

# idrel

## Identities among relations

2.43

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## Abstract

IdRel is a GAP package originally implemented in 1999, using the GAP 3 language, when the first author was studying for a Ph.D. in Bangor.

This package is designed to compute a minimal set of generators for the module of the identities among relators of a group presentation. It does this using

- rewriting and logged rewriting: a self-contained implementation of the Knuth-Bendix process using the monoid presentation associated to the group presentation;
- monoid polynomials: an implementation of the monoid ring;
- module polynomials: an implementation of the right module over this monoid generated by the relators.
- Y-sequences: used as a *rewriting* way of representing elements of a free crossed module (products of conjugates of group relators and inverse relators).

IdRel became an accepted GAP package in May 2015.

Bug reports, suggestions and comments are, of course, welcome. Please contact the last author at [c.d.wensley@bangor.ac.uk](mailto:c.d.wensley@bangor.ac.uk) or submit an issue at the GitHub repository <https://github.com/gap-packages/idrel/issues/>.

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## Acknowledgements

This documentation was prepared using the GAPDoc [LN17] and AutoDoc [GH17] packages.

The procedure used to produce new releases uses the package GitHubPagesForGAP [Hor14] and the package ReleaseTools.

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# Chapter 1

## Introduction

This manual describes the `ldRel` package for GAP 4.7 for computing the identities among relators of a group presentation using rewriting, logged rewriting, monoid polynomials, module polynomials and  $Y$ -sequences.

The theoretical background for these computations is contained in Brown and Huebschmann [BH82], Brown and Razak Salleh [BRS99] and is surveyed in the first author's thesis [Hey99].

`ldRel` is primarily designed for the computation of a minimal set of generators for the module of identities among relators. It also contains functions which compute logged rewrite systems for group presentations (and complete them where possible); functions for operations involving elements of monoid rings; and functions for operations with elements of right modules over monoid rings. The  $Y$ -sequences are used as a *rewriting* way of representing elements of a free crossed module (products of conjugates of group relators and inverse relators). The package is written entirely in GAP4, and requires no compilation.

The package is loaded into GAP with the `LoadPackage` command, and on-line help is available in the usual way.

Example

```
gap> LoadPackage( "ldrel" );
gap> ?ldrel
```

A pdf version of the `ldRel` manual is available in the `doc` directory of the home directory of `ldRel`. The information parameter `InfoIdRel` has default value 0. When raised to a higher value, additional information is printed out. `ldRel` was originally developed in 1999 using GAP3, partially supported by a University of Wales Research Assistantship for the first author, Anne Heyworth.

If you use `ldRel` to solve a problem then please send a short email to the second author, to whom bug reports, suggestions and other comments should also be sent. You may reference the package by mentioning [HW03] and [Hey99].

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

- the `ldRel` GitHub site: <https://github.com/gap-packages.github.io/ldrel/>.
- 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/ldrel/>.

## 1.1 An illustrative example

A typical input for `ldRel` is an fp-group presentation. This requires a free group  $F$  on a set of generators and a set of relators  $R$  (words in the free group). The module of identities among relators for this presentation has as its elements the Peiffer equivalence classes of all products of conjugates of relators which represent the identity in the free group.

In this package the identities among relators are represented by Y-sequences, which are lists  $[[r_1, u_1], \dots, [r_k, u_k]]$  where  $r_1, \dots, r_k$  are the group relators or their inverses, and  $u_1, \dots, u_k$  are words in the free group  $F$ . A Y-sequence is evaluated in  $F$  as the product  $(u_1^{-1} r_1 u_1) \dots (u_k^{-1} r_k u_k)$  and is an identity Y-sequence if it evaluates to the identity in  $F$ . An identity Y-sequence represents an identity among the relators of the group presentation. The main function of the package is to produce a set of Y-sequences which generate the module of identities among relators, and further, that this set be minimal in the sense that every element in it is needed to generate the module.

Before starting on the main example, we consider a simpler example illustrating the use of `ldRel`. All the functions used are described in detail in this manual. We compute a reduced set of identities among relators for the presentation of the symmetric group  $s_3$  with generators  $a, b$  and relators  $[a^3, b^2, (ab)^2]$ . In the listings below, `s3_Ri` is the  $i$ -th relator for  $s_3$ , and `f1, f2` are the generators  $a, b$ .

Example

```
gap> F := FreeGroup( 2 );;
gap> a := F.1;; b:= F.2;;
gap> rels3 := [ a^3 , b^2, a*b*a*b ];
[ f1^3, f2^2, (f1*f2)^2 ]
gap> s3 := F/rels3;
<fp group on the generators [ f1, f2 ]>
gap> SetName( s3, "s3" );
gap> idrels3 := IdentitiesAmongRelators( s3 );;
gap> Display( idrels3 );
[ [ [ s3_R1^-1, <identity ...> ], [ s3_R1, f1^-1 ] ],
  [ [ s3_R2^-1, <identity ...> ], [ s3_R2, f2 ] ],
  [ [ s3_R3^-1, <identity ...> ], [ s3_R3, f1*f2 ] ],
  [ [ s3_R3^-1, <identity ...> ], [ s3_R1, f1 ], [ s3_R3^-1, f1^2 ],
    [ s3_R2, f1^-1*f2^-1*f1 ], [ s3_R1, f2^-1*f1 ],
    [ s3_R3^-1, f1*f2^-1*f1 ], [ s3_R2, f1 ], [ s3_R2, <identity ...> ] ] ]
```

If we write  $\rho = a^3$ ,  $\sigma = b^2$ ,  $\tau = (ab)^2$  then the first identity becomes  $\rho^{-1} \rho^{a^{-1}}$ . Similarly, the second and third identities are the root identities  $\sigma^{-1} \sigma^b$  and  $\tau^{-1} \tau^{ab}$ . The fourth identity, which is not a root identity, is obtained by walking around the Schreier diagram of the presentation, a somewhat truncated triangular prism. Taking the appropriate conjugate of each face in turn, we get:

$$\tau^{-1} \rho^a (\tau^{-1})^{a^2} \sigma^{a^{-1}b^{-1}a} \rho^{b^{-1}a} (\tau^{-1})^{ab^{-1}a} \sigma^a \sigma.$$

In order to form the *module of identities* for  $s_3$  the identities are transformed into module polynomials. The first is  $y_1 = \rho(-1 + a^{-1})$  or  $-y_1 a = \rho(a - 1)$ . The second and third are  $y_2 = \sigma(b - 1)$  and  $y_3 = \tau(ab - 1)$ , while the fourth is  $\rho(a + ba) + \sigma(1 + a + ab) - \tau(1 + a^{-1} + b)$ . Note that, in the fourth polynomial, the conjugators are converted to their normal forms in  $s_3$ , namely  $a^2 = a^{-1}$ ,  $a^{-1}b^{-1}a = ab$ ,  $b^{-1}a = ba$  and  $ab^{-1}a = b$ . Generators for this module are returned by the operation `IdentityYSequences`.

## Example

```
gap> idyseq3 := IdentityYSequences( s3 );
[ ( s3_Y1*( -s3_M1), s3_R1*( s3_M1 - <identity ...> ) ),
  ( s3_Y2*( <identity ...>), s3_R2*( s3_M2 - <identity ...> ) ),
  ( s3_Y3*( s3_M1), s3_R3*( s3_M2 - s3_M1 ) ),
  ( s3_Y9*( -<identity ...>), s3_R1*( -s3_M2*s3_M1 - s3_M1) + s3_R2*( -s3_M1*s\
3_M2 - s3_M1 - <identity ...>) + s3_R3*( s3_M3 + s3_M2 + <identity ...> ) ]
```

Further examples are given in chapter 6.

## Chapter 2

# Rewriting Systems

This chapter describes functions to construct rewriting systems for finitely presented groups which store rewriting information. The main example used is a presentation of the quaternion group  $q8$  with generators  $a, b$  and relators  $[a^4, b^4, abab^{-1}, a^2b^2]$ .

### 2.1 Monoid Presentations of FpGroups

#### 2.1.1 FreeRelatorGroup

- ▷ `FreeRelatorGroup(grp)` (attribute)
- ▷ `FreeRelatorHomomorphism(grp)` (attribute)

The function `FreeRelatorGroup` returns a free group on the set of relators of the given fp-group  $G$ . If `HasName(G)` is true then a name is automatically assigned to the free group.

The function `FreeRelatorHomomorphism` returns the group homomorphism from the free group on the relators to the free group on the generators of  $G$ , mapping each generator to the corresponding word.

Example

```
gap> F := FreeGroup( 2 );;
gap> a := F.1;; b:= F.2;;
gap> rels := [ a^4, b^4, a*b*a*b^-1, a^2*b^2 ];;
gap> q8 := F/rels;;
gap> SetName( q8, "q8" );
gap> frq8 := FreeRelatorGroup( q8 );
q8_R
gap> GeneratorsOfGroup( frq8 );
[ q8_R1, q8_R2, q8_R3, q8_R4 ]
gap> frhomq8 := FreeRelatorHomomorphism( q8 );
[ q8_R1, q8_R2, q8_R3, q8_R4 ] -> [ f1^4, f2^4, f1*f2*f1*f2^-1, f1^2*f2^2 ]
```

#### 2.1.2 MonoidPresentationFpGroup

- ▷ `MonoidPresentationFpGroup(grp)` (attribute)
- ▷ `ArrangementOfMonoidGenerators(grp)` (attribute)

- ▷ `FreeGroupOfPresentation(mon)` (attribute)
- ▷ `GroupRelatorsOfPresentation(mon)` (attribute)
- ▷ `InverseRelatorsOfPresentation(mon)` (attribute)
- ▷ `HomomorphismOfPresentation(mon)` (attribute)

A monoid presentation for a finitely presented group  $G$  has two monoid generators  $g^+, g^-$  for each group generator  $g$ . The relators of the monoid presentation comprise the group relators, and relators  $g^+g^-$  specifying the inverses. The function `MonoidPresentationFpGroup` returns the monoid presentation derived in this way from an fp-presentation.

The function `FreeGroupOfPresentation` returns the free group on the monoid generators.

The function `GroupRelatorsOfPresentation` returns those relators of the monoid which correspond to the relators of the group. All negative powers in the group relators are converted to positive powers of the  $g^-$ . The function `InverseRelatorsOfPresentation` returns relators which specify the inverse pairs of the monoid generators.

The function `HomomorphismOfPresentation` returns the homomorphism from the free group of the monoid presentation to the free group of the group presentation.

The attribute `ArrangementOfMonoidGenerators` will be discussed before the second example in the next section.

In the example below, the four monoid generators  $a^+, b^+, a^-, b^-$  are named `q8_M1`, `q8_M2`, `q8_M3`, `q8_M4` respectively.

Example

```
gap> mon := MonoidPresentationFpGroup( q8 );
monoid presentation with group relators
[ q8_M1^4, q8_M2^4, q8_M1*q8_M2*q8_M1*q8_M4, q8_M1^2*q8_M2^2 ]
gap> fgmon := FreeGroupOfPresentation( mon );
<free group on the generators [ q8_M1, q8_M2, q8_M3, q8_M4 ]>
gap> genfgmon := GeneratorsOfGroup( fgmon );
gap> gprels := GroupRelatorsOfPresentation( mon );
[ q8_M1^4, q8_M2^4, q8_M1*q8_M2*q8_M1*q8_M4, q8_M1^2*q8_M2^2 ]
gap> invrels := InverseRelatorsOfPresentation( mon );
[ q8_M1*q8_M3, q8_M2*q8_M4, q8_M3*q8_M1, q8_M4*q8_M2 ]
gap> hompres := HomomorphismOfPresentation( mon );
[ q8_M1, q8_M2, q8_M3, q8_M4 ] -> [ f1, f2, f1^-1, f2^-1 ]
```

## 2.2 Rewriting systems for FpGroups

These functions duplicate the standard Knuth Bendix functions which are available in the GAP library. There are two reasons for this: (1) these functions were first written before the standard functions were available; (2) we require logged versions of the functions, and these are most conveniently extended versions of the non-logged code.

### 2.2.1 RewritingSystemFpGroup

- ▷ `RewritingSystemFpGroup(grp)` (attribute)



This function attempts to return a complete rewrite system for the group  $G$  obtained from the monoid presentation  $\text{mon}$ , with a length-lexicographical ordering on the words in  $\text{fgmon}$ , by applying Knuth-Bendix completion. Such a rewrite system can be obtained for all finite groups. The rewrite rules are (partially) ordered, starting with the inverse relators, followed by the rules which reduce the word length the most.

In our  $q8$  example there are 16 rewrite rules in the rewriting system  $\text{rws}$ :

$$\begin{array}{l} a^+a^- \rightarrow \text{id}, \quad b^+b^- \rightarrow \text{id}, \quad a^-a^+ \rightarrow \text{id}, \quad b^-b^+ \rightarrow \text{id}, \\ a^{+2}b^- \rightarrow b^+, \quad a^{+2}b^+ \rightarrow b^-, \quad a^{+3} \rightarrow a^-, \quad b^{-2} \rightarrow a^{+2}, \quad b^-a^- \rightarrow a^+b^-, \quad b^-a^+ \rightarrow a^+b^+, \\ a^-b^- \rightarrow a^+b^+, \quad a^{-2} \rightarrow a^{+2}, \quad a^-b^+ \rightarrow a^+b^-, \quad b^+a^- \rightarrow a^+b^+, \quad b^{+2} \rightarrow a^{+2}, \quad b^+a^+ \rightarrow a^+b^-. \end{array}$$

Example

```
gap> rws := RewritingSystemFpGroup( q8 );
[ [q8_M1*q8_M3, <identity ...>], [ q8_M2*q8_M4, <identity ...> ],
  [q8_M3*q8_M1, <identity ...>], [ q8_M4*q8_M2, <identity ...> ],
  [q8_M1^2*q8_M4, q8_M2], [q8_M1^2*q8_M2, q8_M4], [ q8_M1^3, q8_M3 ],
  [ q8_M4^2, q8_M1^2], [ q8_M4*q8_M3, q8_M1*q8_M4],
  [ q8_M4*q8_M1, q8_M1*q8_M2], [q8_M3*q8_M4, q8_M1*q8_M2],
  [ q8_M3^2, q8_M1^2], [q8_M3*q8_M2, q8_M1*q8_M4],
  [ q8_M2*q8_M3, q8_M1*q8_M2], [q8_M2^2, q8_M1^2],
  [ q8_M2*q8_M1, q8_M1*q8_M4] ]
```

The default ordering of the  $2n$  monoid generators is  $[g_1^+, g_2^+, \dots, g_n^+, g_1^-, g_2^-, \dots, g_n^-]$ . In the case of the two-generator abelian group  $T = \langle a, b \mid [a, b] \rangle$  the Knuth-Bendix process starts to generate infinite sets of relations such as  $\{ab^m a^{-1} \rightarrow b^m, m \geq 1\}$ . If, using the `ArrangementOfMonoidGenerators` function, we specify the alternative ordering  $[g_1^+, g_1^-, g_2^+, g_2^-]$ , then a finite set of rules is obtained.

Example

```
gap> F := FreeGroup(2);
gap> T := F/[Comm(a,b)];
<fp group of size infinity on the generators [ f1, f2 ]>
gap> SetName( T, "T" );
gap> SetArrangementOfMonoidGenerators( T, [1,-1,2,-2] );
gap> monT := MonoidPresentationFpGroup(T);
monoid presentation with group relators [ T_M2*T_M4*T_M1*T_M3 ]
gap> rwsT := RewritingSystemFpGroup( T );
[ [ T_M1*T_M2, <identity ...> ], [ T_M2*T_M1, <identity ...> ],
  [ T_M3*T_M4, <identity ...> ], [ T_M4*T_M3, <identity ...> ],
  [ T_M4*T_M2, T_M2*T_M4 ], [ T_M4*T_M1, T_M1*T_M4 ],
  [ T_M3*T_M2, T_M2*T_M3 ], [ T_M3*T_M1, T_M1*T_M3 ] ]
```

The eight rules can be written as follows, showing that the  $a^\pm$  and  $b^\pm$  commute:

$$\begin{array}{l} a^+a^- \rightarrow \text{id}, \quad a^-a^+ \rightarrow \text{id}, \quad b^+b^- \rightarrow \text{id}, \quad b^-b^+ \rightarrow \text{id}, \\ b^-a^- \rightarrow a^-b^-, \quad b^-a^+ \rightarrow a^+b^-, \quad b^+a^- \rightarrow a^-b^+, \quad b^+a^+ \rightarrow a^+b^+. \end{array}$$

The functions called by `RewritingSystemFpGroup` are as follows.

## 2.2.2 OnePassReduceWord

- ▷ `OnePassReduceWord(word, rules)` (operation)
- ▷ `ReduceWordKB(word, rules)` (operation)

Assuming that `word` is an element of a free monoid and `rules` is a list of ordered pairs of such words, the function `OnePassReduceWord` searches the list of rules until it finds that the left-hand side of a rule is a subword of `word`, whereupon it replaces that subword with the right-hand side of the matching rule. The search is continued from the next rule in `rules`, but using the new word. When the end of `rules` is reached, one pass is considered to have been made and the reduced word is returned. If no matches are found then the original word is returned.

The function `ReduceWordKB` repeatedly applies the function `OnePassReduceWord` until the word remaining contains no left-hand side of a rule as a subword. If `rules` is a complete rewrite system, then the irreducible word that is returned is unique, otherwise the order of the rules in `rules` will determine which irreducible word is returned. In the example we see that  $b^9a^9$  reduces to  $ba$  which is not a normal form as we have seen in 2.2.1, where  $b^+a^+ \rightarrow a^+b^-$  is the last rule.

Example

```
gap> monrels := Concatenation( gprels, invrels );
[ q8_M1^4, q8_M2^4, q8_M1*q8_M2*q8_M1*q8_M4, q8_M1^2*q8_M2^2, q8_M1*q8_M3,
  q8_M2*q8_M4, q8_M3*q8_M1, q8_M4*q8_M2 ]
gap> id := One( monrels[1] );;
gap> r0 := List( monrels, r -> [ r, id ] );
[ [ q8_M1^4, <identity ...> ], [ q8_M2^4, <identity ...> ],
  [ q8_M1*q8_M2*q8_M1*q8_M4, <identity ...> ],
  [ q8_M1^2*q8_M2^2, <identity ...> ], [ q8_M1*q8_M3, <identity ...> ],
  [ q8_M2*q8_M4, <identity ...> ], [ q8_M3*q8_M1, <identity ...> ],
  [ q8_M4*q8_M2, <identity ...> ] ]
gap> ap := genfgmon[1];;
gap> bp := genfgmon[2];;
gap> am := genfgmon[3];;
gap> bm := genfgmon[4];;
gap> w0 := bp^9 * ap^9;
q8_M2^9*q8_M1^9
gap> w1 := OnePassReduceWord( w0, r0 );
q8_M2^5*q8_M1^5
gap> w2 := ReduceWordKB( w0, r0 );
q8_M2*q8_M1
```

## 2.2.3 OnePassKB

- ▷ `OnePassKB(rules)` (operation)
- ▷ `RewriteReduce(rules)` (operation)
- ▷ `KnuthBendix(rules)` (operation)
- ▷ `ShorterRule(rule1, rule2)` (operation)

The function `OnePassKB` implements the main loop of the Knuth-Bendix completion algorithm. Rules are compared with each other; all critical pairs are calculated; and the irreducible critical pairs are orientated with respect to the length-lexicographical ordering and added to the rewrite system.

The function `RewriteReduce` will remove unnecessary rules from a rewrite system. A rule is deemed to be unnecessary if it is implied by the other rules, i.e. if both sides can be reduced to the same thing by the remaining rules.

The function `KnuthBendix` implements the Knuth-Bendix algorithm, attempting to complete a rewrite system with respect to a length-lexicographic ordering. It calls first `OnePassKB`, which adds rules, and then (for efficiency) `RewriteReduce` which removes any unnecessary ones. This procedure is repeated until `OnePassKB` adds no more rules. It will not always terminate, but for many examples (all finite groups) it will be successful. The rewrite system returned is complete, that is: it will rewrite any given word in the free monoid to a unique irreducible; there is one irreducible for each element of the quotient monoid; and any two elements of the free monoid which are in the same class will rewrite to the same irreducible.

The function `ShorterRule` gives an ordering on rules. Rules  $(g_1g_2, id)$  that identify two generators (or one generator with the inverse of another) come first in the ordering. Otherwise one precedes another if it reduces the length of a word by a greater amount.

One pass of this procedure for our  $q_8$  example adds 13 relators to the original 8, and these 21 are then reduced to 9. A second pass and reduction gives the list of 16 rules seen above, forming a complete rewrite system for the group. Now  $b^9a^9$  correctly reduces to  $ab^{-1}$ .

Example

```
gap> r1 := OnePassKB( r0 );
[ [ q8_M1^4, <identity ...> ], [ q8_M2^4, <identity ...> ],
  [ q8_M1*q8_M2*q8_M1*q8_M4, <identity ...> ],
  [ q8_M1^2*q8_M2^2, <identity ...> ], [ q8_M1*q8_M3, <identity ...> ],
  [ q8_M2*q8_M4, <identity ...> ], [ q8_M3*q8_M1, <identity ...> ],
  [ q8_M4*q8_M2, <identity ...> ], [ q8_M2*q8_M1*q8_M4, q8_M1^3 ],
  [ q8_M1*q8_M2^2, q8_M1^3 ], [ q8_M2^2, q8_M1^2 ], [ q8_M1^3, q8_M3 ],
  [ q8_M2^3, q8_M4 ], [ q8_M1*q8_M2*q8_M1, q8_M2 ],
  [ q8_M2^3, q8_M1^2*q8_M2 ], [ q8_M2^2, q8_M1^2 ], [ q8_M1^2*q8_M2, q8_M4 ],
  [ q8_M1^3, q8_M3 ], [ q8_M2*q8_M1*q8_M4, q8_M3 ], [ q8_M1*q8_M2^2, q8_M3 ],
  [ q8_M2^3, q8_M4 ] ]
gap> Length( r1 );
21
gap> r1 := RewriteReduce( r1 );
[ [ q8_M1*q8_M3, <identity ...> ], [ q8_M2^2, q8_M1^2 ],
  [ q8_M2*q8_M4, <identity ...> ], [ q8_M3*q8_M1, <identity ...> ],
  [ q8_M4*q8_M2, <identity ...> ], [ q8_M1^3, q8_M3 ],
  [ q8_M1^2*q8_M2, q8_M4 ], [ q8_M1*q8_M2*q8_M1, q8_M2 ],
  [ q8_M2*q8_M1*q8_M4, q8_M3 ] ]
gap> Length( r1 );
9
gap> r2 := KnuthBendix( r1 );
[ [ q8_M1*q8_M3, <identity ...> ], [ q8_M2*q8_M1, q8_M1*q8_M4 ],
  [ q8_M2^2, q8_M1^2 ], [ q8_M2*q8_M3, q8_M1*q8_M2 ],
  [ q8_M2*q8_M4, <identity ...> ], [ q8_M3*q8_M1, <identity ...> ],
  [ q8_M3*q8_M2, q8_M1*q8_M4 ], [ q8_M3^2, q8_M1^2 ],
  [ q8_M3*q8_M4, q8_M1*q8_M2 ], [ q8_M4*q8_M1, q8_M1*q8_M2 ],
  [ q8_M4*q8_M2, <identity ...> ], [ q8_M4*q8_M3, q8_M1*q8_M4 ],
  [ q8_M4^2, q8_M1^2 ], [ q8_M1^3, q8_M3 ], [ q8_M1^2*q8_M2, q8_M4 ],
  [ q8_M1^2*q8_M4, q8_M2 ] ]
gap> Length( r2 );
16
```

```
gap> w2 := ReduceWordKB( w0, r2 );
q8_M1*q8_M4
```

## 2.3 Enumerating elements

### 2.3.1 ElementsOfMonoidPresentation

▷ `ElementsOfMonoidPresentation(mon)`

(attribute)

The function `ElementsOfMonoidPresentation` returns a list of normal forms for the elements of the group given by the monoid presentation `mon`. The normal forms are the least elements in each equivalence class (with respect to length-lex order). When `rules` is a complete rewrite system for  $G$  the list returned is a set of normal forms for the group elements. For `q8` this list is

$$[\text{id}, a^+, b^+, a^-, b^-, a^{+2}, a^+b^+, a^+b^-].$$

Example

```
gap> elq8 := Elements( q8 );
[ <identity ...>, f1, f1^3, f2, f1^2*f2, f1^2, f1*f2, f1^3*f2 ]
gap> elmonq8 := ElementsOfMonoidPresentation( monq8 );
[ <identity. ...>, q8_M1, q8_M2, q8_M3, q8_M4, q8_M1^2, q8_M1*q8_M2,
  q8_M1*q8_M4 ]
```

## Chapter 3

# Logged Rewriting Systems

A *logged rewrite system* is associated with a group presentation. Each *logged rewrite rule* contains, in addition to the standard rewrite rule, a record or *log component* which expresses the rule in terms of the original relators of the group. We represent such a rule by a triple  $[u, [L_1, L_2, \dots, L_k], v]$ , where  $[u, v]$  is a rewrite rule and  $L_i = [n_i, w_i]$  where  $n_i$  is a group relator and  $w_i$  is a word. These three components obey the identity  $u = n_1^{w_1} \dots n_k^{w_k} v$ .

Rules of the form  $g^+ g^- \rightarrow \text{id}$  apply to the monoid presentation, but not to the group presentation, so are given an empty logged component.

### 3.1 Logged Knuth-Bendix Completion

The functions in this section are the logged versions of those in the previous chapter.

#### 3.1.1 LoggedOnePassKB

▷ `LoggedOnePassKB(grp, loggedrules)` (operation)

Given a logged rewrite system for the group *grp*, this function finds all the rules that would be added to complete the rewrite system of `OnePassKB` in 2.2.3, and also the logs which relate the new rules to the originals. The result of applying this function to *loggedrules* is to add new logged rules to the system without changing the monoid it defines.

In the example, we first convert the presentation for *q8* into an initial set of logged rules, and then apply one pass of Knuth-Bendix.

The function returns a two-element list of lists. The first element is a set of logged rules and the second element is an empty list of r-sequences, which will be explained later.

Example

```
gap> l0 := ListWithIdenticalEntries( 8, 0 );;
gap> for j in [1..8] do
>   r := r0[j];
>   if ( j<5 ) then
>     l0[j] := [ r[1], [ [j,id] ], r[2] ];
>   else
>     l0[j] := [ r[1], [ ], r[2] ];
>   fi;
```

```

> od;
gap> l0;
[ [ q8_M1^4, [ [ 1, <identity ...> ] ], <identity. ...> ],
  [ q8_M2^4, [ [ 2, <identity ...> ] ], <identity ...> ],
  [ q8_M1*q8_M2*q8_M1*q8_M4, [ [ 3, <identity ...> ] ], <identity ...> ],
  [ q8_M1^2*q8_M2^2, [ [ 4, <identity ...> ] ], <identity ...> ],
  [ q8_M1*q8_M3, [ ], <identity ...> ], [ q8_M2*q8_M4, [ ], <identity ...> ],
  [ q8_M3*q8_M1, [ ], <identity ...> ], [ q8_M4*q8_M2, [ ], <identity ...> ] ]
gap> l1 := LoggedOnePassKB( q8, l0 );
gap> Length( l1[1] );
21
gap> l1[1][16];
[ q8_M2^2, [ [ -4, <identity ...> ], [ 2, q8_M3^2 ] ], q8_M1^2 ]

```

Note that the length 21 of `l1` is, as expected, the same as that of `r1` in 2.2.3. If we write  $a^+, b^+, a^-, b^-$  for  $M1, M2, M3, M4$  and label the four original relators as  $q = a^{+4}, r = b^{+4}, s = a^+b^+a^+b^-, t = a^{+2}b^{+2}$  then the sixteenth identity (for example) says that  $b^{+2} = (t^{-1}r^{a^{-2}})a^{+2}$ . To verify this, we may expand the right-hand side as follows:

$$(b^{-2}a^{-2}).a^{+2}(b^{+4})a^{-2}.a^{+2} = b^{-2}(a^{+2}a^{-2})b^{+4}(a^{-2}a^{+2}) = b^{-2}b^{+4} = b^{+2}.$$

### 3.1.2 LoggedKnuthBendix

- ▷ `LoggedKnuthBendix(grp, loggedrules)` (operation)
- ▷ `LoggedRewriteReduce(grp, loggedrules)` (operation)

The function `LoggedRewriteReduce` removes unnecessary rules from a logged rewrite system. It works on the same principle as `RewriteReduce` in 2.2.3.

The function `LoggedKnuthBendix` repeatedly applies functions `LoggedOnePassKB` and `LoggedRewriteReduce` until no new rules are added and no unnecessary ones are included. The output is a reduced complete logged rewrite system.

As a further example, consider the second rule in 12 which shows how  $b^+a^+$  reduces to  $a^+b^-$ . For this rule `[u,L,v]` we will verify that  $u = n_1^{w_1}n_2^{w_2}n_3^{w_3}v$ , as in the introduction to this chapter. The rule is:

```
[ q8_M2*q8_M1, [ [3,q8_M1], [-1,<identity...>], [4,q8_M3] ], q8_M1*q8_M4 ].
```

The relators  $3 \equiv s$ ,  $4 \equiv t$  and the inverse relator  $-1 \equiv q^{-1}$  are  $a^+b^+a^+b^-$ ,  $a^{+2}b^{+2}$  and  $a^{-4}$ , and these are conjugated by  $(a^-)^{-1} = a^+$ ,  $(a^+)^{-1} = a^-$  and the identity respectively. So the second and third parts of the rule expand to:

$$(a^-(a^+b^+a^+b^-)a^+)(a^{-4})(a^+(a^{+2}b^{+2})a^-)a^+b^- = (a^-a^+)b^+a^+(b^-(a^+a^{-4}a^{+3})b^+)(b^+(a^-a^+)b^-)$$

which reduces to the first part of the rule,  $b^+a^+$ .

In version 2.41 of this package the function `LoggedOnePassKB` was modified to return a two-element list of lists. The first element is a set of logged rules (as has been returned by earlier versions) while the second element is a list of 51 identities. See chapter 6 for more information about identities.

## Example

```

gap> l11 := LoggedRewriteReduce( q8, l1[1] );;
gap> Perform( l11, Display );
[ q8_M1*q8_M3, [ ], <identity ...> ]
[ q8_M2^2, [ [ -4, <identity ...> ], [ 2, q8_M3^2 ] ], q8_M1^2 ]
[ q8_M2*q8_M4, [ ], <identity ...> ]
[ q8_M3*q8_M1, [ ], <identity ...> ]
[ q8_M4*q8_M2, [ ], <identity ...> ]
[ q8_M1^3, [ [ 1, <identity ...> ] ], q8_M3 ]
[ q8_M1^2*q8_M2, [ [ 4, <identity ...> ] ], q8_M4 ]
[ q8_M1*q8_M2*q8_M1, [ [ 3, <identity ...> ] ], q8_M2 ]
[ q8_M2*q8_M1*q8_M4, [ [ 3, q8_M1 ] ], q8_M3 ]
gap> Length( l11 );
9
gap> l12 := LoggedKnuthBendix( q8, l11 );;
gap> l12[1];
[ [ q8_M1*q8_M3, [ ], <identity ...> ],
  [ q8_M2*q8_M1, [ [ 3, q8_M1 ] ], [ -1, <identity ...> ], [ 4, q8_M3 ] ],
  q8_M1*q8_M4 ],
[ q8_M2^2, [ [ -4, <identity ...> ], [ 2, q8_M3^2 ] ], q8_M1^2 ],
[ q8_M2*q8_M3, [ [ -3, <identity ...> ] ], q8_M1*q8_M2 ],
[ q8_M2*q8_M4, [ ], <identity ...> ], [ q8_M3*q8_M1, [ ], <identity ...> ]
, [ q8_M3*q8_M2, [ [ -1, <identity ...> ], [ 4, q8_M3 ] ], q8_M1*q8_M4 ],
[ q8_M3^2, [ [ -1, <identity ...> ] ], q8_M1^2 ],
[ q8_M3*q8_M4,
  [ [ -1, <identity ...> ], [ -2, q8_M3^2 ], [ 4, <identity ...> ],
    [ 3, q8_M1*q8_M4 ], [ -3, <identity ...> ] ], q8_M1*q8_M2 ],
[ q8_M4*q8_M1, [ [ -4, <identity ...> ], [ 3, q8_M3 ] ], q8_M1*q8_M2 ],
[ q8_M4*q8_M2, [ ], <identity ...> ],
[ q8_M4*q8_M3, [ [ -3, q8_M1*q8_M2 ] ], q8_M1*q8_M4 ],
[ q8_M4^2, [ [ -4, <identity ...> ] ], q8_M1^2 ],
[ q8_M1^3, [ [ 1, <identity ...> ] ], q8_M3 ],
[ q8_M1^2*q8_M2, [ [ 4, <identity ...> ] ], q8_M4 ],
[ q8_M1^2*q8_M4, [ [ -4, q8_M3^2 ], [ 1, <identity ...> ] ], q8_M2 ] ]
gap> Length( l12[1] );
16
gap> Length( l12[2] );
51

```

## 3.2 Logged reduction of a word

### 3.2.1 LoggedReduceWordKB

- ▷ LoggedReduceWordKB(*word*, *loggedrules*) (operation)
- ▷ LoggedOnePassReduceWord(*word*, *loggedrules*) (operation)
- ▷ ShorterLoggedRule(*logrule1*, *logrule2*) (operation)

Given a word and a logged rewrite system, the function `LoggedOnePassReduceWord` makes one reduction pass of the word (possibly involving several reductions) (as does `OnePassReduceWord` in

2.2.2) and records this, using the log part of the rule(s) used and the position in the original word of the replaced part.

The function `LoggedReduceWordKB` repeatedly applies `OnePassLoggedReduceWord` until the word can no longer be reduced. Each step of the reduction is logged, showing how the original word can be expressed in terms of the original relators and the irreducible word. When `loggedrules` is complete the reduced word is a unique normal form for that group element. The log of the reduction depends on the order in which the rules are applied.

The function `ShorterLoggedrule` decides whether one logged rule is better than another, using the same criteria as `ShorterRule` in 2.2.3. In the example we perform logged reductions of  $w_0 = a^9b^9$  corresponding to the ordinary reductions performed in the previous chapter (section 2.2.2).

In order to clarify the following output, note that, in the log below,  $b^9a^9$  reduces to  $b^5a^5$  in `lw1` and to  $ba$  in the first `lw2`. These expand to the initial `w0` using the given logged parts as follows:

$$(b^{+9}a^{+4}b^{-9})(b^{+4})b^{+5}a^{+5} = b^{+9}a^{+9} = (b^{+9}a^{+4}b^{-9})(b^{+4})(b^{+5}a^{+4}b^{-5})(b^{+4})b^{+a^{+5}}.$$

The corresponding expansion of the final `lw2` is too lengthy to include here. (It's hard to believe that the logged part of this identity is the simplest possible. Further investigation is needed to determine whether or not this logged part can be simplified.)

Example

```
gap> w0;
q8_M2^9*q8_M1^9
gap> lw1 := LoggedOnePassReduceWord( w0, 10 );
[ [ [ 1, q8_M2^-9 ], [ 2, <identity ...> ] ], q8_M2^5*q8_M1^5 ]
gap> lw2 := LoggedReduceWordKB( w0, 10 );
[ [ [ 1, q8_M2^-9 ], [ 2, <identity ...> ], [ 1, q8_M2^-5 ],
    [ 2, <identity ...> ] ], q8_M2*q8_M1 ]
gap> lw2 := LoggedReduceWordKB( w0, l2[1] );
[ [ [ 3, q8_M1*q8_M2^-8 ], [ -1, q8_M2^-8 ], [ 4, q8_M3*q8_M2^-8 ],
    [ -4, <identity ...> ], [ 2, q8_M3^2 ],
    [ -4, q8_M1^-1*q8_M2^-6*q8_M1^-2 ],
    [ 3, q8_M3*q8_M1^-1*q8_M2^-6*q8_M1^-2 ],
    [ 1, q8_M2^-1*q8_M1^-2*q8_M2^-6*q8_M1^-2 ], [ 4, <identity ...> ],
    [ 3, q8_M1*q8_M2^-4*q8_M4^-1 ], [ -1, q8_M2^-4*q8_M4^-1 ],
    [ 4, q8_M3*q8_M2^-4*q8_M4^-1 ], [ -4, q8_M4^-1 ],
    [ 2, q8_M3^2*q8_M4^-1 ],
    [ -3, q8_M1^-1*q8_M4^-1*q8_M1^-1*q8_M2^-2*q8_M1^-2*q8_M4^-1 ],
    [ -4, <identity ...> ], [ 3, q8_M3 ],
    [ 1, q8_M2^-1*q8_M1^-2*q8_M4^-1*q8_M1^-1*q8_M2^-1*(q8_M2^-1*q8_M1^-1)^2 ],
    [ 4, q8_M4^-1*q8_M1^-1*q8_M2^-1*(q8_M2^-1*q8_M1^-1)^2 ],
    [ 3, <identity ...> ], [ -1, q8_M1^-1 ], [ 4, q8_M3*q8_M1^-1 ],
    [ -4, q8_M4^-1*q8_M1^-2 ], [ 2, q8_M3^2*q8_M4^-1*q8_M1^-2 ],
    [ -4, q8_M1^-2 ], [ 3, q8_M3*q8_M1^-2 ],
    [ -4, q8_M1^-2*q8_M2^-1*q8_M1^-3 ], [ 1, <identity ...> ],
    [ 3, q8_M1*q8_M3^-1 ], [ -1, q8_M3^-1 ], [ 4, <identity ...> ],
    [ -4, <identity ...> ], [ 3, q8_M3 ], [ 3, <identity ...> ],
    [ -1, q8_M1^-1 ], [ 4, q8_M3*q8_M1^-1 ], [ -4, q8_M1^-2 ],
    [ 3, q8_M3*q8_M1^-2 ], [ 1, <identity ...> ], [ -1, <identity ...> ],
    [ 4, q8_M3 ] ], q8_M1*q8_M4 ]
```



### 3.2.2 LoggedRewritingSystemFpGroup

▷ LoggedRewritingSystemFpGroup(*grp*)

(attribute)

Given a group presentation, the function LoggedRewritingSystemFpGroup determines a logged rewrite system based on the relators. The initial logged rewrite system associated with a group presentation consists of two types of rule. These are logged versions of the two types of rule in the monoid presentation. Corresponding to the  $j$ -th relator  $rel$  of the group there is a logged rule  $[rel, [[j, id]], id]$ . For each inverse relator there is a logged rule  $[gen*inv, [], id]$ . The function then attempts a completion of the logged rewrite system. The rules in the final system are partially ordered by the function ShorterLoggedRule.

Example

```
gap> lrws := LoggedRewritingSystemFpGroup( q8 );;
gap> Perform( lrws, Display );
[ q8_M4*q8_M2, [ ], <identity ...> ]
[ q8_M3*q8_M1, [ ], <identity ...> ]
[ q8_M2*q8_M4, [ ], <identity ...> ]
[ q8_M1*q8_M3, [ ], <identity ...> ]
[ q8_M1^2*q8_M4, [ [ -8, q8_M3^2 ], [ 5, <identity ...> ] ], q8_M2 ]
[ q8_M1^2*q8_M2, [ [ 8, <identity ...> ] ], q8_M4 ]
[ q8_M1^3, [ [ 5, <identity ...> ] ], q8_M3 ]
[ q8_M4^2, [ [ -8, <identity ...> ] ], q8_M1^2 ]
[ q8_M4*q8_M3, [ [ -7, q8_M1*q8_M2 ] ], q8_M1*q8_M4 ]
[ q8_M4*q8_M1, [ [ -8, <identity ...> ], [ 7, q8_M3 ] ], q8_M1*q8_M2 ]
[ q8_M3*q8_M4,
  [ [ -5, <identity ...> ], [ -6, q8_M3^2 ], [ 8, <identity ...> ],
    [ 7, q8_M1*q8_M4 ], [ -7, <identity ...> ] ], q8_M1*q8_M2 ]
[ q8_M3^2, [ [ -5, <identity ...> ] ], q8_M1^2 ]
[ q8_M3*q8_M2, [ [ -5, <identity ...> ], [ 8, q8_M3 ] ], q8_M1*q8_M4 ]
[ q8_M2*q8_M3, [ [ -7, <identity ...> ] ], q8_M1*q8_M2 ]
[ q8_M2^2, [ [ -8, <identity ...> ], [ 6, q8_M3^2 ] ], q8_M1^2 ]
[ q8_M2*q8_M1, [ [ 7, q8_M1 ], [ -5, <identity ...> ], [ 8, q8_M3 ] ],
  q8_M1*q8_M4 ]
gap> Length( lrws );
16
```

Consider now the two-generator abelian group  $T$  considered in the previous chapter (2.2.1). Using the alternative ordering on the monoid generators,  $[ T_M1 = a^+, T_M2 = a^-, T_M3 = b^+, T_M4 = b^- ]$ , we obtain the following set of 8 logged rules. The last of these may be checked as follows:

$$(b^+ a^+ (b^- a^- b^+ a^+) a^- b^-) a^+ b^+ = b^+ a^+ (b^- (a^- (b^+ (a^+ a^-) b^-) a^+) b^+)$$

and is a logged version of the rule  $b^+ a^+ \rightarrow a^+ b^+$ .

Example

```
gap> lrwsT := LoggedRewritingSystemFpGroup( T );
[ [ T_M4*T_M3, [ ], <identity ...> ], [ T_M3*T_M4, [ ], <identity ...> ],
  [ T_M2*T_M1, [ ], <identity ...> ], [ T_M1*T_M2, [ ], <identity ...> ],
  [ T_M4*T_M2, [ [ -5, <identity ...> ] ], T_M2*T_M4 ],
```

```
[ T_M4*T_M1, [ [ 5, T_M2 ] ], T_M1*T_M4 ],  
[ T_M3*T_M2, [ [ 5, T_M4 ] ], T_M2*T_M3 ],  
[ T_M3*T_M1, [ [ -5, T_M2*T_M4 ] ], T_M1*T_M3 ] ]
```

## Chapter 4

# Monoid Polynomials

This chapter describes functions to compute with elements of a free noncommutative algebra. The elements of the algebra are sums of rational multiples of words in a free monoid. These are called *monoid polynomials*, and are stored as lists of pairs [coefficient, word].

### 4.1 Construction of monoid polynomials

#### 4.1.1 MonoidPolyFromCoeffsWords

- ▷ MonoidPolyFromCoeffsWords(*coeffs*, *words*) (operation)
- ▷ MonoidPoly(*terms*) (operation)
- ▷ ZeroMonoidPoly(*F*) (operation)

There are two ways to input a monoid polynomial: by listing the coefficients and then the words; or by listing the terms as a list of pairs [coefficient, word]. If a word occurs more than once in the input list, the coefficients will be added so that the terms of the monoid polynomial recorded do not contain any duplicates. The zero monoid polynomial is the polynomial with no terms.

Example

```
gap> rels := RelatorsOfFpGroup( q8 );
[ f1^4, f2^4, f1*f2*f1*f2^-1, f1^2*f2^2 ]
gap> freeq8 := FreeGroupOfFpGroup( q8 );;
gap> gens := GeneratorsOfGroup( freeq8 );;
gap> famfree := ElementsFamily( FamilyObj( freeq8 ) );;
gap> famfree!.monoidPolyFam := MonoidPolyFam;;
gap> cg := [6,7];;
gap> pg := MonoidPolyFromCoeffsWords( cg, gens );;
gap> Print( pg, "\n" );
7*f2 + 6*f1
gap> cr := [3,4,-5,-2];;
gap> pr := MonoidPolyFromCoeffsWords( cr, rels );;
gap> Print( pr, "\n" );
4*f2^4 - 5*f1*f2*f1*f2^-1 - 2*f1^2*f2^2 + 3*f1^4
gap> Print( ZeroMonoidPoly( freeq8 ), "\n" );
zero monpoly
```

## 4.2 Components of a polynomial

### 4.2.1 Terms (for monoid polynomials)

- ▷ `Terms(poly)` (attribute)
- ▷ `Coeffs(poly)` (attribute)
- ▷ `Words(poly)` (attribute)
- ▷ `LeadTerm(poly)` (attribute)
- ▷ `LeadCoeffMonoidPoly(poly)` (attribute)

The function `Terms` returns the terms of a polynomial as a list of pairs of the form `[word, coefficient]`. The function `Coeffs` returns the coefficients of a polynomial as a list, and the function `Words` returns the words of a polynomial as a list. The function `LeadTerm` returns the term of the polynomial whose word component is the largest with respect to the length-lexicographical ordering. The function `LeadCoeffMonoidPoly` returns the coefficient of the leading term of a polynomial.

Example

```
gap> Coeffs( pr );
[ 4, -5, -2, 3 ]
gap> Terms( pr );
[ [ 4, f2^4 ], [ -5, f1*f2*f1*f2^-1 ], [ -2, f1^2*f2^2 ], [ 3, f1^4 ] ]
gap> Words( pr );
[ f2^4, f1*f2*f1*f2^-1, f1^2*f2^2, f1^4 ]
gap> LeadTerm( pr );
[ 4, f2^4 ]
gap> LeadCoeffMonoidPoly( pr );
4
```

### 4.2.2 Monic

- ▷ `Monic(poly)` (operation)

A monoid polynomial is called *monic* if the coefficient of its leading polynomial is one. The function `Monic` converts a polynomial into a monic polynomial by dividing all the coefficients by the leading coefficient.

Example

```
gap> mpr := Monic( pr );;
gap> Print( mpr, "\n" );
f2^4 - 5/4*f1*f2*f1*f2^-1 - 1/2*f1^2*f2^2 + 3/4*f1^4
```

### 4.2.3 AddTermMonoidPoly

- ▷ `AddTermMonoidPoly(poly, coeff, word)` (operation)

The function `AddTermMonoidPoly` adds a new term, given by its coefficient and word, to an existing polynomial.

## Example

```

gap> w := gens[1]^gens[2];
f2^-1*f1*f2
gap> cw := 3/4;;
gap> wpg:= AddTermMonoidPoly( pg, cw, w);;
gap> Print( wpg, "\n" );
3/4*f2^-1*f1*f2 + 7*f2 + 6*f1

```

### 4.3 Monoid Polynomial Operations

Tests for equality and arithmetic operations are performed in the usual way.

The operation `poly1 = poly2` returns `true` if the monoid polynomials have the same terms, and `false` otherwise. Multiplication of a monoid polynomial (on the left or right) by a coefficient; the addition or subtraction of two monoid polynomials; multiplication (on the right) of a monoid polynomial by a word; and multiplication of two monoid polynomials; are all implemented.

## Example

```

gap> [ pg = pg, pg = pr ];
[ true, false ]
gap> prcw := pr*cw;;
gap> Print( prcw, "\n" );
3*f2^4 - 15/4*f1*f2*f1*f2^-1 - 3/2*f1^2*f2^2 + 9/4*f1^4
gap> cwpr := cw*pr;;
gap> Print( cwpr, "\n" );
3*f2^4 - 15/4*f1*f2*f1*f2^-1 - 3/2*f1^2*f2^2 + 9/4*f1^4
gap> [ pr = prcw, prcw = cwpr ];
[ false, true ]
gap> Print( pg + pr, "\n" );
4*f2^4 - 5*f1*f2*f1*f2^-1 - 2*f1^2*f2^2 + 3*f1^4 + 7*f2 + 6*f1
gap> Print( pg - pr, "\n" );
- 4*f2^4 + 5*f1*f2*f1*f2^-1 + 2*f1^2*f2^2 - 3*f1^4 + 7*f2 + 6*f1
gap> Print( pg * w, "\n" );
6*f1*f2^-1*f1*f2 + 7*f1*f2
gap> Print( pg * pr, "\n" );
28*f2^5 - 35*(f2*f1)^2*f2^-1 - 14*f2*f1^2*f2^2 + 21*f2*f1^4 + 24*f1*f2^4 -
30*f1^2*f2*f1*f2^-1 - 12*f1^3*f2^2 + 18*f1^5

```

#### 4.3.1 Length (for monoid polynomials)

▷ `Length(poly)`

(method)

This function returns the number of distinct terms in the monoid polynomial.

## Example

```

gap> Length( pr );

```

4

The boolean function `poly1 > poly2` returns `true` if the first polynomial has more terms than the second. If the polynomials are the same length it will compare their leading terms. If the leading word of the first is lengthlexicographically greater than the leading word of the second, or if the words are equal but the coefficient of the first is greater than the coefficient of the second then `true` is returned. If the leading terms are equal then the next terms are compared in the same way. If all terms are the same then `false` is returned.

Example

```
gap> [ pr > 3*pr, pr > pg ];
[ false, true ]
```

## 4.4 Reduction of a Monoid Polynomial

### 4.4.1 ReduceMonoidPoly

▷ `ReduceMonoidPoly(poly, rules)`

(operation)

Recall that the words of a monoid polynomial are elements of a free monoid. Given a rewrite system (set of rules) on the free monoid the words can be reduced. This allows us to simulate calculation in monoid rings where the monoid is given by a complete presentation. This function reduces the words of the polynomial (elements of the free monoid) with respect to the complete rewrite system. The words of the reduced polynomial are normal forms for the elements of the monoid presented by that rewrite system. The list of rules `r2` is displayed in section 2.3.3.

Example

```
gap> M := genfgmon;;
gap> mp1 := MonoidPolyFromCoeffsWords(
>      [9,-7,5], [M[1]*M[3], M[2]^3, M[4]*M[3]*M[2]] );;
gap> Print( mp1, "\n" );
5*q8_M4*q8_M3*q8_M2 - 7*q8_M2^3 + 9*q8_M1*q8_M3
gap> rmp1 := ReduceMonoidPoly( mp1, r2 );;
gap> Print( rmp1, "\n" );
- 7*q8_M4 + 5*q8_M1 + 9*<identity ...>
```

## Chapter 5

# Module Polynomials

In this chapter we consider finitely generated modules over the monoid rings considered previously. We call an element of this module a *module polynomial*, and we describe functions to construct module polynomials and the standard algebraic operations for such polynomials.

A module polynomial `modpoly` is recorded as a list of pairs, `[ gen, monpoly ]`, where `gen` is a module generator (basis element), and `monpoly` is a monoid polynomial. The module polynomial is printed as the formal sum of monoid polynomial multiples of the generators. Note that the monoid polynomials are the coefficients of the module polynomials and appear to the right of the generator, as we choose to work with right modules.

The examples we are aiming for are the identities among the relators of a finitely presented group (see section 5.4).

### 5.1 Construction of module polynomials

#### 5.1.1 ModulePoly (with input gens, polys)

- ▷ `ModulePoly(gens, monpolys)` (operation)
- ▷ `ModulePoly(args)` (operation)
- ▷ `ZeroModulePoly(Fgens, Fmon)` (operation)

The function `ModulePoly` returns a module polynomial. The terms of the polynomial may be input as a list of generators followed by a list of monoid polynomials or as one list of `[generator, monoid polynomial]` pairs.

Assuming that `Fgens` is the free group on the module generators and `Fmon` is the free group on the monoid generators, the function `ZeroModulePoly` returns the zero module polynomial, which has no terms, and is an element of the module.

Example

```
gap> frq8 := FreeRelatorGroup( q8 );;
gap> genfrq8 := GeneratorsOfGroup( frq8 );
[ q8_R1, q8_R2, q8_R3, q8_R4 ]
gap> Print( rmp1, "\n" );      ## defined in section 4.4.1
- 7*q8_M4 + 5*q8_M1 + 9*<identity ...>
gap> mp2 := MonoidPolyFromCoeffsWords( [4,-5], [ M[4], M[1] ] );;
gap> Print( mp2, "\n" );
4*q8_M4 - 5*q8_M1
```

```

gap> s1 := ModulePoly( [ genfrq8[4], genfrq8[1] ], [ rmp1, mp2 ] );
q8_R1*(4*q8_M4 - 5*q8_M1) + q8_R4*( - 7*q8_M4 + 5*q8_M1 + 9*<identity ...>)
gap> s2 := ModulePoly( [ genfrq8[3], genfrq8[2], genfrq8[1] ],
> [ -1*rmp1, 3*mp2, (rmp1+mp2) ] );
q8_R1*( - 3*q8_M4 + 9*<identity ...>) + q8_R2*(12*q8_M4 - 15*q8_M1) + q8_R3*(
7*q8_M4 - 5*q8_M1 - 9*<identity ...>)
gap> zeromp := ZeroModulePoly( frq8, freeq8 );
zero modpoly

```

## 5.2 Components of a module polynomial

### 5.2.1 Terms (for module polynomials)

- ▷ `Terms(modpoly)` (attribute)
- ▷ `LeadTerm(modpoly)` (attribute)
- ▷ `LeadMonoidPoly(modpoly)` (attribute)
- ▷ `Length(modpoly)` (method)
- ▷ `One(modpoly)` (attribute)

The function `Terms` returns the terms of a module polynomial as a list of pairs. In `LeadTerm`, the generators are ordered, and the term of `modpoly` with the highest value generator is defined to be the leading term. The monoid polynomial (coefficient) part of the leading term is returned by the function `LeadMonoidPoly`.

The function `Length` counts the number of module generators which occur in `modpoly` (a generator occurs in a polynomial if it has nonzero coefficient). The function `One` returns the identity in the free group on the generators.

Example

```

gap> [ Length(s1), Length(s2) ];
[ 2, 3 ]
gap> One( s1 );
<identity ...>
gap> Terms( s1 );
[ [ q8_R1, 4*q8_M4 - 5*q8_M1 ],
  [ q8_R4, - 7*q8_M4 + 5*q8_M1 + 9*<identity ...> ] ]
gap> Print( LeadTerm( s1 ), "\n" );
[ q8_R4, - 7*q8_M4 + 5*q8_M1 + 9*<identity ...> ]
gap> Print( LeadTerm( s2 ), "\n" );
[ q8_R3, 7*q8_M4 - 5*q8_M1 - 9*<identity ...> ]
gap> Print( LeadMonoidPoly( s1 ), "\n" );
- 7*q8_M4 + 5*q8_M1 + 9*<identity ...>
gap> Print( LeadMonoidPoly( s2 ), "\n" );
7*q8_M4 - 5*q8_M1 - 9*<identity ...>

```



## 5.3 Module Polynomial Operations

### 5.3.1 AddTermModulePoly

▷ `AddTermModulePoly(modpoly, gen, monpoly)` (operation)

The function `AddTermModulePoly` adds a term `[gen, monpoly]` to a module polynomial `modpoly`.

Tests for equality and arithmetic operations are performed in the usual way. Module polynomials may be added or subtracted. A module polynomial can also be multiplied on the right by a word or by a scalar. The effect of this is to multiply the monoid polynomial parts of each term by the word or scalar. This is made clearer in the example.

Example

```
gap> mp0 := MonoidPolyFromCoeffsWords( [6], [ M[2] ] );
gap> Print( mp0, "\n" );
6*q8_M2
gap> s0 := AddTermModulePoly( s1, genfrq8[3], mp0 );
q8_R1*(4*q8_M4 - 5*q8_M1) + q8_R3*(6*q8_M2) + q8_R4*( - 7*q8_M4 + 5*q8_M1 +
9*<identity ...>)
gap> Print( s1 + s2, "\n" );
q8_R1*( q8_M4 - 5*q8_M1 + 9*<identity ...>) + q8_R2*(12*q8_M4 -
15*q8_M1) + q8_R3*(7*q8_M4 - 5*q8_M1 - 9*<identity ...>) + q8_R4*( -
7*q8_M4 + 5*q8_M1 + 9*<identity ...>)
gap> Print( s1 - s0, "\n" );
q8_R3*( - 6*q8_M2)
gap> Print( s1 * 1/2, "\n" );
q8_R1*(2*q8_M4 - 5/2*q8_M1) + q8_R4*( - 7/2*q8_M4 + 5/2*q8_M1 + 9/
2*<identity ...>)
gap> Print( s1 * M[1], "\n" );
q8_R1*(4*q8_M4*q8_M1 - 5*q8_M1^2) + q8_R4*( - 7*q8_M4*q8_M1 + 5*q8_M1^2 +
9*q8_M1)
```

## Chapter 6

# Identities Among Relators

The identities among the relators for a finitely presented group  $G$  are constructed as logged module polynomials. The procedure, described in [HW03] and based on work in [BRS99], is to construct a full set of *group relator sequences* for the group; convert these into module polynomials (eliminating empty sequences); and then apply simplification rules (including the primary identity property) to eliminate obvious duplicates and conjugates.

When a reduced set of polynomials has been obtained, the relator sequences from which they were formed are returned as the *identities among relators* for  $G$ .

Here are some of the details when working with the group  $S_3 = \langle a, b \mid \rho = a^3, \sigma = b^2, \tau = (ab)^2 \rangle$ . The monoid presentation has generators  $\{a^+, b^+, a^-, b^-\}$  and relators

$$[1 = a^+a^-, 2 = b^+b^-, 3 = a^-a^+, 4 = b^-b^+, 5 = a^{+3}, 6 = b^{+2}, 7 = (a^+b^+)^2],$$

and the elements are  $\{\text{id}, a^+, b^+, a^-, a^+b^-, b^+a^+\}$ . The logged rewriting system has relations

$\begin{aligned} a^+a^- &= \text{id}, & b^+b^- &= \text{id}, & a^-a^+ &= \text{id}, & b^-b^+ &= \text{id}, \\ a^{+2} &= [5, \text{id}]a^-, & a^{-2} &= [-5, \text{id}]a^+, & b^{+2} &= [6, \text{id}]a^-, & b^- &= [-6, \text{id}]b^+, \\ b^+a^- &= [-7, a^+b^-][6, \text{id}]a^+b^+, & a^-b^+ &= [-7, a^+][6, a^-b^-]b^+a^+, \\ a^+b^+a^+ &= [7, \text{id}]a^-, & b^+a^+b^+ &= [7, a^+]a^-. \end{aligned}$
---

To construct the *identity monoid relator sequences* we follow in turn the relators  $5 = \rho, 6 = \sigma, 7 = \tau$  at each of the elements of  $S_3$ . For example, applying  $\tau$  at  $a^+$  gives the cycle:

$$a^+ \xrightarrow{a^+} a^- \xrightarrow{b^+} b^+a^+ \xrightarrow{a^+} a^+b^+ \xrightarrow{b^+} a^+.$$

Each of these edges has a non-trivial logged rewrite, particularly the third edge where  $b^+a^+a^+ \rightarrow b^+a^- \rightarrow a^+b^+$ . Combining this log information we obtain the sequence:

$$[5, \text{id}].[-7, a^+][6, a^-b^-].[5, \text{id}]^{b^-}[-7, a^+b^-][6, \text{id}].[6, \text{id}]^{a^-}.$$

Expanding this gives:

$$a^+a^+a^+.a^-b^-a^-b^-a^-a^+.b^+a^+b^+b^+a^-b^-.b^+a^+a^+a^+b^-.b^+a^-b^-a^-b^-a^-a^+b^-.b^+b^+.a^+b^+b^+a^-$$

which cancels to leave, as expected,  $a^+(a^+b^+a^+b^+)a^- = [7, a^-]$ . Adding the inverse  $[-7, a^-]$  to the front of the log expression gives the identity

$$[-7, a^-].[5, \text{id}].[-7, a^+][6, a^-b^-].[5, b^-]^{a^-}[-7, a^+b^-][6, \text{id}].[6, a^-].$$

Converting this back to the group presentation, and conjugating by  $a$ , we obtain the *identity group relator sequence* given in the introduction (1.1):

$$\tau^{-1} \rho^a (\tau^{-1})^{a^2} \sigma^{a^{-1}b^{-1}a} \rho^{b^{-1}a} (\tau^{-1})^{ab^{-1}a} \sigma^a \sigma .$$

This is then transformed into the module polynomial

$$\rho(a^+ + b^+ a^+) + \sigma(\text{id} + a^+ + a^+ b^+) - \tau(\text{id} + a^- + b^+) ,$$

where the monoid elements are transformed into their normal forms.

The collection of saturated sets of these module polynomials is then reduced as far as possible, and the minimal set obtained returned as the `IdentityYSequences` of the group. The group relator sequences corresponding to these module polynomials form the `IdentitiesAmongRelators` for the group.

## 6.1 The original approach

This section describes the approach used from the earliest versions of `IdRel` up to version 2.38 in 2017. For version 2.39 the methods were revised so as to produce some data for infinite groups. This experimental work is described in later sections.

### 6.1.1 IdentitiesAmongRelators

- ▷ `IdentitiesAmongRelators(grp)` (attribute)
- ▷ `IdentityYSequences(grp)` (attribute)
- ▷ `IdentityRelatorSequences(grp)` (attribute)

It is *not* guaranteed that a minimal set of identities is obtained. For `q8` a set of seven identities is returned, whereas a minimal set contains only six. See Example 5.1 of [HW03] for further details.

Example

```
gap> gseq8 := IdentityRelatorSequences( q8 );;
gap> Length( gseq8 );
19
gap> gseq8[1];
[ 1, 9, [ [ q8_R1^-1, <identity ...> ], [ q8_R1, f1^-1 ] ] ]
gap> idsq8 := IdentitiesAmongRelators( q8 );;
gap> Length( idsq8 );
7
gap> Display( idsq8 );
[ [ [ q8_R1^-1, <identity ...> ], [ q8_R1, f1^-1 ] ],
  [ [ q8_R2^-1, <identity ...> ], [ q8_R4^-1, f2^-1 ], [ q8_R2, f1^-2*f2^-1 ],
    [ q8_R4, f2^-1 ] ],
  [ [ q8_R1^-1, <identity ...> ], [ q8_R4^-1, f2^-1 ], [ q8_R3, f1^-1*f2^-1 ],
    [ q8_R3, f2^-1 ], [ q8_R3, f1*f2^-1 ], [ q8_R1^-1, f2^-1 ],
    [ q8_R3, f1^-2*f2^-1 ], [ q8_R4, f2^-1 ] ],
  [ [ q8_R3^-1, <identity ...> ], [ q8_R4^-1, f2^-1 ], [ q8_R3, f1^-1*f2^-1 ],
    [ q8_R4, f1*f2^-1 ] ],
  [ [ q8_R4^-1, <identity ...> ], [ q8_R4^-1, f2^-1 ], [ q8_R3, f1^-1*f2^-1 ],
```

```

      [ q8_R3, f2^-1 ], [ q8_R4^-1, f2^-1 ], [ q8_R2, f1^-2*f2^-1 ],
      [ q8_R4, f2^-1 ] ],
    [ [ q8_R4^-1, <identity ...> ], [ q8_R3, f1*f2 ], [ q8_R1^-1, f2 ],
      [ q8_R3, f1^-2*f2 ], [ q8_R4, f2 ] ] ],
    [ [ q8_R4^-1, <identity ...> ], [ q8_R4^-1, f1^-2 ], [ q8_R2, f1^-4 ],
      [ q8_R1, f1^-1 ] ] ]
gap> idyseq8 := IdentityYSequences( q8 );
[ ( q8_Y1*( -q8_M1), q8_R1*( q8_M1 - <identity ...> ) ),
  ( q8_Y5*( <identity ...>), q8_R2*( q8_M2 - <identity ...> ) ),
  ( q8_Y18*( q8_M2), q8_R1*( -q8_M2 - <identity ...> ) + q8_R3*( q8_M1^2 + q8_M\
3 + q8_M1 + <identity ...> ) ),
  ( q8_Y8*( q8_M2), q8_R3*( q8_M3 - q8_M2) + q8_R4*( q8_M1 - <identity ...> ) )
,
  ( q8_Y17*( -q8_M2), q8_R2*( -q8_M1^2) + q8_R3*( -q8_M3 - <identity ...> ) + q\
8_R4*( q8_M2 + <identity ...> ) ),
  ( q8_Y11*( <identity ...>), q8_R1*( -q8_M2) + q8_R3*( q8_M1*q8_M2 + q8_M4) +\
q8_R4*( q8_M2 - <identity ...> ) ),
  ( q8_Y10*( -q8_M1), q8_R1*( -<identity ...> ) + q8_R2*( -q8_M1) + q8_R4*( q8_\
M3 + q8_M1) ) ]

```

## 6.1.2 RootIdentities

▷ RootIdentities(*grp*)

(attribute)

The *root identities* are identities of the form  $r^w r^{-1}$  where  $r = w^n$  is a relator and  $n > 1$ . (For equivalent forms invert, or permute the factors cyclically, or act with  $w^{-1}$ .)

For *q8* only two of the four relators are proper powers,  $\pi = a^4$  and  $\rho = b^4$ , so the root identities are  $\pi^a \pi^{-1}$  and  $\rho^b \rho^{-1}$ . In the listing below the second of these is displayed as  $\rho^{-1}(\xi^{-1})^{b^{-1}} \rho^{a^{-2}b^{-1}} \xi^{b^{-1}}$ , where  $\xi = a^2 b^2$ . Because the second term is the inverse of the fourth, we may convert the final three terms into a conjugate of the third, so that the identity is equivalent to  $\rho^{-1} \rho^b$ :

$$\left(\rho^{a^{-2}b^{-1}}\right)^{\xi^{b^{-1}}} = \left(\rho^{a^{-2}b^{-1}}\right)^{b(a^2b^2)b^{-1}} = \rho^b.$$

Example

```

gap> RootIdentities( q8 );
[ [ [ q8_R1^-1, <identity ...> ], [ q8_R1, f1^-1 ] ],
  [ [ q8_R2^-1, <identity ...> ], [ q8_R4^-1, f2^-1 ], [ q8_R2, f1^-2*f2^-1 ],
    [ q8_R4, f2^-1 ] ] ]
gap> RootIdentities(s3);
[ [ [ s3_R1^-1, <identity ...> ], [ s3_R1, f1^-1 ] ],
  [ [ s3_R2^-1, <identity ...> ], [ s3_R2, f2 ] ],
  [ [ s3_R3^-1, <identity ...> ], [ s3_R3, f1*f2 ] ] ]

```

## 6.2 Knuth-Bendix identities

Given an initial set of rules, the logged Knuth-Bendix procedure considers overlaps between pairs of logged rules  $l_1 = L_1 r_1$  and  $l_2 = L_2 r_2$ . In the case  $u_1 l_1 = l_2 v_2$  for some words  $u_1, v_2$ , the critical pair resulting from the overlap is  $(u_1 r_1, r_2 v_2)$ . Logged reduction is then applied to these two words giving  $u_1 r_1 = M_1 z_1$  and  $r_2 v_2 = M_2 z_2$ , say. Then, if  $z_1 > z_2$ , the additional rule  $z_1 = (M_1^{-1} L_1^{-u_1^{-1}} L_2 M_2) z_2$  is added. There is a similar formula when  $z_2 > z_1$ .

### 6.2.1 IdentitiesAmongRelatorsKB

- ▷ `IdentitiesAmongRelatorsKB(grp)` (attribute)
- ▷ `IdentityYSequencesKB(grp)` (attribute)
- ▷ `IdentityRelatorSequencesKB(grp)` (attribute)

The third possibility is that  $z_1 = z_2$ , and in this case there is no reduction rule to be added. However the log expression  $M_1^{-1} L_1^{-u_1^{-1}} L_2 M_2$  must reduce to the identity, and so is an identity relator sequence. Since version 2.41 of this package, the function `LoggedRewritingSystemFpGroup` returns two lists: a complete set of reduction rules, and a set of identity relator sequences produced in this way. In the case of the quaternion group `q8` a total of 42 sequences are produced by logged Knuth-Bendix, and these are then reduced to 8 identities.

Example

```
gap> gseqKB8 := IdentityRelatorSequencesKB( q8 );
gap> Length(last);
42
gap> idrelsKB8 := IdentitiesAmongRelatorsKB( q8 );
gap> Display( idrelsKB8 );
[ [ [ q8_R1^-1, <identity ...> ], [ q8_R1, f1^-1 ] ],
  [ [ q8_R3^-1, f1^-1 ], [ q8_R3^-1, f1^-2 ], [ q8_R1, <identity ...> ],
    [ q8_R3^-1, f1 ], [ q8_R1, f2^-1 ], [ q8_R3^-1, <identity ...> ] ],
  [ [ q8_R3, f1*f2 ], [ q8_R4^-1, <identity ...> ], [ q8_R3^-1, f1^-2 ],
    [ q8_R4, f1^-1 ] ],
  [ [ q8_R2^-1, f1^-3 ], [ q8_R4, f1^-1 ], [ q8_R3, <identity ...> ],
    [ q8_R3^-1, f1*f2^-1 ], [ q8_R4^-1, <identity ...> ], [ q8_R2, f1^-2 ] ]
  , [ [ q8_R4^-1, f2 ], [ q8_R2, f1^-2*f2 ], [ q8_R4^-1, <identity ...> ],
    [ q8_R3, f1^-1 ], [ q8_R3, <identity ...> ] ],
  [ [ q8_R4^-1, <identity ...> ], [ q8_R3^-1, f1^-2 ],
    [ q8_R1, <identity ...> ], [ q8_R3^-1, f1 ], [ q8_R4, f2^-1 ] ],
  [ [ q8_R4^-1, <identity ...> ], [ q8_R4^-1, f1^-2 ], [ q8_R2, f1^-4 ],
    [ q8_R1, <identity ...> ] ],
  [ [ q8_R4, f1^-1 ], [ q8_R3, f1*f2 ], [ q8_R1^-1, f2 ],
    [ q8_R2^-1, f1^-2*f2 ], [ q8_R4, f2 ], [ q8_R3, f1 ], [ q8_R3^-1, f2 ],
    [ q8_R4^-1, <identity ...> ], [ q8_R3, f1^-1 ], [ q8_R4^-1, f1^-1 ],
    [ q8_R2, f1^-3 ] ] ]
```

## 6.3 Partial lists of elements

As we have seen, the procedure for obtaining identities involves applying each relator at each element of the group. Since this will not terminate when the group is infinite, we include an operation to construct words up to a given length in the monoid representation of the group.

### 6.3.1 PartialElementsOfMonoidRepresentation

▷ `PartialElementsOfMonoidRepresentation(G, len)` (operation)

As an example we take the group  $\langle u, v, w \mid u^3, v^2, w^2, (uv)^2, (vw)^2 \rangle$ .

Example

```
gap> F := FreeGroup(3);
gap> u := F.1;; v := F.2;; w := F.3;;
gap> rels := [ u^3, v^2, w^2, (u*v)^2, (v*w)^2 ];
gap> q0 := F/rels;;
gap> SetArrangementOfMonoidGenerators( q0, [1,-1,2,-2,3,-3] );
gap> SetName( q0, "q0" );
gap> monq0 := MonoidPresentationFpGroup( q0 );
monoid presentation with group relators
[ q0_M1^3, q0_M3^2, q0_M5^2, (q0_M1*q0_M3)^2, (q0_M3*q0_M5)^2 ]
gap> lrws := LoggedRewritingSystemFpGroup( q0 );
gap> PartialElementsOfMonoidPresentation( q0, 1 );
[ <identity ...>, q0_M1, q0_M2, q0_M3, q0_M5 ]
gap> PartialElementsOfMonoidPresentation( q0, 2 );
[ <identity ...>, q0_M1, q0_M2, q0_M3, q0_M5, q0_M1*q0_M3, q0_M1*q0_M5,
  q0_M2*q0_M3, q0_M2*q0_M5, q0_M3*q0_M5, q0_M5*q0_M1, q0_M5*q0_M2 ]
```

## 6.4 Identities for infinite groups

Because the list of elements is incomplete, it is not guaranteed that the list of identities is complete.

Example

```
gap> idsq0 := IdentitiesAmongRelators( q0 );
[ [ [ q0_R1^-1, <identity ...> ], [ q0_R1, f1^-1 ] ],
  [ [ q0_R2^-1, <identity ...> ], [ q0_R2, f2 ] ],
  [ [ q0_R3^-1, <identity ...> ], [ q0_R3, f3 ] ],
  [ [ q0_R4^-1, <identity ...> ], [ q0_R2^-1, f1^-1 ], [ q0_R4, f1*f2 ],
    [ q0_R2, f1*f2 ] ],
  [ [ q0_R5^-1, <identity ...> ], [ q0_R3^-1, f2^-1 ], [ q0_R5, f2*f3 ],
    [ q0_R3, f2*f3 ] ],
  [ [ q0_R1^-1, <identity ...> ], [ q0_R2^-1, f1^-1 ], [ q0_R4, f1*f2 ],
    [ q0_R2^-1, f1^-1*f2^-1*f1*f2 ], [ q0_R4, f1^2*f2 ], [ q0_R1^-1, f2 ],
    [ q0_R2^-1, f1^-1*f2^-1*f1^-1*f2 ], [ q0_R4, f2 ] ],
  [ [ q0_R2^-1, <identity ...> ], [ q0_R3^-1, f2^-1 ], [ q0_R5, f2*f3 ],
    [ q0_R2^-1, f3 ], [ q0_R3^-1, f2^-1*f3^-1*f2^-1*f3 ], [ q0_R5, f3 ] ] ]
```

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