeXStringDecompositionMatrix( modtbl, 1, options ) );
\[
\begin{array}{r|rrr}
& \varphi_{1} & \varphi_{2} & \varphi_{3} \\
\hline
\chi_{1} & 1 & . & . \\
\chi_{2} & . & 1 & . \\
\chi_{3} & . & . & 1 \\
\chi_{4} & . & 1 & 1 \\
\chi_{5} & 1 & 1 & 1 \\
\hline
\end{array}
\end{verbatim}

71.12 Other Operations for Character Tables

In the following, we list operations for character tables that are not attributes.

71.12.1 Index (for two character tables)

\begin{verbatim}
\gap> \texttt{Index}\texttt{(}tbl, subtbl\texttt{)}
\end{verbatim}

For two character tables \texttt{tbl} and \texttt{subtbl}, \texttt{Index} returns the quotient of the \texttt{Size} (71.8.5) values of \texttt{tbl} and \texttt{subtbl}. The containment of the underlying groups of \texttt{subtbl} and \texttt{tbl} is \textit{not} checked; so the distinction between \texttt{Index} (39.3.2) and \texttt{IndexNC} (39.3.2) is not made for character tables.

71.12.2 IsInternallyConsistent (for character tables)

\begin{verbatim}
\gap> \texttt{IsInternallyConsistent\texttt{(}tbl\texttt{)}}
\end{verbatim}

For an \textit{ordinary} character table \texttt{tbl}, \texttt{IsInternallyConsistent} (12.8.4) checks the consistency of the following attribute values (if stored).

\begin{itemize}
\item Size (30.4.6), SizesCentralizers (71.9.2), and SizesConjugacyClasses (71.9.3).
\item SizesCentralizers (71.9.2) and OrdersClassRepresentatives (71.9.1).
\item ComputedPowerMaps (73.1.1) and OrdersClassRepresentatives (71.9.1).
\item SizesCentralizers (71.9.2) and Irr (71.8.2).
\item Irr (71.8.2) (first orthogonality relation).
\end{itemize}

For a \textit{Brauer} table \texttt{tbl}, \texttt{IsInternallyConsistent} checks the consistency of the following attribute values (if stored).

\begin{itemize}
\item Size (30.4.6), SizesCentralizers (71.9.2), and SizesConjugacyClasses (71.9.3).
\item SizesCentralizers (71.9.2) and OrdersClassRepresentatives (71.9.1).
\end{itemize}
• ComputedPowerMaps (73.1.1) and OrdersClassRepresentatives (71.9.1).

• Irr (71.8.2) (closure under complex conjugation and Frobenius map).

If no inconsistency occurs, true is returned, otherwise each inconsistency is printed to the screen if the level of InfoWarning (7.4.8) is at least 1 (see 7.4), and false is returned at the end.

71.12.3 IsPSolvableCharacterTable

\[ \text{IsPSolvableCharacterTable} \]
\[ \text{IsPSolvableCharacterTableOp} \]
\[ \text{ComputedIsPSolvableCharacterTables} \]
\[ \text{ComputedIsPSolubleCharacterTables} \]

IsPSolvableCharacterTable for the ordinary character table \( \text{tbl} \) corresponds to IsPSolvable (39.15.24) for the group of \( \text{tbl} \), \( p \) must be either a prime integer or 0.

The default method uses the attribute ComputedIsPSolvableCharacterTables for storing the computed value at position \( p \), and calls the operation IsPSolvableCharacterTableOp for computing values that are not yet known.

Example

\[
\text{gap> tbl:= CharacterTable( "Sz(8)" );;}
\text{gap> IsPSolvableCharacterTable( tbl, 2 );}
\text{false}
\text{gap> IsPSolvableCharacterTable( tbl, 3 );}
\text{true}
\]

71.12.4 IsClassFusionOfNormalSubgroup

\[ \text{IsClassFusionOfNormalSubgroup} \]

For two ordinary character tables \( \text{tbl} \) and \( \text{subtbl} \) of a group \( G \) and its subgroup \( U \), say, and a list \( \text{fus} \) of positive integers that describes the class fusion of \( U \) into \( G \), IsClassFusionOfNormalSubgroup returns true if \( U \) is a normal subgroup of \( G \), and false otherwise.

Example

\[
\text{gap> tblc2:= CharacterTable( "Cyclic", 2 );;}
\text{gap> tbld8:= CharacterTable( "Dihedral", 8 );;}
\text{gap> fus:= PossibleClassFusions( tblc2, tbld8 );}
\text{[ [ 1, 3 ], [ 1, 4 ], [ 1, 5 ] ]}
\text{gap> List(fus, map -> IsClassFusionOfNormalSubgroup(tblc2, map, tbld8));}
\text{[ true, false, false ]}
\]

71.12.5 Indicator

\[ \text{Indicator} \]
\[ \text{IndicatorOp} \]
\[ \nu_n(\chi) = \left( \sum_{g \in G} \chi(g^n) \right) / |G| \]

If \( tbl \) is a Brauer table in characteristic \( \neq 2 \) and \( n = 2 \) then \( \text{Indicator} \) returns the second indicator.

The default method uses the attribute \( \text{ComputedIndicators} \) for storing the computed value at position \( n \), and calls the operation \( \text{IndicatorOp} \) for computing values that are not yet known.

Example

\[
\text{gap> tbl:= CharacterTable( "L3(2)" );;}
\text{gap> Indicator( tbl, 2 );}
[ 1, 0, 0, 1, 1, 1 ]
\]

71.12.6 \textbf{NrPolyhedralSubgroups}

\[ \text{NrPolyhedralSubgroups}(tbl, c1, c2, c3) \]

returns the number and isomorphism type of polyhedral subgroups of the group with ordinary character table \( tbl \) which are generated by an element \( g \) of class \( c1 \) and an element \( h \) of class \( c2 \) with the property that the product \( gh \) lies in class \( c3 \).

According to [NPP84, p. 233], the number of polyhedral subgroups of isomorphism type \( V_4, D_{2n}, A_4, S_4, \) and \( A_5 \) can be derived from the class multiplication coefficient (see \text{ClassMultiplicationCoefficient} (71.12.7)) and the number of Galois conjugates of a class (see \text{ClassOrbit} (71.9.12)).

The classes \( c1, c2 \) and \( c3 \) in the parameter list must be ordered according to the order of the elements in these classes. If elements in class \( c1 \) and \( c2 \) do not generate a polyhedral group then \( \text{fail} \) is returned.

Example

\[
\text{gap> NrPolyhedralSubgroups( tbl, 2, 2, 4 );}
\text{rec( number := 21, type := "D8" )}
\]

71.12.7 \textbf{ClassMultiplicationCoefficient} (for character tables)

\[ \text{ClassMultiplicationCoefficient}(tbl, i, j, k) \]

returns the class multiplication coefficient of the classes \( i, j, \) and \( k \) of the group \( G \) with ordinary character table \( tbl \).

The class multiplication coefficient \( c_{i,j,k} \) of the classes \( i, j, k \) equals the number of pairs \((x,y)\) of elements \( x, y \in G \) such that \( x \) lies in class \( i \), \( y \) lies in class \( j \), and their product \( xy \) is a fixed element of class \( k \).

In the center of the group algebra of \( G \), these numbers are found as coefficients of the decomposition of the product of two class sums \( K_i \) and \( K_j \) into class sums:

\[ K_iK_j = \sum_k c_{ijk}K_k. \]
Given the character table of a finite group \( G \), whose classes are \( C_1, \ldots, C_r \) with representatives \( g_i \in C_i \), the class multiplication coefficient \( c_{ijk} \) can be computed with the following formula:

\[
c_{ijk} = |C_i| \cdot |C_j| / |G| \cdot \sum_{\chi \in \text{Irr}(G)} \chi(g_i) \chi(g_j) \chi(g_k^{-1}) / \chi(1).
\]

On the other hand, the knowledge of the class multiplication coefficients admits the computation of the irreducible characters of \( G \), see \( \text{IrrDixonSchneider} \) (71.14.1).

### 71.12.8 ClassStructureCharTable

\[ \text{ClassStructureCharTable}(\text{tbl}, \text{classes}) \]

returns the so-called class structure of the classes in the list \( \text{classes} \), for the character table \( \text{tbl} \) of the group \( G \). The length of \( \text{classes} \) must be at least 2.

Let \( C = (C_1, C_2, \ldots, C_n) \) denote the \( n \)-tuple of conjugacy classes of \( G \) that are indexed by \( \text{classes} \). The class structure \( n(C) \) equals the number of \( n \)-tuples \( (g_1, g_2, \ldots, g_n) \) of elements \( g_i \in C_i \) with \( g_1 g_2 \cdots g_n = 1 \). Note the difference to the definition of the class multiplication coefficients in \( \text{ClassMultiplicationCoefficient} \) (71.12.7).

\[
n(C_1, C_2, \ldots, C_n) = |C_1||C_2|\cdots|C_n|/|G| \cdot \sum_{\chi \in \text{Irr}(G)} \chi(g_1) \chi(g_2) \cdots \chi(g_n) / \chi(1)^{n-2}.
\]

### 71.12.9 MatClassMultCoeffsCharTable

\[ \text{MatClassMultCoeffsCharTable}(\text{tbl}, i) \]

For an ordinary character table \( \text{tbl} \) and a class position \( i \), \text{MatClassMultCoeffsCharTable} returns the matrix \( [a_{ijk}]_{j,k} \) of structure constants (see \( \text{ClassMultiplicationCoefficient} \) (71.12.7)).

**Example**

```gap
gap> tbl := CharacterTable( "L3(2)" );;
gap> ClassMultiplicationCoefficient( tbl, 2, 2, 4 );
gap> ClassStructureCharTable( tbl, [ 2, 2, 4 ] );
gap> ClassStructureCharTable( tbl, [ 2, 2, 4 ] );
gap> MatClassMultCoeffsCharTable( tbl, 2 );
[ [ 0, 1, 0, 0, 0, 0 ], [ 21, 4, 3, 4, 0, 0 ], [ 0, 8, 6, 8, 7, 7 ],
  [ 0, 8, 6, 1, 7, 7 ], [ 0, 0, 3, 4, 0, 7 ], [ 0, 0, 3, 4, 7, 0 ] ]
```

### 71.13 Printing Character Tables

#### 71.13.1 ViewObj (for a character table)

\[ \text{ViewObj}(\text{tbl}) \]

(method)
The default ViewObj (6.3.5) method for ordinary character tables prints the string "CharacterTable", followed by the identifier (see Identifier (71.9.8)) or, if known, the group of the character table enclosed in brackets. ViewObj (6.3.5) for Brauer tables does the same, except that the first string is replaced by "BrauerTable", and that the characteristic is also shown.

71.13.2 PrintObj (for a character table)

▷ PrintObj(tbl)

The default PrintObj (6.3.5) method for character tables does the same as ViewObj (6.3.5), except that PrintObj (6.3.5) is used for the group instead of ViewObj (6.3.5).

71.13.3 Display (for a character table)

▷ Display(tbl)

There are various ways to customize the Display (6.3.6) output for character tables. First we describe the default behaviour, alternatives are then described below.

The default Display (6.3.6) method prepares the data in tbl for a columnwise output. The number of columns printed at one time depends on the actual line length, which can be accessed and changed by the function SizeScreen (6.12.1).

An interesting variant of Display (6.3.6) is the function PageDisplay (GAPDoc: PageDisplay). Convenient ways to print the Display (6.3.6) format to a file are given by the function PrintTo1 (GAPDoc: PrintTo1) or by using PageDisplay (GAPDoc: PageDisplay) and the facilities of the pager used, cf. Pager (2.4.1).

An interactive variant of Display (6.3.6) is the Browse (Browse: Browse) method for character tables that is provided by the GAP package Browse, see Browse (Browse: Browse for character tables).

Display (6.3.6) shows certain characters (by default all irreducible characters) of tbl, together with the orders of the centralizers in factorized form and the available power maps (see ComputedPowerMaps (73.1.1)). The $n$-th displayed character is given the name $X.n$.

The first lines of the output describe the order of the centralizer of an element of the class factorized into its prime divisors.

The next line gives the name of each class. If no class names are stored on tbl, ClassNames (71.9.6) is called.

Preceded by a name $P.n$, the next lines show the $n$th power maps of tbl in terms of the former shown class names.

Every ambiguous or unknown (see Chapter 74) value of the table is displayed as a question mark ?.

Irrational character values are not printed explicitly because the lengths of their printed representation might disturb the layout. Instead of that every irrational value is indicated by a name, which is a string of at least one capital letter.

Once a name for an irrational value is found, it is used all over the printed table. Moreover the complex conjugate (see ComplexConjugate (18.5.2), GaloisCyc (18.5.1)) and the star of an irrationality (see StarCyc (18.5.3)) are represented by that very name preceded by a / and a *, respectively.

The printed character table is then followed by a legend, a list identifying the occurring symbols with their actual values. Occasionally this identification is supplemented by a quadratic represen-
tation of the irrationality (see Quadratic (18.5.4)) together with the corresponding Atlas notation (see [CCN+85]).

This default style can be changed by prescribing a record arec of options, which can be given

1. as an optional argument in the call to Display (6.3.6),
2. as the value of the attribute DisplayOptions (71.13.4) if this value is stored in the table,
3. as the value of the global variable CharacterTableDisplayDefaults.User, or
4. as the value of the global variable CharacterTableDisplayDefaults.Global

(in this order of precedence).

The following components of arec are supported.

centralizers
- false to suppress the printing of the orders of the centralizers, or the string "ATLAS" to force the printing of non-factorized centralizer orders in a style similar to that used in the Atlas of Finite Groups [CCN+85],

chars
- an integer or a list of integers to select a sublist of the irreducible characters of tbl, or a list of characters of tbl (in the latter case, the default letter "X" in the character names is replaced by "Y"),

charnames
- a list of strings of length equal to the number of characters that shall be shown; they are used as labels for the characters,

classes
- an integer or a list of integers to select a sublist of the classes of tbl,

classnames
- a list of strings of length equal to the number of classes that shall be shown; they are used as labels for the classes,

indicator
- true enables the printing of the second Frobenius Schur indicator, a list of integers enables the printing of the corresponding indicators (see Indicator (71.12.5)),

letter
- a single capital letter (e. g. "P" for permutation characters) to replace the default "X" in character names,

powermap
- an integer or a list of integers to select a subset of the available power maps, false to suppress the printing of power maps, or the string "ATLAS" to force a printing of class names and power maps in a style similar to that used in the Atlas of Finite Groups [CCN+85] (the "ATLAS" variant works only if the function CambridgeMaps (CTblLib: CambridgeMaps) is available, which belongs to the CTblLib package),
Display
the function that is actually called in order to display the table; the arguments are the table and
the optional record, whose components can be used inside the Display function.

StringEntry
a function that takes either a character value or a character value and the return value of
StringEntryData (see below), and returns the string that is actually displayed; it is called
for all character values to be displayed, and also for the displayed indicator values (see above),

StringEntryData
a unary function that is called once with argument tbl before the character values are displayed;
it returns an object that is used as second argument of the function StringEntry,

Legend
a function that takes the result of the StringEntryData call as its only argument, after the
character table has been displayed; the return value is a string that describes the symbols used
in the displayed table in a formatted way, it is printed below the displayed table.

71.13.4 DisplayOptions

DisplayOptions(tbl) (attribute)

There is no default method to compute a value, one can set a value with SetDisplayOptions.

Example

```
gap> tbl := CharacterTable("A5");
gap> Display(tbl);
A5
  2  2  2  .  .  .
  3  1  .  1  .  .
  5  1  .  1  1  1

  1a  2a  3a  5a  5b
  2P 1a  1a  3a  5b  5a
  3P 1a  2a  1a  5b  5a
  5P 1a  2a  3a  1a  1a

X.1  1  1  1  1  1
X.2  3  -1  .  A *A
X.3  3  -1  .  *A  A
X.4  4  .  1  -1 -1
X.5  5  1  -1  .  .

A = -E(5)-E(5)^4
   = (1-Sqrt(5))/2 = -b5
gap> CharacterTableDisplayDefaults.User := rec(
  powermap := "ATLAS", centralizers := "ATLAS", chars := false);
gap> Display( CharacterTable("A5") );
A5
  60  4  3  5  5
```
gap> options := rec( chars := 4, classes := [ tbl.3a .. tbl.5a ],
>                   centralizers := false, indicator := true,
>                   powermap := [ 2 ] );
gap> Display( tbl, options );
A5
  3a   5a
  2P 3a 5b
  2
 X.4  +   1 -1

gap> SetDisplayOptions( tbl, options ); Display( tbl );
A5
  3a   5a
  2P 3a 5b
  2
 X.4  +   1 -1

gap> Unbind( CharacterTableDisplayDefaults.User );

71.13.5 PrintCharacterTable

\[ \text{PrintCharacterTable}(\ tbl, \ \text{varname}) \] (function)

Let \( \text{tbl} \) be a nearly character table, and \( \text{varname} \) a string. \text{PrintCharacterTable} prints those values of the supported attributes (see \text{SupportedCharacterTableInfo} (71.3.4)) that are known for \( \text{tbl} \).

The output of \text{PrintCharacterTable} is \text{GAP} readable; actually reading it into \text{GAP} will bind the variable with name \( \text{varname} \) to a character table that coincides with \( \text{tbl} \) for all printed components.

This is used mainly for saving character tables to files. A more human readable form is produced by \text{Display} (6.3.6).

Example

gap> PrintCharacterTable( CharacterTable( "Cyclic", 2 ), "tbl" );
tbl := function()
  local tbl, i;
  tbl := rec();
  tbl.Irr := [
    [ 1, 1 ], [ 1, -1 ] ];
  tbl.IsFinite := true;
  tbl.NrConjugacyClasses := 2;
  tbl.Size := 2;
  tbl.OrdersClassRepresentatives := [ 1, 2 ];
  tbl.SizesCentralizers :=


71.14 Computing the Irreducible Characters of a Group

Several algorithms are available for computing the irreducible characters of a finite group $G$. The default method for arbitrary finite groups is to use the Dixon-Schneider algorithm (see `IrrDixonSchneider (71.14.1)`). For supersolvable groups, Conlon’s algorithm can be used (see `IrrConlon (71.14.2)`). For abelian-by-supersolvable groups, the Baum-Clausen algorithm for computing the irreducible representations (see `IrreducibleRepresentations (71.14.4)` can be used to compute the irreducible characters (see `IrrBaumClausen (71.14.3)`).

These functions are installed in methods for `Irr (71.8.2)`, but explicitly calling one of them will not set the `Irr (71.8.2)` value of $G$.

71.14.1 `IrrDixonSchneider`

`IrrDixonSchneider(G)` computes the irreducible characters of the finite group $G$, using the Dixon-Schneider method (see 71.16). It calls `DixonInit (71.17.2)` and `DixonSplit (71.17.4)`, and finally returns the list returned by `DixontinI (71.17.3)`. See also the sections 71.18 and 71.19.

71.14.2 `IrrConlon`

`IrrConlon(G)` returns a list of certain irreducible characters of $G$, among those all irreducibles that have the supersolvable residuum of $G$ in their kernels; so if $G$ is supersolvable, all irreducible characters of $G$ are returned. An error is signalled if $G$ is not solvable.

The characters are computed using Conlon’s algorithm (see [Con90a] and [Con90b]). For each irreducible character in the returned list, the monomiality information (see `TestMonomial (75.4.1)`) is stored.
71.14.3  IrrBaumClausen

\texttt{IrrBaumClausen(G)}

\texttt{IrrBaumClausen} returns the absolutely irreducible ordinary characters of the factor group of the finite solvable group \(G\) by the derived subgroup of its supersolvable residuum.

The characters are computed using the algorithm by Baum and Clausen (see [BC94]). An error is signalled if \(G\) is not solvable.

\begin{verbatim}
gap> g := SL(2,3);;
gap> irr1 := IrrDixonSchneider( g );
[ Character( CharacterTable( SL(2,3) ), [ 1, 1, 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 1, E(3)^2, E(3), 1, E(3), E(3)^2, 1 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 1, E(3), E(3)^2, 1, E(3)^2, E(3), 1 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 2, 1, 1, -2, -1, -1, 0 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 2, E(3)^2, E(3), -2, -E(3), -E(3)^2, 0 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 2, E(3), E(3)^2, -2, -E(3)^2, -E(3), 0 ] ),
  Character( CharacterTable( SL(2,3) ), [ 3, 0, 0, 3, 0, 0, -1 ] ) ]
gap> irr2 := IrrConlon( g );
[ Character( CharacterTable( SL(2,3) ), [ 1, 1, 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 1, E(3), E(3)^2, 1, E(3)^2, E(3), 1 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 1, E(3)^2, E(3), 1, E(3)^2, E(3), 1 ] ),
  Character( CharacterTable( SL(2,3) ), [ 3, 0, 0, 3, 0, 0, -1 ] ) ]
gap> irr3 := IrrBaumClausen( g );
[ Character( CharacterTable( SL(2,3) ), [ 1, 1, 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 1, E(3), E(3)^2, 1, E(3)^2, E(3), 1 ] ),
  Character( CharacterTable( SL(2,3) ),
    [ 1, E(3)^2, E(3), 1, E(3)^2, E(3), 1 ] ),
  Character( CharacterTable( SL(2,3) ), [ 3, 0, 0, 3, 0, 0, -1 ] ) ]
gap> chi := irr2[4];; HasTestMonomial( chi );
true
\end{verbatim}

71.14.4  IrreducibleRepresentations

\texttt{IrreducibleRepresentations(G[, F])}

 Called with a finite group \(G\) and a field \(F\), \texttt{IrreducibleRepresentations} returns a list of representatives of the irreducible matrix representations of \(G\) over \(F\), up to equivalence.

If \(G\) is the only argument then \texttt{IrreducibleRepresentations} returns a list of representatives of the absolutely irreducible complex representations of \(G\), up to equivalence.

At the moment, methods are available for the following cases: If \(G\) is abelian by supersolvable the method of [BC94] is used.
Otherwise, if $F$ and $G$ are both finite, the regular module of $G$ is split by MeatAxe methods which can make this an expensive operation.

Finally, if $F$ is not given (i.e., it defaults to the cyclotomic numbers) and $G$ is a finite group, the method of [Dix93] (see IrreducibleRepresentationsDixon (71.14.5)) is used.

For other cases no methods are implemented yet.

The representations obtained are not guaranteed to be “nice” (for example preserving a unitary form) in any way.

See also IrreducibleModules (71.15.1), which provides efficient methods for solvable groups.

Example

```gap
gap> g:= AlternatingGroup( 4 );;
gap> repr:= IrreducibleRepresentations( g );
[ Pcgs([ (2,4,3), (1,3)(2,4), (1,2)(3,4) ]) ->
  Pcgs([ (2,4,3), (1,3)(2,4), (1,2)(3,4) ]) ->
  Pcgs([ (2,4,3), (1,3)(2,4), (1,2)(3,4) ]) ->
  Pcgs([ (2,4,3), (1,3)(2,4), (1,2)(3,4) ]) ->
  [ [ [ -1, 0, 0 ], [ 0, 1, 0 ], [ 0, 0, -1 ] ],
    [ 1, 0, 0 ], [ 0, -1, 0 ], [ 0, 0, -1 ] ] ]

gap> ForAll( repr, IsGroupHomomorphism );
true

gap> gens:= GeneratorsOfGroup( g );
[ (1,2,3), (2,3,4) ]

gap> List( gens, x -> x^repr[1] );

gap> List( gens, x -> x^repr[4] );
[ [ [ 0, 0, -1 ], [ 1, 0, 0 ], [ 0, -1, 0 ] ],
  [ 0, 1, 0 ], [ 0, 0, 1 ], [ 1, 0, 0 ] ]
```

71.14.5 IrreducibleRepresentationsDixon

Called with one argument, a group $G$, IrreducibleRepresentationsDixon computes (representatives of) all irreducible complex representations for the finite group $G$, using the method of [Dix93], which computes the character table and computes the representation as constituent of an induced monomial representation of a subgroup.

This method can be quite expensive for larger groups, for example it might involve calculation of the subgroup lattice of $G$.

A character $\chi$ of $G$ can be given as the second argument, in this case only a representation affording $\chi$ is returned.

The second argument can also be a list of characters of $G$, in this case only representations for characters in this list are computed.

Note that this method might fail if for an irreducible representation there is no subgroup in which its reduction has a linear constituent with multiplicity one.
If the option `unitary` is given, GAP tries, at extra cost, to find a unitary representation (and will issue an error if it cannot do so).

```
gap> a5 := AlternatingGroup( 5 );
Alt( [ 1 .. 5 ] )
gap> char := First( Irr( a5 ), x -> x[1] = 4 );
Character( CharacterTable( Alt( [ 1 .. 5 ] ) ), [ 4, 0, 1, -1, -1 ] )
gap> hom := IrreducibleRepresentationsDixon( a5, char: unitary );;
gap> Order( a5.1*a5.2 ) = Order( Image( hom, a5.1 )*Image( hom, a5.2 ) );
true
```

### 71.15 Representations Given by Modules

This section describes functions that return certain modules of a given group. (Extensions by modules can be formed by the command `Extensions` (46.8.4).)

#### 71.15.1 IrreducibleModules

```
\[ \text{IrreducibleModules}(G, F, \text{dim}) \]
```

returns a list of length 2. The first entry is a generating system of \( G \). The second entry is a list of all irreducible modules of \( G \) over the field \( F \) in dimension \( \text{dim} \), given as MeatAxe modules (see `GModuleByMats` (69.1.1)).

#### 71.15.2 AbsolutelyIrreducibleModules

```
\[ \text{AbsolutelyIrreducibleModules}(G, F, \text{dim}) \]
```

returns a list of length 2. The first entry is a generating system of \( G \). The second entry is a list of all absolute irreducible modules of \( G \) over the field \( F \) in dimension \( \text{dim} \), given as MeatAxe modules (see `GModuleByMats` (69.1.1)). The other two names are just synonyms.

#### 71.15.3 RegularModule

```
\[ \text{RegularModule}(G, F) \]
```

returns a list of length 2. The first entry is a generating system of \( G \). The second entry is the regular module of \( G \) over \( F \), given as a MeatAxe module (see `GModuleByMats` (69.1.1)).

### 71.16 The Dixon-Schneider Algorithm

The GAP library implementation of the Dixon-Schneider algorithm first computes the linear characters, using the commutator factor group. If irreducible characters are missing afterwards, they are
computed using the techniques described in [Dix67], [Sch90] and [Hul93].

 Called with a group $G$, the function $\text{CharacterTable}(71.3.1)$ returns a character table object that stores already information such as class lengths, but not the irreducible characters. The routines that compute the irreducibles may use the information that is already contained in this table object. In particular the ordering of classes in the computed characters coincides with the ordering of classes in the character table of $G$ (see 71.6). Thus it is possible to combine computations using the group with character theoretic computations (see 71.17 for details), for example one can enter known characters. Note that the user is responsible for the correctness of the characters. (There is little use in providing the trivial character to the routine.)

 The computation of irreducible characters from the group needs to identify the classes of group elements very often, so it can be helpful to store a class list of all group elements. Since this is obviously limited by the group order, it is controlled by the global function $\text{IsDxLargeGroup}(71.17.8)$.

 The routines compute in a prime field of size $p$, such that the exponent of the group divides $(p - 1)$ and such that $2\sqrt{|G|} < p$. Currently prime fields of size smaller than 65536 are handled more efficiently than larger prime fields, so the runtime of the character calculation depends on how large the chosen prime is.

 The routine stores a Dixon record (see $\text{DixonRecord}(71.17.1)$) in the group that helps routines that identify classes, for example $\text{FusionConjugacyClasses}(73.3.1)$, to work much faster. Note that interrupting Dixon-Schneider calculations will prevent $\text{GAP}$ from cleaning up the Dixon record; when the computation by $\text{IrrDixonSchneider}(71.14.1)$ is complete, the possibly large record is shrunk to an acceptable size.

### 71.17 Advanced Methods for Dixon-Schneider Calculations

The computation of irreducible characters of very large groups may take quite some time. On the other hand, for the expert only a few irreducible characters may be needed, since the other ones can be computed using character theoretic methods such as tensoring, induction, and restriction. Thus $\text{GAP}$ provides also step-by-step routines for doing the calculations. These routines allow one to compute some characters and to stop before all are calculated. Note that there is no “safety net”: The routines (being somehow internal) do no error checking, and assume the information given is correct.

When the info level of $\text{InfoCharacterTable}(71.4.2)$ if positive, information about the progress of splitting is printed. (The default value is zero.)

#### 71.17.1 DixonRecord

$\text{DixonRecord}(G)$ (attribute)

The $\text{DixonRecord}$ of a group contains information used by the routines to compute the irreducible characters and related information via the Dixon-Schneider algorithm such as class arrangement and character spaces split obtained so far. Usually this record is passed as argument to all subfunctions to avoid a long argument list. It has a component $\text{conjugacyClasses}$ which contains the classes of $G$ ordered as the algorithm needs them.

#### 71.17.2 DixonInit

$\text{DixonInit}(G)$ (function)
This function does all the initializations for the Dixon-Schneider algorithm. This includes calculation of conjugacy classes, power maps, linear characters and character morphisms. It returns a record (see DixonRecord (71.17.1) and Section 71.18) that can be used when calculating the irreducible characters of $G$ interactively.

71.17.3 DixontinI

\begin{verbatim}
\> DixontinI(D) (function)
\end{verbatim}

This function ends a Dixon-Schneider calculation. It sorts the characters according to the degree and unbinds components in the Dixon record that are not of use any longer. It returns a list of irreducible characters.

71.17.4 DixonSplit

\begin{verbatim}
\> DixonSplit(D) (function)
\end{verbatim}

This function performs one splitting step in the Dixon-Schneider algorithm. It selects a class, computes the (partial) class sum matrix, uses it to split character spaces and stores all the irreducible characters obtained that way.

The class to use for splitting is chosen via BestSplittingMatrix (71.17.5) and the options described for this function apply here.

DixonSplit returns the number of the class that was used for splitting if a split was performed, and \texttt{fail} otherwise.

71.17.5 BestSplittingMatrix

\begin{verbatim}
\> BestSplittingMatrix(D) (function)
\end{verbatim}

returns the number of the class sum matrix that is assumed to yield the best (cost/earning ration) split. This matrix then will be the next one computed and used.

The global option \texttt{maxclasslen} (defaulting to \texttt{infinity} (18.2.1)) is recognized by BestSplittingMatrix: Only classes whose length is limited by the value of this option will be considered for splitting. If no usable class remains, \texttt{fail} is returned.

71.17.6 DxIncludeIrreducibles

\begin{verbatim}
\> DxIncludeIrreducibles(D, new[, newmod]) (function)
\end{verbatim}

This function takes a list of irreducible characters \texttt{new}, each given as a list of values (corresponding to the class arrangement in $D$), and adds these to a partial computed list of irreducibles as maintained by the Dixon record $D$. This permits one to add characters in interactive use obtained from other sources and to continue the Dixon-Schneider calculation afterwards. If the optional argument \texttt{newmod} is given, it must be a list of reduced characters, corresponding to \texttt{new}. (Otherwise the function has to reduce the characters itself.)

The function closes the new characters under the action of Galois automorphisms and tensor products with linear characters.
71.17.7 SplitCharacters

\[ \text{SplitCharacters}(D, \text{list}) \] (function)

This routine decomposes the characters given in \text{list} according to the character spaces found up to this point. By applying this routine to tensor products etc., it may result in characters with smaller norm, even irreducible ones. Since the recalculation of characters is only possible if the degree is small enough, the splitting process is applied only to characters of sufficiently small degree.

71.17.8 IsDxLargeGroup

\[ \text{IsDxLargeGroup}(G) \] (function)

returns \text{true} if the order of the group \( G \) is smaller than the current value of the global variable \text{DXLARGEGROUPORDER}, and \text{false} otherwise. In Dixon-Schneider calculations, for small groups in the above sense a class map is stored, whereas for large groups, each occurring element is identified individually.

71.18 Components of a Dixon Record

The “Dixon record” \( D \) returned by \text{DixonInit} (71.17.2) stores all the information that is used by the Dixon-Schneider routines while computing the irreducible characters of a group. Some entries, however, may be useful to know about when using the algorithm interactively, see 71.19.

- \text{group}
  - the group \( G \) of which the character table is to be computed,
- \text{conjugacyClasses}
  - classes of \( G \) (all characters stored in the Dixon record correspond to this arrangement of classes),
- \text{irreducibles}
  - the already known irreducible characters (given as lists of their values on the conjugacy classes),
- \text{characterTable}
  - the \text{CharacterTable} (71.3.1) value of \( G \) (whose irreducible characters are not yet known),
- \text{ClassElement}( D, \text{el} )
  - a function that returns the number of the class of \( G \) that contains the element \text{el}.

71.19 An Example of Advanced Dixon-Schneider Calculations

First, we set the appropriate info level higher.

```gap
gap> SetInfoLevel( InfoCharacterTable, 1 );
```

for printout of some internal results. We now define our group, which is isomorphic to \( \text{PSL}_4(3) \).
Example

```gap
g := PrimitiveGroup(40, 5);
PSL(4, 3)
gap> Size(g);
6065280
gap> d := DixonInit(g);
#I 29 classes
#I choosing prime 65521
gap> c := d.characterTable;

After the initialisation, one structure matrix is evaluated, yielding smaller spaces and several irreducible characters.

Example

```gap
dixonsplit(d);
#I Matrix 2, Representative of Order 3, Centralizer: 5832
#I Dimensions: [1, 2, 1, 4, 12, 1, 2, 1, 2, 1]
#I Two-dim space split
#I Two-dim space split
#I Two-dim space split
2
```

In this case spaces of the listed dimensions are a result of the splitting process. The three two-dimensional spaces are split successfully by combinatoric means.

We obtain several irreducible characters by tensor products and notify them to the Dixon record.

Example

```gap
asp := AntiSymmetricParts(c, d.irreducibles, 2);
ro := ReducedCharacters(c, d.irreducibles, asp);
Length(ro.irreducibles);
3
dixonincludeirreducibles(d, ro.irreducibles);
```

The tensor products of the nonlinear characters among each other are reduced with the irreducible characters. The result is split according to the spaces found, which yields characters of smaller norms, but no new irreducibles.

Example

```gap
nlc := Filtered(d.irreducibles, i -> i[1] > 1);
t := Tensored(nlc, nlc);
ro := ReducedCharacters(c, d.irreducibles, t);
[ ]
List(ro.remainders, i -> ScalarProduct(c, i, i));
t := SplitCharacters(d, ro.remainders);
```
Finally we calculate the characters induced from all cyclic subgroups and obtain the missing irreducibles by applying the LLL-algorithm to them.

```gap
gap> ic:= InducedCyclic( c, "all" );;
gap> ro:= ReducedCharacters( c, d.irreducibles, ic );;
gap> Length( ro.irreducibles );
0

gap> l:= LLL( c, ro.remainders );;
gap> Length( l.irreducibles );
13
```

The LLL returns class function objects (see Chapter 72), and the Dixon record works with character values lists. So we convert them to a list of values before feeding them in the machinery of the Dixon-algorithm.

```gap
gap> l := List(l.irreducibles, ValuesOfClassFunction);
gap> DxIncludeIrreducibles( d, l );
gap> Length( d.irreducibles );
29
gap> Length( d.classes );
29
```

It turns out we have found all irreducible characters. As the last step, we obtain the irreducible characters and tell them to the group. This makes them available also to the character table.

```gap
gap> irrs:= DixontinI( d );;
#I Total:1 matrices,[ 2 ]

gap> SetIrr(g,irrs);
gap> Length(Irr(c));
29

gap> SetInfoLevel( InfoCharacterTable, 0 );
```
71.20 Constructing Character Tables from Others

The following operations take one or more character table arguments, and return a character table. This holds also for BrauerTable (71.3.2). Note that the return value of BrauerTable (71.3.2) will in general not know the irreducible Brauer characters, and GAP might be unable to compute these characters.

Note that whenever fusions between input and output tables occur in these operations, they are stored on the concerned tables, and the NamesOfFusionSources (73.3.5) values are updated.

(The interactive construction of character tables using character theoretic methods and incomplete tables is not described here.) Currently it is not supported and will be described in a chapter of its own when it becomes available.

71.20.1 CharacterTableDirectProduct

\[ \text{CharacterTableDirectProduct(tbl1, tbl2)} \]

is the table of the direct product of the character tables tbl1 and tbl2.

The matrix of irreducibles of this table is the Kronecker product (see KroneckerProduct (24.5.8)) of the irreducibles of tbl1 and tbl2.

Products of ordinary and Brauer character tables are supported.

In general, the result will not know an underlying group, so missing power maps (for prime divisors of the result) and irreducibles of the input tables may be computed in order to construct the table of the direct product.

The embeddings of the input tables into the direct product are stored, they can be fetched with GetFusionMap (73.3.3); if tbl1 is equal to tbl2 then the two embeddings are distinguished by their specification components "1" and "2", respectively.

Analogously, the projections from the direct product onto the input tables are stored, and can be distinguished by the specification components.

The attribute FactorsOfDirectProduct (71.20.2) is set to the lists of arguments.

The \* operator for two character tables (see 71.7) delegates to CharacterTableDirectProduct.

\begin{verbatim}
gap> c2:= CharacterTable( "Cyclic", 2 );;
gap> s3:= CharacterTable( "Symmetric", 3 );;
gap> Display( CharacterTableDirectProduct( c2, s3 ) );
C2xSym(3)
  2  2  2  2  2  2
  3  1  .  1  1  1
1a 2a 3a 2b 2c 6a
2P 1a 1a 3a 1a 1a 3a
3P 1a 2a 1a 2b 2c 2b
X.1  1 -1  1  1 -1  1
X.2  2  .-1  2  .-1
X.3  1  1  1  1  1  1
X.4  1 -1  1 -1  1 -1
X.5  2  .-1 -2  .  1
X.6  1  1 -1 -1 -1 -1
\end{verbatim}
71.20.2 FactorsOfDirectProduct

\texttt{FactorsOfDirectProduct(tbl)} \hspace{1cm} \text{(attribute)}

For an ordinary character table that has been constructed via \texttt{CharacterTableDirectProduct (71.20.1)}, the value of \texttt{FactorsOfDirectProduct} is the list of arguments in the \texttt{CharacterTableDirectProduct (71.20.1)} call.

Note that there is no default method for \textit{computing} the value of \texttt{FactorsOfDirectProduct}.

71.20.3 CharacterTableFactorGroup

\texttt{CharacterTableFactorGroup(tbl, classes)} \hspace{1cm} \text{(operation)}

is the character table of the factor group of the ordinary character table \texttt{tbl} by the normal closure of the classes whose positions are contained in the list \texttt{classes}.

The / operator for a character table and a list of class positions (see 71.7) delegates to \texttt{CharacterTableFactorGroup}.

\begin{verbatim}
Example

    gap> s4:= CharacterTable( "Symmetric", 4 );;
    gap> ClassPositionsOfNormalSubgroups( s4 );
    [ [ 1 ], [ 1, 3 ], [ 1, 3, 4 ], [ 1 .. 5 ] ]
    gap> f:= CharacterTableFactorGroup( s4, [ 3 ] );
    CharacterTable( "Sym(4)/[ 1, 3 ]" )
    gap> Display( f );
    Sym(4)/[ 1, 3 ]
    2 1 1 .
    3 1 . 1
    1a 2a 3a
    2P 1a 1a 3a
    3P 1a 2a 1a
    X.1  1  1 -1  1
    X.2  2  -1 -1
    X.3  1  1  1
\end{verbatim}

71.20.4 CharacterTableIsoclinic

\texttt{CharacterTableIsoclinic(tbl[, arec])} \hspace{1cm} \text{(operation)}

\texttt{CharacterTableIsoclinic(tbl[, classes][, centre])} \hspace{1cm} \text{(operation)}

\texttt{SourceOfIsoclinicTable(tbl)} \hspace{1cm} \text{(attribute)}

Let \texttt{tbl} be the (ordinary or modular) character table of a group \( H \), say, with the structure \( p.G.p \) for some prime \( p \), that is, \( H/Z \) has a normal subgroup \( N \) of index \( p \) and a central subgroup \( Z \) of order \( p \) contained in \( N \).

Then \texttt{CharacterTableIsoclinic} returns the table of an isoclinic group in the sense of the \textbf{Atlas} of Finite Groups [CCN+85, Chapter 6, Section 7].
If $p = 2$ then also the case $H = 4.G.2$ is supported, that is, $Z$ has order four and $N$ has index two in $H$.

The optional arguments are needed if tbl does not determine the class positions of $N$ or $Z$ uniquely, and in the case $p > 2$ if one wants to specify a “variant number” for the result.

- In general, the values can be specified via a record arec. If $N$ is not uniquely determined then the positions of the classes forming $N$ must be entered as the value of the component normalSubgroup. If $Z$ is not unique inside $N$ then the class position of a generator of $Z$ must be entered as the value of the component centralElement.

- If $p = 2$ then one may specify the positions of the classes forming $N$ via a list classes, and the positions of the classes in $Z$ as a list centre; if $Z$ has order 2 then centre can be also the position of the involution in $Z$.

Note that also if tbl is a Brauer table then normalSubgroup and centralElement, resp. classes and centre, denote class numbers w.r.t. the ordinary character table.

If $p$ is odd then the Atlas construction describes $p$ isoclinic variants that arise from $p.G.p$. (These groups need not be pairwise nonisomorphic.) Entering an integer $k \in \{1, 2, \ldots, k-1\}$ as the value of the component $k$ of arec yields the $k$-th of the corresponding character tables; the default for $k$ is 1.

```gap
gap> d8 := CharacterTable( "Dihedral", 8 );
CharacterTable( "Dihedral(8)" )
gap> nsg := ClassPositionsOfNormalSubgroups( d8 );
[ [ 1 ], [ 1, 3 ], [ 1 .. 3 ], [ 1, 3, 4 ], [ 1, 3 .. 5 ], [ 1 .. 5 ] ]
gap> isoD8 := CharacterTableIsoclinic( d8, nsg[3] );;
gap> Display( isoD8 );
Isoclinic(Dihedral(8))
2 3 2 3 2 2
1a 4a 2a 4b 4c
2p 1a 2a 1a 2a 2a

X.1 1 1 1 1 1
X.2 1 1 1 -1 -1
X.3 1 -1 1 1 -1
X.4 1 -1 1 -1 1
X.5 2 -2 . . .
gap> t1 := CharacterTable( SmallGroup( 27, 3 ) );;
gap> t2 := CharacterTable( SmallGroup( 27, 4 ) );;
gap> nsg := ClassPositionsOfNormalSubgroups( t1 );
[ [ 1 ], [ 1, 4, 8 ], [ 1, 2, 4, 5, 8 ], [ 1, 3, 4, 7, 8 ],
  [ 1, 4, 6, 8, 11 ], [ 1, 4, 8, 9, 10 ], [ 1 .. 11 ] ]
gap> iso1 := CharacterTableIsoclinic( t1, rec( k := 1,
  > normalSubgroup := nsg[3] ) );;
gap> iso2 := CharacterTableIsoclinic( t1, rec( k := 2,
  > normalSubgroup := nsg[3] ) );;
gap> TransformingPermutationsCharacterTables( iso1, t1 ) <> fail;
false
gap> TransformingPermutationsCharacterTables( iso1, t2 ) <> fail;
```

Example
true

gap> TransformingPermutationsCharacterTables( iso2, t2 ) <> fail;
true

For an ordinary character table that has been constructed via CharacterTableIsoclinic, the value of SourceOfIsoclinicTable encodes this construction, and is defined as follows. If $p = 2$ then the value is the list with entries $tbl$, $classes$, the list of class positions of the nonidentity elements in $Z$, and the class position of a generator of $Z$. If $p$ is an odd prime then the value is a record with the following components.

table  
the character table $tbl$.
p    the prime $p$.
k    the variant number $k$.
outerClasses  
the list of length $p-1$ that contains at position $i$ the sorted list of class positions of the $i$-th coset of the normal subgroup $N$
centralElement  
the class position of a generator of the central subgroup $Z$.

There is no default method for computing the value of SourceOfIsoclinicTable.

Example

```gap
gap> SourceOfIsoclinicTable( isod8 );
[ CharacterTable( "Dihedral(8)" ), [ 1 .. 3 ], [ 3 ], 3 ]
gap> SourceOfIsoclinicTable( isol );
rec( centralElement := 4, k := 1,
    outerClasses := [ [ 3, 6, 9 ], [ 7, 10, 11 ] ], p := 3,
    table := CharacterTable( <pc group of size 27 with 3 generators> ) )
```

If the arguments of CharacterTableIsoclinic are a Brauer table $modtbl$ and an ordinary table $ordiso$ then the SourceOfIsoclinicTable value of $ordiso$ is assumed to be identical with the OrdinaryCharacterTable (71.8.4) value of $modtbl$, and the specified isoclinic table of $modtbl$ is returned. This variant is useful if one has already constructed $ordiso$ in advance.

Example

```gap
gap> g:= GL(2,3);
gap> t:= CharacterTable( g );
gap> iso:= CharacterTableIsoclinic( t );
gap> t3:= t mod 3 ;;
gap> iso3:= CharacterTableIsoclinic( t3, iso );
gap> TransformingPermutationsCharacterTables( iso3,
> CharacterTableIsoclinic( t3 ) ) <> fail;
true
```

Theoretical background: Consider the central product $K$ of $H$ with a cyclic group $C$ of order $p^2$. That is, $K = HC$, $C \leq Z(K)$, and the central subgroup $Z$ of order $p$ in $H$ lies in $C$. There are $p + 1$
subgroups of $K$ that contain the normal subgroup $N$ of index $p$ in $H$. One of them is the central product of $C$ with $N$, and the others are $H_0 = H$ and its isoclinic variants $H_1, H_2, \ldots, H_{p-1}$. We fix $g \in H \setminus N$ and a generator $z$ of $C$, and get $H = N \cup N g \cup N g^2 \cup \cdots \cup N g^{p-1}$. Then $H_k$, $0 \leq k \leq p - 1$, is given by $N \cup N g^k \cup N (g^k)^2 \cup \cdots \cup N (g^k)^{p-1}$. The conjugacy classes of all $H_k$ are in bijection via multiplying the elements with suitable powers of $z$, and the irreducible characters of all $H_k$ extend to $K$ and are in bijection via multiplying the character values with suitable $p^2$-th roots of unity.

71.20.5 CharacterTableOfNormalSubgroup

\Function{CharacterTableOfNormalSubgroup}($\textordtxt{ordtbl}$, $\textordtxt{classes}$)

Let $\textordtxt{ordtbl}$ be the ordinary character table of a group $G$, say, and $\textordtxt{classes}$ be a list of class positions for this table. If the classes given by $\textordtxt{classes}$ form a normal subgroup $N$, say, of $G$ and if these classes are conjugacy classes of $N$ then this function returns the character table of $N$. In all other cases, the function returns fail.

Here is a nontrivial example. We use CharacterTableOfNormalSubgroup for computing the two isoclinic variants of $2.A_5.2$.

\begin{verbatim}
Example
gap> t := CharacterTable( "Symmetric", 4 );
CharacterTable( "Sym(4)" )
gap> nsq := ClassPositionsOfNormalSubgroups( t );
[ [ 1 ], [ 1, 3 ], [ 1, 3, 4 ], [ 1 .. 5 ] ]
gap> rest := List( nsq, c -> CharacterTableOfNormalSubgroup( t, c ) );
[ CharacterTable( "Rest(Sym(4),[ 1 ])", fail, fail,
  CharacterTable( "Rest(Sym(4),[ 1 .. 5 ])") ]
\end{verbatim}

\begin{verbatim}
Example
gap> g := SchurCoverOfSymmetricGroup( 5, 3, 1 );;
CharacterTableOfNormalSubgroup( g );
\end{verbatim}

\begin{verbatim}
Example
gap> c := CyclicGroup( 4 );;
CharacterTableOfNormalSubgroup( c );
\end{verbatim}

\begin{verbatim}
Example
gap> dp := DirectProduct( g, c );;
CharacterTableOfNormalSubgroup( dp );
\end{verbatim}

\begin{verbatim}
Example
gap> diag := First( Elements( Centre( dp ) ),
  x -> Order( x ) = 2 and
  not x in Image( Embedding( dp, 1 ) ) and
  not x in Image( Embedding( dp, 2 ) ) );
CharacterTableOfNormalSubgroup( dp, Subgroup( dp, [ diag ] ) );
\end{verbatim}

\begin{verbatim}
Example
gap> t := CharacterTable( fact );;
CharacterTable( "A5.2" )
\end{verbatim}

\begin{verbatim}
Example
gap> Size( t );
480
\end{verbatim}

\begin{verbatim}
Example
gap> index2 := Filtered( rest, x -> x <> fail and Size( x ) = 240 );;
Length( index2 );
2
\end{verbatim}

\begin{verbatim}
Example
gap> tg := CharacterTable( g );
CharacterTable( "A5.2" )
\end{verbatim}

\begin{verbatim}
Example
gap> TransformingPermutationsCharacterTables( index2[1], tg );
true
\end{verbatim}

\begin{verbatim}
Example
gap> TransformingPermutationsCharacterTables( index2[2], tg );
false
\end{verbatim}
Alternatively, we could construct the character table of the central product with character theoretic methods. Or we could use CharacterTableIsoclinic (71.20.4).

### 71.20.6 CharacterTableWreathSymmetric

\[ \text{CharacterTableWreathSymmetric}(\text{tbl}, n) \]

returns the character table of the wreath product of a group \( G \) with the full symmetric group on \( n \) points, where \( \text{tbl} \) is the character table of \( G \).

The result has values for ClassParameters (71.9.7) and CharacterParameters (71.9.7) stored, the entries in these lists are sequences of partitions. Note that this parametrization prevents the principal character from being the first one in the list of irreducibles.

#### Example

```gap
gap> c3:= CharacterTable( "Cyclic", 3 );;
gap> wr:= CharacterTableWreathSymmetric( c3, 2 );;
gap> Display( wr );
C3wrS2
 2 1 . . 1 1 1 1 1 1
 3 2 2 2 2 2 2 1 1 1
 1a 3a 3b 3c 3d 3e 2a 6a 6b
 2P 1a 3b 3a 3e 3d 3c 1a 3c 3e
 3P 1a 1a 1a 1a 1a 1a 2a 2a 2a
X.1 1 1 1 1 1 1 -1 -1 -1
X.2 2 A /A B -1 /B . . .
X.3 2 /A A /B -1 B . . .
X.4 1 -/A -A -A 1 -/A -1 /A A
X.5 2 -1 -1 2 -1 2 . . .
X.6 1 -A -/A -/A 1 -/A 1 -/A A
X.7 1 1 1 1 1 1 1 1 1
X.8 1 -/A -A -A 1 -/A 1 -/A -A
X.9 1 -A -/A -/A 1 -A 1 -A -/A
A = -E(3)^2
   = (1+Sqrt(-3))/2 = 1+b3
B = 2*E(3)
   = -1+Sqrt(-3) = 2b3
gap> CharacterParameters( wr )[1];
[ [ 1, 1 ], [ ], [ ] ]
```

### 71.20.7 CharacterValueWreathSymmetric

\[ \text{CharacterValueWreathSymmetric}(\text{tbl}, n, \beta, \pi) \]

Let \( \text{tbl} \) be the ordinary character table of a group \( G \), say. The aim of this function is to compute a single character value from the character table of the wreath product of \( G \) with the full symmetric group on \( n \) points.
The conjugacy classes and the irreducible characters of this wreath product are parametrized by \( r \)-tuples of partitions which together form a partition of \( n \) (see \texttt{PartitionTuples (16.2.30)}) where \( r \) is the number of conjugacy classes of \( G \).

We describe the conjugacy class for which we want to compute the value by the \( r \)-tuple \( \pi \) of partitions in question, and describe the character for which we want to compute the value by the \( r \)-tuple \( \beta \) of \texttt{BetaSet (16.2.32)} values of the \( r \)-tuple of partitions in question.

```
Example

gap> n:= 4;;
gap> classpara:= [ [ ], [ 2, 1, 1 ] ];;
gap> charpara:= [ [ 2, 1 ], [ 1 ] ];;
gap> betas:= List( charpara, BetaSet );;
gap> c2:= CharacterTable( "Cyclic", 2 );;
gap> CharacterValueWreathSymmetric( c2, n, betas, classpara );
0

gap> wr:= CharacterTableWreathSymmetric( c2, n );;
gap> classpos:= Position( ClassParameters( wr ), classpara );;
gap> charpos:= Position( CharacterParameters( wr ), charpara );;
gap> Irr( wr )[ charpos, classpos ];
0
```

This function can be useful if one is interested in only a few character values. If many character values are needed then it is probably faster to compute the whole character table of the wreath product using \texttt{CharacterTableWreathSymmetric (71.20.6)}, which uses intermediate results of recursive computations and therefore can avoid repetitions.

### 71.21 Sorted Character Tables

#### 71.21.1 CharacterTableWithSortedCharacters

\[ \texttt{CharacterTableWithSortedCharacters(tbl[, perm])} \]

is a character table that differs from \( tbl \) only by the succession of its irreducible characters. This affects the values of the attributes \texttt{Irr (71.8.2)} and \texttt{CharacterParameters (71.9.7)}. Namely, these lists are permuted by the permutation \( perm \).

If no second argument is given then a permutation is used that yields irreducible characters of increasing degree for the result. For the succession of characters in the result, see \texttt{SortedCharacters (71.21.2)}.

The result has all those attributes and properties of \( tbl \) that are stored in \texttt{SupportedCharacterTableInfo (71.3.4)} and do not depend on the ordering of characters.

#### 71.21.2 SortedCharacters

\[ \texttt{SortedCharacters(tbl, chars[, flag])} \]

is a list containing the characters \( chars \), ordered as specified by the other arguments.

There are three possibilities to sort characters: They can be sorted according to ascending norms (\( flag \) is the string "norm"), to ascending degree (\( flag \) is the string "degree"), or both (no third
argument is given), i.e., characters with same norm are sorted according to ascending degree, and characters with smaller norm precede those with bigger norm.

Rational characters in the result precede other ones with same norm and/or same degree.

The trivial character, if contained in $\text{chars}$, will always be sorted to the first position.

### 71.21.3 CharacterTableWithSortedClasses

```
$\triangleright$ CharacterTableWithSortedClasses(tbl[, flag]) (operation)
```

is a character table obtained by permutation of the classes of $\text{tbl}$. If the second argument $\text{flag}$ is the string "centralizers" then the classes of the result are sorted according to descending centralizer orders. If the second argument is the string "representatives" then the classes of the result are sorted according to ascending representative orders. If no second argument is given then the classes of the result are sorted according to ascending representative orders, and classes with equal representative orders are sorted according to descending centralizer orders.

If the second argument is a permutation then the classes of the result are sorted by application of this permutation.

The result has all those attributes and properties of $\text{tbl}$ that are stored in $\text{SupportedCharacterTableInfo}$ (71.3.4) and do not depend on the ordering of classes.

### 71.21.4 SortedCharacterTable (w.r.t. a normal subgroup)

```
$\triangleright$ SortedCharacterTable(tbl, kernel) (function)
$\triangleright$ SortedCharacterTable(tbl, normalseries) (function)
$\triangleright$ SortedCharacterTable(tbl, facttbl, kernel) (function)
```

is a character table obtained on permutation of the classes and the irreducibles characters of $\text{tbl}$.

The first form sorts the classes at positions contained in the list $\text{kernel}$ to the beginning, and sorts all characters in $\text{Irr}(\text{tbl})$ such that the first characters are those that contain $\text{kernel}$ in their kernel.

The second form does the same successively for all kernels $k_i$ in the list $\text{normalseries} = [k_1,k_2,\ldots,k_n]$ where $k_i$ must be a sublist of $k_{i+1}$ for $1 \leq i \leq n-1$.

The third form computes the table $F$ of the factor group of $\text{tbl}$ modulo the normal subgroup formed by the classes whose positions are contained in the list $\text{kernel}$; $F$ must be permutation equivalent to the table $\text{facttbl}$, in the sense of $\text{TransformingPermutationsCharacterTables}$ (71.22.4), otherwise $\text{fail}$ is returned. The classes of $\text{tbl}$ are sorted such that the preimages of a class of $F$ are consecutive, and that the succession of preimages is that of $\text{facttbl}$. The $\text{Irr}$ (71.8.2) value of $\text{tbl}$ is sorted as with $\text{SortCharTable}(\text{tbl}, \text{kernel})$.

(Note that the transformation is only unique up to table automorphisms of $F$, and this need not be unique up to table automorphisms of $\text{tbl}$.)

All rearrangements of classes and characters are stable, i.e., the relative positions of classes and characters that are not distinguished by any relevant property is not changed.

The result has all those attributes and properties of $\text{tbl}$ that are stored in $\text{SupportedCharacterTableInfo}$ (71.3.4) and do not depend on the ordering of classes and characters.

The $\text{ClassPermutation}$ (71.21.5) value of $\text{tbl}$ is changed if necessary, see 71.5.
SortedCharacterTable uses CharacterTableWithSortedClasses (71.21.3) and CharacterTableWithSortedCharacters (71.21.1).

71.21.5 ClassPermutation

\[ \text{ClassPermutation}(tbl) \]

is a permutation \( \pi \) of classes of the character table \( tbl \). If it is stored then class fusions into \( tbl \) that are stored on other tables must be followed by \( \pi \) in order to describe the correct fusion.

This attribute value is bound only if \( tbl \) was obtained from another table by permuting the classes, using CharacterTableWithSortedClasses (71.21.3) or SortedCharacterTable (71.21.4).

It is necessary because the original table and the sorted table have the same identifier (and the same group if known), and hence the same fusions are valid for the two tables.

Example

```
gap> tbl:= CharacterTable( "Symmetric", 4 );
CharacterTable( "Sym(4)" )
gap> Display( tbl );
Sym(4)
   2 3 2 3 . 2
   3 1 . 1 .
   1a 2a 2b 3a 4a
  2P 1a 1a 1a 3a 2b
  3P 1a 2a 2b 1a 4a
X.1 1 -1 1 1 -1
X.2 3 -1 -1 . 1
X.3 2 . 2 -1 .
X.4 3 1 -1 . -1
X.5 1 1 1 1 1

gap> srt1:= CharacterTableWithSortedCharacters( tbl );
CharacterTable( "Sym(4)" )
gap> List( Irr( srt1 ), Degree );
[ 1, 1, 2, 3, 3 ]
gap> srt2:= CharacterTableWithSortedClasses( tbl );
CharacterTable( "Sym(4)" )
gap> SizesCentralizers( tbl );
[ 24, 4, 8, 3, 4 ]
gap> SizesCentralizers( srt2 );
[ 24, 8, 4, 3, 4 ]
gap> nsg:= ClassPositionsOfNormalSubgroups( tbl );
[ [ 1 ], [ 1, 3 ], [ 1, 3, 4 ], [ 1 .. 5 ] ]
gap> srt3:= SortedCharacterTable( tbl, nsg );
CharacterTable( "Sym(4)" )
gap> nsg:= ClassPositionsOfNormalSubgroups( srt3 );
[ [ 1 ], [ 1, 2 ], [ 1 .. 3 ], [ 1 .. 5 ] ]
gap> Display( srt3 );
Sym(4)
   2 3 3 . 2 2
```
\[ \begin{array}{cccccc}
3 & 1 & 1 & . & . \\
1a & 2a & 3a & 2b & 4a \\
2P & 1a & 1a & 3a & 1a & 2a \\
3P & 1a & 2a & 1a & 2b & 4a \\
\end{array} \]

\[ X.1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \]

\[ X.2 \quad 1 \quad 1 \quad 1 \quad -1 \quad -1 \]

\[ X.3 \quad 2 \quad 2 \quad -1 \quad . \quad . \]

\[ X.4 \quad 3 \quad -1 \quad . \quad -1 \quad 1 \]

\[ X.5 \quad 3 \quad -1 \quad . \quad 1 \quad -1 \]

\texttt{gap> ClassPermutation( srt3 );}

\texttt{((2,4,3))}

### 71.22 Automorphisms and Equivalence of Character Tables

#### 71.22.1 MatrixAutomorphisms

\[ \text{MatrixAutomorphisms(mat[, maps[, subgroup]])} \]

For a matrix \texttt{mat}. \texttt{MatrixAutomorphisms} returns the group of those permutations of the columns of \texttt{mat} that leave the set of rows of \texttt{mat} invariant.

If the arguments \texttt{maps} and \texttt{subgroup} are given, only the group of those permutations is constructed that additionally fix each list in the list \texttt{maps} under pointwise action \texttt{OnTuples (41.2.5)}, and \texttt{subgroup} is a permutation group that is known to be a subgroup of this group of automorphisms.

Each entry in \texttt{maps} must be a list of same length as the rows of \texttt{mat}. For example, if \texttt{mat} is a list of irreducible characters of a group then the list of element orders of the conjugacy classes (see \texttt{OrdersClassRepresentatives (71.9.1)}) may be an entry in \texttt{maps}.

#### 71.22.2 TableAutomorphisms

\[ \text{TableAutomorphisms(tbl, characters[, info])} \]

\texttt{TableAutomorphisms} returns the permutation group of those matrix automorphisms (see \texttt{MatrixAutomorphisms (71.22.1)}) of the list \texttt{characters} that leave the element orders (see \texttt{OrdersClassRepresentatives (71.9.1)}) and all stored power maps (see \texttt{ComputedPowerMaps (73.1.1)}) of the character table \texttt{tbl} invariant.

If \texttt{characters} is closed under Galois conjugacy --this is always fulfilled for the list of all irreducible characters of ordinary character tables-- the string "\texttt{closed}" may be entered as the third argument \texttt{info}. Alternatively, a known subgroup of the table automorphisms can be entered as the third argument \texttt{info}.

The attribute \texttt{AutomorphismsOfTable (71.9.4)} can be used to compute and store the table automorphisms for the case that \texttt{characters} equals the \texttt{Irr (71.8.2)} value of \texttt{tbl}.

Example

\texttt{gap> tblD8:= CharacterTable( "Dihedral", 8 );;}

\texttt{gap> IrrD8:= Irr( tblD8 );}

\texttt{[ Character( CharacterTable( "Dihedral(8)" ), [ 1, 1, 1, 1, 1 ] ),}

\texttt{ Character( CharacterTable( "Dihedral(8)" ), [ 1, 1, 1, -1, -1 ] ),}
Character( CharacterTable( "Dihedral(8)" ), [ 1, -1, 1, 1, -1 ] ),
Character( CharacterTable( "Dihedral(8)" ), [ 1, -1, 1, -1, 1 ] ),
Character( CharacterTable( "Dihedral(8)" ), [ 2, 0, -2, 0, 0 ] ) ]
gap> orders:= OrdersClassRepresentatives( tblq8 );
[ 1, 4, 2, 2, 2 ]
gap> MatrixAutomorphisms( irrq8 );
Group([ (4,5), (2,4) ])
gap> MatrixAutomorphisms( irrq8, [ orders ], Group( () ) );
Group([ (4,5) ])
gap> TableAutomorphisms( tblq8, irrq8 );
Group([ (4,5) ])

71.22.3 TransformingPermutations

\[ \text{TransformingPermutations(mat1, mat2)} \]

Let \( \text{mat1} \) and \( \text{mat2} \) be matrices. \text{TransformingPermutations} tries to construct a permutation \( \pi \) that transforms the set of rows of the matrix \( \text{mat1} \) to the set of rows of the matrix \( \text{mat2} \) by permuting the columns.

If such a permutation exists, a record with the components \( \text{columns}, \text{rows}, \) and \( \text{group} \) is returned, otherwise \( \text{fail} \). For \text{TransformingPermutations(mat1, mat2)} = r \neq \text{fail}, we have \( \text{mat2} = \text{Permuted(List(mat1, x -> Permuted(x, r.columns)), r.rows)} \).

\( r \text{.group} \) is the group of matrix automorphisms of \( \text{mat2} \) (see \text{MatrixAutomorphisms (71.22.1)}). This group stabilizes the transformation in the sense that applying any of its elements to the columns of \( \text{mat2} \) preserves the set of rows of \( \text{mat2} \).

71.22.4 TransformingPermutationsCharacterTables

\[ \text{TransformingPermutationsCharacterTables(tbl11, tbl12)} \]

Let \( \text{tbl11} \) and \( \text{tbl12} \) be character tables. \text{TransformingPermutationsCharacterTables} tries to construct a permutation \( \pi \) that transforms the set of rows of the matrix \( \text{Irr}( \text{tbl11} ) \) to the set of rows of the matrix \( \text{Irr}( \text{tbl12} ) \) by permuting the columns (see \text{TransformingPermutations (71.22.3)}), such that \( \pi \) transforms also the power maps and the element orders.

If such a permutation \( \pi \) exists then a record with the components \( \text{columns}(\pi), \text{rows} \) (the permutation of \( \text{Irr}( \text{tbl1} ) \) corresponding to \( \pi \)), and \( \text{group} \) (the permutation group of table automorphisms of \( \text{tbl12} \), see \text{AutomorphismsOfTable (71.9.4)}) is returned. If no such permutation exists, \( \text{fail} \) is returned.

\[ \text{Example} \]
\[
gap> \text{tb1q8} := \text{CharacterTable( "Quaternionic", 8 )};
gap> \text{irrq8} := \text{Irr( tb1q8 )};
\[
\text{Character( CharacterTable( "Q8" ), [ 1, 1, 1, 1, 1 ] ),}
\text{Character( CharacterTable( "Q8" ), [ 1, 1, 1, -1, -1 ] ),}
\text{Character( CharacterTable( "Q8" ), [ 1, -1, 1, 1, -1 ] ),}
\text{Character( CharacterTable( "Q8" ), [ 1, -1, 1, -1, 1 ] ),}
\text{Character( CharacterTable( "Q8" ), [ 2, 0, -2, 0, 0 ] )}
\]
\[
gap> \text{OrdersClassRepresentatives( tblq8 )};
\text{[ 1, 4, 2, 2, 2 ]}
gap> \text{TransformingPermutations( irr8, irrq8 )};
\]
rec( columns := (), group := Group([ (4,5), (2,4) ]), rows := () )
gap> TransformingPermutationsCharacterTables( tblD6, tblQ8 );
fail
gap> tblD6:= CharacterTable( "Dihedral", 6 );;
gap> tblS3:= CharacterTable( "Symmetric", 3 );;
gap> TransformingPermutationsCharacterTables( tblD6, tblS3 );
rec( columns := (2,3), group := Group(()), rows := (1,3,2) )

71.22.5  FamiliesOfRows

\[ \text{FamiliesOfRows}(\text{mat}, \text{maps}) \]

\text{(function)}

\text{distributes the rows of the matrix mat into families, as follows. Two rows of mat belong to the same family if there is a permutation of columns that maps one row to the other row. Each entry in the list maps is regarded to form a family of length 1.}

\text{FamiliesOfRows returns a record with the components}

\begin{itemize}
  \item \text{famreps} the list of representatives for each family,
  \item \text{permutations} the list that contains at position } i \text{ a list of permutations that map the members of the family with representative famreps}[i] \text{ to that representative,}
  \item \text{families} the list that contains at position } i \text{ the list of positions of members of the family of representative famreps}[i]; (for the element maps } i \text{ the only member of the family will get the number Length( mat } + i).\]

71.23  Storing Normal Subgroup Information

71.23.1  NormalSubgroupClassesInfo

\[ \text{NormalSubgroupClassesInfo}(\text{tbl}) \]

\text{(attribute)}

\text{Let tbl be the ordinary character table of the group } G. \text{ Many computations for group characters of } G \text{ involve computations in normal subgroups or factor groups of } G.

\text{In some cases the character table tbl is sufficient; for example questions about a normal subgroup } N \text{ of } G \text{ can be answered if one knows the conjugacy classes that form } N, \text{ e.g., the question whether a character of } G \text{ restricts irreducibly to } N. \text{ But other questions require the computation of } N \text{ or even more information, like the character table of } N.

\text{In order to do these computations only once, one stores in the group a record with components to store normal subgroups, the corresponding lists of conjugacy classes, and (if necessary) the factor groups, namely}

\begin{itemize}
  \item \text{nsg} list of normal subgroups of } G, \text{ may be incomplete,
nsgclasses
at position \( i \), the list of positions of conjugacy classes of \( tbl \) forming the \( i \)-th entry of the nsg component,

nsgfactors
at position \( i \), if bound, the factor group modulo the \( i \)-th entry of the nsg component.

NormalSubgroupClasses (71.23.3), FactorGroupNormalSubgroupClasses (71.23.4), and ClassPositionsOfNormalSubgroup (71.23.2) each use these components, and they are the only functions to do so.

So if you need information about a normal subgroup for that you know the conjugacy classes, you should get it using NormalSubgroupClasses (71.23.3). If the normal subgroup was already used it is just returned, with all the knowledge it contains. Otherwise the normal subgroup is added to the lists, and will be available for the next call.

For example, if you are dealing with kernels of characters using the KernelOfCharacter (72.8.9) function you make use of this feature because KernelOfCharacter (72.8.9) calls NormalSubgroupClasses (71.23.3).

71.23.2 ClassPositionsOfNormalSubgroup

\[
\text{ClassPositionsOfNormalSubgroup}(\text{tbl}, N)
\]

is the list of positions of conjugacy classes of the character table \( tbl \) that are contained in the normal subgroup \( N \) of the underlying group of \( tbl \).

71.23.3 NormalSubgroupClasses

\[
\text{NormalSubgroupClasses}(\text{tbl}, \text{classes})
\]

returns the normal subgroup of the underlying group \( G \) of the ordinary character table \( tbl \) that consists of those conjugacy classes of \( tbl \) whose positions are in the list \( \text{classes} \).

If NormalSubgroupClassesInfo( \( tbl \) ).nsg does not yet contain the required normal subgroup, and if NormalSubgroupClassesInfo( \( tbl \) ).normalSubgroups is bound then the result will be identical to the group in NormalSubgroupClassesInfo( \( tbl \) ).normalSubgroups.

71.23.4 FactorGroupNormalSubgroupClasses

\[
\text{FactorGroupNormalSubgroupClasses}(\text{tbl}, \text{classes})
\]

is the factor group of the underlying group \( G \) of the ordinary character table \( tbl \) modulo the normal subgroup of \( G \) that consists of those conjugacy classes of \( tbl \) whose positions are in the list \( \text{classes} \).
gap> kernel := KernelOfCharacter(irr[3]);
Group([ (1,2)(3,4), (1,4)(2,3) ])
gap> HasNormalSubgroupClassesInfo(tbl);
true
gap> NormalSubgroupClassesInfo(tbl);
rec( nsg := [ Group([ (1,2)(3,4), (1,4)(2,3) ]),
  nsgclasses := [ [ 1, 3 ] ], nsgfactors := [ ] )
gap> ClassPositionsOfNormalSubgroup(tbl, kernel);
[ 1, 3 ]
gap> G := FactorGroupNormalSubgroupClasses(tbl, [ 1, 3 ]);

true
Chapter 72

Class Functions

This chapter describes operations for class functions of finite groups. For operations concerning character tables, see Chapter 71.

Several examples in this chapter require the GAP Character Table Library to be available. If it is not yet loaded then we load it now.

```
gap> LoadPackage( "ctbllib" );
true
```

72.1 Why Class Functions?

In principle it is possible to represent group characters or more general class functions by the plain lists of their values, and in fact many operations for class functions work with plain lists of class function values. But this has two disadvantages.

First, it is then necessary to regard a values list explicitly as a class function of a particular character table, by supplying this character table as an argument. In practice this means that with this setup, the user has the task to put the objects into the right context. For example, forming the scalar product or the tensor product of two class functions or forming an induced class function or a conjugate class function then needs three arguments in this case; this is particularly inconvenient in cases where infix operations cannot be used because of the additional argument, as for tensor products and induced class functions.

Second, when one says that “\( \chi \) is a character of a group \( G \)” then this object \( \chi \) carries a lot of information. \( \chi \) has certain properties such as being irreducible or not. Several subgroups of \( G \) are related to \( \chi \), such as the kernel and the centre of \( \chi \). Other attributes of characters are the determinant and the central character. This knowledge cannot be stored in a plain list.

For dealing with a group together with its characters, and maybe also subgroups and their characters, it is desirable that GAP keeps track of the interpretation of characters. On the other hand, for using characters without accessing their groups, such as characters of tables from the GAP table library, dealing just with values lists is often sufficient. In particular, if one deals with incomplete character tables then it is often necessary to specify the arguments explicitly, for example one has to choose a fusion map or power map from a set of possibilities.

The main idea behind class function objects is that a class function object is equal to its values list in the sense of \( \equiv \) (31.11.1), so class function objects can be used wherever their values lists can be used, but there are operations for class function objects that do not work just with values lists.
GAP library functions prefer to return class function objects rather than returning just values lists, for example \texttt{Irr} (71.8.2) lists consist of class function objects, and \texttt{TrivialCharacter} (72.7.1) returns a class function object.

Here is an example that shows both approaches. First we define some groups.

\begin{verbatim}
Example

gap> S4 := SymmetricGroup( 4 );; SetName( S4, "S4" );
gap> D8 := SylowSubgroup( S4, 2 );; SetName( D8, "D8" );

We do some computations using the functions described later in this Chapter, first with class function objects.

\begin{verbatim}
Example

gap> irrS4 := Irr( S4 );;
gap> irrD8 := Irr( D8 );;
gap> chi := irrD8[4];
Character( CharacterTable( D8 ), [ 1, -1, 1, -1, 1 ] )
gap> ind := chi * chi;
Character( CharacterTable( D8 ), [ 1, 1, 1, 1, 1 ] )
gap> List( irrS4, x -> ScalarProduct( x, ind ) );
[ 0, 1, 0, 0, 0 ]
gap> det := Determinant( ind );
Character( CharacterTable( S4 ), [ 1, 1, 1, 1, 1 ] )

Now we repeat these calculations with plain lists of character values. Here we need the character tables in some places.

\begin{verbatim}
Example

gap> tS4 := CharacterTable( S4 );;
gap> tD8 := CharacterTable( D8 );;
gap> chi := ValuesOfClassFunction( irrD8[4] );
[ 1, -1, 1, -1, 1 ]
gap> Tensored( [ chi ], [ chi ] )[1];
[ 1, 1, 1, 1, 1 ]
gap> ind := InducedClassFunction( tD8, chi, tS4 );
ClassFunction( CharacterTable( S4 ), [ 3, -1, -1, 0, 1 ] )
gap> List( Irr( tS4 ), x -> ScalarProduct( tS4, x, ind ) );
[ 0, 1, 0, 0, 0 ]
gap> det := DeterminantOfCharacter( tS4, ind );
ClassFunction( CharacterTable( S4 ), [ 1, 1, 1, 1, 1 ] )

If one deals with character tables from the GAP table library then one has no access to their groups, but often the tables provide enough information for computing induced or restricted class functions,
symmetrizations etc., because the relevant class fusions and power maps are often stored on library tables. In these cases it is possible to use the tables instead of the groups as arguments. (If necessary information is not uniquely determined by the tables then an error is signalled.)

Example

```gap
gap> s5 := CharacterTable( "A5.2" );; irrs5 := Irr( s5 );;
gap> m11:= CharacterTable( "M11" );; irrm11:= Irr( m11 );;
gap> chi:= TrivialCharacter( s5 );
Character( CharacterTable( "A5.2" ), [ 1, 1, 1, 1, 1, 1, 1 ] )
gap> chi ^ m11;
Character( CharacterTable( "M11" ), [ 66, 10, 3, 2, 1, 0, 0, 0, 0, 0 ] )
gap> Determinant( irrs5[4] );
Character( CharacterTable( "A5.2" ), [ 1, 1, 1, 1, -1, -1, -1, -1, -1, -1 ] )
```

Functions that compute normal subgroups related to characters have counterparts that return the list of class positions corresponding to these groups.

Example

```gap
gap> ClassPositionsOfKernel( irrs5[2] );
[ 1, 2, 3, 4 ]
gap> ClassPositionsOfCentre( irrs5[2] );
[ 1, 2, 3, 4, 5, 6, 7 ]
```

Non-normal subgroups cannot be described this way, so for example inertia subgroups (see InertiaSubgroup (72.8.13)) can in general not be computed from character tables without access to their groups.

### 72.1.1 IsClassFunction

`IsClassFunction` (Category)

A class function (in characteristic $p$) of a finite group $G$ is a map from the set of ($p$-regular) elements in $G$ to the field of cyclotomics that is constant on conjugacy classes of $G$.

Each class function in GAP is represented by an immutable list, where at the $i$-th position the value on the $i$-th conjugacy class of the character table of $G$ is stored. The ordering of the conjugacy classes is the one used in the underlying character table. Note that if the character table has access to its underlying group then the ordering of conjugacy classes in the group and in the character table may differ (see 71.6); class functions always refer to the ordering of classes in the character table.

Class function objects in GAP are not just plain lists, they store the character table of the group $G$ as value of the attribute UnderlyingCharacterTable (72.2.1). The group $G$ itself is accessible only via the character table and thus only if the character table stores its group, as value of the attribute UnderlyingGroup (71.6.1). The reason for this is that many computations with class functions are possible without using their groups, for example class functions of character tables in the GAP character table library do in general not have access to their underlying groups.

There are (at least) two reasons why class functions in GAP are not implemented as mappings. First, we want to distinguish class functions in different characteristics, for example to be able to define the Frobenius character of a given Brauer character; viewed as mappings, the trivial characters in all characteristics coprime to the order of $G$ are equal. Second, the product of two class functions shall be again a class function, whereas the product of general mappings is defined as composition.
A further argument is that the typical operations for mappings such as `Image` (32.4.6) and `PreImage` (32.5.6) play no important role for class functions.

### 72.2 Basic Operations for Class Functions

Basic operations for class functions are `UnderlyingCharacterTable` (72.2.1), `ValuesOfClassFunction` (72.2.2), and the basic operations for lists (see 21.2).

#### 72.2.1 UnderlyingCharacterTable

\[ \text{UnderlyingCharacterTable}(\psi) \]

(\text{attribute})

For a class function \( \psi \) of the group \( G \), say, the character table of \( G \) is stored as value of `UnderlyingCharacterTable`. The ordering of entries in the list \( \psi \) (see `ValuesOfClassFunction` (72.2.2)) refers to the ordering of conjugacy classes in this character table.

If \( \psi \) is an ordinary class function then the underlying character table is the ordinary character table of \( G \) (see `OrdinaryCharacterTable` (71.8.4)), if \( \psi \) is a class function in characteristic \( p \neq 0 \) then the underlying character table is the \( p \)-modular Brauer table of \( G \) (see `BrauerTable` (71.3.2)). So the underlying characteristic of \( \psi \) can be read off from the underlying character table.

#### 72.2.2 ValuesOfClassFunction

\[ \text{ValuesOfClassFunction}(\psi) \]

(\text{attribute})

is the list of values of the class function \( \psi \), the \( i \)-th entry being the value on the \( i \)-th conjugacy class of the underlying character table (see `UnderlyingCharacterTable` (72.2.1)).

```
gap> g := SymmetricGroup( 4 );
Sym( [ 1 .. 4 ] )
gap> psi := TrivialCharacter( g );
Character( CharacterTable( Sym( [ 1 .. 4 ] ) ), [ 1, 1, 1, 1, 1 ] )
gap> UnderlyingCharacterTable( psi );
CharacterTable( Sym( [ 1 .. 4 ] ) )
gap> ValuesOfClassFunction( psi );
[ 1, 1, 1, 1, 1 ]
gap> IsList( psi );
true
gap> psi[1];
1
gap> Length( psi );
5
gap> IsBound( psi[6] );
false
gap> Concatenation( psi, [ 2, 3 ] );
[ 1, 1, 1, 1, 1, 2, 3 ]```
72.3 Comparison of Class Functions

With respect to $\neq$ (31.11.1) and $<$ (31.11.1), class functions behave equally to their lists of values (see ValuesOfClassFunction (72.2.2)). So two class functions are equal if and only if their lists of values are equal, no matter whether they are class functions of the same character table, of the same group but w.r.t. different class ordering, or of different groups.

Example

gap> grps:= Filtered( AllSmallGroups( 8 ), g -> not IsAbelian( g ) );
[ <pc group of size 8 with 3 generators>,
  <pc group of size 8 with 3 generators> ]
gap> t1:= CharacterTable( grps[1] ); SetName( t1, "t1" );
CharacterTable( <pc group of size 8 with 3 generators> )
gap> t2:= CharacterTable( grps[2] ); SetName( t2, "t2" );
CharacterTable( <pc group of size 8 with 3 generators> )
gap> irr1:= Irr( grps[1] );
[ Character( t1, [ 1, 1, 1, 1, 1 ] ),
  Character( t1, [ 1, -1, 1, -1, 1 ] ),
  Character( t1, [ 1, 1, -1, 1, -1 ] ),
  Character( t1, [ 2, 0, 0, -2, 0 ] ) ]
gap> irr2:= Irr( grps[2] );
[ Character( t2, [ 1, 1, 1, 1, 1 ] ),
  Character( t2, [ 1, -1, 1, -1, 1 ] ),
  Character( t2, [ 1, -1, 1, 1, -1 ] ),
  Character( t2, [ 2, 0, 0, -2, 0 ] ) ]
gap> irr1 = irr2;
true
gap> IsSSortedList( irr1 );
false
gap> irr1[1] < irr1[2];
false
gap> irr1[2] < irr1[3];
true

72.4 Arithmetic Operations for Class Functions

Class functions are row vectors of cyclotomics. The additive behaviour of class functions is defined such that they are equal to the plain lists of class function values except that the results are represented again as class functions whenever this makes sense. The multiplicative behaviour, however, is different. This is motivated by the fact that the tensor product of class functions is a more interesting operation than the vector product of plain lists. (Another candidate for a multiplication of compatible class functions would have been the inner product, which is implemented via the function ScalarProduct (72.8.5). In terms of filters, the arithmetic of class functions is based on the decision that they lie in IsGeneralizedRowVector (21.12.1), with additive nesting depth 1, but they do not lie in IsMultiplicativeGeneralizedRowVector (21.12.2).

More specifically, the scalar multiple of a class function with a cyclotomic is a class function, and the sum and the difference of two class functions of the same underlying character table (see UnderlyingCharacterTable (72.2.1)) are again class functions of this table. The sum and the
difference of a class function and a list that is not a class function are plain lists, as well as the sum and the difference of two class functions of different character tables.

```gap
gap> g:= SymmetricGroup( 4 );; tbl:= CharacterTable( g );;
gap> SetName( tbl, "S4" );; irr:= Irr( g );
[ Character( S4, [ 1, -1, 1, 1, -1 ] ),
  Character( S4, [ 3, -1, -1, 0, 1 ] ),
  Character( S4, [ 2, 0, 2, -1, 0 ] ),
  Character( S4, [ 3, 1, -1, 0, -1 ] ),
  Character( S4, [ 1, 1, 1, 1, 1 ] ) ]
gap> 2 * irr[5]; Character( S4, [ 2, 2, 2, 2, 2 ] )
gap> irr[1] / 7;
ClassFunction( S4, [ 1/7, -1/7, 1/7, 1/7, -1/7 ] )
VirtualCharacter( S4, [ 2, -2, 2, -1, 2 ] )
gap> lincomb:= lincomb + 2 * irr[5];
VirtualCharacter( S4, [ 4, 0, 4, 1, 0 ] )
gap> IsCharacter( lincomb );
true
```

The product of two class functions of the same character table is the tensor product (pointwise product) of these class functions. Thus the set of all class functions of a fixed group forms a ring, and for any field $F$ of cyclotomics, the $F$-span of a given set of class functions forms an algebra.

The product of two class functions of different tables and the product of a class function and a list that is not a class function are not defined, an error is signalled in these cases. Note that in this respect, class functions behave differently from their values lists, for which the product is defined as the standard scalar product.

```gap
gap> tens:= irr[3] * irr[4];
Character( S4, [ 6, 0, -2, 0, 0 ] )
4
```

Class functions without zero values are invertible, the inverse is defined pointwise. As a consequence, for example groups of linear characters can be formed.

```gap
gap> tens / irr[1];
Character( S4, [ 6, 0, -2, 0, 0 ] )
```
Other (somewhat strange) implications of the definition of arithmetic operations for class functions, together with the general rules of list arithmetic (see 21.11), apply to the case of products involving lists of class functions. No inverse of the list of irreducible characters as a matrix is defined; if one is interested in the inverse matrix then one can compute it from the matrix of class function values.

Example

```gap
gap> Inverse( List( irr, ValuesOfClassFunction ) );
[ [ 1/24, 1/8, 1/12, 1/8, 1/24 ], [ -1/4, -1/4, 0, 1/4, 1/4 ],
  [ 1/8, -1/8, 1/4, -1/8, 1/8 ], [ 1/3, 0, -1/3, 0, 1/3 ],
  [ -1/4, 1/4, 0, -1/4, 1/4 ] ]
```

Also the product of a class function with a list of class functions is not a vector-matrix product but the list of pointwise products.

Example

```gap
[ Character( S4, [ 1, 1, 1, 1, 1 ] ),
  Character( S4, [ 3, 1, -1, 0, -1 ] ),
  Character( S4, [ 2, 0, 2, -1, 0 ] ) ]
```

And the product of two lists of class functions is not the matrix product but the sum of the pointwise products.

Example

```gap
gap> irr * irr;
Character( S4, [ 24, 4, 8, 3, 4 ] )
```

The powering operator \(^{\text{(31.12.1)}}\) has several meanings for class functions. The power of a class function by a nonnegative integer is clearly the tensor power. The power of a class function by an element that normalizes the underlying group or by a Galois automorphism is the conjugate class function. (As a consequence, the application of the permutation induced by such an action cannot be denoted by \(^{\text{(31.12.1)}}\); instead one can use Permuted (21.20.18)). The power of a class function by a group or a character table is the induced class function (see InducedClassFunction (72.9.3)). The power of a group element by a class function is the class function value at (the conjugacy class containing) this element.

Example

```gap
gap> irr[3] ^ 3;
Character( S4, [ 8, 0, 8, -1, 0 ] )
```

```gap
gap> lin:= LinearCharacters( DerivedSubgroup( g ) );
[ Character( CharacterTable( Alt( [ 1 .. 4 ] ) ), [ 1, 1, 1, 1 ] ),
  Character( CharacterTable( Alt( [ 1 .. 4 ] ) ),
    [ 1, 1, E(3), E(3)^2 ] ),
  Character( CharacterTable( Alt( [ 1 .. 4 ] ) ),
    [ 1, 1, E(3)^2, E(3) ] ) ]
```

```gap
gap> List( lin, chi -> chi ^ (1,2) );
[ Character( CharacterTable( Alt( [ 1 .. 4 ] ) ), [ 1, 1, 1, 1 ] ),
  Character( CharacterTable( Alt( [ 1 .. 4 ] ) ),
    [ 1, 1, E(3), E(3)^2 ] ),
  Character( CharacterTable( Alt( [ 1 .. 4 ] ) ),
    [ 1, 1, E(3)^2, E(3) ] ) ]
```

```gap
gap> Orbit( GaloisGroup( CF(3) ), lin[2] );
```

72.4.1 Characteristic (for a class function)

\[ \text{Characteristic}(\text{chi}) \]

The characteristic of class functions is zero, as for all list of cyclotomics. For class functions of a \( p \)-modular character table, such as Brauer characters, the prime \( p \) is given by the UnderlyingCharacteristic (71.9.5) value of the character table.

\begin{verbatim}
Example

gap> Characteristic( irr[1] );
0

gap> irrm[2]:= Irr( g, 2 );
[ Character( BrauerTable( Sym( [ 1 .. 4 ] ), 2 ), [ 1, 1 ] ),
  Character( BrauerTable( Sym( [ 1 .. 4 ] ), 2 ), [ 2, -1 ] ) ]

gap> Characteristic( irrm[2][1] );
0

gap> UnderlyingCharacteristic( UnderlyingCharacterTable( irrm[2][1] ) );
2
\end{verbatim}

72.4.2 ComplexConjugate (for a class function)

\[ \text{ComplexConjugate}(\text{chi}) \]

\[ \text{GaloisCyc}(\text{chi}, k) \]

\[ \text{Permuted}(\text{chi}, \pi) \]

The operations ComplexConjugate, GaloisCyc, and Permuted return a class function when they are called with a class function: The complex conjugate of a class function that is known to be a (virtual) character is again known to be a (virtual) character, and applying an arbitrary Galois automorphism to an ordinary (virtual) character yields a (virtual) character.

\begin{verbatim}
Example

gap> ComplexConjugate( lin[2] );
Character( CharacterTable( Alt( [ 1 .. 4 ] ) ),
  [ 1, 1, E(3)^2, E(3) ] )

gap> GaloisCyc( lin[2], 5 );
Character( CharacterTable( Alt( [ 1 .. 4 ] ) ),
  [ 1, 1, E(3)^2, E(3) ] )

gap> Permuted( lin[2], (2,3,4) );
ClassFunction( CharacterTable( Alt( [ 1 .. 4 ] ) ),
  [ 1, E(3)^2, 1, E(3) ] )
\end{verbatim}
72.4.3 Order (for a class function)

\texttt{Order(chi)} (attribute)

By definition of \texttt{Order} (31.10.10) for arbitrary monoid elements, the return value of \texttt{Order} (31.10.10) for a character must be its multiplicative order. The \textit{determinantal order} (see \texttt{DeterminantOfCharacter} (72.8.18)) of a character \texttt{chi} can be computed as \texttt{Order(Determinant(chi))}.

\begin{verbatim}
    gap> det := Determinant(irr[3]);
    Character( S4, [ 1, -1, 1, 1, -1 ] )
    gap> Order(det);
    2
\end{verbatim}

72.5 Printing Class Functions

72.5.1 ViewObj (for class functions)

\texttt{ViewObj(chi)} (method)

The default \texttt{ViewObj} (6.3.5) methods for class functions print one of the strings "ClassFunction", "VirtualCharacter", "Character" (depending on whether the class function is known to be a character or virtual character, see \texttt{IsCharacter} (72.8.1), \texttt{IsVirtualCharacter} (72.8.2)), followed by the \texttt{ViewObj} (6.3.5) output for the underlying character table (see 71.13), and the list of values. The table is chosen (and not the group) in order to distinguish class functions of different underlying characteristic (see \texttt{UnderlyingCharacteristic} (71.9.5)).

72.5.2 PrintObj (for class functions)

\texttt{PrintObj(chi)} (method)

The default \texttt{PrintObj} (6.3.5) method for class functions does the same as \texttt{ViewObj} (6.3.5), except that the character table is is \texttt{Print} (6.3.4)-ed instead of \texttt{View} (6.3.3)-ed.

\textit{Note} that if a class function is shown only with one of the strings "ClassFunction", "VirtualCharacter", it may still be that it is in fact a character; just this was not known at the time when the class function was printed.

In order to reduce the space that is needed to print a class function, it may be useful to give a name (see \texttt{Name} (12.8.2)) to the underlying character table.

72.5.3 Display (for class functions)

\texttt{Display(chi)} (method)

The default \texttt{Display} (6.3.6) method for a class function \texttt{chi} calls \texttt{Display} (6.3.6) for its underlying character table (see 71.13), with \texttt{chi} as the only entry in the \texttt{chars} list of the options record.

\begin{verbatim}
    gap> chi := TrivialCharacter(CharacterTable("A5"));
    Character( CharacterTable("A5"), [ 1, 1, 1, 1 ] )
\end{verbatim}
72.6 Creating Class Functions from Values Lists

72.6.1 ClassFunction (for a character table and a list)

\[
\text{ClassFunction}(\text{tbl}, \text{values}) \quad \text{(operation)}
\]

\[
\text{ClassFunction}(G, \text{values}) \quad \text{(operation)}
\]

In the first form, \text{ClassFunction} returns the class function of the character table \text{tbl} with values given by the list \text{values} of cyclotomics. In the second form, \text{G} must be a group, and the class function of its ordinary character table is returned.

Note that \text{tbl} determines the underlying characteristic of the returned class function (see \text{UnderlyingCharacteristic (71.9.5)}).

72.6.2 VirtualCharacter (for a character table and a list)

\[
\text{VirtualCharacter}(\text{tbl}, \text{values}) \quad \text{(operation)}
\]

\[
\text{VirtualCharacter}(G, \text{values}) \quad \text{(operation)}
\]

\text{VirtualCharacter} returns the virtual character (see \text{IsVirtualCharacter (72.8.2)}) of the character table \text{tbl} or the group \text{G}, respectively, with values given by the list \text{values}.

It is not checked whether the given values really describe a virtual character.

72.6.3 Character (for a character table and a list)

\[
\text{Character}(\text{tbl}, \text{values}) \quad \text{(operation)}
\]

\[
\text{Character}(G, \text{values}) \quad \text{(operation)}
\]

\text{Character} returns the character (see \text{IsCharacter (72.8.1)}) of the character table \text{tbl} or the group \text{G}, respectively, with values given by the list \text{values}.

It is not checked whether the given values really describe a character.

Example

\[
\text{gap> g:= DihedralGroup( 8 ); tbl:= CharacterTable( g );}$
\]
\[
\text{CharacterTable( <pc group of size 8 with 3 generators> )}$
\]
\[
\text{gap> SetName( tbl, "D8" );}$
\]
gap> phi := ClassFunction( g, [ 1, -1, 0, 2, -2 ] );
ClassFunction( D8, [ 1, -1, 0, 2, -2 ] )
gap> psi := ClassFunction( tbl, 
    > List( Irr( g ), chi -> ScalarProduct( chi, phi ) ) );
ClassFunction( D8, [ -3/8, 9/8, 5/8, 1/8, -1/4 ] )
gap> chi := VirtualCharacter( g, [ 0, 0, 8, 0, 0 ] );
VirtualCharacter( D8, [ 0, 0, 8, 0, 0 ] )
gap> reg := Character( tbl, [ 8, 0, 0, 0, 0 ] );
Character( D8, [ 8, 0, 0, 0, 0 ] )

72.6.4 ClassFunctionSameType

\textbf{ClassFunctionSameType( tbl, chi, values )} (function)

Let \textit{tbl} be a character table, \textit{chi} a class function object \textit{(not necessarily a class function of tbl)}, and \textit{values} a list of cyclotomics. \textbf{ClassFunctionSameType} returns the class function \( \psi \) of \textit{tbl} with \textit{values} list \textit{values}, constructed with \textbf{ClassFunction} (72.6.1).

If \textit{chi} is known to be a (virtual) character then \( \psi \) is also known to be a (virtual) character.

\textbf{Example}

\begin{verbatim}
gap> h := Centre( g );;
gap> centbl := CharacterTable( h );; SetName( centbl, "C2" );
gap> ClassFunctionSameType( centbl, phi, [ 1, 1 ] );
ClassFunction( C2, [ 1, 1 ] )
gap> ClassFunctionSameType( centbl, chi, [ 1, 1 ] );
VirtualCharacter( C2, [ 1, 1 ] )
gap> ClassFunctionSameType( centbl, reg, [ 1, 1 ] );
Character( C2, [ 1, 1 ] )
\end{verbatim}

72.7 Creating Class Functions using Groups

72.7.1 TrivialCharacter

\textbf{TrivialCharacter(tbl)} (attribute)

\textbf{TrivialCharacter(G)} (attribute)

is the \textit{trivial character} of the group \textit{G} or its character table \textit{tbl}, respectively. This is the class function with value equal to 1 for each class.

\textbf{Example}

\begin{verbatim}
gap> TrivialCharacter( CharacterTable( "A5" ) );
Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] )
gap> TrivialCharacter( SymmetricGroup( 3 ) );
Character( CharacterTable( Sym( [ 1 .. 3 ] ) ), [ 1, 1, 1 ] )
\end{verbatim}

72.7.2 NaturalCharacter (for a group)

\textbf{NaturalCharacter(G)} (attribute)

\textbf{NaturalCharacter(hom)} (attribute)
If the argument is a permutation group \( G \) then \texttt{NaturalCharacter} returns the (ordinary) character of the natural permutation representation of \( G \) on the set of moved points (see \texttt{MovedPoints} (42.3.3)), that is, the value on each class is the number of points among the moved points of \( G \) that are fixed by any permutation in that class.

If the argument is a matrix group \( G \) in characteristic zero then \texttt{NaturalCharacter} returns the (ordinary) character of the natural matrix representation of \( G \), that is, the value on each class is the trace of any matrix in that class.

If the argument is a group homomorphism \( \text{hom} \) whose image is a permutation group or a matrix group then \texttt{NaturalCharacter} returns the restriction of the natural character of the image of \( \text{hom} \) to the preimage of \( \text{hom} \).

\begin{verbatim}
Example
gap> NaturalCharacter( SymmetricGroup( 3 ) );
Character( CharacterTable( Sym( [ 1 .. 3 ] ) ), [ 3, 1, 0 ] )
gap> NaturalCharacter( Group([ [ 1, -1 ], [ 0, -1 ] ] ) );
Character( CharacterTable( Group([ [ 1, -1 ], [ 0, -1 ] ] ) ),
[ 2, -1, -1 ] )
gap> d8:= DihedralGroup( 8 );; hom:= IsomorphismPermGroup( d8 );;
gap> NaturalCharacter( hom );
Character( CharacterTable( <pc group of size 8 with 3 generators> ),
[ 8, 0, 0, 0 ] )
\end{verbatim}

72.7.3 PermutationCharacter

\texttt{PermutationCharacter}( \( G, D, \text{opr} \) ) (operation)
\texttt{PermutationCharacter}( \( G, U \) ) (operation)

Called with a group \( G \), an action domain or proper set \( D \), and an action function \texttt{opr} (see Chapter 41), \texttt{PermutationCharacter} returns the permutation character of the action of \( G \) on \( D \) via \texttt{opr}, that is, the value on each class is the number of points in \( D \) that are fixed by an element in this class under the action \texttt{opr}.

If the arguments are a group \( G \) and a subgroup \( U \) of \( G \) then \texttt{PermutationCharacter} returns the permutation character of the action of \( G \) on the right cosets of \( U \) via right multiplication.

To compute the permutation character of a transitive permutation group \( G \) on the cosets of a point stabilizer \( U \), the attribute \texttt{NaturalCharacter} (72.7.2) of \( G \) can be used instead of \texttt{PermutationCharacter}( \( G, U \) ).

More facilities concerning permutation characters are the transitivity test (see Section 72.8) and several tools for computing possible permutation characters (see 72.13, 72.14).

\begin{verbatim}
Example
\end{verbatim}

72.8 Operations for Class Functions

In the description of the following operations, the optional first argument \( \text{tbl} \) is needed only if the argument \( \chi \) is a plain list and not a class function object. In this case, \( \text{tbl} \) must always be the
character table of which \( \chi \) shall be regarded as a class function.

### 72.8.1 IsCharacter

\[
\text{IsCharacter([tbl, \chi])}
\]

An ordinary character of a group \( G \) is a class function of \( G \) whose values are the traces of a complex matrix representation of \( G \).

A Brauer character of \( G \) in characteristic \( p \) is a class function of \( G \) whose values are the complex lifts of a matrix representation of \( G \) with image a finite field of characteristic \( p \).

### 72.8.2 IsVirtualCharacter

\[
\text{IsVirtualCharacter([tbl, \chi])}
\]

A virtual character is a class function that can be written as the difference of two proper characters (see IsCharacter (72.8.1)).

### 72.8.3 IsIrreducibleCharacter

\[
\text{IsIrreducibleCharacter([tbl, \chi])}
\]

A character is irreducible if it cannot be written as the sum of two characters. For ordinary characters this can be checked using the scalar product of class functions (see ScalarProduct (72.8.5)). For Brauer characters there is no generic method for checking irreducibility.

```
Example

gap> S4:= SymmetricGroup( 4 );; SetName( S4, "S4" );
gap> psi:= ClassFunction( S4, [ 1, 1, 1, -2, 1 ] );
ClassFunction( CharacterTable( S4 ), [ 1, 1, 1, -2, 1 ] )
gap> IsVirtualCharacter( psi );
true
gap> IsCharacter( psi );
false
gap> chi:= ClassFunction( S4, SizesCentralizers( CharacterTable( S4 ) ) );
ClassFunction( CharacterTable( S4 ), [ 24, 4, 8, 3, 4 ] )
gap> IsCharacter( chi );
true
gap> IsIrreducibleCharacter( chi );
false
gap> IsIrreducibleCharacter( TrivialCharacter( S4 ) );
true
```

### 72.8.4 DegreeOfCharacter

\[
\text{DegreeOfCharacter(\chi)}
\]

is the value of the character \( \chi \) on the identity element. This can also be obtained as \( \chi[1] \).
Example

```gap
gap> List( Irr( S4 ), DegreeOfCharacter );
[ 1, 3, 2, 3, 1 ]
gap> nat:= NaturalCharacter( S4 );
Character( CharacterTable( S4 ), [ 4, 2, 0, 1, 0 ] )
gap> nat[1];
4
```

### 72.8.5 ScalarProduct (for characters)

**Declaration:**
```
> ScalarProduct([tbl, ]chi, psi)
(operation)
```

**Returns:** The scalar product of the class functions `chi` and `psi`, which belong to the same character table `tbl`.

- If `chi` and `psi` are class function objects, the argument `tbl` is not needed, but `tbl` is necessary if at least one of `chi`, `psi` is just a plain list.
- The scalar product of two ordinary class functions \( \chi, \psi \) of a group \( G \) is defined as \( \left( \sum_{g \in G} \chi(g)\psi(g^{-1}) \right)/|G| \).
- For two \( p \)-modular class functions, the scalar product is defined as \( \left( \sum_{g \in S} \chi(g)\psi(g^{-1}) \right)/|G| \), where \( S \) is the set of \( p \)-regular elements in \( G \).

### 72.8.6 MatScalarProducts

**Declaration:**
```
> MatScalarProducts([tbl, ]list[, list2])
(operation)
```

- Called with two lists `list`, `list2` of class functions of the same character table (which may be given as the argument `tbl`), `MatScalarProducts` returns the matrix of scalar products (see `ScalarProduct` (72.8.5)) More precisely, this matrix contains in the \( i \)-th row the list of scalar products of `list2[i]` with the entries of `list`.
- If only one list `list` of class functions is given then a lower triangular matrix of scalar products is returned, containing (for \( j \leq i \)) in the \( i \)-th row in column \( j \) the value \( \text{ScalarProduct(tbl, list[j], list[i])} \).

### 72.8.7 Norm (for a class function)

**Declaration:**
```
> Norm([tbl, ]chi)
(attribute)
```

For an ordinary class function `chi` of the group \( G \), say, we have \( \chi = \sum_{\chi \in \text{Irr}(G)} a_{\chi} \chi \), with complex coefficients \( a_{\chi} \). The **norm** of `chi` is defined as \( \sum_{\chi \in \text{Irr}(G)} a_{\chi} \overline{a_{\chi}} \).
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72.8.8 ConstituentsOfCharacter

\[ \text{ConstituentsOfCharacter}(\text{[tbl, } \chi]) \]

\text{(attribute)}

Let \( \chi \) be an ordinary or modular (virtual) character. If an ordinary or modular character table \( \text{tbl} \) is given then \( \chi \) may also be a list of character values.

\text{ConstituentsOfCharacter} returns the set of those irreducible characters that occur in the decomposition of \( \chi \) with nonzero coefficient.

Example

\[
\text{gap> nat:= NaturalCharacter( S4 );}
\]
\[
\text{Character( CharacterTable( S4 ), [ 4, 2, 0, 1, 0 ] )}
\]
\[
\text{gap> ConstituentsOfCharacter( nat );}
\]
\[
\text{[ Character( CharacterTable( S4 ), [ 1, 1, 1, 1 ] ),
  Character( CharacterTable( S4 ), [ 3, 1, -1, 0, -1 ] ) ]}
\]

72.8.9 KernelOfCharacter

\[ \text{KernelOfCharacter}(\text{[tbl, } \chi]) \]

\text{(attribute)}

For a class function \( \chi \) of the group \( G \), say, \text{KernelOfCharacter} returns the normal subgroup of \( G \) that is formed by those conjugacy classes for which the value of \( \chi \) equals the degree of \( \chi \). If the underlying character table of \( \chi \) does not store the group \( G \) then an error is signalled.

(See \text{ClassPositionsOfKernel (72.8.10)} for a way to handle the kernel implicitly, by listing the positions of conjugacy classes in the kernel.)

The returned group is the kernel of any representation of \( G \) that affords \( \chi \).

Example

\[
\text{gap> List( Irr( S4 ), KernelOfCharacter );}
\]
\[
\text{[ Alt( [ 1 .. 4 ] ), Group(()), Group([ (1,2)(3,4), (1,4)(2,3) ]),
  Group(()), Group([ ()], (1,2), (1,2)(3,4), (1,2,3), (1,2,3,4) ] ) ]}
\]

72.8.10 ClassPositionsOfKernel

\[ \text{ClassPositionsOfKernel}(\chi) \]

\text{(attribute)}
is the list of positions of those conjugacy classes that form the kernel of the character \( \chi \), that is, those positions with character value equal to the character degree.

```gap
gap> List( Irr( S4 ), ClassPositionsOfKernel );
[ [ 1, 3, 4 ], [ 1 ], [ 1, 3 ], [ 1 ], [ 1, 2, 3, 4, 5 ] ]
```

### 72.8.11 CentreOfCharacter

\( \text{CentreOfCharacter}(\{\text{tbl}, \chi\}) \)

(attribute)

For a character \( \chi \) of the group \( G \), say, \( \text{CentreOfCharacter} \) returns the *centre of \( \chi \)*, that is, the normal subgroup of all those elements of \( G \) for which the quotient of the value of \( \chi \) by the degree of \( \chi \) is a root of unity.

If the underlying character table of \( \psi \) does not store the group \( G \) then an error is signalled. (See \( \text{ClassPositionsOfCentre} \) (72.8.12) for a way to handle the centre implicitly, by listing the positions of conjugacy classes in the centre.)

```gap
gap> List( Irr( S4 ), CentreOfCharacter );
[ Group([ (1,2), (1,2)(3,4), (1,2)(3,4) ]), Group(()),
  Group([ (1,2)(3,4), (1,4)(2,3) ]), Group(()), Group([ () ])
```

### 72.8.12 ClassPositionsOfCentre (for a character)

\( \text{ClassPositionsOfCentre}(\chi) \)

(attribute)

is the list of positions of classes forming the centre of the character \( \chi \) (see \( \text{CentreOfCharacter} \) (72.8.11)).

```gap
gap> List( Irr( S4 ), ClassPositionsOfCentre );
[ [ 1, 2, 3, 4, 5 ], [ 1 ], [ 1, 3 ], [ 1 ], [ 1, 2, 3, 4, 5 ] ]
```

### 72.8.13 InertiaSubgroup

\( \text{InertiaSubgroup}(\{\text{tbl}, G, \chi\}) \)

(operation)

Let \( \chi \) be a character of the group \( H \), say, and \( \text{tbl} \) the character table of \( H \); if the argument \( \text{tbl} \) is not given then the underlying character table of \( \chi \) (see \( \text{UnderlyingCharacterTable} \) (72.2.1)) is used instead. Furthermore, let \( G \) be a group that contains \( H \) as a normal subgroup.

\( \text{InertiaSubgroup} \) returns the stabilizer in \( G \) of \( \chi \), w.r.t. the action of \( G \) on the classes of \( H \) via conjugation. In other words, \( \text{InertiaSubgroup} \) returns the group of all those elements \( g \in G \) that satisfy \( \chi^g = \chi \).

```gap
gap> der:= DerivedSubgroup( S4 ); Alt([ 1 .. 4 ])

gap> List( Irr( der ), chi -> InertiaSubgroup( S4, chi ) );
[ S4, Alt([ 1 .. 4 ]), Alt([ 1 .. 4 ]), S4 ]
```
72.8.14 CycleStructureClass

Let $\text{permchar}$ be a permutation character, and $\text{class}$ be the position of a conjugacy class of the character table of $\text{permchar}$. CycleStructureClass returns a list describing the cycle structure of each element in class $\text{class}$ in the underlying permutation representation, in the same format as the result of CycleStructurePerm (42.4.2).

Example

```gap
\text{gap> nat:= NaturalCharacter( S4 );}
Character( CharacterTable( S4 ), [ 4, 2, 0, 1, 0 ] )
\text{gap> List( [ 1 .. 5 ], i -> CycleStructureClass( nat, i ) );}
[ [ ] , [ 1 ], [ 2 ], [ , 1 ], [ , 1 ] ]
```

72.8.15 IsTransitive (for a character)

For a permutation character $\text{chi}$ of the group $G$ that corresponds to an action on the $G$-set $\Omega$ (see PermutationCharacter (72.7.3)), IsTransitive (41.10.1) returns true if the action of $G$ on $\Omega$ is transitive, and false otherwise.

Example

```gap
\text{gap> IsTransitive( nat ); Transitivity( nat );}
true 4
\text{gap> Transitivity( 2 * TrivialCharacter( S4 ) );}
0
```

72.8.16 Transitivity (for a character)

For a permutation character $\text{chi}$ of the group $G$ that corresponds to an action on the $G$-set $\Omega$ (see PermutationCharacter (72.7.3)), Transitivity returns the maximal nonnegative integer $k$ such that the action of $G$ on $\Omega$ is $k$-transitive.

Example

```gap
\text{gap> IsTransitive( nat ); Transitivity( nat );}
true 4
\text{gap> Transitivity( 2 * TrivialCharacter( S4 ) );}
0
```

72.8.17 CentralCharacter

For a character $\text{chi}$ of the group $G$, say, CentralCharacter returns the central character of $\text{chi}$. The central character of $\chi$ is the class function $\omega_{\chi}$ defined by $\omega_{\chi}(g) = |g|^G \cdot \chi(g)/\chi(1)$ for each $g \in G$.

72.8.18 DeterminantOfCharacter

For a character $\text{chi}$ of the group $G$, say, DeterminantOfCharacter returns the determinant of $\text{chi}$. The determinant of $\chi$ is the class function $\text{det}(g) = \chi(g)$ for each $g \in G$. 
DeterminantOfCharacter returns the determinant character of the character \( \chi \). This is defined to be the character obtained by taking the determinant of representing matrices of any representation affording \( \chi \); the determinant can be computed using \( \text{EigenvaluesChar} \) (72.8.19).

It is also possible to call \( \text{Determinant} \) (24.4.4) instead of \( \text{DeterminantOfCharacter} \).

Note that the determinant character is well-defined for virtual characters.

Example

\[
gap> \text{CentralCharacter( TrivialCharacter( S4 ) )};
\]
\[
\text{ClassFunction( CharacterTable( S4 ), [ 1, 6, 3, 8, 6 ] )}
\]
\[
\text{DeterminantOfCharacter( Irr( S4 )[3] )};
\]
\[
\text{Character( CharacterTable( S4 ), [ 1, -1, 1, 1, -1 ] )}
\]

72.8.19 \( \text{EigenvaluesChar} \)

\( \triangleright \) \( \text{EigenvaluesChar( [tbl, ]chi, class) (operation)} \)

Let \( \chi \) be a character of the group \( G \), say. For an element \( g \in G \) in the \( \text{class} \)-th conjugacy class, of order \( n \), let \( M \) be a matrix of a representation affording \( \chi \).

\( \text{EigenvaluesChar} \) returns the list of length \( n \) where at position \( k \) the multiplicity of \( E(n)^k = \exp(2\pi ik/n) \) as an eigenvalue of \( M \) is stored.

We have \( \chi[ \text{class } ] = \text{List( [ 1 .. n ], k -> E(n)^k ) * EigenvaluesChar( tbl, chi, class )} \).

It is also possible to call \( \text{Eigenvalues} \) (24.8.3) instead of \( \text{EigenvaluesChar} \).

Example

\[
gap> \text{chi:= Irr( CharacterTable( "A5" ) )[2]};
\]
\[
\text{Character( CharacterTable( "A5" ),}
\]
\[
\text{[ 3, -1, 0, -E(5)-E(5)^4, -E(5)^2-E(5)^3 ]}
\]
\[
\text{gap> List( [ 1 .. 5 ], i -> Eigenvalues( chi, i ) );}
\]
\[
\text{[ [ 3 ], [ 2, 1 ], [ 1, 1, 1 ], [ 0, 1, 1, 0, 1 ], [ 1, 0, 1, 1 ] ]}
\]

72.8.20 \( \text{Tensored} \)

\( \triangleright \) \( \text{Tensored( chars1, chars2) (operation)} \)

Let \( \text{chars1} \) and \( \text{chars2} \) be lists of (values lists of) class functions of the same character table. \( \text{Tensored} \) returns the list of tensor products of all entries in \( \text{chars1} \) with all entries in \( \text{chars2} \).

Example

\[
gap> \text{irra5:= Irr( CharacterTable( "A5" ) )};
\]
\[
\text{gap> chars1:= irra5[ [ 1 .. 3 ] ]; chars2:= irra5[ [ 2, 3 ] ];}
\]
\[
\text{gap> Tensored( chars1, chars2 );}
\]
\[
\text{[ Character( CharacterTable( "A5" ), [ 3, -1, 0, -E(5)-E(5)^4, -E(5)^2-E(5)^3 ] ), Character( CharacterTable( "A5" ), [ 3, -1, 0, -E(5)^2-E(5)^3, -E(5)-E(5)^4 ] ), Character( CharacterTable( "A5" ), [ 9, 1, 0, -2*E(5)-E(5)^2-E(5)^3-2*E(5)^4, -E(5)-2*E(5)^2-2*E(5)^3-E(5)^4 ] ), Character( CharacterTable( "A5" ), [ 9, 1, 0, -1, -1 ] ), Character( CharacterTable( "A5" ), [ 9, 1, 0, -1, -1 ] ), Character( CharacterTable( "A5" ), [ 9, 1, 0, -1, -1 ] ), Character( CharacterTable( "A5" ), [ 9, 1, 0, -1, -1 ] ), Character( CharacterTable( "A5" ), [ 9, 1, 0, -1, -1 ] )];}
\]
72.9 Restricted and Induced Class Functions

For restricting a class function of a group \( G \) to a subgroup \( H \) and for inducing a class function of \( H \) to \( G \), the class fusion from \( H \) to \( G \) must be known (see 73.3).

If \( F \) is the factor group of \( G \) by the normal subgroup \( N \) then each class function of \( F \) can be naturally regarded as a class function of \( G \), with \( N \) in its kernel. For a class function of \( F \), the corresponding class function of \( G \) is called the inflated class function. Restriction and inflation are in principle the same, namely indirection of a class function by the appropriate fusion map, and thus no extra operation is needed for this process. But note that contrary to the case of a subgroup fusion, the factor fusion can in general not be computed from the groups \( G \) and \( F \); either one needs the natural homomorphism, or the factor fusion to the character table of \( F \) must be stored on the table of \( G \). This explains the different syntax for computing restricted and inflated class functions.

In the following, the meaning of the optional first argument \( tbl \) is the same as in Section 72.8.

72.9.1 RestrictedClassFunction

\[
\text{RestrictedClassFunction}(\text{tbl, } \chi, \text{target})
\]

Let \( \chi \) be a class function of the group \( G \), say, and let \( \text{target} \) be either a subgroup \( H \) of \( G \) or an injective homomorphism from \( H \) to \( G \) or the character table of \( H \). Then \text{RestrictedClassFunction} returns the class function of \( H \) obtained by restricting \( \chi \) to \( H \).

If \( \chi \) is a class function of a factor group \( G \) of \( H \), where \( \text{target} \) is either the group \( H \) or a homomorphism from \( H \) to \( G \) or the character table of \( H \) then the restriction can be computed in the case of the homomorphism; in the other cases, this is possible only if the factor fusion from \( H \) to \( G \) is stored on the character table of \( H \).

72.9.2 RestrictedClassFunctions

\[
\text{RestrictedClassFunctions}(\text{tbl, } \text{chars, target})
\]

RestrictedClassFunctions is similar to RestrictedClassFunction (72.9.1), the only difference is that it takes a list \( \text{chars} \) of class functions instead of one class function, and returns the list of restricted class functions.

Example

\[
\text{gap> a5:= CharacterTable( "A5" );; s5:= CharacterTable( "S5" );;}
\text{gap> RestrictedClassFunction( Irr( s5 )[2], a5 );}
\text{Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] )}
\text{gap> RestrictedClassFunctions( Irr( s5 ), a5 );}
\text{[ Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),}
\text{ Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),}
\text{ Character( CharacterTable( "A5" ), [ 6, -2, 0, 1, 1 ] ),}
\text{ Character( CharacterTable( "A5" ), [ 4, 0, 1, -1, -1 ] ),}
\text{ Character( CharacterTable( "A5" ), [ 4, 0, 1, -1, -1 ] ),}
\text{ Character( CharacterTable( "A5" ), [ 5, 1, -1, 0, 0 ] ),}
\text{ Character( CharacterTable( "A5" ), [ 5, 1, -1, 0, 0 ] ) ]}
\]
gap> hom:= NaturalHomomorphismByNormalSubgroup( S4, der );;
gap> RestrictedClassFunctions( Irr( Image( hom ) ), hom );
[ Character( CharacterTable( S4 ), [ 1, 1, 1, 1 ] ),
  Character( CharacterTable( S4 ), [ 1, -1, 1, -1 ] ) ]

72.9.3 InducedClassFunction

▷ InducedClassFunction([tbl, ]chi, H) (operation)
▷ InducedClassFunction([tbl, ]chi, hom) (operation)
▷ InducedClassFunction([tbl, ]chi, suptbl) (operation)

Let \( \chi \) be a class function of the group \( G \), say, and let \( \text{target} \) be either a supergroup \( H \) of \( G \) or an injective homomorphism from \( H \) to \( G \) or the character table of \( H \). Then \text{InducedClassFunction} returns the class function of \( H \) obtained by inducing \( \chi \) to \( H \).

72.9.4 InducedClassFunctions

▷ InducedClassFunctions([tbl, ]chars, target) (operation)

\text{InducedClassFunctions} is similar to \text{InducedClassFunction} (72.9.3), the only difference is that it takes a list \( \text{chars} \) of class functions instead of one class function, and returns the list of induced class functions.

Example

\begin{verbatim}
gap> InducedClassFunctions( Irr( a5 ), s5 );
[ Character( CharacterTable( "A5.2" ), [ 2, 2, 2, 2, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 6, -2, 0, 1, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 6, -2, 0, 1, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 8, 0, 2, -2, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 10, 2, -2, 0, 0, 0, 0 ] ) ]
\end{verbatim}

72.9.5 InducedClassFunctionsByFusionMap

▷ InducedClassFunctionsByFusionMap(subtbl, tbl, chars, fusionmap) (function)

Let \( \text{subtbl} \) and \( \text{tbl} \) be two character tables of groups \( H \) and \( G \), such that \( H \) is a subgroup of \( G \), let \( \text{chars} \) be a list of class functions of \( \text{subtbl} \), and let \( \text{fusionmap} \) be a fusion map from \( \text{subtbl} \) to \( \text{tbl} \). The function returns the list of induced class functions of \( \text{tbl} \) that correspond to \( \text{chars} \), w.r.t. the given fusion map.

\text{InducedClassFunctionsByFusionMap} is the function that does the work for \text{InducedClassFunction} (72.9.3) and \text{InducedClassFunctions} (72.9.4).

Example

\begin{verbatim}
gap> fus:= PossibleClassFusions( a5, s5 );
[ [ 1, 2, 3, 4, 4 ] ]
gap> InducedClassFunctionsByFusionMap( a5, s5, Irr( a5 ), fus[1] );
[ Character( CharacterTable( "A5.2" ), [ 2, 2, 2, 2, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 6, -2, 0, 1, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 6, -2, 0, 1, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 8, 0, 2, -2, 0, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 10, 2, -2, 0, 0, 0, 0 ] ) ]
\end{verbatim}
72.9.6 InducedCyclic

\[ \text{InducedCyclic} \left( \text{tbl}[, \text{classes}][, "all"] \right) \] (operation)

InducedCyclic calculates characters induced up from cyclic subgroups of the ordinary character table \( \text{tbl} \) to \( \text{tbl} \), and returns the strictly sorted list of the induced characters.

If the string "all" is specified then all irreducible characters of these subgroups are induced, otherwise only the permutation characters are calculated.

If a list \( \text{classes} \) is specified then only those cyclic subgroups generated by these classes are considered, otherwise all classes of \( \text{tbl} \) are considered.

```gap
gap> InducedCyclic( a5, "all" );
[ Character( CharacterTable( "A5" ), [ 12, 0, 0, 2, 2 ] ),
  Character( CharacterTable( "A5" ),
    [ 12, 0, 0, E(5)^2+E(5)^3, E(5)+E(5)^4 ] ),
  Character( CharacterTable( "A5" ),
    [ 12, 0, 0, E(5)+E(5)^4, E(5)^2+E(5)^3 ] ),
  Character( CharacterTable( "A5" ), [ 20, 0, -1, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 20, 0, 2, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 30, -2, 0, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 30, 2, 0, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 60, 0, 0, 0, 0 ] ) ]
```

72.10 Reducing Virtual Characters

The following operations are intended for the situation that one is given a list of virtual characters of a character table and is interested in the irreducible characters of this table. The idea is to compute virtual characters of small norm from the given ones, hoping to get eventually virtual characters of norm 1.

72.10.1 ReducedClassFunctions

\[ \text{ReducedClassFunctions} \left( \text{tbl}[, \text{constituents}][, \text{reducibles}] \right) \] (operation)

Let \( \text{reducibles} \) be a list of ordinary virtual characters of the group \( G \), say. If \( \text{constituents} \) is given then it must also be a list of ordinary virtual characters of \( G \), otherwise we have \( \text{constituents} \) equal to \( \text{reducibles} \) in the following.

ReducedClassFunctions returns a record with the components \( \text{remainders} \) and \( \text{irreducibles} \), both lists of virtual characters of \( G \). These virtual characters are computed as follows.

Let \( \text{rems} \) be the set of nonzero class functions obtained by subtraction of

\[ \sum_{\chi} \left( \text{reducibles}[i], \chi \right) / \left( \chi, \chi \right) \cdot \chi \]

from \( \text{reducibles}[i] \), where the summation runs over \( \text{constituents} \) and \( \left( \chi, \psi \right) \) denotes the scalar product of \( G \)-class functions. Let \( \text{irrs} \) be the list of irreducible characters in \( \text{rems} \).

We project \( \text{rems} \) into the orthogonal space of \( \text{irrs} \) and all those irreducibles found this way until no new irreducibles arise. Then the \( \text{irreducibles} \) list is the set of all found irreducible characters, and the \( \text{remainders} \) list is the set of all nonzero remainders.
72.10.2 ReducedCharacters

ReducedCharacters is similar to ReducedClassFunctions (72.10.1), the only difference is that `constituents` and `reducibles` are assumed to be lists of characters. This means that only those scalar products must be formed where the degree of the character in `constituents` does not exceed the degree of the character in `reducibles`.

```gap
gap> tbl := CharacterTable( "A5" );;
gap> chars := Irr( tbl ){ [ 2 .. 4 ] };;
gap> chars := Set( Tensored( chars, chars ) );;
gap> red := ReducedClassFunctions( chars );
rec(
    irreducibles :=
        [ Character( CharacterTable( "A5" ), [ 1, 1, 1, 1 ] ),
          Character( CharacterTable( "A5" ),
                      [ 3, -1, 0, -E(5)-E(5)^4, -E(5)^2-E(5)^3 ] ),
          Character( CharacterTable( "A5" ),
                      [ 3, -1, 0, -E(5)^2-E(5)^3, -E(5)-E(5)^4 ] ),
          Character( CharacterTable( "A5" ), [ 4, 0, 1, -1, -1 ] ),
          Character( CharacterTable( "A5" ), [ 5, 1, -1, 0, 0 ] ) ],
    remainders := [ ]
)
```

72.10.3 IrreducibleDifferences

IrreducibleDifferences returns the list of irreducible characters which occur as difference of an element of `reducibles` and an element of `reducibles2`, where these two arguments are lists of class functions of the character table `tbl`.

If `reducibles2` is the string "triangle" then the differences of elements in `reducibles` are considered.

If `scprmat` is not specified then it will be calculated, otherwise we must have `scprmat = MatScalarProducts( tbl, reducibles, reducibles2 )` or `scprmat = MatScalarProducts( tbl, reducibles )`, respectively.

```gap
gap> IrreducibleDifferences( a5, chars, "triangle" );
[ Character( CharacterTable( "A5" ),
              [ 3, -1, 0, -E(5)-E(5)^4, -E(5)^2-E(5)^3 ] ),
  Character( CharacterTable( "A5" ),
```

72.10.4 LLL

LLL calls the LLL algorithm (see LLLReducedBasis (25.5.1)) in the case of lattices spanned by the virtual characters `characters` of the ordinary character table `tbl` (see ScalarProduct (72.8.5)).
finding shorter vectors in the lattice spanned by \texttt{characters}, i.e., virtual characters of smaller norm, in some cases \texttt{LLL} is able to find irreducible characters.

\texttt{LLL} returns a record with at least components \texttt{irreducibles} (the list of found irreducible characters), \texttt{remainders} (a list of reducible virtual characters), and \texttt{norms} (the list of norms of the vectors in \texttt{remainders}). \texttt{irreducibles} together with \texttt{remainders} form a basis of the \( \mathbb{Z} \)-lattice spanned by \texttt{characters}.

Note that the vectors in the \texttt{remainders} list are in general not orthogonal (see \texttt{ReducedClassFunctions (72.10.1)}) to the irreducible characters in \texttt{irreducibles}.

Optional arguments of \texttt{LLL} are

\texttt{y} controls the sensitivity of the algorithm, see \texttt{LLLReducedBasis (25.5.1)}.

\texttt{"sort"} \texttt{LLL} sorts \texttt{characters} and the \texttt{remainders} component of the result according to the degrees,

\texttt{"linearcomb"} the returned record contains components \texttt{irreddecomp} and \texttt{reddecomp}, which are decomposition matrices of \texttt{irreducibles} and \texttt{remainders}, with respect to \texttt{characters}.

\begin{verbatim}
Example
gap> s4:= CharacterTable( "Symmetric", 4 );;
gap> chars:= [ [ 8, 0, 0, -1, 0 ], [ 6, 0, 2, 0, 2 ],
  > [ 12, 0, -4, 0, 0 ], [ 6, 0, -2, 0, 0 ], [ 24, 0, 0, 0, 0 ],
  > [ 12, 0, 4, 0, 0 ], [ 6, 0, 2, 0, -2 ], [ 12, -2, 0, 0, 0 ],
  > [ 8, 0, 0, 2, 0 ], [ 12, 2, 0, 0, 0 ], [ 1, 1, 1, 1, 1 ] ];;

gap> LLL( s4, chars );
rec(
  irreducibles :=
    [ Character( CharacterTable( "Sym(4)" ), [ 2, 0, 2, -1, 0 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 1, 1, 1, 1, 1 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 3, 1, -1, 0, -1 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 3, -1, -1, 0, 1 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 1, -1, 1, 1, -1 ] ) ],
  norms := [ ],
  remainders := [ ]
)
\end{verbatim}

\textbf{72.10.5} Extract

\texttt{Extract(tbl, reducibles, grammat [, missing])} (function)

Let \texttt{tbl} be an ordinary character table, \texttt{reducibles} a list of characters of \texttt{tbl}, and \texttt{grammat} the matrix of scalar products of \texttt{reducibles} (see \texttt{MatScalarProducts (72.8.6)}). \texttt{Extract} tries to find irreducible characters by drawing conclusions out of the scalar products, using combinatorial and backtrack means.

The optional argument \texttt{missing} is the maximal number of irreducible characters that occur as constituents of \texttt{reducibles}. Specification of \texttt{missing} may accelerate \texttt{Extract}.

\texttt{Extract} returns a record \texttt{ext} with the components \texttt{solution} and \texttt{choice}, where the value of \texttt{solution} is a list \([M_1, \ldots, M_n]\) of decomposition matrices \(M_i\) (up to permutations of rows) with the property that \(M_i' \cdot X\) is equal to the sublist at the positions \texttt{ext.choice[i]} of \texttt{reducibles}, for a matrix \(X\) of irreducible characters; the value of \texttt{choice} is a list of length \(n\) whose entries are lists of indices.
So the \(j\)-th column in each matrix \(M_i\) corresponds to \texttt{reducibles}[j], and each row in \(M_i\) corresponds to an irreducible character. \texttt{Decreased (72.10.7)} can be used to examine the solution for computable irreducibles.

Example

```gap
gap> s4 := CharacterTable( "Symmetric", 4 );;
gap> red := [ [ 5, 1, 5, 2, 1 ], [ 2, 0, 2, 2, 0 ], [ 3, -1, 3, 0, -1 ], [ 6, 0, -2, 0, 0 ], [ 4, 0, 0, 1, 2 ] ];;
gap> gram := MatScalarProducts( s4, red, red );
[ [ 6, 3, 2, 0, 2 ], [ 3, 2, 1, 0, 1 ], [ 2, 1, 2, 0, 0 ], [ 0, 0, 0, 1, 2 ] ];
gap> ext := Extract( s4, red, gram, 5 );
rec( choice := [ [ 2, 5, 3, 4, 1 ] ],
solution :=
[ [ 1, 1, 0, 2, 1 ], [ 1, 0, 1, 1, 1 ], [ 0, 1, 0, 1, 0 ],
  [ 0, 0, 1, 1, 1 ], [ 0, 0, 0, 1, 0 ] ] )
gap> dec := Decreased( s4, red, ext.solution[1], ext.choice[1] );
rec( irreducibles :=
  [ Character( CharacterTable( "Sym(4)" ), [ 1, 1, 1, 1 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 3, -1, 1, 1 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 1, -1, 1, -1 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 3, 1, -1, 0 ] ),
    Character( CharacterTable( "Sym(4)" ), [ 2, 0, 0, 0 ] ] ),
  matrix := [ ], remainders := [ ] )
```

### 72.10.6 OrthogonalEmbeddingsSpecialDimension

\texttt{OrthogonalEmbeddingsSpecialDimension(tbl, reducibles, grammat [, "positive"], dim)} (function)

\texttt{OrthogonalEmbeddingsSpecialDimension} is a variant of \texttt{OrthogonalEmbeddings (25.6.1)} for the situation that \(tbl\) is an ordinary character table, \texttt{reducibles} is a list of virtual characters of \(tbl\), \texttt{grammat} is the matrix of scalar products (see \texttt{MatScalarProducts (72.8.6)}), and \(dim\) is an upper bound for the number of irreducible characters of \(tbl\) that occur as constituents of \texttt{reducibles}; if the vectors in \texttt{reducibles} are known to be proper characters then the string "positive" may be entered as fourth argument. (See \texttt{OrthogonalEmbeddings (25.6.1)} for information why this may help.)

\texttt{OrthogonalEmbeddingsSpecialDimension} first uses \texttt{OrthogonalEmbeddings (25.6.1)} to compute all orthogonal embeddings of \texttt{grammat} into a standard lattice of dimension up to \(dim\), and then calls \texttt{Decreased (72.10.7)} in order to find irreducible characters of \(tbl\).

\texttt{OrthogonalEmbeddingsSpecialDimension} returns a record with the following components.

- \texttt{irreducibles}: a list of found irreducibles, the intersection of all lists of irreducibles found by \texttt{Decreased (72.10.7)}, for all possible embeddings, and
- \texttt{remainders}: a list of remaining reducible virtual characters.
Example

```gap
gap> s6 := CharacterTable( "S6" );;
gap> red := InducedCyclic( s6, "all" );;
gap> Add( red, TrivialCharacter( s6 ) );
gap> lll := LLL( s6, red );;
gap> irred := lll.irreducibles;
[ Character( CharacterTable( "A6.2_1" ),
  [ 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A6.2_1" ),
  [ 9, 1, 0, 0, 1, -1, -3, -3, 1, 0, 0 ] ),
  Character( CharacterTable( "A6.2_1" ),
  [ 16, 0, -2, -2, 0, 1, 0, 0, 0, 0, 0 ] ) ]
gap> Set( Flat( MatScalarProducts( s6, irred, lll.remainders ) ) );
[ 0 ]
gap> dim := NrConjugacyClasses( s6 ) - Length( lll.irreducibles );
8
gap> rem := lll.remainders;; Length( rem );
8

gap> gram := MatScalarProducts( s6, rem, rem );; RankMat( gram );
8

gap> emb1 := OrthogonalEmbeddings( gram, 8 );
rec( norms := [ 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ],
  solutions := [ [ 1, 2, 3, 7, 11, 12, 13, 15 ],
    [ 1, 2, 4, 8, 10, 12, 13, 14 ], [ 1, 2, 5, 6, 9, 12, 13, 16 ] ],
  vectors :=
    [ [ -1, 0, 0, 0, 0, 0, 0, 0 ], [ 1, 1, 0, 0, 0, 0, 0, 0 ], [ 0, 1, 1, 0, 0, 0, 0, 0 ], [ 0, 1, 1, 0, 0, 0, 0, 0 ], [ 0, 1, 1, 0, 0, 0, 0, 0 ],
     [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ],
     [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ], [ 0, 0, 0, 0, 0, 0, 0, 0 ],
     [ 0, 0, 0, 0, 0, 0, 0, 0 ] ] )
```

In the following example we temporarily decrease the line length limit from its default value 80 to 62 in order to get a nicer output format.

```gap

gap> emb2 := OrthogonalEmbeddingsSpecialDimension( s6, rem, gram, 8 );
rec( irreducibles :=
  [ Character( CharacterTable( "A6.2_1" ),
    [ 5, 1, -1, 2, -1, 0, 1, -3, -1, 1, 0 ] ),
    Character( CharacterTable( "A6.2_1" ),
    [ 5, 1, 2, -1, -1, 0, -3, 1, -1, 0, 1 ] ),
    Character( CharacterTable( "A6.2_1" ),
    [ 10, -2, 1, 0, 0, -2, 2, 0, 1, -1 ] ),
    Character( CharacterTable( "A6.2_1" ),
    [ 10, -2, 1, 0, 0, -2, 2, 0, 1, -1 ] ] ),
reminders :=
  [ VirtualCharacter( CharacterTable( "A6.2_1" ),
    [ 0, 0, 3, -3, 0, 0, 4, -4, 0, 1, -1 ] ),
   VirtualCharacter( CharacterTable( "A6.2_1" ),
```
72.10.7  Decreased

\[ \text{Decreased(tbl, chars, decompmat[, choice])} \]

Let \( \text{tbl} \) be an ordinary character table, \( \text{chars} \) a list of virtual characters of \( \text{tbl} \), and \( \text{decompmat} \) a decomposition matrix, that is, a matrix \( M \) with the property that \( M' \cdot X = \text{chars} \) holds, where \( X \) is a list of irreducible characters of \( \text{tbl} \). \text{Decreased} tries to compute the irreducibles in \( X \) or at least some of them.

Usually \text{Decreased} is applied to the output of \text{Extract} (72.10.5) or \text{OrthogonalEmbeddings} (25.6.1) or \text{OrthogonalEmbeddingsSpecialDimension} (72.10.6). In the case of \text{Extract} (72.10.5), the choice component corresponding to the decomposition matrix must be entered as argument \text{choice} of \text{Decreased}.

\text{Decreased} returns \text{fail} if it can prove that no list \( X \) of irreducible characters corresponding to the arguments exists; otherwise \text{Decreased} returns a record with the following components.

- **irreducibles**
  - the list of found irreducible characters,

- **remainders**
  - the remaining reducible characters, and

- **matrix**
  - the decomposition matrix of the characters in the \text{remainders} component.

In the following example we temporarily decrease the line length limit from its default value 80 to 62 in order to get a nicer output format.

\begin{verbatim}
Example

gap> s4:= CharacterTable( "Symmetric", 4 );;

gap> x:= Irr( s4 );;


gap> mat:= MatScalarProducts( s4, red, red );
[ [ 2, -1, -1, -1 ], [ -1, 2, 0, 0 ], [ -1, 0, 2, 0 ],
  [ -1, 0, 0, 2 ] ]

gap> emb:= OrthogonalEmbeddings( mat );
rec( norms := [ 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ],
  solutions := [ [ 1, 6, 7, 12 ], [ 2, 5, 8, 11 ], [ 3, 4, 9, 10 ] ],
  vectors := [ [ -1, 1, 1, 0 ], [ -1, 1, 0, 1 ], [ 1, -1, 0, 0 ],
               [ -1, 0, 1, 1 ], [ -1, 0, 1, 0 ], [ -1, 0, 0, 1 ],
               [ 0, -1, 1, 0 ], [ 0, 1, 0, 1 ], [ 0, 1, 0, 0 ],
               [ 0, 0, -1, 1 ], [ 0, 0, 1, 1 ], [ 0, 0, 0, 1 ] ] )

gap> dec:= Decreased( s4, red, emb.vectors{ emb.solutions[1] } );
rec(
  irreducibles :=
  [ Character( CharacterTable( "Sym(4)" ), [ 3, -1, -1, 0, 1 ] ),
  ])
\end{verbatim}
\section*{72.10.8 \texttt{DnLattice}}

\par \texttt{DnLattice(tbl, grammat, reducibles)} (function)

Let \texttt{tbl} be an ordinary character table, and \texttt{reducibles} a list of virtual characters of \texttt{tbl}.

\texttt{DnLattice} searches for sublattices isomorphic to root lattices of type \(D_n\), for \(n \geq 4\), in the lattice that is generated by \texttt{reducibles}; each vector in \texttt{reducibles} must have norm 2, and the matrix of scalar products (see \texttt{MatScalarProducts (72.8.6)}) of \texttt{reducibles} must be entered as argument \texttt{grammat}.

\texttt{DnLattice} is able to find irreducible characters if there is a lattice of type \(D_n\) with \(n > 4\). In the case \(n = 4\), \texttt{DnLattice} may fail to determine irreducibles.

\texttt{DnLattice} returns a record with components

- \texttt{irreducibles} \hspace{1cm} the list of found irreducible characters,
- \texttt{remainders} \hspace{1cm} the list of remaining reducible virtual characters, and
- \texttt{gram} \hspace{1cm} the Gram matrix of the vectors in \texttt{remainders}.

The \texttt{remainders} list is transformed in such a way that the \texttt{gram} matrix is a block diagonal matrix that exhibits the structure of the lattice generated by the vectors in \texttt{remainders}. So \texttt{DnLattice} might be useful even if it fails to find irreducible characters.

In the following example we temporarily decrease the line length limit from its default value 80 to 62 in order to get a nicer output format.

\begin{verbatim}
Example

\begin{verbatim}
gap> s4:= CharacterTable( "Symmetric", 4 );;
gap> red:= [ [ 2, 0, 2, 2, 0 ], [ 4, 0, 0, 1, 2 ],
         [ 5, -1, 1, -1, 1 ], [ -1, 1, 3, -1, -1 ] ];;

gap> gram:= MatScalarProducts( s4, red, red );
[ [ 2, 1, 0, 0 ], [ 1, 2, 1, -1 ], [ 0, 1, 2, 0 ], [ 0, -1, 0, 2 ] ]

gap> dn:= DnLattice( s4, red, red );
rec( gram := [ ],
    irreducibles :=
    [ Character( CharacterTable( "Sym(4)" ), [ 2, 0, 2, -1, 0 ] ),
      Character( CharacterTable( "Sym(4)" ), [ 1, -1, 1, 1, 1 ] ),
      Character( CharacterTable( "Sym(4)" ), [ 1, 1, 1, 1 ] ),
      Character( CharacterTable( "Sym(4)" ), [ 3, -1, -1, 0, 1 ] ) ],
    remainders := [ ] )
\end{verbatim}
\end{verbatim}

\end{verbatim}
72.10.9 DnLatticeIterative

\[ DnLatticeIterative(tbl, reducibles) \]

Let \( tbl \) be an ordinary character table, and \( reducibles \) either a list of virtual characters of \( tbl \) or a record with components \( \text{remainders} \) and \( \text{norms} \), for example a record returned by LLL (72.10.4).

\( DnLatticeIterative \) was designed for iterative use of \( DnLattice \) (72.10.8). \( DnLatticeIterative \) selects the vectors of norm 2 among the given virtual character, calls \( DnLattice \) (72.10.8) for them, reduces the virtual characters with found irreducibles, calls \( DnLattice \) (72.10.8) again for the remaining virtual characters, and so on, until no new irreducibles are found.

\( DnLatticeIterative \) returns a record with the same components and meaning of components as LLL (72.10.4).

Example

\begin{verbatim}
gap> s4 := CharacterTable( "Symmetric", 4 );;
gap> red := [ [ 2, 0, 2, 2, 0 ], [ 4, 0, 1, 2 ], > [ 5, -1, 1, -1, 1 ], [ -1, 1, 3, -1, -1 ] ];;
gap> dn := DnLatticeIterative( s4, red );
rec( irreducibles := [ Character( CharacterTable( "Sym(4)" ), [ 2, 0, 2, -1, 0 ] ), Character( CharacterTable( "Sym(4)" ), [ 1, -1, 1, 1, -1 ] ), Character( CharacterTable( "Sym(4)" ), [ 1, 1, 1, 1, 1 ] ), Character( CharacterTable( "Sym(4)" ), [ 3, -1, -1, 0, 1 ] ) ], norms := [ ], remainders := [ ] )
\end{verbatim}

72.11 Symmetrizations of Class Functions

72.11.1 Symmetrizations

\[ \text{Symmetrizations([tbl, ]characters, n)} \]

\( \text{Symmetrizations} \) returns the list of symmetrizations of the characters \( \text{characters} \) of the ordinary character table \( tbl \) with the ordinary irreducible characters of the symmetric group of degree \( n \); instead of the integer \( n \), the character table of the symmetric group can be entered.

The symmetrization \( \chi^{[\lambda]} \) of the character \( \chi \) of \( tbl \) with the character \( \lambda \) of the symmetric group \( S_n \) of degree \( n \) is defined by

\[ \chi^{[\lambda]}(g) = \left( \sum_{\rho \in S_n} \lambda(\rho) \prod_{k=1}^{n} \chi(g^k)^{a_k(\rho)} \right) / n!, \]

where \( a_k(\rho) \) is the number of cycles of length \( k \) in \( \rho \).

For special kinds of symmetrizations, see \( \text{SymmetricParts} \) (72.11.2), \( \text{AntiSymmetricParts} \) (72.11.3), \( \text{MinusCharacter} \) (73.6.5) and \( \text{OrthogonalComponents} \) (72.11.4), \( \text{SymplecticComponents} \) (72.11.5).

Note that the returned list may contain zero class functions, and duplicates are not deleted.
Example

```gap
gap> tbl:= CharacterTable( "A5" );;
gap> Symmetrizations( Irr( tbl ){ [ 1 .. 3 ] }, 3 );
[ VirtualCharacter( CharacterTable( "A5" ), [ 0, 0, 0, 0, 0 ] ),
  VirtualCharacter( CharacterTable( "A5" ), [ 0, 0, 0, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A5" ),
    [ 8, 0, -1, -E(5)-E(5)^4, -E(5)^2-E(5)^3 ] ),
  Character( CharacterTable( "A5" ), [ 10, -2, 1, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 10, -2, 1, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 20, 0, 2, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 35, 3, 2, 0, 0 ] ) ]
```

72.11.2 SymmetricParts

\[ \text{SymmetricParts}(t, c, n) \]

is the list of symmetrizations of the characters \(c\) of the character table \(t\) with the trivial character of the symmetric group of degree \(n\) (see Symmetrizations (72.11.1)).

Example

```gap
gap> SymmetricParts( tbl, Irr( tbl ), 3 );
[ Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A5" ), [ 10, -2, 1, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 10, -2, 1, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 20, 0, 2, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 35, 3, 2, 0, 0 ] ) ]
```

72.11.3 AntiSymmetricParts

\[ \text{AntiSymmetricParts}(t, c, n) \]

is the list of symmetrizations of the characters \(c\) of the character table \(t\) with the alternating character of the symmetric group of degree \(n\) (see Symmetrizations (72.11.1)).

Example

```gap
gap> AntiSymmetricParts( tbl, Irr( tbl ), 3 );
[ VirtualCharacter( CharacterTable( "A5" ), [ 0, 0, 0, 0, 0 ] ),
  Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A5" ), [ 4, 0, 1, -1, -1 ] ),
  Character( CharacterTable( "A5" ), [ 10, -2, 1, 0, 0 ] ) ]
```

72.11.4 OrthogonalComponents

\[ \text{OrthogonalComponents}(t, c, m) \]

If \(\chi\) is a nonlinear character with indicator \(+1\), a splitting of the tensor power \(\chi^m\) is given by the so-called Murnaghan functions (see [Mur58]). These components in general have fewer irreducible
constituents than the symmetrizations with the symmetric group of degree \( m \) (see Symmetrizations (72.11.1)).

OrthogonalComponents returns the Murnaghan components of the nonlinear characters of the character table \( \text{tbl} \) in the list \( \text{chars} \) up to the power \( m \), where \( m \) is an integer between 2 and 6.

The Murnaghan functions are implemented as in [Fra82].

Note: If \( \text{chars} \) is a list of character objects (see IsCharacter (72.8.1)) then also the result consists of class function objects. It is not checked whether all characters in \( \text{chars} \) do really have indicator \( +1 \); if there are characters with indicator 0 or \(-1\), the result might contain virtual characters (see also SymplecticComponents (72.11.5)), therefore the entries of the result do in general not know that they are characters.

Example

```gap
gap> tbl:= CharacterTable( "A8" );;  \chi:= \text{Irr}( \text{tbl} )[2];
Character( CharacterTable( "A8" ), [ 7, -1, 3, 4, 1, -1, 1, 2, 0, -1, 
0, 0, -1, -1 ] )
gap> \text{OrthogonalComponents}( \text{tbl}, [ \chi ], 3 );
[ \text{ClassFunction}( \text{CharacterTable}( "A8" ),
[ 21, -3, 1, 6, 0, 1, -1, 1, -2, 0, 0, 0, 1, 1 ] ),
\text{ClassFunction}( \text{CharacterTable}( "A8" ),
[ 27, 3, 7, 9, 0, -1, 1, 2, 1, 0, -1, -1, -1 ] ),
\text{ClassFunction}( \text{CharacterTable}( "A8" ),
[ 105, 1, 5, 15, -3, 1, -1, 0, -1, 1, 0, 0, 0, 0 ] ),
\text{ClassFunction}( \text{CharacterTable}( "A8" ),
[ 35, 3, -5, 5, 2, -1, -1, 0, 1, 0, 0, 0, 0, 0 ] ),
\text{ClassFunction}( \text{CharacterTable}( "A8" ),
[ 77, -3, 13, 17, 2, 1, 1, 2, 1, 0, 0, 0, 2, 2 ] ) ]
```

72.11.5 SymplecticComponents

\( \triangleleft \) SymplecticComponents(\( \text{tbl} \), \( \text{chars} \), \( m \))

(function)

If \( \chi \) is a (nonlinear) character with indicator \(-1\), a splitting of the tensor power \( \chi^m \) is given in terms of the so-called Murnaghan functions (see [Mur58]). These components in general have fewer irreducible constituents than the symmetrizations with the symmetric group of degree \( m \) (see Symmetrizations (72.11.1)).

SymplecticComponents returns the symplectic symmetrizations of the nonlinear characters of the character table \( \text{tbl} \) in the list \( \text{chars} \) up to the power \( m \), where \( m \) is an integer between 2 and 5.

Note: If \( \text{chars} \) is a list of character objects (see IsCharacter (72.8.1)) then also the result consists of class function objects. It is not checked whether all characters in \( \text{chars} \) do really have indicator \(-1\); if there are characters with indicator 0 or \(+1\), the result might contain virtual characters (see also OrthogonalComponents (72.11.4)), therefore the entries of the result do in general not know that they are characters.

Example

```gap
gap> tbl:= CharacterTable( "U3(3)" );;  \chi:= \text{Irr}( \text{tbl} )[2];
Character( CharacterTable( "U3(3)" ),
[ 6, -2, -3, 0, -2, -2, 2, 1, -1, -1, 0, 0, 1, 1 ] )
gap> \text{SymplecticComponents}( \text{tbl}, [ \chi ], 3 );
[ \text{ClassFunction}( \text{CharacterTable}( "U3(3)" ),
[ 14, -2, 5, -1, 2, 2, 1, 0, 0, 0, 0, 0, -1, -1 ] ),
\text{ClassFunction}( \text{CharacterTable}( "U3(3)" ),
[ 77, -3, 13, 17, 2, 1, 1, 2, 1, 0, 0, 0, 2, 2 ] ) ]
```
72.12 Molien Series

72.12.1 MolienSeries

\texttt{MolienSeries([tbl, psi[, chi]])} (function)

The \textit{Molien series} of the character \( \psi \), relative to the character \( \chi \), is the rational function given by the series \( M_{\psi, \chi}(z) = \sum_{d=0}^{\infty} [\chi, \psi^d] z^d \), where \( \psi^d \) denotes the symmetrization of \( \psi \) with the trivial character of the symmetric group \( S_d \) (see \texttt{SymmetricParts(72.11.2)}).

\texttt{MolienSeries} returns the Molien series of \( psi \), relative to \( chi \), where \( psi \) and \( chi \) must be characters of the same character table; this table must be entered as \( tbl \) if \( chi \) and \( psi \) are only lists of character values. The default for \( chi \) is the trivial character of \( tbl \).

The return value of \texttt{MolienSeries} stores a value for the attribute \texttt{MolienSeriesInfo (72.12.2)}. This admits the computation of coefficients of the series with \texttt{ValueMolienSeries (72.12.3)}. Furthermore, this attribute gives access to numerator and denominator of the Molien series viewed as rational function, where the denominator is a product of polynomials of the form \( (1 - z^r)^k \); the Molien series is also displayed in this form. Note that such a representation is not unique, one can use \texttt{MolienSeriesWithGivenDenominator (72.12.4)} to obtain the series with a prescribed denominator.

For more information about Molien series, see [NPP84].

\textbf{Example}

\begin{verbatim}
gap> t:= CharacterTable( AlternatingGroup( 5 ) );;
gap> psi:= First( Irr( t ), x -> Degree( x ) = 3 );;
gap> mol:= MolienSeries( psi );
( 1-z^2-z^3+3z^6+z^7-z^9 ) / ( (1-z^5)*(1-z^3)*(1-z^2)^2 )
\end{verbatim}

72.12.2 MolienSeriesInfo

\texttt{MolienSeriesInfo(ratfun)} (attribute)

If the rational function \( ratfun \) was constructed by \texttt{MolienSeries (72.12.1)}, a representation as quotient of polynomials is known such that the denominator is a product of terms of the form \( (1 - z^r)^k \). This information is encoded as value of \texttt{MolienSeriesInfo}. Additionally, there is a special \texttt{PrintObj (6.3.5)} method for Molien series based on this.

\texttt{MolienSeriesInfo} returns a record that describes the rational function \( ratfun \) as a Molien series. The components of this record are

\begin{itemize}
  \item \texttt{numerator} of \( ratfun \) (in general a multiple of the numerator one gets by \texttt{NumeratorOfRationalFunction (66.4.2)}),
\end{itemize}
denom
denominator of \textit{ratfun} (in general a multiple of the denominator one gets by \textit{NumeratorOfRationalFunction} (66.4.2)),

\textit{ratfun}
the rational function \textit{ratfun} itself,

\textit{numerstring}
string corresponding to the polynomial \textit{numer}, expressed in terms of \(z\),

\textit{denomstring}
string corresponding to the polynomial \textit{denom}, expressed in terms of \(z\),

\textit{denominfo}
a list of the form \([ [r_1, k_1], \ldots, [r_n, k_n] ] \) such that \(\text{denom} = \prod_{i=1}^{n} (1 - z^{r_i})^{k_i}\).

\textit{summands}
a list of records, each with the components \textit{numer}, \textit{r}, and \textit{k}, describing the summand \(\text{numer}/(1 - z^{\text{r}})^{\text{k}}\),

\textit{pol}
a list of coefficients, describing a final polynomial which is added to those described by \textit{summands},

\textit{size}
the order of the underlying matrix group,

\textit{degree}
the degree of the underlying matrix representation.

\begin{verbatim}
> HasMolienSeriesInfo( mol );
true
> MolienSeriesInfo( mol );
rec( degree := 3,
    denom := x_1^12-2*x_1^10-x_1^9+9*x_1^8+x_1^7+7*x_1^5+x_1^4-x_1^3-2*x_1^2+x_1+1,
    denominfo := [ 5, 1, 3, 1, 2, 2 ],
    denomstring := "(1-z^5)*(1-z^3)*(1-z^2)^2",
    numer := -x_1^9+x_1^7+x_1^6-x_1^3-x_1^2+1,
    numerstring := "1-z^2-z^3+z^6+z^7-z^9",
    pol := [ ],
    ratfun := ( 1-z^2-z^3+z^6+z^7-z^9 ) / ( (1-z^5)*(1-z^3)*(1-z^2)^2 ),
    size := 60,
    summands := [ rec( k := 1, numer := [ -24, -12, -24 ], r := 5 ),
                  rec( k := 1, numer := [ -20 ], r := 3 ),
                  rec( k := 2, numer := [ -45/4, 75/4, -15/4, -15/4 ], r := 2 ),
                  rec( k := 3, numer := [ -1 ], r := 1 ),
                  rec( k := 1, numer := [ -15/4 ], r := 1 ) ] )

72.12.3 ValueMolienSeries

\verb|
\textbf{ValueMolienSeries}\(\textit{molser}, \textit{i}\) \textbf{(function)}
\end{verbatim}

is the \textit{i}-th coefficient of the Molien series \textit{series} computed by \textit{MolienSeries} (72.12.1).
Example

```gap
gap> List([0 .. 20], i -> ValueMolienSeries(mol, i));
[ 1, 0, 1, 0, 1, 0, 2, 0, 2, 0, 3, 0, 4, 0, 4, 1, 5, 1, 6, 1, 7 ]
```

72.12.4 MolienSeriesWithGivenDenominator

\[ \text{MolienSeriesWithGivenDenominator}(\text{molser}, \text{list}) \]

is a Molien series equal to \( \text{molser} \) as rational function, but viewed as quotient with denominator \( \prod_{i=1}^{n} (1-z^{r_i}) \), where \( \text{list} = [r_1, r_2, \ldots, r_n] \). If \( \text{molser} \) cannot be represented this way, \( \text{fail} \) is returned.

Example

```gap
gap> MolienSeriesWithGivenDenominator(mol, [2, 6, 10]);
(1+z^15) / ( (1-z^10)*(1-z^6)*(1-z^2) )
```

72.13 Possible Permutation Characters

For groups \( H \) and \( G \) with \( H \leq G \), the induced character \( (1_G)^H \) is called the permutation character of the operation of \( G \) on the right cosets of \( H \). If only the character table of \( G \) is available and not the group \( G \) itself, one can try to get information about possible subgroups of \( G \) by inspection of those \( G \)-class functions that might be permutation characters, using that such a class function \( \pi \) must have at least the following properties. (For details, see [Isa76, Theorem 5.18.]),

(a) \( \pi \) is a character of \( G \),
(b) \( \pi(g) \) is a nonnegative integer for all \( g \in G \),
(c) \( \pi(1) \) divides \( |G| \),
(d) \( \pi(g^n) \geq \pi(g) \) for \( g \in G \) and integers \( n \),
(e) \( [\pi, 1_G] = 1 \),
(f) the multiplicity of any rational irreducible \( G \)-character \( \psi \) as a constituent of \( \pi \) is at most \( \psi(1)/[\psi, \psi] \),
(g) \( \pi(g) = 0 \) if the order of \( g \) does not divide \( |G|/\pi(1) \),
(h) \( \pi(1)|N_G(g)| \) divides \( \pi(g)|G| \) for all \( g \in G \),
(i) \( \pi(g) \leq (|G| - \pi(1))/|g^G| |Gal_G(g)| \) for all nonidentity \( g \in G \), where \( |Gal_G(g)| \) denotes the number of conjugacy classes of \( G \) that contain generators of the group \( \langle g \rangle \),
(j) if \( p \) is a prime that divides \( |G|/\pi(1) \) only once then \( s/(p-1) \) divides \( |G|/\pi(1) \) and is congruent to 1 modulo \( p \), where \( s \) is the number of elements of order \( p \) in the (hypothetical) subgroup \( H \) for which \( \pi = (1_H)^G \) holds. (Note that \( s/(p-1) \) equals the number of Sylow \( p \) subgroups in \( H \).)
Any $G$-class function with these properties is called a possible permutation character in GAP.

(Condition (d) is checked only for those power maps that are stored in the character table of $G$; clearly (d) holds for all integers if it holds for all prime divisors of the group order $|G|$.)

GAP provides some algorithms to compute possible permutation characters (see PermChars (72.14.1)), and also provides functions to check a few more criteria whether a given character can be a transitive permutation character (see TestPerm1 (72.14.2)).

Some information about the subgroup $U$ can be computed from the permutation character $(1_U)^G$ using PermCharInfo (72.13.1).

### 72.13.1 PermCharInfo

\textbf{PermCharInfo}(tbl, permchars[, format])

Let $tbl$ be the ordinary character table of the group $G$, and $permchars$ either the permutation character $(1_U)^G$, for a subgroup $U$ of $G$, or a list of such permutation characters. \textbf{PermCharInfo} returns a record with the following components.

- **contained**: a list containing, for each character $\psi = (1_U)^G$ in $permchars$, a list containing at position $i$ the number $\psi[i]|U|/\text{SizesCentralizers}(\ tbl \ )[i]$, which equals the number of those elements of $U$ that are contained in class $i$ of $tbl$,

- **bound**: a list containing, for each character $\psi = (1_U)^G$ in $permchars$, a list containing at position $i$ the number $|U|/\gcd(|U|,\text{SizesCentralizers}(\ tbl \ )[i])$, which divides the class length in $U$ of an element in class $i$ of $tbl$,

- **display**: a record that can be used as second argument of Display (6.3.6) to display each permutation character in $permchars$ and the corresponding components contained and bound, for those classes where at least one character of $permchars$ is nonzero.

- **ATLAS**: a list of strings describing the decomposition of the permutation characters in $permchars$ into the irreducible characters of $tbl$, given in an Atlas-like notation. This means that the irreducible constituents are indicated by their degrees followed by lower case letters a, b, c, ..., which indicate the successive irreducible characters of $tbl$ of that degree, in the order in which they appear in $\text{Irr}(\ tbl \ )$. A sequence of small letters (not necessarily distinct) after a single number indicates a sum of irreducible constituents all of the same degree, an exponent $n$ for the letter $\text{lett}$ means that $\text{lett}$ is repeated $n$ times. The default notation for exponentiation is $\text{lett} \sim \{n\}$, this is also chosen if the optional third argument format is the string "LaTeX"; if the third argument is the string "HTML" then exponentiation is denoted by $\text{lett} <\text{sup}> n </\text{sup}>$. 

```gap
gap> t := CharacterTable( "A6" );;
gap> psi := Sum( Irr( t ){ [ 1, 3, 6 ] } );
gap> info := PermCharInfo( t, psi );
gap> info
rec( ATLAS := [ "1a+5b+9a" ],
    bound := [ [ 1, 3, 8, 8, 6, 24, 24 ] ],
    contained := [ [ 1, 9, 0, 8, 6, 0, 0 ] ] )
gap> Display( info );
  [ [ 1, 9, 0, 8, 6, 0, 0 ] ]
  [ [ 1, 3, 8, 8, 6, 24, 24 ] ]
```

Example
display :=
rec(
  chars := [ [ 15, 3, 0, 3, 1, 0, 0 ], [ 1, 9, 0, 8, 6, 0, 0 ],
            [ 1, 3, 8, 8, 6, 24, 24 ] ],
  classes := [ 1, 2, 4, 5 ],
  letter := "I" )
)
gap> Display( t, info.display );

A6

2 3 3 . 2
3 2 . 2 .
5 1 . . .

1a 2a 3b 4a
2P 1a 1a 3b 2a
3P 1a 2a 1a 4a
5P 1a 2a 3b 4a

I.1 15 3 3 1
I.2 1 9 8 6
I.3 1 3 8 6

gap> j1:= CharacterTable( "J1" );;
gap> psi:= TrivialCharacter( CharacterTable( "7:6" ) )^j1;
Character( CharacterTable( "J1" ), [ 4180, 20, 10, 0, 0, 2, 1, 0, 0,
  0, 0, 0, 0, 0, 0 ] )
gap> PermCharInfo( j1, psi ).ATLAS;
[ "1a+56aabb+76aaab+77aabbcc+120aabbbccc+133a^{4}bbcc+209a^{5}" ]

72.13.2  PermCharInfoRelative

PermCharInfoRelative(tbl, tbl2, permchars)

Let tbl and tbl2 be the ordinary character tables of two groups \( H \) and \( G \), respectively, where \( H \) is of index two in \( G \), and \( \text{permchars} \) either the permutation character \( (1_U)^G \), for a subgroup \( U \) of \( G \), or a list of such permutation characters. \( \text{PermCharInfoRelative} \) returns a record with the same components as \( \text{PermCharInfo} \) (72.13.1), the only exception is that the entries of the ATLAS component are names relative to \( tbl \).

More precisely, the \( i \)-th entry of the ATLAS component is a string describing the decomposition of the \( i \)-th entry in \( \text{permchars} \). The degrees and distinguishing letters of the constituents refer to the irreducibles of \( tbl \), as follows. The two irreducible characters of \( tbl2 \) of degree \( N \), say, that extend the irreducible character \( N a \) of \( tbl \) are denoted by \( N a^+ \) and \( N a^- \). The irreducible character of \( tbl2 \) of degree \( 2N \), say, whose restriction to \( tbl \) is the sum of the irreducible characters \( N a \) and \( N b \) is denoted as \( N a b \). Multiplicities larger than 1 of constituents are denoted by exponents.

(This format is useful mainly for multiplicity free permutation characters.)

Example

\[
\begin{align*}
gap> t:= \text{CharacterTable}( "A5" );;
gap> t2:= \text{CharacterTable}( "A5.2" );;
gap> \text{List}( \text{Irr}( t2 ), x -> x[1] );
[ 1, 1, 6, 4, 4, 5, 5 ]
gap> \text{List}( \text{Irr}( t ), x -> x[1] );
[ 1, 3, 3, 4, 5 ]
\end{align*}
\]
gap> permchars:= List( [ [1], [1,2], [1,7], [1,3,4,4,6,6,7] ], 
>  l -> Sum( Irr( t2 ){ l } ));

[ Character( CharacterTable( "A5.2" ), [ 1, 1, 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A5.2" ), [ 1, 2, 1, 2, 2, 0, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 2, 2, 0, 1, 0, 2, 0 ] ),
  Character( CharacterTable( "A5.2" ), [ 6, 2, 0, 0, 6, 0, 0 ] ) ]

gap> info:= PermCharInfoRelative( t, t2, permchars );;

[ "1a^+", "1a^{\pm}", "1a^++5a^-", "1a^++3ab+4(a^+)^{2}+5a^+a^{\pm}" ]

72.14 Computing Possible Permutation Characters

72.14.1 PermChars

\texttt{PermChars(tbl [, cond])}

GAP provides several algorithms to determine possible permutation characters from a given character table. They are described in detail in [BP98]. The algorithm is selected from the choice of the optional argument \texttt{cond}. The user is encouraged to try different approaches, especially if one choice fails to come to an end.

Regardless of the algorithm used in a specific case, \texttt{PermChars} returns a list of all possible permutation characters with the properties described by \texttt{cond}. There is no guarantee that a character of this list is in fact a permutation character. But an empty list always means there is no permutation character with these properties (e.g., of a certain degree).

Called with only one argument, a character table \texttt{tbl}, \texttt{PermChars} returns the list of all possible permutation characters of the group with this character table. This list might be rather long for big groups, and its computation might take much time. The algorithm is described in [BP98, Section 3.2]; it depends on a preprocessing step, where the inequalities arising from the condition $\pi(g) \geq 0$ are transformed into a system of inequalities that guides the search (see \texttt{Inequalities (72.14.5)}). So the following commands compute the list of 39 possible permutation characters of the Mathieu group $M_{11}$.

\textbf{Example}

\begin{verbatim}
    gap> m11:= CharacterTable( "M11" );;
    gap> SetName( m11, "m11" );
    gap> perms:= PermChars( m11 );;
    gap> Length( perms );
    39
\end{verbatim}

There are two different search strategies for this algorithm. The default strategy simply constructs all characters with nonnegative values and then tests for each such character whether its degree is a divisor of the order of the group. The other strategy uses the inequalities to predict whether a character of a certain degree can lie in the currently searched part of the search tree. To choose this strategy, enter a record as the second argument of \texttt{PermChars}, and set its component \texttt{degree} to the range of degrees (which might also be a range containing all divisors of the group order) you want to look for; additionally, the record component \texttt{ineq} can take the inequalities computed by \texttt{Inequalities (72.14.5)} if they are needed more than once.
If a positive integer is given as the second argument \texttt{cond}, \texttt{PermChars} returns the list of all possible permutation characters of \texttt{tbl} that have degree \texttt{cond}. For that purpose, a preprocessing step is performed where essentially the rational character table is inverted in order to determine boundary points for the simplex in which the possible permutation characters of the given degree must lie (see \texttt{PermBounds}) (72.14.3). The algorithm is described at the end of \cite[Section 3.2]{BP98}. Note that inverting big integer matrices needs a lot of time and space. So this preprocessing is restricted to groups with less than 100 classes, say.

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
gap> deg220:= PermChars( m11, 220 );
[ Character( m11, [ 220, 4, 4, 0, 0, 4, 0, 0, 0, 0 ] ),
  Character( m11, [ 220, 12, 4, 4, 0, 0, 0, 0, 0, 0 ] ),
  Character( m11, [ 220, 20, 4, 0, 0, 2, 0, 0, 0, 0 ] ) ]
\end{verbatim}

If a record is given as the second argument \texttt{cond}, \texttt{PermChars} returns the list of all possible permutation characters that have the properties described by the components of this record. One such situation has been mentioned above. If \texttt{cond} contains a degree as value of the record component \texttt{degree} then \texttt{PermChars} will behave exactly as if this degree was entered as \texttt{cond}.

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
gap> deg220 = PermChars( m11, rec( degree:= 220 ) );
true
\end{verbatim}

For the meaning of additional components of \texttt{cond} besides \texttt{degree}, see \texttt{PermComb} (72.14.4).

Instead of \texttt{degree}, \texttt{cond} may have the component \texttt{torso} bound to a list that contains some known values of the required characters at the right positions; at least the degree \texttt{cond}.\texttt{torso}[1] must be an integer. In this case, the algorithm described in \cite[Section 3.3]{BP98} is chosen. The component \texttt{chars}, if present, holds a list of all those rational irreducible characters of \texttt{tbl} that might be constituents of the required characters. (Note: If \texttt{cond}.\texttt{chars} is bound and does not contain all rational irreducible characters of \texttt{tbl}, \texttt{GAP} checks whether the scalar products of all class functions in the result list with the omitted rational irreducible characters of \texttt{tbl} are nonnegative; so there should be nontrivial reasons for excluding a character that is known to be not a constituent of the desired possible permutation characters.)

\begin{verbatim}
Example
\end{verbatim}

\begin{verbatim}
gap> PermChars( m11, rec( torso:= [ 220 ] ) );
[ Character( m11, [ 220, 4, 4, 0, 0, 4, 0, 0, 0, 0 ] ),
  Character( m11, [ 220, 20, 4, 0, 0, 2, 0, 0, 0, 0 ] ),
  Character( m11, [ 220, 12, 4, 0, 0, 0, 0, 0, 0, 0 ] ) ]
\end{verbatim}

An additional restriction on the possible permutation characters computed can be forced if \texttt{cond} contains, in addition to \texttt{torso}, the components \texttt{normal subgroup} and \texttt{nonfaithful}, with values a list of class positions of a normal subgroup \(N\) of the group \(G\) of \texttt{tbl} and a possible permutation character \(\pi\) of \(G\), respectively, such that \(N\) is contained in the kernel of \(\pi\). In this case, \texttt{PermChars} returns the list of those possible permutation characters \(\psi\) of \texttt{tbl} coinciding with \texttt{torso} wherever its values are bound and having the property that no irreducible constituent of \(\psi - \pi\) has \(N\) in its kernel. If the component \texttt{chars} is bound in \texttt{cond} then the above statements apply. An interpretation of the computed characters is the following. Suppose there exists a subgroup \(V\) of \(G\) such that \(\pi = (1_V)^G\). Then \(N \leq V\), and if a computed character is of the form \((1_U)^G\), for a subgroup \(U\) of \(G\), then \(V = UN\).
Example

gap> s4:= CharacterTable( "Symmetric", 4 );;
gap> nsg:= ClassPositionsOfDerivedSubgroup( s4 );;
gap> pi:= TrivialCharacter( s4 );;
gap> PermChars( s4, rec( torso:= [ 12 ], normalsubgroup:= nsg, nonfaithful:= pi ) );
[ Character( CharacterTable( "Sym(4)" ), [ 12, 2, 0, 0, 0 ] ) ]
gap> pi:= Sum( Filtered( Irr( s4 ), chi -> IsSubset( ClassPositionsOfKernel( chi ), nsg ) ) );
Character( CharacterTable( "Sym(4)" ), [ 2, 0, 2, 0, 0 ] )
gap> PermChars( s4, rec( torso:= [ 12 ], normalsubgroup:= nsg, nonfaithful:= pi ) );
[ Character( CharacterTable( "Sym(4)" ), [ 12, 0, 4, 0, 0 ] ) ]

The class functions returned by PermChars have the properties tested by TestPerm1 (72.14.2), TestPerm2 (72.14.2), and TestPerm3 (72.14.2). So they are possible permutation characters. See TestPerm1 (72.14.2) for criteria whether a possible permutation character can in fact be a permutation character.

72.14.2 TestPerm1, ..., TestPerm5

TestPerm1(tbl, char) (function)
TestPerm2(tbl, char) (function)
TestPerm3(tbl, chars) (function)
TestPerm4(tbl, chars) (function)
TestPerm5(tbl, chars, modtbl) (function)

The first three of these functions implement tests of the properties of possible permutation characters listed in Section 72.13. The other two implement test of additional properties. Let tbl be the ordinary character table of a group $G$, say, char a rational character of tbl, and chars a list of rational characters of tbl. For applying TestPerm5, the knowledge of a $p$-modular Brauer table modtbl of $G$ is required. TestPerm4 and TestPerm5 expect the characters in chars to satisfy the conditions checked by TestPerm1 and TestPerm2 (see below).

The return values of the functions were chosen parallel to the tests listed in [NPP84].

TestPerm1 return 1 or 2 if char fails because of (T1) or (T2), respectively; this corresponds to the criteria (b) and (d). Note that only those power maps are considered that are stored on tbl. If char satisfies the conditions, 0 is returned.

TestPerm2 returns 1 if char fails because of the criterion (c), it returns 3, 4, or 5 if char fails because of (T3), (T4), or (T5), respectively; these tests correspond to (g), a weaker form of (h), and (j). If char satisfies the conditions, 0 is returned.

TestPerm3 returns the list of all those class functions in the list chars that satisfy criterion (h); this is a stronger version of (T6).

TestPerm4 returns the list of all those class functions in the list chars that satisfy (T8) and (T9) for each prime divisor $p$ of the order of $G$; these tests use modular representation theory but do not require the knowledge of decomposition matrices (cf. TestPerm5 below).

(T8) implements the test of the fact that in the case that $p$ divides $|G|$ and the degree of a transitive permutation character $\pi$ exactly once, the projective cover of the trivial character is a summand of $\pi$. (This test is omitted if the projective cover cannot be identified.)
Given a permutation character \( \pi \) of a group \( G \) and a prime integer \( p \), the restriction \( \pi_B \) to a \( p \)-block \( B \) of \( G \) has the following property, which is checked by (T9). For each \( g \in G \) such that \( g^n \) is a \( p \)-element of \( G \), \( \pi_B(g^n) \) is a nonnegative integer that satisfies \( |\pi_B(g^n)| \leq \pi_B(g^n) \leq \pi(g^n) \). (This is [Sco73, Corollary A on p. 113].)

TestPerm5 requires the \( p \)-modular Brauer table \( \text{modtbl} \) of \( G \), for some prime \( p \) dividing the order of \( G \), and checks whether those characters in the list \( \text{chars} \) whose degree is divisible by the \( p \)-part of the order of \( G \) can be decomposed into projective indecomposable characters; TestPerm5 returns the sublist of all those characters in \( \text{chars} \) that either satisfy this condition or to which the test does not apply.

Example

```gap
gap> tbl:= CharacterTable( "A5" );;
gap> rat:= RationalizedMat( Irr( tbl ) );
[ Character( CharacterTable( "A5" ), [ 1, 1, 1, 1, 1 ] ),
  Character( CharacterTable( "A5" ), [ 6, -2, 0, 1, 1 ] ),
  Character( CharacterTable( "A5" ), [ 4, 0, 1, -1, -1 ] ),
  Character( CharacterTable( "A5" ), [ 5, 1, -1, 0, 0 ] ) ]
gap> tup:= Filtered( Tuples( [ 0, 1 ], 4 ), x -> not IsZero( x ) );
[ [ 0, 0, 0, 1 ], [ 0, 0, 1, 0 ], [ 0, 1, 0, 0 ],
  [ 1, 0, 1, 0 ] ]
gap> lincomb:= List( tup, coeff -> coeff * rat );;
gap> List( lincomb, psi -> TestPerm1( tbl, psi ) );
[ 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 0 ]
gap> List( lincomb, psi -> TestPerm2( tbl, psi ) );
[ 0, 5, 1, 0, 1, 0, 0, 0, 0, 0, 0, 1, 0, 1, 1 ]
gap> Set( List( TestPerm3(tbl, lincomb), x -> Position(lincomb, x) ) );
[ 1, 4, 6, 11, 13 ]

gap> tbl:= CharacterTable( "A7" );
CharacterTable( "A7" )
gap> perms:= PermChars( tbl, rec( degree:= 315 ) );
[ Character( CharacterTable( "A7" ), [ 315, 3, 0, 3, 0, 0, 0, 0 ] ),
  Character( CharacterTable( "A7" ), [ 315, 15, 0, 1, 0, 0, 0, 0 ] )]
gap> TestPerm4( tbl, perms );
[ Character( CharacterTable( "A7" ), [ 315, 15, 0, 1, 0, 0, 0, 0 ] ) ]
gap> perms:= PermChars( tbl, rec( degree:= 15 ) );
[ Character( CharacterTable( "A7" ), [ 15, 3, 0, 3, 1, 0, 1, 1 ] ),
  Character( CharacterTable( "A7" ), [ 15, 3, 0, 3, 1, 0, 1, 1 ] )]
gap> TestPerm5( tbl, perms, tbl mod 5 );
[ Character( CharacterTable( "A7" ), [ 15, 3, 0, 3, 1, 0, 1, 1 ] )
```

### 72.14.3 PermBounds

```
PermBounds(tbl, d) (function)
```

Let \( tbl \) be the ordinary character table of the group \( G \). All \( G \)-characters \( \pi \) satisfying \( \pi(g) > 0 \) and \( \pi(1) = d \), for a given degree \( d \), lie in a simplex described by these conditions. \texttt{PermBounds} computes
the boundary points of this simplex for $d = 0$, from which the boundary points for any other $d$ are easily derived. (Some conditions from the power maps of $tbl$ are also involved.) For this purpose, a matrix similar to the rational character table of $G$ has to be inverted. These boundary points are used by PermChars (72.14.1) to construct all possible permutation characters (see 72.13) of a given degree. PermChars (72.14.1) either calls PermBounds or takes this information from the bounds component of its argument record.

### 72.14.4 PermComb

PermComb computes possible permutation characters of the character table $tbl$ by the improved combinatorial approach described at the end of [BP98, Section 3.2].

For computing the possible linear combinations without prescribing better bounds (i.e., when the computation of bounds shall be suppressed), enter

```gap
arec := rec( degree := degree, bounds := false ),
```

where `degree` is the character degree; this is useful if the multiplicities are expected to be small, and if this is forced by high irreducible degrees.

A list of upper bounds on the multiplicities of the rational irreducibles characters can be explicitly prescribed as a `maxmult` component in `arec`.

### 72.14.5 Inequalities

Let $tbl$ be the ordinary character table of a group $G$. The condition $\pi(g) \geq 0$ for every possible permutation character $\pi$ of $G$ places restrictions on the multiplicities $a_i$ of the irreducible constituents $\chi_i$ of $\pi = \sum_{i=1}^r a_i \chi_i$. For every element $g \in G$, we have $\sum_{i=1}^r a_i \chi_i(g) \geq 0$. The power maps provide even stronger conditions.

This system of inequalities is kind of diagonalized, resulting in a system of inequalities restricting $a_i$ in terms of $a_j$, $j < i$. These inequalities are used to construct characters with nonnegative values (see PermChars (72.14.1)). PermChars (72.14.1) either calls Inequalities or takes this information from the `ineq` component of its argument record.

The number of inequalities arising in the process of diagonalization may grow very strongly.

There are two ways to organize the projection. The first, which is chosen if no `option` argument is present, is the straight approach which takes the rational irreducible characters in their original order and by this guarantees the character with the smallest degree to be considered first. The other way, which is chosen if the string "small" is entered as third argument `option`, tries to keep the number of intermediate inequalities small by eventually changing the order of characters.

```gap
Example

```

```
Now compute only multiplicity free permutation characters.
\begin{verbatim}
gap> bounds:= List( RationalizedMat( Irr( tbl ) ), x -> 1 );;

\end{verbatim}
\begin{verbatim}
gap> PermComb( tbl, rec( degree:= 110, maxmult:= bounds ) );
[ Character( CharacterTable( "M11" ),
  [ 110, 6, 2, 2, 0, 0, 2, 2, 0, 0 ] ) ]
\end{verbatim}

\section{Operations for Brauer Characters}
\subsection{FrobeniusCharacterValue}
\begin{verbatim}
\begin{verbatim}
\texttt{FrobeniusCharacterValue}\texttt{(value, p)}\texttt{\texttt{(function)}\end{verbatim}
\end{verbatim}

Let \texttt{value} be a cyclotomic whose coefficients over the rationals are in the ring \mathbb{Z}_p of \(p\)-local numbers, where \(p\) is a prime integer. Assume that \texttt{value} lies in \mathbb{Z}_p[\zeta] for \(\zeta = \exp(p^n - 1)\), for some positive integer \(n\).

\texttt{FrobeniusCharacterValue} returns the image of \texttt{value} under the ring homomorphism from \mathbb{Z}_p[\zeta] to the field with \(p^n\) elements that is defined with the help of Conway polynomials (see \texttt{ConwayPolynomial}(59.5.1)), more information can be found in \cite[Sections 2-5]{JLPW95}.

If \texttt{value} is a Brauer character value in characteristic \(p\) then the result can be described as the corresponding value of the Frobenius character, that is, as the trace of a representing matrix with the given Brauer character value.

If the result of \texttt{FrobeniusCharacterValue} cannot be expressed as an element of a finite field in \texttt{GAP} (see Chapter 59) then \texttt{FrobeniusCharacterValue} returns \texttt{fail}.

If the Conway polynomial of degree \(n\) is required for the computation then it is computed only if \texttt{IsCheapConwayPolynomial}(59.5.2) returns \texttt{true} when it is called with \(p\) and \(n\), otherwise \texttt{fail} is returned.

\subsection{BrauerCharacterValue}
\begin{verbatim}
\begin{verbatim}
\texttt{BrauerCharacterValue}\texttt{(mat)}\texttt{\texttt{(attribute)}\end{verbatim}
\end{verbatim}

For an invertible matrix \texttt{mat} over a finite field \(F\), \texttt{BrauerCharacterValue} returns the Brauer character value of \texttt{mat} if the order of \texttt{mat} is coprime to the characteristic of \(F\), and \texttt{fail} otherwise.

The \textit{Brauer character value} of a matrix is the sum of complex lifts of its eigenvalues.

\begin{verbatim}
\begin{verbatim}
gap> g:= SL(2,4);; # 2-dim. irreducible representation of A5

\end{verbatim}
\end{verbatim}
\begin{verbatim}
\begin{verbatim}
gap> rep:= List( ccl, Representative );

\end{verbatim}
\end{verbatim}
\begin{verbatim}
\begin{verbatim}
gap> List( rep, BrauerCharacterValue );
[ 1, 2, 5, 5, 3 ]

\end{verbatim}
\end{verbatim}
\begin{verbatim}
\begin{verbatim}
gap> List( x -> FrobeniusCharacterValue( x, 2 ) );
[ 0*Z(2), Z(2)^2, Z(2)^2, Z(2)^0 ]

\end{verbatim}
\end{verbatim}
\begin{verbatim}
\begin{verbatim}
gap> List( TraceMat );
[ 0*Z(2), Z(2)^2, Z(2)^2, Z(2)^0 ]
\end{verbatim}
\end{verbatim}
72.15.3 SizeOfFieldOfDefinition

\[ \text{SizeOfFieldOfDefinition}(\text{val}, p) \]

For a cyclotomic or a list of cyclotomics \text{val}, and a prime integer \( p \), \text{SizeOfFieldOfDefinition} returns the size of the smallest finite field in characteristic \( p \) that contains the \( p \)-modular reduction of \text{val}.

The reduction map is defined as in [JLPW95], that is, the complex \((p^d - 1)\)-th root of unity \( \exp(p^d - 1) \) is mapped to the residue class of the indeterminate, modulo the ideal spanned by the Conway polynomial (see \text{ConwayPolynomial} (59.5.1)) of degree \( d \) over the field with \( p \) elements.

If \text{val} is a Brauer character then the value returned is the size of the smallest finite field in characteristic \( p \) over which the corresponding representation lives.

72.15.4 RealizableBrauerCharacters

\[ \text{RealizableBrauerCharacters}(\text{matrix}, q) \]

For a list \text{matrix} of absolutely irreducible Brauer characters in characteristic \( p \), and a power \( q \) of \( p \), \text{RealizableBrauerCharacters} returns a duplicate-free list of sums of Frobenius conjugates of the rows of \text{matrix}, each irreducible over the field with \( q \) elements.

```
gap> irr := Irr( CharacterTable( "A5" ) mod 2 );
[ Character( BrauerTable( "A5", 2 ), [ 1, 1, 1, 1 ] ),
  Character( BrauerTable( "A5", 2 ),
  Character( BrauerTable( "A5", 2 ),
  Character( BrauerTable( "A5", 2 ), [ 4, 1, -1, -1 ] ) ]
gap> List( irr, phi -> SizeOfFieldOfDefinition( phi, 2 ) );
[ 2, 4, 4, 2 ]
gap> RealizableBrauerCharacters( irr, 2 );
[ Character( BrauerTable( "A5", 2 ), [ 1, 1, 1, 1 ] ),
  ClassFunction( BrauerTable( "A5", 2 ), [ 4, -2, -1, -1 ] ),
  Character( BrauerTable( "A5", 2 ), [ 4, 1, -1, -1 ] ) ]
```

72.16 Domains Generated by Class Functions

GAP supports groups, vector spaces, and algebras generated by class functions.
Chapter 73

Maps Concerning Character Tables

Besides the characters, power maps are an important part of a character table, see Section 73.1. Often their computation is not easy, and if the table has no access to the underlying group then in general they cannot be obtained from the matrix of irreducible characters; so it is useful to store them on the table.

If not only a single table is considered but different tables of a group and a subgroup or of a group and a factor group are used, also class fusion maps (see Section 73.3) must be known to get information about the embedding or simply to induce or restrict characters, see Section 72.9).

These are examples of functions from conjugacy classes which will be called maps in the following. (This should not be confused with the term mapping, cf. Chapter 32.) In GAP, maps are represented by lists. Also each character, each list of element orders, of centralizer orders, or of class lengths are maps, and the list returned by ListPerm (42.5.1), when this function is called with a permutation of classes, is a map.

When maps are constructed without access to a group, often one only knows that the image of a given class is contained in a set of possible images, e. g., that the image of a class under a subgroup fusion is in the set of all classes with the same element order. Using further information, such as centralizer orders, power maps and the restriction of characters, the sets of possible images can be restricted further. In many cases, at the end the images are uniquely determined.

Because of this approach, many functions in this chapter work not only with maps but with parametrized maps (or paramaps for short). More about parametrized maps can be found in Section 73.5.

The implementation follows [Bre91], a description of the main ideas together with several examples can be found in [Bre99].

Several examples in this chapter require the GAP Character Table Library to be available. If it is not yet loaded then we load it now.

Example

```
    gap> LoadPackage( "ctbllib" );
    true
```

73.1 Power Maps

The \( n \)-th power map of a character table is represented by a list that stores at position \( i \) the position of the class containing the \( n \)-th powers of the elements in the \( i \)-th class. The \( n \)-th power map can be
composed from the power maps of the prime divisors of \( n \), so usually only power maps for primes are actually stored in the character table.

For an ordinary character table \( tbl \) with access to its underlying group \( G \), the \( p \)-th power map of \( tbl \) can be computed using the identification of the conjugacy classes of \( G \) with the classes of \( tbl \). For an ordinary character table without access to a group, in general the \( p \)-th power maps (and hence also the element orders) for prime divisors \( p \) of the group order are not uniquely determined by the matrix of irreducible characters. So only necessary conditions can be checked in this case, which in general yields only a list of several possibilities for the desired power map. Character tables of the GAP character table library store all \( p \)-th power maps for prime divisors \( p \) of the group order.

Power maps of Brauer tables can be derived from the power maps of the underlying ordinary tables.

For (computing and) accessing the \( n \)-th power map of a character table, \texttt{PowerMap} (73.1.1) can be used; if the \( n \)-th power map cannot be uniquely determined then \texttt{PowerMap} (73.1.1) returns \texttt{fail}.

The list of all possible \( p \)-th power maps of a table in the sense that certain necessary conditions are satisfied can be computed with \texttt{PossiblePowerMaps} (73.1.2). This provides a default strategy, the subroutines are listed in Section 73.6.

### 73.1.1 PowerMap

\[
\begin{align*}
\texttt{PowerMap}(tbl, n[, class]) & \quad \text{(operation)} \\
\texttt{PowerMapOp}(tbl, n[, class]) & \quad \text{(operation)} \\
\texttt{ComputedPowerMaps}(tbl) & \quad \text{(attribute)}
\end{align*}
\]

Called with first argument a character table \( tbl \) and second argument an integer \( n \), \texttt{PowerMap} returns the \( n \)-th power map of \( tbl \). This is a list containing at position \( i \) the position of the class of \( n \)-th powers of the elements in the \( i \)-th class of \( tbl \).

If the additional third argument \texttt{class} is present then the position of \( n \)-th powers of the \texttt{class} -th class is returned.

If the \( n \)-th power map is not uniquely determined by \( tbl \) then \texttt{fail} is returned. This can happen only if \( tbl \) has no access to its underlying group.

The power maps of \( tbl \) that were computed already by \texttt{PowerMap} are stored in \( tbl \) as value of the attribute \texttt{ComputedPowerMaps}, the \( n \)-th power map at position \( n \). \texttt{PowerMap} checks whether the desired power map is already stored, computes it using the operation \texttt{PowerMapOp} if it is not yet known, and stores it. So methods for the computation of power maps can be installed for the operation \texttt{PowerMapOp}.

#### Example

```gap
gap> tbl:= CharacterTable( "L3(2)" );
gap> ComputedPowerMaps( tbl );
[ [ 1, 1, 3, 2, 5, 6 ], [ 1, 2, 1, 4, 6, 5 ], [ 1, 2, 3, 4, 1, 1 ] ]
gap> PowerMap( tbl, 5 );
[ 1, 2, 3, 4, 6, 5 ]
gap> ComputedPowerMaps( tbl );
[ [ 1, 1, 3, 2, 5, 6 ], [ 1, 2, 1, 4, 6, 5 ], [ 1, 2, 3, 4, 1, 1 ] ]
gap> PowerMap( tbl, 137, 2 );
2
```
73.1.2 PossiblePowerMaps

\[ \text{PossiblePowerMaps}(\text{tbl}, p[, \text{options}]) \]

For the ordinary character table \( \text{tbl} \) of the group \( G \), say, and a prime integer \( p \), PossiblePowerMaps returns the list of all maps that have the following properties of the \( p \)-th power map of \( \text{tbl} \). (Representative orders are used only if the OrdersClassRepresentatives (71.9.1) value of \( \text{tbl} \) is known.

1. For class \( i \), the centralizer order of the image is a multiple of the \( i \)-th centralizer order; if the elements in the \( i \)-th class have order coprime to \( p \) then the centralizer orders of class \( i \) and its image are equal.

2. Let \( n \) be the order of elements in class \( i \). If \( \text{prime} \) divides \( n \) then the images have order \( n/p \); otherwise the images have order \( n \). These criteria are checked in InitPowerMap (73.6.1).

3. For each character \( \chi \) of \( G \) and each element \( g \) in \( G \), the values \( \chi(g^p) \) and GaloisCyc(\( \chi(g) \), \( p \)) are algebraic integers that are congruent modulo \( p \); if \( p \) does not divide the element order of \( g \) then the two values are equal. This congruence is checked for the characters specified below in the discussion of the options argument; For linear characters \( \lambda \) among these characters, the condition \( \chi(g^p) = \chi(g^p) \) is checked. The corresponding function is Congruences (73.6.2).

4. For each character \( \chi \) of \( G \), the kernel is a normal subgroup \( N \), and \( g^p \in N \) for all \( g \in N \); moreover, if \( N \) has index \( p \) in \( G \) then \( g^p \in N \) for all \( g \in G \), and if the index of \( N \) in \( G \) is coprime to \( p \) then \( g^p \notin N \) for each \( g \notin N \). These conditions are checked for the kernels of all characters \( \chi \) specified below, the corresponding function is ConsiderKernels (73.6.3).

5. If \( p \) is larger than the order \( m \) of an element \( g \in G \) then the class of \( g^p \) is determined by the power maps for primes dividing the residue of \( p \) modulo \( m \). If these power maps are stored in the ComputedPowerMaps (73.1.1) value of \( \text{tbl} \) then this information is used. This criterion is checked in ConsiderSmallerPowerMaps (73.6.4).

6. For each character \( \chi \) of \( G \), the symmetrization \( \psi \) defined by \( \psi(g) = (\chi(g)^p - \chi(g^p))/p \) is a character. This condition is checked for the kernels of all characters \( \chi \) specified below, the corresponding function is PowerMapsAllowedBySymmetrizations (73.6.6).

If \( \text{tbl} \) is a Brauer table, the possibilities are computed from those for the underlying ordinary table.

The optional argument \text{options}, if given, must be a record that may have the following components:

chars:
- a list of characters which are used for the check of the criteria 3., 4., and 6.; the default is \text{Irr} ( \text{tbl} ),

powermap:
- a parametrized map which is an approximation of the desired map

decompose:
- a Boolean; a \text{true} value indicates that all constituents of the symmetrizations of \text{chars} computed for criterion 6. lie in \text{chars}, so the symmetrizations can be decomposed into elements
of chars; the default value of decompose is true if chars is not bound and Irr(tbl) is known, otherwise false.

quick:
a Boolean; if true then the subroutines are called with value true for the argument quick; especially, as soon as only one candidate remains this candidate is returned immediately; the default value is false.

parameters:
a record with components maxamb, minamb and maxlen which control the subroutine PowerMapsAllowedBySymmetrizations (73.6.6); it only uses characters with current indeterminateness up to maxamb, tests decomposability only for characters with current indeterminateness at least minamb, and admits a branch according to a character only if there is one with at most maxlen possible symmetrizations.

Example

```
gap> tbl:= CharacterTable( "U4(3).4" );;
gap> PossiblePowerMaps( tbl, 2 );
[ [ 1, 1, 3, 4, 5, 2, 2, 8, 3, 4, 11, 12, 6, 14, 9, 1, 1, 2, 2, 3, 4, 5, 6, 8, 9, 9, 10, 11, 12, 16, 16, 16, 16, 17, 17, 18, 18, 18, 18, 18, 20, 20, 20, 20, 22, 22, 24, 24, 25, 26, 28, 28, 28, 28, 29, 29 ] ]
```

73.1.3 ElementOrdersPowerMap

\[ ElementOrdersPowerMap(\text{powermap}) \]

Let powermap be a nonempty list containing at position \(p\), if bound, the \(p\)-th power map of a character table or group. ElementOrdersPowerMap returns a list of the same length as each entry in powermap, with entry at position \(i\) equal to the order of elements in class \(i\) if this order is uniquely determined by powermap, and equal to an unknown (see Chapter 74) otherwise.

Example

```
gap> tbl:= CharacterTable( "U4(3).4" );;
gap> known:= ComputedPowerMaps( tbl );;
gap> Length( known );
7

gap> sub:= ShallowCopy( known );; Unbind( sub[7] );

gap> ElementOrdersPowerMap( sub );
[ 1, 2, 3, 3, 4, 4, 5, 6, 6, Unknown(1), Unknown(2), 8, 9, 12, 2, 2, 4, 4, 6, 6, 6, 8, 10, 12, 12, 12, 12, Unknown(3), Unknown(4), 4, 4, 4, 4, 4, 8, 8, 8, 8, 12, 12, 12, 12, 12, 12, 20, 20, 20, 24, 24, Unknown(5), Unknown(6), Unknown(7), Unknown(8) ]

gap> ord:= ElementOrdersPowerMap( known );
[ 1, 2, 3, 3, 4, 4, 5, 6, 6, 7, 7, 8, 9, 12, 2, 2, 4, 4, 6, 6, 6, 8, 10, 12, 12, 14, 14, 4, 4, 4, 4, 4, 4, 4, 8, 8, 8, 8, 8, 12, 12, 12, 12, 20, 20, 24, 24, 28, 28, 28, 28 ]

gap> ord = OrdersClassRepresentatives( tbl );
true
```
73.1.4 PowerMapByComposition

\[ \text{PowerMapByComposition}(tbl, n) \] (function)

`tbl` must be a nearly character table, and `n` a positive integer. If the power maps for all prime divisors of `n` are stored in the `ComputedPowerMaps` (73.1.1) list of `tbl` then `PowerMapByComposition` returns the `n`-th power map of `tbl`. Otherwise `fail` is returned.

Example

```gap
gap> tbl:= CharacterTable( "U4(3).4" );; exp:= Exponent( tbl ); 2520
gap> PowerMapByComposition( tbl, exp ); [ 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ]
gap> Length( ComputedPowerMaps( tbl ) ); 7
```

73.2 Orbits on Sets of Possible Power Maps

The permutation group of matrix automorphisms (see MatrixAutomorphisms (71.22.1)) acts on the possible power maps returned by PossiblePowerMaps (73.1.2) by permuting a list via Permuted (21.20.18) and then mapping the images via OnPoints (41.2.1). Note that by definition, the group of table automorphisms acts trivially.

73.2.1 OrbitPowerMaps

\[ \text{OrbitPowerMaps}(map, permgrp) \] (function)

returns the orbit of the power map `map` under the action of the permutation group `permgrp` via a combination of Permuted (21.20.18) and OnPoints (41.2.1).

73.2.2 RepresentativesPowerMaps

\[ \text{RepresentativesPowerMaps}(listofmaps, permgrp) \] (function)

returns a list of orbit representatives of the power maps in the list `listofmaps` under the action of the permutation group `permgrp` via a combination of Permuted (21.20.18) and OnPoints (41.2.1).
73.3 Class Fusions between Character Tables

For a group $G$ and a subgroup $H$ of $G$, the fusion map between the character table of $H$ and the character table of $G$ is represented by a list that stores at position $i$ the position of the $i$-th class of the table of $H$ in the classes list of the table of $G$.

For ordinary character tables tbl1 and tbl2 of $H$ and $G$, with access to the groups $H$ and $G$, the class fusion between tbl1 and tbl2 can be computed using the identifications of the conjugacy classes of $H$ with the classes of tbl1 and the conjugacy classes of $G$ with the classes of tbl2. For two ordinary character tables without access to an underlying group, or in the situation that the group stored in tbl1 is not physically a subgroup of the group stored in tbl2 but an isomorphic copy, in general the class fusion is not uniquely determined by the information stored on the tables such as irreducible characters and power maps. So only necessary conditions can be checked in this case, which in general yields only a list of several possibilities for the desired class fusion. Character tables of the GAP character table library store various class fusions that are regarded as important, for example fusions from maximal subgroups (see ComputedClassFusions (73.3.2) and Maxes (CTblLib: Maxes) in the manual for the GAP Character Table Library).

Class fusions between Brauer tables can be derived from the class fusions between the underlying ordinary tables. The class fusion from a Brauer table to the underlying ordinary table is stored when the Brauer table is constructed from the ordinary table, so no method is needed to compute such a fusion.
For (computing and) accessing the class fusion between two character tables, \texttt{FusionConjugacyClasses} (73.3.1) can be used; if the class fusion cannot be uniquely determined then \texttt{FusionConjugacyClasses} (73.3.1) returns \texttt{fail}.

The list of all possible class fusion between two tables in the sense that certain necessary conditions are satisfied can be computed with \texttt{PossibleClassFusions} (73.3.6). This provides a default strategy, the subroutines are listed in Section 73.7.

It should be noted that all the following functions except \texttt{FusionConjugacyClasses} (73.3.1) deal only with the situation of class fusions from subgroups. The computation of factor fusions from a character table to the table of a factor group is not dealt with here. Since the ordinary character table of a group \( G \) determines the character tables of all factor groups of \( G \), the factor fusion to a given character table of a factor group of \( G \) is determined up to table automorphisms (see \texttt{AutomorphismsOfTable} (71.9.4)) once the class positions of the kernel of the natural epimorphism have been fixed.

### 73.3.1 FusionConjugacyClasses

\begin{verbatim}
\texttt{FusionConjugacyClasses(tbl1, tbl2)} (operation)
\texttt{FusionConjugacyClasses(H, G)} (operation)
\texttt{FusionConjugacyClasses(hom[, tbl1, tbl2])} (operation)
\texttt{FusionConjugacyClassesOp(tbl1, tbl2)} (operation)
\texttt{FusionConjugacyClassesOp(hom)} (attribute)
\end{verbatim}

Called with two character tables \texttt{tbl1} and \texttt{tbl2}, \texttt{FusionConjugacyClasses} returns the fusion of conjugacy classes between \texttt{tbl1} and \texttt{tbl2}. (If one of the tables is a Brauer table, it will delegate this task to the underlying ordinary table.)

Called with two groups \( H \) and \( G \) where \( H \) is a subgroup of \( G \), \texttt{FusionConjugacyClasses} returns the fusion of conjugacy classes between \( H \) and \( G \). This is done by delegating to the ordinary character tables of \( H \) and \( G \), since class fusions are stored only for character tables and not for groups.

Note that the returned class fusion refers to the ordering of conjugacy classes in the character tables if the arguments are character tables and to the ordering of conjugacy classes in the groups if the arguments are groups (see \texttt{ConjugacyClasses} (71.6.2)).

Called with a group homomorphism \texttt{hom}, \texttt{FusionConjugacyClasses} returns the fusion of conjugacy classes between the preimage and the image of \texttt{hom}; contrary to the two cases above, also factor fusions can be handled by this variant. If \texttt{hom} is the only argument then the class fusion refers to the ordering of conjugacy classes in the groups. If the character tables of preimage and image are given as \texttt{tbl1} and \texttt{tbl2}, respectively (each table with its group stored), then the fusion refers to the ordering of classes in these tables.

If no class fusion exists or if the class fusion is not uniquely determined, \texttt{fail} is returned; this may happen when \texttt{FusionConjugacyClasses} is called with two character tables that do not know compatible underlying groups.

Methods for the computation of class fusions can be installed for the operation \texttt{FusionConjugacyClassesOp}.

---

**Example**

\begin{verbatim}
gap> s4:= SymmetricGroup( 4 );
Sym( [ 1 .. 4 ] )
gap> tbls4:= CharacterTable( s4 );;
gap> d8:= SylowSubgroup( s4, 2 );
Group([ (1,2), (3,4), (1,3)(2,4) ])
\end{verbatim}
gap> FusionConjugacyClasses( d8, s4 );
[ 1, 2, 3, 3, 5 ]
gap> tbls5:= CharacterTable( "S5" );;
gap> FusionConjugacyClasses( CharacterTable( "A5" ), tbls5 );
[ 1, 2, 3, 4, 4 ]
gap> FusionConjugacyClasses( CharacterTable("A5"), CharacterTable("J1"));
fail
gap> PossibleClassFusions( CharacterTable("A5"), CharacterTable("J1"));
[ [ 1, 2, 3, 4, 5 ], [ 1, 2, 3, 5, 4 ] ]

73.3.2 ComputedClassFusions

- **ComputedClassFusions**

  The class fusions from the character table `tbl` that have been computed already by `FusionConjugacyClasses` (73.3.1) or explicitly stored by `StoreFusion` (73.3.4) are stored in the `ComputedClassFusions` list of `tbl`. Each entry of this list is a record with the following components.

  - **name**: the `Identifier` (71.9.8) value of the character table to which the fusion maps,
  - **map**: the list of positions of image classes,
  - **text** *(optional)*: a string giving additional information about the fusion map, for example whether the map is uniquely determined by the character tables,
  - **specification** *(optional, rarely used)*: a value that distinguishes different fusions between the same tables.

  Note that stored fusion maps may differ from the maps returned by `GetFusionMap` (73.3.3) and the maps entered by `StoreFusion` (73.3.4) if the table `destination` has a nonidentity `ClassPermutation` (71.21.5) value. So if one fetches a fusion map from a table `tbl1` to a table `tbl2` via access to the data in the `ComputedClassFusions` list of `tbl1` then the stored value must be composed with the `ClassPermutation` (71.21.5) value of `tbl2` in order to obtain the correct class fusion. (If one handles fusions only via `GetFusionMap` (73.3.3) and `StoreFusion` (73.3.4) then this adjustment is made automatically.)

  Fusions are identified via the `Identifier` (71.9.8) value of the destination table and not by this table itself because many fusions between character tables in the GAP character table library are stored on library tables, and it is not desirable to load together with a library table also all those character tables that occur as destinations of fusions from this table.

  For storing fusions and accessing stored fusions, see also `GetFusionMap` (73.3.3), `StoreFusion` (73.3.4). For accessing the identifiers of tables that store a fusion into a given character table, see `NamesOfFusionSources` (73.3.5).

73.3.3 GetFusionMap

- **GetFusionMap**

  - `GetFusionMap(source, destination[, specification])` *(function)*

  The function `GetFusionMap` returns a fusion map from the source character table to the destination character table. The optional `specification` argument is rarely used.
For two ordinary character tables source and destination, GetFusionMap checks whether the ComputedClassFusions (73.3.2) list of source contains a record with name component Identifier( destination ), and returns returns the map component of the first such record. GetFusionMap( source, destination, specification ) fetches that fusion map for which the record additionally has the specification component specification.

If both source and destination are Brauer tables, first the same is done, and if no fusion map was found then GetFusionMap looks whether a fusion map between the ordinary tables is stored; if so then the fusion map between source and destination is stored on source, and then returned.

If no appropriate fusion is found, GetFusionMap returns fail. For the computation of class fusions, see FusionConjugacyClasses (73.3.1).

73.3.4 StoreFusion

\[ \text{StoreFusion}(\text{source, fusion, destination}) \] (function)

For two character tables source and destination, StoreFusion stores the fusion fusion from source to destination in the ComputedClassFusions (73.3.2) list of source, and adds the Identifier (71.9.8) string of destination to the NamesOfFusionSources (73.3.5) list of destination.

fusion can either be a fusion map (that is, the list of positions of the image classes) or a record as described in ComputedClassFusions (73.3.2).

If fusions to destination are already stored on source then another fusion can be stored only if it has a record component specification that distinguishes it from the stored fusions. In the case of such an ambiguity, StoreFusion raises an error.

Example

```
gap> tbld8:= CharacterTable( d8 );;
gap> ComputedClassFusions( tbld8 );
[ \text{rec}( \text{map} := [ 1, 2, 3, 3, 5 ], \text{name} := "CT1" ) ]
gap> Identifier( tbls4 );
"CT1"
gap> GetFusionMap( tbld8, tbls4 );
[ 1, 2, 3, 3, 5 ]
gap> GetFusionMap( tbls4, tbls5 );
fail
gap> poss:= PossibleClassFusions( tbls4, tbls5 );
[ [ 1, 5, 2, 3, 6 ] ]
gap> StoreFusion( tbls4, poss[1], tbls5 );
gap> GetFusionMap( tbls4, tbls5 );
[ 1, 5, 2, 3, 6 ]
```

73.3.5 NamesOfFusionSources

\[ \text{NamesOfFusionSources}(\text{tbl}) \] (attribute)

For a character table tbl, NamesOfFusionSources returns the list of identifiers of all those character tables that are known to have fusions to tbl stored. The NamesOfFusionSources value is updated whenever a fusion to tbl is stored using StoreFusion (73.3.4).
73.3.6 PossibleClassFusions

\texttt{PossibleClassFusions(subtbl, tbl[, options])} (operation)

For two ordinary character tables \texttt{subtbl} and \texttt{tbl} of the groups \texttt{H} and \texttt{G}, say, \texttt{PossibleClassFusions} returns the list of all maps that have the following properties of class fusions from \texttt{subtbl} to \texttt{tbl}.

1. For class \texttt{i}, the centralizer order of the image in \texttt{G} is a multiple of the \texttt{i}-th centralizer order in \texttt{H}, and the element orders in the \texttt{i}-th class and its image are equal. These criteria are checked in \texttt{InitFusion (73.7.1)}.

2. The class fusion commutes with power maps. This is checked using \texttt{TestConsistencyMaps (73.5.12)}.

3. If the permutation character of \texttt{G} corresponding to the action of \texttt{G} on the cosets of \texttt{H} is specified (see the discussion of the \texttt{options} argument below) then it prescribes for each class \texttt{C} of \texttt{G} the number of elements of \texttt{H} fusing into \texttt{C}. The corresponding function is \texttt{CheckPermChar (73.7.2)}.

4. The table automorphisms of \texttt{tbl} (see \texttt{AutomorphismsOfTable (71.9.4)}) are used in order to compute only orbit representatives. (But note that the list returned by \texttt{PossibleClassFusions} contains the full orbits.)

5. For each character \texttt{\chi} of \texttt{G}, the restriction to \texttt{H} via the class fusion is a character of \texttt{H}. This condition is checked for all characters specified below, the corresponding function is \texttt{FusionsAllowedByRestrictions (73.7.4)}.

6. The class multiplication coefficients in \texttt{subtbl} do not exceed the corresponding coefficients in \texttt{tbl}. This is checked in \texttt{ConsiderStructureConstants (73.3.7)}, see also the comment on the parameter \texttt{verify} below.

If \texttt{subtbl} and \texttt{tbl} are Brauer tables then the possibilities are computed from those for the underlying ordinary tables.

The optional argument \texttt{options} must be a record that may have the following components:

- \texttt{chars}:
  a list of characters of \texttt{tbl} which are used for the check of 5.; the default is \texttt{Irr( tbl )},

- \texttt{subchars}:
  a list of characters of \texttt{subtbl} which are constituents of the restrictions of \texttt{chars}, the default is \texttt{Irr( subtbl )},

- \texttt{fusionmap}:
  a parametrized map which is an approximation of the desired map,
decompose
   a Boolean; a true value indicates that all constituents of the restrictions of chars computed for
criterion 5. lie in subchars, so the restrictions can be decomposed into elements of subchars;
the default value of decompose is true if subchars is not bound and Irr( subtbl ) is
known, otherwise false,

permchar
   (a values list of) a permutation character; only those fusions affording that permutation character
are computed,

quick
   a Boolean; if true then the subroutines are called with value true for the argument quick;
especially, as soon as only one possibility remains then this possibility is returned immediately;
the default value is false,

verify
   a Boolean; if false then ConsiderStructureConstants (73.3.7) is called only if more than
one orbit of possible class fusions exists, under the action of the groups of table automorphisms;
the default value is false (because the computation of the structure constants is usually very
time consuming, compared with checking the other criteria),

parameters
   a record with components maxamb, minamb and maxlen (and perhaps some optional compo-
nents) which control the subroutine FusionsAllowedByRestrictions (73.7.4); it only uses
characters with current indeterminateness up to maxamb, tests decomposability only for charac-
ters with current indeterminateness at least minamb, and admits a branch according to a character
only if there is one with at most maxlen possible restrictions.

Example

\begin{verbatim}
 gap> subtbl:= CharacterTable( "U3(3)" );; tbl:= CharacterTable( "J4" );;
gap> PossibleClassFusions( subtbl, tbl );
[ [ 1, 2, 4, 4, 5, 6, 10, 12, 13, 14, 14, 21, 21 ],
 [ 1, 2, 4, 4, 5, 6, 10, 13, 12, 14, 14, 21, 21 ],
 [ 1, 2, 4, 4, 6, 6, 10, 12, 13, 15, 15, 22, 22 ],
 [ 1, 2, 4, 4, 6, 6, 10, 12, 13, 16, 15, 22, 22 ],
 [ 1, 2, 4, 4, 6, 6, 10, 13, 12, 15, 15, 22, 22 ],
 [ 1, 2, 4, 4, 6, 6, 10, 13, 12, 16, 15, 22, 22 ] ]
\end{verbatim}

73.3.7 ConsiderStructureConstants

\texttt{\textbackslash \textbackslash ConsiderStructureConstants} (function)

Let subtbl and tbl be ordinary character tables and fusions be a list of
possible class fusions from subtbl to tbl. ConsiderStructureConstants returns
the list of those maps $\sigma$ in fusions with the property that for all triples
$(i,j,k)$ of class positions, ClassMultiplicationCoefficient(subtbl, i, j, k)
is not bigger than ClassMultiplicationCoefficient(tbl, $\sigma[i],\sigma[j],\sigma[k]$);
see ClassMultiplicationCoefficient (71.12.7) for the definition of class multiplication
coefficients/structure constants.
The argument `quick` must be a Boolean; if it is `true` then only those triples are checked for which for which at least two entries in `fusions` have different images.

### 73.4 Orbits on Sets of Possible Class Fusions

The permutation groups of table automorphisms (see `AutomorphismsOfTable (71.9.4)`) of the subgroup table `subtbl` and the supergroup table `tbl` act on the possible class fusions from `subtbl` to `tbl` that are returned by `PossibleClassFusions (73.3.6)`, the former by permuting a list via `Permuted (21.20.18)`, the latter by mapping the images via `OnPoints (41.2.1)`.

If a set of possible fusions with certain properties was computed that are not invariant under the full groups of table automorphisms then only a smaller group acts on this set. This may happen for example if a permutation or if an explicit approximation of the fusion map was prescribed in the call of `PossibleClassFusions (73.3.6)`.

#### 73.4.1 OrbitFusions

```gap
doctenv
 OrbitFusions(subtblautomorphisms, fusionmap, tblautomorphisms)  (function)
```

returns the orbit of the class fusion map `fusionmap` under the actions of the permutation groups `subtblautomorphisms` and `tblautomorphisms` of automorphisms of the character table of the subgroup and the supergroup, respectively.

#### 73.4.2 RepresentativesFusions

```gap
doctenv
 RepresentativesFusions(subtbl, listofmaps, tbl)  (function)
```

Let `listofmaps` be a list of class fusions from the character table `subtbl` to the character table `tbl`. `RepresentativesFusions` returns a list of orbit representatives of the class fusions under the action of maximal admissible subgroups of the table automorphism groups of these character tables.

Instead of the character tables `subtbl` and `tbl`, also the permutation groups of their table automorphisms (see `AutomorphismsOfTable (71.9.4)`) may be entered.

**Example**

```gap
 gap> fus:= GetFusionMap( subtbl, tbl );
 [ 1, 2, 4, 4, 5, 5, 6, 10, 12, 13, 14, 14, 21, 21 ]
 gap> orb:= OrbitFusions( AutomorphismsOfTable( subtbl ), fus,
 >   AutomorphismsOfTable( tbl ) );
 [ [ 1, 2, 4, 4, 5, 5, 6, 10, 12, 13, 14, 14, 21, 21 ],
   [ 1, 2, 4, 4, 5, 5, 6, 10, 13, 12, 14, 14, 21, 21 ] ]
 gap> rep:= RepresentativesFusions( subtbl, orb, tbl );
 [ [ 1, 2, 4, 4, 5, 5, 6, 10, 12, 13, 14, 14, 21, 21 ] ]
```

### 73.5 Parametrized Maps

A *parametrized map* is a list whose `i`-th entry is either unbound (which means that nothing is known about the image(s) of the `i`-th class) or the image of the `i`-th class (i.e., an integer for fusion maps, power maps, element orders etc., and a cyclotomic for characters), or a list of possible images of the `i`-th class. In this sense, maps are special parametrized maps. We often identify a parametrized
map \textit{paramap} with the set of all maps \textit{map} with the property that either \textit{map}[i] = \textit{paramap}[i] or \textit{map}[i] is contained in the list \textit{paramap}[i]; we say then that \textit{map} is contained in \textit{paramap}.

This definition implies that parametrized maps cannot be used to describe sets of maps where lists are possible images. An exception are strings which naturally arise as images when class names are considered. So strings and lists of strings are allowed in parametrized maps, and character constants (see Chapter 27) are not allowed in maps.

### 73.5.1 CompositionMaps

\[ \text{CompositionMaps}(\text{paramap}_2, \text{paramap}_1[, \text{class}]) \]

The composition of two parametrized maps \textit{paramap}_1, \textit{paramap}_2 is defined as the parametrized map \textit{comp} that contains all compositions \( f_2 \circ f_1 \) of elements \( f_1 \) of \textit{paramap}_1 and \( f_2 \) of \textit{paramap}_2. For example, the composition of a character \( \chi \) of a group \( G \) by a parametrized class fusion map from a subgroup \( H \) to \( G \) is the parametrized map that contains all restrictions of \( \chi \) by elements of the parametrized fusion map.

\text{CompositionMaps}(\text{paramap}_2, \text{paramap}_1) \) is a parametrized map with entry \text{CompositionMaps}(\text{paramap}_2, \text{paramap}_1, \text{class}) at position \text{class}. If \text{paramap}_1[\text{class}] is an integer then \text{CompositionMaps}(\text{paramap}_2, \text{paramap}_1, \text{class}) is equal to \text{paramap}_2[\text{paramap}_1[\text{class}]]. Otherwise it is the union of \text{paramap}_2[i] for \( i \) in \text{paramap}_1[\text{class}].

**Example**

\[
\text{gap> map1:= } [ 1, [ 2 .. 4 ], [ 4, 5 ], 1 ];
\text{gap> map2:= } [ [ 1, 2 ], 2, 2, 3, 3 ];
\text{gap> CompositionMaps( map2, map1 );}
\text{[[ 1, 2 ], [ 2, 3 ], 3, [ 1, 2 ] ]}
\text{gap> CompositionMaps( map1, map2 );}
\text{[[ 1, 2, 3, 4 ], [ 2, 3, 4 ], [ 2, 3, 4 ], [ 4, 5 ], [ 4, 5 ] ]}
\]

### 73.5.2 InverseMap

\[ \text{InverseMap}(\text{paramap}) \]

For a parametrized map \textit{paramap}, \text{InverseMap} returns a mutable parametrized map whose \( i \)-th entry is unbound if \( i \) is not in the image of \textit{paramap}, equal to \( j \) if \( i \) is (in) the image of \textit{paramap}[j] exactly for \( j \), and equal to the set of all preimages of \( i \) under \textit{paramap} otherwise.

We have \text{CompositionMaps}( \text{paramap}, \text{InverseMap}( \text{paramap} ) ) the identity map.

**Example**

\[
\text{gap> tbl:= CharacterTable( "2.A5" );} \text{; f:= CharacterTable( "A5" );}
\text{gap> fus:= GetFusionMap( tbl, f );}
[ 1, 1, 2, 3, 4, 4, 4, 5, 5 ]
\text{gap> inv:= InverseMap( fus );}
[ [ 1, 2 ], 3, [ 4, 5 ], [ 6, 7 ], [ 8, 9 ] ]
\text{gap> CompositionMaps( fus, inv );}
[ 1, 2, 3, 4, 5 ]
\text{gap> # transfer a power map ‘‘up’’ to the factor group}
\text{gap> pow:= PowerMap( tbl, 2 );}
[ 1, 1, 2, 4, 4, 8, 8, 6, 6 ]
\text{gap> CompositionMaps( fus, CompositionMaps( pow, inv ) );}
[ 1, 1, 3, 5, 4 ]
\]
gap> last = PowerMap( f, 2 );
true
gap> # transfer a power map of the factor group `down' to the group
gap> CompositionMaps( inv, CompositionMaps( PowerMap( f, 2 ), fus ) );
[ [ 1, 2 ], [ 1, 2 ], [ 1, 2 ], [ 4, 5 ], [ 4, 5 ], [ 8, 9 ],
  [ 8, 9 ], [ 6, 7 ], [ 6, 7 ] ]

73.5.3 ProjectionMap

ProjectionMap(fusionmap)

For a map fusionmap, ProjectionMap returns a parametrized map whose $i$-th entry is unbound if $i$ is not in the image of fusionmap, and equal to $j$ if $j$ is the smallest position such that $i$ is the image of fusionmap[$j$].

We have CompositionMaps( fusionmap, ProjectionMap( fusionmap ) ) the identity map, i.e., first projecting and then fusing yields the identity. Note that fusionmap must not be a parametrized map.

Example

gap> ProjectionMap( [ 1, 1, 1, 2, 2, 2, 3, 4, 5, 5, 5, 6, 6, 6 ] );
[ 1, 4, 7, 8, 9, 12 ]

73.5.4 Indirected

Indirected(character, paramap)

For a map character and a parametrized map paramap, Indirected returns a parametrized map whose entry at position $i$ is character[paramap[$i$]] if paramap[$i$] is an integer, and an unknown (see Chapter 74) otherwise.

Example

gap> tbl:= CharacterTable( "M12" );;
gap> fus:= [ 1, 3, 4, [ 6, 7 ], 8, 10, [ 11, 12 ], [ 11, 12 ],
  [ 14, 15 ], [ 14, 15 ] ];;
gap> List( Irr( tbl ){ [ 1 .. 6 ] }, x -> Indirected( x, fus ) );
[ [ 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ],
  [ 11, 3, 2, Unknown(9), 1, 0, Unknown(10), Unknown(11), 0, 0 ],
  [ 11, 3, 2, Unknown(12), 1, 0, Unknown(13), Unknown(14), 0, 0 ],
  [ 16, 0, -2, 0, 1, 0, 0, Unknown(15), Unknown(16) ],
  [ 16, 0, -2, 0, 1, 0, 0, Unknown(17), Unknown(18) ],
  [ 45, -3, 0, 1, 0, 0, -1, -1, 1, 1 ] ]

73.5.5 Parametrized

Parametrized(list)

For a list list of (parametrized) maps of the same length, Parametrized returns the smallest parametrized map containing all elements of list.

Parametrized is the inverse function to ContainedMaps (73.5.6).
73.5.6 ContainedMaps

\textbf{ContainedMaps}(\textit{paramap})

For a parametrized map \textit{paramap}, \textit{ContainedMaps} returns the set of all maps contained in \textit{paramap}.

\textit{ContainedMaps} is the inverse function to \textit{Parametrized} (73.5.5) in the sense that \textit{Parametrized( ContainedMaps( paramap ) )} is equal to \textit{paramap}.

\textbf{Example}

\begin{verbatim}
gap> ContainedMaps( [ [ 1, 2, 3, 4, 5 ], [ 1, 2, 3, 4, 6 ], [ 1, 2, 3, 4, 5 ], [ 1, 2, 3, 4, 6 ], [ 1, 3, 2, 4, 5 ], [ 1, 3, 2, 4, 6 ], [ 1, 3, 3, 4, 5 ], [ 1, 3, 3, 4, 6 ] ] );
[ [ 1, 2, 2, 4, 5 ], [ 1, 2, 2, 4, 6 ], [ 1, 2, 3, 4, 5 ], [ 1, 2, 3, 4, 6 ], [ 1, 3, 2, 4, 5 ], [ 1, 3, 2, 4, 6 ], [ 1, 3, 3, 4, 5 ], [ 1, 3, 3, 4, 6 ] ]
\end{verbatim}

73.5.7 UpdateMap

\textbf{UpdateMap}(\textit{character}, \textit{paramap}, \textit{indirected})

Let \textit{character} be a map, \textit{paramap} a parametrized map, and \textit{indirected} a parametrized map that is contained in \textit{CompositionMaps( character, paramap )}.

Then \textit{UpdateMap} changes \textit{paramap} to the parametrized map containing exactly the maps whose composition with \textit{character} is equal to \textit{indirected}.

If a contradiction is detected then \texttt{false} is returned immediately, otherwise \texttt{true}.

\textbf{Example}

\begin{verbatim}
gap> subtbl:= CharacterTable("S4(4).2");; tbl:= CharacterTable("He");;
gap> fus:= InitFusion( subtbl, tbl );;
gap> fus;
[ 1, 2, 2, [ 2, 3 ], 4, 4, [ 7, 8 ], [ 7, 8 ], 9, 9, 9, [ 10, 11 ], [ 10, 11 ], 18, 18, 25, 26, [ 26, 27 ], [ 26, 27 ], 2, [ 6, 7 ], [ 6, 7 ], [ 6, 7, 8 ], 10, 10, 17, 17, 18, [ 19, 20 ], [ 19, 20 ] ]
gap> chi:= Irr( tbl )[2];
Character( CharacterTable( "He" ), [ 51, 11, 3, 6, 0, 3, 3, -1, 1, 2, 0, 3*E(7)+3*E(7)^2+3*E(7)^4, 3*E(7)+3*E(7)^3+3*E(7)^5+3*E(7)^6, 2, E(7)+E(7)^2+2*E(7)^3+2*E(7)^4+2*E(7)^5+2*E(7)^6+6, 2*E(7)+2*E(7)^2+2*E(7)^4+2*E(7)^5+2*E(7)^6, -E(7)+E(7)^2+2*E(7)^3+2*E(7)^4+2*E(7)^5+2*E(7)^6, E(7)+E(7)^2+2*E(7)^3+2*E(7)^4+E(7)^5+2*E(7)^6, E(7)^2+2*E(7)^3+2*E(7)^4+E(7)^5+2*E(7)^6 ] )
gap> filt:= Filtered( Irr( subtbl ), x -> x[1] = 50 );
[ Character( CharacterTable( "S4(4).2" ), [ 50, 10, 10, 2, 5, 5, -2, 2, 0, 0, 0, 1, 1, 0, 0, 0, -1, -1, 10, 2, 2, 1, 1, 0, 0, -1, -1 ] ), Character( CharacterTable( "S4(4).2" ), [ 50, 10, 10, 2, 5, 5, -2, 2, 0, 0, 0, 1, 1, 0, 0, 0, -1, -1, 
\end{verbatim}
gap> UpdateMap( chi, fus, filt[1] + TrivialCharacter( subtbl ) );
true

gap> fus;
[ 1, 2, 3, 4, 4, 8, 7, 9, 9, 9, 10, 10, 18, 18, 25, 25,
  26, 27 ], [ 26, 27 ], 2, [ 6, 7 ], [ 6, 7 ], [ 6, 7 ], 10, 10,
  17, 17, 18, [ 19, 20 ], [ 19, 20 ] ]

73.5.8 MeetMaps

Example

gap> map1:= [ [ 1, 2 ], [ 3, 4 ] ];
   ;
gap> map2:= [ [ 1, 3 ], [ 3, 4 ], [ 5, 6 ] ];
   ;
gap> map3:= [ [ 2, 3 ], 3 ];
   ;
gap> map4:= [ [ 1, 2 ] ];
   ;

gap> MeetMaps( map1, map2 );
true

[ 1, [ 3, 4 ], 5, 6, [ 8, 9 ] ]

73.5.9 CommutativeDiagram

Example

gap> map1:= [ [ 1, 2 ], [ 1, 3 ] ];
   ;
gap> map2:= [ [ 1, 3 ], [ 3, 4 ], [ 5, 6 ] ];
   ;
gap> map3:= [ [ 2, 3 ], 3 ];
   ;
gap> map4:= [ [ 1, 2 ] ];
   ;

gap> imp:= CommutativeDiagram( map1, map2, map3, map4 );
rec( imp1 := [ 2 ], imp2 := [ 1 ], imp3 := [ ], imp4 := [ ] )

gap> map1; map2; map3; map4;
73.5.10 CheckFixedPoints

\[ \text{CheckFixedPoints}( \text{inside1}, \text{between}, \text{inside2} ) \] (function)

Let \text{inside1}, \text{between}, \text{inside2} be parametrized maps, where \text{between} is assumed to map each fixed point of \text{inside1} (that is, \text{inside1}[i] = i) to a fixed point of \text{inside2} (that is, \text{between}[i] is either an integer that is fixed by \text{inside2} or a list that has nonempty intersection with the union of its images under \text{inside2}). CheckFixedPoints changes \text{between} and \text{inside2} by removing all those entries violate this condition.

When an inconsistency is detected, CheckFixedPoints immediately returns \text{fail}. Otherwise the list of positions is returned where changes occurred.

Example

\begin{verbatim}
gap> subtbl:= CharacterTable( "L4(3).2_2" );;
gap> tbl:= CharacterTable( "O7(3)" );;
gap> fus:= InitFusion( subtbl, tbl );; fus{ [ 48, 49 ] }; [ [ 54, 55, 56, 57 ], [ 54, 55, 56, 57 ] ]
gap> CheckFixedPoints( ComputedPowerMaps( subtbl )[5], fus,
>                   ComputedPowerMaps( tbl )[5] );
[ 48, 49 ]
gap> fus{ [ 48, 49 ] }; [ [ 56, 57 ], [ 56, 57 ] ]
\end{verbatim}

73.5.11 TransferDiagram

\[ \text{TransferDiagram}( \text{inside1}, \text{between}, \text{inside2}[\text{improvements}] ) \] (function)

Let \text{inside1}, \text{between}, \text{inside2} be parametrized maps covering parametrized maps \(m_1, f, m_2\) with the property that CompositionMaps\((m_2, f)\) is equal to CompositionMaps\((f, m_1)\).

TransferDiagram checks this consistency, and changes the arguments such that all possible images are removed that cannot occur in the parametrized maps \(m_i\) and \(f\).

So TransferDiagram is similar to CommutativeDiagram (73.5.9), but \text{between} occurs twice in each diagram checked.

If a record \text{improvements} with fields \text{impinside1}, \text{impbetween}, and \text{impinside2} is specified, only those diagrams with elements of \text{impinside1} as preimages of \text{inside1}, elements of \text{impbetween} as preimages of \text{between} or elements of \text{impinside2} as preimages of \text{inside2} are considered.

When an inconsistency is detected, TransferDiagram immediately returns \text{fail}. Otherwise a record is returned that contains three lists \text{impinside1}, \text{impbetween}, and \text{impinside2} of positions where the arguments were changed.
73.5.12 TestConsistencyMaps

Let powermap1 and powermap2 be lists of parametrized maps, and fusionmap a parametrized map, such that for each $i$, the $i$-th entry in powermap1, fusionmap, and the $i$-th entry in powermap2 (if bound) are valid arguments for TransferDiagram (73.5.11). So a typical situation for applying TestConsistencyMaps is that fusionmap is an approximation of a class fusion, and powermap1, powermap2 are the lists of power maps of the subgroup and the group.

TestConsistencyMaps repeatedly applies TransferDiagram (73.5.11) to these arguments for all $i$ until no more changes occur.

If a list fusimp is specified then only those diagrams with elements of fusimp as preimages of fusionmap are considered.

When an inconsistency is detected, TestConsistencyMaps immediately returns false. Otherwise true is returned.

Example

```gap
gap> subtbl:= CharacterTable("2F4(2)"));;
gap> tbl:= CharacterTable("Ru"));;
gap> fus:= InitFusion( subtbl, tbl );;
gap> permchar:= Sum( Irr( tbl ){ [ 1, 5, 6 ] } );;
gap> fus;
[ 1, 2, 4, 5, 7, 8, 9, 11, 14, 14, [ 13, 15 ], 16, [ 18, 19 ], 20, [ 25, 26 ], [ 25, 26 ], 5, 5, 6, 8, 14, [ 13, 15 ], [ 18, 19 ], [ 18, 19 ], [ 25, 26 ], [ 25, 26 ], 27, 27 ]
gap> fus;
[ 1, 2, 4, 5, 7, 8, 9, 11, 14, 14, 15, 16, 18, 20, [ 25, 26 ], [ 25, 26 ], 5, 5, 6, 8, 14, 13, 19, 19, [ 25, 26 ], [ 25, 26 ], 27, 27 ]
gap> TestConsistencyMaps( ComputedPowerMaps( subtbl ), fus, ComputedPowerMaps( tbl ), fusimp ];
true
```

73.5.13 Indeterminateness

\( \text{\tt Indeterminateness( paramap )} \)

For a parametrized map \( \text{paramap} \), \text{Indeterminateness} returns the number of maps contained in \( \text{paramap} \), that is, the product of lengths of lists in \( \text{paramap} \) denoting lists of several images.

Example

\[
\text{gap> Indeterminateness([ 1, [ 2, 3 ], [ 4, 5 ], [ 6, 7, 8, 9, 10 ], 11 ]);}
\]

\[ 20 \]

73.5.14 PrintAmbiguity

\( \text{\tt PrintAmbiguity( list, paramap )} \)

For each map in the list \( \text{list} \), \text{PrintAmbiguity} prints its position in \( \text{list} \), the indeterminateness (see \text{Indeterminateness (73.5.13)}) of the composition with the parametrized map \( \text{paramap} \), and the list of positions where a list of images occurs in this composition.

Example

\[
\text{gap> paramap := [ 1, [ 2, 3 ], [ 3, 4 ], [ 2, 3, 4 ], 5 ];}
\]
\[
\text{gap> list := [ [ 1, 1, 1, 1, 1 ], [ 1, 1, 2, 2, 3 ], [ 1, 2, 3, 4, 5 ] ];}
\]
\[
\text{gap> PrintAmbiguity( list, paramap );}
\]
\[
1 1 [ ]
\]
\[
2 4 [ 2, 4 ]
\]
\[
3 12 [ 2, 3, 4 ]
\]

73.5.15 ContainedSpecialVectors

\( \text{\tt ContainedSpecialVectors( tbl, chars, paracharacter, func) } \)
\( \text{\tt IntScalarProducts( tbl, chars, candidate) } \)
\( \text{\tt NonnegIntScalarProducts( tbl, chars, candidate) } \)
\( \text{\tt ContainedPossibleVirtualCharacters( tbl, chars, paracharacter) } \)
\( \text{\tt ContainedPossibleCharacters( tbl, chars, paracharacter) } \)

Let \( \text{tbl} \) be an ordinary character table, \( \text{chars} \) a list of class functions (or values lists), \( \text{paracharacter} \) a parametrized class function of \( \text{tbl} \), and \( \text{func} \) a function that expects the three arguments \( \text{tbl}, \text{chars} \), and a values list of a class function, and that returns either \text{true} or \text{false}.

\text{ContainedSpecialVectors} returns the list of all those elements \( \text{vec} \) of \( \text{paracharacter} \) that have integral norm, have integral scalar product with the principal character of \( \text{tbl} \), and that satisfy \( \text{func}( \text{tbl}, \text{chars}, \text{vec} ) = \text{true} \).

Two special cases of \( \text{func} \) are the check whether the scalar products in \( \text{tbl} \) between the vector \( \text{vec} \) and all lists in \( \text{chars} \) are integers or nonnegative integers, respectively. These functions are accessible as global variables \text{IntScalarProducts} and \text{NonnegIntScalarProducts}, and
ContainedPossibleVirtualCharacters and ContainedPossibleCharacters provide access to these special cases of ContainedSpecialVectors.

Example

```gap
gap> subtbl:= CharacterTable( "HSM12" );;
gap> tbl:= CharacterTable( "HS" );;
gap> fus:= InitFusion( subtbl, tbl );;
gap> rest:= CompositionMaps( Irr( tbl )[8], fus );
[ [ 231, -9, 7 ], [ -9, 7 ], [ -9, 7 ], [ -9, 7 ], 6, 15, 15, [ -1, 15 ],
  [ -1, 15 ], 1, [ 1, 6 ], [ 1, 6 ], [ 1, 6 ], [ 1, 6 ], [ -2, 0 ],
  [ 1, 2 ], [ 1, 2 ], [ 1, 2 ], 0, 0, 1, 0, 0, 0, 0 ]
gap> irr:= Irr( subtbl );;
gap> # no further condition
gap> cont1:= ContainedSpecialVectors( subtbl, irr, rest,
  > function( tbl, chars, vec ) return true; end );;
Length( cont1 ); 24
gap> # require scalar products to be integral
gap> cont2:= ContainedSpecialVectors( subtbl, irr, rest,
  > IntScalarProducts );
[ [ 231, 7, -9, -9, 6, 15, 15, -1, -1, 1, 6, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ],
  [ 231, 7, -9, 7, 6, 15, 15, -1, -1, 1, 6, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ],
  [ 231, 7, -9, -9, 6, 15, 15, 15, 15, 1, 6, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ],
  [ 231, 7, -9, 7, 6, 15, 15, 15, 15, 1, 6, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ] ]
gap> # additionally require scalar products to be nonnegative
gap> cont3:= ContainedSpecialVectors( subtbl, irr, rest,
  > NonnegIntScalarProducts );
[ [ 231, 7, -9, -9, 6, 15, 15, -1, -1, 1, 6, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ],
  [ 231, 7, -9, 7, 6, 15, 15, -1, -1, 1, 6, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ] ]
gap> cont2 = ContainedPossibleVirtualCharacters( subtbl, irr, rest );
true
gap> cont3 = ContainedPossibleCharacters( subtbl, irr, rest );
true
```

73.5.16 CollapsedMat

is a record with the components

- **fusion**
  - fusion that collapses those columns of **mat** that are equal in **mat** and also for all maps in the list **maps**.

- **mat**
  - the image of **mat** under that fusion.

Example

```gap
gap> mat:= [ [ 1, 1, 1, 1 ], [ 2, -1, 0, 0 ], [ 4, 4, 1, 1 ] ];;
gap> coll:= CollapsedMat( mat, [] );
```
rec( fusion := [ 1, 2, 3, 3 ],
    mat := [ [ 1, 1, 1 ], [ 2, -1, 0 ], [ 4, 4, 1 ] ] )
gap> List( last.mat, x -> x{ last.fusion } ) = mat;
true
gap> coll:= CollapsedMat( mat, [ [ 1, 1, 1, 2 ] ] );
rec( fusion := [ 1, 2, 3, 4 ],
    mat := [ [ 1, 1, 1, 1 ], [ 2, -1, 0, 0 ], [ 4, 4, 1, 1 ] ] )

73.5.17 ContainedDecomposables

> ContainedDecomposables(constituents, moduls, parachar, func) (function)
> ContainedCharacters(tbl, constituents, parachar) (function)

For these functions, let constituents be a list of rational class functions, moduls a list of positive integers, parachar a parametrized rational class function, func a function that returns either true or false when called with (a values list of) a class function, and tbl a character table.

ContainedDecomposables returns the set of all elements \( \chi \) of parachar that satisfy \( \text{func}(\chi) = true \) and that lie in the \( \mathbb{Z} \)-lattice spanned by constituents, modulo moduls. The latter means they lie in the \( \mathbb{Z} \)-lattice spanned by constituents and the set \( \{ \text{moduls}[i] \cdot e_i ; 1 \leq i \leq n \} \) where \( n \) is the length of parachar and \( e_i \) is the \( i \)-th standard basis vector.

One application of ContainedDecomposables is the following. constituents is a list of values lists of rational characters of an ordinary character table tbl, moduls is the list of centralizer orders of tbl (see SizesCentralizers(71.9.2)), and func checks whether a vector in the lattice mentioned above has nonnegative integral scalar product in tbl with all entries of constituents. This situation is handled by ContainedCharacters. Note that the entries of the result list are not necessary linear combinations of constituents, and they are not necessarily characters of tbl.

Example

```gap
gap> subtbl:= CharacterTable( "HSM12" );; tbl:= CharacterTable( "HS" );;
gap> rat:= RationalizedMat( Irr( subtbl ) );;
gap> fus:= InitFusion( subtbl, tbl );
gap> rest:= CompositionMaps( Irr( tbl )[8], fus );
[ 231, [ -9, 7 ], [ -9, 7 ], [ -9, 7 ], 6, 15, 15, [ -1, 15 ],
  [ -1, 15 ], 1, [ 1, 6 ], [ 1, 6 ], [ 1, 6 ], [ -2, 0 ],
  [ 1, 2 ], [ 1, 2 ], [ 1, 2 ], 0, 0, 1, 0, 0, 0, 0 ]
gap> # compute all vectors in the lattice
gap> ContainedDecomposables( rat, SizesCentralizers( subtbl ), rest,
>   returntrue );
[ [ 231, 7, -9, -9, 6, 15, 15, -1, -1, 1, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ],
 [ 231, 7, -9, -9, 6, 15, 15, 15, 1, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ],
 [ 231, 7, -9, 7, 6, 15, 15, -1, -1, 1, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ],
 [ 231, 7, -9, 7, 6, 15, 15, 15, 1, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ]]
gap> # compute only those vectors that are characters
gap> ContainedDecomposables( rat, SizesCentralizers( subtbl ), rest,
>   x -> NonnegIntScalarProducts( subtbl, Irr( subtbl ), x ) );
[ [ 231, 7, -9, -9, 6, 15, 15, -1, -1, 1, 6, 1, 1, -2, 1, 2, 2, 0,
  0, 1, 0, 0, 0, 0 ]]
```
73.6 Subroutines for the Construction of Power Maps

In the argument lists of the functions Congruences (73.6.2), ConsiderKernels (73.6.3), and ConsiderSmallerPowerMaps (73.6.4), tbl is an ordinary character table, chars a list of (values lists of) characters of tbl, prime a prime integer, approxmap a parametrized map that is an approximation for the prime-th power map of tbl (e.g., a list returned by InitPowerMap (73.6.1), and quick a Boolean.

The quick value true means that only those classes are considered for which approxmap lists more than one possible image.

73.6.1 InitPowerMap

\[ \text{InitPowerMap}(tbl, \text{prime}) \] (function)

For an ordinary character table tbl and a prime prime, InitPowerMap returns a parametrized map that is a first approximation of the prime-th powermap of tbl, using the conditions 1. and 2. listed in the description of PossiblePowerMaps (73.1.2).

If there are classes for which no images are possible, according to these criteria, then fail is returned.

```
gap> t := CharacterTable( "U4(3).4" );;
gap> pow := InitPowerMap( t, 2 );
[ 1, 1, 3, 4, 5, [ 2, 16 ], [ 2, 16, 17 ], 8, 3, [ 3, 4 ],
  [ 11, 12 ], [ 11, 12 ], [ 6, 7, 18, 19, 30, 31, 32, 33 ], 14,
  [ 9, 20 ], 1, 1, 2, 2, 3, [ 3, 4, 5 ], [ 3, 4, 5 ],
  [ 6, 7, 18, 19, 30, 31, 32, 33 ], 8, 9, 9, [ 9, 10, 20, 21, 22 ],
  [ 11, 12 ], [ 11, 12 ], 16, 16, [ 2, 16 ], [ 2, 16 ], 17, 17,
  [ 6, 18, 30, 31, 32, 33 ], 6, 18, 30, 31, 32, 33,
  [ 6, 7, 18, 19, 30, 31, 32, 33 ], [ 6, 7, 18, 19, 30, 31, 32, 33 ],
  20, 20, [ 9, 20 ], [ 9, 20 ], [ 9, 10, 20, 21, 22 ],
  [ 9, 10, 20, 21, 22 ], 24, 24, [ 15, 25, 26, 40, 41, 42, 43 ],
  [ 15, 25, 26, 40, 41, 42, 43 ], [ 28, 29 ], [ 28, 29 ], [ 28, 29 ],
  [ 28, 29 ],
]
```

73.6.2 Congruences (for character tables)

\[ \text{Congruences}(tbl, \text{chars}, \text{approxmap}, \text{prime}, \text{quick}) \] (function)

Congruences replaces the entries of approxmap by improved values, according to condition 3. listed in the description of PossiblePowerMaps (73.1.2).

For each class for which no images are possible according to the tests, the new value of approxmap is an empty list. Congruences returns true if no such inconsistencies occur, and false otherwise.

```
gap> Congruences( t, Irr( t ), pow, 2, false );
true
```
73.6.3 ConsiderKernels

ConsiderKernels(tbl, chars, approxmap, prime, quick)

ConsiderKernels replaces the entries of approxmap by improved values, according to condition 4. listed in the description of PossiblePowerMaps (73.1.2).

Congruences (73.6.2) returns true if the orders of the kernels of all characters in chars divide the order of the group of tbl, and false otherwise.

Example

```
gap> t:= CharacterTable( "A7.2" );; init:= InitPowerMap( t, 2 );
[ 1, 1, 3, 4, [ 2, 9, 10 ], 6, 3, 8, 1, 1, [ 2, 9, 10 ], 3, [ 3, 4 ],
 6, [ 7, 12 ] ]
gap> ConsiderKernels( t, Irr( t ), init, 2, false );
true
gap> init;
[ 1, 1, 3, 4, 2, 6, 3, 8, 1, 1, 2, 3, [ 3, 4 ], 6, 7 ]
```

73.6.4 ConsiderSmallerPowerMaps

ConsiderSmallerPowerMaps replaces the entries of approxmap by improved values, according to condition 5. listed in the description of PossiblePowerMaps (73.1.2).

ConsiderSmallerPowerMaps returns true if each class admits at least one image after the checks, otherwise false is returned. If no element orders of tbl are stored (see OrdersClassRepresentatives (71.9.1)) then true is returned without any tests.

Example

```
gap> t:= CharacterTable( "3.A6" );; init:= InitPowerMap( t, 5 );
[ 1, [ 2, 3 ], [ 2, 3 ], 4, [ 5, 6 ], [ 5, 6 ], [ 7, 8 ], [ 7, 8 ],
 9, [ 10, 11 ], [ 10, 11 ], 1, [ 2, 3 ], [ 2, 3 ], 1, [ 2, 3 ],
 2, [ 2, 3 ] ]
gap> Indeterminateness( init );
4096
gap> ConsiderSmallerPowerMaps( t, init, 5, false );
true
gap> Indeterminateness( init );
256
```

73.6.5 MinusCharacter

MinusCharacter(character, primepowermap, prime)

Example

```
[ 1, 1, 3, 4, 5, 2, 2, 8, 3, 4, 11, 12, [ 6, 7 ], 14, 9, 1, 1, 2, 2,
 3, 4, 5, [ 6, 7 ], 8, 9, 9, 10, 11, 12, 16, 16, 16, 16, 17, 17, 18,
 [ 18, 19 ], [ 18, 19 ], 20, 20, 20, 20, 22, 22, 24, 24,
 [ 25, 26 ], [ 25, 26 ], 28, 28, 29, 29 ]
```
Let \textit{character} be (the list of values of) a class function \(\chi\), \textit{prime} a prime integer \(p\), and \textit{primepowermap} a parametrized map that is an approximation of the \(p\)-th power map for the character table of \(\chi\). \textit{MinusCharacter} returns the parametrized map of values of \(\chi^p - \chi\), which is defined by \(\chi^p(g) = (\chi(g)^p - \chi(g^p))/p\).

\begin{verbatim}
Example

gap> tbl := CharacterTable( "S7" );;
gap> pow := InitPowerMap( tbl, 2 );;
gap> pow;
[ 1, 1, 3, 4, [ 2, 9, 10 ], 6, 3, 8, 1, 1, [ 2, 9, 10 ], 3, [ 3, 4 ],
  6, [ 7, 12 ] ]
gap> chars := Irr( tbl ){ [ 2 .. 5 ] };;
gap> List( chars, x -> MinusCharacter( x, pow, 2 ) );
[ [ 0, 0, 0, 0, [ 0, 1 ], 0, 0, 0, 0, [ 0, 1 ], 0, 0, 0, [ 0, 1 ] ],
  [ 15, -1, 3, 0, [ -2, -1, 0 ], 0, -1, 1, 5, -3, [ 0, 1, 2 ], -1, 0,
    0, [ 0, 1 ] ],
  [ 15, -1, 3, 0, [ -1, 0, 2 ], 0, -1, 1, 5, -3, [ 1, 2, 4 ], -1, 0,
    0, 1 ] ],
  [ 190, -2, 1, 1, [ 0, 2 ], 0, 1, 1, -10, -10, [ 0, 2 ], -1, -1, 0,
    [ -1, 0 ] ] ]
\end{verbatim}

73.6.6 PowerMapsAllowedBySymmetrizations

\begin{verbatim}
function PowerMapsAllowedBySymmetrizations( tbl, subchars, chars, approxmap, prime,
  parameters )
  \end{verbatim}

Let \(\text{tbl}\) be an ordinary character table, \(\text{prime}\) a prime integer, \(\text{approxmap}\) a parametrized map that is an approximation of the \(\text{prime}\)-th power map of \(\text{tbl}\) (e.g., a list returned by \text{InitPowerMap} (73.6.1)), \(\text{chars}\) and \(\text{subchars}\) two lists of (values lists of) characters of \(\text{tbl}\), and \textit{parameters} a record with components \texttt{maxlen}, \texttt{minamb}, \texttt{maxamb} (three integers), \texttt{quick} (a Boolean), and \texttt{contained} (a function). Usual values of \texttt{contained} are \texttt{ContainedCharacters} (73.5.17) or \texttt{ContainedPossibleCharacters} (73.5.15).

\text{PowerMapsAllowedBySymmetrizations} replaces the entries of \texttt{approxmap} by improved values, according to condition 6. listed in the description of \texttt{PossiblePowerMaps} (73.1.2).

More precisely, the strategy used is as follows. First, for each \(\chi \in \text{chars}\), let \(\text{minus} := \text{MinusCharacter}(\chi, \text{approxmap}, \text{prime})\).

- If \(\text{Indeterminateness( minus )} = 1\) and \texttt{parameters.quick} = \texttt{false} then the scalar products of \(\text{minus}\) with \texttt{subchars} are checked; if not all scalar products are nonnegative integers then an empty list is returned, otherwise \(\chi\) is deleted from the list of characters to inspect.
- Otherwise if \(\text{Indeterminateness( minus )} \leq \text{parameters.minamb}\) then \(\chi\) is deleted from the list of characters.
- If \(\text{parameters.minamb} \leq \text{Indeterminateness( minus )} \leq \text{parameters.maxamb}\) then construct the list of contained class functions \(\text{poss} := \text{parameters.contains( tbl, subchars, minus) and Parametrized( poss )}\), and improve the approximation of the power map using \texttt{UpdateMap} (73.5.7).

If this yields no further immediate improvements then we branch. If there is a character from \texttt{chars} left with less or equal \texttt{parameters.maxlen} possible symmetrizations, compute the union of...
power maps allowed by these possibilities. Otherwise we choose a class \( C \) such that the possible symmetrizations of a character in \( \text{chars} \) differ at \( C \), and compute recursively the union of all allowed power maps with image at \( C \) fixed in the set given by the current approximation of the power map.

Example

```
 gap> tbl:= CharacterTable( "U4(3).4" );;
 gap> pow:= InitPowerMap( tbl, 2 );;
 gap> Congruences( tbl, Irr( tbl ), pow, 2 );;
 [ 1, 1, 3, 4, 5, 2, 2, 8, 3, 4, 11, 12, [ 6, 7 ], 14, 9, 1, 1, 2, 2,
  3, 4, 5, [ 6, 7 ], 8, 9, 9, 10, 11, 12, 16, 16, 16, 16, 17, 17, 18,
  18, [ 18, 19 ], [ 18, 19 ], 20, 20, 20, 20, 22, 22, 24, 24,
  [ 25, 26 ], [ 25, 26 ], 28, 28, 29, 29 ]
 gap> PowerMapsAllowedBySymmetrizations( tbl, Irr( tbl ), Irr( tbl ),
  pow, 2, rec( maxlen:= 10, contained:= ContainedPossibleCharacters,
  minamb:= 2, maxamb:= infinity, quick:= false ) );
 [ [ 1, 1, 3, 4, 5, 2, 2, 8, 3, 4, 11, 12, 6, 14, 9, 1, 1, 2, 2, 3, 4,
  5, 6, 8, 9, 9, 10, 11, 12, 16, 16, 16, 16, 17, 17, 18, 18, 18, 18,
  18, 20, 20, 20, 20, 22, 22, 24, 24, 26, 26, 28, 28, 29, 29 ] ]
```

73.7 Subroutines for the Construction of Class Fusions

73.7.1 InitFusion

\( \text{InitFusion(} \text{subtbl, tbl} \text{)} \)

For two ordinary character tables \( \text{subtbl} \) and \( \text{tbl} \), \text{InitFusion} returns a parametrized map that is a first approximation of the class fusion from \( \text{subtbl} \) to \( \text{tbl} \), using condition 1. listed in the description of \text{PossibleClassFusions} (73.3.6).

If there are classes for which no images are possible, according to this criterion, then \text{fail} is returned.

Example

```
 gap> subtbl:= CharacterTable( "2F4(2)" );; tbl:= CharacterTable( "Ru" );;
 gap> fus:= InitFusion( subtbl, tbl );
 [ 1, 2, 2, 4, [ 5, 6 ], [ 5, 6, 7, 8 ], [ 5, 6, 7, 8 ], [ 9, 10 ],
  11, 14, 14, [ 13, 14, 15 ], [ 16, 17 ], [ 18, 19 ], 20, [ 25, 26 ],
  [ 25, 26 ], [ 5, 6 ], [ 5, 6 ], [ 5, 6 ], [ 5, 6, 7, 8 ],
  [ 13, 14, 15 ], [ 13, 14, 15 ], [ 18, 19 ], [ 18, 19 ], [ 25, 26 ],
  [ 25, 26 ], [ 27, 28, 29 ], [ 27, 28, 29 ] ]
```

73.7.2 CheckPermChar

\( \text{CheckPermChar(} \text{subtbl, tbl, approxmap, permchar} \text{)} \)

\text{CheckPermChar} replaces the entries of the parametrized map \( \text{approxmap} \) by improved values, according to condition 3. listed in the description of \text{PossibleClassFusions} (73.3.6).

\text{CheckPermChar} returns \text{true} if no inconsistency occurred, and \text{false} otherwise.

Example

```
 gap> permchar:= Sum( Irr( tbl ){ [ 1, 5, 6 ] } );;
 gap> CheckPermChar( subtbl, tbl, fus, permchar ); fus;
 true
```
ConsiderTableAutomorphisms

ConsiderTableAutomorphisms\(\text{approxmap, grp}\)

ConsiderTableAutomorphisms replaces the entries of the parametrized map \(\text{approxmap}\) by improved values, according to condition 4. listed in the description of PossibleClassFusions (73.3.6).

Afterwards exactly one representative of fusion maps (contained in \(\text{approxmap}\)) in each orbit under the action of the permutation group \(\text{grp}\) is contained in the modified parametrized map.

ConsiderTableAutomorphisms returns the list of positions where \(\text{approxmap}\) was changed.

Example

\begin{verbatim}
 gap> ConsiderTableAutomorphisms( fus, AutomorphismsOfTable( tbl ) );
 [ 16 ]
 gap> fus;
 [ 1, 2, 2, 4, 5, 7, 8, 9, 11, 14, 14, [ 13, 15 ], 16, [ 18, 19 ], 20,
  [ 25, 26 ], [ 25, 26 ], 5, 5, 6, 8, 14, [ 13, 15 ], [ 18, 19 ],
  [ 18, 19 ], [ 25, 26 ], [ 25, 26 ], 27, 27 ]
\end{verbatim}

FusionsAllowedByRestrictions

FusionsAllowedByRestrictions\(\text{subtbl, tbl, subchars, chars, approxmap, parameters}\)

FusionsAllowedByRestrictions replaces the entries of \(\text{approxmap}\) by improved values, according to condition 5. listed in the description of PossibleClassFusions (73.3.6).

More precisely, the strategy used is as follows.

First, for each \(\chi \in \text{chars}\), let \(\text{restricted} := \text{CompositionMaps}(\chi, \text{approxmap})\).

- If \(\text{Indeterminateness}(\text{restricted}) = 1\) and \(\text{parameters}.\text{quick} = \text{false}\) then the scalar products of \(\text{restricted}\) with \(\text{subchars}\) are checked; if not all scalar products are non-negative integers then an empty list is returned, otherwise \(\chi\) is deleted from the list of characters to inspect.

- Otherwise if \(\text{Indeterminateness}(\text{minus})\) is smaller than \(\text{parameters}.\text{minamb}\) then \(\chi\) is deleted from the list of characters.
• If $\text{parameters\.minamb} \leq \text{Indeterminateness (restricted)} \leq \text{parameters\.maxamb}$ then construct $\text{poss:= parameters\.contained ( subtbl, subchars, restricted )}$ and $\text{Parametrized ( poss )}$, and improve the approximation of the fusion map using $\text{UpdateMap (73.5.7)}$.

If this yields no further immediate improvements then we branch. If there is a character from $\text{chars}$ left with less or equal $\text{parameters\.maxlen}$ possible restrictions, compute the union of fusion maps allowed by these possibilities. Otherwise we choose a class $C$ such that the possible restrictions of a character in $\text{chars}$ differ at $C$, and compute recursively the union of all allowed fusion maps with image at $C$ fixed in the set given by the current approximation of the fusion map.

Example

```
gap> subtbl:= CharacterTable( "U3(3)" );; tbl:= CharacterTable( "J4" );;
gap> fus:= InitFusion( subtbl, tbl );;
gap> TestConsistencyMaps( ComputedPowerMaps( subtbl ), fus,
> ComputedPowerMaps( tbl ) );
true

gap> ConsiderTableAutomorphisms( fus, AutomorphismsOfTable( tbl ) );
gap> fus;
[ 1, 2, 4, 4, [ 5, 6 ], [ 5, 6 ], 10, [ 12, 13 ],
  [ 12, 13 ], [ 14, 15, 16 ], [ 14, 15, 16 ], [ 21, 22 ], [ 21, 22 ] ]
gap> ConsiderTableAutomorphisms( fus, AutomorphismsOfTable( tbl ) );
true

gap> fus;
[ 1, 2, 4, 4, [ 5, 6 ], [ 5, 6 ], [ 5, 6 ], 10, 12, [ 12, 13 ],
  [ 12, 13 ], [ 14, 15, 16 ], [ 14, 15, 16 ], [ 21, 22 ], [ 21, 22 ] ]
gap> FusionsAllowedByRestrictions( subtbl, tbl, Irr( subtbl ),
  > Irr( tbl ), fus, rec( maxlen:= 10,
  > contained:= ContainedPossibleCharacters, minamb:= 2,
  > maxamb:= infinity, quick:= false ) );
[ [ 1, 2, 4, 4, 5, 5, 6, 10, 12, 13, 14, 14, 21, 21 ],
  [ 1, 2, 4, 4, 6, 6, 6, 10, 12, 13, 15, 15, 22, 22 ],
  [ 1, 2, 4, 4, 6, 6, 10, 12, 13, 16, 16, 22, 22 ] ]
```
Chapter 74

Unknowns

Sometimes the result of an operation does not allow further computations with it. In many cases, then
an error is signalled, and the computation is stopped.

This is not appropriate for some applications in character theory. For example, if one wants to
induce a character of a group to a supergroup (see InducedClassFunction (72.9.3)) but the class
fusion is only a parametrized map (see Chapter 73), there may be values of the induced character
which are determined by the fusion map, whereas other values are not known.

For this and other situations, GAP provides the data type unknown. An object of this type, further
on called an unknown, may stand for any cyclotomic (see Chapter 18), in particular its family (see 13.1)
is CyclotomicsFamily.

Unknowns are parametrized by positive integers. When a GAP session is started, no unknowns
exist.

The only ways to create unknowns are to call the function Unknown (74.1.1) or a function that calls
it, or to do arithmetical operations with unknowns.

GAP objects containing unknowns will contain fixed unknowns when they are printed to files, i.e.,
function calls Unknown (n) instead of Unknown (). So be careful to read files printed in different GAP
sessions, since there may be the same unknown at different places.

The rest of this chapter contains information about the unknown constructor, the category, and
comparison of and arithmetical operations for unknowns. More is not known about unknowns in
GAP.

74.1 More about Unknowns

74.1.1 Unknown

\texttt{Unknown ([n])}

(definition)

Called without argument, Unknown returns a new unknown value, i.e., the first one that is larger
than all unknowns which exist in the current GAP session.

Called with a positive integer \( n \), Unknown returns the \( n \)-th unknown; if this did not exist yet, it is
created.
74.1.2 LargestUnknown

LargestUnknown is the largest \( n \) that is used in any \( \text{Unknown}(n) \) in the current GAP session. This is used in \( \text{Unknown}(74.1.1) \) which increments this value when asked to make a new unknown.

74.1.3 IsUnknown

is the category of unknowns in GAP.

Example

\begin{verbatim}
gap> Unknown(); List([1..20], i -> Unknown());
Unknown(1)
gap> Unknown(); # note that we have already created 21 unknowns.
Unknown(22)
gap> Unknown(2000); Unknown();
Unknown(2000)
Unknown(2001)
gap> LargestUnknown;
2001
gap> IsUnknown( Unknown ); IsUnknown( Unknown() );
false
true
\end{verbatim}

74.1.4 Comparison of Unknowns

Unknowns can be \textit{compared} via \( = \) and \( < \) with all cyclotomics and with certain other GAP objects (see 4.12). We have \( \text{Unknown}(n) \geq \text{Unknown}(m) \) if and only if \( n \geq m \) holds, unknowns are larger than all cyclotomics that are not unknowns.

Example

\begin{verbatim}
gap> Unknown() \geq Unknown(); Unknown(2) < Unknown(3);
false
true
gap> Unknown() > 3; Unknown() > E(3);
true
true
gap> Unknown() > Z(8); Unknown() > [];
false
false
\end{verbatim}

74.1.5 Arithmetical Operations for Unknowns

The usual arithmetic operations \( +, -, \ast \) and \( / \) are defined for addition, subtraction, multiplication and division of unknowns and cyclotomics. The result will be a new unknown except in one of the following cases.

Multiplication with zero yields zero, and multiplication with one or addition of zero yields the old unknown. \textit{Note} that division by an unknown causes an error, since an unknown might stand for zero.
As unknowns are cyclotomics, dense lists of unknowns and other cyclotomics are row vectors and they can be added and multiplied in the usual way. Consequently, lists of such row vectors of equal length are (ordinary) matrices (see IsOrdinaryMatrix (24.2.2)).
Chapter 75

Monomiality Questions

This chapter describes functions dealing with the monomiality of finite (solvable) groups and their characters.

All these functions assume characters to be class function objects as described in Chapter 72, lists of character values are not allowed.

The usual property tests of GAP that return either true or false are not sufficient for us. When we ask whether a group character $\chi$ has a certain property, such as quasiprimitivity, we usually want more information than just yes or no. Often we are interested in the reason why a group character $\chi$ was proved to have a certain property, e.g., whether monomiality of $\chi$ was proved by the observation that the underlying group is nilpotent, or whether it was necessary to construct a linear character of a subgroup from which $\chi$ can be induced. In the latter case we also may be interested in this linear character. Therefore we need test functions that return a record containing such useful information. For example, the record returned by the function TestQuasiPrimitive (75.3.3) contains the component isQuasiPrimitive (which is the known boolean property flag), and additionally the component comment, a string telling the reason for the value of the isQuasiPrimitive component, and in the case that the argument $\chi$ was not quasiprimitive also the component character, which is an irreducible constituent of a nonhomogeneous restriction of $\chi$ to a normal subgroup. Besides these test functions there are also the known properties, e.g., the property IsQuasiPrimitive (75.3.3) which will call the attribute TestQuasiPrimitive (75.3.3), and return the value of the isQuasiPrimitive component of the result.

A few words about how to use the monomiality functions seem to be necessary. Monomiality questions usually involve computations in many subgroups and factor groups of a given group, and for these groups often expensive calculations such as that of the character table are necessary. So one should be careful not to construct the same group over and over again, instead the same group object should be reused, such that its character table need to be computed only once. For example, suppose you want to restrict a character to a normal subgroup $N$ that was constructed as a normal closure of some group elements, and suppose that you have already computed with normal subgroups (by calls to NormalSubgroups (39.19.9) or MaximalNormalSubgroups (39.19.10)) and their character tables. Then you should look in the lists of known normal subgroups whether $N$ is contained, and if so you can use the known character table. A mechanism that supports this for normal subgroups is described in 71.23.

Also the following hint may be useful in this context. If you know that sooner or later you will compute the character table of a group $G$ then it may be advisable to compute it as soon as possible. For example, if you need the normal subgroups of $G$ then they can be computed more efficiently if
the character table of \( G \) is known, and they can be stored compatibly to the contained \( G \)-conjugacy classes. This correspondence of classes list and normal subgroup can be used very often.

Several examples in this chapter use the symmetric group \( S_4 \) and the special linear group \( SL(2,3) \). For running the examples, you must first define the groups, for example as follows.

```gap
gap> S4:= SymmetricGroup( 4 );; SetName( S4, "S4" );
gap> Sl23:= SL( 2, 3 );;
```

### 75.1 InfoMonomial (Info Class)

#### 75.1.1 InfoMonomial

\( ▶ \) InfoMonomial

(info class)

Most of the functions described in this chapter print some (hopefully useful) information if the info level of the info class InfoMonomial is at least 1, see 7.4 for details.

### 75.2 Character Degrees and Derived Length

#### 75.2.1 Alpha

\( ▶ \) Alpha(\( G \))

(attribute)

For a group \( G \), Alpha returns a list whose \( i \)-th entry is the maximal derived length of groups \( G/\ker(\chi) \) for \( \chi \in \text{Irr}(G) \) with \( \chi(1) \) at most the \( i \)-th irreducible degree of \( G \).

#### 75.2.2 Delta

\( ▶ \) Delta(\( G \))

(attribute)

For a group \( G \), Delta returns the list \([1, alp[2] - alp[1], \ldots, alp[n] - alp[n - 1]]\), where \( alp = \text{Alpha}(\ G \) ) (see Alpha (75.2.1)).

#### 75.2.3 IsBergerCondition

\( ▶ \) IsBergerCondition(\( G \))

(property)

\( ▶ \) IsBergerCondition(\( \chi \))

(property)

Called with an irreducible character \( \chi \) of a group \( G \), IsBergerCondition returns true if \( \chi \) satisfies \( M' \leq \ker(\chi) \) for every normal subgroup \( M \) of \( G \) with the property that \( M \leq \ker(\psi) \) holds for all \( \psi \in \text{Irr}(G) \) with \( \psi(1) < \chi(1) \), and false otherwise.

Called with a group \( G \), IsBergerCondition returns true if all irreducible characters of \( G \) satisfy the inequality above, and false otherwise.

For groups of odd order the result is always true by a theorem of T. R. Berger (see [Ber76, Thm. 2.2]).

In the case that false is returned, InfoMonomial (75.1.1) tells about a degree for which the inequality is violated.
Example

```gap
gap> Alpha( Sl23 );
[ 1, 3, 3 ]
gap> Alpha( S4 );
[ 1, 2, 3 ]
gap> Delta( Sl23 );
[ 1, 2, 0 ]
gap> Delta( S4 );
[ 1, 1, 1 ]
gap> IsBergerCondition( S4 );
true
gap> IsBergerCondition( Sl23 );
false
gap> List( Irr( Sl23 ), IsBergerCondition );
[ true, true, true, false, false, false, true ]
gap> List( Irr( Sl23 ), Degree );
[ 1, 1, 1, 2, 2, 2, 3 ]
```

### 75.3 Primitivity of Characters

#### 75.3.1 TestHomogeneous

| TestHomogeneous(chi, N) |

For a group character \( \chi \) of the group \( G \), say, and a normal subgroup \( N \) of \( G \), `TestHomogeneous` returns a record with information whether the restriction of \( \chi \) to \( N \) is homogeneous, i.e., is a multiple of an irreducible character.

\( N \) may be given also as list of conjugacy class positions w.r.t. the character table of \( G \).

The components of the result are:

- `isHomogeneous`:
  - `true` or `false`.
- `comment`:
  - A string telling a reason for the value of the `isHomogeneous` component.
- `character`:
  - Irreducible constituent of the restriction, only bound if the restriction had to be checked.
- `multiplicity`:
  - Multiplicity of the character component in the restriction of \( \chi \).  

Example

```gap
gap> n:= DerivedSubgroup( Sl23 );;
gap> chi:= Irr( Sl23 )[7];
Character( CharacterTable( Group( 
  [ [ [ 0*Z(3), Z(3) ], [ Z(3)^0, 0*Z(3) ] ], 
    [ [ Z(3), 0*Z(3) ], [ 0*Z(3), Z(3) ] ],
    [ [ Z(3)^0, Z(3) ], [ Z(3), Z(3) ] ] ] ) ),
  [ 3, 0, 0, 3, 0, 0, -1 ] )
gap> TestHomogeneous( chi, n );
rec( character := Character( CharacterTable( Group( 
  [ [ [ 0*Z(3), Z(3) ], [ Z(3)^0, 0*Z(3) ] ], 
    [ [ Z(3), 0*Z(3) ], [ 0*Z(3), Z(3) ] ],
    [ [ Z(3)^0, Z(3) ], [ Z(3), Z(3) ] ] ] ) ),
  [ 3, 0, 0, 3, 0, 0, -1 ] ) )
```
GAP> chi:= Irr( Sl23 )[4];
Character( CharacterTable( SL(2,3) ), [ 2, 1, 1, -2, -1, -1, 0 ] )
GAP> cln:= ClassPositionsOfNormalSubgroup( CharacterTable( Sl23 ), n );
[ 1, 4, 7 ]
GAP> TestHomogeneous( chi, cln );
rec( comment := "restricts irreducibly", isHomogeneous := true )

75.3.2 IsPrimitiveCharacter
▷ IsPrimitiveCharacter(chi)

For a character \( \chi \) of the group \( G \), say, IsPrimitiveCharacter returns \( \text{true} \) if \( \chi \) is not induced from any proper subgroup, and \( \text{false} \) otherwise.

Example

```
GAP> IsPrimitive( Irr( Sl23 )[4] );
true
GAP> IsPrimitive( Irr( Sl23 )[7] );
fake
```

75.3.3 TestQuasiPrimitive
▷ TestQuasiPrimitive(chi)
▷ IsQuasiPrimitive(chi)

TestQuasiPrimitive returns a record with information about quasiprimitivity of the group character \( \chi \), i.e., whether \( \chi \) restricts homogeneously to every normal subgroup of its group. The result record contains at least the components isQuasiPrimitive (with value either \( \text{true} \) or \( \text{false} \)) and comment (a string telling a reason for the value of the component isQuasiPrimitive). If \( \chi \) is not quasiprimitive then there is additionally a component character, with value an irreducible constituent of a nonhomogeneous restriction of \( \chi \).

IsQuasiPrimitive returns \( \text{true} \) or \( \text{false} \), depending on whether the character \( \chi \) is quasiprimitive.

Note that for solvable groups, quasiprimitivity is the same as primitivity (see IsPrimitiveCharacter (75.3.2)).

Example

```
GAP> chi:= Irr( Sl23 )[4];
Character( CharacterTable( SL(2,3) ), [ 2, 1, 1, -2, -1, -1, 0 ] )
GAP> TestQuasiPrimitive( chi );
rec( comment := "all restrictions checked", isQuasiPrimitive := true )
GAP> chi:= Irr( Sl23 )[7];
Character( CharacterTable( SL(2,3) ), [ 3, 0, 0, 3, 0, 0, -1 ] )
GAP> TestQuasiPrimitive( chi );
rec( character := Character( CharacterTable( Group( [ [ 0*Z(3), Z(3) ], [ Z(3)^0, 0*Z(3) ] ],
            [ [ Z(3), 0*Z(3) ], [ 0*Z(3), Z(3) ] ],
            [ [ Z(3)^0, Z(3) ], [ Z(3), Z(3) ] ] ) ) ),
```
75.3.4 TestInducedFromNormalSubgroup

TestInducedFromNormalSubgroup returns a record with information whether the irreducible character \( \chi \) of the group \( G \), say, is induced from a proper normal subgroup of \( G \). If the second argument \( N \) is present, which must be a normal subgroup of \( G \) or the list of class positions of a normal subgroup of \( G \), it is checked whether \( \chi \) is induced from \( N \).

The result contains always the components \( \text{isInduced} \) (either \text{true} or \text{false}) and \( \text{comment} \) (a string telling a reason for the value of the component \( \text{isInduced} \)). In the \text{true} case there is a component \( \text{character} \) which contains a character of a maximal normal subgroup from which \( \chi \) is induced.

IsInducedFromNormalSubgroup returns \text{true} if \( \chi \) is induced from a proper normal subgroup of \( G \), and \text{false} otherwise.

Example

\[
\text{gap> List( Irr( S123 ), IsInducedFromNormalSubgroup );}
\]\[false, false, false, false, false, false, true\]

\[
\text{gap> List( Irr( S4 ){ [ 1, 3, 4 ] },}
\]
\[
\text{ TestInducedFromNormalSubgroup );}
\]\[\text{rec( comment := "linear character", isInduced := false ),}
\]\[\text{rec( character := Character( CharacterTable( Alt( [ 1 .. 4 ] ) ),}
\]\[\text{ [ 1, 1, E(3)^2, E(3) ] ),}
\]\[\text{ comment := "induced from component \'.character'",}
\]\[\text{ isInduced := true ),}
\]\[\text{rec( comment := "all maximal normal subgroups checked",}
\]\[\text{ isInduced := false ) ]}

75.4 Testing Monomiality

A character \( \chi \) of a finite group \( G \) is called \textit{monomial} if \( \chi \) is induced from a linear character of a subgroup of \( G \). A finite group \( G \) is called \textit{monomial} (or \textit{M-group}) if each ordinary irreducible character of \( G \) is monomial.

75.4.1 TestMonomial

Called with a group character \( \chi \) of a group \( G \), TestMonomial returns a record containing information about monomiality of the group \( G \) or the group character \( \chi \), respectively.

\[
[ 1, -1, 1, -1, 1 ] ), \text{comment := "restriction checked",}
\]
\[
\text{isQuasiPrimitive := false })
\]
If TestMonomial proves the character \(\chi\) to be monomial then the result contains components \(\text{isMonomial}\) (with value true), \(\text{comment}\) (a string telling a reason for monomiality), and if it was necessary to compute a linear character from which \(\chi\) is induced, also a component \(\text{character}\).

If TestMonomial proves \(\chi\) or \(G\) to be nonmonomial then the value of the component \(\text{isMonomial}\) is false, and in the case of \(G\) a nonmonomial character is the value of the component \(\text{character}\) if it had been necessary to compute it.

A Boolean can be entered as the second argument \(\text{uselattice}\); if the value is true then the subgroup lattice of the underlying group is used if necessary, if the value is false then the subgroup lattice is used only for groups of order at most TestMonomialUseLattice (75.4.2). The default value of \(\text{uselattice}\) is false.

For a group whose lattice must not be used, it may happen that TestMonomial cannot prove or disprove monomiality; then the result record contains the component \(\text{isMonomial}\) with value "?". This case occurs in the call for a character \(\chi\) if and only if \(\chi\) is not induced from the inertia subgroup of a component of any reducible restriction to a normal subgroup. It can happen that \(\chi\) is monomial in this situation. For a group, this case occurs if no irreducible character can be proved to be nonmonomial, and if no decision is possible for at least one irreducible character.

```gap
gap> TestMonomial( S4 );
rec( comment := "abelian by supersolvable group", isMonomial := true )
gap> TestMonomial( S123 );
rec( comment := "list Delta( G ) contains entry > 1",
    isMonomial := false )
```

75.4.2 TestMonomialUseLattice

\(\text{TestMonomialUseLattice}\) (global variable)

This global variable controls for which groups the operation \(\text{TestMonomial}\) (75.4.1) may compute the subgroup lattice. The value can be set to a positive integer or infinity (18.2.1), the default is 1000.

75.4.3 IsMonomialNumber

\(\text{IsMonomialNumber}(n)\) (property)

For a positive integer \(n\), \(\text{IsMonomialNumber}\) returns true if every solvable group of order \(n\) is monomial, and false otherwise. One can also use \(\text{IsMonomial}\) instead.

Let \(v_p(n)\) denote the multiplicity of the prime \(p\) as factor of \(n\), and \(ord(p, q)\) the multiplicative order of \(p \mod q\).

Then there exists a solvable nonmonomial group of order \(n\) if and only if one of the following conditions is satisfied.

1. \(v_2(n) \geq 2\) and there is a \(p\) such that \(v_p(n) \geq 3\) and \(p \equiv -1 \mod 4\),
2. \(v_2(n) \geq 3\) and there is a \(p\) such that \(v_p(n) \geq 3\) and \(p \equiv 1 \mod 4\),
3. there are odd prime divisors \(p\) and \(q\) of \(n\) such that \(ord(p, q)\) is even and \(ord(p, q) < v_p(n)\) (especially \(v_p(n) \geq 3\)).
4. there is a prime divisor $q$ of $n$ such that $v_2(n) \geq 2 \text{ord}(2,q) + 2$ (especially $v_2(n) \geq 4$),

5. $v_2(n) \geq 2$ and there is a $p$ such that $p \equiv 1 \pmod{4}$, $\text{ord}(p,q)$ is odd, and $2 \text{ord}(p,q) < v_p(n)$ (especially $v_p(n) \geq 3$).

These five possibilities correspond to the five types of solvable minimal nonmonomial groups (see \texttt{MinimalNonmonomialGroup (75.5.2)}) that can occur as subgroups and factor groups of groups of order $n$.

\begin{verbatim}
    gap> Filtered( [ 1 .. 111 ], x -> not IsMonomial( x ) );
    [ 24, 48, 72, 96, 108 ]
\end{verbatim}

\section*{75.4.4 \texttt{TestMonomialQuick}}

\begin{verbatim}
▷ \texttt{TestMonomialQuick(chi)}
▷ \texttt{TestMonomialQuick(G)}
\end{verbatim}

\texttt{TestMonomialQuick} does some cheap tests whether the irreducible character $\chi$ or the group $G$, respectively, is monomial. Here “cheap” means in particular that no computations of character tables are involved, and it is not checked whether $\chi$ is a character and irreducible. The return value is a record with components

\begin{itemize}
    \item \texttt{isMonomial} either \texttt{true} or \texttt{false} or the string "?", depending on whether (non)monomiality could be proved, and
    \item \texttt{comment} a string telling the reason for the value of the \texttt{isMonomial} component.
\end{itemize}

A group $G$ is proved to be monomial by \texttt{TestMonomialQuick} if $G$ is nilpotent or Sylow abelian by supersolvable, or if $G$ is solvable and its order is not divisible by the third power of a prime. Nonsolvable groups are proved to be nonmonomial by \texttt{TestMonomialQuick}.

An irreducible character $\chi$ is proved to be monomial if it is linear, or if its codegree is a prime power, or if its group knows to be monomial, or if the factor group modulo the kernel can be proved to be monomial by \texttt{TestMonomialQuick}.

\begin{verbatim}
    gap> TestMonomialQuick( Irr( S4 )[3] );
    rec( comment := "whole group is monomial", isMonomial := true )
    gap> TestMonomialQuick( S4 );
    rec( comment := "abelian by supersolvable group", isMonomial := true )
    gap> TestMonomialQuick( S123 );
    rec( comment := "no decision by cheap tests", isMonomial := "?" )
\end{verbatim}

\section*{75.4.5 \texttt{TestSubnormallyMonomial}}

\begin{verbatim}
▷ \texttt{TestSubnormallyMonomial(G)}
▷ \texttt{TestSubnormallyMonomial(chi)}
▷ \texttt{IsSubnormallyMonomial(G)}
\end{verbatim}
An irreducible character of the group \( G \) is called *subnormally monomial* (SM for short) if it is induced from a linear character of a subnormal subgroup of \( G \). A group \( G \) is called SM if all its irreducible characters are SM.

\textbf{TestSubnormallyMonomial} returns a record with information whether the group \( G \) or the irreducible character \( \chi \) of \( G \) is SM.

The result has the components \texttt{isSubnormallyMonomial} (either \texttt{true} or \texttt{false}) and \texttt{comment} (a string telling a reason for the value of the component \texttt{isSubnormallyMonomial}); in the case that the \texttt{isSubnormallyMonomial} component has value \texttt{false} there is also a component \texttt{character}, with value an irreducible character of \( G \) that is not SM.

\textbf{IsSubnormallyMonomial} returns \texttt{true} if the group \( G \) or the group character \( \chi \) of \( G \) is subnormally monomial, and \texttt{false} otherwise.

```gap
gap> TestSubnormallyMonomial( S4 );
rec( character := Character( CharacterTable( S4 ), [ 3, -1, -1, 0, 1 ] ),
  comment := "found non-SM character",
  isSubnormallyMonomial := false )
gap> TestSubnormallyMonomial( Irr( S4 )[4] );
rec( comment := "all subnormal subgroups checked",
  isSubnormallyMonomial := false )
gap> TestSubnormallyMonomial( DerivedSubgroup( S4 ) );
rec( comment := "all irreducibles checked",
  isSubnormallyMonomial := true )
```

\section*{75.4.6 \textbf{TestRelativelySM}}

\textbf{TestRelativelySM}(\( G \)) \hspace{1cm} (attribute)

\textbf{TestRelativelySM}(\( \chi \)) \hspace{1cm} (attribute)

\textbf{TestRelativelySM}(\( G, N \)) \hspace{1cm} (operation)

\textbf{TestRelativelySM}(\( \chi, N \)) \hspace{1cm} (operation)

\textbf{IsRelativelySM}(\( G \)) \hspace{1cm} (property)

\textbf{IsRelativelySM}(\( \chi \)) \hspace{1cm} (property)

In the first two cases, \textbf{TestRelativelySM} returns a record with information whether the argument, which must be a SM group \( G \) or an irreducible character \( \chi \) of a SM group \( G \), is relatively SM with respect to every normal subgroup of \( G \).

In the second two cases, a normal subgroup \( N \) of \( G \) is the second argument. Here \textbf{TestRelativelySM} returns a record with information whether the first argument is relatively SM with respect to \( N \), i.e., whether there is a subnormal subgroup \( H \) of \( G \) that contains \( N \) such that the character \( \chi \) resp. every irreducible character of \( G \) is induced from a character \( \psi \) of \( H \) such that the restriction of \( \psi \) to \( N \) is irreducible.

The result record has the components \texttt{isRelativelySM} (with value either \texttt{true} or \texttt{false}) and \texttt{comment} (a string that describes a reason). If the argument is a group \( G \) that is not relatively SM with respect to a normal subgroup then additionally the component \texttt{character} is bound, with value a not relatively SM character of such a normal subgroup.

\textbf{IsRelativelySM} returns \texttt{true} if the SM group \( G \) or the irreducible character \( \chi \) of the SM group \( G \) is relatively SM with respect to every normal subgroup of \( G \), and \texttt{false} otherwise.
Note that it is not checked whether $G$ is SM.

```gap
gap> IsSubnormallyMonomial( DerivedSubgroup( S4 ) );
true
gap> TestRelativelySM( DerivedSubgroup( S4 ) );
rec(
  comment := "normal subgroups are abelian or have nilpotent factor group",
  isRelativelySM := true )
```

### 75.5 Minimal Nonmonomial Groups

#### 75.5.1 IsMinimalNonmonomial

**IsMinimalNonmonomial**

A group $G$ is called *minimal nonmonomial* if it is nonmonomial, and all proper subgroups and factor groups are monomial.

```gap
gap> IsMinimalNonmonomial( Sl23 ); IsMinimalNonmonomial( S4 );
true false
```

#### 75.5.2 MinimalNonmonomialGroup

**MinimalNonmonomialGroup**

is a solvable minimal nonmonomial group described by the parameters `factsize` and $p$ if such a group exists, and `false` otherwise.

Suppose that the required group $K$ exists. Then `factsize` is the size of the Fitting factor $K/F(K)$, and this value is 4, 8, an odd prime, twice an odd prime, or four times an odd prime. In the case that `factsize` is twice an odd prime, the centre $Z(K)$ is cyclic of order $2^{p+1}$. In all other cases $p$ is the (unique) prime that divides the order of $F(K)$.

The solvable minimal nonmonomial groups were classified by van der Waall, see [vdW76].

```gap
gap> MinimalNonmonomialGroup( 2, 3 ); # the group SL(2,3)
2^2:(1+2):3
gap> MinimalNonmonomialGroup( 3, 4 );
3^3:(1+2):4
gap> MinimalNonmonomialGroup( 5, 8 );
5^5:(1+2):Q8
gap> MinimalNonmonomialGroup( 13, 12 );
13^13:(1+2):2.D6
gap> MinimalNonmonomialGroup( 1, 14 );
2^2:(1+6):D14
gap> MinimalNonmonomialGroup( 2, 14 );
(2^2:(1+6)Y4):D14
```
Chapter 76

Using and Developing GAP Packages

The functionality of GAP can be extended by loading GAP packages. The GAP distribution already contains all currently redistributed GAP packages in the gap-4.11.1/pkg directory.

GAP packages are written by (groups of) GAP users who may not necessarily be members of the GAP developer team. The responsibility and copyright of a GAP package remains with the original author(s).

GAP packages have their own documentation which is smoothly integrated into the GAP help system. (When GAP is started, LoadPackageDocumentation is called for all packages.)

All GAP users who develop new code are invited to share the results of their efforts with other GAP users by making the code and its documentation available in form of a package. Guidance on how to do this is available from the GAP website (https://www.gap-system.org) and in the GAP package Example (see https://www.gap-system.org/Packages/example.html).

The GAP development team will assist in making any new package suitable for distribution with GAP. It is also possible to submit a package to a formal refereeing process.

In this chapter we first describe how to use existing packages, and then provide guidelines for writing a GAP package.

76.1 Installing a GAP Package

Before a package can be used it must be installed. A standard distribution of GAP already contains all the packages currently redistributed with GAP. This set of packages has been checked for compatibility with the system and with each other during release preparation. Most of the packages can be used immediately, but some of them may require further installation steps (see below).

Also, since GAP packages are released independently of the main GAP system, it may sometimes be useful to upgrade or install new packages between upgrades of your GAP installation, e.g. if a new version of a package adds new capabilities or bug fixes that you need.

A package consists of a collection of files within a single directory that must be a subdirectory of the pkg directory in one of the GAP root directories (see 9.2). If you don’t have access to the pkg directory in your main GAP installation you can add private root directories as explained in section 9.2.

Whenever you download or clone an archive of a GAP package, it will contain a README file (or README.md etc.) that explains how it should be installed. Some packages just consist of GAP code and the installation is done by unpacking the archive in one of the places described above. There are also packages that need further installation steps, such as compilation or installing additional software.
to satisfy their dependencies. If there are some external programs which have to be compiled, this is often done by executing ./configure; make inside the unpacked package directory (but check the individual README files).

Most of the packages that require compilation can be compiled in a single step by changing to the pkg directory of your GAP installation and calling the ./bin/BuildPackages.sh script.

Note that if you use Windows you may not be able to use some or all external binaries.

### 76.2 Loading a GAP Package

If a package is not already loaded, it may be loaded using the function LoadPackage (76.2.1).

Some GAP packages are prepared for automatic loading, that is they will be loaded automatically when GAP starts (see 76.2.2).

#### 76.2.1 LoadPackage

\[\text{LoadPackage}(\text{name}[, \text{version}][, \text{banner}]) \]

loads the GAP package with name \text{name}.

As an example, the following loads the GAP package SONATA (case insensitive) which provides methods for the construction and analysis of finite nearrings:

```
\begin{verbatim}
gap> LoadPackage("sonata");
... some more lines with package banner(s) ...
true
\end{verbatim}
```

The package name is case insensitive and may be appropriately abbreviated. At the time of writing, for example, \text{LoadPackage("semi")} will load the \text{Semigroups} package, and \text{LoadPackage("j")} will load the \text{json} package. If the abbreviation cannot be uniquely completed, a list of available completions will be offered, and \text{LoadPackage} returns \text{fail}. Thus the names of all installed packages can be shown by calling \text{LoadPackage("")};

When the optional argument string \text{version} is present, the package will only be loaded in a version number equal to or greater than \text{version} (see \text{CompareVersionNumbers} (76.3.9)). If the first character of \text{version} is = then only that version will be loaded.

\text{LoadPackage} will return \text{true} if the package has been successfully loaded, and will return \text{fail} if the package could not be loaded. The latter may be the case if the package is not installed, if necessary binaries have not been compiled, or if the version number of the available version is too small. If the package cannot be loaded, \text{TestPackageAvailability} (76.3.2) can be used to find the reasons. Also, \text{DisplayPackageLoadingLog} (76.2.5) can be used to find out more about the failure. To see the problems directly, one can change the verbosity using the user preference \text{InfoPackageLoadingLevel}, see \text{InfoPackageLoading} (76.2.5) for details.

If the package \text{name} has already been loaded in a version number equal to or greater than \text{version}, \text{LoadPackage} returns \text{true} without doing anything else.

If the optional argument \text{banner} is present then it must be either \text{true} or \text{false}; in the latter case, the effect is that no package banner is printed.

After a package has been loaded, all its code becomes available to use with the rest of the GAP library.
76.2.2 Automatic loading of GAP packages

When GAP is started some packages are loaded automatically, and these belong to two categories. The first are those packages which are needed to start GAP (at the present time, the only such package is GAPDoc). Their list is contained in GAPInfo.Dependencies.NeededOtherPackages. The second are packages which are loaded during GAP startup by default. The latter list may be obtained by calling UserPreference("PackagesToLoad") and is customisable as described in Section (Reference: Configuring User preferences).

While GAP will not start if any of the packages from the former group is missing, loading of the packages from the latter group may be suppressed by using the -A command line option (see 3.1).

If for some reason you don’t want certain packages to be automatically loaded, GAP provides three levels for disabling autoloading.

The autoloading of specific packages can be overwritten for the whole GAP installation by putting a file NOAUTO into a pkg directory that contains lines with the names of packages which should not be automatically loaded.

Furthermore, individual users can disable the autoloading of specific packages by putting the names of these packages into the list that is assigned to the user preference “ExcludeFromAutoload”, for example in the user’s gap.ini file (see 3.2.1).

Using the -A command line option when starting GAP (see 3.1), automatic loading of packages is switched off for this GAP session.

In any of the above three cases, the packages listed in GAPInfo.Dependencies.NeededOtherPackages are still loaded automatically, and an error is signalled if any of these packages is unavailable.

See SetPackagePath (76.2.3) for a way to force the loading of a prescribed package version. See also ExtendRootDirectories (76.2.4) for a method of adding directories containing packages after GAP has been started.

76.2.3 SetPackagePath

> SetPackagePath(pkgname, pkgpath) (function)

This function can be used to force GAP to load a particular version of a package, even though newer versions of the package are available.

Let pkgname and pkgpath be strings denoting the name of a GAP package and the path to a directory where a version of this package can be found (i.e., calling Directory (9.3.2) with the argument pkgpath will yield a directory that contains the file PackageInfo.g of the package).

If the package pkgname is already loaded with an installation path different from pkgpath then SetPackagePath signals an error. If the package pkgname is not yet loaded then SetPackagePath erases the information about available versions of the package pkgname, and stores the record that is contained in the PackageInfo.g file at pkgpath instead, such that only the version installed at pkgpath can be loaded with LoadPackage (76.2.1).

76.2.4 ExtendRootDirectories

> ExtendRootDirectories(paths) (function)
Let \texttt{paths} be a list of strings that denote paths to intended \texttt{GAP} root directories (see 9.2). The function \texttt{ExtendRootDirectories} adds these paths to the global list \texttt{GAPInfo.RootPaths} and calls the initialization of available \texttt{GAP} packages, such that later calls to \texttt{LoadPackage} (76.2.1) will find the \texttt{GAP} packages that are contained in \texttt{pkg} subdirectories of the directories given by \texttt{paths}.

Note that the purpose of this function is to make \texttt{GAP} packages in the given directories available. It cannot be used to influence the start of \texttt{GAP}, because the \texttt{GAP} library is loaded before \texttt{ExtendRootDirectories} can be called (and because \texttt{GAPInfo.RootPaths} is not used for reading the \texttt{GAP} library).

### 76.2.5 DisplayPackageLoadingLog

- \texttt{DisplayPackageLoadingLog([severity])} (function)
- \texttt{InfoPackageLoading} (info class)
- \texttt{PACKAGE_ERROR} (global variable)
- \texttt{PACKAGE_WARNING} (global variable)
- \texttt{PACKAGE_INFO} (global variable)
- \texttt{PACKAGE_DEBUG} (global variable)
- \texttt{LogPackageLoadingMessage(severity, message[, name])} (function)

Whenever \texttt{GAP} considers loading a package, log messages are collected in a global list. The messages for the current \texttt{GAP} session can be displayed with \texttt{DisplayPackageLoadingLog}. To each message, a “severity” is assigned, which is one of \texttt{PACKAGE_ERROR} (76.2.5), \texttt{PACKAGE_WARNING} (76.2.5), \texttt{PACKAGE_INFO} (76.2.5), \texttt{PACKAGE_DEBUG} (76.2.5), in increasing order. The function \texttt{DisplayPackageLoadingLog} shows only the messages whose severity is at most \texttt{severity}, the default for \texttt{severity} is \texttt{PACKAGE_WARNING} (76.2.5).

The intended meaning of the severity levels is as follows.

**PACKAGE_ERROR**

should be used whenever \texttt{GAP} will run into an error during package loading, where the reason of the error shall be documented in the global list.

**PACKAGE_WARNING**

should be used whenever \texttt{GAP} has detected a reason why a package cannot be loaded, and where the message describes how to solve this problem, for example if a package binary is missing.

**PACKAGE_INFO**

should be used whenever \texttt{GAP} has detected a reason why a package cannot be loaded, and where it is not clear how to solve this problem, for example if the package is not compatible with other installed packages.

**PACKAGE_DEBUG**

should be used for other messages reporting what \texttt{GAP} does when it loads packages (checking dependencies, reading files, etc.). One purpose is to record in which order packages have been considered for loading or have actually been loaded.

The log messages are created either by the functions of \texttt{GAP}'s package loading mechanism or in the code of your package, for example in the \texttt{AvailabilityTest} function of the package's...
PackageInfo.g file (see 76.3.13), using LogPackageLoadingMessage. The arguments of this function are severity (which must be one of the above severity levels), message (which must be either a string or a list of strings), and optionally name (which must be the name of the package to which the message belongs). The argument name is not needed if the function is called from a call of a package's AvailabilityTest function (see 76.3.13) or is called from a package file that is read from init.g or read.g; in these cases, the name of the current package (stored in the record GAPInfo.PackageCurrent) is taken. According to the above list, the severity argument of LogPackageLoadingMessage calls in a package's AvailabilityTest function is either PACKAGE_WARNING (76.2.5) or PACKAGE_INFO (76.2.5).

If you want to see the log messages already during the package loading process, you can set the level of the info class InfoPackageLoading to one of the severity values listed above; afterwards the messages with at most this severity are shown immediately when they arise. In order to make this work already for autoloaded packages, you can call SetUserPreference(“InfoPackageLoadingLevel”, lev); to set the desired severity level lev. This can for example be done in your gap.ini file, see Section 3.2.1.

76.3 Functions for GAP Packages

The following functions are mainly used in files contained in a package and not by users of a package. They are needed to organise reading package files into GAP in the right order, performing maintenance tasks like building documentation and running package tests, checking package dependencies, etc. You will find further information about their use in Section 76.4 and subsequent sections.

76.3.1 ReadPackage

Called with two strings name and file, ReadPackage reads the file file of the GAP package name, where file is given as a path relative to the home directory of name. Note that file is read in the namespace of the package, see Section 4.10 for details.

If only one argument file is given, this should be the path of a file relative to the pkg subdirectory of GAP root paths (see 9.2). Note that in this case, the package name is assumed to be equal to the first part of file, so the one argument form is not recommended.

The absolute path is determined as follows. If the package in question has already been loaded then the file in the directory of the loaded version is read. If the package is available but not yet loaded then the directory given by TestPackageAvailability (76.3.2) is used, without prescribed version number. (Note that the ReadPackage call does not force the package to be loaded.)

If the file is readable then true is returned, otherwise false.

Each of name and file should be a string. The name argument is case insensitive.

RereadPackage does the same as ReadPackage, except that also read-only global variables are overwritten (cf. Reread (9.7.10)).

76.3.2 TestPackageAvailability

Called with two strings name and file, TestPackageAvailability checks if the file file of the GAP package name is readable and the user has permission to read it. Note that file is read in the namespace of the package, see Section 4.10 for details.

If only one argument file is given, this should be a path relative to the pkg subdirectory of GAP root paths (see 9.2). Note that in this case, the package name is assumed to be equal to the first part of file.
For strings `name` and `version`, this function tests whether the GAP package `name` is available for loading in a version that is at least `version`, or equal to `version` if the first character of `version` is `=` (see `CompareVersionNumbers` for further details about version numbers).

The result is `true` if the package is already loaded, `fail` if it is not available, and the string denoting the GAP root path where the package resides if it is available, but not yet loaded. So the package `name` is available if the result of `TestPackageAvailability` is not equal to `fail`.

If the optional argument `checkall` is `true` then all dependencies are checked, even if some have turned out to be not satisfied. This is useful when one is interested in the reasons why the package `name` cannot be loaded. In this situation, calling first `TestPackageAvailability` and then `DisplayPackageLoadingLog` with argument `PACKAGE_INFO` will give an overview of these reasons.

You should *not* call `TestPackageAvailability` in the test function of a package (the value of the component `AvailabilityTest` in the `PackageInfo.g` file of the package, see 76.3.13), because `TestPackageAvailability` calls this test function.

The argument `name` is case insensitive.

### 76.3.3 IsPackageLoaded

```
▷ IsPackageLoaded(name [, version])
```

For strings `name` and `version`, this function tests whether the GAP package `name` is already loaded in a version that is at least `version`, or equal to `version` if the first character of `version` is `=` (see `CompareVersionNumbers` for further details about version numbers).

The result is `true` if the package is already loaded, `false` otherwise.

### 76.3.4 IsPackageMarkedForLoading

```
▷ IsPackageMarkedForLoading(name, version)
```

This function can be used in the code of a package `A`, say, for testing whether the package `name` in version `version` will be loaded after the `LoadPackage` call for the package `A` has been executed. This means that the package `name` had been loaded before, or has been (directly or indirectly) requested as a needed or suggested package of the package `A` or of a package whose loading requested that `A` was loaded.

### 76.3.5 TestPackage

```
▷ TestPackage(pkgname)
```

It is recommended that a GAP package specifies a standard test in its `PackageInfo.g` file. If `pkgname` is a string with the name of a GAP package, then `TestPackage(pkgname)` will check if this package is loadable and has the standard test, and will run this test in the current GAP session.

The output of the test depends on the particular package, and it also may depend on the current GAP session (loaded packages, state of the random sources, defined global variables etc.). If you would like to run the test for the same package in the same setting that is used for the testing of GAP releases, you have to call.
Example

```
make testpackage PKGNAME=pkgname
```

in the UNIX shell (without quotes around `pkgname`). This will run the standard test for the package `pkgname` three times in different settings, and will write test output to three files in the `dev/log` directory. These output files will be named in the format `testpackageX_timestamp.pkgname`, where $X=A$ for the test with packages loaded by default, $X=1$ for the test without other packages (i.e. when GAP is started with `-A` command line option), and $X=2$ when the test is run with all packages loaded.

### 76.3.6 `InstalledPackageVersion`

```
▷ InstalledPackageVersion(name) (function)
```

If the GAP package with name `name` has already been loaded then `InstalledPackageVersion` returns the string denoting the version number of this version of the package. If the package is available but has not yet been loaded then the version number string for that version of the package that currently would be loaded. (Note that loading another package might force loading another version of the package `name`, so the result of `InstalledPackageVersion` will be different afterwards.) If the package is not available then `fail` is returned.

The argument `name` is case insensitive.

### 76.3.7 `DirectoriesPackageLibrary`

```
▷ DirectoriesPackageLibrary(name [, path]) (function)
```

takes the string `name`, a name of a GAP package, and returns a list of directory objects for those sub-directory/ies containing the library functions of this GAP package, for the version that is already loaded or is currently going to be loaded or would be the first version GAP would try to load if no other version is explicitly prescribed. (If the package `name` is not yet loaded then we cannot guarantee that the returned directories belong to a version that really can be loaded.)

The default is that the library functions are in the subdirectory `lib` of the GAP package’s home directory. If this is not the case, then the second argument `path` needs to be present and must be a string that is a path name relative to the home directory of the GAP package with name `name`.

Note that `DirectoriesPackageLibrary` is likely to be called in the `AvailabilityTest` function in the package’s `PackageInfo.g` file (see 76.3.13).

As an example, the following returns a directory object for the library functions of the GAP package `Example`:

```
gap> DirectoriesPackageLibrary( "Example", "gap" );
[ dir("/home/werner/gap/4.0/pkg/example/gap") ]
```

Observe that we needed the second argument "gap" here, since `Example`’s library functions are in the subdirectory `gap` rather than `lib`.

In order to find a subdirectory deeper than one level in a package directory, the second argument is again necessary whether or not the desired subdirectory relative to the package’s directory begins with `lib`. The directories in `path` should be separated by `/` (even on systems, like Windows, which use `\` as the directory separator). For example, suppose there is a package `somepackage` with a subdirectory `m11` in the directory data, then we might expect the following:
76.3.8 DirectoriesPackagePrograms

\[ \text{DirectoriesPackagePrograms(name)} \]

returns a list of the bin/architecture subdirectories of all packages name where architecture is the architecture on which GAP has been compiled (this can be accessed as GAPInfo.Architecture, see GAPInfo (3.5.1)) and the version of the installed package coincides with the version of the package name that is already loaded or is currently going to be loaded or would be the first version GAP would try to load if no other version is explicitly prescribed. (If the package name is not yet loaded then we cannot guarantee that the returned directories belong to a version that really can be loaded.)

Note that DirectoriesPackagePrograms is likely to be called in the AvailabilityTest function in the package's PackageInfo.g file (see 76.3.13).

The directories returned by DirectoriesPackagePrograms are the place where external binaries of the GAP package name for the current package version and the current architecture should be located.

\[ \text{Example} \]
\[ \text{gap> DirectoriesPackagePrograms( "nq" );} \]
\[ \text{[ dir("/home/gap/4.0/pkg/nq/bin/x86_64-unknown-linux-gnu-gcc/64-bit/")}, \]
\[ \text{dir("/home/gap/4.0/pkg/nq/bin/x86_64-unknown-linux-gnu-gcc/"})] \]

76.3.9 CompareVersionNumbers

\[ \text{CompareVersionNumbers(supplied, required[, "equal"])} \]

A version number is a string which contains nonnegative integers separated by non-numeric characters. Examples of valid version numbers are for example:

\[ \text{Example} \]
\[ "1.0" "3.141.59" "2.7-8.3" "5 release 2 patchlevel 666" \]

CompareVersionNumbers compares two version numbers, given as strings. They are split at non-digit characters, the resulting integer lists are compared lexicographically. The routine tests whether supplied is at least as large as required, and returns true or false accordingly. A version number ending in dev is considered to be infinite.

76.3.10 DeclareAutoreadableVariables

\[ \text{DeclareAutoreadableVariables(pkgname, filename, varlist)} \]

Let pkgname be the name of a package, let filename be the name of a file relative to the home directory of this package, and let varlist be a list of strings that are the names of global variables which get bound when the file is read. DeclareAutoreadableVariables notifies the names in varlist such that the first attempt to access one of the variables causes the file to be read.
76.3.11 Kernel modules in GAP packages

If the package has a kernel module, then it can be compiled using the gac script. A kernel module is implemented in C and follows certain conventions to comply with the GAP kernel interface, which we plan to document later. In the meantime, we advice to get in touch with GAP developers if you plan to develop such a package.

To use the gac script to produce dynamically loadable modules, call it with the -d option, for example:

```bash
$ gap4/bin/i386-ibm-linux-gcc2/gac -d test.c
```

This will produce a file `test.so`, which then can be loaded into GAP with `LoadDynamicModule` (76.3.12).

76.3.12 LoadDynamicModule

```gap
LoadDynamicModule(filename [, crc])
```

To load a compiled file, the command `LoadDynamicModule` is used. This command loads `filename` as module. If given, the CRC checksum `crc` must match the value of the module (see 9.7.7).

```gap
gap> LoadDynamicModule("./test.so");
gap> CrcFile("test.so");
2906458206
gap> LoadDynamicModule("./test.so",1); 
Error, <crc> mismatch (or no support for dynamic loading) called from
<function>( <arguments> ) called from read-eval-loop
Entering break read-eval-print loop ...
you can 'quit;' to quit to outer loop, or
you can 'return;' to continue
brk> quit;
gap> LoadDynamicModule("./test.so",2906458206);
```

On some operating systems, once you have loaded a dynamic module with a certain filename, loading another with the same filename will have no effect, even if the file on disk has changed.

76.3.13 The PackageInfo.g File

Each package has the file `PackageInfo.g` which contains meta-information about the package (package name, version, author(s), relations to other packages, homepage, download archives, etc.). This file is used by the package loading mechanism and also for the redistribution of a package with GAP.

76.3.14 ValidatePackageInfo

```gap
ValidatePackageInfo(info)
```


This function is intended to support package authors who create or modify PackageInfo.g files. (It is not called when these files are read during the startup of GAP or when packages are actually loaded.)

The argument info must be either a record as is contained in a PackageInfo.g file or a a string which describes the path to such a file. The result is true if the record or the contents of the file, respectively, has correct format, and false otherwise; in the latter case information about the incorrect components is printed.

Note that the components used for package loading are checked as well as the components that are needed for composing the package overview web page or for updating the package archives.

If info is a string then ValidatePackageInfo checks additionally whether those package files exist that are mentioned in the file info, for example the manual.six file of the package documentation.

76.3.15 ShowPackageVariables

⊿ ShowPackageVariables(pkgname[, version][, arec]) (function)
⊿ PackageVariablesInfo(pkgname, version) (function)

Let pkgname be the name of a GAP package. If the package pkgname is available but not yet loaded then ShowPackageVariables prints a list of global variables that become bound and of methods that become installed when the package is loaded. (For that, GAP actually loads the package.)

If a version number version is given (see Section (Reference: Version Numbers)) then this version of the package is considered.

An error message is printed if (the given version of) the package is not available or already loaded.

Information is printed about new and redeclared global variables, and about names of global variables introduced in the package that differ from existing globals only by case; note that the GAP help system is case insensitive, so it is difficult to document identifiers that differ only by case.

Info lines for undocumented variables are marked with an asterisk *

The following entries are omitted from the list: default setter methods for attributes and properties that are declared in the package, and Setattr and Hasattr type variables where attr is an attribute or property.

The output can be customized using the optional record arec, the following components of this record are supported.

show

a list of strings describing those kinds of variables which shall be shown, such as "new global functions"; the default are all kinds that appear in the package,

showDocumented

true (the default) if documented variables shall be shown, and false otherwise,

showUndocumented

true (the default) if undocumented variables shall be shown, and false otherwise,

showPrivate

true (the default) if variables from the package’s name space (see Section 4.10) shall be shown, and false otherwise,
Display

a function that takes a string and shows it on the screen; the default is Print (6.3.4), another
useful value is Pager (2.4.1).

An interactive variant of ShowPackageVariables is the function BrowsePackageVariables (Browse: BrowsePackageVariables) that is provided by the GAP package Browse. For this function, it is not sensible to assume that the package \texttt{pkgname} is not yet loaded before the function call, because one might be interested in packages that must be loaded before Browse itself can be loaded. The solution is that BrowsePackageVariables (Browse: BrowsePackageVariables) takes the output of PackageVariablesInfo as its second argument. The function PackageVariablesInfo is used by both ShowPackageVariables and BrowsePackageVariables (Browse: BrowsePackageVariables) for collecting the information about the package in question, and can be called before the package Browse is loaded.

### 76.3.16 BibEntry

\begin{verbatim}
\texttt{\textbackslash d\textbackslash d\texttt{BibEntry( \texttt{pkgname}, \texttt{key})}}
\end{verbatim}

\textbf{Returns:} a string in BibXMLext format (see (GAPDoc: The BibXMLext Format)) that can be used for referencing the GAP system or a GAP package.

If the argument \texttt{pkgname} is the string "GAP", the function returns an entry for the current version of GAP.

Otherwise, if a string \texttt{pkgname} is given, which is the name of a GAP package, an entry for this package is returned; this entry is computed from the PackageInfo.g file of the current version of the package, see InstalledPackageVersion (76.3.6). If no package with name \texttt{pkgname} is installed then the empty string is returned.

A string for a different version of GAP or a package can be computed by entering, as the argument \texttt{pkgname}, the desired record from the PackageInfo.g file. (One can access these records using the function PackageInfo.)

In each of the above cases, an optional argument \texttt{key} can be given, a string which is then used as the key of the Bib\TeX entry instead of the default key that is generated from the system/package name and the version number.

BibEntry requires the functions FormatParagraph (GAPDoc: FormatParagraph) and NormalizedNameAndKey (GAPDoc: NormalizedNameAndKey) from the GAP package GAPDoc.

The functions ParseBibXMLextString (GAPDoc: ParseBibXMLextString) and StringBibXMLEntry (GAPDoc: StringBibXMLEntry) can be used to create for example a Bib\TeX entry from the return value, as follows.

\begin{verbatim}
Example

gap> bib:= BibEntry( "GAP", "GAP4.5" );;
gap> Print( bib, "\n" );
<entry id="GAP4.5"><misc>
  <title><C>GAP</C> &ndash; <C>G</C>roups, <C>A</C>lgorithms, and <C>P</C>rogramming, <C>V</C>ersion 4.5.1<title>
  <howpublished><URL>https://www.gap-system.org</URL></howpublished>
  <key>GAP</key>
  <keywords>groups; *; gap; manual</keywords>
  <other type="organization">The GAP <C>G</C>roup</other>
</misc></entry>
gap> parse:= ParseBibXMLextString( bib );;
gap> Print( StringBibXMLEntry( parse.entries[1], "BibTeX" ) );
\end{verbatim}
76.3.17 Cite

Used with no arguments or with argument "GAP" (case-insensitive), Cite displays instructions on citing the version of GAP that is being used. Suggestions are given in plain text, HTML, BibXML and BibTeX formats. The same instructions are also contained in the CITATION file in the GAP root directory.

If pkgname is the name of a GAP package, instructions on citing this package will be displayed. They will be produced from the PackageInfo.g file of the working version of this package that must be available in the GAP installation being used. Otherwise, one will get a warning that no working version of the package is available.

The optional 2nd argument key has the same meaning as in BibEntry (76.3.16).

76.4 Guidelines for Writing a GAP Package

The remaining part of this chapter explains the basics of how to write a GAP package so that it integrates properly into GAP.

There are two basic aspects of creating a GAP package.

First, it is a convenient possibility to load additional functionality into GAP including a smooth integration of the package documentation. Second, a package is a way to make your code available to other GAP users.

Moreover, the GAP Group may provide some help with redistributing your package via the GAP website after checking if the package provides some new or improved functionality which looks interesting for other users, if it contains reasonable documentation, and if it seems to work smoothly with the GAP library and other distributed packages. In this case the package can take part in the GAP distribution update mechanism and becomes a deposited package.

Furthermore, package authors are encouraged to check if the package would be appropriate for the refereeing process and submit it. If the refereeing has been successful, the package becomes an accepted package. Check out https://www.gap-system.org/Packages/Authors/authors.html on the GAP website for more details.

Below we start with a description how the directory structure of a GAP package should be constructed and then add remarks on certain aspects of creating a package, some of these only apply to some packages. Finally, we provide guidelines for the release preparation and its distribution.
76.5 Structure of a GAP Package

A GAP package should have an alphanumeric name \( \text{packagename} \), say; mixed case is fine, but there should be no whitespace characters. All files of a GAP package \( \text{packagename} \) must be collected in a single directory \( \text{packageDir} \), where \( \text{packageDir} \) should be just \( \text{packagename} \) optionally converted to lowercase and optionally followed by the package version (with or without hyphen to separate the version from \( \text{packagename} \)). Let us call this directory the home directory of the package.

To use the package with GAP, the directory \( \text{packageDir} \) must be a subdirectory of a pkg directory in (one of) the GAP root directories (see 9.2). For example, if GAP is installed in \( /usr/local/gap4 \) then the files of the package MyPack may be placed in the directory \( /usr/local/gap4/pkg/mypack \). The directory \( \text{packageDir} \) preferably should have the following structure (below, a trailing / distinguishes directories from ordinary files):
This layout of directories and files may be created manually, or automatically using the tool called `PackageMaker`, available at [https://github.com/gap-system/PackageMaker](https://github.com/gap-system/PackageMaker). The `PackageMaker` asks several questions about the intended package and then creates a new directory for it and populates it with all the files needed for a basic package.

Packages that contain some code that requires compilation will usually have it in the `src` subdirectory. They may also have extra files such as `configure`, `Makefile.in` etc. that automate the build procedure. There are three file names with a special meaning in the home directory of a package: `PackageInfo.g` and `init.g` which must be present, and `read.g` which is optional.

On the other hand, the names of `CHANGES`, `LICENSE` and `README` files are not strictly fixed. They may have extensions `.txt` or `.md`, and instead of `LICENSE` one could use e.g. `COPYING` or `GPL` for packages distributed under the GNU General Public License, or use `HISTORY` instead of `CHANGES`.

We now describe the above files and directories in more details:

**README**

The filename may optionally have an extension, e.g. `.txt` or `.md`.

This should contain “how to get it” instructions (covering the way of getting it with the GAP distribution and from the GAP website, if applicable), as well as installation instructions and names of the package authors and their email addresses. These installation instructions should be repeated or referenced from the package’s documentation, which should be in the `doc` directory (see 76.6). Authors’ names and addresses should be repeated both in the package’s documentation and in the `PackageInfo.g` (see below).

**CHANGES**

For further versions of the package, it will be also useful to have a `CHANGES` file that records the main changes between versions of the package.

The filename may optionally have an extension, e.g. `.txt` or `.md`.

**LICENSE**

The file which explains conditions on which the package is distributed.

We advise all package authors to make clear in the documentation of their package the basis on which it is being distributed to users. Technically, this is the terms of the license which you give the users to copy, modify and redistribute your software (of which you presumably own the copyright) for their purposes.

GAP itself is distributed under the GNU General Public License version 2, a popular “free software” license which allows users to redistribute it freely under the same terms, and requires that
any software which incorporates GAP (technically, any “derived work”) also be distributed under those terms. We would encourage you to consider the GPL for your packages, but you might wish to be more restrictive (for instance forbidding redistribution for profit) or less restrictive (allowing your software to be incorporated into commercial software).

The filename may optionally have an extension, e.g. .txt or .md. Some packages also use different filenames, like COPYING.

configure, Makefile.in

These files are typically only used by packages which have a non-GAP component, e.g. some C code (the files of which should be in the src directory). The configure and Makefile.in files of the Example package provide prototypes (or they may be created using the PackageMaker mentioned above). The configure file typically takes a path to the GAP root directory as argument and uses the value assigned to GAParch in the file sysinfo.gap, created when GAP was compiled to determine the compilation architecture, inserts this in place of the string @GAPARCH@ in Makefile.in and creates a file Makefile. When make is run (which, of course, reads the constructed Makefile), a directory bin (if necessary) and subdirectories of bin with the path equal to the string assigned to GAParch in the file sysinfo.gap should be created; any binaries constructed by compiling the code in src should end up in this subdirectory of bin.

PackageInfo.g

Every GAP package must have a PackageInfo.g file which contains meta-information about the package (package name, version, author(s), relations to other packages, homepage, download archives, etc.). This information is used by the package loading mechanism and also for the redistribution of a package with GAP. The Example package’s PackageInfo.g file is well-commented and can be used as a prototype (see also 76.3.13 for further details). It may also be created using the PackageMaker mentioned above.

init.g, read.g

A GAP package must have a file init.g. Typical init.g and read.g files should normally consist entirely of ReadPackage (76.3.1) commands (and possibly also Read (9.7.1) commands) for reading further files of the package. If the “declaration” and “implementation” parts of the package are separated (and this is recommended), there should be a read.g file. The “declaration” part of a package consists of function and variable name declarations and these go in files with .gd extensions; these files are read in via ReadPackage commands in the init.g file. The “implementation” part of a package consists of the actual definitions of the functions and variables whose names were declared in the “declaration” part, and these go in files with .gi extensions; these files are read in via ReadPackage commands in the read.g file. The reason for following the above dichotomy is that the read.g file is read after the init.g file, thus enabling the possibility of a function’s implementation to refer to another function whose name is known but is not actually defined yet (see 76.12 below for more details).

The GAP code (whether or not it is split into “declaration” and “implementation” parts) should go in the package’s lib directory (see below).

doc

This directory should contain the package’s documentation, written in an XML-based documentation format supported by the GAP package GAPDoc (see (GAPDoc: Introduction and Example)) which is used for the GAP documentation itself.

The Example package’s documentation (see its doc directory) may be used as a prototype. It consists of the master file main.xml, further .xml files for manual chapters (included in the
manual via \texttt{Include} directives in the master file) and the GAP input file \texttt{../makedocrel.g} which generates the manuals. Generally, one should also provide a \texttt{manual.bib} \LaTeX\ database file or an \texttt{xml} file in the BibXMLext format (see \texttt{GAPDoc: The BibXMLext Format}).

One could also use the \texttt{AutoDoc} which simplifies writing documentation by generating most of the \texttt{GAPDoc} code automatically.

\texttt{lib} This is the preferred place for the GAP code of the package, i.e. the \texttt{.g}, \texttt{.gd} and \texttt{.gi} files (other than \texttt{PackageInfo.g}, \texttt{init.g} and \texttt{read.g}). For some packages, the directory \texttt{gap} has been used instead of \texttt{lib}; \texttt{lib} has the advantage that it is the default subdirectory of a package directory searched for by the \texttt{DirectoriesPackageLibrary (76.3.7)} command.

\texttt{src} If the package contains non-GAP code, e.g. C code, then this source code should go in the \texttt{src} directory. If there are \texttt{.h} “include” files you may prefer to put these all together in a separate \texttt{include} directory. There is one further rule for the location of kernel library modules or external programs which is explained in \texttt{76.14.1} below.

\texttt{tst} It is highly recommended that a package should have test files, which then should go in the \texttt{tst} directory. For a deposited package, a test file with a basic test of the package (for example, to check that it works as expected and/or that the manual examples are correct) may be specified in the \texttt{PackageInfo.g} to be included in the GAP standard test suite and run as a part of the GAP release preparation. More specific and time consuming tests are not supposed to be a part of the GAP standard test suite but may be placed in the \texttt{tst} directory with further instructions on how to run them. See Section \texttt{76.18} about the requirements to the test files formats and further recommendations.

All other files can be organised as you like. But we suggest that you have a look at existing packages and use a similar scheme, for example, put examples in the \texttt{examples} subdirectory, data libraries in extra subdirectories, and so on.

Sometimes there may be a need to include an empty directory in the package distribution (for example, as a place to store some data that may appear at runtime). In this case package authors are advised to put in this directory a short \texttt{README} file describing its purpose to ensure that such directory will be included in the redistribution.

Concerning the GAP code in packages, it is recommended to use only documented GAP functions, see \texttt{83.3}. In particular if you want to make your package available to other GAP users it is advisable to avoid using “obsolete” variables (see \texttt{77}). To test that the package does not use obsolete variables you can set the \texttt{ReadObsolete} component in your \texttt{gap.ini} file to \texttt{false} (see \texttt{3.2}) or start \texttt{GAP} with \texttt{-A -O} command line options (note that this may also cause problems with loading other packages that use “obsolete” variables).

### 76.6 Writing Documentation and Tools Needed

If you intend to make your package available to other users it is essential to include documentation explaining how to install and use your programs.

Concerning the installation you should produce a \texttt{README} file which gives a short description of the purpose of the package and contains proper instructions how to install your package. Again, check out some existing packages to get an idea how this could look like.
Documentation for GAP package should be prepared in an XML-based documentation format that is defined in and can be used with the GAPDoc package (see (GAPDoc: Introduction and Example)).

There should be at least a text version of your documentation provided for use in the terminal running GAP and some nicely printable version in .pdf format. Many GAP users like to browse the documentation in HTML format via their Web browser. As a package author, you are not obliged to provide an HTML version of your package manual, but if you use the GAPDoc package you should have no trouble in producing one.

Moreover, using the GAPDoc package, it is also possible to produce HTML version of the documentation supporting MathJax (https://www.mathjax.org/) for the high quality rendering of mathematical symbols while viewing it online. For example, if you are viewing the HTML version of the manual, compare how this formula will look with MathJax turned on/off:

$$[\chi, \psi] = \left( \sum_{g \in G} \chi(g) \psi(g^{-1}) \right) / |G|.$$

The manual of the Example package is written in the GAPDoc format, and commands needed to build it are contained in the file makedocrel.g (you don’t need to re-build the manual since it is already included in the package). You will also need to have certain \TeX tools installed: to produce manuals in the .pdf format, you need pdflatex.

In principle it is also possible to use alternative documentation systems. Historically, there is one such \TeX-based system, which predates GAPDoc, and which is still in use by several packages. However, we do not recommend using it for new packages.

### 76.7 An Example of a GAP Package

We illustrate the creation of a GAP package by an example of a very basic package.

Create the following directories in your home directory: .gap, .gap/pkg and .gap/pkg/test. Then inside the directory .gap/pkg/test create an empty file init.g, and a file PackageInfo.g with the following contents:

```golang
SetPackageInfo( rec(
    PackageName := "test",
    Version := "1.0",
    PackageDoc := rec(
        BookName := "test",
        SixFile := "doc/manual.six",
        Autoload := true ),
    Dependencies := rec(
        GAP := "4.9",
        NeededOtherPackages := [ ["GAPDoc", "1.6"] ],
        SuggestedOtherPackages := [] ),
    AvailabilityTest := ReturnTrue ) );
```

This file declares the GAP package with name “test” in version 1.0. The package documentation consists of one autoloaded book; the SixFile component is needed by the GAP help system. Package dependencies (picked for the purposes of this example) require at least GAP 4.9 and GAPDoc.
package at version at least 1.6, and these conditions will be checked when the package will be loaded (see 76.17). Since there are no requirements that have to be tested, AvailabilityTest just uses ReturnTrue (5.4.1).

Now start GAP (without using the -r option) and the .gap directory will be added to the GAP root directory to allow GAP to find the packages installed there (see 9.2).

```gap
gap> LoadPackage("test");
true
```

This GAP package is too simple to be useful, but we have succeeded in loading it via LoadPackage (76.2.1), satisfying all specified dependencies.

### 76.8 File Structure

Package files may follow the style used for the GAP library. Every file in the GAP library starts with a header that lists the filename, copyright, a short description of the file contents and the original authors of this file, and ends with a comment line `#. Indentation in functions and the use of decorative spaces in the code are left to the decision of the authors of each file. Global (i.e. re-used elsewhere) comments usually are indented by two hash marks and two blanks, in particular, every declaration or method or function installation which is not only of local scope is separated by a header.

Facilities to distribute a document over several files to allow the documentation for parts of some code to be stored in the same file as the code itself are provided by the GAPDoc package (see (GAPDoc: Distributing a Document into Several Files)). The same approach is demonstrated by the Example package. E.g. example/doc/example.xml has the statement `<#Include Label="ListDirectory">` and example/lib/files.gd contains

```gd
## <#GAPDoc Label="ListDirectory">
## <ManSection>
## <Func Name="ListDirectory" Arg="[dir]"/>
##
## lists the files in directory <A>dir</A> (a string)
## or the current directory if called with no arguments.
## </Description>
## </ManSection>
## </GAPDoc>
DeclareGlobalFunction( "ListDirectory" );
```

This is all put together in the file example/makedocrel.g which builds the package documentation, calling MakeGAPDocDoc (GAPDoc: MakeGAPDocDoc) with locations of library files containing parts of the documentation.

Alternatively, one could use the AutoDoc, which simplifies writing documentation by generating most of the GAPDoc code automatically. The equivalent of the fragment of the code above for AutoDoc would look like

```gd
#!/ @Arguments [dir]
#!/ @Description
#!/ lists the files in directory <A>dir</A> (a string)
```
#! or the current directory if called with no arguments.
DeclareGlobalFunction( "ListDirectory" );

76.9 Creating the PackageInfo.g File

While the minimalistic PackageInfo.g file described in 76.7 is enough to let GAP load the package, and check all specified dependencies, it is actually missing many extra fields which become relevant if you want to distribute your package: they contain lists of authors and/or maintainers including contact information, URLs of the package archives and README files, status information, text for a package overview webpage, and so on. All these details are required for a package to be redistributed with GAP.

The command ValidatePackageInfo (76.3.14) can be used to get a quick idea about which fields are missing:

```
gap> ValidatePackageInfo("PackageInfo.g");
#E component `Subtitle' must be bound to a string
#E component `Date' must be bound to a string of the form `dd/mm/yyyy'
#E component `ArchiveURL' must be bound to a string started with http://, https:// or ftp://
#E component `ArchiveFormats' must be bound to a string
#E component `Status' must be bound to one of "accepted", "deposited", "dev", "other"
#E component `README_URL' must be bound to a string started with http://, https:// or ftp://
#E component `PackageInfoURL' must be bound to a string started with http://, https:// or ftp://
#E component `AbstractHTML' must be bound to a string
#E component `PackageWWWHome' must be bound to a string started with http://, https:// or ftp://
#E component `ArchiveURLSubset' must be bound to a list of strings denoting relative paths to readable files or directories
#E component `HTMLStart' must be bound to a string denoting a relative path to a readable file
#E component `PDFFile' must be bound to a string denoting a relative path to a readable file
#E component `SixFile' must be bound to a string denoting a relative path to a readable file
#E component `LongTitle' must be bound to a string
false
```

We suggest to create a PackageInfo.g file for your package by copying the one in the Example package, distributed with GAP, or using the PackageMaker (https://github.com/gap-system/PackageMaker), and then adjusting it for your package. Within GAP you can look at this template file for a list and explanation of all recognised entries by

```
Pager(StringFile(Filename(DirectoriesLibrary(),
    "../pkg/example/PackageInfo.g")))
```

Instead of populating the rest of the PackageInfo.g by hands, you can also create a basic GAP package with the help of the tool called PackageMaker, available at https://github.com/gap-system/PackageMaker. The PackageMaker asks several questions about the intended package and then creates a new directory for it and populates it with all the files needed for a basic package.

76.10 Functions and Variables and Choices of Their Names

In writing the GAP code for your package you need to be a little careful on just how you define your functions and variables.
Firstly, in general one should avoid defining functions and variables via assignment statements in the way you would interactively, e.g.

\[
\begin{align*}
gap> \text{Squared} := x \rightarrow x^2; \\
gap> \text{Cubed} := \text{function}(x) \text{ return } x^3; \text{ end};
\end{align*}
\]

The reason for this is that such functions and variables are easily overwritten and what’s more you are not warned about it when it happens.

To protect a function or variable against overwriting there is the function `BindGlobal` (4.9.8), or alternatively (and equivalently) you may define a global function via a `DeclareGlobalFunction` (79.10.4) and `InstallGlobalFunction` (79.10.4) pair or a global variable via a `DeclareGlobalVariable` (79.10.1) and `InstallValue` (79.10.2) pair. There are also operations and their methods, and related objects like attributes and filters which also have `Declare...` and `Install...` pairs.

Secondly, it’s a good idea to reduce the chance of accidental overwriting by choosing names for your functions and variables that begin with a string that identifies it with the package, e.g. some of the undocumented functions in the `Example` package begin with `Eg`. This is especially important in cases where you actually want the user to be able to change the value of a function or variable defined by your package, for which you have used direct assignments (for which the user will receive no warning if she accidentally overwrites them). It’s also important for functions and variables defined via `BindGlobal`, `DeclareGlobalFunction/InstallGlobalFunction` and `DeclareGlobalVariable/InstallValue`, in order to avoid name clashes that may occur with (extensions of) the GAP library and other packages.

Additionally, since GAP 4.5 a package may place global variables into a local namespace as explained in 4.10 in order to avoid name clashes and preserve compatibility. This new feature allows you to define in your package global variables with the identifier ending with the @ symbol, e.g. `xYz@`. Such variables may be used in your package code safely, as they may be accessed from outside the package only by their full name, i.e. `xYz@YourPackageName`. This helps to prevent clashes between different packages or between a package and the GAP library because of the same variable names.

On the other hand, operations and their methods (defined via `DeclareOperation` (78.1.5), `InstallMethod` (78.3.1) etc. pairs) and their relatives do not need this consideration, as they avoid name clashes by allowing for more than one “method” for the same-named object.

To demonstrate the definition of a function via a `DeclareOperation/InstallMethod` pair, the method `Recipe` (`Example: Recipe`) was included in the `Example` package; `Recipe( FruitCake );` gives a “method” for making a fruit cake (forgive the pun).

Thirdly, functions or variables with `SetXXX` or `HasXXX` names (even if they are defined as operations) should be avoided as these may clash with objects associated with attributes or properties (attributes and properties XXX declared via the `DeclareAttribute` and `DeclareProperty` commands have associated with them testers of form `HasXXX` and setters of form `SetXXX`).

Fourthly, it is a good idea to have some convention for internal functions and variables (i.e. the functions and variables you don’t intend for the user to use). For example, they might be entirely CAPITALISED.

Additionally, there is a recommended naming convention that the GAP core system and GAP packages should not use global variables starting in the lowercase. This allows to reserve variables with names starting in lowercase to the GAP user so they will never clash with the system. It is extremely important to avoid using for package global variables very short names started in lowercase. For example, such names like `cs`, `exp`, `ngens`, `pc`, `pow` which are perfectly fine for local variables,
should never be used for globals. Additionally, the package must not have writable global variables
with very short names even if they are starting in uppercase, for example, C1 or ORB, since they also
could be easily overwritten by the user.

It is a good practice to follow naming conventions used in GAP as explained in 5.6 and (Tutorial:
Changing the Structure), which might help users to memorize or even guess names of functions
provided by the package.

Finally, note the advantage of using DeclareGlobalFunction/InstallGlobalFunction, DeclareGlobalVariable/InstallValue, etc. pairs (rather than BindGlobal) to define functions
and variables, which allow the package author to organise her function- and variable- definitions in
any order without worrying about any interdependence. The Declare... statements should go in
files with .gd extensions and be loaded by ReadPackage statements in the package init.g file, and
the Install... definitions should go in files with .gi extensions and be loaded by ReadPackage
statements in the package read.g file; this ensures that the .gi files are read after the .gd files. All
other package code should go in .g files (other than the init.g and read.g files themselves) and be
loaded via ReadPackage statements in the init.g file.

In conclusion, here is some practical advice on how to check which variables are used by the
package.

Firstly, there is a function ShowPackageVariables (76.3.15). If the package pkgname is avail-
able but not yet loaded then ShowPackageVariables( pkgname ) prints a list of global variables
that become bound and of methods that become installed when the package is loaded (for that, the
package will be actually loaded, so ShowPackageVariables can be called only once for the same
package in the same GAP session.) The second optional argument version may specify a particular
package version to be loaded. An error message will be printed if (the given version of) the package
is not available or already loaded.

Info lines for undocumented variables will be marked with an asterisk *. Note that the GAP help
system is case insensitive, so it is difficult to document identifiers that differ only by case.

The following entries are omitted from the list: default setter methods for attributes and properties
that are declared in the package, and Setattr and Hasattr type variables where attr is an attribute
or property.

For example, for the Example package it may produce the output looking like this:

```gap
gap> ShowPackageVariables("example");
Loading Example 3.3 (Example/Template of a GAP Package)
by Werner Nickel (http://www.mathematik.tu-darmstadt.de/~nickel),
Greg Gamble (http://www.math.rwth-aachen.de/~Greg.Gamble), and
Alexander Konovalov (http://www.cs.st-andrews.ac.uk/~alexk/).

new global functions:
  EgSeparatedString( str, c )*
  FindFile( dir, file )
  HelloWorld( )
  ListDirectory( arg )
  LoadedPackages( )
  WhereIsPkgProgram( prg )
  Which( prg )

new global variables:
  FruitCake
```
new operations:
   Recipe( arg )

new methods:
   Recipe( cake )

Another trick is to start GAP with -r -A options, immediately load your package and then call NamesUserGVars (4.9.11) which returns a list of the global variable names created since the library was read, to which a value is currently bound. For example, for the Example it produces

\begin{verbatim}
gap> NamesUserGVars();
[ "EgSeparatedString", "FindFile", "FruitCake", "HelloWorld", "ListDirectory",
  "LoadedPackages", "Recipe", "WhereIsPkgProgram", "Which" ]
\end{verbatim}

but for packages with dependencies it will also contain variables created by other packages. Nevertheless, it may be a useful check to search for unwanted variables appearing after package loading. A potentially dangerous situation which should be avoided is when the package uses some simply named temporary variables at the loading stage. Such “phantom” variables may then remain unnoticed and, as a result, there will be no warnings if the user occasionally uses the same name as a local variable name in a function. Even more dangerous is the case when the user variable with the same name already exists before the package is loaded so it will be silently overwritten.

\section{76.11 Package Dependencies (Requesting one GAP Package from within Another)}

It is possible for one GAP package \( A \), say, to require another package \( B \). For that, one simply adds the name and the (least) version number of the package \( B \) to the NeededOtherPackages component of the Dependencies component of the PackageInfo.g file of the package \( A \). In this situation, loading the package \( A \) forces that also the package \( B \) is loaded, and that \( A \) cannot be loaded if \( B \) is not available.

If \( B \) is not essential for \( A \) but should be loaded if it is available (for example because \( B \) provides some improvements of the main system that are useful for \( A \)) then the name and the (least) version number of \( B \) should be added to the SuggestedOtherPackages component of the Dependencies component of the PackageInfo.g file of \( A \). In this situation, loading \( A \) forces an attempt to load also \( B \), but \( A \) is loaded even if \( B \) is not available.

Also the component Dependencies.OtherPackagesLoadedInAdvance in PackageInfo.g is supported, which describes needed packages that shall be loaded before the current package is loaded. See 76.12 for details about this and more generally about the order in which the files of the packages in question are read.

All package dependencies must be documented explicitly in the PackageInfo.g file. It is important to properly identify package dependencies and make the right decision whether the other package should be “needed” or “suggested.” For example, declaring package as “needed” when “suggested” might be sufficient may prevent loading of packages under Windows for no good reason.

It is not appropriate to explicitly call LoadPackage (76.2.1) when the package is loaded, since this may distort the order of package loading and result in warning messages. It is recommended to turn such dependencies into needed or suggested packages. For example, a package can be designed in such a way that it can be loaded with restricted functionality if another package (or standalone
program) is missing, and in this case the missing package (or binary) is suggested. Alternatively, if the package author decides that loading the package in this situation makes no sense, then the missing component is needed.

On the other hand, if LoadPackage (76.2.1) is called inside functions of the package then there is no such problem, provided that these functions are called only after the package has been loaded, so it is not necessary to specify the other package as suggested. The same applies to test files and manual examples, which may be simply extended by calls to LoadPackage (76.2.1).

It may happen that a package B that is listed as a suggested package of package A is actually needed by A. If no explicit LoadPackage (76.2.1) calls for B occur in A at loading time, this can now be detected using the new possibility to load a package without loading its suggested packages using the global option OnlyNeeded which can be used to (recursively) suppress loading the suggested packages of the package in question. Using this option, one can check whether errors or warnings appear when B is not available (note that this option should be used only for such checks to simulate the situation when package B is not available; it is not supposed to be used in an actual GAP session when package B will be loaded later, since this may cause problems). In case of any errors or warnings, their consequence can then be either turning B into a needed package (or since apparently B was not intended to become a needed package) changing the code accordingly. Only if package A calls LoadPackage (76.2.1) for B at loading time (see above) then package B needs to be deinstalled (i.e. removed) to test loading of A without B.

Finally, if the package manual is in the GAPDoc format, then GAPDoc should still be listed as needed for this package (not as suggested), even though GAPDoc is now a needed package for GAP itself.

76.12 Declaration and Implementation Part of a Package

When GAP packages require each other in a circular way, a “bootstrapping” problem arises of defining functions before they are called. The same problem occurs in the GAP library, and it is resolved there by separating declarations (which define global variables such as filters and operations) and implementations (which install global functions and methods) in different files. Any implementation file may use global variables defined in any declaration file. GAP initially reads all declaration files (in the library they have a .gd suffix) and afterwards reads all implementation files (which have a .gi suffix).

Something similar is possible for GAP packages: if a file read.g exists in the home directory of the package, this file is read only after all the init.g files of all (implicitly) required GAP packages are read. Thus one can separate declaration and implementation for a GAP package in the same way as is done for the GAP library, by creating a file read.g, restricting the ReadPackage (76.3.1) statements in init.g to only read those files of the package that provide declarations, and to read the implementation files from read.g.

Examples:

Suppose that there are two packages A and B, each with files init.g and read.g.

- If package A suggests or needs package B and package B does not need or suggest any other package then first init.g of B is read, then read.g of B, then init.g of A, then read.g of A.

- If package A suggests or needs package B and package B (or a package that is suggested or needed by B) suggests or needs package A then first the files init.g of A and B are read (in an unspecified order) and then the files read.g of A and B (in the same order).
In general, when GAP is asked to load a package then first the dependencies between this packages and its needed and suggested packages are inspected (recursively), and a list of package sets is computed such that no cyclic dependencies occur between different package sets and such that no package in any of the package sets needs any package in later package sets. Then GAP runs through the package sets and reads for each set first all `init.g` files and then all `read.g` files of the packages in the set. (There is one exception from this rule: Whenever packages are autoloaded before the implementation part of the GAP library is read, only the `init.g` files of the packages are read; as soon as the GAP library has been read, the `read.g` files of these packages are also read, and afterwards the above rule holds.)

It can happen that some code of a package depends on the availability of suggested packages, i.e., different initialisations are performed depending on whether a suggested package will eventually be loaded or not. One can test this condition with the function `IsPackageMarkedForLoading` (76.3.4). In particular, one should not call (and use the value returned by this call) the function `LoadPackage` (76.2.1) inside package code that is read during package loading. Note that for debugging purposes loading suggested packages may have been deliberately disabled via the global option `OnlyNeeded`.

Note that the separation of the GAP code of packages into declaration part and implementation part does in general not allow one to actually call functions from a package when the implementation part is read. For example, in the case of a "cyclic dependency" as in the second example above, suppose that B provides a new function f or a new global record r, say, which are declared in the declaration part of B. Then the code in the implementation part of A may contain calls to the functions defined in the declaration part of B. However, the implementation part of A may be read before the implementation part of B. So one can in general not assume that during the loading of A, the function f can be called, or that one can access components of the record r.

If one wants to call the function f or to access components of the record r in the code of the package A then the problem is that it may be not possible to determine a cyclic dependency between A and B from the packages A and B alone. A safe solution is then to add the name of B to the component `Dependencies.OtherPackagesLoadedInAdvance` of the `PackageInfo.g` file of A. The effect is that package B is completed loaded before the file `read.g` of A is read, provided that there is no cyclic dependency between A and B, and that package A is regarded as not available in the case that such a cyclic dependency between A and B exists.

A special case where `Dependencies.OtherPackagesLoadedInAdvance` can be useful is that a package wants to force the complete GAP library to be read before the file `read.g` of the package A is read. In this situation, the "package name" "gap" should be added to this component in the `PackageInfo.g` file of A.

In the case of cyclic dependencies, one solution for the above problem might be to delay those computations (typically initialisations) in package A that require package B to be loaded until all required packages are completely loaded. This can be done by moving the declaration and implementation of the variables that are created in the initialisation into a separate file and to declare these variables in the `init.g` file of the package, via a call to `DeclareAutoreadableVariables` (76.3.10) (see also 76.13).

### 76.13 Autoreadable Variables

Package files containing method installations must be read when the package is loaded. For package files not containing method installations (this applies, for example, to many data files) another mechanism allows one to delay reading such files until the data are actually accessed. See 76.3.10 for further
76.14 Standalone Programs in a GAP Package

GAP packages that involve stand-alone programs are fundamentally different from GAP packages that consist entirely of GAP code.

This difference is threefold: A user who installs the GAP package must also compile (or install) the package’s binaries, the package must check whether the binaries are indeed available, and finally the GAP code of the package has to start the external binary and to communicate with it. We will cover these three points in the following sections.

If the package does not solely consist of an interface to an external binary and if the external program called is not just special-purpose code, but a generally available program, chances are high that sooner or later other GAP packages might also require this program. We therefore strongly recommend the provision of a documented GAP function that will call the external binary. We also suggest to create actually two GAP packages; the first providing only the binary and the interface and the second (requiring the first, see 76.11) being the actual GAP package.

76.14.1 Installation of GAP Package Binaries

The scheme for the installation of package binaries which is described further on is intended to permit the installation on different architectures which share a common file system (and share the architecture independent file).

A GAP package which includes external binaries contains a bin subdirectory. This subdirectory in turn contains subdirectories for the different architectures on which the GAP package binaries are installed. The names of these directories must be the same as the names of the architecture dependent subdirectories of the main bin directory. Unless you use a tool like autoconf yourself, you must obtain the correct name of the binary directory from the main GAP branch. To help with this, the main GAP directory contains a file sysinfo.gap which assigns the shell variable GAParch to the proper name as determined by GAP’s configure process. For example on a Linux system, the file sysinfo.gap may look like this:

```
Example GAParch=i586-unknown-linux2.0.31-gcc
```

We suggest that your GAP package contains a file configure which is called with the path of the GAP root directory as parameter. This file then will read sysinfo.gap and set up everything for compiling under the given architecture (for example creating a Makefile from Makefile.in). As initial templates, you may use installation scripts of the Example package or files generated with the help of PackageMaker.

76.14.2 Test for the Existence of GAP Package Binaries

If an external binary is essential for the workings of a GAP package, the function stored in the component AvailabilityTest of the PackageInfo.g file of the package should test whether the program has been compiled on the architecture (and inhibit package loading if this is not the case). This is especially important if the package is loaded automatically.

The easiest way to accomplish this is to use Filename (9.4.1) for checking for the actual binaries in the path given by DirectoriesPackagePrograms (76.3.8) for the respective package. For example
the example GAP package could use the following function to test whether the binary hello has been compiled; it will issue a warning if not, and will only load the package if the binary is indeed available:

```gap
Example
... AvailabilityTest := function()
  local path, file;
  # test for existence of the compiled binary
  path := DirectoriesPackagePrograms( "example" );
  file := Filename( path, "hello" );
  if file = fail then
    LogPackageLoadingMessage( PACKAGE_WARNING,
      [ "The program `hello’ is not compiled,",
        '"HelloWorld()’ is thus unavailable.",
        "See the installation instructions;",
        "type: ?Installing the Example package" ] );
  fi;
  return file <> fail;
end,
...```

However, if you look at the actual PackageInfo.g file of the example package, you will see that its AvailabilityTest function always returns true, and just logs the warning if the binary is not available (which may be later viewed with DisplayPackageLoadingLog (76.2.5)). This means that the binary is not regarded as essential for this package.

You might also have to cope with the situation that external binaries will only run under UNIX (and not, say, under Windows), or may not compile with some compilers or default compiler options. See 3.4 for information on how to test for the architecture.

Last but not least: do not print anything in the AvailabilityTest function of the package via Print or Info. Instead one should call LogPackageLoadingMessage (76.2.5) to store a message which may be viewed later with DisplayPackageLoadingLog (76.2.5) (the latter two functions have been introduced in GAP 4.5).

### 76.14.3 Calling of and Communication with External Binaries

There are two reasons for this: the input data has to be passed on to the stand-alone program and the stand-alone program has to be started from within GAP.

There are two principal ways of doing this.

The first possibility is to write all the data for the stand-alone to one or several files, then start the stand-alone with Process (11.1.1) or Exec (11.1.2) which then writes the output data to file, and finally read in the stand-alone’s output file.

The second way is interfacing via input-output streams, see Section 10.8.

Some GAP packages use kernel modules (see 76.3.11) instead of external binaries. A kernel module is implemented in C and follows certain conventions to comply with the GAP kernel interface, which we plan to document later. In the meantime, we advise you to look at existing examples of such packages and get in touch with GAP developers if you plan to develop such a package.
76.15 Having an InfoClass

It is a good idea to declare an InfoClass for your package. This gives the package user the opportunity to control the verbosity of output and/or the possibility of receiving debugging information (see 7.4). Below, we give a quick overview of its utility.

An InfoClass is defined with a \texttt{DeclareInfoClass(InfoPkgname)}; statement and may be set to have an initial InfoLevel other than the zero default (which means no Info statement is to output information) via a \texttt{SetInfoLevel(InfoPkgname, level)}; statement. An initial InfoLevel of 1 is typical.

Info statements have the form: \texttt{Info(InfoPkgname, level, expr1, expr2, ...)}; where the expression list \texttt{expr1, expr2, ...} appears just like it would in a Print statement. The only difference is that the expression list is only printed (or even executed) if the InfoLevel of \texttt{InfoPkgname} is at least \texttt{level}.

76.16 The Banner

When the package is loaded, GAP will display a default package banner, constructed from the package metadata provided in the PackageInfo.g file.

Alternatively, the package may establish its own banner by assigning a string to the BannerString field of the record argument of SetPackageInfo in the PackageInfo.g file.

If you will be designing a banner for your package, it is a good idea to suggest there how to access package documentation. For example, the banner of the \texttt{Example} package says:

\begin{verbatim}
Example

For help, type: ?Example package
\end{verbatim}

In order for this to display the introduction of the Example package the index-entry \texttt{<Index>Example package</Index>} was added just before the first paragraph of the introductory section in the file doc/example.xml of the Example package.

76.17 Version Numbers

Version numbers are strings containing nonnegative integers separated by non-numeric characters. They are compared by \texttt{CompareVersionNumbers (76.3.9)} which first splits them at non-digit characters and then lexicographically compares the resulting integer lists. Thus version "2-3" is larger than version "2-2-5" but smaller than "4r2p3" or "11.0".

It is possible for code to require GAP packages in certain versions. In this case, all versions, whose number is equal or larger than the requested number are acceptable. It is the task of the package author to provide upwards compatibility.

Loading a specific version of a package (that is, not one with a larger version number) can be achieved by prepending = to the desired version number. For example, \texttt{LoadPackage( "example", =1.0 )} will load version "1.0" of the package "example", even if version "1.1" is available. As a consequence, version numbers must not start with =, so "=1.0" is not a valid version number.

Package authors should choose a version numbering scheme that admits a new version number even after tiny changes to the package, and ensure that version numbers of successive package versions increase. The automatic update of package archives in the GAP distribution will only work if a package has a new version number.
It is a well-established custom to name package archives like `name-version.tar.gz`, `name-version.tar.bz2` etc., where `name` is the lower case name, and `version` is the version (another custom is that the archive then should extract to a directory that has exactly the name `name-version`).

It is very important that there should not ever be, for a given GAP package, two different archives with the same package version number. If you make changes to your package and place a new archive of the package onto the public server, please ensure that a new archive has a new version number. This should be done even for very minor changes.

For most of the packages it will be inappropriate to re-use the date of the release as a version number. It’s much more obvious how big are the changes between versions "4.4.12", "4.5.1" and "4.5.2" than between versions "2008.12.17", "2011.04.15" and "2011.09.14". The concept of using version numbers to convey the meaning of the status of the code and the way it has been modified is known as “Semantic Versioning”, see [https://semver.org/](https://semver.org/) for further recommendations on its use.

Since version information is duplicated in several places throughout the package documentation, for GAPDoc-based manuals you may define the version and the release manual in the comments in `PackageInfo.g` file close to the place where you specified its `Version` and `Date` components, for example

```gaps
## <#GAPDoc Label="PKGVERSIONDATA">
## <!ENTITY VERSION "3.3">
## <!ENTITY RELEASEDATE "12/09/2017">
## <!ENTITY RELEASEYEAR "2017">
## <#/GAPDoc>
```

notify MakeGAPDocDoc ([GAPDoc: MakeGAPDocDoc](#)) that a part of the document is stored in `PackageInfo.g` (see example/makedocrel.g), read this data into the header of the main document via `<#Include Label="PKGVERSIONDATA">` directive and then use them via `&VERSION;` and `&RELEASEDATE;` entities almost everywhere where you need to refer to them (most commonly, in the title page and installation instructions).

### 76.18 Testing a GAP package

There are several aspects of testing a GAP package.

First, one should ensure that the package functionality works as expected. Below we give an advice on creating test files for automated tests that may be run by package authors, by GAP developers as part of the release preparation, and by package users interested in checking that the package works. Such tests should be included in the package distribution, and the responsibility for ensuring that they pass stays with package authors.

Second, the package should cleanly integrate into the GAP system and other packages, and should not break their functionality. In particular, all tests from the standard GAP testing suite should pass if the package is loaded. This is more comprehensive and time consuming test, which GAP developers regularly run using special tools. They will report to you any detected issues. Below we explain how to do several simple and less time consuming checks which package authors are recommended to perform themselves.
76.18.1 Tests files for a GAP package

The (optional) `tst` directory of your package may contain as many tests of the package functionality as appears appropriate. These tests should be organised into test files similarly to those in the `tst` directory of the GAP distribution as documented in 7.10.

For a deposited package, a test file with a basic test of the package (for example, to check that it works as expected and/or that the manual examples are correct) may be specified in the component `TestFile` in the `PackageInfo.g` to be included in the GAP standard test suite. This file can either consist of calls of `TestDirectory (7.10.3)` or `Test (7.10.2)` (in this case, it is common to call it `testall.g`) or be itself a test file having an extension `.tst` and supposed to be read via `Test (7.10.2)`. It is assumed that the latter case occurs if and only if the file contains the substring

"gap> START_TEST(
(with exactly one space after the GAP prompt).

For deposited packages, these tests are run by the GAP Group regularly, as a part of the standard GAP test suite. For the efficient testing it is important that the test specified in the `PackageInfo.g` file does not display any output (e.g. no test progress indicators) except reporting discrepancies if such occur and the completion report as in the example below:

```
Example

gap> Test("tst/testall.tst");
Example package: testall.tst
GAP4stones: 3333
true
```

Tests which produce extended output and/or require substantial runtime are not supposed to be a part of the GAP standard test suite but may be placed in the `tst` directory of the packages with further instructions on how to run them elsewhere.

Because of different approaches to testing, used by different packages, it is not always easy to identify whether an automated test passed or failed. Presently, automated detection works fine if a package uses a single `.tst` file or uses `TestDirectory (7.10.3)` to run a collection of tests. Otherwise, one should follow the convention to output a string of a fixed format to indicate the result of the test in the test script along the following lines:

```
Example

if testresult then
  Print("#I No errors detected while testing\n");
else
  Print("#I Errors detected while testing\n");
fi;
```

76.18.2 Testing GAP package loading

To test that your package may be loaded into GAP without any problems and conflicts with other packages, test that it may be loaded in various configurations:

- starting GAP with no packages (except needed for GAP) using `-r` `-A` options and calling `LoadPackage("packagename")`;
- starting GAP with no packages (except needed for GAP) using `-r` `-A` options and calling `LoadPackage("packagename" : OnlyNeeded );

```
• starting GAP in the default configuration (with no options) and calling 
  \texttt{LoadPackage("packagename");}

• starting GAP in the default configuration (with no options) and calling 
  \texttt{LoadPackage("packagename" : OnlyNeeded );}

• finally, together with all other packages using \texttt{LoadAllPackages (76.18.3)} (see below) 
in four possible combinations of starting GAP with/without \texttt{-r -A} options and calling 
\texttt{LoadAllPackages (76.18.3)} with/without reversed option.

The test of loading all packages is the most subtle one. Quite often it reveals problems which do not 
occur in the default configuration but may cause difficulties to the users of specialised packages.

For your convenience, \texttt{make testpackagesload} called in the GAP root directory will run all 
package loading tests listed in this subsection and write their output in its \texttt{dev/log} directory.

It will produce four files with test logs, corresponding to the four cases above (the letter N in the 
filename stands for “needed”, A stands for “autoloaded”):

\begin{itemize}
  \item \texttt{dev/log/testpackagesload1_...}
  \item \texttt{dev/log/testpackagesloadN1_...}
  \item \texttt{dev/log/testpackagesloadA_...}
  \item \texttt{dev/log/testpackagesloadNA_...}
\end{itemize}

Each file contains small sections for loading individual packages: among those, you need to find the 
section related to your package and may ignore all other sections. For example, the section for the 
\texttt{Example} package looks like

```
%%% Loading example 3.3.3
[ ]
### Loaded example 3.3.3
```

so it has clearly passed the test. If there are any error messages displayed between \texttt{Loading ...} and 
\texttt{Loaded ...} lines, they will signal on errors during loading of your package.

Additionally, this test collects information about variables created since the library was read (ob-
tained using \texttt{NamesUserGVars (4.9.11)}) with either short names (no more than three characters) or 
names breaking a recommended naming convention that the GAP core system and GAP packages 
should not use global variables starting in the lowercase (see Section 76.10). Their list will be dis-
played in the test log (in the example above, \texttt{Example} packages does not create any such variables, so 
an empty list is displayed). It may be hard to attribute a particular identifier to a package, since it may 
be created by another package loaded because of dependencies, so when a more detailed and precise 
report on package variables is needed, it may be obtained using \texttt{ShowPackageVariables (76.3.15)} 
(also, \texttt{make testpackagesvars} called in the GAP root directory produces such reports for each 
package and writes them to a file \texttt{dev/log/testpackagesvars_...}).

Finally, each log file finishes with two large sections for loading all packages in the alphabetical 
and reverse alphabetical order (to check more combinations of loading one package after another). We 
are aiming at releasing only collections of package which do not break \texttt{LoadAllPackages (76.18.3)} 
in any of the four configurations, so if it is broken when you plug in the development version of 
your package into the released version of GAP, it is likely that your package triggers this error. If 
you observe that \texttt{LoadAllPackages (76.18.3)} is broken and suspect that this is not the fault of your 
package, please contact the GAP Support.
76.18.3 LoadAllPackages

\[ \text{LoadAllPackages(\text{ reversed})} \]

loads all GAP packages from their list sorted in alphabetical order (needed and suggested packages will be loaded when required). This is a technical function to check packages compatibility, so it should NOT be used to run anything except tests; it is known that GAP performance is slower if all packages are loaded. To introduce some variations of the order in which packages will be loaded for testing purposes, LoadAllPackages accepts option \text{reversed} to load packages from their list sorted in the reverse alphabetical order.

76.18.4 Testing a GAP package with the GAP standard test suite

The \text{tst} directory of the GAP installation contains a selection of test files and scripts such as \text{testinstall.g} and \text{teststandard.g} which are a part of the GAP standard test suite.

It is important to check that your package does not break GAP standard tests. To perform a clean test and avoid interfering with other packages, first you must start a new GAP session and then read either \text{testinstall.g} or \text{teststandard.g} as demonstrated below.

The quicker test, \text{testinstall.g}, requires about 1 GB of memory and runs for several minutes. It may be started with the command

\begin{verbatim}
gap> Read( Filename( DirectoriesLibrary( "tst" ), "testinstall.g" ) );
\end{verbatim}

You will get a large number of lines with output about the progress of the tests, for example:

\begin{verbatim}
You should start GAP4 using 'gap -A -x 80 -r -m 100m -o 1g -K 2g'.

Architecture: SOMETHING-SOMETHING-gcc-default64

testing: ....../gap-4.X.Y/tst/testinstall/alghom.tst
  84 ms (55 ms GC) and 2.90MB allocated for alghom.tst
testing: ....../gap-4.X.Y/tst/testinstall/algmat.tst
  839 ms (114 ms GC) and 219MB allocated for algmat.tst
[ further lines deleted ]
testing: ....../gap-4.X.Y/tst/testinstall/zmodnze.tst
  127 ms (119 ms GC) and 1.29MB allocated for zmodnze.tst

-----------------------------------
total 62829 ms (24136 ms GC) and 8.61GB allocated
  0 failures in 252 files

#I No errors detected while testing
\end{verbatim}

(optionally, you may start GAP with the command line options which you will see in the test output, to run it in a more conservative settings).

The more thorough test is \text{teststandard.g} which exercises more of GAP’s capabilities, also including all test files from \text{teststandard.g}. It requires about 1 GB of memory, runs for about one hour, and produces an output similar to the testinstall.g test. To run it, also start a new GAP session and then call

\begin{verbatim}
gap> Read( Filename( DirectoriesLibrary( "tst" ), "testall.g" ) );
\end{verbatim}
You may repeat the same check loading your package with onlyneeded option. Remember to perform each subsequent test in a new GAP session.

Also you may perform individual tests from the \texttt{tst} directory of the GAP installation loading them with \texttt{Test} (7.10.2).

\section{Access to the GAP Development Version}

We are aiming at providing a stable platform for package development and testing with official GAP releases. We also invite everyone to contribute by submitting patches, pull requests, and bug reports. We would like to make the contributing process as easy as possible.

The main GAP development repository is hosted on GitHub at \url{https://github.com/gap-system/gap}. Many GAP packages also have public repositories and issue trackers, and we are keeping a list of such packages at \url{https://gap-packages.github.io/}.

For further information about contributing to the GAP development, please see \url{https://github.com/gap-system/gap/blob/master/CONTRIBUTING.md}.

\section{Version control and continuous integration for GAP packages}

As we have mentioned above, many GAP packages have public repositories and issue trackers on GitHub, and we are keeping a list of such packages at \url{https://gap-packages.github.io/}. We welcome establishing public repositories for new packages and migrating existing package repositories there as well. Such repositories may be hosted under their authors’ accounts or under the gap-packages organisation (\url{https://github.com/gap-packages/}). The latter has the benefit that while the authors will preserve their deciding role on all aspects of the package development, the package will become more visible for potential collaborators and GAP developers may help to set up continuous integration for your package so that every commit to the repository will trigger automated running of package tests and reporting any failures to package maintainers.

\section{Selecting a license for a GAP Package}

As it was mentioned above, many GAP packages have public repositories and issue trackers on GitHub, and we are keeping a list of such packages at \url{https://gap-packages.github.io/}. We welcome establishing public repositories for new packages and migrating existing package repositories there as well. Such repositories may be hosted under their authors’ accounts or under the gap-packages organisation (\url{https://github.com/gap-packages/}). The latter has the benefit that while the authors will preserve their deciding role on all aspects of the package development, the package will become more visible for potential collaborators and GAP developers may help to set up continuous integration for your package so that every commit to the repository will trigger automated running of package tests and reporting any failures to package maintainers.

In the past many GAP packages used the text “We adopt the copyright regulations of GAP as detailed in the copyright notice in the GAP manual” or a similar statement. We now advise to be more explicit by making the exact reference to the GPL license, for example:

\begin{quote}
\texttt{packagename} is free software; you can redistribute it and/or modify it under the terms of the \texttt{GNU General Public License} as published by the \texttt{Free Software Foundation}; either version 2 of the License, or (at your option) any later version. and also including a copy of the full text of the license.
\end{quote}
76.22 Releasing a GAP Package

Currently, the GAP distribution provides archives in four different formats.

.tar.gz
   a standard UNIX tar archive, compressed with gzip
.tar.bz2
   a standard UNIX tar archive, compressed with bzip2
.zip
   an archive in zip format, where text files should have UNIX style line breaks
-\textsc{win}.zip
   an archive in zip format, where text files should have Windows style line breaks

For convenience of possible users it is sensible that you provide an archive of your package in at least one of these formats.

For example, if you wish to supply a .tar.gz archive, you may create it with the command
\begin{verbatim}
tar -cvzf packagename-version.tar.gz packagename
\end{verbatim}

Because the release of the GAP package is independent of the version of GAP, a GAP package should be wrapped up in separate file that can be installed onto any version of GAP. In this way, a package can be upgraded any time without the need to wait for new GAP releases. To ensure this, the package should be archived from the GAP \texttt{pkg} directory, that is all files are archived with the path starting at the package’s name.

The archive of a GAP package should contain all files necessary for the package to work. In particular there should be a compiled documentation, which includes the manual.six, manual.toc and manual.lab file in the documentation subdirectory which are created by GAPDoc while \texttt{TeX}ing the documentation. (The first two files are needed by the GAP help system, and the manual.lab file is needed if the main manuals or another package is referring to your package. Use the command GAPDocManualLab( packagename ); to create this file for your help books if you use GAPDoc.)

For packages which are redistributed via the GAP website, we offer an automatic conversion of any of the formats listed above to all the others (note that this, as well as wrapping the GAP distribution as a single archive containing the core system and all currently redistributed packages, will change file timestamps, so one should not rely on them anywhere in the package).

To use the conversion and repackaging service, you can provide any of the four archive formats or even more than one, however you should adhere to the following rule: text files in .tar.gz and .tar.bz2 archives must have UNIX style line breaks, while text files in -\textsc{win}.zip archives must have DOS/Windows line breaks.

The package wrapping tools for the GAP distribution and webpages then will use a sensible list of file extensions to decide if a file is a text file (being conservative, it may miss a few text files). These rules may be prepended by the application of rules from the PackageInfo.g file:

- if it has a .TextFiles component, then consider the given files as text files before GAP defaults will be applied;
- if it has a .BinaryFiles component, then consider given files as binary files before GAP defaults will be applied;
• if it has a .TextBinaryFilesPatterns component, then apply it before GAP defaults will be applied;

Utility functions from the lib/lbutil.g file in GAP, namely DosUnixLinebreaks, UnixDosLinebreaks, MacUnixLinebreaks may be helpful. They are described in the comments to their source code.

For packages hosted on GitHub publishing package release and establishing its website can be very efficiently automated using two tools: ReleaseTools (https://github.com/gap-system/ReleaseTools) and GitHubPagesForGAP (https://github.com/gap-system/GitHubPagesForGAP).

76.23 The homepage of a Package

If you want to distribute your package you should create its homepage containing some basic information, archives for download, the README file with installation instructions, and a copy of the package’s PackageInfo.g file.

The responsibility to maintain this homepage is with the package authors/maintainers.

If you tell the GAP Group about your package (say, by mail to support@gap-system.org) we may consider either

• adding a link to your package homepage from the GAP website (thus, the package will be an undeposited contribution);

• or redistributing the current version of your package as a part of the GAP distribution (this, the package will be deposited), also ;

In the latter case we can also provide some services for producing several archive formats from the archive you provide (e.g., you produce a .tar.gz version of your archive and we produce also a .tar.bz2, .zip and a -win.zip version from it).

Please also consider submitting your package to the GAP package refereeing process (see https://www.gap-system.org/Contacts/submit.html for further information).

For packages hosted on GitHub publishing package release and establishing its website can be very efficiently automated using two tools: GitHubPagesForGAP (https://github.com/gap-system/GitHubPagesForGAP) and ReleaseTools (https://github.com/gap-system/ReleaseTools).

76.24 Some things to keep in mind

• Some packages still use for their manuals the old “gapmacro” format, support for which may be discontinued in the future. We encourage authors of those packages to eventually convert their documentation GAPDoc. New packages are recommended to use GAPDoc, which, for example, is capable of creating HTML documentation with MathJax support, allows easy extraction of examples from documentation for testing, etc. One could also use the AutoDoc which simplifies writing documentation by generating most of the GAPDoc code automatically.

• The concept of an autoloaded package, which existed before GAP 4.5, has been integrated with the needed and suggested mechanism that exists between packages. GAP itself now “needs” certain packages (for instance GAPDoc) and “suggests” others (typically the packages that
were autoloaded). The decisions which packages GAP should need or suggest are made by developers based on technical criteria. They can be easily overridden by a user using the new gap.ini (see 3.2). The default file ensures that all formerly autoloaded packages are still loaded if present.

- Optional ~/.gap directory for user’s customisations which may contain e.g. locally installed packages (see 9.2). If package installation instructions explain how to install the package in a non-standard location, they should mention this.

- Packages loading mechanism allows to make loading packages more informative, while avoiding confusing the user with warning and error messages for packages they didn’t know they were loading. For example, many messages are stored but not displayed using the function LogPackageLoadingMessage (76.2.5) and there is a function DisplayPackageLoadingLog (76.2.5) to show log messages that occur during package loading. Packages are encouraged to use these mechanisms to report problems in loading (e.g. binaries not compiled), rather than printing messages directly.

### 76.25 Package release checklists

The following checklists should be useful to package authors and maintainers, as well as to everyone involved in the depositing and refereeing of GAP packages.

#### 76.25.1 Checklist for releasing a new package

- Test that the package:
  - does not break testinstall.g and teststandard.g, and does not slow them down noticeably (see 76.18.4);
  - may be loaded in various configurations (see 76.18.2);
  - follows the guidelines of Section 76.10 about names of functions and variables;

- PackageInfo.g file:
  - correctly specifies package version, release date, and package authors;
  - passes validation using ValidatePackageInfo (76.3.14);
  - besides mandatory components, which are required to pass validation, also has relevant optional components (such as, for example, URLs of public source code repository and issue tracker; hints to distinguish binary and text files in case of non-standard file names and extensions, etc.);

- Package documentation:
  - is built and included in the package archive together with its source files;
  - states the same version, release date and package authors as specified in the PackageInfo.g file;
  - has the same version, release date and package authors details as stated in the PackageInfo.g file;
- is searchable using the GAP help system in all formats (text, HTML and PDF);
- is clear about the license under which the package is distributed, and refers to the LICENSE file which should be included in the package;

- Package archive(s):
  - have correct permissions for all files and directories after their unpacking (755 for directories and executables, if any; 644 for other files);
  - contain files with correct line breaks for the given format (see Section 76.22);
  - contain no hidden system files and directories that are not supposed to be included in the package, e.g. .gitignore, .git etc.;

- Package availability:
  - not only the package archive(s), but also the PackageInfo.g and README files are available online;

### 76.25.2 Checklist for upgrading the package for the next major release of GAP

GAP ecosystem is not static: both the core GAP system and packages redistributed with GAP are in constant development. GAP has a policy that changes that may have a disruptive effect on packages redistributed with GAP should only be introduced in major GAP releases. When the next GAP major release is prepared, a beta version for package authors will be made available in order to give them an opportunity to check and update, if necessary, their packages for the public release of the next major version of GAP.

The following checklist will help you to check how well your package is ready to work with the next major release of GAP

- Check that the package functionality works as expected, package tests run with no discrepancies, and manual examples correspond to new version of GAP. This is a convenient opportunity to polish existing and add new tests, and improve manual examples.

- Revise package dependencies: check that the PackageInfo.g file has correct list of needed and suggested packages (see Section 76.11).

- Revise licensing information: check that the package states clearly under which conditions it is distributed and includes a LICENSING file with the text of a license (see Section 76.21).

- Rebuild the package documentation to update cross-references to main GAP manuals and, if relevant, to the documentation of other GAP packages. This will ensure that cross-references from the package manual to the main GAP manuals are correct and that the GAP help system will be able to navigate to the more precise location in the package manual. This will also improve the layout of the package documentation by picking up the changes in documenting tools.

- Check if the package still relies on some obsolete variables (see Chapter 77) and replace their usage by the new commands. To perform such check, start GAP with ‘-O’ command line option to disable loading obsoletes, and then load your package.

- Check for any specific advice in release notes for the beta release for package authors.
Chapter 77

Replaced and Removed Command Names

In general we try to keep GAP 4 compatible with former releases as much as possible. Nevertheless, from time to time it seems appropriate to remove some commands or to change the names of some commands or variables. There are various reasons for that: Some functionality was improved and got another (hopefully better) interface, names turned out to be too special or too general for the underlying functionality, or names are found to be unintuitive or inconsistent with other names.

In this chapter we collect such old names while pointing to the sections which explain how to substitute them. Usually, old names will be available for several releases; they may be removed when they don’t seem to be used any more.

Information about obsolete names is printed by Info (7.4.6) using the InfoObsolete Info class. By default InfoObsolete is set to 1. Newly obsoleted identifiers should at first be outputted at info level 2. Once they have been removed from all packages, they should then be moved to info level 1, so they are visible to normal users, for at least one major release before being removed.

The functions DeclareObsoleteSynonym and DeclareObsoleteSynonymAttr take an optional final parameter, specifying the info level at which the given obsolete symbol should be reported. It defaults to 1.

The obsolete GAP code is collected in two library files, lib/obsolete.gd and lib/obsolete.gi. By default, these files are read when GAP is started. It may be useful to omit reading these files, for example in order to make sure that one’s own GAP code does not rely on the obsolete variables. For that, one can use the --infolevel 0 command line option (see 3.1) or set the component ReadObsolete in the file gap.ini to false (see 3.2). Note that --infolevel 0 command line option overrides ReadObsolete.

(Note that the condition whether the library files with the obsolete GAP code shall be read has changed. In GAP 4.3 and 4.4, the global variables GAP_OBSOLESCENT and GAPInfo.ReadObsolete –to be set in the user’s .gaprc file– were used to control this behaviour.)

77.1 Group Actions – Name Changes

The concept of a group action is sometimes referred to as a “group operation”. In GAP 3 as well as in older versions of GAP 4 the term Operation was used instead of Action. We decided to change the names to avoid confusion with the term “operation” as in DeclareOperation (78.1.5) and “operations for Xyz”.

Here are some examples of such name changes.
77.2 Package Interface – Obsolete Functions and Name Changes

With GAP 4.4 the package interface was changed. Thereby some functions became obsolete and the names of some others were made more consistent.

The following functions are no longer needed: DeclarePackage, DeclareAutoPackage, DeclarePackageDocumentation and DeclarePackageAutoDocumentation. They are substituted by entries in the packages’ PackageInfo.g files, see 76.3.13.

Furthermore, the global variable PACKAGES_VERSIONS is no longer needed, since this information is now contained in the GAPInfo.PackagesInfo record (see 3.5.1). The global variable Revisions is also no longer needed, since the function DisplayRevision was made obsolete in GAP 4.5 and removed in GAP 4.7.

The following function names were changed.

<table>
<thead>
<tr>
<th>OLD</th>
<th>NOW USE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RequirePackage</td>
<td>LoadPackage (76.2.1)</td>
</tr>
<tr>
<td>ReadPkg</td>
<td>ReadPackage (76.3.1)</td>
</tr>
<tr>
<td>RereadPkg</td>
<td>RereadPackage (76.3.1)</td>
</tr>
</tbody>
</table>

77.3 Normal Forms of Integer Matrices – Name Changes

Former versions of GAP 4 documented several functions for computing the Smith or Hermite normal form of integer matrices. Some of them were never implemented and it was unclear which commands to use. The functionality of all of these commands is now available with NormalFormIntMat (25.2.9) and a few interface functions.

77.4 Miscellaneous Name Changes or Removed Names

In former releases of GAP 4 there were some global variable names bound to general information about the running GAP, such as path names or command line options. Although they were not officially documented they were used by several users and in some packages. We mention here BANNER and QUIET. This type of information is now collected in the global record GAPInfo (3.5.1).

Here are some further name changes.

<table>
<thead>
<tr>
<th>OLD</th>
<th>NOW USE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MonomialTotalDegreeLess</td>
<td>MonomialExtGrlexLess (66.17.14)</td>
</tr>
<tr>
<td>NormedVectors</td>
<td>NormedRowVectors (61.9.11)</td>
</tr>
<tr>
<td>MutableIdentityMat</td>
<td>IdentityMat (24.5.1)</td>
</tr>
<tr>
<td>MutableNullMat</td>
<td>NullMat (24.5.2)</td>
</tr>
<tr>
<td>MultRowVector</td>
<td>MultVectorLeft (23.4.3)</td>
</tr>
</tbody>
</table>
The operation PositionFirstComponent has been deprecated in GAP 4.8 due to issues with its documentation and implementation, and was removed in GAP 4.10. Instead of PositionFirstComponent(list, obj), you may use PositionSorted(list, [obj]) or PositionProperty(list, x → x[1] = obj) as a replacement, depending on your specific use case. The five argument version of the operation MultRowVector has been deprecated in GAP 4.10 since it was unused and only available for coefficient lists. Note that MultRowVector was also renamed to MultVectorLeft. The function TemporaryGlobalVarName has been deprecated in GAP 4.11. Code using it typically can be restructured to not need it, e.g. by using EvalString (27.9.5).

77.4.1 InfoObsolete

is an info class to display warnings when an obsolete variable is used. By default, the info level for this class is set to 1, which will only show variables which will be removed in the next major version of GAP. Setting it to 2 will trigger further warnings, for variables which have alternative names, or may be removed in future. This class can be set to 0 to disable all obsolete warnings.

To check that the GAP code does not use any obsolete variables at parsing time, and not at a runtime, use the -O command line option, see 3.1.

77.5 The former .gaprc file

Up to GAP 4.4, a file .gaprc in the user’s home directory (if available, and GAP was started without -r option) was read automatically during startup, early enough for influencing the autoloading of packages and late enough for being allowed to execute any GAP code. On Windows machines this file was called gap.rc.

In GAP 4.5 the startup mechanism has changed, see 3.2 for details. These new configuration files are now contained in a directory GAPInfo.UserGapRoot.

For the sake of partial backwards compatibility, also the former file ~/.gaprc is still supported for such initializations, but this file is read only if the directory GAPInfo.UserGapRoot does not exist. In that case the ~/.gaprc is read at the same time as gaprc would be read, i.e., too late for influencing the startup of GAP.

As before, the command line option -r disables reading ~/.gaprc, see 3.1.

To migrate from the old setup to the new one introduced with GAP 4.5, first have a look at the function WriteGapIniFile (3.2.3). Many users will find that all or most of what was set in the old ~/.gaprc file can now be done via the user preferences in a gap.ini file. If you had code for new functions or abbreviations in your old ~/.gaprc file or you were reading additional files, then move this into the file gaprc (without the leading dot, same name for all operating systems) in the directory GAPInfo.UserGapRoot.

77.6 Semigroup properties

Until Version 4.8 of GAP there was inconsistent use of the following properties of semigroups: IsGroupAsSemigroup, IsMonoidAsSemigroup, and IsSemilatticeAsSemigroup. IsGroupAsSemigroup was true for semigroups that mathematically defined a group, and for semigroups in the category IsGroup (39.2.7); IsMonoidAsSemigroup was true for semigroups
that mathematically defined monoids, but did not belong to the category IsMonoid (51.2.1); and IsSemilatticeAsSemigroup was simply a property of semigroups, there is no category IsSemilattice.

From Version 4.8 onwards, IsMonoidAsSemigroup returns true for semigroups in the category IsMonoid (51.2.1), and IsSemilatticeAsSemigroup has been moved to the Semigroups under the new name IsSemilattice (Semigroups: IsSemilattice).
Chapter 78

Method Selection

This chapter explains how GAP decides which function to call for which types of objects. It assumes that you have read the chapters about objects (Chapter 12) and types (Chapter 13).

An operation is a special GAP function that bundles a set of functions, its methods.

All methods of an operation compute the same result. But each method is installed for specific types of arguments.

If an operation is called with a tuple of arguments, one of the applicable methods is selected and called.

Special cases of methods are partial methods, immediate methods, and logical implications.

78.1 Operations and Methods

Operations are functions in the category IsOperation (78.1.1).

So on the one hand, operations are GAP functions, that is, they can be applied to arguments and return a result or cause a side-effect.

On the other hand, operations are more. Namely, an operation corresponds to a set of GAP functions, called the methods of the operation.

Each call of an operation causes a suitable method to be selected and then called. The choice of which method to select is made according to the types of the arguments, the underlying mechanism is described in the following sections.

Examples of operations are the binary infix operators =, + etc., and PrintObj (6.3.5) is the operation that is called for each argument of Print (6.3.4).

Also all attributes and properties are operations. Each attribute has a special method which is called if the attribute value is already stored; this method of course simply returns this value.

The setter of an attribute is called automatically if an attribute value has been computed. Attribute setters are operations, too. They have a default method that ignores the request to store the value. Depending on the type of the object, there may be another method to store the value in a suitable way, and then set the attribute tester for the object to true.

78.1.1 IsOperation

\[ \text{IsOperation}(\text{obj}) \] (Category)

is the category of operations. Every operation is a function, but not vice versa.
Example

```gap
gap> MinimalPolynomial;
<Operation "MinimalPolynomial">
gap> IsOperation(MinimalPolynomial);
true
gap> IsFunction(MinimalPolynomial);
true
gap> Factorial;
function( n ) ... end
gap> IsOperation(Factorial);
false
```

78.1.2 TypeOfOperation

`TypeOfOperation(object)`

returns a string from the list [ "Attribute", "Operation", "Property", "Category", "Representation", "Filter", "Setter"] reflecting which type of operation `op` is.

(see 13.3, 13.4, 13.5, 13.6, 13.7, 13.8)

78.1.3 ShowDeclarationsOfOperation

`ShowDeclarationsOfOperation(oper)`

Displays information about all declarations of the operation `oper`, including the location of each declaration and the argument filters.

Example

```gap
gap> ShowDeclarationsOfOperation(IsFinite);
Available declarations for operation <Property "IsFinite">:
  1: GAPROOT/lib/coll.gd:1451 with 1 arguments, and filters [ IsListOrCollection ]
  2: GAPROOT/lib/float.gd:212 with 1 arguments, and filters [ IsFloat ]
  3: GAPROOT/lib/ctbl.gd:1195 with 1 arguments, and filters [ IsNearlyCharacterTable ]
```

78.1.4 NewOperation

`NewOperation(name, args-filts)`

`NewOperation` returns an operation `opr` with name `name`. The list `args-filts` describes requirements about the arguments of `opr`, namely the number of arguments must be equal to the length of `args-filts`, and the `i`-th argument must lie in the filter `args-filts[i]`.

Each method that is installed for `opr` via `InstallMethod (78.3.1)` must require that the `i`-th argument lies in the filter `args-filts[i]`.

One can install methods for other argument tuples via `InstallOtherMethod (78.3.2)`, this way it is also possible to install methods for a different number of arguments than the length of `args-filts`.

78.1.5 DeclareOperation

`DeclareOperation(name, filters)`

(function)
does the same as NewOperation (78.1.4) and additionally makes the variable name read-only.

### 78.2 Constructors

Constructors are a special type of operation used to make new objects. The key difference compared to regular operations is that method selection works slightly differently for them: The first argument in a call to a constructor must always be a filter 13.2. The result of a method is expected to lie in that filter. Moreover, while normally method selection matches on the type of each argument, for a constructor the first argument is treated differently: instead of matching its type, the argument itself (which is a filter) must be a subset of the filter specified by the method which is being tested for match. In other words, the argument filter must imply the method filter.

Also, method ranking works differently: instead of the sum of the ranks of the types of all arguments, only the rank of the filter given as first argument is considered; and for it, the normal ranking order is reversed. This ensures that if multiple constructor methods match, the “most general” method is selected.

#### Example

```gap
gap> DeclareConstructor("XCons",[IsMagma,IsInt]);
gap> InstallMethod(XCons, [IsGroup, IsInt], function(t,x) return CyclicGroup(x); end);
gap> InstallMethod(XCons, [IsPermGroup, IsInt], function(t,x) return SymmetricGroup(x); end);
gap> InstallMethod(XCons, [IsSemigroup, IsInt], function(t,x) return FullTransformationMonoid(x); end);
gap> XCons(IsGroup,3);
<pc group of size 3 with 1 generators>
gap> XCons(IsPermGroup,3);
Sym( [ 1 .. 3 ] )
gap> XCons(IsSemigroup,4);
<full transformation monoid of degree 4>
gap> # if multiple methods match, the most general is selected:
gap> XCons(IsMagma,3);
<full transformation monoid of degree 3>
```

The example above shows some basic examples (usually a constructor will produce isomorphic objects in different representations, not different objects as in this case).

If no method has been installed which guarantees to produce a suitable object, a "No Method Found" error will be returned.

#### Example

```gap
gap> XCons(IsFullTransformationMonoid,4);
Error, no method found! For debugging hints type ?Recovery from NoMethodFound Error, no 1st choice method found for 'XCons' on 2 arguments called from <function "HANDLE_METHOD_NOT_FOUND">( <arguments> )
called from read-eval loop at line 8 of *stdin*
you can 'quit;' to quit to outer loop, or
you can 'return;' to continue
brk> quit;
gap> XCons(IsNilpotentGroup,4);
Error, no method found! For debugging hints type ?Recovery from NoMethodFound Error, no 1st choice method found for 'XCons' on 2 arguments called from <function "HANDLE_METHOD_NOT_FOUND">( <arguments> )
called from read-eval loop at line 9 of *stdin*
you can 'quit;' to quit to outer loop, or
```
Note that in both these cases there are methods that actually produce results of the required types, but they have not been installed with this information, so are not selected.

### 78.2.1 NewConstructor

\[ \text{NewConstructor} \text{(name, args-filts)} \] (function)

**NewConstructor** returns a constructor \textit{cons} with name \textit{name}. The list \textit{args-filts} describes requirements about the arguments of \textit{cons}. Namely the number of arguments must be equal to the length of \textit{args-filts}, and the \(i\)-th argument must lie in the filter \textit{args-filts}[\(i\)] for \(i \neq 1\). A constructor expects the first argument to be a \textit{filter} instead of an object and it must be a subset of the filter \textit{args-filts}[1].

Each method that is installed for \textit{cons} via InstallMethod (78.3.1) must require that the \(i\)-th argument lies in the filter \textit{args-filts}[\(i\)] for \(i \neq 1\). Its first argument is a filter and must be a subset of the filter \textit{args-filts}[1].

One can install methods for other argument tuples via InstallOtherMethod (78.3.2), this way it is also possible to install methods for a different number of arguments than the length of \textit{args-filts}.

Note that the method selection for constructors works slightly differently than for usual operations. As stated above, applicability to the first argument in an argument tuple is tested by determining whether the argument-filter is a subset of \textit{args-filts}[1].

The rank of a method installed for a constructor is determined solely by \textit{args-filts}[1] of the method. Instead of taking the sum of the ranks of filters involved in its \textit{args-filts}[1], the sum of \(-1\) times these values is taken. The result is added to the number \textit{val} used in the call of InstallMethod (78.3.1).

This has the following effects on the method selection for constructors. If \textit{cons} is called with an argument tuple whose first argument is the filter \textit{filt}, any method whose first argument is more specific than \textit{filt} is applicable (if its other \textit{args-filts} also match). Then the method with the "most general" filter \textit{args-filts}[1] is chosen, since the rank is computed by taking \(-1\) times the ranks of the involved filters. Thus, a constructor is chosen which returns an object in \textit{filt} using as few extra filters as possible, which presumably is both more flexible to use and easier to construct.

The following example showcases this behaviour. Note that the argument \textit{filter} is only used for method dispatch.

```plaintext
Example

DeclareFilter( "IsMyObj" );
DeclareFilter( "IsMyFilter" );
DeclareFilter( "IsMyOtherFilter" );
BindGlobal( "MyFamily", NewFamily( "MyFamily" ) );

DeclareConstructor( "NewMyObj", [ IsMyObj ] );

InstallMethod( NewMyObj, 
[ IsMyObj ],
function( filter )
local type;
Print("General constructor\n");
type := NewType( MyFamily, IsMyObj ] );
```

```plaintext
you can 'return;' to continue
brk>
```
return Objectify( type, [] );
end );
InstallMethod( NewMyObj,
[ IsMyObj and IsMyFilter and IsMyOtherFilter ],
function( filter )
  local type;
  Print( "Special constructor\n" );
type := NewType( MyFamily, IsMyObj and IsMyFilter and IsMyOtherFilter );
  return Objectify( type, [] );
end );

If only IsMyObj is given, both methods are applicable and the general constructor is called. If also IsMyFilter is given, only the special constructor is applicable.

Example

```
gap> a := NewMyObj( IsMyObj );;
General constructor
gap> IsMyOtherFilter(a);
false
gap> b := NewMyObj( IsMyObj and IsMyFilter );;
Special constructor
gap> IsMyOtherFilter(b);
true
gap> c := NewMyObj( IsMyObj and IsMyFilter and IsMyOtherFilter );;
Special constructor
gap> IsMyOtherFilter(c);
true
```

78.2.2 DeclareConstructor

```
function
```

\[ \text{DeclareConstructor}( \text{name}, \text{filters} ) \]

\( \text{does the same as NewConstructor (78.2.1)} \) and additionally makes the variable \text{name} read-only.

Note that for operations which are constructors special rules with respect to applicability and rank of the corresponding methods apply (see section NewConstructor (78.2.1)).

78.3 Method Installation

In order to describe what it means to select a method of an operation, we must describe how the methods are connected to their operations.

For attributes and properties there is InstallImmediateMethod (78.7.1).

For declaring that a filter is implied by other filters there is InstallTrueMethod (78.8.1).

78.3.1 InstallMethod

```
function
```

\[ \text{InstallMethod}( \text{opr[, info][, famp], args-filts[, val], method} ) \]

\( \text{installs a function method method for the operation opr; args-filts should be a list of requirements for the arguments, each entry being a filter; if supplied info should be a short but informative string that describes for what situation the method is installed, famp should be a function to be applied} \)
to the families of the arguments. \texttt{val} should be an integer that measures the priority of the method, or a function of no arguments which should return such an integer and will be called each time method order is being recalculated (see \texttt{InstallTrueMethod} (78.8.1)).

The default values for \texttt{info}, \texttt{famp}, and \texttt{val} are the empty string, the function \texttt{ReturnTrue} (5.4.1), and the integer zero, respectively.

The exact meaning of the arguments \texttt{famp}, \texttt{args-filts}, and \texttt{val} is explained in Section 78.4. \texttt{opr} expects its methods to require certain filters for their arguments. For example, the argument of a method for the operation \texttt{Zero} (31.10.3) must be in the category \texttt{IsAdditiveElementWithZero} (31.14.5). It is not possible to use \texttt{InstallMethod} to install a method for which the entries of \texttt{args-filts} do not imply the respective requirements of the operation \texttt{opr}. If one wants to override this restriction, one has to use \texttt{InstallOtherMethod} (78.3.2) instead.

78.3.2 InstallOtherMethod

\>[\texttt{InstallOtherMethod(opr[, info][, famp], args-filts[, val], method)}](function)

installs a function method \texttt{method} for the operation \texttt{opr}, in the same way as for \texttt{InstallMethod} (78.3.1), but without the restriction that the number of arguments must match a declaration of \texttt{opr} and without the restriction that \texttt{args-filts} imply the respective requirements of the operation \texttt{opr}.

78.3.3 InstallMethodWithRandomSource

\>[\texttt{InstallMethodWithRandomSource(opr, info[, famp], args-filts[, val], method)}](function)
\>[\texttt{InstallOtherMethodWithRandomSource(opr, info[, famp], args-filts[, val], method)}](function)

These functions are designed to simplify adding new methods for \texttt{Random} (30.7.1), \texttt{PseudoRandom} (30.7.2), and \texttt{Randomize} (26.4.9) to \texttt{GAP} which can be called both with, and without, a random source.

They accept the same arguments as \texttt{InstallMethod} (78.3.1) and \texttt{InstallOtherMethod} (78.3.2), with the extra requirement that the first member of \texttt{args-filts} must be \texttt{IsRandomSource} (14.7.1), and the \texttt{info} argument is compulsory and must begin 'for a random source and'.

This function then installs two methods: first it calls \texttt{InstallMethod} (78.3.1) (or \texttt{InstallOtherMethod} (78.3.2)) with unchanged arguments. Then it calls \texttt{InstallMethod} (78.3.1) (or \texttt{InstallOtherMethod} (78.3.2)) a second time to install another method which lacks the initial random source argument; this additional method simply invokes the original method, with \texttt{GlobalMersenneTwister} (14.7.4) added as first argument.

78.4 Applicable Methods and Method Selection

A method installed as above is \textit{applicable} for an arguments tuple if the following conditions are satisfied.

The number of arguments equals the length of the list \texttt{args-filts}, the \texttt{i}-th argument lies in the filter \texttt{args-filts}[\texttt{i}], and \texttt{famp} returns \texttt{true} when applied to the families of the arguments. The maximal number of arguments supported for methods is six, one gets an error message if one tries to install a method with at least seven arguments.
So \texttt{args-filt} describes conditions for each argument, and \texttt{famp} describes a relation between the arguments.

For unary operations such as attributes and properties, there is no such relation to postulate, \texttt{famp} is \texttt{ReturnTrue} (5.4.1) for these operations, a function that always returns \texttt{true}. For binary operations, the usual value of \texttt{famp} is \texttt{IsIdenticalObj} (12.5.1), which means that both arguments must lie in the same family.

Note that any properties which occur among the filters in the filter list will not be tested by the method selection if they are not yet known. (More exact: if \texttt{prop} is a property then the filter implicitly uses not \texttt{prop} but \texttt{Hasprop and prop}.) If this is desired you must explicitly enforce a test (see section 78.6) below.

If no method is applicable, the error message “no method found” is signaled.

Otherwise, the applicable method with highest \textit{rank} is selected and then called. This rank is given by the sum of the ranks of the filters in the list \texttt{args-filt}, including involved filters, plus the number \texttt{val} used in the call of \texttt{InstallMethod} (78.3.1). So the argument \texttt{val} can be used to raise the priority of a method relative to other methods for \texttt{opr}.

Note that for operations which are constructors special rules with respect to applicability and rank of the corresponding methods apply (see \texttt{NewConstructor} (78.2.1)).

Note that from the applicable methods an efficient one shall be selected. This is a method that needs only little time and storage for the computations.

It seems to be impossible for \texttt{GAP} to select an optimal method in all cases. The present ranking of methods is based on the assumption that a method installed for a special situation shall be preferred to a method installed for a more general situation.

For example, a method for computing a Sylow subgroup of a nilpotent group is expected to be more efficient than a method for arbitrary groups. So the more specific method will be selected if \texttt{GAP} knows that the group given as argument is nilpotent.

Of course there is no obvious way to decide between the efficiency of incommensurable methods. For example, take an operation with one method for permutation groups, another method for nilpotent groups, but no method for nilpotent permutation groups, and call this operation with a permutation group known to be nilpotent.

### 78.5 Partial Methods

#### 78.5.1 TryNextMethod

\begin{verbatim}
\texttt{TryNextMethod()}
\end{verbatim}

After a method has been selected and called, the method may recognize that it cannot compute the desired result, and give up by calling \texttt{TryNextMethod()}. In effect, the execution of the method is terminated, and the method selection calls the next method that is applicable w.r.t. the original arguments. In other words, the applicable method is called that is subsequent to the one that called \texttt{TryNextMethod}, according to decreasing rank of the methods.

For example, since every finite group of odd order is solvable, one may install a method for the property \texttt{IsSolvableGroup} (39.15.6) that checks whether the size of the argument is an odd integer, returns \texttt{true} if so, and gives up otherwise.

Care is needed if a partial method might modify the type of one of its arguments, for example by computing an attribute or property. If this happens, and the type has really changed, then the method
should not exit using \texttt{TryNextMethod()} but should call the operation again, as the new information in
the type may cause some methods previously judged inapplicable to be applicable. For example, if the
above method for \texttt{IsSolvableGroup (39.15.6)} actually computes the size, (rather than just examining
a stored size), then it must take care to check whether the type of the group has changed.

\section*{78.6 Redispatching}

As mentioned above the method selection will not test unknown properties. In situations, in which
algorithms are only known (or implemented) under certain conditions, however such a test might be
actually desired.

One way to achieve this would be to install the method under weaker conditions and explicitly test
the properties first, exiting via \texttt{TryNextMethod (78.5.1)} if some of them are not fulfilled. A problem
of this approach however is that such methods then automatically are ranked lower and that the code
does not look nice.

A much better way is to use redispatching: Before deciding that no method has been found one
tests these properties and if they turn out to be true the method selection is started anew (and will then
find a method).

This can be achieved via the following function:

\section*{78.6.1 RedispatchOnCondition}

\begin{verbatim}
\texttt{RedispatchOnCondition(oper[, info], fampred, reqs, cond, val})
\end{verbatim}

This function installs a method for the operation \texttt{oper} under the conditions \texttt{fampred} and \texttt{reqs}
which has absolute value \texttt{val}; that is, the value of the filters \texttt{reqs} is disregarded. \texttt{cond} is a list of
filters. If not all the values of properties involved in these filters are already known for actual arguments
of the method, they are explicitly tested and if they are fulfilled and stored after this test, the operation
is dispatched again. Otherwise the method exits with \texttt{TryNextMethod (78.5.1)}. If supplied, \texttt{info}
should be a short but informative string that describes these conditions. This can be used to enforce
tests like \texttt{IsFinite (30.4.2)} in situations when all existing methods require this property. The list \texttt{cond}
may have unbound entries in which case the corresponding argument is ignored for further
tests.

\section*{78.7 Immediate Methods}

Usually a method is called only if its operation has been called and if this method has been selected,
see \texttt{InstallMethod (78.3.1)}.

For attributes and properties, one can install also \textit{immediate methods}.

\section*{78.7.1 InstallImmediateMethod}

\begin{verbatim}
\texttt{InstallImmediateMethod(opr[, info], filter, rank, method})
\end{verbatim}

\texttt{InstallImmediateMethod} installs \texttt{method} as an immediate method for \texttt{opr}, which must be an
attribute or a property, with requirement \texttt{filter} and rank \texttt{rank} (the rank can be omitted, in which
case 0 is used as rank). The rank must be an integer value that measures the priority of \texttt{method}
among the immediate methods for `opr`. If supplied, `info` should be a short but informative string that describes the situation in which the method is called.

An immediate method is called automatically as soon as the object lies in `filter`, provided that the value is not yet known. Afterwards the attribute setter is called in order to store the value, unless the method exits via `TryNextMethod` (78.5.1).

Note the difference to `InstallMethod` (78.3.1) that no family predicate occurs because `opr` expects only one argument, and that `filter` is not a list of requirements but the argument requirement itself.

Immediate methods are thought of as a possibility for objects to gain useful knowledge. They must not be used to force the storing of “defining information” in an object. In other words, GAP should work even if all immediate methods are completely disabled. Therefore, the call to `InstallImmediateMethod` installs `method` also as an ordinary method for `opr` with requirement `filter`.

Note that in such a case GAP executes a computation for which it was not explicitly asked by the user. So one should install only those methods as immediate methods that are extremely cheap. To emphasize this, immediate methods are also called zero cost methods. The time for their execution should really be approximately zero.

For example, the size of a permutation group can be computed very cheaply if a stabilizer chain of the group is known. So it is reasonable to install an immediate method for `Size` (30.4.6) with requirement `IsGroup` and `Tester(stab)`, where `stab` is the attribute corresponding to the stabilizer chain.

Another example would be the implementation of the conclusion that every finite group of prime power order is nilpotent. This could be done by installing an immediate method for the attribute `IsNilpotentGroup` (39.15.3) with requirement `IsGroup` and `Tester(Size)`. This method would then check whether the size is a finite prime power, return `true` in this case and otherwise call `TryNextMethod` (78.5.1). But this requires factoring of an integer, which cannot be guaranteed to be very cheap, so one should not install this method as an immediate method.

### 78.8 Logical Implications

#### 78.8.1 InstallTrueMethod

D `InstallTrueMethod(newfil, filt)`  

It may happen that a filter `newfil` shall be implied by another filter `filt`, which is usually a meet of other properties, or the meet of some properties and some categories. Such a logical implication can be installed as an “immediate method” for `newfil` that requires `filt` and that always returns `true`. (This should not be mixed up with the methods installed via `InstallImmediateMethod` (78.7.1), which have to be called at runtime for the actual objects.)

`InstallTrueMethod` has the effect that `newfil` becomes an implied filter of `filt`, see 13.2.

For example, each cyclic group is abelian, each finite vector space is finite dimensional, and each division ring is integral. The first of these implications is installed as follows.

```
Example

InstallTrueMethod( IsCommutative, IsGroup and IsCyclic );
```

Contrary to the immediate methods installed with `InstallImmediateMethod` (78.7.1), logical implications cannot be switched off. This means that after the above implication has been installed,
one can rely on the fact that every object in the filter `IsGroup` and `IsCyclic` will also be in the filter `IsCommutative` (35.4.9).

Adding logical implications can change the rank of filters (see `RankFilter` (13.2.1)) and consequently the rank, and so choice of methods for operations (see 78.4). By default `InstallTrueMethod` adjusts the method selection data structures to take care of this, but this process can be time-consuming, so functions `SuspendMethodReordering` (78.8.2) and `ResumeMethodReordering` (78.8.2) are provided to allow control of this process.

### 78.8.2 SuspendMethodReordering

- `SuspendMethodReordering()` (function)
- `ResumeMethodReordering()` (function)
- `ResetMethodReordering()` (function)

These functions control whether the method reordering process described in `InstallTrueMethod` (78.8.1) is invoked or not. Since this process can be comparatively time-consuming, it is usually suspended when a lot of implications are due to be installed, for instance when loading the library, or a package. This is done by calling `SuspendMethodReordering` once the installations are done, `ResumeMethodReordering` should be called. These pairs of calls can be nested. When the outermost pair is complete, method reordering takes place and is enabled in `InstallTrueMethod` (78.8.1) thereafter. `ResetMethodReordering` effectively exits all nested suspensions, resuming reordering immediately. This function is mainly provided for error recovery and similar purposes and is called on quitting from a break loop.

### 78.9 Operations and Mathematical Terms

Usually an operation stands for a mathematical concept, and the name of the operation describes this uniquely. Examples are the property `IsFinite` (30.4.2) and the attribute `Size` (30.4.6). But there are cases where the same mathematical term is used to denote different concepts, for example `Degree` is defined for polynomials, group characters, and permutation actions, and `Rank` is defined for matrices, free modules, $p$-groups, and transitive permutation actions.

It is in principle possible to install methods for the operation `Rank` that are applicable to the different types of arguments, corresponding to the different contexts. But this is not the approach taken in the GAP library. Instead there are operations such as `RankMat` (24.7.1) for matrices and `DegreeOfCharacter` (72.8.4) (in fact these are attributes) which are installed as methods of the “ambiguous” operations `Rank` and `Degree`.

The idea is to distinguish between on the one hand different ways to compute the same thing (e.g. different methods for `$=$` (31.11.1), `Size` (30.4.6), etc.), and on the other hand genuinely different things (such as the degree of a polynomial and a permutation action).

The former is the basic purpose of operations and attributes. The latter is provided as a user convenience where mathematical usage forces it on us and where no conflicts arise. In programming the library, we use the underlying mathematically precise operations or attributes, such as `RankMat` (24.7.1) and `RankOperation`. These should be attributes if appropriate, and the only role of the operation `Rank` is to decide which attribute the user meant. That way, stored information is stored with “full mathematical precision” and is less likely to be retrieved for a wrong purpose later.
One word about possible conflicts. A typical example is the mathematical term “centre”, which is defined as \( \{ x \in M | a \ast x = x \ast a \forall a \in M \} \) for a magma \( M \), and as \( \{ x \in L | l \ast x = 0 \forall l \in L \} \) for a Lie algebra \( L \). Here it is not possible to introduce an operation \texttt{Centre(35.4.5)} that delegates to attributes \texttt{CentreOfMagma} and \texttt{CentreOfLieAlgebra}, depending on the type of the argument. This is because any Lie algebra in \texttt{GAP} is also a magma, so both \texttt{CentreOfMagma} and \texttt{CentreOfLieAlgebra} would be defined for a Lie algebra, with different meaning if the characteristic is two. So we cannot achieve that one operation in \texttt{GAP} corresponds to the mathematical term “centre”.

“Ambiguous” operations such as \texttt{Rank} are declared in the library file \texttt{lib/overload.g}. 
Chapter 79

Creating New Objects

This chapter is divided into three parts.

In the first part, it is explained how to create objects with given type (see 79.1).

In the second part, first a few small examples are given, for dealing with the usual cases of component objects (see 79.2) and positional objects (see 79.3), and for the implementation of new kinds of lists (see 79.4 and 79.7). Finally, the external representation of objects is introduced (see 79.8), as a tool for representation independent access to an object.

The third part deals with some rules concerning the organization of the GAP library; namely, some commands for creating global variables are explained (see 79.10) that correspond to the ones discussed in the first part of the chapter, and the idea of distinguishing declaration and implementation part of GAP packages is outlined (see 79.11).

See also Chapter 81 for examples how the functions from the first part are used, and why it is useful to have a declaration part and an implementation part.

79.1 Creating Objects

79.1.1 Objectify

\[ \text{Objectify(type, data)} \] (function)

New objects are created by \text{Objectify}. \text{data} is a list or a record, and \text{type} is the type that the desired object shall have. \text{Objectify} turns \text{data} into an object with type \text{type}. That is, \text{data} is changed, and afterwards it will not be a list or a record unless \text{type} is of type list resp. record.

If \text{data} is a list then \text{Objectify} turns it into a positional object, if \text{data} is a record then \text{Objectify} turns it into a component object (for examples, see 79.2 and 79.3).

\text{Objectify} does also return the object that it made out of \text{data}.

For examples where \text{Objectify} is used, see 79.2, 79.3, and the example in Chapter 81.

79.1.2 ObjectifyWithAttributes

\[ \text{ObjectifyWithAttributes(obj, type, attr1, val1, attr2, val2, ...)} \] (function)

Attribute assignments will change the type of an object. If you create many objects, code of the form
will take a lot of time for type changes. You can avoid this by setting the attributes immediately while the object is created, as follows. `ObjectifyWithAttributes` changes the type of object `obj` to type `type` and sets attribute `attr1` to `val1`, sets attribute `attr2` to `val2` and so forth.

If the filter list of `type` includes that these attributes are set (and the properties also include values of the properties) and if no special setter methods are installed for any of the involved attributes then they are set simultaneously without type changes. This can produce a substantial speedup.

If the conditions of the last sentence are not fulfilled, an ordinary `Objectify (79.1.1)` with subsequent setter calls for the attributes is performed instead.

### 79.2 Component Objects

A *component object* is an object in the representation `IsComponentObjectRep (13.4.1)` or a subrepresentation of it. Such an object `cobj` is built from subobjects that can be accessed via `cobj !. name`, similar to components of a record. Also analogously to records, values can be assigned to components of `cobj` via `cobj !. name := val`. For the creation of component objects, see 79.1. One must be *very careful* when using the `!.` operator, in order to interpret the component in the right way, and even more careful when using the assignment to components using `!.`., in order to keep the information stored in `cobj` consistent.

First of all, in the access or assignment to a component as shown above, `name` must be among the admissible component names for the representation of `cobj`, see `NewRepresentation (13.4.4)`. Second, preferably only few low level functions should use `!..`, whereas this operator should not occur in "user interactions".

Note that even if `cobj` claims that it is immutable, i.e., if `cobj` is not in the category `IsMutable (12.6.2)`, access and assignment via `!.` and `!..:=` work. This is necessary for being able to store newly discovered information in immutable objects.

The following example shows the implementation of an iterator (see 30.8) for the domain of integers, which is represented as component object. See 79.3 for an implementation using positional objects. (In practice, such an iterator can be implemented more elegantly using `IteratorByFunctions (30.8.8)`, see 79.6.)

The used succession of integers is $0, 1, -1, 2, -2, 3, -3, \ldots$, that is, $a_n = n/2$ if $n$ is even, and $a_n = (1-n)/2$ otherwise.

```
Example
IsIntegersIteratorCompRep := NewRepresentation( "IsIntegersIteratorRep", IsComponentObjectRep, [ "counter" ] );
```

The above command creates a new representation (see `NewRepresentation (13.4.4)`) `IsIntegersIteratorCompRep`, as a subrepresentation of `IsComponentObjectRep (13.4.1)`, and with one admissible component `counter`. So no other components than `counter` will be needed.

```
Example
InstallMethod( Iterator, "method for 'Integers'", [ IsIntegers ],
```

function( Integers )
return Objectify( NewType( IteratorsFamily,
   IsIterator
   and IsIntegersIteratorCompRep ),
   rec( counter := 0 ) );
end );

After the above method installation, one can already ask for Iterator( Integers ). Note that exactly the domain of integers is described by the filter IsIntegers (14.1.2).

By the call to NewType (13.9.3), the returned object lies in the family containing all iterators, which is IteratorsFamily, it lies in the category IsIterator (30.8.3) and in the representation IsIntegersIteratorCompRep; furthermore, it has the component counter with value 0.

What is missing now are methods for the two basic operations of iterators, namely IsDoneIterator (30.8.4) and NextIterator (30.8.5). The former must always return false, since there are infinitely many integers. The latter must return the next integer in the iteration, and update the information stored in the iterator, that is, increase the value of the component counter.

--- Example ---

InstallMethod( IsDoneIterator,
   "method for iterator of `Integers'",
   [ IsIterator and IsIntegersIteratorCompRep ],
   ReturnFalse );

InstallMethod( NextIterator,
   "method for iterator of `Integers'",
   [ IsIntegersIteratorCompRep ],
   function( iter )
   iter!.counter:= iter!.counter + 1;
   if iter!.counter mod 2 = 0 then
     return iter!.counter / 2;
   else
     return ( 1 - iter!.counter ) / 2;
   fi;
end );

79.2.1 NamesOfComponents

\textbf{NamesOfComponents(}\texttt{comobj})

For a component object \texttt{comobj}, \texttt{NamesOfComponents} returns a list of strings, which are the names of components currently bound in \texttt{comobj}.

For a record \texttt{comobj}, \texttt{NamesOfComponents} returns the result of \texttt{RecNames (29.1.2)}.

79.3 Positional Objects

A \textit{positional object} is an object in the representation \texttt{IsPositionalObjectRep (13.4.1)} or a subrepresentation of it. Such an object \texttt{pobj} is built from subobjects that can be accessed via \texttt{pobj ![pos]}, similar to positions in a list. Also analogously to lists, values can be assigned to positions of \texttt{pobj} via \texttt{pobj ![pos]:= val}. For the creation of positional objects, see \texttt{79.1}.
One must be very careful when using the ![] operator, in order to interpret the position in the right way, and even more careful when using the assignment to positions using ![], in order to keep the information stored in pobj consistent.

First of all, in the access or assignment to a position as shown above, pos must be among the admissible positions for the representation of pobj, see NewRepresentation (13.4.4). Second, preferably only few low level functions should use ![], whereas this operator should not occur in “user interactions”.

Note that even if pobj claims that it is immutable, i.e., if pobj is not in the category IsMutable (12.6.2), access and assignment via ![] work. This is necessary for being able to store newly discovered information in immutable objects.

The following example shows the implementation of an iterator (see 30.8) for the domain of integers, which is represented as positional object. See 79.2 for an implementation using component objects, and more details.

Example

```plaintext
```

The above command creates a new representation (see NewRepresentation (13.4.4)) IsIntegersIteratorPosRep, as a subrepresentation of IsPositionalObjectRep (13.4.1), and with only the first position being admissible for storing data.

Example

```plaintext
InstallMethod( Iterator, "method for `Integers'", IsIntegers ], function( Integers ) return Objectify( NewType( IteratorsFamily, IsIterator and IsIntegersIteratorRep ), [ 0 ] ); end );
```

After the above method installation, one can already ask for Iterator( Integers ). Note that exactly the domain of integers is described by the filter IsIntegers (14.1.2).

By the call to NewType (13.9.3), the returned object lies in the family containing all iterators, which is IteratorsFamily, it lies in the category IsIterator (30.8.3) and in the representation IsIntegersIteratorPosRep; furthermore, the first position has value 0.

What is missing now are methods for the two basic operations of iterators, namely IsDoneIterator (30.8.4) and NextIterator (30.8.5). The former must always return false, since there are infinitely many integers. The latter must return the next integer in the iteration, and update the information stored in the iterator, that is, increase the value stored in the first position.

Example

```plaintext
InstallMethod( IsDoneIterator, "method for iterator of `Integers'", [ IsIterator and IsIntegersIteratorPosRep ], ReturnFalse );

InstallMethod( NextIterator, "method for iterator of `Integers'",
```
function( iter )
  iter![1] := iter![1] + 1;
  if iter![1] mod 2 = 0 then
    return iter![1] / 2;
  else
    return ( 1 - iter![1] ) / 2;
  fi;
end );

It should be noted that one can of course install both the methods shown in Section 79.2 and 79.3. The call \Iterator\(\(\, \text{Integers}\, \)\) will cause one of the methods to be selected, and for the returned iterator, which will have one of the representations we constructed, the right \NextIterator\(\(\, (30.8.5)\, \)\) method will be chosen.

### 79.4 Implementing New List Objects

This section gives some hints for the quite usual situation that one wants to implement new objects that are lists. More precisely, one either wants to deal with lists that have additional features, or one wants that some objects also behave as lists. An example can be found in 79.5.

A list in GAP is an object in the category `IsList\(\, (21.1.1)\, \)`. Basic operations for lists are `Length\(\, (21.17.5)\, \)`, `\`\`\, `\`\`\, and `IsBound\(\, (21.2.1)\, \)` (see 21.2).

Note that the access to the position `pos` in the list `list` via `list\[\, pos\, \]` is handled by the call `\`\`\, `\`\`\, to the operation `\`\`\, (21.2.1)`. To explain the somewhat strange name `\`\`\, of this operation, note that non-alphanumeric characters like `[` and `]` may occur in GAP variable names only if they are escaped by a `\` character.

Analogously, the check `IsBound\(\, list\[\, pos\, \]\, \)` whether the position `pos` of the list `list` is bound is handled by the call `\`\`\, `\`\`\, to the operation `\`\`\, (21.2.1). For mutable lists, also assignment to positions and unbinding of positions via the operations `\, `\`\, and `Unbind\(\, `\`\, `\`\, `\`\, are basic operations. The assignment `list\[\, pos\, :=\, val\, `\`\, is handled by the call `\`\`\, `\`\`\, `\`\`\, to the operation `\`\`\, (21.2.1).

All other operations for lists, e.g., `Add\(\, (21.4.2)\, \)`, `Append\(\, (21.4.5)\, \)`, `Sum\(\, (21.20.27)\, \)` are based on these operations. This means that it is sufficient to install methods for the new list objects only for the basic operations.

So if one wants to implement new list objects then one creates them as objects in the category `IsList\(\, (21.1.1)\, \)`, and installs methods for `Length\(\, (21.17.5)\, \)` `\`\`, and `IsBound\(\, (21.2.1)\, \)` (21.2.1). If the new lists shall be mutable, one needs to install also methods for `\`\`\, `\`\`\, and `Unbind\(\, `\`\, `\`\, (21.2.1).

One application for this is the implementation of enumerators for domains. An enumerator for the domain `D` is a dense list whose entries are in bijection with the elements of `D`. If `D` is large then it is not useful to write down all elements. Instead one can implement such a bijection implicitly. This works also for infinite domains.

In this situation, one implements a new representation of the lists that are already available in GAP, in particular the family of such a list is the same as the family of the domain `D`.

But it is also possible to implement new kinds of lists that lie in new families, and thus are not equal to lists that were available in GAP before. An example for this is the implementation of matrices
whose multiplication via “∗” is the Lie product of matrices.

In this situation, it makes no sense to put the new matrices into the same family as the original matrices. Note that the product of two Lie matrices shall be defined but not the product of an ordinary matrix and a Lie matrix. So it is possible to have two lists that have the same entries but that are not equal w.r.t. “=” because they lie in different families.

79.5 Example – Constructing Enumerators

When dealing with countable sets, a usual task is to define enumerations, i.e., bijections to the positive integers. In GAP, this can be implemented via enumerators (see 21.23). These are lists containing the elements in a specified ordering, and the operations Position (21.16.1) and list access via \[\] (21.2.1) define the desired bijection. For implementing such an enumerator, one mainly needs to install the appropriate functions for these operations.

A general setup for creating such lists is given by EnumeratorByFunctions (30.3.4). If the set in question is a domain D for which a Size (30.4.6) method is available then all one has to do is to write down the functions for computing the n-th element of the list and for computing the position of a given GAP object in the list, to put them into the components ElementNumber and NumberElement of a record, and to call EnumeratorByFunctions (30.3.4) with the domain D and this record as arguments. For example, the following lines of code install an Enumerator (30.3.2) method for the case that D is the domain of rational integers. (Note that IsIntegers (14.1.2) is a filter that describes exactly the domain of rational integers.)

Example

```
InstallMethod( Enumerator, 
    "for integers",
    [ IsIntegers ],
    Integers -> EnumeratorByFunctions( Integers, rec( 
        ElementNumber := function( e, n ) ... end, 
        NumberElement := function( e, x ) ... end ) ) );
```

The bodies of the functions have been omitted above; here is the code that is actually used in GAP. (The ordering coincides with that for the iterators for the domain of rational integers that have been discussed in 79.2 and 79.3.)

```
gap> enum:= Enumerator( Integers );
<enumerator of Integers>
gap> Print( enum!.NumberElement, "\n" );
function ( e, x )
    local pos;
    if not IsInt( x ) then
        return fail;
    elif 0 < x then
        pos := 2 * x;
    else
        pos := -2 * x + 1;
    fi;
    return pos;
gap> Print( enum!.ElementNumber, "\n" );
```

(The ordering coincides with that for the iterators for the domain of rational integers that have been discussed in 79.2 and 79.3.)
function ( e, n )
    if n mod 2 = 0 then
        return n / 2;
    else
        return (1 - n) / 2;
    fi;
    return;
end

The situation becomes slightly more complicated if the set \( S \) in question is not a domain. This is because one must provide also at least a method for computing the length of the list, and because one has to determine the family in which it lies (see 79.1). The latter should usually not be a problem since either \( S \) is nonempty and all its elements lie in the same family—in this case one takes the collections family of any element in \( S \)—or the family of the enumerator must be \text{ListsFamily}.

An example in the GAP library is an enumerator for the set of \( k \)-tuples over a finite set; the function is called \text{EnumeratorOfTuples} (16.2.9).

Example

\begin{verbatim}
gap> Print( EnumeratorOfTuples, "\n" );
function ( set, k )
    local enum;
    if k = 0 then
        return Immutable( [ [ ] ] );
    elif IsEmpty( set ) then
        return Immutable( [ ] );
    fi;
    enum := EnumeratorByFunctions( CollectionsFamily( FamilyObj( set ) ),
        rec(
            ElementNumber := function ( enum, n )
                local nn, t, i;
                nn := n - 1;
                t := [ ];
                for i in [ 1 .. enum!.k ] do
                    t[i] := RemInt( nn, Length( enum!.set ) ) + 1;
                    nn := QuoInt( nn, Length( enum!.set ) );
                od;
                if nn <> 0 then
                    Error( "<enum>[", n, "] must have an assigned value" );
                fi;
                nn := enum!.set{Reversed( t )};
                MakeImmutable( nn );
                return nn;
            end,
            NumberElement := function ( enum, elm )
                local n, i;
                if not IsList( elm ) then
                    return fail;
                fi;
                elm := List( elm, function ( x )
                    return Position( enum!.set, x );
                end)
                return Position( enum!.set, x );
        end);
    return enum;
end
\end{verbatim}
We see that the enumerator is a homogeneous list that stores individual functions $\text{ElementNumber}$, $\text{NumberElement}$, $\text{Length}$, and $\text{PrintObj}$; besides that, the data components $S$ and $k$ are contained.

### 79.6 Example – Constructing Iterators

Iterators are a kind of objects that is implemented for several collections in the GAP library and which might be interesting also in other cases, see 30.8. A general setup for implementing new iterators is provided by $\text{IteratorByFunctions}$ (30.8.8).

All one has to do is to write down the functions for $\text{NextIterator}$ (30.8.5), $\text{IsDoneIterator}$ (30.8.4), and $\text{ShallowCopy}$ (12.7.1), and to call $\text{IteratorByFunctions}$ (30.8.8) with this record as argument. For example, the following lines of code install an $\text{Iterator}$ (30.8.1) method for the case that the argument is the domain of rational integers.

(Nota that $\text{IsIntegers}$ (14.1.2) is a filter that describes exactly the domain of rational integers.)

```gap
InstallMethod( Iterator, "for integers", [ IsIntegers ], Integers -> IteratorByFunctions( rec( NextIterator:= function( iter ) ... end, IsDoneIterator := ReturnFalse, ShallowCopy := function( iter ) ... end ) ) );
```

The bodies of two of the functions have been omitted above; here is the code that is actually used in GAP. (The ordering coincides with that for the iterators for the domain of rational integers that have been discussed in 79.2 and 79.3.)
Example

```gap
gap> iter := Iterator( Integers );
<iterator of Integers at 0>
gap> Print( iter!.NextIterator, "\n" );
function ( iter )
    iter!.counter := iter!.counter + 1;
    if iter!.counter mod 2 = 0 then
        return iter!.counter / 2;
    else
        return (1 - iter!.counter) / 2;
    fi;
    return;
end
 gap> Print( iter!.ShallowCopy, "\n" );
function ( iter )
    return rec(
        counter := iter!.counter );
end
```

Note that the ShallowCopy component of the record must be a function that does not return an iterator but a record that can be used as the argument of IteratorByFunctions (30.8.8) in order to create the desired shallow copy.

### 79.7 Arithmetic Issues in the Implementation of New Kinds of Lists

When designing a new kind of list objects in GAP, defining the arithmetic behaviour of these objects is an issue.

There are situations where arithmetic operations of list objects are unimportant in the sense that adding two such lists need not be represented in a special way. In such cases it might be useful either to support no arithmetics at all for the new lists, or to enable the default arithmetic methods. The former can be achieved by not setting the filters IsGeneralizedRowVector (21.12.1) and IsMultiplicativeGeneralizedRowVector (21.12.2) in the types of the lists, the latter can be achieved by setting the filter IsListDefault (21.12.3). (for details, see 21.12). An example for “wrapped lists” with default behaviour are vector space bases; they are lists with additional properties concerning the computation of coefficients, but arithmetic properties are not important. So it is no loss to enable the default methods for these lists.

However, often the arithmetic behaviour of new list objects is important, and one wants to keep these lists away from default methods for addition, multiplication etc. For example, the sum and the product of (compatible) block matrices shall be represented as a block matrix, so the default methods for sum and product of matrices shall not be applicable, although the results will be equal to those of the default methods in the sense that their entries at corresponding positions are equal.

So one does not set the filter IsListDefault (21.12.3) in such cases, and thus one can implement one’s own methods for arithmetic operations. (Of course “can” means on the other hand that one must implement such methods if one is interested in arithmetics of the new lists.)

The specific binary arithmetic methods for the new lists will usually cover the case that both arguments are of the new kind, and perhaps also the interaction between a list of the new kind and certain other kinds of lists may be handled if this appears to be useful.
For the last situation, interaction between a new kind of lists and other kinds of lists, GAP provides already a setup. Namely, there are the categories IsGeneralizedRowVector (21.12.1) and IsMultiplicativeGeneralizedRowVector (21.12.2), which are concerned with the additive and the multiplicative behaviour, respectively, of lists. For lists in these filters, the structure of the results of arithmetic operations is prescribed (see 21.13 and 21.14).

For example, if one implements block matrices in IsMultiplicativeGeneralizedRowVector (21.12.2) then automatically the product of such a block matrix and a (plain) list of such block matrices will be defined as the obvious list of matrix products, and a default method for plain lists will handle this multiplication. (Note that this method will rely on a method for computing the product of the block matrices, and of course no default method is available for that.) Conversely, if the block matrices are not in IsMultiplicativeGeneralizedRowVector (21.12.2) then the product of a block matrix and a (plain) list of block matrices is not defined. (There is no default method for it, and one can define the result and provide a method for computing it.)

Thus if one decides to set the filters IsGeneralizedRowVector (21.12.1) and IsMultiplicativeGeneralizedRowVector (21.12.2) for the new lists, on the one hand one loses freedom in defining arithmetic behaviour, but on the other hand one gains several default methods for a more or less natural behaviour.

If a list in the filter IsGeneralizedRowVector (21.12.1) (IsMultiplicativeGeneralizedRowVector (21.12.2)) lies in IsAttributeStoringRep (13.5.5), the values of additive (multiplicative) nesting depth is stored in the list and need not be calculated for each arithmetic operation. One can then store the value(s) already upon creation of the lists, with the effect that the default arithmetic operations will access elements of these lists only if this is unavoidable. For example, the sum of two plain lists of “wrapped matrices” with stored nesting depths are computed via the method for adding two such wrapped lists, and without accessing any of their rows (which might be expensive). In this sense, the wrapped lists are treated as black boxes.

79.8 External Representation

An operation is defined for elements rather than for objects in the sense that if the arguments are replaced by objects that are equal to the old arguments w.r.t. the equivalence relation “=” then the result must be equal to the old result w.r.t. “=”.

But the implementation of many methods is representation dependent in the sense that certain representation dependent subobjects are accessed.

For example, a method that implements the addition of univariate polynomials may access coefficients lists of its arguments only if they are really stored, while in the case of sparsely represented polynomials a different approach is needed.

In spite of this, for many operations one does not want to write an own method for each possible representations of each argument, for example because none of the methods could in fact take advantage of the actually given representations of the objects. Another reason could be that one wants to install first a representation independent method, and then add specific methods as they are needed to gain more efficiency, by really exploiting the fact that the arguments have certain representations.

For the purpose of admitting representation independent code, one can define an external representation of objects in a given family, install methods to compute this external representation for each representation of the objects, and then use this external representation of the objects whenever they occur.

We cannot provide conversion functions that allow us to first convert any object in question to one
particular “standard representation”, and then access the data in the way defined for this representation, simply because it may be impossible to choose such a “standard representation” uniformly for all objects in the given family.

So the aim of an external representation of an object $obj$ is a different one, namely to describe the data from which $obj$ is composed. In particular, the external representation of $obj$ is not one possible (“standard”) representation of $obj$, in fact the external representation of $obj$ is in general different from $obj$ w.r.t. “=”, first of all because the external representation of $obj$ does in general not lie in the same family as $obj$.

For example the external representation of a rational function is a list of length two or three, the first entry being the zero coefficient, the second being a list describing the coefficients and monomials of the numerator, and the third, if bound, being a list describing the coefficients and monomials of the denominator. In particular, the external representation of a polynomial is a list and not a polynomial.

The other way round, the external representation of $obj$ encodes $obj$ in such a way that from this data and the family of $obj$, one can create an object that is equal to $obj$. Usually the external representation of an object is a list or a record.

Although the external representation of $obj$ is by definition independent of the actually available representations for $obj$, it is usual that a representation of $obj$ exists for which the computation of the external representation is obtained by just “unpacking” $obj$, in the sense that the desired data is stored in a component or a position of $obj$, if $obj$ is a component object (see 79.2) or a positional object (see 79.3).

To implement an external representation means to install methods for the following two operations.

### 79.8.1 ExtRepOfObj

\[\text{ExtRepOfObj}(\text{obj})\] (operation)
\[\text{ObjByExtRep}(\text{fam, data})\] (operation)

ExtRepOfObj returns the external representation of its argument, and ObjByExtRep returns an object in the family fam that has external representation data.

Of course, \text{ObjByExtRep( FamilyObj( obj ), ExtRepOfObj( obj ) )} must be equal to obj w.r.t. the operation \(\mathrel{=}(31.11.1)\). But it is not required that equal objects have equal external representations.

Note that if one defines a new representation of objects for which an external representation does already exist then one must install a method to compute this external representation for the objects in the new representation.

### 79.9 Mutability and Copying

Any GAP object is either mutable or immutable. This can be tested with the function \text{IsMutable} (12.6.2). The intended meaning of (im)mutability is a mathematical one: an immutable object should never change in such a way that it represents a different Element. Objects may change in other ways, for instance to store more information, or represent an element in a different way.

Immutability is enforced in different ways for built-in objects (like records, or lists) and for external objects (made using \text{Objectify} (79.1.1)).

For built-in objects which are immutable, the kernel will prevent you from changing them. Thus
For external objects, the situation is different. An external object which claims to be immutable (i.e. its type does not contain IsMutable (12.6.2)) should not admit any methods which change the element it represents. The kernel does not prevent the use of !. and ![ to change the underlying data structure. This is used for instance by the code that stores attribute values for reuse. In general, these ! operations should only be used in methods which depend on the representation of the object. Furthermore, we would not recommend users to install methods which depend on the representations of objects created by the library or by GAP packages, as there is certainly no guarantee of the representations being the same in future versions of GAP.

Here we see an immutable object (the group $S_4$), in which we improperly install a new component.

```gap
gap> g := SymmetricGroup(IsPermGroup,4);
Sym( [ 1 .. 4 ] )
gap> IsMutable(g);
false
gap> NamesOfComponents(g);
[ "Size", "NrMovedPoints", "MovedPoints",
  "GeneratorsOfMagmaWithInverses" ]
gap> g!.silly := "rubbish";
"rubbish"
gap> NamesOfComponents(g);
[ "Size", "NrMovedPoints", "MovedPoints",
  "GeneratorsOfMagmaWithInverses", "silly" ]
```

On the other hand, if we form an immutable externally represented list, we find that GAP will not let us change the object.

```gap
gap> e := Enumerator(g);
<enumerator of perm group>
```

When we consider copying objects, another filter IsCopyable (12.6.1), enters the game and we find that ShallowCopy (12.7.1) and StructuralCopy (12.7.2) behave quite differently. Objects can
be divided for this purpose into three: mutable objects, immutable but copyable objects, and non-
copyable objects (called constants).

A mutable or copyable object should have a method for the operation \texttt{ShallowCopy} (12.7.1),
which should make a new mutable object, sharing its top-level subobjects with the original. The exact
definition of top-level subobject may be defined by the implementor for new kinds of object.

\texttt{ShallowCopy} (12.7.1) applied to a constant simply returns the constant.

\texttt{StructuralCopy} (12.7.2) is expected to be much less used than \texttt{ShallowCopy} (12.7.1). Applied
to a mutable object, it returns a new mutable object which shares no mutable sub-objects with the
input. Applied to an immutable object (even a copyable one), it just returns the object. It is not an
operation (indeed, it’s a rather special kernel function).

\begin{verbatim}
gap> e1 := StructuralCopy(e);
<enumerator of perm group>
gap> IsMutable(e1); false
gap> e2 := ShallowCopy(e);
[ (), (1,4), (1,2,4), (1,3,4), (2,4), (1,4,2), (1,3,4,2),
  (2,3,4), (1,4,2,3), (1,2,3), (1,3)(2,4), (3,4), (1,4,3), (1,2,4,3),
  (1,3), (2,4,3), (1,4,3,2), (1,2)(3,4), (1,3,2), (2,3), (1,4)(2,3),
  (1,2,3,4), (1,3,2,4) ]
gap>
\end{verbatim}

There are two other related functions: \texttt{Immutable} (12.6.3), which makes a new immutable object
which shares no mutable subobjects with its input and \texttt{MakeImmutable} (12.6.4) which changes an
object and its mutable subobjects \textit{in place} to be immutable. It should only be used on “new” objects
that you have just created, and which cannot share mutable subobjects with anything else.

Both \texttt{Immutable} (12.6.3) and \texttt{MakeImmutable} (12.6.4) work on external objects by just resetting
the \texttt{IsMutable} (12.6.2) filter in the object’s type. This should make ineligible any methods that might
change the object. As a consequence, you must allow for the possibility of immutable versions of any
objects you create.

So, if you are implementing your own external objects. The rules amount to the following:

1. You decide if your objects should be mutable or copyable or constants, by fixing whether their
type includes \texttt{IsMutable} (12.6.2) or \texttt{IsCopyable} (12.6.1).

2. You install methods for your objects respecting that decision:

   \textbf{for constants:}
   
   no methods change the underlying elements;

   \textbf{for copyables:}
   
   you provide a method for \texttt{ShallowCopy} (12.7.1);

   \textbf{for mutables:}
   
   you may have methods that change the underlying elements and these should explicitly
   require \texttt{IsMutable} (12.6.2).

\section{Global Variables in the Library}

Global variables in the \texttt{GAP} library are usually read-only in order to avoid their being overwritten
accidentally. See also Section 4.9.
79.10.1 DeclareGlobalVariable

\[\text{DeclareGlobalVariable}(\text{name}[, \text{description}])\]

For global variables that are not functions, instead of using BindGlobal (4.9.8) one can also declare the variable with DeclareGlobalVariable which creates a new global variable named by the string name. If the second argument description is entered then this must be a string that describes the meaning of the global variable. DeclareGlobalVariable shall be used in the declaration part of the respective package (see 79.11), values can then be assigned to the new variable with InstallValue (79.10.2), InstallFlushableValue (79.10.2) or InstallFlushableValueFromFunction (79.10.2), in the implementation part (again, see 79.11).

79.10.2 InstallValue

\[\text{InstallValue}(\text{gvar, value})\]
\[\text{InstallFlushableValue}(\text{gvar, value})\]
\[\text{InstallFlushableValueFromFunction}(\text{gvar, func})\]

InstallValue assigns the value value to the global variable gvar. InstallFlushableValue does the same but additionally provides that each call of FlushCaches (79.10.3) will assign a structural copy of value to gvar. InstallFlushableValueFromFunction instead assigns the result of func to gvar (func is re-evaluated for each invocation of FlushCaches (79.10.3))

InstallValue does not work if value is an “immediate object”, i.e., an internally represented small integer or finite field element. It also fails for booleans. Furthermore, InstallFlushableValue works only if value is a list or a record. (Note that InstallFlushableValue makes sense only for mutable global variables.)

79.10.3 FlushCaches

\[\text{FlushCaches}()\]

FlushCaches resets the value of each global variable that has been declared with DeclareGlobalVariable (79.10.1) and for which the initial value has been set with InstallFlushableValue (79.10.2) or InstallFlushableValueFromFunction (79.10.2) to this initial value.

FlushCaches should be used only for debugging purposes, since the involved global variables include for example lists that store finite fields and cyclotomic fields used in the current GAP session, in order to avoid that these fields are constructed anew in each call to GF (59.3.2) and CF (60.1.1).

79.10.4 DeclareGlobalFunction

\[\text{DeclareGlobalFunction}(\text{name})\]
\[\text{InstallGlobalFunction}(\text{oper, func})\]

DeclareGlobalFunction GAP functions that are not operations and that are intended to be called by users should be notified to GAP in the declaration part of the respective package (see Section 79.11) via DeclareGlobalFunction, which returns a function that serves as a place holder
for the function that will be installed later, and that will print an error message if it is called. See also \texttt{DeclareSynonym} (79.10.5).

A global function declared with \texttt{DeclareGlobalFunction} can be given its value \texttt{func} via \texttt{InstallGlobalFunction}: \texttt{gvar} is the global variable (or a string denoting its name) named with the \texttt{name} argument of the call to \texttt{DeclareGlobalFunction}. For example, a declaration like

\begin{verbatim}
Example
DeclareGlobalFunction( "SumOfTwoCubes" );
\end{verbatim}

in the “declaration part” (see Section 79.11) might have a corresponding “implementation part” of:

\begin{verbatim}
Example
InstallGlobalFunction( SumOfTwoCubes, function(x, y) return x^3 + y^3; end);
\end{verbatim}

\section{79.10.5 \texttt{DeclareSynonym}}

\begin{verbatim}
• \texttt{DeclareSynonym(name, value)}
• \texttt{DeclareSynonymAttr(name, value)}
\end{verbatim}

\texttt{DeclareSynonym} assigns the string \texttt{name} to a global variable as a synonym for \texttt{value}. Two typical intended usages are to declare an “and-filter”, e.g.

\begin{verbatim}
Example
DeclareSynonym( "IsGroup", IsMagmaWithInverses and IsAssociative );
\end{verbatim}

and to provide a previously declared global function with an alternative name, e.g.

\begin{verbatim}
Example
DeclareGlobalFunction( "SizeOfSomething" );
DeclareSynonym( "OrderOfSomething", SizeOfSomething );
\end{verbatim}

\textit{Note:} Before using \texttt{DeclareSynonym} in the way of this second example, one should determine whether the synonym is really needed. Perhaps an extra index entry in the documentation would be sufficient.

When \texttt{value} is actually an attribute then \texttt{DeclareSynonymAttr} should be used; this binds also globals variables \texttt{Setname} and \texttt{Hasname} for its setter and tester, respectively.

\begin{verbatim}
Example
DeclareSynonymAttr( "IsField", IsDivisionRing and IsCommutative );
DeclareAttribute( "GeneratorsOfDivisionRing", IsDivisionRing );
DeclareSynonymAttr( "GeneratorsOfField", GeneratorsOfDivisionRing );
\end{verbatim}

\section{79.11 Declaration and Implementation Part}

Each package of \texttt{GAP} code consists of two parts, the \textit{declaration part} that defines the new categories and operations for the objects the package deals with, and the \textit{implementation part} where the corresponding methods are installed. The declaration part should be representation independent, representation dependent information should be dealt with in the implementation part.

\texttt{GAP} functions that are not operations and that are intended to be called by users should be notified to \texttt{GAP} in the declaration part via \texttt{DeclareGlobalFunction} (79.10.4). Values for these functions can be installed in the implementation part via \texttt{InstallGlobalFunction} (79.10.4).

Calls to the following functions belong to the declaration part.
• DeclareAttribute (13.5.4),
• DeclareCategory (13.3.5),
• DeclareFilter (13.8.2),
• DeclareOperation (78.1.5),
• DeclareGlobalFunction (79.10.4),
• DeclareSynonym (79.10.5),
• DeclareSynonymAttr (79.10.5),
• DeclareProperty (13.7.5),
• InstallTrueMethod (78.8.1).

Calls to the following functions belong to the implementation part.

• DeclareRepresentation (13.4.5),
• InstallGlobalFunction (79.10.4),
• InstallMethod (78.3.1),
• InstallImmediateMethod (78.7.1),
• InstallOtherMethod (78.3.2),
• NewFamily (13.1.2),
• NewType (13.9.3),
• Objectify (79.1.1).

Whenever both a NewSomething and a DeclareSomething variant of a function exist (see 79.10), the use of DeclareSomething is recommended because this protects the variables in question from being overwritten. Note that there are no functions DeclareFamily and DeclareType since families and types are created dynamically, hence usually no global variables are associated to them. Further note that DeclareRepresentation (13.4.5) is regarded as belonging to the implementation part, because usually representations of objects are accessed only in very few places, and all code that involves a particular representation is contained in one file; additionally, representations of objects are often not interesting for the user, so there is no need to provide a user interface or documentation about representations.

It should be emphasized that “declaration” means only an explicit notification of mathematical or technical terms or of concepts to GAP. For example, declaring a category or property with name IsInteresting does of course not tell GAP what this shall mean, and it is necessary to implement possibilities to create objects that know already that they lie in IsInteresting in the case that it is a category, or to install implications or methods in order to compute for a given object whether IsInteresting is true or false for it in the case that IsInteresting is a property.
Chapter 80

Examples of Extending the System

This chapter gives a few examples of how one can extend the functionality of GAP.

They are arranged in ascending difficulty. We show how to install new methods, add new operations and attributes and how to implement new features using categories and representations. (As we do not introduce completely new kinds of objects in these example it will not be necessary to declare any families.) Finally we show a simple way how to create new objects with an own arithmetic.

The examples given are all very rudimentary – no particular error checks are performed and the user interface sometimes is quite clumsy. These examples may be constructed for presentation purposes only and they do not necessarily constitute parts of the GAP library.

Even more complex examples that create whole classes of objects anew will be given in the following two chapters 81 and 82.

80.1 Addition of a Method

The easiest case is the addition of a new algorithm as a method for an existing operation for the existing structures.

For example, assume we wanted to implement a better method for computing the exponent of a nilpotent group (it is the product of the exponents of the Sylow subgroups).

The first task is to find which operation is used by GAP (it is Exponent (39.16.2)) and how it is declared. We can find this in the Reference Manual (in our particular case in section 39.16) and the declaration in the library file lib/grp.gd. The easiest way to find the place of the declaration is usually to grep over all .gd and .g files, see section 83.

In our example the declaration in the library is:

```plaintext
Example DeclareAttribute("Exponent",IsGroup);
```

Similarly we find that the filter IsNilpotentGroup (39.15.3) represents the concept of being nilpotent.

We then write a function that implements the new algorithm which takes the right set of arguments and install it as a method. In our example this installation would be:

```plaintext
Example InstallMethod(Exponent,"for nilpotent groups",
                        [IsGroup and IsNilpotent],
                        function(G)
```

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We have left out the optional rank argument of InstallMethod (78.3.1), which normally is a wise choice – GAP automatically uses an internal ranking based on the filters that is only offset by the given rank. So our method will certainly be regarded as “better” than a method that has been installed for mere groups or for solvable groups but will be ranked lower than the library method for abelian groups.

That’s all. Using 7.2.1 we can check for a nilpotent group that indeed our new method will be used.

When testing, remember that the method selection will not check for properties that are not known. (This is done internally by checking the property tester first.) Therefore the method would not be applicable for the group $g$ in the following definition but only for the – mathematically identical but endowed with more knowledge by GAP – group $h$. (Section 80.3 shows a way around this.)

```
Example
gap> g:=Group((1,2),(1,3)(2,4));;
gap> h:=Group((1,2),(1,3)(2,4));;
gap> IsNilpotentGroup(h); # enforce test
true
gap> HasIsNilpotentGroup(g);  # false
false
```

Let’s now look at a slightly more complicated example: We want to implement a better method for computing normalizers in a nilpotent permutation group. (Such an algorithm can be found for example in [LRW97].)

We already know IsNilpotentGroup (39.15.3), the filter IsPermGroup (43.1.1) represents the concept of being a group of permutations. GAP uses Normalizer (39.11.1) to compute normalizers, however the declaration is a bit more complicated. In the library we find

```
Example
InParent FOA( "Normalizer", IsGroup, IsObject, NewAttribute );
```

The full mechanism of InParent FOA (85.2.1) is described in chapter 85, however for our purposes it is sufficient to know that for such a function the actual work is done by an operation NormalizerOp, an underlying operation for Normalizer (39.11.1) (and all the complications are just there to be able to remember certain results) and that the declaration of this operation is given by the first arguments, it would be:

```
Example
DeclareOperation( "NormalizerOp", [IsGroup, IsObject] );
```

This time we decide to enter a non-default family predicate in the call to InstallMethod (78.3.1). We could just leave it out as in the previous call: this would yield the default value, the function ReturnTrue (5.4.1) of arbitrary many arguments which always returns true. However, then the method might be called in some cases of inconsistent input (for example matrix groups in different characteristics) that ought to fall through the method selection to raise an error.
In our situation, we want the second group to be a subgroup of the first, so necessarily both must have the same family and we can use IsIdenticalObj (12.5.1) as family predicate.

Now we can install the method. Again this manual is lazy and does not show you the actual code:

```
InstallMethod(NormalizerOp,"for nilpotent permutation groups",IsIdenticalObj,
    [IsPermGroup and IsNilpotentGroup,
    IsPermGroup and IsNilpotentGroup],
    function(G,U)
    [ function body omitted ]
end);
```

### 80.2 Extending the Range of Definition of an Existing Operation

It might be that the operation has been defined so far only for a set of objects that is too restrictive for our purposes (or we want to install a method that takes another number of arguments). If this is the case, the call to InstallMethod (78.3.1) causes an error message. We can avoid this by using InstallOtherMethod (78.3.2) instead. It is also possible to re-declare an operation with another number of arguments and/or different filters for its arguments.

### 80.3 Enforcing Property Tests

As mentioned in Section 78.4, GAP does not check unknown properties to test whether a method might be applicable. In some cases one wants to enforce this, however, because the gain from knowing the property outweighs the cost of its determination.

In this situation one has to install a method *without* the additional property (so it can be tried even if the property is not yet known) and at high rank (so it will be used before other methods). The first thing to do in the actual function then is to test the property and to bail out with TryNextMethod (78.5.1) if it turns out to be false.

The above `Exponent` (39.16.2) example thus would become:

```
InstallMethod(Exponent,"test abelianity", [IsGroup],
    50,# enforced high rank
    function(G)
    if not IsAbelian(G) then
    TryNextMethod();
    fi;
    [remaining function body omitted]
end);
```

The value "50" used in this example is quite arbitrary. A better way is to use values that are given by the system inherently: We want this method still to be ranked as high, *as if it had* the IsAbelian (35.4.9) requirement. So we have GAP compute the extra rank of this:

```
InstallMethod(Exponent,"test abelianity", [IsGroup],
    # enforced absolute rank of 'IsGroup and IsAbelian' installation: Subtract
    # the rank of 'IsGroup' and add the rank of 'IsGroup and IsAbelian':
    RankFilter(IsGroup and IsAbelian)
    -RankFilter(IsGroup),
    function(G)
```
the slightly complicated construction of addition and subtraction is necessary because IsGroup (39.2.7) and IsAbelian (35.4.9) might imply the same elementary filters which we otherwise would count twice.

A somehow similar situation occurs with matrix groups. Most methods for matrix groups are only applicable if the group is known to be finite.

However we should not enforce a finiteness test early (someone else later might install good methods for infinite groups while the finiteness test would be too expensive) but just before GAP would give a “no method found” error. This is done by redispersing, see 78.6. For example to enforce such a final finiteness test for normalizer calculations could be done by:

```
Example
RedispatchOnCondition(NormalizerOp,IsIdenticalObj,
  [IsMatrixGroup,IsMatrixGroup],[IsFinite,IsFinite],0);
```

### 80.4 Adding a new Operation

Next, we will consider how to add own operations. As an example we take the Sylow normalizer in a group of a given prime. This operation gets two arguments, the first has to be a group, the second a prime number.

There is a function IsPrimeInt (14.4.2), but no property for being prime (which would be pointless as integers cannot store property values anyhow). So the second argument gets specified only as positive integer:

```
Example
SylowNormalizer:=NewOperation("SylowNormalizer",[IsGroup,IsPosInt]);
```

(As we are using NewOperation (78.1.4) instead of DeclareOperation (78.1.5) as used in the library. The only difference other than that DeclareOperation (78.1.5) saves some typing, is that it also protects the variables against overwriting. When testing code (when one probably wants to change things) this might be restricting. If this does not bother you, you can use

```
Example
DeclareOperation("SylowNormalizer",[IsGroup,IsPosInt]);
```

as well.)

The filters IsGroup (39.2.7) and IsPosInt (14.2.2) given are only used to test that InstallMethod (78.3.1) installs methods with suitable arguments and will be completely ignored when using InstallOtherMethod (78.3.2). Technically one could therefore simply use IsObject (12.1.1) for all arguments in the declaration. The main point of using more specific filters here is to help documenting with which arguments the function is to be used (so for example a call SylowNormalizer(5,G) would be invalid).

Of course initially there are no useful methods for newly declared operations; you will have to write and install them yourself.

If the operation only takes one argument and has reproducible results without side effects, it might be worth declaring it as an attribute instead; see Section 80.5.

### 80.5 Adding a new Attribute

Now we look at an example of how to add a new attribute. As example we consider the set of all primes that divide the size of a group.
First we have to declare the attribute:

```
PrimesDividingSize:=NewAttribute("PrimesDividingSize",IsGroup);
```

(See `NewAttribute (13.5.3)`). This implicitly declares attribute tester and setter, it is convenient however to assign these to variables as well:

```
HasPrimesDividingSize:=Tester(PrimesDividingSize);
SetPrimesDividingSize:=Setter(PrimesDividingSize);
```

Alternatively, there is a declaration command `DeclareAttribute (13.5.4)` that executes all three assignments simultaneously and protects the variables against overwriting:

```
DeclareAttribute("PrimesDividingSize",IsGroup);
```

Next we have to install method(s) for the attribute that compute its value. (This is not strictly necessary. We could use the attribute also without methods only for storing and retrieving information, but calling it for objects for which the value is not known would produce a “no method found” error.) For this purpose we can imagine the attribute simply as an one-argument operation:

```
InstallMethod(PrimesDividingSize,"for finite groups",
    [IsGroup and IsFinite],
    function(G)
        return PrimeDivisors(Size(G));
    end);
```

The function installed must always return a value (or call `TryNextMethod (78.5.1)`). If the object is in the representation `IsAttributeStoringRep (13.5.5)` this return value once computed will be automatically stored and retrieved if the attribute is called a second time. We don’t have to call setter or tester ourselves. (This storage happens by GAP internally calling the attribute setter with the return value of the function. Retrieval is by a high-ranking method which is installed under the condition `HasPrimesDividingSize`. This method was installed automatically when the attribute was declared.)

### 80.6 Adding a new Representation

Next, we look at the implementation of a new representation of existing objects. In most cases we want to implement this representation only for efficiency reasons while keeping all the existing functionality.

For example, assume we wanted (following [Wie69]) to implement permutation groups defined by relations.

Next, we have to decide a few basics about the representation. All existing permutation groups in the library are attribute storing and we probably want to keep this for our new objects. Thus the representation must be a subrepresentation of `IsComponentObjectRep (13.4.1)` and `IsAttributeStoringRep (13.5.5)`. Furthermore we want each object to be a permutation group and we can imply this directly in the representation.
We also decide that we store the degree (the largest point that might be moved) in a component `degree` and the defining relations in a component `relations` (we do not specify the format of relations here. In an actual implementation one would have to design this as well, but it does not affect the declarations this chapter is about).

```
Example
IsPermutationGroupByRelations:=NewRepresentation(
    "IsPermutationGroupByRelations",
    IsComponentObjectRep and IsAttributeStoringRep and IsPermGroup,
    ["degree","relations"]);
```

(If we wanted to implement sparse matrices we might for example rather settle for a positional object in which we store a list of the nonzero entries.)

We can make the new representation a subrepresentation of an existing one. In such a case of course we have to provide all structure of this “parent” representation as well.

Next we need to check in which family our new objects will be. This will be the same family as of every other permutation group, namely the CollectionsFamily(PermutationsFamily) (where the family PermutationsFamily = FamilyObj((1,2,3)) has been defined already in the library).

Now we can write a function to create our new objects. Usually it is helpful to look at functions from the library that are used in similar situations (for example GroupByGenerators (39.2.2) in our case) to make sure we have not forgotten any further requirements in the declaration we might have to add here. However in most cases the function is straightforward:

```
Example
PermutationGroupByRelations:=function(degree,relations)
    local g;
    g:=Objectify(NewType(CollectionsFamily(PermutationsFamily),
        IsPermutationGroupByRelations),
        rec(degree:=degree,relations:=relations));
end;
```

It also is a good idea to install a `PrintObj` (6.3.5) and possibly also a `ViewObj` (6.3.5) method –otherwise testing becomes quite hard:

```
Example
InstallMethod(PrintObj,"for perm grps. given by relations",
    [IsPermutationGroupByRelations],
    function(G)
        Print("PermutationGroupByRelations(" , G!.degree,"",G!.relations,"")");
    end);
```

Next we have to write enough methods for the new representation so that the existing algorithms can be used. In particular we will have to implement methods for all operations for which library or kernel provides methods for the existing (alternative) representations. In our particular case there are no such methods. (If we would have implemented sparse matrices we would have had to implement methods for the list access and assignment functions, see 21.2.) However the existing way permutation groups are represented is by generators. To be able to use the existing machinery we want to be able to obtain a generating set also for groups in our new representation. This can be done (albeit not very effectively) by a stabilizer calculation in the symmetric group given by the `degree` component. The operation function to use is probably a bit complicated and will depend on the format of the `relations` (we have not specified in this example). In the following method we use `operationfunction` as a placeholder:
Example

```gap
InstallMethod(GeneratorsOfGroup,"for perm grps. given by relations",
[IsPermutationGroupByRelations],
function(G)
  local S,U;
  S:=SymmetricGroup(G!.degree);
  U:=Stabilizer(S,G!.relations, operationfunction);
  return GeneratorsOfGroup(U);
end);
```

This is all we must do. Of course for performance reasons one might want to install methods for further operations as well.

### 80.7 Components versus Attributes

In the last section we introduced two new components, `G!.degree` and `G!.relations`. Technically, we could have used attributes instead. There is no clear distinction which variant is to be preferred: An attribute expresses part of the functionality available to certain objects (and thus could be computed later and probably even for a wider class of objects), a component is just part of the internal definition of an object.

So if the data is “of general interest”, if we want the user to have access to it, attributes are preferable. Moreover, attributes can be used by the method selection (by specifying the filter `HasAttr` for an attribute `Attr`). They provide a clean interface and their immutability makes it safe to hand the data to a user who potentially could corrupt a components entries.

On the other hand more “technical” data (say the encoding of a sparse matrix) is better hidden from the user in a component, as declaring it as an attribute would not give any advantage.

Resource-wise, attributes need more memory (the attribute setter and tester are implicitly declared, and one filter bit is required), the attribute access is one further function call in the kernel, thus components might be an immeasurable bit faster.

### 80.8 Adding new Concepts

Now we look how to implement a new concept for existing objects and fit this in the method selection. Three examples that will be made more explicit below would be groups for which a “length” of elements (as a word in certain generators) is defined, groups that can be decomposed as a semidirect product and M-groups.

In each case we have two possibilities for the declaration. We can either declare it as a property or as a category. Both are eventually filter(s) and in this way indistinguishable for the method selection. However, the value of a property for a particular object can be unknown at first and later in the session be computed (to be `true` or `false`). This is implemented by reserving two filters for each property, one indicating whether the property value is known, and one, provided the value is known, to indicate the actual boolean value. Contrary to this, the decision whether or not an object lies in a category is taken at creation time and this is implemented using a single filter.

**Property:**

Properties also are attributes: If a property value is not known for an object, GAP tries to find a method to compute the property value. If no suitable method is found, an error is raised.
Category:

An object is in a category if it has been created in it. Testing the category for an object simply returns this value. Existing objects cannot enter a new category later in life. This means that in most cases one has to write own code to create objects in a new category.

If we want to implement a completely new concept so that new operations are defined only for the new objects—for example bialgebras for which a second scalar multiplication is defined—usually a category is chosen.

Technically, the behaviour of the category \texttt{IsXYZ}, declared as subcategory of \texttt{IsABC} is therefore exactly the same as if we would declare \texttt{IsXYZ} to be a property for \texttt{IsABC} and install the following method:

```plaintext
Example
InstallMethod(IsXYZ,"return false if not known",[IsABC],ReturnFalse);
```

(The word category also has a well-defined mathematical meaning, but this does not need to concern us at this point. The set of objects which is defined to be a (GAP) category does not need to be a category in the mathematical sense, vice versa not every mathematical category is declared as a (GAP) category.)

Eventually the choice between category and property often becomes a matter of taste or style. Sometimes there is even a third possibility (if you have GAP 3 experience this might reflect most closely “an object whose operations record is \texttt{XYOps}”): We might want to indicate this new concept simply by the fact that certain attributes are set. In this case we could simply use the respective attribute tester(s).

The examples given below each give a short argument why the respective solution was chosen, but one could argue as well for other choices.

80.8.1 Example: M-groups

M-groups are finite groups for which all irreducible complex representations are induced from linear representations of subgroups, it turns out that they are all solvable and that every supersolvable group is an M-group. See [Isa76] for further details.

Solvability and supersolvability both are testable properties. We therefore declare \texttt{IsMGroup} as a property for solvable groups:

```plaintext
Example
IsMGroup:=NewProperty("IsMGroup",IsSolvableGroup);
```

The filter \texttt{IsSolvableGroup} (39.15.6) in this declaration only means that methods for \texttt{IsMGroup} by default can only be installed for groups that are (and know to be) solvable (though they could be installed for more general situations using \texttt{InstallOtherMethod} (78.3.2)). It does not yet imply that M-groups are solvable. We must do this deliberately via an implication and we use the same technique to imply that every supersolvable group is an M-group.

```plaintext
Example
InstallTrueMethod(IsSolvableGroup,IsMGroup);
InstallTrueMethod(IsMGroup,IsSupersolvableGroup);
```

Now we might install a method that tests for solvable groups whether they are M-groups:
Example

InstallMethod(IsMGroup,"for solvable groups",[IsSolvableGroup],
    function(G)
        [... code omitted. The function must return 'true' or 'false' ...]
    end);

Note that this example of declaring the IsMGroup property for solvable groups is not a part of the
GAP library, which uses a similar but different filter IsMonomialGroup (39.15.9).

80.8.2 Example: Groups with a word length

Our second example is that of groups for whose elements a word length is defined. (We assume that
the word length is only defined in the context of the group with respect to a preselected generating set
but not for single elements alone. However we will not delve into any details of how this length is
defined and how it could be computed.)

Having a word length is a feature which enables other operations (for example a “word length”
function). This is exactly what categories are intended for and therefore we use one.

First, we declare the category. All objects in this category are groups and so we inherit the super-
category IsGroup (39.2.7):

Example

DeclareCategory("IsGroupWithWordLength",IsGroup);

We also define the operation which is “enabled” by this category, the word length of a group
element, which is defined for a group and an element (remember that group elements are described by
the category IsMultiplicativeElementWithInverse (31.14.13)):

Example

DeclareOperation("WordLengthOfElement",[IsGroupWithWordLength,
    IsMultiplicativeElementWithInverse]);

We then would proceed by installing methods to compute the word length in concrete cases and
might for example add further operations to get shortest words in cosets.

80.8.3 Example: Groups with a decomposition as semidirect product

The third example is groups which have a (nontrivial) decomposition as a semidirect product. If this
information has been found out, we want to be able to use it in algorithms. (Thus we do not only need
the fact that there is a decomposition, but also the decomposition itself.)

We also want this to be applicable to every group and not only for groups which have been explic-
itly constructed via SemidirectProduct (49.2.1).

Instead we simply declare an attribute SemidirectProductDecomposition for groups. (Again,
in this manual we don’t go in the details of how such an decomposition would look like).

Example

DeclareAttribute("SemidirectProductDecomposition",IsGroup);

If a decomposition has been found, it can be stored in a group using
SetSemidirectProductDecomposition. (At the moment all groups in GAP are attribute
storing.)

Methods that rely on the existence of such a decomposition then get installed for the tester filter
HasSemidirectProductDecomposition.
80.9 Creating Own Arithmetic Objects

Finally let’s look at a way to create new objects with a user-defined arithmetic such that one can form for example groups, rings or vector spaces of these elements. This topic is discussed in much more detail in chapter 82, in this section we present a simple approach that may be useful to get started but does not permit you to exploit all potential features.

The basic design is that the user designs some way to represent her objects in terms of GAP’s built-in types, for example as a list or a record. We call this the “defining data” of the new objects. Also provided are functions that perform arithmetic on this “defining data”, that is they take objects of this form and return objects that represent the result of the operation. The function ArithmeticElementCreator (80.9.1) then is called to provide a wrapping such that proper new GAP-objects are created which can be multiplied etc. with the default infix operations such as *.

80.9.1 ArithmeticElementCreator

\[ \text{ArithmeticElementCreator}(\text{spec}) \]


ArithmeticElementCreator offers a simple interface to create new arithmetic elements by providing functions that perform addition, multiplication and so forth, conforming to the specification spec. ArithmeticElementCreator creates a new category, representation and family for the new arithmetic elements being defined, and returns a function which takes the “defining data” of an element and returns the corresponding new arithmetic element.

spec is a record with one or more of the following components:

- **ElementName**
  - string used to identify the new type of object. A global identifier IsElementName will be defined to indicate a category for these new objects. (Therefore it is not clever to have blanks in the name). Also a collections category is defined. (You will get an error message if the identifier IsElementName is already defined.)

- **Equality, LessThan, One, Zero, Multiplication, Inverse, Addition, AdditiveInverse**
  - functions defining the arithmetic operations. The functions interface on the level of “defining data”, the actual methods installed will perform the unwrapping and wrapping as objects. Components are optional, but of course if no multiplication is defined elements cannot be multiplied and so forth.

There are default methods for Equality and LessThan which simply calculate on the defining data. If one is defined, it must be ensured that the other is compatible (so that \( a < b \) implies not \( a = b \)).

- **Print**
  - a function which prints the object. By default, just the defining data is printed.

- **MathInfo**
  - filters determining the mathematical properties of the elements created. A typical value is for example IsMultiplicativeElementWithInverse for group elements.

- **RepInfo**
  - filters determining the representational properties of the elements created. The objects
created are always component objects, so in most cases the only reasonable option is \texttt{IsAttributeStoringRep} to permit the storing of attributes.

All components are optional and will be filled in with default values (though of course an empty record will not result in useful objects).

Note that the resulting objects are not equal to their defining data (even though by default they print as only the defining data). The operation \texttt{UnderlyingElement} can be used to obtain the defining data of such an element.

\section*{80.9.2 Example: ArithmeticElementCreator}

As the first example we look at subsets of \{1,\ldots,4\} and define an “addition” as union and “multiplication” as intersection. These operations are both commutative and we want the resulting elements to know this.

We therefore use the following specification:

\begin{verbatim}
Example

gap> # the whole set
gap> w := [1,2,3,4];
[ 1, 2, 3, 4 ]
gap> PosetElementSpec := rec(  
  > # name of the new elements  
  > ElementName := "PosetOn4",  
  > # arithmetic operations  
  > One := a -> w,  
  > Zero := a -> [],  
  > Multiplication := function(a, b) return Intersection(a, b); end,  
  > Addition := function(a, b) return Union(a, b); end,  
  > # Mathematical properties of the elements  
  > MathInfo := IsCommutativeElement and  
  > IsAssociativeElement and  
  > IsAdditivelyCommutativeElement  
  > );;

gap> mkposet := ArithmeticElementCreator(PosetElementSpec);
function( x ) ... end
\end{verbatim}

Now we can create new elements, perform arithmetic on them and form domains:

\begin{verbatim}
Example

gap> a := mkposet([1,2,3]);
[ 1, 2, 3 ]
gap> CategoriesOfObject(a);
[ "IsExtAElement", "IsNearAdditiveElement",  
  "IsNearAdditiveElementWithZero", "IsAdditiveElement",  
  "IsExtElement", "IsExtElement", "IsMultiplicativeElement",  
  "IsMultiplicativeElementWithOne", "IsAssociativeElement",  
  "IsAdditivelyCommutativeElement", "IsCommutativeElement",  
  "IsPosetOn4" ]

gap> a=[1,2,3];
false
gap> UnderlyingElement(a)=[1,2,3];
true
gap> b:=mkposet([2,3,4]);
\end{verbatim}
The categories IsPoset0n4 and IsPoset0n4Collection can be used to install methods specific to the new objects.

Example

```gap
gap> IsPoset0n4Collection(s);
true
```
Chapter 81

An Example – Residue Class Rings

In this chapter, we give an example how GAP can be extended by new data structures and new functionality. In order to focus on the issues of the implementation, the mathematics in the example chosen is trivial. Namely, we will discuss computations with elements of residue class rings $\mathbb{Z}/n\mathbb{Z}$.

The first attempt is straightforward (see Section 81.1), it deals with the implementation of the necessary arithmetic operations. Section 81.2 deals with the question why it might be useful to use an approach that involves creating a new data structure and integrating the algorithms dealing with these new GAP objects into the system. Section 81.3 shows how this can be done in our example, and Section 81.4, the question of further compatibility of the new objects with known GAP objects is discussed. Finally, Section 81.5 gives some hints how to improve the implementation presented before.

81.1 A First Attempt to Implement Elements of Residue Class Rings

Suppose we want to do computations with elements of a ring $\mathbb{Z}/n\mathbb{Z}$, where $n$ is a positive integer.

First we have to decide how to represent the element $k + n\mathbb{Z}$ in GAP. If the modulus $n$ is fixed then we can use the integer $k$. More precisely, we can use any integer $k'$ such that $k - k'$ is a multiple of $n$. If different moduli are likely to occur then using a list of the form $[k, n]$, or a record of the form $\text{rec}(\text{residue} := k, \text{modulus} := n)$ is more appropriate. In the following, let us assume the list representation $[k, n]$ is chosen. Moreover, we decide that the residue $k$ in all such lists satisfies $0 \leq k < n$, i.e., the result of adding two residue classes represented by $[k_1, n]$ and $[k_2, n]$ (of course with same modulus $n$) will be $[k, n]$ with $k_1 + k_2$ congruent to $k$ modulo $n$ and $0 \leq k < n$.

Now we can implement the arithmetic operations for residue classes. Note that the result of the mod operator is normalized as required. The division by a noninvertible residue class results in fail.

Example

```gap
resclass_sum := function( c1, c2 )
  if c1[2] <> c2[2] then Error( "different moduli" ); fi;
end;;

resclass_diff := function( c1, c2 )
  if c1[2] <> c2[2] then Error( "different moduli" ); fi;
end;;
```

1315
gap> resclass_prod := function( c1, c2 )
>     if c1[2] <> c2[2] then Error( "different moduli" ); fi;
> end;;

With these functions, we can in principle compute with residue classes.

Example

... 

81.2 Why Proceed in a Different Way?

It depends on the computations we intended to do with residue classes whether or not the implementation described in the previous section is satisfactory for us.

Probably we are mainly interested in more complex data structures than the residue classes themselves, for example in matrix algebras or matrix groups over a ring such as \( \mathbb{Z}/4\mathbb{Z} \). For this, we need functions to add, multiply, invert etc. matrices of residue classes. Of course this is not a difficult task, but it requires to write additional GAP code.

And when we have implemented the arithmetic operations for matrices of residue classes, we might be interested in domain operations such as computing the order of a matrix group over \( \mathbb{Z}/4\mathbb{Z} \), a Sylow 2 subgroup, and so on. The problem is that a residue class represented as a pair \([k,n]\) is not regarded as a group element by GAP. We have not yet discussed how a matrix of residue classes shall be represented, but if we choose the obvious representation of a list of lists of our residue classes then also this is not a valid group element in GAP. Hence we cannot apply the function Group (39.2.1) to create a group of residue classes or a group of matrices of residue classes. This is because GAP assumes that group elements can be multiplied via the infix operator \(*\) (equivalently, via the operation \(\backslash\star\) (31.12.1)). Note that in fact the multiplication of two lists \([k_1,n]\), \([k_2,n]\) is defined, but we have \([k_1,n]*[k_2,n] = k_1 * k_2 + n * n\), the standard scalar product of two row vectors of same length. That...
is, the multiplication with $\ast$ is not compatible with the function \texttt{resclass\_prod} introduced in the previous section. Similarly, ring elements are assumed to be added via the infix operator $\ast$; the addition of residue classes is not compatible with the available addition of row vectors.

What we have done in the previous section can be described as implementation of a “standalone” arithmetic for residue classes. In order to use the machinery of the \texttt{GAP} library for creating higher level objects such as matrices, polynomials, or domains over residue class rings, we have to “integrate” this implementation into the \texttt{GAP} library. The key step will be to create a new kind of \texttt{GAP} objects. This will be done in the following sections; there we assume that residue classes and residue class rings are not yet available in \texttt{GAP}; in fact they are available, and their implementation is very close to what is described here.

### 81.3 A Second Attempt to Implement Elements of Residue Class Rings

Faced with the problem to implement elements of the rings $\mathbb{Z}/n\mathbb{Z}$, we must define the \textit{types} of these elements as far as is necessary to distinguish them from other \texttt{GAP} objects.

As is described in Chapter 13, the type of an object comprises several aspects of information about this object; the \textit{family} determines the relation of the object to other objects, the \textit{categories} determine what operations the object admits, the \textit{representation} determines how an object is actually represented, and the \textit{attributes} describe knowledge about the object.

First of all, we must decide about the \textit{family} of each residue class. A natural way to do this is to put the elements of each ring $\mathbb{Z}/n\mathbb{Z}$ into a family of their own. This means that for example elements of $\mathbb{Z}/3\mathbb{Z}$ and $\mathbb{Z}/9\mathbb{Z}$ lie in different families. So the only interesting relation between the families of two residue classes is equality; binary arithmetic operations with two residue classes will be admissible only if their families are equal. Note that in the naive approach in Section 81.1, we had to take care of different moduli by a check in each function; these checks may disappear in the new approach because of our choice of families.

Note that we do not need to tell \texttt{GAP} anything about the above decision concerning the families of the objects that we are going to implement, that is, the \textit{declaration part} (see 79.11) of the little \texttt{GAP} package we are writing contains nothing about the distribution of the new objects into families. (The actual construction of a family happens in the function \texttt{MyZmodnZ} shown below.)

Second, we want to describe methods to add or multiply two elements in $\mathbb{Z}/n\mathbb{Z}$, and these methods shall be not applicable to other \texttt{GAP} objects. The natural way to do this is to create a new \textit{category} in which all elements of all rings $\mathbb{Z}/n\mathbb{Z}$ lie. This is done as follows.

```
Example

\begin{verbatim}
gap> DeclareCategory( "IsMyZmodnZObj", IsScalar );
gap> cat:= CategoryCollections( IsMyZmodnZObj );;
\end{verbatim}
```

So all elements in the rings $\mathbb{Z}/n\mathbb{Z}$ will lie in the category \texttt{IsMyZmodnZObj}, which is a subcategory of \texttt{IsScalar} (31.14.20). The latter means that one can add, subtract, multiply and divide two such elements that lie in the same family, with the obvious restriction that the second operand of a division must be invertible. (The name \texttt{IsMyZmodnZObj} is chosen because \texttt{IsZmodnZObj} (14.5.4) is already defined in \texttt{GAP}, for an implementation of residue classes that is very similar to the one developed in this manual chapter. Using this different name, one can simply enter the \texttt{GAP} code of this chapter into a \texttt{GAP} session, either interactively or by reading a file with this code, and experiment after each step whether the expected behaviour has been achieved, and what is still missing.)
The next lines of GAP code above create the categories $\text{CategoryCollections(}\text{IsMyZmodnZObj})$ and two higher levels of collections categories of this, which will be needed later; it is important to create these categories before collections of the objects in $\text{IsMyZmodnZObj}$ actually arise.

Note that the only difference between $\text{DeclareCategory (13.3.5)}$ and $\text{NewCategory (13.3.4)}$ is that in a call to $\text{DeclareCategory (13.3.5)}$, a variable corresponding to the first argument is set to the new category, and this variable is read-only. The same holds for $\text{DeclareRepresentation (13.4.5)}$ and $\text{NewRepresentation (13.4.4)}$ etc.

There is no analogue of categories in the implementation in Section 81.1, since there it was not necessary to distinguish residue classes from other GAP objects. Note that the functions there assumed that their arguments were residue classes, and the user was responsible not to call them with other arguments. Thus an important aspect of types is to describe arguments of functions explicitly.

Third, we must decide about the representation of our objects. This is something we know already from Section 81.1, where we chose a list of length two. Here we may choose between two essentially different representations for the new GAP objects, namely as “component object” (record-like) or “positional object” (list-like). We decide to store the modulus of each residue class in its family, and to encode the element $k + n\mathbb{Z}$ by the unique residue in the range $[0..n-1]$ that is congruent to $k$ modulo $n$, and the object itself is chosen to be a positional object with this residue at the first and only position (see 79.3).

Example

```
gap> DeclareRepresentation("IsMyModulusRep", IsPositionalObjectRep, [1]);
```

The fourth ingredients of a type, attributes, are usually of minor importance for element objects. In particular, we do not need to introduce special attributes for residue classes.

Having defined what the new objects shall look like, we now declare a global function (see 79.11), to create an element when family and residue are given.

Example

```
gap> DeclareGlobalFunction( "MyZmodnZObj" );
```

Now we have declared what we need, and we can start to implement the missing methods resp. functions; so the following command belongs to the implementation part of our package (see 79.11). The probably most interesting function is the one to construct a residue class.

Example

```
gap> InstallGlobalFunction( MyZmodnZObj, function( Fam, residue )
>     return Objectify( NewType( Fam, IsMyZmodnZObj and IsMyModulusRep ),
>         [ residue mod Fam!.modulus ]);  
> end );
```

Note that we normalize residue explicitly using mod; we assumed that the modulus is stored in Fam, so we must take care of this below. If Fam is a family of residue classes, and residue is an integer, MyZmodnZObj returns the corresponding object in the family Fam, which lies in the category IsMyZmodnZObj and in the representation IsMyModulusRep. MyZmodnZObj needs an appropriate family as first argument, so let us see how to get our hands on this. Of course we could write a handy function to create such a family for given modulus, but we choose another way. In fact we do not really want to call MyZmodnZObj explicitly when we want to create residue classes. For example, if we want to enter a matrix of residues then usually we start with a
matrix of corresponding integers, and it is more elegant to do the conversion via multiplying the matrix with the identity of the required ring $\mathbb{Z}/n\mathbb{Z}$; this is also done for the conversion of integral matrices to finite field matrices. (Note that we will have to install a method for this.) So it is often sufficient to access this identity, for example via one( MyZmodnZ( n ) ), where MyZmodnZ returns a domain representing the ring $\mathbb{Z}/n\mathbb{Z}$ when called with the argument $n$. We decide that constructing this ring is a natural place where the creation of the family can be hidden, and implement the function. (Note that the declaration belongs to the declaration part, and the installation belongs to the implementation part, see 79.11).

Example

```gap
gap> DeclareGlobalFunction( "MyZmodnZ" );
gap> InstallGlobalFunction( MyZmodnZ, function( n )
 gap>   local F, R;
 gap>   if not IsPosInt( n ) then
 gap>     Error( "<n> must be a positive integer" );
 gap>   fi;
 gap>   # Construct the family of element objects of our ring.
 gap>   F:= NewFamily( Concatenation( "MyZmod", String( n ), "Z" ),
 gap>                   IsMyZmodnZObj );
 gap>   # Install the data.
 gap>   F!.modulus:= n;
 gap>   # Make the domain.
 gap>   R:= RingWithOneByGenerators( [ MyZmodnZObj( F, 1 ) ] );
 gap>   SetIsWholeFamily( R, true );
 gap>  SetName( R, Concatenation( "(Integers mod ", String(n), ")" ) );
 gap>   # Return the ring.
 gap>   return R;
 gap> end );
```

Note that the modulus $n$ is stored in the component modulus of the family, as is assumed by MyZmodnZ. Thus it is not necessary to store the modulus in each element. When storing $n$ with the !. operator as value of the component modulus, we used that all families are in fact represented as component objects (see 79.2).

We see that we can use RingWithOneByGenerators (56.3.3) to construct a ring with one if we have the appropriate generators. The construction via RingWithOneByGenerators (56.3.3) makes sure that IsRingWithOne (56.3.1) (and IsRing (56.1.1)) is true for each output of MyZmodnZ. So the main problem is to create the identity element of the ring, which in our case suffices to generate the ring. In order to create this element via MyZmodnZObj, we have to construct its family first, at each call of MyZmodnZ.

Also note that we may enter known information about the ring. Here we store that it contains the whole family of elements; this is useful for example when we want to check the membership of an element in the ring, which can be decided from the type of the element if the ring contains its whole elements family. Giving a name to the ring causes that it will be printed via printing the name. (By the way: This name (Integers mod n) looks like a call to \mod (31.12.1) with the arguments Integers
(14) and n; a construction of the ring via this call seems to be more natural than by calling MyZmodnZ; later we shall install a \mod (31.12.1) method in order to admit this construction.)

Now we can read the above code into GAP, and the following works already.

```
Example

gap> R := MyZmodnZ( 4 );
(Integers mod 4)
gap> IsRing( R );
true
gap> gens := GeneratorsOfRingWithOne( R );
[ <object> ]
```

But of course this means just to ask for the information we have explicitly stored in the ring. Already the questions whether the ring is finite and how many elements it has, cannot be answered by GAP. Clearly we know the answers, and we could store them in the ring, by setting the value of the property IsFinite (30.4.2) to true and the value of the attribute Size (30.4.6) to n (the argument of the call to MyZmodnZ). If we do not want to do so then GAP could only try to find out the number of elements of the ring via forming the closure of the generators under addition and multiplication, but up to now, GAP does not know how to add or multiply two elements of our ring.

So we must install some methods for arithmetic and other operations if the elements are to behave as we want.

We start with a method for showing elements nicely on the screen. There are different operations for this purpose. One of them is PrintObj (6.3.5), which is called for each argument in an explicit call to Print (6.3.4). Another one is ViewObj (6.3.5), which is called in the read-eval-print loop for each object. ViewObj (6.3.5) shall produce short and human readable information about the object in question, whereas PrintObj (6.3.5) shall produce information that may be longer and is (if reasonable) readable by GAP. We cannot satisfy the latter requirement for a PrintObj (6.3.5) method because there is no way to make a family GAP readable. So we decide to display the expression ( k mod n ) for an object that is given by the residue k and the modulus n, which would be fine as a ViewObj (6.3.5) method. Since the default for ViewObj (6.3.5) is to call PrintObj (6.3.5), and since no other ViewObj (6.3.5) method is applicable to our elements, we need only a PrintObj (6.3.5) method.

```
Example

gap> InstallMethod( PrintObj,
>   "for element in Z/nZ (ModulusRep)",
>   [ IsMyZmodnZObj and IsMyModulusRep ],
>   function( x )
>   Print("( \( k \) mod \( n \) )");
> end );
```

So we installed a method for the operation PrintObj (6.3.5) (first argument), and we gave it a suitable information message (second argument), see 7.2.1 and 7.3 for applications of this information string. The third argument tells GAP that the method is applicable for objects that lie in the category IsMyZmodnZObj and in the representation IsMyModulusRep, and the fourth argument is the method itself. More details about InstallMethod (78.3.1) can be found in 78.3.

Note that the requirement IsMyModulusRep for the argument x allows us to access the residue as x!{1}. Since the family of x has the component modulus bound if it is constructed by MyZmodnZ, we may access this component. We check whether the method installation has some effect.
Next we install methods for the comparison operations. Note that we can assume that the residues in the representation chosen are normalized.

Example

```
> InstallMethod( \=,
  >  "for two elements in \mathbb{Z}/n\mathbb{Z} (ModulusRep)",
  >  IsIdenticalObj,
  >  [IsMyZmodnZObj and IsMyModulusRep, IsMyZmodnZObj and IsMyModulusRep],
  >  function( x, y ) return x![1] = y![1]; end );
```

Example

```
> InstallMethod( \<,
  >  "for two elements in \mathbb{Z}/n\mathbb{Z} (ModulusRep)",
  >  IsIdenticalObj,
  >  [IsMyZmodnZObj and IsMyModulusRep, IsMyZmodnZObj and IsMyModulusRep],
  >  function( x, y ) return x![1] < y![1]; end );
```

The third argument used in these installations specifies the required relation between the families of the arguments (see 13.1). This argument of a method installation, if present, is a function that shall be applied to the families of the arguments. IsIdenticalObj (12.5.1) means that the methods are applicable only if both arguments lie in the same family. (In installations for unary methods, obviously no relation is required, so this argument is left out there.)

Up to now, we see no advantage of the new approach over the one in Section 81.1. For a residue class represented as \([ k, n ]\), the way it is printed on the screen is sufficient, and equality and comparison of lists are good enough to define equality and comparison of residue classes if needed. But this is not the case in other situations. For example, if we would have decided that the residue \(k\) need not be normalized then we would have needed functions in Section 81.1 that compute whether two residue classes are equal, and which of two residue classes is regarded as larger than another. Note that we are free to define what “larger” means for objects that are newly introduced.

Next we install methods for the arithmetic operations, first for the additive structure.

Example

```
> InstallMethod( \+,
  >  "for two elements in \mathbb{Z}/n\mathbb{Z} (ModulusRep)",
  >  IsIdenticalObj,
  >  [IsMyZmodnZObj and IsMyModulusRep, IsMyZmodnZObj and IsMyModulusRep],
  >  function( x, y ) return MyZmodnZObj( FamilyObj( x ), x![1] + y![1] );
  > end );
```

```
> InstallMethod( ZeroOp,
  >  "for element in \mathbb{Z}/n\mathbb{Z} (ModulusRep)",
  >  [ IsMyZmodnZObj ],
  >  x -> MyZmodnZObj( FamilyObj( x ), 0 ) );
```

```
> InstallMethod( AdditiveInverseOp,
  >  "for element in \mathbb{Z}/n\mathbb{Z} (ModulusRep)",
  >  [ IsMyZmodnZObj and IsMyModulusRep ],
  >  x -> MyZmodnZObj( FamilyObj( x ), AdditiveInverse( x![1] ) ) );
```
Here the new approach starts to pay off. The method for the operation $\ \oplus \ (31.12.1)$ allows us to use the infix operator $\oplus$ for residue classes. The method for $\text{ZeroOp} \ (31.10.3)$ is used when we call this operation or the attribute $\text{Zero} \ (31.10.3)$ explicitly, and $\text{ZeroOp} \ (31.10.3)$ it is also used when we ask for $0 \ast \text{rescl}$, where $\text{rescl}$ is a residue class.

(Note that $\text{Zero} \ (31.10.3)$ and $\text{ZeroOp} \ (31.10.3)$ are distinguished because $0 \ast \text{obj}$ is guaranteed to return a mutable result whenever a mutable version of this result exists in GAP—for example if $\text{obj}$ is a matrix—whereas $\text{Zero} \ (31.10.3)$ is an attribute and therefore returns immutable results; for our example there is no difference since the residue classes are always immutable, nevertheless we have to install the method for $\text{ZeroOp} \ (31.10.3)$.) The same holds for $\text{AdditiveInverse} \ (31.10.9)$, $\text{One} \ (31.10.2)$, and $\text{Inverse} \ (31.10.8)$.

Similarly, $\text{AdditiveInverseOp} \ (31.10.9)$ can be either called directly or via the unary $-\text{operator}$; so we can compute the additive inverse of the residue class $\text{rescl}$ as $-\text{rescl}$.

It is not necessary to install methods for subtraction, since this is handled via addition of the additive inverse of the second argument if no other method is installed.

Let us try what we can do with the methods that are available now.

```
Example
gap> x:= gens[1]; y:= x + x;
( 1 mod 4 )
( 2 mod 4 )
gap> 0 * x; -x;
( 0 mod 4 )
( 3 mod 4 )
gap> y = -y; x = y; x < y; -x < y;
true
false
true
false
```

We might want to admit the addition of integers and elements in rings $\mathbb{Z}/n\mathbb{Z}$, where an integer is implicitly identified with its residue modulo $n$. To achieve this, we install methods to add an integer to an object in $\text{IsMyZmodnZObj}$ from the left and from the right.

```
Example
gap> InstallMethod( \+,
  "for element in $\mathbb{Z}/n\mathbb{Z}$ (ModulusRep) and integer",
  [ IsMyZmodnZObj and IsMyModulusRep, IsInt ],
  function( x, y )
  return MyZmodnZObj( FamilyObj( x ), x!1 + y );
  end );

gap> InstallMethod( \+,
  "for integer and element in $\mathbb{Z}/n\mathbb{Z}$ (ModulusRep)",
  [ IsInt, IsMyZmodnZObj and IsMyModulusRep ],
  function( x, y )
  return MyZmodnZObj( FamilyObj( y ), x + y!1 );
  end );
```

Now we can do also the following.

```
Example
gap> 2 + x; 7 - x; y - 2;
( 3 mod 4 )
```
Similarly we install the methods dealing with the multiplicative structure. We need methods to multiply two of our objects, and to compute identity and inverse. The operation OneOp (31.10.2) is called when we ask for \texttt{rescl}^0, and InverseOp (31.10.8) is called when we ask for \texttt{rescl}^{-1}. Note that the method for InverseOp (31.10.8) returns \texttt{fail} if the argument is not invertible.

Example

```gap
gap> InstallMethod( \*,
    > "for two elements in \texttt{Z/nZ (ModulusRep)}",
    > IsIdenticalObj,
    > [IsMyZmodnZObj and IsMyModulusRep, IsMyZmodnZObj and IsMyModulusRep],
    > function( x, y )
    > return MyZmodnZObj( FamilyObj( x ), x![1] * y![1] );
    > end );

gap> InstallMethod( OneOp,
    > "for element in \texttt{Z/nZ (ModulusRep)}",
    > [ IsMyZmodnZObj ],
    > elm -> MyZmodnZObj( FamilyObj( elm ), 1 ) );

gap> InstallMethod( InverseOp,
    > "for element in \texttt{Z/nZ (ModulusRep)}",
    > [ IsMyZmodnZObj and IsMyModulusRep ],
    > function( elm )
    > local residue;
    > residue:= QuotientMod( 1, elm![1], FamilyObj( elm )!.modulus );
    > if residue <> fail then
    >    residue:= MyZmodnZObj( FamilyObj( elm ), residue );
    > fi;
    > return residue;
    > end );
```

To be able to multiply our objects with integers, we need not (but we may, and we should if we are going for efficiency) install special methods. This is because in general, \texttt{GAP} interprets the multiplication of an integer and an additive object as abbreviation of successive additions, and there is one generic method for such a multiplication that uses only additions and –in the case of a negative integer– taking the additive inverse. Analogously, there is a generic method for powering by integers that uses only multiplications and taking the multiplicative inverse.

Note that we could also interpret the multiplication with an integer as a shorthand for the multiplication with the corresponding residue class. We are lucky that this interpretation is compatible with the one that is already available. If this would not be the case then of course we would get into trouble by installing a concurrent multiplication that computes something different from the multiplication that is already defined, since \texttt{GAP} does not guarantee which of the applicable methods is actually chosen (see 78.4).

Now we have implemented methods for the arithmetic operations for our elements, and the following calculations work.

```
gap> y:= 2 * x;  z:= (-5) * x;
( 2 \mod 4 )
```
There are some other operations in GAP that we may want to accept our elements as arguments. An example is the operation \texttt{Int (14.2.3)} that returns, e.g., the integral part of a rational number or the integer corresponding to an element in a finite prime field. For our objects, we may define that \texttt{Int (14.2.3)} returns the normalized residue.

Note that we define this behaviour for elements but we implement it for objects in the representation \texttt{IsMyModulusRep}. This means that if someone implements another representation of residue classes then this person must be careful to implement \texttt{Int (14.2.3)} methods for objects in this new representation compatibly with our definition, i.e., such that the result is independent of the representation.

Another example of an operation for which we might want to install a method is \texttt{\mod (31.12.1)}. We make the ring print itself as \texttt{Integers (14)} mod the modulus, and then it is reasonable to allow a construction this way, which makes the \texttt{PrintObj (6.3.5)} output of the ring GAP readable.

Let us try this.
Probably it is not necessary to emphasize that with the approach of Section 81.1, installing methods for existing operations is usually not possible or at least not recommended. For example, installing the function \texttt{resclass\_sum} defined in Section 81.1 as a \texttt{\(+\)} (31.12.1) method for adding two lists of length two (with integer entries) would not be compatible with the general definition of the addition of two lists of same length. Installing a method for the operation \texttt{Int} (14.2.3) that takes a list \([ k, n ]\) and returns \(k\) would in principle be possible, since there is no \texttt{Int} (14.2.3) method for lists yet, but it is not sensible to do so because one can think of other interpretations of such a list where different \texttt{Int} (14.2.3) methods could be installed with the same right.

As mentioned in Section 81.2, one advantage of the new approach is that with the implementation we have up to now, automatically also matrices of residue classes can be treated.

Example

\begin{verbatim}
 gap> r:= Integers mod 16;
 (Integers mod 16)
 gap> x:= One( r );
 ( 1 mod 16 )
 gap> mat:= IdentityMat( 2 ) * x;
 [ [ ( 1 mod 16 ), ( 0 mod 16 ) ], [ ( 0 mod 16 ), ( 1 mod 16 ) ] ]
 gap> mat[1][2]:= x;;
 gap> mat;
 [ [ ( 1 mod 16 ), ( 1 mod 16 ) ], [ ( 0 mod 16 ), ( 1 mod 16 ) ] ]
 gap> Order( mat )
 16
 gap> mat + mat;
 [ [ ( 2 mod 16 ), ( 2 mod 16 ) ], [ ( 0 mod 16 ), ( 2 mod 16 ) ] ]
 gap> last^4;
 [ [ ( 0 mod 16 ), ( 0 mod 16 ) ], [ ( 0 mod 16 ), ( 0 mod 16 ) ] ]
\end{verbatim}

Such matrices, if they are invertible, are valid as group elements. One technical problem is that the default algorithm for inverting matrices may give up since Gaussian elimination need not be successful over rings containing zero divisors. Therefore we install a simpleminded inversion method that inverts an integer matrix.

Example

\begin{verbatim}
 gap> InstallMethod( InverseOp,
 > "for an ordinary matrix over a ring \(\mathbb{Z}/n\mathbb{Z}\)",
 > [ IsMatrix and IsOrdinaryMatrix
 >   and CategoryCollections( CategoryCollections( IsMyZmodnZObj ) ) ],
 > function( mat )
 >   local one, modulus;
 >   one:= One( mat[1][1] )
 >   modulus:= FamilyObj( one )!.modulus;
 >   mat:= InverseOp( List( mat, row -> List( row, Int ) ) )
 > if mat <> fail then
 >   mat:= ( mat mod modulus ) * one;
 > fi;
 > if not IsMatrix( mat ) then
 >   mat:= fail;
 > fi;
 > return mat;
 > end );
\end{verbatim}
Additionally we install a method for finding a domain that contains the matrix entries; this is used by some GAP library functions.

```
Example

gap> InstallMethod( DefaultFieldOfMatrixGroup,
> G -> RingWithOneByGenerators([ One( Representative( G )[1][1] ) ]));
```

Now we can deal with matrix groups over residue class rings.

```
Example

gap> mat2:= IdentityMat( 2 ) * x;;
gap> mat2[2][1]:= x;;
gap> g:= Group( mat, mat2 );;
gap> Size( g );
3072
```

It should be noted that this way more involved methods for matrix groups may not be available. For example, many questions about a finite matrix group can be delegated to an isomorphic permutation group via a so-called “nice monomorphism”; this can be controlled by the filter `IsHandledByNiceMonomorphism (40.5.1).

By the way, also groups of (invertible) residue classes can be formed, but this may be of minor interest.

```
Example

gap> g:= Group( x );;  Size( g );
   #I  default 'IsGeneratorsOfMagmaWithInverses' method returns 'true' for
   [ ( 1 mod 16 ) ]
   1
```

(The messages above tell that GAP does not know a method for deciding whether the given elements are valid group elements. We could add an appropriate `IsGeneratorsOfMagmaWithInverses` method if we would want.)

Having done enough for the elements, we may install some more methods for the rings if we want to use them as arguments. These rings are finite, and there are many generic methods that will work if they are able to compute the list of elements of the ring, so we install a method for this.

```
Example

gap> InstallMethod( Enumerator,
> "for full collection Z/nZ",
```
Note that this method is applicable only to full rings $\mathbb{Z}/n\mathbb{Z}$, for proper subrings it would return a wrong result. Furthermore, it is not required that the argument is a ring; in fact this method is applicable also to the additive group formed by all elements in the family, provided that it knows to contain the whole family.

Analogously, we install methods to compute the size, a random element, and the units of full rings $\mathbb{Z}/n\mathbb{Z}$.

```gap
Example

```
Each ring \( \mathbb{Z}/n\mathbb{Z} \) is finite, and we could install a method that returns \texttt{true} when \texttt{IsFinite} is called with \( \mathbb{Z}/n\mathbb{Z} \) as argument. But we can do this more elegantly via installing a logical implication.

\begin{verbatim}
Example
gap> InstallTrueMethod( IsFinite, CategoryCollections( IsMyZmodnZObj ) and IsDomain );
\end{verbatim}

In effect, every domain that consists of elements in \texttt{IsMyZmodnZObj} will automatically store that it is finite, even if \texttt{IsFinite} is not called for it.

### 81.4 Compatibility of Residue Class Rings with Prime Fields

The above implementation of residue classes and residue class rings has at least two disadvantages. First, if \( p \) is a prime then the ring \( \mathbb{Z}/p\mathbb{Z} \) is in fact a field, but the return values of \texttt{MyZmodnZ} are never regarded as fields because they are not in the category \texttt{IsMagmaWithInversesIfNonzero} (35.1.3). Second, and this makes the example really interesting, there are already elements of finite prime fields implemented in \texttt{GAP}, and we may want to identify them with elements in \( \mathbb{Z}/p\mathbb{Z} \).

To be more precise, elements of finite fields in \texttt{GAP} lie in the category \texttt{IsFFE} (59.1.1), and there is already a representation, \texttt{IsInternalRep} (13.4.1), of these elements via discrete logarithms. The aim of this section is to make \texttt{IsMyModulusRep} an alternative representation of elements in finite prime fields.

Note that this is only one step towards the desired compatibility. Namely, after having a second representation of elements in finite prime fields, we may wish that the function \texttt{GF} (59.3.2) (which is the usual function to create finite fields in \texttt{GAP}) is able to return \texttt{MyZmodnZ( p )} when \texttt{GF( p )} is called for a prime \( p \). Moreover, then we have to decide about a default representation of elements in \texttt{GF( p )} for primes \( p \) for which both representations are available. Of course we can force the new representation by explicitly calling \texttt{MyZmodnZ} and \texttt{MyZmodnZObj} whenever we want, but it is not a priori clear in which situation which representation is preferable.

The same questions will occur when we want to implement a new representation for non-prime fields. The steps of this implementation will be the same as described in this chapter, and we will have to achieve compatibility with both the internal representation of elements in small finite fields and the representation \texttt{IsMyModulusRep} of elements in arbitrary prime fields.

But let us now turn back to the task of this section. We first adjust the setup of the declaration part of the previous section, and then repeat the installations with suitable modifications.

(We should start a new \texttt{GAP} session for that, otherwise \texttt{GAP} will complain that the objects to be declared are already bound; additionally, the methods installed above may be not compatible with the ones we want.)

\begin{verbatim}
Example
gap> DeclareCategory( "IsMyZmodnZObj", IsScalar );
gap>
gap> DeclareCategory( "IsMyZmodnZObjNonprime", IsMyZmodnZObj );
gap>
 gap> DeclareSynonym( "IsMyZmodpZObj", IsMyZmodnZObj and IsFFE );
\end{verbatim}
As in the previous section, all (newly introduced) elements of rings $\mathbb{Z}/n\mathbb{Z}$ lie in the category IsMyZmodnZObj. But now we introduce two subcategories, namely IsMyZmodnZObjNonprime for all elements in rings $\mathbb{Z}/n\mathbb{Z}$ where $n$ is not a prime, and IsMyZmodpZObj for elements in finite prime fields. All objects in the latter are automatically known to lie in the category IsFFE (59.1.1) of finite field elements.

It would be reasonable if also those internally represented elements in the category IsFFE (59.1.1) that do in fact lie in a prime field would also lie in the category IsMyZmodnZObj (and thus in fact in IsMyZmodpZObj). But this cannot be achieved because internally represented finite field elements do in general not store whether they lie in a prime field.

As for the implementation part, again let us start with the definitions of MyZmodnZObj and MyZmodnZ.

```
gap> InstallGlobalFunction( MyZmodnZObj, function( Fam, residue )
  >   if IsFFEFamily( Fam ) then
  >     return Objectify( NewType( Fam, IsMyZmodpZObj
  >       and IsMyModulusRep ),
  >       [ residue mod Characteristic( Fam ) ] );
  >   else
  >     return Objectify( NewType( Fam, IsMyZmodnZObjNonprime
  >       and IsMyModulusRep ),
  >       [ residue mod Fam!.modulus ] );
  > fi;
  > end );
```

```
gap> InstallGlobalFunction( MyZmodnZ, function( n )
  >   local F, R;
  >   if not ( IsInt( n ) and IsPosRat( n ) ) then
  >     Error( "<n> must be a positive integer" );
  >   elif IsPrimeInt( n ) then
  >     # Construct the family of element objects of our field.
  >     F:= FFEFamily( n );
  >     # Make the domain.
  >     R:= FieldOverItselfByGenerators( [ MyZmodnZObj( F, 1 ) ] );
  >     SetIsPrimeField( R, true );
  >   else
  >     # Construct the family of element objects of our ring.
  >     F:= NewFamily( Concatenation( "MyZmod", String( n ), "Z" ),
  >       IsMyZmodnZObjNonprime );
  >     # Install the data.
  >     F!.modulus:= n;
  >     # Make the domain.
  >     R:= RingWithOneByGenerators( [ MyZmodnZObj( F, 1 ) ] );
  >     SetIsWholeFamily( R, true );
```

```
gap> DeclareRepresentation( "IsMyModulusRep", IsPositionalObjectRep, [ 1 ] );
```

```
gap> DeclareGlobalFunction( "MyZmodnZObj" );
```

```
gap> DeclareGlobalFunction( "MyZmodnZ" );
```
Note that the result of `MyZmodnZ` with a prime as argument is a field that does not contain the whole family of its elements, since all finite field elements of a fixed characteristic lie in the same family. Further note that we cannot expect a family of finite field elements to have a component `modulus`, so we use `Characteristic` to get the modulus. Requiring that `Fam!.modulus` works also if `Fam` is a family of finite field elements would violate the rule that an extension of GAP should not force changes in existing code, in this case code dealing with families of finite field elements.

```
gap> InstallMethod( PrintObj, 
    "for element in Z/nZ (ModulusRep)", 
    [ IsMyZmodnZObjNonprime and IsMyModulusRep ], 
    function( x ) 
    Print( "( \( \text{integers mod } \), \text{mod } \), FamilyObj(x)!.modulus, " )" );
    end );
gap> InstallMethod( PrintObj, 
    "for element in Z/pZ (ModulusRep)", 
    [ IsMyZmodpZObj and IsMyModulusRep ], 
    function( x ) 
    Print( "( \( \text{integers mod } \), \text{mod } \), Characteristic(x), " )" );
    end );
gap> InstallMethod( \=, 
    "for two elements in Z/nZ (ModulusRep)", 
    IsIdenticalObj, 
    [ IsMyZmodnZObj and IsMyModulusRep, 
      IsMyZmodnZObj and IsMyModulusRep ], 
    function( x, y ) return x![1] = y![1]; end );
gap> InstallMethod( \=, 
    "for element in Z/pZ (ModulusRep) and internal FFE", 
    IsIdenticalObj, 
    [ IsMyZmodpZObj and IsMyModulusRep, IsFFE and IsInternalRep ], 
    function( x, y ) 
    return DegreeFFE( y ) = 1 and x![1] = IntFFE( y );
    end );
gap> InstallMethod( \=, 
    "for internal FFE and element in Z/pZ (ModulusRep)", 
    IsIdenticalObj,
```
The situation with the operation $<$ is more difficult. Of course we are free to define the comparison of objects in IsMyZmodnZObjNonprime, but for the finite field elements, the comparison must be compatible with the predefined comparison of the “old” finite field elements. The definition of the $<$ comparison of internally represented finite field elements can be found in Chapter 59. In situations where the documentation does not provide the required information, one has to look it up in the GAP code; for example, the comparison in our case can be found in the appropriate source code file of the GAP kernel.

```
gap> InstallMethod( <,  
>     "for two elements in \text{Z}/n\text{Z} (\text{ModulusRep}, nonprime)",  
>     IsIdenticalObj,  
>     [ IsMyZmodnZObjNonprime and IsMyModulusRep,  
>       IsMyZmodnZObjNonprime and IsMyModulusRep ],  
>     function( x, y ) return x[1] < y[1]; end );  
gap> InstallMethod( <,  
>     "for two elements in \text{Z}/p\text{Z} (\text{ModulusRep})",  
>     IsIdenticalObj,  
>     [ IsMyZmodpZObj and IsMyModulusRep,  
>       IsMyZmodpZObj and IsMyModulusRep ],  
>     function( x, y )  
>       local p, r;  
>           # characteristic and primitive root  
>       if x[1] = 0 then  
>          return y[1] <> 0;  
>       elif y[1] = 0 then  
>          return false;  
>       else  
>          p:= Characteristic( x );  
>          r:= PrimitiveRootMod( p );  
>          return LogMod( x[1], r, p ) < LogMod( y[1], r, p );  
>       fi;  
>     end );  
gap> InstallMethod( <,  
>     "for element in \text{Z}/p\text{Z} (\text{ModulusRep}) and internal FFE",  
>     IsIdenticalObj,  
>     [ IsMyZmodpZObj and IsMyModulusRep, IsFFE and IsInternalRep ],  
>     function( x, y ) return x[1] * One( y ) < y;  
>     end );  
gap> InstallMethod( <,  
>     "for internal FFE and element in \text{Z}/p\text{Z} (\text{ModulusRep})",  
>     IsIdenticalObj,  
>     [ IsFFE and IsInternalRep, IsMyZmodpZObj and IsMyModulusRep ],  
>     function( x, y )  
```
Now we install the same methods for the arithmetic operations \( + \) (31.12.1), \( \text{ZeroOp} \) (31.10.3), \( \text{AdditiveInverseOp} \) (31.10.9), \( \text{OneOp} \) (31.10.2) as in the previous section, without listing them below. Also the same \( \text{Int} \) (14.2.3) method is installed for objects in \( \text{IsMyZmodnZObj} \). Note that it is compatible with the definition of \( \text{Int} \) (14.2.3) for finite field elements. And of course the same method for \( \mod \) (31.12.1) is installed.

We have to be careful, however, with the methods for \( \text{InverseOp} \) (31.10.8), \( \div \) (31.12.1), and \( ^{\text{\textdagger}} \) (31.12.1). These methods and the missing methods for arithmetic operations with one argument in \( \text{IsMyModulusRep} \) and the other in \( \text{IsInternalRep} \) (13.4.1) are given below.

```gap
gap> InstallMethod( \+, 
>     "for element in \( \mathbb{Z}/p\mathbb{Z} \) (ModulusRep) and internal FFE",
>     IsIdenticalObj,
>     [ IsMyZmodpZObj and IsMyModulusRep, IsFFE and IsInternalRep ],
>     function( x, y ) return x![1] + y; end );

gap> InstallMethod( \-, 
>     "for internal FFE and element in \( \mathbb{Z}/p\mathbb{Z} \) (ModulusRep)",
>     IsIdenticalObj,
>     [ IsFFE and IsInternalRep, IsMyZmodpZObj and IsMyModulusRep ],
>     function( x, y ) return x + y![1]; end );

gap> InstallMethod( \*, 
>     "for element in \( \mathbb{Z}/p\mathbb{Z} \) (ModulusRep) and internal FFE",
>     IsIdenticalObj,
>     [ IsMyZmodpZObj and IsMyModulusRep, IsFFE and IsInternalRep ],
>     function( x, y ) return x![1] * y; end );

gap> InstallMethod( InverseOp, 
>     "for element in \( \mathbb{Z}/n\mathbb{Z} \) (ModulusRep, nonprime)",
>     [ IsMyZmodnZObjNonprime and IsMyModulusRep ],
>     function( x )
>     local residue;
>     residue:= QuotientMod( 1, x![1], FamilyObj(x)!.modulus );
>     if residue <> fail then
>         residue:= MyZmodnZObj( FamilyObj(x), residue );
>     fi;
>     return residue;
> end );
```

```
function( x )
  local residue;
  residue:= QuotientMod( 1, x![]1, Characteristic( FamilyObj(x) ) );
  if residue <> fail then
    residue:= MyZmodnZObj( FamilyObj(x), residue );
  fi;
  return residue;
end;

The operation \texttt{DegreeFFE (59.2.1)} is defined for finite field elements, we need a method for objects in \texttt{IsMyZmodpZObj}. Note that we need not require \texttt{IsMyModulusRep} since no access to representation dependent data occurs.

\texttt{Example}

\begin{verbatim}
gap> InstallMethod( DegreeFFE, "> for element in \texttt{Z/pZ},
> [ IsMyZmodpZObj ],
> z -> 1 );
\end{verbatim}

The methods for \texttt{Enumerator (30.3.2)}, \texttt{Random (30.7.1)}, \texttt{Size (30.4.6)}, and \texttt{Units (56.5.2)}, that we had installed in the previous section had all assumed that their argument contains the whole family of its elements. So these methods make sense only for the nonprime case. For the prime case, there are already methods for these operations with argument a field.

\texttt{Example}

\begin{verbatim}
gap> InstallMethod( Enumerator, "> for full ring \texttt{Z/nZ},
> [ CategoryCollections( IsMyZmodnZObjNonprime ) and IsWholeFamily ],
> function( R )
> local F;
> F:= ElementsFamily( FamilyObj( R ) );
> return List( [ 0 .. Size( R ) - 1 ], x -> MyZmodnZObj( F, x ) );
> end );

\end{verbatim}

\begin{verbatim}
gap> InstallMethod( Random, "> for full ring \texttt{Z/nZ},
> [ CategoryCollections( IsMyZmodnZObjNonprime ) and IsWholeFamily ],
> R -> MyZmodnZObj( ElementsFamily( FamilyObj( R ) ),
> Random( 0, Size( R ) - 1 ) ) );

\end{verbatim}

\begin{verbatim}
gap> InstallMethod( Size, "> for full ring \texttt{Z/nZ},
> [ CategoryCollections( IsMyZmodnZObjNonprime ) and IsWholeFamily ],
> R -> ElementsFamily( FamilyObj( R ) )!.modulus );

\end{verbatim}

\begin{verbatim}
gap> InstallMethod( Units, "> for full ring \texttt{Z/nZ},
> [ CategoryCollections( IsMyZmodnZObjNonprime )
> and IsWholeFamily and IsRing ],
> function( R )
> local G, gens;
> gens:= GeneratorsPrimeResidues( Size( R ) ).generators;
\end{verbatim}
if not IsEmpty( gens ) and gens[ 1 ] = 1 then
gens:= gens{ [ 2 .. Length( gens ) ] };
fi;
gens:= Flat( gens ) * One( R );
return GroupByGenerators( gens, One( R ) );
end );
gap> InstallTrueMethod( IsFinite,
CategoryCollections( IsMyZmodnZObjNonprime ) and IsDomain );

81.5 Further Improvements in Implementing Residue Class Rings

There are of course many possibilities to improve the implementation.

With the setup as described above, subsequent calls MyZmodnZ( n ) with the same n yield incompatible rings in the sense that elements of one ring cannot be added to elements of an other one. The solution for this problem is to keep a global list of all results of MyZmodnZ in the current GAP session, and to return the stored values whenever possible. Note that this approach would admit PrintObj (6.3.5) methods that produce GAP readable output.

One can improve the Units (56.5.2) method for the full ring in such a way that a group is returned and not only a list of its elements; then the result of Units (56.5.2) can be used, e. g., as input for the operation SylowSubgroup (39.13.1).

To make computations more efficient, one can install methods for -, \/, and ^ (31.12.1); one reason for doing so may be that this avoids the unnecessary construction of the additive or multiplicative inverse, or of intermediate powers.

The call to NewType (13.9.3) in MyZmodnZObj can be avoided by storing the required type, e. g., in the family. But note that it is not admissible to take the type of an existing object as first argument of Objectify (79.1.1). For example, suppose two objects in IsMyZmodnZObj shall be added. Then we must not use the type of one of the arguments in a call of Objectify (79.1.1), because the argument may have knowledge that is not correct for the result of the addition. One may think of the property IsOne (31.10.5) that may hold for both arguments but certainly not for their sum.

<table>
<thead>
<tr>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>InstallMethod( -, &quot;two elements in ( \mathbb{Z}/n\mathbb{Z} ) (ModulusRep)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( -, &quot;( \mathbb{Z}/n\mathbb{Z} )-obj. (ModulusRep) and integer&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( -, &quot;integer and ( \mathbb{Z}/n\mathbb{Z} )-obj. (ModulusRep)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( -, &quot;( \mathbb{Z}/p\mathbb{Z} )-obj. (ModulusRep) and internal FFE&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( -, &quot;internal FFE and ( \mathbb{Z}/p\mathbb{Z} )-obj. (ModulusRep)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( *, &quot;( \mathbb{Z}/n\mathbb{Z} )-obj. (ModulusRep) and integer&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( *, &quot;integer and ( \mathbb{Z}/n\mathbb{Z} )-obj. (ModulusRep)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( /, &quot;two ( \mathbb{Z}/n\mathbb{Z} )-objs. (ModulusRep, nonprime)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( /, &quot;two ( \mathbb{Z}/p\mathbb{Z} )-objs. (ModulusRep)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( /, &quot;( \mathbb{Z}/n\mathbb{Z} )-obj. (ModulusRep) and integer&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( /, &quot;integer and ( \mathbb{Z}/n\mathbb{Z} )-obj. (ModulusRep)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( /, &quot;( \mathbb{Z}/p\mathbb{Z} )-obj. (ModulusRep) and internal FFE&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( /, &quot;internal FFE and ( \mathbb{Z}/p\mathbb{Z} )-obj. (ModulusRep)&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( ^, &quot;( \mathbb{Z}/n\mathbb{Z} )-obj. (ModulusRep, nonprime) &amp; int.&quot; , ... );</td>
</tr>
<tr>
<td>InstallMethod( ^, &quot;( \mathbb{Z}/p\mathbb{Z} )-obj. (ModulusRep) and integer&quot; , ... );</td>
</tr>
</tbody>
</table>
For comparing two objects in \texttt{IsMyZmodpZObj} via “<”, we had to install a quite expensive method because of the compatibility with the comparison of finite field elements that did already exist. In fact GAP supports finite fields with elements represented via discrete logarithms only up to a given size. So in principle we have the freedom to define a cheaper comparison via “<” for objects in \texttt{IsMyZmodpZObj} if the modulus is large enough. This is possible by introducing two categories \texttt{IsMyZmodpZObjSmall} and \texttt{IsMyZmodpZObjLarge}, which are subcategories of \texttt{IsMyZmodpZObj}, and to install different \texttt{<} (31.11.1) methods for pairs of objects in these categories.
Chapter 82

An Example – Designing Arithmetic Operations

In this chapter, we give a –hopefully typical– example of extending GAP by new objects with prescribed arithmetic operations (for a simple approach that may be useful to get started though does not permit to exploit all potential features, see also ArithmeticElementCreator (80.9.1)).

82.1 New Arithmetic Operations vs. New Objects

A usual procedure in mathematics is the definition of new operations for given objects; here are a few typical examples. The Lie bracket defines an interesting new multiplicative structure on a given (associative) algebra. Forming a group ring can be viewed as defining a new addition for the elements of the given group, and extending the multiplication to sums of group elements in a natural way. Forming the exterior algebra of a given vector space can be viewed as defining a new multiplication for the vectors in a natural way.

GAP does not support such a procedure. The main reason for this is that in GAP, the multiplication in a group, a ring etc. is always written as *, and the addition in a vector space, a ring etc. is always written as +. Therefore it is not possible to define the Lie bracket as a “second multiplication” for the elements of a given algebra; in fact, the multiplication in Lie algebras in GAP is denoted by *. Analogously, constructing the group ring as sketched above is impossible if an addition is already defined for the elements; note the difference between the usual addition of matrices and the addition in the group ring of a matrix group! (See Chapter 65 for an example.) Similarly, there is already a multiplication defined for row vectors (yielding the standard scalar product), hence these vectors cannot be regarded as elements of the exterior algebra of the space.

In situations such as the ones mentioned above, GAP’s way to deal with the structures in question is the following. Instead of defining new operations for the given objects, new objects are created to which the given arithmetic operations * and + are then made applicable.

With this construction, matrix Lie algebras consist of matrices that are different from the matrices with associative multiplication; technically, the type of a matrix determines how it is multiplied with other matrices (see IsMatrix (24.2.1)). A matrix with the Lie bracket as its multiplication can be created with the function LieObject (64.1.1) from a matrix with the usual associative multiplication.

Group rings (more general: magma rings, see Chapter 65) can be constructed with FreeMagmaRing (65.1.1) from a coefficient ring and a group. The elements of the group are not
contained in such a group ring, one has to use an embedding map for creating a group ring element that corresponds to a given group element.

It should be noted that the GAP approach to the construction of Lie algebras from associative algebras is generic in the sense that all objects in the filter \texttt{IsLieObject (64.1.2)} use the same methods for their addition, multiplication etc., by delegating to the “underlying” objects of the associative algebra, no matter what these objects actually are. Analogously, also the construction of group rings is generic.

82.2 Designing new Multiplicative Objects

The goal of this section is to implement objects with a prescribed multiplication. Let us assume that we are given a field \( F \), and that we want to define a new multiplication \( \ast \) on \( F \) that is given by \( a \ast b = ab - a - b + 2; \) here \( ab \) denotes the ordinary product in \( F \).

By the discussion in Section 82.1, we know that we cannot define a new multiplication on \( F \) itself but have to create new objects.

We want to distinguish these new objects from all other GAP objects, in order to describe for example the situation that two of our objects shall be multiplied. This distinction is made via the type of the objects. More precisely, we declare a new filter, a function that will return \texttt{true} for our new objects, and \texttt{false} for all other GAP objects. This can be done by calling \texttt{DeclareFilter (13.8.2)}, but since our objects will know about the value already when they are constructed, the filter can be created with \texttt{DeclareCategory (13.3.5)} or \texttt{NewCategory (13.3.4)}.

\begin{verbatim}
Example
DeclareCategory( "IsMyObject", IsObject );
\end{verbatim}

The idea is that the new multiplication will be installed only for objects that “lie in the category \texttt{IsMyObject}”.

The next question is what internal data our new objects store, and how they are accessed. The easiest solution is to store the “underlying” object from the field \( F \). GAP provides two general possibilities how to store this, namely record-like and list-like structures (for examples, see 79.2 and 79.3). We decide to store the data in a list-like structure, at position 1. This representation is declared as follows.

\begin{verbatim}
Example
DeclareRepresentation( "IsMyObjectListRep", IsPositionalObjectRep, [ 1 ] );
\end{verbatim}

Of course we can argue that this declaration is superfluous because all objects in the category \texttt{IsMyObject} will be represented this way; it is possible to proceed like that, but often (in more complicated situations) it turns out to be useful that several representations are available for “the same element”.

For creating the type of our objects, we need to specify to which family (see 13.1) the objects shall belong. For the moment, we need not say anything about relations to other GAP objects, thus the only requirement is that all new objects lie in the same family; therefore we create a new family. Also we are not interested in properties that some of our objects have and others do not have, thus we need only one type, and store it in a global variable.

\begin{verbatim}
Example
MyType:= NewType( NewFamily( "MyFamily" ),
                  IsMyObject and IsMyObjectListRep );
\end{verbatim}
The next step is to write a function that creates a new object. It may look as follows.

```
Example
MyObject:= val -> Objectify( MyType, [ Immutable( val ) ] );
```

Note that we store an immutable copy of the argument in the returned object; without doing so, for example if the argument would be a mutable matrix then the corresponding new object would be changed whenever the matrix is changed (see 12.6 for more details about mutability).

Having entered the above GAP code, we can create some of our objects.

```
Example
gap> a:= MyObject( 3 ); b:= MyObject( 5 );
<object>
<object>
gap> a![1]; b![1];
3
5
```

But clearly a lot is missing. Besides the fact that the desired multiplication is not yet installed, we see that also the way how the objects are printed is not satisfactory.

Let us improve the latter first. There are two GAP functions \texttt{View} (6.3.3) and \texttt{Print} (6.3.4) for showing objects on the screen. \texttt{View} (6.3.3) is thought to show a short and human readable form of the object, and \texttt{Print} (6.3.4) is thought to show a not necessarily short form that is GAP readable whenever this makes sense. We decide to show \texttt{a} as 3 by \texttt{View} (6.3.3), and to show the construction \texttt{MyObject( 3 )} by \texttt{Print} (6.3.4); the methods are installed for the underlying operations \texttt{ViewObj} (6.3.5) and \texttt{PrintObj} (6.3.5).

```
Example
InstallMethod( ViewObj,
  "for object in `IsMyObject'",
  [ IsMyObject and IsMyObjectListRep ],
  function( obj )
    Print( "<", obj![1], ">");
  end );

InstallMethod( PrintObj,
  "for object in `IsMyObject'",
  [ IsMyObject and IsMyObjectListRep ],
  function( obj )
    Print( "MyObject( ", obj![1], ", " )" );
  end );
```

This is the result of the above installations.

```
Example
gap> a; Print( a, \"\n\" );
3
MyObject( 3 )
```

And now we try to install the multiplication.

```
Example
InstallMethod( \*,
  "for two objects in `IsMyObject'",
  [ IsMyObject and IsMyObjectListRep,
```
When we enter the above code, GAP runs into an error. This is due to the fact that the operation \(*\) (31.12.1) is declared for two arguments that lie in the category IsMultiplicativeElement (31.14.10). One could circumvent the check whether the method matches the declaration of the operation, by calling InstallOtherMethod (78.3.2) instead of InstallMethod (78.3.1). But it would make sense if our objects would lie in IsMultiplicativeElement (31.14.10), for example because some generic methods for objects with multiplication would be available then, such as powering by positive integers via repeated squaring. So we want that IsMyObject implies IsMultiplicativeElement (31.14.10). The easiest way to achieve such implications is to use the implied filter as second argument of the DeclareCategory (13.3.5) call; but since we do not want to start anew, we can also install the implication afterwards.

Example

\[
\text{InstallTrueMethod( IsMultiplicativeElement, IsMyObject );}
\]

Afterwards, installing the multiplication works without problems. Note that MyType and therefore also a and b are not affected by this implication, so we construct them anew.

Example

\[
\text{gap> MyType:= NewType( NewFamily( "MyFamily" ),}
\text{ IsMyObject and IsMyObjectListRep );;}
\text{gap> a:= MyObject( 3 );; b:= MyObject( 5 );;}
\text{gap> a*b; a^27;}
\text{<9>}
\text{<134217729>}
\]

Powering the new objects by negative integers is not possible yet, because GAP does not know how to compute the inverse of an element a, say, which is defined as the unique element $a'$ such that both $aa'$ and $a'a$ are “the unique multiplicative neutral element that belongs to $a$”.

And also this neutral element, if it exists, cannot be computed by GAP in our current situation. It does, however, make sense to ask for the multiplicative neutral element of a given magma, and for inverses of elements in the magma.

But before we can form domains of our objects, we must define when two objects are regarded as equal; note that this is necessary in order to decide about the uniqueness of neutral and inverse elements. In our situation, equality is defined in the obvious way. For being able to form sets of our objects, also an ordering via $\prec$ (31.11.1) is defined for them.

Example

\[
\text{InstallMethod( \=,}
\text{ "for two objects in `IsMyObject',}
\text{ [ IsMyObject and IsMyObjectListRep,}
\text{ IsMyObject and IsMyObjectListRep ],}
\text{ function( a, b )}
\text{ return a![1] = b![1];}
\text{ end );}
\text{ InstallMethod( \prec,}
\text{ "for two objects in `IsMyObject',}
\text{ [ IsMyObject and IsMyObjectListRep,}
\text{ IsMyObject and IsMyObjectListRep ],}
\text{ function( a, b )}
\text{ return a![1] < b![1];}
\text{ end );}
\]

Let us look at an example. We start with finite field elements because then the domains are finite, hence the generic methods for such domains will have a chance to succeed.

```gap
Example

gap> a:= MyObject( Z(7) );
<Z(7)>

gap> m:= Magma( a );
<magma with 1 generators>

gap> e:= MultiplicativeNeutralElement( m );
<Z(7)>^2

gap> elms:= AsList( m );
[ <Z(7)>^2, <Z(7)^5> ]

gap> ForAll( elms, x -> ForAny( elms, y -> x*y = e and y*x = e ) );
true

gap> List( elms, x -> First( elms, y -> x*y = e and y*x = e ) );
[ <Z(7)>^5, <Z(7)>^2, <Z(7)> ]
```

So a multiplicative neutral element exists, in fact all elements in the magma \( m \) are invertible. But what about the following.

```gap
Example

gap> b:= MyObject( Z(7)^0 ); m:= Magma( a, b );
<magma with 2 generators>

gap> elms:= AsList( m );
[ <Z(7)^0>, <Z(7)>^2, <Z(7)^5> ]

gap> e:= MultiplicativeNeutralElement( m );
<Z(7)>^2

gap> ForAll( elms, x -> ForAny( elms, y -> x*y = e and y*x = e ) );
false

gap> List( elms, x -> b * x );
[ <Z(7)^0>, <Z(7)>^0, <Z(7)>^0, <Z(7)>^0 ]
```

Here we found a multiplicative neutral element, but the element \( b \) does not have an inverse. If an addition would be defined for our elements then we would say that \( b \) behaves like a zero element.

When we started to implement the new objects, we said that we wanted to define the new multiplication for elements of a given field \( F \). In principle, the current implementation would admit also something like \( \text{MyObject}(2) \ast \text{MyObject}(Z(7)) \). But if we decide that our initial assumption holds, we may define the identity and the inverse of the object \( <a> \) as \( <2*e> \) and \( <a/(a-e)> \), respectively, where \( e \) is the identity element in \( F \) and \( / \) denotes the division in \( F \); note that the element \( <e> \) is not invertible, and that the above definitions are determined by the multiplication defined for our objects. Further note that after the installations shown below, also \( \text{One}(\text{MyObject}(1)) \) is defined.
For technical reasons, we do not install the intended methods for the attributes `One` (31.10.2) and `Inverse` (31.10.8) but for the operations `OneOp` (31.10.2) and `InverseOp` (31.10.8). This is because for certain kinds of objects –mainly matrices– one wants to support a method to compute a mutable identity or inverse, and the attribute needs only a method that takes this object, makes it immutable, and then returns this object. As stated above, we only want to deal with immutable objects, so this distinction is not really interesting for us.

A more interesting point to note is that we should mark our objects as likely to be invertible, since we add the possibility to invert them. Again, this could have been part of the declaration of `IsMyObject`, but we may also formulate an implication for the existing category.

Example

```gap
InstallTrueMethod( IsMultiplicativeElementWithInverse, IsMyObject );

InstallMethod( OneOp,
   "for an object in `IsMyObject`,",
   [ IsMyObject and IsMyObjectListRep ],
   a -> MyObject( 2 * One( a![1] ) );

InstallMethod( InverseOp,
   "for an object in `IsMyObject`,",
   [ IsMyObject and IsMyObjectListRep ],
   a -> MyObject( a![1] / ( a![1] - One( a![1] ) ) );
```

Now we can form groups of our (nonzero) elements.

Example

```gap
MyType:= NewType( NewFamily( "MyFamily" ),
   IsMyObject and IsMyObjectListRep );;

a:= MyObject( Z(7) );
b:= MyObject( 0*Z(7) );
g:= Group( a, b );
gap> Size( g );
6
```

We are completely free to define an addition for our elements, a natural one is given by `a + b = a+b-1`. As we did for the multiplication, we first change `IsMyObject` such that the additive structure is also known.

Example

```gap
InstallTrueMethod( IsAdditiveElementWithInverse, IsMyObject );
```

Next we install the methods for the addition, and those to compute the additive neutral element and the additive inverse.

Example

```gap
InstallMethod( "+",
   "for two objects in `IsMyObject`,",
   [ IsMyObject and IsMyObjectListRep, IsMyObject and IsMyObjectListRep ],
   function( a, b )
   return MyObject( a![1] + b![1] - 1 );
```
Let us try whether the addition works.

Example

```gap
gap> MyType:= NewType( NewFamily( "MyFamily" ),
> IsMyObject and IsMyObjectListRep );;
> a:= MyObject( Z(7) );; b:= MyObject( 0*Z(7) );;
> m:= AdditiveMagma( a, b );
<additive magma with 2 generators>
> Size( m );
7
```

Similar as installing a multiplication automatically makes powering by integers available, multiplication with integers becomes available with the addition.

Example

```gap
gap> 2 * a;
<Z(7)^5>
gap> a+a;
<Z(7)^5>
gap> MyObject( 2*Z(7)^0 ) * a;
<Z(7)>
```

In particular we see that this multiplication does not coincide with the multiplication of two of our objects, that is, an integer cannot be used as a shorthand for one of the new objects in a multiplication.

(It should be possible to create a field with the new multiplication and addition. Currently this fails, due to missing methods for computing several kinds of generators from field generators, for computing the characteristic in the case that the family does not know this in advance, for checking with `AsField` (58.1.9) whether a domain is in fact a field, for computing the closure as a field.)

It should be emphasized that the mechanism described above may be not suitable for the situation that one wants to consider many different multiplications “on the same set of objects”, since the installation of a new multiplication requires the declaration of at least one new filter and the installation of several methods. But the design of GAP is not suitable for such dynamic method installations.

Turning this argument the other way round, the implementation of the new arithmetics defined by the above multiplication and addition is available for any field \( F \), one need not repeat it for each field one is interested in.

Similar to the above situation, the construction of a magma ring \( RM \) from a coefficient ring \( R \) and a magma \( M \) is implemented only once, since the definition of the arithmetic operations depends only on the given multiplication of \( M \) and not on \( M \) itself. So the addition is not implemented for the elements
in $M$ or –more precisely– for an isomorphic copy. In some sense, the addition is installed “for the multiplication”, and as mentioned in Section 82.1, there is only one multiplication $\ast$ (31.12.1) in GAP.
Chapter 83

Library Files

This chapter describes some of the conventions used in the GAP library files. These conventions are intended as a help on how to read library files and how to find information in them. So everybody is recommended to follow these conventions, although they do not prescribe a compulsory programming style – GAP itself will not bother with the formatting of files.

File names have traditionally GAP adhered to the 8+3 convention (to make it possible to use the same filenames even on a MS-DOS file system) and been in lower case (systems that do not recognize lower case in file names will convert them automatically to upper case). It is no longer so important to adhere to these conventions, but at the very least filenames should adhere to a 16+5 convention, and be distinct even after identifying upper and lower case. Directory names of packages, however, must be in lower case (the LoadPackage (76.2.1) command assumes this).

83.1 File Types

The GAP library consists of the following types of files, distinguished by their suffixes:

- .g Files which contain parts of the “inner workings” of GAP. These files usually do not contain mathematical functionality, except for providing links to kernel functions.
- .gd Declaration files. These files contain declarations of all categories, attributes, operations, and global functions. These files also contain the operation definitions in comments.
- .gi Implementation files. These files contain all installations of methods and global functions. Usually declarations of representations are also considered to be part of the implementation and are therefore found in the .gi files.

As a rule of thumb, all .gd files are read in before the .gi files are read. Therefore a .gi file usually may use any operation or global function (it has been declared before), and no care has to be taken towards the order in which the .gi files are read.

83.2 Finding Implementations in the Library

For a concretely given function, you can use FilenameFunc (5.1.4) and StartlineFunc (5.1.5) for finding the file where this function is defined, and the line in this file where the definition of this
function starts. This does not work for arbitrary functions, see Section `FilenamFunc` (5.1.4) for the restrictions.

If you are interested in getting the function which implements a method for specific arguments, you can use 7.2.1. If `FilenamFunc` (5.1.4) does not work for this method then setting the print level of 7.2.1 higher will give you the installation string for this method, which can be used for searching in library files.

To find the occurrence of functions, methods, function names, and installation strings in the library, one can use the `grep` tool under UNIX. To find a function, search for the function name in the .gd files; as global variables are usually declared only once, only few files will show up. The function installation is likely to occur in the corresponding .gi file.

To find a method from the known operation name and the installation string, search for the string `"Method("` (this catches both `InstallMethod` (78.3.1) and `InstallOtherMethod` (78.3.2)) and the installation string or the operation name.

The following tools from the GAP package `Browse` can be used for accessing the code of functions.

- `BrowseGapMethods` (**Browse: BrowseGapMethods see BrowseGapData**) shows an overview of GAP’s operations and methods, and allows one to navigate through the files that contain the implementations of the methods, using a pager.

- `BrowseProfile` (**Browse: BrowseProfile**) shows profiling results (similar to `DisplayProfile` (7.8.9)) and allows one to navigate through the files that contain the implementations of the functions that were actually used, using a pager.

## 83.3 Undocumented Variables

For several global variables in GAP, no information is available via the help system (see Section (**Tutorial: Help**), for a quick overview of the help system, or Chapter 2, for details). There are various reasons for “hiding” a variable from the user; namely, the variable may be regarded as of minor importance (for example, it may be a function called by documented GAP functions that first compute many input parameters for the undocumented function), or it belongs to a part of GAP that is still experimental in the sense that the meaning of the variable has not yet been fixed or even that it is not clear whether the variable will vanish in a more developed version.

As a consequence, it is dangerous to use undocumented variables because they are not guaranteed to exist or to behave the same in future versions of GAP.

Conversely, for documented variables, the definitions in the GAP manual can be relied on for future GAP versions (unless they turn out to be erroneous); if the GAP developers find that some piece of minor, but documented functionality is an insurmountable obstacle to important developments, they may make the smallest possible incompatible change to the functionality at the time of a major release. However, in any such case it will be announced clearly in the GAP Forum what has been changed and why.

So on the one hand, the developers of GAP want to keep the freedom of changing undocumented GAP code. On the other hand, users may be interested in using undocumented variables.

In this case, whenever you write GAP code involving undocumented variables, and want to make sure that this code will work in future versions of GAP, you may ask at support@gap-system.org for documentation about the variables in question. The GAP developers then decide whether these variables shall be documented or not, and if yes, what the definitions shall be.
In the former case, the new documentation is added to the GAP manual, this means that from then on, this definition is protected against changes.

In the latter case (which may occur for example if the variables in question are still experimental), you may add the current values of these variables to your private code if you want to be sure that nothing will be broken later due to changes in GAP.
Chapter 84

Interface to the GAP Help System

In this chapter we describe which information the help system needs about a manual book and how to tell it this information. The code which implements this interface can be found in `lib/helpbase.gi`.

If you are intending to use a documentation format that is already used by some other help book you probably don’t need to know anything from this chapter. However, if you want to create a new format and make it available to GAP then hopefully you will find the necessary information here.

The basic idea of the help system is as follows: One tells GAP a directory which contains a file `manual.six`, see 84.1. When the GAP help is asked something about this book it reads in some basic information from the file `manual.six`: strings like section headers, function names, and index entries to be searched by the online help; information about the available formats of this book like text, html, dvi, and pdf; the actual files containing the documentation, corresponding section numbers, and page numbers: and so on. See 84.2 for a description of the format of the `manual.six` file.

It turns out that there is almost no restriction on the format of the `manual.six` file, except that it must provide a string, say "myownformat" which identifies the format of the help book. Then the basic actions on a help book are delegated by the help system to handler functions stored in a record `HELP_BOOK_HANDLER.myownformat`. See 84.3 for information which functions must be provided by the handler and what they are supposed to do. The main work to teach GAP to use a new document format is to write these handler functions and to produce an appropriate `manual.six` file.

84.1 Installing and Removing a Help Book

84.1.1 HELP_ADD_BOOK

This command tells GAP that in directory `dir` (given as either a string describing the path relative to the GAP root directory `GAPInfo.RootPaths[1]` or as directory object) contains the basic information about a help book. The string `short` is used as an identifying name for that book by the online help. The string `long` should be a short explanation of the content of the book. Both strings together should easily fit on a line, since they are displayed with `?books`.

It is possible to reinstall a book with different strings `short`, `long`; (for example, documentation of a not-loaded GAP package indicates this in the string `short` and if you later load the package, GAP quietly changes the string `short` as it reinstall its documentation).
The only condition necessary to make the installation of a book valid is that the directory \texttt{dir} must contain a file \texttt{manual.six}. The next section explains how this file must look.

### 84.1.2 HELP\_REMOVE\_BOOK

\begin{verbatim}
HELP\_REMOVE\_BOOK\(short\)
\end{verbatim}

This command tells GAP not to use the help book with identifying name \texttt{short} any more. The book can be re-installed using HELP\_ADD\_BOOK (84.1.1).

### 84.2 The manual.six File

The first non-empty line of \texttt{manual.six} should be of the form

\begin{verbatim}
#SIXFORMAT myownformat
\end{verbatim}

where \texttt{myownformat} is an identifying string for this format. The reading of the (remainder of the) file is then delegated to the function HELP\_BOOK\_HANDLER.\texttt{myownformat}.ReadSix which must exist. Thus there are no further regulations for the format of the \texttt{manual.six} file, other than what you yourself impose. If such a line is missing then it is assumed that the \texttt{manual.six} file complies with the \texttt{gapmacro.tex} documentation format, which internally is referred to as the default format for historical reasons. In that case reading the file is delegated to HELP\_BOOK\_HANDLER.default.ReadSix.

Section 84.3 explains how the return value of HELP\_BOOK\_HANDLER.\texttt{myownformat}.ReadSix should look like and which further function should be contained in HELP\_BOOK\_HANDLER.\texttt{myownformat}.

### 84.3 The Help Book Handler

For each document format \texttt{myownformat} there must be a record HELP\_BOOK\_HANDLER.\texttt{myownformat} of functions with the following names and functionality.

An implementation example of such a set of handler functions is the default format, which is the format name used for the \texttt{gapmacro.tex} documentation format, and this is contained in the file \texttt{lib/helpdef.gi}.

The package GAPDoc (see Chapter (GAPDoc: Introduction and Example)) also defines a format (as it should) which is called: \texttt{GapDocGAP} (the case is significant).

As you can see by the above two examples, the name for a document format can be anything, but it should be in some way meaningful.

\begin{verbatim}
ReadSix( stream )
\end{verbatim}

For an input text stream \texttt{stream} to a \texttt{manual.six} file, this must return a record \texttt{info} which has at least the following two components: \texttt{bookname} which is the short identifying name of the help book, and \texttt{entries}. Here \texttt{info.entries} must be a list with one entry per search string (which can be a section header, function name, index entry, or whatever seems sensible to be searched for matching a help query). A match for the GAP help is a pair (\texttt{info.i}) where \texttt{i} refers to an index for the list \texttt{info.entries} and this corresponds to a certain position in the document. There is one further regulation for the format of the entries of \texttt{info.entries}. They must be lists and the first element of such a list must be a string which is printed by GAP for example when several matches are found for a query (so it should essentially be the string
which is searched for the match, except that it may contain upper and lower case letters or some markup). There may be other components in info which are needed by the functions below, but their names and formats are not prescribed. The stream argument is typically generated using InputTextFile (10.5.1), e.g.

Example

```gap
gap> dirs := DirectoriesLibrary( "doc/ref" );;
gap> file := Filename( dirs, "manual.six" );;
gap> stream := InputTextFile( file );;
```

ShowChapters( info )

This must return a text string or list of text lines which contains the chapter headers of the book info.bookname.

ShowSection( info )

This must return a text string or list of text lines which contains the section (and chapter) headers of the book info.bookname.

SearchMatches( info, topic, frombegin )

This function must return a list of indices of info.entries for entries which match the search string topic. If frombegin is true then those parts of topic which are separated by spaces should be considered as the beginnings of words to decide the matching. It frombegin is false, a substring search should be performed. The string topic can be assumed to be already normalized (transformed to lower case, and whitespace normalized). The function must return a list with two entries [exact, match] where exact is the list of indices for exact matches and match a list of indices of the remaining matches.

MatchPrevChap( info, i )

This should return the match [info,j] which points to the beginning of the chapter containing match [info,i], respectively to the beginning of the previous chapter if [info,i] is already the beginning of a chapter. (Corresponds to ?<.)

MatchNextChap( info, i )

Like the previous function except that it should return the match for the beginning of the next chapter. (Corresponds to ?>.)

MatchPrev( info, i )

This should return the previous section (or appropriate portion of the document). (Corresponds to ?<.)

MatchNext( info, i )

Like the previous function except that it should return the next section (or appropriate portion of the document). (Corresponds to ?>.)

HelpData( info, i, type )

This returns for match [info,i] some data whose format depends on the string type, or fail if these data are not available. The values of type which currently must be handled and the corresponding result format are described in the list below.
SubsectionNumber( info, i )

This returns some GAP object that identifies the position in the book where the display of this entry is started. This can be useful to detect if several help book entries actually point to the same place.

The HELP_BOOK_HANDLER. myownformat . HelpData function must recognize the following values of the type argument.

"text"

This must return a corresponding text string in a format which can be fed into the Pager, see Pager (2.4.1).

"url"

If the help book is available in HTML format this must return an URL as a string (Probably a file:// URL containing a label for the exact start position in that file). Otherwise it returns fail.

"dvi"

If the help book is available in dvi-format this must return a record of form rec( file := filename, page := pagename ). Otherwise it returns fail.

"pdf"

Same as case "dvi", but for the corresponding pdf-file.

"seccnr"

This must return a pair like [[3,3,1], "3.3.1"] which gives the section number as chapter number, section number, subsection number triple and a corresponding string (a chapter itself is encoded like [[4,0,0], "4."] ). Useful for cross-referencing between help books.

84.4 Introducing new Viewer for the Online Help

To introduce a new viewer for the online help, one should extend the global record HELP_VIEWER_INFO (84.4.1), the structure of which is explained below.

84.4.1 HELP_VIEWER_INFO

The record HELP_VIEWER_INFO (84.4.1) contains one component for each help viewer. Each such component is a record with two components: .type and .show.

The component .type refers to one of the types recognized by the HelpData handler function explained in the previous section (currently one of "text", "url", "dvi", or "pdf").

The component .show is a function which gets as input the result of a corresponding HelpData handler call, if it was not fail. This function has to perform the actual display of the data. (E.g., by calling a function like Pager (2.4.1) or by starting up an external viewer program.)
Chapter 85

Function-Operation-Attribute Triples

GAP is eager to maintain information that it has gathered about an object, possibly by lengthy calculations. The most important mechanism for information maintenance is the automatic storage and look-up that takes place for attributes; and this was already mentioned in section (Tutorial: Attributes). In this chapter we will describe further mechanisms that allow storage of results that are not values of attributes.

The idea which is common to all sections is that certain operations, which are not themselves attributes, have an attribute associated with them. To automatically delegate tasks to the attribute, GAP knows, in addition to the operation and the attributes also a function, which is “wrapped around” the other two. This “wrapper function” is called by the user and decides whether to call the operation or the attribute or possibly both. The whole function-operation-attribute triple (or FOA triple) is set up by a single GAP command which writes the wrapper function and already installs some methods, e.g., for the attribute to fall back on the operation. The idea is then that subsequent methods, which perform the actual computation, are installed only for the operation, whereas the wrapper function remains unaltered, and in general no additional methods for the attribute are required either.

85.1 Key Dependent Operations

85.1.1 KeyDependentOperation

\begin{verbatim}
> KeyDependentOperation(name, dom-req, key-req, key-test)
\end{verbatim}

There are several functions that require as first argument a domain, e.g., a group, and as second argument something much simpler, e.g., a prime. SylowSubgroup (39.13.1) is an example. Since its value depends on two arguments, it cannot be an attribute, yet one would like to store the Sylow subgroups once they have been computed.

The idea is to provide an attribute of the group, called ComputedSylowSubgroups, and to store the subgroups in this list. The name implies that the value of this attribute may change in the course of a GAP session, whenever a newly-computed Sylow subgroup is put into the list. Therefore, this is a mutable attribute (see 13.5). The list contains primes in each bound odd position and a corresponding Sylow subgroup in the following even position. More precisely, if \( p \) = ComputedSylowSubgroups( \( G \) )[ even - 1 ] then ComputedSylowSubgroups( \( G \) )[ even ] holds the value of SylowSubgroup( \( G, p \) ). The pairs are sorted in increasing order of \( p \), in particular at most one Sylow \( p \) subgroup of \( G \) is stored for each prime \( p \). This attribute value is maintained by the function SylowSubgroup.
(39.13.1), which calls the operation \texttt{SylowSubgroupOp}( G, p ) to do the real work, if the prime \texttt{p} cannot be found in the list. So methods that do the real work should be installed for \texttt{SylowSubgroupOp} and not for \texttt{SylowSubgroup} (39.13.1).

The same mechanism works for other functions as well, e.g., for \texttt{PCore} (39.11.3), but also for \texttt{HallSubgroup} (39.13.3), where the second argument is not a prime but a set of primes.

\texttt{KeyDependentOperation} declares the two operations and the attribute as described above, with names \texttt{name}, \texttt{nameOp}, and \texttt{Computedname}s, as well as tester and setter operations \texttt{Hasname} and \texttt{Setname}, respectively. Note, however, that the tester is not a filter. \texttt{dom-req} and \texttt{key-req} specify the required filters for the first and second argument of the operation \texttt{nameOp}, which are needed to create this operation with \texttt{DeclareOperation} (78.1.5). \texttt{dom-req} is also the required filter for the corresponding attribute \texttt{Computedname}s. The fourth argument \texttt{key-test} is in general a function to which the second argument \texttt{info} of \texttt{name} ( \textit{D}, \textit{info} ) will be passed. This function can perform tests on \textit{info} and raise an error if appropriate.

For example, to set up the three objects \texttt{SylowSubgroup} (39.13.1), \texttt{SylowSubgroupOp}, \texttt{ComputedSylowSubgroups} together, the declaration file \texttt{lib/grp.gd} contains the following line of code.

\begin{verbatim}
Example
KeyDependentOperation( "SylowSubgroup", IsGroup, IsPosInt, "prime" );
\end{verbatim}

In this example, \texttt{key-test} has the value "prime", which is silently replaced by a function that tests whether its argument is a prime.

\begin{verbatim}
Example
s4 := Group((1,2,3,4),(1,2));;
SylowSubgroup( s4, 7 );; ComputedSylowSubgroups( s4 );
[ 7, Group(()) ]
SylowSubgroup( s4, 2 );; ComputedSylowSubgroups( s4 );
[ 2, Group([ (3,4), (1,4)(2,3), (1,3)(2,4) ]), 7, Group(()) ]
HasSylowSubgroup( s4, 5 );
false
SetSylowSubgroup( s4, 5, Group(()) );; ComputedSylowSubgroups( s4 );
[ 2, Group([ (3,4), (1,4)(2,3), (1,3)(2,4) ]), 5, Group(()), 7, Group(()) ]
SylowSubgroup( s4, 6 );
Error, SylowSubgroup: <p> must be a prime called from
<compiled or corrupted call value> called from
<function>(<arguments>) called from read-eval-loop
Entering break read-eval-print loop ... you can 'quit;' to quit to outer loop, or
you can 'return;' to continue
brk> quit;
\end{verbatim}

Thus the prime test need not be repeated in the methods for the operation \texttt{SylowSubgroupOp} (which are installed to do the real work). Note that no methods need be installed for \texttt{SylowSubgroup} (39.13.1) and \texttt{ComputedSylowSubgroups}. If a method is installed with \texttt{InstallMethod} (78.3.1) for a wrapper operation such as \texttt{SylowSubgroup} (39.13.1) then a warning is signalled provided the \texttt{InfoWarning} (7.4.8) level is at least 1. (Use \texttt{InstallMethod} (78.3.1) in order to suppress the warning.)
85.2 In Parent Attributes

85.2.1 InParentFOA

\( \texttt{InParentFOA(name, super, sub, AorP)} \)

This section describes how you can add new “in parent attributes” (see 31.8 and 31.7). As an example, we describe how \texttt{Index (39.3.2)} and its related functions are implemented.

There are two operations \texttt{Index (39.3.2)} and \texttt{IndexOp}, and an attribute \texttt{IndexInParent}. They are created together as shown below, and after they have been created, methods need be installed only for \texttt{IndexOp}. In the creation process, \texttt{IndexInParent} already gets one default method installed (in addition to the usual system getter of each attribute, see 13.5), namely \( D \rightarrow \texttt{IndexOp( Parent(D), D )} \).

The operation \texttt{Index (39.3.2)} proceeds as follows.

- If it is called with the two arguments \texttt{super} and \texttt{sub}, and if \texttt{HasParent(sub)} and \texttt{IsIdenticalObj(super, Parent(sub))} are true, \texttt{IndexInParent} is called with argument \texttt{sub}, and the result is returned.
- Otherwise, \texttt{IndexOp} is called with the same arguments that \texttt{Index (39.3.2)} was called with, and the result is returned.

(Note that it is in principle possible to install even \texttt{Index (39.3.2)} and \texttt{IndexOp} methods for a number of arguments different from two, with \texttt{InstallOtherMethod (78.3.2)}, see 13.5).

The call of \texttt{InParentFOA} declares the operations and the attribute as described above, with names \texttt{name, name Op, and name InParent}. \texttt{super-req} and \texttt{sub-req} specify the required filters for the first and second argument of the operation \texttt{name Op}, which are needed to create this operation with \texttt{DeclareOperation (78.1.5)}. \texttt{sub-req} is also the required filter for the corresponding attribute \texttt{name InParent}; note that \texttt{HasParent (31.7.1)} is not required for the argument \( U \) of \texttt{name InParent}, because even without a parent stored, \texttt{Parent(U)} is legal, meaning \( U \) itself (see 31.7). The fourth argument must be \texttt{DeclareProperty (13.7.5)} if \texttt{name InParent} takes only boolean values (for example in the case \texttt{IsNormalInParent}), and \texttt{DeclareAttribute (13.5.4)} otherwise.

For example, to set up the three objects \texttt{Index (39.3.2)}, \texttt{IndexOp}, and \texttt{IndexInParent} together, the declaration file \texttt{lib/domain.gd} contains the following line of code.

\begin{verbatim}
Example
InParentFOA( "Index", IsGroup, IsGroup, DeclareAttribute );
\end{verbatim}

Note that no methods need be installed for \texttt{Index (39.3.2)} and \texttt{IndexInParent}.

85.3 Operation Functions

Chapter 41 and, in particular, the Section 41.1 explain that certain operations such as 41.4), besides their usual usage with arguments \( G, D, \) and \( opr \), can also be applied to an external set (\( G \)-set), in which case they can be interpreted as attributes. Moreover, they can also be interpreted as attributes for permutation groups, meaning the natural action on the set of its moved points.

The definition of 41.4 says that a method should be a function with arguments \( G, D, gens, oprs, \) and \( opr \), as in the case of the operation \texttt{ExternalSet (41.12.2)} when specified via \texttt{gens} and \texttt{oprs}.

(see 41.12). All other syntax variants allowed for 41.4 (e.g., leaving out gens and oprs) are handled by default methods.

The default methods for 41.4 support the following behaviour.

1. If the only argument is an external set xset and the attribute tester HasOrbits( xset ) returns true, the stored value of that attribute is returned.

2. If the only argument is an external set xset and the attribute value is not known, the default arguments are obtained from the data of xset.

3. If gens and oprs are not specified, gens is set to Pcgs( G ) if CanEasilyComputePcgs( G ) is true, and to GeneratorsOfGroup( G ) otherwise; oprs is set to gens.

4. The default value of opr is OnPoints (41.2.1).

5. In the case of an operation of a permutation group G on MovedPoints( G ) via OnPoints (41.2.1), if the attribute tester HasOrbits( G ) returns true, the stored attribute value is returned.

6. The operation is called as \( \text{result} := \text{Orbits}( G, D, \text{gens}, \text{oprs}, \text{opr} ) \).

7. In the case of an external set xset or a permutation group G in its natural action, the attribute setter is called to store result.

8. result is returned.

The declaration of operations that match the above pattern is done as follows.

\texttt{85.3.1 OrbitsishOperation}  
\texttt{OrbitsishOperation( \text{name, reqs, usetype, AorP} )} (function)

declares an attribute op, with name name. The second argument reqs specifies the list of required filters for the usual (five-argument) methods that do the real work.

If the third argument usetype is true, the function call op( xset ) will –if the value of op for xset is not yet known– delegate to the five-argument call of op with second argument xset rather than with \( D \). This allows certain methods for op to make use of the type of xset, in which the types of the external subsets of xset and of the external orbits in xset are stored. (This is used to avoid repeated calls of NewType (13.9.3) in functions like ExternalOrbits( xset ), which call ExternalOrbit( xset, pnt ) for several values of pnt.)

For property testing functions such as IsTransitive (41.10.1), the fourth argument AorP must be NewProperty (13.7.4), otherwise it must be NewAttribute (13.5.3); in the former case, a property is returned, in the latter case an attribute that is not a property.

For example, to set up the operation Orbits (41.4.2), the declaration file lib/oprt.gd contains the following line of code:

\texttt{Example OrbitsishOperation( "Orbits", OrbitsishReq, false, NewAttribute );}

The global variable OrbitsishReq contains the standard requirements
which are usually entered in calls to \texttt{OrbitsishOperation}.

The new operation, e.g., \texttt{Orbits(41.4.2)}, can be called either as \texttt{Orbits(\textit{xset})} for an external set \textit{xset}, or as \texttt{Orbits(\textit{G})} for a permutation group \textit{G}, meaning the orbits on the moved points of \textit{G} via \texttt{OnPoints(41.2.1)}, or as \texttt{Orbits(\textit{G}, \textit{Omega}, \textit{gens}, \textit{acts}[\textit{act}])},

with a group \textit{G}, a domain or list \textit{Omega}, generators \textit{gens} of \textit{G}, and corresponding elements \textit{acts} that act on \textit{Omega} via the function \textit{act}; the default of \textit{gens} and \textit{acts} is a list of group generators of \textit{G}, the default of \textit{act} is \texttt{OnPoints(41.2.1)}.

Only methods for the five-argument version need to be installed for doing the real work. (And of course methods for one argument in case one wants to define a new meaning of the attribute.)

### 85.3.2 OrbitishFO

\texttt{OrbitishFO(\textit{name}, \textit{reqs}, \textit{famrel}, \textit{usetype}, \textit{realenum})} (function)

is used to create operations like \texttt{Orbit(41.4.1)}. This function is analogous to \texttt{OrbitsishOperation(85.3.1)}, but for operations \textit{orbish} like \texttt{Orbit(\textit{G}, \textit{Omega}, \textit{pnt})}. Since the return values of these operations depend on the additional argument \textit{pnt}, there is no associated attribute.

The call of \texttt{OrbitishFO} declares a wrapper function and its operation, with names \textit{name} and \textit{nameOp}.

The second argument \textit{reqs} specifies the list of required filters for the operation \textit{nameOp}.

The third argument \textit{famrel} is used to test the family relation between the second and third argument of \texttt{\textit{name}(\textit{G}, \textit{D}, \textit{pnt})}. For example, \texttt{famrel} is \texttt{IsCollsElms} in the case of \texttt{Orbit(41.4.1)} because \textit{pnt} must be an element of \textit{D}. Similarly, in the call \texttt{Blocks(\textit{G}, \textit{D}, \textit{seed})}, \textit{seed} must be a subset of \textit{D}, and the family relation must be \texttt{IsIdenticalObj(12.5.1)}.

The fourth argument \textit{usetype} serves the same purpose as in the case of \texttt{OrbitsishOperation(85.3.1)}. \textit{usetype} can also be an attribute, such as \texttt{BlocksAttr} or \texttt{MaximalBlocksAttr}. In this case, if only one of the two arguments \textit{Omega} and \textit{pnt} is given, blocks with no seed are computed, they are stored as attribute values according to the rules of \texttt{OrbitsishOperation(85.3.1)}.

If the 5th argument is set to \texttt{true}, the action for an external set should use the enumerator, otherwise it uses the \texttt{HomeEnumerator(41.12.5)} value. This will make a difference for external orbits as part of a larger domain.

### 85.3.3 Example: Orbit and OrbitOp

For example, to setup the function \texttt{Orbit(41.4.1)} and its operation \texttt{ OrbitOp}, the declaration file \texttt{lib/oprt.gd} contains the following line of code:

\texttt{OrbitishFO( "Orbit", OrbitishReq, IsCollsElms, false, false );}

The variable \texttt{OrbitishReq} contains the standard requirements
Example

OrbitishReq := [ IsGroup, IsList, IsObject,
                 IsList,
                 IsList,
                 IsFunction ];

which are usually entered in calls to OrbitishFO (85.3.2).

The relation test via famrel is used to provide a uniform construction of the wrapper functions created by OrbitishFO (85.3.2), in spite of the different syntax of the specific functions. For example, Orbit (41.4.1) admits the calls Orbit( G, D, pnt, opr ) and Orbit( G, pnt, opr ). i.e., the second argument D may be omitted; Blocks (41.11.1) admits the calls Blocks( G, D, seed, opr ) and Blocks( G, D, opr ). i.e., the third argument may be omitted. The translation to the appropriate call of OrbitOp or Blocks0p, for either operation with five or six arguments, is handled via famrel.

As a consequence, there must not only be methods for OrbitOp with the six arguments corresponding to OrbitishReq, but also methods for only five arguments (i.e., without D). Plenty of examples are contained in the implementation file lib/oprt.gi.

In order to handle a few special cases (currently Blocks (41.11.1) and MaximalBlocks (41.11.2)), also the following form of OrbitishFO (85.3.2) is supported.

OrbitishFO( name, reqs, famrel, attr )

The functions in question depend upon an argument seed, so they cannot be regarded as attributes. However, they are most often called without giving seed, meaning "choose any minimal resp. maximal block system". In this case, the result can be stored as the value of the attribute attr that was entered as fourth argument of OrbitishFO (85.3.2). This attribute is considered by a call Blocks( G, D, opr ) (i.e., without seed) in the same way as Orbits (41.4.2) considers OrbitsAttr.

To set this up, the declaration file lib/oprt.gd contains the following lines:

Example

DeclareAttribute( "BlocksAttr", IsExternalSet );
OrbitishFO( "Blocks",
            [ IsGroup, IsList, IsList,
              IsList, IsList,
              IsFunction ], IsIdenticalObj, BlocksAttr, true );

And this extraordinary FOA triple works as follows:

Example

gap> s4 := Group((1,2,3,4),(1,2));;
gap> Blocks( s4, MovedPoints(s4), [1,2] );
[ [ 1, 2, 3, 4 ] ]
gap> Tester( BlocksAttr )( s4 );
false
gap> Blocks( s4, MovedPoints(s4) );
[ [ 1, 2, 3, 4 ] ]
gap> Tester( BlocksAttr )( s4 ); BlocksAttr( s4 );
true
[ [ 1, 2, 3, 4 ] ]
Chapter 86

Weak Pointers

This chapter describes the use of the kernel feature of weak pointers. This feature is primarily intended for use only in GAP internals, and should be used extremely carefully otherwise.

The GASMAN garbage collector is the part of the kernel that manages memory in the users workspace. It will normally only reclaim the storage used by an object when the object cannot be reached as a subobject of any GAP variable, or from any reference in the kernel. We say that any link to object $a$ from object $b$ “keeps object $a$ alive”, as long as $b$ is alive. It is occasionally convenient, however, to have a link to an object which does not keep it alive, and this is a weak pointer. The most common use is in caches, and similar structures, where it is only necessary to remember how to solve problem $x$ as long as some other link to $x$ exists.

The following section 86.1 describes the semantics of the objects that contain weak pointers. Following sections describe the functions available to manipulate them.

86.1 Weak Pointer Objects

A weak pointer object is similar to a mutable plain list, except that it does not keep its subobjects alive during a garbage collection. From the GAP viewpoint this means that its entries may become unbound, apparently spontaneously, at any time. Considerable care is therefore needed in programming with such an object.

86.1.1 WeakPointerObj

Example

```gap
gap> w := WeakPointerObj( [ 1, , [2,3], fail, rec( a := 1) ] );
WeakPointerObj( [ 1, , [ 2, 3 ], fail, rec( a := 1 ) ] )
```

After some computations involving garbage collections (but not necessarily in the first garbage collection after the above assignment), GAP will notice that the list and the record stored in $w$ are not referenced by other objects than $w$, and that therefore these entries may disappear.
Note that \texttt{w} has failed to keep its list and record subobjects alive during the garbage collections. Certain subobjects, such as small integers and elements of small finite fields, are not stored in the workspace, and so are not subject to garbage collection, while certain other objects, such as the boolean values, are always reachable from global variables or the kernel and so are never garbage collected.

Subobjects reachable without going through a weak pointer object do not evaporate, as in:

\begin{verbatim}
Example
gap> w := WeakPointerObj([1, , , fail]);
WeakPointerObj([1, , , fail])
gap> l := [1,2,3];;
gap> w[1] := l;;
gap> w;
WeakPointerObj([ [1,2,3], , , fail ])
gap> GASMAN("collect");
gap> w;
WeakPointerObj([ [1,2,3], , , fail ])
\end{verbatim}

Note also that the global variables \texttt{last}, \texttt{last2} and \texttt{last3} will keep things alive – this can be confusing when debugging.

### 86.2 Low Level Access Functions for Weak Pointer Objects

#### 86.2.1 SetElmWPObj

\begin{verbatim}
Example
gap> GASMAN("collect");
... (perhaps more computations and garbage collections) ...
gap> GASMAN("collect");
gap> w;
WeakPointerObj([1, , , fail])
\end{verbatim}

The functions \texttt{SetElmWPObj} and \texttt{UnbindElmWPObj} set and unbind entries in a weak pointer object. The function \texttt{ElmWPObj} returns the element at position \texttt{pos} of the weak pointer object \texttt{wp}, if there is one, and \texttt{fail} otherwise. A return value of \texttt{fail} can thus arise either because (a) the value \texttt{fail} is stored at position \texttt{pos}, or (b) no value is stored at position \texttt{pos}. Since \texttt{fail} cannot vanish in a garbage collection, these two cases can safely be distinguished by a \textit{subsequent} call to \texttt{IsBoundElmWPObj}, which returns \texttt{true} if there is currently a value bound at position \texttt{pos} of \texttt{wp} and \texttt{false} otherwise.

Note that it is not safe to write:

\begin{verbatim}
if IsBoundElmWPObj(w,i) then x := ElmWPObj(w,i); fi;
\end{verbatim}

and treat \texttt{x} as reliably containing a value taken from \texttt{w}, as a badly timed garbage collection could leave \texttt{x} containing \texttt{fail}. Instead use...
x := ElmWPObj(w,i); if x <> fail or IsBoundElmWPObj(w,i) then . . . .
Here is an example.

```gap
gap> w := WeakPointerObj([ 1, , [2,3], fail, rec() ]);  
WeakPointerObj( [ 1, , [ 2, 3 ], fail, rec( ) ] )
gap> SetElmWPObj(w,5,[]);
gap> w;
WeakPointerObj( [ 1, , [ 2, 3 ], fail, [ ] ] )
gap> UnbindElmWPObj(w,1);  
gap> w;
WeakPointerObj( [ , , [ 2, 3 ], fail, [ ] ] )
gap> ElmWPObj(w,3);
[ 2, 3 ]
gap> ElmWPObj(w,1);
fail
```

Now after some computations and garbage collections ...

```gap
gap> 2;;3;;4;;GASMAN("collect"); # clear last, last2, last3
```

... we get the following.

```gap
gap> ElmWPObj(w,3);
fail
gap> w;
WeakPointerObj( [ , , [ fail ] ] )
gap> ElmWPObj(w,4);
fail
gap> IsBoundElmWPObj(w,3);
false
gap> IsBoundElmWPObj(w,4);
true
```

### 86.3 Accessing Weak Pointer Objects as Lists

Weak pointer objects are members of `ListsFamily` and the categories `IsList (21.1.1)` and `IsMutable (12.6.2)`. Methods based on the low-level functions in the previous section, are installed for the list access operations, enabling them to be used as lists. However, it is *not recommended* that these be used in programming. They are supplied mainly as a convenience for interactive working, and may not be safe, since functions and methods for lists may assume that after `IsBound(w[i])` returns `true`, access to `w[i]` is safe.

### 86.4 Copying Weak Pointer Objects

A `ShallowCopy (12.7.1)` method is installed, which makes a new weak pointer object containing the same objects as the original.
It is possible to apply `StructuralCopy (12.7.2)` to a weak pointer object, obtaining a new weak pointer object containing copies of the objects in the original. This may not be safe if a badly timed garbage collection occurs during copying.

Applying `Immutable (12.6.3)` to a weak pointer object produces an immutable plain list containing immutable copies of the objects contained in the weak pointer object. An immutable weak pointer object is a contradiction in terms.

### 86.5 The GASMAN Interface for Weak Pointer Objects

The key support for weak pointers is in the files `src/gasman.c` and `src/gasman.h`. This document assumes familiarity with the rest of the operation of GASMAN. A kernel type (tnum) of bags which are intended to act as weak pointers to their subobjects must meet three conditions. Firstly, the marking function installed for that tnum must use `MarkBagWeakly` for those subbags, rather than `MarkBag`.

Secondly, before any access to such a subbag, it must be checked with `IsWeakDeadBag`. If that returns `true`, then the subbag has evaporated in a recent garbage collection and must not be accessed. Typically the reference to it should be removed. Thirdly, a sweeping function must be installed for that tnum which copies the bag, removing all references to dead weakly held subbags.

The files `src/weakptr.c` and `src/weakptr.h` use this interface to support weak pointer objects. Other objects with weak behaviour could be implemented in a similar way.
Chapter 87

More about Stabilizer Chains

This chapter contains some rather technical complements to the material handled in the chapters 42
and 43.

87.1 Generalized Conjugation Technique

The command \texttt{ConjugateGroup\( G, p \)} (see \texttt{ConjugateGroup} (39.2.6)) for a permutation group
\( G \) with stabilizer chain equips its result also with a stabilizer chain, namely with the chain of \( G \) con-
jugate by \( p \). Conjugating a stabilizer chain by a permutation \( p \) means replacing all the points which
appear in the orbit components by their images under \( p \) and replacing every permutation \( g \) which
appears in a labels or transversal component by its conjugate \( g^p \). The conjugate \( g^p \) acts on the
mapped points exactly as \( g \) did on the original points, i.e., \((\text{pnt}.p).g^p = (\text{pnt}.g).p \). Since the entries in
the translabels components are integers pointing to positions of the labels list, the translabels
lists just have to be permuted by \( p \) for the conjugated stabilizer. Then generators is reconstructed
as labels\{ genlabels \} and transversal\{ orbit \} as labels\{ translabels\{ orbit \} \}.

This conjugation technique can be generalized. Instead of mapping points and permutations under
the same permutation \( p \), it is sometimes desirable (e.g., in the context of permutation group homomor-
phisms) to map the points with an arbitrary mapping \( \text{map} \) and the permutations with a homomorphism
\( \text{hom} \) such that the compatibility of the actions is still valid: \( \text{map}(\text{pnt}).\text{hom}(g) = \text{map}(\text{pnt}.g) \). (Of
course the ordinary conjugation is a special case of this, with \( \text{map}(\text{pnt}) = \text{pnt}.p \) and \( \text{hom}(g) = g^p \).)

In the generalized case, the “conjugated” chain need not be a stabilizer chain for the image of \( \text{hom} \),
since the “preimage” of the stabilizer of \( \text{map}(b) \) (where \( b \) is a base point) need not fix \( b \), but only fixes
the preimage \( \text{map}^{-1}(\text{map}(b)) \) setwise. Therefore the method can be applied only to one level and the
next stabilizer must be computed explicitly. But if \( \text{map} \) is injective, we have \( \text{map}(b).\text{hom}(g) = \text{map}(b) \)
if and only if \( b.g = b \), and if this holds, then \( g = w(g_1,\ldots,g_n) \) is a word in the generators \( g_1,\ldots,g_n \)
of the stabilizer of \( b \) and \( \text{hom}(g) = w(\text{hom}(g_1),\ldots,\text{hom}(g_n)) \) is in the “conjugated” stabilizer. If,
more generally, \( \text{hom} \) is a right inverse to a homomorphism \( \varphi \) (i.e., \( \varphi(\text{hom}(g)) = g \) for all \( g \)), equality
\( \ast \) holds modulo the kernel of \( \varphi \); in this case the “conjugated” chain can be made into a real stabilizer
chain by extending each level with the generators of the kernel and appending a proper stabilizer
chain of the kernel at the end. These special cases will occur in the algorithms for permutation group
homomorphisms (see 40).

To “conjugate” the points (i.e., orbit) and permutations (i.e., labels) of the Schreier tree, a loop
is set up over the orbit list constructed during the orbit algorithm, and for each vertex \( b \) with unique
edge \( a(l)b \) ending at \( b \), the label \( l \) is mapped with \( \text{hom} \) and \( b \) with \( \text{map} \). We assume that the orbit
list was built w.r.t. a certain ordering \(<\) of the labels, where \(l' < l\) means that every point in the orbit was mapped with \(l'\) before it was mapped with \(l\). This shape of the orbit list is guaranteed if the Schreier tree is extended only by \AddGeneratorsExtendSchreierTree\ (43.11.10), and it is then also guaranteed for the “conjugated” Schreier tree. (The ordering of the labels cannot be read from the Schreier tree, however.)

In the generalized case, it can happen that the edge \(a(l)b\) bears a label \(l\) whose image is “old”, i.e., equal to the image of an earlier label \(l' < l\). Because of the compatibility of the actions we then have \(\text{map}(b) = \text{map}(a).\text{hom}(l)^{-1} = \text{map}(a).\text{hom}(l')^{-1} = \text{map}(a'l^{-1})\), so \(\text{map}(b)\) is already equal to the image of the vertex \(a'l^{-1}\). This vertex must have been encountered before \(b = a'l^{-1}\) because \(l' < l\).

We conclude that the image of a label can be “old” only if the vertex at the end of the corresponding edge has an “old” image, too, but then it need not be “conjugated” at all. A similar remark applies to labels which map under \text{hom}\ to the identity.

### 87.2 The General Backtrack Algorithm with Ordered Partitions

Section 43.12 describes the basic functions for a backtrack search. The purpose of this section is to document how the general backtrack algorithm is implemented in GAP and which parts you have to modify if you want to write your own backtrack routines.

#### 87.2.1 Internal representation of ordered partitions

GAP represents an ordered partition as a record with the following components.

- **points**
  a list of all points contained in the partition, such that the points of each cell from lie consecutively,

- **cellno**
  a list whose \(i\)th entry is the number of the cell which contains the point \(i\),

- **firsts**
  a list such that \(\text{points}[\text{firsts}[j]]\) is the first point in \text{points} which is in cell \(j\),

- **lengths**
  a list of the cell lengths.

Some of the information is redundant, e.g., the **lengths** could also be read off the **firsts** list, but since this need not be increasing, it would require some searching. Similar for **cellno**, which could be replaced by a systematic search of **points**, keeping track of what cell is currently being traversed. With the above components, the \(m\)th cell of a partition \(P\) is expressed as \(P\.\text{points}\{ [ P\.\text{firsts}[m] .. P\.\text{firsts}[m] + P\.\text{lengths}[m] - 1 ] \}\). The most important operations, however, to be performed upon \(P\) are the splitting of a cell and the reuniting of the two parts. Following the strategy of J. Leon, this is done as follows:

1. The points which make up the cell that is to be split are sorted so that the ones that remain inside occupy positions \([ P\.\text{firsts}[m] .. \text{last} ]\) in the list \(P\.\text{points}\) (for a suitable value of \text{last}).
(2) The points at positions \([\text{last} + 1 .. \ P\text{.firsts}[m] + P\text{.lengths}[m] - 1]\) will form the additional cell. For this new cell requires additional entries are added to the lists \(P\text{.firsts}\) (namely, \(\text{last} + 1\)) and \(P\text{.lengths}\) (namely, \(P\text{.firsts}[m] + P\text{.lengths}[m] - \text{last} - 1\)).

(3) The entries of the sublist \(P\text{.cellno}\{[\text{last} + 1 .. \ P\text{.firsts}[m] + P\text{.lengths}[m] - 1]\}\) must be set to the number of the new cell.

(4) The entry \(P\text{.lengths}[m]\) must be reduced to \(\text{last} - P\text{.firsts}[m] + 1\).

Then reuniting the two cells requires only the reversal of steps 2 to 4 above. The list \(P\text{.points}\) need not be rearranged.

### 87.2.2 Functions for setting up an R-base

This subsection explains some GAP functions which are local to the library file \(\text{lib/stbcbckt.gi}\) which contains the code for backtracking in permutation groups. They are mentioned here because you might find them helpful when you want to implement your own backtracking function based on the partition concept. An important argument to most of the functions is the R-base \(R\), which you should regard as a black box. We will tell you how to set it up, how to maintain it and where to pass it as argument, but it is not necessary for you to know its internal representation. However, if you insist to learn the whole story: Here are the record components from which an R-base is made up:

- **domain**: the set \(\Omega\) on which the group \(G\) operates
- **base**: the sequence \((a_1, \ldots, a_r)\) of base points
- **partition**: an ordered partition, initially \(\Pi_0\), this will be refined to \(\Pi_1, \ldots, \Pi_r\) during the backtrack algorithm

**where**
- a list such that \(a_i\) lies in cell number \(\text{where}[i]\) of \(\Pi_i\)
- **rfm**: a list whose \(i\)th entry is a list of refinements which take \(\Sigma_i\) to \(\Sigma_{i+1}\); the structure of a refinement is described below
- **chain**: a (copy of a) stabilizer chain for \(G\) (not if \(G\) is a symmetric group)
- **fix**: only if \(G\) is a symmetric group: a list whose \(i\) entry contains \(\text{Fixcells}(\ \Pi_i \ )\)
- **level**: initially equal to **chain**, this will be changed to chains for the stabilizers \(G_{a_1 \ldots a_i}\) for \(i = 1, \ldots, r\) during the backtrack algorithm; if \(G\) is a symmetric group, only the number of moved points is stored for each stabilizer
- **lev**: a list whose \(i\)th entry remembers the level entry for \(G_{a_1 \ldots a_i}\)
level2, lev2
  a similar construction for a second group (used in intersection calculations), false otherwise.
  This second group $H$ activated if the R-base is constructed as \texttt{EmptyRBase( [G,H], \Omega, \Pi_0 )} (if $G = H$, \texttt{GAP} sets level2 = true instead).

\textit{nextLevel}
  this is described below

As our guiding example, we present code for the function \texttt{Centralizer} (35.4.4) which calculates the centralizer of an element $g$ in the group $G$. (The real code is more general and has a few more subtleties.)

\begin{verbatim}
P := TrivialPartition( omega );
R := EmptyRBase( G, omega, Pi_0 );
R.nextLevel := function( Pi, rbase )
  local fix, p, q, where;
  NextRBasePoint( Pi, rbase );
  fix := Fixcells( Pi );
  for p in fix do
    q := p ^ g;
    where := IsolatePoint( Pi, q );
    if where <> false then
      Add( fix, q );
      ProcessFixpoint( R, q );
      AddRefinement( R, "Centralizer", [ Pi.cellno[ p ], q, where ] );
      if Pi.lengths[ where ] = 1 then
        p := FixpointCellNo( Pi, where );
        ProcessFixpoint( R, p );
        AddRefinement( R, "ProcessFixpoint", [ p, where ] );
      fi;
    fi;
  od;
end;
return PartitionBacktrack( G,
  c -> g ^ c = g,
  false,
  R,
  [ Pi_0, g ],
  L, R );
\end{verbatim}

The list numbers below refer to the line numbers of the code above.

1. \texttt{omega} is the set on which $G$ acts and \texttt{Pi_0} is the first member of the decreasing sequence of partitions mentioned in 43.12. We set \texttt{Pi_0 = omega}, which is constructed as \texttt{TrivialPartition( omega )}, but we could have started with a finer partition, e.g., into unions of $g$-cycles of the same length.

2. This statement sets up the R-base in the variable R.
3.-21. These lines define a function \( R\text{.nextLevel} \) which is called whenever an additional member in the sequence \( \Pi_0 \geq \Pi_1 \geq \ldots \) of partitions is needed. If \( \Pi_i \) does not yet contain enough base points in one-point cells, \textit{GAP} will call \( R\text{.nextLevel}(\ \Pi_i,\ R) \), and this function will choose a new base point \( a_{i+1} \), refine \( \Pi_i \) to \( \Pi_{i+1} \) (thereby changing the first argument) and store all necessary information in \( \textit{R} \).

5. This statement selects a new base point \( a_{i+1} \), which is not yet in a one-point cell of \( \Pi \) and still moved by the stabilizer \( G_{a_1 \ldots a_i} \) of the earlier base points. If certain points of \( \omega \) should be preferred as base point (e.g., because they belong to long cycles of \( g \)), a list of points starting with the most wanted ones, can be given as an optional third argument to \textit{NextRBasePoint} (actually, this is done in the real code for \textit{Centralizer} (35.4.4)).

6. \textit{Fixcells}(\ \Pi \) returns the list of points in one-point cells of \( \Pi \) (ordered as the cells are ordered in \( \Pi \)).

7. For every point \( p \in \text{fix} \), if we know the image \( p^g \) under \( c \in C_G(e) \), we also know \( (p^g)^c = (p^c)^g \). We therefore want to isolate these extra points in \( \Pi \).

9. This statement puts point \( q \) in a cell of its own, returning in \textit{where} the number of the cell of \( \Pi \) from which \( q \) was taken. If \( q \) was already the only point in its cell, \textit{where} = false instead.

12. This command does the necessary bookkeeping for the extra base point \( q \): It prescribes \( q \) as next base in the stabilizer chain for \( G \) (needed, e.g., in line 5) and returns false if \( q \) was already fixed the stabilizer of the earlier base points (and true otherwise; this is not used here). Another call to \textit{ProcessFixpoint} like this was implicitly made by the function \textit{NextRBasePoint} to register the chosen base point. By contrast, the point \( q \) was not chosen this way, so \textit{ProcessFixpoint} must be called explicitly for \( q \).

13. This statement registers the function which will be used during the backtrack search to perform the corresponding refinements on the “image partition” \( \Sigma \) (to yield the refined \( \Sigma_{i+1} \)). After choosing an image \( b_{i+1} \) for the base point \( a_{i+1} \), \textit{GAP} will compute \( \Sigma_i \wedge (\{b_{i+1}\}, \Omega \setminus \{b_{i+1}\}) \) and store this partition in \( I\text{.partition} \), where \( I \) is a black box similar to \( \textit{R} \), but corresponding to the current “image partition” (hence it is an “R-image” in analogy to the R-base). Then \textit{GAP} will call the function \textit{Refinements.Centralizer}( \( R, \ I, \ Pi\text{.cellno}[\ p\ ], \ p, \ \textit{where} \)), with the then current values of \( R \) and \( I \), but where \( \Pi\text{.cellno}[p], p, \textit{where} \) still have the values they have at the time of this \textit{AddRefinement} command. This function call will further refine \( I\text{.partition} \) to yield \( \Sigma_{i+1} \) as it is programmed in the function \textit{Refinements.Centralizer}, which is described below. (The global variable \textit{Refinements} is a record which contains all refinement functions for all backtracking procedures.)

14.-19. If the cell from which \( q \) was taken out had only two points, we now have an additional one-point cell. This condition is checked in line 13 and if it is true, this extra fixpoint \( p \) is taken (line 15), processed like \( q \) before (line 16) and is then (line 17) passed to another refinement function \textit{Refinements.ProcessFixpoint}( \( R, \ I, \ p, \ \textit{where} \)), which is also described below.

23.-29. This command starts the backtrack search. Its result will be the centralizer as a subgroup of \( G \). Its arguments are
24. the group we want to run through,
25. the property we want to test, as a GAP function,
26. \texttt{false} if we are looking for a subgroup, \texttt{true} in the case of a representative search (when the result would be one representative),
27. the R-base,
28. a list of data, to be stored in I.data, which has in position 1 the first member $\Sigma_0$ of the decreasing sequence of “image partitions” mentioned in 43.12. In the centralizer example, position 2 contains the element that is to be centralized. In the case of a representative search, i.e., a conjugacy test $g^c \neq h$, we would have $h$ instead of $g$ here, and possibly a $\Sigma_0$ different from $\Pi_0$ (e.g., a partition into unions of $h$-cycles of same length).
29. two subgroups $L \leq C_G(g)$ and $R \leq C_G(h)$ known in advance (we have $L = R$ in the centralizer case).

87.2.3 Refinement functions for the backtrack search

The last subsection showed how the refinement process leading from $\Pi_i$ to $\Pi_{i+1}$ is coded in the function $R$.nextLevel, this has to be executed once the base point $a_{i+1}$. The analogous refinement step from $\Sigma_i$ to $\Sigma_{i+1}$ must be performed for each choice of an image $b_{i+1}$ for $a_{i+1}$, and it will depend on the corresponding value of $\Sigma_i \land (\{b_{i+1}\}, \Omega \setminus \{b_{i+1}\})$. But before we can continue our centralizer example, we must, for the interested reader, document the record components of the other black box I, as we did above for the R-base black box $R$. Most of the components change as \texttt{GAP} walks up and down the levels of the search tree.

data
  this will be mentioned below

depth
  the level $i$ in the search tree of the current node $\Sigma_i$

bimg
  a list of images of the points in $R$.base

partition
  the partition $\Sigma_i$ of the current node

level
  the stabilizer chain $R$.lev[$i$] at the current level

perm
  a permutation mapping \texttt{Fixcells($\Pi_i$)} to \texttt{Fixcells($\Sigma_i$)}; this implies mapping $(a_1, \ldots, a_i)$ to $(b_1, \ldots, b_i)$

level2, perm2
  a similar construction for the second stabilizer chain, \texttt{false} otherwise (and \texttt{true} if $R$.level2 = \texttt{true})
As declared in the above code for `Centralizer` (35.4.4), the refinement is performed by the function `Refinement.Centralizer(R, I, Π, cellno[p], p, where)`. The functions in the record `Refinement` always take two additional arguments before the ones specified in the `AddRefinement` call (in line 13 above), namely the R-base `R` and the current value `I` of the “R-image”. In our example, `p` is a fixpoint of \( \Pi = \Pi_I \land (\{a_{i+1}\}, \Omega \setminus \{b_{i+1}\}) \) such that `where = Π.cellno[p]`. The `Refinement` functions must return `false` if the refinement is unsuccessful (e.g., because it leads to \( \Sigma_{i+1} \) having different cell sizes from \( \Pi_{i+1} \)) and `true` otherwise. Our particular function looks like this.

```gap
Refinements.Centralizer := function( R, I, cellno, p, where )
local Sigma, q;
Sigma := I.partition;
q := FixpointCellNo( Sigma, cellno ) \* I.data[2];
return IsolatePoint( Sigma, q ) = where and ProcessFixpoint( I, p, q );
end;
```

The list numbers below refer to the line numbers of the code immediately above.

3. The current value of \( \Sigma_i \land (\{b_{i+1}\}, \Omega \setminus \{b_{i+1}\}) \) is always found in `I.partition`.

4. The image of the only point in cell number `cellno = Π_i.cellno[p]` in `Σ` under \( g = I.data[2] \) is calculated.

5. The function returns `true` only if the image \( q \) has the same cell number in `Σ` as `p` had in `Π` (i.e., `where`) and if \( q \) can be prescribed as an image for `p` under the coset of the stabilizer \( G_{a_1...a_{i+1}, c} \) where `c` is an (already constructed) element mapping the earlier base points `a_1,...,a_{i+1}` to the already chosen images `b_1,...,b_{i+1}`. This latter condition is tested by `ProcessFixpoint(I, p, q)` which, if successful, also does the necessary bookkeeping in `I`. In analogy to the remark about line 12 in the program above, the chosen image `b_{i+1}` for the base point `a_{i+1}` has already been processed implicitly by the function `PartitionBacktrack`, and this processing includes the construction of an element `c \in G` which maps `Fixcells(Σ)` to `Fixcells(Π)` and `a_{i+1}` to `b_{i+1}`. By contrast, the extra fixpoints `p` and `q` in `Π_{i+1}` and `Σ_{i+1}` were not chosen automatically, so they require an explicit call of `ProcessFixpoint`, which replaces the element `c` by some `c'.c` (with `c' \in G_{a_1...a_{i+1}}`) which in addition maps `p` to `q`, or returns `false` if this is impossible.

You should now be able to guess what `Refinements.ProcessFixpoint(R, I, p, where)` does: it simply returns `ProcessFixpoint(I, p, FixpointCellNo(Π.partition, where))`.

**Summary.**

When you write your own backtrack functions using the partition technique, you have to supply an R-base, including a component `nextLevel`, and the functions in the `Refinements` record which you need. Then you can start the backtrack by passing the R-base and the additional data (for the data component of the “R-image”) to `PartitionBacktrack`.

### 87.2.4 Functions for meeting ordered partitions

A kind of refinement that occurs in particular in the normalizer calculation involves computing the meet of `Π` (cf. lines 6ff. above) with an arbitrary other partition `Λ`, not just with one point. To do this efficiently, GAP uses the following two functions.
StratMeetPartition( \( R, \Pi, \Lambda [, g ] \) )
MeetPartitionStrat( \( R, I', \Lambda' [, \{ g' \}], \text{strat} \) )

Such a StratMeetPartition command would typically appear in the function call \( R_.nextLevel(\Pi, R) \) (during the refinement of \( \Pi_i \) to \( \Pi_{i+1} \)). This command replaces \( \Pi \) by \( \Pi \land \Lambda \) (thereby changing the second argument) and returns a “meet strategy” \( \text{strat} \). This is (for us) a black box which serves two purposes: First, it allows GAP to calculate faster the corresponding meet \( \Sigma \land \Lambda' \), which must then appear in a Refinements function (during the refinement of \( \Sigma_i \) to \( \Sigma_{i+1} \)). It is faster to compute \( \Sigma \land \Lambda' \) with the “meet strategy” of \( \Pi \land \Lambda \) because if the refinement of \( \Sigma \) is successful at all, the intersection of a cell from the left hand side of the \( \land \) sign with a cell from the right hand side must have the same size in both cases (and \( \text{strat} \) records these sizes, so that only non-empty intersections must be calculated for \( \Sigma \land \Lambda' \)). Second, if there is a discrepancy between the behaviour prescribed by \( \text{strat} \) and the behaviour observed when refining \( \Sigma \), the refinement can immediately be abandoned.

On the other hand, if you only want to meet a partition \( \Pi \) with \( \Lambda \) for a one-time use, without recording a strategy, you can simply type StratMeetPartition(\( \Pi, \Lambda \)) as in the following example, which also demonstrates some other partition-related commands.

Example

\begin{verbatim}
gap> P := Partition( [[1,2],[3,4,5],[6]] );; Cells( P );
[ [ 1, 2 ], [ 3, 4, 5 ], [ 6 ] ]
gap> Q := Partition( OnTuplesTuples( last, (1,3,6) ) );; Cells( Q );
[ [ 3, 2 ], [ 6, 4, 5 ], [ 1 ] ]
gap> StratMeetPartition( P, Q );
[ ]
gap> # The 'meet strategy' was not recorded, ignore this result.
gap> Cells( P );
[ [ 1 ], [ 5, 4 ], [ 6 ], [ 2 ], [ 3 ] ]
\end{verbatim}

You can even say StratMeetPartition(\( \Pi, \Lambda \)) where \( \Lambda \) is simply a subset of \( \Omega \), it will then be interpreted as the partition \( (\Lambda, \Omega \setminus \Lambda) \).

GAP makes use of the advantages of a “meet strategy” if the refinement function in Refinements contains a MeetPartitionStrat command where \( \text{strat} \) is the “meet strategy” calculated by StratMeetPartition before. Such a command replaces \( I_.partition \) by its meet with \( \Lambda' \), again changing the argument \( I \). The necessary reversal of these changes when backtracking from a node (and prescribing the next possible image for a base point) is automatically done by the function PartitionBacktrack.

In all cases, an additional argument \( g \) means that the meet is to be taken not with \( \Lambda \), but instead with \( \Lambda . g^{-1} \), where operation on ordered partitions is meant cellwise (and setwise on each cell). (Analogously for the primed arguments.)

Example

\begin{verbatim}
-gap> P := Partition( [[1,2],[3,4,5],[6]] );;
 gap> StratMeetPartition( P, P, (1,6,3) );; Cells( P );
 [ [ 1 ], [ 5, 4 ], [ 6 ], [ 2 ], [ 3 ] ]
\end{verbatim}

Note that \( P.(1,3,6) = Q \).

87.3 Stabilizer Chains for Automorphisms Acting on Enumerators

This section describes a way of representing the automorphism group of a group as permutation group, following [Sim97]. The code however is not yet included in the GAP library.
In this section we present an example in which objects we already know (namely, automorphisms of solvable groups) are equipped with the permutation-like operations $\cdot$ and $/$ for action on positive integers. To achieve this, we must define a new type of objects which behave like permutations but are represented as automorphisms acting on an enumerator. Our goal is to generalize the Schreier-Sims algorithm for construction of a stabilizer chain to groups of such new automorphisms.

### 87.3.1 An operation domain for automorphisms

The idea we describe here is due to C. Sims. We consider a group $A$ of automorphisms of a group $G$, given by generators, and we would like to know its order. Of course we could follow the strategy of the Schreier-Sims algorithm (described in 43.6) for $A$ acting on $G$. This would involve a call of 

```plaintext
StabChainStrong( EmptyStabChain( [], One( A ) ), GroupGenerators( A ) )
```

where `StabChainStrong` is a function as the one described in the pseudo-code below:

```plaintext
StabChainStrong := function( S, newgens )
  Extend the Schreier tree of S with newgens.
  for sch in Schreier generators do
    if not sch in S.stabilizer then
      StabChainStrong( S.stabilizer, [ sch ] );
    fi;
  od;
end;
```

The membership test $sch \notin S.stabilizer$ can be performed because the stabilizer chain of $S.stabilizer$ is already correct at that moment. We even know a base in advance, namely any generating set for $G$. Fix such a generating set $(g_1, \ldots, g_d)$ and observe that this base is generally very short compared to the degree $|G|$ of the operation. The problem with the Schreier-Sims algorithm, however, is that the length of the first basic orbit $g_1 A$ would already have the magnitude of $|G|$, and the basic orbits at deeper levels would not be much shorter. For the advantage of a short base we pay the high price of long basic orbits, since the product of the (few) basic orbit lengths must equal $|A|$. Such long orbits make the Schreier-Sims algorithm infeasible, so we have to look for a longer base with shorter basic orbits.

Assume that $G$ is solvable and choose a characteristic series with elementary abelian factors. For the sake of simplicity we assume that $N < G$ is an elementary abelian characteristic subgroup with elementary abelian factor group $G/N$. Since $N$ is characteristic, $A$ also acts as a group of automorphisms on the factor group $G/N$, but of course not necessarily faithfully. To retain a faithful action, we let $A$ act on the disjoint union $G/N$ with $G$, and choose as base $(g_1 N, \ldots, g_d N, g_1, \ldots, g_d)$. Now the first $d$ basic orbits lie inside $G/N$ and can have length at most $[G : N]$. Since the base points $g_1 N, \ldots, g_d N$ form a generating set for $G/N$, their iterated stabilizer $A^{(d+1)}$ acts trivially on the factor group $G/N$, i.e., it leaves the cosets $g_i N$ invariant. Accordingly, the next $d$ basic orbits lie inside $g_i N$ (for $i = 1, \ldots, d$) and can have length at most $|N|$.

Generalizing this method to a characteristic series $G = N_0 > N_1 > \ldots > N_l = \{1\}$ of length $l > 2$, we can always find a base of length $l.d$ such that each basic orbit is contained in a coset of a characteristic factor, i.e. in a set of the form $g_i N_{j-1}/N_j$ (where $g_i$ is one of the generators of $G$ and $1 \leq j \leq l$). In particular, the length of the basic orbits is bounded by the size of the corresponding characteristic factors. To implement a Schreier-Sims algorithm for such a base, we must be able to let automorphisms act on cosets of characteristic factors $g_i N_{j-1}/N_j$, for varying $i$ and $j$. We would like to
translate each such action into an action on \( \{ 1, \ldots, [N_{j-1} : N_j] \} \), because then we need not enumerate
the operation domain, which is the disjoint union of \( G/N_1, G/N_2 \ldots G/N_i \), as a whole. Enumerating it
as a whole would result in basic orbits like \( \text{orbit} \subseteq \{ 1001, \ldots, 1100 \} \) with a transversal list whose
first 1000 entries would be unbound, but still require 4 bytes of memory each (see 43.9).

Identifying each coset \( g N_{j-1}/N_j \) into \( \{ 1, \ldots, [N_{j-1} : N_j] \} \) of course means that we have to change
the action of the automorphisms on every level of the stabilizer chain. Such flexibility is not possible
with permutations because their effect on positive integers is “hardwired” into them, but we can install
new operations for automorphisms.

87.3.2 Enumerators for cosets of characteristic factors

So far we have not used the fact that the characteristic factors are elementary abelian, but we will do
so from here on. Our first task is to implement an enumerator (see \texttt{AsList} (30.3.8) and 21.23) for a
coset of a characteristic factor in a solvable group \( G \). We assume that such a coset \( g N/M \) is given by

1. a pcgs for the group \( G \) (see \texttt{Pcgs} (45.2.1)), let \( n = \text{Length} ( \text{pcgs} ) \);
2. a range \( \text{range} = [\text{start}..\text{stop}] \) indicating that \( N = \langle \text{pcgs} \{ \text{start}..n \} \rangle \) and \( M = \langle \text{pcgs} \{ \text{stop}+1..n \} \rangle \), i.e., the cosets of \( \text{pcgs} \{ \text{range} \} \) form a base for the vector space \( N/M \);
3. the representative \( g \).

We first define a new representation for such enumerators and then construct them by simply
putting these three pieces of data into a record object. The enumerator should behave as a list of group
elements (representing cosets modulo \( M \)), consequently, its family will be the family of the \texttt{pcgs} itself.

```gap
DeclareRepresentation( "IsCosetSolvableFactorEnumeratorRep", IsEnumerator,
[ "pcgs", "range", "representative" ] );

EnumeratorCosetSolvableFactor := function( pcgs, range, g )
    return Objectify( NewType( FamilyObj( pcgs ),
        IsCosetSolvableFactorEnumeratorRep ),
        rec( pcgs := pcgs,
            range := range,
            representative := g ) );
end;
```

The definition of the operations \texttt{Length} (21.17.5), \texttt{\[\]} (21.2.1) and \texttt{Position} (21.16.1) is now
straightforward. The code has sometimes been abbreviated and is meant “cum grano salis”, e.g., the
declaration of the local variables has been left out.

```gap
InstallMethod( Length, [ IsCosetSolvableFactorEnumeratorRep ],
    enum -> Product( RelativeOrdersPcgs( enum!.pcgs ){ enum!.range } ) );

InstallMethod( \[\], [ IsCosetSolvableFactorEnumeratorRep,
    IsPosInt and IsInt ],
    function( enum, pos )
        elm := ();
        pos := pos - 1;
        for i in Reversed( enum!.range ) do
```
87.3.3 Making automorphisms act on such enumerators

Our next task is to make automorphisms of the solvable group \( pcgs!.\text{group} \) act on \([1..\text{Length}(enum)]\) for such an enumerator \( enum \). We achieve this by introducing a new representation of automorphisms on enumerators and by putting the enumerator together with the automorphism into an object which behaves like a permutation. Turning an ordinary automorphism into such a special automorphism requires then the construction of a new object which has the new type. We provide an operation \( \text{PermOnEnumerator}(\text{model}, \text{aut}) \) which constructs such a new object having the same type as \( \text{model} \), but representing the automorphism \( \text{aut} \). So \( \text{aut} \) can be either an ordinary automorphism or one which already has an enumerator in its type, but perhaps different from the one we want (i.e. from the one in \( \text{model} \)).

---

Example

```gap
DeclareCategory( "IsPermOnEnumerator",  
    IsMultiplicativeElementWithInverse and IsPerm );

DeclareRepresentation( "IsPermOnEnumeratorDefaultRep",  
    IsPermOnEnumerator and IsAttributeStoringRep,  
    [ "perm" ] );

DeclareOperation( "PermOnEnumerator",  
    [ IsEnumerator, IsObject ] );

InstallMethod( PermOnEnumerator,  
    [ IsEnumerator, IsObject ],  
    function( enum, a )  
        SetFilterObj( a, IsMultiplicativeElementWithInverse );  
        a := Objectify( NewKind( PermutationsOnEnumeratorsFamily,  
            IsPermOnEnumeratorDefaultRep ),  
            rec( perm := a ) );  
        SetEnumerator( a, enum );  
        return a;  
    end );
```
InstallMethod( PermOnEnumerator, 
    [ IsEnumerator, IsPermOnEnumeratorDefaultRep ],
    function( enum, a )
        a := Objectify( TypeObj( a ), rec( perm := a!.perm ) );
        SetEnumerator( a, enum );
        return a;
    end );

Next we have to install new methods for the operations which calculate the product of two automorphisms, because this product must again have the right type. We also have to write a function which uses the enumerators to apply such an automorphism to positive integers.

Example

InstallMethod( \*, IsIdenticalObj, 
    [ IsPermOnEnumeratorDefaultRep, IsPermOnEnumeratorDefaultRep ],
    function( a, b )
        perm := a!.perm * b!.perm;
        SetIsBijective( perm, true );
        return PermOnEnumerator( Enumerator( a ), perm );
    end );

InstallMethod( \(^\), 
    [ IsPosRat and IsInt, IsPermOnEnumeratorDefaultRep ],
    function( p, a )
        return PositionCanonical( Enumerator( a ),
            Enumerator( a )[ p ] ^ a!.perm );
    end );

How the corresponding methods for $p / \text{aut}$ and $\text{aut} ^ n$ look like is obvious.

Now we can formulate the recursive procedure StabChainStrong which extends the stabilizer chain by adding in new generators $\text{newgens}$. We content ourselves again with pseudo-code, emphasizing only the lines which set the EnumeratorDomainPermutation. We assume that initially $S$ is a stabilizer chain for the trivial subgroup with a level for each pair $(\text{range}, g)$ characterizing an enumerator (as described above). We also assume that the identity element at each level already has the type corresponding to that level.

StabChainStrong := function( S, newgens )
    for i in [ 1 .. Length( newgens ) ] do
        newgens[ i ] := AutomorphismOnEnumerator( S.identity, newgens[ i ] );
    od;
    Extend the Schreier tree of S with newgens.
    for sch in Schreier generators do
        if not sch in S.stabilizer then
            StabChainStrong( S.stabilizer, [ sch ] );
        fi;
    od;
    end;
References


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