

# MatricesForHomalg

**Matrices for the homalg project**

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**Mohamed Barakat**

**Markus Lange-Hegermann**

**Vinay Wagh**

*(this manual is still under construction)*

This manual is best viewed as an HTML document. The latest version is available ONLINE at:

[https://homalg-project.github.io/homalg\\_project/MatricesForHomalg/doc/chap0.html](https://homalg-project.github.io/homalg_project/MatricesForHomalg/doc/chap0.html)

An OFFLINE version should be included in the documentation subfolder of the package. This package is part of the homalg-project:

<http://homalg.math.rwth-aachen.de/index.php/core-packages/matricesforhomalg>

**Mohamed Barakat**

Email: [mohamed.barakat@uni-siegen.de](mailto:mohamed.barakat@uni-siegen.de)

Homepage: <https://mohamed-barakat.github.io>

Address: Department of Mathematics,  
University of Siegen,  
57072 Siegen,  
Germany

**Markus Lange-Hegermann**

Email: [markus.lange.hegermann@rwth-aachen.de](mailto:markus.lange.hegermann@rwth-aachen.de)

Homepage: <http://wwwb.math.rwth-aachen.de/~markus/>

Address: Lehrstuhl B für Mathematik, RWTH Aachen, Templer-  
graben 64, 52056 Aachen, Germany

**Vinay Wagh**

Email: [waghoba@gmail.com](mailto:waghoba@gmail.com)

Homepage: <http://www.iitg.ernet.in/vinay.wagh/>

Address: E-102, Department of Mathematics,  
Indian Institute of Technology Guwahati,  
Guwahati, Assam, India.  
PIN: 781 039.

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# Chapter 1

## Introduction

### 1.1 What is the role of the **MatricesForHomalg** package in the **homalg** project?

#### 1.1.1 **MatricesForHomalg** provides ...

The package **MatricesForHomalg** provides:

- rings
- ring elements
- ring maps
- matrices

#### 1.1.2 **homalg** delegates ...

The package **homalg** *delegates all* matrix operations as it treats matrices and their rings as *black boxes*. **homalg** comes with a single predefined class of rings and a single predefined class of matrices over these rings – the so-called internal matrices (→ 5.1.2) over so-called internal rings (→ 3.1.4). An internal matrix (resp. ring) is simply a wrapper containing a **GAP**-builtin matrix (resp. ring). **homalg** allows other packages to define further classes or extend existing classes of rings and matrices *together* with their operations. For example:

- The **homalg** subpackage **ResidueClassRingForHomalg** (→ Appendix D) defines the classes of residue class rings, residue class ring elements, and matrices over residue class rings. Such a matrix is defined by a matrix over the ambient ring which is nevertheless interpreted modulo the ring relations, i.e. modulo the generators of the defining ideal.
- The package **GaussForHomalg** extends the class of internal matrices enabling it to wrap sparse matrices provided by the package **Gauss**. **GaussForHomalg** delegates the essential part of the matrix creation and all matrix operations to **Gauss**.
- The package **HomalgToCAS** defines the classes of so-called external rings and matrices and the package **RingsForHomalg** delegates the essential part of the matrix creation and all matrix operations to external computer algebra systems like **Singular**, **Macaulay2**, **Sage**, **Macaulay2**,

MAGMA, Maple, ... . The package `homalg` accesses external matrices via pointers. The pointer of an external matrix is simply its name in the external system. `HomalgToCAS` chooses these names.

- The package `LocalizeRingForHomalg` defines the classes of local(ized) rings, local ring elements, and local matrices. A `homalg` local matrix contains a `homalg` matrix as a numerator and an element of the global ring as a denominator.

The matrix operations are divided into two classes called “Tools” and “Basic”. The “Tools” operations include addition, subtraction, multiplication, extracting certain rows or columns, stacking, and augmenting matrices (→ Appendix B). The “Basic” operations include the two basic operations in linear algebra needed to solve an inhomogeneous linear system  $XA = B$  with coefficients in a not necessarily commutative ring  $R$  (→ Appendix A):

- Effectively reducing  $B$  modulo  $A$ , i.e. effectively deciding if a row (or a set of rows)  $B$  lies in the  $R$ -span of the rows of the matrix  $A$ .
- Computing an  $R$ -generating set of row syzygies ( $=R$ -relations among the rows) of  $A$ , i.e. computing an  $R$ -generating set of the left kernel of  $A$ . This generating set is then given as the rows of a matrix  $Y$  and  $YA = 0$ .

The first operation is nothing but deciding the solvability of the inhomogeneous system  $XA = B$  and if solvable to compute a particular solution  $X$ , while the second is to compute an  $R$ -generating set for the homogeneous solution space, i.e. the solution space of the homogeneous system  $YA = 0$ . The above is of course also valid for the column convention.

### 1.1.3 The black box concept

Now we address the following concerns: Wouldn't the idea of using algorithms like the Gröbnerbasis algorithm(s) as a black box (→ 1.1.2) contradict the following facts?

- It is known that an efficient Gröbnerbasis algorithm depends on the ring  $R$  under consideration. For example the implementation of the algorithm depends on the ground ring (or field)  $k$ .
- Often enough highly specialized implementations are used to address specific types of linear systems of equations (occurring in specific homological problems) in order to increase the speed or reduce the space needed for the computations.

The following should clarify the above concerns.

- Since each ring comes with its own black box, the first point is automatically resolved.
- Allow the black box coming with each ring to contain the different available implementations and make them accessible to `homalg` via standardized names, independent of the computer algebra system used to perform computations.

## 1.2 This manual

Chapter 2 describes the installation of this package. The remaining chapters are each devoted to one of the `MatricesForHomalg` objects (→ 1.1.1) with its constructors, properties, attributes, and operations.

## Chapter 2

# Installation of the **MatricesForHomalg** Package

To install this package just extract the package's archive file to the GAP pkg directory.

By default the **MatricesForHomalg** package is not automatically loaded by GAP when it is installed. You must load the package with

```
LoadPackage( "MatricesForHomalg" );
```

before its functions become available.

Please, send me an e-mail if you have any questions, remarks, suggestions, etc. concerning this package. Also, I would be pleased to hear about applications of this package.

Mohamed Barakat



# Chapter 3

## Rings

### 3.1 Rings: Category and Representations

#### 3.1.1 IsHomalgRing

▷ IsHomalgRing( $R$ ) (Category)

**Returns:** true or false

The GAP category of homalg rings.

(It is a subcategory of the GAP categories IsStructureObject and IsHomalgRingOrModule.)

```
Code
DeclareCategory( "IsHomalgRing",
  IsStructureObject and
  IsRingWithOne and
  IsHomalgRingOrModule );
```

#### 3.1.2 IsPreHomalgRing

▷ IsPreHomalgRing( $R$ ) (Category)

**Returns:** true or false

The GAP category of pre homalg rings.

(It is a subcategory of the GAP category IsHomalgRing.)

These are rings with an incomplete homalgTable. They provide flexibility for developers to support a wider class of rings, as was necessary for the development of the LocalizeRingForHomalg package. They are not suited for direct usage.

```
Code
DeclareCategory( "IsPreHomalgRing",
  IsHomalgRing );
```

#### 3.1.3 IsHomalgRingElement

▷ IsHomalgRingElement( $r$ ) (Category)

**Returns:** true or false

The GAP category of elements of homalg rings which are not GAP4 built-in.

Code

```

DeclareCategory( "IsHomalgRingElement",
  IsExtAElement and
  IsExtLElement and
  IsExtRElement and
  IsAdditiveElementWithInverse and
  IsMultiplicativeElementWithInverse and
  IsAssociativeElement and
  IsAdditivelyCommutativeElement and
  ## all the above guarantees IsHomalgRingElement => IsRingElement (in GAP4)
  IsAttributeStoringRep );

```

### 3.1.4 IsHomalgInternalRingRep

▷ `IsHomalgInternalRingRep(R)` (Representation)

**Returns:** true or false

The internal representation of homalg rings.

(It is a representation of the GAP category `IsHomalgRing`.)

## 3.2 Rings: Constructors

This section describes how to construct rings for use with `MatricesForHomalg`, which exploit the GAP4-built-in abilities to perform the necessary ring operations. By this we also mean necessary matrix operations over such rings. For the purposes of `MatricesForHomalg` only the ring of integers is properly supported in GAP4. The GAP4 extension packages `Gauss` and `GaussForHomalg` extend these built-in abilities to operations with sparse matrices over the ring  $\mathbb{Z}/p^n$  for  $p$  prime and  $n$  positive.

If a ring  $R$  is supported in `MatricesForHomalg` any of its residue class rings  $R/I$  is supported as well, provided the ideal  $I$  of relations admits a finite set of generators as a left resp. right ideal ( $\rightarrow \setminus /$  (3.2.2)). This is immediate for commutative noetherian rings.

### 3.2.1 HomalgRingOfIntegers (constructor for the integers)

▷ `HomalgRingOfIntegers()` (function)

**Returns:** a homalg ring

▷ `HomalgRingOfIntegers(c)` (function)

**Returns:** a homalg ring

The no-argument form returns the ring of integers  $\mathbb{Z}$  for homalg.

The one-argument form accepts an integer  $c$  and returns the ring  $\mathbb{Z}/c$  for homalg:

- $c = 0$  defaults to  $\mathbb{Z}$
- if  $c$  is a prime power then the package `GaussForHomalg` is loaded (if it fails to load an error is issued)
- otherwise, the residue class ring constructor  $/ (\rightarrow \setminus /$  (3.2.2)) is invoked

The operation `SetRingProperties` is automatically invoked to set the ring properties.

If for some reason you don't want to use the `GaussForHomalg` package (maybe because you didn't install it), then use

`HomalgRingOfIntegers() / c;`  
 but note that the computations will then be considerably slower.

### 3.2.2 $\backslash/$ (constructor for residue class rings)

▷  $\backslash/(R, \text{ring\_rel})$  (operation)

**Returns:** a homalg ring

This is the homalg constructor for residue class rings  $R/I$ , where  $R$  is a homalg ring and  $I = \text{ring\_rel}$  is the ideal of relations generated by  $\text{ring\_rel}$ .  $\text{ring\_rel}$  might be:

- a set of ring relations of a left resp. right ideal
- a list of ring elements of  $R$
- a ring element of  $R$

For noncommutative rings: In the first case the set of ring relations should generate the ideal of relations  $I$  as left resp. right ideal, and their involutions should generate  $I$  as right resp. left ideal. If  $\text{ring\_rel}$  is not a set of relations, a *left* set of relations is constructed.

The operation `SetRingProperties` is automatically invoked to set the ring properties.

Example

```
gap> ZZ := HomalgRingOfIntegers( );
Z
gap> Display( ZZ );
<An internal ring>
gap> Z256 := ZZ / 2^8;
Z/( 256 )
gap> Display( Z256 );
<A residue class ring>
gap> Z2 := Z256 / 6;
Z/( 256, 6 )
gap> BasisOfRows( MatrixOfRelations( Z2 ) );
<An unevaluated non-zero 1 x 1 matrix over an internal ring>
gap> Z2;
Z/( 2 )
gap> Display( Z2 );
<A residue class ring>
```

## 3.3 Rings: Properties

The following properties are declared for homalg rings. Note that (apart from so-called true and immediate methods ( $\rightarrow$  C.1)) there are no methods installed for ring properties. This means that if the value of the ring property `Prop` is not set for a homalg ring  $R$ , then

`Prop( R );`

will cause an error. One can use the usual GAP4 mechanism to check if the value of the property is set or not

`HasProp( R );`

If you discover that a specific property `Prop` is missing for a certain homalg ring  $R$  you can it add using the usual GAP4 mechanism

```
SetProp( R, true );
```

or

```
SetProp( R, false );
```

Be very cautious with setting "missing" properties to homalg objects: If the value you set is mathematically wrong homalg will probably draw wrong conclusions and might return wrong results.

### 3.3.1 IsZero (for rings)

▷ IsZero( $R$ ) (property)

**Returns:** true or false

Check if the ring  $R$  is the zero ring, i.e., if  $\text{One}(R) = \text{Zero}(R)$ .

### 3.3.2 IsNonZeroRing (for rings)

▷ IsNonZeroRing( $R$ ) (property)

**Returns:** true or false

Check if the ring  $R$  is not the zero ring, i.e., if  $\text{One}(R)$  is different from  $\text{Zero}(R)$ .

### 3.3.3 ContainsAField

▷ ContainsAField( $R$ ) (property)

**Returns:** true or false

$R$  is a ring for homalg.

### 3.3.4 IsRationalsForHomalg

▷ IsRationalsForHomalg( $R$ ) (property)

**Returns:** true or false

$R$  is a ring for homalg.

### 3.3.5 IsFieldForHomalg

▷ IsFieldForHomalg( $R$ ) (property)

**Returns:** true or false

$R$  is a ring for homalg.

### 3.3.6 IsDivisionRingForHomalg

▷ IsDivisionRingForHomalg( $R$ ) (property)

**Returns:** true or false

$R$  is a ring for homalg.

### 3.3.7 IsIntegersForHomalg

▷ IsIntegersForHomalg( $R$ ) (property)

**Returns:** true or false

$R$  is a ring for homalg.

### 3.3.8 IsResidueClassRingOfTheIntegers

- ▷ `IsResidueClassRingOfTheIntegers( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.9 IsBezoutRing

- ▷ `IsBezoutRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.10 IsIntegrallyClosedDomain

- ▷ `IsIntegrallyClosedDomain( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.11 IsUniqueFactorizationDomain

- ▷ `IsUniqueFactorizationDomain( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.12 IsKaplanskyHermite

- ▷ `IsKaplanskyHermite( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.13 IsDedekindDomain

- ▷ `IsDedekindDomain( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.14 IsDiscreteValuationRing

- ▷ `IsDiscreteValuationRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.15 IsFreePolynomialRing

- ▷ `IsFreePolynomialRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.16 IsWeylRing**

- ▷ `IsWeylRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.17 IsLocalizedWeylRing**

- ▷ `IsLocalizedWeylRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.18 IsGlobalDimensionFinite**

- ▷ `IsGlobalDimensionFinite( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.19 IsLeftGlobalDimensionFinite**

- ▷ `IsLeftGlobalDimensionFinite( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.20 IsRightGlobalDimensionFinite**

- ▷ `IsRightGlobalDimensionFinite( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.21 HasInvariantBasisProperty**

- ▷ `HasInvariantBasisProperty( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.22 IsLocal**

- ▷ `IsLocal( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.23 IsSemiLocalRing**

- ▷ `IsSemiLocalRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.24 IsIntegralDomain**

- ▷ `IsIntegralDomain( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.25 IsHereditary**

- ▷ `IsHereditary( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.26 IsLeftHereditary**

- ▷ `IsLeftHereditary( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.27 IsRightHereditary**

- ▷ `IsRightHereditary( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.28 IsHermite**

- ▷ `IsHermite( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.29 IsLeftHermite**

- ▷ `IsLeftHermite( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.30 IsRightHermite**

- ▷ `IsRightHermite( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.31 IsNoetherian**

- ▷ `IsNoetherian( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.32 IsLeftNoetherian**

- ▷ `IsLeftNoetherian( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.33 IsRightNoetherian**

- ▷ `IsRightNoetherian( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.34 IsCohenMacaulay**

- ▷ `IsCohenMacaulay( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.35 IsGorenstein**

- ▷ `IsGorenstein( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.36 IsKoszul**

- ▷ `IsKoszul( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.37 IsArtinian (for rings)**

- ▷ `IsArtinian( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.38 IsLeftArtinian**

- ▷ `IsLeftArtinian( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.39 IsRightArtinian**

- ▷ `IsRightArtinian( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.



**3.3.40 IsOreDomain**

- ▷ `IsOreDomain( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.41 IsLeftOreDomain**

- ▷ `IsLeftOreDomain( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.42 IsRightOreDomain**

- ▷ `IsRightOreDomain( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.43 IsPrincipalIdealRing**

- ▷ `IsPrincipalIdealRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.44 IsLeftPrincipalIdealRing**

- ▷ `IsLeftPrincipalIdealRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.45 IsRightPrincipalIdealRing**

- ▷ `IsRightPrincipalIdealRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.46 IsRegular**

- ▷ `IsRegular( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

**3.3.47 IsFiniteFreePresentationRing**

- ▷ `IsFiniteFreePresentationRing( $R$ )` (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.48 IsLeftFiniteFreePresentationRing

- ▷ IsLeftFiniteFreePresentationRing( $R$ ) (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.49 IsRightFiniteFreePresentationRing

- ▷ IsRightFiniteFreePresentationRing( $R$ ) (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.50 IsSimpleRing

- ▷ IsSimpleRing( $R$ ) (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.51 IsSemiSimpleRing

- ▷ IsSemiSimpleRing( $R$ ) (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.52 IsSuperCommutative

- ▷ IsSuperCommutative( $R$ ) (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.53 BasisAlgorithmRespectsPrincipalIdeals

- ▷ BasisAlgorithmRespectsPrincipalIdeals( $R$ ) (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.54 AreUnitsCentral

- ▷ AreUnitsCentral( $R$ ) (property)  
**Returns:** true or false  
 $R$  is a ring for homalg.

### 3.3.55 IsMinusOne

- ▷ IsMinusOne( $r$ ) (property)  
**Returns:** true or false  
 Check if the ring element  $r$  is the additive inverse of one.

### 3.3.56 IsMonic (for homalg ring elements)

- ▷ `IsMonic(r)` (property)  
**Returns:** true or false  
 Check if the homalg ring element  $r$  is monic.

### 3.3.57 IsMonicUptoUnit (for homalg ring elements)

- ▷ `IsMonicUptoUnit(r)` (property)  
**Returns:** true or false  
 Check if leading coefficient of the homalg ring element  $r$  is a unit.

### 3.3.58 IsLeftRegular (for homalg ring elements)

- ▷ `IsLeftRegular(r)` (property)  
**Returns:** true or false  
 Check if the homalg ring element  $r$  is left regular.

### 3.3.59 IsRightRegular (for homalg ring elements)

- ▷ `IsRightRegular(r)` (property)  
**Returns:** true or false  
 Check if the homalg ring element  $r$  is right regular.

### 3.3.60 IsRegular (for homalg ring elements)

- ▷ `IsRegular(r)` (property)  
**Returns:** true or false  
 Check if the homalg ring element  $r$  is regular, i.e. left and right regular.

## 3.4 Rings: Attributes

### 3.4.1 Inverse (for homalg ring elements)

- ▷ `Inverse(r)` (attribute)  
**Returns:** a homalg ring element or fail  
 The inverse of the homalg ring element  $r$ .

Example

```
gap> ZZ := HomalgRingOfIntegers( );
gap> R := ZZ / 2^8;
Z/( 256 )
gap> r := (1/3*One(R)+1/5)+3/7;
|[ 157 ]|
gap> 1 / r;      ## = r^-1;
|[ 181 ]|
gap> s := (1/3*One(R)+2/5)+3/7;
|[ 106 ]|
gap> s^(-1);
fail
```

### 3.4.2 homalgTable

▷ `homalgTable( $R$ )` (attribute)

**Returns:** a homalg table

The homalg table of  $R$  is a ring dictionary, i.e. the translator between homalg and the (specific implementation of the) ring.

Every homalg ring has a homalg table.

### 3.4.3 RingElementConstructor

▷ `RingElementConstructor( $R$ )` (attribute)

**Returns:** a function

The constructor of ring elements in the homalg ring  $R$ .

### 3.4.4 TypeOfHomalgMatrix

▷ `TypeOfHomalgMatrix( $R$ )` (attribute)

**Returns:** a type

The GAP4-type of homalg matrices over the homalg ring  $R$ .

### 3.4.5 ConstructorForHomalgMatrices

▷ `ConstructorForHomalgMatrices( $R$ )` (attribute)

**Returns:** a type

The constructor for homalg matrices over the homalg ring  $R$ .

### 3.4.6 Zero (for homalg rings)

▷ `Zero( $R$ )` (attribute)

**Returns:** a homalg ring element

The zero of the homalg ring  $R$ .

### 3.4.7 One (for homalg rings)

▷ `One( $R$ )` (attribute)

**Returns:** a homalg ring element

The one of the homalg ring  $R$ .

### 3.4.8 MinusOne

▷ `MinusOne( $R$ )` (attribute)

**Returns:** a homalg ring element

The minus one of the homalg ring  $R$ .

### 3.4.9 ProductOfIndeterminates

▷ `ProductOfIndeterminates( $R$ )` (attribute)

**Returns:** a homalg ring element

The product of indeterminates of the homalg ring  $R$ .

### 3.4.10 RationalParameters

- ▷ `RationalParameters(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of rational parameters of the homalg ring  $R$ .

### 3.4.11 IndeterminatesOfPolynomialRing

- ▷ `IndeterminatesOfPolynomialRing(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of indeterminates of the homalg polynomial ring  $R$ .

### 3.4.12 RelativeIndeterminatesOfPolynomialRing

- ▷ `RelativeIndeterminatesOfPolynomialRing(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of relative indeterminates of the homalg polynomial ring  $R$ .

### 3.4.13 IndeterminateCoordinatesOfRingOfDerivations

- ▷ `IndeterminateCoordinatesOfRingOfDerivations(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of indeterminate coordinates of the homalg Weyl ring  $R$ .

### 3.4.14 RelativeIndeterminateCoordinatesOfRingOfDerivations

- ▷ `RelativeIndeterminateCoordinatesOfRingOfDerivations(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of relative indeterminate coordinates of the homalg Weyl ring  $R$ .

### 3.4.15 IndeterminateDerivationsOfRingOfDerivations

- ▷ `IndeterminateDerivationsOfRingOfDerivations(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of indeterminate derivations of the homalg Weyl ring  $R$ .

### 3.4.16 RelativeIndeterminateDerivationsOfRingOfDerivations

- ▷ `RelativeIndeterminateDerivationsOfRingOfDerivations(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of relative indeterminate derivations of the homalg Weyl ring  $R$ .

### 3.4.17 IndeterminateAntiCommutingVariablesOfExteriorRing

- ▷ `IndeterminateAntiCommutingVariablesOfExteriorRing(R)` (attribute)  
**Returns:** a list of homalg ring elements  
 The list of anti-commuting indeterminates of the homalg exterior ring  $R$ .

### 3.4.18 RelativeIndeterminateAntiCommutingVariablesOfExteriorRing

▷ `RelativeIndeterminateAntiCommutingVariablesOfExteriorRing(R)` (attribute)

**Returns:** a list of homalg ring elements

The list of anti-commuting relative indeterminates of the homalg exterior ring  $R$ .

### 3.4.19 IndeterminatesOfExteriorRing

▷ `IndeterminatesOfExteriorRing(R)` (attribute)

**Returns:** a list of homalg ring elements

The list of all indeterminates (commuting and anti-commuting) of the homalg exterior ring  $R$ .

### 3.4.20 CoefficientsRing

▷ `CoefficientsRing(R)` (attribute)

**Returns:** a homalg ring

The ring of coefficients of the homalg ring  $R$ .

### 3.4.21 KrullDimension

▷ `KrullDimension(R)` (attribute)

**Returns:** a non-negative integer

The Krull dimension of the commutative homalg ring  $R$ .

### 3.4.22 LeftGlobalDimension

▷ `LeftGlobalDimension(R)` (attribute)

**Returns:** a non-negative integer

The left global dimension of the homalg ring  $R$ .

### 3.4.23 RightGlobalDimension

▷ `RightGlobalDimension(R)` (attribute)

**Returns:** a non-negative integer

The right global dimension of the homalg ring  $R$ .

### 3.4.24 GlobalDimension

▷ `GlobalDimension(R)` (attribute)

**Returns:** a non-negative integer

The global dimension of the homalg ring  $R$ . The global dimension is defined, only if the left and right global dimensions coincide.

### 3.4.25 GeneralLinearRank

▷ `GeneralLinearRank(R)` (attribute)

**Returns:** a non-negative integer

The general linear rank of the homalg ring  $R$  ([MR01], 11.1.14).

### 3.4.26 ElementaryRank

▷ `ElementaryRank( $R$ )` (attribute)

**Returns:** a non-negative integer

The elementary rank of the homalg ring  $R$  ([MR01], 11.3.10).

### 3.4.27 StableRank

▷ `StableRank( $R$ )` (attribute)

**Returns:** a non-negative integer

The stable rank of the homalg ring  $R$  ([MR01], 11.3.4).

### 3.4.28 AssociatedGradedRing

▷ `AssociatedGradedRing( $R$ )` (attribute)

**Returns:** a homalg ring

The graded ring associated to the filtered ring  $R$ .

## 3.5 Rings: Operations and Functions

## Chapter 4

# Ring Maps

A `homalg` ring map is a data structure for maps between finitely generated rings. `homalg` more or less provides the basic declarations and installs the generic methods for ring maps, but it is up to other high level packages to install methods applicable to specific rings. For example, the package `Sheaves` provides methods for ring maps of (finitely generated) affine rings.

### 4.1 Ring Maps: Category and Representations

#### 4.1.1 `IsHomalgRingMap`

▷ `IsHomalgRingMap(phi)` (Category)  
**Returns:** true or false  
The GAP category of ring maps.

#### 4.1.2 `IsHomalgRingSelfMap`

▷ `IsHomalgRingSelfMap(phi)` (Category)  
**Returns:** true or false  
The GAP category of ring self-maps.  
(It is a subcategory of the GAP category `IsHomalgRingMap`.)

#### 4.1.3 `IsHomalgRingMapRep`

▷ `IsHomalgRingMapRep(phi)` (Representation)  
**Returns:** true or false  
The GAP representation of `homalg` ring maps.  
(It is a representation of the GAP category `IsHomalgRingMap` (4.1.1).)

### 4.2 Ring Maps: Constructors

#### 4.2.1 `RingMap` (constructor for ring maps)

▷ `RingMap(images, S, T)` (operation)  
**Returns:** a `homalg` ring map



This constructor returns a ring map (homomorphism) of finitely generated rings/algebras. It is represented by the images *images* of the set of generators of the source `homalg` ring  $S$  in terms of the generators of the target ring  $T$  ( $\rightarrow$  3.2). Unless the source ring is free *and* given on free ring/algebra generators the returned map will cautiously be indicated using parenthesis: “homomorphism”. If source and target are identical objects, and only then, the ring map is created as a selfmap.

## 4.3 Ring Maps: Properties

### 4.3.1 IsMorphism (for ring maps)

- ▷ `IsMorphism(phi)` (property)  
**Returns:** true or false  
 Check if *phi* is a well-defined map, i.e. independent of all involved presentations.

### 4.3.2 IsIdentityMorphism (for ring maps)

- ▷ `IsIdentityMorphism(phi)` (property)  
**Returns:** true or false  
 Check if the `homalg` ring map *phi* is the identity morphism.

### 4.3.3 IsMonomorphism (for ring maps)

- ▷ `IsMonomorphism(phi)` (property)  
**Returns:** true or false  
 Check if the `homalg` ring map *phi* is a monomorphism.

### 4.3.4 IsEpimorphism (for ring maps)

- ▷ `IsEpimorphism(phi)` (property)  
**Returns:** true or false  
 Check if the `homalg` ring map *phi* is an epimorphism.

### 4.3.5 IsIsomorphism (for ring maps)

- ▷ `IsIsomorphism(phi)` (property)  
**Returns:** true or false  
 Check if the `homalg` ring map *phi* is an isomorphism.

### 4.3.6 IsAutomorphism (for ring maps)

- ▷ `IsAutomorphism(phi)` (property)  
**Returns:** true or false  
 Check if the `homalg` ring map *phi* is an automorphism.

## 4.4 Ring Maps: Attributes

### 4.4.1 Source (for ring maps)

- ▷ `Source(phi)` (attribute)  
**Returns:** a homalg ring  
 The source of the homalg ring map *phi*.

### 4.4.2 Range (for ring maps)

- ▷ `Range(phi)` (attribute)  
**Returns:** a homalg ring  
 The target (range) of the homalg ring map *phi*.

### 4.4.3 DegreeOfMorphism (for ring maps)

- ▷ `DegreeOfMorphism(phi)` (attribute)  
**Returns:** an integer  
 The degree of the morphism *phi* of graded rings.  
 (no method installed)

### 4.4.4 CoordinateRingOfGraph (for ring maps)

- ▷ `CoordinateRingOfGraph(phi)` (attribute)  
**Returns:** a homalg ring  
 The coordinate ring of the graph of the ring map *phi*.

## 4.5 Ring Maps: Operations and Functions

## Chapter 5

# Matrices

### 5.1 Matrices: Category and Representations

#### 5.1.1 IsHomalgMatrix

- ▷ `IsHomalgMatrix( $A$ )` (Category)  
**Returns:** true or false  
The GAP category of homalg matrices.

Code

```
DeclareCategory( "IsHomalgMatrix",  
    IsMatrixObj and  
    IsAttributeStoringRep );
```

#### 5.1.2 IsHomalgInternalMatrixRep

- ▷ `IsHomalgInternalMatrixRep( $A$ )` (Representation)  
**Returns:** true or false  
The internal representation of homalg matrices.  
(It is a representation of the GAP category `IsHomalgMatrix` (5.1.1).)

### 5.2 Matrices: Constructors

#### 5.2.1 HomalgInitialMatrix (constructor for initial matrices filled with zeros)

- ▷ `HomalgInitialMatrix( $m$ ,  $n$ ,  $R$ )` (function)  
**Returns:** a homalg matrix  
A mutable unevaluated initial  $m \times n$  homalg matrix filled with zeros over the homalg ring  $R$ . This construction is useful in case one wants to define a matrix by assigning its nonzero entries. The property `IsInitialMatrix` (5.3.26) is reset as soon as the matrix is evaluated. New computed properties or attributes of the matrix won't be cached, until the matrix is explicitly made immutable using ( $\rightarrow$  `MakeImmutable` (**Reference: MakeImmutable**)).

Example

```
gap> ZZ := HomalgRingOfIntegers( );  
Z  
gap> z := HomalgInitialMatrix( 2, 3, ZZ );  
<An initial 2 x 3 matrix over an internal ring>
```

```
gap> HasIsZero( z );
false
gap> IsZero( z );
true
gap> z;
<A 2 x 3 mutable matrix over an internal ring>
gap> HasIsZero( z );
false
```

Example

```
gap> n := HomalgInitialMatrix( 2, 3, ZZ );
<An initial 2 x 3 matrix over an internal ring>
gap> n[ 1, 1 ] := "1";;
gap> n[ 2, 3 ] := "1";;
gap> MakeImmutable( n );
<A 2 x 3 matrix over an internal ring>
gap> Display( n );
[ [ 1, 0, 0 ],
  [ 0, 0, 1 ] ]
gap> IsZero( n );
false
gap> n;
<A non-zero 2 x 3 matrix over an internal ring>
```

## 5.2.2 HomalgInitialIdentityMatrix (constructor for initial quadratic matrices with ones on the diagonal)

▷ HomalgInitialIdentityMatrix( $m$ ,  $R$ ) (function)

**Returns:** a homalg matrix

A mutable unevaluated initial  $m \times m$  homalg quadratic matrix with ones on the diagonal over the homalg ring  $R$ . This construction is useful in case one wants to define an elementary matrix by assigning its off-diagonal nonzero entries. The property `IsInitialIdentityMatrix` (5.3.27) is reset as soon as the matrix is evaluated. New computed properties or attributes of the matrix won't be cached, until the matrix is explicitly made immutable using ( $\rightarrow$  `MakeImmutable` (**Reference: MakeImmutable**)).

Example

```
gap> ZZ := HomalgRingOfIntegers( );
Z
gap> id := HomalgInitialIdentityMatrix( 3, ZZ );
<An initial identity 3 x 3 matrix over an internal ring>
gap> HasIsOne( id );
false
gap> IsOne( id );
true
gap> id;
<A 3 x 3 mutable matrix over an internal ring>
gap> HasIsOne( id );
false
```

Example

```
gap> e := HomalgInitialIdentityMatrix( 3, ZZ );
<An initial identity 3 x 3 matrix over an internal ring>
```

```

gap> e[ 1, 2 ] := "1";;
gap> e[ 2, 1 ] := "-1";;
gap> MakeImmutable( e );
<A 3 x 3 matrix over an internal ring>
gap> Display( e );
[ [ 1, 1, 0 ],
  [ -1, 1, 0 ],
  [ 0, 0, 1 ] ]
gap> IsOne( e );
false
gap> e;
<A 3 x 3 matrix over an internal ring>

```

### 5.2.3 HomalgZeroMatrix (constructor for zero matrices)

▷ HomalgZeroMatrix( $m$ ,  $n$ ,  $R$ )

(function)

**Returns:** a homalg matrix

An immutable unevaluated  $m \times n$  homalg zero matrix over the homalg ring  $R$ .

Example

```

gap> ZZ := HomalgRingOfIntegers( );
Z
gap> z := HomalgZeroMatrix( 2, 3, ZZ );
<An unevaluated 2 x 3 zero matrix over an internal ring>
gap> Display( z );
[ [ 0, 0, 0 ],
  [ 0, 0, 0 ] ]
gap> z;
<A 2 x 3 zero matrix over an internal ring>

```

### 5.2.4 HomalgIdentityMatrix (constructor for identity matrices)

▷ HomalgIdentityMatrix( $m$ ,  $R$ )

(function)

**Returns:** a homalg matrix

An immutable unevaluated  $m \times m$  homalg identity matrix over the homalg ring  $R$ .

Example

```

gap> ZZ := HomalgRingOfIntegers( );
Z
gap> id := HomalgIdentityMatrix( 3, ZZ );
<An unevaluated 3 x 3 identity matrix over an internal ring>
gap> Display( id );
[ [ 1, 0, 0 ],
  [ 0, 1, 0 ],
  [ 0, 0, 1 ] ]
gap> id;
<A 3 x 3 identity matrix over an internal ring>

```

### 5.2.5 HomalgVoidMatrix (constructor for void matrices)

▷ HomalgVoidMatrix( $[m, ] [n, ] R$ )

(function)

**Returns:** a homalg matrix

A void  $m \times n$  homalg matrix.

### 5.2.6 HomalgMatrix (constructor for matrices using a listlist)

- ▷ HomalgMatrix(llist, R) (function)
- ▷ HomalgMatrix(list, m, n, R) (function)
- ▷ HomalgMatrix(str\_llist, R) (function)
- ▷ HomalgMatrix(str\_list, m, n, R) (function)

**Returns:** a homalg matrix

An immutable evaluated  $m \times n$  homalg matrix over the homalg ring  $R$ .

Example

```
gap> ZZ := HomalgRingOfIntegers( );
Z
gap> m := HomalgMatrix( [ [ 1, 2, 3 ], [ 4, 5, 6 ] ], ZZ );
<A 2 x 3 matrix over an internal ring>
gap> Display( m );
[ [ 1, 2, 3 ],
  [ 4, 5, 6 ] ]
```

Example

```
gap> m := HomalgMatrix( [ [ 1, 2, 3 ], [ 4, 5, 6 ] ], 2, 3, ZZ );
<A 2 x 3 matrix over an internal ring>
gap> Display( m );
[ [ 1, 2, 3 ],
  [ 4, 5, 6 ] ]
```

Example

```
gap> m := HomalgMatrix( [ 1, 2, 3, 4, 5, 6 ], 2, 3, ZZ );
<A 2 x 3 matrix over an internal ring>
gap> Display( m );
[ [ 1, 2, 3 ],
  [ 4, 5, 6 ] ]
```

Example

```
gap> m := HomalgMatrix( "[ [ 1, 2, 3 ], [ 4, 5, 6 ] ]", ZZ );
<A 2 x 3 matrix over an internal ring>
gap> Display( m );
[ [ 1, 2, 3 ],
  [ 4, 5, 6 ] ]
```

Example

```
gap> m := HomalgMatrix( "[ [ 1, 2, 3 ], [ 4, 5, 6 ] ]", 2, 3, ZZ );
<A 2 x 3 matrix over an internal ring>
gap> Display( m );
[ [ 1, 2, 3 ],
  [ 4, 5, 6 ] ]
```

It is nevertheless recommended to use the following form to create homalg matrices. This form can also be used to define external matrices. Since whitespaces (→ **Reference: Whitespaces**) are ignored, they can be used as optical delimiters:

Example

```
gap> m := HomalgMatrix( "[ 1, 2, 3, 4, 5, 6 ]", 2, 3, ZZ );
<A 2 x 3 matrix over an internal ring>
```

```
gap> Display( m );
[ [ 1, 2, 3 ],
  [ 4, 5, 6 ] ]
```

One can split the input string over several lines using the backslash character '\' to end each line

Example

```
gap> m := HomalgMatrix( "[ \
> 1, 2, 3, \
> 4, 5, 6 \
> ]", 2, 3, ZZ );
<A 2 x 3 matrix over an internal ring>
gap> Display( m );
[ [ 1, 2, 3 ],
  [ 4, 5, 6 ] ]
```

### 5.2.7 HomalgDiagonalMatrix (constructor for diagonal matrices)

▷ HomalgDiagonalMatrix(*diag*, *R*)

(function)

**Returns:** a homalg matrix

An immutable unevaluated diagonal homalg matrix over the homalg ring *R*. The diagonal consists of the entries of the list *diag*.

Example

```
gap> ZZ := HomalgRingOfIntegers( );
Z
gap> d := HomalgDiagonalMatrix( [ 1, 2, 3 ], ZZ );
<An unevaluated diagonal 3 x 3 matrix over an internal ring>
gap> Display( d );
[ [ 1, 0, 0 ],
  [ 0, 2, 0 ],
  [ 0, 0, 3 ] ]
gap> d;
<A diagonal 3 x 3 matrix over an internal ring>
```

### 5.2.8 \\* (copy a matrix over a different ring)

▷ \\*(*R*, *mat*)

(operation)

▷ \\*(*mat*, *R*)

(operation)

**Returns:** a homalg matrix

An immutable evaluated homalg matrix over the homalg ring *R* having the same entries as the matrix *mat*. Syntax: *R* \* *mat* or *mat* \* *R*

Example

```
gap> ZZ := HomalgRingOfIntegers( );
Z
gap> Z4 := ZZ / 4;
Z/( 4 )
gap> Display( Z4 );
<A residue class ring>
gap> d := HomalgDiagonalMatrix( [ 2 .. 4 ], ZZ );
<An unevaluated diagonal 3 x 3 matrix over an internal ring>
gap> d2 := Z4 * d; ## or d2 := d * Z4;
```

```

<A 3 x 3 matrix over a residue class ring>
gap> Display( d2 );
[ [ 2, 0, 0 ],
  [ 0, 3, 0 ],
  [ 0, 0, 4 ] ]

modulo [ 4 ]
gap> d;
<A diagonal 3 x 3 matrix over an internal ring>
gap> ZeroRows( d );
[ ]
gap> ZeroRows( d2 );
[ 3 ]
gap> d;
<A non-zero diagonal 3 x 3 matrix over an internal ring>
gap> d2;
<A non-zero 3 x 3 matrix over a residue class ring>

```

## 5.3 Matrices: Properties

### 5.3.1 IsZero (for matrices)

▷ IsZero(*A*) (property)

**Returns:** true or false

Check if the homalg matrix *A* is a zero matrix, taking possible ring relations into account.

(for the installed standard method see IsZeroMatrix (B.1.20))

Example

```

gap> ZZ := HomalgRingOfIntegers( );
Z
gap> A := HomalgMatrix( "[ 2 ]", ZZ );
<A 1 x 1 matrix over an internal ring>
gap> Z2 := ZZ / 2;
Z/( 2 )
gap> A := Z2 * A;
<A 1 x 1 matrix over a residue class ring>
gap> Display( A );
[ [ 2 ] ]

modulo [ 2 ]
gap> IsZero( A );
true

```

### 5.3.2 IsOne

▷ IsOne(*A*) (property)

**Returns:** true or false

Check if the homalg matrix *A* is an identity matrix, taking possible ring relations into account.

(for the installed standard method see IsIdentityMatrix (B.2.2))



### 5.3.3 IsUnitFree

- ▷ `IsUnitFree( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.4 IsPermutationMatrix

- ▷ `IsPermutationMatrix( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.5 IsSpecialSubidentityMatrix

- ▷ `IsSpecialSubidentityMatrix( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.6 IsSubidentityMatrix

- ▷ `IsSubidentityMatrix( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.7 IsLeftRegular

- ▷ `IsLeftRegular( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.8 IsRightRegular

- ▷ `IsRightRegular( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.9 IsInvertibleMatrix

- ▷ `IsInvertibleMatrix( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.10 IsLeftInvertibleMatrix

- ▷ `IsLeftInvertibleMatrix( $A$ )` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.11 IsRightInvertibleMatrix

- ▷ `IsRightInvertibleMatrix(A)` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.12 IsEmptyMatrix

- ▷ `IsEmptyMatrix(A)` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.13 IsDiagonalMatrix

- ▷ `IsDiagonalMatrix(A)` (property)  
**Returns:** true or false  
Check if the homalg matrix  $A$  is a diagonal matrix, taking possible ring relations into account.  
(for the installed standard method see `IsDiagonalMatrix` ([B.2.3](#)))

### 5.3.14 IsScalarlMatrix

- ▷ `IsScalarlMatrix(A)` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.15 IsUpperTriangularMatrix

- ▷ `IsUpperTriangularMatrix(A)` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.16 IsLowerTriangularMatrix

- ▷ `IsLowerTriangularMatrix(A)` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.17 IsStrictUpperTriangularMatrix

- ▷ `IsStrictUpperTriangularMatrix(A)` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.18 IsStrictLowerTriangularMatrix

- ▷ `IsStrictLowerTriangularMatrix(A)` (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.19 IsUpperStairCaseMatrix**

- ▷ IsUpperStairCaseMatrix( $A$ ) (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.20 IsLowerStairCaseMatrix**

- ▷ IsLowerStairCaseMatrix( $A$ ) (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.21 IsTriangularMatrix**

- ▷ IsTriangularMatrix( $A$ ) (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.22 IsBasisOfRowsMatrix**

- ▷ IsBasisOfRowsMatrix( $A$ ) (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.23 IsBasisOfColumnsMatrix**

- ▷ IsBasisOfColumnsMatrix( $A$ ) (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.24 IsReducedBasisOfRowsMatrix**

- ▷ IsReducedBasisOfRowsMatrix( $A$ ) (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.25 IsReducedBasisOfColumnsMatrix**

- ▷ IsReducedBasisOfColumnsMatrix( $A$ ) (property)  
**Returns:** true or false  
 $A$  is a homalg matrix.

**5.3.26 IsInitialMatrix**

- ▷ IsInitialMatrix( $A$ ) (filter)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.27 IsInitialIdentityMatrix

- ▷ `IsInitialIdentityMatrix(A)` (filter)  
**Returns:** true or false  
 $A$  is a homalg matrix.

### 5.3.28 IsVoidMatrix

- ▷ `IsVoidMatrix(A)` (filter)  
**Returns:** true or false  
 $A$  is a homalg matrix.

## 5.4 Matrices: Attributes

### 5.4.1 NrRows

- ▷ `NrRows(A)` (attribute)  
**Returns:** a nonnegative integer  
 The number of rows of the matrix  $A$ .  
 (for the installed standard method see `NrRows` (B.1.21))

### 5.4.2 NrColumns

- ▷ `NrColumns(A)` (attribute)  
**Returns:** a nonnegative integer  
 The number of columns of the matrix  $A$ .  
 (for the installed standard method see `NrColumns` (B.1.22))

### 5.4.3 DeterminantMat

- ▷ `DeterminantMat(A)` (attribute)  
**Returns:** a ring element  
 The determinant of the quadratic matrix  $A$ .  
 You can invoke it with `Determinant(A)`.  
 (for the installed standard method see `Determinant` (B.1.23))

### 5.4.4 ZeroRows

- ▷ `ZeroRows(A)` (attribute)  
**Returns:** a (possibly empty) list of positive integers  
 The list of zero rows of the matrix  $A$ .  
 (for the installed standard method see `ZeroRows` (B.2.4))

### 5.4.5 ZeroColumns

- ▷ `ZeroColumns(A)` (attribute)  
**Returns:** a (possibly empty) list of positive integers  
 The list of zero columns of the matrix  $A$ .

(for the installed standard method see `ZeroColumns` (B.2.5))

#### 5.4.6 NonZeroRows

- ▷ `NonZeroRows(A)` (attribute)  
**Returns:** a (possibly empty) list of positive integers  
 The list of nonzero rows of the matrix  $A$ .

#### 5.4.7 NonZeroColumns

- ▷ `NonZeroColumns(A)` (attribute)  
**Returns:** a (possibly empty) list of positive integers  
 The list of nonzero columns of the matrix  $A$ .

#### 5.4.8 PositionOfFirstNonZeroEntryPerRow

- ▷ `PositionOfFirstNonZeroEntryPerRow(A)` (attribute)  
**Returns:** a list of nonnegative integers  
 The list of positions of the first nonzero entry per row of the matrix  $A$ , else zero.

#### 5.4.9 PositionOfFirstNonZeroEntryPerColumn

- ▷ `PositionOfFirstNonZeroEntryPerColumn(A)` (attribute)  
**Returns:** a list of nonnegative integers  
 The list of positions of the first nonzero entry per column of the matrix  $A$ , else zero.

#### 5.4.10 RowRankOfMatrix

- ▷ `RowRankOfMatrix(A)` (attribute)  
**Returns:** a nonnegative integer  
 The row rank of the matrix  $A$ .

#### 5.4.11 ColumnRankOfMatrix

- ▷ `ColumnRankOfMatrix(A)` (attribute)  
**Returns:** a nonnegative integer  
 The column rank of the matrix  $A$ .

#### 5.4.12 LeftInverse

- ▷ `LeftInverse(M)` (attribute)  
**Returns:** a homalg matrix  
 A left inverse  $C$  of the matrix  $M$ . If no left inverse exists then false is returned. (→ `RightDivide` (5.5.47))  
 (for the installed standard method see `LeftInverse` (5.5.2))

### 5.4.13 RightInverse

- ▷ `RightInverse(M)` (attribute)  
**Returns:** a homalg matrix  
A right inverse  $C$  of the matrix  $M$ . If no right inverse exists then false is returned. ( $\rightarrow$  `LeftDivide` (5.5.48))  
(for the installed standard method see `RightInverse` (5.5.3))

### 5.4.14 CoefficientsOfUnreducedNumeratorOfHilbertPoincareSeries

- ▷ `CoefficientsOfUnreducedNumeratorOfHilbertPoincareSeries(A)` (attribute)  
**Returns:** a list of integers  
 $A$  is a homalg matrix (row convention).

### 5.4.15 CoefficientsOfNumeratorOfHilbertPoincareSeries

- ▷ `CoefficientsOfNumeratorOfHilbertPoincareSeries(A)` (attribute)  
**Returns:** a list of integers  
 $A$  is a homalg matrix (row convention).

### 5.4.16 UnreducedNumeratorOfHilbertPoincareSeries

- ▷ `UnreducedNumeratorOfHilbertPoincareSeries(A)` (attribute)  
**Returns:** a univariate polynomial with rational coefficients  
 $A$  is a homalg matrix (row convention).

### 5.4.17 NumeratorOfHilbertPoincareSeries

- ▷ `NumeratorOfHilbertPoincareSeries(A)` (attribute)  
**Returns:** a univariate polynomial with rational coefficients  
 $A$  is a homalg matrix (row convention).

### 5.4.18 HilbertPoincareSeries

- ▷ `HilbertPoincareSeries(A)` (attribute)  
**Returns:** a univariate rational function with rational coefficients  
 $A$  is a homalg matrix (row convention).

### 5.4.19 HilbertPolynomial

- ▷ `HilbertPolynomial(A)` (attribute)  
**Returns:** a univariate polynomial with rational coefficients  
 $A$  is a homalg matrix (row convention).

### 5.4.20 AffineDimension

- ▷ `AffineDimension(A)` (attribute)  
**Returns:** an integer  
 $A$  is a homalg matrix (row convention).

### 5.4.21 AffineDegree

- ▷ `AffineDegree( $A$ )` (attribute)  
**Returns:** a nonnegative integer  
 $A$  is a homalg matrix (row convention).

### 5.4.22 ProjectiveDegree

- ▷ `ProjectiveDegree( $A$ )` (attribute)  
**Returns:** a nonnegative integer  
 $A$  is a homalg matrix (row convention).

### 5.4.23 ConstantTermOfHilbertPolynomialn

- ▷ `ConstantTermOfHilbertPolynomialn( $A$ )` (attribute)  
**Returns:** an integer  
 $A$  is a homalg matrix (row convention).

### 5.4.24 MatrixOfSymbols

- ▷ `MatrixOfSymbols( $A$ )` (attribute)  
**Returns:** an integer  
 $A$  is a homalg matrix.

## 5.5 Matrices: Operations and Functions

### 5.5.1 HomalgRing (for matrices)

- ▷ `HomalgRing( $mat$ )` (operation)  
**Returns:** a homalg ring  
The homalg ring of the homalg matrix  $mat$ .

Example

```
gap> ZZ := HomalgRingOfIntegers( );
Z
gap> d := HomalgDiagonalMatrix( [ 2 .. 4 ], ZZ );
<An unevaluated diagonal 3 x 3 matrix over an internal ring>
gap> R := HomalgRing( d );
Z
gap> IsIdenticalObj( R, ZZ );
true
```

### 5.5.2 LeftInverse (for matrices)

- ▷ `LeftInverse( $RI$ )` (method)  
**Returns:** a homalg matrix or fail  
The left inverse of the matrix  $RI$ . The lazy version of this operation is `LeftInverseLazy` (5.5.4).  
( $\rightarrow$  `RightDivide` (5.5.47))

Code

```

InstallMethod( LeftInverse,
              "for homalg matrices",
              [ IsHomalgMatrix ],

function( RI )
  local Id, LI;

  Id := HomalgIdentityMatrix( NrColumns( RI ), HomalgRing( RI ) );

  LI := RightDivide( Id, RI );          ## ( cf. [BR08, Subsection 3.1.3] )

  ## CAUTION: for the following SetXXX RightDivide is assumed
  ## NOT to be lazy evaluated!!!

  SetIsLeftInvertibleMatrix( RI, IsHomalgMatrix( LI ) );

  if IsBool( LI ) then
    return fail;
  fi;

  if HasIsInvertibleMatrix( RI ) and IsInvertibleMatrix( RI ) then
    SetIsInvertibleMatrix( LI, true );
  else
    SetIsRightInvertibleMatrix( LI, true );
  fi;

  SetRightInverse( LI, RI );

  SetNrColumns( LI, NrRows( RI ) );

  if NrRows( RI ) = NrColumns( RI ) then
    ## a left inverse of a ring element is unique
    ## and coincides with the right inverse
    SetRightInverse( RI, LI );
    SetLeftInverse( LI, RI );
  fi;

  return LI;

end );

```

### 5.5.3 RightInverse (for matrices)

▷ `RightInverse(LI)`

(method)

**Returns:** a homalg matrix or fail

The right inverse of the matrix  $LI$ . The lazy version of this operation is `RightInverseLazy` (5.5.5). ( $\rightarrow$  `LeftDivide` (5.5.48))

Code

```

InstallMethod( RightInverse,
              "for homalg matrices",
              [ IsHomalgMatrix ],

```



```

function( LI )
  local Id, RI;

  Id := HomalgIdentityMatrix( NrRows( LI ), HomalgRing( LI ) );

  RI := LeftDivide( LI, Id );      ## ( cf. [BR08, Subsection 3.1.3] )

  ## CAUTION: for the following SetXXX LeftDivide is assumed
  ## NOT to be lazy evaluated!!!

  SetIsRightInvertibleMatrix( LI, IsHomalgMatrix( RI ) );

  if IsBool( RI ) then
    return fail;
  fi;

  if HasIsInvertibleMatrix( LI ) and IsInvertibleMatrix( LI ) then
    SetIsInvertibleMatrix( RI, true );
  else
    SetIsLeftInvertibleMatrix( RI, true );
  fi;

  SetLeftInverse( RI, LI );

  SetNrRows( RI, NrColumns( LI ) );

  if NrRows( LI ) = NrColumns( LI ) then
    ## a right inverse of a ring element is unique
    ## and coincides with the left inverse
    SetLeftInverse( LI, RI );
    SetRightInverse( RI, LI );
  fi;

  return RI;

end );

```

#### 5.5.4 LeftInverseLazy (for matrices)

▷ LeftInverseLazy( $M$ ) (operation)

**Returns:** a homalg matrix

A lazy evaluated left inverse  $C$  of the matrix  $M$ . If no left inverse exists then Eval( $C$ ) will issue an error.

(for the installed standard method see Eval (C.4.5))

#### 5.5.5 RightInverseLazy (for matrices)

▷ RightInverseLazy( $M$ ) (operation)

**Returns:** a homalg matrix

A lazy evaluated right inverse  $C$  of the matrix  $M$ . If no right inverse exists then `Eval( C )` will issue an error.

(for the installed standard method see `Eval (C.4.6)`)

### 5.5.6 Involution (for matrices)

▷ `Involution(M)` (method)

**Returns:** a homalg matrix

The twisted transpose of the homalg matrix  $M$ . If the underlying ring is commutative, the twist is the identity.

(for the installed standard method see `Eval (C.4.7)`)

### 5.5.7 TransposedMatrix (for matrices)

▷ `TransposedMatrix(M)` (method)

**Returns:** a homalg matrix

The transpose of the homalg matrix  $M$ .

(for the installed standard method see `Eval (C.4.8)`)

### 5.5.8 CertainRows (for matrices)

▷ `CertainRows(M, plist)` (method)

**Returns:** a homalg matrix

The matrix of which the  $i$ -th row is the  $k$ -th row of the homalg matrix  $M$ , where  $k = \text{plist}[i]$ .

(for the installed standard method see `Eval (C.4.9)`)

### 5.5.9 CertainColumns (for matrices)

▷ `CertainColumns(M, plist)` (method)

**Returns:** a homalg matrix

The matrix of which the  $j$ -th column is the  $l$ -th column of the homalg matrix  $M$ , where  $l = \text{plist}[j]$ .

(for the installed standard method see `Eval (C.4.10)`)

### 5.5.10 UnionOfRows (for a list of homalg matrices)

▷ `UnionOfRows(L)` (function)

**Returns:** a homalg matrix

Stack the homalg matrices in the non-empty list  $L$ .

(for the installed standard method see `Eval (C.4.11)`)

### 5.5.11 UnionOfColumns (for a list of homalg matrices)

▷ `UnionOfColumns(L)` (function)

**Returns:** a homalg matrix

Augment the homalg matrices in the non-empty list  $L$ .

(for the installed standard method see `Eval (C.4.12)`)

### 5.5.12 DiagMat (for matrices)

- ▷ `DiagMat(list)` (method)  
**Returns:** a homalg matrix  
 Build the block diagonal matrix out of the homalg matrices listed in *list*. An error is issued if *list* is empty or if one of the arguments is not a homalg matrix.  
 (for the installed standard method see Eval (C.4.13))

### 5.5.13 KroneckerMat (for matrices)

- ▷ `KroneckerMat(A, B)` (method)  
**Returns:** a homalg matrix  
 The Kronecker (or tensor) product of the two homalg matrices *A* and *B*.  
 (for the installed standard method see Eval (C.4.14))

### 5.5.14 DualKroneckerMat (for matrices)

- ▷ `DualKroneckerMat(A, B)` (method)  
**Returns:** a homalg matrix  
 The dual Kronecker product of the two homalg matrices *A* and *B*.  
 (for the installed standard method see Eval (C.4.15))

### 5.5.15 \\* (for ring elements and matrices)

- ▷ `\*(a, A)` (method)  
**Returns:** a homalg matrix  
 The product of the ring element *a* with the homalg matrix *A* (enter: *a \* A*;  
 (for the installed standard method see Eval (C.4.16))

### 5.5.16 \+ (for matrices)

- ▷ `\+(A, B)` (method)  
**Returns:** a homalg matrix  
 The sum of the two homalg matrices *A* and *B* (enter: *A + B*;  
 (for the installed standard method see Eval (C.4.17))

### 5.5.17 \- (for matrices)

- ▷ `\-(A, B)` (method)  
**Returns:** a homalg matrix  
 The difference of the two homalg matrices *A* and *B* (enter: *A - B*;  
 (for the installed standard method see Eval (C.4.18))

### 5.5.18 \\* (for composable matrices)

- ▷ `\*(A, B)` (method)  
**Returns:** a homalg matrix  
 The matrix product of the two homalg matrices *A* and *B* (enter: *A \* B*;  
 (for the installed standard method see Eval (C.4.19))

### 5.5.19 $\backslash=$ (for matrices)

▷  $\backslash=(A, B)$  (operation)

**Returns:** true or false

Check if the homalg matrices  $A$  and  $B$  are equal (enter:  $A = B;$ ), taking possible ring relations into account.

(for the installed standard method see `AreEqualMatrices` (B.2.1))

Example

```
gap> ZZ := HomalgRingOfIntegers( );
Z
gap> A := HomalgMatrix( "[ 1 ]", ZZ );
<A 1 x 1 matrix over an internal ring>
gap> B := HomalgMatrix( "[ 3 ]", ZZ );
<A 1 x 1 matrix over an internal ring>
gap> Z2 := ZZ / 2;
Z/( 2 )
gap> A := Z2 * A;
<A 1 x 1 matrix over a residue class ring>
gap> B := Z2 * B;
<A 1 x 1 matrix over a residue class ring>
gap> Display( A );
[ [ 1 ] ]

modulo [ 2 ]
gap> Display( B );
[ [ 3 ] ]

modulo [ 2 ]
gap> A = B;
true
```

### 5.5.20 GetColumnIndependentUnitPositions (for matrices)

▷ `GetColumnIndependentUnitPositions(A, poslist)` (operation)

**Returns:** a (possibly empty) list of pairs of positive integers

The list of column independent unit position of the matrix  $A$ . We say that a unit  $A[i, k]$  is column independent from the unit  $A[l, j]$  if  $i > l$  and  $A[l, k] = 0$ . The rows are scanned from top to bottom and within each row the columns are scanned from right to left searching for new units, column independent from the preceding ones. If  $A[i, k]$  is a new column independent unit then  $[i, k]$  is added to the output list. If  $A$  has no units the empty list is returned.

(for the installed standard method see `GetColumnIndependentUnitPositions` (B.2.6))

### 5.5.21 GetRowIndependentUnitPositions (for matrices)

▷ `GetRowIndependentUnitPositions(A, poslist)` (operation)

**Returns:** a (possibly empty) list of pairs of positive integers

The list of row independent unit position of the matrix  $A$ . We say that a unit  $A[k, j]$  is row independent from the unit  $A[i, l]$  if  $j > l$  and  $A[k, l] = 0$ . The columns are scanned from left to right and within each column the rows are scanned from bottom to top searching for new units, row independent from the

preceding ones. If  $A[k, j]$  is a new row independent unit then  $[j, k]$  (yes  $[j, k]$ ) is added to the output list. If  $A$  has no units the empty list is returned.

(for the installed standard method see `GetRowIndependentUnitPositions` (B.2.7))

### 5.5.22 GetUnitPosition (for matrices)

▷ `GetUnitPosition(A, poslist)` (operation)

**Returns:** a (possibly empty) list of pairs of positive integers

The position  $[i, j]$  of the first unit  $A[i, j]$  in the matrix  $A$ , where the rows are scanned from top to bottom and within each row the columns are scanned from left to right. If  $A[i, j]$  is the first occurrence of a unit then the position pair  $[i, j]$  is returned. Otherwise fail is returned.

(for the installed standard method see `GetUnitPosition` (B.2.8))

### 5.5.23 Eliminate

▷ `Eliminate(rel, indets)` (operation)

**Returns:** a homalg matrix

Eliminate the independents  $indets$  from the matrix (or list of ring elements)  $rel$ , i.e. compute a generating set of the ideal defined as the intersection of the ideal generated by the entries of the list  $rel$  with the subring generated by all indeterminates except those in  $indets$ . by the list of indeterminates  $indets$ .

### 5.5.24 BasisOfRowModule (for matrices)

▷ `BasisOfRowModule(M)` (operation)

**Returns:** a homalg matrix

Let  $R$  be the ring over which  $M$  is defined ( $R := \text{HomalgRing}(M)$ ) and  $S$  be the row span of  $M$ , i.e. the  $R$ -submodule of the free left module  $R^{(1 \times \text{NrColumns}(M))}$  spanned by the rows of  $M$ . A solution to the “submodule membership problem” is an algorithm which can decide if an element  $m$  in  $R^{(1 \times \text{NrColumns}(M))}$  is contained in  $S$  or not. And exactly like the Gaussian (resp. Hermite) normal form when  $R$  is a field (resp. principal ideal ring), the row span of the resulting matrix  $B$  coincides with the row span  $S$  of  $M$ , and computing  $B$  is typically the first step of such an algorithm. (→ Appendix A)

### 5.5.25 BasisOfColumnModule (for matrices)

▷ `BasisOfColumnModule(M)` (operation)

**Returns:** a homalg matrix

Let  $R$  be the ring over which  $M$  is defined ( $R := \text{HomalgRing}(M)$ ) and  $S$  be the column span of  $M$ , i.e. the  $R$ -submodule of the free right module  $R^{(\text{NrRows}(M) \times 1)}$  spanned by the columns of  $M$ . A solution to the “submodule membership problem” is an algorithm which can decide if an element  $m$  in  $R^{(\text{NrRows}(M) \times 1)}$  is contained in  $S$  or not. And exactly like the Gaussian (resp. Hermite) normal form when  $R$  is a field (resp. principal ideal ring), the column span of the resulting matrix  $B$  coincides with the column span  $S$  of  $M$ , and computing  $B$  is typically the first step of such an algorithm. (→ Appendix A)

### 5.5.26 DecideZeroRows (for pairs of matrices)

▷ `DecideZeroRows(A, B)` (operation)

**Returns:** a homalg matrix

Let  $A$  and  $B$  be matrices having the same number of columns and defined over the same ring  $R$  ( $:=\text{HomalgRing}(A)$ ) and  $S$  be the row span of  $B$ , i.e. the  $R$ -submodule of the free left module  $R^{(1 \times \text{NrColumns}(B))}$  spanned by the rows of  $B$ . The result is a matrix  $C$  having the same shape as  $A$ , for which the  $i$ -th row  $C^i$  is equivalent to the  $i$ -th row  $A^i$  of  $A$  modulo  $S$ , i.e.  $C^i - A^i$  is an element of the row span  $S$  of  $B$ . Moreover, the row  $C^i$  is zero, if and only if the row  $A^i$  is an element of  $S$ . So `DecideZeroRows` decides which rows of  $A$  are zero modulo the rows of  $B$ . ( $\rightarrow$  Appendix A)

### 5.5.27 DecideZeroColumns (for pairs of matrices)

▷ `DecideZeroColumns(A, B)` (operation)

**Returns:** a homalg matrix

Let  $A$  and  $B$  be matrices having the same number of rows and defined over the same ring  $R$  ( $:=\text{HomalgRing}(A)$ ) and  $S$  be the column span of  $B$ , i.e. the  $R$ -submodule of the free right module  $R^{(\text{NrRows}(B) \times 1)}$  spanned by the columns of  $B$ . The result is a matrix  $C$  having the same shape as  $A$ , for which the  $i$ -th column  $C_i$  is equivalent to the  $i$ -th column  $A_i$  of  $A$  modulo  $S$ , i.e.  $C_i - A_i$  is an element of the column span  $S$  of  $B$ . Moreover, the column  $C_i$  is zero, if and only if the column  $A_i$  is an element of  $S$ . So `DecideZeroColumns` decides which columns of  $A$  are zero modulo the columns of  $B$ . ( $\rightarrow$  Appendix A)

### 5.5.28 SyzygiesGeneratorsOfRows (for matrices)

▷ `SyzygiesGeneratorsOfRows(M)` (operation)

**Returns:** a homalg matrix

Let  $R$  be the ring over which  $M$  is defined ( $R:=\text{HomalgRing}(M)$ ). The matrix of row syzygies `SyzygiesGeneratorsOfRows(M)` is a matrix whose rows span the left kernel of  $M$ , i.e. the  $R$ -submodule of the free left module  $R^{(1 \times \text{NrRows}(M))}$  consisting of all rows  $X$  satisfying  $XM = 0$ . ( $\rightarrow$  Appendix A)

### 5.5.29 SyzygiesGeneratorsOfColumns (for matrices)

▷ `SyzygiesGeneratorsOfColumns(M)` (operation)

**Returns:** a homalg matrix

Let  $R$  be the ring over which  $M$  is defined ( $R:=\text{HomalgRing}(M)$ ). The matrix of column syzygies `SyzygiesGeneratorsOfColumns(M)` is a matrix whose columns span the right kernel of  $M$ , i.e. the  $R$ -submodule of the free right module  $R^{(\text{NrColumns}(M) \times 1)}$  consisting of all columns  $X$  satisfying  $MX = 0$ . ( $\rightarrow$  Appendix A)

### 5.5.30 SyzygiesGeneratorsOfRows (for pairs of matrices)

▷ `SyzygiesGeneratorsOfRows(M, M2)` (operation)

**Returns:** a homalg matrix

Let  $R$  be the ring over which  $M$  is defined ( $R:=\text{HomalgRing}(M)$ ). The matrix of *relative* row syzygies `SyzygiesGeneratorsOfRows(M, M2)` is a matrix whose rows span the left kernel of  $M$

modulo  $M2$ , i.e. the  $R$ -submodule of the free left module  $R^{(1 \times \text{NrRows}(M))}$  consisting of all rows  $X$  satisfying  $XM + YM2 = 0$  for some row  $Y \in R^{(1 \times \text{NrRows}(M2))}$ . (→ Appendix A)

### 5.5.31 SyzygiesGeneratorsOfColumns (for pairs of matrices)

▷ `SyzygiesGeneratorsOfColumns( $M, M2$ )` (operation)

**Returns:** a homalg matrix

Let  $R$  be the ring over which  $M$  is defined ( $R := \text{HomalgRing}(M)$ ). The matrix of *relative* column syzygies `SyzygiesGeneratorsOfColumns( $M, M2$ )` is a matrix whose columns span the right kernel of  $M$  modulo  $M2$ , i.e. the  $R$ -submodule of the free right module  $R^{(\text{NrColumns}(M) \times 1)}$  consisting of all columns  $X$  satisfying  $MX + M2Y = 0$  for some column  $Y \in R^{(\text{NrColumns}(M2) \times 1)}$ . (→ Appendix A)

### 5.5.32 ReducedBasisOfRowModule (for matrices)

▷ `ReducedBasisOfRowModule( $M$ )` (operation)

**Returns:** a homalg matrix

Like `BasisOfRowModule( $M$ )` but where the matrix `SyzygiesGeneratorsOfRows(ReducedBasisOfRowModule( $M$ ))` contains no units. This can easily be achieved starting from  $B := \text{BasisOfRowModule}(M)$  (and using `GetColumnIndependentUnitPositions` (5.5.20) applied to the matrix of row syzygies of  $B$ , etc.). (→ Appendix A)

### 5.5.33 ReducedBasisOfColumnModule (for matrices)

▷ `ReducedBasisOfColumnModule( $M$ )` (operation)

**Returns:** a homalg matrix

Like `BasisOfColumnModule( $M$ )` but where the matrix `SyzygiesGeneratorsOfColumns(ReducedBasisOfColumnModule( $M$ ))` contains no units. This can easily be achieved starting from  $B := \text{BasisOfColumnModule}(M)$  (and using `GetRowIndependentUnitPositions` (5.5.21) applied to the matrix of column syzygies of  $B$ , etc.). (→ Appendix A)

### 5.5.34 ReducedSyzygiesGeneratorsOfRows (for matrices)

▷ `ReducedSyzygiesGeneratorsOfRows( $M$ )` (operation)

**Returns:** a homalg matrix

Like `SyzygiesGeneratorsOfRows( $M$ )` but where the matrix `SyzygiesGeneratorsOfRows(ReducedSyzygiesGeneratorsOfRows( $M$ ))` contains no units. This can easily be achieved starting from  $C := \text{SyzygiesGeneratorsOfRows}(M)$  (and using `GetColumnIndependentUnitPositions` (5.5.20) applied to the matrix of row syzygies of  $C$ , etc.). (→ Appendix A)

### 5.5.35 ReducedSyzygiesGeneratorsOfColumns (for matrices)

▷ `ReducedSyzygiesGeneratorsOfColumns( $M$ )` (operation)

**Returns:** a homalg matrix

Like `SyzygiesGeneratorsOfColumns( $M$ )` but where the matrix `SyzygiesGeneratorsOfColumns(ReducedSyzygiesGeneratorsOfColumns( $M$ ))` contains no units. This can easily be achieved starting from  $C := \text{SyzygiesGeneratorsOfColumns}(M)$  (and using `GetRowIndependentUnitPositions` (5.5.21) applied to the matrix of column syzygies of  $C$ , etc.). (→ Appendix A)

### 5.5.36 BasisOfRowsCoeff (for matrices)

- ▷ `BasisOfRowsCoeff( $M$ ,  $T$ )` (operation)  
**Returns:** a homalg matrix  
 Returns  $B := \text{BasisOfRowModule}(M)$  and assigns the *void* matrix  $T$  ( $\rightarrow \text{HomalgVoidMatrix}$  (5.2.5)) such that  $B = TM$ . ( $\rightarrow$  Appendix A)

### 5.5.37 BasisOfColumnsCoeff (for matrices)

- ▷ `BasisOfColumnsCoeff( $M$ ,  $T$ )` (operation)  
**Returns:** a homalg matrix  
 Returns  $B := \text{BasisOfRowModule}(M)$  and assigns the *void* matrix  $T$  ( $\rightarrow \text{HomalgVoidMatrix}$  (5.2.5)) such that  $B = MT$ . ( $\rightarrow$  Appendix A)

### 5.5.38 DecideZeroRowsEffectively (for pairs of matrices)

- ▷ `DecideZeroRowsEffectively( $A$ ,  $B$ ,  $T$ )` (operation)  
**Returns:** a homalg matrix  
 Returns  $M := \text{DecideZeroRows}(A, B)$  and assigns the *void* matrix  $T$  ( $\rightarrow \text{HomalgVoidMatrix}$  (5.2.5)) such that  $M = A + TB$ . ( $\rightarrow$  Appendix A)

### 5.5.39 DecideZeroColumnsEffectively (for pairs of matrices)

- ▷ `DecideZeroColumnsEffectively( $A$ ,  $B$ ,  $T$ )` (operation)  
**Returns:** a homalg matrix  
 Returns  $M := \text{DecideZeroColumns}(A, B)$  and assigns the *void* matrix  $T$  ( $\rightarrow \text{HomalgVoidMatrix}$  (5.2.5)) such that  $M = A + BT$ . ( $\rightarrow$  Appendix A)

### 5.5.40 BasisOfRows (for matrices)

- ▷ `BasisOfRows( $M$ )` (operation)  
 ▷ `BasisOfRows( $M$ ,  $T$ )` (operation)  
**Returns:** a homalg matrix  
 With one argument it is a synonym of `BasisOfRowModule` (5.5.24). with two arguments it is a synonym of `BasisOfRowsCoeff` (5.5.36).

### 5.5.41 BasisOfColumns (for matrices)

- ▷ `BasisOfColumns( $M$ )` (operation)  
 ▷ `BasisOfColumns( $M$ ,  $T$ )` (operation)  
**Returns:** a homalg matrix  
 With one argument it is a synonym of `BasisOfColumnModule` (5.5.25). with two arguments it is a synonym of `BasisOfColumnsCoeff` (5.5.37).

### 5.5.42 DecideZero (for matrices and relations)

- ▷ `DecideZero( $mat$ ,  $rel$ )` (operation)  
**Returns:** a homalg matrix



```

Code
InstallMethod( DecideZero,
  "for sets of ring relations",
  [ IsHomalgMatrix, IsHomalgRingRelations ],

  function( mat, rel )

    return DecideZero( mat, MatrixOfRelations( rel ) );

  end );

```

### 5.5.43 SyzygiesOfRows (for matrices)

- ▷ `SyzygiesOfRows( $M$ )` (operation)
- ▷ `SyzygiesOfRows( $M$ ,  $M2$ )` (operation)

**Returns:** a homalg matrix

With one argument it is a synonym of `SyzygiesGeneratorsOfRows` (5.5.28). with two arguments it is a synonym of `SyzygiesGeneratorsOfRows` (5.5.30).

### 5.5.44 SyzygiesOfColumns (for matrices)

- ▷ `SyzygiesOfColumns( $M$ )` (operation)
- ▷ `SyzygiesOfColumns( $M$ ,  $M2$ )` (operation)

**Returns:** a homalg matrix

With one argument it is a synonym of `SyzygiesGeneratorsOfColumns` (5.5.29). with two arguments it is a synonym of `SyzygiesGeneratorsOfColumns` (5.5.31).

### 5.5.45 ReducedSyzygiesOfRows (for matrices)

- ▷ `ReducedSyzygiesOfRows( $M$ )` (operation)
- ▷ `ReducedSyzygiesOfRows( $M$ ,  $M2$ )` (operation)

**Returns:** a homalg matrix

With one argument it is a synonym of `ReducedSyzygiesGeneratorsOfRows` (5.5.34). With two arguments it calls `ReducedBasisOfRowModule( SyzygiesGeneratorsOfRows(  $M$ ,  $M2$  ) )`. ( $\rightarrow$  `ReducedBasisOfRowModule` (5.5.32) and `SyzygiesGeneratorsOfRows` (5.5.30))

### 5.5.46 ReducedSyzygiesOfColumns (for matrices)

- ▷ `ReducedSyzygiesOfColumns( $M$ )` (operation)
- ▷ `ReducedSyzygiesOfColumns( $M$ ,  $M2$ )` (operation)

**Returns:** a homalg matrix

With one argument it is a synonym of `ReducedSyzygiesGeneratorsOfColumns` (5.5.35). With two arguments it calls `ReducedBasisOfColumnModule( SyzygiesGeneratorsOfColumns(  $M$ ,  $M2$  ) )`. ( $\rightarrow$  `ReducedBasisOfColumnModule` (5.5.33) and `SyzygiesGeneratorsOfColumns` (5.5.31))

### 5.5.47 RightDivide (for pairs of matrices)

- ▷ `RightDivide( $B$ ,  $A$ )` (operation)

**Returns:** a homalg matrix or fail

Let  $B$  and  $A$  be matrices having the same number of columns and defined over the same ring. The matrix `RightDivide( B, A )` is a particular solution of the inhomogeneous (one sided) linear system of equations  $XA = B$  in case it is solvable. Otherwise `fail` is returned. The name `RightDivide` suggests “ $X = BA^{-1}$ ”. This generalizes `LeftInverse` (5.5.2) for which  $B$  becomes the identity matrix. ( $\rightarrow$  `SyzygiesGeneratorsOfRows` (5.5.28))

### 5.5.48 LeftDivide (for pairs of matrices)

▷ `LeftDivide( A, B )` (operation)

**Returns:** a `homalg` matrix or `fail`

Let  $A$  and  $B$  be matrices having the same number of rows and defined over the same ring. The matrix `LeftDivide( A, B )` is a particular solution of the inhomogeneous (one sided) linear system of equations  $AX = B$  in case it is solvable. Otherwise `fail` is returned. The name `LeftDivide` suggests “ $X = A^{-1}B$ ”. This generalizes `RightInverse` (5.5.3) for which  $B$  becomes the identity matrix. ( $\rightarrow$  `SyzygiesGeneratorsOfColumns` (5.5.29))

### 5.5.49 RightDivide (for triples of matrices)

▷ `RightDivide( B, A, L )` (operation)

**Returns:** a `homalg` matrix or `fail`

Let  $B$ ,  $A$  and  $L$  be matrices having the same number of columns and defined over the same ring. The matrix `RightDivide( B, A, L )` is a particular solution of the inhomogeneous (one sided) linear system of equations  $XA + YL = B$  in case it is solvable (for some  $Y$  which is forgotten). Otherwise `fail` is returned. The name `RightDivide` suggests “ $X = BA^{-1}$  modulo  $L$ ”. (Cf. [BR08, Subsection 3.1.1])

Code

```
InstallMethod( RightDivide,
  "for homalg matrices",
  [ IsHomalgMatrix, IsHomalgMatrix, IsHomalgMatrix ],

  function( B, A, L )      ## CAUTION: Do not use lazy evaluation here!!!
    local R, BL, ZA, AL, ZB, T, B_;

    R := HomalgRing( B );

    BL := BasisOfRows( L );

    ## first reduce A modulo L
    ZA := DecideZeroRows( A, BL );

    AL := UnionOfRows( ZA, BL );

    ## also reduce B modulo L
    ZB := DecideZeroRows( B, BL );

    ## B_ = ZB + T * AL
    T := HomalgVoidMatrix( R );
    B_ := DecideZeroRowsEffectively( ZB, AL, T );

    ## if B_ does not vanish
```

```

    if not IsZero( B_ ) then
        return fail;
    fi;

    T := CertainColumns( T, [ 1 .. NrRows( A ) ] );

    ## check assertion
    Assert( 5, IsZero( DecideZeroRows( B + T * A, BL ) ) );

    return -T;

end );

```

### 5.5.50 LeftDivide (for triples of matrices)

▷ LeftDivide( $A$ ,  $B$ ,  $L$ )

(operation)

**Returns:** a homalg matrix or fail

Let  $A$ ,  $B$  and  $L$  be matrices having the same number of columns and defined over the same ring. The matrix  $\text{LeftDivide}(A, B, L)$  is a particular solution of the inhomogeneous (one sided) linear system of equations  $AX + LY = B$  in case it is solvable (for some  $Y$  which is forgotten). Otherwise fail is returned. The name  $\text{LeftDivide}$  suggests “ $X = A^{-1}B$  modulo  $L$ ”. (Cf. [BR08, Subsection 3.1.1])

Code

```

InstallMethod( LeftDivide,
    "for homalg matrices",
    [ IsHomalgMatrix, IsHomalgMatrix, IsHomalgMatrix ],

function( A, B, L )          ## CAUTION: Do not use lazy evaluation here!!!
    local R, BL, ZA, AL, ZB, T, B_;

    R := HomalgRing( B );

    BL := BasisOfColumns( L );

    ## first reduce A modulo L
    ZA := DecideZeroColumns( A, BL );

    AL := UnionOfColumns( ZA, BL );

    ## also reduce B modulo L
    ZB := DecideZeroColumns( B, BL );

    ## B_ = ZB + AL * T
    T := HomalgVoidMatrix( R );
    B_ := DecideZeroColumnsEffectively( ZB, AL, T );

    ## if B_ does not vanish
    if not IsZero( B_ ) then
        return fail;
    fi;

```

```

    T := CertainRows( T, [ 1 .. NrColumns( A ) ] );

    ## check assertion
    Assert( 5, IsZero( DecideZeroColumns( B + A * T, BL ) ) );

    return -T;

end );

```

### 5.5.51 GenerateSameRowModule (for pairs of matrices)

- ▷ `GenerateSameRowModule( $M$ ,  $N$ )` (operation)  
**Returns:** true or false  
 Check if the row span of  $M$  and of  $N$  are identical or not ( $\rightarrow$  `RightDivide` (5.5.47)).

### 5.5.52 GenerateSameColumnModule (for pairs of matrices)

- ▷ `GenerateSameColumnModule( $M$ ,  $N$ )` (operation)  
**Returns:** true or false  
 Check if the column span of  $M$  and of  $N$  are identical or not ( $\rightarrow$  `LeftDivide` (5.5.48)).

### 5.5.53 SimplifyHomalgMatrixByLeftAndRightMultiplicationWithInvertibleMatrices (for matrices)

- ▷ `SimplifyHomalgMatrixByLeftAndRightMultiplicationWithInvertibleMatrices( $M$ )` (operation)  
**Returns:** a list of 5 homalg matrices  
 The input is a homalg matrix  $M$ . The output is a 5-tuple of homalg matrices  $S$ ,  $U$ ,  $V$ ,  $UI$ ,  $VI$ , such that  $U M V = S$ . Moreover,  $U$  and  $V$  are invertible with inverses  $UI$ ,  $VI$ , respectively. The idea is that the matrix  $S$  should look "simpler" than  $M$ .

### 5.5.54 SimplifyHomalgMatrixByLeftMultiplicationWithInvertibleMatrix (for matrices)

- ▷ `SimplifyHomalgMatrixByLeftMultiplicationWithInvertibleMatrix( $M$ )` (operation)  
**Returns:** a list of 3 homalg matrices  
 The input is a homalg matrix  $M$ . The output is a 3-tuple of homalg matrices  $S$ ,  $T$ ,  $TI$  such that  $T M = S$ . Moreover,  $T$  is invertible with inverse  $TI$ . The idea is that the matrix  $S$  should look "simpler" than  $M$ .

### 5.5.55 SimplifyHomalgMatrixByRightMultiplicationWithInvertibleMatrix (for matrices)

- ▷ `SimplifyHomalgMatrixByRightMultiplicationWithInvertibleMatrix( $M$ )` (operation)  
**Returns:** a list of 3 homalg matrices  
 The input is a homalg matrix  $M$ . The output is a 3-tuple of homalg matrices  $S$ ,  $T$ ,  $TI$  such that  $M T = S$ . Moreover,  $T$  is invertible with inverse  $TI$ . The idea is that the matrix  $S$  should look "simpler" than  $M$ .

### 5.5.56 CoefficientsWithGivenMonomials (for two homalg matrices)

▷ `CoefficientsWithGivenMonomials(M, monomials)` (method)

**Returns:** a homalg matrix

Let  $R := \text{HomalgRing}(M)$ . *monomials* must be a homalg matrix with the same number of columns as *M* consisting of monomials of *R*. This method computes a homalg matrix *coeffs* (with entries in the coefficients ring of *R*, yet still considered as elements of *R*) such that  $M = \text{coeffs} * \text{monomials}$ . If no such matrix exists, the behavior is undefined. If the first argument is a homalg ring element, it is viewed as a homalg matrix with a single entry. If the second argument is a list of monomials, it is viewed as a column matrix with the list elements as entries.

## Chapter 6

# Ring Relations

### 6.1 Ring Relations: Categories and Representations

#### 6.1.1 IsHomalgRingRelations

▷ `IsHomalgRingRelations(rel)` (Category)  
**Returns:** true or false  
The GAP category of homalg ring relations.

#### 6.1.2 IsHomalgRingRelationsAsGeneratorsOfLeftIdeal

▷ `IsHomalgRingRelationsAsGeneratorsOfLeftIdeal(rel)` (Category)  
**Returns:** true or false  
The GAP category of homalg ring relations as generators of a left ideal.  
(It is a subcategory of the GAP category `IsHomalgRingRelations`.)

#### 6.1.3 IsHomalgRingRelationsAsGeneratorsOfRightIdeal

▷ `IsHomalgRingRelationsAsGeneratorsOfRightIdeal(rel)` (Category)  
**Returns:** true or false  
The GAP category of homalg ring relations as generators of a right ideal.  
(It is a subcategory of the GAP category `IsHomalgRingRelations`.)

#### 6.1.4 IsRingRelationsRep

▷ `IsRingRelationsRep(rel)` (Representation)  
**Returns:** true or false  
The GAP representation of a finite set of relations of a homalg ring.  
(It is a representation of the GAP category `IsHomalgRingRelations` ([6.1.1](#)))

## 6.2 Ring Relations: Constructors

## 6.3 Ring Relations: Properties

### 6.3.1 CanBeUsedToDecideZero

▷ `CanBeUsedToDecideZero(rel)` (property)

**Returns:** true or false

Check if the `homalg` set of relations `rel` can be used for normal form reductions.  
(no method installed)

### 6.3.2 IsInjectivePresentation

▷ `IsInjectivePresentation(rel)` (property)

**Returns:** true or false

Check if the `homalg` set of relations `rel` has zero syzygies.

## 6.4 Ring Relations: Attributes

## 6.5 Ring Relations: Operations and Functions

## Appendix A

# The Basic Matrix Operations

These are the operations used to solve one-sided (in)homogeneous linear systems  $XA = B$  resp.  $AX = B$ .

### A.1 Main

- `BasisOfRowModule` ([5.5.24](#))
- `BasisOfColumnModule` ([5.5.25](#))
- `DecideZeroRows` ([5.5.26](#))
- `DecideZeroColumns` ([5.5.27](#))
- `SyzygiesGeneratorsOfRows` ([5.5.28](#))
- `SyzygiesGeneratorsOfColumns` ([5.5.29](#))

### A.2 Effective

- `BasisOfRowsCoeff` ([5.5.36](#))
- `BasisOfColumnsCoeff` ([5.5.37](#))
- `DecideZeroRowsEffectively` ([5.5.38](#))
- `DecideZeroColumnsEffectively` ([5.5.39](#))

### A.3 Relative

- `SyzygiesGeneratorsOfRows` ([5.5.30](#))
- `SyzygiesGeneratorsOfColumns` ([5.5.31](#))



## A.4 Reduced

- ReducedBasisOfRowModule ([5.5.32](#))
- ReducedBasisOfColumnModule ([5.5.33](#))
- ReducedSyzygiesGeneratorsOfRows ([5.5.34](#))
- ReducedSyzygiesGeneratorsOfColumns ([5.5.35](#))

## Appendix B

# The Matrix Tool Operations

The functions listed below are components of the `homalgTable` object stored in the ring. They are only indirectly accessible through standard methods that invoke them.

### B.1 The Tool Operations *without* a Fallback Method

There are matrix methods for which `homalg` needs a `homalgTable` entry for non-internal rings, as it cannot provide a suitable fallback. Below is the list of these `homalgTable` entries.

#### B.1.1 InitialMatrix (homalgTable entry for initial matrices)

▷ `InitialMatrix( $\mathcal{C}$ )` (function)  
**Returns:** the Eval value of a `homalg` matrix  $\mathcal{C}$   
Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.InitialMatrix$  is bound then the method Eval (C.4.1) resets the filter `IsInitialMatrix` and returns  $RP!.InitialMatrix(\mathcal{C})$ .

#### B.1.2 InitialIdentityMatrix (homalgTable entry for initial identity matrices)

▷ `InitialIdentityMatrix( $\mathcal{C}$ )` (function)  
**Returns:** the Eval value of a `homalg` matrix  $\mathcal{C}$   
Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.InitialIdentityMatrix$  is bound then the method Eval (C.4.2) resets the filter `IsInitialIdentityMatrix` and returns  $RP!.InitialIdentityMatrix(\mathcal{C})$ .

#### B.1.3 ZeroMatrix (homalgTable entry)

▷ `ZeroMatrix( $\mathcal{C}$ )` (function)  
**Returns:** the Eval value of a `homalg` matrix  $\mathcal{C}$   
Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.ZeroMatrix$  is bound then the method Eval (C.4.3) returns  $RP!.ZeroMatrix(\mathcal{C})$ .

### B.1.4 IdentityMatrix (homalgTable entry)

▷ IdentityMatrix( $\mathcal{C}$ ) (function)

**Returns:** the Eval value of a homalg matrix  $\mathcal{C}$

Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.IdentityMatrix$  is bound then the method Eval (C.4.4) returns  $RP!.IdentityMatrix(\mathcal{C})$ .

### B.1.5 Involution (homalgTable entry)

▷ Involution( $M$ ) (function)

**Returns:** the Eval value of a homalg matrix  $\mathcal{C}$

Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.Involution$  is bound then the method Eval (C.4.7) returns  $RP!.Involution$  applied to the content of the attribute EvalInvolution( $\mathcal{C}$ ) =  $M$ .

### B.1.6 TransposedMatrix (homalgTable entry)

▷ TransposedMatrix( $M$ ) (function)

**Returns:** the Eval value of a homalg matrix  $\mathcal{C}$

Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.TransposedMatrix$  is bound then the method Eval (C.4.8) returns  $RP!.TransposedMatrix$  applied to the content of the attribute EvalTransposedMatrix( $\mathcal{C}$ ) =  $M$ .

### B.1.7 CertainRows (homalgTable entry)

▷ CertainRows( $M$ ,  $plist$ ) (function)

**Returns:** the Eval value of a homalg matrix  $\mathcal{C}$

Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.CertainRows$  is bound then the method Eval (C.4.9) returns  $RP!.CertainRows$  applied to the content of the attribute EvalCertainRows( $\mathcal{C}$ ) =  $[M, plist]$ .

### B.1.8 CertainColumns (homalgTable entry)

▷ CertainColumns( $M$ ,  $plist$ ) (function)

**Returns:** the Eval value of a homalg matrix  $\mathcal{C}$

Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.CertainColumns$  is bound then the method Eval (C.4.10) returns  $RP!.CertainColumns$  applied to the content of the attribute EvalCertainColumns( $\mathcal{C}$ ) =  $[M, plist]$ .

### B.1.9 UnionOfRows (homalgTable entry)

▷ UnionOfRows( $L$ ) (function)

**Returns:** the Eval value of a homalg matrix  $\mathcal{C}$

Let  $R := \text{HomalgRing}(\mathcal{C})$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.UnionOfRows$  is bound then the method Eval (C.4.11) returns  $RP!.UnionOfRows$  applied to the content of the attribute EvalUnionOfRows( $\mathcal{C}$ ) =  $L$ .

**B.1.10 UnionOfRowsPair (homalgTable entry)**

▷ UnionOfRowsPair( $A$ ,  $B$ )

(function)

**Returns:** the Eval value of a homalg matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.UnionOfRowsPair$  is bound and the homalgTable component  $RP!.UnionOfRows$  is not bound then the method Eval (C.4.11) returns  $RP!.UnionOfRowsPair$  applied recursively to a balanced binary tree created from the content of the attribute EvalUnionOfRows( $C$ ).

**B.1.11 UnionOfColumns (homalgTable entry)**

▷ UnionOfColumns( $L$ )

(function)

**Returns:** the Eval value of a homalg matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.UnionOfColumns$  is bound then the method Eval (C.4.12) returns  $RP!.UnionOfColumns$  applied to the content of the attribute EvalUnionOfColumns( $C$ ) =  $L$ .

**B.1.12 UnionOfColumnsPair (homalgTable entry)**

▷ UnionOfColumnsPair( $A$ ,  $B$ )

(function)

**Returns:** the Eval value of a homalg matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.UnionOfColumnsPair$  is bound and the homalgTable component  $RP!.UnionOfColumns$  is not bound then the method Eval (C.4.12) returns  $RP!.UnionOfColumnsPair$  applied recursively to a balanced binary tree created from the content of the attribute EvalUnionOfRows( $C$ ).

**B.1.13 DiagMat (homalgTable entry)**

▷ DiagMat( $e$ )

(function)

**Returns:** the Eval value of a homalg matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.DiagMat$  is bound then the method Eval (C.4.13) returns  $RP!.DiagMat$  applied to the content of the attribute EvalDiagMat( $C$ ) =  $e$ .

**B.1.14 KroneckerMat (homalgTable entry)**

▷ KroneckerMat( $A$ ,  $B$ )

(function)

**Returns:** the Eval value of a homalg matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.KroneckerMat$  is bound then the method Eval (C.4.14) returns  $RP!.KroneckerMat$  applied to the content of the attribute EvalKroneckerMat( $C$ ) =  $[A, B]$ .

**B.1.15 DualKroneckerMat (homalgTable entry)**

▷ DualKroneckerMat( $A$ ,  $B$ )

(function)

**Returns:** the Eval value of a homalg matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!\text{DualKroneckerMat}$  is bound then the method `Eval` (C.4.15) returns  $RP!\text{DualKroneckerMat}$  applied to the content of the attribute  $\text{EvalDualKroneckerMat}(C) = [A, B]$ .

### B.1.16 MulMat (homalgTable entry)

▷ `MulMat(a, A)` (function)

**Returns:** the `Eval` value of a `homalg` matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!\text{MulMat}$  is bound then the method `Eval` (C.4.16) returns  $RP!\text{MulMat}$  applied to the content of the attribute  $\text{EvalMulMat}(C) = [a, A]$ .

### B.1.17 AddMat (homalgTable entry)

▷ `AddMat(A, B)` (function)

**Returns:** the `Eval` value of a `homalg` matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!\text{AddMat}$  is bound then the method `Eval` (C.4.17) returns  $RP!\text{AddMat}$  applied to the content of the attribute  $\text{EvalAddMat}(C) = [A, B]$ .

### B.1.18 SubMat (homalgTable entry)

▷ `SubMat(A, B)` (function)

**Returns:** the `Eval` value of a `homalg` matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!\text{SubMat}$  is bound then the method `Eval` (C.4.18) returns  $RP!\text{SubMat}$  applied to the content of the attribute  $\text{EvalSubMat}(C) = [A, B]$ .

### B.1.19 Compose (homalgTable entry)

▷ `Compose(A, B)` (function)

**Returns:** the `Eval` value of a `homalg` matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!\text{Compose}$  is bound then the method `Eval` (C.4.19) returns  $RP!\text{Compose}$  applied to the content of the attribute  $\text{EvalCompose}(C) = [A, B]$ .

### B.1.20 IsZeroMatrix (homalgTable entry)

▷ `IsZeroMatrix(M)` (function)

**Returns:** true or false

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!\text{IsZeroMatrix}$  is bound then the standard method for the property `IsZero` (5.3.1) shown below returns  $RP!\text{IsZeroMatrix}(M)$ .

```

Code
InstallMethod( IsZero,
               "for homalg matrices",
               [ IsHomalgMatrix ],

               function( M )

```

```

local R, RP;

R := HomalgRing( M );

RP := homalgTable( R );

if IsBound(RP!.IsZeroMatrix) then
  ## CAUTION: the external system must be able
  ## to check zero modulo possible ring relations!

  return RP!.IsZeroMatrix( M ); ## with this, \= can fall back to IsZero
fi;

##### the fallback method #####

## from the GAP4 documentation: ?Zero
## 'ZeroSameMutability( <obj> )' is equivalent to '0 * <obj>'.

return M = 0 * M; ## hence, by default, IsZero falls back to \= (see below)

end );

```

### B.1.21 NrRows (homalgTable entry)

▷ NrRows(*C*)

(function)

**Returns:** a nonnegative integer

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.NrRows$  is bound then the standard method for the attribute `NrRows` (5.4.1) shown below returns  $RP!.NrRows(C)$ .

Code

```

InstallMethod( NrRows,
  "for homalg matrices",
  [ IsHomalgMatrix ],

function( C )
  local R, RP;

  R := HomalgRing( C );

  RP := homalgTable( R );

  if IsBound(RP!.NrRows) then
    return RP!.NrRows( C );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called NrRows ",
      "in the homalgTable of the non-internal ring\n" );
  fi;

  ##### can only work for homalg internal matrices #####

```

```

    return Length( Eval( C )!.matrix );

end );

```

### B.1.22 NrColumns (homalgTable entry)

▷ NrColumns( $C$ )

(function)

**Returns:** a nonnegative integer

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.NrColumns$  is bound then the standard method for the attribute `NrColumns` (5.4.2) shown below returns  $RP!.NrColumns(C)$ .

```

Code
InstallMethod( NrColumns,
    "for homalg matrices",
    [ IsHomalgMatrix ],

    function( C )
        local R, RP;

        R := HomalgRing( C );

        RP := homalgTable( R );

        if IsBound(RP!.NrColumns) then
            return RP!.NrColumns( C );
        fi;

        if not IsHomalgInternalMatrixRep( C ) then
            Error( "could not find a procedure called NrColumns ",
                "in the homalgTable of the non-internal ring\n" );
        fi;

        #=====# can only work for homalg internal matrices #=====#

        return Length( Eval( C )!.matrix[ 1 ] );

    end );

```

### B.1.23 Determinant (homalgTable entry)

▷ Determinant( $C$ )

(function)

**Returns:** a ring element

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.Determinant$  is bound then the standard method for the attribute `DeterminantMat` (5.4.3) shown below returns  $RP!.Determinant(C)$ .

```

Code
InstallMethod( DeterminantMat,
    "for homalg matrices",
    [ IsHomalgMatrix ],

```

```

function( C )
  local R, RP;

  R := HomalgRing( C );

  RP := homalgTable( R );

  if NrRows( C ) <> NrColumns( C ) then
    Error( "the matrix is not a square matrix\n" );
  fi;

  if IsEmptyMatrix( C ) then
    return One( R );
  elif IsZero( C ) then
    return Zero( R );
  fi;

  if IsBound(RP!.Determinant) then
    return RingElementConstructor( R )( RP!.Determinant( C ), R );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called Determinant ",
          "in the homalgTable of the non-internal ring\n" );
  fi;

  #=====# can only work for homalg internal matrices #=====#

  return Determinant( Eval( C )!.matrix );

end );

InstallMethod( Determinant,
  "for homalg matrices",
  [ IsHomalgMatrix ],

  function( C )

    return DeterminantMat( C );

  end );

```

### B.1.24 CoefficientsWithGivenMonomials (homalgTable entry)

▷ CoefficientsWithGivenMonomials( $M$ ,  $monomials$ )

(function)

**Returns:** the Eval value of a homalg matrix  $C$

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.CoefficientsWithGivenMonomials$  is bound then the method Eval (C.4.20) returns  $RP!.CoefficientsWithGivenMonomials$  applied to the content of the attribute



$\text{EvalCoefficientsWithGivenMonomials}(C) = [M, \text{monomials}]$ .

## B.2 The Tool Operations with a Fallback Method

These are the methods for which it is recommended for performance reasons to have a `homalgTable` entry for non-internal rings. `homalg` only provides a generic fallback method.

### B.2.1 AreEqualMatrices (homalgTable entry)

▷ `AreEqualMatrices(M1, M2)` (function)

**Returns:** true or false

Let  $R := \text{HomalgRing}(M1)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.AreEqualMatrices$  is bound then the standard method for the operation `\=` (5.5.19) shown below returns  $RP!.AreEqualMatrices(M1, M2)$ .

```

----- Code -----
InstallMethod( \=,
  "for homalg comparable matrices",
  [ IsHomalgMatrix, IsHomalgMatrix ],

  function( M1, M2 )
    local R, RP, are_equal;

    ## do not touch mutable matrices
    if not ( IsMutable( M1 ) or IsMutable( M2 ) ) then

      if IsBound( M1!.AreEqual ) then
        are_equal := _ElmWPObj_ForHomalg( M1!.AreEqual, M2, fail );
        if are_equal <> fail then
          return are_equal;
        fi;
      else
        M1!.AreEqual :=
          ContainerForWeakPointers(
            TheTypeContainerForWeakPointersOnComputedValues,
            [ "operation", "AreEqual" ] );
        fi;

      if IsBound( M2!.AreEqual ) then
        are_equal := _ElmWPObj_ForHomalg( M2!.AreEqual, M1, fail );
        if are_equal <> fail then
          return are_equal;
        fi;
      fi;

      ## do not store things symmetrically below to "save" memory

    fi;

    R := HomalgRing( M1 );

    RP := homalgTable( R );

```

```

if IsBound(RP!.AreEqualMatrices) then
  ## CAUTION: the external system must be able to check equality
  ## modulo possible ring relations (known to the external system)!
  are_equal := RP!.AreEqualMatrices( M1, M2 );
elif IsBound(RP!.Equal) then
  ## CAUTION: the external system must be able to check equality
  ## modulo possible ring relations (known to the external system)!
  are_equal := RP!.Equal( M1, M2 );
elif IsBound(RP!.IsZeroMatrix) then  ## ensuring this avoids infinite loops
  are_equal := IsZero( M1 - M2 );
fi;

if IsBound( are_equal ) then

  ## do not touch mutable matrices
  if not ( IsMutable( M1 ) or IsMutable( M2 ) ) then

    if are_equal then
      MatchPropertiesAndAttributes( M1, M2,
        LIMAT.intrinsic_properties,
        LIMAT.intrinsic_attributes,
        LIMAT.intrinsic_components,
        LIMAT.intrinsic_attributes_do_not_check_their_equality
      );
    fi;

    ## do not store things symmetrically to ‘‘save’’ memory
    _AddTwoElmWP0bj_ForHomalg( M1!.AreEqual, M2, are_equal );

  fi;

  return are_equal;
fi;

TryNextMethod( );

end );

```

### B.2.2 IsIdentityMatrix (homalgTable entry)

▷ IsIdentityMatrix( $M$ )

(function)

**Returns:** true or false

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the homalgTable component  $RP!.IsIdentityMatrix$  is bound then the standard method for the property IsOne (5.3.2) shown below returns  $RP!.IsIdentityMatrix(M)$ .

```

----- Code -----
InstallMethod( IsOne,
  "for homalg matrices",
  [ IsHomalgMatrix ],

  function( M )

```

```

local R, RP;

if NrRows( M ) <> NrColumns( M ) then
  return false;
fi;

R := HomalgRing( M );

RP := homalgTable( R );

if IsBound(RP!.IsIdentityMatrix) then
  return RP!.IsIdentityMatrix( M );
fi;

#=====# the fallback method #=====#

return M = HomalgIdentityMatrix( NrRows( M ), HomalgRing( M ) );

end );

```

### B.2.3 IsDiagonalMatrix (homalgTable entry)

▷ IsDiagonalMatrix( $M$ )

(function)

**Returns:** true or false

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.IsDiagonalMatrix$  is bound then the standard method for the property `IsDiagonalMatrix` (5.3.13) shown below returns  $RP!.IsDiagonalMatrix(M)$ .

Code

```

InstallMethod( IsDiagonalMatrix,
  "for homalg matrices",
  [ IsHomalgMatrix ],

function( M )
  local R, RP, diag;

  R := HomalgRing( M );

  RP := homalgTable( R );

  if IsBound(RP!.IsDiagonalMatrix) then
    return RP!.IsDiagonalMatrix( M );
  fi;

  #=====# the fallback method #=====#

  diag := DiagonalEntries( M );

  return M = HomalgDiagonalMatrix( diag, NrRows( M ), NrColumns( M ), R );

end );

```

### B.2.4 ZeroRows (homalgTable entry)

▷ ZeroRows( $C$ ) (function)

**Returns:** a (possibly empty) list of positive integers

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.ZeroRows$  is bound then the standard method of the attribute `ZeroRows` (5.4.4) shown below returns  $RP!.ZeroRows(C)$ .

```

Code
InstallMethod( ZeroRows,
               "for homalg matrices",
               [ IsHomalgMatrix ],

               function( C )
                 local R, RP, z;

                 R := HomalgRing( C );

                 RP := homalgTable( R );

                 if IsBound(RP!.ZeroRows) then
                   return RP!.ZeroRows( C );
                 fi;

                 #====# the fallback method #====#

                 z := HomalgZeroMatrix( 1, NrColumns( C ), R );

                 return Filtered( [ 1 .. NrRows( C ) ], a -> CertainRows( C, [ a ] ) = z );

               end );
```

### B.2.5 ZeroColumns (homalgTable entry)

▷ ZeroColumns( $C$ ) (function)

**Returns:** a (possibly empty) list of positive integers

Let  $R := \text{HomalgRing}(C)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.ZeroColumns$  is bound then the standard method of the attribute `ZeroColumns` (5.4.5) shown below returns  $RP!.ZeroColumns(C)$ .

```

Code
InstallMethod( ZeroColumns,
               "for homalg matrices",
               [ IsHomalgMatrix ],

               function( C )
                 local R, RP, z;

                 R := HomalgRing( C );

                 RP := homalgTable( R );

                 if IsBound(RP!.ZeroColumns) then
```

```

        return RP!.ZeroColumns( C );
    fi;

    #=====# the fallback method #=====#

    z := HomalgZeroMatrix( NrRows( C ), 1, R );

    return Filtered( [ 1 .. NrColumns( C ) ], a -> CertainColumns( C, [ a ] ) = z );

end );

```

### B.2.6 GetColumnIndependentUnitPositions (homalgTable entry)

▷ GetColumnIndependentUnitPositions( $M$ ,  $poslist$ ) (function)

**Returns:** a (possibly empty) list of pairs of positive integers

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component `RP!.GetColumnIndependentUnitPositions` is bound then the standard method of the operation `GetColumnIndependentUnitPositions` (5.5.20) shown below returns `RP!.GetColumnIndependentUnitPositions(M, poslist)`.

```

                                Code
InstallMethod( GetColumnIndependentUnitPositions,
               "for homalg matrices",
               [ IsHomalgMatrix, IsHomogeneousList ],

function( M, poslist )
    local cache, R, RP, rest, pos, i, j, k;

    if IsBound( M!.GetColumnIndependentUnitPositions ) then
        cache := M!.GetColumnIndependentUnitPositions;
        if IsBound( cache.(String( poslist )) ) then
            return cache.(String( poslist ));
        fi;
    else
        cache := rec( );
        M!.GetColumnIndependentUnitPositions := cache;
    fi;

    R := HomalgRing( M );

    RP := homalgTable( R );

    if IsBound(RP!.GetColumnIndependentUnitPositions) then
        pos := RP!.GetColumnIndependentUnitPositions( M, poslist );
        if pos <> [ ] then
            SetIsZero( M, false );
        fi;
        cache.(String( poslist )) := pos;
        return pos;
    fi;

    #=====# the fallback method #=====#

```

```

rest := [ 1 .. NrColumns( M ) ];

pos := [ ];

for i in [ 1 .. NrRows( M ) ] do
  for k in Reversed( rest ) do
    if not [ i, k ] in poslist and
      IsUnit( R, M[ i, k ] ) then
      Add( pos, [ i, k ] );
      rest := Filtered( rest,
        a -> IsZero( M[ i, a ] ) );
      break;
    fi;
  od;
od;

if pos <> [ ] then
  SetIsZero( M, false );
fi;

cache.(String( poslist )) := pos;

return pos;

end );

```

### B.2.7 GetRowIndependentUnitPositions (homalgTable entry)

▷ `GetRowIndependentUnitPositions(M, poslist)` (function)

**Returns:** a (possibly empty) list of pairs of positive integers

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.GetRowIndependentUnitPositions$  is bound then the standard method of the operation `GetRowIndependentUnitPositions` (5.5.21) shown below returns  $RP!.GetRowIndependentUnitPositions(M, poslist)$ .

```

Code
InstallMethod( GetRowIndependentUnitPositions,
  "for homalg matrices",
  [ IsHomalgMatrix, IsHomogeneousList ],

function( M, poslist )
  local cache, R, RP, rest, pos, j, i, k;

  if IsBound( M!.GetRowIndependentUnitPositions ) then
    cache := M!.GetRowIndependentUnitPositions;
    if IsBound( cache.(String( poslist )) ) then
      return cache.(String( poslist ));
    fi;
  else
    cache := rec( );
    M!.GetRowIndependentUnitPositions := cache;

```

```

fi;

R := HomalgRing( M );

RP := homalgTable( R );

if IsBound(RP!.GetRowIndependentUnitPositions) then
  pos := RP!.GetRowIndependentUnitPositions( M, poslist );
  if pos <> [ ] then
    SetIsZero( M, false );
  fi;
  cache.( String( poslist ) ) := pos;
  return pos;
fi;

#=====# the fallback method #=====#

rest := [ 1 .. NrRows( M ) ];

pos := [ ];

for j in [ 1 .. NrColumns( M ) ] do
  for k in Reversed( rest ) do
    if not [ j, k ] in poslist and
      IsUnit( R, M[ k, j ] ) then
      Add( pos, [ j, k ] );
      rest := Filtered( rest,
        a -> IsZero( M[ a, j ] ) );
      break;
    fi;
  od;
od;

if pos <> [ ] then
  SetIsZero( M, false );
fi;

cache.( String( poslist ) ) := pos;

return pos;

end );

```

### B.2.8 GetUnitPosition (homalgTable entry)

▷ GetUnitPosition( $M$ ,  $poslist$ )

(function)

**Returns:** a (possibly empty) list of pairs of positive integers

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.GetUnitPosition$  is bound then the standard method of the operation `GetUnitPosition` (5.5.22) shown below returns  $RP!.GetUnitPosition(M, poslist)$ .

Code

```
InstallMethod( GetUnitPosition,
```

```

    "for homalg matrices",
    [ IsHomalgMatrix, IsHomogeneousList ],

function( M, poslist )
  local R, RP, pos, m, n, i, j;

  R := HomalgRing( M );

  RP := homalgTable( R );

  if IsBound(RP!.GetUnitPosition) then
    pos := RP!.GetUnitPosition( M, poslist );
    if IsList( pos ) and IsPosInt( pos[1] ) and IsPosInt( pos[2] ) then
      SetIsZero( M, false );
    fi;
    return pos;
  fi;

  #=====# the fallback method #=====#

  m := NrRows( M );
  n := NrColumns( M );

  for i in [ 1 .. m ] do
    for j in [ 1 .. n ] do
      if not [ i, j ] in poslist and not j in poslist and
        IsUnit( R, M[ i, j ] ) then
        SetIsZero( M, false );
        return [ i, j ];
      fi;
    od;
  od;

  return fail;

end );

```

### B.2.9 PositionOfFirstNonZeroEntryPerRow (homalgTable entry)

▷ PositionOfFirstNonZeroEntryPerRow( $M$ ,  $poslist$ )

(function)

**Returns:** a list of nonnegative integers

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.PositionOfFirstNonZeroEntryPerRow$  is bound then the standard method of the attribute `PositionOfFirstNonZeroEntryPerRow` (5.4.8) shown below returns  $RP!.PositionOfFirstNonZeroEntryPerRow(M)$ .

```

Code
InstallMethod( PositionOfFirstNonZeroEntryPerRow,
  "for homalg matrices",
  [ IsHomalgMatrix ],

  function( M )

```



```

local R, RP, pos, entries, r, c, i, k, j;

R := HomalgRing( M );

RP := homalgTable( R );

if IsBound(RP!.PositionOfFirstNonZeroEntryPerRow) then
  return RP!.PositionOfFirstNonZeroEntryPerRow( M );
elif IsBound(RP!.PositionOfFirstNonZeroEntryPerColumn) then
  return PositionOfFirstNonZeroEntryPerColumn( Involution( M ) );
fi;

#=====# the fallback method #=====#

entries := EntriesOfHomalgMatrix( M );

r := NrRows( M );
c := NrColumns( M );

pos := ListWithIdenticalEntries( r, 0 );

for i in [ 1 .. r ] do
  k := (i - 1) * c;
  for j in [ 1 .. c ] do
    if not IsZero( entries[k + j] ) then
      pos[i] := j;
      break;
    fi;
  od;
od;

return pos;

end );

```

### B.2.10 PositionOfFirstNonZeroEntryPerColumn (homalgTable entry)

▷ PositionOfFirstNonZeroEntryPerColumn( $M$ ,  $poslist$ )

(function)

**Returns:** a list of nonnegative integers

Let  $R := \text{HomalgRing}(M)$  and  $RP := \text{homalgTable}(R)$ . If the `homalgTable` component  $RP!.PositionOfFirstNonZeroEntryPerColumn$  is bound then the standard method of the attribute `PositionOfFirstNonZeroEntryPerColumn` (5.4.9) shown below returns  $RP!.PositionOfFirstNonZeroEntryPerColumn(M)$ .

```

----- Code -----
InstallMethod( PositionOfFirstNonZeroEntryPerColumn,
  "for homalg matrices",
  [ IsHomalgMatrix ],

function( M )
  local R, RP, pos, entries, r, c, j, i, k;

```

```

R := HomalgRing( M );

RP := homalgTable( R );

if IsBound(RP!.PositionOfFirstNonZeroEntryPerColumn) then
  return RP!.PositionOfFirstNonZeroEntryPerColumn( M );
elif IsBound(RP!.PositionOfFirstNonZeroEntryPerRow) then
  return PositionOfFirstNonZeroEntryPerRow( Involution( M ) );
fi;

##### the fallback method #####

entries := EntriesOfHomalgMatrix( M );

r := NrRows( M );
c := NrColumns( M );

pos := ListWithIdenticalEntries( c, 0 );

for j in [ 1 .. c ] do
  for i in [ 1 .. r ] do
    k := (i - 1) * c;
    if not IsZero( entries[k + j] ) then
      pos[j] := i;
      break;
    fi;
  od;
od;

return pos;

end );

```

# Appendix C

## Logic Subpackages

### C.1 LIRNG: Logical Implications for Rings

### C.2 LIMAP: Logical Implications for Ring Maps

### C.3 LIMAT: Logical Implications for Matrices

### C.4 COLEM: Clever Operations for Lazy Evaluated Matrices

Most of the matrix tool operations listed in Appendix B.1 which return a new matrix are lazy evaluated. The value of a `homalg` matrix is stored in the attribute `Eval`. Below is the list of the installed methods for the attribute `Eval`.

#### C.4.1 Eval (for matrices created with `HomalgInitialMatrix`)

▷ `Eval(C)` (method)

**Returns:** the `Eval` value of a `homalg` matrix `C`

In case the matrix `C` was created using `HomalgInitialMatrix` (5.2.1) then the filter `IsInitialMatrix` for `C` is set to true and the `homalgTable` function ( $\rightarrow$  `InitialMatrix` (B.1.1)) will be used to set the attribute `Eval` and resets the filter `IsInitialMatrix`.

```
Code
InstallMethod( Eval,
  "for homalg matrices (IsInitialMatrix)",
  [ IsHomalgMatrix and IsInitialMatrix and
    HasNrRows and HasNrColumns ],

function( C )
  local R, RP, z, zz;

  R := HomalgRing( C );

  RP := homalgTable( R );

  if IsBound( RP!.InitialMatrix ) then
    ResetFilterObj( C, IsInitialMatrix );
    SetEval( C, RP!.InitialMatrix( C ) );
```

```

        return Eval( C );
    fi;

    if not IsHomalgInternalMatrixRep( C ) then
        Error( "could not find a procedure called InitialMatrix in the ",
              "homalgTable to evaluate a non-internal initial matrix\n" );
    fi;

    #=====# can only work for homalg internal matrices #=====#

    z := Zero( HomalgRing( C ) );

    ResetFilterObj( C, IsInitialMatrix );

    zz := ListWithIdenticalEntries( NrColumns( C ), z );

    SetEval( C, homalgInternalMatrixHull( List( [ 1 .. NrRows( C ) ], i -> ShallowCopy( zz ) ) ) );

    return Eval( C );

end );

```

#### C.4.2 Eval (for matrices created with HomalgInitialIdentityMatrix)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix *C* was created using HomalgInitialIdentityMatrix (5.2.2) then the filter IsInitialIdentityMatrix for *C* is set to true and the homalgTable function (→ InitialIdentityMatrix (B.1.2)) will be used to set the attribute Eval and resets the filter IsInitialIdentityMatrix.

```

----- Code -----
InstallMethod( Eval,
    "for homalg matrices (IsInitialIdentityMatrix)",
    [ IsHomalgMatrix and IsInitialIdentityMatrix and
      HasNrRows and HasNrColumns ],

    function( C )
        local R, RP, o, z, zz, id;

        R := HomalgRing( C );

        RP := homalgTable( R );

        if IsBound( RP!.InitialIdentityMatrix ) then
            ResetFilterObj( C, IsInitialIdentityMatrix );
            SetEval( C, RP!.InitialIdentityMatrix( C ) );
            return Eval( C );
        fi;

        if not IsHomalgInternalMatrixRep( C ) then
            Error( "could not find a procedure called InitialIdentityMatrix in the ",

```

```

        "homalgTable to evaluate a non-internal initial identity matrix\n" );
fi;

##### can only work for homalg internal matrices #####

z := Zero( HomalgRing( C ) );
o := One( HomalgRing( C ) );

ResetFilterObj( C, IsInitialIdentityMatrix );

zz := ListWithIdenticalEntries( NrColumns( C ), z );

id := List( [ 1 .. NrRows( C ) ],
            function(i)
              local z;
              z := ShallowCopy( zz ); z[i] := o; return z;
            end );

SetEval( C, homalgInternalMatrixHull( id ) );

return Eval( C );

end );

```

### C.4.3 Eval (for matrices created with HomalgZeroMatrix)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix *C* was created using HomalgZeroMatrix (5.2.3) then the filter IsZeroMatrix for *C* is set to true and the homalgTable function ( $\rightarrow$  ZeroMatrix (B.1.3)) will be used to set the attribute Eval.

```

----- Code -----
InstallMethod( Eval,
              "for homalg matrices (IsZero)",
              [ IsHomalgMatrix and IsZero and HasNrRows and HasNrColumns ], 40,

function( C )
  local R, RP, z;

  R := HomalgRing( C );

  RP := homalgTable( R );

  if ( NrRows( C ) = 0 or NrColumns( C ) = 0 ) and
      not ( IsBound( R!.SafeToEvaluateEmptyMatrices ) and
            R!.SafeToEvaluateEmptyMatrices = true ) then
    Info( InfoWarning, 1, "\033[01m\033[5;31;47m",
          "an empty matrix is about to get evaluated!",
          "\033[0m" );
  fi;

  if IsBound( RP!.ZeroMatrix ) then

```

```

        return RP!.ZeroMatrix( C );
    fi;

    if not IsHomalgInternalMatrixRep( C ) then
        Error( "could not find a procedure called ZeroMatrix ",
              "homalgTable to evaluate a non-internal zero matrix\n" );
    fi;

    #=====# can only work for homalg internal matrices #=====#

    z := Zero( HomalgRing( C ) );

    ## copying the rows saves memory;
    ## we assume that the entries are never modified!!!
    return homalgInternalMatrixHull(
        ListWithIdenticalEntries( NrRows( C ),
                                   ListWithIdenticalEntries( NrColumns( C ), z ) ) );

end );

```

#### C.4.4 Eval (for matrices created with HomalgIdentityMatrix)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix *C* was created using HomalgIdentityMatrix (5.2.4) then the filter IsOne for *C* is set to true and the homalgTable function ( $\rightarrow$  IdentityMatrix (B.1.4)) will be used to set the attribute Eval.

```

----- Code -----
InstallMethod( Eval,
    "for homalg matrices (IsOne)",
    [ IsHomalgMatrix and IsOne and HasNrRows and HasNrColumns ], 10,

    function( C )
        local R, id, RP, o, z, zz;

        R := HomalgRing( C );

        if IsBound( R!.IdentityMatrices ) then
            id := ElmWPObj( R!.IdentityMatrices!.weak_pointers, NrColumns( C ) );
            if id <> fail then
                R!.IdentityMatrices!.cache_hits := R!.IdentityMatrices!.cache_hits + 1;
                return id;
            fi;
            ## we do not count cache_misses as it is equivalent to counter
        fi;

        RP := homalgTable( R );

        if IsBound( RP!.IdentityMatrix ) then
            id := RP!.IdentityMatrix( C );
            SetElmWPObj( R!.IdentityMatrices!.weak_pointers, NrColumns( C ), id );
            R!.IdentityMatrices!.counter := R!.IdentityMatrices!.counter + 1;
        fi;
    end function

```

```

        return id;
    fi;

    if not IsHomalgInternalMatrixRep( C ) then
        Error( "could not find a procedure called IdentityMatrix ",
              "homalgTable to evaluate a non-internal identity matrix\n" );
    fi;

    #=====# can only work for homalg internal matrices #=====#

    z := Zero( HomalgRing( C ) );
    o := One( HomalgRing( C ) );

    zz := ListWithIdenticalEntries( NrColumns( C ), z );

    id := List( [ 1 .. NrRows( C ) ],
               function(i)
                   local z;
                   z := ShallowCopy( zz ); z[i] := o; return z;
               end );

    id := homalgInternalMatrixHull( id );

    SetElmWPObj( R!.IdentityMatrices!.weak_pointers, NrColumns( C ), id );

    return id;

end );

```

### C.4.5 Eval (for matrices created with LeftInverseLazy)

▷ Eval(LI)

(method)

**Returns:** see below

In case the matrix *LI* was created using `LeftInverseLazy` (5.5.4) then the filter `HasEvalLeftInverse` for *LI* is set to true and the method listed below will be used to set the attribute `Eval`. (→ `LeftInverse` (5.5.2))

```

----- Code -----
InstallMethod( Eval,
               "for homalg matrices",
               [ IsHomalgMatrix and HasEvalLeftInverse ],

    function( LI )
        local left_inv;

        left_inv := LeftInverse( EvalLeftInverse( LI ) );

        if IsBool( left_inv ) then
            return false;
        fi;

        return Eval( left_inv );
    end );

```

```
end );
```

### C.4.6 Eval (for matrices created with RightInverseLazy)

▷ Eval(*RI*)

(method)

**Returns:** see below

In case the matrix *RI* was created using `RightInverseLazy` (5.5.5) then the filter `HasEvalRightInverse` for *RI* is set to true and the method listed below will be used to set the attribute `Eval`. (→ `RightInverse` (5.5.3))

```

Code
InstallMethod( Eval,
  "for homalg matrices",
  [ IsHomalgMatrix and HasEvalRightInverse ],

  function( RI )
    local right_inv;

    right_inv := RightInverse( EvalRightInverse( RI ) );

    if IsBool( right_inv ) then
      return false;
    fi;

    return Eval( right_inv );
  end );

```

### C.4.7 Eval (for matrices created with Involution)

▷ Eval(*C*)

(method)

**Returns:** the `Eval` value of a homalg matrix *C*

In case the matrix was created using `Involution` (5.5.6) then the filter `HasEvalInvolution` for *C* is set to true and the homalgTable function `Involution` (B.1.5) will be used to set the attribute `Eval`.

```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalInvolution)",
  [ IsHomalgMatrix and HasEvalInvolution ],

  function( C )
    local R, RP, M;

    R := HomalgRing( C );

    RP := homalgTable( R );

    M := EvalInvolution( C );

    if IsBound(RP!.Involution) then

```



```

        return RP!.Involution( M );
    fi;

    if not IsHomalgInternalMatrixRep( C ) then
        Error( "could not find a procedure called Involution ",
              "in the homalgTable of the non-internal ring\n" );
    fi;

    #=====# can only work for homalg internal matrices #=====#

    return homalgInternalMatrixHull( TransposedMat( Eval( M )!.matrix ) );

end );

```

### C.4.8 Eval (for matrices created with TransposedMatrix)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using TransposedMatrix (5.5.7) then the filter HasEvalTransposedMatrix for *C* is set to true and the homalgTable function TransposedMatrix (B.1.6) will be used to set the attribute Eval.

Code

```

InstallMethod( Eval,
    "for homalg matrices (HasEvalTransposedMatrix)",
    [ IsHomalgMatrix and HasEvalTransposedMatrix ],

    function( C )
        local R, RP, M;

        R := HomalgRing( C );

        RP := homalgTable( R );

        M := EvalTransposedMatrix( C );

        if IsBound(RP!.TransposedMatrix) then
            return RP!.TransposedMatrix( M );
        fi;

        if not IsHomalgInternalMatrixRep( C ) then
            Error( "could not find a procedure called TransposedMatrix ",
                  "in the homalgTable of the non-internal ring\n" );
        fi;

        #=====# can only work for homalg internal matrices #=====#

        return homalgInternalMatrixHull( TransposedMat( Eval( M )!.matrix ) );

    end );

```

### C.4.9 Eval (for matrices created with CertainRows)

▷ `Eval(C)` (method)

**Returns:** the Eval value of a homalg matrix  $C$

In case the matrix was created using `CertainRows` (5.5.8) then the filter `HasEvalCertainRows` for  $C$  is set to true and the `homalgTable` function `CertainRows` (B.1.7) will be used to set the attribute `Eval`.

```

Code
InstallMethod( Eval,
    "for homalg matrices (HasEvalCertainRows)",
    [ IsHomalgMatrix and HasEvalCertainRows ],

function( C )
    local R, RP, e, M, plist;

    R := HomalgRing( C );

    RP := homalgTable( R );

    e := EvalCertainRows( C );

    M := e[1];
    plist := e[2];

    ResetFilterObj( C, HasEvalCertainRows );

    ## delete the component which was left over by GAP
    Unbind( C!.EvalCertainRows );

    if IsBound(RP!.CertainRows) then
        return RP!.CertainRows( M, plist );
    fi;

    if not IsHomalgInternalMatrixRep( C ) then
        Error( "could not find a procedure called CertainRows ",
            "in the homalgTable of the non-internal ring\n" );
    fi;

    #=====# can only work for homalg internal matrices #=====#

    return homalgInternalMatrixHull( Eval( M )!.matrix{ plist } );

end );
```

### C.4.10 Eval (for matrices created with CertainColumns)

▷ `Eval(C)` (method)

**Returns:** the Eval value of a homalg matrix  $C$

In case the matrix was created using `CertainColumns` (5.5.9) then the filter `HasEvalCertainColumns` for  $C$  is set to true and the `homalgTable` function `CertainColumns` (B.1.8) will be used to set the attribute `Eval`.

```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalCertainColumns)",
  [ IsHomalgMatrix and HasEvalCertainColumns ],

function( C )
  local R, RP, e, M, plist;

  R := HomalgRing( C );

  RP := homalgTable( R );

  e := EvalCertainColumns( C );

  M := e[1];
  plist := e[2];

  ResetFilterObj( C, HasEvalCertainColumns );

  ## delete the component which was left over by GAP
  Unbind( C!.EvalCertainColumns );

  if IsBound(RP!.CertainColumns) then
    return RP!.CertainColumns( M, plist );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called CertainColumns ",
      "in the homalgTable of the non-internal ring\n" );
  fi;

  #=====# can only work for homalg internal matrices #=====#

  return homalgInternalMatrixHull(
    Eval( M )!.matrix{[ 1 .. NrRows( M ) ]}{plist} );

end );

```

### C.4.11 Eval (for matrices created with UnionOfRows)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using UnionOfRows (5.5.10) then the filter HasEvalUnionOfRows for *C* is set to true and the homalgTable function UnionOfRows (B.1.9) or the homalgTable function UnionOfRowsPair (B.1.10) will be used to set the attribute Eval.

```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalUnionOfRows)",
  [ IsHomalgMatrix and HasEvalUnionOfRows ],

function( C )
  local R, RP, e, i, combine;

```

```

R := HomalgRing( C );

RP := homalgTable( R );

# Make it mutable
e := ShallowCopy( EvalUnionOfRows( C ) );

# In case of nested UnionOfRows, we try to avoid
# recursion, since the gap stack is rather small
# additionally unpack PreEvals
i := 1;
while i <= Length( e ) do

    if HasPreEval( e[i] ) and not HasEval( e[i] ) then

        e[i] := PreEval( e[i] );

    elif HasEvalUnionOfRows( e[i] ) and not HasEval( e[i] ) then

        e := Concatenation( e[ 1 .. (i-1) ], EvalUnionOfRows( e[i] ), e[ (i+1) .. Length(
    else

        i := i + 1;

    fi;

od;

# Combine zero matrices
i := 1;
while i + 1 <= Length( e ) do

    if HasIsZero( e[i] ) and IsZero( e[i] ) and HasIsZero( e[i+1] ) and IsZero( e[i+1] ) then

        e[i] := HomalgZeroMatrix( NrRows( e[i] ) + NrRows( e[i+1] ), NrColumns( e[i] ), Homalg
        Remove( e, i + 1 );

    else

        i := i + 1;

    fi;

od;

# After combining zero matrices only a single one might be left
if Length( e ) = 1 then

    return e[1];

```

```

fi;

# Use RP!.UnionOfRows if available
if IsBound(RP!.UnionOfRows) then

    return RP!.UnionOfRows( e );

fi;

# Fall back to RP!.UnionOfRowsPair or manual fallback for internal matrices
# Combine the matrices
# Use a balanced binary tree to keep the sizes small (heuristically)
# to avoid a huge memory footprint

if not IsBound(RP!.UnionOfRowsPair) and not IsHomalgInternalMatrixRep( C ) then
    Error( "could neither find a procedure called UnionOfRows ",
           "nor a procedure called UnionOfRowsPair ",
           "in the homalgTable of the non-internal ring\n" );
fi;

combine := function( A, B )
    local result, U;

    if IsBound(RP!.UnionOfRowsPair) then

        result := RP!.UnionOfRowsPair( A, B );

    else

        #=====# can only work for homalg internal matrices #=====#

        U := ShallowCopy( Eval( A )!.matrix );

        U{ [ NrRows( A ) + 1 .. NrRows( A ) + NrRows( B ) ] } := Eval( B )!.matrix;

        result := homalgInternalMatrixHull( U );

    fi;

    return HomalgMatrixWithAttributes( [
        Eval, result,
        EvalUnionOfRows, [ A, B ],
        NrRows, NrRows( A ) + NrRows( B ),
        NrColumns, NrColumns( A ),
        ], R );

end;

while Length( e ) > 1 do

    for i in [ 1 .. Int( Length( e ) / 2 ) ] do

```

```

        e[ 2 * i - 1 ] := combine( e[ 2 * i - 1 ], e[ 2 * i ] );
        Unbind( e[ 2 * i ] );

    od;

    e := Compacted( e );

od;

return Eval( e[1] );

end );

```

### C.4.12 Eval (for matrices created with UnionOfColumns)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using UnionOfColumns (5.5.11) then the filter HasEvalUnionOfColumns for *C* is set to true and the homalgTable function UnionOfColumns (B.1.11) or the homalgTable function UnionOfColumnsPair (B.1.12) will be used to set the attribute Eval.

```

----- Code -----
InstallMethod( Eval,
    "for homalg matrices (HasEvalUnionOfColumns)",
    [ IsHomalgMatrix and HasEvalUnionOfColumns ],

function( C )
    local R, RP, e, i, combine;

    R := HomalgRing( C );

    RP := homalgTable( R );

    # Make it mutable
    e := ShallowCopy( EvalUnionOfColumns( C ) );

    # In case of nested UnionOfColumns, we try to avoid
    # recursion, since the gap stack is rather small
    # additionally unpack PreEvals
    i := 1;
    while i <= Length( e ) do

        if HasPreEval( e[i] ) and not HasEval( e[i] ) then

            e[i] := PreEval( e[i] );

        elif HasEvalUnionOfColumns( e[i] ) and not HasEval( e[i] ) then

            e := Concatenation( e[ 1 .. (i-1) ], EvalUnionOfColumns( e[i] ), e[ (i+1) .. Length( e ) ] );

        else

```

```

        i := i + 1;

    fi;

od;

# Combine zero matrices
i := 1;
while i + 1 <= Length( e ) do

    if HasIsZero( e[i] ) and IsZero( e[i] ) and HasIsZero( e[i+1] ) and IsZero( e[i+1] ) then

        e[i] := HomalgZeroMatrix( NrRows( e[i] ), NrColumns( e[i] ) + NrColumns( e[i+1] ), Ho

        Remove( e, i + 1 );

    else

        i := i + 1;

    fi;

od;

# After combining zero matrices only a single one might be left
if Length( e ) = 1 then

    return e[1];

fi;

# Use RP!.UnionOfColumns if available
if IsBound(RP!.UnionOfColumns) then

    return RP!.UnionOfColumns( e );

fi;

# Fall back to RP!.UnionOfColumnsPair or manual fallback for internal matrices
# Combine the matrices
# Use a balanced binary tree to keep the sizes small (heuristically)
# to avoid a huge memory footprint

if not IsBound(RP!.UnionOfColumnsPair) and not IsHomalgInternalMatrixRep( C ) then
    Error( "could neither find a procedure called UnionOfColumns ",
          "nor a procedure called UnionOfColumnsPair ",
          "in the homalgTable of the non-internal ring\n" );
fi;

combine := function( A, B )
    local result, U;

```

```

    if IsBound(RP!.UnionOfColumnsPair) then

        result := RP!.UnionOfColumnsPair( A, B );

    else

        ##### can only work for homalg internal matrices #####

        U := List( Eval( A )!.matrix, ShallowCopy );

        U{ [ 1 .. NrRows( A ) ] }
          { [ NrColumns( A ) + 1 .. NrColumns( A ) + NrColumns( B ) ] }
          := Eval( B )!.matrix;

        result := homalgInternalMatrixHull( U );

    fi;

    return HomalgMatrixWithAttributes( [
        Eval, result,
        EvalUnionOfColumns, [ A, B ],
        NrRows, NrRows( A ),
        NrColumns, NrColumns( A ) + NrColumns( B )
    ], R );

end;

while Length( e ) > 1 do

    for i in [ 1 .. Int( Length( e ) / 2 ) ] do

        e[ 2 * i - 1 ] := combine( e[ 2 * i - 1 ], e[ 2 * i ] );
        Unbind( e[ 2 * i ] );

    od;

    e := Compacted( e );

od;

return Eval( e[1] );

end );

```

### C.4.13 Eval (for matrices created with DiagMat)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using DiagMat (5.5.12) then the filter HasEvalDiagMat for *C* is set to true and the homalgTable function DiagMat (B.1.13) will be used to set the attribute Eval.



```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalDiagMat)",
  [ IsHomalgMatrix and HasEvalDiagMat ],

function( C )
  local R, RP, e, z, m, n, diag, mat;

  R := HomalgRing( C );

  RP := homalgTable( R );

  e := EvalDiagMat( C );

  if IsBound(RP!.DiagMat) then
    return RP!.DiagMat( e );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called DiagMat ",
      "in the homalgTable of the non-internal ring\n" );
  fi;

  #=====# can only work for homalg internal matrices #=====#

  z := Zero( R );

  m := Sum( List( e, NrRows ) );
  n := Sum( List( e, NrColumns ) );

  diag := List( [ 1 .. m ], a -> List( [ 1 .. n ], b -> z ) );

  m := 0;
  n := 0;

  for mat in e do
    diag{ [ m + 1 .. m + NrRows( mat ) ] }{ [ n + 1 .. n + NrColumns( mat ) ] }
      := Eval( mat )!.matrix;

    m := m + NrRows( mat );
    n := n + NrColumns( mat );
  od;

  return homalgInternalMatrixHull( diag );

end );

```

#### C.4.14 Eval (for matrices created with KroneckerMat)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using `KroneckerMat` (5.5.13) then the filter `HasEvalKroneckerMat` for  $C$  is set to true and the `homalgTable` function `KroneckerMat` (B.1.14) will be used to set the attribute `Eval`.

```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalKroneckerMat)",
  [ IsHomalgMatrix and HasEvalKroneckerMat ],

function( C )
  local R, RP, A, B;

  R := HomalgRing( C );

  if ( HasIsCommutative( R ) and not IsCommutative( R ) ) and
    ( HasIsSuperCommutative( R ) and not IsSuperCommutative( R ) ) then
    Info( InfoWarning, 1, "\033[01m\033[5;31;47m",
      "the Kronecker product is only defined for (super) commutative rings!",
      "\033[0m" );
  fi;

  RP := homalgTable( R );

  A := EvalKroneckerMat( C )[1];
  B := EvalKroneckerMat( C )[2];

  if IsBound(RP!.KroneckerMat) then
    return RP!.KroneckerMat( A, B );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called KroneckerMat ",
      "in the homalgTable of the non-internal ring\n" );
  fi;

  #=====# can only work for homalg internal matrices #=====#

  return homalgInternalMatrixHull(
    KroneckerProduct( Eval( A )!.matrix, Eval( B )!.matrix ) );
  ## this was easy, thanks GAP :)

end );

```

### C.4.15 Eval (for matrices created with DualKroneckerMat)

▷ `Eval(C)`

(method)

**Returns:** the `Eval` value of a `homalg` matrix  $C$

In case the matrix was created using `DualKroneckerMat` (5.5.14) then the filter `HasEvalDualKroneckerMat` for  $C$  is set to true and the `homalgTable` function `DualKroneckerMat` (B.1.15) will be used to set the attribute `Eval`.

```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalDualKroneckerMat)",

```

```

[ IsHomalgMatrix and HasEvalDualKroneckerMat ],

function( C )
  local R, RP, A, B;

  R := HomalgRing( C );

  if ( HasIsCommutative( R ) and not IsCommutative( R ) ) and
    ( HasIsSuperCommutative( R ) and not IsSuperCommutative( R ) ) then
    Info( InfoWarning, 1, "\033[01m\033[5;31;47m",
      "the dual Kronecker product is only defined for (super) commutative rings!",
      "\033[0m" );
  fi;

  RP := homalgTable( R );

  A := EvalDualKroneckerMat( C )[1];
  B := EvalDualKroneckerMat( C )[2];

  # work around errors in Singular when taking the opposite ring of a ring with ordering lp
  # https://github.com/Singular/Singular/issues/1011
  if IsBound(RP!.DualKroneckerMat) and not ( IsBound( R!.ring ) and IsBound( R!.ring!.cas ) and

    return RP!.DualKroneckerMat( A, B );

  fi;

  if HasIsCommutative( R ) and IsCommutative( R ) then

    return Eval( KroneckerMat( B, A ) );

  else

    return Eval(
      TransposedMatrix( Involution(
        KroneckerMat( TransposedMatrix( Involution( B ) ), TransposedMatrix( Involution(
          ) )
        ) );
    );

  fi;

end );

```

### C.4.16 Eval (for matrices created with MulMat)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using `\*` (5.5.15) then the filter `HasEvalMulMat` for *C* is set to true and the `homalgTable` function `MulMat` (B.1.16) will be used to set the attribute `Eval`.

```

InstallMethod( Eval,
  "for homalg matrices (HasEvalMulMat)",

```

```

[ IsHomalgMatrix and HasEvalMulMat ],

function( C )
  local R, RP, e, a, A;

  R := HomalgRing( C );

  RP := homalgTable( R );

  e := EvalMulMat( C );

  a := e[1];
  A := e[2];

  if IsBound(RP!.MulMat) then
    return RP!.MulMat( a, A );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called MulMat ",
           "in the homalgTable of the non-internal ring\n" );
  fi;

  ##### can only work for homalg internal matrices #####

  return a * Eval( A );

end );

InstallMethod( Eval,
  "for homalg matrices (HasEvalMulMatRight)",
  [ IsHomalgMatrix and HasEvalMulMatRight ],

function( C )
  local R, RP, e, A, a;

  R := HomalgRing( C );

  RP := homalgTable( R );

  e := EvalMulMatRight( C );

  A := e[1];
  a := e[2];

  if IsBound(RP!.MulMatRight) then
    return RP!.MulMatRight( A, a );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called MulMatRight ",
           "in the homalgTable of the non-internal ring\n" );
  fi;

```

```

fi;

#=====# can only work for homalg internal matrices #=====#

return Eval( A ) * a;

end );

```

### C.4.17 Eval (for matrices created with AddMat)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using \+ (5.5.16) then the filter HasEvalAddMat for *C* is set to true and the homalgTable function AddMat (B.1.17) will be used to set the attribute Eval.

```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalAddMat)",
  [ IsHomalgMatrix and HasEvalAddMat ],

function( C )
  local R, RP, e, A, B;

  R := HomalgRing( C );

  RP := homalgTable( R );

  e := EvalAddMat( C );

  A := e[1];
  B := e[2];

  ResetFilterObj( C, HasEvalAddMat );

  ## delete the component which was left over by GAP
  Unbind( C!.EvalAddMat );

  if IsBound(RP!.AddMat) then
    return RP!.AddMat( A, B );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called AddMat ",
      "in the homalgTable of the non-internal ring\n" );
  fi;

  #=====# can only work for homalg internal matrices #=====#

  return Eval( A ) + Eval( B );

end );

```

### C.4.18 Eval (for matrices created with SubMat)

▷ Eval( $C$ )

(method)

**Returns:** the Eval value of a homalg matrix  $C$

In case the matrix was created using \- (5.5.17) then the filter HasEvalSubMat for  $C$  is set to true and the homalgTable function SubMat (B.1.18) will be used to set the attribute Eval.

```

Code
InstallMethod( Eval,
    "for homalg matrices (HasEvalSubMat)",
    [ IsHomalgMatrix and HasEvalSubMat ],

    function( C )
        local R, RP, e, A, B;

        R := HomalgRing( C );

        RP := homalgTable( R );

        e := EvalSubMat( C );

        A := e[1];
        B := e[2];

        ResetFilterObj( C, HasEvalSubMat );

        ## delete the component which was left over by GAP
        Unbind( C!.EvalSubMat );

        if IsBound(RP!.SubMat) then
            return RP!.SubMat( A, B );
        fi;

        if not IsHomalgInternalMatrixRep( C ) then
            Error( "could not find a procedure called SubMat ",
                "in the homalgTable of the non-internal ring\n" );
        fi;

        #=====# can only work for homalg internal matrices #=====#

        return Eval( A ) - Eval( B );

    end );

```

### C.4.19 Eval (for matrices created with Compose)

▷ Eval( $C$ )

(method)

**Returns:** the Eval value of a homalg matrix  $C$

In case the matrix was created using \\* (5.5.18) then the filter HasEvalCompose for  $C$  is set to true and the homalgTable function Compose (B.1.19) will be used to set the attribute Eval.

```

Code
InstallMethod( Eval,
    "for homalg matrices (HasEvalCompose)",

```

```

[ IsHomalgMatrix and HasEvalCompose ],

function( C )
  local R, RP, e, A, B;

  R := HomalgRing( C );

  RP := homalgTable( R );

  e := EvalCompose( C );

  A := e[1];
  B := e[2];

  ResetFilterObj( C, HasEvalCompose );

  ## delete the component which was left over by GAP
  Unbind( C!.EvalCompose );

  if IsBound(RP!.Compose) then
    return RP!.Compose( A, B );
  fi;

  if not IsHomalgInternalMatrixRep( C ) then
    Error( "could not find a procedure called Compose ",
          "in the homalgTable of the non-internal ring\n" );
  fi;

  #=====# can only work for homalg internal matrices #=====#

  return Eval( A ) * Eval( B );

end );

```

#### C.4.20 Eval (for matrices created with CoefficientsWithGivenMonomials)

▷ Eval(*C*)

(method)

**Returns:** the Eval value of a homalg matrix *C*

In case the matrix was created using CoefficientsWithGivenMonomials (5.5.56) then the filter HasEvalCoefficientsWithGivenMonomials for *C* is set to true and the homalgTable function CoefficientsWithGivenMonomials (B.1.24) will be used to set the attribute Eval.

```

Code
InstallMethod( Eval,
  "for homalg matrices (HasEvalCoefficientsWithGivenMonomials)",
  [ IsHomalgMatrix and HasEvalCoefficientsWithGivenMonomials ],

function( C )
  local R, RP, pair, M, monomials;

  R := HomalgRing( C );

  RP := homalgTable( R );

```

```
pair := EvalCoefficientsWithGivenMonomials( C );

M := pair[1];
monomials := pair[2];

if IsBound( RP!.CoefficientsWithGivenMonomials ) then
    return RP!.CoefficientsWithGivenMonomials( M, monomials );
fi;

Error( "could not find a procedure called CoefficientsWithGivenMonomials ",
      "in the homalgTable of the ring\n" );

end );
```



## Appendix D

# The subpackage ResidueClassRingForHomalg as a sample ring package

### D.1 The Mandatory Basic Operations

#### D.1.1 BasisOfRowModule (ResidueClassRing)

▷ BasisOfRowModule( $M$ ) (function)

**Returns:** a homalg matrix over the ambient ring

```
Code
BasisOfRowModule :=
function( M )
  local Mrel;

  Mrel := StackedRelations( M );

  Mrel := HomalgResidueClassMatrix(
    BasisOfRowModule( Mrel ), HomalgRing( M ) );

  return GetRidOfObsoleteRows( Mrel );

end,
```

#### D.1.2 BasisOfColumnModule (ResidueClassRing)

▷ BasisOfColumnModule( $M$ ) (function)

**Returns:** a homalg matrix over the ambient ring

```
Code
BasisOfColumnModule :=
function( M )
  local Mrel;

  Mrel := AugmentedRelations( M );
```

```

Mrel := HomalgResidueClassMatrix(
    BasisOfColumnModule( Mrel ), HomalgRing( M ) );

return GetRidOfObsoleteColumns( Mrel );

end,

```

### D.1.3 DecideZeroRows (ResidueClassRing)

▷ DecideZeroRows( $A$ ,  $B$ )

(function)

**Returns:** a homalg matrix over the ambient ring

```

Code
DecideZeroRows :=
function( A, B )
    local Brel;

    Brel := StackedRelations( B );

    Brel := BasisOfRowModule( Brel );

    return HomalgResidueClassMatrix(
        DecideZeroRows( Eval( A ), Brel ), HomalgRing( A ) );

end,

```

### D.1.4 DecideZeroColumns (ResidueClassRing)

▷ DecideZeroColumns( $A$ ,  $B$ )

(function)

**Returns:** a homalg matrix over the ambient ring

```

Code
DecideZeroColumns :=
function( A, B )
    local Brel;

    Brel := AugmentedRelations( B );

    Brel := BasisOfColumnModule( Brel );

    return HomalgResidueClassMatrix(
        DecideZeroColumns( Eval( A ), Brel ), HomalgRing( A ) );

end,

```

### D.1.5 SyzygiesGeneratorsOfRows (ResidueClassRing)

▷ SyzygiesGeneratorsOfRows( $M$ )

(function)

**Returns:** a homalg matrix over the ambient ring

```

Code
SyzygiesGeneratorsOfRows :=
function( M )

```

```

local R, ring_rel, rel, S;

R := HomalgRing( M );

ring_rel := RingRelations( R );

rel := MatrixOfRelations( ring_rel );

if IsHomalgRingRelationsAsGeneratorsOfRightIdeal( ring_rel ) then
    rel := Involution( rel );
fi;

rel := DiagMat( ListWithIdenticalEntries( NrColumns( M ), rel ) );

S := SyzygiesGeneratorsOfRows( Eval( M ), rel );

S := HomalgResidueClassMatrix( S, R );

S := GetRidOfObsoleteRows( S );

if IsZero( S ) then
    SetIsLeftRegular( M, true );
fi;

return S;

end,

```

### D.1.6 SyzygiesGeneratorsOfColumns (ResidueClassRing)

▷ SyzygiesGeneratorsOfColumns( $M$ )

(function)

**Returns:** a homalg matrix over the ambient ring

Code

```

SyzygiesGeneratorsOfColumns :=
function( M )
    local R, ring_rel, rel, S;

    R := HomalgRing( M );

    ring_rel := RingRelations( R );

    rel := MatrixOfRelations( ring_rel );

    if IsHomalgRingRelationsAsGeneratorsOfLeftIdeal( ring_rel ) then
        rel := Involution( rel );
    fi;

    rel := DiagMat( ListWithIdenticalEntries( NrRows( M ), rel ) );

    S := SyzygiesGeneratorsOfColumns( Eval( M ), rel );

```

```

S := HomalgResidueClassMatrix( S, R );

S := GetRidOfObsoleteColumns( S );

if IsZero( S ) then

    SetIsRightRegular( M, true );

fi;

return S;

end,

```

### D.1.7 BasisOfRowsCoeff (ResidueClassRing)

▷ BasisOfRowsCoeff( $M$ ,  $T$ )

(function)

**Returns:** a homalg matrix over the ambient ring

Code

```

BasisOfRowsCoeff :=
function( M, T )
    local Mrel, TT, bas, nz;

    Mrel := StackedRelations( M );

    TT := HomalgVoidMatrix( HomalgRing( Mrel ) );

    bas := BasisOfRowsCoeff( Mrel, TT );

    bas := HomalgResidueClassMatrix( bas, HomalgRing( M ) );

    nz := NonZeroRows( bas );

    SetEval( T, CertainRows( CertainColumns( TT, [ 1 .. NrRows( M ) ] ), nz ) );

    ResetFilterObj( T, IsVoidMatrix );

    ## the generic BasisOfRowsCoeff will assume that
    ## ( NrRows( B ) = 0 ) = IsZero( B )
    return CertainRows( bas, nz );

end,

```

### D.1.8 BasisOfColumnsCoeff (ResidueClassRing)

▷ BasisOfColumnsCoeff( $M$ ,  $T$ )

(function)

**Returns:** a homalg matrix over the ambient ring

Code

```

BasisOfColumnsCoeff :=
function( M, T )

```

```

local Mrel, TT, bas, nz;

Mrel := AugmentedRelations( M );

TT := HomalgVoidMatrix( HomalgRing( Mrel ) );

bas := BasisOfColumnsCoeff( Mrel, TT );

bas := HomalgResidueClassMatrix( bas, HomalgRing( M ) );

nz := NonZeroColumns( bas );

SetEval( T, CertainColumns( CertainRows( TT, [ 1 .. NrColumns( M ) ] ), nz ) );

ResetFilterObj( T, IsVoidMatrix );

## the generic BasisOfColumnsCoeff will assume that
## ( NrColumns( B ) = 0 ) = IsZero( B )
return CertainColumns( bas, nz );

end,

```

### D.1.9 DecideZeroRowsEffectively (ResidueClassRing)

▷ DecideZeroRowsEffectively( $A$ ,  $B$ ,  $T$ )

(function)

**Returns:** a homalg matrix over the ambient ring

Code

```

DecideZeroRowsEffectively :=
function( A, B, T )
  local Brel, TT, red;

  Brel := StackedRelations( B );

  TT := HomalgVoidMatrix( HomalgRing( Brel ) );

  red := DecideZeroRowsEffectively( Eval( A ), Brel, TT );

  SetEval( T, CertainColumns( TT, [ 1 .. NrRows( B ) ] ) );

  ResetFilterObj( T, IsVoidMatrix );

  return HomalgResidueClassMatrix( red, HomalgRing( A ) );

end,

```

### D.1.10 DecideZeroColumnsEffectively (ResidueClassRing)

▷ DecideZeroColumnsEffectively( $A$ ,  $B$ ,  $T$ )

(function)

**Returns:** a homalg matrix over the ambient ring

Code

```
DecideZeroColumnsEffectively :=
function( A, B, T )
  local Brel, TT, red;

  Brel := AugmentedRelations( B );

  TT := HomalgVoidMatrix( HomalgRing( Brel ) );

  red := DecideZeroColumnsEffectively( Eval( A ), Brel, TT );

  SetEval( T, CertainRows( TT, [ 1 .. NrColumns( B ) ] ) );

  ResetFilterObj( T, IsVoidMatrix );

  return HomalgResidueClassMatrix( red, HomalgRing( A ) );

end,
```

### D.1.11 RelativeSyzygiesGeneratorsOfRows (ResidueClassRing)

▷ RelativeSyzygiesGeneratorsOfRows( $M$ ,  $M2$ )

(function)

**Returns:** a homalg matrix over the ambient ring

Code

```
RelativeSyzygiesGeneratorsOfRows :=
function( M, M2 )
  local M2rel, S;

  M2rel := StackedRelations( M2 );

  S := SyzygiesGeneratorsOfRows( Eval( M ), M2rel );

  S := HomalgResidueClassMatrix( S, HomalgRing( M ) );

  S := GetRidOfObsoleteRows( S );

  if IsZero( S ) then
    SetIsLeftRegular( M, true );
  fi;

  return S;

end,
```

### D.1.12 RelativeSyzygiesGeneratorsOfColumns (ResidueClassRing)

▷ RelativeSyzygiesGeneratorsOfColumns( $M$ ,  $M2$ )

(function)

**Returns:** a homalg matrix over the ambient ring

```

Code
-----
RelativeSyzygiesGeneratorsOfColumns :=
function( M, M2 )
  local M2rel, S;

  M2rel := AugmentedRelations( M2 );

  S := SyzygiesGeneratorsOfColumns( Eval( M ), M2rel );

  S := HomalgResidueClassMatrix( S, HomalgRing( M ) );

  S := GetRidOfObsoleteColumns( S );

  if IsZero( S ) then
    SetIsRightRegular( M, true );
  fi;

  return S;

end,

```

## D.2 The Mandatory Tool Operations

Here we list those matrix operations for which homalg provides no fallback method.

### D.2.1 InitialMatrix (ResidueClassRing)

▷ InitialMatrix() (function)  
**Returns:** a homalg matrix over the ambient ring  
 (→ InitialMatrix (B.1.1))

```

Code
-----
InitialMatrix := C -> HomalgInitialMatrix(
  NrRows( C ), NrColumns( C ), AmbientRing( HomalgRing( C ) ) ),

```

### D.2.2 InitialIdentityMatrix (ResidueClassRing)

▷ InitialIdentityMatrix() (function)  
**Returns:** a homalg matrix over the ambient ring  
 (→ InitialIdentityMatrix (B.1.2))

```

Code
-----
InitialIdentityMatrix := C -> HomalgInitialIdentityMatrix(
  NrRows( C ), AmbientRing( HomalgRing( C ) ) ),

```

### D.2.3 ZeroMatrix (ResidueClassRing)

▷ ZeroMatrix() (function)  
**Returns:** a homalg matrix over the ambient ring

( $\rightarrow$  ZeroMatrix (B.1.3))

Code

```
ZeroMatrix := C -> HomalgZeroMatrix(
    NrRows( C ), NrColumns( C ), AmbientRing( HomalgRing( C ) ) ),
```

## D.2.4 IdentityMatrix (ResidueClassRing)

▷ IdentityMatrix()

(function)

**Returns:** a homalg matrix over the ambient ring

( $\rightarrow$  IdentityMatrix (B.1.4))

Code

```
IdentityMatrix := C -> HomalgIdentityMatrix(
    NrRows( C ), AmbientRing( HomalgRing( C ) ) ),
```

## D.2.5 Involution (ResidueClassRing)

▷ Involution()

(function)

**Returns:** a homalg matrix over the ambient ring

( $\rightarrow$  Involution (B.1.5))

Code

```
Involution :=
function( M )
    local N, R;

    N := Involution( Eval( M ) );

    R := HomalgRing( N );

    if not ( HasIsCommutative( R ) and IsCommutative( R ) and
        HasIsReducedModuloRingRelations( M ) and
        IsReducedModuloRingRelations( M ) ) then

        ## reduce the matrix N w.r.t. the ring relations
        N := DecideZero( N, HomalgRing( M ) );
    fi;

    return N;

end,
```

## D.2.6 TransposedMatrix (ResidueClassRing)

▷ TransposedMatrix()

(function)

**Returns:** a homalg matrix over the ambient ring

( $\rightarrow$  TransposedMatrix (B.1.6))

Code

```
TransposedMatrix :=
function( M )
    local N, R;
```



```

N := TransposedMatrix( Eval( M ) );

R := HomalgRing( N );

if not ( HasIsCommutative( R ) and IsCommutative( R ) and
        HasIsReducedModuloRingRelations( M ) and
        IsReducedModuloRingRelations( M ) ) then

    ## reduce the matrix N w.r.t. the ring relations
    N := DecideZero( N, HomalgRing( M ) );
fi;

return N;

end,

```

### D.2.7 CertainRows (ResidueClassRing)

▷ CertainRows()

(function)

**Returns:** a homalg matrix over the ambient ring  
 (→ CertainRows (B.1.7))

Code

```

CertainRows :=
function( M, plist )
  local N;

  N := CertainRows( Eval( M ), plist );

  if not ( HasIsReducedModuloRingRelations( M ) and
          IsReducedModuloRingRelations( M ) ) then

      ## reduce the matrix N w.r.t. the ring relations
      N := DecideZero( N, HomalgRing( M ) );
  fi;

  return N;

end,

```

### D.2.8 CertainColumns (ResidueClassRing)

▷ CertainColumns()

(function)

**Returns:** a homalg matrix over the ambient ring  
 (→ CertainColumns (B.1.8))

Code

```

CertainColumns :=
function( M, plist )
  local N;

  N := CertainColumns( Eval( M ), plist );

```

```

    if not ( HasIsReducedModuloRingRelations( M ) and
              IsReducedModuloRingRelations( M ) ) then

        ## reduce the matrix N w.r.t. the ring relations
        N := DecideZero( N, HomalgRing( M ) );
    fi;

    return N;

end,

```

### D.2.9 UnionOfRows (ResidueClassRing)

▷ UnionOfRows()

(function)

**Returns:** a homalg matrix over the ambient ring

(→ UnionOfRows ([B.1.9](#)))

Code

```

UnionOfRows :=
function( L )
    local N;

    N := UnionOfRows( List( L, Eval ) );

    if not ForAll( L, HasIsReducedModuloRingRelations and
                  IsReducedModuloRingRelations ) then

        ## reduce the matrix N w.r.t. the ring relations
        N := DecideZero( N, HomalgRing( L[1] ) );
    fi;

    return N;

end,

```

### D.2.10 UnionOfColumns (ResidueClassRing)

▷ UnionOfColumns()

(function)

**Returns:** a homalg matrix over the ambient ring

(→ UnionOfColumns ([B.1.11](#)))

Code

```

UnionOfColumns :=
function( L )
    local N;

    N := UnionOfColumns( List( L, Eval ) );

    if not ForAll( L, HasIsReducedModuloRingRelations and
                  IsReducedModuloRingRelations ) then

        ## reduce the matrix N w.r.t. the ring relations
        N := DecideZero( N, HomalgRing( L[1] ) );
    fi;

    return N;

end,

```

```

    fi;

    return N;

end,

```

### D.2.11 DiagMat (ResidueClassRing)

▷ `DiagMat()` (function)

**Returns:** a homalg matrix over the ambient ring  
(→ `DiagMat` (B.1.13))

Code

```

DiagMat :=
function( e )
  local N;

  N := DiagMat( List( e, Eval ) );

  if not ForAll( e, HasIsReducedModuloRingRelations and
    IsReducedModuloRingRelations ) then

    ## reduce the matrix N w.r.t. the ring relations
    N := DecideZero( N, HomalgRing( e[1] ) );
  fi;

  return N;

end,

```

### D.2.12 KroneckerMat (ResidueClassRing)

▷ `KroneckerMat()` (function)

**Returns:** a homalg matrix over the ambient ring  
(→ `KroneckerMat` (B.1.14))

Code

```

KroneckerMat :=
function( A, B )
  local N;

  N := KroneckerMat( Eval( A ), Eval( B ) );

  if not ForAll( [ A, B ], HasIsReducedModuloRingRelations and
    IsReducedModuloRingRelations ) then

    ## reduce the matrix N w.r.t. the ring relations
    N := DecideZero( N, HomalgRing( A ) );
  fi;

  return N;

end,

```

**D.2.13 DualKroneckerMat (ResidueClassRing)**

▷ DualKroneckerMat() (function)

**Returns:** a homalg matrix over the ambient ring

(→ DualKroneckerMat (B.1.15))

```

Code
DualKroneckerMat :=
function( A, B )
  local N;

  N := DualKroneckerMat( Eval( A ), Eval( B ) );

  if not ForAll( [ A, B ], HasIsReducedModuloRingRelations and
    IsReducedModuloRingRelations ) then

    ## reduce the matrix N w.r.t. the ring relations
    N := DecideZero( N, HomalgRing( A ) );
  fi;

  return N;

end,

```

**D.2.14 MulMat (ResidueClassRing)**

▷ MulMat() (function)

**Returns:** a homalg matrix over the ambient ring

(→ MulMat (B.1.16))

```

Code
MulMat :=
function( a, A )

  return DecideZero( EvalRingElement( a ) * Eval( A ), HomalgRing( A ) );

end,
MulMatRight :=
function( A, a )

  return DecideZero( Eval( A ) * EvalRingElement( a ), HomalgRing( A ) );

end,

```

**D.2.15 AddMat (ResidueClassRing)**

▷ AddMat() (function)

**Returns:** a homalg matrix over the ambient ring

(→ AddMat (B.1.17))

```

Code
AddMat :=
function( A, B )

```

```

    return DecideZero( Eval( A ) + Eval( B ), HomalgRing( A ) );
end,

```

### D.2.16 SubMat (ResidueClassRing)

▷ SubMat() (function)

**Returns:** a homalg matrix over the ambient ring  
 (→ SubMat (B.1.18))

```

SubMat :=
function( A, B )

    return DecideZero( Eval( A ) - Eval( B ), HomalgRing( A ) );

end,

```

### D.2.17 Compose (ResidueClassRing)

▷ Compose() (function)

**Returns:** a homalg matrix over the ambient ring  
 (→ Compose (B.1.19))

```

Compose :=
function( A, B )

    return DecideZero( Eval( A ) * Eval( B ), HomalgRing( A ) );

end,

```

### D.2.18 IsZeroMatrix (ResidueClassRing)

▷ IsZeroMatrix(M) (function)

**Returns:** true or false  
 (→ IsZeroMatrix (B.1.20))

```

IsZeroMatrix := M -> IsZero( DecideZero( Eval( M ), HomalgRing( M ) ) ),

```

### D.2.19 NrRows (ResidueClassRing)

▷ NrRows(C) (function)

**Returns:** a nonnegative integer  
 (→ NrRows (B.1.21))

```

NrRows := C -> NrRows( Eval( C ) ),

```

### D.2.20 NrColumns (ResidueClassRing)

▷ NrColumns( $C$ ) (function)

**Returns:** a nonnegative integer

(→ NrColumns (B.1.22))

```
NrColumns := C -> NrColumns( Eval( C ) ),
```

### D.2.21 Determinant (ResidueClassRing)

▷ Determinant( $C$ ) (function)

**Returns:** an element of ambient homalg ring

(→ Determinant (B.1.23))

```
Determinant := C -> DecideZero( Determinant( Eval( C ) ), HomalgRing( C ) ),
```

## D.3 Some of the Recommended Tool Operations

Here we list those matrix operations for which homalg does provide a fallback method. But specifying the below homalgTable functions increases the performance by replacing the fallback method.

### D.3.1 AreEqualMatrices (ResidueClassRing)

▷ AreEqualMatrices( $A$ ,  $B$ ) (function)

**Returns:** true or false

(→ AreEqualMatrices (B.2.1))

```
AreEqualMatrices :=
function( A, B )

    return IsZero( DecideZero( Eval( A ) - Eval( B ), HomalgRing( A ) ) );

end,
```

### D.3.2 IsOne (ResidueClassRing)

▷ IsOne( $M$ ) (function)

**Returns:** true or false

(→ IsIdentityMatrix (B.2.2))

```
IsIdentityMatrix := M ->
    IsOne( DecideZero( Eval( M ), HomalgRing( M ) ) ),
```

### D.3.3 IsDiagonalMatrix (ResidueClassRing)

▷ IsDiagonalMatrix( $M$ ) (function)

**Returns:** true or false

(→ IsDiagonalMatrix (B.2.3))

Code

```
IsDiagonalMatrix := M ->
  IsDiagonalMatrix( DecideZero( Eval( M ), HomalgRing( M ) ) ),
```

### D.3.4 ZeroRows (ResidueClassRing)

▷ ZeroRows(*C*) (function)  
**Returns:** a homalg matrix over the ambient ring  
 (→ ZeroRows ([B.2.4](#)))

Code

```
ZeroRows := C -> ZeroRows( DecideZero( Eval( C ), HomalgRing( C ) ) ),
```

### D.3.5 ZeroColumns (ResidueClassRing)

▷ ZeroColumns(*C*) (function)  
**Returns:** a homalg matrix over the ambient ring  
 (→ ZeroColumns ([B.2.5](#)))

Code

```
ZeroColumns := C -> ZeroColumns( DecideZero( Eval( C ), HomalgRing( C ) ) ),
```

## Appendix E

# Debugging MatricesForHomalg

Beside the GAP builtin debugging facilities ( $\rightarrow$  (**Reference: Debugging and Profiling Facilities**)) `MatricesForHomalg` provides two ways to debug the computations.

### E.1 Increase the assertion level

`MatricesForHomalg` comes with numerous builtin assertion checks. They are activated if the user increases the assertion level using

```
SetAssertionLevel( level );
```

( $\rightarrow$  (**Reference: AssertionLevel**)), where `level` is one of the values below:

level	description
0	no assertion checks whatsoever
4	assertions about basic matrix operations are checked ( $\rightarrow$ <a href="#">Appendix A</a> ) (these are among the operations often delegated to external systems)

In particular, if `MatricesForHomalg` delegates matrix operations to an external system then `SetAssertionLevel( 4 );` can be used to let `MatricesForHomalg` debug the external system.

Below you can find the record of the available level-4 assertions, which is a GAP-component of every `homalg` ring. Each assertion can thus be overwritten by package developers or even ordinary users.

```
Code
asserts :=
  rec(
    BasisOfRowModule :=
      function( B ) return ( NrRows( B ) = 0 ) = IsZero( B ); end,
    BasisOfColumnModule :=
      function( B ) return ( NrColumns( B ) = 0 ) = IsZero( B ); end,
```



```

BasisOfRowsCoeff :=
  function( B, T, M ) return B = T * M; end,

BasisOfColumnsCoeff :=
  function( B, M, T ) return B = M * T; end,

DecideZeroRows_Effectively :=
  function( M, A, B ) return M = DecideZeroRows( A, B ); end,

DecideZeroColumns_Effectively :=
  function( M, A, B ) return M = DecideZeroColumns( A, B ); end,

DecideZeroRowsEffectively :=
  function( M, A, T, B ) return M = A + T * B; end,

DecideZeroColumnsEffectively :=
  function( M, A, B, T ) return M = A + B * T; end,

DecideZeroRowsWRTNonBasis :=
  function( B )
    local R;
    R := HomalgRing( B );
    if not ( HasIsBasisOfRowsMatrix( B ) and
              IsBasisOfRowsMatrix( B ) ) and
      IsBound( R!.DecideZeroWRTNonBasis ) then
      if R!.DecideZeroWRTNonBasis = "warn" then
        Info( InfoWarning, 1,
              "about to reduce with respect to a matrix",
              "with IsBasisOfRowsMatrix not set to true" );
      elif R!.DecideZeroWRTNonBasis = "error" then
        Error( "about to reduce with respect to a matrix",
              "with IsBasisOfRowsMatrix not set to true\n" );
      fi;
    fi;
  end,

DecideZeroColumnsWRTNonBasis :=
  function( B )
    local R;
    R := HomalgRing( B );
    if not ( HasIsBasisOfColumnsMatrix( B ) and
              IsBasisOfColumnsMatrix( B ) ) and
      IsBound( R!.DecideZeroWRTNonBasis ) then
      if R!.DecideZeroWRTNonBasis = "warn" then
        Info( InfoWarning, 1,
              "about to reduce with respect to a matrix",
              "with IsBasisOfColumnsMatrix not set to true" );
      elif R!.DecideZeroWRTNonBasis = "error" then
        Error( "about to reduce with respect to a matrix",
              "with IsBasisOfColumnsMatrix not set to true\n" );
      fi;
    fi;
  end,

```

```

end,

ReducedBasisOfRowModule :=
function( M, B )
  return GenerateSameRowModule( B, BasisOfRowModule( M ) );
end,

ReducedBasisOfColumnModule :=
function( M, B )
  return GenerateSameColumnModule( B, BasisOfColumnModule( M ) );
end,

ReducedSyzygiesGeneratorsOfRows :=
function( M, S )
  return GenerateSameRowModule( S, SyzygiesGeneratorsOfRows( M ) );
end,

ReducedSyzygiesGeneratorsOfColumns :=
function( M, S )
  return GenerateSameColumnModule( S, SyzygiesGeneratorsOfColumns( M ) );
end,

);

```

## E.2 Using homalgMode

### E.2.1 homalgMode

▷ `homalgMode(str[, str2])` (method)

This function sets different modes which influence how much of the basic matrix operations and the logical matrix methods become visible (→ Appendices A, C). Handling the string *str* is *not* case-sensitive. If a second string *str2* is given, then `homalgMode( str2 )` is invoked at the end. In case you let `homalg` delegate matrix operations to an external system the you might also want to check `homalgIOMode` in the `HomalgToCAS` package manual.

<i>str</i>	<i>str</i> (long form)	mode description
""	""	the default mode, i.e. the computation protocol won't be visible ( <code>homalgMode( )</code> is a short form for <code>homalgMode( "" )</code> )
"b"	"basic"	make the basic matrix operations visible + <code>homalgMode( "logic" )</code>
"d"	"debug"	same as "basic" but also makes <code>Row/ColumnReducedEchelonForm</code> visible
"l"	"logic"	make the logical methods in <code>LIMAT</code> and <code>COLEM</code> visible

All modes other than the "default"-mode only set their specific values and leave the other values

untouched, which allows combining them to some extent. This also means that in order to get from one mode to a new mode (without the aim to combine them) one needs to reset to the "default"-mode first. This can be done using `homalgMode( "", new_mode );`

```

Code
InstallGlobalFunction( homalgMode,
function( arg )
  local nargs, mode, s;

  nargs := Length( arg );

  if nargs = 0 or ( IsString( arg[1] ) and arg[1] = "" ) then
    mode := "default";
  elif IsString( arg[1] ) then      ## now we know, the string is not empty
    s := arg[1];
    if LowercaseString( s{[1]} ) = "b" then
      mode := "basic";
    elif LowercaseString( s{[1]} ) = "d" then
      mode := "debug";
    elif LowercaseString( s{[1]} ) = "l" then
      mode := "logic";
    else
      mode := "";
    fi;
  else
    Error( "the first argument must be a string\n" );
  fi;

  if mode = "default" then
    HOMALG_MATRICES.color_display := false;
    for s in HOMALG_MATRICES.matrix_logic_infolevels do
      SetInfoLevel( s, 1 );
    od;
    SetInfoLevel( InfoHomalgBasicOperations, 1 );
  elif mode = "basic" then
    SetInfoLevel( InfoHomalgBasicOperations, 3 );
    homalgMode( "logic" );
  elif mode = "debug" then
    SetInfoLevel( InfoHomalgBasicOperations, 4 );
    homalgMode( "logic" );
  elif mode = "logic" then
    HOMALG_MATRICES.color_display := true;
    for s in HOMALG_MATRICES.matrix_logic_infolevels do
      SetInfoLevel( s, 2 );
    od;
  fi;

  if nargs > 1 and IsString( arg[2] ) then
    homalgMode( arg[2] );
  fi;

end );

```

## Appendix F

# Overview of the **MatricesForHomalg** Package Source Code

### F.1 Rings, Ring Maps, Matrices, Ring Relations

Filename .gd/.gi	Content
homalg	definitions of the basic GAP4 categories and some tool functions (e.g. homalgMode)
homalgTable	dictionaries between MatricesForHomalg and the computing engines
HomalgRing	internal and external rings
HomalgRingMap	ring maps
HomalgMatrix	internal and external matrices
HomalgRingRelations	a set of ring relations

**Table:** *The MatricesForHomalg package files*

### F.2 The Low Level Algorithms

In the following CAS or CASystem mean computer algebra systems.

Filename .gd/.gi	Content
Tools	the elementary matrix operations that can be overwritten using the homalgTable (and hence delegable even to other CASystems)
Service	the three operations: basis, reduction, and syzygies; they can also be overwritten using the homalgTable (and hence delegable even to other CASystems)
Basic	higher level operations for matrices (cannot be overwritten using the homalgTable)

**Table:** *The MatricesForHomalg package files (continued)*

### F.3 Logical Implications for MatricesForHomalg Objects

Filename .gd/.gi	Content
LIRNG	logical implications for rings
LIMAP	logical implications for ring maps
LIMAT	logical implications for matrices
COLEM	clever operations for lazy evaluated matrices

**Table:** *The MatricesForHomalg package files (continued)*

### F.4 The subpackage ResidueClassRingForHomalg

Filename .gd/.gi	Content
ResidueClassRingForHomalg	some global variables
ResidueClassRing	residue class rings, their elements, and matrices, together with their constructors and operations
ResidueClassRingTools	the elementary matrix operations for matrices over residue class rings
ResidueClassRingBasic	the three operations: basis, reduction, and syzygies for matrices over residue class rings

**Table:** *The MatricesForHomalg package files (continued)*

## F.5 The homalgTable for GAP4 built-in rings

For the purposes of homalg, the ring of integers is, at least up till now, the only ring which is properly supported in GAP4. The GAP4 built-in capabilities for polynomial rings (also univariate) and group rings do not satisfy the minimum requirements of homalg. The GAP4 package Gauss enables GAP to fulfil the homalg requirements for prime fields, and  $\mathbb{Z}/p^n$ .

Filename .gi	Content
Integers	the homalgTable for the ring of integers

**Table:** *The MatricesForHomalg package files (continued)*

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