

XMod

Crossed Modules and Cat1-Groups

2.73

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Abstract

The XMod package provides functions for computation with

- finite crossed modules of groups and cat1-groups, and morphisms of these structures;
- finite pre-crossed modules, pre-cat1-groups, and their Peiffer quotients;
- isoclinism classes of groups and crossed modules;
- derivations of crossed modules and sections of cat1-groups;
- crossed squares and their morphisms, including the actor crossed square of a crossed module;
- crossed modules of finite groupoids (experimental version).

XMod was originally implemented in 1996 using the GAP3 language, when the second author was studying for a Ph.D. [Alp97] in Bangor.

In April 2002 the first and third parts were converted to GAP4, the pre-structures were added, and version 2.001 was released. The final two parts, covering derivations, sections and actors, were included in the January 2004 release 2.002 for GAP 4.4.

In October 2015 functions for computing isoclinism classes of crossed modules, written by Alper Odabaş and Enver Uslu, were added. These are contained in Chapter 4, and are described in detail in the paper [IOU16].

Bug reports, suggestions and comments are, of course, welcome. Please submit an issue at <http://github.com/gap-packages/xmod/issues/> or send an email to the first author at c.d.wensley@bangor.ac.uk.

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Chapter 1

Introduction

The XMod package provides functions for computation with

- finite crossed modules of groups and cat1-groups, and morphisms of these structures;
- finite pre-crossed modules, pre-cat1-groups, and their Peiffer quotients;
- derivations of crossed modules and sections of cat1-groups;
- isoclinism of groups and crossed modules;
- the actor crossed square of a crossed module;
- crossed squares, cat2-groups, and their morphisms (experimental version);
- crossed modules of groupoids (experimental version).

It is loaded with the command

Example

```
gap> LoadPackage( "xmod" );
```

The term crossed module was introduced by J. H. C. Whitehead in [Whi48], [Whi49]. Loday, in [Lod82], reformulated the notion of a crossed module as a cat1-group. Norrie [Nor90], [Nor87] and Gilbert [Gil90] have studied derivations, automorphisms of crossed modules and the actor of a crossed module, while Ellis [Ell84] has investigated higher dimensional analogues. Properties of induced crossed modules have been determined by Brown, Higgins and Wensley in [BH78], [BW95] and [BW96]. For further references see [AW00], where we discuss some of the data structures and algorithms used in this package, and also tabulate isomorphism classes of cat1-groups up to size 30.

XMod was originally implemented in 1997 using the GAP 3 language. In April 2002 the first and third parts were converted to GAP 4, the pre-structures were added, and version 2.001 was released. The final two parts, covering derivations, sections and actors, were included in the January 2004 release 2.002 for GAP 4.4. Many of the function names have been changed during the conversion, for example `ConjugationXMod` has become `XModByNormalSubgroup` (2.1.2). For a list of name changes see the file `names.pdf` in the `doc` directory.

In October 2015 Alper Odabaş and Enver Uslu were added to the list of package authors. Their functions for computing isoclinism classes of groups and crossed modules are contained in Chapter 4, and are described in detail in their paper [IOU16].

The package may be obtained as a compressed tar file `XMod-version.number.tar.gz` by ftp from one of the following sites:

- the XMod GitHub release site: <https://github.com/gap-packages.github.io/xmod/>.
- any GAP archive, e.g. <https://www.gap-system.org/Packages/packages.html>;

The package also has a GitHub repository at: <https://github.com/gap-packages/xmod/>.

Crossed modules and `cat1`-groups are special types of *2-dimensional groups* [Bro82], [BHS11], and are implemented as `2DimensionalDomains` and `2DimensionalGroups` having a `Source` and a `Range`.

The package divides into eight parts. The first part is concerned with the standard constructions for pre-crossed modules and crossed modules; together with direct products; normal sub-crossed modules; and quotients. Operations for constructing pre-`cat1`-groups and `cat1`-groups, and for converting between `cat1`-groups and crossed modules, are also included.

The second part is concerned with *morphisms* of (pre-)crossed modules and (pre-)`cat1`-groups, together with standard operations for morphisms, such as composition, image and kernel.

The third part is the most recent part of the package, introduced in October 2015. Additional operations and properties for crossed modules are included in Section 4.1. Then, in 4.2 and 4.3 there are functions for isoclinism of groups and crossed modules.

The fourth part is concerned with the equivalent notions of *derivation* for a crossed module and *section* for a `cat1`-group, and the monoids which they form under the Whitehead multiplication.

The fifth part deals with actor crossed modules and actor `cat1`-groups. For the actor crossed module `Act(\mathcal{X})` of a crossed module \mathcal{X} we require representations for the Whitehead group of regular derivations of \mathcal{X} and for the group of automorphisms of \mathcal{X} . The construction also provides an inner morphism from \mathcal{X} to `Act(\mathcal{X})` whose kernel is the centre of \mathcal{X} .

The sixth part, which remains under development, contains functions to compute induced crossed modules.

Since version 2.007 there are experimental functions for *crossed squares* and their morphisms, structures which arise as 3-dimensional groups. Examples of these are inclusions of normal sub-crossed modules, and the inner morphism from a crossed module to its actor.

The eighth part has some experimental functions for crossed modules of groupoids, interacting with the package `groupoids`. Much more work on this is needed.

Future plans include the implementation of *group-graphs* which will provide examples of pre-crossed modules (their implementation will require interaction with graph-theoretic functions in GAP 4). There are also plans to implement `cat2`-groups, and conversion between these and crossed squares.

The equivalent categories `XMod` (crossed modules) and `Cat1` (`cat1`-groups) are also equivalent to `GpGpd`, the subcategory of group objects in the category `Gpd` of groupoids. Finite groupoids have been implemented in Emma Moore's package `groupoids` [Moo01] for groupoids and crossed resolutions.

In order that the user has some control of the verbosity of the `XMod` package's functions, an `InfoClass InfoXMod` is provided (see Chapter `ref:Info` Functions in the GAP Reference Manual for a description of the `Info` mechanism). By default, the `InfoLevel` of `InfoXMod` is 0; progressively more information is supplied by raising the `InfoLevel` to 1, 2 and 3.

Example

```
gap> SetInfoLevel( InfoXMod, 1); #sets the InfoXMod level to 1
```

Once the package is loaded, the manual `doc/manual.pdf` can be found in the documentation folder. The html versions, with or without MathJax, should be rebuilt as follows:

Example

```
gap> ReadPackage( "xmod", "makedoc.g" );
```

It is possible to check that the package has been installed correctly by running the test files:

Example

```
gap> ReadPackage( "xmod", "tst/testall.g" );
#I Testing .../pkg/xmod/tst/gp2obj.tst
...
```

Additional information can be found on the *Computational Higher-dimensional Discrete Algebra* website at: <http://pages.bangor.ac.uk/~mas023/chda/intro.html>.

Chapter 2

2d-groups : crossed modules and cat1-groups

The term *2d-group* refers to a set of equivalent categories of which the most common are the categories of *crossed modules*; *cat1-groups*; and *group-groupoids*, all of which involve a pair of groups.

2.1 Constructions for crossed modules

A crossed module (of groups) $\mathcal{X} = (\partial : S \rightarrow R)$ consists of a group homomorphism ∂ , called the *boundary* of \mathcal{X} , with *source* S and *range* R . The group R acts on itself by conjugation, and on S by an *action* $\alpha : R \rightarrow \text{Aut}(S)$ such that, for all $s, s_1, s_2 \in S$ and $r \in R$,

$$\mathbf{XMod\ 1} : \partial(s^r) = r^{-1}(\partial s)r = (\partial s)^r, \quad \mathbf{XMod\ 2} : s_1^{\partial s_2} = s_2^{-1}s_1s_2 = s_1^{s_2}.$$

When only the first of these axioms is satisfied, the resulting structure is a *pre-crossed module* (see section 2.3). The kernel of ∂ is abelian.

(Much of the literature on crossed modules uses left actions, but we have chosen to use right actions in this package since that is the standard choice for group actions in GAP.)

2.1.1 XMod

- ▷ `XMod(args)` (function)
- ▷ `XModByBoundaryAndAction(bdy, act)` (operation)

The global function `XMod` calls one of the standard constructions described in the following subsections. In the example the boundary is the identity mapping on `c5` and the action is trivial.

Example

```
gap> c5 := Group( (5,6,7,8,9) );;
gap> SetName( c5, "c5" );
gap> id5 := IdentityMapping( c5 );;
gap> ac5 := AutomorphismGroup( c5 );;
gap> act := MappingToOne( c5, ac5 );;
gap> XMod( id5, act ) = XModByBoundaryAndAction( id5, act );
true
```

2.1.2 XModByNormalSubgroup

▷ `XModByNormalSubgroup(G, N)` (operation)

A *conjugation crossed module* is the inclusion of a normal subgroup $S \trianglelefteq R$, where R acts on S by conjugation.

2.1.3 XModByTrivialAction

▷ `XModByTrivialAction(bdy)` (operation)

A *trivial action crossed module* ($\partial : S \rightarrow R$) has $s^r = s$ for all $s \in S, r \in R$, the source is abelian and the image lies in the centre of the range.

Example

```
gap> q8 := QuaternionGroup( IsPermGroup, 8 );
Group([ (1,5,3,7)(2,8,4,6), (1,2,3,4)(5,6,7,8) ])
gap> SetName( q8, "q8" );
gap> c2 := Centre( q8 );
Group([ (1,3)(2,4)(5,7)(6,8) ])
gap> SetName( c2, "<-1>" );
gap> bdy := InclusionMappingGroups( q8, c2 );;
gap> X8a := XModByTrivialAction( bdy );
[<-1>->q8]
gap> c4 := Subgroup( q8, [q8.1] );;
gap> SetName( c4, "<i>" );
gap> X8b := XModByNormalSubgroup( q8, c4 );
[<i>->q8]
gap> Display(X8b);
Crossed module [<i>->q8] :-
: Source group has generators:
  [ (1,5,3,7)(2,8,4,6) ]
: Range group q8 has generators:
  [ (1,5,3,7)(2,8,4,6), (1,2,3,4)(5,6,7,8) ]
: Boundary homomorphism maps source generators to:
  [ (1,5,3,7)(2,8,4,6) ]
: Action homomorphism maps range generators to automorphisms:
  (1,5,3,7)(2,8,4,6) --> { source gens --> [ (1,5,3,7)(2,8,4,6) ] }
  (1,2,3,4)(5,6,7,8) --> { source gens --> [ (1,7,3,5)(2,6,4,8) ] }
  These 2 automorphisms generate the group of automorphisms.
```

2.1.4 XModByAutomorphismGroup

▷ `XModByAutomorphismGroup(grp)` (attribute)

▷ `XModByInnerAutomorphismGroup(grp)` (attribute)

▷ `XModByGroupOfAutomorphisms(G, A)` (operation)

An *automorphism crossed module* has as range a subgroup R of the automorphism group $\text{Aut}(S)$ of S which contains the inner automorphism group of S . The boundary maps $s \in S$ to the inner automorphism of S by s .

Example

```

gap> X5 := XModByAutomorphismGroup( c5 );
[c5 -> Aut(c5)]
gap> Display( X5 );
Crossed module [c5->Aut(c5)] :-
: Source group c5 has generators:
  [ (5,6,7,8,9) ]
: Range group Aut(c5) has generators:
  [ GroupHomomorphismByImages( c5, c5, [ (5,6,7,8,9) ], [ (5,7,9,6,8) ] ) ]
: Boundary homomorphism maps source generators to:
  [ IdentityMapping( c5 ) ]
: Action homomorphism maps range generators to automorphisms:
  GroupHomomorphismByImages( c5, c5, [ (5,6,7,8,9) ],
  [ (5,7,9,6,8) ] ) --> { source gens --> [ (5,7,9,6,8) ] }
  This automorphism generates the group of automorphisms.

```

2.1.5 XModByCentralExtension

▷ XModByCentralExtension(*bdy*)

(operation)

A *central extension crossed module* has as boundary a surjection $\partial : S \rightarrow R$, with central kernel, where $r \in R$ acts on S by conjugation with $\partial^{-1}r$.

Example

```

gap> gen12 := [ (1,2,3,4,5,6), (2,6)(3,5) ];;
gap> d12 := Group( gen12 );;
gap> gen6 := [ (7,8,9), (8,9) ];;
gap> s3 := Group( gen6 );;
gap> pr12 := GroupHomomorphismByImages( d12, s3, gen12, gen6 );;
gap> Kernel( pr12 ) = Centre( d12 );
true
gap> X12 := XModByCentralExtension( pr12 );;
gap> Display( X12 );
Crossed module :-
: Source group has generators:
  [ (1,2,3,4,5,6), (2,6)(3,5) ]
: Range group has generators:
  [ (7,8,9), (8,9) ]
: Boundary homomorphism maps source generators to:
  [ (7,8,9), (8,9) ]
: Action homomorphism maps range generators to automorphisms:
  (7,8,9) --> { source gens --> [ (1,2,3,4,5,6), (1,3)(4,6) ] }
  (8,9) --> { source gens --> [ (1,6,5,4,3,2), (2,6)(3,5) ] }
  These 2 automorphisms generate the group of automorphisms.

```

2.1.6 XModByPullback

▷ `XModByPullback(xmod, hom)` (operation)

Let $\mathcal{X}_0 = (\mu : M \rightarrow P)$ be a crossed module. If $v : N \rightarrow P$ is a group homomorphism with the same range as \mathcal{X}_0 , form the pullback group $L = M \times_P N$, with projection $\lambda : L \rightarrow N$ (as defined in the `Utils` package). Then N acts on L by $(m, n)^{n'} := (m^{vn'}, n^{n'})$, so that $\mathcal{X}_1 = (\lambda : L \rightarrow N)$ is the *pullback crossed module* determined by \mathcal{X}_0 and v . There is also a morphism of crossed modules $(\kappa, v) : \mathcal{X}_1 \rightarrow \mathcal{X}_2$.

The example forms a pullback of the crossed module `X12` of the previous subsection.

Example

```
gap> gens4 := [ (11,12), (12,13), (13,14) ];;
gap> s4 := Group( gens4 );;
gap> theta := GroupHomomorphismByImages( s4, s3, gens4, [(7,8),(8,9),(7,8)] );;
gap> X1 := XModByPullback( X12, theta );;
gap> StructureDescription( Source( X1 ) );
"C2 x S4"
gap> info := PullbackInfo( Source( X1 ) );;
gap> info!.directProduct;
Group([ (1,2,3,4,5,6), (2,6)(3,5), (7,8), (8,9), (9,10) ])
gap> info!.projections[1];
[ (7,8)(9,10), (7,9)(8,10), (2,6)(3,5)(8,9), (1,5,3)(2,6,4)(8,10,9),
  (1,6,5,4,3,2)(8,9,10) ] -> [ (), (), (2,6)(3,5), (1,5,3)(2,6,4),
  (1,6,5,4,3,2) ]
gap> info!.projections[2];
[ (7,8)(9,10), (7,9)(8,10), (2,6)(3,5)(8,9), (1,5,3)(2,6,4)(8,10,9),
  (1,6,5,4,3,2)(8,9,10) ] -> [ (11,12)(13,14), (11,13)(12,14), (12,13),
  (12,14,13), (12,13,14) ]
```

2.1.7 XModByAbelianModule

▷ `XModByAbelianModule(abmod)` (operation)

A *crossed abelian module* has an abelian module as source and the zero map as boundary. See section 11.2 for an example.

2.1.8 DirectProductOp (for crossed modules)

▷ `DirectProductOp(L, X1)` (operation)

The direct product $\mathcal{X}_1 \times \mathcal{X}_2$ of two crossed modules has source $S_1 \times S_2$, range $R_1 \times R_2$ and boundary $\partial_1 \times \partial_2$, with R_1, R_2 acting trivially on S_2, S_1 respectively.

Since `DirectProduct` is a global function which only accepts groups, it is necessary to provide an "other method" for the operation `DirectProductOp`. This operation takes as parameters a list of crossed modules, followed by the first of these: `DirectProductOp([X1,X2],X1)`; . At present only the direct product of two crossed modules is implemented.

The example constructs the product of the two crossed modules formed in subsection `XModByTrivialAction` (2.1.3).

Example

```
gap> DirectProductOp( [X8a,X8b], X8a );
[<-1>x<i>->q8xq8]
```

2.1.9 Source (for crossed modules)

- ▷ Source($X0$) (attribute)
- ▷ Range($X0$) (attribute)
- ▷ Boundary($X0$) (attribute)
- ▷ XModAction($X0$) (attribute)

The following attributes are used in the construction of a crossed module $X0$.

- Source($X0$) and Range($X0$) are the source S and range R of ∂ , the boundary Boundary($X0$);
- XModAction($X0$) is a homomorphism from R to a group of automorphisms of $X0$.

(Up until version 2.63 there was an additional attribute AutoGroup, the range of XModAction($X0$).)

The example uses the crossed module X12 constructed in subsection XModByCentralExtension (2.1.5).

Example

```
gap> Source( X12 );
Group([ (1,2,3,4,5,6), (2,6)(3,5) ])
gap> Range( X12 );
Group([ (7,8,9), (8,9) ])
gap> Boundary( X12 );
[ (1,2,3,4,5,6), (2,6)(3,5) ] -> [ (7,8,9), (8,9) ]
gap> XModAction( X12 );
[ (7,8,9), (8,9) ] ->
[ [ (1,2,3,4,5,6), (2,6)(3,5) ] -> [ (1,2,3,4,5,6), (1,3)(4,6) ],
  [ (1,2,3,4,5,6), (2,6)(3,5) ] -> [ (1,6,5,4,3,2), (2,6)(3,5) ] ]
```

2.1.10 ImageElmXModAction

- ▷ ImageElmXModAction($X0, s, r$) (operation)

This function returns the element s^r given by XModAction($X0$).

2.1.11 Size (for crossed modules)

- ▷ Size($X0$) (attribute)
- ▷ Name($X0$) (attribute)
- ▷ IdGroup($X0$) (attribute)
- ▷ ExternalSetXMod($X0$) (attribute)

More familiar attributes are Name, Size and IdGroup. The name is formed by concatenating the names of the source and range (if these exist). Size and IdGroup return two-element lists.

The ExternalSetXMod for a crossed module is the source group considered as a G-set of the range group using the crossed module action.

The Display function is used to print details of 2d-groups.

In the simple example below, X5 is the automorphism crossed module constructed in subsection XModByAutomorphismGroup (2.1.4). The Print statements at the end of the example list the GAP representations and attributes of X5.

Example

```
gap> Size( X5 ); IdGroup( X5 );
[ 5, 4 ]
[ [ 5, 1 ], [ 4, 1 ] ]
gap> ext := ExternalSetXMod( X5 );
<xset:[ ( ), (5,6,7,8,9), (5,7,9,6,8), (5,8,6,9,7), (5,9,8,7,6) ]>
gap> Orbits( ext );
[ [ ( ) ], [ (5,6,7,8,9), (5,7,9,6,8), (5,9,8,7,6), (5,8,6,9,7) ] ]
gap> a := GeneratorsOfGroup( Range( X5 ) )[1]^2;
[ (5,6,7,8,9) ] -> [ (5,9,8,7,6) ]
gap> ImageElmXModAction( X5, (5,7,9,6,8), a );
(5,8,6,9,7)
gap> RepresentationsOfObject( X5 );
[ "IsComponentObjectRep", "IsAttributeStoringRep", "IsPreXModObj" ]
gap> KnownAttributesOfObject( X5 );
[ "Name", "Size", "Range", "Source", "IdGroup", "Boundary", "XModAction",
  "ExternalSetXMod", "IsomorphismPerm2DimensionalGroup" ]
```

2.2 Properties of crossed modules

The underlying category structures for the objects constructed in this chapter follow the sequence Is2DimensionalDomain; Is2DimensionalMagma; Is2DimensionalMagmaWithOne; Is2DimensionalMagmaWithInverses, mirroring the situation for (one-dimensional) groups. From these we construct Is2DimensionalSemigroup, Is2DimensionalMonoid and Is2DimensionalGroup.

There are then a variety of properties associated with crossed modules, starting with IsPreXMod and IsXMod.

2.2.1 IsXMod

- ▷ IsXMod($X0$) (property)
- ▷ IsPreXMod($X0$) (property)
- ▷ IsPerm2DimensionalGroup($X0$) (property)
- ▷ IsPc2DimensionalGroup($X0$) (property)
- ▷ IsFp2DimensionalGroup($X0$) (property)

A structure which has IsPerm2DimensionalGroup is a precrossed module or a pre-cat1-group (see section 2.4) whose source and range are both permutation groups. The prop-

erties `IsPc2DimensionalGroup`, `IsFp2DimensionalGroup` are defined similarly. In the example below we see that `X5` has `IsPreXMod`, `IsXMod` and `IsPerm2DimensionalGroup`. There are also properties corresponding to the various construction methods listed in section 2.1: `IsTrivialAction2DimensionalGroup`; `IsNormalSubgroup2DimensionalGroup`; `IsCentralExtension2DimensionalGroup`; `IsAutomorphismGroup2DimensionalGroup`; `IsAbelianModule2DimensionalGroup`.

Example

```
gap> KnownPropertiesOfObject( X5 );
[ "IsEmpty", "IsTrivial", "IsNonTrivial", "IsFinite",
  "CanEasilyCompareElements", "CanEasilySortElements", "IsDuplicateFree",
  "IsGeneratorsOfSemigroup", "IsPreXModDomain", "IsPerm2DimensionalGroup",
  "IsPreXMod", "IsXMod", "IsAutomorphismGroup2DimensionalGroup" ]
```

2.2.2 SubXMod

- ▷ `SubXMod(X0, src, rng)` (operation)
- ▷ `TrivialSubXMod(X0)` (attribute)
- ▷ `NormalSubXMods(X0)` (attribute)

With the standard crossed module constructors listed above as building blocks, sub-crossed modules, normal sub-crossed modules $\mathcal{N} \triangleleft \mathcal{X}$, and also quotients \mathcal{X}/\mathcal{N} may be constructed. A sub-crossed module $\mathcal{S} = (\delta : N \rightarrow M)$ is *normal* in $\mathcal{X} = (\partial : S \rightarrow R)$ if

- N, M are normal subgroups of S, R respectively,
- δ is the restriction of ∂ ,
- $n^r \in N$ for all $n \in N, r \in R$,
- $(s^{-1})^m s \in N$ for all $m \in M, s \in S$.

These conditions ensure that $M \times N$ is normal in the semidirect product $R \times S$. (Note that $\langle s, m \rangle = (s^{-1})^m s$ is a displacement: see [Displacement \(4.1.3\)](#).)

A method for `IsNormal` for precrossed modules is provided. See section 4.1 for factor crossed modules and their natural morphisms.

The five normal subcrossed modules of `X4` found in the following example are `[id,id]`, `[k4,k4]`, `[k4,a4]`, `[a4,a4]` and `X4` itself.

Example

```
gap> s4 := Group( (1,2), (2,3), (3,4) );;
gap> a4 := Subgroup( s4, [ (1,2,3), (2,3,4) ] );;
gap> k4 := Subgroup( a4, [ (1,2)(3,4), (1,3)(2,4) ] );;
gap> SetName(s4,"s4"); SetName(a4,"a4"); SetName(k4,"k4");
gap> X4 := XModByNormalSubgroup( s4, a4 );
[a4->s4]
gap> Y4 := SubXMod( X4, k4, a4 );
[k4->a4]
```

```

gap> IsNormal(X4,Y4);
true
gap> NX4 := NormalSubXMods( X4 );;
gap> Length( NX4 );
5

```

2.2.3 KernelCokernelXMod

▷ KernelCokernelXMod($X0$) (attribute)

Let $\mathcal{X} = (\partial : S \rightarrow R)$. If $K \leq S$ is the kernel of ∂ , and $J \leq R$ is the image of ∂ , form $C = R/J$. Then $(v\partial|_K : K \rightarrow C)$ is a crossed module where $v : R \rightarrow C, r \mapsto Jr$ is the natural map, and the action of C on K is given by $k^{Jr} = k^r$.

Example

```

gap> d8d8 := Group( (1,2,3,4), (1,3), (5,6,7,8), (5,7) );;
gap> X88 := XModByAutomorphismGroup( d8d8 );;
gap> Size( X88 );
[ 64, 2048 ]
gap> Y88 := KernelCokernelXMod( X88 );;
gap> StructureDescription( Y88 );
[ "C2 x C2", "(D8 x D8) : C2" ]

```

2.3 Pre-crossed modules

2.3.1 PreXModByBoundaryAndAction

▷ PreXModByBoundaryAndAction(bdy, act) (operation)
 ▷ SubPreXMod($X0, src, rng$) (operation)

If axiom **XMod 2** is *not* satisfied, the corresponding structure is known as a *pre-crossed module*.

Example

```

gap> b1 := (11,12,13,14,15,16,17,18);; b2 := (12,18)(13,17)(14,16);;
gap> d16 := Group( b1, b2 );;
gap> sk4 := Subgroup( d16, [ b1^4, b2 ] );;
gap> SetName( d16, "d16" ); SetName( sk4, "sk4" );
gap> bdy16 := GroupHomomorphismByImages( d16, sk4, [b1,b2], [b1^4,b2] );;
gap> aut1 := GroupHomomorphismByImages( d16, d16, [b1,b2], [b1^5,b2] );;
gap> aut2 := GroupHomomorphismByImages( d16, d16, [b1,b2], [b1,b2^4*b2] );;
gap> aut16 := Group( [ aut1, aut2 ] );;
gap> act16 := GroupHomomorphismByImages( sk4, aut16, [b1^4,b2], [aut1,aut2] );;
gap> P16 := PreXModByBoundaryAndAction( bdy16, act16 );
[d16->sk4]
gap> IsXMod(P16);
false

```


2.3.2 PeifferSubgroup

- ▷ PeifferSubgroup($X0$) (attribute)
- ▷ XModByPeifferQuotient($prexmod$) (attribute)

The *Peiffer subgroup* P of a pre-crossed module \mathcal{X} is the subgroup of $\ker(\partial)$ generated by *Peiffer commutators*

$$[s_1, s_2] = (s_1^{-1})^{\partial s_2} s_2^{-1} s_1 s_2 = \langle \partial s_2, s_1 \rangle [s_1, s_2].$$

Then $\mathcal{P} = (0 : P \rightarrow \{1_R\})$ is a normal sub-pre-crossed module of \mathcal{X} and $\mathcal{X}/\mathcal{P} = (\partial : S/P \rightarrow R)$ is a crossed module.

In the following example the Peiffer subgroup is cyclic of size 4.

Example

```
gap> P := PeifferSubgroup( P16 );
Group( [ (11,15)(12,16)(13,17)(14,18), (11,17,15,13)(12,18,16,14) ] )
gap> X16 := XModByPeifferQuotient( P16 );
Peiffer([d16->sk4])
gap> Display( X16 );
Crossed module Peiffer([d16->sk4]) :-
: Source group has generators:
  [ f1, f2 ]
: Range group has generators:
  [ (11,15)(12,16)(13,17)(14,18), (12,18)(13,17)(14,16) ]
: Boundary homomorphism maps source generators to:
  [ (12,18)(13,17)(14,16), (11,15)(12,16)(13,17)(14,18) ]
The automorphism group is trivial
gap> iso16 := IsomorphismPermGroup( Source( X16 ) );;
gap> S16 := Image( iso16 );
Group([ (1,2), (3,4) ])
```

2.4 Cat1-groups and pre-cat1-groups

In [Lod82], Loday reformulated the notion of a crossed module as a cat1-group, namely a group G with a pair of endomorphisms $t, h : G \rightarrow G$ having a common image R and satisfying certain axioms. We find it computationally convenient to define a cat1-group $\mathcal{C} = (e; t, h : G \rightarrow R)$ as having source group G , range group R , and three homomorphisms: two surjections $t, h : G \rightarrow R$ and an embedding $e : R \rightarrow G$ satisfying:

$$\mathbf{Cat\ 1} : t \circ e = h \circ e = \text{id}_R, \quad \mathbf{Cat\ 2} : [kert, kerh] = \{1_G\}.$$

It follows that $t \circ e \circ h = h$, $h \circ e \circ t = t$, $t \circ e \circ t = t$ and $h \circ e \circ h = h$. (See section 2.5 for the case when t, h are endomorphisms.)

2.4.1 Cat1Group

- ▷ Cat1Group($args$) (function)
- ▷ PreCat1Group($args$) (function)
- ▷ PreCat1GroupByTailHeadEmbedding(t, h, e) (operation)

▷ `PreCat1GroupByEndomorphisms(t, h)` (operation)

The global functions `Cat1Group` and `PreCat1Group` can be called in various ways.

- as `Cat1Group(t,h,e)`; when t, h, e are three homomorphisms, which is equivalent to `PreCat1GroupByTailHeadEmbedding(t,h,e)`;
- as `Cat1Group(t,h)`; when t, h are two endomorphisms, which is equivalent to `PreCat1GroupByEndomorphisms(t,h)`;
- as `Cat1Group(t)`; when $t = h$ is an endomorphism, which is equivalent to `PreCat1GroupByEndomorphisms(t,t)`;
- as `Cat1Group(t,e)`; when $t = h$ and e are homomorphisms, which is equivalent to `PreCat1GroupByTailHeadEmbedding(t,t,e)`;
- as `Cat1Group(i,j,k)`; when i, j, k are integers, which is equivalent to `Cat1Select(i,j,k)`; as described in section 2.6.

Example

```
gap> g18gens := [ (1,2,3), (4,5,6), (2,3)(5,6) ];;
gap> s3agens := [ (7,8,9), (8,9) ];;
gap> g18 := Group( g18gens );; SetName( g18, "g18" );
gap> s3a := Group( s3agens );; SetName( s3a, "s3a" );
gap> t1 := GroupHomomorphismByImages(g18,s3a,g18gens,[(7,8,9),(),(8,9)]);
[ (1,2,3), (4,5,6), (2,3)(5,6) ] -> [ (7,8,9), (), (8,9) ]
gap> h1 := GroupHomomorphismByImages(g18,s3a,g18gens,[(7,8,9),(7,8,9),(8,9)]);
[ (1,2,3), (4,5,6), (2,3)(5,6) ] -> [ (7,8,9), (7,8,9), (8,9) ]
gap> e1 := GroupHomomorphismByImages(s3a,g18,s3agens,[(1,2,3),(2,3)(5,6)]);
[ (7,8,9), (8,9) ] -> [ (1,2,3), (2,3)(5,6) ]
gap> C18 := Cat1Group( t1, h1, e1 );
[g18=>s3a]
```

2.4.2 Source (for cat1-groups)

▷ `Source(C)` (attribute)
 ▷ `Range(C)` (attribute)
 ▷ `TailMap(C)` (attribute)
 ▷ `HeadMap(C)` (attribute)
 ▷ `RangeEmbedding(C)` (attribute)
 ▷ `KernelEmbedding(C)` (attribute)
 ▷ `Boundary(C)` (attribute)
 ▷ `Name(C)` (attribute)
 ▷ `Size(C)` (attribute)

These are the attributes of a cat1-group \mathcal{C} in this implementation.

The maps t, h are often referred to as the *source* and *target*, but we choose to call them the *tail* and *head* of \mathcal{C} , because *source* is the GAP term for the domain of a function. The `RangeEmbedding` is the embedding of R in G , the `KernelEmbedding` is the inclusion of the kernel of t in G , and the `Boundary`

is the restriction of h to the kernel of t . It is frequently the case that $t = h$, but not in the example C18 above.

Example

```

gap> Source( C18 );
g18
gap> Range( C18 );
s3a
gap> TailMap( C18 );
[ (1,2,3), (4,5,6), (2,3)(5,6) ] -> [ (7,8,9), (), (8,9) ]
gap> HeadMap( C18 );
[ (1,2,3), (4,5,6), (2,3)(5,6) ] -> [ (7,8,9), (7,8,9), (8,9) ]
gap> RangeEmbedding( C18 );
[ (7,8,9), (8,9) ] -> [ (1,2,3), (2,3)(5,6) ]
gap> Kernel( C18 );
Group([ (4,5,6) ])
gap> KernelEmbedding( C18 );
[ (4,5,6) ] -> [ (4,5,6) ]
gap> Name( C18 );
"[g18=>s3a]"
gap> Size( C18 );
[ 18, 6 ]
gap> StructureDescription( C18 );
[ "(C3 x C3) : C2", "S3" ]

```

2.4.3 DiagonalCat1Group

- ▷ DiagonalCat1Group(*gen1*) (operation)
- ▷ PreCat1GroupByNormalSubgroup(*G*, *M*) (operation)
- ▷ Cat1GroupByPeifferQuotient(*P*) (operation)
- ▷ ReverseCat1Group(*C0*) (attribute)

These are some more constructors for cat1-groups. The following listing shows an example of a permutation cat1-group of size [576,24] with source group $S_4 \times S_4$, range group a third S_4 , and $t \neq h$. A similar example may be reproduced using the command $C := \text{DiagonalCat1Group}([(1,2,3,4), (3,4)])$;

Example

```

gap> G4 := Group( (1,2,3,4), (3,4), (5,6,7,8), (7,8) );;
gap> R4 := Group( (9,10,11,12), (11,12) );;
gap> SetName( G4, "s4s4" ); SetName( R4, "s4d" );
gap> G4gens := GeneratorsOfGroup( G4 );;
gap> R4gens := GeneratorsOfGroup( R4 );;
gap> t := GroupHomomorphismByImages( G4, R4, G4gens,
> Concatenation( R4gens, [ (), () ] ) );;
gap> h := GroupHomomorphismByImages( G4, R4, G4gens,
> Concatenation( [ (), () ], R4gens ) );;
gap> e := GroupHomomorphismByImages( R4, G4, R4gens,
> [ (1,2,3,4)(5,6,7,8), (3,4)(7,8) ] );;
gap> C4 := PreCat1GroupByTailHeadEmbedding( t, h, e );;

```

```

gap> Display(C4);
Cat1-group [s4s4=>s4d] :-
: Source group s4s4 has generators:
  [ (1,2,3,4), (3,4), (5,6,7,8), (7,8) ]
: Range group s4d has generators:
  [ ( 9,10,11,12), (11,12) ]
: tail homomorphism maps source generators to:
  [ ( 9,10,11,12), (11,12), (), () ]
: head homomorphism maps source generators to:
  [ (), (), ( 9,10,11,12), (11,12) ]
: range embedding maps range generators to:
  [ (1,2,3,4)(5,6,7,8), (3,4)(7,8) ]
: kernel has generators:
  [ (5,6,7,8), (7,8) ]
: boundary homomorphism maps generators of kernel to:
  [ ( 9,10,11,12), (11,12) ]
: kernel embedding maps generators of kernel to:
  [ (5,6,7,8), (7,8) ]

```

2.5 Properties of cat1-groups and pre-cat1-groups

Many of the properties listed in section 2.2 apply to pre-cat1-groups and to cat1-groups since these are also 2d-groups. There are also more specific properties.

2.5.1 IsCat1Group

- ▷ IsCat1Group($C0$) (property)
- ▷ IsPreXCat1Group($C0$) (property)
- ▷ IsIdentityCat1Group($C0$) (property)
- ▷ IsEndomorphismPreCat1Group($C0$) (property)
- ▷ EndomorphismPreCat1Group($C0$) (attribute)

IsIdentityCat1Group($C0$) is true when the head and tail maps of $C0$ are identity mappings. IsEndomorphismPreCat1Group($C0$) is true when the range of $C0$ is a subgroup of the source. When this is not the case, replacing t, h, e by $t * e, h * e$ and the inclusion mapping of the image of e gives an isomorphic cat1-group for which IsEndomorphismPreCat1Group is true.

Example

```

gap> G2 := SmallGroup( 288, 956 ); SetName( G2, "G2" );
<pc group of size 288 with 7 generators>
gap> d12 := DihedralGroup( 12 ); SetName( d12, "d12" );
<pc group of size 12 with 3 generators>
gap> a1 := d12.1;; a2 := d12.2;; a3 := d12.3;; a0 := One( d12 );;
gap> gensG2 := GeneratorsOfGroup( G2 );;
gap> t2 := GroupHomomorphismByImages( G2, d12, gensG2,
>      [ a0, a1*a3, a2*a3, a0, a0, a3, a0 ] );;
gap> h2 := GroupHomomorphismByImages( G2, d12, gensG2,
>      [ a1*a2*a3, a0, a0, a2*a3, a0, a0, a3^2 ] );;

```

```

gap> e2 := GroupHomomorphismByImages( d12, G2, [a1,a2,a3],
>      [ G2.1*G2.2*G2.4*G2.6^2, G2.3*G2.4*G2.6^2*G2.7, G2.6*G2.7^2 ] );
[ f1, f2, f3 ] -> [ f1*f2*f4*f6^2, f3*f4*f6^2*f7, f6*f7^2 ]
gap> C2 := PreCat1GroupByTailHeadEmbedding( t2, h2, e2 );
[G2=>d12]
gap> IsCat1Group( C2 );
true
gap> KnownPropertiesOfObject( C2 );
[ "CanEasilyCompareElements", "CanEasilySortElements", "IsDuplicateFree",
  "IsGeneratorsOfSemigroup", "IsPreCat1Domain", "IsPerm2DimensionalGroup",
  "IsPreCat1Group", "IsCat1Group", "IsEndomorphismPreCat1Group" ]
gap> IsEndomorphismPreCat1Group( C2 );
false
gap> EC4 := EndomorphismPreCat1Group( C4 );
[ s4s4=>Group( [ (1,2,3,4)(5,6,7,8), (3,4)(7,8), (), () ] ) ]

```

2.5.2 Cat1GroupOfXMod

- ▷ Cat1GroupOfXMod($X0$) (attribute)
- ▷ XModOfCat1Group($C0$) (attribute)
- ▷ PreCat1GroupOfPreXMod($P0$) (attribute)
- ▷ PreXModOfPreCat1Group($P0$) (attribute)

The category of crossed modules is equivalent to the category of cat1-groups, and the functors between these two categories may be described as follows. Starting with the crossed module $\mathcal{X} = (\partial : S \rightarrow R)$ the group G is defined as the semidirect product $G = R \ltimes S$ using the action from \mathcal{X} , with multiplication rule

$$(r_1, s_1)(r_2, s_2) = (r_1 r_2, s_1 {}^{r_2} s_2).$$

The structural morphisms are given by

$$t(r, s) = r, \quad h(r, s) = r(\partial s), \quad er = (r, 1).$$

On the other hand, starting with a cat1-group $\mathcal{C} = (e; t, h : G \rightarrow R)$, we define $S = \ker t$, the range R is unchanged, and $\partial = h|_S$. The action of R on S is conjugation in G via the embedding of R in G .

Example

```

gap> X2 := XModOfCat1Group( C2 );;
gap> Display( X2 );

Crossed module X([G2=>d12]) :-
: Source group has generators:
  [ f1, f4, f5, f7 ]
: Range group d12 has generators:
  [ f1, f2, f3 ]
: Boundary homomorphism maps source generators to:
  [ f1*f2*f3, f2*f3, <identity> of ..., f3^2 ]
: Action homomorphism maps range generators to automorphisms:
  f1 --> { source gens --> [ f1*f5, f4*f5, f5, f7^2 ] }
  f2 --> { source gens --> [ f1*f5*f7^2, f4, f5, f7 ] }

```

```

f3 --> { source gens --> [ f1*f7, f4, f5, f7 ] }
These 3 automorphisms generate the group of automorphisms.
: associated cat1-group is [G2=>d12]

gap> StructureDescription(X2);
[ "D24", "D12" ]

```

2.6 Selection of a small cat1-group

The `Cat1Group` function may also be used to select a cat1-group from a data file. All cat1-structures on groups of size up to 70 (ordered according to the GAP 4 numbering of small groups) are stored in a list in file `cat1data.g`. Global variables `CAT1_LIST_MAX_SIZE := 70` and `CAT1_LIST_CLASS_SIZES` are also stored. The data is read into the list `CAT1_LIST` only when this function is called.

2.6.1 Cat1Select

▷ `Cat1Select(size, gpnum, num)` (operation)

The function `Cat1Select` may be used in three ways. `Cat1Select(size)` returns the names of the groups with this size, while `Cat1Select(size, gpnum)` prints a list of cat1-structures for this chosen group. `Cat1Select(size, gpnum, num)` returns the chosen cat1-group.

The example below is the first case in which $t \neq h$ and the associated conjugation crossed module is given by the normal subgroup `c3` of `s3`.

Example

```

gap> ## check the number of groups of size 18
gap> L18 := Cat1Select( 18 );
Usage: Cat1Select( size, gpnum, num );
[ "D18", "C18", "C3 x S3", "(C3 x C3) : C2", "C6 x C3" ]
gap> ## check the number of cat1-structures on the fourth of these
gap> Cat1Select( 18, 4 );
Usage: Cat1Select( size, gpnum, num );
There are 4 cat1-structures for the group (C3 x C3) : C2.
Using small generating set [ f1, f2, f2*f3 ] for source of homs.
[ [range gens], [tail genimages], [head genimages] ] :-
(1) [ [ f1 ], [ f1, <identity> of ..., <identity> of ... ],
      [ f1, <identity> of ..., <identity> of ... ] ]
(2) [ [ f1, f3 ], [ f1, <identity> of ..., f3 ],
      [ f1, <identity> of ..., f3 ] ]
(3) [ [ f1, f3 ], [ f1, <identity> of ..., f3 ],
      [ f1, f3^2, <identity> of ... ] ]
(4) [ [ f1, f2, f2*f3 ], tail = head = identity mapping ]
4
gap> ## select the third of these cat1-structures
gap> C18 := Cat1Group( 18, 4, 3 );
[(C3 x C3) : C2=>Group( [ f1, <identity> of ..., f3 ] )]

```

```

gap> ## convert from a pc-cat1-group to a permutation cat1-group
gap> iso18 := IsomorphismPermObject( C18 );;
gap> PC18 := Image( iso18 );;
gap> Display( PC18 );
Cat1-group :-
: Source group has generators:
  [ (2,3)(5,6), (4,5,6), (1,2,3) ]
: Range group has generators:
  [ (2,3), (), (1,2,3) ]
: tail homomorphism maps source generators to:
  [ (2,3), (), (1,2,3) ]
: head homomorphism maps source generators to:
  [ (2,3), (1,3,2), (1,2,3) ]
: range embedding maps range generators to:
  [ (2,3)(5,6), (), (1,2,3) ]
: kernel has generators:
  [ (4,5,6) ]
: boundary homomorphism maps generators of kernel to:
  [ (1,3,2) ]
: kernel embedding maps generators of kernel to:
  [ (4,5,6) ]
gap> convert the result to the associated permutation crossed module
gap> X18 := XModOfCat1Group( PC18 );;
gap> Display( X18 );
Crossed module:-
: Source group has generators:
  [ (4,5,6) ]
: Range group has generators:
  [ (2,3), (), (1,2,3) ]
: Boundary homomorphism maps source generators to:
  [ (1,3,2) ]
: Action homomorphism maps range generators to automorphisms:
  (2,3) --> { source gens --> [ (4,6,5) ] }
  () --> { source gens --> [ (4,5,6) ] }
  (1,2,3) --> { source gens --> [ (4,5,6) ] }
  These 3 automorphisms generate the group of automorphisms.
: associated cat1-group is [..=>..]

```

2.6.2 AllCat1DataGroupsBasic

▷ AllCat1DataGroupsBasic(*gp*)

(operation)

For a group G of size greater than 70 which is reasonably straightforward this function may be used to construct a list of all cat1-group structures on G . The operation also attempts to write output to a file in the folder `xmod/lib`. (Other operations in the file `cat1data.gi` have been used to deal with the more complicated groups of size up to 70, but these are not described here.)

Van Luyen Le has a more efficient algorithm, extending the data up to groups of size 171, which is expected to appear in a future release of HAP.

Example

```

gap> gp := SmallGroup( 102, 2 );
<pc group of size 102 with 3 generators>
gap> StructureDescription( gp );
"C3 x D34"
gap> all := AllCat1DataGroupsBasic( gp );
#I Edit last line of ../xmod/lib/mn.kk.out to end with ] ] ] ]
[ [Group( [ f1, f2, f3 ] )=>Group( [ f1, <identity> of ..., <identity> of ...
  ] )], [Group( [ f1, f2, f3 ] )=>Group( [ f1, f2, <identity> of ... ] )],
  [Group( [ f1, f2, f3 ] )=>Group( [ f1, <identity> of ..., f3 ] )],
  [Group( [ f1, f2, f3 ] )=>Group( [ f1, f2, f3 ] )] ] ]

```

2.7 More functions for crossed modules and cat1-groups

Chapter 4 contains functions for quotient crossed modules; centre of a crossed module; commutator and derived subcrossed modules; etc.

Here we mention two functions for groups which have been extended to the two-dimensional case.

2.7.1 IdGroup (for 2d-groups)

- ▷ `IdGroup(2DimensionalGroup)` (operation)
- ▷ `StructureDescription(2DimensionalGroup)` (operation)

These functions return two-element lists formed by applying the function to the source and range of the 2d-group.

Example

```

gap> IdGroup( X2 );
[ [ 24, 6 ], [ 12, 4 ] ]
gap> StructureDescription( C2 );
[ "(S3 x D24) : C2", "D12" ]

```


Chapter 3

2d-mappings

3.1 Morphisms of 2-dimensional groups

This chapter describes morphisms of (pre-)crossed modules and (pre-)cat1-groups.

3.1.1 Source (for 2d-group mappings)

- ▷ `Source(map)` (attribute)
- ▷ `Range(map)` (attribute)
- ▷ `SourceHom(map)` (attribute)
- ▷ `RangeHom(map)` (attribute)

Morphisms of *2-dimensional groups* are implemented as *2-dimensional mappings*. These have a pair of 2-dimensional groups as source and range, together with two group homomorphisms mapping between corresponding source and range groups. These functions return `fail` when invalid data is supplied.

3.2 Morphisms of pre-crossed modules

3.2.1 IsXModMorphism

- ▷ `IsXModMorphism(map)` (property)
- ▷ `IsPreXModMorphism(map)` (property)

A morphism between two pre-crossed modules $\mathcal{X}_1 = (\partial_1 : S_1 \rightarrow R_1)$ and $\mathcal{X}_2 = (\partial_2 : S_2 \rightarrow R_2)$ is a pair (σ, ρ) , where $\sigma : S_1 \rightarrow S_2$ and $\rho : R_1 \rightarrow R_2$ commute with the two boundary maps and are morphisms for the two actions:

$$\partial_2 \circ \sigma = \rho \circ \partial_1, \quad \sigma(s^r) = (\sigma s)^{\rho r}.$$

Here σ is the `SourceHom` (3.1.1) and ρ is the `RangeHom` (3.1.1) of the morphism. When $\mathcal{X}_1 = \mathcal{X}_2$ and σ, ρ are automorphisms then (σ, ρ) is an automorphism of \mathcal{X}_1 . The group of automorphisms is denoted by $\text{Aut}(\mathcal{X}_1)$.

3.2.2 IsInjective (for pre-xmod morphisms)

▷ IsInjective(<i>map</i>)	(method)
▷ IsSurjective(<i>map</i>)	(method)
▷ IsSingleValued(<i>map</i>)	(method)
▷ IsTotal(<i>map</i>)	(method)
▷ IsBijective(<i>map</i>)	(method)
▷ IsEndo2DimensionalMapping(<i>map</i>)	(property)

The usual properties of mappings are easily checked. It is usually sufficient to verify that both the SourceHom (3.1.1) and the RangeHom (3.1.1) have the required property.

3.2.3 XModMorphism

▷ XModMorphism(<i>args</i>)	(function)
▷ XModMorphismByGroupHomomorphisms(<i>X1</i> , <i>X2</i> , <i>sigma</i> , <i>rho</i>)	(operation)
▷ PreXModMorphism(<i>args</i>)	(function)
▷ PreXModMorphismByGroupHomomorphisms(<i>P1</i> , <i>P2</i> , <i>sigma</i> , <i>rho</i>)	(operation)
▷ InclusionMorphism2DimensionalDomains(<i>X1</i> , <i>S1</i>)	(operation)
▷ InnerAutomorphismXMod(<i>X1</i> , <i>r</i>)	(operation)
▷ IdentityMapping(<i>X1</i>)	(attribute)

These are the constructors for morphisms of pre-crossed and crossed modules.

In the following example we construct a simple automorphism of the crossed module *X1* constructed in the previous chapter.

Example

```
gap> sigma1 := GroupHomomorphismByImages( c5, c5, [ (5,6,7,8,9) ]
      [ (5,9,8,7,6) ] );;
gap> rho1 := IdentityMapping( Range( X1 ) );
IdentityMapping( PAut(c5) )
gap> mor1 := XModMorphism( X1, X1, sigma1, rho1 );
[[c5->Aut(c5)] => [c5->Aut(c5)]]
gap> Display( mor1 );
Morphism of crossed modules :-
: Source = [c5->Aut(c5)] with generating sets:
  [ (5,6,7,8,9) ]
  [ GroupHomomorphismByImages( c5, c5, [ (5,6,7,8,9) ], [ (5,7,9,6,8) ] ) ]
: Range = Source
: Source Homomorphism maps source generators to:
  [ (5,9,8,7,6) ]
: Range Homomorphism maps range generators to:
  [ GroupHomomorphismByImages( c5, c5, [ (5,6,7,8,9) ], [ (5,7,9,6,8) ] ) ]
gap> IsAutomorphism2DimensionalDomain( mor1 );
true
gap> Order( mor1 );
2
gap> RepresentationsOfObject( mor1 );
[ "IsComponentObjectRep", "IsAttributeStoringRep", "Is2DimensionalMappingRep" ]
gap> KnownPropertiesOfObject( mor1 );
```

```
[ "CanEasilyCompareElements", "CanEasilySortElements", "IsTotal",
  "IsSingleValued", "IsInjective", "IsSurjective", "RespectsMultiplication",
  "IsPreXModMorphism", "IsXModMorphism", "IsEndomorphism2DimensionalDomain",
  "IsAutomorphism2DimensionalDomain" ]
gap> KnownAttributesOfObject( mor1 );
[ "Name", "Order", "Range", "Source", "SourceHom", "RangeHom" ]
```

3.2.4 IsomorphismPerm2DimensionalGroup (for pre-xmod morphisms)

- ▷ IsomorphismPerm2DimensionalGroup(*obj*) (attribute)
- ▷ IsomorphismPc2DimensionalGroup(*obj*) (attribute)
- ▷ IsomorphismByIsomorphisms(*D*, *list*) (operation)

When \mathcal{D} is a 2-dimensional domain with source S and range R and $\sigma : S \rightarrow S'$, $\rho : R \rightarrow R'$ are isomorphisms, then `IsomorphismByIsomorphisms(D, [sigma, rho])` returns an isomorphism $(\sigma, \rho) : \mathcal{D} \rightarrow \mathcal{D}'$ where \mathcal{D}' has source S' and range R' . Be sure to test `IsBijective` for the two functions σ, ρ before applying this operation.

Using `IsomorphismByIsomorphisms` with a pair of isomorphisms obtained using `IsomorphismPermGroup` or `IsomorphismPcGroup`, we may construct a crossed module or a `cat1`-group of permutation groups or `pc`-groups.

Example

```
gap> q8 := SmallGroup(8,4);; ## quaternion group
gap> Xq8 := XModByAutomorphismGroup( q8 );
[Group( [ f1, f2, f3 ] )->Group( [ f1, f2, f3, f4 ] )]
gap> iso := IsomorphismPerm2DimensionalGroup( Xq8 );;
gap> Yq8 := Image( iso );
[Group( [ (1,2,4,6)(3,8,7,5), (1,3,4,7)(2,5,6,8), (1,4)(2,6)(3,7)(5,8)
  ] )->Group( [ (2,6,5,4), (1,2,4)(3,5,6), (2,5)(4,6), (1,3)(2,5) ] )]
gap> s4 := SymmetricGroup(4);;
gap> isos4 := IsomorphismGroups( Range(Yq8), s4 );;
gap> id := IdentityMapping( Source( Yq8 ) );;
gap> IsBijective( id );; IsBijective( isos4 );;
gap> mor := IsomorphismByIsomorphisms( Yq8, [id, isos4] );;
gap> Zq8 := Image( mor );
[Group( [ (1,2,4,6)(3,8,7,5), (1,3,4,7)(2,5,6,8), (1,4)(2,6)(3,7)(5,8)
  ] )->SymmetricGroup( [ 1 .. 4 ] )]
```

3.2.5 MorphismOfPullback (for a crossed module by pullback)

- ▷ MorphismOfPullback(*xmod*) (attribute)

Let $\mathcal{X}_1 = (\lambda : L \rightarrow N)$ be the pullback crossed module obtained from a crossed module $\mathcal{X}_0 = (\mu : M \rightarrow P)$ and a group homomorphism $\nu : N \rightarrow P$. Then the associated crossed module morphism is $(\kappa, \nu) : \mathcal{X}_1 \rightarrow \mathcal{X}_0$ where κ is the projection from L to M .

3.3 Morphisms of pre-cat1-groups

A morphism of pre-cat1-groups from $\mathcal{C}_1 = (e_1; t_1, h_1 : G_1 \rightarrow R_1)$ to $\mathcal{C}_2 = (e_2; t_2, h_2 : G_2 \rightarrow R_2)$ is a pair (γ, ρ) where $\gamma : G_1 \rightarrow G_2$ and $\rho : R_1 \rightarrow R_2$ are homomorphisms satisfying

$$h_2 \circ \gamma = \rho \circ h_1, \quad t_2 \circ \gamma = \rho \circ t_1, \quad e_2 \circ \rho = \gamma \circ e_1.$$

3.3.1 IsCat1GroupMorphism

▷ IsCat1GroupMorphism(<i>map</i>)	(property)
▷ IsPreCat1GroupMorphism(<i>map</i>)	(property)
▷ Cat1GroupMorphism(<i>args</i>)	(function)
▷ Cat1GroupMorphismByHoms(<i>C1, C2, gamma, rho</i>)	(operation)
▷ PreCat1GroupMorphism(<i>args</i>)	(function)
▷ PreCat1GroupMorphismByHoms(<i>P1, P2, gamma, rho</i>)	(operation)
▷ InclusionMorphism2DimensionalDomains(<i>C1, S1</i>)	(operation)
▷ InnerAutomorphismCat1(<i>C1, r</i>)	(operation)
▷ IdentityMapping(<i>C1</i>)	(attribute)

For an example we form a second cat1-group $C2=[g18=>s3a]$, similar to $C1$ in 2.4.1, then construct an isomorphism (γ, ρ) between them.

Example

```
gap> t2 := GroupHomomorphismByImages(g18,s3a,g18gens,[( ),(7,8,9),(8,9)]);;
gap> e2 := GroupHomomorphismByImages(s3a,g18,s3agens,[(4,5,6),(2,3)(5,6)]);;
gap> C2 := Cat1Group( t2, h1, e2 );;
gap> imgamma := [ (4,5,6), (1,2,3), (2,3)(5,6) ];;
gap> gamma := GroupHomomorphismByImages( g18, g18, g18gens, imgamma );;
gap> rho := IdentityMapping( s3a );;
gap> mor := Cat1GroupMorphism( C1, C2, gamma, rho );;
gap> Display( mor );;
Morphism of cat1-groups :-
: Source = [g18=>s3a] with generating sets:
  [ (1,2,3), (4,5,6), (2,3)(5,6) ]
  [ (7,8,9), (8,9) ]
: Range = [g18=>s3a] with generating sets:
  [ (1,2,3), (4,5,6), (2,3)(5,6) ]
  [ (7,8,9), (8,9) ]
: Source Homomorphism maps source generators to:
  [ (4,5,6), (1,2,3), (2,3)(5,6) ]
: Range Homomorphism maps range generators to:
  [ (7,8,9), (8,9) ]
```

3.3.2 IsomorphismPermObject

▷ IsomorphismPermObject(<i>obj</i>)	(function)
▷ IsomorphismPerm2DimensionalGroup(<i>2DimensionalGroup</i>)	(attribute)
▷ IsomorphismFp2DimensionalGroup(<i>2DimensionalGroup</i>)	(attribute)

- ▷ `IsomorphismPc2DimensionalGroup(2DimensionalGroup)` (attribute)
- ▷ `SmallerDegreePerm2DimensionalDomain(2DimensionalDomain)` (function)

The global function `IsomorphismPermObject` calls `IsomorphismPerm2DimensionalGroup`, which constructs a morphism whose `SourceHom` (3.1.1) and `RangeHom` (3.1.1) are calculated using `IsomorphismPermGroup` on the source and range. Similarly the operation `SmallerDegreePermutationRepresentation` may be used on the two groups to obtain the attribute `SmallerDegreePerm2DimensionalDomain`. Names are assigned automatically.

Example

```
gap> iso2 := IsomorphismPerm2DimensionalGroup( C2 );
[[G2=>d12] => [..]]
gap> Display( iso2 );
Morphism of cat1-groups :-
: Source = [G2=>d12] with generating sets:
  [ f1, f2, f3, f4, f5, f6, f7 ]
  [ f1, f2, f3 ]
: Range = P[G2=>d12] with generating sets:
  [ ( 6,12)( 8,15)( 9,16)(11,19)(13,26)(14,22)(17,27)(18,25)(20,21)(23,24),
    ( 2, 3)( 5,10)( 9,16)(11,18)(17,23)(19,25)(24,27),
    ( 4, 5, 7,10)( 6, 9,12,16)( 8,11,14,18)(13,17,20,23)(15,19,22,25)
    (21,24,26,27), ( 4, 6, 7,12)( 5, 9,10,16)( 8,13,14,20)(11,17,18,23)
    (15,21,22,26)(19,24,25,27), ( 4, 7)( 5,10)( 6,12)( 8,14)( 9,16)(11,18)
    (13,20)(15,22)(17,23)(19,25)(21,26)(24,27), ( 1, 2, 3),
    ( 4, 8,15)( 5,11,19)( 6,13,21)( 7,14,22)( 9,17,24)(10,18,25)(12,20,26)
    (16,23,27) ]
  [ (2,6)(3,5), (1,2,3,4,5,6), (1,3,5)(2,4,6) ]
: Source Homomorphism maps source generators to:
  [ ( 6,12)( 8,15)( 9,16)(11,19)(13,26)(14,22)(17,27)(18,25)(20,21)(23,24),
    ( 2, 3)( 5,10)( 9,16)(11,18)(17,23)(19,25)(24,27),
    ( 4, 5, 7,10)( 6, 9,12,16)( 8,11,14,18)(13,17,20,23)(15,19,22,25)
    (21,24,26,27), ( 4, 6, 7,12)( 5, 9,10,16)( 8,13,14,20)(11,17,18,23)
    (15,21,22,26)(19,24,25,27), ( 4, 7)( 5,10)( 6,12)( 8,14)( 9,16)(11,18)
    (13,20)(15,22)(17,23)(19,25)(21,26)(24,27), ( 1, 2, 3),
    ( 4, 8,15)( 5,11,19)( 6,13,21)( 7,14,22)( 9,17,24)(10,18,25)(12,20,26)
    (16,23,27) ]
: Range Homomorphism maps range generators to:
  [ (2,6)(3,5), (1,2,3,4,5,6), (1,3,5)(2,4,6) ]
```

3.4 Operations on morphisms

3.4.1 CompositionMorphism

- ▷ `CompositionMorphism(map2, map1)` (operation)

Composition of morphisms (written `<map1> * <map2>`) when maps act on the right) calls the `CompositionMorphism` function for maps (acting on the left), applied to the appropriate type of 2d-mapping.

Example

```

gap> H2 := Subgroup(G2,[G2.3,G2.4,G2.6,G2.7]); SetName( H2, "H2" );
Group([ f3, f4, f6, f7 ])
gap> c6 := Subgroup( d12, [b,c] ); SetName( c6, "c6" );
Group([ f2, f3 ])
gap> SC2 := Sub2DimensionalGroup( C2, H2, c6 );
[H2=>c6]
gap> IsCat1Group( SC2 );
true
gap> inc2 := InclusionMorphism2DimensionalDomains( C2, SC2 );
[[H2=>c6] => [G2=>d12]]
gap> CompositionMorphism( iso2, inc );
[[H2=>c6] => P[G2=>d12]]

```

3.4.2 Kernel (for 2d-mappings)

- ▷ Kernel(*map*) (operation)
- ▷ Kernel2DimensionalMapping(*map*) (attribute)

The kernel of a morphism of crossed modules is a normal subcrossed module whose groups are the kernels of the source and target homomorphisms. The inclusion of the kernel is a standard example of a crossed square, but these have not yet been implemented.

Example

```

gap> c2 := Group( (19,20) );
Group([ (19,20) ])
gap> X0 := XModByNormalSubgroup( c2, c2 ); SetName( X0, "X0" );
[Group( [ (19,20) ] )->Group( [ (19,20) ] )]
gap> SX2 := Source( X2 );
gap> genSX2 := GeneratorsOfGroup( SX2 );
[ f1, f4, f5, f7 ]
gap> sigma0 := GroupHomomorphismByImages(SX2,c2,genSX2,[(19,20),(),(),()]);
[ f1, f4, f5, f7 ] -> [ (19,20), (), (), () ]
gap> rho0 := GroupHomomorphismByImages(d12,c2,[a1,a2,a3],[(19,20),(),()]);
[ f1, f2, f3 ] -> [ (19,20), (), () ]
gap> mor0 := XModMorphism( X2, X0, sigma0, rho0 );
gap> K0 := Kernel( mor0 );
gap> StructureDescription( K0 );
[ "C12", "C6" ]

```

Chapter 4

Isoclinism of groups and crossed modules

This chapter describes some functions written by Alper Odabaş and Enver Uslu, and reported in their paper [IOU16]. Section 4.1 contains some additional basic functions for crossed modules, constructing quotients, centres, centralizers and normalizers. In Sections 4.2 and 4.3 there are functions dealing specifically with isoclinism for groups and for crossed modules. Since these functions represent a recent addition to the package (as of November 2015), the function names are liable to change in future versions. The notion of isoclinism has been crucial to the enumeration of groups of prime power order, see for example James, Newman and O'Brien, [JNO90].

4.1 More operations for crossed modules

4.1.1 FactorPreXMod

- ▷ FactorPreXMod(X_1 , X_2) (operation)
- ▷ NaturalMorphismByNormalSubPreXMod(X_1 , X_2) (operation)

When $\mathcal{X}_2 = (\partial_2 : S_2 \rightarrow R_2)$ is a normal sub-precrossed module of $\mathcal{X}_1 = (\partial_1 : S_1 \rightarrow R_1)$, then the quotient precrossed module is $(\partial : S_2/S_1 \rightarrow R_2/R_1)$ with the induced boundary and action maps. Quotienting a precrossed module by its Peiffer subgroup is a special case of this construction.

Example

```
gap> d24 := DihedralGroup( IsPermGroup, 24 );;
gap> SetName( d24, "d24" );
gap> Y24 := XModByAutomorphismGroup( d24 );;
gap> Size( Y24 );
[ 24, 48 ]
gap> X24 := Image( IsomorphismPerm2DimensionalGroup( Y24 ) );
[d24->Group( [ ( 2, 4), ( 1, 2, 3, 4)( 5, 8)( 6, 9)( 7,10), ( 6,10)( 7, 9),
( 5, 9, 7)( 6,10, 8) ] )]
gap> nsx := NormalSubXMods( X24 );;
gap> Length( nsx );
40
gap> ids := List( nsx, n -> IdGroup(n) );;
gap> pos1 := Position( ids, [ [4,1], [8,3] ] );;
gap> Xn1 := nsx[pos1];
[Group( [ f2*f4^2, f3*f4 ] )->Group( [ f3, f4, f5 ] )]
```

```

gap> nat1 := NaturalMorphismByNormalSubPreXMod( X24, Xn1 );;
gap> Qn1 := FactorPreXMod( X24, Xn1 );;
gap> [ Size( Xn1 ), Size( Qn1 ) ];
[ [ 4, 8 ], [ 6, 6 ] ]

```

4.1.2 IntersectionSubXMods

▷ IntersectionSubXMods(X_0, X_1, X_2) (operation)

When X_1, X_2 are subcrossed modules of X_0 , then the source and range of their intersection are the intersections of the sources and ranges of X_1 and X_2 respectively.

Example

```

gap> pos2 := Position( ids, [ [24,6], [12,4] ] );;
gap> Xn2 := nsx[pos2];;
gap> IdGroup( Xn2 );
[ [ 24, 6 ], [ 12, 4 ] ]
gap> pos3 := Position( ids, [ [12,2], [24,5] ] );;
gap> Xn3 := nsx[pos3];;
gap> IdGroup( Xn3 );
[ [ 12, 2 ], [ 24, 5 ] ]
gap> Xn23 := IntersectionSubXMods( X24, Xn2, Xn3 );;
gap> IdGroup( Xn23 );
[ [ 12, 2 ], [ 6, 2 ] ]

```

4.1.3 Displacement

▷ Displacement(α, r, s) (operation)
 ▷ DisplacementGroup(X_0, Q, T) (operation)
 ▷ DisplacementSubgroup(X_0) (attribute)

Commutators may be written $[r, q] = r^{-1}q^{-1}rq = (q^{-1})^r q = r^{-1}r^q$, and satisfy identities

$$[r, q]^p = [r^p, q^p], \quad [pr, q] = [p, q]^r [r, q], \quad [r, pq] = [r, q][r, p]^q, \quad [r, q]^{-1} = [q, r].$$

In a similar way, when a group R acts on a group S , the *displacement* of $s \in S$ by $r \in R$ is defined to be $\langle r, s \rangle := (s^{-1})^r s \in S$. When $\mathcal{X} = (\partial : S \rightarrow R)$ is a pre-crossed module, the first crossed module axiom requires $\partial \langle r, s \rangle = [r, \partial s]$. When α is the action of \mathcal{X} , the Displacement function may be used to calculate $\langle r, s \rangle$. Displacements satisfy the following identities, where $s, t \in S, p, q, r \in R$:

$$\langle r, s \rangle^p = \langle r^p, s^p \rangle, \quad \langle qr, s \rangle = \langle q, s \rangle^r \langle r, s \rangle, \quad \langle r, st \rangle = \langle r, t \rangle \langle r, s \rangle^t, \quad \langle r, s \rangle^{-1} = \langle r^{-1}, s^r \rangle.$$

The operation DisplacementGroup applied to X_0, Q, T is the subgroup of S consisting of all the displacements $\langle r, s \rangle, r \in Q \leq R, s \in T \leq S$. The DisplacementSubgroup of \mathcal{X} is the subgroup $\text{Disp}(\mathcal{X})$ of S given by DisplacementGroup(X_0, R, S). The identities imply $\langle r, s \rangle^t = \langle r, st^{r^{-1}} \rangle \langle r^{-1}, t \rangle$, so $\text{Disp}(\mathcal{X})$ is normal in S .

Example

```

gap> pos4 := Position( ids, [ [6,2], [24,14] ] );;
gap> Xn4 := nsx[pos4];;
gap> bn4 := Boundary( Xn4 );;
gap> Sn4 := Source(Xn4);;
gap> Rn4 := Range(Xn4);;
gap> genRn4 := GeneratorsOfGroup( Rn4 );;
gap> L := List( genRn4, g -> ( Order(g) = 2 ) and
>         not ( IsNormal( Rn4, Subgroup( Rn4, [g] ) ) ) );;
gap> pos := Position( L, true );;
gap> s := Sn4.1; r := genRn4[pos];
(1,3,5,7,9,11)(2,4,6,8,10,12)
(6,10)(7,9)
gap> act := XModAction( Xn4 );;
gap> d := Displacement( act, r, s );
(1,5,9)(2,6,10)(3,7,11)(4,8,12)
gap> Image( bn4, d ) = Comm( r, Image( bn4, s ) );
true
gap> Qn4 := Subgroup( Rn4, [ (6,10)(7,9), (1,3), (2,4) ] );;
gap> Tn4 := Subgroup( Sn4, [ (1,3,5,7,9,11)(2,4,6,8,10,12) ] );;
gap> DisplacementGroup( Xn4, Qn4, Tn4 );
Group([ (1,5,9)(2,6,10)(3,7,11)(4,8,12) ])
gap> DisplacementSubgroup( Xn4 );
Group([ (1,5,9)(2,6,10)(3,7,11)(4,8,12) ])

```

4.1.4 CommutatorSubXMod

- ▷ `CommutatorSubXMod(X, X1, X2)` (operation)
- ▷ `CrossActionSubgroup(X, X1, X2)` (operation)

When $\mathcal{X}_1 = (N \rightarrow Q)$, $\mathcal{X}_2 = (M \rightarrow P)$ are two normal subcrossed modules of $\mathcal{X} = (\partial : S \rightarrow R)$, the displacements $\langle p, n \rangle$ and $\langle q, m \rangle$ all map by ∂ into $[Q, P]$. These displacements form a normal subgroup of S , called the `CrossActionSubgroup`. The `CommutatorSubXMod` $[\mathcal{X}_1, \mathcal{X}_2]$ has this subgroup as source and $[P, Q]$ as range, and is normal in \mathcal{X} .

Example

```

gap> CAn23 := CrossActionSubgroup( X24, Xn2, Xn3 );;
gap> IdGroup( CAn23 );
[ 12, 2 ]
gap> Cn23 := CommutatorSubXMod( X24, Xn2, Xn3 );;
gap> IdGroup( Cn23 );
[ [ 12, 2 ], [ 6, 2 ] ]
gap> Xn23 = Cn23;
true

```

4.1.5 DerivedSubXMod

▷ `DerivedSubXMod(X0)` (attribute)

The `DerivedSubXMod` of \mathcal{X} is the normal subcrossed module $[\mathcal{X}, \mathcal{X}] = (\partial' : \text{Disp}(\mathcal{X}) \rightarrow [R, R])$ where ∂' is the restriction of ∂ (see page 66 of Norrie's thesis [Nor87]).

Example

```
gap> DXn4 := DerivedSubXMod( Xn4 );;
gap> IdGroup( DXn4 );
[ [ 3, 1 ], [ 3, 1 ] ]
```

4.1.6 FixedPointSubgroupXMod

▷ `FixedPointSubgroupXMod(X0, T, Q)` (operation)

▷ `StabilizerSubgroupXMod(X0, T, Q)` (operation)

The `FixedPointSubgroupXMod(X, T, Q)` for $\mathcal{X} = (\partial : S \rightarrow R)$ is the subgroup $\text{Fix}(\mathcal{X}, T, Q)$ of elements $t \in T \leq S$ individually fixed under the action of $Q \leq R$.

The `StabilizerSubgroupXMod(X, T, Q)` for \mathcal{X} is the subgroup $\text{Stab}(\mathcal{X}, T, Q)$ of $Q \leq R$ whose elements act trivially on the whole of $T \leq S$ (see page 19 of Norrie's thesis [Nor87]).

Example

```
gap> fix := FixedPointSubgroupXMod( Xn4, Sn4, Rn4 );
Group( [ (1,7)(2,8)(3,9)(4,10)(5,11)(6,12) ] )
gap> stab := StabilizerSubgroupXMod( Xn4, Sn4, Rn4 );;
gap> IdGroup( stab );
[ 12, 5 ]
```

4.1.7 CentreXMod

▷ `CentreXMod(X0)` (attribute)

▷ `Centralizer(X, Y)` (operation)

▷ `Normalizer(X, Y)` (operation)

The *centre* $Z(\mathcal{X})$ of $\mathcal{X} = (\partial : S \rightarrow R)$ has as source the fixed point subgroup $\text{Fix}(\mathcal{X}, S, R)$. The range is the intersection of the centre $Z(R)$ with the stabilizer subgroup.

When $\mathcal{Y} = (T \rightarrow Q)$ is a subcrossed module of $\mathcal{X} = (\partial : S \rightarrow R)$, the *centralizer* $C_{\mathcal{X}}(\mathcal{Y})$ of \mathcal{Y} has as source the fixed point subgroup $\text{Fix}(\mathcal{X}, S, Q)$. The range is the intersection of the centralizer $C_R(Q)$ with $\text{Stab}(\mathcal{X}, T, R)$.

The *normalizer* $N_{\mathcal{X}}(\mathcal{Y})$ of \mathcal{Y} has as source the subgroup of S consisting of the displacements $\langle s, q \rangle$ which lie in S .

Example

```
gap> ZXn4 := CentreXMod( Xn4 );
[Group( [ f3*f4 ] )->Group( [ f3, f5 ] )]
```

```

gap> IdGroup( ZXn4 );
[ [ 2, 1 ], [ 4, 2 ] ]
gap> CDXn4 := Centralizer( Xn4, DXn4 );
[Group( [ f3*f4 ] )->Group( [ f2 ] )]
gap> IdGroup( CDXn4 );
[ [ 2, 1 ], [ 3, 1 ] ]
gap> NDXn4 := Normalizer( Xn4, DXn4 );
[Group( <identity> of ... )->Group( [ f5, f2*f3 ] )]
gap> IdGroup( NDXn4 );
[ [ 1, 1 ], [ 12, 5 ] ]

```

4.1.8 CentralQuotient

▷ CentralQuotient(G) (attribute)

The CentralQuotient of a group G is the crossed module $(G \rightarrow G/Z(G))$ with the natural homomorphism as the boundary map. This is a special case of XModByCentralExtension (2.1.5).

Similarly, the central quotient of a crossed module \mathcal{X} is the crossed square $(\mathcal{X} \Rightarrow \mathcal{X}/Z(\mathcal{X}))$ (see section 8.2).

Example

```

gap> Q24 := CentralQuotient( d24); IdGroup( Q24 );
[d24->d24/Z(d24)]
[ [ 24, 6 ], [ 12, 4 ] ]

```

4.1.9 IsAbelian2DimensionalGroup

▷ IsAbelian2DimensionalGroup($X0$) (property)
 ▷ IsAspherical2DimensionalGroup($X0$) (property)
 ▷ IsSimplyConnected2DimensionalGroup($X0$) (property)
 ▷ IsFaithful2DimensionalGroup($X0$) (property)

A crossed module is *abelian* if it equal to its centre. This is the case when the range group is abelian and the action is trivial.

A crossed module is *aspherical* if the boundary has trivial kernel.

A crossed module is *simply connected* if the boundary has trivial cokernel.

A crossed module is *faithful* if the action is faithful.

Example

```

gap> [ IsAbelian2DimensionalGroup(Xn4), IsAbelian2DimensionalGroup(X24) ];
[ false, false ]
gap> pos7 := Position( ids, [ [3,1], [6,1] ] );;
gap> [ IsAspherical2DimensionalGroup(nsx[pos7]), IsAspherical2DimensionalGroup(X24) ];
[ true, false ]
gap> [ IsSimplyConnected2DimensionalGroup(Xn4), IsSimplyConnected2DimensionalGroup(X24) ];
[ true, true ]
gap> [ IsFaithful2DimensionalGroup(Xn4), IsFaithful2DimensionalGroup(X24) ];

```

```
[ false, true ]
```

4.1.10 LowerCentralSeriesOfXMod

- ▷ LowerCentralSeriesOfXMod(X0) (attribute)
- ▷ IsNilpotent2DimensionalGroup(X0) (property)
- ▷ NilpotencyClass2DimensionalGroup(X0) (attribute)

Let \mathcal{Y} be a subcrossed module of \mathcal{X} . A *series of length n* from \mathcal{X} to \mathcal{Y} has the form

$$\mathcal{X} = \mathcal{X}_0 \triangleright \mathcal{X}_1 \triangleright \cdots \triangleright \mathcal{X}_i \triangleright \cdots \triangleright \mathcal{X}_n = \mathcal{Y} \quad (1 \leq i \leq n).$$

The quotients $\mathcal{F}_i = \mathcal{X}_i / \mathcal{X}_{i-1}$ are the *factors* of the series.

A factor \mathcal{F}_i is *central* if $\mathcal{X}_{i-1} \trianglelefteq \mathcal{X}$ and \mathcal{F}_i is a subcrossed module of the centre of $\mathcal{X} / \mathcal{X}_{i-1}$.

A series is *central* if all its factors are central.

\mathcal{X} is *soluble* if it has a series all of whose factors are abelian.

\mathcal{X} is *nilpotent* if it has a series all of whose factors are central factors of \mathcal{X} .

The *lower central series* of \mathcal{X} is the sequence (see [Nor87], p.77):

$$\mathcal{X} = \Gamma_1(\mathcal{X}) \triangleright \Gamma_2(\mathcal{X}) \triangleright \cdots \quad \text{where} \quad \Gamma_j(\mathcal{X}) = [\Gamma_{j-1}(\mathcal{X}), \mathcal{X}].$$

If \mathcal{X} is nilpotent, then its lower central series is its most rapidly descending central series.

The least integer c such that $\Gamma_{c+1}(\mathcal{X})$ is the trivial crossed module is the *nilpotency class* of \mathcal{X} .

Example

```
gap> lcs := LowerCentralSeries( X24 );;
gap> List( lcs, g -> IdGroup(g) );
[[ [ 24, 6 ], [ 48, 38 ] ], [ [ 12, 2 ], [ 6, 2 ] ], [ [ 6, 2 ], [ 3, 1 ] ],
  [ [ 3, 1 ], [ 3, 1 ] ] ]
gap> IsNilpotent2DimensionalGroup( X24 );
false
gap> NilpotencyClassOf2DimensionalGroup( X24 );
0
```

4.1.11 AllXMods

- ▷ AllXMods(args) (function)

The global function AllXMods may be called in three ways: as AllXMods(S,R) to compute all crossed modules with chosen source and range groups; as AllXMods([n,m]) to compute all crossed modules with a given size; or as AllXMods(ord) to compute all crossed modules whose associated cat1-groups have a given size ord.

In the example we see that there are 4 crossed modules ($C_6 \rightarrow S_3$); forming a subset of the 17 crossed modules with size [6,6]; and that these form a subset of the 205 crossed modules whose cat1-group has size 36. There are 40 precrossed modules with size [6,6].

Example

```

gap> xc6s3 := AllXMods( SmallGroup(6,2), SmallGroup(6,1) );;
gap> Length( xc6s3 );
4
gap> x66 := AllXMods( [6,6] );;
gap> Length( x66 );
17
gap> x36 := AllXMods( 36 );;
gap> Length( x36 );
205
gap> size36 := List( x36, x -> [ Size(Source(x)), Size(Range(x)) ] );;
gap> Collected( size36 );
[[ [ [ 1, 36 ], 14 ], [ [ 2, 18 ], 7 ], [ [ 3, 12 ], 21 ], [ [ 4, 9 ], 14 ],
  [ [ 6, 6 ], 17 ], [ [ 9, 4 ], 102 ], [ [ 12, 3 ], 8 ], [ [ 18, 2 ], 18 ],
  [ [ 36, 1 ], 4 ] ]

```

4.1.12 IsomorphismXMods

- ▷ IsomorphismXMods($X1$, $X2$) (operation)
- ▷ AllXModsUpToIsomorphism($list$) (operation)

The function `IsomorphismXMods` computes an isomorphism $\mu : \mathcal{X}_1 \rightarrow \mathcal{X}_2$, provided one exists, or else returns `fail`. In the example below we see that the 17 crossed modules of size $[6, 6]$ in `x66` (see the previous subsection) fall into 9 isomorphism classes.

The function `AllXModsUpToIsomorphism` takes a list of crossed modules and partitions them into isomorphism classes.

Example

```

gap> IsomorphismXMods( x66[1], x66[2] );
[[Group( [ f1, f2 ] )->Group( [ f1, f2 ] )] => [Group( [ f1, f2 ] )->Group(
  [ f1, f2 ] )]]
gap> iso66 := AllXModsUpToIsomorphism( x66 );; Length( iso66 );
9

```

4.2 Isoclinism for groups

4.2.1 Isoclinism (for groups)

- ▷ Isoclinism(G , H) (operation)
- ▷ AreIsoclinicDomains(G , H) (operation)

Let G, H be groups with central quotients $Q(G)$ and $Q(H)$ and derived subgroups $[G, G]$ and $[H, H]$ respectively. Let $c_G : G/Z(G) \times G/Z(G) \rightarrow [G, G]$ and $c_H : H/Z(H) \times H/Z(H) \rightarrow [H, H]$ be the two commutator maps. An *isoclinism* $G \sim H$ is a pair of isomorphisms (η, ξ) where $\eta : G/Z(G) \rightarrow H/Z(H)$ and $\xi : [G, G] \rightarrow [H, H]$ such that $c_G * \xi = (\eta \times \eta) * c_H$. Isoclinism is an equivalence relation, and all abelian groups are isoclinic to the trivial group.

Example

```

gap> G := SmallGroup( 64, 6 );; StructureDescription( G );
"(C8 x C4) : C2"
gap> QG := CentralQuotient( G );; IdGroup( QG );
[[ 64, 6 ], [ 8, 3 ] ]
gap> H := SmallGroup( 32, 41 );; StructureDescription( H );
"C2 x Q16"
gap> QH := CentralQuotient( H );; IdGroup( QH );
[[ 32, 41 ], [ 8, 3 ] ]
gap> Isoclinism( G, H );
[[ f1, f2, f3 ] -> [ f1, f2*f3, f3 ], [ f3, f5 ] -> [ f4*f5, f5 ] ]
gap> K := SmallGroup( 32, 43 );; StructureDescription( K );
"(C2 x D8) : C2"
gap> QK := CentralQuotient( K );; IdGroup( QK );
[[ 32, 43 ], [ 16, 11 ] ]
gap> AreIsoclinicDomains( G, K );
false

```

4.2.2 IsStemDomain (for groups)

- ▷ IsStemDomain(G) (property)
- ▷ IsoclinicStemDomain(G) (attribute)
- ▷ AllStemGroupIds(n) (operation)
- ▷ AllStemGroupFamilies(n) (operation)

A group G is a *stem group* if $Z(G) \leq [G, G]$. Every group is isoclinic to a stem group, but distinct stem groups may be isoclinic. For example, groups D_8, Q_8 are two isoclinic stem groups.

The function `IsoclinicStemDomain` returns a stem group isoclinic to G .

The function `AllStemGroupIds` returns the `IdGroup` list of the stem groups of a specified size, while `AllStemGroupFamilies` splits this list into isoclinism classes.

Example

```

gap> DerivedSubgroup(G);
Group([ f3, f5 ])
gap> IsStemDomain( G );
false
gap> IsoclinicStemDomain( G );
<pc group of size 16 with 4 generators>
gap> AllStemGroupIds( 32 );
[[ [ 32, 6 ], [ 32, 7 ], [ 32, 8 ], [ 32, 18 ], [ 32, 19 ], [ 32, 20 ],
  [ 32, 27 ], [ 32, 28 ], [ 32, 29 ], [ 32, 30 ], [ 32, 31 ], [ 32, 32 ],
  [ 32, 33 ], [ 32, 34 ], [ 32, 35 ], [ 32, 43 ], [ 32, 44 ], [ 32, 49 ],
  [ 32, 50 ] ] ]
gap> AllStemGroupFamilies( 32 );
[[ [ [ 32, 6 ], [ 32, 7 ], [ 32, 8 ] ], [ [ 32, 18 ], [ 32, 19 ], [ 32, 20 ] ],
  [ [ 32, 27 ], [ 32, 28 ], [ 32, 29 ], [ 32, 30 ], [ 32, 31 ], [ 32, 32 ],
    [ 32, 33 ], [ 32, 34 ], [ 32, 35 ] ], [ [ 32, 43 ], [ 32, 44 ] ],
  [ [ 32, 49 ], [ 32, 50 ] ] ] ]

```

4.2.3 IsoclinicRank (for groups)

- ▷ IsoclinicRank(G) (attribute)
- ▷ IsoclinicMiddleLength(G) (attribute)

Let G be a finite p -group. Then $\log_p |[G, G]/(Z(G) \cap [G, G])|$ is called the *middle length* of G . Also $\log_p |Z(G) \cap [G, G]| + \log_p |G/Z(G)|$ is called the *rank* of G . These invariants appear in the tables of isoclinism families of groups of order 128 in [JNO90].

Example

```
gap> IsoclinicMiddleLength( G );
1
gap> IsoclinicRank( G );
4
```

4.3 Isoclinism for crossed modules

4.3.1 Isoclinism (for crossed modules)

- ▷ Isoclinism($X0, Y0$) (operation)
- ▷ AreIsoclinicDomains($X0, Y0$) (operation)

Let \mathcal{X}, \mathcal{Y} be crossed modules with central quotients $Q(\mathcal{X})$ and $Q(\mathcal{Y})$, and derived subcrossed modules $[\mathcal{X}, \mathcal{X}]$ and $[\mathcal{Y}, \mathcal{Y}]$ respectively. Let $c_{\mathcal{X}} : Q(\mathcal{X}) \times Q(\mathcal{X}) \rightarrow [\mathcal{X}, \mathcal{X}]$ and $c_{\mathcal{Y}} : Q(\mathcal{Y}) \times Q(\mathcal{Y}) \rightarrow [\mathcal{Y}, \mathcal{Y}]$ be the two commutator maps. An *isoclinism* $\mathcal{X} \sim \mathcal{Y}$ is a pair of bijective morphisms (η, ξ) where $\eta : Q(\mathcal{X}) \rightarrow Q(\mathcal{Y})$ and $\xi : [\mathcal{X}, \mathcal{X}] \rightarrow [\mathcal{Y}, \mathcal{Y}]$ such that $c_{\mathcal{X}} * \xi = (\eta \times \eta) * c_{\mathcal{Y}}$. Isoclinism is an equivalence relation, and all abelian crossed modules are isoclinic to the trivial crossed module.

Example

```
gap> C8 := Cat1Group( 16, 8, 1 );;
gap> X8 := XMod(C8); IdGroup( X8 );
[Group( [ f1*f2*f3, f3, f4 ] )->Group( [ f2, f2 ] )]
[ [ 8, 1 ], [ 2, 1 ] ]
gap> C9 := Cat1Group( 32, 9, 1 );;
[(C8 x C2) : C2=>Group( [ f2, f2 ] )]
gap> X9 := XMod( C9 ); IdGroup( X9 );
[Group( [ f1*f2*f3, f3, f4, f5 ] )->Group( [ f2, f2 ] )]
[ [ 16, 5 ], [ 2, 1 ] ]
gap> AreIsoclinicDomains( X8, X9 );
true
gap> ism89 := Isoclinism( X8, X9 );;
gap> Display( ism89 );
[[[Group( [ f1, f2, <identity> of ... ] ) -> Group( [ f2, f2 ] )] => [Group(
[ f1, f2, <identity> of ..., <identity> of ... ] ) -> Group(
[ f2, f2 ] )]],
```

```
[[Group( [ f3 ] ) -> Group( <identity> of ... )] => [Group(
  [ f3 ] ) -> Group( <identity> of ... )]] ]
```

4.3.2 IsStemDomain (for crossed modules of groups)

- ▷ IsStemDomain($X0$) (property)
- ▷ IsoclinicStemDomain($X0$) (attribute)

A crossed module \mathcal{X} is a *stem crossed module* if $Z(\mathcal{X}) \leq [\mathcal{X}, \mathcal{X}]$. Every crossed module is isoclinic to a stem crossed module, but distinct stem crossed modules may be isoclinic.

A method for IsoclinicStemDomain has yet to be implemented.

Example

```
gap> IsStemDomain(X8);
true
gap> IsStemDomain(X9);
false
```

4.3.3 IsoclinicRank (for crossed modules of groups)

- ▷ IsoclinicRank($X0$) (attribute)
- ▷ IsoclinicMiddleLength($X0$) (attribute)

The formulae in subsection 4.2.3 are applied to the crossed module.

Example

```
gap> IsoclinicMiddleLength(X8);
[ 1, 0 ]
gap> IsoclinicRank(X8);
[ 3, 1 ]
```


Chapter 5

Whitehead group of a crossed module

5.1 Derivations and Sections

The Whitehead monoid $\text{Der}(\mathcal{X})$ of \mathcal{X} was defined in [Whi48] to be the monoid of all *derivations* from R to S , that is the set of all maps $\chi : R \rightarrow S$, with *Whitehead multiplication* \star (on the *right*) satisfying:

$$\mathbf{Der\ 1} : \chi(qr) = (\chi q)^r (\chi r), \quad \mathbf{Der\ 2} : (\chi_1 \star \chi_2)(r) = (\chi_2 r)(\chi_1 r)(\chi_2 \partial \chi_1 r).$$

The zero map is the identity for this composition. Invertible elements in the monoid are called *regular*. The Whitehead group of \mathcal{X} is the group of regular derivations in $\text{Der}(\mathcal{X})$. In the next chapter the *actor* of \mathcal{X} is defined as a crossed module whose source and range are permutation representations of the Whitehead group and the automorphism group of \mathcal{X} .

The construction for cat1-groups equivalent to the derivation of a crossed module is the *section*. The monoid of sections of $\mathcal{C} = (e; t, h : G \rightarrow R)$ is the set of group homomorphisms $\xi : R \rightarrow G$, with Whitehead multiplication \star (on the *right*) satisfying:

$$\mathbf{Sect\ 1} : t \circ \xi = \text{id}_R, \quad \mathbf{Sect\ 2} : (\xi_1 \star \xi_2)(r) = (\xi_1 r)(eh\xi_1 r)^{-1}(\xi_2 h\xi_1 r) = (\xi_2 h\xi_1 r)(eh\xi_1 r)^{-1}(\xi_1 r).$$

The embedding e is the identity for this composition, and $h(\xi_1 \star \xi_2) = (h\xi_1)(h\xi_2)$. A section is *regular* when $h\xi$ is an automorphism, and the group of regular sections is isomorphic to the Whitehead group.

If ε denotes the inclusion of $S = \ker t$ in G then $\partial = h\varepsilon : S \rightarrow R$ and

$$\xi r = (er)(e\chi r), \quad \text{which equals} \quad (r, \chi r) \in R \ltimes S,$$

determines a section ξ of \mathcal{C} in terms of the corresponding derivation χ of \mathcal{X} , and conversely.

5.1.1 DerivationByImages

- ▷ `DerivationByImages(XO, ims)` (operation)
- ▷ `IsDerivation(map)` (property)
- ▷ `IsUp2DimensionalMapping(map)` (property)
- ▷ `UpImagePositions(chi)` (attribute)
- ▷ `UpGeneratorImages(chi)` (attribute)

Derivations are stored like group homomorphisms by specifying the images of a generating set. Images of the remaining elements may then be obtained using axiom **Der 1**. The function `IsDerivation` is automatically called to check that this procedure is well-defined.

In the following example a cat1-group `C3` and the associated crossed module `X3` are constructed, where `X3` is isomorphic to the inclusion of the normal cyclic group `c3` in the symmetric group `s3`.

Example

```
gap> g18 := Group( (1,2,3), (4,5,6), (2,3)(5,6) );;
gap> SetName( g18, "g18" );
gap> gen18 := GeneratorsOfGroup( g18 );;
gap> g1 := gen18[1];; g2 := gen18[2];; g3 := gen18[3];;
gap> s3 := Subgroup( g18, gen18{[2..3]} );;
gap> SetName( s3, "s3" );;
gap> t := GroupHomomorphismByImages( g18, s3, gen18, [g2,g2,g3] );;
gap> h := GroupHomomorphismByImages( g18, s3, gen18, [(),g2,g3] );;
gap> e := GroupHomomorphismByImages( s3, g18, [g2,g3], [g2,g3] );;
gap> C3 := Cat1Group( t, h, e );
[g18=>s3]
gap> SetName( Kernel(t), "c3" );;
gap> X3 := XModOfCat1Group( C3 );
[c3->s3]
gap> imchi1 := [ (), (1,2,3)(4,6,5) ];;
gap> chi1 := DerivationByImages( X3, imchi1 );
DerivationByImages( s3, c3, [ (4,5,6), (2,3)(5,6) ],
[ (), (1,2,3)(4,6,5) ] )
gap> [ IsUp2DimensionalMapping( chi1 ), IsDerivation( chi1 ) ];
[ true, true ]
gap> UpImagePositions( chi1 );
[ 1, 1, 1, 2, 2, 2 ]
gap> UpGeneratorImages( chi1 );
[ (), (1,2,3)(4,6,5) ]
```

5.1.2 PrincipalDerivation

▷ `PrincipalDerivation($X0$, s)` (operation)

The *principal derivation* determined by $s \in S$ is the derivation $\eta_s : R \rightarrow S$, $r \mapsto (s^{-1})^r s$.

Example

```
gap> eta := PrincipalDerivation( X3, (1,2,3)(4,6,5) );
DerivationByImages( s3, c3, [ (4,5,6), (2,3)(5,6) ], [ (), (1,3,2)(4,5,6) ] )
```

5.1.3 SectionByHomomorphism

▷ `SectionByHomomorphism(C , hom)` (operation)

▷ `IsSection(hom)` (property)

▷ `SectionByDerivation(chi)` (operation)

▷ `DerivationBySection(xi)` (operation)

Sections *are* group homomorphisms, so do not need a special representation. Operations `SectionByDerivation` and `DerivationBySection` convert derivations to sections, and vice-versa, calling `Cat1GroupOfXMod` (2.5.2) and `XModOfCat1Group` (2.5.2) automatically.

Two strategies for calculating derivations and sections are implemented, see [AW00]. The default method for `AllDerivations` (5.2.1) is to search for all possible sets of images using a backtracking procedure, and when all the derivations are found it is not known which are regular. In early versions of this package, the default method for `AllSections`(`<C>`) was to compute all endomorphisms on the range group R of C as possibilities for the composite $h\xi$. A backtrack method then found possible images for such a section. In the current version the derivations of the associated crossed module are calculated, and these are all converted to sections using `SectionByDerivation`.

Example

```
gap> hom2 := GroupHomomorphismByImages( s3, g18, [ (4,5,6), (2,3)(5,6) ],
> [ (1,3,2)(4,6,5), (1,2)(4,6) ] );
gap> xi2 := SectionByHomomorphism( C3, hom2 );
SectionByHomomorphism( s3, g18, [ (4,5,6), (2,3)(5,6) ],
[ (1,3,2)(4,6,5), (1,2)(4,6) ] )
gap> [ IsUp2DimensionalMapping( xi2 ), IsSection( xi2 ) ];
[ true, true ]
gap> chi2 := DerivationBySection( xi2 );
DerivationByImages( s3, c3, [ (4,5,6), (2,3)(5,6) ],
[ (1,3,2)(4,5,6), (1,2,3)(4,6,5) ] )
gap> xi1 := SectionByDerivation( chi1 );
SectionByHomomorphism( s3, g18, [ (4,5,6), (2,3)(5,6) ],
[ (1,2,3), (1,2)(4,6) ] )
```

5.1.4 IdentityDerivation

▷ `IdentityDerivation(X0)` (attribute)

▷ `IdentitySection(C0)` (attribute)

The identity derivation maps the range group to the identity subgroup of the source, while the identity section is just the range embedding considered as a section.

Example

```
gap> IdentityDerivation( X3 );
DerivationByImages( s3, c3, [ (4,5,6), (2,3)(5,6) ], [ (), () ] )
gap> IdentitySection(C3);
SectionByHomomorphism( s3, g18, [ (4,5,6), (2,3)(5,6) ],
[ (4,5,6), (2,3)(5,6) ] )
```

5.1.5 WhiteheadProduct

▷ `WhiteheadProduct(chi1, chi2)` (operation)

▷ `WhiteheadOrder(chi)` (operation)

The `WhiteheadProduct` may be applied to two derivations to form $\chi_1 \star \chi_2$, or to two sections to form $\xi_1 \star \xi_2$. The `WhiteheadOrder` of a regular derivation χ is the smallest power of χ , using this product, equal to the `IdentityDerivation` (5.1.4).

Example

```
gap> chi12 := WhiteheadProduct( chi1, chi2 );
DerivationByImages( s3, c3, [ (4,5,6), (2,3)(5,6) ], [ (1,2,3)(4,6,5), () ] )
gap> xi12 := WhiteheadProduct( xi1, xi2 );
SectionByHomomorphism( s3, g18, [ (4,5,6), (2,3)(5,6) ],
[ (1,2,3), (2,3)(5,6) ] )
gap> xi12 = SectionByDerivation( chi12 );
true
gap> [ WhiteheadOrder( chi2 ), WhiteheadOrder( xi2 ) ];
[ 2, 2 ]
```

5.2 Whitehead Groups and Monoids

As mentioned at the beginning of this chapter, the Whitehead monoid $\text{Der}(\mathcal{X})$ of \mathcal{X} is the monoid of all derivations from R to S . Monoids of derivations have representation `IsMonoidOfUp2DimensionalMappingsObj`. Multiplication tables for Whitehead monoids enable the construction of transformation representations.

5.2.1 AllDerivations

- ▷ `AllDerivations(X0)` (attribute)
- ▷ `ImagesTable(obj)` (attribute)
- ▷ `DerivationClass(mon)` (attribute)
- ▷ `WhiteheadMonoidTable(X0)` (attribute)
- ▷ `WhiteheadTransformationMonoid(X0)` (attribute)

Using our example `X3` we find that there are just nine derivations.

Example

```
gap> all3 := AllDerivations( X3 );
monoid of derivations with images list:
[ (), () ]
[ (), (1,3,2)(4,5,6) ]
[ (), (1,2,3)(4,6,5) ]
[ (1,3,2)(4,5,6), () ]
[ (1,3,2)(4,5,6), (1,3,2)(4,5,6) ]
[ (1,3,2)(4,5,6), (1,2,3)(4,6,5) ]
[ (1,2,3)(4,6,5), () ]
[ (1,2,3)(4,6,5), (1,3,2)(4,5,6) ]
[ (1,2,3)(4,6,5), (1,2,3)(4,6,5) ]
gap> DerivationClass( all3 );
"all"
gap> Perform( ImagesTable( all3 ), Display );
```

```

[ 1, 1, 1, 1, 1, 1 ]
[ 1, 1, 1, 3, 3, 3 ]
[ 1, 1, 1, 2, 2, 2 ]
[ 1, 3, 2, 1, 3, 2 ]
[ 1, 3, 2, 3, 2, 1 ]
[ 1, 3, 2, 2, 1, 3 ]
[ 1, 2, 3, 1, 2, 3 ]
[ 1, 2, 3, 3, 1, 2 ]
[ 1, 2, 3, 2, 3, 1 ]
gap> wmt3 := WhiteheadMonoidTable( X3 );;
gap> Perform( wmt3, Display );
[ 1, 2, 3, 4, 5, 6, 7, 8, 9 ]
[ 2, 3, 1, 5, 6, 4, 8, 9, 7 ]
[ 3, 1, 2, 6, 4, 5, 9, 7, 8 ]
[ 4, 6, 5, 1, 3, 2, 7, 9, 8 ]
[ 5, 4, 6, 2, 1, 3, 8, 7, 9 ]
[ 6, 5, 4, 3, 2, 1, 9, 8, 7 ]
[ 7, 7, 7, 7, 7, 7, 7, 7, 7 ]
[ 8, 8, 8, 8, 8, 8, 8, 8, 8 ]
[ 9, 9, 9, 9, 9, 9, 9, 9, 9 ]
gap> wtm3 := WhiteheadTransformationMonoid( X3 );
<transformation monoid of degree 9 with 3 generators>
gap> GeneratorsOfMonoid( wtm3 );
[ Transformation( [ 2, 3, 1, 5, 6, 4, 8, 9, 7 ] ),
  Transformation( [ 4, 6, 5, 1, 3, 2, 7, 9, 8 ] ),
  Transformation( [ 7, 7, 7, 7, 7, 7, 7, 7, 7 ] ) ]

```

5.2.2 RegularDerivations

- ▷ RegularDerivations($X0$) (attribute)
- ▷ ImagesList(obj) (attribute)
- ▷ WhiteheadGroupTable($X0$) (attribute)
- ▷ WhiteheadPermGroup($X0$) (attribute)

RegularDerivations are those derivations which are invertible in the monoid. Multiplication tables for the Whitehead group enable the construction of permutation representations.

Of the nine derivations of $X3$ just six are regular. The associated group is isomorphic to the symmetric group s_3 .

— Example —

```

gap> reg3 := RegularDerivations( X3 );
monoid of derivations with images list:
[ (), () ]
[ (), (1,3,2)(4,5,6) ]
[ (), (1,2,3)(4,6,5) ]
[ (1,3,2)(4,5,6), () ]
[ (1,3,2)(4,5,6), (1,3,2)(4,5,6) ]
[ (1,3,2)(4,5,6), (1,2,3)(4,6,5) ]
gap> wgt3 := WhiteheadGroupTable( X3 );;
gap> Perform( wgt3, Display );

```

```

[ [ 1, 2, 3, 4, 5, 6 ],
  [ 2, 3, 1, 5, 6, 4 ],
  [ 3, 1, 2, 6, 4, 5 ],
  [ 4, 6, 5, 1, 3, 2 ],
  [ 5, 4, 6, 2, 1, 3 ],
  [ 6, 5, 4, 3, 2, 1 ] ]
gap> wpg3 := WhiteheadPermGroup( X3 );
Group([ (1,2,3)(4,5,6), (1,4)(2,6)(3,5) ])

```

5.2.3 PrincipalDerivations

▷ PrincipalDerivations($X0$)

(attribute)

The principal derivations form a subgroup of the Whitehead group.

Example

```

gap> PDX3 := PrincipalDerivations( X3 );
monoid of derivations with images list:
[ (), () ]
[ (), (1,3,2)(4,5,6) ]
[ (), (1,2,3)(4,6,5) ]

```

5.2.4 AllSections

▷ AllSections($C0$)

(attribute)

▷ RegularSections($C0$)

(attribute)

These operations have been declared but are not yet implemented. The interested user should, instead, work with the corresponding derivations.

Chapter 6

Actors of 2d-groups

6.1 Actor of a crossed module

The *actor* of \mathcal{X} is a crossed module $\text{Act}(\mathcal{X}) = (\Delta : \mathcal{W}(\mathcal{X}) \rightarrow \text{Aut}(\mathcal{X}))$ which was shown by Lue and Norrie, in [Nor87] and [Nor90] to give the automorphism object of a crossed module \mathcal{X} . In this implementation, the source of the actor is a permutation representation W of the Whitehead group of regular derivations, and the range of the actor is a permutation representation A of the automorphism group $\text{Aut}(\mathcal{X})$ of \mathcal{X} .

6.1.1 AutomorphismPermGroup

- ▷ `AutomorphismPermGroup(xmod)` (attribute)
- ▷ `GeneratingAutomorphisms(xmod)` (attribute)
- ▷ `PermAutomorphismAsXModMorphism(xmod, perm)` (operation)

The automorphisms (σ, ρ) of \mathcal{X} form a group $\text{Aut}(\mathcal{X})$ of crossed module isomorphisms. The function `AutomorphismPermGroup` finds a set of `GeneratingAutomorphisms` for $\text{Aut}(\mathcal{X})$, and then constructs a permutation representation of this group, which is used as the range of the actor crossed module of \mathcal{X} . The individual automorphisms can be constructed from the permutation group using the function `PermAutomorphismAsXModMorphism`. The example below uses the crossed module $X3=[c3 \rightarrow s3]$ constructed in section 5.1.

Example

```
gap> APX3 := AutomorphismPermGroup( X3 );
Group([ (5,7,6), (1,2)(3,4)(6,7) ])
gap> Size( APX3 );
6
gap> genX3 := GeneratingAutomorphisms( X3 );
[ [[c3->s3] => [c3->s3]], [[c3->s3] => [c3->s3]] ]
gap> e6 := Elements( APX3 )[6];
(1,2)(3,4)(5,7)
gap> m6 := PermAutomorphismAsXModMorphism( X3, e6 );;
gap> Display( m6 );
Morphism of crossed modules :-
: Source = [c3->s3] with generating sets:
  [ (1,2,3)(4,6,5) ]
```

```

[ (4,5,6), (2,3)(5,6) ]
: Range = Source
: Source Homomorphism maps source generators to:
[ (1,3,2)(4,5,6) ]
: Range Homomorphism maps range generators to:
[ (4,6,5), (2,3)(4,5) ]

```

6.1.2 WhiteheadXMod

- ▷ WhiteheadXMod(*xmod*) (attribute)
- ▷ LueXMod(*xmod*) (attribute)
- ▷ NorrieXMod(*xmod*) (attribute)
- ▷ ActorXMod(*xmod*) (attribute)

An automorphism (σ, ρ) of X acts on the Whitehead monoid by $\chi^{(\sigma, \rho)} = \sigma \circ \chi \circ \rho^{-1}$, and this determines the action for the actor. In fact the four groups S, W, R, A , the homomorphisms between them, and the various actions, give five crossed modules forming a *crossed square* (see ActorCrossedSquare (8.2.3)).

- $\mathcal{W}(\mathcal{X}) = (\eta : S \rightarrow W)$, the Whitehead crossed module of \mathcal{X} , at the top,
- $\mathcal{X} = (\partial : S \rightarrow R)$, the initial crossed module, on the left,
- $\text{Act}(\mathcal{X}) = (\Delta : W \rightarrow A)$, the actor crossed module of \mathcal{X} , on the right,
- $\mathcal{N}(X) = (\alpha : R \rightarrow A)$, the Norrie crossed module of \mathcal{X} , on the bottom, and
- $\mathcal{L}(\mathcal{X}) = (\Delta \circ \eta = \alpha \circ \partial : S \rightarrow A)$, the Lue crossed module of \mathcal{X} , along the top-left to bottom-right diagonal.

Example

```

gap> WG3 := WhiteheadPermGroup( X3 );
Group([ (1,2,3)(4,5,6), (1,4)(2,6)(3,5) ])
gap> WX3 := WhiteheadXMod( X3 );;
gap> Display( WX3 );
Crossed module Whitehead[c3->s3] :-
: Source group has generators:
[ (1,2,3)(4,6,5) ]
: Range group has generators:
[ (1,2,3)(4,5,6), (1,4)(2,6)(3,5) ]
: Boundary homomorphism maps source generators to:
[ (1,2,3)(4,5,6) ]
: Action homomorphism maps range generators to automorphisms:
(1,2,3)(4,5,6) --> { source gens --> [ (1,2,3)(4,6,5) ] }
(1,4)(2,6)(3,5) --> { source gens --> [ (1,3,2)(4,5,6) ] }
These 2 automorphisms generate the group of automorphisms.
gap> LX3 := LueXMod( X3 );;
gap> Display( LX3 );
Crossed module Lue[c3->s3] :-
: Source group has generators:

```



```

[ (1,2,3)(4,6,5) ]
: Range group has generators:
[ (5,7,6), (1,2)(3,4)(6,7) ]
: Boundary homomorphism maps source generators to:
[ (5,7,6) ]
: Action homomorphism maps range generators to automorphisms:
(5,7,6) --> { source gens --> [ (1,2,3)(4,6,5) ] }
(1,2)(3,4)(6,7) --> { source gens --> [ (1,3,2)(4,5,6) ] }
These 2 automorphisms generate the group of automorphisms.
gap> NX3 := NorrieXMod( X3 );;
gap> Display( NX3 );
Crossed module Norrie[c3->s3] :-
: Source group has generators:
[ (4,5,6), (2,3)(5,6) ]
: Range group has generators:
[ (5,7,6), (1,2)(3,4)(6,7) ]
: Boundary homomorphism maps source generators to:
[ (5,6,7), (1,2)(3,4)(6,7) ]
: Action homomorphism maps range generators to automorphisms:
(5,7,6) --> { source gens --> [ (4,5,6), (2,3)(4,5) ] }
(1,2)(3,4)(6,7) --> { source gens --> [ (4,6,5), (2,3)(5,6) ] }
These 2 automorphisms generate the group of automorphisms.
gap> AX3 := ActorXMod( X3 );;
gap> Display( AX3 );
Crossed module Actor[c3->s3] :-
: Source group has generators:
[ (1,2,3)(4,5,6), (1,4)(2,6)(3,5) ]
: Range group has generators:
[ (5,7,6), (1,2)(3,4)(6,7) ]
: Boundary homomorphism maps source generators to:
[ (5,7,6), (1,2)(3,4)(6,7) ]
: Action homomorphism maps range generators to automorphisms:
(5,7,6) --> { source gens --> [ (1,2,3)(4,5,6), (1,6)(2,5)(3,4) ] }
(1,2)(3,4)(6,7) --> { source gens --> [ (1,3,2)(4,6,5), (1,4)(2,6)(3,5) ] }
These 2 automorphisms generate the group of automorphisms.

gap> IAX3 := InnerActorXMod( X3 );;
gap> Display( IAX3 );
Crossed module InnerActor[c3->s3] :-
: Source group has generators:
[ (1,2,3)(4,5,6) ]
: Range group has generators:
[ (5,6,7), (1,2)(3,4)(6,7) ]
: Boundary homomorphism maps source generators to:
[ (5,7,6) ]
: Action homomorphism maps range generators to automorphisms:
(5,6,7) --> { source gens --> [ (1,2,3)(4,5,6) ] }
(1,2)(3,4)(6,7) --> { source gens --> [ (1,3,2)(4,6,5) ] }
These 2 automorphisms generate the group of automorphisms.

```

6.1.3 XModCentre

- ▷ XModCentre(*xmod*) (attribute)
- ▷ InnerActorXMod(*xmod*) (attribute)
- ▷ InnerMorphism(*xmod*) (attribute)

Pairs of boundaries or identity mappings provide six morphisms of crossed modules. In particular, the boundaries of $\mathcal{W}(\mathcal{X})$ and $\mathcal{N}(\mathcal{X})$ form the *inner morphism* of \mathcal{X} , mapping source elements to principal derivations and range elements to inner automorphisms. The image of \mathcal{X} under this morphism is the *inner actor* of \mathcal{X} , while the kernel is the *centre* of \mathcal{X} . In the example which follows, the inner morphism of $X3=(c3 \rightarrow s3)$, from Chapter 5, is an inclusion of crossed modules.

Note that we appear to have defined *two* sorts of *centre* for a crossed module: XModCentre here, and CentreXMod (4.1.7) in the chapter on isoclinism. We suspect that these two definitions give the same answer, but this remains to be resolved.

Example

```

gap> IMX3 := InnerMorphism( X3 );;
gap> Display( IMX3 );
Morphism of crossed modules :-
: Source = [c3->s3] with generating sets:
  [ (1,2,3)(4,6,5) ]
  [ (4,5,6), (2,3)(5,6) ]
: Range = Actor[c3->s3] with generating sets:
  [ (1,2,3)(4,5,6), (1,4)(2,6)(3,5) ]
  [ (5,7,6), (1,2)(3,4)(6,7) ]
: Source Homomorphism maps source generators to:
  [ (1,2,3)(4,5,6) ]
: Range Homomorphism maps range generators to:
  [ (5,6,7), (1,2)(3,4)(6,7) ]
gap> IsInjective( IMX3 );
true
gap> ZX3 := XModCentre( X3 );
[Group( () )->Group( () )]
```

Chapter 7

Induced constructions

Before describing general functions for computing induced structures, we consider coproducts of crossed modules which provide induced crossed modules in certain cases.

7.1 Coproducts of crossed modules

Need to add here a reference (or two) for coproducts.

7.1.1 CoproductXMod

- ▷ `CoproductXMod(X1, X2)` (operation)
- ▷ `CoproductInfo(X0)` (attribute)

This function calculates the coproduct crossed module of two or more crossed modules which have a common range R . The standard method applies to $\mathcal{X}_1 = (\partial_1 : S_1 \rightarrow R)$ and $\mathcal{X}_2 = (\partial_2 : S_2 \rightarrow R)$. See below for the case of three or more crossed modules.

The source S_2 of \mathcal{X}_2 acts on S_1 via ∂_2 and the action of \mathcal{X}_1 , so we can form a precrossed module $(\partial' : S_1 \times S_2 \rightarrow R)$ where $\partial'(s_1, s_2) = (\partial_1 s_1)(\partial_2 s_2)$. The action of this precrossed module is the diagonal action $(s_1, s_2)^r = (s_1^r, s_2^r)$. Factoring out by the Peiffer subgroup, we obtain the coproduct crossed module $\mathcal{X}_1 \circ \mathcal{X}_2$.

In the example the structure descriptions of the precrossed module, the Peiffer subgroup, and the resulting coproduct are printed out when `InfoLevel(InfoXMod)` is at least 1. The coproduct comes supplied with attribute `CoproductInfo`, which includes the embedding morphisms of the two factors.

Example

```
gap> q8 := Group( (1,2,3,4)(5,8,7,6), (1,5,3,7)(2,6,4,8) );;
gap> X8 := XModByAutomorphismGroup( q8 );;
gap> s4b := Range( X8 );;
gap> SetName( q8, "q8" ); SetName( s4b, "s4b" );
gap> a := q8.1;; b := q8.2;;
gap> alpha := GroupHomomorphismByImages( q8, q8, [a,b], [a^-1,b] );;
gap> beta := GroupHomomorphismByImages( q8, q8, [a,b], [a,b^-1] );;
gap> k4b := Subgroup( s4b, [ alpha, beta ] );; SetName( k4b, "k4b" );
gap> Z8 := XModByNormalSubgroup( s4b, k4b );;
gap> SetName( X8, "X8" ); SetName( Z8, "Z8" );
gap> SetInfoLevel( InfoXMod, 1 );;
```

```

gap> XZ8 := CoproductXMod( X8, Z8 );
#I prexmod is [ [ 32, 47 ], [ 24, 12 ] ]
#I peiffer subgroup is C2, [ 2, 1 ]
#I the coproduct is [ "C2 x C2 x C2 x C2", "S4" ], [ [ 16, 14 ], [ 24, 12 ] ]
[Group( [ f1, f2, f3, f4 ] )->s4b]
gap> SetName( XZ8, "XZ8" );
gap> info := CoproductInfo( XZ8 );
rec( embeddings := [ [X8 => XZ8], [Z8 => XZ8] ], xmods := [ X8, Z8 ] )
gap> SetInfoLevel( InfoXMod, 0 );

```

Given a list of more than two crossed modules with a common range R , then an iterated coproduct is formed:

$$\bigcirc [\mathcal{X}_1, \mathcal{X}_2, \dots, \mathcal{X}_n] = \mathcal{X}_1 \circ (\mathcal{X}_2 \circ (\dots (\mathcal{X}_{n-1} \circ \mathcal{X}_n) \dots)).$$

The embeddings field of the CoproductInfo of the resulting crossed module \mathcal{Y} contains the n morphisms $\varepsilon_i: \mathcal{X}_i \rightarrow \mathcal{Y}$ ($1 \leq i \leq n$).

Example

```

gap> Y := CoproductXMod( [ X8, X8, Z8, Z8 ] );
[Group( [ f1, f2, f3, f4, f5, f6, f7, f8 ] )->s4b]
gap> StructureDescription( Y );
[ "C2 x C2 x C2 x C2 x C2 x C2 x C2 x C2", "S4" ]
gap> CoproductInfo( Y );
rec(
  embeddings :=
    [ [X8 => [Group( [ f1, f2, f3, f4, f5, f6, f7, f8 ] ) -> s4b]],
      [X8 => [Group( [ f1, f2, f3, f4, f5, f6, f7, f8 ] ) -> s4b]],
      [Z8 => [Group( [ f1, f2, f3, f4, f5, f6, f7, f8 ] ) -> s4b]],
      [Z8 => [Group( [ f1, f2, f3, f4, f5, f6, f7, f8 ] ) -> s4b]] ],
  xmods := [ X8, X8, Z8, Z8 ] )

```

7.2 Induced crossed modules

7.2.1 InducedXMod

- ▷ InducedXMod(*args*) (function)
- ▷ IsInducedXMod(*xmod*) (property)
- ▷ InducedXModBySurjection(*xmod*, *hom*) (operation)
- ▷ InducedXModByCoproduct(*xmod*, *hom*, *list*) (operation)
- ▷ MorphismOfInducedXMod(*xmod*) (attribute)

A morphism of crossed modules $(\sigma, \rho): \mathcal{X}_1 \rightarrow \mathcal{X}_2$ factors uniquely through an induced crossed module $\rho_* \mathcal{X}_1 = (\delta: \rho_* \mathcal{S}_1 \rightarrow R_2)$. Similarly, a morphism of cat1-groups factors through an induced cat1-group. Calculation of induced crossed modules of \mathcal{X} also provides an algebraic means of determining the homotopy 2-type of homotopy pushouts of the classifying space of \mathcal{X} . For more background from algebraic topology see references in [BH78], [BW95], [BW96]. Induced crossed modules

and induced cat1-groups also provide the building blocks for constructing pushouts in the categories *XMod* and *Cat1*.

Data for the cases of algebraic interest is provided by a crossed module $\mathcal{X} = (\partial : S \rightarrow R)$ and a homomorphism $\iota : R \rightarrow Q$. The output from the calculation is a crossed module $\iota_*\mathcal{X} = (\delta : \iota_*S \rightarrow Q)$ together with a morphism of crossed modules $\mathcal{X} \rightarrow \iota_*\mathcal{X}$. When ι is a surjection with kernel K then $\iota_*S = S/[K, S]$ (see [BH78]). (For many years, up until June 2018, this manual has stated the result to be $[K, S]$, though the correct quotient has been calculated.) When ι is an inclusion the induced crossed module may be calculated using a copower construction [BW95] or, in the case when R is normal in Q , as a coproduct of crossed modules ([BW96], but not yet implemented). When ι is neither a surjection nor an inclusion, ι is factored as the composite of the surjection onto the image and the inclusion of the image in Q , and then the composite induced crossed module is constructed. These constructions use Tietze transformation routines in the library file `tietze.gi`.

As a first, surjective example, we take for \mathcal{X} the normal inclusion crossed module of `a4` in `s4`, and for ι the surjection from `s4` to `s3` with kernel `k4`. The induced crossed module is isomorphic to `X3 = [c3->s3]`.

Example

```
gap> s4gens := GeneratorsOfGroup( s4 );
[ (1,2), (2,3), (3,4) ]
gap> a4gens := GeneratorsOfGroup( a4 );
[ (1,2,3), (2,3,4) ]
gap> s3b := Group( (5,6), (6,7) );; SetName( s3b, "s3b" );
gap> epi := GroupHomomorphismByImages( s4, s3b, s4gens, [(5,6), (6,7), (5,6)] );;
gap> X4 := XModByNormalSubgroup( s4, a4 );;
gap> indX4 := InducedXModBySurjection( X4, epi );
[a4/ker->s3b]
gap> Display( indX4 );

Crossed module [a4/ker->s3b] :-
: Source group a4/ker has generators:
  [ (1,3,2), (1,2,3) ]
: Range group s3b has generators:
  [ (5,6), (6,7) ]
: Boundary homomorphism maps source generators to:
  [ (5,6,7), (5,7,6) ]
: Action homomorphism maps range generators to automorphisms:
  (5,6) --> { source gens --> [ (1,2,3), (1,3,2) ] }
  (6,7) --> { source gens --> [ (1,2,3), (1,3,2) ] }
  These 2 automorphisms generate the group of automorphisms.

gap> morX4 := MorphismOfInducedXMod( indX4 );
[[a4->s4] => [a4/ker->s3b]]
```

For a second, injective example we take for \mathcal{X} the automorphism crossed module `X8` of `CoproductXMod (7.1.1)`, and for ι an inclusion of `s4b` in `s5`. The resulting source group is `SL(2,5)`.

Example

```
gap> iso4 := IsomorphismGroups( s4b, s4 );;
gap> s5 := Group( (1,2,3,4,5), (4,5) );;
```

```

gap> SetName( s5, "s5" );
gap> inc45 := InclusionMappingGroups( s5, s4 );;
gap> iota45 := iso4 * inc45;;
gap> indX8 := InducedXMod( X8, iota45 );
i*(X8)
gap> Size( indX8 );
[ 120, 120 ]
gap> StructureDescription( indX8 );
[ "SL(2,5)", "S5" ]

```

For a third example we use the version $\text{InducedXMod}(Q, R, S)$ of this global function, with $Q \geq R \triangleright S$. We take the identity mapping on $s3c$ as boundary, and the inclusion of $s3c$ in $s4$ as ι . The induced group is a general linear group $\text{GL}(2, 3)$.

Example

```

gap> s3c := Subgroup( s4, [ (2,3), (3,4) ] );;
gap> SetName( s3c, "s3c" );
gap> indXs3c := InducedXMod( s4, s3c, s3c );
#I induced group has Size: 48
i*([s3c->s3c])
gap> StructureDescription( indXs3c );
[ "GL(2,3)", "S4" ]

```

7.2.2 AllInducedXMods

▷ $\text{AllInducedXMods}(Q)$

(operation)

This function calculates all the induced crossed modules $\text{InducedXMod}(Q, R, S)$, where R runs over all conjugacy classes of subgroups of Q and S runs over all non-trivial normal subgroups of R .

Example

```

gap> all := AllInducedXMods( q8 );;
gap> ids := List( all, x -> IdGroup(x) );;
gap> Sort( ids );
gap> ids;
[ [ [ 1, 1 ], [ 8, 4 ] ], [ [ 1, 1 ], [ 8, 4 ] ], [ [ 1, 1 ], [ 8, 4 ] ],
  [ [ 1, 1 ], [ 8, 4 ] ], [ [ 4, 2 ], [ 8, 4 ] ], [ [ 4, 2 ], [ 8, 4 ] ],
  [ [ 4, 2 ], [ 8, 4 ] ], [ [ 16, 2 ], [ 8, 4 ] ], [ [ 16, 2 ], [ 8, 4 ] ],
  [ [ 16, 2 ], [ 8, 4 ] ], [ [ 16, 14 ], [ 8, 4 ] ] ]

```

7.3 Induced cat^1 -groups

7.3.1 InducedCat1Group

▷ $\text{InducedCat1Group}(args)$

(function)

▷ $\text{InducedCat1GroupByFreeProduct}(grp, hom)$

(property)

This area awaits development.

Chapter 8

Crossed squares and Cat^2 -groups

The term *3d-group* refers to a set of equivalent categories of which the most common are the categories of *crossed squares* and *cat²-groups*. A *3d-mapping* is a function between two 3d-groups which preserves all the structure.

The material in this chapter should be considered experimental. A major overhaul took place in time for XMod version 2.73, with the names of a number of operations being changed.

8.1 Definition of a crossed square and a crossed n -cube of groups

Crossed squares were introduced by Guin-Waléry and Loday (see, for example, [BL87]) as fundamental crossed squares of commutative squares of spaces, but are also of purely algebraic interest. We denote by $[n]$ the set $\{1, 2, \dots, n\}$. We use the $n = 2$ version of the definition of crossed n -cube as given by Ellis and Steiner [ES87].

A *crossed square* \mathcal{S} consists of the following:

- groups S_J for each of the four subsets $J \subseteq [2]$ (we often find it convenient to write $L = S_{[2]}$, $M = S_{\{1\}}$, $N = S_{\{2\}}$ and $P = S_\emptyset$);
- a commutative diagram of group homomorphisms:

$$\partial_1 : S_{[2]} \rightarrow S_{\{2\}}, \quad \partial_2 : S_{[2]} \rightarrow S_{\{1\}}, \quad \partial_2 : S_{\{2\}} \rightarrow S_\emptyset, \quad \partial_1 : S_{\{1\}} \rightarrow S_\emptyset$$

(again we often write $\kappa = \partial_1$, $\lambda = \partial_2$, $\mu = \partial_2$ and $\nu = \partial_1$);

- actions of S_\emptyset on $S_{\{1\}}$, $S_{\{2\}}$ and $S_{[2]}$ which determine actions of $S_{\{1\}}$ on $S_{\{2\}}$ and $S_{[2]}$ via ∂_1 and actions of $S_{\{2\}}$ on $S_{\{1\}}$ and $S_{[2]}$ via ∂_2 ;
- a function $\boxtimes : S_{\{1\}} \times S_{\{2\}} \rightarrow S_{[2]}$.

Here is a picture of the situation:

$$\mathcal{S} = \begin{array}{ccc} S_{[2]} & \xrightarrow{\partial_1} & S_{\{2\}} \\ \partial_2 \downarrow & & \downarrow \partial_2 \\ S_{\{1\}} & \xrightarrow{\partial_1} & S_\emptyset \end{array} = \begin{array}{ccc} L & \xrightarrow{\kappa} & M \\ \lambda \downarrow & & \downarrow \mu \\ N & \xrightarrow{\nu} & P \end{array}$$

The following axioms must be satisfied for all $l \in L$, $m, m_1, m_2 \in M$, $n, n_1, n_2 \in N$, $p \in P$.

- The homomorphisms κ, λ preserve the action of P .
- Each of the upper, left-hand, right-hand and lower sides of the square,

$$\mathcal{J}_1 = (\kappa : L \rightarrow M), \quad \mathcal{J}_2 = (\lambda : L \rightarrow N), \quad \mathcal{J}_2 = (\mu : M \rightarrow P), \quad \mathcal{J}_1 = (\nu : N \rightarrow P),$$

and the diagonal

$$\mathcal{S}_{12} = (\partial_{12} := \mu \circ \kappa = \nu \circ \lambda : L \rightarrow P)$$

are crossed modules (with actions via P).

The first four of these are called the *up*, *left*, *right* and *down* crossed modules of \mathcal{S} .

- \boxtimes is a *crossed pairing*:
 - $(n_1 n_2 \boxtimes m) = (n_1 \boxtimes m)^{n_2} (n_2 \boxtimes m)$,
 - $(n \boxtimes m_1 m_2) = (n \boxtimes m_2) (n \boxtimes m_1)^{m_2}$,
 - $(n \boxtimes m)^p = (n^p \boxtimes m^p)$.
- $\check{\partial}_1(n \boxtimes m) = (m^{-1})^n m$ and $\check{\partial}_2(n \boxtimes m) = n^{-1} n^m$.
- $(n \boxtimes \check{\partial}_1 l) = (l^{-1})^n l$ and $(\check{\partial}_2 l \boxtimes m) = l^{-1} l^m$.

Note that the actions of M on N and N on M via P are compatible since

$$n_1^{(m^n)} = n_1^{\check{\partial}_2(m^n)} = n_1^{n^{-1}(\check{\partial}_2 m)^n} = ((n_1^{n^{-1}})^m)^n.$$

(A *precrossed square* is a similar structure which satisfies some subset of these axioms. This notion needs to be clarified.)

Crossed squares are the $k = 2$ case of a crossed k -cube of groups, defined as follows. (This is an attempt to translate Definition 2.1 in Ronnie Brown's *Computing homotopy types using crossed n -cubes of groups* into right actions – but this definition is not yet completely understood!)

A *crossed k -cube of groups* consists of the following:

- groups S_A for every subset $A \subseteq [k]$;
- a commutative diagram of group homomorphisms $\partial_i : S_A \rightarrow S_{A \setminus \{i\}}$, $i \in [k]$; with composites $\partial_B : S_A \rightarrow S_{A \setminus B}$, $B \subseteq [k]$;
- actions of S_\emptyset on each S_A ; and hence actions of S_B on S_A via ∂_B for each $B \subseteq [k]$;
- functions $\boxtimes_{A,B} : S_A \times S_B \rightarrow S_{A \cup B}$, $(A, B \subseteq [k])$.

There is then a long list of axioms which must be satisfied.

8.2 Constructions for crossed squares

Analogously to the data structure used for crossed modules, crossed squares are implemented as 3d-groups. There are also experimental implementations of cat^2 -groups, with conversion between the two types of structure. Some standard constructions of crossed squares are listed below. At present, a limited number of constructions is implemented. Morphisms of crossed squares have also been implemented, though there is still a lot to be done.

8.2.1 CrossedSquareByNormalSubgroups

▷ `CrossedSquareByNormalSubgroups(L, M, N, P)` (operation)

If L, M, N are normal subgroups of a group P , and $[M, N] \leq L \leq M \cap N$, then the four inclusions $L \rightarrow M$, $L \rightarrow N$, $M \rightarrow P$, $N \rightarrow P$, together with the actions of P on M, N and L given by conjugation, form a crossed square with crossed pairing

$$\boxtimes : N \times M \rightarrow L, \quad (n, m) \mapsto [n, m] = n^{-1}m^{-1}nm = (m^{-1})^n m = n^{-1}n^m.$$

This construction is implemented as `CrossedSquareByNormalSubgroups(L, M, N, P)`; (note that the parent group come last).

Example

```
gap> d20 := DihedralGroup( IsPermGroup, 20 );;
gap> gend20 := GeneratorsOfGroup( d20 );
[ (1,2,3,4,5,6,7,8,9,10), (2,10)(3,9)(4,8)(5,7) ]
gap> p1 := gend20[1];; p2 := gend20[2];; p12 := p1*p2;
(1,10)(2,9)(3,8)(4,7)(5,6)
gap> d10a := Subgroup( d20, [ p1^2, p2 ] );;
gap> d10b := Subgroup( d20, [ p1^2, p12 ] );;
gap> c5d := Subgroup( d20, [ p1^2 ] );;
gap> SetName( d20, "d20" ); SetName( d10a, "d10a" );
gap> SetName( d10b, "d10b" ); SetName( c5d, "c5d" );
gap> XSconj := CrossedSquareByNormalSubgroups( c5d, d10a, d10b, d20 );
[ c5d -> d10a ]
[ | | ]
[ d10b -> d20 ]
```

8.2.2 CrossedSquareByNormalSubXMod

▷ `CrossedSquareByNormalSubXMod(X0, X1)` (operation)

If $\mathcal{X}_1 = (\partial_1 : S_1 \rightarrow R_1)$ is a normal sub-crossed module of $\mathcal{X}_0 = (\partial_0 : S_0 \rightarrow R_0)$ then the inclusion morphism gives a crossed square with crossed pairing

$$\boxtimes : R_1 \times S_0 \rightarrow S_1, \quad (r_1, s_0) \mapsto (s_0^{-1})^{r_1} s_0.$$

The example constructs the same crossed square as in the previous subsection.

Example

```
gap> X20 := XModByNormalSubgroup( d20, d10a );;
gap> X10 := XModByNormalSubgroup( d10b, c5d );;
gap> ok := IsNormalSub2DimensionalDomain( X20, X10 );
true
gap> XS20 := CrossedSquareByNormalSubXMod( X20, X10 );
[ c5d -> d10a ]
[ | | ]
[ d10b -> d20 ]
```

8.2.3 ActorCrossedSquare

▷ ActorCrossedSquare($X0$) (operation)

The actor $\mathcal{A}(\mathcal{X}_0)$ of a crossed module \mathcal{X}_0 has been described in Chapter 5 (see ActorXMod (6.1.2)). The crossed pairing is given by

$$\boxtimes : R \times W \rightarrow S, \quad (\chi, r) \mapsto \chi r.$$

This is implemented as ActorCrossedSquare($X0$);.

Example

```
gap> XSact := ActorCrossedSquare( X20 );
crossed square with:
  up = Whitehead[d10a->d20]
  left = [d10a->d20]
  right = Actor[d10a->d20]
  down = Norrie[d10a->d20]
```

8.2.4 CrossedSquareByAutomorphismGroup

▷ CrossedSquareByAutomorphismGroup(G) (operation)

For G a group let $\text{Inn}(G)$ be its inner automorphism group and $\text{Aut}(G)$ its full automorphism group. Then there is a crossed square with groups $[G, \text{Inn}(G), \text{Inn}(G), \text{Aut}(G)]$ where the upper and left boundaries are the maps $g \mapsto \iota_g$, where ι_g is conjugation of G by g , and the right and down boundaries are inclusions. The crossed pairing is given by $\iota_g \boxtimes \iota_h = [g, h]$.

Example

```
gap> AXS20 := CrossedSquareByAutomorphismGroup( d20 );
[      d20  -> Inn(d20) ]
[      |      |      ]
[ Inn(d20) -> Aut(d20) ]

gap> StructureDescription( AXS20 );
[ "D20", "D10", "D10", "C2 x (C5 : C4)" ]
```

8.2.5 CrossedSquareByPullback

▷ CrossedSquareByPullback($X1, X2$) (operation)

If crossed modules $\mathcal{X}_1 = (v : N \rightarrow P)$ and $\mathcal{X}_2 = (\mu : M \rightarrow P)$ have a common range P , let L be the pullback of $\{v, \mu\}$. Then N acts on L by $(n, m)^{n'} = (n^{n'}, m^{vn'})$, and M acts on L by $(n, m)^{m'} = (n^{\mu m'}, m^{m'})$. So $(\pi_1 : L \rightarrow N)$ and $(\pi_2 : L \rightarrow M)$ are crossed modules, where π_1, π_2 are the two projections. The crossed pairing is given by:

$$\boxtimes : N \times M \rightarrow L, \quad (n, m) \mapsto (n^{-1}n^{\mu m}, (m^{-1})^{vn}m).$$

The second example uses the central extension crossed module $X_{12}=(D_{12} \rightarrow S_3)$ constructed in subsection (XModByCentralExtension (2.1.5)), with pullback group $D_{12} \times C_2$.

Example

```
gap> dn := Down2DimensionalGroup( XSconj );;
gap> rt := Right2DimensionalGroup( XSconj );;
gap> XSP := CrossedSquareByPullback( dn, rt );
gap> StructureDescription( XSP );
[ "C5", "D10", "D10", "D20" ]
gap> XS12 := CrossedSquareByPullback( X12, X12 );;
gap> StructureDescription( XS12 );
[ "C2 x C2 x S3", "D12", "D12", "S3" ]
```

8.2.6 CrossedSquareByXModSplitting

▷ CrossedSquareByXModSplitting(X_0)

(attribute)

For $\mathcal{X} = (\partial : S \rightarrow R)$ let Q be the image of ∂ . Then $\partial = \partial' \circ \iota$ where $\partial' : S \rightarrow Q$ and ι is the inclusion of Q in R . The diagonal of the square is then the initial \mathcal{X} , and the crossed pairing is given by commutators.

A particular case is when S is an R -module A and ∂ is the zero map.

$$\begin{array}{ccc}
 S & \xrightarrow{\partial'} & Q \\
 \downarrow \partial' & & \downarrow \iota \\
 Q & \xrightarrow{\iota} & R
 \end{array}
 \qquad
 \begin{array}{ccc}
 A & \xrightarrow{0} & 1 \\
 \downarrow 0 & & \downarrow \iota \\
 1 & \xrightarrow{\iota} & R
 \end{array}$$

Example

```
gap> k4 := Group( (1,2), (3,4) );;
gap> AX4 := XModByAutomorphismGroup( k4 );;
gap> X4 := Image( IsomorphismPermObject( AX4 ) );;
gap> XSS4 := CrossedSquareByXModSplitting( X4 );;
gap> StructureDescription( XSS4 );
[ "C2 x C2", "1", "1", "S3" ]
gap> XSS20 := CrossedSquareByXModSplitting( X20 );;
gap> up20 := Up2DimensionalGroup( XSS20 );;
gap> Range( up20 ) = d10a;
true
gap> SetName( Range( up20 ), "d10a" );
gap> Name( XSS20 );
"[d10a->d10a,d10a->d20]"
```

8.2.7 CrossedSquare

▷ `CrossedSquare(args)` (function)

The function `CrossedSquare` may be used to call some of the constructions described in the previous subsections.

- `CrossedSquare(X0)` calls `CrossedSquareByXModSplitting`.
- `CrossedSquare(C0)` calls `CrossedSquareOfCat2Group`.
- `CrossedSquare(X0,X1)` calls `CrossedSquareByPullback` when there is a common range.
- `CrossedSquare(X0,X1)` calls `CrossedSquareByNormalXMod` when $X1$ is normal in $X0$.
- `CrossedSquare(L,M,N,P)` calls `CrossedSquareByNormalSubgroups`.

Example

```
gap> diag := Diagonal2DimensionalGroup( AXS20 );
[d20->Aut(d20)]
gap> XSdiag := CrossedSquare( diag );
gap> StructureDescription( XSdiag );
[ "D20", "D10", "D10", "C2 x (C5 : C4)" ]
```

8.2.8 Transpose3DimensionalGroup

▷ `Transpose3DimensionalGroup(S0)` (attribute)

The *transpose* of a crossed square \mathcal{S} is the crossed square $\tilde{\mathcal{S}}$ obtained by interchanging M with N , κ with λ , and ν with μ . The crossed pairing is given by

$$\tilde{\boxtimes} : M \times N \rightarrow L, \quad (m,n) \mapsto m\tilde{\boxtimes}n := (n\boxtimes m)^{-1}.$$

Example

```
gap> XStrans := Transpose3DimensionalGroup( XSconj );
[ c5d -> d10b ]
[ | | ]
[ d10a -> d20 ]
```

8.2.9 CentralQuotient (for crossed modules)

▷ `CentralQuotient(X0)` (attribute)

The central quotient of a crossed module $\mathcal{X} = (\partial : S \rightarrow R)$ is the crossed square where:

- the left crossed module is \mathcal{X} ;

- the right crossed module is the quotient $\mathcal{X}/Z(\mathcal{X})$ (see CentreXMod (4.1.7));
- the up and down homomorphisms are the natural homomorphisms onto the quotient groups;
- the crossed pairing $\boxtimes : (R \times F) \rightarrow S$, where $F = \text{Fix}(\mathcal{X}, S, R)$, is the displacement element $\boxtimes(r, Fs) = \langle r, s \rangle = (s^{-1})^r s$ (see Displacement (4.1.3) and section 4.3).

This is the special case of an intended function `CrossedSquareByCentralExtension` which has not yet been implemented. In the example $X_{n7} \trianglelefteq X_{24}$, constructed in section 4.1.

Example

```
gap> pos7 := Position( ids, [ [12,2], [24,5] ] );;
gap> Xn7 := nsx[pos7];;
gap> IdGroup( Xn7 );
[ [ 12, 2 ], [ 24, 5 ] ]
gap> IdGroup( CentreXMod( Xn7 ) );
[ [ 4, 1 ], [ 4, 1 ] ]
gap> CQXn7 := CentralQuotient( Xn7 );;
gap> StructureDescription( CQXn7 );
[ "C12", "C3", "C4 x S3", "S3" ]
```

8.2.10 IsCrossedSquare

- ▷ `IsCrossedSquare(obj)` (property)
- ▷ `Is3dObject(obj)` (property)
- ▷ `IsPerm3dObject(obj)` (property)
- ▷ `IsPc3dObject(obj)` (property)
- ▷ `IsFp3dObject(obj)` (property)
- ▷ `IsPreCrossedSquare(obj)` (property)

These are the basic properties for 3d-groups, and crossed squares in particular.

8.2.11 Up2DimensionalGroup

- ▷ `Up2DimensionalGroup(XS)` (attribute)
- ▷ `Left2DimensionalGroup(XS)` (attribute)
- ▷ `Down2DimensionalGroup(XS)` (attribute)
- ▷ `Right2DimensionalGroup(XS)` (attribute)
- ▷ `DiagonalAction(XS)` (attribute)
- ▷ `CrossedPairing(XS)` (attribute)
- ▷ `Diagonal2DimensionalGroup(XS)` (attribute)
- ▷ `Name(SO)` (method)

These are the basic attributes of a crossed square \mathcal{S} . The six objects used in the construction of \mathcal{S} are the four crossed modules (2d-groups) on the sides of the square (up; left; right and down); the diagonal action of P on L ; and the crossed pairing $\{M, N\} \rightarrow L$. The diagonal crossed module ($L \rightarrow P$) is an additional attribute.

Crossed pairings have been implemented using an operation `Mapping2ArgumentsByFunction`. This encodes a map $\{M, N\} \rightarrow L$ as a map $M \times N \rightarrow L$.

Example

```

gap> Up2DimensionalGroup( XSconj );
[c5d->d10a]
gap> Right2DimensionalGroup( XSact );
Actor[d10a->d20]
gap> diact := DiagonalAction( XSact );;
gap> ImageElm( diact, (1,4)(2,3)(6,9)(7,8) );
^(1,5,7,3)(2,8,6,10)
gap> Diagonal2DimensionalGroup( XSconj );
[c5d->d20]
gap> Name( XSconj );
"[c5d->d10a,d10b->d20]"

```

8.2.12 ImageElmCrossedPairing

▷ ImageElmCrossedPairing(XS , $pair$) (operation)

This operation returns the image when a crossed pairing $\{M, N\} \rightarrow L$ is applied to the pair $[m, n]$ with $m \in M$, $n \in N$.

Example

```

gap> xp := CrossedPairing( XSconj );;
gap> ImageElmCrossedPairing( xp,
> [ (1,6)(2,5)(3,4)(7,10)(8,9), (1,5)(2,4)(6,9)(7,8) ] );
(1,7,8,5,3)(2,9,10,6,4)

```

8.3 Morphisms of crossed squares

This section describes an initial implementation of morphisms of (pre-)crossed squares.

8.3.1 CrossedSquareMorphism

▷ CrossedSquareMorphism($args$) (function)
 ▷ CrossedSquareMorphismByXModMorphisms(src , rng , $mors$) (operation)
 ▷ CrossedSquareMorphismByGroupHomomorphisms(src , rng , $homs$) (operation)
 ▷ PreCrossedSquareMorphismByPreXModMorphisms(src , rng , $mors$) (operation)
 ▷ PreCrossedSquareMorphismByGroupHomomorphisms(src , rng , $homs$) (operation)

8.3.2 Source

▷ Source(map) (attribute)
 ▷ Range(map) (attribute)
 ▷ Up2DimensionalMorphism(map) (attribute)
 ▷ Left2DimensionalMorphism(map) (attribute)

- ▷ `Down2DimensionalMorphism(map)` (attribute)
- ▷ `Right2DimensionalMorphism(map)` (attribute)

Morphisms of `3dObjects` are implemented as `3dMappings`. These have a pair of 3d-groups as source and range, together with four 2d-morphisms mapping between the four pairs of crossed modules on the four sides of the squares. These functions return `fail` when invalid data is supplied.

8.3.3 IsCrossedSquareMorphism

- ▷ `IsCrossedSquareMorphism(map)` (property)
- ▷ `IsPreCrossedSquareMorphism(map)` (property)
- ▷ `IsBijective(mor)` (method)
- ▷ `IsEndomorphism3dObject(mor)` (property)
- ▷ `IsAutomorphism3dObject(mor)` (property)

A morphism `mor` between two pre-crossed squares \mathcal{S}_1 and \mathcal{S}_2 consists of four crossed module morphisms `Up2DimensionalMorphism(mor)`, mapping the `Up2DimensionalGroup` of \mathcal{S}_1 to that of \mathcal{S}_2 , `Left2DimensionalMorphism(mor)`, `Right2DimensionalMorphism(mor)` and `Down2DimensionalMorphism(mor)`. These four morphisms are required to commute with the four boundary maps and to preserve the rest of the structure. The current version of `IsCrossedSquareMorphism` does not perform all the required checks.

Example

```
gap> ad20 := GroupHomomorphismByImages( d20, d20, [p1,p2], [p1,p2^p1] );;
gap> ad10a := GroupHomomorphismByImages( d10a, d10a, [p1^2,p2], [p1^2,p2^p1] );;
gap> ad10b := GroupHomomorphismByImages( d10b, d10b, [p1^2,p12], [p1^2,p12^p1] );;
gap> idc5d := IdentityMapping( c5d );;
gap> up := Up2DimensionalGroup( XSconj );;
gap> lt := Left2DimensionalGroup( XSconj );;
gap> rt := Right2DimensionalGroup( XSconj );;
gap> dn := Down2DimensionalGroup( XSconj );;
gap> mup := XModMorphismByGroupHomomorphisms( up, up, idc5d, ad10a );
[[c5d->d10a] => [c5d->d10a]]
gap> mlt := XModMorphismByGroupHomomorphisms( lt, lt, idc5d, ad10b );
[[c5d->d10b] => [c5d->d10b]]
gap> mrt := XModMorphismByGroupHomomorphisms( rt, rt, ad10a, ad20 );
[[d10a->d20] => [d10a->d20]]
gap> mdn := XModMorphismByGroupHomomorphisms( dn, dn, ad10b, ad20 );
[[d10b->d20] => [d10b->d20]]
gap> autoconj := CrossedSquareMorphism( XSconj, XSconj, [mup,mlt,mrt,mdn] );;
gap> ord := Order( autoconj );;
gap> Display( autoconj );
Morphism of crossed squares :-
: Source = [c5d->d10a,d10b->d20]
: Range = [c5d->d10a,d10b->d20]
:   order = 5
:   up-left: [ [ ( 1, 3, 5, 7, 9)( 2, 4, 6, 8,10) ],
:             [ ( 1, 3, 5, 7, 9)( 2, 4, 6, 8,10) ] ]
:   up-right:
[ [ ( 1, 3, 5, 7, 9)( 2, 4, 6, 8,10), ( 2,10)( 3, 9)( 4, 8)( 5, 7) ],
```



```

[ ( 1, 3, 5, 7, 9)( 2, 4, 6, 8,10), ( 1, 3)( 4,10)( 5, 9)( 6, 8) ] ]
: down-left:
[ [ ( 1, 3, 5, 7, 9)( 2, 4, 6, 8,10), ( 1,10)( 2, 9)( 3, 8)( 4, 7)( 5, 6) ],
  [ ( 1, 3, 5, 7, 9)( 2, 4, 6, 8,10), ( 1, 2)( 3,10)( 4, 9)( 5, 8)( 6, 7) ] ]
: down-right:
[ [ ( 1, 2, 3, 4, 5, 6, 7, 8, 9,10), ( 2,10)( 3, 9)( 4, 8)( 5, 7) ],
  [ ( 1, 2, 3, 4, 5, 6, 7, 8, 9,10), ( 1, 3)( 4,10)( 5, 9)( 6, 8) ] ]
gap> IsAutomorphismHigherDimensionalDomain( autoconj );
true
gap> KnownPropertiesOfObject( autoconj );
[ "CanEasilyCompareElements", "CanEasilySortElements", "IsTotal",
  "IsSingleValued", "IsInjective", "IsSurjective",
  "IsPreCrossedSquareMorphism", "IsCrossedSquareMorphism",
  "IsEndomorphismHigherDimensionalDomain",
  "IsAutomorphismHigherDimensionalDomain" ]

```

8.3.4 InclusionMorphismHigherDimensionalDomains

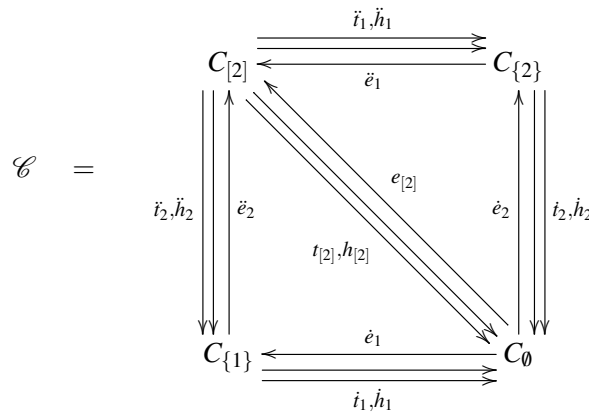
▷ InclusionMorphismHigherDimensionalDomains(*obj*, *sub*)

(operation)

8.4 Definitions and constructions for cat^2 -groups and their morphisms

We shall give three definitions of cat^2 -groups and show that they are equivalent. When we come to define cat^n -groups we shall give a similar set of three definitions.

Firstly, we take the definition of a cat^2 -group from Section 5 of Brown and Loday [BL87], suitably modified. A cat^2 -group $\mathcal{C} = (C_{[2]}, C_{\{2\}}, C_{\{1\}}, C_{\emptyset})$ comprises four groups (one for each of the subsets of [2]) and 15 homomorphisms, as shown in the following diagram:



The following axioms are satisfied by these homomorphisms:

- the four sides of the square are cat^1 -groups, denoted $\mathcal{C}_1, \mathcal{C}_2, \mathcal{C}_1, \mathcal{C}_2$,
- $\dot{t}_1 \circ \dot{h}_2 = \dot{h}_2 \circ \dot{i}_1$, $\dot{t}_2 \circ \dot{h}_1 = \dot{h}_1 \circ \dot{i}_2$, $\dot{e}_1 \circ \dot{t}_2 = \dot{t}_2 \circ \dot{e}_1$, $\dot{e}_2 \circ \dot{t}_1 = \dot{t}_1 \circ \dot{e}_2$, $\dot{e}_1 \circ \dot{h}_2 = \dot{h}_2 \circ \dot{e}_1$, $\dot{e}_2 \circ \dot{h}_1 = \dot{h}_1 \circ \dot{e}_2$,

- $i_1 \circ \ddot{i}_2 = i_2 \circ \ddot{i}_1 = t_{[2]}$, $\dot{h}_1 \circ \ddot{h}_2 = \dot{h}_2 \circ \ddot{h}_1 = h_{[2]}$, $\dot{e}_1 \circ \ddot{e}_2 = \dot{e}_2 \circ \ddot{e}_1 = e_{[2]}$, making the diagonal a pre-cat¹-group $(e_{[2]}; t_{[2]}, h_{[2]} : C_{[2]} \rightarrow C_0)$.

It follows from these identities that (\dot{i}_1, \dot{i}_1) , (\dot{h}_1, \dot{h}_1) and (\dot{e}_1, \dot{e}_1) are morphisms of cat¹-groups.

Secondly, we give the simplest of the three definitions, adapted from Ellis-Steiner [ES87]. A cat²-group \mathcal{C} consists of groups G, R_1, R_2 and six homomorphisms $t_1, h_1 : G \rightarrow R_2$, $e_1 : R_2 \rightarrow G$, $t_2, h_2 : G \rightarrow R_1$, $e_2 : R_1 \rightarrow G$, satisfying the following axioms for all $1 \leq i \leq 2$,

- $(t_i \circ e_i)r = r$, $(h_i \circ e_i)r = r$, $\forall r \in R_{[2] \setminus \{i\}}$, $[\ker t_i, \ker h_i] = 1$,
- $(e_1 \circ t_1) \circ (e_2 \circ t_2) = (e_2 \circ t_2) \circ (e_1 \circ t_1)$, $(e_1 \circ h_1) \circ (e_2 \circ h_2) = (e_2 \circ h_2) \circ (e_1 \circ h_1)$,
- $(e_1 \circ t_1) \circ (e_2 \circ h_2) = (e_2 \circ h_2) \circ (e_1 \circ t_1)$, $(e_2 \circ t_2) \circ (e_1 \circ h_1) = (e_1 \circ h_1) \circ (e_2 \circ t_2)$.

Our third definition defines a cat²-group as a "cat¹-group of cat¹-groups". A cat²-group \mathcal{C} consists of two cat¹-groups $\mathcal{C}_1 = (e_1; t_1, h_1 : G_1 \rightarrow R_1)$ and $\mathcal{C}_2 = (e_2; t_2, h_2 : G_2 \rightarrow R_2)$ and cat¹-morphisms $t = (\dot{i}, \dot{i})$, $h = (\dot{h}, \dot{h}) : \mathcal{C}_1 \rightarrow \mathcal{C}_2$, $e = (\ddot{e}, \ddot{e}) : \mathcal{C}_2 \rightarrow \mathcal{C}_1$, subject to the following conditions:

$$(t \circ e) \text{ and } (h \circ e) \text{ are the identity mapping on } \mathcal{C}_2, \quad [\ker t, \ker h] = \{1_{\mathcal{C}_1}\},$$

where $\ker t = (\ker \dot{i}, \ker \dot{i})$, and similarly for $\ker h$.

8.4.1 Cat2Group

- ▷ Cat2Group(*args*) (function)
- ▷ PreCat2Group(*args*) (function)
- ▷ IsCat2Group(*C*) (property)
- ▷ PreCat2GroupByPreCat1Groups(*L*) (operation)

The global functions Cat2Group and PreCat2Group are normally called with a single argument, a list of cat¹-groups.

Example

```
gap> a := (1,2,3,4)(5,6,7,8);;
gap> b := (1,5)(2,6)(3,7)(4,8);;
gap> c := (2,6)(4,8);;
gap> G16 := Group( a, b, c );;
gap> SetName( G16, "c4c2:c2" );
gap> t1a := GroupHomomorphismByImages( G16, G16, [a,b,c], [( ), ( ), c] );;
gap> C1a := PreCat1GroupByEndomorphisms( t1a, t1a );;
gap> t1b := GroupHomomorphismByImages( G16, G16, [a,b,c], [a, ( ), ( )] );;
gap> C1b := PreCat1GroupByEndomorphisms( t1b, t1b );;
gap> C16 := Cat2Group( C1a, C1b );
cat2-group with generating (pre-)cat1-groups:
1 : [c4c2:c2 => Group( [ ( ), ( ), (2,6)(4,8) ] )]
2 : [c4c2:c2 => Group( [ (1,2,3,4)(5,6,7,8), ( ), ( ) ] )]
gap> IsCat2Group( C16 );
true
gap> IsCat1Group( Diagonal2DimensionalGroup( C16 ) );
false
```

8.4.2 Cat2GroupMorphism

- ▷ `Cat2GroupMorphism(args)` (function)
- ▷ `Cat2GroupMorphismByCat1GroupMorphisms(src, rng, mors)` (operation)
- ▷ `Cat2GroupMorphismByGroupHomomorphisms(src, rng, mors)` (operation)
- ▷ `PreCat2GroupMorphismByPreCat1GroupMorphisms(src, rng, mors)` (operation)
- ▷ `PreCat2GroupMorphismByGroupHomomorphisms(src, rng, mors)` (operation)

8.4.3 Cat2GroupOfCrossedSquare

- ▷ `Cat2GroupOfCrossedSquare(xsq)` (attribute)
- ▷ `CrossedSquareOfCat2Group(CC)` (attribute)

These functions are very experimental!

These functions provide the conversion from crossed square to cat2-group, and conversely. (They are the 3-dimensional equivalents of `Cat1GroupOfXMod` (2.5.2) and `XModOfCat1Group` (2.5.2).)

Example

```
gap> xsC16 := CrossedSquareOfCat2Group( C16 );
crossed square with crossed modules:
  up = [Group( [ (1,5)(2,6)(3,7)(4,8) ] ) -> Group( [ ( 2, 6)( 4, 8) ] )]
  left = [Group( [ (1,5)(2,6)(3,7)(4,8) ] ) -> Group(
[ (1,2,3,4)(5,6,7,8), (), () ] )]
  right = [Group( [ ( 2, 6)( 4, 8) ] ) -> Group( () )]
  down = [Group( [ (1,2,3,4)(5,6,7,8), (), () ] ) -> Group( () )]

gap> IdGroup( xsC16 );
[ [ 2, 1 ], [ 2, 1 ], [ 4, 1 ], [ 1, 1 ] ]

gap> SetName( Source( Right2DimensionalGroup( XSact ) ), "c5:c4" );
gap> SetName( Range( Right2DimensionalGroup( XSact ) ), "c5:c4" );
gap> Name( XSact );
"[d10a->c5:c4,d20->c5:c4]"

gap> C2act := Cat2GroupOfCrossedSquare( XSact );
cat2-group with generating (pre-)cat1-groups:
1 : [((c5:c4 |X c5:c4) |X (d20 |X d10a))=>(c5:c4 |X c5:c4)]
2 : [((c5:c4 |X c5:c4) |X (d20 |X d10a))=>(c5:c4 |X d20)]
gap> Size( C2act );
[ 80000, 400, 400, 20 ]
```

8.5 Definition and constructions for cat^n -groups and their morphisms

In this chapter we are interested in cat^2 -groups, but it is convenient in this section to give the more general definition. There are three equivalent description of a cat^n -group.

A cat^n -group consists of the following.

- 2^n groups G_A , one for each subset A of $[n]$, the *vertices* of an n -cube.

- Group homomorphisms forming $n2^{n-1}$ commuting cat^1 -groups,

$$\mathcal{C}_{A,i} = (e_{A,i}; t_{A,i}, h_{A,i} : G_A \rightarrow G_{A \setminus \{i\}}), \quad \text{for all } A \subseteq [n], i \in A,$$

the *edges* of the cube.

- These cat^1 -groups combine (in sets of 4) to form $n(n-1)2^{n-3}$ cat^2 -groups $\mathcal{C}_{A,\{i,j\}}$ for all $\{i,j\} \subseteq A \subseteq [n]$, $i \neq j$, the *faces* of the cube.

Note that, since the $t_{A,i}, h_{A,i}$ and $e_{A,i}$ commute, composite homomorphisms $t_{A,B}, h_{A,B} : G_A \rightarrow G_{A \setminus B}$ and $e_{A,B} : G_{A \setminus B} \rightarrow G_A$ are well defined for all $B \subseteq A \subseteq [n]$.

Secondly, we give the simplest of the three descriptions, again adapted from Ellis-Steiner [ES87].

A cat^n -group \mathcal{C} consists of 2^n groups G_A , one for each subset A of $[n]$, and $3n$ homomorphisms

$$t_{[n],i}, h_{[n],i} : G_{[n]} \rightarrow G_{[n] \setminus \{i\}}, \quad e_{[n],i} : G_{[n] \setminus \{i\}} \rightarrow G_{[n]},$$

satisfying the following axioms for all $1 \leq i \leq n$,

- the $\mathcal{C}_{[n],i} = (e_{[n],i}; t_{[n],i}, h_{[n],i} : G_{[n]} \rightarrow G_{[n] \setminus \{i\}})$ are *commuting* cat^1 -groups, so that:
- $(e_1 \circ t_1) \circ (e_2 \circ t_2) = (e_2 \circ t_2) \circ (e_1 \circ t_1)$, $(e_1 \circ h_1) \circ (e_2 \circ h_2) = (e_2 \circ h_2) \circ (e_1 \circ h_1)$,
- $(e_1 \circ t_1) \circ (e_2 \circ h_2) = (e_2 \circ h_2) \circ (e_1 \circ t_1)$, $(e_2 \circ t_2) \circ (e_1 \circ h_1) = (e_1 \circ h_1) \circ (e_2 \circ t_2)$.

Our third description defines a cat^n -group as a " cat^1 -group of $\text{cat}^{(n-1)}$ -groups".

A cat^n -group \mathcal{C} consists of two $\text{cat}^{(n-1)}$ -groups:

- \mathcal{A} with groups G_A , $A \subseteq [n-1]$, and homomorphisms $\check{i}_{A,i}, \check{h}_{A,i}, \check{e}_{A,i}$,
- \mathcal{B} with groups H_B , $B \subseteq [n-1]$, and homomorphisms $\check{i}_{B,i}, \check{h}_{B,i}, \check{e}_{B,i}$, and
- $\text{cat}^{(n-1)}$ -morphisms $t, h : \mathcal{A} \rightarrow \mathcal{B}$ and $e : \mathcal{B} \rightarrow \mathcal{A}$ subject to the following conditions:

$$(t \circ e) \text{ and } (h \circ e) \text{ are the identity mapping on } \mathcal{B}, \quad [\ker t, \ker h] = \{1_{\mathcal{A}}\}.$$

Chapter 9

Crossed modules of groupoids

The material documented in this chapter is experimental, and is likely to be changed very soon.

9.1 Constructions for crossed modules of groupoids

A typical example of a crossed module \mathcal{X} over a groupoid has for its range a connected groupoid. This is a direct product of a group with a complete graph, and we call the vertices of the graph the *objects* of the crossed module. The source of \mathcal{X} is a groupoid, with the same objects, which is either discrete or connected. The boundary morphism is constant on objects. For details and other references see [AW10].

9.1.1 SinglePiecePreXModWithObjects

▷ `SinglePiecePreXModWithObjects(pxmod, obs, isdisc)` (operation)

At present the experimental operation `SinglePiecePreXModWithObjects` accepts a precrossed module `pxmod`, a set of objects `obs`, and a boolean `isdisc` which is `true` when the source groupoid is homogeneous and discrete and `false` when the source groupoid is connected. Other operations will be added as time permits.

In the example the crossed module `DX4` has discrete source, while the crossed module `CX4` has connected source. These are groupoid equivalents of `XModByNormalSubgroup` (2.1.2).

Example

```
gap> s4 := Group( (1,2,3,4), (3,4) );;
gap> SetName( s4, "s4" );
gap> a4 := Subgroup( s4, [ (1,2,3), (2,3,4) ] );;
gap> SetName( a4, "a4" );
gap> X4 := XModByNormalSubgroup( s4, a4 );;
gap> DX4 := SinglePiecePreXModWithObjects( X4, [-9,-8,-7], true );
precrossed module with source groupoid:
homogeneous, discrete groupoid: < a4, [ -9, -8, -7 ] >
and range groupoid:
single piece groupoid: < s4, [ -9, -8, -7 ] >
gap> Da4 := Source( DX4 );;
gap> Ds4 := Range( DX4 );;
gap> CX4 := SinglePiecePreXModWithObjects( X4, [-9,-8,-7], false );;
```

```

precrossed module with source groupoid:
single piece groupoid: < a4, [ -9, -8, -7 ] >
and range groupoid:
single piece groupoid: < s4, [ -9, -8, -7 ] >
gap> Ca4 := Source( CX4 );;
gap> Cs4 := Range( CX4 );;

```

9.1.2 IsXModWithObjects

- ▷ IsXModWithObjects(*pxmod*) (property)
- ▷ IsPreXModWithObjects(*pxmod*) (property)
- ▷ IsDirectProductWithCompleteDigraphDomain(*pxmod*) (property)

The precrossed module DX4 belongs to the category Is2DimensionalGroupWithObjects and is, of course, a crossed module.

Example

```

gap> IsXModWithObjects( DX4 );
true
gap> KnownPropertiesOfObject( DX4 );
[ "CanEasilyCompareElements", "CanEasilySortElements", "IsDuplicateFree",
  "IsGeneratorsOfSemigroup", "IsSinglePieceDomain",
  "IsDirectProductWithCompleteDigraphDomain", "IsPreXModWithObjects",
  "IsXModWithObjects" ]

```

9.1.3 IsPermPreXModWithObjects

- ▷ IsPermPreXModWithObjects(*pxmod*) (property)
- ▷ IsPcPreXModWithObjects(*pxmod*) (property)
- ▷ IsFpPreXModWithObjects(*pxmod*) (property)

To test these properties we test the precrossed modules from which they were constructed.

Example

```

gap> IsPermPreXModWithObjects( CX4 );
true
gap> IsPcPreXModWithObjects( CX4 );
false
gap> IsFpPreXModWithObjects( CX4 );
false

```

9.1.4 Root2dGroup

- ▷ Root2dGroup(*pxmod*) (attribute)
- ▷ XModAction(*pxmod*) (attribute)

The attributes of a precrossed module with objects include the standard `Source`; `Range`; `Boundary` (2.1.9); and `XModAction` (2.1.9) as with precrossed modules of groups. There is also `ObjectList`, as in the `groupoids` package. Additionally there is `Root2dGroup` which is the underlying precrossed module used in the construction.

Note that `XModAction` is now a groupoid homomorphism from the source groupoid to a one-object groupoid (with object 0) where the group is the automorphism group of the range groupoid.

Example

```
gap> Set( KnownAttributesOfObject( CX4 ) );
[ "Boundary", "ObjectList", "Range", "Root2dGroup", "Source", "XModAction" ]
gap> Root2dGroup( CX4 );
[a4->s4]
gap> act := XModAction( CX4 );;
gap> r := Arrow( Cs4, (1,2,3,4), -7, -8 );;
gap> ImageElm( act, r );
[groupoid homomorphism :
[ [ [(1,2,3) : -9 -> -9], [(2,3,4) : -9 -> -9], [() : -9 -> -8],
  [() : -9 -> -7] ],
  [ [(2,3,4) : -9 -> -9], [(1,3,4) : -9 -> -9], [() : -9 -> -7],
  [() : -9 -> -8] ] ] : 0 -> 0]
gap> s := Arrow( Ca4, (1,2,4), -8, -8 );;
gap> ## calculate s^r
gap> ims := ImageElmXModAction( CX4, s, r );
[(1,2,3) : -7 -> -7]
```

There is much more to be done with these constructions.

Chapter 10

Applications

This chapter was added in April 2018 for version 2.66 of XMod. Initially it describes crossed modules for free loop spaces. Further applications may arise in due course.

10.1 Free Loop Spaces

These functions have been used to produce examples for Ronald Brown's paper *Crossed modules, and the homotopy 2-type of a free loop space* [Bro18]. The relevant theorem in that paper is as follows.

THEOREM 2.1 *Let $\mathcal{M} = (\partial : M \rightarrow P)$ be a crossed module of groups and let $X = B\mathcal{M}$ be the classifying space of \mathcal{M} . Then the components of LX , the free loop space on X , are determined by equivalence classes of elements $a \in P$ where a, a' are equivalent if and only if there are elements $m \in M, p \in P$ such that $a' = p + a - \partial m - p$.*

Further the homotopy 2-type of a component of LX given by $a \in P$ is determined by the crossed module of groups $L\mathcal{M}[a] = (\partial_a : M \rightarrow P(a))$ where:

- $P(a)$ is the subgroup of the cat^1 -group $G = P \rtimes M$ such that $\partial m = [p, a] = -p - a + p + a$;
- $\partial_a(m) = (\partial m, m^{-1}m^a)$ for $m \in M$;
- the action of $P(a)$ on M is given by $n^{(p,m)} = n^p$ for $n \in M, (p, m) \in P(a)$.

*In particular $\pi_1(LX, a)$ is isomorphic to $\text{cokernel}(\partial_a)$, and $\pi_2(LX, a) \cong \pi_2(X, *)^{\bar{a}}$, the elements of $\pi_2(X, *)$ fixed under the action of \bar{a} , the class of a in $\pi_1(X, *)$.*

*There is an exact sequence $\pi \xrightarrow{\phi} \pi \rightarrow \pi_1(LX, a) \rightarrow C_{\bar{a}}(\pi_1(X, *)) \rightarrow 1$, in which $\pi = \pi_2(X, *)$, and ϕ is the morphism $m \mapsto m^{-1}m^a$.*

10.1.1 LoopsXMod

- ▷ `LoopsXMod(M, a)` (operation)
- ▷ `AllLoopsXMod(M)` (operation)

The operation `LoopsXMod(M, a)` calculates the crossed module $L\mathcal{M}[a]$ described in the theorem.

The operation `AllLoopsXMod(M)` returns a list of crossed modules, one for each equivalence class of elements $p \in P$. THESE OPERATIONS SHOULD BE CONSIDERED EXPERIMENTAL AT PRESENT.

In the example below the automorphism crossed module $X8$ has $M \cong C_2^3$ and $P = PSL(3,2)$ is the automorphism group of M . There are 6 equivalence classes and, for each LX calculated, the `Size` (2.1.11) and `StructureDescription` (2.7.1) are printed out.

Example

```

gap> k8 := Group( (3,4), (5,6), (7,8) );;
gap> SetName( k8, "k8" );
gap> Y8 := XModByAutomorphismGroup( k8 );;
gap> X8 := Image( IsomorphismPerm2DimensionalGroup( Y8 ) );;
gap> SetName( X8, "X8" );
gap> Print( "X8: ", Size( X8 ), " : ", StructureDescription( X8 ), "\n" );
X8: [ 8, 168 ] : [ "C2 x C2 x C2", "PSL(3,2)" ]
gap> LX := LoopsXMod( X8, (1,2)(5,6) );;
gap> Size( LX ); StructureDescription( LX );
[ 8, 64 ]
[ "C2 x C2 x C2", "((C2 x C2 x C2 x C2) : C2) : C2" ]
gap> SetInfoLevel( InfoXMod, 1 );
gap> LX8 := AllLoopsXMod( X8 );;
#I LoopsXMod with a = (), [ 8, 1344 ]
#I LoopsXMod with a = (4,5)(6,7), [ 8, 64 ]
#I LoopsXMod with a = (2,3)(4,6,5,7), [ 8, 32 ]
#I LoopsXMod with a = (2,4,6)(3,5,7), [ 8, 24 ]
#I LoopsXMod with a = (1,2,4,3,6,7,5), [ 8, 56 ]
#I LoopsXMod with a = (1,2,4,5,7,3,6), [ 8, 56 ]
gap> iso := IsomorphismGroups( Range( LX ), Range( LX8[2] ) );
[ (1,2)(3,4)(5,6)(7,8), (1,3)(2,4)(5,7)(6,8), (1,5)(2,6)(3,7)(4,8),
  (5,8)(6,7), (2,3)(6,7), (2,7)(3,6) ] ->
[ (1,5)(2,6)(3,7)(4,8), (1,6)(2,5)(3,8)(4,7), (1,4)(2,3)(5,8)(6,7),
  (1,2)(5,6), (1,2)(3,4), (1,3)(2,4) ]

```

Chapter 11

Utility functions

By a utility function we mean a GAP function which is

- needed by other functions in this package,
- not (as far as we know) provided by the standard GAP library,
- more suitable for inclusion in the main library than in this package.

Sections on *Printing Lists* and *Distinct and Common Representatives* were moved to the Utils package with version 2.56.

11.1 Inclusion and Restriction Mappings

These functions have been moved to the `gpd` package, but are still documented here.

11.1.1 InclusionMappingGroups

- ▷ `InclusionMappingGroups(G, H)` (operation)
- ▷ `MappingToOne(G, H)` (operation)

This set of utilities concerns mappings. The map `incd8` is the inclusion of `d8` in `d16` used in Section 3.4. `MappingToOne(G, H)` maps the whole of G to the identity element in H .

Example

```
gap> Print( incd8, "\n" );
[ (11,13,15,17)(12,14,16,18), (11,18)(12,17)(13,16)(14,15) ] ->
[ (11,13,15,17)(12,14,16,18), (11,18)(12,17)(13,16)(14,15) ]
gap> imd8 := Image( incd8 );
gap> MappingToOne( c4, imd8 );
[ (11,13,15,17)(12,14,16,18) ] -> [ ( ) ]
```

11.1.2 InnerAutomorphismsByNormalSubgroup

- ▷ InnerAutomorphismsByNormalSubgroup(G, N) (operation)
- ▷ IsGroupOfAutomorphisms(A) (property)

Inner automorphisms of a group G by the elements of a normal subgroup N are calculated with the first of these functions, usually with $G = N$.

Example

```
gap> autd8 := AutomorphismGroup( d8 );;
gap> innd8 := InnerAutomorphismsByNormalSubgroup( d8, d8 );;
gap> GeneratorsOfGroup( innd8 );
[ ^(1,2,3,4), ^(1,3) ]
gap> IsGroupOfAutomorphisms( innd8 );
true
```

11.2 Abelian Modules

11.2.1 AbelianModuleObject

- ▷ AbelianModuleObject(grp, act) (operation)
- ▷ IsAbelianModule(obj) (property)
- ▷ AbelianModuleGroup(obj) (attribute)
- ▷ AbelianModuleAction(obj) (attribute)

An abelian module is an abelian group together with a group action. These are used by the crossed module constructor `XModByAbelianModule` (2.1.7).

The resulting `Xabmod` is isomorphic to the output from `XModByAutomorphismGroup(k4)`.

Example

```
gap> x := (6,7)(8,9);; y := (6,8)(7,9);; z := (6,9)(7,8);;
gap> k4a := Group( x, y );; SetName( k4a, "k4a" );
gap> gens3a := [ (1,2), (2,3) ];;
gap> s3a := Group( gens3a );; SetName( s3a, "s3a" );
gap> alpha := GroupHomomorphismByImages( k4a, k4a, [x,y], [y,x] );;
gap> beta := GroupHomomorphismByImages( k4a, k4a, [x,y], [x,z] );;
gap> auta := Group( alpha, beta );;
gap> acta := GroupHomomorphismByImages( s3a, auta, gens3a, [alpha,beta] );;
gap> abmod := AbelianModuleObject( k4a, acta );;
gap> Xabmod := XModByAbelianModule( abmod );
[k4a->s3a]
gap> Display( Xabmod );
```

```
Crossed module [k4a->s3a] :-
: Source group k4a has generators:
  [ (6,7)(8,9), (6,8)(7,9) ]
: Range group s3a has generators:
  [ (1,2), (2,3) ]
: Boundary homomorphism maps source generators to:
```

```
[ (), () ]
: Action homomorphism maps range generators to automorphisms:
(1,2) --> { source gens --> [ (6,8)(7,9), (6,7)(8,9) ] }
(2,3) --> { source gens --> [ (6,7)(8,9), (6,9)(7,8) ] }
These 2 automorphisms generate the group of automorphisms.
```

Chapter 12

Development history

This chapter, which contains details of the major changes to the package as it develops, was first created in April 2002. Details of the changes from XMod 1 to XMod 2.001 are far from complete. Starting with version 2.009 the file `CHANGES` lists the minor changes as well as the more fundamental ones.

The inspiration for this package was the need, in the mid-1990's, to calculate induced crossed modules (see [BW95], [BW96], [BW03]). GAP was chosen over other computational group theory systems because the code was freely available, and it was possible to modify the Tietze transformation code so as to record the images of the original generators of a presentation as words in the simplified presentation. (These modifications are now a standard part of the Tietze transformation package in GAP.)

12.1 Changes from version to version

12.1.1 Version 1 for GAP 3

The first version of XMod became an accepted package for GAP 3.4.3 in December 1996.

12.1.2 Version 2

Conversion of XMod 1 from GAP 3.4.3 to the new GAP syntax began soon after GAP 4 was released, and had a lengthy gestation. The new GAP syntax encouraged a re-naming of many of the function names. An early decision was to introduce generic categories `2dDomain` for (pre-)crossed modules and (pre-)cat1-groups, and `2dMapping` for the various types of morphism. In 2.009 `3dDomain` was used for crossed squares and cat2-groups, and `3dMapping` for their morphisms. A generic name for derivations and sections is also required, and `Up2dMapping` is currently used.

12.1.3 Version 2.001 for GAP 4

This was the first version of XMod for GAP 4, completed in April 2002 in time for the release of GAP 4.3. Functions for actors and induced crossed modules were not included, nor many of the functions for derivations and sections, for example `InnerDerivation`.

12.1.4 Induced crossed modules

During May 2002 converted the code for induced crossed modules. (Induced cat1-groups may be converted one day.)

12.1.5 Versions 2.002 – 2.006

Version 2.004 of April 14th 2004 added the `Cat1Select` (2.6.1) functionality of version 1 to the `Cat1Group` (2.4.1) function.

A significant addition in Version 2.005 was the conversion of the actor crossed module functions from the 3.4.4 version. This included `AutomorphismPermGroup` (6.1.1) for a crossed module; `WhiteheadXMod` (6.1.2); `NorrieXMod` (6.1.2); `LueXMod` (6.1.2); `ActorXMod` (6.1.2); `CentreXMod` (4.1.7) of a crossed module; `InnerMorphism` (6.1.3); and `InnerActorXMod` (6.1.3).

12.1.6 Versions 2.007 – 2.010

These versions contain changes made between September 2004 and October 2007.

- Added basic functions for crossed squares, considered as `3dObjects` with crossed pairings, and their morphisms. Groups with two normal subgroups, and the actor of a crossed module, provide standard examples of crossed squares. (Cat2-groups are not yet implemented.)
- Converted the documentation to the format of the `GAPDoc` package.
- Improved `AutomorphismPermGroup` (6.1.1) for crossed modules, and introduced a special method for conjugation crossed modules.
- Substantial revisions made to `XModByCentralExtension` (2.1.5); `NorrieXMod` (6.1.2); `LueXMod` (6.1.2); `ActorXMod` (6.1.2); and `InclusionInducedXModByCoproduct` (??).
- Version 2.010, of October 2007, was timed to coincide with the release of GAP 4.4.10, and included a change of filenames; and correct file protection codes.

12.2 Versions for GAP [4.5 .. 4.8]

Version 2.19, released on 9th June 2012, included the following changes:

- The file `makedocre1.g` was copied, with appropriate changes, from `GAPDoc`, and now provides the correct way to update the documentation.
- The first functions for crossed modules of groupoids were introduced.
- A GNU General Public License declaration was added.

12.2.1 AllCat1s

Version 2.21 contained major changes to the `Cat1Select` (2.6.1) operation: the list `CAT1_LIST` of cat1-structures in the data file `cat1data.g` was changed from permutation groups to pc-groups, with the generators of subgroups; images of the tail map; and images of the head map being given as `ExtRepOfObj` of words in the generators.

The `AllCat1s` function was reintroduced from the GAP3 version, and renamed as the operation `AllCat1DataGroupsBasic` (2.6.2).

In version 2.25 the data in `cat1data.g` was extended from groups of size up to 48 to groups of size up to 70. In particular, the 267 groups of size 64 give rise to a total of 1275 `cat1`-groups. The authors are indebted to Van Luyen Le in Galway for pointing out a number of errors in the version of this list distributed with version 2.24 of this package.

12.2.2 Versions 2.43 - 2.56

Version 2.43, released on 11th November 2015, included the following changes:

- The material on isoclinism in Chapter 4 was added.
- The package webpage has moved to <http://pages.bangor.ac.uk/~mas023/chda/>.
- A GitHub repository was started at: <https://github.com/gap-packages/xmod>.
- The section on *Distinct and Common Representatives* was moved to the `Utils` package.

12.2.3 Version 2.61

Major changes in names took place, with `2dDomain`, `2dGroup`, `2dMapping`, etc. becoming `2DimensionalDomain`, `2DimensionalGroup`, `2DimensionalMapping`, etc., and similarly for 3-dimensional versions. Also `HigherDimensionalDomain` and related categories, domains, properties, attributes and operations were introduced. At the same time, functions for `cat2`-groups were introduced by Alper Odabas.

12.2.4 Latest Version

The latest version contains additional material on crossed modules of groupoids.

12.3 What needs doing next?

- Speed up the calculation of Whitehead groups.
- Add more functions for `3dObjects` and implement `cat2`-groups.
- Improve interaction with the package `groupoids` implementing the group groupoid version of a crossed module, and adding more functions for crossed modules of groupoids.
- Add interaction with `IdRel` (and possibly `XRes` and `natp`).
- Need `InverseGeneralMapping` for morphisms and more features for `FpXMods`, `PcXMods`, etc.
- Implement actions of a crossed module.
- Implement `FreeXMods` and an operation `Isomorphism2dDomains`.
- Allow the construction of a group of morphisms of crossed modules.
- Complete the conversion from Version 1 of the calculation of sections using `EndoClasses`.

- More crossed square constructions:

- If M, N are ordinary P -modules and A is an arbitrary abelian group on which P acts trivially, then there is a crossed square with sides

$$0 : A \rightarrow N, \quad 0 : A \rightarrow M, \quad 0 : M \rightarrow P, \quad 0 : N \rightarrow P.$$

- For a group L , the automorphism crossed module $\text{Act } L = (\iota : L \rightarrow \text{Aut } L)$ splits to form the square with $(\iota_1 : L \rightarrow \text{Inn } L)$ on two sides, and $(\iota_2 : \text{Inn } L \rightarrow \text{Aut } L)$ on the other two sides, where ι_1 maps $l \in L$ to the inner automorphism $\beta_l : L \rightarrow L, l' \mapsto l^{-1}l'l$, and ι_2 is the inclusion of $\text{Inn } L$ in $\text{Aut } L$. The actions are standard, and the crossed pairing is

$$\boxtimes : \text{Inn } L \times \text{Inn } L \rightarrow L, \quad (\beta_l, \beta_{l'}) \mapsto [l, l'].$$

- Improve the interaction with the HAP package.

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