Abstract

HAP is a homological algebra library for use with the GAP computer algebra system, and is still under development. The current version 1.29 was released on 07 January 2021.

The initial focus of the library was on computations related to the cohomology of finite and infinite groups, with particular emphasis on integral coefficients. The focus has since broadened to include Steenrod algebras of finite groups, Bredon homology, cohomology of simplicial groups, and general computations in algebraic topology relating to finite CW-complexes, covering spaces, knots, knotted surfaces, and topics such as persistent homology arising in topological data analysis.

This document describes the functions available in HAP. Examples illustrating these functions are available in the HAP tutorial.

Copyright

© 2005-2019 by Graham Ellis

Acknowledgements

The HAP project has been supported by the School of Maths at NUI Galway, various PhD students and postdoctoral researchers at NUI Galway, the Irish Research Council, Science Foundation Ireland, and the EU Marie Curie programme.
Contents

1 Basic functionality for cellular complexes, fundamental groups and homology ................................................................. 7
  1.1 Data  → Cellular Complexes ......................................................... 7
  1.2 Metric Spaces ......................................................................... 12
  1.3 Cellular Complexes  → Cellular Complexes ................................ 13
  1.4 Cellular Complexes  → Cellular Complexes (Preserving Data Types) ......................................................... 16
  1.5 Cellular Complexes  → Homotopy Invariants ................................ 19
  1.6 Data  → Homotopy Invariants ...................................................... 22
  1.7 Cellular Complexes  → Non Homotopy Invariants ......................... 22
  1.8 (Co)chain Complexes  → (Co)chain Complexes ......................... 24
  1.9 (Co)chain Complexes  → Homotopy Invariants ......................... 25
  1.10 Visualization ......................................................................... 27

2 Basic functionality for \(Z^G\)-resolutions and group cohomology ................................................................. 29
  2.1 Resolutions ........................................................................... 29
  2.2 Algebras  → (Co)chain Complexes ............................................. 31
  2.3 Resolutions  → (Co)chain Complexes ........................................... 31
  2.4 Cohomology rings ................................................................... 33
  2.5 Group Invariants ..................................................................... 35
  2.6 \(\mathbb{F}_p\)-modules ................................................................... 37

3 Basic functionality for homological group theory .................................................................................. 38
  3.1 Cocycles .............................................................................. 38
  3.2 G-Outer Groups .................................................................... 39
  3.3 G-cocomplexes .................................................................... 40

4 Basic functionality for parallel computation .......................................................................................... 41
  4.1 Six Core Functions ................................................................. 41

5 Resolutions of the ground ring .............................................................................................................. 43
  5.1 ........................................................................................... 43

6 Resolutions of modules ....................................................................................................................... 52
  6.1 ........................................................................................... 52

7 Induced equivariant chain maps ........................................................................................................... 53
  7.1 ........................................................................................... 53
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Functors</td>
<td>54</td>
</tr>
<tr>
<td>8.1</td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>9</td>
<td>Chain complexes</td>
<td>58</td>
</tr>
<tr>
<td>9.1</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>Sparse Chain complexes</td>
<td>61</td>
</tr>
<tr>
<td>10.1</td>
<td></td>
<td>61</td>
</tr>
<tr>
<td>11</td>
<td>Homology and cohomology groups</td>
<td>64</td>
</tr>
<tr>
<td>11.1</td>
<td></td>
<td>64</td>
</tr>
<tr>
<td>12</td>
<td>Poincare series</td>
<td>72</td>
</tr>
<tr>
<td>12.1</td>
<td></td>
<td>72</td>
</tr>
<tr>
<td>13</td>
<td>Cohomology ring structure</td>
<td>74</td>
</tr>
<tr>
<td>13.1</td>
<td></td>
<td>74</td>
</tr>
<tr>
<td>14</td>
<td>Cohomology rings of $p$-groups (mainly $p = 2$)</td>
<td>77</td>
</tr>
<tr>
<td>14.1</td>
<td></td>
<td>77</td>
</tr>
<tr>
<td>15</td>
<td>Commutator and nonabelian tensor computations</td>
<td>79</td>
</tr>
<tr>
<td>15.1</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>16</td>
<td>Lie commutators and nonabelian Lie tensors</td>
<td>84</td>
</tr>
<tr>
<td>16.1</td>
<td></td>
<td>84</td>
</tr>
<tr>
<td>17</td>
<td>Generators and relators of groups</td>
<td>86</td>
</tr>
<tr>
<td>17.1</td>
<td></td>
<td>86</td>
</tr>
<tr>
<td>18</td>
<td>Orbit polytopes and fundamental domains</td>
<td>88</td>
</tr>
<tr>
<td>18.1</td>
<td></td>
<td>88</td>
</tr>
<tr>
<td>19</td>
<td>Cocycles</td>
<td>92</td>
</tr>
<tr>
<td>19.1</td>
<td></td>
<td>92</td>
</tr>
<tr>
<td>20</td>
<td>Words in free $ZG$-modules</td>
<td>94</td>
</tr>
<tr>
<td>20.1</td>
<td></td>
<td>94</td>
</tr>
<tr>
<td>21</td>
<td>$FpG$-modules</td>
<td>96</td>
</tr>
<tr>
<td>21.1</td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>22</td>
<td>Meataxe modules</td>
<td>101</td>
</tr>
<tr>
<td>22.1</td>
<td></td>
<td>101</td>
</tr>
<tr>
<td>23</td>
<td>G-Outer Groups</td>
<td>102</td>
</tr>
<tr>
<td>23.1</td>
<td></td>
<td>102</td>
</tr>
<tr>
<td>Chapter</td>
<td>Title</td>
<td>Section</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>24</td>
<td>Cat-1-groups</td>
<td>24.1</td>
</tr>
<tr>
<td>25</td>
<td>Simplicial groups</td>
<td>25.1</td>
</tr>
<tr>
<td>26</td>
<td>Coxeter diagrams and graphs of groups</td>
<td>26.1</td>
</tr>
<tr>
<td>27</td>
<td>Torsion Subcomplexes</td>
<td>27.1</td>
</tr>
<tr>
<td>28</td>
<td>Simplicial Complexes</td>
<td>28.1</td>
</tr>
<tr>
<td>29</td>
<td>Cubical Complexes</td>
<td>29.1</td>
</tr>
<tr>
<td>30</td>
<td>Regular CW-Complexes</td>
<td>30.1</td>
</tr>
<tr>
<td>31</td>
<td>Knots and Links</td>
<td>31.1</td>
</tr>
<tr>
<td>32</td>
<td>Knots and Quandles</td>
<td>32.1</td>
</tr>
<tr>
<td>33</td>
<td>Finite metric spaces and their filtered complexes</td>
<td>33.1</td>
</tr>
<tr>
<td>34</td>
<td>Commutative diagrams and abstract categories</td>
<td>34.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>34.2</td>
</tr>
<tr>
<td>35</td>
<td>Arrays and Pseudo lists</td>
<td>35.1</td>
</tr>
<tr>
<td>36</td>
<td>Parallel Computation - Core Functions</td>
<td>36.1</td>
</tr>
<tr>
<td>37</td>
<td>Parallel Computation - Extra Functions</td>
<td>37.1</td>
</tr>
<tr>
<td>38</td>
<td>Some functions for accessing basic data</td>
<td>38.1</td>
</tr>
<tr>
<td>39</td>
<td>Miscellaneous</td>
<td>39.1</td>
</tr>
</tbody>
</table>
40 HAP variables that are not yet documented
   40.1 ................................................................. 163

Index ......................................................... 221
Chapter 1

Basic functionality for cellular complexes, fundamental groups and homology

This page covers the functions used in chapters 1 and 2 of the book An Invitation to Computational Homotopy.

1.1 Data → Cellular Complexes

1.1.1 RegularCWPolytope

\( \text{Inputs a list } L \text{ of vectors in } \mathbb{R}^n \text{ and outputs their convex hull as a regular CW-complex.} \)
\( \text{Inputs a permutation group } G \text{ of degree } d \text{ and vector } v \in \mathbb{R}^d, \text{ and outputs the convex hull of the orbit } \{ v^g : g \in G \} \text{ as a regular CW-complex.} \)

EXAMPLES:

1.1.2 CubicalComplex

\( \text{Inputs a binary array } A \text{ and returns the cubical complex represented by } A. \text{ The array } A \text{ must of course be such that it represents a cubical complex.} \)

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

1.1.3 PureCubicalComplex

\( \text{Inputs a binary array } A \text{ and returns the pure cubical complex represented by } A. \)

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
1.1.4 PureCubicalKnot

\[ \text{PureCubicalKnot}(n, k) \] (function)
\[ \text{PureCubicalKnot}(L) \] (function)

Inputs integers \( n, k \) and returns the \( k \)-th prime knot on \( n \) crossings as a pure cubical complex (if this prime knot exists).
Inputs a list \( L \) describing an arc presentation for a knot or link and returns the knot or link as a pure cubical complex.

\textbf{Examples:} 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

1.1.5 PurePermutahedralKnot

\[ \text{PurePermutahedralKnot}(n, k) \] (function)
\[ \text{PurePermutahedralKnot}(L) \] (function)

Inputs integers \( n, k \) and returns the \( k \)-th prime knot on \( n \) crossings as a pure permutahedral complex (if this prime knot exists).
Inputs a list \( L \) describing an arc presentation for a knot or link and returns the knot or link as a pure permutahedral complex.

\textbf{Examples:}

1.1.6 PurePermutahedralComplex

\[ \text{PurePermutahedralComplex}(A) \] (function)

Inputs a binary array \( A \) and returns the pure permutahedral complex represented by \( A \).

\textbf{Examples:} 1, 2, 3

1.1.7 CayleyGraphOfGroup

\[ \text{CayleyGraphOfGroup}(G, L) \] (function)

Inputs a finite group \( G \) and a list \( L \) of elements in \( G \). It returns the Cayley graph of the group generated by \( L \).

\textbf{Examples:}

1.1.8 EquivariantEuclideanSpace

\[ \text{EquivariantEuclideanSpace}(G, v) \] (function)

Inputs a crystallographic group \( G \) with left action on \( \mathbb{R}^n \) together with a row vector \( v \in \mathbb{R}^n \). It returns an equivariant regular CW-space corresponding to the Dirichlet-Voronoi tessellation of \( \mathbb{R}^n \) produced from the orbit of \( v \) under the action.

\textbf{Examples:}
1.1.9  EquivariantOrbitPolytope

\[ \text{EquivariantOrbitPolytope}(G, v) \] (function)

Inputs a permutation group \( G \) of degree \( n \) together with a row vector \( v \in \mathbb{R}^n \). It returns, as an equivariant regular CW-space, the convex hull of the orbit of \( v \) under the canonical left action of \( G \) on \( \mathbb{R}^n \).

**EXAMPLES:**

1.1.10  EquivariantTwoComplex

\[ \text{EquivariantTwoComplex}(G) \] (function)

Inputs a suitable group \( G \) and returns, as an equivariant regular CW-space, the 2-complex associated to some presentation of \( G \).

**EXAMPLES:**

1.1.11  QuillenComplex

\[ \text{QuillenComplex}(G, p) \] (function)

Inputs a finite group \( G \) and prime \( p \), and returns the simplicial complex arising as the order complex of the poset of elementary abelian \( p \)-subgroups of \( G \).

**EXAMPLES:** 1, 2, 3

1.1.12  RestrictedEquivariantCWComplex

\[ \text{RestrictedEquivariantCWComplex}(Y, H) \] (function)

Inputs a \( G \)-equivariant regular CW-space \( Y \) and a subgroup \( H \leq G \) for which GAP can find a transversal. It returns the equivariant regular CW-complex obtained by restricting the action to \( H \).

**EXAMPLES:**

1.1.13  RandomSimplicialGraph

\[ \text{RandomSimplicialGraph}(n, p) \] (function)

Inputs an integer \( n \geq 1 \) and positive prime \( p \), and returns an Erdős–Rényi random graph as a 1-dimensional simplicial complex. The graph has \( n \) vertices. Each pair of vertices is, with probability \( p \), directly connected by an edge.

**EXAMPLES:** 1

1.1.14  RandomSimplicialTwoComplex

\[ \text{RandomSimplicialTwoComplex}(n, p) \] (function)
Inputs an integer $n \geq 1$ and positive prime $p$, and returns a Linial-Meshulam random simplicial 2-complex. The 1-skeleton of this simplicial complex is the complete graph on $n$ vertices. Each triple of vertices lies, with probability $p$, in a common 2-simplex of the complex.

**EXAMPLES:**

1.1.15 **ReadCSVfileAsPureCubicalKnot**

\[ \text{ReadCSVfileAsPureCubicalKnot(str)} \] (function)

\[ \text{ReadCSVfileAsPureCubicalKnot(str, r)} \] (function)

\[ \text{ReadCSVfileAsPureCubicalKnot(L)} \] (function)

\[ \text{ReadCSVfileAsPureCubicalKnot(L, R)} \] (function)

Reads a CSV file identified by a string str such as "file.pdb" or "path/file.pdb" and returns a 3-dimensional pure cubical complex $K$. Each line of the file should contain the coordinates of a point in $\mathbb{R}^3$ and the complex $K$ should represent a knot determined by the sequence of points, though the latter is not guaranteed. A useful check in this direction is to test that $K$ has the homotopy type of a circle.

If the test fails then try the function again with an integer $r \geq 2$ entered as the optional second argument. The integer determines the resolution with which the knot is constructed.

The function can also read in a list $L$ of strings identifying CSV files for several knots. In this case a list $R$ of integer resolutions can also be entered. The lists $L$ and $R$ must be of equal length.

**EXAMPLES:**

1.1.16 **ReadImageAsPureCubicalComplex**

\[ \text{ReadImageAsPureCubicalComplex(str, t)} \] (function)

Reads an image file identified by a string str such as "file.bmp", "file.eps", "file.jpg", "path/file.png" etc., together with an integer $t$ between 0 and 765. It returns a 2-dimensional pure cubical complex corresponding to a black/white version of the image determined by the threshold $t$. The 2-cells of the pure cubical complex correspond to pixels with RGB value $R + G + B \leq t$.

**EXAMPLES:** 1, 2, 3

1.1.17 **ReadImageAsFilteredPureCubicalComplex**

\[ \text{ReadImageAsFilteredPureCubicalComplex(str, n)} \] (function)

Reads an image file identified by a string str such as "file.bmp", "file.eps", "file.jpg", "path/file.png" etc., together with a positive integer $n$. It returns a 2-dimensional filtered pure cubical complex of filtration length $n$. The $k$th term in the filtration is a pure cubical complex corresponding to a black/white version of the image determined by the threshold $t_k = k \times 765/n$. The 2-cells of the $k$th term correspond to pixels with RGB value $R + G + B \leq t_k$.

**EXAMPLES:** 1

1.1.18 **ReadImageAsWeightFunction**

\[ \text{ReadImageAsWeightFunction(str, t)} \] (function)
Reads an image file identified by a string str such as "file.bmp", "file.eps", "file.jpg", "path/file.png" etc., together with an integer \( t \). It constructs a 2-dimensional regular CW-complex \( Y \) from the image, together with a weight function \( w: Y \to \mathbb{Z} \) corresponding to a filtration on \( Y \) of filtration length \( t \). The pair \( [Y, w] \) is returned.

**Examples:**

1.1.19 **ReadPDBfileAsPureCubicalComplex**

\[ \text{{ReadPDBfileAsPureCubicalComplex(str) \quad (function)}} \]
\[ \text{{ReadPDBfileAsPureCubicalComplex(str, r) \quad (function)}} \]

Reads a PDB (Protein Database) file identified by a string str such as "file.pdb" or "path/file.pdb" and returns a 3-dimensional pure cubical complex \( K \). The complex \( K \) should represent a (protein backbone) knot but this is not guaranteed. A useful check in this direction is to test that \( K \) has the homotopy type of a circle.

If the test fails then try the function again with an integer \( r \geq 2 \) entered as the optional second argument. The integer determines the resolution with which the knot is constructed.

**Examples:** 1, 2

1.1.20 **ReadPDBfileAsPurepermahedralComplex**

\[ \text{{ReadPDBfileAsPurepermahedralComplex(str, r) \quad (function)}} \]

Reads a PDB (Protein Database) file identified by a string str such as "file.pdb" or "path/file.pdb" and returns a 3-dimensional pure permutahedral complex \( K \). The complex \( K \) should represent a (protein backbone) knot but this is not guaranteed. A useful check in this direction is to test that \( K \) has the homotopy type of a circle.

If the test fails then try the function again with an integer \( r \geq 2 \) entered as the optional second argument. The integer determines the resolution with which the knot is constructed.

**Examples:**

1.1.21 **RegularCWPolytope**

\[ \text{{RegularCWPolytope(L) \quad (function)}} \]
\[ \text{{RegularCWPolytope(G, v) \quad (function)}} \]

Inputs a list \( L \) of vectors in \( \mathbb{R}^n \) and outputs their convex hull as a regular CW-complex.

Inputs a permutation group \( G \) of degree \( d \) and vector \( v \in \mathbb{R}^d \), and outputs the convex hull of the orbit \( \{ v^g : g \in G \} \) as a regular CW-complex.

**Examples:**

1.1.22 **SimplicialComplex**

\[ \text{{SimplicialComplex(L) \quad (function)}} \]
Inputs a list \( L \) whose entries are lists of vertices representing the maximal simplices of a simplicial complex, and returns the simplicial complex. Here a “vertex” is a GAP object such as an integer or a subgroup. The list \( L \) can also contain non-maximal simplices.

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

### 1.1.23 SymmetricMatrixToFilteredGraph

\[ \text{SymmetricMatrixToFilteredGraph}(A, m, s) \]

\[ \text{SymmetricMatrixToFilteredGraph}(A, m) \]

Inputs an \( n \times n \) symmetric matrix \( A \), a positive integer \( m \) and a positive rational \( s \). The function returns a filtered graph of filtration length \( m \). The \( t \)-th term of the filtration is a graph with \( n \) vertices and an edge between the \( i \)-th and \( j \)-th vertices if the \((i, j)\) entry of \( A \) is less than or equal to \( t \times s / m \).

If the optional input \( s \) is omitted then it is set equal to the largest entry in the matrix \( A \).

**EXAMPLES:** 1, 2

### 1.1.24 SymmetricMatrixToGraph

\[ \text{SymmetricMatrixToGraph}(A, t) \]

Inputs an \( n \times n \) symmetric matrix \( A \) over the rationals and a rational number \( t \geq 0 \), and returns the graph on the vertices 1, 2, ..., \( n \) with an edge between distinct vertices \( i \) and \( j \) precisely when the \( (i, j) \) entry of \( A \) is \( \leq t \).

**EXAMPLES:** 1

### 1.2 Metric Spaces

#### 1.2.1 CayleyMetric

\[ \text{CayleyMetric}(g, h) \]

Inputs two permutations \( g, h \) and optionally the degree \( N \) of a symmetric group containing them. It returns the minimum number of transpositions needed to express \( g \ast h^{-1} \) as a product of transpositions.

**EXAMPLES:** 1

#### 1.2.2 EuclideanMetric

\[ \text{EuclideanMetric} \]

Inputs two vectors \( v, w \in \mathbb{R}^n \) and returns a rational number approximating the Euclidean distance between them.

**EXAMPLES:**

#### 1.2.3 EuclideanSquaredMetric

\[ \text{EuclideanSquaredMetric}(g, h) \]

Inputs two vectors \( v, w \in \mathbb{R}^n \) and returns a rational number approximating the Euclidean distance between them.
Inputs two vectors \( v, w \in \mathbb{R}^n \) and returns the square of the Euclidean distance between them.

**Examples:**

### 1.2.4 HammingMetric

\[ \texttt{HammingMetric}(g, h) \]

- Inputs two permutations \( g, h \) and optionally the degree \( N \) of a symmetric group containing them.
- It returns the minimum number of integers moved by the permutation \( g \ast h^{-1} \).

**Examples:**

### 1.2.5 KendallMetric

\[ \texttt{KendallMetric}(g, h) \]

- Inputs two permutations \( g, h \) and optionally the degree \( N \) of a symmetric group containing them.
- It returns the minimum number of adjacent transpositions needed to express \( g \ast h^{-1} \) as a product of adjacent transpositions. An *adjacent* transposition is of the form \((i, i+1)\).

**Examples:**

### 1.2.6 ManhattanMetric

\[ \texttt{ManhattanMetric}(g, h) \]

- Inputs two vectors \( v, w \in \mathbb{R}^n \) and returns the Manhattan distance between them.

**Examples:**

### 1.2.7 VectorsToSymmetricMatrix

\[ \texttt{VectorsToSymmetricMatrix}(V) \]
\[ \texttt{VectorsToSymmetricMatrix}(V, d) \]

- Inputs a list \( V = \{v_1, \ldots, v_k\} \in \mathbb{R}^n \) and returns the \( k \times k \) symmetric matrix of Euclidean distances \( d(v_i, v_j) \). When these distances are irrational they are approximated by a rational number.
- As an optional second argument any rational valued function \( d(x, y) \) can be entered.

**Examples:**

### 1.3 Cellular Complexes → Cellular Complexes

#### 1.3.1 BoundaryMap

\[ \texttt{BoundaryMap}(K) \]

- Inputs a pure regular CW-complex \( K \) and returns the regular CW-inclusion map \( t: \partial K \hookrightarrow K \) from the boundary \( \partial K \) into the complex \( K \).

**Examples:**

1.3.2 CliqueComplex

\[ \text{CliqueComplex}(G, n) \] (function)
\[ \text{CliqueComplex}(F, n) \] (function)
\[ \text{CliqueComplex}(K, n) \] (function)

Inputs a graph \( G \) and integer \( n \geq 1 \). It returns the \( n \)-skeleton of a simplicial complex \( K \) with one \( k \)-simplex for each complete subgraph of \( G \) on \( k + 1 \) vertices.

Inputs a filtered graph \( F \) and integer \( n \geq 1 \). It returns the \( n \)-skeleton of a filtered simplicial complex \( K \) whose \( t \)-term has one \( k \)-simplex for each complete subgraph of the \( t \)-th term of \( G \) on \( k + 1 \) vertices.

Inputs a simplicial complex of dimension \( d = 1 \) or \( d = 2 \). If \( d = 1 \) then the clique complex of a graph returned. If \( d = 2 \) then the clique complex of a 2-complex is returned.

EXAMPLES: 1

1.3.3 ConcentricFiltration

\[ \text{ConcentricFiltration}(K, n) \] (function)

Inputs a pure cubical complex \( K \) and integer \( n \geq 1 \), and returns a filtered pure cubical complex of filtration length \( n \). The \( t \)-th term of the filtration is the intersection of \( K \) with the ball of radius \( r_t \) centred on the centre of gravity of \( K \), where \( 0 = r_1 \leq r_2 \leq r_3 \leq \cdots \leq r_n \) are equally spaced rational numbers. The complex \( K \) is contained in the ball of radius \( r_n \). (At present, this is implemented only for 2- and 3-dimensional complexes.)

EXAMPLES:

1.3.4 DirectProduct

\[ \text{DirectProduct}(M, N) \] (function)
\[ \text{DirectProduct}(M, N) \] (function)

Inputs two or more regular CW-complexes or two or more pure cubical complexes and returns their direct product.

EXAMPLES: 1, 2, 3, 4, 5, 6

1.3.5 FiltrationTerm

\[ \text{FiltrationTerm}(K, t) \] (function)
\[ \text{FiltrationTerm}(K, t) \] (function)

Inputs a filtered regular CW-complex or a filtered pure cubical complex \( K \) together with an integer \( t \geq 1 \). The \( t \)-th term of the filtration is returned.

EXAMPLES: 1

1.3.6 Graph

\[ \text{Graph}(K) \] (function)
\[ \text{Graph}(K) \] (function)
Homological Algebra Programming

Inputs a regular CW-complex or a simplicial complex \(K\) and returns its 1-skeleton as a graph.

**Examples:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

1.3.7 HomotopyGraph

\[ \text{HomotopyGraph}(Y) \]

Inputs a regular CW-complex \(Y\) and returns a subgraph \(M \subset Y^1\) of the 1-skeleton for which the induced homology homomorphisms \(H_1(M, \mathbb{Z}) \to H_1(Y, \mathbb{Z})\) and \(H_1(Y^1, \mathbb{Z}) \to H_1(Y, \mathbb{Z})\) have identical images. The construction tries to include as few edges in \(M\) as possible, though a minimum is not guaranteed.

**Examples:** 1

1.3.8 Nerve

\[ \text{Nerve}(M) \]

\[ \text{Nerve}(M) \]

\[ \text{Nerve}(M, n) \]

\[ \text{Nerve}(M, n) \]

Inputs a pure cubical complex or pure permutahedral complex \(M\) and returns the simplicial complex \(K\) obtained by taking the nerve of an open cover of \(|M|\), the open sets in the cover being sufficiently small neighbourhoods of the top-dimensional cells of \(|M|\). The spaces \(|M|\) and \(|K|\) are homotopy equivalent by the Nerve Theorem. If an integer \(n \geq 0\) is supplied as the second argument then only the \(n\)-skeleton of \(K\) is returned.

**Examples:** 1, 2, 3, 4, 5, 6, 7

1.3.9 RegularCWComplex

\[ \text{RegularCWComplex}(K) \]

\[ \text{RegularCWComplex}(K) \]

\[ \text{RegularCWComplex}(K) \]

\[ \text{RegularCWComplex}(K) \]

\[ \text{RegularCWComplex}(L) \]

\[ \text{RegularCWComplex}(L, M) \]

Inputs a simplicial, pure cubical, cubical or pure permutahedral complex \(K\) and returns the corresponding regular CW-complex. Inputs a list \(L = Y!.boundaries\) of boundary incidences of a regular CW-complex \(Y\) and returns \(Y\). Inputs a list \(L = Y!.boundaries\) of boundary incidences of a regular CW-complex \(Y\) together with a list \(M = Y!.orientation\) of incidence numbers and returns a regular CW-complex \(Y\). The availability of precomputed incidence numbers saves recalculating them.

**Examples:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

1.3.10 RegularCWMap

\[ \text{RegularCWMap}(M, A) \]

(function)
Inputs a pure cubical complex \( M \) and a subcomplex \( A \) and returns the inclusion map \( A \to M \) as a map of regular CW complexes.

**EXAMPLES:** 1, 2

### 1.3.11 ThickeningFiltration

\[ \text{ThickeningFiltration}(K, n) \] (function)

\[ \text{ThickeningFiltration}(K, n, s) \] (function)

Inputs a pure cubical complex \( K \) and integer \( n \geq 1 \), and returns a filtered pure cubical complex of filtration length \( n \). The \( t \)-th term of the filtration is the \( t \)-fold thickening of \( K \). If an integer \( s \geq 1 \) is entered as the optional third argument then the \( t \)-th term of the filtration is the \( ts \)-fold thickening of \( K \).

**EXAMPLES:** 1

### 1.4 Cellular Complexes \( \to \) Cellular Complexes (Preserving Data Types)

#### 1.4.1 ContractedComplex

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(K, S) \] (function)

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(K, S) \] (function)

\[ \text{ContractedComplex}(K) \] (function)

\[ \text{ContractedComplex}(\emptyset) \] (function)

Inputs a complex (regular CW, Filtered regular CW, pure cubical etc.) and returns a homotopy equivalent subcomplex.

Inputs a pure cubical complex or pure permutahedral complex \( K \) and a subcomplex \( S \). It returns a homotopy equivalent subcomplex of \( K \) that contains \( S \).

Inputs a graph \( G \) and returns a subgraph \( S \) such that the clique complexes of \( G \) and \( S \) are homotopy equivalent.

**EXAMPLES:** 1, 2, 3, 4, 5, 6

#### 1.4.2 ContractibleSubcomplex

\[ \text{ContractibleSubcomplex}(K) \] (function)

\[ \text{ContractibleSubcomplex}(K) \] (function)

\[ \text{ContractibleSubcomplex}(K) \] (function)

\[ \text{ContractibleSubcomplex}(K) \] (function)

Inputs a non-empty pure cubical, pure permutahedral or simplicial complex \( K \) and returns a contractible subcomplex.

**EXAMPLES:** 1
1.4.3 KnotReflection

\[ \text{KnotReflection}(K) \]

Inputs a pure cubical knot and returns the reflected knot.

**EXAMPLES:**

1.4.4 KnotSum

\[ \text{KnotSum}(K, L) \]

Inputs two pure cubical knots and returns their sum.

**EXAMPLES:** 1, 2, 3, 4, 5

1.4.5 OrientRegularCWComplex

\[ \text{OrientRegularCWComplex}(Y) \]

Inputs a regular CW-complex \( Y \) and computes and stores incidence numbers for \( Y \). If \( Y \) already has incidence numbers then the function does nothing.

**EXAMPLES:**

1.4.6 PathComponent

\[ \text{PathComponent}(K, n) \]

Inputs a simplicial, pure cubical or pure permutahedral complex \( K \) together with an integer \( 1 \leq n \leq \beta_0(K) \). The \( n \)-th path component of \( K \) is returned.

**EXAMPLES:** 1, 2

1.4.7 PureComplexBoundary

\[ \text{PureComplexBoundary}(M) \]

Inputs a \( d \)-dimensional pure cubical or pure permutahedral complex \( M \) and returns a \( d \)-dimensional complex consisting of the closure of those \( d \)-cells whose boundaries contains some cell with coboundary of size less than the maximal possible size.

**EXAMPLES:**

1.4.8 PureComplexComplement

\[ \text{PureComplexComplement}(M) \]

Inputs a pure cubical complex or a pure permutahedral complex and returns its complement.
EXAM PLE S: 1, 2, 3, 4

1.4.9 PureComplexDifference

\[ \text{PureComplexDifference}(M, N) \]

Inputs two pure cubical complexes or two pure permutahedral complexes and returns the difference \( M - N \).

EXAM PLE S:

1.4.10 PureComplexInterst ection

\[ \text{PureComplexIntersection}(M, N) \]

Inputs two pure cubical complexes or two pure permutahedral complexes and returns their intersection.

EXAM PLE S:

1.4.11 PureComplexThickened

\[ \text{PureComplexThickened}(M) \]

Inputs a pure cubical complex or a pure permutahedral complex and returns the a thickened complex.

EXAM PLE S:

1.4.12 PureComplexUnion

\[ \text{PureComplexUnion}(M, N) \]

Inputs two pure cubical complexes or two pure permutahedral complexes and returns their union.

EXAM PLE S:

1.4.13 SimplifiedComplex

\[ \text{SimplifiedComplex}(K) \]
\[ \text{SimplifiedComplex}(R) \]
\[ \text{SimplifiedComplex}(C) \]

Inputs a regular CW-complex or a pure permutahedral complex \( K \) and returns a homeomorphic complex with possibly fewer cells and certainly no more cells.

Inputs a free \( \mathbb{Z}G \)-resolution \( R \) of \( \mathbb{Z} \) and returns a \( \mathbb{Z}G \)-resolution \( S \) with potentially fewer free generators.
Homological Algebra Programming

Inputs a chain complex C of free abelian groups and returns a chain homotopic chain complex D with potentially fewer free generators.

EXAMPLES: 1, 2, 3

1.4.14 ZigZagContractedComplex

\[ \text{ZigZagContractedComplex}(K) \]

Inputs a pure cubical, filtered pure cubical or pure permutahedral complex and returns a homotopy equivalent complex. In the filtered case, the \( t \)-th term of the output is homotopy equivalent to the \( t \)-th term of the input for all \( t \).

EXAMPLES: 1

1.5 Cellular Complexes \( \rightarrow \) Homotopy Invariants

1.5.1 AlexanderPolynomial

\[ \text{AlexanderPolynomial}(K) \]

Inputs a 3-dimensional pure cubical or pure permutahedral complex \( K \) representing a knot and returns the Alexander polynomial of the fundamental group \( G = \pi_1(\mathbb{R}^3 \setminus K) \).

EXAMPLES: 1, 2

1.5.2 BettiNumber

\[ \text{BettiNumber}(K, n) \]

Inputs a simplicial, cubical, pure cubical, pure permutahedral, regular CW, chain or sparse chain complex \( K \) together with an integer \( n \geq 0 \) and returns the \( n \)th Betti number of \( K \).
Inputs a simplicial, cubical, pure cubical, pure permutahedral or regular CW-complex $K$ together with an integer $n \geq 0$ and a prime $p \geq 0$ or $p = 0$. In this case the $n$th Betti number of $K$ over a field of characteristic $p$ is returned.

**Examples:** 1

### 1.5.3 EulerCharacteristic

- `EulerCharacteristic(C)`
- `EulerCharacteristic(K)`

Inputs a chain complex $C$ and returns its Euler characteristic.

Inputs a cubical, or pure cubical, or pure permutahedral or regular CW- or simplicial complex $K$ and returns its Euler characteristic.

**Examples:**

### 1.5.4 EulerIntegral

- `EulerIntegral(Y, w)`

Inputs a regular CW-complex $Y$ and a weight function $w: Y \rightarrow \mathbb{Z}$, and returns the Euler integral $\int_Y wd\chi$.

**Examples:**

### 1.5.5 FundamentalGroup

- `FundamentalGroup(K)`
- `FundamentalGroup(K, n)`

Inputs a regular CW, simplicial, pure cubical or pure permutahedral complex $K$ and returns the fundamental group.

Inputs a regular CW complex $K$ and the number $n$ of some zero cell. It returns the fundamental group of $K$ based at the $n$-th zero cell.

Inputs a regular CW map $F$ and returns the induced homomorphism of fundamental groups. If the number of some zero cell in the domain of $F$ is entered as an optional second variable then the fundamental group is based at this zero cell.

**Examples:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
1.5.6 FundamentalGroupOfQuotient

\[ \text{FundamentalGroupOfQuotient}(Y) \]

Inputs a \( G \)-equivariant regular CW complex \( Y \) and returns the group \( G \).

EXAMPLES:

1.5.7 IsAspherical

\[ \text{IsAspherical}(F, R) \]

Inputs a free group \( F \) and a list \( R \) of words in \( F \). The function attempts to test if the quotient group \( G = F/\langle R \rangle^F \) is aspherical. If it succeeds it returns true. Otherwise the test is inconclusive and fail is returned.

EXAMPLES: 1, 2, 3

1.5.8 KnotGroup

\[ \text{KnotGroup}(K) \]

Inputs a pure cubical or pure permutahedral complex \( K \) and returns the fundamental group of its complement. If the complement is path-connected then this fundamental group is unique up to isomorphism. Otherwise it will depend on the path-component in which the randomly chosen base-point lies.

EXAMPLES: 1

1.5.9 PiZero

\[ \text{PiZero}(Y) \]

Inputs a regular CW-complex \( Y \), or graph \( Y \), or simplicial complex \( Y \) and returns a pair \([\text{cells}, r]\) where: \( \text{cells} \) is a list of vertices of \( Y \) representing the distinct path-components; \( r(v) \) is a function which, for each vertex \( v \) of \( Y \) returns the representative vertex \( r(v) \in \text{cells} \).

EXAMPLES: 1

1.5.10 PersistentBettiNumbers

\[ \text{PersistentBettiNumbers}(K, n) \]
\[ \text{PersistentBettiNumbers}(K, n) \]
\[ \text{PersistentBettiNumbers}(K, n) \]
\[ \text{PersistentBettiNumbers}(K, n) \]
\[ \text{PersistentBettiNumbers}(K, n) \]
\[ \text{PersistentBettiNumbers}(K, n) \]
\[ \text{PersistentBettiNumbers}(K, n, p) \]
\[ \text{PersistentBettiNumbers}(K, n, p) \]
\[ \text{PersistentBettiNumbers}(K, n, p) \]

(function)
\textbf{Homological Algebra Programming}

\texttt{PersistentBettiNumbers(K, n, p)(function)}

Inputs a filtered simplicial, filtered pure cubical, filtered regular CW, filtered chain or filtered sparse chain complex $K$ together with an integer $n \geq 0$ and returns the $n$th PersistentBetti numbers of $K$ as a list of lists of integers.

Inputs a filtered simplicial, filtered pure cubical, filtered regular CW, filtered chain or filtered sparse chain complex $K$ together with an integer $n \geq 0$ and a prime $p \geq 0$ or $p = 0$. In this case the $n$th PersistentBetti numbers of $K$ over a field of characteristic $p$ are returned.

\textbf{EXAMPLES:} 1

\section{Data $\rightarrow$ Homotopy Invariants}

\subsection{DendrogramMat}

\texttt{DendrogramMat(A, t, s)(function)}

Inputs an $n \times n$ symmetric matrix $A$ over the rationals, a rational $t \geq 0$ and an integer $s \geq 1$. A list $[v_1, \ldots, v_{t+1}]$ is returned with each $v_k$ a list of positive integers. Let $t_k = (k - 1)s$. Let $G(A, t_k)$ denote the graph with vertices $1, \ldots, n$ and with distinct vertices $i$ and $j$ connected by an edge when the $(i, j)$ entry of $A$ is $\leq t_k$. The $i$-th path component of $G(A, t_k)$ is included in the $v_k[i]$-th path component of $G(A, t_{k+1})$. This defines the integer vector $v_k$. The vector $v_k$ has length equal to the number of path components of $G(A, t_k)$.

\textbf{EXAMPLES:}

\section{Cellular Complexes $\rightarrow$ Non Homotopy Invariants}

\subsection{ChainComplex}

\texttt{ChainComplex(K)(function)}

Inputs a cubical, or pure cubical, or pure permutahedral or simplicial complex $K$ and returns its chain complex of free abelian groups. In degree $n$ this chain complex has one free generator for each $n$-dimensional cell of $K$.

Inputs a regular CW-complex $Y$ and returns a chain complex $C$ which is chain homotopy equivalent to the cellular chain complex of $Y$. In degree $n$ the free abelian chain group $C_n$ has one free generator for each critical $n$-dimensional cell of $Y$ with respect to some discrete vector field on $Y$.

\textbf{EXAMPLES:} 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

\subsection{ChainComplexEquivalence}

\texttt{ChainComplexEquivalence}(global variable)
Inputs a regular CW-complex \( X \) and returns a pair \([f_*, g_*]\) of chain maps \( f_*: C_*(X) \to D_*(X) \), \( g_*: D_*(X) \to C_*(X) \). Here \( C_*(X) \) is the standard cellular chain complex of \( X \) with one free generator for each cell in \( X \). The chain complex \( D_*(X) \) is a typically smaller chain complex arising from a discrete vector field on \( X \). The chain maps \( f_* \), \( g_* \) are chain homotopy equivalences.

**Examples:**

### 1.7.3 ChainComplexOfQuotient

\[ \text{ChainComplexOfQuotient}(Y) \]

Inputs a \( G \)-equivariant regular CW-complex \( Y \) and returns the cellular chain complex of the quotient space \( Y/G \).

**Examples:**

### 1.7.4 ChainMap

\[ \text{ChainMap}(X, A, Y, B) \]

\[ \text{ChainMap}(f) \]

\[ \text{ChainMap}(f) \]

Inputs a pure cubical complex \( Y \) and pure cubical subcomplexes \( X \subset Y, B \subset Y, A \subset B \). It returns the induced chain map \( f_*: C_*(X/A) \to C_*(Y/B) \) of cellular chain complexes of pairs. (Typically one takes \( A \) and \( B \) to be empty or contractible subspaces, in which case \( C_*(X/A) \simeq C_*(X), C_*(Y/B) \simeq C_*(Y) \).)

Inputs a map \( f:X \to Y \) between two regular CW-complexes \( X, Y \) and returns an induced chain map \( f_*: C_*(X) \to C_*(Y) \) where \( C_*(X), C_*(Y) \) are chain homotopic to (but usually smaller than) the cellular chain complexes of \( X, Y \).

Inputs a map \( f:X \to Y \) between two simplicial complexes \( X, Y \) and returns the induced chain map \( f_*: C_*(X) \to C_*(Y) \) of cellular chain complexes.

**Examples:** 1, 2, 3, 4, 5, 6

### 1.7.5 CochainComplex

\[ \text{CochainComplex}(K) \]

\[ \text{CochainComplex}(K) \]

\[ \text{CochainComplex}(K) \]

\[ \text{CochainComplex}(Y) \]

\[ \text{CochainComplex}(K) \]

Inputs a cubical, or pure cubical, or pure permahedral or simplicial complex \( K \) and returns its cochain complex of free abelian groups. In degree \( n \) this cochain complex has one free generator for each \( n \)-dimensional cell of \( K \).

Inputs a regular CW-complex \( Y \) and returns a cochain complex \( C \) which is chain homotopy equivalent to the cellular cochain complex of \( Y \). In degree \( n \) the free abelian cochain group \( C_\text{c}(Y) \) has one free generator for each critical \( n \)-dimensional cell of \( Y \) with respect to some discrete vector field on \( Y \).

**Examples:**
1.7.6 CriticalCells

\[ \text{CriticalCells}(K) \]

(function)

Inputs a regular CW-complex \( K \) and returns its critical cells with respect to some discrete vector field on \( K \). If no discrete vector field on \( K \) is available then one will be computed and stored.

**EXAMPLES:** 1, 2, 3, 4, 5, 6

1.7.7 DiagonalApproximation

\[ \text{DiagonalApproximation}(X) \]

(function)

Inputs a regular CW-complex \( X \) and outputs a pair \([p, \iota]\) of maps of CW-complexes. The map \( p: X^\Delta \rightarrow X \) will often be a homotopy equivalence. This is always the case if \( X \) is the CW-space of any pure cubical complex. In general, one can test to see if the induced chain map \( p_*: C_*(X^\Delta) \rightarrow C_*(X) \) is an isomorphism on integral homology. The second map \( \iota: X^\Delta \hookrightarrow X \times X \) is an inclusion into the direct product. If \( p_* \) induces an isomorphism on homology then the chain map \( \iota_*: C_*(X^\Delta) \rightarrow C_*(X \times X) \) can be used to compute the cup product.

**EXAMPLES:** 1

1.7.8 Size

\[ \text{Size}(Y) \]

(function)

\[ \text{Size}(K) \]

(function)

Inputs a regular CW complex or a simplicial complex \( Y \) and returns the number of cells in the complex.

Inputs a \( d \)-dimensional pure cubical or pure permutahedral complex \( K \) and returns the number of \( d \)-dimensional cells in the complex.

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16

1.8 (Co)chain Complexes

1.8.1 FilteredTensorWithIntegers

\[ \text{FilteredTensorWithIntegers}(R) \]

(function)

Inputs a free \( \mathbb{Z}G \)-resolution \( R \) for which ”filteredDimension” lies in \text{NAMEsofComponents}(R). (Such a resolution can be produced using \text{TWISTERTENSORPRODUCT()}, \text{RESOLUTIONNORMALSUBGROUPS()} or \text{FREGRESOLUTION()}.) It returns the filtered chain complex obtained by tensoring with the trivial module \( \mathbb{Z} \).

**EXAMPLES:** 1
1.8.2 FilteredTensorWithIntegersModP

\[ \text{Inputs a free } \mathbb{Z}_G\text{-resolution } R \text{ for which "filteredDimension" lies in NamesOfComponents}(R), \text{together with a prime } p. \text{ (Such a resolution can be produced using TwisterTensorProduct(), ResolutionNormalSubgroups() or FreeResolution().) It returns the filtered chain complex obtained by tensoring with the trivial module } F, \text{ the field of } p \text{ elements.} \]

\text{EXAMPLES: 1}

1.8.3 HomToIntegers

\[ \text{Inputs a chain complex } C \text{ of free abelian groups and returns the cochain complex } \text{Hom}_\mathbb{Z}(C, \mathbb{Z}). \]

\[ \text{Inputs a free } \mathbb{Z}_G\text{-resolution } R \text{ in characteristic 0 and returns the cochain complex } \text{Hom}_\mathbb{Z}_G(R, \mathbb{Z}). \]

\[ \text{Inputs an equivariant chain map } F: R \to S \text{ of resolutions and returns the induced cochain map } \text{Hom}_\mathbb{Z}_G(S, \mathbb{Z}) \to \text{Hom}_\mathbb{Z}_G(R, \mathbb{Z}). \]

\text{EXAMPLES: 1, 2, 3, 4, 5, 6}

1.8.4 TensorWithIntegersModP

\[ \text{Inputs a chain complex } C \text{ of characteristic 0 and a prime integer } p. \text{ It returns the chain complex } C \otimes \mathbb{Z}_p \text{ of characteristic } p. \]

\[ \text{Inputs a free } \mathbb{Z}_G\text{-resolution } R \text{ of characteristic 0 and a prime integer } p. \text{ It returns the chain complex } R \otimes \mathbb{Z}_G \mathbb{Z}_p \text{ of characteristic } p. \]

\[ \text{Inputs an equivariant chain map } F: R \to S \text{ in characteristic 0 a prime integer } p. \text{ It returns the induced chain map } F \otimes \mathbb{Z}_G \mathbb{Z}_p : R \otimes \mathbb{Z}_G \mathbb{Z}_p \to S \otimes \mathbb{Z}_G \mathbb{Z}_p. \]

\text{EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8}

1.9 (Co)chain Complexes \to Homotopy Invariants

1.9.1 Cohomology
Cohomology($K$, $n$) (function)

Inputs a cochain complex $C$ and integer $n \geq 0$ and returns the $n$-th cohomology group of $C$ as a list of its abelian invariants.

Inputs a chain map $F$ and integer $n \geq 0$. It returns the induced cohomology homomorphism $H_n(F)$ as a homomorphism of finitely presented groups.

Inputs a cubical, or pure cubical, or pure permutahedral or regular CW or simplicial complex $K$ together with an integer $n \geq 0$. It returns the $n$-th integral cohomology group of $K$ as a list of its abelian invariants.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22

1.9.2 CupProduct

CupProduct($Y$) (function)

CupProduct($R$, $p$, $q$, $P$, $Q$) (function)

Inputs a regular CW-complex $Y$ and returns a function $f(p,q,P,Q)$. This function $f$ inputs two integers $p,q \geq 0$ and two integer lists $P = [p_1, \ldots, p_m], Q = [q_1, \ldots, q_n]$ representing elements $P \in H^p(Y,Z)$ and $Q \in H^q(Y,Z)$. The function $f$ returns a list $P \cup Q$ representing the cup product $P \cup Q \in H^{p+q}(Y,Z)$.

Inputs a free $\mathbb{Z}G$ resolution $R$ of $\mathbb{Z}$ for some group $G$, together with integers $p, q \geq 0$ and integer lists $P, Q$ representing cohomology classes $P \in H^p(G,\mathbb{Z}), Q \in H^q(G,\mathbb{Z})$. An integer list representing the cup product $P \cup Q \in H^{p+q}(G,\mathbb{Z})$ is returned.

EXAMPLES: 1, 2

1.9.3 Homology

Homology($C$, $n$) (function)

Homology($F$, $n$) (function)

Homology($K$, $n$) (function)

Homology($K$, $n$) (function)

Homology($K$, $n$) (function)

Homology($K$, $n$) (function)

Homology($K$, $n$) (function)

Inputs a chain complex $C$ and integer $n \geq 0$ and returns the $n$-th homology group of $C$ as a list of its abelian invariants.

Inputs a chain map $F$ and integer $n \geq 0$. It returns the induced homology homomorphism $H_n(F)$ as a homomorphism of finitely presented groups.

Inputs a cubical, or pure cubical, or pure permutahedral or regular CW or simplicial complex $K$ together with an integer $n \geq 0$. It returns the $n$-th integral homology group of $K$ as a list of its abelian invariants.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39
1.10 Visualization

1.10.1 BarCodeDisplay

\[ \text{BarCodeDisplay}(L) \]

Displays a barcode \( L = \text{PERSISTENT_BETTI_NUMBERS}(X,N) \).

\text{EXAMPLES: 1}

1.10.2 BarCodeCompactDisplay

\[ \text{BarCodeCompactDisplay}(L) \]

Displays a barcode \( L = \text{PERSISTENT_BETTI_NUMBERS}(X,N) \) in compact form.

\text{EXAMPLES: 1, 2}

1.10.3 CayleyGraphOfGroup

\[ \text{CayleyGraphOfGroup}(G, L) \]

Inputs a finite group \( G \) and a list \( L \) of elements in \( G \). It displays the Cayley graph of the group generated by \( L \) where edge colours correspond to generators.

\text{EXAMPLES:}

1.10.4 Display

\[ \text{Display}(G) \]
\[ \text{Display}(M) \]
\[ \text{Display}(M) \]

Displays a graph \( G \); a 2- or 3-dimensional pure cubical complex \( M \); a 3-dimensional pure permutohedral complex \( M \).

\text{EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18}

1.10.5 DisplayArcPresentation

\[ \text{DisplayArcPresentation}(K) \]

Displays a 3-dimensional pure cubical knot \( K = \text{PURE_CUBICAL_KNOT}(L) \) in the form of an arc presentation.

\text{EXAMPLES:}

1.10.6 DisplayCSVKnotFile

\[ \text{DisplayCSVKnotFile} \]

Inputs a string \( str \) that identifies a csv file containing the points on a piecewise linear knot in \( \mathbb{R}^3 \). It displays the knot.

\text{EXAMPLES:}
1.10.7 DisplayDendrogram

▷ DisplayDendrogram(L)

Displays the dendrogram \( L := \text{DENDROGRAMMAT}(A, T, S) \).

**EXAMPLES:**

1.10.8 DisplayDendrogramMat

▷ DisplayDendrogramMat(A, t, s)

Inputs an \( n \times n \) symmetric matrix \( A \) over the rationals, a rational \( t \geq 0 \) and an integer \( s \geq 1 \). The dendrogram defined by \( \text{DENDROGRAMMAT}(A, T, S) \) is displayed.

**EXAMPLES:**

1.10.9 DisplayPDBfile

▷ DisplayPDBfile(str)

Displays the protein backbone described in a PDB (Protein Database) file identified by a string \( str \) such as "file.pdb" or "path/file.pdb".

**EXAMPLES:**

1.10.10 OrbitPolytope

▷ OrbitPolytope(G, v, L)

Inputs a permutation group or finite matrix group \( G \) of degree \( d \) and a rational vector \( v \in \mathbb{R}^d \). In both cases there is a natural action of \( G \) on \( \mathbb{R}^d \). Let \( P(G, v) \) be the convex hull of the orbit of \( v \) under the action of \( G \). The function also inputs a sublist \( L \) of the following list of strings: ["dimension", "vertex_degree", "visual_graph", "schlegel", "visual"]

Depending on \( L \), the function displays the following information:
- the dimension of the orbit polytope \( P(G, v) \);
- the degree of a vertex in the graph of \( P(G, v) \);
- a visualization of the graph of \( P(G, v) \);
- a visualization of the Schlegel diagram of \( P(G, v) \);
- a visualization of the polytope \( P(G, v) \) if \( d = 2, 3 \).

The function requires Polymake software.

**EXAMPLES:**

1.10.11 ScatterPlot

▷ ScatterPlot(L)

Inputs a list \( L = [[x_1, y_1], \ldots, [x_n, y_n]] \) of pairs of rational numbers and displays a scatter plot of the points in the \( x-y \)-plane.

**EXAMPLES:**
Chapter 2

Basic functionality for $\mathbb{Z}G$-resolutions and group cohomology

This page covers the functions used in chapter 3 of the book *An Invitation to Computational Homotopy*.

2.1 Resolutions

2.1.1 EquivariantChainMap

\[ \text{EquivariantChainMap}(R, S, f) \]

- Inputs a free $\mathbb{Z}G$-resolution $R$ of $\mathbb{Z}$, a free $\mathbb{Z}Q$-resolution $S$ of $\mathbb{Z}$, and a group homomorphism $f: G \to Q$. It returns the induced $f$-equivariant chain map $F: R \to S$.
- **Examples:** 1, 2, 3

2.1.2 FreeGResolution

\[ \text{FreeGResolution}(P, n) \]

- Inputs a non-free $\mathbb{Z}G$-resolution $P$, and a positive integer $n$. It attempts to return $n$ terms of a free $\mathbb{Z}G$-resolution of $\mathbb{Z}$. However, the stabilizer groups in the non-free resolution must be such that HAP can construct free resolutions with contracting homotopies for them.
- The contracting homotopy on the resolution was implemented by Bui Anh Tuan.
- **Examples:** 1, 2, 3, 4, 5, 6

2.1.3 ResolutionBieberbachGroup

\[ \text{ResolutionBieberbachGroup}(G) \]
\[ \text{ResolutionBieberbachGroup}(G, v) \]

- Inputs a torsion free crystallographic group $G$, also known as a Bieberbach group, represented using `AFFINECRYSTGROUPONRIGHT` as in the GAP package Cryst. It also optionally inputs a choice of vector $v$ in the Euclidean space $\mathbb{R}^n$ on which $G$ acts freely. The function returns $n + 1$ terms of the free $\mathbb{Z}G$-resolution of $\mathbb{Z}$ arising as the cellular chain complex of the tessellation of $\mathbb{R}^n$ by the
Dirichlet-Voronoi fundamental domain determined by \( v \). No contracting homotopy is returned with the resolution.

This function is part of the HAPcryst package written by Marc Roeder and thus requires the HAPcryst package to be loaded.

The function requires the use of Polymake software.

**EXAMPLES:**

2.1.4 ResolutionCubicalCrystGroup

\[ \text{ResolutionCubicalCrystGroup}(G, k) \] (function)

Inputs a crystallographic group \( G \) represented using AFFINECRYSTGROUPONRIGHT as in the GAP package Cryst together with an integer \( k \geq 1 \). The function tries to find a cubical fundamental domain in the Euclidean space \( \mathbb{R}^n \) on which \( G \) acts. If it succeeds it uses this domain to return \( k+1 \) terms of a free \( \mathbb{Z}G \)-resolution of \( \mathbb{Z} \).

This function was written by Bui Anh Tuan.

**EXAMPLES:**

2.1.5 ResolutionFiniteGroup

\[ \text{ResolutionFiniteGroup}(G, k) \] (function)

Inputs a finite group \( G \) and an integer \( k \geq 1 \). It returns \( k+1 \) terms of a free \( \mathbb{Z}G \)-resolution of \( \mathbb{Z} \).

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15

2.1.6 ResolutionNilpotentGroup

\[ \text{ResolutionNilpotentGroup}(G, k) \] (function)

Inputs a nilpotent group \( G \) (which can be infinite) and an integer \( k \geq 1 \). It returns \( k+1 \) terms of a free \( \mathbb{Z}G \)-resolution of \( \mathbb{Z} \).

**EXAMPLES:** 1, 2, 3

2.1.7 ResolutionNormalSeries

\[ \text{ResolutionNormalSeries}(L, k) \] (function)

Inputs a list \( L \) consisting of a chain \( 1 = N_1 \leq N_2 \leq \cdots \leq N_n = G \) of normal subgroups of \( G \), together with an integer \( k \geq 1 \). It returns \( k+1 \) terms of a free \( \mathbb{Z}G \)-resolution of \( \mathbb{Z} \).

**EXAMPLES:** 1, 2, 3, 4, 5

2.1.8 ResolutionPrimePowerGroup

\[ \text{ResolutionPrimePowerGroup}(G, k) \] (function)

Inputs a finite \( p \)-group \( G \) and an integer \( k \geq 1 \). It returns \( k+1 \) terms of a minimal free \( \mathbb{F}G \)-resolution of the field \( \mathbb{F} \) of \( p \) elements.

**EXAMPLES:** 1, 2, 3
2.1.9 ResolutionSL2Z

\[\text{ResolutionSL2Z}(m, k)\]

Inputs positive integers \(m, n\) and returns \(n\) terms of a free \(\mathbb{Z}G\)-resolution of \(\mathbb{Z}\) for the group \(G = SL_2(\mathbb{Z}[1/m])\).

This function is joint work with Bui Anh Tuan.

**EXAMPLES:** 1, 2, 3

2.1.10 ResolutionSmallGroup

\[\text{ResolutionSmallGroup}(G, k)\]

Inputs a small group \(G\) and an integer \(k \geq 1\). It returns \(k + 1\) terms of a free \(\mathbb{Z}G\)-resolution of \(\mathbb{Z}\).

If \(G\) is a finitely presented group then up to degree 2 the resolution coincides with cellular chain complex of the universal cover of the 2 complex associated to the presentation of \(G\). Thus the boundaries of the generators in degree 3 provide a generating set for the module of identities of the presentation.

This function was written by Irina Kholodna.

**EXAMPLES:**

2.1.11 ResolutionSubgroup

\[\text{ResolutionSubgroup}(R, H)\]

Inputs a free \(\mathbb{Z}G\)-resolution of \(\mathbb{Z}\) and a finite index subgroup \(H \leq G\). It returns a free \(\mathbb{Z}H\)-resolution of \(\mathbb{Z}\).

**EXAMPLES:** 1, 2, 3

2.2 Algebras \(\rightarrow\) (Co)chain Complexes

2.2.1 LeibnizComplex

\[\text{LeibnizComplex}(g, n)\]

Inputs a Leibniz algebra, or Lie algebra, \(g\) over a ring \(K\) together with an integer \(n \geq 0\). It returns the first \(n\) terms of the Leibniz chain complex over \(K\). The complex was implemented by Pablo Fernandez Ascariz.

**EXAMPLES:**

2.3 Resolutions \(\rightarrow\) (Co)chain Complexes

2.3.1 HomToIntegers

\[\text{HomToIntegers}(C)\]

\[\text{HomToIntegers}(R)\]
\[ \text{HomToIntegers}(F) \] (function)

Inputs a chain complex \( C \) of free abelian groups and returns the cochain complex \( \text{Hom}_\mathbb{Z}(C, \mathbb{Z}) \).

Inputs a free \( \mathbb{Z}G \)-resolution \( R \) in characteristic 0 and returns the cochain complex \( \text{Hom}_{\mathbb{Z}G}(R, \mathbb{Z}) \).

Inputs an equivariant chain map \( F: R \to S \) of resolutions and returns the induced cochain map \( \text{Hom}_{\mathbb{Z}G}(S, \mathbb{Z}) \to \text{Hom}_{\mathbb{Z}G}(R, \mathbb{Z}) \).

\text{EXAMPLES:} 1, 2, 3, 4, 5, 6

2.3.2 HomToIntegralModule

\[ \text{HomToIntegralModule}(R, A) \] (function)

Inputs a free \( \mathbb{Z}G \)-resolution \( R \) in characteristic 0 and a group homomorphism \( A: G \to \text{GL}_n(\mathbb{Z}) \). The homomorphism \( A \) can be viewed as the \( \mathbb{Z}G \)-module with underlying abelian group \( \mathbb{Z}^n \) on which \( G \) acts via the homomorphism \( A \). It returns the cochain complex \( \text{Hom}_{\mathbb{Z}G}(R, A) \).

\text{EXAMPLES:} 1, 2

2.3.3 TensorWithIntegers

\[ \text{TensorWithIntegers}(R) \] (function)

\[ \text{TensorWithIntegers}(F) \] (function)

Inputs a free \( \mathbb{Z}G \)-resolution \( R \) of characteristic 0 and returns the chain complex \( R \otimes_{\mathbb{Z}G} \mathbb{Z} \).

Inputs an equivariant chain map \( F: R \to S \) in characteristic 0 and returns the induced chain map \( F \otimes_{\mathbb{Z}G} \mathbb{Z}: R \otimes_{\mathbb{Z}G} \mathbb{Z} \to S \otimes_{\mathbb{Z}G} \mathbb{Z} \).

\text{EXAMPLES:} 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26

2.3.4 TensorWithIntegersModP

\[ \text{TensorWithIntegersModP}(C, p) \] (function)

\[ \text{TensorWithIntegersModP}(R, p) \] (function)

\[ \text{TensorWithIntegersModP}(F, p) \] (function)

Inputs a chain complex \( C \) of characteristic 0 and a prime integer \( p \). It returns the chain complex \( C \otimes_{\mathbb{Z}} \mathbb{Z}_p \) of characteristic \( p \).

Inputs a free \( \mathbb{Z}G \)-resolution \( R \) of characteristic 0 and a prime integer \( p \). It returns the chain complex \( R \otimes_{\mathbb{Z}G} \mathbb{Z}_p \) of characteristic \( p \).

Inputs an equivariant chain map \( F: R \to S \) in characteristic 0 a prime integer \( p \). It returns the induced chain map \( F \otimes_{\mathbb{Z}G} \mathbb{Z}_p: R \otimes_{\mathbb{Z}G} \mathbb{Z}_p \to S \otimes_{\mathbb{Z}G} \mathbb{Z}_p \).

\text{EXAMPLES:} 1, 2, 3, 4, 5, 6, 7, 8
2.4 Cohomology rings

2.4.1 AreIsomorphicGradedAlgebras

\[ \text{AreIsomorphicGradedAlgebras}(A, B) \]

Inputs two freely presented graded algebras \( A = \mathbb{F}[x_1, \ldots, x_m]/I \) and \( B = \mathbb{F}[y_1, \ldots, y_n]/J \) and returns \( \text{TRUE} \) if they are isomorphic, and \( \text{FALSE} \) otherwise. This function was implemented by Paul Smith.

\textbf{EXAMPLES:}

2.4.2 HAPDerivation

\[ \text{HAPDerivation}(R, I, L) \]

Inputs a polynomial ring \( R = \mathbb{F}[x_1, \ldots, x_m] \) over a field \( \mathbb{F} \) together with a list \( I \) of generators for an ideal in \( R \) and a list \( L = [y_1, \ldots, y_n] \subset R \). It returns the derivation \( d: E \rightarrow E \) for \( E = R/I \) defined by \( d(x_i) = y_i \). This function was written by Paul Smith. It uses the Singular commutative algebra package.

\textbf{EXAMPLES:}

2.4.3 HilbertPoincareSeries

\[ \text{HilbertPoincareSeries}(E) \]

Inputs a presentation \( E = \mathbb{F}[x_1, \ldots, x_m]/I \) of a graded algebra and returns its Hilbert–Poincaré series. This function was written by Paul Smith and uses the Singular commutative algebra package. It is essentially a wrapper for Singular’s Hilbert–Poincaré series.

\textbf{EXAMPLES:}

2.4.4 HomologyOfDerivation

\[ \text{HomologyOfDerivation}(d) \]

Inputs a derivation \( d: E \rightarrow E \) on a quotient \( E = R/I \) of a polynomial ring \( R = \mathbb{F}[x_1, \ldots, x_m] \) over a field \( \mathbb{F} \). It returns a list \([S, J, h]\) where \( S \) is a polynomial ring and \( J \) is a list of generators for an ideal in \( S \) such that there is an isomorphism \( \alpha: S/J \rightarrow \ker d/\im d \). This isomorphism lifts to the ring homomorphism \( h: S \rightarrow \ker d \). This function was written by Paul Smith. It uses the Singular commutative algebra package.

\textbf{EXAMPLES:}

2.4.5 IntegralCohomologyGenerators

\[ \text{IntegralCohomologyGenerators}(R, n) \]

Inputs at least \( n + 1 \) terms of a free \( \mathbb{Z}G \)-resolution of \( \mathbb{Z} \) and the integer \( n \geq 1 \). It returns a minimal list of cohomology classes in \( H^n(G, \mathbb{Z}) \) which, together with all cup products of lower degree classes, generate the group \( H^n(G, \mathbb{Z}) \). (Let \( a_i \) be the \( i \)-th canonical generator of the \( d \)-generator abelian group
H^n(G, Z). The cohomology class \( n_1a_1 + \ldots + n_da_d \) is represented by the integer vector \( u = (n_1, \ldots, n_d) \).

**EXAMPLES:**

### 2.4.6 LHSSpectralSequence

\( \text{LHSSpectralSequence}(G, N, r) \) (function)

Inputs a finite 2-group \( G \), and normal subgroup \( N \) and an integer \( r \). It returns a list of length \( r \) whose \( i \)-th term is a presentation for the \( i \)-th page of the Lyndon-Hochschild-Serre spectral sequence. This function was written by Paul Smith. It uses the Singular commutative algebra package.

**EXAMPLES:**

### 2.4.7 LHSSpectralSequenceLastSheet

\( \text{LHSSpectralSequenceLastSheet}(G, N) \) (function)

Inputs a finite 2-group \( G \) and normal subgroup \( N \). It returns presentation for the \( E_\infty \) page of the Lyndon-Hochschild-Serre spectral sequence. This function was written by Paul Smith. It uses the Singular commutative algebra package.

**EXAMPLES:**

### 2.4.8 ModPCohomologyGenerators

\( \text{ModPCohomologyGenerators}(G, n) \) (function)

\( \text{ModPCohomologyGenerators}(R) \) (function)

Inputs either a \( p \)-group \( G \) and positive integer \( n \), or else \( n + 1 \) terms of a minimal \( FG \)-resolution \( R \) of the field \( F \) of \( p \) elements. It returns a pair whose first entry is a minimal list of homogeneous generators for the cohomology ring \( A = H^*(G, F) \) modulo all elements in degree greater than \( n \). The second entry of the pair is a function \( \text{DEG} \) which, when applied to a minimal generator, yields its degree. WARNING: the following rule must be applied when multiplying generators \( x_i \) together. Only products of the form \( x_1 \ast (x_2 \ast (x_3 \ast (x_4 \ast \ldots))) \) with \( \text{deg}(x_i) \leq \text{deg}(x_{i+1}) \) should be computed (since the \( x_i \) belong to a structure constant algebra with only a partially defined structure constants table).

**EXAMPLES:** 1

### 2.4.9 ModPCohomologyRing

\( \text{ModPCohomologyRing}(R) \) (function)

\( \text{ModPCohomologyRing}(R, \text{level}) \) (function)

\( \text{ModPCohomologyRing}(G, n) \) (function)

\( \text{ModPCohomologyRing}(G, n, \text{level}) \) (function)

Inputs either a \( p \)-group \( G \) and positive integer \( n \), or else \( n \) terms of a minimal \( FG \)-resolution \( R \) of the field \( F \) of \( p \) elements. It returns the cohomology ring \( A = H^*(G, F) \) modulo all elements in degree greater than \( n \). The ring is returned as a structure constant algebra \( A \). The ring \( A \) is graded. It has a component \( A^! \). \( \text{DEGREE}(x) \) which is a function returning the degree of each (homogeneous) element \( x \).
in \texttt{GeneratorsOfAlgebra}(A). An optional input variable "level" can be set to one of the strings "medium" or "high". These settings determine parameters in the algorithm. The default setting is "medium". When "level" is set to "high" the ring $A$ is returned with a component $A!$.\texttt{NiceBasis}. This component is a pair $[\texttt{Coeff}, \texttt{Bas}]$. Here $\texttt{Bas}$ is a list of integer lists; a "nice" basis for the vector space $A$ can be constructed using the command \texttt{List(Bas,x->Product(List(x,I->Basis(A))[I])}). The coefficients of the canonical basis element $\texttt{Basis(A)}[I]$ are stored as $\texttt{Coeff}[I]$. If the ring $A$ is computed using the setting "level" = "medium" then the component $A!$.\texttt{NiceBasis}$ can be added to $A$ using the command $A:=\texttt{ModPCohomologyRing}_\texttt{Part}_2(A)$.

\textbf{Examples: 1}

\subsection{2.4.10 Mod2CohomologyRingPresentation}

\begin{itemize}
  \item $\texttt{Mod2CohomologyRingPresentation}(G)$  
  \item $\texttt{Mod2CohomologyRingPresentation}(G, n)$  
  \item $\texttt{Mod2CohomologyRingPresentation}(A)$  
  \item $\texttt{Mod2CohomologyRingPresentation}(R)$
\end{itemize}

When applied to a finite 2-group $G$ this function returns a presentation for the mod-2 cohomology ring $H^\ast(G, \mathbb{F})$. The Lyndon-Hochschild-Serre spectral sequence is used to prove that the presentation is complete. When the function is applied to a 2-group $G$ and positive integer $n$ the function first constructs $n + 1$ terms of a free $\mathbb{F}G$-resolution $R$, then constructs the finite-dimensional graded algebra $A = H^{(\ast \leq n)}(G, \mathbb{F})$, and finally uses $A$ to approximate a presentation for $H^\ast(G, \mathbb{F})$. For "sufficiently large" $n$ the approximation will be a correct presentation for $H^\ast(G, \mathbb{F})$. Alternatively, the function can be applied directly to either the resolution $R$ or graded algebra $A$. This function was written by Paul Smith. It uses the Singular commutative algebra package to handle the Lyndon-Hochschild-Serre spectral sequence.

\textbf{Examples: 1, 2}

\section{2.5 Group Invariants}

\subsection{2.5.1 GroupCohomology}

\begin{itemize}
  \item $\texttt{GroupCohomology}(G, k)$  
  \item $\texttt{GroupCohomology}(G, k, p)$
\end{itemize}

Inputs a group $G$ and integer $k \geq 0$. The group $G$ should either be finite or else lie in one of a range of classes of infinite groups (such as nilpotent, crystallographic, Artin etc.). The function returns the list of abelian invariants of $H^k(G, \mathbb{Z})$.

If a prime $p$ is given as an optional third input variable then the function returns the list of abelian invariants of $H^k(G, \mathbb{Z}_p)$. In this case each abelian invariant will be equal to $p$ and the length of the list will be the dimension of the vector space $H^k(G, \mathbb{Z}_p)$.

\textbf{Examples: 1}

\subsection{2.5.2 GroupHomology}

\begin{itemize}
  \item $\texttt{GroupHomology}(G, k)$  
  \item $\texttt{GroupHomology}(G, k, p)$
\end{itemize}
Inputs a group $G$ and integer $k \geq 0$. The group $G$ should either be finite or else lie in one of a range of classes of infinite groups (such as nilpotent, crystallographic, Artin etc.). The function returns the list of abelian invariants of $H_k(G, \mathbb{Z})$.

If a prime $p$ is given as an optional third input variable then the function returns the list of abelian invariants of $H_k(G, \mathbb{Z}_p)$. In this case each abelian invariant will be equal to $p$ and the length of the list will be the dimension of the vector space $H_k(G, \mathbb{Z}_p)$.

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9

### 2.5.3 PrimePartDerivedFunctor

$\triangleright$ **PrimePartDerivedFunctor($G, R, A, k$)** (function)

Inputs a group $G$, an integer $k \geq 0$, at least $k+1$ terms of a free $\mathbb{Z}P$-resolution of $\mathbb{Z}$ for $P$ a Sylow $p$-subgroup of $G$. A function such as $A=TENSORWITHINTEGERS$ is also entered. The abelian invariants of the $p$-primary part $H_k(G,A)_{(p)}$ of the homology with coefficients in $A$ is returned.

**EXAMPLES:** 1, 2, 3

### 2.5.4 PoincareSeries

$\triangleright$ **PoincareSeries($G, n$)** (function)

$\triangleright$ **PoincareSeries($G$)** (function)

$\triangleright$ **PoincareSeries($R, n$)** (function)

$\triangleright$ **PoincareSeries($L, n$)** (function)

Inputs a finite $p$-group $G$ and a positive integer $n$. It returns a quotient of polynomials $f(x) = P(x)/Q(x)$ whose expansion has coefficient of $x^k$ equal to the rank of the vector space $H_k(G, \mathbb{F}_p)$ for all $k$ in the range $1 \leq k \leq n$. (The second input variable can be omitted, in which case the function tries to choose a ‘reasonable’ value for $n$. For 2-groups the function **POINCARESERIESLHS($G$)** can be used to produce an $f(x)$ that is correct in all degrees.) In place of the group $G$ the function can also input (at least $n$ terms of) a minimal mod-$p$ resolution $R$ for $G$. Alternatively, the first input variable can be a list $L$ of integers. In this case the coefficient of $x^k$ in $f(x)$ is equal to the $(k+1)$st term in the list.

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7

### 2.5.5 PoincareSeries

$\triangleright$ **PoincareSeries($G, n$)** (function)

$\triangleright$ **PoincareSeries($G$)** (function)

$\triangleright$ **PoincareSeries($R, n$)** (function)

$\triangleright$ **PoincareSeries($L, n$)** (function)

Inputs a finite $p$-group $G$ and a positive integer $n$. It returns a quotient of polynomials $f(x) = P(x)/Q(x)$ whose expansion has coefficient of $x^k$ equal to the rank of the vector space $H_k(G, \mathbb{F}_p)$ for all $k$ in the range $1 \leq k \leq n$. (The second input variable can be omitted, in which case the function tries to choose a ‘reasonable’ value for $n$. For 2-groups the function **POINCARESERIESLHS($G$)** can be used to produce an $f(x)$ that is correct in all degrees.) In place of the group $G$ the function can also
input (at least \( n \) terms of) a minimal mod-\( p \) resolution \( R \) for \( G \). Alternatively, the first input variable can be a list \( L \) of integers. In this case the coefficient of \( x^k \) in \( f(x) \) is equal to the \((k + 1)\)st term in the list.

**EXAMPLES:** \(1, 2, 3, 4, 5, 6, 7\)

### 2.5.6 RankHomologyPGroup

\[\text{RankHomologyPGroup}(G, P, n)\]

Inputs a \( p \)-group \( G \), a rational function \( P \) representing the Poincaré series of the mod-\( p \) cohomology of \( G \) and a positive integer \( n \). It returns the minimum number of generators for the finite abelian \( p \)-group \( H_n(G, \mathbb{Z}) \).

**EXAMPLES:**

### 2.6 \( \mathbb{F}_p \)-modules

#### 2.6.1 GroupAlgebraAsFpGModule

\[\text{GroupAlgebraAsFpGModule}(G)\]

Inputs a finite \( p \)-group \( G \) and returns the modular group algebra \( \mathbb{F}_p G \) in the form of an \( \mathbb{F}_p G \)-module.

**EXAMPLES:**

#### 2.6.2 Radical

\[\text{Radical}(M)\]

Inputs an \( \mathbb{F}_p G \)-module and returns its radical.

**EXAMPLES:**

#### 2.6.3 RadicalSeries

\[\text{RadicalSeries}(M)\], \[\text{RadicalSeries}(R)\]

Inputs an \( \mathbb{F}_p G \)-module \( M \) and returns its radical series as a list of \( \mathbb{F}_p G \)-modules.

Inputs a free \( \mathbb{F}_p G \)-resolution \( R \) and returns the filtered chain complex \( \cdots \text{Rad}_2(\mathbb{F}_p G)R \leq \text{Rad}_1(\mathbb{F}_p G)R \leq R \).

**EXAMPLES:**
Chapter 3

Basic functionality for homological group theory

This page covers the functions used in chapter 4 of the book An Invitation to Computational Homotopy.

3.1 Cocycles

3.1.1 CcGroup

\[ \text{CcGroup}(N, f) \]

Inputs a \( G \)-outer group \( N \) with nonabelian cocycle describing some extension \( N \rightarrow E \rightarrow G \) together with standard 2-cocycle \( f: G \times G \rightarrow A \) where \( A = \mathbb{Z}(N) \). It returns the extension group determined by the cocycle \( f \). The group is returned as a cocyclic group.

This function is part of the HAPcocyclic package of functions implemented by Robert F. Morse.

EXAMPLES: 1

3.1.2 CocycleCondition

\[ \text{CocycleCondition}(R, n) \]

\[ \text{CocycleCondition}(R, f, n, q) \]

Inputs a free \( \mathbb{Z}G \)-resolution \( R \) of \( \mathbb{Z} \) and an integer \( n \geq 1 \). It returns an integer matrix \( M \) with the following property. Let \( d \) be the \( \mathbb{Z}G \)-rank of \( R_n \). An integer vector \( f = [f_1, \ldots, f_d] \) then represents a \( \mathbb{Z}G \)-homomorphism \( R_n \rightarrow \mathbb{Z}_q \) which sends the \( i \)th generator of \( R_n \) to the integer \( f_i \) in the trivial \( \mathbb{Z}G \)-module \( \mathbb{Z}_q = \mathbb{Z}/q\mathbb{Z} \) (where possibly \( q = 0 \)). The homomorphism \( f \) is a cocycle if and only if \( Mf = 0 \) mod \( q \).

EXAMPLES: 1

3.1.3 StandardCocycle

\[ \text{StandardCocycle}(R, f, n) \]

\[ \text{StandardCocycle}(R, f, n, q) \]
Inputs a free $\mathbb{Z}G$-resolution $R$ (with contracting homotopy), a positive integer $n$ and an integer vector $f$ representing an $n$-cocycle $R_n \to \mathbb{Z}_q = \mathbb{Z}/q\mathbb{Z}$ where $G$ acts trivially on $\mathbb{Z}_q$. It is assumed $q = 0$ unless a value for $q$ is entered. The command returns a function $F(g_1, \ldots, g_n)$ which is the standard cocycle $G^n \to \mathbb{Z}_q$ corresponding to $f$. At present the command is implemented only for $n = 2$ or 3.

**Examples:** 1

### 3.2 G-Outer Groups

#### 3.2.1 ActedGroup

▶ ActedGroup($M$)  

*function*

Inputs a $G$-outer group $M$ corresponding to a homomorphism $\alpha: G \to \text{Out}(N)$ and returns the group $N$.

**Examples:** 1, 2

#### 3.2.2 ActingGroup

▶ ActingGroup($M$)  

*function*

Inputs a $G$-outer group $M$ corresponding to a homomorphism $\alpha: G \to \text{Out}(N)$ and returns the group $G$.

**Examples:** 1

#### 3.2.3 Centre

▶ Centre($M$)  

*function*

Inputs a $G$-outer group $M$ and returns its group-theoretic centre as a $G$-outer group.

**Examples:** 1, 2, 3, 4

#### 3.2.4 GOuterGroup

▶ GOuterGroup($E, N$)  

*function*

▶ GOuterGroup()  

*function*

Inputs a group $E$ and normal subgroup $N$. It returns $N$ as a $G$-outer group where $G = E/N$. A nonabelian cocycle $f: G \times G \to N$ is attached as a component of the $G$-Outer group.

The function can be used without an argument. In this case an empty outer group $C$ is returned. The components must be set using \texttt{SETACTINGGROUP}(C,G), \texttt{SETACTEDGROUP}(C,N) and \texttt{SETOUTERACTION}(C,\alpha).

**Examples:** 1, 2
3.3 $G$-cocomplexes

3.3.1 CohomologyModule

\[ \text{CohomologyModule}(C, n) \] (function)

Inputs a $G$-cocomplex $C$ together with a non-negative integer $n$. It returns the cohomology $H^n(C)$ as a $G$-outer group. If $C$ was constructed from a $\mathbb{Z}G$-resolution $R$ by homing to an abelian $G$-outer group $A$ then, for each $x$ in $H := \text{CohomologyModule}(C, n)$, there is a function $f := H!.\text{representativeCocycle}(x)$ which is a standard $n$-cocycle corresponding to the cohomology class $x$. (At present this is implemented only for $n = 1, 2, 3$.)

EXAMPLES: 1, 2

3.3.2 HomToGModule

\[ \text{HomToGModule}(R, A) \] (function)

Inputs a $\mathbb{Z}G$-resolution $R$ and an abelian $G$-outer group $A$. It returns the $G$-cocomplex obtained by applying $\text{HomZG}(\_, A)$. (At present this function does not handle equivariant chain maps.)

EXAMPLES: 1, 2
Chapter 4

Basic functionality for parallel computation

This page covers the functions used for parallel computation in the book An Invitation to Computational Homotopy.

4.1 Six Core Functions

4.1.1 ChildCreate

Starts a GAP session as a child process and returns a stream to the child process. If no argument is given then the child process is created on the local machine; otherwise the argument should be: (1) \( \text{str} = "\text{computer.address.ie}" \) the address of a remote computer for which ssh has been configured to require no password from the user; (2) \( \text{str} = ["\text{-m", "100000M", "-T"] \) a list of GAP command line options; (3) \( \text{str} = "\text{computer.ac.wales", ["\text{-m", "100000M", "-T"] \) the address of a computer followed by a list of command line options.

EXAMPLES:

4.1.2 ChildCreate
options; (3) \texttt{str}="computer.ac.wales", \texttt{["-m", "100000M", ",-T"]} the address of a computer followed by a list of command line options.

\textbf{EXAMPLES}:
Chapter 5

Resolutions of the ground ring

5.1

5.1.1 TietzeReducedResolution

\[ \text{TietzeReducedResolution}(R) \]

Inputs a \( \mathbb{Z}G \)-resolution \( R \) and returns a \( \mathbb{Z}G \)-resolution \( S \) which is obtained from \( R \) by applying "Tietze like operations" in each dimension. The hope is that \( S \) has fewer free generators than \( R \).

EXAMPLES: 1

5.1.2 ResolutionArithmeticGroup

\[ \text{ResolutionArithmeticGroup}(P, n) \]

Inputs a positive integer \( n \) and a string \( P \) equal to one of the following:


or the string

"GL(2,O(-d))"

for \( d=1, 2, 3, 5, 6, 7, 10, 11, 13, 14, 15, 17, 19, 21, 22, 23, 26, 43 \)

or the string

"SL(2,O(-d))"

for \( d=2, 3, 5, 7, 10, 11, 13, 14, 15, 17, 19, 21, 22, 23, 26, 43, 67, 163 \)

or the string

"SL(2,O(-d))_a"
for d=2, 7, 11, 19.

It returns n terms of a free ZG-resolution for the group G described by the string. Here O(-d)

\[ O(-d) \]

denotes the ring of integers of \( \mathbb{Q}(\sqrt{-d}) \) and subscripts \( _a, _b, _c, _d \) denote alternative non-free ZG-resolutions for a given group G.

Data for the first list of resolutions was provided provided by MATHIEU DUTOUR. Data for GL(2,O(-d)) was provided by SEBASTIAN SCHOENNENBECK. Data for SL(2,O(-d)) was provided by SEBASTIAN SCHOENNENBECK for d <= 26 and by ALEXANDER RAHM for d>26 and for the alternative complexes.

**EXAMPLES:**

1

5.1.3 FreeGResolution

\[ \texttt{FreeGResolution}(P, n) \] (function)

\[ \texttt{FreeGResolution}(P, n, p) \] (function)

Inputs a non-free ZG-resolution P with finite stabilizer groups, and a positive integer n. It returns a free ZG-resolution of length equal to the minimum of n and the length of P. If one requires only a mod p resolution then the prime p can be entered as an optional third argument.

The free resolution is returned without a contracting homotopy.

**EXAMPLES:** 1, 2, 3, 4, 5, 6

5.1.4 ResolutionGTree

\[ \texttt{ResolutionGTree}(P, n) \] (function)

Inputs a non-free ZG-resolution P of dimension 1 (i.e. a G-tree) with finite stabilizer groups, and a positive integer n. It returns a free ZG-resolution of length equal to n.

If P has a contracting homotopy then the free resolution is returned with a contracting homotopy.

This function was written by BUI ANH TUAN.

**EXAMPLES:**

5.1.5 ResolutionSL2Z

\[ \texttt{ResolutionSL2Z}(p, n) \] (function)

Inputs positive integers m, n and returns n terms of a ZG-resolution for the group \( G = SL(2,\mathbb{Z}[1/m]) \).

This function is joint work with BUI ANH TUAN.

**EXAMPLES:** 1, 2, 3

5.1.6 ResolutionAbelianGroup

\[ \texttt{ResolutionAbelianGroup}(L, n) \] (function)

\[ \texttt{ResolutionAbelianGroup}(G, n) \] (function)
Inputs a list \( L := [m_1, m_2, ..., m_d] \) of nonnegative integers, and a positive integer \( n \). It returns \( n \) terms of a \( \mathbb{Z}G \)-resolution for the abelian group \( G = \mathbb{Z}_{L[1]} + \mathbb{Z}_{L[2]} + + \mathbb{Z}_{L[d]} \).

If \( G \) is finite then the first argument can also be the abelian group \( G \) itself.

**EXAMPLES:** 1, 2

### 5.1.7 ResolutionAlmostCrystalGroup

\[ \triangleright \text{ResolutionAlmostCrystalGroup}(G, n) \]  

Inputs a positive integer \( n \) and an almost crystallographic pcp group \( G \). It returns \( n \) terms of a free \( \mathbb{Z}G \)-resolution. (A group is almost crystallographic if it is nilpotent-by-finite and has no non-trivial finite normal subgroup. Such groups can be constructed using the ACLIB package.)

**EXAMPLES:** 1

### 5.1.8 ResolutionAlmostCrystalQuotient

\[ \triangleright \text{ResolutionAlmostCrystalQuotient}(G, n, c) \]  
\[ \triangleright \text{ResolutionAlmostCrystalQuotient}(G, n, c, false) \]

An almost crystallographic group \( G \) is an extension of a finite group \( P \) by a nilpotent group \( T \), and has no non-trivial finite normal subgroup. We define the relative lower central series by setting \( T_1 = T \) and \( T_{i+1} = [T_i, G] \).

This function inputs an almost crystallographic group \( G \) together with positive integers \( n \) and \( c \). It returns \( n \) terms of a free \( \mathbb{Z}Q \)-resolution \( R \) for the group \( Q = G/T_c \).

In addition to the usual components, the resolution \( R \) has the component \( R.quotientHomomorphism \) which gives the quotient homomorphism \( G \rightarrow Q \).

If a fourth optional variable is set equal to "false" then the function omits to test whether \( Q \) is finite and a "more canonical" resolution is constructed.

**EXAMPLES:** 1

### 5.1.9 ResolutionArtinGroup

\[ \triangleright \text{ResolutionArtinGroup}(D, n) \]

Inputs a Coxeter diagram \( D \) and an integer \( n > 1 \). It returns \( n \) terms of a free \( \mathbb{Z}G \)-resolution \( R \) where \( G \) is the Artin monoid associated to \( D \). It is conjectured that \( R \) is also a free resolution for the Artin group \( G \). The conjecture is known to hold in certain cases.

\( G = R.group \) is infinite and returned as a finitely presented group. The list \( R.elts \) is a partial listing of the elements of \( G \) which grows as \( R \) is used. Initially \( R.elts \) is empty and then, any time the boundary of a resolution generator is called, \( R.elts \) is updated to include elements of \( G \) involved in the boundary.

The contracting homotopy on \( R \) has not yet been implemented! Furthermore, the group \( G \) is currently returned only as a finitely presented group (without any method for solving the word problem).

**EXAMPLES:** 1, 2, 3, 4
5.1.10 ResolutionAsphericalPresentation

\[ \text{ResolutionAsphericalPresentation}(F, R, n) \]

Inputs a free group \( F \), a set \( R \) of words in \( F \) which constitute an aspherical presentation for a group \( G \), and a positive integer \( n \). (Asphericity can be a difficult property to verify. The function \text{IsAspherical}(F, R) \) could be of help.)

The function returns \( n \) terms of a free \( \mathbb{Z}G \)-resolution \( R \) which has generators in dimensions \(< 3\) only. No contracting homotopy on \( R \) will be returned.

\text{EXAMPLES}: 1

5.1.11 ResolutionBieberbachGroup

\[ \text{ResolutionBieberbachGroup}(G) \]
\[ \text{ResolutionBieberbachGroup}(G, v) \]

Inputs a torsion free crystallographic group \( G \), also known as a Bieberbach group, represented using \text{AffineCrystGroupOnRight} as in the GAP package \text{Cryst}. It also optionally inputs a choice of vector \( v \) in the euclidean space \( \mathbb{R}^n \) on which \( G \) acts freely. The function returns \( n + 1 \) terms of the free \( \mathbb{Z}G \)-resolution of \( \mathbb{Z} \) arising as the cellular chain complex of the tesselation of \( \mathbb{R}^n \) by the Dirichlet-Voronoi fundamental domain determined by \( v \).

This function is part of the HAPcryst package written by MARC ROEDER and thus requires the HAPcryst package to be loaded.

The function requires the use of Polymake software.

\text{EXAMPLES}:

5.1.12 ResolutionCoxeterGroup

\[ \text{ResolutionCoxeterGroup}(D, n) \]

Inputs a Coxeter diagram \( D \) and an integer \( n > 1 \). It returns \( k \) terms of a free \( \mathbb{Z}G \)-resolution \( R \) where \( G \) is the Coxeter group associated to \( D \). Here \( k \) is the maximum of \( n \) and the number of vertices in the Coxeter diagram. At present the implementation is only for finite Coxeter groups and the group \( G \) is returned as a permutation group. The contracting homotopy on \( R \) has not yet been implemented!

\text{EXAMPLES}: 1, 2

5.1.13 ResolutionDirectProduct

\[ \text{ResolutionDirectProduct}(R, S) \]
\[ \text{ResolutionDirectProduct}(R, S, \text{str}) \]

Inputs a \( \mathbb{Z}G \)-resolution \( R \) and \( \mathbb{Z}H \)-resolution \( S \). It outputs a \( \mathbb{Z}D \)-resolution for the direct product \( D = GxH \).

If \( G \) and \( H \) lie in a common group \( K \), and if they commute and have trivial intersection, then an optional third variable \text{str}="internal" can be used. This will force \( D \) to be the subgroup \( GH \) in \( K \).

\text{EXAMPLES}: 1
5.1.14 ResolutionExtension

\[ \text{ResolutionExtension}(g, R, S) \] (function)

\[ \text{ResolutionExtension}(g, R, S, \text{str}) \] (function)

\[ \text{ResolutionExtension}(g, R, S, \text{str}, \text{GmapE}) \] (function)

Inputs a surjective group homomorphism \( g : E \rightarrow G \) with kernel \( N \). It also inputs a \( ZN \)-resolution \( R \) and a \( ZG \)-resolution \( S \). It returns a \( ZE \)-resolution. The groups \( E \) and \( G \) can be infinite.

If an optional fourth argument \( \text{str} \) is set equal to "TestFiniteness" then the groups \( N \) and \( G \) will be tested to see if they are finite. If they are finite then some speed saving routines will be invoked. One can also set \( \text{str} = "NoTest" \).

If the homomorphism \( g \) is such that the GAP function \( \text{PreImagesElement}(g, x) \) doesn’t work, then a function \( \text{GmapE}(x) \) should be included as a fifth input. For any \( x \) in \( G \) this function should return an element \( \text{GmapE}(x) \) in \( E \) which gets mapped onto \( x \) by \( g \).

The contracting homotopy on the \( ZE \)-resolution has not yet been fully implemented for infinite groups!

Examples: 1, 2

5.1.15 ResolutionFiniteDirectProduct

\[ \text{ResolutionFiniteDirectProduct}(R, S) \] (function)

\[ \text{ResolutionFiniteDirectProduct}(R, S, \text{str}) \] (function)

Inputs a \( ZG \)-resolution \( R \) and \( ZH \)-resolution \( S \) where \( G \) and \( H \) are finite groups. It outputs a \( ZD \)-resolution for the direct product \( D = G \times H \).

If \( G \) and \( H \) lie in a common group \( K \), and if they commute and have trivial intersection, then an optional third variable \( \text{str} = "internal" \) can be used. This will force \( D \) to be the subgroup \( GH \) in \( K \).

Examples:

5.1.16 ResolutionFiniteExtension

\[ \text{ResolutionFiniteExtension}(\text{gensE}, \text{gensG}, R, n) \] (function)

\[ \text{ResolutionFiniteExtension}(\text{gensE}, \text{gensG}, R, n, \text{true}) \] (function)

\[ \text{ResolutionFiniteExtension}(\text{gensE}, \text{gensG}, R, n, \text{false}, S) \] (function)

Inputs: a set \( \text{gensE} \) of generators for a finite group \( E \); a set \( \text{gensG} \) equal to the image of \( \text{gensE} \) in a quotient group \( G \) of \( E \); a \( ZG \)-resolution \( R \) up to dimension at least \( n \); a positive integer \( n \). It uses the \( \text{TwistedTensorProduct}() \) construction to return \( n \) terms of a \( ZE \)-resolution.

The function has an optional fourth argument which, when set equal to "true", invokes tietze reductions in the construction of a resolution for the kernel of \( E \rightarrow G \).

If a \( ZN \)-resolution \( S \) is available, where \( N \) is the kernel of the quotient \( E \rightarrow G \), then this can be incorporated into the computations using an optional fifth argument.

Examples: 1, 2

5.1.17 ResolutionFiniteGroup

\[ \text{ResolutionFiniteGroup}(\text{gens}, n) \] (function)

\[ \text{ResolutionFiniteGroup}(\text{gens}, n, \text{true}) \] (function)
Inputs a set \( \text{gens} \) of generators for a finite group \( G \) and a positive integer \( n \). It outputs \( n \) terms of a \( \mathbb{Z}G \)-resolution.

The function has an optional third argument which, when set equal to \( \text{true} \), invokes tietze reductions in the construction of the resolution.

The function has an optional fourth argument which, when set equal to a prime \( p \), records the fact that the resolution will only be used for mod \( p \) calculations. This could speed up subsequent constructions.

The function has an optional fifth argument \( \text{str} \) which, when set equal to "extendible", returns a resolution whose length can be increased using the command \( R!\text{extend}() \).

**Examples:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15

### 5.1.18 ResolutionFiniteSubgroup

- \( \text{ResolutionFiniteSubgroup}(R, K) \) (function)
- \( \text{ResolutionFiniteSubgroup}(R, \text{gensG}, \text{gensK}) \) (function)

Inputs a \( \mathbb{Z}G \)-resolution for a finite group \( G \) and a subgroup \( K \) of index \( |G:K| \). It returns a free \( \mathbb{Z}K \)-resolution whose \( \mathbb{Z}K \)-rank is \( |G:K| \) times the \( \mathbb{Z}G \)-rank in each dimension.

Generating sets \( \text{gensG}, \text{gensK} \) for \( G \) and \( K \) can also be input to the function (though the method does not depend on a choice of generators).

This \( \mathbb{Z}K \)-resolution is not reduced. i.e. it has more than one generator in dimension 0.

**Examples:** 1, 2, 3

### 5.1.19 ResolutionGraphOfGroups

- \( \text{ResolutionGraphOfGroups}(D, n) \) (function)
- \( \text{ResolutionGraphOfGroups}(D, n, L) \) (function)

Inputs a graph of groups \( D \) and a positive integer \( n \). It returns \( n \) terms of a free \( \mathbb{Z}G \)-resolution for the fundamental group \( G \) of \( D \).

An optional third argument \( L = [R_1, \ldots, R_t] \) can be used to list (in any order) free resolutions for some/all of the vertex and edge groups in \( D \). If for some vertex or edge group no resolution is listed in \( L \) then the function \( \text{ResolutionFiniteGroup()} \) will be used to try to construct the resolution.

The \( \mathbb{Z}G \)-resolution is usually not reduced. i.e. it has more than one generator in dimension 0.

The contracting homotopy on the \( \mathbb{Z}G \)-resolution has not yet been implemented! Furthermore, the group \( G \) is currently returned only as a finitely presented group (without any method for solving the word problem).

**Examples:** 1, 2

### 5.1.20 ResolutionNilpotentGroup

- \( \text{ResolutionNilpotentGroup}(G, n) \) (function)
- \( \text{ResolutionNilpotentGroup}(G, n, \text{str}) \) (function)
Inputs a nilpotent group \( G \) and positive integer \( n \). It returns \( n \) terms of a free \( ZG \)-resolution. The resolution is computed using a divide-and-conquer technique involving the lower central series.

This function can be applied to infinite groups \( G \). For finite groups the function \( \text{ResolutionNormalSeries()} \) probably gives better results.

If an optional third argument \( str \) is set equal to "TestFiniteness" then the groups \( N \) and \( G \) will be tested to see if they are finite. If they are finite then some speed saving routines will be invoked.

The contracting homotopy on the \( ZE \)-resolution has not yet been fully implemented for infinite groups.

**Examples:** 1, 2, 3

5.1.21 **ResolutionNormalSeries**

\[ \text{ResolutionNormalSeries}(L, n) \] (function)
\[ \text{ResolutionNormalSeries}(L, n, true) \] (function)
\[ \text{ResolutionNormalSeries}(L, n, false, p) \] (function)

Inputs a positive integer \( n \) and a list \( L = [L_1, \ldots, L_k] \) of normal subgroups \( L_i \) of a finite group \( G \) satisfying \( G = L_1 > L_2 > \ldots > L_k \). Alternatively, \( L = [\text{gensL}_1, \ldots, \text{gensL}_k] \) can be a list of generating sets for the \( L_i \) (and these particular generators will be used in the construction of resolutions). It returns a \( ZG \)-resolution by repeatedly using the function \( \text{ResolutionFiniteExtension()} \).

The function has an optional third argument which, if set equal to true, invokes tietze reductions in the construction of resolutions.

The function has an optional fourth argument which, if set equal to \( p > 0 \), produces a resolution which is only valid for mod \( p \) calculations.

**Examples:** 1, 2, 3, 4, 5

5.1.22 **ResolutionPrimePowerGroup**

\[ \text{ResolutionPrimePowerGroup}(P, n) \] (function)
\[ \text{ResolutionPrimePowerGroup}(G, n, p) \] (function)

Inputs a \( p \)-group \( P \) and integer \( n > 0 \). It uses GAP’s standard linear algebra functions over the field \( F \) of \( p \) elements to construct a free \( FP \)-resolution for mod \( p \) calculations only. The resolution is minimal - meaning that the number of generators of \( R_n \) equals the rank of \( H_n(P, F) \).

The function can also be used to obtain a free non-minimal \( FG \)-resolution of a small group \( G \) of non-prime-power order. In this case the prime \( p \) must be entered as the third input variable. (In the non-prime-power case the algorithm is naive and not very good.)

**Examples:** 1, 2, 3

5.1.23 **ResolutionSmallFpGroup**

\[ \text{ResolutionSmallFpGroup}(G, n) \] (function)
\[ \text{ResolutionSmallFpGroup}(G, n, p) \] (function)

Inputs a small finitely presented group \( G \) and an integer \( n > 0 \). It returns \( n \) terms of a \( ZG \)-resolution which, in dimensions 1 and 2, corresponds to the given presentation for \( G \). The method returns no contracting homotopy for the resolution.
The function has an optional fourth argument which, when set equal to a prime $p$, records the fact that the resolution will only be used for mod $p$ calculations. This could speed up subsequent constructions.

This function was written by Irina Kholodna.

**EXAMPLES:** 1, 2

### 5.1.24 ResolutionSubgroup

- **Function:** ResolutionSubgroup($R, K$)

Inputs a $\mathbb{Z}G$-resolution for an (infinite) group $G$ and a subgroup $K$ of finite index $|G : K|$. It returns a free $\mathbb{Z}K$-resolution whose $\mathbb{Z}K$-rank is $|G : K|$ times the $\mathbb{Z}G$-rank in each dimension.

If $G$ is finite then the function ResolutionFiniteSubgroup($R, G, K$) will probably work better. In particular, resolutions from this function probably won't work with the function EquivariantChainMap(). This $\mathbb{Z}K$-resolution is not reduced, i.e. it has more than one generator in dimension 0.

**EXAMPLES:** 1, 2, 3

### 5.1.25 ResolutionSubnormalSeries

- **Function:** ResolutionSubnormalSeries($L, n$)

Inputs a positive integer $n$ and a list $L = [L_1, \ldots, L_k]$ of subgroups $L_i$ of a finite group $G = L_1$ such that $L_1 > L_2 \ldots > L_k$ is a subnormal series in $G$ (meaning that each $L_{i+1}$ must be normal in $L_i$). It returns a $\mathbb{Z}G$-resolution by repeatedly using the function ResolutionFiniteExtension().

If $L$ is a series of normal subgroups in $G$ then the function ResolutionNormalSeries($L, n$) will possibly work more efficiently.

**EXAMPLES:** 1

### 5.1.26 TwistedTensorProduct

- **Function:** TwistedTensorProduct($R, S, E\text{hom}G, G\text{map}E, N\text{hom}E, NE\text{hom}N, EltsE, Mult, InvE$)

Inputs a $\mathbb{Z}G$-resolution $R$, a $\mathbb{Z}N$-resolution $S$, and other data relating to a short exact sequence $1 \rightarrow N \rightarrow E \rightarrow G \rightarrow 1$. It uses a perturbation technique of CTC Wall to construct a $\mathbb{Z}E$-resolution $F$. Both $G$ and $N$ could be infinite. The "length" of $F$ is equal to the minimum of the "length"s of $R$ and $S$. The resolution $R$ needs no contracting homotopy if no such homotopy is required for $F$.

**EXAMPLES:** 1

### 5.1.27 ConjugatedResolution

- **Function:** ConjugatedResolution($R, x$)

Inputs a $\mathbb{Z}G$-resolution $R$ and an element $x$ from some group containing $G$. It returns a $\mathbb{Z}G^x$-resolution $S$ where the group $G^x$ is the conjugate of $G$ by $x$. (The component $S! \text{elts}$ will be a pseudolist rather than a list.)

**EXAMPLES:**
5.1.28 RecalculateIncidenceNumbers

▷ RecalculateIncidenceNumbers(R) (function)

Inputs a ZG-resolution $R$ which arises as the cellular chain complex of a regular CW-complex. (Thus the boundary of any cell is a list of distinct cells.) It recalculates the incidence numbers for $R$. If it is applied to a resolution that is not regular then a wrong answer may be returned.

EXAMPLES:
Chapter 6

Resolutions of modules

6.1

6.1.1 ResolutionFpGModule

\[ \text{ResolutionFpGModule}(M, n) \]

Inputs an \( FpG \)-module \( M \) and a positive integer \( n \). It returns \( n \) terms of a minimal free \( FG \)-resolution of the module \( M \) (where \( G \) is a finite group and \( F \) the field of \( p \) elements).

**EXAMPLES:** 1, 2
Chapter 7

Induced equivariant chain maps

7.1

7.1.1 EquivariantChainMap

\[ \text{EquivariantChainMap}(R, S, f) \]

(function)

Inputs a $\mathbb{Z}G$-resolution $R$, a $\mathbb{Z}G'$-resolution $S$, and a group homomorphism $f : G \rightarrow G'$. It outputs a component object $M$ with the following components.

- $M!.source$ is the resolution $R$.
- $M!.target$ is the resolution $S$.
- $M!.mapping(w, n)$ is a function which gives the image in $S_n$, under a chain map induced by $f$, of a word $w$ in $R_n$. (Here $R_n$ and $S_n$ are the $n$-th modules in the resolutions $R$ and $S$.)
- $M!.properties$ is a list of pairs such as ["type", "equivariantChainMap"].

The resolution $S$ must have a contracting homotopy.

EXAMPLES: 1, 2, 3
Chapter 8

Functors

8.1

8.1.1 ExtendScalars

\[ \text{ExtendScalars}(R, G, \text{EltsG}) \]

Inputs a \( ZH \)-resolution \( R \), a group \( G \) containing \( H \) as a subgroup, and a list \( \text{EltsG} \) of elements of \( G \). It returns the free \( ZG \)-resolution \( (R \otimes_{ZH} ZG) \). The returned resolution \( S \) has \( S!.elts:=\text{EltsG} \). This is a resolution of the \( ZG \)-module \( (Z \otimes_{ZH} ZG) \). (Here \( \otimes_{ZH} \) means tensor over \( ZH \).

**EXAMPLES:**

8.1.2 HomToIntegers

\[ \text{HomToIntegers}(X) \]

Inputs either a \( ZG \)-resolution \( X = R \), or an equivariant chain map \( X = (F : R \rightarrow S) \). It returns the cochain complex or cochain map obtained by applying \( \text{HomZG}(Z) \) where \( Z \) is the trivial module of integers (characteristic 0).

**EXAMPLES:** 1, 2, 3, 4, 5, 6

8.1.3 HomToIntegersModP

\[ \text{HomToIntegersModP}(R) \]

Inputs a \( ZG \)-resolution \( R \) and returns the cochain complex obtained by applying \( \text{HomZG}(Z_p) \) where \( Z_p \) is the trivial module of integers mod \( p \). (At present this functor does not handle equivariant chain maps.)

**EXAMPLES:** 1, 2, 3

8.1.4 HomToIntegralModule

\[ \text{HomToIntegralModule}(R, f) \]

(function)
Inputs a $\mathbb{Z}G$-resolution $R$ and a group homomorphism $f : G \rightarrow GL_n(\mathbb{Z})$ to the group of $n \times n$ invertible integer matrices. Here $\mathbb{Z}$ must have characteristic 0. It returns the cochain complex obtained by applying $\text{Hom}_{\mathbb{Z}G}(A)$ where $A$ is the $\mathbb{Z}G$-module $\mathbb{Z}^n$ with $G$ action via $f$. (At present this function does not handle equivariant chain maps.)

**EXAMPLES:** 1, 2

### 8.1.5 TensorWithIntegralModule

\[ \text{\textbackslash TensorWithIntegralModule}(R, f) \]

Inputs a $\mathbb{Z}G$-resolution $R$ and a group homomorphism $f : G \rightarrow GL_n(\mathbb{Z})$ to the group of $n \times n$ invertible integer matrices. Here $\mathbb{Z}$ must have characteristic 0. It returns the chain complex obtained by tensoring over $\mathbb{Z}G$ with the $\mathbb{Z}G$-module $A = \mathbb{Z}^n$ with $G$ action via $f$. (At present this function does not handle equivariant chain maps.)

**EXAMPLES:**

### 8.1.6 HomToGModule

\[ \text{\textbackslash HomToGModule}(R, A) \]

Inputs a $\mathbb{Z}G$-resolution $R$ and an abelian $G$-outer group $A$. It returns the $G$-cocomplex obtained by applying $\text{Hom}_{\mathbb{Z}G}(A)$. (At present this function does not handle equivariant chain maps.)

**EXAMPLES:** 1, 2

### 8.1.7 InduceScalars

\[ \text{\textbackslash InduceScalars}(R, \text{hom}) \]

Inputs a $\mathbb{Z}Q$-resolution $R$ and a surjective group homomorphism $\text{hom} : G \rightarrow Q$. It returns the unduced non-free $\mathbb{Z}G$-resolution.

**EXAMPLES:**

### 8.1.8 LowerCentralSeriesLieAlgebra

\[ \text{\textbackslash LowerCentralSeriesLieAlgebra}(G) \]

\[ \text{\textbackslash LowerCentralSeriesLieAlgebra}(f) \]

Inputs a pcp group $G$. If each quotient $G_c/G_{c+1}$ of the lower central series is free abelian or $p$-elementary abelian (for fixed prime $p$) then a Lie algebra $L(G)$ is returned. The abelian group underlying $L(G)$ is the direct sum of the quotients $G_c/G_{c+1}$. The Lie bracket on $L(G)$ is induced by the commutator in $G$. (Here $G_1 = G$, $G_{c+1} = [G_c, G]$.)

The function can also be applied to a group homomorphism $f : G \rightarrow G'$. In this case the induced homomorphism of Lie algebras $L(f) : L(G) \rightarrow L(G')$ is returned.

If the quotients of the lower central series are not all free or $p$-elementary abelian then the function returns fail.

This function was written by Pablo Fernandez Ascariz

**EXAMPLES:** 1, 2
8.1.9 TensorWithIntegers

\[ \text{TensorWithIntegers}(X) \]

Inputs either a \( \mathbb{Z}G \)-resolution \( X = R \), or an equivariant chain map \( X = (F : R \rightarrow S) \). It returns the chain complex or chain map obtained by tensoring with the trivial module of integers (characteristic 0).

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26

8.1.10 FilteredTensorWithIntegers

\[ \text{FilteredTensorWithIntegers}(R) \]

Inputs a \( \mathbb{Z}G \)-resolution \( R \) for which "filteredDimension" lies in NamesOfComponents(R). (Such a resolution can be produced using TwisterTensorProduct(), ResolutionNormalSubgroups() or Free-GResolution().) It returns the filtered chain complex obtained by tensoring with the trivial module of integers (characteristic 0).

**EXAMPLES:** 1

8.1.11 TensorWithTwistedIntegers

\[ \text{TensorWithTwistedIntegers}(X, \rho) \]

Inputs either a \( \mathbb{Z}G \)-resolution \( X = R \), or an equivariant chain map \( X = (F : R \rightarrow S) \). It also inputs a function \( \rho : G \rightarrow \mathbb{Z} \) where the action of \( g \in G \) on \( \mathbb{Z} \) is such that \( g.1 = \rho(g) \). It returns the chain complex or chain map obtained by tensoring with the (twisted) module of integers (characteristic 0).

**EXAMPLES:** 1, 2, 3, 4

8.1.12 TensorWithIntegersModP

\[ \text{TensorWithIntegersModP}(X, p) \]

Inputs either a \( \mathbb{Z}G \)-resolution \( X = R \), or a characteristics 0 chain complex, or an equivariant chain map \( X = (F : R \rightarrow S) \), or a chain map between characteristic 0 chain complexes, together with a prime \( p \). It returns the chain complex or chain map obtained by tensoring with the trivial module of integers modulo \( p \).

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8

8.1.13 TensorWithTwistedIntegersModP

\[ \text{TensorWithTwistedIntegersModP}(X, p, \rho) \]

Inputs either a \( \mathbb{Z}G \)-resolution \( X = R \), or an equivariant chain map \( X = (F : R \rightarrow S) \), and a prime \( p \). It also inputs a function \( \rho : G \rightarrow \mathbb{Z} \) where the action of \( g \in G \) on \( \mathbb{Z} \) is such that \( g.1 = \rho(g) \). It returns the chain complex or chain map obtained by tensoring with the trivial module of integers modulo \( p \).

**EXAMPLES:** 1
8.1.14 TensorWithRationals

\[ \text{TensorWithRationals}(R) \]

Inputs a \( \mathbb{Z}G \)-resolution \( R \) and returns the chain complex obtained by tensoring with the trivial module of rational numbers.

EXAMPLES: 1
Chapter 9

Chain complexes

9.1

9.1.1 ChainComplex

\( \text{ChainComplex}(T) \)

Inputs a pure cubical complex, or cubical complex, or simplicial complex \( T \) and returns the (often very large) cellular chain complex of \( T \).

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

9.1.2 ChainComplexOfPair

\( \text{ChainComplexOfPair}(T, S) \)

Inputs a pure cubical complex or cubical complex \( T \) and contractible subcomplex \( S \). It returns the quotient \( C(T)/C(S) \) of cellular chain complexes.

**EXAMPLES:** 1

9.1.3 ChevalleyEilenbergComplex

\( \text{ChevalleyEilenbergComplex}(X, n) \)

Inputs either a Lie algebra \( X = A \) (over the ring of integers \( Z \) or over a field \( K \)) or a homomorphism of Lie algebras \( X = (f : A \rightarrow B) \), together with a positive integer \( n \). It returns either the first \( n \) terms of the Chevalley-Eilenberg chain complex \( C(A) \), or the induced map of Chevalley-Eilenberg complexes \( C(f) : C(A) \rightarrow C(B) \).

(The homology of the Chevalley-Eilenberg complex \( C(A) \) is by definition the homology of the Lie algebra \( A \) with trivial coefficients in \( Z \) or \( K \)).

This function was written by **PABLO FERNANDEZ ASCARIZ**

**EXAMPLES:**
9.1.4 LeibnizComplex

\[ \text{LeibnizComplex}(X, n) \]

Inputs either a Lie or Leibniz algebra \( X = A \) (over the ring of integers \( \mathbb{Z} \) or over a field \( K \)) or a homomorphism of Lie or Leibniz algebras \( X = (f : A \rightarrow B) \), together with a positive integer \( n \). It returns either the first \( n \) terms of the Leibniz chain complex \( C(A) \), or the induced map of Leibniz complexes \( C(f) : C(A) \rightarrow C(B) \).

(The Leibniz complex \( C(A) \) was defined by J.-L.Loday. Its homology is by definition the Leibniz homology of the algebra \( A \)).

This function was written by Pablo Fernandez Ascarize.

Examples:

9.1.5 SuspendedChainComplex

\[ \text{SuspendedChainComplex}(C) \]

Inputs a chain complex \( C \) and returns the chain complex \( S \) defined by applying the degree shift \( S_n = C_{n-1} \) to chain groups and boundary homomorphisms.

Examples:

9.1.6 ReducedSuspendedChainComplex

\[ \text{ReducedSuspendedChainComplex}(C) \]

\[ \text{ReducedSuspendedChainComplex}(C, 2) \]

Inputs a chain complex \( C \) and returns the chain complex \( S \) defined by applying the degree shift \( S_n = C_{n-1} \) to chain groups and boundary homomorphisms for all \( n > 0 \). The chain complex \( S \) has trivial homology in degree 0 and \( S_0 = \mathbb{Z} \).

Examples:

9.1.7 CoreducedChainComplex

\[ \text{CoreducedChainComplex}(C) \]

\[ \text{CoreducedChainComplex}(C, 2) \]

Inputs a chain complex \( C \) and returns a quasi-isomorphic chain complex \( D \). In many cases the complex \( D \) should be smaller than \( C \). If an optional second input argument is set equal to 2 then an alternative method is used for reducing the size of the chain complex.

Examples: 1

9.1.8 TensorProductOfChainComplexes

\[ \text{TensorProductOfChainComplexes}(C, D) \]

Inputs two chain complexes \( C \) and \( D \) of the same characteristic and returns their tensor product as a chain complex.

This function was written by Le Van Luyen.

Examples: 1
9.1.9 LefschetzNumber

LefschetzNumber(F)

Inputs a chain map \( F: C \to C \) with common source and target. It returns the Lefschetz number of the map (that is, the alternating sum of the traces of the homology maps in each degree).

EXAMPLES:
Chapter 10

Sparse Chain complexes

10.1

10.1.1 SparseMat

\[ \text{SparseMat}(A) \] (function)

Inputs a matrix \( A \) and returns the matrix in sparse format.

\text{EXAMPLES:}

10.1.2 TransposeOfSparseMat

\[ \text{TransposeOfSparseMat}(A) \] (function)

Inputs a sparse matrix \( A \) and returns its transpose sparse format.

\text{EXAMPLES:}

10.1.3 ReverseSparseMat

\[ \text{ReverseSparseMat}(A) \] (function)

Inputs a sparse matrix \( A \) and modifies it by reversing the order of the columns. This function modifies \( A \) and returns no value.

\text{EXAMPLES:}

10.1.4 SparseRowMult

\[ \text{SparseRowMult}(A, i, k) \] (function)

Multiplies the \( i \)-th row of a sparse matrix \( A \) by \( k \). The sparse matrix \( A \) is modified but nothing is returned.

\text{EXAMPLES:}
10.1.5 SparseRowInterchange

\[ \text{SparseRowInterchange}(A, i, k) \]

Interchanges the i-th and j-th rows of a sparse matrix A by k. The sparse matrix A is modified but nothing is returned.

\textbf{EXAMPLES:}

10.1.6 SparseRowAdd

\[ \text{SparseRowAdd}(A, i, j, k) \]

Adds k times the j-th row to the i-th row of a sparse matrix A. The sparse matrix A is modified but nothing is returned.

\textbf{EXAMPLES:}

10.1.7 SparseSemiEchelon

\[ \text{SparseSemiEchelon}(A) \]

Converts a sparse matrix A to semi-echelon form (which means echelon form up to a permutation of rows). The sparse matrix A is modified but nothing is returned.

\textbf{EXAMPLES:}

10.1.8 RankMatDestructive

\[ \text{RankMatDestructive}(A) \]

Returns the rank of a sparse matrix A. The sparse matrix A is modified during the calculation.

\textbf{EXAMPLES:}

10.1.9 RankMat

\[ \text{RankMat}(A) \]

Returns the rank of a sparse matrix A.

\textbf{EXAMPLES:}

10.1.10 SparseChainComplex

\[ \text{SparseChainComplex}(Y) \]

Inputs a regular CW-complex Y and returns a sparse chain complex which is chain homotopy equivalent to the cellular chain complex of Y. The function uses discrete vector fields to calculate a smallish chain complex.

\textbf{EXAMPLES: 1}
10.1.11 SparseChainComplexOfRegularCWComplex

\[ \text{Inputs a regular CW-complex } Y \text{ and returns its cellular chain complex as a sparse chain complex.} \]

The function SparseChainComplex(Y) will usually return a smaller chain complex.

**EXAMPLES:**

10.1.12 SparseBoundaryMatrix

\[ \text{Inputs a sparse chain complex } C \text{ and integer } n. \text{ Returns the } n\text{-th boundary matrix of the chain complex in sparse format.} \]

**EXAMPLES:**

10.1.13 Bettinumbers

\[ \text{Inputs a sparse chain complex } C \text{ and integer } n. \text{ Returns the } n\text{-th Netti number of the chain complex.} \]

**EXAMPLES:** 1, 2
Chapter 11

Homology and cohomology groups

11.1

11.1.1 Cohomology

\( \text{Cohomology}(X, n) \) (function)

Inputs either a cochain complex \( X = C \) (or \( G \)-cocomplex \( C \)) or a cochain map \( X = (C \rightarrow D) \) in characteristic \( p \) together with a non-negative integer \( n \).

- If \( X = C \) and \( p = 0 \) then the torsion coefficients of \( H^n(C) \) are returned. If \( X = C \) and \( p \) is prime then the dimension of \( H^n(C) \) are returned.

- If \( X = (C \rightarrow D) \) then the induced homomorphism \( H^n(C) \rightarrow H^n(D) \) is returned as a homomorphism of finitely presented groups.

A \( G \)-cocomplex \( C \) can also be input. The cohomology groups of such a complex may not be abelian. **WARNING:** in this case \( \text{Cohomology}(C,n) \) returns the abelian invariants of the \( n \)-th cohomology group of \( C \).

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22

11.1.2 CohomologyModule

\( \text{CohomologyModule}(C, n) \) (function)

Inputs a \( G \)-cocomplex \( C \) together with a non-negative integer \( n \). It returns the cohomology \( H^n(C) \) as a \( G \)-outer group. If \( C \) was constructed from a resolution \( R \) by homing to an abelian \( G \)-outer group \( A \) then, for each \( x \) in \( H := \text{CohomologyModule}(C,n) \), there is a function \( f := H!.\text{representativeCocycle}(x) \) which is a standard \( n \)-cocycle corresponding to the cohomology class \( x \). (At present this works only for \( n=1,2,3 \).)

**EXAMPLES:** 1, 2

11.1.3 CohomologyPrimePart

\( \text{CohomologyPrimePart}(C, n, p) \) (function)
Inputs a cochain complex $C$ in characteristic 0, a positive integer $n$, and a prime $p$. It returns a list of those torsion coefficients of $H^n(C)$ that are positive powers of $p$. The function uses the EDIM package by Frank Luebeck.

**EXAMPLES:**

### 11.1.4 GroupCohomology

- GroupCohomology($X, n$) (function)
- GroupCohomology($X, n, p$) (function)

Inputs a positive integer $n$ and either

- a finite group $X = G$
- or a nilpotent Pcp-group $X = G$
- or a space group $X = G$
- or a list $X = D$ representing a graph of groups
- or a pair $X = ["Artin", D]$ where $D$ is a Coxeter diagram representing an infinite Artin group $G$.
- or a pair $X = ["Coxeter", D]$ where $D$ is a Coxeter diagram representing a finite Coxeter group $G$.

It returns the torsion coefficients of the integral cohomology $H^n(G, \mathbb{Z})$.

There is an optional third argument which, when set equal to a prime $p$, causes the function to return the the mod $p$ cohomology $H^n(G, \mathbb{Z}_p)$ as a list of length equal to its rank.

This function is a composite of more basic functions, and makes choices for a number of parameters. For a particular group you would almost certainly be better using the more basic functions and making the choices yourself!

**EXAMPLES:** 1

### 11.1.5 GroupHomology

- GroupHomology($X, n$) (function)
- GroupHomology($X, n, p$) (function)

Inputs a positive integer $n$ and either

- a finite group $X = G$
- or a nilpotent Pcp-group $X = G$
- or a space group $X = G$
- or a list $X = D$ representing a graph of groups
- or a pair $X = ["Artin", D]$ where $D$ is a Coxeter diagram representing an infinite Artin group $G$.
- or a pair $X = ["Coxeter", D]$ where $D$ is a Coxeter diagram representing a finite Coxeter group $G$. 
It returns the torsion coefficients of the integral homology $H_n(G, Z)$.

There is an optional third argument which, when set equal to a prime $p$, causes the function to return the mod $p$ homology $H_n(G, Z_p)$ as a list of length equal to its rank.

This function is a composite of more basic functions, and makes choices for a number of parameters. For a particular group you would almost certainly be better using the more basic functions and making the choices yourself!

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7, 8, 9

### 11.1.6 PersistentHomologyOfQuotientGroupSeries

|$\triangledown$ PersistentHomologyOfQuotientGroupSeries($S, n$)  \hspace{1cm} \text{(function)}

|$\triangledown$ PersistentHomologyOfQuotientGroupSeries($S, n, p, Resolution\_Algorithm$)  \hspace{1cm} \text{(function)}

Inputs a positive integer $n$ and a decreasing chain $S = [S_1, S_2, ..., S_k]$ of normal subgroups in a finite $p$-group $G = S_1$. It returns the bar code of the persistent mod $p$ homology in degree $n$ of the sequence of quotient homomorphisms $G \rightarrow G/S_k \rightarrow G/S_{k-1} \rightarrow ... \rightarrow G/S_2$. The bar code is returned as a matrix containing the dimensions of the images of the induced homology maps.

If one sets $p = 0$ then the integral persistent homology bar code is returned. This is a matrix whose entries are pairs of the lists: the list of abelian invariants of the images of the induced homology maps and the cokernels of the induced homology maps. (The matrix probably does not uniquely determine the induced homology maps.)

Non prime-power (and possibly infinite) groups $G$ can also be handled; in this case the prime must be entered as a third argument, and the resolution algorithm (e.g. ResolutionNilpotentGroup) can be entered as a fourth argument. (The default algorithm is ResolutionFiniteGroup, so this must be changed for infinite groups.)

**EXAMPLES:**

### 11.1.7 PersistentCohomologyOfQuotientGroupSeries

|$\triangledown$ PersistentCohomologyOfQuotientGroupSeries($S, n$)  \hspace{1cm} \text{(function)}

|$\triangledown$ PersistentCohomologyOfQuotientGroupSeries($S, n, p, Resolution\_Algorithm$)  \hspace{1cm} \text{(function)}

Inputs a positive integer $n$ and a decreasing chain $S = [S_1, S_2, ..., S_k]$ of normal subgroups in a finite $p$-group $G = S_1$. It returns the bar code of the persistent mod $p$ cohomology in degree $n$ of the sequence of quotient homomorphisms $G \rightarrow G/S_k \rightarrow G/S_{k-1} \rightarrow ... \rightarrow G/S_2$. The bar code is returned as a matrix containing the dimensions of the images of the induced homology maps.

If one sets $p = 0$ then the integral persistent cohomology bar code is returned. This is a matrix whose entries are pairs of the lists: the list of abelian invariants of the images of the induced cohomology maps and the cokernels of the induced cohomology maps. (The matrix probably does not uniquely determine the induced homology maps.)

Non prime-power (and possibly infinite) groups $G$ can also be handled; in this case the prime must be entered as a third argument, and the resolution algorithm (e.g. ResolutionNilpotentGroup) can be entered as a fourth argument. (The default algorithm is ResolutionFiniteGroup, so this must be changed for infinite groups.)
(The implementation is possibly a little less efficient than that of the corresponding persistent homology function.)

**EXAMPLES:**

11.1.8 **UniversalBarCode**

- UniversalBarCode(str, n, d)
- UniversalBarCode(str, n, d, k)

Inputs integers $n, d$ that identify a prime power group $G=\text{SmallGroup}(n,d)$, together with one of the strings $str=\"UpperCentralSeries\", \text{LowerCentralSeries}\", \text{DerivedSeries}\", \text{UpperPCentralSeries}\", \text{LowerPCentralSeries}\". The function returns a matrix of rational functions; the coefficients of $x^k$ in their expansions yield the persistence matrix for the degree $k$ homology with trivial mod $p$ coefficients associated to the quotients of $G$ by the terms of the given series.

If the additional integer argument $k$ is supplied then the function returns the degree $k$ homology persistence matrix.

**EXAMPLES:**

11.1.9 **PersistentHomologyOfSubGroupSeries**

- PersistentHomologyOfSubGroupSeries(S, n)
- PersistentHomologyOfSubGroupSeries(S, n, p, Resolution_Algorithm)

Inputs a positive integer $n$ and a decreasing chain $S = [S_1, S_2, ..., S_k]$ of subgroups in a finite $p$-group $G = S_1$. It returns the bar code of the persistent mod $p$ homology in degree $n$ of the sequence of inclusion homomorphisms $S_k \to S_{k-1} \to ... \to S_1 = G$. The bar code is returned as a binary matrix.

Non prime-power (and possibly infinite) groups $G$ can also be handled; in this case the prime must be entered as a third argument, and the resolution algorithm (e.g. ResolutionNilpotentGroup) must be entered as a fourth argument.

**EXAMPLES:**

11.1.10 **PersistentHomologyOfFilteredChainComplex**

- PersistentHomologyOfFilteredChainComplex(C, n, p)

Inputs a filtered chain complex $C$ (of characteristic $0$ or $p$) together with a positive integer $n$ and prime $p$. It returns the bar code of the persistent mod $p$ homology in degree $n$ of the filtered chain complex $C$. (This function needs a more efficient implementation. Its fine as it stands for investigation in group homology, but not sufficiently efficient for the homology of large complexes arising in applied topology.)

**EXAMPLES:**

11.1.11 **PersistentHomologyOfCommutativeDiagramOfPGroups**

- PersistentHomologyOfCommutativeDiagramOfPGroups(D, n)

Inputs a commutative diagram $D$ of finite $p$-groups and a positive integer $n$. It returns a list containing, for each homomorphism in the nerve of $D$, a triple $[k, l, m]$ where $k$ is the dimension of the
source of the induced mod \( p \) homology map in degree \( n \), \( l \) is the dimension of the image, and \( m \) is the dimension of the cokernel.

**Examples:**

11.1.12 `PersistentHomologyOfFilteredPureCubicalComplex`

\[ \text{PersistentHomologyOfFilteredPureCubicalComplex}(M, n) \]

Inputs a filtered pure cubical complex \( M \) and a non-negative integer \( n \). It returns the degree \( n \) persistent homology of \( M \) with rational coefficients.

**Examples:**

11.1.13 `PersistentHomologyOfPureCubicalComplex`

\[ \text{PersistentHomologyOfPureCubicalComplex}(L, n, p) \]

Inputs a positive integer \( n \), a prime \( p \) and an increasing chain \( L = [L_1, L_2, ..., L_k] \) of subcomplexes in a pure cubical complex \( L_k \). It returns the bar code of the persistent mod \( p \) homology in degree \( n \) of the sequence of inclusion maps. The bar code is returned as a matrix. (This function is extremely inefficient and it is better to use `PersistentHomologyOfFilteredPureCubicalComplex`.

**Examples:**

11.1.14 `ZZPersistentHomologyOfPureCubicalComplex`

\[ \text{ZZPersistentHomologyOfPureCubicalComplex}(L, n, p) \]

Inputs a positive integer \( n \), a prime \( p \) and any sequence \( L = [L_1, L_2, ..., L_k] \) of subcomplexes of some pure cubical complex. It returns the bar code of the zig-zag persistent mod \( p \) homology in degree \( n \) of the sequence of maps \( L_1 \to L_1 \cup L_2 \leftarrow L_2 \to L_2 \cup L_3 \leftarrow L_3 \to \ldots \leftarrow L_k \). The bar code is returned as a matrix.

**Examples:**

11.1.15 `RipsHomology`

\[ \text{RipsHomology}(G, n) \]

\[ \text{RipsHomology}(G, n, p) \]

Inputs a graph \( G \), a non-negative integer \( n \) (and optionally a prime number \( p \)). It returns the integral homology (or mod \( p \) homology) in degree \( n \) of the Rips complex of \( G \).

**Examples:**

11.1.16 `Barcode`

\[ \text{Barcode}(P) \]

Inputs an integer persistence matrix \( P \) and returns the same information in the form of a binary matrix (corresponding to the usual bar code).

**Examples:** 1, 2
11.1.17 BarCodeDisplay

\[ \text{BarCodeDisplay}(P) \]  
\[ \text{BarCodeDisplay}(P, \text{str}) \]  
\[ \text{BarCodeCompactDisplay}(P) \]  
\[ \text{BarCodeCompactDisplay}(P, \text{str}) \]

Inputs an integer persistence matrix \( P \) and an optional string, such as \( \text{str} = \text{"mozilla"} \) specifying a viewer/browser. It displays a picture of the bar code (using GraphViz software). The compact display is better for large bar codes.

**Examples:** 1

11.1.18 Homology

\[ \text{Homology}(X, n) \]

Inputs either a chain complex \( X = C \) or a chain map \( X = (C \rightarrow D) \).

- If \( X = C \) then the torsion coefficients of \( H_n(C) \) are retuned.
- If \( X = (C \rightarrow D) \) then the induced homomorphism \( H_n(C) \rightarrow H_n(D) \) is returned as a homomorphism of finitely presented groups.

A \( G \)-complex \( C \) can also be input. The homology groups of such a complex may not be abelian. **Warning:** in this case \( \text{Homology}(C, n) \) returns the abelian invariants of the \( n \)-th homology group of \( C \).

**Examples:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39

11.1.19 HomologyPb

\[ \text{HomologyPb}(C, n) \]

This is a back-up function which might work in some instances where \( \text{Homology}(C, n) \) fails. It is most useful for chain complexes whose boundary homomorphisms are sparse.

It inputs a chain complex \( C \) in characteristic 0 and returns the torsion coefficients of \( H_n(C) \). There is a small probability that an incorrect answer could be returned. The computation relies on probabilistic Smith Normal Form algorithms implemented in the Simplicial Homology GAP package. This package therefore needs to be loaded. The computation is stored as a component of \( C \) so, when called a second time for a given \( C \) and \( n \), the calculation is recalled without rerunning the algorithm.

The choice of probabilistic algorithm can be changed using the command
\[ \text{SetHomologyAlgorithm(HomologyAlgorithm[i])}; \]
where \( i = 1, 2, 3 \) or 4. The upper limit for the probability of an incorrect answer can be set to any rational number \( 0 \leq e \leq 1 \) using the following command.
\[ \text{SetUncertaintyTolerance}(e); \]
See the Simplicial Homology package manual for further details.

**Examples:**
11.1.20 HomologyVectorSpace

\textbf{HomologyVectorSpace}(X, n) \quad \text{(function)}

Inputs either a chain complex \( X = C \) or a chain map \( X = (C \rightarrow D) \) in prime characteristic.

- If \( X = C \) then \( H_n(C) \) is returned as a vector space.
- If \( X = (C \rightarrow D) \) then the induced homomorphism \( H_n(C) \rightarrow H_n(D) \) is returned as a homomorphism of vector spaces.

\textbf{Examples}:

11.1.21 HomologyPrimePart

\textbf{HomologyPrimePart}(C, n, p) \quad \text{(function)}

Inputs a chain complex \( C \) in characteristic 0, a positive integer \( n \), and a prime \( p \). It returns a list of those torsion coefficients of \( H_n(C) \) that are positive powers of \( p \). The function uses the EDIM GAP package by Frank Luebeck.

\textbf{Examples}:

11.1.22 LeibnizAlgebraHomology

\textbf{LeibnizAlgebraHomology}(A, n) \quad \text{(function)}

Inputs a Lie or Leibniz algebra \( X = A \) (over the ring of integers \( Z \) or over a field \( K \)), together with a positive integer \( n \). It returns the \( n \)-dimensional Leibniz homology of \( A \).

\textbf{Examples}: 1, 2

11.1.23 LieAlgebraHomology

\textbf{LieAlgebraHomology}(A, n) \quad \text{(function)}

Inputs a Lie algebra \( A \) (over the integers or a field) and a positive integer \( n \). It returns the homology \( H_n(A,k) \) where \( k \) denotes the ground ring.

\textbf{Examples}: 1, 2, 3

11.1.24 PrimePartDerivedFunctor

\textbf{PrimePartDerivedFunctor}(G, R, F, n) \quad \text{(function)}

Inputs a finite group \( G \), a positive integer \( n \), at least \( n+1 \) terms of a \( ZP \)-resolution for a Sylow subgroup \( P \leq G \) and a "mathematically suitable" covariant additive functor \( F \) such as TensorWithIntegers . It returns the abelian invariants of the \( p \)-component of the homology \( H_n(F(R)) \).

\textbf{Warning}: All calculations are assumed to be in characteristic 0. The function should not be used if the coefficient module is over the field of \( p \) elements.

"Mathematically suitable" means that the Cartan-Eilenberg double coset formula must hold.

\textbf{Examples}: 1, 2, 3
11.1.25 RankHomologyPGroup

\[ \text{RankHomologyPGroup}(G, n) \]  (function)
\[ \text{RankHomologyPGroup}(R, n) \]  (function)
\[ \text{RankHomologyPGroup}(G, n, \text{str}) \]  (function)

Inputs a (smallish) \( p \)-group \( G \), or \( n \) terms of a minimal \( Z_pG \)-resolution \( R \) of \( Z_p \), together with a positive integer \( n \). It returns the minimal number of generators of the integral homology group \( H_n(G, Z) \).

If an option third string argument \( \text{str} = \text{"empirical"} \) is included then an empirical algorithm will be used. This is one which always seems to yield the right answer but which we can’t prove yields the correct answer.

\text{EXAMPLES:}

11.1.26 RankPrimeHomology

\[ \text{RankPrimeHomology}(G, n) \]  (function)

Inputs a (smallish) \( p \)-group \( G \) together with a positive integer \( n \). It returns a function \( \text{dim}(k) \) which gives the rank of the vector space \( H_k(G, Z_p) \) for all \( 0 \leq k \leq n \).

\text{EXAMPLES:}
Chapter 12

Poincare series

12.1

12.1.1 EfficientNormalSubgroups

\[ \text{EfficientNormalSubgroups}(G) \]  (function)
\[ \text{EfficientNormalSubgroups}(G, k) \]  (function)

Inputs a prime-power group \( G \) and, optionally, a positive integer \( k \). The default is \( k = 4 \). The function returns a list of normal subgroups \( N \) in \( G \) such that the Poincare series for \( G \) equals the Poincare series for the direct product \( (N \times (G/N)) \) up to degree \( k \).

Examples:

12.1.2 ExpansionOfRationalFunction

\[ \text{ExpansionOfRationalFunction}(f, n) \]  (function)

Inputs a positive integer \( n \) and a rational function \( f(x) = p(x)/q(x) \) where the degree of the polynomial \( p(x) \) is less than that of \( q(x) \). It returns a list \([a_0, a_1, a_2, \ldots, a_n]\) of the first \( n+1 \) coefficients of the infinite expansion
\[ f(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + \ldots. \]

Examples:

12.1.3 PoincareSeries

\[ \text{PoincareSeries}(G, n) \]  (function)
\[ \text{PoincareSeries}(R, n) \]  (function)
\[ \text{PoincareSeries}(L, n) \]  (function)
\[ \text{PoincareSeries}(G) \]  (function)

Inputs a finite \( p \)-group \( G \) and a positive integer \( n \). It returns a quotient of polynomials \( f(x) = P(x)/Q(x) \) whose coefficient of \( x^k \) equals the rank of the vector space \( H_k(G, \mathbb{Z}_p) \) for all \( k \) in the range \( k = 1 \) to \( k = n \). (The second input variable can be omitted, in which case the function tries to choose a "reasonable" value for \( n \). For 2-groups the function PoincareSeriesLHS(G) can be used to produce an \( f(x) \) that is correct in all degrees.)
In place of the group \( G \) the function can also input (at least \( n \) terms of) a minimal mod \( p \) resolution \( R \) for \( G \).

Alternatively, the first input variable can be a list \( L \) of integers. In this case the coefficient of \( x^k \) in \( f(x) \) is equal to the \((k + 1)\)st term in the list.

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7

### 12.1.4 PoincareSeriesPrimePart

\( \square \) \texttt{PoincareSeriesPrimePart}(\( G, p, n \))  

Inputs a finite group \( G \), a prime \( p \), and a positive integer \( n \). It returns a quotient of polynomials \( f(x) = P(x)/Q(x) \) whose coefficient of \( x^k \) equals the rank of the vector space \( H_k(G, \mathbb{Z}_p) \) for all \( k \) in the range \( k = 1 \) to \( k = n \).

The efficiency of this function needs to be improved.

**EXAMPLES:** 1, 2

### 12.1.5 PoincareSeriesLHS

\( \square \) \texttt{PoincareSeriesLHS}  

Inputs a finite 2-group \( G \) and returns a quotient of polynomials \( f(x) = P(x)/Q(x) \) whose coefficient of \( x^k \) equals the rank of the vector space \( H_k(G, \mathbb{Z}_2) \) for all \( k \).

This function was written by PAUL SMITH. It use the Singular system for commutative algebra.

**EXAMPLES:**

### 12.1.6 Prank

\( \square \) \texttt{Prank}(\( G \))  

Inputs a \( p \)-group \( G \) and returns the rank of the largest elementary abelian subgroup.

**EXAMPLES:**
Chapter 13
Cohomology ring structure

13.1

13.1.1 IntegralCupProduct

\[ \text{IntegralCupProduct}(R, u, v, p, q) \] (function)

\[ \text{IntegralCupProduct}(R, u, v, p, q, P, Q, N) \] (function)

(Various functions used to construct the cup product are also available.)

Inputs a $\mathbb{Z}G$-resolution $R$, a vector $u$ representing an element in $H^p(G, \mathbb{Z})$, a vector $v$ representing an element in $H^q(G, \mathbb{Z})$ and the two integers $p, q > 0$. It returns a vector $w$ representing the cup product $u \cdot v$ in $H^{p+q}(G, \mathbb{Z})$. This product is associative and $u \cdot v = (-1)^{pq}v \cdot u$. It provides $H^*(G, \mathbb{Z})$ with the structure of an anti-commutative graded ring. This function implements the cup product for characteristic 0 only.

The resolution $R$ needs a contracting homotopy.

To save the function from having to calculate the abelian groups $H^n(G, \mathbb{Z})$ additional input variables can be used in the form $\text{IntegralCupProduct}(R, u, v, p, q, P, Q, N)$, where

- $P$ is the output of the command $\text{CRcocyclesAndCoboundaries}(R, p, \text{true})$
- $Q$ is the output of the command $\text{CRcocyclesAndCoboundaries}(R, q, \text{true})$
- $N$ is the output of the command $\text{CRcocyclesAndCoboundaries}(R, p+q, \text{true})$.

EXAMPLES: 1

13.1.2 IntegralRingGenerators

\[ \text{IntegralRingGenerators}(R, n) \] (function)

Inputs at least $n + 1$ terms of a $\mathbb{Z}G$-resolution and integer $n > 0$. It returns a minimal list of cohomology classes in $H^n(G, \mathbb{Z})$ which, together with all cup products of lower degree classes, generate the group $H^n(G, \mathbb{Z})$.

(Let $a_i$ be the $i$-th canonical generator of the $d$-generator abelian group $H^n(G, \mathbb{Z})$. The cohomology class $n_1a_1 + \ldots + n_d a_d$ is represented by the integer vector $u = (n_1, \ldots, n_d)$.)

EXAMPLES: 1

74
13.1.3 ModPCohomologyGenerators

\[
\text{ModPCohomologyGenerators}(G, n) \quad \text{(function)}
\]
\[
\text{ModPCohomologyGenerators}(R) \quad \text{(function)}
\]

Inputs either a $p$-group $G$ and positive integer $n$, or else $n$ terms of a minimal $\mathbb{Z}_p G$-resolution $R$ of $\mathbb{Z}_p$. It returns a pair whose first entry is a minimal set of homogeneous generators for the cohomology ring $A = H^*(G, \mathbb{Z}_p)$ modulo all elements in degree greater than $n$. The second entry of the pair is a function $\text{deg}$ which, when applied to a minimal generator, yields its degree.

**WARNING:** the following rule must be applied when multiplying generators $x_i$ together. Only products of the form $x_1 \ast (x_2 \ast (x_3 \ast (x_4 \ast ...)))$ with $\text{deg}(x_i) \leq \text{deg}(x_{i+1})$ should be computed (since the $x_i$ belong to a structure constant algebra with only a partially defined structure constants table).

**EXAMPLES:** 1

13.1.4 ModPCohomologyRing

\[
\text{ModPCohomologyRing}(G, n) \quad \text{(function)}
\]
\[
\text{ModPCohomologyRing}(G, n, \text{level}) \quad \text{(function)}
\]
\[
\text{ModPCohomologyRing}(R) \quad \text{(function)}
\]
\[
\text{ModPCohomologyRing}(R, \text{level}) \quad \text{(function)}
\]

Inputs either a $p$-group $G$ and positive integer $n$, or else $n$ terms of a minimal $\mathbb{Z}_p G$-resolution $R$ of $\mathbb{Z}_p$. It returns the cohomology ring $A = H^*(G, \mathbb{Z}_p)$ modulo all elements in degree greater than $n$.

The ring is returned as a structure constant algebra $A$.

The ring $A$ is graded. It has a component $A!$.\text{degree}(x) which is a function returning the degree of each (homogeneous) element $x$ in $\text{GeneratorsOfAlgebra}(A)$.

An optional input variable "level" can be set to one of the strings "medium" or "high". These settings determine parameters in the algorithm. The default setting is "medium".

When "level" is set to "high" the ring $A$ is returned with a component $A!$.\text{niceBasis}. This component is a pair [\text{Coeff}, \text{Bas}]. Here \text{Bas} is a list of integer lists; a "nice" basis for the vector space $A$ can be constructed using the command \text{List}(\text{Bas}, x -> \text{Product}(\text{List}(x, i -> \text{Basis}(A)[i])))$. The coefficients of the canonical basis element $\text{Basis}(A)[i]$ are stored as $\text{Coeff}[i]$.

If the ring $A$ is computed using the setting "level"="medium" then the component $A!$.\text{niceBasis}$ can be added to $A$ using the command $A := \text{ModPCohomologyRing,part2}(A)$.

**EXAMPLES:** 1

13.1.5 ModPRingGenerators

\[
\text{ModPRingGenerators}(A) \quad \text{(function)}
\]

Inputs a mod $p$ cohomology ring $A$ (created using the preceeding function). It returns a minimal generating set for the ring $A$. Each generator is homogeneous.

**EXAMPLES:** 1, 2

13.1.6 Mod2CohomologyRingPresentation

\[
\text{Mod2CohomologyRingPresentation}(G) \quad \text{(function)}
\]
\[
\text{Mod2CohomologyRingPresentation}(G, n) \quad \text{(function)}
\]
When applied to a finite 2-group $G$ this function returns a presentation for the mod 2 cohomology ring $H^*(G, \mathbb{Z}_2)$. The Lyndon-Hochschild-Serre spectral sequence is used to prove that the presentation is correct.

When the function is applied to a 2-group $G$ and positive integer $n$ the function first constructs $n$ terms of a free $\mathbb{Z}_2 G$-resolution $R$, then constructs the finite-dimensional graded algebra $A = H^{i \leq n}(G, \mathbb{Z}_2)$, and finally uses $A$ to approximate a presentation for $H^*(G, \mathbb{Z}_2)$. For "sufficiently large" the approximation will be a correct presentation for $H^*(G, \mathbb{Z}_2)$.

Alternatively, the function can be applied directly to either the resolution $R$ or graded algebra $A$.

This function was written by Paul Smith. It uses the Singular commutative algebra package to handle the Lyndon-Hochschild-Serre spectral sequence.

**Examples:** 1, 2
Chapter 14

Cohomology rings of $p$-groups (mainly $p = 2$)

The functions on this page were written by PAUL SMITH. (They are included in HAP but they are also independently included in Paul Smiths HAPprime package.)

14.1

14.1.1 Mod2CohomologyRingPresentation

- Mod2CohomologyRingPresentation($G$) (function)
- Mod2CohomologyRingPresentation($G$, $n$) (function)
- Mod2CohomologyRingPresentation($A$) (function)
- Mod2CohomologyRingPresentation($R$) (function)

When applied to a finite 2-group $G$ this function returns a presentation for the mod 2 cohomology ring $H^*(G, \mathbb{Z}_2)$. The Lyndon-Hochschild-Serre spectral sequence is used to prove that the presentation is correct.

When the function is applied to a 2-group $G$ and positive integer $n$ the function first constructs $n$ terms of a free $\mathbb{Z}_2G$-resolution $R$, then constructs the finite-dimensional graded algebra $A = H^*_{\leq n}(G, \mathbb{Z}_2)$, and finally uses $A$ to approximate a presentation for $H^*(G, \mathbb{Z}_2)$. For "sufficiently large" the approximation will be a correct presentation for $H^*(G, \mathbb{Z}_2)$.

Alternatively, the function can be applied directly to either the resolution $R$ or graded algebra $A$.

This function was written by PAUL SMITH. It uses the Singular commutative algebra package to handle the Lyndon-Hochschild-Serre spectral sequence.

EXAMPLES: 1, 2

14.1.2 PoincareSeriesLHS

- PoincareSeriesLHS (global variable)

Inputs a finite 2-group $G$ and returns a quotient of polynomials $f(x) = P(x)/Q(x)$ whose coefficient of $x^k$ equals the rank of the vector space $H_k(G, \mathbb{Z}_2)$ for all $k$.

This function was written by PAUL SMITH. It use the Singular system for commutative algebra.
EXAMPLES:
Chapter 15

Commutator and nonabelian tensor computations

15.1

15.1.1 BaerInvariant

\texttt{BaerInvariant}(G, c) (function)

Inputs a nilpotent group $G$ and integer $c>0$. It returns the Baer invariant $M(c)(G)$ defined as follows. For an arbitrary group $G$ let $L_{c+1}^\ast(G)$ be the $(c+1)$-st term of the upper central series of the group $U = F / [[[R,F],[F],...$ (with $c$ copies of $F$ in the denominator) where $F/R$ is any free presentation of $G$. This is an invariant of $G$ and we define $M(c)(G)$ to be the kernel of the canonical homomorphism $M(c)(G) \rightarrow G$. For $c = 1$ the Baer invariant $M(1)(G)$ is isomorphic to the second integral homology $H_2(G,Z)$.

This function requires the NQ package.

\textbf{EXAMPLES}: 1

15.1.2 BogomolovMultiplier

\texttt{BogomolovMultiplier}(G) (function)

\texttt{BogomolovMultiplier}(G, str) (function)

Inputs a finite group $G$ and an optional string str="standard" or str="homology" or str="tensor". It returns the quotient $H_2(G,Z)/K(G)$ of the second integral homology of $G$ where $K(G)$ is the subgroup of $H_2(G,Z)$ generated by the images of all homomorphisms $H_2(A,Z) \rightarrow H_2(G,Z)$ induced from abelian subgroups of $G$.

Three slight variants of the implementation are available. The default "standard" implementation seems to work best on average. But for some groups the "homology" implementation or the "tensor" implementation will be faster. The variants are called by including the appropriate string as the second argument.

\textbf{EXAMPLES}: 1, 2
15.1.3 Bogomology

\( \text{Bogomology}(G, n) \)

Inputs a finite group \( G \) and positive integer \( n \), and returns the quotient \( H_n(G, \mathbb{Z})/K(G) \) of the degree \( n \) integral homology of \( G \) where \( K(G) \) is the subgroup of \( H_n(G, \mathbb{Z}) \) generated by the images of all homomorphisms \( H_n(A, \mathbb{Z}) \to H_n(G, \mathbb{Z}) \) induced from abelian subgroups of \( G \).

**EXAMPLES:** 1

15.1.4 Coclass

\( \text{Coclass} \)

Inputs a group \( G \) of prime-power order \( p^n \) and nilpotency class \( c \) say. It returns the integer \( r = n - c \).

**EXAMPLES:**

15.1.5 EpiCentre

\( \text{EpiCentre}(G, N) \)
\( \text{EpiCentre}(G) \)

Inputs a finite group \( G \) and normal subgroup \( N \) and returns a subgroup \( Z^*(G, N) \) of the centre of \( N \). The group \( Z^*(G, N) \) is trivial if and only if there is a crossed module \( d : E \to G \) with \( N = \text{Image}(d) \) and with \( \text{Ker}(d) \) equal to the subgroup of \( E \) consisting of those elements on which \( G \) acts trivially.

If no value for \( N \) is entered then it is assumed that \( N = G \). In this case the group \( Z^*(G, G) \) is trivial if and only if \( G \) is isomorphic to a quotient \( G = E/Z(E) \) of some group \( E \) by the centre of \( E \). (See also the command \textit{UpperEpicentralSeries}(G, c).)

**EXAMPLES:** 1, 2

15.1.6 NonabelianExteriorProduct

\( \text{NonabelianExteriorProduct}(G, N) \)

Inputs a finite group \( G \) and normal subgroup \( N \). It returns a record \( E \) with the following components.

- \textit{E.homomorphism} is a group homomorphism \( \mu : (G \land N) \to G \) from the nonabelian exterior product \( (G \land N) \) to \( G \). The kernel of \( \mu \) is the relative Schur multiplier.

- \textit{E.pairing}(x, y) is a function which inputs an element \( x \) in \( G \) and an element \( y \) in \( N \) and returns \((x \land y)\) in the exterior product \((G \land N)\).

This function should work for reasonably small nilpotent groups or extremely small non-nilpotent groups.

**EXAMPLES:** 1
15.1.7 NonabelianSymmetricKernel

\[ \text{NonabelianSymmetricKernel}(G) \]
\[ \text{NonabelianSymmetricKernel}(G, m) \]

Inputs a finite or nilpotent infinite group \( G \) and returns the abelian invariants of the Fourth homotopy group \( S_G \) of the double suspension \( SSK(G, 1) \) of the Eilenberg-Mac Lane space \( K(G, 1) \).

For non-nilpotent groups the implementation of the function \( \text{NonabelianSymmetricKernel}(G) \) is far from optimal and will soon be improved. As a temporary solution to this problem, an optional second variable \( m \) can be set equal to 0, and then the function efficiently returns the abelian invariants of groups \( A \) and \( B \) such that there is an exact sequence \( 0 \to B \to S_G \to A \to 0 \).

Alternatively, the optional second variable \( m \) can be set equal to a positive multiple of the order of the symmetric square \( (G \hat{\otimes} G) \). In this case the function returns the abelian invariants of \( S_G \). This might help when \( G \) is solvable but not nilpotent (especially if the estimated upper bound \( m \) is reasonable accurate).

**Examples:**

15.1.8 NonabelianSymmetricSquare

\[ \text{NonabelianSymmetricSquare}(G) \]
\[ \text{NonabelianSymmetricSquare}(G, m) \]

Inputs a finite or nilpotent infinite group \( G \) and returns a record \( T \) with the following components.

- \( T.\text{homomorphism} \) is a group homomorphism \( \mu : (G \hat{\otimes} G) \to G \) from the nonabelian symmetric square of \( G \) to \( G \). The kernel of \( \mu \) is isomorphic to the fourth homotopy group of the double suspension \( SSK(G, 1) \) of an Eilenberg-Mac Lane space.

- \( T.\text{pairing}(x, y) \) is a function which inputs two elements \( x, y \) in \( G \) and returns the tensor \( (x \otimes y) \) in the symmetric square \( (G \otimes G) \).

An optional second variable \( m \) can be set equal to a multiple of the order of the symmetric square \( (G \hat{\otimes} G) \). This might help when \( G \) is solvable but not nilpotent (especially if the estimated upper bound \( m \) is reasonable accurate) as the bound is used in the solvable quotient algorithm.

The optional second variable \( m \) can also be set equal to 0. In this case the Todd-Coxeter procedure will be used to enumerate the symmetric square even when \( G \) is solvable.

This function should work for reasonably small solvable groups or extremely small non-solvable groups.

**Examples:**

15.1.9 NonabelianTensorProduct

\[ \text{NonabelianTensorProduct}(G, N) \]

Inputs a finite group \( G \) and normal subgroup \( N \). It returns a record \( E \) with the following components.

- \( E.\text{homomorphism} \) is a group homomorphism \( \mu : (G \otimes N) \to G \) from the nonabelian exterior product \( (G \otimes N) \) to \( G \).
• *E.*pairing*(x, y)* is a function which inputs an element *x* in *G* and an element *y* in *N* and returns

\((x \otimes y)\) in the tensor product \((G \otimes N)\).

This function should work for reasonably small nilpotent groups or extremely small non-nilpotent groups.

**Examples:** 1

### 15.1.10 NonabelianTensorSquare

\[\text{NonabelianTensorSquare}(G)\]  
\[\text{NonabelianTensorSquare}(G, m)\]

Inputs a finite or nilpotent infinite group *G* and returns a record *T* with the following components.

- *T*.homomorphism is a group homomorphism \(\mu : (G \otimes G) \rightarrow G\) from the nonabelian tensor square of *G* to *G*. The kernel of \(\mu\) is isomorphic to the third homotopy group of the suspension \(\text{SK}(G, 1)\) of an Eilenberg-Mac Lane space.
- *T*.pairing\((x, y)\) is a function which inputs two elements *x, y* in *G* and returns the tensor \((x \otimes y)\) in the tensor square \((G \otimes G)\).

An optional second variable *m* can be set equal to a multiple of the order of the tensor square \((G \otimes G)\). This might help when *G* is solvable but not nilpotent (especially if the estimated upper bound *m* is reasonable accurate) as the bound is used in the solvable quotient algorithm.

The optional second variable *m* can also be set equal to 0. In this case the Todd-Coxeter procedure will be used to enumerate the tensor square even when *G* is solvable.

This function should work for reasonably small solvable groups or extremely small non-solvable groups.

**Examples:** 1

### 15.1.11 RelativeSchurMultiplier

\[\text{RelativeSchurMultiplier}(G, N)\]

Inputs a finite group *G* and normal subgroup *N*. It returns the homology group \(H_2(G, N, Z)\) that fits into the exact sequence

\[\ldots \rightarrow H_3(G, Z) \rightarrow H_3(G/N, Z) \rightarrow H_3(G, N, Z) \rightarrow H_3(G, Z) \rightarrow H_3(G/N, Z) \rightarrow \ldots.\]

This function should work for reasonably small nilpotent groups *G* or extremely small non-nilpotent groups.

**Examples:** 1

### 15.1.12 TensorCentre

\[\text{TensorCentre}(G)\]

Inputs a group *G* and returns the largest central subgroup *N* such that the induced homomorphism of nonabelian tensor squares \((G \otimes G) \rightarrow (G/N \otimes G/N)\) is an isomorphism. Equivalently, *N* is the largest central subgroup such that \(\pi_3(\text{SK}(G, 1)) \rightarrow \pi_3(\text{SK}(G/N, 1))\) is injective.

**Examples:**
15.1.13 ThirdHomotopyGroupOfSuspensionB

▷ ThirdHomotopyGroupOfSuspensionB(G) (function)
▷ ThirdHomotopyGroupOfSuspensionB(G, m) (function)

Inputs a finite or nilpotent infinite group $G$ and returns the abelian invariants of the third homotopy group $JG$ of the suspension $SK(G, 1)$ of the Eilenberg-Mac Lane space $K(G, 1)$.
For non-nilpotent groups the implementation of the function ThirdHomotopyGroupOfSuspensionB($G$) is far from optimal and will soon be improved. As a temporary solution to this problem, an optional second variable $m$ can be set equal to 0, and then the function efficiently returns the abelian invariants of groups $A$ and $B$ such that there is an exact sequence $0 \rightarrow B \rightarrow JG \rightarrow A \rightarrow 0$.
Alternatively, the optional second variable $m$ can be set equal to a positive multiple of the order of the tensor square $(G \otimes G)$. In this case the function returns the abelian invariants of $JG$. This might help when $G$ is solvable but not nilpotent (especially if the estimated upper bound $m$ is reasonable accurate).

**Examples:** 1, 2, 3

15.1.14 UpperEpicentralSeries

▷ UpperEpicentralSeries(G, c) (function)

Inputs a nilpotent group $G$ and an integer $c$. It returns the $c$-th term of the upper epicentral series $1 < Z_1^c(G) < Z_2^c(G) < \ldots$.
The upper epicentral series is defined for an arbitrary group $G$. The group $Z_c^e(G)$ is the image in $G$ of the $c$-th term $Z_c(U)$ of the upper central series of the group $U = F / [[[R, F], F] \ldots]$ (with $c$ copies of $F$ in the denominator) where $F/R$ is any free presentation of $G$.
This function requires the NQ package.

**Examples:** 1
Chapter 16

Lie commutators and nonabelian Lie tensors

Functions on this page are joint work with Hamid Mohammadzadeh, and implemented by him.

16.1

16.1.1 LieCoveringHomomorphism

\[ \text{LieCoveringHomomorphism}(L) \]

Inputs a finite dimensional Lie algebra \( L \) over a field, and returns a surjective Lie homomorphism \( \phi : C \rightarrow L \) where:

- the kernel of \( \phi \) lies in both the centre of \( C \) and the derived subalgebra of \( C \),
- the kernel of \( \phi \) is a vector space of rank equal to the rank of the second Chevalley-Eilenberg homology of \( L \).

**Examples:** 1

16.1.2 LeibnizQuasiCoveringHomomorphism

\[ \text{LeibnizQuasiCoveringHomomorphism}(L) \]

Inputs a finite dimensional Lie algebra \( L \) over a field, and returns a surjective homomorphism \( \phi : C \rightarrow L \) of Leibniz algebras where:

- the kernel of \( \phi \) lies in both the centre of \( C \) and the derived subalgebra of \( C \),
- the kernel of \( \phi \) is a vector space of rank equal to the rank of the kernel \( J \) of the homomorphism \( L \otimes L \rightarrow L \) from the tensor square to \( L \). (We note that, in general, \( J \) is NOT equal to the second Leibniz homology of \( L \)).

**Examples:**
16.1.3 LieEpiCentre

\( \text{LieEpiCentre}(L) \) (function)

Inputs a finite dimensional Lie algebra \( L \) over a field, and returns an ideal \( Z^*(L) \) of the centre of \( L \). The ideal \( Z^*(L) \) is trivial if and only if \( L \) is isomorphic to a quotient \( L = E/Z(E) \) of some Lie algebra \( E \) by the centre of \( E \).

EXAMPLES: 1

16.1.4 LieExteriorSquare

\( \text{LieExteriorSquare}(L) \) (function)

Inputs a finite dimensional Lie algebra \( L \) over a field. It returns a record \( E \) with the following components.

- \( E \text{.homomorphism} \) is a Lie homomorphism \( \mu : (L \wedge L) \rightarrow L \) from the nonabelian exterior square \( (L \wedge L) \) to \( L \). The kernel of \( \mu \) is the Lie multiplier.

- \( E \text{.pairing}(x,y) \) is a function which inputs elements \( x,y \) in \( L \) and returns \( (x \wedge y) \) in the exterior square \( (L \wedge L) \).

EXAMPLES:

16.1.5 LieTensorSquare

\( \text{LieTensorSquare}(L) \) (function)

Inputs a finite dimensional Lie algebra \( L \) over a field and returns a record \( T \) with the following components.

- \( T \text{.homomorphism} \) is a Lie homomorphism \( \mu : (L \otimes L) \rightarrow L \) from the nonabelian tensor square of \( L \) to \( L \).

- \( T \text{.pairing}(x,y) \) is a function which inputs two elements \( x,y \) in \( L \) and returns the tensor \( (x \otimes y) \) in the tensor square \( (L \otimes L) \).

EXAMPLES:

16.1.6 LieTensorCentre

\( \text{LieTensorCentre}(L) \) (function)

Inputs a finite dimensional Lie algebra \( L \) over a field and returns the largest ideal \( N \) such that the induced homomorphism of nonabelian tensor squares \( (L \otimes L) \rightarrow (L/N \otimes L/N) \) is an isomorphism.

EXAMPLES:
Chapter 17

Generators and relators of groups

17.1

17.1.1 CayleyGraphOfGroupDisplay

\[ \text{CayleyGraphOfGroupDisplay}(G, X) \]

\[ \text{CayleyGraphOfGroupDisplay}(G, X, str) \]

\text{(function)}

Inputs a finite group \( G \) together with a subset \( X \) of \( G \). It displays the corresponding Cayley graph as a .gif file. It uses the Mozilla web browser as a default to view the diagram. An alternative browser can be set using a second argument \( str=\text{"mozilla"} \).

The argument \( G \) can also be a finite set of elements in a (possibly infinite) group containing \( X \). The edges of the graph are coloured according to which element of \( X \) they are labelled by. The list \( X \) corresponds to the list of colours [blue, red, green, yellow, brown, black] in that order.

This function requires Graphviz software.

\text{EXAMPLES:}

17.1.2 IdentityAmongRelatorsDisplay

\[ \text{IdentityAmongRelatorsDisplay}(R, n) \]

\[ \text{IdentityAmongRelatorsDisplay}(R, n, str) \]

\text{(function)}

Inputs a free \( ZG \)-resolution \( R \) and an integer \( n \). It displays the boundary \( R!.boundary(3,n) \) as a tessellation of a sphere. It displays the tessellation as a .gif file and uses the Mozilla web browser as a default display mechanism. An alternative browser can be set using the second argument \( str=\text{"mozilla"} \).

(The resolution \( R \) should be reduced and, preferably, in dimension 1 it should correspond to a Cayley graph for \( G \).)

This function uses GraphViz software.

\text{EXAMPLES: 1, 2}

17.1.3 IsAspherical

\[ \text{IsAspherical}(F, R) \]

\text{(function)}
Inputs a free group $F$ and a set $R$ of words in $F$. It performs a test on the 2-dimensional CW-space $K$ associated to this presentation for the group $G = F / \langle R \rangle^F$.

The function returns "true" if $K$ has trivial second homotopy group. In this case it prints: Presentation is aspherical.

Otherwise it returns "fail" and prints: Presentation is NOT piece-wise Euclidean non-positively curved. (In this case $K$ may or may not have trivial second homotopy group. But it is NOT possible to impose a metric on $K$ which restricts to a Euclidean metric on each 2-cell.)

The function uses Polymake software.

**EXAMPLES:** 1, 2, 3

### 17.1.4 PresentationOfResolution

\texttt{PresentationOfResolution}(R) \hspace{1cm} (function)

Inputs at least two terms of a reduced $ZG$-resolution $R$ and returns a record $P$ with components

- $P$.freeGroup is a free group $F$,
- $P$.relators is a list $S$ of words in $F$,
- $P$.gens is a list of positive integers such that the $i$-th generator of the presentation corresponds to the group element $R!.elts[P[i]]$.

where $G$ is isomorphic to $F$ modulo the normal closure of $S$. This presentation for $G$ corresponds to the 2-skeleton of the classifying CW-space from which $R$ was constructed. The resolution $R$ requires no contracting homotopy.

**EXAMPLES:** 1, 2, 3, 4

### 17.1.5 TorsionGeneratorsAbelianGroup

\texttt{TorsionGeneratorsAbelianGroup}(G) \hspace{1cm} (function)

Inputs an abelian group $G$ and returns a generating set $[x_1, \ldots, x_n]$ where no pair of generators have coprime orders.

**EXAMPLES:**
Chapter 18

Orbit polytopes and fundamental domains

18.1

18.1.1 CoxeterComplex

\[ \text{CoxeterComplex}(D) \] (function)
\[ \text{CoxeterComplex}(D, n) \] (function)

Inputs a Coxeter diagram \( D \) of finite type. It returns a non-free \( \mathbb{Z}W \)-resolution for the associated Coxeter group \( W \). The non-free resolution is obtained from the permutahedron of type \( W \). A positive integer \( n \) can be entered as an optional second variable; just the first \( n \) terms of the non-free resolution are then returned.

EXAMPLES: 1

18.1.2 ContractibleGcomplex

\[ \text{ContractibleGcomplex}(\text{str}) \] (function)

Inputs one of the following strings \( \text{str} = \)


or one of the following strings

"SL(2,O-2)" , "SL(2,O-7)" , "SL(2,O-11)" , "SL(2,O-19)" , "SL(2,O-43)" , "SL(2,O-67)" , "SL(2,O-163)"

It returns a non-free \( \mathbb{Z}G \)-resolution for the group \( G \) described by the string. The stabilizer groups of cells are finite. (Subscripts \( _b \) , \( _c \) , \( _d \) denote alternative non-free \( \mathbb{Z}G \)-resolutions for a given group \( G \).)

Data for the first list of non-free resolutions was provided by MATHIEU DUTOUR. Data for the second list was provided by ALEXANDER RAHM.
**Examples:** 1, 2, 3, 4, 5, 6

### 18.1.3 QuotientOfContractibleGcomplex

**QuotientOfContractibleGcomplex(C, D)** (function)

Inputs a non-free \( ZG \)-resolution \( C \) and a finite subgroup \( D \) of \( G \) which is a subgroup of each cell stabilizer group for \( C \). Each element of \( D \) must preserves the orientation of any cell stabilized by it. It returns the corresponding non-free \( Z(G/D) \)-resolution. (So, for instance, from the \( SL(2,O) \) complex \( C = \text{ContractibleGcomplex}("SL(2,O-2)") \); we can construct a \( PSL(2,O) \)-complex using this function.)

**Examples:** 1

### 18.1.4 TruncatedGComplex

**TruncatedGComplex(R, m, n)** (function)

Inputs a non-free \( ZG \)-resolution \( R \) and two positive integers \( m \) and \( n \). It returns the non-free \( ZG \)-resolution consisting of those modules in \( R \) of degree at least \( m \) and at most \( n \).

**Examples:**

### 18.1.5 FundamentalDomainStandardSpaceGroup

**FundamentalDomainStandardSpaceGroup(v, G)** (function)

Inputs a crystallographic group \( G \) (represented using AffineCrystGroupOnRight as in the GAP package Cryst). It also inputs a choice of vector \( v \) in the euclidean space \( R^n \) on which \( G \) acts. It returns the Dirichlet-Voronoï fundamental cell for the action of \( G \) on euclidean space corresponding to the vector \( v \). The fundamental cell is a fundamental domain if \( G \) is Bieberbach. The fundamental cell/domain is returned as a “Polymake object”. Currently the function only applies to certain crystallographic groups. See the manuals to HAPcryst and HAPpolymake for full details.

This function is part of the HAPcryst package written by MARC ROEDER and is thus only available if HAPcryst is loaded.

The function requires the use of Polymake software.

**Examples:** 1

### 18.1.6 OrbitPolytope

**OrbitPolytope(G, v, L)** (function)

Inputs a permutation group or matrix group \( G \) of degree \( n \) and a rational vector \( v \) of length \( n \). In both cases there is a natural action of \( G \) on \( v \). Let \( P(G,v) \) be the convex polytope arising as the convex hull of the Euclidean points in the orbit of \( v \) under the action of \( G \). The function also inputs a sublist \( L \) of the following list of strings:

- "dimension",
- "vertex_degree",
- "visual_graph",
- "schlegel",
- "visual"

Depending on the sublist, the function:

- prints the dimension of the orbit polytope \( P(G,v) \);
• prints the degree of a vertex in the graph of \( P(G,v) \);
• visualizes the graph of \( P(G,v) \);
• visualizes the Schlegel diagram of \( P(G,v) \);
• visualizes \( P(G,v) \) if the polytope is of dimension 2 or 3.

The function uses Polymake software.

EXAMPLES: 1

18.1.7 PolytopalComplex

\( \text{\texttt{PolytopalComplex}}(G, v) \) (function)

\( \text{\texttt{PolytopalComplex}}(G, v, n) \) (function)

Inputs a permutation group or matrix group \( G \) of degree \( n \) and a rational vector \( v \) of length \( n \). In both cases there is a natural action of \( G \) on \( v \). Let \( P(G,v) \) be the convex polytope arising as the convex hull of the Euclidean points in the orbit of \( v \) under the action of \( G \). The cellular chain complex \( C_* = C_*(P(G,v)) \) is an exact sequence of (not necessarily free) \( \mathbb{Z}G \)-modules. The function returns a component object \( R \) with components:

• \( R!.\text{dimension}(k) \) is a function which returns the number of \( G \)-orbits of the \( k \)-dimensional faces in \( P(G,v) \). If each \( k \)-face has trivial stabilizer subgroup in \( G \) then \( C_k \) is a free \( \mathbb{Z}G \)-module of rank \( R!.\text{dimension}(k) \).

• \( R!.\text{stabilizer}(k, n) \) is a function which returns the stabilizer subgroup for a face in the \( n \)-th orbit of \( k \)-faces.

• If all faces of dimension \( <k+1 \) have trivial stabilizer group then the first \( k \) terms of \( C_* \) constitute part of a free \( \mathbb{Z}G \)-resolution. The boundary map is described by the function \( \text{boundary}(k, n) \). (If some faces have non-trivial stabilizer group then \( C_* \) is not free and no attempt is made to determine signs for the boundary map.)

• \( R!.\text{elements}, R!.\text{group}, R!.\text{properties} \) are as in a \( \mathbb{Z}G \)-resolution.

If an optional third input variable \( n \) is used, then only the first \( n \) terms of the resolution \( C_* \) will be computed.

The function uses Polymake software.

EXAMPLES: 1

18.1.8 PolytopalGenerators

\( \text{\texttt{PolytopalGenerators}}(G, v) \) (function)

Inputs a permutation group or matrix group \( G \) of degree \( n \) and a rational vector \( v \) of length \( n \). In both cases there is a natural action of \( G \) on \( v \), and the vector \( v \) must be chosen so that it has trivial stabilizer subgroup in \( G \). Let \( P(G,v) \) be the convex polytope arising as the convex hull of the Euclidean points in the orbit of \( v \) under the action of \( G \). The function returns a record \( P \) with components:
• \textit{P.generators} is a list of all those elements \( g \) in \( G \) such that \( g \cdot v \) has an edge in common with \( v \). The list is a generating set for \( G \).

• \textit{P.vector} is the vector \( v \).

• \textit{P.hasseDiagram} is the Hasse diagram of the cone at \( v \).

The function uses Polymake software. The function is joint work with Seamus Kelly.

\textbf{EXAMPLES:}

\section*{18.1.9 VectorStabilizer}

\begin{verbatim}
\texttt{VectorStabilizer(G, v)}
\end{verbatim}

Inputs a permutation group or matrix group \( G \) of degree \( n \) and a rational vector of degree \( n \). In both cases there is a natural action of \( G \) on \( v \) and the function returns the group of elements in \( G \) that fix \( v \).

\textbf{EXAMPLES:}
Chapter 19

Cocycles

19.1

19.1.1 CcGroup

\[ \text{CcGroup}(A, f) \] (function)

Inputs a \( G \)-module \( A \) (i.e. an abelian \( G \)-outer group) and a standard 2-cocycle \( f \) \( G \times G \rightarrow A \).

It returns the extension group determined by the cocycle. The group is returned as a CcGroup.

This is a HAPcocyclic function and thus only works when HAPcocyclic is loaded.

Examples: 1

19.1.2 CocycleCondition

\[ \text{CocycleCondition}(R, n) \] (function)

Inputs a resolution \( R \) and an integer \( n > 0 \). It returns an integer matrix \( M \) with the following property. Suppose \( d = R.\text{dimension}(n) \). An integer vector \( f = [f_1, \ldots, f_d] \) then represents a \( \mathbb{Z}G \)-homomorphism \( R_n \rightarrow \mathbb{Z}_q \) which sends the \( i \)th generator of \( R_n \) to the integer \( f_i \) in the trivial \( \mathbb{Z}G \)-module \( \mathbb{Z}_q \) (where possibly \( q = 0 \)). The homomorphism \( f \) is a cocycle if and only if \( M^t f = 0 \mod q \).

Examples: 1

19.1.3 StandardCocycle

\[ \text{StandardCocycle}(R, f, n) \] (function)

\[ \text{StandardCocycle}(R, f, n, q) \] (function)

Inputs a \( \mathbb{Z}G \)-resolution \( R \) (with contracting homotopy), a positive integer \( n \) and an integer vector \( f \) representing an \( n \)-cocycle \( R_n \rightarrow \mathbb{Z}_q \) where \( G \) acts trivially on \( \mathbb{Z}_q \). It is assumed \( q = 0 \) unless a value for \( q \) is entered. The command returns a function \( F(g_1, \ldots, g_n) \) which is the standard cocycle \( G_n \rightarrow \mathbb{Z}_q \) corresponding to \( f \). At present the command is implemented only for \( n = 2 \) or 3.

Examples: 1
19.1.4 Syzygy

\[ \text{Syzygy}(R, g) \]

Inputs a $ZG$-resolution $R$ (with contracting homotopy) and a list $g = [g[1], \ldots, g[n]]$ of elements in $G$. It returns a word $w$ in $R_n$. The word $w$ is the image of the $n$-simplex in the standard bar resolution corresponding to the $n$-tuple $g$. This function can be used to construct explicit standard $n$-cocycles. (Currently implemented only for $n<4$.)

Examples:
Chapter 20

Words in free $ZG$-modules

20.1

20.1.1 AddFreeWords

\[ \text{AddFreeWords}(v, w) \] (function)

Inputs two words $v, w$ in a free $ZG$-module and returns their sum $v + w$. If the characteristic of $Z$ is greater than 0 then the next function might be more efficient.

**EXAMPLES:**

20.1.2 AddFreeWordsModP

\[ \text{AddFreeWordsModP}(v, w, p) \] (function)

Inputs two words $v, w$ in a free $ZG$-module and the characteristic $p$ of $Z$. It returns the sum $v + w$. If $p = 0$ the previous function might be fractionally quicker.

**EXAMPLES:**

20.1.3 AlgebraicReduction

\[ \text{AlgebraicReduction}(w) \] (function)

\[ \text{AlgebraicReduction}(w, p) \] (function)

Inputs a word $w$ in a free $ZG$-module and returns a reduced version of the word in which all pairs of mutually inverse letters have been cancelled. The reduction is performed in a free abelian group unless the characteristic $p$ of $Z$ is entered.

**EXAMPLES:**

20.1.4 MultiplyWord

\[ \text{MultiplyWord}(n, w) \] (function)

Inputs a word $w$ and integer $n$. It returns the scalar multiple $n \cdot w$.

**EXAMPLES:**
20.1.5 Negate

▷ Negate([i, j])  

Inputs a pair [i, j] of integers and returns [−i, j].

EXAMPLES:

20.1.6 NegateWord

▷ NegateWord(w)  

Inputs a word w in a free ZG-module and returns the negated word −w.

EXAMPLES:

20.1.7 PrintZGword

▷ PrintZGword(w, elts)  

Inputs a word w in a free ZG-module and a (possibly partial but sufficient) listing elts of the elements of G. The function prints the word w to the screen in the form 
\[ r_1E_1 + \ldots + r_nE_n \]
where \( r_i \) are elements in the group ring \( ZG \), and \( E_i \) denotes the i-th free generator of the module.

EXAMPLES: 1

20.1.8 TietzeReduction

▷ TietzeReduction(S, w)  

Inputs a set S of words in a free ZG-module, and a word w in the module. The function returns a word \( w' \) such that \{S, w'\} generates the same abelian group as \{S, w\}. The word \( w' \) is possibly shorter (and certainly no longer) than w. This function needs to be improved!

EXAMPLES:

20.1.9 ResolutionBoundaryOfWord

▷ ResolutionBoundaryOfWord(R, n, w)  

Inputs a resolution R, a positive integer n and a list w representing a word in the free module \( R_n \). It returns the image of w under the n-th boundary homomorphism.

EXAMPLES:
Chapter 21

\textbf{FpG-modules}

21.1

\subsection{CompositionSeriesOfFpGModules}

\[
\text{CompositionSeriesOfFpGModules}( \text{M} )
\]

Inputs an \( FpG \)-module \( M \) and returns a list of \( FpG \)-modules that constitute a composition series for \( M \).

\textbf{EXAMPLES:}

\subsection{DirectSumOfFpGModules}

\[
\text{DirectSumOfFpGModules}( \text{M, N} )
\]
\[
\text{DirectSumOfFpGModules}([ \text{M[1], M[2], ..., M[k]} ])
\]

Inputs two \( FpG \)-modules \( M \) and \( N \) with common group and characteristic. It returns the direct sum of \( M \) and \( N \) as an \( FpG \)-Module.

Alternatively, the function can input a list of \( FpG \)-modules with common group \( G \). It returns the direct sum of the list.

\textbf{EXAMPLES:}

\subsection{FpGModule}

\[
\text{FpGModule}( \text{A, P} )
\]
\[
\text{FpGModule}( \text{A, G, p} )
\]

Inputs a \( p \)-group \( P \) and a matrix \( A \) whose rows have length a multiple of the order of \( G \). It returns the “canonical” \( FpG \)-module generated by the rows of \( A \).

A small non-prime-power group \( G \) can also be input, provided the characteristic \( p \) is entered as a third input variable.

\textbf{EXAMPLES:} 1, 2, 3
21.1.4 FpGModuleDualBasis

\( \text{FpGModuleDualBasis}(M) \) (function)

Inputs an \( \text{FpG} \)-module \( M \). It returns a record \( R \) with two components:

- \( R.\text{freeModule} \) is the free module \( \text{FG} \) of rank one.
- \( R.\text{basis} \) is a list representing an \( \text{F} \)-basis for the module \( \text{Hom}_{\text{FG}}(M, \text{FG}) \). Each term in the list is a matrix \( A \) whose rows are vectors in \( \text{FG} \) such that \( M!.\text{generators}[i] \To A[i] \) extends to a module homomorphism \( M \To \text{FG} \).

**EXAMPLES:**

21.1.5 FpGModuleHomomorphism

\( \text{FpGModuleHomomorphism}(M, N, A) \) (function)
\( \text{FpGModuleHomomorphismNC}(M, N, A) \) (function)

Inputs \( \text{FpG} \)-modules \( M \) and \( N \) over a common \( p \)-group \( G \). Also inputs a list \( A \) of vectors in the vector space spanned by \( N!.\text{matrix} \). It tests that the function

\( M!.\text{generators}[i] \To A[i] \)

extends to a homomorphism of \( \text{FpG} \)-modules and, if the test is passed, returns the corresponding \( \text{FpG} \)-module homomorphism. If the test is failed it returns fail.

The "NC" version of the function assumes that the input defines a homomorphism and simply returns the \( \text{FpG} \)-module homomorphism.

**EXAMPLES:**

21.1.6 DesuspensionFpGModule

\( \text{DesuspensionFpGModule}(M, n) \) (function)
\( \text{DesuspensionFpGModule}(R, n) \) (function)

Inputs a positive integer \( n \) and an \( \text{FpG} \)-module \( M \). It returns an \( \text{FpG} \)-module \( D^nM \) which is mathematically related to \( M \) via an exact sequence \( 0 \To D^nM \To R_n \To \ldots \To R_0 \To M \To 0 \) where \( R_0 \) is a free resolution. (If \( G = \text{Group}(M) \) is of prime-power order then the resolution is minimal.)

Alternatively, the function can input a positive integer \( n \) and at least \( n \) terms of a free resolution \( R \) of \( M \).

**EXAMPLES:**

21.1.7 RadicalOfFpGModule

\( \text{RadicalOfFpGModule}(M) \) (function)

Inputs an \( \text{FpG} \)-module \( M \) with \( G \) a \( p \)-group, and returns the Radical of \( M \) as an \( \text{FpG} \)-module. (If \( G \) is not a \( p \)-group then a submodule of the radical is returned.

**EXAMPLES:**
21.1.8 RadicalSeriesOfFpGModule

\[ \text{RadicalSeriesOfFpGModule}(M) \]

Inputs an \( FpG \)-module \( M \) and returns a list of \( FpG \)-modules that constitute the radical series for \( M \).

**EXAMPLES:**

21.1.9 GeneratorsOfFpGModule

\[ \text{GeneratorsOfFpGModule}(M) \]

Inputs an \( FpG \)-module \( M \) and returns a matrix whose rows correspond to a minimal generating set for \( M \).

**EXAMPLES:**

21.1.10 ImageOfFpGModuleHomomorphism

\[ \text{ImageOfFpGModuleHomomorphism}(f) \]

Inputs an \( FpG \)-module homomorphism \( f : M \rightarrow N \) and returns its image \( f(M) \) as an \( FpG \)-module.

**EXAMPLES:**

21.1.11 GroupAlgebraAsFpGModule

\[ \text{GroupAlgebraAsFpGModule}(G) \]

Inputs a \( p \)-group \( G \) and returns its mod \( p \) group algebra as an \( FpG \)-module.

**EXAMPLES:**

21.1.12 IntersectionOfFpGModules

\[ \text{IntersectionOfFpGModules}(M, N) \]

Inputs two \( FpG \)-modules \( M, N \) arising as submodules in a common free module \((FG)^n\) where \( G \) is a finite group and \( F \) the field of \( p \)-elements. It returns the \( FpG \)-module arising as the intersection of \( M \) and \( N \).

**EXAMPLES:**

21.1.13 IsFpGModuleHomomorphismData

\[ \text{IsFpGModuleHomomorphismData}(M, N, A) \]

Inputs \( FpG \)-modules \( M \) and \( N \) over a common \( p \)-group \( G \). Also inputs a list \( A \) of vectors in the vector space spanned by \( N.matrix \). It returns true if the function \( M!.generators[i] \rightarrow A[i] \) extends to a homomorphism of \( FpG \)-modules. Otherwise it returns false.
EXAMPLES:

21.1.14 MaximalSubmoduleOfFpGModule

MaximalSubmoduleOfFpGModule(M) (function)

Inputs an \( FpG \)-module \( M \) and returns one maximal \( FpG \)-submodule of \( M \).

EXAMPLES:

21.1.15 MaximalSubmodulesOfFpGModule

MaximalSubmodulesOfFpGModule(M) (function)

Inputs an \( FpG \)-module \( M \) and returns the list of maximal \( FpG \)-submodules of \( M \).

EXAMPLES:

21.1.16 MultipleOfFpGModule

MultipleOfFpGModule(w, M) (function)

Inputs an \( FpG \)-module \( M \) and a list \( w := [g_1, ..., g_t] \) of elements in the group \( G = M! \). The list \( w \) can be thought of as representing the element \( w = g_1 + \ldots + g_t \) in the group algebra \( FG \), and the function returns a semi-echelon matrix \( B \) which is a basis for the vector subspace \( wM \).

EXAMPLES:

21.1.17 ProjectedFpGModule

ProjectedFpGModule(M, k) (function)

Inputs an \( FpG \)-module \( M \) of ambient dimension \( n|G| \), and an integer \( k \) between 1 and \( n \). The module \( M \) is a submodule of the free module \( (FG)^n \). Let \( M_k \) denote the intersection of \( M \) with the last \( k \) summands of \( (FG)^n \). The function returns the image of the projection of \( M_k \) onto the \( k \)-th summand of \( (FG)^n \). This image is returned an \( FpG \)-module with ambient dimension \( |G| \).

EXAMPLES:

21.1.18 RandomHomomorphismOfFpGModules

RandomHomomorphismOfFpGModules(M, N) (function)

Inputs two \( FpG \)-modules \( M \) and \( N \) over a common group \( G \). It returns a random matrix \( A \) whose rows are vectors in \( N \) such that the function

\[ M!.generators[i] \rightarrow A[i] \]

extends to a homomorphism \( M \rightarrow N \) of \( FpG \)-modules. (There is a problem with this function at present.)

EXAMPLES:
21.1.19  Rank

▷ Rank(f)  (function)

Inputs an $FpG$-module homomorphism $f: M \rightarrow N$ and returns the dimension of the image of $f$ as a vector space over the field $F$ of $p$ elements.

**EXAMPLES:** 1

21.1.20  SumOfFpGModules

▷ SumOfFpGModules(M, N)  (function)

Inputs two $FpG$-modules $M, N$ arising as submodules in a common free module $(FG)^n$ where $G$ is a finite group and $F$ the field of $p$-elements. It returns the $FpG$-Module arising as the sum of $M$ and $N$.

**EXAMPLES:**

21.1.21  SumOp

▷ SumOp(f, g)  (function)

Inputs two $FpG$-module homomorphisms $f, g: M \rightarrow N$ with common source and common target. It returns the sum $f + g: M \rightarrow N$. (This operation is also available using "+".

**EXAMPLES:**

21.1.22  VectorsToFpGModuleWords

▷ VectorsToFpGModuleWords(M, L)  (function)

Inputs an $FpG$-module $M$ and a list $L = [v_1, \ldots, v_k]$ of vectors in $M$. It returns a list $L' = [x_1, \ldots, x_k]$ . Each $x_j = [[W_1, G_1], \ldots, [W_t, G_t]]$ is a list of integer pairs corresponding to an expression of $v_j$ as a word $v_j = g_1 * w_1 + g_2 * w_1 + \ldots + g_t * w_t$

where $g_i = Elements(M!.group)[G_i]$ $w_i = GeneratorsOfFpGModule(M)[W_i]$ .

**EXAMPLES:**
Chapter 22

Meataxe modules

22.1

22.1.1 DesuspensionMtxModule

\[
\text{DesuspensionMtxModule}(M)
\]

(function)

Inputs a meataxe module \(M\) over the field of \(p\) elements and returns an FpG-module DM. The two modules are related mathematically by the existence of a short exact sequence \(DM \rightarrow FM \rightarrow M\) with \(FM\) a free module. Thus the homological properties of \(DM\) are equal to those of \(M\) with a dimension shift.

(If \(G := \text{Group}(M\text{.generators})\) is a \(p\)-group then \(FM\) is a projective cover of \(M\) in the sense that the homomorphism \(FM \rightarrow M\) does not factor as \(FM \rightarrow P \rightarrow M\) for any projective module \(P\).)

**EXAMPLES:** 1, 2

22.1.2 FpG_to_MtxModule

\[
\text{FpG\_to\_MtxModule}(M)
\]

(function)

Inputs an FpG-module \(M\) and returns an isomorphic meataxe module.

**EXAMPLES:**

22.1.3 GeneratorsOfMtxModule

\[
\text{GeneratorsOfMtxModule}(M)
\]

(function)

Inputs a meataxe module \(M\) acting on, say, the vector space \(V\). The function returns a minimal list of row vectors in \(V\) which generate \(V\) as a \(G\)-module (where \(G=\text{Group}(M\text{.generators})\)).

**EXAMPLES:**

101
Chapter 23

G-Outer Groups

23.1

23.1.1 GOuterGroup

\[ \text{GOuterGroup}(E, N) \]  
\[ \text{GOuterGroup()} \]

Inputs a group \( E \) and normal subgroup \( N \). It returns \( N \) as a \( G \)-outer group where \( G = E/N \).

The function can be used without an argument. In this case an empty outer group \( C \) is returned. The components must be set using \( \text{SetActingGroup}(C,G) \), \( \text{SetActedGroup}(C,N) \) and \( \text{SetOuterAction}(C,\alpha) \).

\text{EXAMPLES: 1, 2}

23.1.2 GOuterGroupHomomorphismNC

\[ \text{GOuterGroupHomomorphismNC} \]
\[ \text{GOuterGroupHomomorphismNC} \]

Inputs \( G \)-outer groups \( A \) and \( B \) with common acting group, and a group homomorphism \( \phi: \text{ActedGroup}(A) \rightarrow \text{ActedGroup}(B) \). It returns the corresponding \( G \)-outer homomorphism \( \text{PHI}:A \rightarrow B \). No check is made to verify that \( \phi \) is actually a group homomorphism which preserves the \( G \)-action.

The function can be used without an argument. In this case an empty outer group homomorphism \( \text{PHI} \) is returned. The components must then be set.

\text{EXAMPLES:}

23.1.3 GOuterHomomorphismTester

\[ \text{GOuterHomomorphismTester}(A, B, \phi) \]

Inputs \( G \)-outer groups \( A \) and \( B \) with common acting group, and a group homomorphism \( \phi: \text{ActedGroup}(A) \rightarrow \text{ActedGroup}(B) \). It tests whether \( \phi \) is a group homomorphism which preserves the \( G \)-action.
The function can be used without an argument. In this case an empty outer group homomorphism \( \phi \) is returned. The components must then be set.

**EXAMPLES:**

### 23.1.4 Centre

\[ \text{Centre}(A) \] (function)

Inputs G-outer group \( A \) and returns the group theoretic centre of \( \text{ActedGroup}(A) \) as a G-outer group.

**EXAMPLES:** 1, 2, 3, 4

### 23.1.5 DirectProductGog

\[ \text{DirectProductGog}(A, B) \] (function)

\[ \text{DirectProductGog}(\text{Lst}) \] (function)

Inputs G-outer groups \( A \) and \( B \) with common acting group, and returns their group-theoretic direct product as a G-outer group. The outer action on the direct product is the diagonal one.

The function also applies to a list \( \text{Lst} \) of G-outer groups with common acting group.

For a direct product \( D \) constructed using this function, the embeddings and projections can be obtained (as G-outer group homomorphisms) using the functions \( \text{Embedding}(D, i) \) and \( \text{Projection}(D, i) \).

**EXAMPLES:**
Chapter 24

Cat-1-groups

24.1

24.1.1 AutomorphismGroupAsCatOneGroup

\( \text{AutomorphismGroupAsCatOneGroup}(G) \) (function)

Inputs a group \( G \) and returns the Cat-1-group \( C \) corresponding to the crossed module \( G \to \text{Aut}(G) \).

EXAMPLES: 1, 2, 3, 4, 5

24.1.2 HomotopyGroup

\( \text{HomotopyGroup}(C, n) \) (function)

Inputs a cat-1-group \( C \) and an integer \( n \). It returns the \( n \)th homotopy group of \( C \).

EXAMPLES: 1, 2, 3, 4, 5, 6, 7

24.1.3 HomotopyModule

\( \text{HomotopyModule}(C, 2) \) (function)

Inputs a cat-1-group \( C \) and an integer \( n=2 \). It returns the second homotopy group of \( C \) as a \( G \)-module (i.e. abelian \( G \)-outer group) where \( G \) is the fundamental group of \( C \).

EXAMPLES: 1

24.1.4 QuasiIsomorph

\( \text{QuasiIsomorph}(C) \) (function)

Inputs a cat-1-group \( C \) and returns a cat-1-group \( D \) for which there exists some homomorphism \( C \to D \) that induces isomorphisms on homotopy groups.

This function was implemented by LE VAN LUYEN.

EXAMPLES: 1, 2, 3
24.1.5 ModuleAsCatOneGroup

\[ \text{ModuleAsCatOneGroup} \]

Inputs a group \( G \), an abelian group \( M \) and a homomorphism \( \alpha : G \rightarrow Aut(M) \). It returns the Cat-1-group \( C \) corresponding to the zero crossed module \( 0 : M \rightarrow G \).
\[ \text{EXAMPLES:} \]

24.1.6 MooreComplex

\[ \text{MooreComplex}(C) \]

Inputs a cat-1-group \( C \) and returns its Moore complex as a G-complex (i.e. as a complex of groups considered as 1-outer groups).
\[ \text{EXAMPLES:} \]

24.1.7 NormalSubgroupAsCatOneGroup

\[ \text{NormalSubgroupAsCatOneGroup}(G, N) \]

Inputs a group \( G \) with normal subgroup \( N \). It returns the Cat-1-group \( C \) corresponding to the inclusion crossed module \( N \rightarrow G \).
\[ \text{EXAMPLES:} \]

24.1.8 XmodToHAP

\[ \text{XmodToHAP}(C) \]

Inputs a cat-1-group \( C \) obtained from the Xmod package and returns a cat-1-group \( D \) for which \( \text{IsHapCatOneGroup}(D) \) returns true.
\[ \text{It returns "fail" if} \ C \text{has not been produced by the Xmod package.} \]
\[ \text{EXAMPLES:} 1 \]
Chapter 25

Simplicial groups

25.1

25.1.1 NerveOfCatOneGroup

\[ \text{NerveOfCatOneGroup}(G, n) \]

Inputs a cat-1-group \( G \) and a positive integer \( n \). It returns the low-dimensional part of the nerve of \( G \) as a simplicial group of length \( n \).

This function applies both to cat-1-groups for which \( \text{IsHapCatOneGroup}(G) \) is true, and to cat-1-groups produced using the Xmod package.

This function was implemented by VAN LUYEN LE.

EXAMPLES: 1, 2, 3

25.1.2 EilenbergMacLaneSimplicialGroup

\[ \text{EilenbergMacLaneSimplicialGroup}(G, n, dim) \]

Inputs a group \( G \), a positive integer \( n \), and a positive integer \( dim \). The function returns the first \( 1 + dim \) terms of a simplicial group with \( n - 1 \)st homotopy group equal to \( G \) and all other homotopy groups equal to zero.

This function was implemented by VAN LUYEN LE.

EXAMPLES: 1, 2, 3, 4, 5

25.1.3 EilenbergMacLaneSimplicialGroupMap

\[ \text{EilenbergMacLaneSimplicialGroupMap} \]

Inputs a group homomorphism \( f : G \to Q \), a positive integer \( n \), and a positive integer \( dim \). The function returns the first \( 1 + dim \) terms of a simplicial group homomorphism \( f : K(G,n) \to K(Q,n) \) of Eilenberg-MacLane simplicial groups.
This function was implemented by Van Luyen Le.

**EXAMPLES:**

### 25.1.4 MooreComplex

```plaintext
∥ MooreComplex(G) (function)
```

Inputs a simplicial group $G$ and returns its Moore complex as a $G$-complex.

This function was implemented by Van Luyen Le.

**EXAMPLES:**

### 25.1.5 ChainComplexOfSimplicialGroup

```plaintext
∥ ChainComplexOfSimplicialGroup(G) (function)
```

Inputs a simplicial group $G$ and returns the cellular chain complex $C$ of a CW-space $X$ represented by the homotopy type of the simplicial group. Thus the homology groups of $C$ are the integral homology groups of $X$.

This function was implemented by Van Luyen Le.

**EXAMPLES:** $1, 2, 3, 4, 5, 6$

### 25.1.6 SimplicialGroupMap

```plaintext
∥ SimplicialGroupMap (global variable)
```

Inputs a homomorphism $f: G \rightarrow Q$ of simplicial groups. The function returns an induced map $f: C(G) \rightarrow C(Q)$ of chain complexes whose homology is the integral homology of the simplicial group $G$ and $Q$ respectively.

This function was implemented by Van Luyen Le.

**EXAMPLES:**

### 25.1.7 HomotopyGroup

```plaintext
∥ HomotopyGroup(G, n) (function)
```

Inputs a simplicial group $G$ and a positive integer $n$. The integer $n$ must be less than the length of $G$. It returns, as a group, the $(n)$-th homology group of its Moore complex. Thus HomotopyGroup($G, 0$) returns the "fundamental group" of $G$.

**EXAMPLES:** $1, 2, 3, 4, 5, 6, 7$

### 25.1.8 Representation of elements in the bar resolution

```plaintext
∥ Representation of elements in the bar resolution (global variable)
```
For a group $G$ we denote by $B_n(G)$ the free $\mathbb{Z}G$-module with basis the lists $[g_1|g_2|...|g_n]$ where the $g_i$ range over $G$.

We represent a word

$$w = h_1, [g_{11}|g_{12}|...|g_{1n}] - h_2, [g_{21}|g_{22}|...|g_{2n}] + ... + h_k, [g_{k1}|g_{k2}|...|g_{kn}]$$

in $B_n(G)$ as a list of lists:

$$[[+1, h_1, g_{11}, g_{12}, ... | g_{1n}], [-1, h_2, g_{21}, g_{22}, ... | g_{2n}] + ... + [+1, h_k, g_{k1}, g_{k2}, ..., g_{kn}]].$$

**EXAMPLES:**

### 25.1.9 BarResolutionBoundary

**BarResolutionBoundary**

This function inputs a word $w$ in the bar resolution module $B_n(G)$ and returns its image under the boundary homomorphism $d_n: B_n(G) \rightarrow B_{n-1}(G)$ in the bar resolution.

This function was implemented by VAN LUYEN LE.

**EXAMPLES:**

### 25.1.10 BarResolutionHomotopy

**BarResolutionHomotopy**

This function inputs a word $w$ in the bar resolution module $B_n(G)$ and returns its image under the contracting homotopy $h_n: B_n(G) \rightarrow B_{n+1}(G)$ in the bar resolution.

This function is currently being implemented by VAN LUYEN LE.

**EXAMPLES:**

### 25.1.11 Representation of elements in the bar complex

**Representation of elements in the bar complex**

For a group $G$ we denote by $BC_n(G)$ the free abelian group with basis the lists $[g_1|g_2|...|g_n]$ where the $g_i$ range over $G$.

We represent a word

$$w = [g_{11}|g_{12}|...|g_{1n}] - [g_{21}|g_{22}|...|g_{2n}] + ... + [g_{k1}|g_{k2}|...|g_{kn}]$$

in $BC_n(G)$ as a list of lists:

$$[[+1, g_{11}, g_{12}, ..., g_{1n}], [-1, g_{21}, g_{22}, ... | g_{2n}] + ... + [+1, g_{k1}, g_{k2}, ..., g_{kn}]].$$

**EXAMPLES:**
25.1.12 BarComplexBoundary

This function inputs a word $w$ in the $n$-th term of the bar complex $BC_n(G)$ and returns its image under the boundary homomorphism $d_n: BC_n(G) \to BC_{n-1}(G)$ in the bar complex.

This function was implemented by Van Luyen Le.

**EXAMPLES:**

25.1.13 BarResolutionEquivalence

This function inputs a free $\mathbb{Z}G$-resolution $R$. It returns a component object $HE$ with components

- $HE!.phi(n,w)$ is a function which inputs a non-negative integer $n$ and a word $w$ in $B_n(G)$. It returns the image of $w$ in $R_n$ under a chain equivalence $\phi: B_n(G) \to R_n$.

- $HE!.psi(n,w)$ is a function which inputs a non-negative integer $n$ and a word $w$ in $B_n(G)$. It returns the image of $w$ in $B_n(G)$ under a chain equivalence $\psi: R_n \to B_n(G)$.

- $HE!.equiv(n,w)$ is a function which inputs a non-negative integer $n$ and a word $w$ in $B_n(G)$. It returns the image of $w$ in $B_n(G)$ under a $\mathbb{Z}G$-equivariant homomorphism $equiv(n, -): B_n(G) \to B_{n+1}(G)$ satisfying

  $$w - \psi(\phi(w)) = d(n, equiv(n, w)) \equivquiv(n, d(n, w)).$$

where $d(n, -): B_n(G) \to B_{n-1}(G)$ is the boundary homomorphism in the bar resolution.

This function was implemented by Van Luyen Le.

**EXAMPLES:**

25.1.14 BarComplexEquivalence

This function inputs a free $\mathbb{Z}G$-resolution $R$. It first constructs the chain complex $T = TensorWithIntegers(R)$. The function returns a component object $HE$ with components

- $HE!.phi(n,w)$ is a function which inputs a non-negative integer $n$ and a word $w$ in $BC_n(G)$. It returns the image of $w$ in $T_n$ under a chain equivalence $\phi: BC_n(G) \to T_n$.

- $HE!.psi(n,w)$ is a function which inputs a non-negative integer $n$ and an element $w$ in $T_n$. It returns the image of $w$ in $BC_n(G)$ under a chain equivalence $\psi: T_n \to BC_n(G)$.

- $HE!.equiv(n,w)$ is a function which inputs a non-negative integer $n$ and a word $w$ in $BC_n(G)$. It returns the image of $w$ in $BC_{n+1}(G)$ under a homomorphism.
equiv(n, −): BC_n(G) → BC_{n+1}(G)

satisfying

w − ψ(φ(w)) = d(n + 1, equiv(n, w)) + equiv(n − 1, d(n, w)).

where d(n, −): BC_n(G) → BC_{n−1}(G) is the boundary homomorphism in the bar complex.

This function was implemented by Van Luyen Le.

EXAMPLES:

25.1.15 Representation of elements in the bar cocomplex

For a group G we denote by BC_n(G) the free abelian group with basis the lists [g_1 | g_2 | ... | g_n] where the g_i range over G.

We represent a word

w = [g_11 | g_12 | ... | g_{1n}] − [g_21 | g_22 | ... | g_{2n}] + ... + [g_{k1} | g_{k2} | ... | g_{kn}]

in BC_n(G) as a list of lists:

[[+1, g_11, g_12, ..., g_{1n}], [+1, g_{k1}, g_{k2}, ..., g_{kn}].

EXAMPLES:

25.1.16 BarCocomplexCoboundary

This function inputs a word w in the n-th term of the bar cocomplex BC_n(G) and returns its image under the coboundary homomorphism d^n: BC_n(G) → BC_{n+1}(G) in the bar cocomplex.

This function was implemented by Van Luyen Le.

EXAMPLES:
Chapter 26

Coxeter diagrams and graphs of groups

26.1

26.1.1 CoxeterDiagramComponents

\[ \text{CoxeterDiagramComponents}(D) \] (function)

Inputs a Coxeter diagram \( D \) and returns a list \([D_1, \ldots, D_d]\) of the maximal connected subgraphs \( D_i \).

\text{EXAMPLES:}

26.1.2 CoxeterDiagramDegree

\[ \text{CoxeterDiagramDegree}(D, v) \] (function)

Inputs a Coxeter diagram \( D \) and vertex \( v \). It returns the degree of \( v \) (i.e. the number of edges incident with \( v \)).

\text{EXAMPLES:}

26.1.3 CoxeterDiagramDisplay

\[ \text{CoxeterDiagramDisplay}(D) \] (function)
\[ \text{CoxeterDiagramDisplay}(D, \text{str}) \] (function)

Inputs a Coxeter diagram \( D \) and displays it as a .gif file. It uses the Mozilla web browser as a default to view the diagram. An alternative browser can be set using a second argument \( \text{str}="\text{mozilla}" \).

This function requires Graphviz software.

\text{EXAMPLES: 1, 2, 3, 4, 5, 6}

26.1.4 CoxeterDiagramFpArtinGroup

\[ \text{CoxeterDiagramFpArtinGroup}(D) \] (function)

Inputs a Coxeter diagram \( D \) and returns the corresponding finitely presented Artin group.

\text{EXAMPLES: 1}
26.1.5 CoxeterDiagramFpCoxeterGroup

\[ \text{CoxeterDiagramFpCoxeterGroup}(D) \]

Inputs a Coxeter diagram \( D \) and returns the corresponding finitely presented Coxeter group.

EXAMPLES: 1

26.1.6 CoxeterDiagramIsSpherical

\[ \text{CoxeterDiagramIsSpherical}(D) \]

Inputs a Coxeter diagram \( D \) and returns "true" if the associated Coxeter groups is finite, and returns "false" otherwise.

EXAMPLES: 1

26.1.7 CoxeterDiagramMatrix

\[ \text{CoxeterDiagramMatrix}(D) \]

Inputs a Coxeter diagram \( D \) and returns a matrix representation of it. The matrix is given as a function \( \text{DiagramMatrix}(D)(i, j) \) where \( i, j \) can range over the vertices.

EXAMPLES:

26.1.8 CoxeterSubDiagram

\[ \text{CoxeterSubDiagram}(D, V) \]

Inputs a Coxeter diagram \( D \) and a subset \( V \) of its vertices. It returns the full sub-diagram of \( D \) with vertex set \( V \).

EXAMPLES:

26.1.9 CoxeterDiagramVertices

\[ \text{CoxeterDiagramVertices}(D) \]

Inputs a Coxeter diagram \( D \) and returns its set of vertices.

EXAMPLES:

26.1.10 EvenSubgroup

\[ \text{EvenSubgroup}(G) \]

Inputs a group \( G \) and returns a subgroup \( G^+ \). The subgroup is that generated by all products \( xy \) where \( x \) and \( y \) range over the generating set for \( G \) stored by GAP. The subgroup is probably only meaningful when \( G \) is an Artin or Coxeter group.

EXAMPLES: 1, 2
26.1.11 GraphOfGroupsDisplay

- `GraphOfGroupsDisplay(D)`
- `GraphOfGroupsDisplay(D, str)`

Inputs a graph of groups $D$ and displays it as a .gif file. It uses the Mozilla web browser as a default to view the diagram. An alternative browser can be set using the second argument `str="mozilla"`. This function requires Graphviz software. **Examples:** 1, 2, 3

26.1.12 GraphOfResolutions

- `GraphOfResolutions(D, n)`

Inputs a graph of groups $D$ and a positive integer $n$. It returns a graph of resolutions, each resolution being of length $n$. It uses the function `ResolutionGenericGroup()` to produce the resolutions. **Examples:**

26.1.13 GraphOfGroups

- `GraphOfGroups(D)`

Inputs a graph of resolutions $D$ and returns the corresponding graph of groups. **Examples:** 1, 2, 3

26.1.14 GraphOfResolutionsDisplay

- `GraphOfResolutionsDisplay(D)`

Inputs a graph of resolutions $D$ and displays it as a .gif file. It uses the Mozilla web browser as a default to view the diagram. This function requires Graphviz software. **Examples:**

26.1.15 GraphOfGroupsTest

- `GraphOfGroupsTest(D)`

Inputs an object $D$ and it tries to test whether it is a Graph of Groups. However, it DOES NOT test the injectivity of any homomorphisms. It returns true if $D$ passes the test, and false otherwise. Note that there is no function `IsHapGraphOfGroups()` because no special data type has been created for these graphs. **Examples:**

26.1.16 TreeOfGroupsToContractibleGcomplex

- `TreeOfGroupsToContractibleGcomplex(D, G)`


Inputs a graph of groups $D$ which is a tree, and also inputs the fundamental group $G$ of the tree in a form which contains each of the groups in the graph as subgroups. It returns a corresponding contractible $G$-complex.

**EXAMPLES:**

26.1.17 **TreeOfResolutionsToContractibleGcomplex**

\[ \text{TreeOfResolutionsToContractibleGcomplex}(D, G) \]

Inputs a graph of resolutions $D$ which is a tree, and also inputs the fundamental group $G$ of the tree in a form which contains each of the groups in the graph as subgroups. It returns a corresponding contractible $G$-complex. The resolutions are stored as a component of the contractible $G$-complex.

**EXAMPLES:**
Chapter 27

Torsion Subcomplexes

The Torsion Subcomplex subpackage has been conceived and implemented by BUI ANH TUAN and ALEXANDER D. RAHM.

27.1

27.1.1 RigidFacetsSubdivision

\texttt{apasym(RigidFacetsSubdivision(X))} (function)

It inputs an $n$-dimensional $G$-equivariant CW-complex $X$ on which all the cell stabilizer subgroups in $G$ are finite. It returns an $n$-dimensional $G$-equivariant CW-complex $Y$ which is topologically the same as $X$, but equipped with a $G$-CW-structure which is rigid.

\textbf{EXAMPLES:}

27.1.2 IsPNormal

\texttt{apasym(IsPNormal(G, p))} (function)

Inputs a finite group $G$ and a prime $p$. Checks if the group $G$ is $p$-normal for the prime $p$. Zassenhaus defines a finite group to be $p$-normal if the center of one of its Sylow $p$-groups is the center of every Sylow $p$-group in which it is contained.

\textbf{EXAMPLES:}

27.1.3 TorsionSubcomplex

\texttt{apasym(TorsionSubcomplex(C, p))} (function)

Inputs either a cell complex with action of a group as a variable or a group name. In HAP, presently the following cell complexes with stabilisers fixing their cells pointwise are available, specified by the following "groupName" strings:

"SL(2,O-2)" , "SL(2,O-7)" , "SL(2,O-11)" , "SL(2,O-19)" , "SL(2,O-43)" , "SL(2,O-67)" , "SL(2,O-163)",
where the symbol $\mathbb{O}[-m]$ stands for the ring of integers in the imaginary quadratic number field $\mathbb{Q}(\sqrt{-m})$, the latter being the extension of the field of rational numbers by the square root of minus the square-free positive integer $m$. The additive structure of this ring $\mathbb{O}[-m]$ is given as the module $\mathbb{Z}[\omega]$ over the natural integers $\mathbb{Z}$ with basis $\{1, \omega\}$, and $\omega$ being the square root of minus $m$ if $m$ is congruent to 1 or 2 modulo four; else, in the case $m$ congruent 3 modulo 4, the element $\omega$ is the arithmetic mean with 1, namely $(1 + \sqrt{-m})/2$.

The function TorsionSubcomplex prints the cells with $p$-torsion in their stabilizer on the screen and returns the incidence matrix of the 1-skeleton of this cellular subcomplex, as well as a Boolean value on whether the cell complex has its cell stabilisers fixing their cells pointwise.

It is also possible to input the cell complexes

"SL(2,Z)" , "SL(3,Z)" , "PGL(3,\text{Eisenstein}\_\text{Integers})" , "PSL(4,Z)" , "PSL(4,Z)_b" ,
"PSL(4,Z)_c" , "PSL(4,Z)_d" , "Sp(4,Z)"

provided by Mathieu Dutour.

**EXAMPLES:** 1 , 2 , 3

### 27.1.4 DisplayAvailableCellComplexes

**DisplayAvailableCellComplexes()**

Displays the cell complexes that are available in HAP.

**EXAMPLES:**

### 27.1.5 VisualizeTorsionSkeleton

**VisualizeTorsionSkeleton(groupName, p)**

Executes the function TorsionSubcomplex( groupName, p) and visualizes its output, namely the incidence matrix of the 1-skeleton of the $p$-torsion subcomplex, as a graph.

**EXAMPLES:**

### 27.1.6 ReduceTorsionSubcomplex

**ReduceTorsionSubcomplex(C, p)**

This function start with the same operations as the function TorsionSubcomplex( C, p), and if the cell stabilisers are fixing their cells pointwise, it continues as follows.

It prints on the screen which cells to merge and which edges to cut off in order to reduce the $p$-torsion subcomplex without changing the equivariant Farrell cohomology. Finally, it prints the representative cells, their stabilizers and the Abelianization of the latter.

**EXAMPLES:**
27.1.7 EquivariantEulerCharacteristic

\[ \text{EquivariantEulerCharacteristic}(X) \]

It inputs an \( n \)-dimensional \( \Gamma \)-equivariant CW-complex \( X \) all the cell stabilizer subgroups in \( \Gamma \) are finite. It returns the equivariant euler characteristic obtained by using mass formula \( \sum_{\sigma} (-1)^{\text{dim} \sigma} \frac{1}{\text{card}(\Gamma_{\sigma})} \)

\text{EXAMPLES:}

27.1.8 CountingCellsOfACellComplex

\[ \text{CountingCellsOfACellComplex}(X) \]

It inputs an \( n \)-dimensional \( \Gamma \)-equivariant CW-complex \( X \) on which all the cell stabilizer subgroups in \( \Gamma \) are finite. It returns the number of cells in \( X \)

\text{EXAMPLES:}

27.1.9 CountingControlledSubdividedCells

\[ \text{CountingControlledSubdividedCells}(X) \]

It inputs an \( n \)-dimensional \( \Gamma \)-equivariant CW-complex \( X \) on which all the cell stabilizer subgroups in \( \Gamma \) are finite. It returns the number of cells in \( X \) appear during the subdivision process using the \text{RigidFacetsSubdivision}.

\text{EXAMPLES:}

27.1.10 CountingBaryCentricSubdividedCells

\[ \text{CountingBaryCentricSubdividedCells}(X) \]

It inputs an \( n \)-dimensional \( \Gamma \)-equivariant CW-complex \( X \) on which all the cell stabilizer subgroups in \( \Gamma \) are finite. It returns the number of cells in \( X \) appear during the subdivision process using the barycentric subdivision.

\text{EXAMPLES:}

27.1.11 EquivariantSpectralSequencePage

\[ \text{EquivariantSpectralSequencePage}(C, m, n) \]

It inputs a triple \((C,m,n)\) where \( C \) is either a groupName explained as in \text{TorsionSubcomplex}, \( m \) is the dimension of the reduced torsion subcomplex, and \( n \) is the highest vertical degree in the spectral sequence page. At the moment, the function works only when \( m=1 \), i.e., after reduction the torsion subcomplex has degree 1. It returns a component object \( R \) consists of the first page of spectral sequence, and \( i \)-th cohomology groups for \( i \) less than \( n \).

\text{EXAMPLES:}
27.1.12 ExportHapCellcomplexToDisk

\[ \text{ExportHapCellcomplexToDisk}(C, \text{groupName}) \] (function)

It inputs a cell complex \( C \) which is stored as a variable in the memory, together with a user’s desire name. In case, the input is a torsion cell complex then the user’s desire name should be in the form "group_ptorsion" in order to use the function EquivariantSpectralSequencePage. The function will export \( C \) to the hard disk.

**Examples:**
Chapter 28

Simplicial Complexes

28.1

28.1.1 Homology

\[ \text{Homology}(T, n) \]

\[ \text{Homology}(T) \]

Inputs a pure cubical complex, or cubical complex, or simplicial complex \( T \) and a non-negative integer \( n \). It returns the \( n \)-th integral homology of \( T \) as a list of torsion integers. If no value of \( n \) is input then the list of all homologies of \( T \) in dimensions 0 to Dimension(\( T \)) is returned.

Examples: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39

28.1.2 RipsHomology

\[ \text{RipsHomology}(G, n) \]

\[ \text{RipsHomology}(G, n, p) \]

Inputs a graph \( G \), a non-negative integer \( n \) (and optionally a prime number \( p \)). It returns the integral homology (or mod \( p \) homology) in degree \( n \) of the Rips complex of \( G \).

Examples:

28.1.3 Bettinumbers

\[ \text{Bettinumbers}(T, n) \]

\[ \text{Bettinumbers}(T) \]

Inputs a pure cubical complex, or cubical complex, simplicial complex or chain complex \( T \) and a non-negative integer \( n \). The rank of the \( n \)-th rational homology group \( H_n(T, \mathbb{Q}) \) is returned. If no value for \( n \) is input then the list of Betti numbers in dimensions 0 to Dimension(\( T \)) is returned.

Examples: 1, 2
28.1.4 ChainComplex

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

Inputs a pure cubical complex, or cubical complex, or simplicial complex \( T \) and returns the (often very large) cellular chain complex of \( T \).

**Examples:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

28.1.5 CechComplexOfPureCubicalComplex

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

Inputs a d-dimensional pure cubical complex \( T \) and returns a simplicial complex \( S \). The simplicial complex \( S \) has one vertex for each d-cube in \( T \), and an n-simplex for each collection of n+1 d-cubes with non-trivial common intersection. The homotopy types of \( T \) and \( S \) are equal.

**Examples:** 1

28.1.6 PureComplexToSimplicialComplex

\[ \text{PureComplexToSimplicialComplex}(T, k) \] (function)

Inputs either a d-dimensional pure cubical complex \( T \) or a d-dimensional pure permutahedral complex \( T \) together with a non-negative integer \( k \). It returns the first \( k \) dimensions of a simplicial complex \( S \). The simplicial complex \( S \) has one vertex for each d-cell in \( T \), and an n-simplex for each collection of n+1 d-cells with non-trivial common intersection. The homotopy types of \( T \) and \( S \) are equal.

For a pure cubical complex \( T \) this uses a slightly different algorithm to the function CechComplexOfPureCubicalComplex(T) but constructs the same simplicial complex.

**Examples:** 1

28.1.7 RipsChainComplex

\[ \text{RipsChainComplex}(G, n) \] (function)

Inputs a graph \( G \) and a non-negative integer \( n \). It returns \( n+1 \) terms of a chain complex whose homology is that of the nerve (or Rips complex) of the graph in degrees up to \( n \).

**Examples:** 1

28.1.8 VectorsToSymmetricMatrix

\[ \text{VectorsToSymmetricMatrix}(M) \] (function)
\[ \text{VectorsToSymmetricMatrix}(M, \text{distance}) \] (function)

Inputs a matrix \( M \) of rational numbers and returns a symmetric matrix \( S \) whose \((i, j)\) entry is the distance between the \( i \)-th row and \( j \)-th rows of \( M \) where distance is given by the sum of the absolute values of the coordinate differences.

Optionally, a function \( \text{distance}(v, w) \) can be entered as a second argument. This function has to return a rational number for each pair of rational vectors \( v, w \) of length \( \text{Length}(M[1]) \).
**Examples:** 1

### 28.1.9 EulerCharacteristic

\[ \text{EulerCharacteristic}(T) \]

Inputs a pure cubical complex, or cubical complex, or simplicial complex \( T \) and returns its Euler characteristic.

**Examples:**

### 28.1.10 MaximalSimplicesToSimplicialComplex

\[ \text{MaximalSimplicesToSimplicialComplex}(L) \]

Inputs a list \( L \) whose entries are lists of vertices representing the maximal simplices of a simplicial complex. The simplicial complex is returned. Here a "vertex" is a GAP object such as an integer or a subgroup.

**Examples:** 1, 2, 3, 4

### 28.1.11 SkeletonOfSimplicialComplex

\[ \text{SkeletonOfSimplicialComplex}(S, k) \]

Inputs a simplicial complex \( S \) and a positive integer \( k \) less than or equal to the dimension of \( S \). It returns the truncated \( k \)-dimensional simplicial complex \( S^k \) (and leaves \( S \) unchanged).

**Examples:**

### 28.1.12 GraphOfSimplicialComplex

\[ \text{GraphOfSimplicialComplex}(S) \]

Inputs a simplicial complex \( S \) and returns the graph of \( S \).

**Examples:** 1, 2, 3

### 28.1.13 ContractibleSubcomplexOfSimplicialComplex

\[ \text{ContractibleSubcomplexOfSimplicialComplex}(S) \]

Inputs a simplicial complex \( S \) and returns a (probably maximal) contractible subcomplex of \( S \).

**Examples:**

### 28.1.14 PathComponentsOfSimplicialComplex

\[ \text{PathComponentsOfSimplicialComplex}(S, n) \]

Inputs a simplicial complex \( S \) and a nonnegative integer \( n \). If \( n = 0 \) the number of path components of \( S \) is returned. Otherwise the \( n \)-th path component is returned (as a simplicial complex).

**Examples:**
28.1.15 QuillenComplex

\( \text{QuillenComplex}(G) \) (function)

Inputs a finite group \( G \) and returns, as a simplicial complex, the order complex of the poset of non-trivial elementary abelian subgroups of \( G \).

\textbf{EXAMPLES:} 1, 2, 3

28.1.16 SymmetricMatrixToIncidenceMatrix

\( \text{SymmetricMatrixToIncidenceMatrix}(S, t) \) (function)

\( \text{SymmetricMatrixToIncidenceMatrix}(S, t, d) \) (function)

Inputs a symmetric integer matrix \( S \) and an integer \( t \). It returns the matrix \( M \) with \( M_{ij} = 1 \) if \( I_{ij} < t \) and \( I_{ij} = 1 \) otherwise.

An optional integer \( d \) can be given as a third argument. In this case the incidence matrix should have roughly at most \( d \) entries in each row (corresponding to the \( d \) smallest entries in each row of \( S \)).

\textbf{EXAMPLES:}

28.1.17 IncidenceMatrixToGraph

\( \text{IncidenceMatrixToGraph}(M) \) (function)

Inputs a symmetric 0/1 matrix \( M \). It returns the graph with one vertex for each row of \( M \) and an edge between vertices \( i \) and \( j \) if the \((i, j)\) entry in \( M \) equals 1.

\textbf{EXAMPLES:}

28.1.18 CayleyGraphOfGroup

\( \text{CayleyGraphOfGroup}(G, A) \) (function)

Inputs a group \( G \) and a set \( A \) of generators. It returns the Cayley graph.

\textbf{EXAMPLES:}

28.1.19 PathComponentsOfGraph

\( \text{PathComponentsOfGraph}(G, n) \) (function)

Inputs a graph \( G \) and a nonnegative integer \( n \). If \( n = 0 \) the number of path components is returned. Otherwise the \( n \)-th path component is returned (as a graph).

\textbf{EXAMPLES:}

28.1.20 ContractGraph

\( \text{ContractGraph}(G) \) (function)
Inputs a graph $G$ and tries to remove vertices and edges to produce a smaller graph $G'$ such that the inclusion $G' \to G$ induces a homotopy equivalence $RG \to RG'$ of Rips complexes. If the graph $G$ is modified the function returns true, and otherwise returns false.

**EXAMPLES:** 1

### 28.1.21 GraphDisplay

 genesis GraphDisplay($G$) (function)

This function uses GraphViz software to display a graph $G$.

**EXAMPLES:** 1, 2

### 28.1.22 SimplicialMap

 genesis SimplicialMap($K, L, f$) (function)
genesis SimplicialMapNC($K, L, f$) (function)

Inputs simplicial complexes $K, L$ and a function $f:K!.vertices \to L!.vertices$ representing a simplicial map. It returns a simplicial map $K \to L$. If $f$ does not happen to represent a simplicial map then SimplicialMap($K,L,f$) will return fail; SimplicialMapNC($K,L,f$) will not do any check and always return something of the data type "simplicial map".

**EXAMPLES:**

### 28.1.23 ChainMapOfSimplicialMap

 genesis ChainMapOfSimplicialMap($f$) (function)

Inputs a simplicial map $f:K \to L$ and returns the corresponding chain map $C_*(f):C_*(K) \to C_*(L)$ of the simplicial chain complexes.

**EXAMPLES:**

### 28.1.24 SimplicialNerveOfGraph

 genesis SimplicialNerveOfGraph($G, d$) (function)

Inputs a graph $G$ and returns a $d$-dimensional simplicial complex $K$ whose 1-skeleton is equal to $G$. There is a simplicial inclusion $K \to RG$ where: (i) the inclusion induces isomorphisms on homotopy groups in dimensions less than $d$; (ii) the complex $RG$ is the Rips complex (with one $n$-simplex for each complete subgraph of $G$ on $n+1$ vertices).

**EXAMPLES:** 1, 2
Chapter 29

Cubical Complexes

29.1

29.1.1 ArrayToPureCubicalComplex

\[ \text{ArrayToPureCubicalComplex}(A, n) \] (function)

Inputs an integer array \( A \) of dimension \( d \) and an integer \( n \). It returns a \( d \)-dimensional pure cubical complex corresponding to the black/white “image” determined by the threshold \( n \) and the values of the entries in \( A \). (Integers below the threshold correspond to a black pixel, and higher integers correspond to a white pixel.)

EXAMPLES:

29.1.2 PureCubicalComplex

\[ \text{PureCubicalComplex}(A, n) \] (function)

Inputs a binary array \( A \) of dimension \( d \). It returns the corresponding \( d \)-dimensional pure cubical complex.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

29.1.3 FramedPureCubicalComplex

\[ \text{FramedPureCubicalComplex}(M) \] (function)

Inputs a pure cubical complex \( M \) and returns the pure cubical complex with a border of zeros attached to each face of the boundary array \( M!.boundaryArray \). This function just adds a bit of space for performing operations such as thickenings to \( M \).

EXAMPLES: 1

29.1.4 RandomCubeOfPureCubicalComplex

\[ \text{RandomCubeOfPureCubicalComplex}(M) \] (function)
Inputs a pure cubical complex $M$ and returns a pure cubical complex $R$ with precisely the same dimensions as $M$. The complex $R$ consist of one cube selected at random from $M$.

**EXAMPLES:** 1

### 29.1.5 PureCubicalComplexIntersection

▷ PureCubicalComplexIntersection($S$, $T$) (function)

Inputs two pure cubical complexes with common dimension and array size. It returns the intersection of the two complexes. (An entry in the binary array of the intersection has value 1 if and only if the corresponding entries in the binary arrays of $S$ and $T$ both have value 1.)

**EXAMPLES:** 1

### 29.1.6 PureCubicalComplexUnion

▷ PureCubicalComplexUnion($S$, $T$) (function)

Inputs two pure cubical complexes with common dimension and array size. It returns the union of the two complexes. (An entry in the binary array of the union has value 1 if and only if at least one of the corresponding entries in the binary arrays of $S$ and $T$ has value 1.)

**EXAMPLES:** 1

### 29.1.7 PureCubicalComplexDifference

▷ PureCubicalComplexDifference($S$, $T$) (function)

Inputs two pure cubical complexes with common dimension and array size. It returns the difference $S$-$T$. (An entry in the binary array of the difference has value 1 if and only if the corresponding entry in the binary array of $S$ is 1 and the corresponding entry in the binary array of $T$ is 0.)

**EXAMPLES:** 1, 2

### 29.1.8 ReadImageAsPureCubicalComplex

▷ ReadImageAsPureCubicalComplex($str$, $n$) (function)

Reads an image file $str$ (= "file.png", "file.eps", "file.bmp" etc) and an integer $n$ between 0 and 765. It returns a 2-dimensional pure cubical complex based on the black/white version of the image determined by the threshold $n$.

**EXAMPLES:** 1, 2, 3

### 29.1.9 ReadLinkImageAsPureCubicalComplex

▷ ReadLinkImageAsPureCubicalComplex($str$) (function)

▷ ReadLinkImageAsPureCubicalComplex($str$, $n$) (function)

Reads an image file $str$ (= "file.png", "file.eps", "file.bmp" etc) containing a knot or link diagram, and optionally a positive integer $n$. The integer $n$ should be a little larger than the line thickness in the link diagram, and if not provided then $n$ is set equal to 10. The function tries to output the
corresponding knot or link as a 3-dimensional pure cubical complex. Ideally the link diagram should be produced with line thickness 6 in Xfig, and the under-crossing spaces should not be too large or too small or too near one another. The function does not always succeed: it applies several checks, and if one of these checks fails then the function returns "fail".

EXAMPLES: 1

29.1.10  ReadImageSequenceAsPureCubicalComplex

Reads the name of a directory \textit{dir} containing a sequence of image files (ordered alphanumerically), and an integer \textit{n} between 0 and 765. It returns a 3-dimensional pure cubical complex based on the black/white version of the images determined by the threshold \textit{n}.

EXAMPLES: 1

29.1.11  Size

This returns the number of non-zero entries in the binary array of the cubical complex, or pure cubical complex \textit{T}.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16

29.1.12  Dimension

This returns the dimension of the cubical complex, or pure cubical complex \textit{T}.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7

29.1.13  WritePureCubicalComplexAsImage

Inputs a 2-dimensional pure cubical complex \textit{T}, and a filename \textit{str1} followed by its extension \textit{str2} (e.g. \textit{str1}="myfile" followed by \textit{str2}="png"). A black/white image is saved to the file.

EXAMPLES:

29.1.14  ViewPureCubicalComplex

Inputs a 2-dimensional pure cubical complex \textit{T}, and optionally a command such as \textit{str}="mozilla" for viewing image files. A black/white image is displayed.

EXAMPLES: 1, 2, 3
29.1.15 Homology

\[ \text{Homology}(T, n) \] (function)
\[ \text{Homology}(T) \] (function)

Inputs a pure cubical complex, or cubical complex, or simplicial complex \( T \) and a non-negative integer \( n \). It returns the \( n \)-th integral homology of \( T \) as a list of torsion integers. If no value of \( n \) is input then the list of all homologies of \( T \) in dimensions 0 to Dimension\( (T) \) is returned.

**Examples:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39

29.1.16 Bettinumbers

\[ \text{Bettinumbers}(T, n) \] (function)
\[ \text{Bettinumbers}(T) \] (function)

Inputs a pure cubical complex, or cubical complex, simplicial complex or chain complex \( T \) and a non-negative integer \( n \). The rank of the \( n \)-th rational homology group \( H_n(T, \mathbb{Q}) \) is returned. If no value for \( n \) is input then the list of Betti numbers in dimensions 0 to Dimension\( (T) \) is returned.

**Examples:** 1, 2

29.1.17 DirectProductOfPureCubicalComplexes

\[ \text{DirectProductOfPureCubicalComplexes}(M, N) \] (function)

Inputs two pure cubical complexes \( M, N \) and returns their direct product \( D \) as a pure cubical complex. The dimension of \( D \) is the sum of the dimensions of \( M \) and \( N \).

**Examples:** 1

29.1.18 SuspensionOfPureCubicalComplex

\[ \text{SuspensionOfPureCubicalComplex}(M) \] (function)

Inputs a pure cubical complex \( M \) and returns a pure cubical complex with the homotopy type of the suspension of \( M \).

**Examples:** 1

29.1.19 EulerCharacteristic

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

Inputs a pure cubical complex, or cubical complex, or simplicial complex \( T \) and returns its Euler characteristic.

**Examples:**
29.1.20 PathComponentOfPureCubicalComplex

\textbf{PathComponentOfPureCubicalComplex}(T, n) \hspace{1cm} \text{(function)}

Inputs a pure cubical complex $T$ and an integer $n$ in the range $1, \ldots, \text{Bettinumbers}(T)[1]$. It returns the $n$-th path component of $T$ as a pure cubical complex. The value $n = 0$ is also allowed, in which case the number of path components is returned.

\textbf{EXAMPLES}: 1

29.1.21 ChainComplex

\textbf{ChainComplex}(T) \hspace{1cm} \text{(function)}

Inputs a pure cubical complex, or cubical complex, or simplicial complex $T$ and returns the (often very large) cellular chain complex of $T$.

\textbf{EXAMPLES}: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

29.1.22 ChainComplexOfPair

\textbf{ChainComplexOfPair}(T, S) \hspace{1cm} \text{(function)}

Inputs a pure cubical complex or cubical complex $T$ and subcomplex $S$. It returns the quotient $C(T)/C(S)$ of cellular chain complexes.

\textbf{EXAMPLES}: 1

29.1.23 ExcisedPureCubicalPair

\textbf{ExcisedPureCubicalPair}(T, S) \hspace{1cm} \text{(function)}

Inputs a pure cubical complex $T$ and subcomplex $S$. It returns the pair $[T \setminus \text{int} S, S \setminus \text{int} S]$ of pure cubical complexes where $\text{int} S$ is the pure cubical complex obtained from $S$ by removing its boundary.

\textbf{EXAMPLES}:

29.1.24 ChainInclusionOfPureCubicalPair

\textbf{ChainInclusionOfPureCubicalPair}(S, T) \hspace{1cm} \text{(function)}

Inputs a pure cubical complex $T$ and subcomplex $S$. It returns the chain inclusion $C(S) \to C(T)$ of cellular chain complexes.

\textbf{EXAMPLES}:

29.1.25 ChainMapOfPureCubicalPairs

\textbf{ChainMapOfPureCubicalPairs} \hspace{1cm} \text{(global variable)}

Inputs a pure cubical complex $N$ and subcomplexes $M, T$ and $S$ in $T$. It returns the chain map $C(M/S) \to C(N/T)$ of quotient cellular chain complexes.

\textbf{EXAMPLES}:
29.1.26 ContractPureCubicalComplex

\[ \text{ContractPureCubicalComplex}(T) \]

Inputs a pure cubical complex \( T \) of dimension \( d \) and removes \( d \)-dimensional cells from \( T \) without changing the homotopy type of \( T \). When the function has been applied, no further \( d \)-cells can be removed from \( T \) without changing its homotopy type. This function modifies \( T \).

**Examples:** 1

29.1.27 ContractedComplex

\[ \text{ContractedComplex}(T) \]

Inputs a pure cubical complex \( T \) and returns a structural copy of the complex obtained from \( T \) by applying the function \( \text{ContractPureCubicalComplex}(T) \).

**Examples:** 1, 2, 3, 4, 5, 6

29.1.28 ZigZagContractedPureCubicalComplex

\[ \text{ZigZagContractedPureCubicalComplex}(T) \]

Inputs a pure cubical complex \( T \) and returns a homotopy equivalent pure cubical complex \( S \). The aim is for \( S \) to involve fewer cells than \( T \) and certainly to involve no more cells than \( T \).

**Examples:** 1, 2, 3

29.1.29 ContractCubicalComplex

\[ \text{ContractCubicalComplex}(T) \]

Inputs a cubical complex \( T \) and removes cells without changing the homotopy type of \( T \). It changes \( T \). In particular, it adds the components \( T.vectors \) and \( T.rewrite \) of a discrete vector field.

At present this function only works for cubical complexes of dimension 2 or 3.

**Examples:** 1

29.1.30 DVFReducedCubicalComplex

\[ \text{DVFReducedCubicalComplex}(T) \]

Inputs a cubical complex \( T \) and returns a non-regular cubical complex \( R \) by constructing a discrete vector field. The vector field is designed to minimize the number of critical cells in \( R \) at the cost of allowing cell attaching maps that are not homeomorphisms on boundaries.

At present this function works only for 2- and 3-dimensional cubical complexes.
The function \( \text{ChainComplex}(R) \) can be used to obtain the cellular chain complex of \( R \).

**Examples:** 1
29.1.31 SkeletonOfCubicalComplex

\( \text{SkeletonOfCubicalComplex}(T, n) \) (function)

Inputs a cubical complex, or pure cubical complex \( T \) and positive integer \( n \). It returns the \( n \)-skeleton of \( T \) as a cubical complex.

**EXAMPLES:**

29.1.32 ContractibleSubcomplexOfPureCubicalComplex

\( \text{ContractibleSubcomplexOfPureCubicalComplex} \) (global variable)

Inputs a pure cubical complex \( T \) and returns a maximal contractible pure cubical subcomplex.

**EXAMPLES:**

29.1.33 AcyclicSubcomplexOfPureCubicalComplex

\( \text{AcyclicSubcomplexOfPureCubicalComplex} \) (global variable)

Inputs a pure cubical complex \( T \) and returns a (not necessarily connected) pure cubical subcomplex having trivial homology in all degrees greater than 0.

**EXAMPLES:**

29.1.34 HomotopyEquivalentMaximalPureCubicalSubcomplex

\( \text{HomotopyEquivalentMaximalPureCubicalSubcomplex}(T, S) \) (function)

Inputs a pure cubical complex \( T \) together with a pure cubical subcomplex \( S \). It returns a pure cubical subcomplex \( H \) of \( T \) which contains \( S \) and is maximal with respect to the property that it is homotopy equivalent to \( S \).

**EXAMPLES:**

29.1.35 HomotopyEquivalentMinimalPureCubicalSubcomplex

\( \text{HomotopyEquivalentMinimalPureCubicalSubcomplex}(T, S) \) (function)

Inputs a pure cubical complex \( T \) together with a pure cubical subcomplex \( S \). It returns a pure cubical subcomplex \( H \) of \( T \) which contains \( S \) and is minimal with respect to the property that it is homotopy equivalent to \( T \).

**EXAMPLES:**

29.1.36 BoundaryOfPureCubicalComplex

\( \text{BoundaryOfPureCubicalComplex}(T) \) (function)

Inputs a pure cubical complex \( T \) and returns its boundary as a pure cubical complex. The boundary consists of all cubes which have one or more facets that lie in just the one cube.

**EXAMPLES:**
29.1.37 **SingularitiesOfPureCubicalComplex**

\begin{verbatim}
SingularitiesOfPureCubicalComplex(T, radius, tolerance)
\end{verbatim}

Inputs a pure cubical complex \( T \) together with a positive integer "radius" and an integer "tolerance" in the range 1..100. It returns the pure cubical subcomplex of those cells in the boundary where the boundary is not differentiable. (The method for deciding differentiability at a point is crude/discrete, prone to errors and depends on the radius and tolerance.)

**EXAMPLES:** 1

29.1.38 **ThickenedPureCubicalComplex**

\begin{verbatim}
ThickenedPureCubicalComplex(T)
\end{verbatim}

Inputs a pure cubical complex \( T \) and returns a pure cubical complex \( S \). If a euclidean cube is in \( T \) then this cube and all its neighbouring cubes are included in \( S \).

**EXAMPLES:** 1, 2, 3

29.1.39 **CropPureCubicalComplex**

\begin{verbatim}
CropPureCubicalComplex(T)
\end{verbatim}

Inputs a pure cubical complex \( T \) and returns a pure cubical complex \( S \) obtained from \( T \) by removing any "zero boundary sheets" of the binary array. Thus \( S \) and \( T \) are isometric as euclidean spaces but there may be fewer zero entries in the binary array for \( S \).

**EXAMPLES:**

29.1.40 **BoundingPureCubicalComplex**

\begin{verbatim}
BoundingPureCubicalComplex(T)
\end{verbatim}

Inputs a pure cubical complex \( T \) and returns a contractible pure cubical complex \( S \) containing \( T \).

**EXAMPLES:**

29.1.41 **MorseFiltration**

\begin{verbatim}
MorseFiltration(M, i, t, bool)
MorseFiltration(M, i, t)
\end{verbatim}

Inputs a pure cubical complex \( M \) of dimension \( d \), an integer \( i \) between 1 and \( d \), a positive integer \( t \) and a boolean value True or False. The function returns a list \([M_1, M_2, ..., M_t]\) of pure cubical complexes with \( M_k \) a subcomplex of \( M_{k+1} \). The list is constructed by setting all slices of \( M \) perpendicular to the \( i \)-th axis equal to zero if they meet the \( i \)th axis at a sufficiently high coordinate (if \( \text{bool}=\text{True} \)) or sufficiently low coordinate (if \( \text{bool}=\text{False} \)).

If the variable \( \text{bool} \) is not specified then it is assumed to have the value True.

**EXAMPLES:**
29.1.42 ComplementOfPureCubicalComplex

\[ \text{ComplementOfPureCubicalComplex}(T) \]

Inputs a pure cubical complex \( T \) and returns a pure cubical complex \( S \). A euclidean cube is in \( S \) precisely when the cube is not in \( T \).

**EXAMPLES:** 1, 2, 3

29.1.43 PureCubicalComplexToTextFile

\[ \text{PureCubicalComplexToTextFile}(file, M) \]

Inputs a pure cubical complex \( M \) and a string containing the address of a file. A representation of this complex is written to the file in a format that can be read by the CAPD (Computer Assisted Proofs in Dynamics) software developed by Marian Mrozek and others.

**EXAMPLES:**

29.1.44 ThickeningFiltration

\[ \text{ThickeningFiltration}(M, n) \]
\[ \text{ThickeningFiltration}(M, n, k) \]

Inputs a pure cubical complex \( M \) and a positive integer \( n \). It returns a filtered pure cubical complex constructed from \( n \) thickenings of \( M \). If a positive integer \( k \) is supplied as an optional third argument, then each step of the filtration is obtained from a \( k \)-fold thickening.

**EXAMPLES:**

29.1.45 Dendrogram

\[ \text{Dendrogram}(M) \]

Inputs a filtered pure cubical complex \( M \) and returns data that specifies the dendrogram (or phylogenetic tree) describing how path components are born and then merge during the filtration.

**EXAMPLES:**

29.1.46 DendrogramDisplay

\[ \text{DendrogramDisplay} \]

**GLOBAL VARIABLE**

Inputs a filtered pure cubical complex \( M \), or alternatively inputs the output from the command Dendrogram(M), and then uses GraphViz software to display the path component dendrogram of \( M \).

**EXAMPLES:**

29.1.47 DendrogramToPersistenceMat

\[ \text{DendrogramToPersistenceMat}(D) \]

**FUNCTION**
Inputs the output of the function Dendrogram(M) and returns the corresponding degree 0 Betti bar code.

**EXAMPLES:**

29.1.48 ReadImageAsFilteredPureCubicalComplex

▷ ReadImageAsFilteredPureCubicalComplex(file, n) (function)

Inputs a string containing the path to an image file, together with a positive integer n. It returns a filtered pure cubical complex of filtration length n.

**EXAMPLES:** 1

29.1.49 ComplementOfFilteredPureCubicalComplex

▷ ComplementOfFilteredPureCubicalComplex(M) (function)

Inputs a filtered pure cubical complex M and returns the complement as a filtered pure cubical complex.

**EXAMPLES:**

29.1.50 PersistentHomologyOfFilteredPureCubicalComplex

▷ PersistentHomologyOfFilteredPureCubicalComplex(M, n) (function)

Inputs a filtered pure cubical complex M and a non-negative integer n. It returns the degree n persistent homology of M with rational coefficients.

**EXAMPLES:**
Chapter 30

Regular CW-Complexes

30.1

30.1.1 SimplicialComplexToRegularCWComplex

\[ \text{SimplicialComplexToRegularCWComplex}(K) \]

(function)

Inputs a simplicial complex \( K \) and returns the corresponding regular CW-complex.

EXAMPLES: 1, 2

30.1.2 CubicalComplexToRegularCWComplex

\[ \text{CubicalComplexToRegularCWComplex}(K) \]

(function)

\[ \text{CubicalComplexToRegularCWComplex}(K, n) \]

(function)

Inputs a pure cubical complex (or cubical complex) \( K \) and returns the corresponding regular CW-complex. If a positive integer \( n \) is entered as an optional second argument, then just the \( n \)-skeleton of \( K \) is returned.

EXAMPLES: 1

30.1.3 CriticalCellsOfRegularCWComplex

\[ \text{CriticalCellsOfRegularCWComplex}(Y) \]

(function)

\[ \text{CriticalCellsOfRegularCWComplex}(Y, n) \]

(function)

Inputs a regular CW-complex \( Y \) and returns the critical cells of \( Y \) with respect to some discrete vector field. If \( Y \) does not initially have a discrete vector field then one is constructed.

If a positive integer \( n \) is given as a second optional input, then just the critical cells in dimensions up to and including \( n \) are returned.

The function \( \text{CriticalCellsOfRegularCWComplex}(Y) \) works by homotopy reducing cells starting at the top dimension. The function \( \text{CriticalCellsOfRegularCWComplex}(Y, n) \) works by homotopy coreducing cells starting at dimension 0. The two methods may well return different numbers of cells.

EXAMPLES: 1, 2, 3
30.1.4 ChainComplex

▷ ChainComplex(Y) (function)

Inputs a regular CW-complex $Y$ and returns the cellular chain complex of a CW-complex $W$ whose cells correspond to the critical cells of $Y$ with respect to some discrete vector field. If $Y$ does not initially have a discrete vector field then one is constructed.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

30.1.5 ChainComplexOfRegularCWComplex

▷ ChainComplexOfRegularCWComplex(Y) (function)

Inputs a regular CW-complex $Y$ and returns the cellular chain complex of $Y$.

EXAMPLES: 1

30.1.6 FundamentalGroup

▷ FundamentalGroup(Y) (function)
▷ FundamentalGroup(Y, n) (function)

Inputs a regular CW-complex $Y$ and, optionally, the number of some 0-cell. It returns the fundamental group of $Y$ based at the 0-cell $n$. The group is returned as a finitely presented group. If $n$ is not specified then it is set $n = 1$. The algorithm requires a discrete vector field on $Y$. If $Y$ does not initially have a discrete vector field then one is constructed.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
Chapter 31

Knots and Links

31.1

31.1.1 PureCubicalKnot

▷ PureCubicalKnot(L) (function)
▷ PureCubicalKnot(n, i) (function)

Inputs a list $L = [[m_1, n_1], [m_2, n_2], ..., [m_k, n_k]]$ of pairs of integers describing a cubical arc presentation of a link with all vertical lines at the front and all horizontal lines at the back. The bottom horizontal line extends from the $m_1$-th column to the $n_1$-th column. The second to bottom horizontal line extends from the $m_2$-th column to the $n_2$-th column. And so on. The link is returned as a 3-dimensional pure cubical complex.

Alternatively the function inputs two integers $n, i$ and returns the $i$-th prime knot on $n$ crossings.

Examples: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

31.1.2 ViewPureCubicalKnot

▷ ViewPureCubicalKnot(L) (function)

Inputs a pure cubical link $L$ and displays it.

Examples: 1, 2

31.1.3 KnotSum

▷ KnotSum(K, L) (function)

Inputs two pure cubical knots $K, L$ and returns their sum as a pure cubical knot. This function is not defined for links with more than one component.

Examples: 1, 2, 3, 4, 5

31.1.4 KnotGroup

▷ KnotGroup(K) (function)
Inputs a pure cubical link $K$ and returns the fundamental group of its complement. The group is returned as a finitely presented group.

EXAMPLES: 1

31.1.5 **AlexanderMatrix**

\[ \text{AlexanderMatrix}(G) \] (function)

Inputs a finitely presented group $G$ whose abelianization is infinite cyclic. It returns the Alexander matrix of the presentation.

EXAMPLES:

31.1.6 **AlexanderPolynomial**

\[ \text{AlexanderPolynomial}(K) \] (function)
\[ \text{AlexanderPolynomial}(G) \] (function)

Inputs either a pure cubical knot $K$ or a finitely presented group $G$ whose abelianization is infinite cyclic. The Alexander Polynomial is returned.

EXAMPLES: 1, 2

31.1.7 **ProjectionOfPureCubicalComplex**

\[ \text{ProjectionOfPureCubicalComplex}(K) \] (function)

Inputs an $n$-dimensional pure cubical complex $K$ and returns an $n$-1-dimensional pure cubical complex $K'$. The returned complex is obtained by projecting Euclidean $n$-space onto Euclidean $n$-1-space.

EXAMPLES:

31.1.8 **ReadPDBfileAsPureCubicalComplex**

\[ \text{ReadPDBfileAsPureCubicalComplex}(file) \] (function)
\[ \text{ReadPDBfileAsPureCubicalComplex}(file, m, c) \] (function)

Inputs a protein database file describing a protein, and optionally inputs a positive integer $m$ and character string $c$. The default values for the optional inputs are $m=5$ and $c=\text{"A"}$. It loads the chain of amino acids labelled by $c$ in the file as a 3-dimensional pure cubical complex of the homotopy type of a circle.

It might happen that the function fails to construct a pure cubical complex of the homotopy type of a circle. In this case retry with a larger integer $m$.

EXAMPLES: 1, 2
Chapter 32

Knots and Quandles

32.1

Knots

32.1.1 PresentationKnotQuandle

▷ PresentationKnotQuandle(gaussCode) (function)

Inputs a Gauss Code of a knot (with the orientations; see GaussCodeOfPureCubicalKnot in HAP package) and outputs the generators and relators of the knot quandle associated (in the form of a record).

EXAMPLES: 1, 2, 3, 4

32.1.2 PD2GC

▷ PD2GC(PD) (function)

Inputs a Planar Diagram of a knot; outputs the Gauss Code associated (with the orientations).

EXAMPLES: 1, 2, 3

32.1.3 PlanarDiagramKnot

▷ PlanarDiagramKnot(n, k) (function)

Returns a Planar Diagram for the k-th knot with n crossings \( n \leq 12 \) if it exists; fail otherwise.

EXAMPLES: 1, 2, 3

32.1.4 GaussCodeKnot

▷ GaussCodeKnot(n, k) (function)

Returns a Gauss Code (with orientations) for the k-th knot with n crossings \( n \leq 12 \) if it exists; fail otherwise.

EXAMPLES:
32.1.5 PresentationKnotQuandleKnot

\(\text{PresentationKnotQuandleKnot}(n, k)\)  

Returns generators and relators (in the form of a record) for the \(k\)-th knot with \(n\) crossings \((n \leq 12)\) if it exists; fail otherwise.  

**EXAMPLES:** 1, 2, 3

32.1.6 NumberOfHomomorphisms

\(\text{NumberOfHomomorphisms}(\text{genRelQ}, \text{finiteQ})\)  

Inputs generators and relators \(\text{genRelQ}\) of a knot quandle (in the form of a record, see above) and a finite quandle \(\text{finiteQ}\); outputs the number of homomorphisms from the former to the latter.  

**EXAMPLES:** 1, 2, 3

32.1.7 PartitionedNumberOfHomomorphisms

\(\text{PartitionedNumberOfHomomorphisms}(\text{genRelQ}, \text{finiteQ})\)  

Inputs generators and relators \(\text{genRelQ}\) of a knot quandle (in the form of a record, see above) and a finite connected quandle \(\text{finiteQ}\); outputs a partition of the number of homomorphisms from the former to the latter.  

**EXAMPLES:** 1

32.1.8 ConjugationQuandle

\(\text{ConjugationQuandle}(G, n)\)  

Inputs a finite group \(G\) and an integer \(n\); outputs the associated \(n\)-fold conjugation quandle.  

**EXAMPLES:** 1, 2

32.1.9 FirstQuandleAxiomIsSatisfied

\(\text{FirstQuandleAxiomIsSatisfied}(M)\)  
\(\text{SecondQuandleAxiomIsSatisfied}(M)\)  
\(\text{ThirdQuandleAxiomIsSatisfied}(M)\)  

Inputs a finite magma \(M\); returns true if \(M\) satisfy the first/second/third axiom of a quandle, false otherwise.  

**EXAMPLES:**

32.1.10 IsQuandle

\(\text{IsQuandle}(M)\)  

Inputs a finite magma \(M\); returns true if \(M\) is a quandle, false otherwise.
32.1.11 Quandles

\( \text{Quandles}(n) \) (function)

Returns a list of all quandles of size \( n \), \( n \leq 6 \). If \( n \geq 7 \), it returns fail.

**EXAMPLES:** 1, 2, 3, 4, 5, 6

32.1.12 Quandle

\( \text{Quandle}(n,k) \) (function)

Returns the \( k \)-th quandle of size \( n \) (\( n \leq 6 \)) if such a quandle exists, fail otherwise.

**EXAMPLES:** 1, 2, 3, 4, 5, 6, 7

32.1.13 IdQuandle

\( \text{IdQuandle}(Q) \) (function)

Inputs a quandle \( Q \); and outputs a list of integers \([n,k]\) such that \( Q \) is isomorphic to \( \text{Quandle}(n,k) \).
If \( n \geq 7 \), then it returns \([n,fail]\) (where \( n \) is the size of \( Q \)).

**EXAMPLES:**

32.1.14 IsLatin

\( \text{IsLatin} \) (global variable)

Inputs a finite quandle \( Q \); returns true if \( Q \) is latin, false otherwise.

**EXAMPLES:**

32.1.15 IsConnectedQuandle

\( \text{IsConnectedQuandle} \) (global variable)

Inputs a finite quandle \( Q \); returns true if \( Q \) is connected, false otherwise.

**EXAMPLES:**

32.1.16 ConnectedQuandles

\( \text{ConnectedQuandles}(n) \) (function)

Returns a list of all connected quandles of size \( n \).

**EXAMPLES:** 1, 2, 3
32.1.17 ConnectedQuandle

\texttt{ConnectedQuandle}(n, k) \hspace{1cm} \text{(function)}

Returns the \(k\)-th quandle of size \(n\) if such a quandle exists, fail otherwise.
\textsc{Examples}: 1, 2, 3, 4

32.1.18 IdConnectedQuandle

\texttt{IdConnectedQuandle}(Q) \hspace{1cm} \text{(function)}

Inputs a connected quandle \(Q\); and outputs a list of integers \([n, k]\) such that \(Q\) is isomorphic to \(\text{ConnectedQuandle}(n, k)\).
\textsc{Examples}: 1

32.1.19 IsQuandleEnvelope

\texttt{IsQuandleEnvelope}(Q, G, e, stigma) \hspace{1cm} \text{(function)}

Inputs a set \(Q\), a permutation group \(G\), an element \(e \in Q\) and an element \(stigma \in G\); returns true if this structure describes a quandle envelope, false otherwise.
\textsc{Examples}: 1, 2, 3

32.1.20 QuandleQuandleEnvelope

\texttt{QuandleQuandleEnvelope}(Q, G, e, stigma) \hspace{1cm} \text{(function)}

Inputs a set \(Q\), a permutation group \(G\), an element \(e \in Q\) and an element \(stigma \in G\). If this structure describes a quandle envelope, the function returns the quandle from this quandle envelope; and fail otherwise. Nb: this quandle is a connected quandle.
\textsc{Examples}: 1, 2, 3

32.1.21 KnotInvariantCedric

\texttt{KnotInvariantCedric}(genRelQ, n, m) \hspace{1cm} \text{(function)}

Inputs generators and relators of a knot quandle (in the form of a record, see above) and two integers \(n\) and \(m\); outputs a list \([n1, n2, ..., nk]\) where \(nj\) is a partition of the number of homomorphisms from the considered knot quandle to the \(j\)-th connected quandle of size \(n \leq i \leq m\).
\textsc{Examples}:

32.1.22 RightMultiplicationGroupAsPerm

\texttt{RightMultiplicationGroupAsPerm} \hspace{1cm} \text{(global variable)}

Inputs a connected quandle \(Q\); output its right multiplication group whose elements are permutations.
\textsc{Examples}:
32.1.23 RightMultiplicationGroup

▷ RightMultiplicationGroup

(global variable)

Inputs a connected quandle $Q$; output its right multiplication group whose elements are mappings from $Q$ to $Q$.

EXAMPLES:

32.1.24 AutomorphismGroupQuandleAsPerm

▷ AutomorphismGroupQuandleAsPerm($Q$)

(function)

Inputs a connected quandle $Q$; outputs its automorphism group whose elements are permutations.

EXAMPLES:

32.1.25 AutomorphismGroupQuandle

▷ AutomorphismGroupQuandle($Q$)

(function)

Inputs a connected quandle $Q$; outputs its automorphism group whose elements are mappings from $Q$ to $Q$.

EXAMPLES: 1, 2, 3
Chapter 33

Finite metric spaces and their filtered complexes

33.1

33.1.1 CayleyMetric

\[ \text{CayleyMetric}(g, h, N) \] (function)

\[ \text{CayleyMetric}(g, h) \] (function)

Inputs two permutations \( g, h \) and optionally the degree \( N \) of a symmetric group containing them. It returns the minimum number of transpositions needed to express \( g \ast h^{-1} \) as a product of transpositions.

EXAMPLES: 1

33.1.2 HammingMetric

\[ \text{HammingMetric}(g, h, N) \] (function)

\[ \text{HammingMetric}(g, h) \] (function)

Inputs two permutations \( g, h \) and optionally the degree \( N \) of a symmetric group containing them. It returns the number of integers moved by the permutation \( g \ast h^{-1} \).

EXAMPLES:

33.1.3 KendallMetric

\[ \text{KendallMetric}(g, h, N) \] (function)

\[ \text{KendallMetric}(g, h) \] (function)

Inputs two permutations \( g, h \) and optionally the degree \( N \) of a symmetric group containing them. It returns the minimum number of adjacent transpositions needed to express \( g \ast h^{-1} \) as a product of adjacent transpositions. An adjacent transposition has the form \((i, i+1)\).

EXAMPLES:
33.1.4 EuclideanSquaredMetric

\[ \text{EuclideanSquaredMetric}(v, w) \]

Inputs two vectors \( v, w \) of equal length and returns the sum of the squares of the components of \( v - w \). In other words, it returns the square of the Euclidean distance between \( v \) and \( w \).

**Examples:**

33.1.5 EuclideanApproximatedMetric

\[ \text{EuclideanApproximatedMetric}(v, w) \]

Inputs two vectors \( v, w \) of equal length and returns a rational approximation to the square root of the sum of the squares of the components of \( v - w \). In other words, it returns an approximation to the Euclidean distance between \( v \) and \( w \).

**Examples:**

33.1.6 ManhattanMetric

\[ \text{ManhattanMetric}(v, w) \]

Inputs two vectors \( v, w \) of equal length and returns the sum of the absolute values of the components of \( v - w \). This is often referred to as the taxi-cab distance between \( v \) and \( w \).

**Examples:**

33.1.7 VectorsToSymmetricMatrix

\[ \text{VectorsToSymmetricMatrix}(L) \]
\[ \text{VectorsToSymmetricMatrix}(L, D) \]

Inputs a list \( L \) of vectors and optionally a metric \( D \). The default is \( D = \text{ManhattanMetric} \). It returns the symmetric matrix whose i-j-entry is \( S[i][j] = D(L[i], L[j]) \).

**Examples:**

33.1.8 SymmetricMatDisplay

\[ \text{SymmetricMatDisplay}(S) \]
\[ \text{SymmetricMatDisplay}(L, V) \]

Inputs an \( n \times n \) symmetric matrix \( S \) of non-negative integers and an integer \( t \) in \([0..100]\). Optionally it inputs a list \( V = [V_1, ..., V_k] \) of disjoint subsets of \([1..n]\). It displays the graph with vertex set \([1..n]\) and with an edge between \( i \) and \( j \) if \( S[i][j] < t \). If the optional list \( V \) is input then the vertices in \( V_i \) will be given a common colour distinct from other vertices.

**Examples:**
33.1.9 SymmetricMatrixToFilteredGraph

Inputs an integer symmetric matrix $S$, a positive integer $t$ and a positive integer $m$. The function returns a filtered graph of filtration length $t$. The $k$-th term of the filtration is a graph with one vertex for each row of $S$. There is an edge in this graph between the $i$-th and $j$-th vertices if the entry $S[i][j]$ is less than or equal to $k \times m / t$.

**EXAMPLES:** 1, 2

33.1.10 PermGroupToFilteredGraph

Inputs a permutation group $G$ and a metric $D$ defined on permutations. The function returns a filtered graph. The $k$-th term of the filtration is a graph with one vertex for each element of the group $G$. There is an edge in this graph between vertices $g$ and $h$ if $D(g,h)$ is less than some integer threshold $t_k$. The thresholds $t_1 < t_2 < ... < t_N$ are chosen to form as long a sequence as possible subject to each term of the filtration being a distinct graph.

**EXAMPLES:**
Chapter 34

Commutative diagrams and abstract categories

COMMUTATIVE DIAGRAMS

34.1

34.1.1 HomomorphismChainToCommutativeDiagram

\[ \text{HomomorphismChainToCommutativeDiagram}(H) \]

Inputs a list \( H = [h_1, h_2, \ldots, h_n] \) of mappings such that the composite \( h_1 \circ h_2 \ldots h_n \) is defined. It returns the list of composable homomorphism as a commutative diagram.

\text{EXAMPLES}:

34.1.2 NormalSeriesToQuotientDiagram

\[ \text{NormalSeriesToQuotientDiagram}(L) \]
\[ \text{NormalSeriesToQuotientDiagram}(L, M) \]

Inputs an increasing (or decreasing) list \( L = [L_1, L_2, \ldots, L_n] \) of normal subgroups of a group \( G \) with \( G = L_n \). It returns the chain of quotient homomorphisms \( G/L_i \to G/L_{i+1} \) as a commutative diagram.

Optionally a subseries \( M \) of \( L \) can be entered as a second variable. Then the resulting diagram of quotient groups has two rows of horizontal arrows and one row of vertical arrows.

\text{EXAMPLES}:

34.1.3 NerveOfCommutativeDiagram

\[ \text{NerveOfCommutativeDiagram}(D) \]

Inputs a commutative diagram \( D \) and returns the commutative diagram \( ND \) consisting of all possible composites of the arrows in \( D \).

\text{EXAMPLES}:
34.1.4 GroupHomologyOfCommutativeDiagram

\[ \text{GroupHomologyOfCommutativeDiagram}(D, n) \]  
\[ \text{GroupHomologyOfCommutativeDiagram}(D, n, \text{prime}) \]  
\[ \text{GroupHomologyOfCommutativeDiagram}(D, n, \text{prime}, \text{Resolution\_Algorithm}) \]

Inputs a commutative diagram $D$ of $p$-groups and positive integer $n$. It returns the commutative diagram of vector spaces obtained by applying mod $p$ homology.

Non-prime power groups can also be handled if a prime $p$ is entered as the third argument. Integral homology can be obtained by setting $p = 0$. For $p = 0$ the result is a diagram of groups.

A particular resolution algorithm, such as ResolutionNilpotentGroup, can be entered as a fourth argument. For positive $p$ the default is ResolutionPrimePowerGroup. For $p = 0$ the default is ResolutionFiniteGroup.

**EXAMPLES:**

34.1.5 PersistentHomologyOfCommutativeDiagramOfPGroups

\[ \text{PersistentHomologyOfCommutativeDiagramOfPGroups}(D, n) \]

Inputs a commutative diagram $D$ of finite $p$-groups and a positive integer $n$. It returns a list containing, for each homomorphism in the nerve of $D$, a triple $[k, l, m]$ where $k$ is the dimension of the source of the induced mod $p$ homology map in degree $n$, $l$ is the dimension of the image, and $m$ is the dimension of the cokernel.

**EXAMPLES:**

34.2

34.2.1 CategoricalEnrichment

\[ \text{CategoricalEnrichment}(X, \text{Name}) \]

Inputs a structure $X$ such as a group or group homomorphism, together with the name of some existing category such as Name:=Category\_of\_Groups or Category\_of\_Abelian\_Groups. It returns, as appropriate, an object or arrow in the named category.

**EXAMPLES:** 1

34.2.2 IdentityArrow

\[ \text{IdentityArrow}(X) \]

Inputs an object $X$ in some category, and returns the identity arrow on the object $X$.

**EXAMPLES:** 1
34.2.3 InitialArrow

\[ \text{InitialArrow}(X) \]  

Inputs an object \( X \) in some category, and returns the arrow from the initial object in the category to \( X \).

EXAMPLES: 1

34.2.4 TerminalArrow

\[ \text{TerminalArrow}(X) \]  

Inputs an object \( X \) in some category, and returns the arrow from \( X \) to the terminal object in the category.

EXAMPLES: 1

34.2.5 HasInitialObject

\[ \text{HasInitialObject}(Name) \]  

Inputs the name of a category and returns true or false depending on whether the category has an initial object.

EXAMPLES: 1

34.2.6 HasTerminalObject

\[ \text{HasTerminalObject}(Name) \]  

Inputs the name of a category and returns true or false depending on whether the category has a terminal object.

EXAMPLES:

34.2.7 Source

\[ \text{Source}(f) \]  

Inputs an arrow \( f \) in some category, and returns its source.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9

34.2.8 Target

\[ \text{Target}(f) \]  

Inputs an arrow \( f \) in some category, and returns its target.

EXAMPLES: 1, 2, 3, 4, 5, 6
34.2.9  CategoryName

\[ \text{CategoryName}(X) \]

Inputs an object or arrow \( X \) in some category, and returns the name of the category.

**EXAMPLES:** 1

34.2.10  CompositionEqualityAdditionMinus

\[ \text{CompositionEqualityAdditionMinus} \]

Composition of suitable arrows \( f, g \) is given by \( f \ast g \) when the source of \( f \) equals the target of \( g \).

(Warning: this differs to the standard GAP convention.)

Equality is tested using \( f = g \).

In an additive category the sum and difference of suitable arrows is given by \( f + g \) and \( f - g \).

**EXAMPLES:**

34.2.11  Object

\[ \text{Object}(X) \]

Inputs an object \( X \) in some category, and returns the GAP structure \( Y \) such that \( X = \text{CategoricalEnrichment}(Y, \text{CategoryName}(X)) \).

**EXAMPLES:** 1

34.2.12  Mapping

\[ \text{Mapping}(X) \]

Inputs an arrow \( f \) in some category, and returns the GAP structure \( Y \) such that \( f = \text{CategoricalEnrichment}(Y, \text{CategoryName}(X)) \).

**EXAMPLES:** 1, 2, 3

34.2.13  IsCategoryObject

\[ \text{IsCategoryObject}(X) \]

Inputs \( X \) and returns true if \( X \) is an object in some category.

**EXAMPLES:**

34.2.14  IsCategoryArrow

\[ \text{IsCategoryArrow}(X) \]

Inputs \( X \) and returns true if \( X \) is an arrow in some category.

**EXAMPLES:**
Chapter 35

Arrays and Pseudo lists

35.1

35.1.1 Array

\[ \text{Array}(A, f) \] (function)

Inputs an array \( A \) and a function \( f \). It returns the array obtained by applying \( f \) to each entry of \( A \) (and leaves \( A \) unchanged).

EXAMPLES: 1, 2

35.1.2 PermuteArray

\[ \text{PermuteArray}(A, f) \] (function)

Inputs an array \( A \) of dimension \( d \) and a permutation \( f \) of degree at most \( d \). It returns the array \( B \) defined by \( B[i_1][i_2]...[i_d] = A[f(i_1)][f(i_2)]...A[f(id)] \) (and leaves \( A \) unchanged).

EXAMPLES:

35.1.3 ArrayDimension

\[ \text{ArrayDimension}(A) \] (function)

Inputs an array \( A \) and returns its dimension.

EXAMPLES:

35.1.4 ArrayDimensions

\[ \text{ArrayDimensions}(A) \] (function)

Inputs an array \( A \) and returns its dimensions.

EXAMPLES:
35.1.5 ArraySum

▷ ArraySum(A) (function)

Inputs an array $A$ and returns the sum of its entries.

**Examples:**

35.1.6 ArrayValue

▷ ArrayValue($A, x$) (function)

Inputs an array $A$ and a coordinate vector $x$. It returns the value of the entry in $A$ with coordinate $x$.

**Examples:**

35.1.7 ArrayValueFunctions

▷ ArrayValueFunctions($d$) (function)

Inputs a positive integer $d$ and returns an efficient version of the function ArrayValue for arrays of dimension $d$.

**Examples:**

35.1.8 ArrayAssign

▷ ArrayAssign($A, x, n$) (function)

Inputs an array $A$ and a coordinate vector $x$ and an integer $n$. It sets the entry of $A$ with coordinate $x$ equal to $n$.

**Examples:**

35.1.9 ArrayAssignFunctions

▷ ArrayAssignFunctions($d$) (function)

Inputs a positive integer $d$ and returns an efficient version of the function ArrayAssign for arrays of dimension $d$.

**Examples:**

35.1.10 ArrayIterate

▷ ArrayIterate($d$) (function)

Inputs a positive integer $d$ and returns a function $\text{ArrayIt}(\text{Dimensions}, f)$. This function inputs a list $\text{Dimensions}$ of $d$ positive integers and also a function $f(x)$. It applies the function $f(x)$ to each integer list $x$ of length $d$ with entries $x[i]$ in the range $[1..\text{Dimension}[i]]$.

**Examples:**
35.1.11 BinaryArrayToTextFile
("BinaryArrayToTextFile(file, A") (function)

Inputs a string containing the address of a file, and an array \( A \) of 0s and 1s. The array represents a pure cubical complex. A representation of this complex is written to the file in a format that can be read by the CAPD (Computer Assisted Proofs in Dynamics) software developed by Marian Mrozek and others.

The second input \( A \) can also be a pure cubical complex.

EXAMPLES:

35.1.12 FrameArray
("FrameArray(A") (function)

Inputs an array \( A \) and returns the array obtained by appending a 0 to the beginning and end of each "row" of the array.

EXAMPLES: 1

35.1.13 UnframeArray
("UnframeArray(A") (function)

Inputs an array \( A \) and returns the array obtained by removing the first and last entry in each "row" of the array.

EXAMPLES:

35.1.14 Add
("Add(L, x") (function)

Let \( L \) be a pseudo list of length \( n \), and \( x \) an object compatible with the entries in \( L \). If \( x \) is not in \( L \) then this operation converts \( L \) into a pseudo list of length \( n+1 \) by adding \( x \) as the final entry. If \( x \) is in \( L \) the operation has no effect on \( L \).

EXAMPLES: 1, 2, 3, 4, 5, 6

35.1.15 Append
("Append(L, K") (function)

Let \( L \) be a pseudo list and \( K \) a list whose objects are compatible with those in \( L \). This operation applies Add(L,x) for each \( x \) in \( K \).

EXAMPLES: 1, 2, 3, 4

35.1.16 ListToPseudoList
("ListToPseudoList(L") (function)
Inputs a list $L$ and returns the pseudo list representation of $L$.

**EXAMPLES:**
Chapter 36

Parallel Computation - Core Functions

36.1

36.1.1 ChildProcess

This starts a GAP session as a child process and returns a stream to the child process. If no argument is given then the child process is created on the local machine; otherwise the argument should be:

1) \texttt{arg}="computer.ac.wales" the address of a remote computer for which ssh has been configured to require no password from the user;
2) \texttt{arg}=\texttt{[-m, "100000M", ":T"]} a list of GAP command line options;
3) \texttt{arg}="computer.ac.wales", \texttt{[-m, "100000M", ":T"]} the address of a computer followed by a list of command line options.

(To configure ssh so that the user can login without a password prompt from "thishost" to "remotehost" either consult "man ssh" or

- open a shell on thishost
- \texttt{cd .ssh}
- \texttt{ls}
- \texttt{ls} if id\_dsa, id\_rsa etc exists, skip the next two steps!
- \texttt{ssh-keygen -t rsa}
- \texttt{ssh-keygen -t dsa}
- \texttt{scp *.pub userremotehost:~/}
- \texttt{ssh remotehost -l user}
- \texttt{cat id\_rsa.pub >> .ssh/authorized\_keys}
- \texttt{cat id\_dsa.pub >> .ssh/authorized\_keys}
- \texttt{rm id\_rsa.pub id\_dsa.pub}
- \texttt{exit}

You should now be able to connect from "thishost" to "remotehost" without a password prompt.)

\textbf{EXAMPLES: 1, 2}
36.1.2 ChildClose

\[ \text{ChildClose}(s) \]  \hspace{1cm} (function)

This closes the stream \( s \) to a child GAP process.

\textbf{EXAMPLES:} 1

36.1.3 ChildCommand

\[ \text{ChildCommand}(\text{str}, s) \]  \hspace{1cm} (function)

This runs a GAP command \( \text{str}="\text{cmd;}" \) on the child process accessed by the stream \( s \). Here "cmd;" is a string representing the command.

\textbf{EXAMPLES:} 1, 2

36.1.4 NextAvailableChild

\[ \text{NextAvailableChild}(L) \]  \hspace{1cm} (function)

Inputs a list \( L \) of child processes and returns a child in \( L \) which is ready for computation (as soon as such a child is available).

\textbf{EXAMPLES:} 1, 2

36.1.5 IsAvailableChild

\[ \text{IsAvailableChild}(s) \]  \hspace{1cm} (function)

Inputs a child process \( s \) and returns true if \( s \) is currently available for computations, and false otherwise.

\textbf{EXAMPLES:} 1

36.1.6 ChildPut

\[ \text{ChildPut}(A, \text{str}, s) \]  \hspace{1cm} (function)

This copies a GAP object \( A \) on the parent process to an object \( B=\text{str} \) on the child process \( s \). (The copying relies on the function \text{PrintObj}(A);)

\textbf{EXAMPLES:} 1, 2

36.1.7 ChildGet

\[ \text{ChildGet}(\text{str}, s) \]  \hspace{1cm} (function)

This functions copies a GAP object \( A="\text{str}" \) on the child process \( s \) and returns it on the parent process. (The copying relies on the function \text{PrintObj}(A);)

\textbf{EXAMPLES:} 1, 2
36.1.8 HAPPrintTo

\[ \text{HAPPrintTo}(\text{str}, R) \]  

Inputs a string \( \text{str} = "\text{file}" \) giving the address of a new text file and a HAP object \( R \). It writes the object \( R \) to "file". Currently this is only implemented for \( R \) equal to a resolution.

**EXAMPLES:** 1

36.1.9 HAPRead

\[ \text{HAPRead}(\text{str}, R) \]  

Inputs an address \( \text{str} = "\text{file}" \) of a file containing a HAP object \( R \) and returns the object. Currently this is only implemented for \( R \) equal to a resolution.

**EXAMPLES:** 1
Chapter 37

Parallel Computation - Extra Functions

37.1

37.1.1 ChildFunction

⊿ ChildFunction(str, s) (function)

This runs the GAP function str="function(arg);" on a child process accessed by the stream s. The output from "func;" can be accessed via the stream.

EXAMPLES:

37.1.2 ChildRead

⊿ ChildRead(s) (function)

This returns, as a string, the output of the last application of ChildFunction("function(arg);", s).

EXAMPLES:

37.1.3 ChildReadEval

⊿ ChildReadEval(s) (function)

This returns, as an evaluated string, the output of the last application of ChildFunction("function(arg);", s).

EXAMPLES:

37.1.4 ParallelList

⊿ ParallelList(I, fn, L) (function)

Inputs a list I, a function fn such that fn(x) is defined for all x in I, and a list of children L. It uses the children in L to compute List(I, x → fn(x)). (Obviously the function fn must be defined on all child processes in L.)

EXAMPLES: 1, 2
Chapter 38

Some functions for accessing basic data

38.1

38.1.1 BoundaryMap

\[ \text{BoundaryMap}(C) \]

Inputs a resolution, chain complex or cochain complex \( C \) and returns the function \( C!.boundary. \)

Examples: 1, 2

38.1.2 BoundaryMatrix

\[ \text{BoundaryMatrix}(C, n) \]

Inputs a chain or cochain complex \( C \) and integer \( n>0 \). It returns the \( n \)-th boundary map of \( C \) as a matrix.

Examples:

38.1.3 Dimension

\[ \text{Dimension}(C) \]

\[ \text{Dimension}(M) \]

Inputs a resolution, chain complex or cochain complex \( C \) and returns the function \( C!.dimension. \)

Alternatively, inputs an \( FpG \)-module \( M \) and returns its dimension as a vector space over the field of \( p \) elements.

Examples: 1, 2, 3, 4, 5, 6, 7

38.1.4 EvaluateProperty

\[ \text{EvaluateProperty}(X, \text{str}) \]

Inputs a component object \( X \) (such as a \( ZG \)-resolution or chain map) and a string \( \text{str} \)="name" (such as "characteristic" or "type"). It searches \( X.property \) for the pair ["name",value] and returns value. If \( X.property \) does not exist, or if ["name",value] does not exist, it returns fail.
38.1.5 GroupOfResolution

▷ GroupOfResolution(R) (function)

Inputs a $\mathbb{Z}G$-resolution $R$ and returns the group $G$.

EXAMPLES:

38.1.6 Length

▷ Length(R) (function)

Inputs a resolution $R$ and returns its length (i.e. the number of terms of $R$ that HAP has computed).

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15

38.1.7 Map

▷ Map(f) (function)

Inputs a chain map, or cochain map or equivariant chain map $f$ and returns the mapping function (as opposed to the target or the source of $f$).

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

38.1.8 Source

▷ Source(f) (function)

Inputs a chain map, or cochain map, or equivariant chain map, or $FpG$-module homomorphism $f$ and returns its source.

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9

38.1.9 Target

▷ Target(f) (function)

Inputs a chain map, or cochain map, or equivariant chain map, or $FpG$-module homomorphism $f$ and returns its target.

EXAMPLES: 1, 2, 3, 4, 5, 6
Chapter 39

Miscellaneous

39.1

39.1.1 SL2Z

▷ SL2Z(p) (function)
▷ SL2Z(1/m) (function)

Inputs a prime \( p \) or the reciprocal \( 1/m \) of a square free integer \( m \). In the first case the function returns the conjugate \( SL(2, Z)^p \) of the special linear group \( SL(2, Z) \) by the matrix \( P = [[1, 0], [0, p]] \). In the second case it returns the group \( SL(2, Z[1/m]) \).

EXAMPLES: 1, 2, 3

39.1.2 BigStepLCS

▷ BigStepLCS(G, n) (function)

Inputs a group \( G \) and a positive integer \( n \). It returns a subseries \( G = L_1 > L_2 > \ldots L_k = 1 \) of the lower central series of \( G \) such that \( L_i/L_{i+1} \) has order greater than \( n \).

EXAMPLES: 1, 2

39.1.3 Classify

▷ Classify(L, Inv) (function)

Inputs a list of objects \( L \) and a function \( Inv \) which computes an invariant of each object. It returns a list of lists which classifies the objects of \( L \) according to the invariant.

EXAMPLES: 1, 2, 3, 4, 5

39.1.4 RefineClassification

▷ RefineClassification(C, Inv) (function)

Inputs a list \( C := Classify(L, OldInv) \) and returns a refined classification according to the invariant \( Inv \).
39.1.5 Compose

\[ \text{Compose}(f, g) \]

Inputs two \( F pG \)-module homomorphisms \( f : M \to N \) and \( g : L \to M \) with \( \text{Source}(f) = \text{Target}(g) \). It returns the composite homomorphism \( f g : L \to N \).

This also applies to group homomorphisms \( f, g \).

**Examples:**

39.1.6 HAPcopyright

\[ \text{HAPcopyright}() \]

This function provides details of HAP’S GNU public copyright licence.

**Examples:**

39.1.7 IsLieAlgebraHomomorphism

\[ \text{IsLieAlgebraHomomorphism}(f) \]

Inputs an object \( f \) and returns true if \( f \) is a homomorphism \( f : A \to B \) of Lie algebras (preserving the Lie bracket).

**Examples:**

39.1.8 IsSuperperfect

\[ \text{IsSuperperfect}(G) \]

Inputs a group \( G \) and returns "true" if both the first and second integral homology of \( G \) is trivial. Otherwise, it returns "false".

**Examples:**

39.1.9 MakeHAPManual

\[ \text{MakeHAPManual}() \]

This function creates the manual for HAP from an XML file.

**Examples:**

39.1.10 PermToMatrixGroup

\[ \text{PermToMatrixGroup}(G, n) \]

Inputs a permutation group \( G \) and its degree \( n \). Returns a bijective homomorphism \( f : G \to M \) where \( M \) is a group of permutation matrices.

**Examples:**

39.1.11 SolutionsMatDestructive

\[ \text{SolutionsMatDestructive}(M, B) \]

Inputs an \( m \times n \) matrix \( M \) and a \( k \times n \) matrix \( B \) over a field. It returns a \( k \times m \) matrix \( S \) satisfying \( SM = B \).

The function will leave matrix \( M \) unchanged but will probably change matrix \( B \).

(This is a trivial rewrite of the standard GAP function \( \text{SolutionMatDestructive}(\text{<mat>}, \text{<vec>}) \).)

\textbf{EXAMPLES:}

39.1.12 LinearHomomorphismsPersistenceMat

\[ \text{LinearHomomorphismsPersistenceMat}(L) \]

Inputs a composable sequence \( L \) of vector space homomorphisms. It returns an integer matrix containing the dimensions of the images of the various composites. The sequence \( L \) is determined up to isomorphism by this matrix.

\textbf{EXAMPLES:}

39.1.13 NormalSeriesToQuotientHomomorphisms

\[ \text{NormalSeriesToQuotientHomomorphisms}(L) \]

Inputs an (increasing or decreasing) chain \( L \) of normal subgroups in some group \( G \). This \( G \) is the largest group in the chain. It returns the sequence of composable group homomorphisms \( G/L[i] \rightarrow G/L[i+/-1] \).

\textbf{EXAMPLES:}

39.1.14 TestHap

\[ \text{TestHap()} \]

This runs a representative sample of HAP functions and checks to see that they produce the correct output.

\textbf{EXAMPLES:}
Chapter 40

HAP variables that are not yet documented

40.1

2CoreducedChainComplex  EXAMPLES:
AbelianGOuterGroupToCatOneGroup  EXAMPLES:
AbelianInvariantsToTorsionCoefficients  EXAMPLES:
AcyclicSubcomplexOfPureCubicalComplex  EXAMPLES:
AddCell  EXAMPLES:
AddFirst  EXAMPLES:
AdjointGroupOfQuandle  EXAMPLES: 1
AlgebraicReduction_alt  EXAMPLES:
AppendFreeWord  EXAMPLES:
ArcPresentation  EXAMPLES: 1, 2, 3
ArcPresentationToKnottedOneComplex  EXAMPLES:
ArcPresentationToKnottedOneComplex_Alt  EXAMPLES:
AreIsoclinic  EXAMPLES:
ArrayIterateBreak  EXAMPLES:
ArrayValueKD  EXAMPLES:
AsWordInSL2Z  EXAMPLES: 1

AutomorphismGroupQuandleAsPerm_nonconnected  EXAMPLES:

AverageInnerProduct  EXAMPLES:

BarcodeOfFilteredPureCubicalComplex  EXAMPLES:

BarcodeOfSymmetricMatrix  EXAMPLES:

BaryCentricSubdivision  EXAMPLES: 1

BarycentricallySubdivideCell  EXAMPLES:

BettiNumbersOfPureCubicalComplex_dim_2  EXAMPLES:

BocksteinHomology  EXAMPLES:

BogomolovMultiplier_viaTensorSquare  EXAMPLES:

BoundariesOfFilteredChainComplex  EXAMPLES:

BoundaryOfPureComplex  EXAMPLES: 1

BoundaryOfPureRegularCWComplex  EXAMPLES:

BoundaryOfRegularCWCell  EXAMPLES:

BoundaryPairOfPureRegularCWComplex  EXAMPLES:

BoundingPureComplex  EXAMPLES:

CR_ChainMapFromCocycle  EXAMPLES:

CR_CocyclesAndCoboundaries  EXAMPLES:

CR_IntegralClassToCocycle  EXAMPLES:

CR_IntegralCocycleToClass  EXAMPLES:

CR_IntegralCohomology  EXAMPLES:

CR_IntegralCycleToClass  EXAMPLES:

CWMap2ChainMap  EXAMPLES:
CWSubcomplexToRegularCWMap EXAMPLES:
CanonicalRightCountableCosetElement EXAMPLES:
CatOneGroupByCrossedModule EXAMPLES:
CatOneGroupsByGroup EXAMPLES:
CcElement EXAMPLES:
Cedric_CheckThirdAxiomRow EXAMPLES:
Cedric_ConjugateQuandleElement EXAMPLES:
Cedric_FromAutGeReToAutQe EXAMPLES:
Cedric_IsHomomorphism EXAMPLES:
Cedric_Permute EXAMPLES:
Cedric_Quandle1 EXAMPLES:
Cedric_Quandle2 EXAMPLES:
Cedric_Quandle3 EXAMPLES:
Cedric_Quandle4 EXAMPLES:
Cedric_Quandle5 EXAMPLES:
Cedric_Quandle6 EXAMPLES:
CellComplexBoundaryCheck EXAMPLES:
ChainComplexEquivalenceOfRegularCWComplex EXAMPLES:
ChainComplexOfCubicalComplex EXAMPLES:
ChainComplexOfCubicalPair EXAMPLES:
ChainComplexOfRegularCWComplexWithVectorField EXAMPLES:
ChainComplexOfSimplicialComplex EXAMPLES:
ChainComplexOfSimplicialPair EXAMPLES:
ChainComplexOfUniversalCover  EXAMPLES: 1, 2, 3
ChainComplexToSparseChainComplex  EXAMPLES:
ChainMapOfCubicalPairs  EXAMPLES:
ChainMapOfRegularCWMap  EXAMPLES:
ChildRestart  EXAMPLES:
ClosureCWCell  EXAMPLES:
CoClass  EXAMPLES:
CocriticalCellsOfRegularCWComplex  EXAMPLES:
CocyclicHadamardMatrices  EXAMPLES:
CocyclicMatrices  EXAMPLES:
CohomologyHomomorphism  EXAMPLES: 1, 2
CohomologyHomomorphismOfRepresentation  EXAMPLES:
CohomologyModule_AsAutModule  EXAMPLES:
CohomologyModule_Gmap  EXAMPLES:
CombinationDisjointSets  EXAMPLES:
CommonEndomorphisms  EXAMPLES:
ComplementOfPureComplex  EXAMPLES: 1
ComplementaryBasis  EXAMPLES:
CompositionOfFpGModuleHomomorphisms  EXAMPLES:
CompositionSeriesOfFpGModule  EXAMPLES:
ConcentricallyFilteredPureCubicalComplex  EXAMPLES: 1
CongruenceSubgroup  EXAMPLES: 1, 2
ConjugateSL2ZGroup  EXAMPLES:
ConnectingCohomologyHomomorphism  EXAMPLES: 1

ContractArray  EXAMPLES:

ContractCubicalComplex_dim2  EXAMPLES:

ContractCubicalComplex_dim3  EXAMPLES:

ContractMatrix  EXAMPLES:

ContractPermArray  EXAMPLES:

ContractPermMatrix  EXAMPLES:

ContractPureComplex  EXAMPLES:

ContractSimplicialComplex  EXAMPLES:

ContractedFilteredPureCubicalComplex  EXAMPLES:

ContractedFilteredRegularCWComplex  EXAMPLES:

ContractedRegularCWComplex  EXAMPLES:

ContractibleSL2ZComplex  EXAMPLES:

ContractibleSL2ZComplex_alt  EXAMPLES:

ContractibleSubArray  EXAMPLES:

ContractibleSubMatrix  EXAMPLES:

ContractibleSubcomplexOfPureCubicalComplex  EXAMPLES: 1

ConvertTorsionComplexToGcomplex  EXAMPLES:

CosetsQuandle  EXAMPLES:

CountingCellsOfBaryCentricSubdivision  EXAMPLES:

CountingNumberOfCellsInBaryCentricSubdivision  EXAMPLES:

CoxeterComplex_alt  EXAMPLES: 1

CoxeterDiagramMatCoxeterGroup  EXAMPLES:
CoxeterWythoffComplex  EXAMPLES:
CreateCoxeterMatrix  EXAMPLES: 1
CropPureComplex  EXAMPLES:
CrossedInvariant  EXAMPLES:
CrossedModuleByAutomorphismGroup  EXAMPLES:
CrossedModuleByCatOneGroup  EXAMPLES:
CrossedModuleByNormalSubgroup  EXAMPLES: 1
CrystCubicalTiling  EXAMPLES:
CrystFinitePartOfMatrix  EXAMPLES:
CrystGFullBasis  EXAMPLES: 1, 2
CrystGcomplex  EXAMPLES: 1, 2
CrystMatrix  EXAMPLES:
CrystTranslationMatrixToVector  EXAMPLES:
CubicalToPermutahedralArray  EXAMPLES:
CupProductOfRegularCWComplex  EXAMPLES:
CuspidalCohomologyHomomorphism  EXAMPLES: 1
CyclesOfFilteredChainComplex  EXAMPLES:
DavisComplex  EXAMPLES: 1, 2, 3, 4
DeformationRetract  EXAMPLES:
DensityMat  EXAMPLES:
DerivedGroupOfQuandle  EXAMPLES: 1
DirectProductOfRegularCWComplexes  EXAMPLES:
DisplayCSVknotFile  EXAMPLES:
ElementsLazy EXAMPLES:

EquivariantCWComplexToRegularCWComplex EXAMPLES: \(1, 2, 3\)

EquivariantCWComplexToRegularCWMap EXAMPLES: \(1, 2\)

EquivariantCWComplexToResolution EXAMPLES:

ExcisedPureCubicalPair_dim_2 EXAMPLES:

ExtractTorsionSubcomplex EXAMPLES:

FactorizationNParts EXAMPLES:

FilteredChainComplexToFilteredSparseChainComplex EXAMPLES:

FilteredCubicalComplexToFilteredRegularCWComplex EXAMPLES:

FilteredPureCubicalComplexToCubicalComplex EXAMPLES:

FiltrationTermOfGraph EXAMPLES:

FiltrationTermOfPureCubicalComplex EXAMPLES:

FiltrationTermOfRegularCWComplex EXAMPLES:

FirstHomologyCoveringCokernels EXAMPLES: \(1, 2\)

FirstHomologySimplicialTwoComplex EXAMPLES:

Fp2PcpAbelianGroupHomomorphism EXAMPLES:

FpGModuleSection EXAMPLES:

FreeZGResolution EXAMPLES:

FundamentalGroupOfRegularCWComplex EXAMPLES:

FundamentalGroupOfRegularCWMap EXAMPLES:

FundamentalGroupSimplicialTwoComplex EXAMPLES:

FundamentalMultiplesOfStiefelWhitneyClasses EXAMPLES:

GChainComplex EXAMPLES: \(1\)
GModuleAsCatOneGroup  EXAMPLES:
GammaSubgroupInSL3Z  EXAMPLES:
GaussCodeOfPureCubicalKnot  EXAMPLES: 1, 2, 3, 4
GetTorsionSubcomplex  EXAMPLES:
GraphOfRegularCWComplex  EXAMPLES:
GraphOfResolutionsTest  EXAMPLES:
GraphOfResolutionsToGroups  EXAMPLES:
GroupHomomorphismToMatrix  EXAMPLES:
HAPcocontractRegularCWComplex  EXAMPLES:
HAPContractFilteredRegularCWComplex  EXAMPLES:
HAPContractRegularCWComplex  EXAMPLES:
HAPContractRegularCWComplex_Alt  EXAMPLES:
HAPPRIME_Algebra2Polynomial  EXAMPLES:
HAPPRIME_CohomologyRingWithoutResolution  EXAMPLES:
HAPPRIME_CombineIndeterminateMaps  EXAMPLES:
HAPPRIME_GradedAlgebraPresentationAvoidingIndeterminates  EXAMPLES:
HAPPRIME_LHSSpectralSequence  EXAMPLES:
HAPPRIME_MakeEliminationOrdering  EXAMPLES:
HAPPRIME_MapPolynomialIndeterminates  EXAMPLES:
HAPPRIME_Polynomial2Algebra  EXAMPLES:
HAPPRIME_RingHomomorphismsAreComposable  EXAMPLES:
HAPPRIME_SModule  EXAMPLES:
HAPPRIME_SingularGroebnerBasis  EXAMPLES:
HAPPRIME_SingularReducedGroebnerBasis  EXAMPLES:
HAPPRIME_SwitchGradedAlgebraRing  EXAMPLES:
HAPPRIME_SwitchPolynomialIndeterminates  EXAMPLES:
HAPPRIME_VersionWithSVN  EXAMPLES:
HAPRegularCWComplex  EXAMPLES:
HAPRegularCWPolytope  EXAMPLES:
HAPRemoveCellFromRegularCWComplex  EXAMPLES:
HAPRemoveVectorField  EXAMPLES:
HAPRingModIdeal  EXAMPLES:
HAPRingModIdealObj  EXAMPLES:
HAPTietzeReduction_Inf  EXAMPLES:
HAPTietzeReduction_OneLevel  EXAMPLES:
HAPTietzeReduction_OneStep  EXAMPLES:
HAP_4x4MatTo2x2Mat  EXAMPLES:
HAP_AddGenerator  EXAMPLES:
HAP_AppendTo  EXAMPLES:
HAP_Binlisttoint  EXAMPLES:
HAP_CocyclesAndCoboundaries  EXAMPLES:
HAP_CongruenceSubgroupGamma0  EXAMPLES: 1
HAP_CongruenceSubgroupGamma0Ideal  EXAMPLES:
HAP_CupProductOfPresentation  EXAMPLES:
HAP_ElmentsSL2Zfn  EXAMPLES:
HAP_GenericSL20Subgroup  EXAMPLES:
HAP_GenericSL2ZSubgroup EXAMPLES:

HAP_IntegralClassToCocycle EXAMPLES:

HAP_IntegralCocycleToClass EXAMPLES:

HAP_IntegralCohomology EXAMPLES:

HAP_PHI EXAMPLES:

HAP_PermBinlisttoint EXAMPLES:

HAP_PrincipalCongruenceSubgroup EXAMPLES: 1

HAP_PrincipalCongruenceSubgroupIdeal EXAMPLES:

HAP_PrintTo EXAMPLES:

HAP_PureComplexSubcomplex EXAMPLES:

HAP_PureCubicalPairToCWMap EXAMPLES:

HAP_RightTransversalSL2ZSubgroups EXAMPLES:

HAP_SL20SubgroupTree_slow EXAMPLES:

HAP_SL2SubgroupTree EXAMPLES:

HAP_SL2TreeDisplay EXAMPLES: 1

HAP_SL2ZSubgroupTree_fast EXAMPLES:

HAP_SL2ZSubgroupTree_slow EXAMPLES:

HAP_Sequence2Boundaries EXAMPLES:

HAP_SimplicialPairToCWMap EXAMPLES:

HAP_StiefelWhitney EXAMPLES:

HAP_Tensor EXAMPLES:

HAP_TransversalCongruenceSubgroups EXAMPLES:

HAP_TransversalCongruenceSubgroupsIdeal EXAMPLES:
HAP_TransversalCongruenceSubgroupsIdeal_alt EXAMPLES:
HAP_TransversalGamma0SubgroupsIdeal EXAMPLES:
HAP_TzPair EXAMPLES:
HAP_coho_isoms EXAMPLES:
HAP_nxnMatTo2nx2nMat EXAMPLES:
HadamardGraph EXAMPLES:
HapExample EXAMPLES:
HapFile EXAMPLES: 1, 2
HasTrivialPostnikovInvariant EXAMPLES:
HeckeOperatorWeight2 EXAMPLES:
HenonOrbit EXAMPLES: 1
HomToGModule_hom EXAMPLES:
HomToInt.ChainComplex EXAMPLES:
HomToInt.ChainMap EXAMPLES:
HomToInt.CochainComplex EXAMPLES:
HomogeneousPolynomials EXAMPLES: 1
HomogeneousPolynomials_Bianchi EXAMPLES:
HomologyOfPureCubicalComplex EXAMPLES:
HomologyPbs EXAMPLES:
HomomorphismAsMatrix EXAMPLES: 1
HomotopyCatOneGroup EXAMPLES:
HomotopyCrossedModule EXAMPLES:
HomotopyEquivalentLargerSubArray EXAMPLES:
Homological Algebra Programming

HomotopyEquivalentLargerSubArray3D  EXAMPLES:
HomotopyEquivalentLargerSubMatrix  EXAMPLES:
HomotopyEquivalentLargerSubPermArray  EXAMPLES:
HomotopyEquivalentLargerSubPermArray3D  EXAMPLES:
HomotopyEquivalentLargerSubPermMatrix  EXAMPLES:
HomotopyEquivalentMaximalPureSubcomplex  EXAMPLES:
HomotopyEquivalentMinimalPureSubcomplex  EXAMPLES:
HomotopyEquivalentSmallerSubArray  EXAMPLES:
HomotopyEquivalentSmallerSubArray3D  EXAMPLES:
HomotopyEquivalentSmallerSubMatrix  EXAMPLES:
HomotopyEquivalentSmallerSubPermArray  EXAMPLES:
HomotopyEquivalentSmallerSubPermArray3D  EXAMPLES:
HomotopyEquivalentSmallerSubPermMatrix  EXAMPLES:
HomotopyLowerCentralSeries  EXAMPLES:
HomotopyLowerCentralSeriesOfCrossedModule  EXAMPLES:
HomotopyTruncation  EXAMPLES:
HopfSatohSurface  EXAMPLES: 1, 2
HybridSubdivision  EXAMPLES:
IdCatOneGroup  EXAMPLES: 1
IdCrossedModule  EXAMPLES:
IdQuasiCatOneGroup  EXAMPLES:
IdQuasiCrossedModule  EXAMPLES:
IdentityAmongRelators  EXAMPLES: 1, 2
ImageOfGOuterGroupHomomorphism  EXAMPLES: 1

ImageOfMap  EXAMPLES:

InducedSteenrodHomomorphisms  EXAMPLES:

IntegerSimplicialComplex  EXAMPLES:

IntegralCellularHomology  EXAMPLES:

IntegralCohomology  EXAMPLES:

IntegralCohomologyOfCochainComplex  EXAMPLES:

IntegralHomology  EXAMPLES: 1

IntegralHomologyOfChainComplex  EXAMPLES:

IntersectionCWSubcomplex  EXAMPLES:

IsContractibleCube_higherdims  EXAMPLES:

IsCrystSameOrbit  EXAMPLES:

IsCrystSufficientLattice  EXAMPLES:

IsHadamardMatrix  EXAMPLES:

IsIntList  EXAMPLES:

IsIsomorphismOfAbelianFpGroups  EXAMPLES: 1

IsMetricMatrix  EXAMPLES:

IsPureComplex  EXAMPLES:

IsPureRegularCWComplex  EXAMPLES:

IsRigid  EXAMPLES: 1

IsRigidOnRight  EXAMPLES:

IsSphericalCoxeterGroup  EXAMPLES:

IsoclinismClasses  EXAMPLES: 1, 2
IsomorphismCatOneGroups  EXAMPLES: 1
IsomorphismCrossedModules  EXAMPLES:
KernelOfGOuterGroupHomomorphism  EXAMPLES: 1
KernelOfMap  EXAMPLES:
KernelWG  EXAMPLES:
KnotComplement  EXAMPLES: 1, 2, 3
KnotComplementWithBoundary  EXAMPLES: 1, 2, 3
LazyList  EXAMPLES:
LefschetzNumberOfChainMap  EXAMPLES:
Lfunction  EXAMPLES: 1
LiftedRegularCWMap  EXAMPLES:
LinearHomomorphismsZZPersistenceMat  EXAMPLES:
ListsOfCellsToRegularCWComplex  EXAMPLES:
MakeHAPprimeDoc  EXAMPLES:
Mapper  EXAMPLES: 1
Mapper_alt  EXAMPLES:
MatrixSize  EXAMPLES:
MaximalSimplicesOfSimplicialComplex  EXAMPLES:
MaximalSphericalCoxeterSubgroupsFromAbove  EXAMPLES:
Mod2SteenrodAlgebra  EXAMPLES: 1
ModPCohomologyRing_part_1  EXAMPLES:
ModPCohomologyRing_part_2  EXAMPLES:
ModPRingGeneratorsAlt  EXAMPLES:
ModPSteenrodAlgebra  EXAMPLES: 1, 2

ModularCohomology  EXAMPLES:

ModularEquivariantChainMap  EXAMPLES:

ModularHomology  EXAMPLES:

NonRegularCWBoundary  EXAMPLES:

NonabelianSymmetricKernel_alt  EXAMPLES: 1

NonabelianSymmetricSquare_inf  EXAMPLES:

NonabelianTensorProduct_Inf  EXAMPLES:

NonabelianTensorProduct_alt  EXAMPLES:

NonabelianTensorSquareAsCatOneGroup  EXAMPLES:

NonabelianTensorSquareAsCrossedModule  EXAMPLES:

NonabelianTensorSquare_inf  EXAMPLES:

NoncrossingPartitionsLatticeDisplay  EXAMPLES: 1

NullspaceSparseMatDestructive  EXAMPLES:

NumberConnectedQuandles  EXAMPLES:

NumberGeneratorsOfGroupHomology  EXAMPLES:

NumberOfHomomorphisms_connected  EXAMPLES:

NumberOfHomomorphisms_groups  EXAMPLES:

NumberOfPrimeKnots  EXAMPLES: 1, 2

NumberSmallCatOneGroups  EXAMPLES:

NumberSmallCrossedModules  EXAMPLES:

NumberSmallQuasiCatOneGroups  EXAMPLES:

NumberSmallQuasiCrossedModules  EXAMPLES:
OppositeGroup EXAMPLES:

OrthogonalizeBasisByAverageInnerProduct EXAMPLES:

PCentre EXAMPLES:

PUpperCentralSeries EXAMPLES:

PartialIsoclinismClasses EXAMPLES: 1

PartsOfQuadraticInteger EXAMPLES:

PathComponentOfPureComplex EXAMPLES:

PathComponentOfSimplicialComplex_alt EXAMPLES:

PermutohedralComplexToRegularCWComplex EXAMPLES: 1

PermutohedralToCubicalArray EXAMPLES:

PersistentHomologyOfCrossedModule EXAMPLES:

PersistentHomologyOfFilteredPureCubicalComplex_alt EXAMPLES:

PersistentHomologyOfFilteredSparseChainComplex EXAMPLES: 1

PersistentHomologyOfPureCubicalComplex_Alt EXAMPLES:

PersistentHomologyOfQuotientGroupSeries_Int EXAMPLES:

PiZeroOfRegularCWComplex EXAMPLES:

PoincareSeriesApproximation EXAMPLES:

PoincareSeries_alt EXAMPLES:

PolymakeFaceLattice EXAMPLES:

PolytopalRepresentationComplex EXAMPLES:

PrankAlt EXAMPLES:

PresentationOfResolution_alt EXAMPLES:
PrimePartDerivedFunctorViaSubgroupChain  EXAMPLES:

PrintAlgebraWordAsPolynomial  EXAMPLES:

PrintTorsionSubcomplex  EXAMPLES:

PureComplex  EXAMPLES: 1, 2, 3, 4, 5, 6

PureCubicalComplexToCubicalComplex  EXAMPLES: 1

PureCubicalLink  EXAMPLES: 1, 2

PushoutOfFpGroups  EXAMPLES:

QuadraticCharacter  EXAMPLES:

QuadraticNumberField  EXAMPLES: 1

QuandleIsomorphismRepresentatives  EXAMPLES:

QuotientByTorsionSubcomplex  EXAMPLES:

QuotientGroup  EXAMPLES:

QuotientQuasiIsomorph  EXAMPLES:

RadicalSeriesOfResolution  EXAMPLES:

RandomCellOfPureComplex  EXAMPLES:

ReadMatrixAsPureCubicalComplex  EXAMPLES:

ReduceGenerators  EXAMPLES:

ReduceGenerators_alt  EXAMPLES:

ReflectedCubicalKnot  EXAMPLES: 1, 2, 3, 4

RegularCWComplexComplement  EXAMPLES:

RegularCWMapToCWSubcomplex  EXAMPLES:

RegularCWOrbitPolytope  EXAMPLES:

RelativeCentralQuotientSpaceGroup  EXAMPLES:
RelativeGroupHomology  EXAMPLES:
ResolutionAbelianGroup_alt  EXAMPLES:
ResolutionAbelianPcpGroup  EXAMPLES:
ResolutionAffineCrystGroup  EXAMPLES:
ResolutionBoundaryOfWordOnRight  EXAMPLES:
ResolutionDirectProductLazy  EXAMPLES:
ResolutionFiniteCyclicGroup  EXAMPLES:
ResolutionGL2QuadraticIntegers  EXAMPLES: 1
ResolutionGL3QuadraticIntegers  EXAMPLES: 1
ResolutionGenericGroup  EXAMPLES:
ResolutionInfiniteCyclicGroup  EXAMPLES:
ResolutionPGL2QuadraticIntegers  EXAMPLES: 1
ResolutionPGL3QuadraticIntegers  EXAMPLES: 1
ResolutionPSL2QuadraticIntegers  EXAMPLES: 1
ResolutionPrimePowerGroupSparse  EXAMPLES:
ResolutionSL2QuadraticIntegers  EXAMPLES: 1
ResolutionSL2Z_alt  EXAMPLES: 1
ResolutionToEquivariantCWComplex  EXAMPLES:
ResolutionToResolutionOfFpGroup  EXAMPLES: 1
SL2QuadraticIntegers  EXAMPLES: 1
SL2ZResolution  EXAMPLES:
SL2ZResolution_alt  EXAMPLES:
SL2ZTree  EXAMPLES:
SL2ZmElementsDecomposition  EXAMPLES:
SignedPermutationGroup  EXAMPLES:
SimplicesToSimplicialComplex  EXAMPLES: 1, 2, 3, 4
SimplicialNerveOfFilteredGraph  EXAMPLES: 1
SimplicialNerveOfTwoComplex  EXAMPLES:
SimplifiedQuandlePresentation  EXAMPLES:
SimplifiedRegularCWComplex  EXAMPLES: 1
SimplifiedSparseChainComplex  EXAMPLES:
SmallCatOneGroup  EXAMPLES: 1
SmallCrossedModule  EXAMPLES:
SmallQuasiCatOneGroup  EXAMPLES:
SmallQuasiCrossedModule  EXAMPLES:
SmoothedFpGroup  EXAMPLES:
SparseChainComplexOfCubicalComplex  EXAMPLES:
SparseChainComplexOfCubicalPair  EXAMPLES:
SparseChainComplexOfFilteredRegularCWComplex  EXAMPLES:
SparseChainComplexOfRegularCWComplexWithVectorField  EXAMPLES:
SparseChainComplexOfSimplicialComplex  EXAMPLES:
SparseChainComplexToChainComplex  EXAMPLES:
SparseChainMapOfCubicalPairs  EXAMPLES:
SparseFilteredChainComplexOfFilteredCubicalComplex  EXAMPLES:
SparseFilteredChainComplexOfFilteredSimplicialComplex  EXAMPLES: 1
SparseMattoMat  EXAMPLES:
SparseRowReduce \textsc{Examples}:
Spin \textsc{Examples}:
SpunAboutHyperplane \textsc{Examples}:
SpunKnotComplement \textsc{Examples}: 1
SpunLinkComplement \textsc{Examples}:
StrongGeneratorsOfDerivedSubgroup \textsc{Examples}:
StrongGeneratorsOfDerivedSubgroup\_alt \textsc{Examples}:
StructuralCopyOfFilteredRegularCWComplex \textsc{Examples}:
SubQuasiIso\textsc{morp}h \textsc{Examples}:
SylowSubgroupOfCatOneGroup \textsc{Examples}:
SymmetricCentre \textsc{Examples}:
TensorWithBurnsideRing \textsc{Examples}: 1, 2
TensorWithComplexRepresentationRing \textsc{Examples}: 1, 2
TensorWithComplexRepresentationRingOnRight \textsc{Examples}:
TensorWithIntegersModPSparse \textsc{Examples}:
TensorWithIntegersOverSubgroup \textsc{Examples}: 1, 2, 3
TensorWithIntegersSparse \textsc{Examples}:
TestHapBook \textsc{Examples}:
ThickenedHEPureCubicalComplex \textsc{Examples}:
ThickenedPureComplex \textsc{Examples}:
ThickenedPureCubicalComplex\_dim2 \textsc{Examples}:
ThirdHomotopyGroupOfSuspensionB\_alt \textsc{Examples}: 1
TransferChainMap \textsc{Examples}:
TranslationSubGroup  EXAMPLES:
TreeOfResolutionsToSL2Zcomplex  EXAMPLES:
TruncatedRegularCWComplex  EXAMPLES:
TupleOrbitReps  EXAMPLES:
TupleOrbitReps_perm  EXAMPLES:
TwistedResolution  EXAMPLES:
UnboundedArrayAssign  EXAMPLES:
UnitBall  EXAMPLES:
UnitCubicalBall  EXAMPLES:
UnitPermutahedralBall  EXAMPLES:
UniversalBarCodeEval  EXAMPLES:
UniversalCover  EXAMPLES: 1, 2, 3
VectorToCrystMatrix  EXAMPLES:
VectorsToOneSkeleton  EXAMPLES: 1
VerticesOfRegularCWCell  EXAMPLES:
View3dPureComplex  EXAMPLES:
ViewPureComplex  EXAMPLES:
VirtuallySimplicialSubdivision  EXAMPLES:
WirtingerGroup  EXAMPLES: 1
WirtingerGroup_gc  EXAMPLES:
WordModP  EXAMPLES:
ZigZagContractedFilteredPureCubicalComplex  EXAMPLES:
ZigZagContractedPureComplex  EXAMPLES: 1
Sq  EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
ElementsSL2Z  EXAMPLES:
PathComponentOfSimplicialComplex  EXAMPLES:
ResolutionSL2ZInvertedInteger  EXAMPLES: 1
ViewGraph  EXAMPLES:
AsFpGroup  EXAMPLES:
Bockstein  EXAMPLES: 1, 2
CategoryArrow  EXAMPLES:
CategoryObject  EXAMPLES:
CoboundaryMatrix  EXAMPLES:
CoefficientsOfPoincareSeries  EXAMPLES:
CohomologyClass  EXAMPLES: 1
CompositionRingHomomorphism  EXAMPLES:
ConnectedComponentsQuandle  EXAMPLES:
DegreeOfRepresentative  EXAMPLES:
Dimensions  EXAMPLES:
ExcisedPair  EXAMPLES:
FilteredRegularCWComplex  EXAMPLES: 1
GDerivedSubgroup  EXAMPLES:
GOuterGroupHomomorphism  EXAMPLES: 1
GOuterGroupHomomorphism  EXAMPLES: 1
GradedAlgebraPresentation  EXAMPLES:
GradedAlgebraPresentationNC  EXAMPLES:
HAPDerivationNC  EXAMPLES:
HAPRingHomomorphismByIndeterminateMap  EXAMPLES:
HAPRingReductionHomomorphism  EXAMPLES:
HAPRingReductionHomomorphism  EXAMPLES:
HAPRingToSubringHomomorphism  EXAMPLES:
HAPSubringToRingHomomorphism  EXAMPLES:
HAPSubringToRingHomomorphism  EXAMPLES:
HAPZeroRingHomomorphism  EXAMPLES:
HAP_EquivalenceClasses  EXAMPLES:
HomomorphismsImages  EXAMPLES:
ImageOfDerivation  EXAMPLES:
ImageOfRingHomomorphism  EXAMPLES:
IsAssociatedGradedRing  EXAMPLES:
KernelOfDerivation  EXAMPLES:
LowerGCentralSeries  EXAMPLES:
PathComponents  EXAMPLES: 1
PersistentHomology  EXAMPLES: 1
PersistentHomology  EXAMPLES: 1
PersistentHomology  EXAMPLES: 1
PolynomialToRModuleRep  EXAMPLES:
PreimageOfRingHomomorphism  EXAMPLES:
PureComplexMeet  EXAMPLES:
PureComplexRandomCell  EXAMPLES:
PureComplexSubcomplex EXAMPLES:

Pushout EXAMPLES:

QuadraticIdeal EXAMPLES:

ReduceIdeal EXAMPLES:

ReducedPolynomialRingPresentation EXAMPLES:

ReducedPolynomialRingPresentationMap EXAMPLES:

RefinedColouring EXAMPLES:

Resolution EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29

RightTransversal_alt EXAMPLES:

RingOfIntegers EXAMPLES:

SingularPolynomialNormalForm EXAMPLES:

SingularSetNormalFormIdeal EXAMPLES:

SingularSetNormalFormIdealNC EXAMPLES:

SparseChainComplexOfPair EXAMPLES:

Sq EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

Standard2Cocycle EXAMPLES:

Standard2Cocycle EXAMPLES:

StandardNCocycle EXAMPLES:

StandardNCocycle EXAMPLES:

SubspaceBasisRepsByDegree EXAMPLES:

SubspaceDimensionDegree EXAMPLES:

TrivialGModuleAsGOuterGroup EXAMPLES: 1, 2
TensorProductOp  EXAMPLES:

Arity  EXAMPLES:

AssociatedNumberField  EXAMPLES:

AssociatedRing  EXAMPLES:

Base  EXAMPLES: 1

BaseElement  EXAMPLES:

BaseRing  EXAMPLES:

Cocycle  EXAMPLES: 1, 2, 3, 4, 5, 6

CoefficientModule  EXAMPLES:

CohomologicalPeriod  EXAMPLES: 1

CoxeterMatrix  EXAMPLES: 1

DerivationImages  EXAMPLES:

DerivationRelations  EXAMPLES:

DerivationRing  EXAMPLES:

Fibre  EXAMPLES:

FibreElement  EXAMPLES:

Generators  EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20

GeneratorsOfPresentationIdeal  EXAMPLES:

GradedAlgebraPresentationFamily  EXAMPLES:

HAPDerivationFamily  EXAMPLES:

HAPPRIME_HilbertSeries  EXAMPLES:

HAPRingHomomorphismFamily  EXAMPLES:

HAP_MultiplicativeGenerators  EXAMPLES:
IdentityMap  EXAMPLES:
ImageGenerators  EXAMPLES:
ImagePolynomialRing  EXAMPLES:
ImageRelations  EXAMPLES:
InCcGroup  EXAMPLES:
IndeterminateAndExponentOfUnivariateMonomial  EXAMPLES:
IndeterminateDegrees  EXAMPLES:
IndeterminatesOfGradedAlgebraPresentation  EXAMPLES:
IndeterminatesOfPolynomial  EXAMPLES:
IndexInSL20  EXAMPLES: 1
InitialObject  EXAMPLES: 1
InnerAutomorphismGroupQuandle  EXAMPLES:
InnerAutomorphismGroupQuandleAsPerm  EXAMPLES:
InverseRingHomomorphism  EXAMPLES:
IsConnected  EXAMPLES: 1, 2, 3
IsHomogeneousQuandle  EXAMPLES:
IsLatinQuandle  EXAMPLES: 1
MaximumDegreeForPresentation  EXAMPLES:
ModPRingBasisAsPolynomials  EXAMPLES:
ModPRingGeneratorDegrees  EXAMPLES:
ModPRingNiceBasis  EXAMPLES:
ModPRingNiceBasisAsPolynomials  EXAMPLES:
Module  EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
NormOfIdeal Examples:

OuterAction Examples:

OuterGroup Examples: 1, 2

PresentationIdeal Examples:

PresentationOfGradedStructureConstantAlgebra Examples:

Pullbacks Examples:

Pushouts Examples:

RightMultiplicationGroupOfQuandle Examples: 1, 2, 3

RightMultiplicationGroupOfQuandleAsPerm Examples: 1

SingularGroebnerBasis Examples:

SingularReducedGroebnerBasis Examples:

SourceGenerators Examples:

SourcePolynomialRing Examples:

SourceRelations Examples:

StarGraph Examples:

TerminalObject Examples:

TermsOfPolynomial Examples:

UnivariateMonomialsOfMonomial Examples:

CoefficientsRing Examples:

ElementsFamily Examples:

IndexInSL2Z Examples:

Name Examples: 1, 2, 3, 4

Order Examples: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17,
IsAbelianCategory EXAMPLES:
IsAdditiveCategory EXAMPLES:
IsCategoryName EXAMPLES:
IsCcGroup EXAMPLES:
IsCrystTranslationSubGroup EXAMPLES:
IsGoOuterGroup EXAMPLES:
IsGoOuterGroupHomomorphism EXAMPLES:
IsGammaSubgroupInSL3Z EXAMPLES:
IsHAPRationalMatrixGroup EXAMPLES:
IsHAPRationalSpecialLinearGroup EXAMPLES:
IsIdealOfQuadraticIntegers EXAMPLES:
IsPeriodic EXAMPLES: 1
IsPseudoListWithFunction EXAMPLES:
IsQuadraticNumberField EXAMPLES:
IsRingOfQuadraticIntegers EXAMPLES:
IsStandard2Cocycle EXAMPLES:
IsStandardNCocycle EXAMPLES:
IsCcElement EXAMPLES:
IsGradedAlgebraPresentation EXAMPLES:
IsHAPDerivation EXAMPLES:
IsHAPRingHomomorphism EXAMPLES:
IsHAPRingModIdealObj EXAMPLES:
IsHapCatOneGroup EXAMPLES:

IsHapCatOneGroupMorphism EXAMPLES:

IsHapChainComplex EXAMPLES:

IsHapChainMap EXAMPLES:

IsHapCochainComplex EXAMPLES:

IsHapCochainMap EXAMPLES:

IsHapCommutativeDiagram EXAMPLES:

IsHapConjQuandElt EXAMPLES:

IsHapCrossedModule EXAMPLES:

IsHapCrossedModuleMorphism EXAMPLES:

IsHapCubicalComplex EXAMPLES:

IsHapEquivariantCWComplex EXAMPLES:

IsHapEquivariantChainComplex EXAMPLES:

IsHapEquivariantChainMap EXAMPLES:

IsHapEquivariantSpectralSequencePage EXAMPLES:

IsHapFilteredChainComplex EXAMPLES:

IsHapFilteredCubicalComplex EXAMPLES:

IsHapFilteredGraph EXAMPLES:

IsHapFilteredPureCubicalComplex EXAMPLES:

IsHapFilteredRegularCWComplex EXAMPLES:

IsHapFilteredSimplicialComplex EXAMPLES:

IsHapFilteredSparseChainComplex EXAMPLES:

IsHapGCocomplex EXAMPLES:
IsHapGComplex    EXAMPLES:
IsHapGComplexMap EXAMPLES:
IsHapGraph      EXAMPLES:
IsHapOppositeElement EXAMPLES:
IsHapPureCubicalComplex EXAMPLES:
IsHapPureCubicalLink EXAMPLES:
IsHapPurePermutedalComplex EXAMPLES:
IsHapQuandlePresentation EXAMPLES:
IsHapQuotientElement EXAMPLES:
IsHapRegularCWComplex EXAMPLES:
IsHapRegularCWMap EXAMPLES:
IsHapResolution EXAMPLES:
IsHapSimplicialComplex EXAMPLES:
IsHapSimplicialGroup EXAMPLES:
IsHapSimplicialGroupMorphism EXAMPLES:
IsHapSimplicialMap EXAMPLES:
IsHapSparseChainComplex EXAMPLES:
IsHapSparseChainMap EXAMPLES:
IsHapSparseMat EXAMPLES:
IsHapTorsionSubcomplex EXAMPLES:
IsPseudoList    EXAMPLES:
IsCcElementRep EXAMPLES:
IsGradedAlgebraPresentationRep EXAMPLES:
IsHAPDerivationRep  EXAMPLES:

IsHAPIdealRep  EXAMPLES:

IsHAPRingHomomorphismIndeterminateMapRep  EXAMPLES:

IsHAPRingReductionHomomorphismRep  EXAMPLES:

IsHAPRingToSubringHomomorphismRep  EXAMPLES:

IsHAPSubringToRingHomomorphismRep  EXAMPLES:

IsHAPZeroRingHomomorphismRep  EXAMPLES:

IsHapCatOneGroupMorphismRep  EXAMPLES:

IsHapCatOneGroupRep  EXAMPLES:

IsHapChainComplexRep  EXAMPLES:

IsHapChainMapRep  EXAMPLES:

IsHapCochainComplexRep  EXAMPLES:

IsHapCochainMapRep  EXAMPLES:

IsHapCommutativeDiagramRep  EXAMPLES:

IsHapConjQuandEltRep  EXAMPLES:

IsHapCrossedModuleMorphismRep  EXAMPLES:

IsHapCrossedModuleRep  EXAMPLES:

IsHapCubicalComplexRep  EXAMPLES:

IsHapEquivariantCWComplexRep  EXAMPLES:

IsHapEquivariantChainComplexRep  EXAMPLES:

IsHapEquivariantChainMapRep  EXAMPLES:

IsHapEquivariantSpectralSequencePageRep  EXAMPLES:

IsHapFilteredChainComplexRep  EXAMPLES:
IsHapFilteredCubicalComplexRep EXAMPLES:

IsHapFilteredGraphRep EXAMPLES:

IsHapFilteredPureCubicalComplexRep EXAMPLES:

IsHapFilteredRegularCWComplexRep EXAMPLES:

IsHapFilteredSimplicialComplexRep EXAMPLES:

IsHapFilteredSparseChainComplexRep EXAMPLES:

IsHapGCocomplexRep EXAMPLES:

IsHapGComplexMapRep EXAMPLES:

IsHapGComplexRep EXAMPLES:

IsHapGraphRep EXAMPLES:

IsHapOppositeElementRep EXAMPLES:

IsHapPureCubicalComplexRep EXAMPLES:

IsHapPureCubicalLinkRep EXAMPLES:

IsHapPurePermutahedralComplexRep EXAMPLES:

IsHapQuandlePresentationRep EXAMPLES:

IsHapQuotientElementRep EXAMPLES:

IsHapRegularCWComplexRep EXAMPLES:

IsHapRegularCWMapRep EXAMPLES:

IsHapResolutionRep EXAMPLES:

IsHapSimplicialComplexRep EXAMPLES:

IsHapSimplicialGroupMorphismRep EXAMPLES:

IsHapSimplicialGroupRep EXAMPLES:

IsHapSimplicialMapRep EXAMPLES:
IsHapSparseChainComplexRep EXAMPLES:

IsHapSparseChainMapRep EXAMPLES:

IsHapSparseMatRep EXAMPLES:

IsHapTorsionSubcomplexRep EXAMPLES:

IsPseudoListRep EXAMPLES:

IdealOfQuadraticIntegers EXAMPLES:

QuadraticNF EXAMPLES:

RingOfQuadraticIntegers EXAMPLES:

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

EXAMPLES:

EXAMPLES:

= EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

= EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,
AdditiveInverseMutable Examples:

AsFpGroup Examples:

AsList Examples:

AsSSortedList Examples:

BaseRing Examples:

Bockstein Examples: 1, 2

CategoryArrow Examples:

CategoryObject Examples:

CoboundaryMatrix Examples:

CoefficientsOfPoincareSeries Examples:

CoefficientsRing Examples:

CohomologicalPeriod Examples: 1

CohomologyClass Examples: 1

CompositionRingHomomorphism Examples:

CompositionRingHomomorphism Examples:

CompositionRingHomomorphism Examples:

CompositionRingHomomorphism Examples:

CompositionRingHomomorphism Examples:

ConnectedComponentsQuandle Examples:

CoxeterMatrix Examples: 1
DefaultFieldOfMatrixGroup\ EXAMPLES:\
DegreeOfRepresentative\ EXAMPLES:\
DerivationImages\ EXAMPLES:\
DerivationRelations\ EXAMPLES:\
DerivationRing\ EXAMPLES:\
Dimensions\ EXAMPLES:\
Enumerator\ EXAMPLES:\
ExcisedPair\ EXAMPLES:\
FilteredRegularCWComplex\ EXAMPLES:\ 1
GOuterGroupHomomorphism\ EXAMPLES:\ 1
GOuterGroupHomomorphism\ EXAMPLES:\ 1
Generators\ EXAMPLES:\ 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
GeneratorsOfMagmaWithInverses\ EXAMPLES:\
GeneratorsOfPresentationIdeal\ EXAMPLES:\
GradedAlgebraPresentation\ EXAMPLES:\
GradedAlgebraPresentationNC\ EXAMPLES:\
HAPDerivationNC\ EXAMPLES:\
HAPPRIME_HilbertSeries\ EXAMPLES:\
HAPRingHomomorphismByIndeterminateMap\ EXAMPLES:\
HAPRingReductionHomomorphism\ EXAMPLES:\
HAPRingToSubringHomomorphism\ EXAMPLES:\
HAPSubringToRingHomomorphism  EXAMPLES:
HAPSubringToRingHomomorphism  EXAMPLES:
HAPZeroRingHomomorphism  EXAMPLES:
HAP_MultiplicativeGenerators  EXAMPLES:
HomomorphismsImages  EXAMPLES:
IdGroup  EXAMPLES: 1, 2, 3, 4, 5, 6
IdentityMap  EXAMPLES:
ImageOfDerivation  EXAMPLES:
ImageOfRingHomomorphism  EXAMPLES:
ImageOfRingHomomorphism  EXAMPLES:
ImageOfRingHomomorphism  EXAMPLES:
ImageOfRingHomomorphism  EXAMPLES:
ImageOfRingHomomorphism  EXAMPLES:
IndeterminateAndExponentOfUnivariateMonomial  EXAMPLES:
IndeterminateDegrees  EXAMPLES:
IndeterminatesOfGradedAlgebraPresentation  EXAMPLES:
IndeterminatesOfPolynomial  EXAMPLES:
IndexInSL2O  EXAMPLES: 1
IndexInSL2Z  EXAMPLES:
InnerAutomorphismGroupQuandle  EXAMPLES:
InnerAutomorphismGroupQuandleAsPerm  EXAMPLES:
Int  EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34
InverseMutable  EXAMPLES:
InverseMutable EXAMPLES:

InverseRingHomomorphism EXAMPLES:

InverseRingHomomorphism EXAMPLES:

InverseRingHomomorphism EXAMPLES:

InverseRingHomomorphism EXAMPLES:

InverseRingHomomorphism EXAMPLES:

InverseSameMutability EXAMPLES:

IsAssociatedGradedRing EXAMPLES:

IsConnected EXAMPLES: 1, 2, 3

IsHomogeneousQuandle EXAMPLES:

IsLatinQuandle EXAMPLES: 1

IsMonomial EXAMPLES:

IsOne EXAMPLES:

IsPeriodic EXAMPLES: 1

Kernel EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8

KernelOfDerivation EXAMPLES:

MaximumDegreeForPresentation EXAMPLES:

ModPRingBasisAsPolynomials EXAMPLES:

ModPRingGeneratorDegrees EXAMPLES:

ModPRingNiceBasis EXAMPLES:

ModPRingNiceBasisAsPolynomials EXAMPLES:

OneImmutable EXAMPLES:
OneMutable EXAMPLES:

PathComponents EXAMPLES: 1

PreimageOfRingHomomorphism EXAMPLES:

PresentationIdeal EXAMPLES:

PresentationOfGradedStructureConstantAlgebra EXAMPLES:

PrintObj EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
PrintObj  EXAMPLES:
Projection EXAMPLES:

PureComplexMeet EXAMPLES:

PureComplexRandomCell EXAMPLES:

PureComplexSubcomplex EXAMPLES:

Pushout EXAMPLES:

QuadraticIdeal EXAMPLES: 1

Random EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

ReduceIdeal EXAMPLES:

ReducedPolynomialRingPresentation EXAMPLES:

ReducedPolynomialRingPresentationMap EXAMPLES:

RefinedColouring EXAMPLES:

Resolution EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29

RightMultiplicationGroupOfQuandle EXAMPLES: 1, 2, 3

RightMultiplicationGroupOfQuandleAsPerm EXAMPLES: 1

RightTransversal EXAMPLES:

RingOfIntegers EXAMPLES: 1

SingularGroebnerBasis EXAMPLES:

SingularPolynomialNormalForm EXAMPLES:

SingularReducedGroebnerBasis EXAMPLES:

SingularSetNormalFormIdeal EXAMPLES:

SingularSetNormalFormIdealNC EXAMPLES:

SparseChainComplexOfPair EXAMPLES:
Sq  EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

Standard2Cocycle  EXAMPLES:

Standard2Cocycle  EXAMPLES:

StandardNCocycle  EXAMPLES:

StandardNCocycle  EXAMPLES:

StarGraph  EXAMPLES:

SubspaceBasisRepsByDegree  EXAMPLES:

SubspaceDimensionDegree  EXAMPLES:

TensorProductOp  EXAMPLES:

TermsOfPolynomial  EXAMPLES:

TrivialGModuleAsGOuterGroup  EXAMPLES: 1, 2

Units  EXAMPLES:

Units  EXAMPLES:

UnivariateMonomialsOfMonomial  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:

ViewObj  EXAMPLES:
<table>
<thead>
<tr>
<th>ViewObj</th>
<th>EXAMPLES:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj  EXAMPLES:
ViewObj EXAMPLES:

ViewObj EXAMPLES:

ViewObj EXAMPLES:

ViewObj EXAMPLES:

ViewObj EXAMPLES:

ZeroMutable EXAMPLES:

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39

EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39

in EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

in EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

in EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

in EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

mod EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

* EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38
Examples:

Examples:

Examples:

Examples:

Examples:

Examples:
AbelianInvariants  EXAMPLES: 1 , 2 , 3 , 4 , 5 , 6 , 7 , 8 , 9 , 10

AbelianInvariants  EXAMPLES: 1 , 2 , 3 , 4 , 5 , 6 , 7 , 8 , 9 , 10

CanonicalRightCosetElement  EXAMPLES:

Dimensions  EXAMPLES:

DirectProductOp  EXAMPLES:

DirectProductOp  EXAMPLES:

Discriminant  EXAMPLES: 1

Discriminant  EXAMPLES: 1

Embedding  EXAMPLES:

GDerivedSubgroup  EXAMPLES:

Generators  EXAMPLES: 1 , 2 , 3 , 4 , 5 , 6 , 7 , 8 , 9 , 10 , 11 , 12 , 13 , 14 , 15 , 16 , 17 , 18 , 19

HAPRingReductionHomomorphism  EXAMPLES:

HAPRingReductionHomomorphism  EXAMPLES:

HAP_EquivalenceClasses  EXAMPLES:

ImageOfRingHomomorphism  EXAMPLES:
ImageOfRingHomomorphism EXAMPLES:

IndexNC EXAMPLES:

InverseMutable EXAMPLES:

InverseSameMutability EXAMPLES:

IsPrime EXAMPLES: 1, 2, 3

IsomorphismFpGroup EXAMPLES: 1, 2

Iterator EXAMPLES:

KernelOfDerivation EXAMPLES:

ListUp EXAMPLES:

LowerGCentralSeries EXAMPLES:

NaturalHomomorphism EXAMPLES: 1, 2, 3, 4, 5

Norm EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13

Norm EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13

OneImmutable EXAMPLES:

Order EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20

Order EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20

PersistentHomology EXAMPLES: 1
PersistentHomology  EXAMPLES: 1
Position  EXAMPLES: 1,2
Position  EXAMPLES: 1,2
Position  EXAMPLES: 1,2
PositionCanonical  EXAMPLES:
PreimageOfRingHomomorphism  EXAMPLES:
Projection  EXAMPLES:
PureComplexMeet  EXAMPLES:
PureComplexRandomCell  EXAMPLES:
PureComplexSubcomplex  EXAMPLES:
QuadraticIdeal  EXAMPLES: 1
Range  EXAMPLES: 1
ReduceIdeal  EXAMPLES:
ReduceIdeal  EXAMPLES:
ReducedPolynomialRingPresentation  EXAMPLES:
ReducedPolynomialRingPresentation  EXAMPLES:
ReducedPolynomialRingPresentationMap  EXAMPLES:
ReducedPolynomialRingPresentationMap  EXAMPLES:
ReducedPolynomialRingPresentationMap  EXAMPLES:
RefinedColouring  EXAMPLES:
RightTransversal  EXAMPLES:
RightTransversal  EXAMPLES:
RightTransversal  EXAMPLES:
RightTransversal  EXAMPLES:
RightTransversal_alt  EXAMPLES:
SingularPolynomialNormalForm  EXAMPLES:
SparseChainComplexOfPair  EXAMPLES:
SubspaceBasisRepsByDegree  EXAMPLES:
SubspaceDimensionDegree  EXAMPLES:
TensorProductOp  EXAMPLES:
TensorProductOp  EXAMPLES:
TensorProductOp  EXAMPLES:
Trace  EXAMPLES:
Units  EXAMPLES:

- EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8
- EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8
- EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8
  - EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39
  - EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39
  - EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39
  - EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39

in  EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

in  EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18,
in Examples: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

mod Examples: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64

InfoHAPprime Examples:

ASY_PATH Examples:

AutomorphismGroupAsCrossedModule Examples:

BROWSER_PATH Examples:

CATONEGROUP_DATA_PERM Examples:

CATONEGROUP_DATA_SIZE Examples:

Category_Of_Groups Examples: 1

Cedric_PlanarDiagram Examples:

ChildKill Examples:

DISPLAY_PATH Examples:

DOT_PATH Examples:

FilteredSimplicialComplexToFilteredCWComplex Examples:

GradedAlgebraPresentationType Examples:

HAPTEMPORARYFUNCTION Examples:
HAP_Knots  EXAMPLES:
HAP_ROOT  EXAMPLES:
HapCatOneGroup  EXAMPLES:
HapCatOneGroupFamily  EXAMPLES:
HapCatOneGroupMorphism  EXAMPLES:
HapCatOneGroupMorphismFamily  EXAMPLES:
HapChainComplex  EXAMPLES:
HapChainComplexFamily  EXAMPLES:
HapChainMap  EXAMPLES:
HapChainMapFamily  EXAMPLES:
HapCochainComplex  EXAMPLES:
HapCochainComplexFamily  EXAMPLES:
HapCochainMap  EXAMPLES:
HapCochainMapFamily  EXAMPLES:
HapCommutativeDiagram  EXAMPLES:
HapCommutativeDiagramFamily  EXAMPLES:
HapCrossedModule  EXAMPLES:
HapCrossedModuleFamily  EXAMPLES:
HapCrossedModuleMorphism  EXAMPLES:
HapCrossedModuleMorphismFamily  EXAMPLES:
HapCubicalComplex  EXAMPLES:
HapCubicalComplexFamily  EXAMPLES:
HapEquivariantCWComplex  EXAMPLES:
HapEquivariantCWComplexFamily EXAMPLES:

HapEquivariantChainMap EXAMPLES:

HapEquivariantChainMapFamily EXAMPLES:

HapFPGModule EXAMPLES:

HapFPGModuleHomomorphism EXAMPLES:

HapFilteredChainComplex EXAMPLES:

HapFilteredChainComplexFamily EXAMPLES:

HapFilteredCubicalComplex EXAMPLES:

HapFilteredCubicalComplexFamily EXAMPLES:

HapFilteredGraph EXAMPLES:

HapFilteredGraphFamily EXAMPLES:

HapFilteredPureCubicalComplex EXAMPLES:

HapFilteredPureCubicalComplexFamily EXAMPLES:

HapFilteredRegularCWComplex EXAMPLES:

HapFilteredRegularCWComplexFamily EXAMPLES:

HapFilteredSimplicialComplex EXAMPLES:

HapFilteredSimplicialComplexFamily EXAMPLES:

HapFilteredSparseChainComplex EXAMPLES:

HapFilteredSparseChainComplexFamily EXAMPLES:

HapGChainComplex EXAMPLES:

HapGCocomplex EXAMPLES:

HapGCocomplexFamily EXAMPLES:

HapGComplex EXAMPLES:
HapGComplexFamily EXAMPLES:

HapGlobalDeclarationsAreAlreadyLoaded EXAMPLES:

HapGraph EXAMPLES:

HapGraphFamily EXAMPLES:

HapNonFreeResolution EXAMPLES:

HapOppositeElement EXAMPLES:

HapOppositeElementFamily EXAMPLES:

HapPureCubicalComplex EXAMPLES:

HapPureCubicalComplexFamily EXAMPLES:

HapPureCubicalLink EXAMPLES:

HapPureCubicalLinkFamily EXAMPLES:

HapPurePermutahedralComplex EXAMPLES:

HapPurePermutahedralComplexFamily EXAMPLES:

HapQuotientElement EXAMPLES:

HapQuotientElementFamily EXAMPLES:

HapRegularCWComplex EXAMPLES:

HapRegularCWComplexFamily EXAMPLES:

HapRegularCWMap EXAMPLES:

HapRegularCWMapFamily EXAMPLES:

HapResolution EXAMPLES:

HapResolutionFamily EXAMPLES:

HapSimplicialComplex EXAMPLES:

HapSimplicialComplexFamily EXAMPLES:
HapSimplicialGroup EXAMPLES:

HapSimplicialGroupFamily EXAMPLES:

HapSimplicialGroupMorphism EXAMPLES:

HapSimplicialGroupMorphismFamily EXAMPLES:

HapSimplicialMap EXAMPLES:

HapSimplicialMapFamily EXAMPLES:

HapSparseChainComplex EXAMPLES:

HapSparseChainComplexFamily EXAMPLES:

HapSparseChainMap EXAMPLES:

HapSparseChainMapFamily EXAMPLES:

HapSparseMat EXAMPLES:

HapSparseMatFamily EXAMPLES:

HomomorphismOfDirectProduct EXAMPLES:

IDQUASICATONEGROUP_DATA EXAMPLES:

IsHapChain EXAMPLES:

IsHapCochain EXAMPLES:

IsHapComplex EXAMPLES:

IsHapFPGModule EXAMPLES:

IsHapFPGModuleHomomorphism EXAMPLES:

IsHapGChainComplex EXAMPLES:

IsHapMap EXAMPLES:

IsHapNonFreeResolution EXAMPLES:

NEATO_PATH EXAMPLES:
NerveOfCover  EXAMPLES:

POLYMAKE_PATH  EXAMPLES:

PseudoList  EXAMPLES:

PseudoListFamily  EXAMPLES:

QUASICATONEGROUP_DATA_NOT  EXAMPLES:

QUASICATONEGROUP_DATA_SIZE  EXAMPLES:

ReadBioData  EXAMPLES:

SMALLQUASICATONEGROUP_DATA  EXAMPLES:

CATONEGROUP_DATA  EXAMPLES:

COMPILED  EXAMPLES:

cedric_XXYYConnQuan  EXAMPLES:

cedric_XXYYQuandles  EXAMPLES:

CohomologicalData  EXAMPLES: 1

CommutingProbability  EXAMPLES:

GroupIsomorphismRepresentatives  EXAMPLES:

HAPAAA  EXAMPLES:

HAPBARCODE  EXAMPLES:

HAPDerivationType  EXAMPLES:

HAPPRIME_LastLHSBicomplexSize  EXAMPLES:

HAPPRIME_ShuffleRandomSource  EXAMPLES:

HAPRIGXXX  EXAMPLES:

HAP_GCOMPLEX_LIST  EXAMPLES:

HAP_GCOMPLEX_SETUP  EXAMPLES:
HAP_MOVES_DIM_2  EXAMPLES:
HAP_MOVES_DIM_3  EXAMPLES:
HAP_PERMMOVES_DIM_2  EXAMPLES:
HAP_PERMMOVES_DIM_3  EXAMPLES:
HAP_XYXYXYXY  EXAMPLES:
HAP_type  EXAMPLES:
HAPchildFunctionToggle  EXAMPLES:
HAPchildToggle  EXAMPLES:
HAPchildren  EXAMPLES:
HapConjQuandElt  EXAMPLES:
HapConjQuandEltFamily  EXAMPLES:
HapConstantPolRing  EXAMPLES:
HapEquivariantChainComplex  EXAMPLES:
HapEquivariantChainComplexFamily  EXAMPLES:
HapEquivariantSpectralSequencePage  EXAMPLES:
HapEquivariantSpectralSequencePageFamily  EXAMPLES:
HapGComplexMap  EXAMPLES:
HapGComplexMapFamily  EXAMPLES:
HapQuandlePresentation  EXAMPLES:
HapQuandlePresentationFamily  EXAMPLES:
HapRightTransversalSL2ZSubgroup  EXAMPLES:
HapSL2ZSubgroup  EXAMPLES:
HapTorsionSubcomplex  EXAMPLES:
HapTorsionSubcomplexFamily EXAMPLES:

IsHapRightTransversalSL2ZSubgroup EXAMPLES:

IsHapSL20Subgroup EXAMPLES:

IsHapSL2Subgroup EXAMPLES:

IsHapSL2ZSubgroup EXAMPLES:

MinimizeRingRelations EXAMPLES:

RefinedColouring_gc EXAMPLES:

RefinedColouring_group EXAMPLES:

StemGroups EXAMPLES:

cat EXAMPLES: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23

cnt EXAMPLES:
Index

ActedGroup, 39
ActingGroup, 39
AcyclicSubcomplexOfPureCubicalComplex, 130
Add, 152
AddFreeWords, 94
AddFreeWordsModP, 94
AlexanderMatrix, 137
AlexanderPolynomial, 19, 137
AlgebraicReduction, 94
Append, 152
AreIsomorphicGradedAlgebras, 33
Array, 150
ArrayAssign, 151
ArrayAssignFunctions, 151
ArrayDimension, 150
ArrayDimensions, 150
ArrayIterate, 151
ArraySum, 151
ArrayToPureCubicalComplex, 124
ArrayValue, 151
ArrayValueFunctions, 151
AutomorphismGroupAsCatOneGroup, 104
AutomorphismGroupQuandle, 142
AutomorphismGroupQuandleAsPerm, 142
BaerInvariant, 79
BarCocycleCoboundary, 110
BarCode, 68
BarCodeCompactDisplay, 27, 69
BarCodeDisplay, 27, 69
BarComplexBoundary, 109
BarComplexEquivalence, 109
BarResolutionBoundary, 108
BarResolutionEquivalence, 109
BarResolutionHomotopy, 108
BettiNumber, 19
Bettinumbers, 63, 119, 127
BigStepLCS, 160
BinaryArrayToTextFile, 152
Bogomology, 80
BogomolovMultiplier, 79
BoundaryMap, 13, 158
BoundaryMatrix, 158
BoundaryOfPureCubicalComplex, 130
BoundingPureCubicalComplex, 131
CategoricalEnrichment, 147
CategoryName, 149
CayleyGraphOfGroup, 8, 27, 122
CayleyGraphOfGroupDisplay, 86
CayleyMetric, 12, 143
CcGroup, 38, 92
CechComplexOfPureCubicalComplex, 120
Centre, 39, 103
ChainComplex, 22, 58, 120, 128, 135
ChainComplexEquivalence, 22
ChainComplexOfPair, 58, 128
ChainComplexOfQuotient, 23
ChainComplexOfRegularCWComplex, 135
ChainComplexOfSimplicialGroup, 107
ChainInclusionOfPureCubicalPair, 128
ChainMap, 23
ChainMapOfPureCubicalPairs, 128
ChainMapOfSimplicialMap, 123
ChevalleyEilenbergComplex, 58
ChildClose, 155
ChildCommand, 155
ChildCreate, 41
ChildFunction, 157
ChildGet, 155
ChildProcess, 41, 154
ChildPut, 155
ChildRead, 157
ChildReadEval, 157
Classify, 160
CliqueComplex, 14
CochainComplex, 23
Coclass, 80
CocycleCondition, 38, 92
Cohomology, 25, 26, 64
CohomologyModule, 40, 64
CohomologyPrimePart, 64
ComplementOfFilteredPureCubicalComplex, 133
ComplementOfPureCubicalComplex, 132
Compose, 161
CompositionEqualityAdditionMinus, 149
CompositionSeriesOfFpGModules, 96
ConcentricFiltration, 14
ConjugatedResolution, 50
ConjugationQuandle, 139
ConnectedQuandle, 141
ConnectedQuandles, 140
ContractCubicalComplex, 129
ContractedComplex, 16, 129
ContractGraph, 122
ContractibleComplex, 88
ContractibleSubcomplex, 16
ContractibleSubcomplexOfSimplicialComplex, 121
ContractibleSubcomplexOfPureCubicalComplex, 130
ContractPureCubicalComplex, 129
CoreducedChainComplex, 59
CountingBaryCentricSubdividedCells, 117
CountingCellsOfACellComplex, 117
CountingControlledSubdividedCells, 117
CoxeterComplex, 88
CoxeterDiagramComponents, 111
CoxeterDiagramDegree, 111
CoxeterDiagramDisplay, 111
CoxeterDiagramFpArtinGroup, 111
CoxeterDiagramFpCoxeterGroup, 112
CoxeterDiagramIsSpherical, 112
CoxeterDiagramMatrix, 112
CoxeterDiagramVertices, 112
CoxeterSubDiagram, 112
CriticalCells, 24
CriticalCellsOfRegularCWComplex, 134
CropPureCubicalComplex, 131
CubicalComplex, 7
CubicalComplexToRegularCWComplex, 134
CupProduct, 26
Dendrogram, 132
DendrogramDisplay, 132
DendrogramMat, 22
DendrogramToPersistenceMat, 132
DesuspensionFpGModule, 97
DesuspensionMtxModule, 101
DiagonalApproximation, 24
Dimension, 126, 158
DirectProduct, 14
DirectProductGog, 103
DirectProductOfPureCubicalComplexes, 127
DirectSumOfFpGModules, 96
Display, 27
DisplayArcPresentation, 27
DisplayAvailableCellComplexes, 116
DisplayCSVKnotFile, 27
DisplayDendrogram, 28
DisplayDendrogramMat, 28
DisplayPDBfile, 28
DVFReducedCubicalComplex, 129
EfficientNormalSubgroups, 72
EilenbergMacLaneSimplicialGroup, 106
EilenbergMacLaneSimplicialGroupMap, 106
EpiCentre, 80
EquivariantChainMap, 29, 53
EquivariantEuclideanSpace, 8
EquivariantEulerCharacteristic, 117
EquivariantOrbitPolytope, 9
EquivariantSpectralSequencePage, 117
EquivariantTwoComplex, 9
EuclideanApproximatedMetric, 144
EuclideanMetric, 12
EuclideanSquaredMetric, 12, 144
EulerCharacteristic, 20, 121, 127
EulerIntegral, 20
EvaluateProperty, 158
EvenSubgroup, 112
ExcisedPureCubicalPair, 128
ExpansionOfRationalFunction, 72
ExportHapCellcomplexToDisk, 118
ExtendScalars, 54
FilteredTensorWithIntegers, 24, 56
FilteredTensorWithIntegersModP, 25
FiltrationTerm, 14
FirstQuandleAxiomIsSatisfied, 139
FpGModule, 96
FpGModuleDualBasis, 97
FpGModuleHomomorphism, 97
FpGModuleHomomorphismNC, 97
FpG_to_MtxModule, 101
FrameArray, 152
FramedPureCubicalComplex, 124
FreeGResolution, 29, 44
FundamentalDomainStandardSpaceGroup, 89
FundamentalGroup, 20, 135
FundamentalGroupOfQuotient, 21
GaussCodeKnot, 138
GeneratorsOfFpGModule, 98
GeneratorsOfMtxModule, 101
GOuterGroup, 39, 102
GOuterGroupHomomorphismNC, 102
GOuterHomomorphismTester, 102
Graph, 14
GraphDisplay, 123
GraphOfGroups, 113
GraphOfGroupsDisplay, 113
GraphOfGroupsTest, 113
GraphOfResolutions, 113
GraphOfResolutionsDisplay, 113
GraphOfSimplicialComplex, 121
GroupAlgebraAsFpGModule, 37, 98
GroupCohomology, 35, 65
GroupHomology, 35, 65
GroupHomologyOfCommutativeDiagram, 147
GroupOfResolution, 159
HammingMetric, 13, 143
HAPcopyright, 161
HAPDerivation, 33
HAPPrintTo, 156
HAPRead, 156
HasInitialObject, 148
HasTerminalObject, 148
HilbertPoincareSeries, 33
Homology, 26, 69, 119, 127
HomologyOfDerivation, 33
HomologyPb, 69
HomologyPrimePart, 70
HomologyVectorSpace, 70
HomomorphismChainToCommutativeDiagram, 146
HomotopyEquivalentMaximalPureCubicalSubcomplex, 130
HomotopyEquivalentMinimalPureCubicalSubcomplex, 130
HomotopyGraph, 15
HomotopyGroup, 104, 107
HomotopyModule, 104
HomToGModule, 40, 55
HomToIntegers, 25, 31, 32, 54
HomToIntegersModP, 54
HomToIntegralModule, 32, 54
IdConnectedQuandle, 141
IdentityAmongRelatorsDisplay, 86
IdentityArrow, 147
IdQuandle, 140
ImageOfFpGModuleHomomorphism, 98
IncidenceMatrixToGraph, 122
InduceScalars, 55
InitialArrow, 148
IntegralCohomologyGenerators, 33
IntegralCupProduct, 74
IntegralRingGenerators, 74
IntersectionOfFpGModules, 98
IsAspherical, 21, 86
IsAvailableChild, 155
IsCategoryArrow, 149
IsCategoryObject, 149
IsConnectedQuandle, 140
IsFpGModuleHomomorphismData, 98
IsLatin, 140
IsLieAlgebraHomomorphism, 161
IsPHNormal, 115
IsQuandle, 139
IsQuandleEnvelope, 141
IsSuperperfect, 161
KendallMetric, 13, 143
KnotGroup, 21, 136
KnotInvariantCedric, 141
KnotReflection, 17
KnotSum, 17, 136
LefschetzNumber, 60
LeibnizAlgebraHomology, 70
ReverseSparseMat, 61
RightMultiplicationGroup, 142
RightMultiplicationGroupAsPerm, 141
RigidFacetsSubdivision, 115
RipsChainComplex, 120
RipsHomology, 68, 119
ScatterPlot, 28
SecondQuandleAxiomIsSatisfied, 139
SimplicialComplex, 11
SimplicialComplexToRegularCWComplex, 134
SimplicialGroupMap, 107
SimplicialMap, 123
SimplicialMapNC, 123
SimplicialNerveOfGraph, 123
SimplifiedComplex, 18
SingularitiesOfPureCubicalComplex, 131
Size, 24, 126
SkeletonOfCubicalComplex, 130
SkeletonOfSimplicialComplex, 121
SL2Z, 160
SolutionsMatDestructive, 162
Source, 148, 159
SparseBoundaryMatrix, 63
SparseChainComplex, 62
SparseChainComplexOfRegularCWComplex, 63
SparseMat, 61
SparseRowAdd, 62
SparseRowInterchange, 62
SparseRowMult, 61
SparseSemiEchelon, 62
StandardCocycle, 38, 92
SumOfFpGModules, 100
SumOp, 100
SuspendedChainComplex, 59
SuspensionOfPureCubicalComplex, 127
SymmetricMatDisplay, 144
SymmetricMatrixToFilteredGraph, 12, 145
SymmetricMatrixToGraph, 12
SymmetricMatrixToIncidenceMatrix, 122
Syzygy, 93
Target, 148, 159
TensorCentre, 82
TensorProductOfChainComplexes, 59
TensorWithIntegers, 32, 56
TensorWithIntegersModP, 25, 32, 56
TensorWithIntegralModule, 55
TensorWithRationals, 57
TensorWithTwistedIntegers, 56
TensorWithTwistedIntegersModP, 56
TerminalArrow, 148
TestHap, 162
ThickenedPureCubicalComplex, 131
ThickeningFiltration, 16, 132
ThirdHomotopyGroupOfSuspensionB, 83
ThirdQuandleAxiomIsSatisfied, 139
TietzeReducedResolution, 43
TietzeReduction, 95
TorsionGeneratorsAbelianGroup, 87
TorsionSubcomplex, 115
TransposeOfSparseMat, 61
TreeOfGroupsToContractibleGcomplex, 113
TreeOfResolutionsToContractibleGcomplex, 114
TruncatedGComplex, 89
TwistedTensorProduct, 50
UnframeArray, 152
UniversalBarCode, 67
UpperEpicentralSeries, 83
VectorStabilizer, 91
VectorsToFpGModuleWords, 100
VectorsToSymmetricMatrix, 13, 120, 144
ViewPureCubicalComplex, 126
ViewPureCubicalKnot, 136
VisualizeTorsionSkeleton, 116
WritePureCubicalComplexAsImage, 126
XmodToHAP, 105
ZigZagContractedComplex, 19
ZigZagContractedPureCubicalComplex, 129
ZZPersistentHomologyOfPureCubicalComplex, 68