

# Iterated monodromy groups

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Groups and dynamical systems

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## **Abstract**

This document describes the package IMG, which implements in GAP the iterated monodromy groups of Nekrashevych. It depends on the package FR.

For comments or questions on IMG please contact the author; this package is still under development.

## **Copyright**

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## **Acknowledgements**

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## **Colophon**

This project started as a part of the GAP package FR. It expanded so much that I decided in 2012 to split it off, so as to keep more cleanly separated the group theory on one side, and the complex analysis, on the other side.

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# Chapter 1

## Licensing

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## Chapter 2

# IMG package

### 2.1 A brief mathematical introduction

This chapter assumes that you have no familiarity with iterated monodromy groups. If you do, and wish to see their usage within **GAP** through a sample session, please skip to Section 2.2. For a more thorough introduction on self-similar groups and iterated monodromy groups, see [BGN03] or [Nek05].

Basic knowledge of the package **FR** is assumed, however. Please refer to its online documentation, or the same references as above.

The fundamental objects are *Thurston maps*: branched self-coverings of the sphere  $S^2$ . These are continuous maps  $f : S^2 \rightarrow S^2$  that, locally, are modelled on the complex map  $z \mapsto z^n$ . The *critical points* are those points  $z$  at which the map is modelled on  $z \mapsto z^n$  for some  $n > 1$ . The *post-critical set* is the union  $P$  of strictly forward orbits of critical points. It is assumed finite.

Two Thurston maps  $f : (S^2, P) \rightarrow (S^2, P)$  and  $g : (S^2, Q) \rightarrow (S^2, Q)$  are *combinatorially equivalent* if they are isotopic through isotopies  $(S^2, P) \rightarrow (S^2, Q)$  that are constant on  $P$ .

Denote by  $G$  the fundamental group  $\pi_1(S^2 \setminus P, *)$  at a basepoint  $*$ . Then combinatorial equivalence classes of Thurston maps are classified by wreath recursions for  $G$ , namely homomorphisms  $\phi : G \rightarrow G \wr \text{Sym}_d$ . They are encoded, in **IMG**, by a new kind of **FR** machine, called a *sphere machine*. Generators of the machine correspond to loops in the fundamental group of the sphere (punctured at post-critical points), that circle once counter-clockwise around a post-critical point.

By a fundamental theorem of Thurston, every Thurston map (apart from a few low-complexity examples) is either combinatorially equivalent to a rational map, or is *obstructed*: there exists a system of curves on  $S^2 \setminus P$  with some appropriate non-contraction property.

The operations in this package let one manipulate Thurston maps, and in particular

- compute the rational map, or the obstruction, associated with a sphere machine;
- compute the sphere machine associated with a rational map;
- construct sphere machines algebraically, and identify their combinatorial parameters, in the case of polynomial maps;
- compute combinations of sphere machines, such as matings.

## 2.2 An example session

This is a brief introduction describing some of the simpler features of the IMG package. It assumes you have some familiarity with the theory of groups defined by automata, and of holomorphic dynamical systems; if not, a brief mathematical introduction may be found in Section 2.1. We show here and comment a typical use of the package.

The package is installed by unpacking the archive in the `pkg/` directory of your GAP installation. It can also be placed in a local directory, which must be added to the load-path by invoking gap with the `-l` option.

Example

```
gap> LoadPackage("img");
true
```

Many maps and sphere machines are predefined by the IMG, see Chapter 4.

We may start by defining a machine by its polynomial:

Example

```
gap> basilica := PolynomialSphereMachine(2,[1/3]);
<sphere machine with alphabet [ 1 .. 2 ] and adder FRElement(...,f3) on Group( [ f1, f2, f3 ] )/
3*f2*f1 ]>
gap> Display(basilica);
G |      1      2
----+-----+-----+
f1 | f1^-1,2   f3^-1,1
f2 |   f1,1    <id>,2
f3 |   f3,2    <id>,1
----+-----+-----+
Adding element: FRElement(...,f3)
Relators: [ f3*f2*f1 ]
```

We have just created the basilica machine, with group  $G = \langle f1, f2, f3 | f3f2f1 \rangle$ .

...

## Chapter 3

# Iterated monodromy groups

Iterated monodromy machines are a special class of group FR machines (see Section **FR: FRMachineNC (family,free,listlist,list)**) whose underlying StateSet (**FR: StateSet (FR machine)**) is a sphere group, namely a group given by a redundant generator and a relation involving all generators once.

### 3.1 Creators and operations for sphere machines

```
DeclareProperty("IsSphereMachine", IsFRMachine);
```

#### 3.1.1 IsSphereMachine

▷ `IsSphereMachine(m)` (filter)  
▷ `IsPolynomialSphereMachine(m)` (filter)

The categories of *Sphere* and *polynomial* machines. Sphere machines are group FR machines whose underlying group is a sphere group, see `SphereGroup` (3.1.12).

A polynomial machine is a group FR machine with a distinguished state (which must be a generator of the stateset), stored as the attribute `AddingElement` (3.1.25); see `AsPolynomialSphereMachine` (3.1.26). If it is normalized, in the sense that the wreath recursion of the adding element *a* is  $[[a, 1, \dots, 1], [d, 1, \dots, d-1]]$ , then the basepoint is assumed to be at  $+\infty$ ; the element *a* describes a clockwise loop around infinity; the *k*th preimage of the basepoint is at  $\exp(2i\pi(k-1)/d)\infty$ , for  $k = 1, \dots, d$ ; and there is a direct connection from basepoint *k* to *k* + 1 for all  $k = 1, \dots, d-1$ .

The last category is the intersection of the first two.

```
DeclareAttribute("AsSphereMachine", IsFRMachine); DeclareOperation("AsSphereMachine",  
[IsFRMachine, IsWord]); DeclareOperation("AsSphereMachine", [IsFRMachine, IsSphereGroup]);
```

#### 3.1.2 AsSphereMachine

▷ `AsSphereMachine(m [, w])` (operation)

**Returns:** A sphere machine.

This function creates a new sphere machine, starting from a group FR machine *m*. If a state *w* is specified, and that state defines the trivial FR element, then it is used as relator; if *w* is a sphere group, then it is used as the new stateset. Finally, if no relator and no group is specified, and the product

(in some ordering) of the generators is trivial, then that product is used as relator. In other cases, the method returns fail.

A standard FR machine can be recovered from a sphere machine by `AsGroupFRMachine` (**FR:** `AsGroupFRMachine`), `AsMonoidFRMachine` (**FR:** `AsMonoidFRMachine`), and `AsSemigroupFRMachine` (**FR:** `AsSemigroupFRMachine`).

Example

```
gap> m := UnderlyingFRMachine(BasilicaGroup);
<Mealy machine on alphabet [ 1 .. 2 ] with 3 states>
gap> g := AsGroupFRMachine(m);
<FR machine with alphabet [ 1 .. 2 ] on Group( [ f1, f2 ] )>
gap> AsSphereMachine(g, Product(GeneratorsOfFRMachine(g)));
<FR machine with alphabet [ 1 .. 2 ] on Group( [ f1, f2, t ] )/[ f1*f2*t ]>
gap> Display(last);
  G |               1               2
  ---+-----+-----+-----+
  f1 |               <id>,2         f2,1
  f2 |               <id>,1         f1,2
  t  | f2^-1*f1*f2*t,2   f1^-1,1
  ---+-----+-----+-----+
Relator: f1*f2*t
```

```
DeclareAttribute("CleanedSphereMachine", IsSphereMachine);
```

### 3.1.3 CleanedSphereMachine

▷ `CleanedSphereMachine(m)` (attribute)

**Returns:** A cleaned-up version of  $m$ .

This command attempts to shorten the length of the transitions in  $m$ , and ensure (if possible) that the product along every cycle of the states of a generator is a conjugate of a generator. It returns the new machine.

```
DeclareGlobalFunction("NewSphereMachine");
```

### 3.1.4 NewSphereMachine

▷ `NewSphereMachine(...)` (attribute)

**Returns:** A new sphere machine, based on string descriptions.

This command constructs a new sphere machine, in a format similar to `FRGroup` (**FR:** `FRGroup`); namely, the arguments are strings of the form "gen=<word-1,...,word-d>perm"; each word- $i$  is a word in the generators; and perm is a transformation, either written in disjoint cycle or in images notation. The underlying group of the machine is a sphere group.

word- $i$  is allowed to be the empty string; and the "<...>" may be skipped altogether. Each word- $i$  may also contain inverses.

The extra final arguments describe relations in the underlying sphere group; at least one relation is required, the product of the generators in an appropriate order.

The following examples construct realizable foldings of the polynomial  $z^3 + i$ , following Cui's arguments.

Example

```
gap> fold1 := NewSphereMachine("a=<,,b,,B>(1,2,3)(4,5,6)", "b=<,,b*a/b,,B*A/B>",
  "A=<,,b*a,,B*A>(3,6)", "B=(1,6,5,4,3,2)", "a*B*A*b");
```



```

gap> <FR machine with alphabet [ 1, 2, 3, 4, 5, 6 ] on Group( [ a, b, A, B ] )/[ a*B*A*b ]>
gap> fold2 := NewSphereMachine("a=<,,b,,,B>(1,2,3)(4,5,6)", "b=<,,b*a/b,,,B*A/B>",
    "A=(1,6)(2,5)(3,4)", "B=<B*A,,,b*a,,,>(1,4)(2,6)(3,5)", "a*B*A*b");;
gap> RationalFunction(fold1); RationalFunction(fold2);
...

```

```

DeclareProperty("IsSphereGroup", IsFpGroup); DeclareCategory("IsElementOfSphereGroup",
IsElementOfFpGroup and IsAssocWord); DeclareCategoryCollections("IsElementOfSphereGroup");
DeclareCategoryCollections("IsElementOfSphereGroupCollection"); DeclareProp-
erty("IsElementOfSphereGroupFamily", IsElementOfFpGroupFamily); DeclareOpera-
tion("ElementOfSphereGroup", [IsFamily, IsAssocWordWithInverse]);

```

### 3.1.5 IsSphereGroup

▷ IsSphereGroup (filter)

A sphere group is a special kind of finitely presented group, in which exactly one relation is a product, in some order, of all the generators, and all the other relations (possibly none) are powers of generators.

Sphere groups are used to represent the fundamental groups of punctured spheres, or more generally orbifolds whose underlying space is a sphere.

```

DeclareAttribute("IsomorphismSphereGroup", IsFpGroup); DeclareAttribute("AsSphereGroup",
IsFpGroup);

```

### 3.1.6 IsomorphismSphereGroup

▷ IsomorphismSphereGroup( $g$ ) (attribute)  
 ▷ AsSphereGroup( $g$ ) (attribute)

These functions compute an isomorphism from  $g$  to a sphere group; the first form returns the isomorphism, while the second one returns its image.

```

DeclareAttribute("EulerCharacteristic", IsGroup);

```

### 3.1.7 EulerCharacteristic

▷ EulerCharacteristic( $g$ ) (attribute)

**Returns:** The Euler characteristic of  $g$ .

The Euler characteristic of a free group of rank  $n$  is  $1 - n$ ; and it multiplies by the index on subgroups. A sphere group is finite if and only if its Euler characteristic is positive, and is virtually abelian if and only if its Euler characteristic is 0.

```

DeclareAttribute("RankOfSphereGroup", IsSphereGroup);

```

### 3.1.8 RankOfSphereGroup

▷ RankOfSphereGroup( $g$ ) (attribute)

**Returns:** The number of generators of  $g$ .

```

DeclareAttribute("OrderingOfSphereGroup", IsSphereGroup);

```

### 3.1.9 OrderingOfSphereGroup

▷ `OrderingOfSphereGroup( $g$ )` (attribute)

**Returns:** The list of the orders of the generators.

This attribute has the property that `Product(GeneratorsOfGroup( $g$ ){OrderingOfSphereGroup( $g$ )})` is the identity.

`DeclareAttribute("ExponentsOfSphereGroup", IsSphereGroup);`

### 3.1.10 ExponentsOfSphereGroup

▷ `ExponentsOfSphereGroup( $g$ )` (attribute)

**Returns:** The list of exponents of the generators.

This attribute has the property that `GeneratorsOfGroup( $g$ )[ $i$ ]ExponentsOfSphereGroup( $g$ )[ $i$ ]` is the identity for all  $i$ . If an element has infinite order, the value stored is 0.

`DeclareAttribute("IsomorphismFreeGroup", IsSphereGroup);`

### 3.1.11 IsomorphismFreeGroup

▷ `IsomorphismFreeGroup( $g$ )` (attribute)

**Returns:** An isomorphism to a free group, if it exists.

If  $g$  was created as a sphere group with all exponents infinity, then  $g$  is isomorphic to a free group on all the generators but one; this attribute stores such an isomorphism.

`DeclareGlobalFunction("SphereGroup");`

### 3.1.12 SphereGroup

▷ `SphereGroup( $ordering$  [,  $exponent$ ])` (function)

**Returns:** A new sphere group.

$ordering$  is either a list of integers, describing the order of the generators that is to be trivial; or an integer  $m$ , in which case the ordering is  $[m, m-1, \dots, 1]$ .

The optional second argument  $exponent$  is a list of integers describing the exponents of the generators. The value 0 specifies a generator of infinite order.

`DeclareProperty("IsSphereConjugacyClass", IsAssociativeElementCollection and IsMultiplicativeElementWithInverseCollection);` `DeclareProperty("IsSphereConjugacyClassCollection", IsAssociativeElementCollColl and IsMultiplicativeElementWithInverseCollColl);` `DeclareSynonym("IsMulticurve", IsSphereConjugacyClassCollection);` `DeclareOperation("InverseMutable", [IsSphereConjugacyClass]);` `DeclareOperation("InverseSameMutability", [IsSphereConjugacyClass]);` `DeclareAttribute("InverseImmutable", IsSphereConjugacyClass);` `DeclareOperation("POW", [IsSphereConjugacyClass, IsInt]);`

### 3.1.13 IsSphereConjugacyClass

▷ `IsSphereConjugacyClass` (filter)

Elements of a sphere group represent based loops on a punctured sphere. Loops (without specified basepoint) are represented by conjugacy classes. A *multicurve* is a collection of non-intersecting loops.

Conjugacy classes may be raised to integer powers; the  $n$ th power of a conjugacy class is the conjugacy class of the  $n$ th power of an element.

DeclareProperty("IsPeripheral", IsElementOfSphereGroup); DeclareProperty("IsPeripheral", IsSphereConjugacyClass);

### 3.1.14

▷  $(c)$  (property)

**Returns:** Whether the conjugacy class  $c$  is peripheral.

A conjugacy class is *peripheral* if it contains a generator of the sphere group.

DeclareAttribute("PeripheralClasses", IsSphereGroup);

### 3.1.15 PeripheralClasses

▷ PeripheralClasses( $g$ ) (attribute)

**Returns:** The peripheral conjugacy classes of  $g$ .

DeclareOperation("IntersectionNumber", [IsSphereConjugacyClass, IsSphereConjugacyClass]);  
DeclareOperation("SelfIntersectionNumber", [IsSphereConjugacyClass]);

### 3.1.16 IntersectionNumber

▷ IntersectionNumber( $c, d$ ) (attribute)

**Returns:** The intersection number of the conjugacy classes  $c$  and  $d$ .

The *geometric intersection number* of two loops is the minimal number of intersections they may have. The *self-intersection number* of a loop is the intersection number of the loop with a small translate.

DeclareProperty("IsAutomorphismGroupOfSphereGroup", IsAutomorphismGroup); InstallTrueMethod(IsAutomorphismGroup, IsAutomorphismGroupOfSphereGroup); DeclareAttribute("EpimorphismToOut", IsAutomorphismGroupOfSphereGroup);

### 3.1.17 AutomorphismGroup

▷ AutomorphismGroup( $g$ ) (attribute)

▷ EpimorphismToOut( $a$ ) (attribute)

This function computes the *pure* automorphism group of the sphere group  $g$ , namely the group of automorphisms that preserves all the peripheral conjugacy classes (conjugacy classes of generators).

The attribute EpimorphismToOut stores an epimorphism from the automorphism group to the group of outer automorphisms.

DeclareOperation("AmalgamatedFreeProduct", [IsSphereGroup, IsSphereGroup, IsElementOfSphereGroup, IsElementOfSphereGroup]);  
DeclareAttribute("EmbeddingsOfAmalgamatedFreeProduct", IsSphereGroup);

### 3.1.18 AmalgamateFreeProduct

▷ AmalgamateFreeProduct( $g, h, x, y$ ) (operation)

This function computes the amalgamated free product of two sphere groups  $g$  and  $h$ , along the cyclic subgroups  $\langle x \rangle$  of  $g$  and  $\langle y \rangle$  of  $h$ .

The attribute `EmbeddingsOfAmalgamatedFreeProduct` is a list of length two, storing the embeddings of  $g$  and  $h$  respectively into the amalgam.

```
DeclareGlobalFunction("NormalizedP1Map"); DeclareProperty("IsBicritical", IsObject);
```

### 3.1.19 NormalizedP1Map

▷ `NormalizedP1Map( $f$ ,  $M$ ,  $param$ )` (function)

**Returns:** [A canonical conjugate of  $f$ , the conjugator].

The last argument  $param$  is either `IsPolynomial`, `IsBicritical` or a positive integer.

In the first case, the map  $f$  is assumed conjugate to a polynomial. It is conjugated by a Möbius transformation that makes it a *centered* polynomial, namely a polynomial of the form  $z^d + a_{d-2}z^{d-2} + \dots + a_0$ .

In the second case, the map  $f$  is assumed to have only two critical values; it is normalized as  $(az^d + b)/(cz^d + e)$ .

In the third case, the map  $f$  is assumed to have degree 2; it is normalized in the form  $1 + a/z + b/z^2$ , such that 0 is on a cycle of length  $param$ .

```
DeclareOperation("ThurstonAlgorithm", [IsSphereMachine]);
```

### 3.1.20 ThurstonAlgorithm

▷ `ThurstonAlgorithm( $m$ )` (operation)

**Returns:** `rec(map := f, machine := M, markedsphere := s)`.

This command runs Thurston's algorithm on the sphere machine  $m$ . It either returns a record with the P1 map  $f$  to which the algorithm converged, as well as the marked sphere with  $f$ 's post-critical set and a simplified machine equivalent to  $m$ ; or a record returned by `ThurstonObstruction` (3.1.23).

```
DeclareOperation("P1MapBySphereMachine", [IsSphereMachine]);
```

### 3.1.21 P1MapBySphereMachine

▷ `P1MapBySphereMachine( $m$ )` (operation)

**Returns:** Either a map or an obstruction.

This command returns either the map computed by `ThurstonAlgorithm` (3.1.20) or a Thurston obstruction.

It runs a modification of Hubbard and Schleicher's "spider algorithm" [HS94] on the sphere machine  $m$ .

The command accepts the following options, to return a map in a given normalization:

```
P1MapBySphereMachine(m:param:=IsPolynomial)
```

returns  $f = z^d + A_{d-2}z^{d-2} + \dots + A_0$ ;

```
P1MapBySphereMachine(m:param:=IsBicritical)
```

returns  $f = ((pz + q)/(rz + s))^d$ , with 1 postcritical;

```
P1MapBySphereMachine(m:param:=n)
```

returns  $f = 1 + a/z + b/z^2$  or  $f = a/(z^2 + 2z)$  if  $n=2$ .

Example

```
gap> m := PolynomialSphereMachine(2, [1/3], []);
<FR machine with alphabet [ 1, 2 ] on Group( [ f1, f2, f3 ] )/[ f3*f2*f1 ]>
```

```
gap> P1MapBySphereMachine(m);
0.866025*z^2+(-1)*z+(-0.288675)
```

```
DeclareOperation("ThurstonMatrix", [IsSphereMachine, IsMulticurve]);
```

### 3.1.22 ThurstonMatrix

▷ `ThurstonMatrix(m, multicurve)` (operation)

**Returns:** The transition matrix of the multicurve.

This command computes the iterated preimages of the multicurve *multicurve* till it obtains a backwards-invariant multicurve or some preimages intersect. In the latter case, `fail` returned, while in the former case the Thurston matrix of the multicurve is returned.

Example

```
gap> r := PolynomialSphereMachine(2, [], [1/6]);;
gap> F := StateSet(r);;
gap> twist := GroupHomomorphismByImages(F, F, GeneratorsOfGroup(F), [F.1, F.2^(F.3*F.2), F.3^F.2, F.4]);
gap> SupportingRays(r*twist^-1);
rec( machine := <FR machine with alphabet [ 1, 2 ] on F/[ f4*f1*f2*f3 ]>,
      twist := [ f1, f2, f3, f4 ] -> [ f1, f3^-1*f2*f3, f3^-1*f2^-1*f3*f2*f3, f4 ],
      obstruction := "Dehn twist" )
gap> ThurstonMatrix(last.machine, [ConjugacyClass(F.2*F.3)]);
[ [ 1 ] ]
```

```
DeclareOperation("ThurstonObstruction", [IsSphereMachine, IsMarkedSphere]);
```

### 3.1.23 ThurstonObstruction

▷ `ThurstonObstruction(m, sphere)` (operation)

**Returns:** `rec(multicurve := mc, matrix := m)` or `fail`.

This command tries to find a Thurston obstruction (multicurve such that its Thurston matrix has spectral radius at least 1); it either returns `fail` if the search was inconclusive, or a record describing the obstruction.

The obstruction is searched for by considering small subtrees of the minimal spanning tree of *sphere*, computing loops surrounding these subtrees, and saturating them into a multicurve by taking their iterated preimages, see `ThurstonMatrix` (3.1.22).

```
DeclareProperty("IsKneadingMachine", IsFRMachine);
DeclareProperty("IsPlanarKneadingMachine", IsFRMachine);
InstallTrueMethod(IsBoundedFRMachine, IsKneadingMachine);
InstallTrueMethod(IsLevelTransitive, IsKneadingMachine);
```

### 3.1.24 IsKneadingMachine

▷ `IsKneadingMachine(m)` (property)

▷ `IsPlanarKneadingMachine(m)` (property)

**Returns:** Whether *m* is a (planar) kneading machine.

A *kneading machine* is a special kind of Mealy machine, used to describe postcritically finite complex polynomials. It is a machine such that its set of permutations is "treelike" (see [Nek05, §6.7]) and such that each non-trivial state occurs exactly once among the outputs.

Furthermore, this set of permutations is *treelike* if there exists an ordering of the states that their product in that order *t* is an adding machine; i.e. such that *t*'s activity is a full cycle, and the product

of its states along that cycle is conjugate to  $t$ . This element  $t$  represents the Carathéodory loop around infinity.

Example

```
gap> M := BinaryKneadingMachine("0");
BinaryKneadingMachine("0*")
gap> Display(M);
  | 1 2
---+---+---+
a | c,2 b,1
b | a,1 c,2
c | c,1 c,2
---+---+---+
gap> IsPlanarKneadingMachine(M);
true
gap> IsPlanarKneadingMachine(GrigorchukMachine);
false
```

```
DeclareAttribute("AddingElement", IsSphereMachine);
```

### 3.1.25 AddingElement

▷ AddingElement( $m$ )

(attribute)

**Returns:** The element generating the adding submachine.

This attribute stores the product of generators that is an adding machine. In essence, it records an ordering of the generators whose product corresponds to the Carathéodory loop around infinity.

The following example illustrates Wittner's shared mating of the airplane and the rabbit. In the machine  $m$ , an airplane is represented by  $\text{Group}(a, b, c)$  and a rabbit is represented by  $\text{Group}(x, y, z)$ ; in the machine  $\text{newm}$ , it is the other way round. The effect of  $\text{CleanedIMGMachine}$  was to remove unnecessary instances of the IMG relator from  $\text{newm}$ 's recursion.

Example

```
gap> f := FreeGroup("a", "b", "c", "x", "y", "z");;
gap> AssignGeneratorVariables(f);
gap> m := AsSphereMachine(FRMachine(f, [[a^-1, b*a], [One(f), c], [a, One(f)], [z*y*x,
x^-1*y^-1], [One(f), x], [One(f), y]], [(1,2), (), (), (1,2), (), ())]);;
gap> Display(m);
G | 1 2
---+---+---+
a | a^-1,2 b*a,1
b | <id>,1 c,2
c | a,1 <id>,2
x | z*y*x,2 x^-1*y^-1,1
y | <id>,1 x,2
z | <id>,1 y,2
---+---+---+
Relator: z*y*x*c*b*a
gap> iso := GroupHomomorphismByImages(f, f, [a, b^(y^-1), c^(x^-1*y^-1*a^-1), x^(b*a*z*a^-1), y, z^(a^-1)], [a, b^(y^-1), c^(x^-1*y^-1*a^-1), x^(b*a*z*a^-1), y, z^(a^-1)]);;
gap> newm := CleanedSphereMachine(ChangeFRMachineBasis(m^iso, [a^-1*y^-1, y^-1*a^-1*c^-1]));;
gap> Display(newm);
G | 1 2
---+---+---+
a | a^-1*c^-1,2 c*a*b,1
```

b	<id>,1	c,2
c	a,1	<id>,2
x	z*x,2	x <sup>-1</sup> ,1
y	<id>,1	x,2
z	y,1	<id>,2
---+-----+-----+		
Relator: c*a*b*y*z*x		

```

DeclareSynonym("IsPolynomialSphereMachine",IsSphereMachine and HasAddingElement);
DeclareAttribute("AsPolynomialSphereMachine",IsFRMachine);
DeclareOperation("AsPolynomialSphereMachine",[IsFRMachine,IsWord]);

```

### 3.1.26 AsPolynomialSphereMachine

▷ `AsPolynomialSphereMachine(m[, adder[, relator]])` (operation)

**Returns:** A polynomial sphere machine.

The first function creates a new polynomial sphere machine, starting from a group or Mealy machine. A *polynomial* machine is one that has a distinguished adding element, `AddingElement` (3.1.25).

If the argument is a Mealy machine, it must be planar (see `IsPlanarKneadingMachine` (3.1.24)). If the argument is a group machine, its permutations must be treelike, and its outputs must be such that, up to conjugation, each non-trivial state appears exactly once as the product along all cycles of all states.

If a second argument *adder* is supplied, it is checked to represent an adding element, and is used as such.

Example

```

gap> M := PolynomialMealyMachine(2,[1/7],[]);
!!!
gap> Mi := AsPolynomialSphereMachine(M);
!!!

```

```

DeclareOperation("PolynomialMealyMachine",[IsPosInt,IsList,IsList]);
DeclareOperation("PolynomialMealyMachine",[IsPosInt,IsList]);
DeclareOperation("PolynomialSphereMachine",[IsPosInt,IsList,IsList,IsRecord]);
DeclareOperation("PolynomialSphereMachine",[IsPosInt,IsList,IsList]);
DeclareOperation("PolynomialSphereMachine",[IsPosInt,IsList,IsRecord]);
DeclareOperation("PolynomialSphereMachine",[IsPosInt,IsList]);

```

### 3.1.27 PolynomialSphereMachine

▷ `PolynomialSphereMachine(d, per[, pre])` (operation)

▷ `PolynomialMealyMachine(d, per[, pre])` (operation)

**Returns:** A sphere or Mealy machine.

This function creates a sphere or Mealy machine that describes a topological polynomial. The polynomial is described symbolically in the language of *external angles*. For more details, see [DH84] and [DH85] (in the quadratic case), [BFH92] (in the preperiodic case), and [Poi] (in the general case).

*d* is the degree of the polynomial. *per* and *pre* are lists of angles or preangles. In what follows, angles are rational numbers, considered modulo 1. Each entry in *per* or *pre* is either a rational

(interpreted as an angle), or a list of angles  $[a_1, \dots, a_i]$  such that  $da_1 = \dots = da_i$ . The angles in *per* are angles landing at the root of a Fatou component, and the angles in *pre* land on the Julia set.

Note that, for sphere machines, the last generator of the machine produced is an adding machine, representing a loop going counterclockwise around infinity (in the compactification of  $\mathbb{C}$  by a disk, this loop goes *clockwise* around that disk).

In constructing a polynomial sphere machine, one may specify a boolean flag *formal*, which defaults to true. In a *formal* recursion, distinct angles give distinct generators; while in a non-formal recursion, distinct angles, which land at the same point in the Julia set, give a single generator. The simplest example where this occurs is angle  $5/12$  in the quadratic family, in which angles  $1/3$  and  $2/3$  land at the same point – see the example below.

The attribute `Correspondence(m)` records the angles landing on the generators: `Correspondence(m)[i]` is a list  $[a, s]$  where  $a$  is an angle landing on generator  $i$  and  $s$  is "Julia" or "Fatou".

If only one list of angles is supplied, then IMG guesses that all angles with denominator coprime to  $n$  are Fatou, and all the others are Julia.

The inverse operation, reconstructing the angles from the sphere machine, is `SupportingRays` (3.1.28).

#### Example

```
gap> PolynomialSphereMachine(2, [0], []); # the adding machine
<FR machine with alphabet [ 1 .. 2 ] on Group( [ f1, f2 ] )/[ f2*f1 ]>
gap> Display(last);
G |      1      2
---+-----+-----+
f1 | <id>,2      f1,1
f2 | f2,2      <id>,1
---+-----+-----+
Relator: f2*f1
gap> Display(PolynomialSphereMachine(2, [1/3], [])); # the Basilica
G |      1      2
---+-----+-----+
f1 | f1^-1,2      f2*f1,1
f2 | f1,1      <id>,2
f3 | f3,2      <id>,1
---+-----+-----+
Relator: f3*f2*f1
gap> Display(PolynomialSphereMachine(2, [], [1/6])); # z^2+I
G |      1      2
---+-----+-----+
f1 | f1^-1*f2^-1,2      f2*f1,1
f2 | f1,1      f3,2
f3 | f2,1      <id>,2
f4 | f4,2      <id>,1
---+-----+-----+
Relator: f4*f3*f2*f1
gap> PolynomialSphereMachine(2, [], [5/12]);
gap> PolynomialSphereMachine(2, [], [5/12]);
<FR machine with alphabet [ 1, 2 ] and adder f5 on Group( [ f1, f2, f3, f4, f5 ] )/[ f5*f4*f3*f2*f1 ]>
gap> Correspondence(last);
[ [ 1/3, "Julia" ], [ 5/12, "Julia" ], [ 2/3, "Julia" ], [ 5/6, "Julia" ] ]
gap> PolynomialSphereMachine(2, [], [5/12], false);
<FR machine with alphabet [ 1, 2 ] and adder f4 on Group( [ f1, f2, f3, f4 ] )/[ f4*f3*f2*f1 ]>
```



```
gap> Correspondence(last);
[[ [ 1/3, 2/3 ], "Julia" ], [ [ 5/12 ], "Julia" ], [ [ 5/6 ], "Julia" ] ]
```

The following construct the examples in Poirier's paper:

```
PoirierExamples := function(arg)
  if arg=[1] then
    return PolynomialSphereMachine(2, [1/7], []);
  elif arg=[2] then
    return PolynomialSphereMachine(2, [], [1/2]);
  elif arg=[3,1] then
    return PolynomialSphereMachine(2, [], [5/12]);
  elif arg=[3,2] then
    return PolynomialSphereMachine(2, [], [7/12]);
  elif arg=[4,1] then
    return PolynomialSphereMachine(3, [[3/4, 1/12], [1/4, 7/12]], []);
  elif arg=[4,2] then
    return PolynomialSphereMachine(3, [[7/8, 5/24], [5/8, 7/24]], []);
  elif arg=[4,3] then
    return PolynomialSphereMachine(3, [[1/8, 19/24], [3/8, 17/24]], []);
  elif arg=[5] then
    return PolynomialSphereMachine(3, [[3/4, 1/12], [3/8, 17/24]], []);
  elif arg=[6,1] then
    return PolynomialSphereMachine(4, [], [[1/4, 3/4], [1/16, 13/16], [5/16, 9/16]]);
  elif arg=[6,2] then
    return PolynomialSphereMachine(4, [], [[1/4, 3/4], [3/16, 15/16], [7/16, 11/16]]);
  elif arg=[7] then
    return PolynomialSphereMachine(5, [[0, 4/5], [1/5, 2/5, 3/5]], [[1/5, 4/5]]);
  elif arg=[9,1] then
    return PolynomialSphereMachine(3, [[0, 1/3], [5/9, 8/9]], []);
  elif arg=[9,2] then
    return PolynomialSphereMachine(3, [[0, 1/3]], [[5/9, 8/9]]);
  else
    Error("Unknown Poirier example ", arg);
  fi;
end;
```

```
DeclareAttribute("SupportingRays", IsFRMachine);
```

### 3.1.28 SupportingRays

▷ `SupportingRays( $m$ )` (attribute)

**Returns:** A `[degree, fatou, julia]` description of  $m$ .

This operation is the inverse of `PolynomialSphereMachine` (3.1.27): it computes a choice of angles, describing landing rays on Fatou/Julia critical points.

If there does not exist a complex realization, namely if the machine is obstructed, then this command returns an obstruction, as a record. The field `minimal` is set to `false`, and a proper submachine is set as the field `submachine`. The field `homomorphism` gives an embedding of the stateset of submachine into the original machine, and `relation` is the equivalence relation on the set of generators of  $m$  that describes the pinching.

## Example

```

gap> r := PolynomialSphereMachine(2,[1/7],[]);
<FR machine with alphabet [ 1, 2 ] and adder f4 on Group( [ f1, f2, f3, f4 ] )/[ f4*f3*f2*f1 ]>
gap> F := StateSet(r);; SetName(F,"F");
gap> SupportingRays(r);
[ 2, [ [ 1/7, 9/14 ] ], [ ] ] # actually returns the angle 2/7
gap> # now CallFuncList(PolynomialSphereMachine,last) would return the machine r
gap> twist := GroupHomomorphismByImages(F,F,GeneratorsOfGroup(F),[F.1^(F.2*F.1),F.2^F.1,F.3,F.4]
[ f1, f2, f3, f4 ] -> [ f1*f2*f1^-1, f2*f1*f2*f1^-1*f2^-1, f3, f4 ]
gap> List([-5..5],i->2*SupportingRays(r*twist^i)[2][1][1]);
[ 4/7, 5/7, 4/7, 4/7, 5/7, 2/7, 4/7, 4/7, 2/7, 4/7, 4/7 ]
gap> r := PolynomialSphereMachine(2,[],[1/6]);;
gap> F := StateSet(r);;
gap> twist := GroupHomomorphismByImages(F,F,GeneratorsOfGroup(F),[F.1,F.2^(F.3*F.2),F.3^F.2,F.4]
gap> SupportingRays(r);
[ 2, [ ], [ [ 1/12, 7/12 ] ] ]
gap> SupportingRays(r*twist);
[ 2, [ ], [ [ 5/12, 11/12 ] ] ]
gap> SupportingRays(r*twist^2);
rec(
  transformation := [ [ f1, f2^-1*f3^-1*f2^-1*f3^-1*f2*f3*f2*f3*f2, f2^-1*f3^-1*f2^-1*f3*f2*f3*f
    f4 ] -> [ f1, f2, f3, f4 ],
    [ f1^-1*f2^-1*f1^-1*f2^-1*f1*f2*f1*f2*f1, f1^-1*f2^-1*f1^-1*f2*f1*f2*f1, f3, f4 ] ->
    [ f1, f2, f3, f4 ],
    [ f1^-1*f2^-1*f3^-1*f2*f1*f2^-1*f3*f2*f1, f2, f2*f1^-1*f2^-1*f3*f2*f1*f2^-1, f4 ] ->
    [ f1, f2, f3, f4 ], [ f1, f3*f2*f3^-1, f3, f4 ] -> [ f1, f2, f3, f4 ],
    [ f1, f2, f2*f3*f2^-1, f4 ] -> [ f1, f2, f3, f4 ],
    [ f1, f3*f2*f3^-1, f3, f4 ] -> [ f1, f2, f3, f4 ],
    [ f1, f2, f2*f3*f2^-1, f4 ] -> [ f1, f2, f3, f4 ],
    [ f1, f3*f2*f3^-1, f3, f4 ] -> [ f1, f2, f3, f4 ] ], machine := <FR machine with alphabet
    [ 1, 2 ] and adder f4 on Group( [ f1, f2, f3, f4 ] )/[ f4*f3*f2*f1 ]>, minimal := false,
    submachine := <FR machine with alphabet [ 1, 2 ] and adder f3 on Group( [ f1, f2, f3 ] )>,
    homomorphism := [ f1, f2, f3 ] -> [ f1, f2*f3, f4 ],
    relation := <equivalence relation on <object> >, niter := 8 )

```

DeclareAttribute("NormalizedPolynomialSphereMachine",IsSphereMachine);

### 3.1.29 NormalizedPolynomialSphereMachine

▷ NormalizedPolynomialSphereMachine( $m$ )

(attribute)

**Returns:** A polynomial sphere machine.

This function returns a new sphere machine, in which the adding element has been put into a standard form  $t = [t, 1, \dots, 1]_s$ , where  $s$  is the long cycle  $i \mapsto i - 1$ .

DeclareAttribute("SimplifiedSphereMachine",IsSphereMachine);

### 3.1.30 SimplifiedSphereMachine

▷ SimplifiedSphereMachine( $m$ )

(attribute)

**Returns:** A simpler sphere machine.

This function returns a new sphere machine, with hopefully simpler transitions. The simplified machine is obtained by applying automorphisms to the stateset. The sequence of automorphisms (in

increasing order) is stored as a correspondence; namely, if  $n = \text{SimplifiedSphereMachine}(m)$ , then  $m \sim \text{Product}(\text{Correspondence}(n)) = n$ .

Example

```
gap> r := PolynomialSphereMachine(2, [1/7], []);;
gap> F := StateSet(r);; SetName(F, "F");
gap> twist := GroupHomomorphismByImages(F, F, GeneratorsOfGroup(F), [F.1^(F.2*F.1), F.2^F.1, F.3, F.4]);
gap> m := r*twist;; Display(m);
G | 1 2
---+-----+-----+
f1 | f1^-1*f2^-1,2 f3*f2*f1,1
f2 | f1^-1*f2^-1*f1*f2*f1,1 <id>,2
f3 | f1^-1*f2*f1,1 <id>,2
f4 | f4,2 <id>,1
---+-----+-----+
Adding element: f4
Relator: f4*f3*f2*f1
gap> n := SimplifiedSphereMachine(m);
<FR machine with alphabet [ 1, 2 ] and adder f4 on F>
gap> Display(n);
G | 1 2
---+-----+-----+
f1 | f2^-1*f1^-1,2 f1*f2*f3,1
f2 | <id>,1 f1,2
f3 | <id>,1 f2,2
f4 | f4,2 <id>,1
---+-----+-----+
Adding element: f4
Relator: f4*f1*f2*f3
gap> n = m~Product(Correspondence(n));
true
```

```
DeclareOperation("Mating",[IsPolynomialSphereMachine,IsPolynomialSphereMachine]);
DeclareOperation("Mating",[IsPolynomialSphereMachine,IsPolynomialSphereMachine,IsBool]);
```

### 3.1.31 Mating

▷  $\text{Mating}(m1, m2[, \text{formal}])$  (operation)

**Returns:** A sphere machine.

This function "mates" two polynomial sphere machines.

The mating is defined as follows: one removes a disc around the adding machine in  $m1$  and  $m2$ ; one applies complex conjugation to  $m2$ ; and one glues the hollowed spheres along their boundary circle.

The optional argument *formal*, which defaults to `true`, specifies whether a *formal* mating should be done; in a non-formal mating, generators of  $m1$  and  $m2$  which have identical angle should be treated as a single generator. A non-formal mating is of course possible only if the machines are realizable – see [SupportingRays \(3.1.28\)](#).

The attribute `Correspondence` is a pair of homomorphisms, from the statesets of  $m1, m2$  respectively to the stateset of the mating.

Example

```
gap> # the Tan-Shishikura examples
gap> z := Indeterminate(MPC_PSEUDOFIELD);;
```

```

gap> a := RootsFloat((z-1)*(3*z^2-2*z^3)+1));
gap> c := RootsFloat((z^3+z)^3+z);
gap> am := List(a,a->SphereMachine((a-1)*(3*z^2-2*z^3)+1));
gap> cm := List(c,c->SphereMachine(z^3+c));
gap> m := ListX(am,cm,Mating);
gap> # m[2] is realizable
gap> RationalFunction(m[2]);
((1.66408+I*0.668485)*z^3+(-2.59772+I*0.627498)*z^2+(-1.80694-I*0.833718)*z
+(1.14397-I*1.38991))/((-1.52357-I*1.27895)*z^3+(2.95502+I*0.234926)*z^2
+(1.61715+I*1.50244)*z+1)
gap> # m[6] is obstructed
gap> RationalFunction(m[6]);
rec( matrix := [ [ 1/2, 1 ], [ 1/2, 0 ] ], machine := <FR machine with alphabet
[ 1, 2, 3 ] on Group( [ f1, f2, f3, g1, g2, g3 ] )/[ f2*f3*f1*g1*g3*g2 ]>,
obstruction := [ f1^-1*f3^-1*f2^-1*f1*f2*f3*f1*g2^-1*g3^-1*f1^-1*f3^-1*f2^-1,
f2*f3*f1*f2*f3*f1*g2*f1^-1*f3^-1*f2^-1*f1^-1*f3^-1 ],
spider := <spider on <triangulation with 8 vertices, 36 edges and
12 faces> marked by GroupHomomorphismByImages( Group( [ f1, f2, f3, g1, g2, g3 ]
), Group( [ f1, f2, f3, f4, f5 ] ), [ f1, f2, f3, g1, g2, g3 ],
[ f1*f4*f2^-1*f1*f4^-1*f1^-1, f1*f4*f2^-1*f1*f4*f5^-1*f1^-1*f2*f4^-1*f1^-1,
f1*f4*f2^-1*f1*f5*f1^-1*f2*f4^-1*f1^-1, f2*f4^-1*f1^-1*f2*f1*f4*f2^-1,
f2*f4^-1*f3*f2^-1, f2*f4^-1*f1^-1*f3^-1*f4*f2^-1 ] )> )

```

DeclareOperation("AutomorphismVirtualEndomorphism",[IsGroupHomomorphism]); Declare-  
Operation("AutomorphismSphereMachine",[IsSphereMachine]);

### 3.1.32 AutomorphismVirtualEndomorphism

- ▷ AutomorphismVirtualEndomorphism( $v$ ) (attribute)
- ▷ AutomorphismSphereMachine( $m$ ) (attribute)

**Returns:** A description of the pullback map on Teichmüller space.

Let  $m$  be a sphere machine, thought of as a biset for the fundamental group  $G$  of a punctured sphere. Let  $M$  denote the automorphism of the surface, seen as a group of outer automorphisms of  $G$  that fixes the conjugacy classes of punctures.

Choose an alphabet letter  $a$ , and consider the virtual endomorphism  $v : G_a \rightarrow G$ . Let  $H$  denote the subgroup of  $M$  that fixes all conjugacy classes of  $G_a$ . then there is an induced virtual endomorphism  $\alpha : H \rightarrow M$ , defined by  $t^\alpha = v^{-1}tv$ . This is the homomorphism computed by the first command. Its source and range are in fact groups of automorphisms of range of  $v$ .

The second command constructs an FR machine associated with  $\backslash alpha$ . Its stateset is a free group generated by elementary Dehn twists of the generators of  $G$ .

Example

```

gap> z := Indeterminate(COMPLEX_FIELD);
gap> # a Sierpinski carpet map without multicurves
gap> m := SphereMachine((z^2-z^2)/2/COMPLEX_I);
<FR machine with alphabet [ 1, 2, 3, 4 ] on Group( [ f1, f2, f3, f4 ] )/[ f3*f2*f1*f4 ]>
gap> AutomorphismSphereMachine(i);
<FR machine with alphabet [ 1, 2 ] on Group( [ x1, x2, x3, x4, x5, x6 ] )>
gap> Display(last);
G |      1      2
---+-----+-----+
x1 | <id>,2    <id>,1

```

```

x2 | <id>,1  <id>,2
x3 | <id>,2  <id>,1
x4 | <id>,2  <id>,1
x5 | <id>,1  <id>,2
x6 | <id>,2  <id>,1
-----+-----+-----+
gap> # the original rabbit problem
gap> m := PolynomialSphereMachine(2,[1/7],[1]);;
gap> v := VirtualEndomorphism(m,1);;
gap> a := AutomorphismVirtualEndomorphism(v);
MappingByFunction( <group with 20 generators>, <group with 6 generators>, function( a ) ... end
gap> Source(a).1;
[ f1, f2, f3, f4 ] -> [ f3*f2*f1*f2~-1*f3~-1, f2, f3, f3*f2*f1~-1*f2~-1*f3~-1*f2~-1*f3~-1 ]
gap> Image(a,last);
[ f1, f2, f3, f4 ] -> [ f1, f2, f2*f1*f3*f1~-1*f2~-1, f3~-1*f1~-1*f2~-1 ]
gap> # so last2*m is equivalent to m*last

```

```
DeclareGlobalFunction("DBRationalIMGGroup");
```

### 3.1.33 DBRationalIMGGroup

▷ DBRationalIMGGroup(*sequence/map*) (function)

**Returns:** An IMG group from Dau's database.

This function returns the iterated monodromy group from a database of groups associated to quadratic rational maps. This database has been compiled by Dau Truong Tan [Tan02].

When called with no arguments, this command returns the database contents in raw form.

The arguments can be a sequence; the first integer is the size of the postcritical set, the second argument is an index for the postcritical graph, and sometimes a third argument distinguishes between maps with same post-critical graph.

If the argument is a rational map, the command returns the IMG group of that map, assuming its canonical quadratic rational form exists in the database.

Example

```

gap> DBRationalIMGGroup(z^2-1);
IMG((z-1)^2)
gap> DBRationalIMGGroup(z^2+1); # not post-critically finite
fail
gap> DBRationalIMGGroup(4,1,1);
IMG((z/h+1)^2|2h^3+2h^2+2h+1=0,h~-0.64)

```

```
DeclareGlobalFunction("PostCriticalMachine");
```

### 3.1.34 PostCriticalMachine

▷ PostCriticalMachine(*f*) (function)

**Returns:** The Mealy machine of *f*'s post-critical orbit.

This function constructs a Mealy machine *P* on the alphabet [1], which describes the post-critical set of *f*. It is in fact an oriented graph with constant out-degree 1. It is most conveniently passed to Draw (**FR: Draw**).

The attribute Correspondence(*P*) is the list of values associated with the stateset of *P*.

## Example

```

gap> z := Indeterminate(Rationals,"z");
gap> m := PostCriticalMachine(z^2);
<Mealy machine on alphabet [ 1 ] with 2 states>
gap> Display(m);
  | 1
---+-----+
a | a,1
b | b,1
---+-----+
gap> Correspondence(m);
[ 0, infinity ]
gap> m := PostCriticalMachine(z^2-1); Display(m); Correspondence(m);
  | 1
---+-----+
a | c,1
b | b,1
c | a,1
---+-----+
[ -1, infinity, 0 ]

```

### 3.2 Spiders

IMG contains an implementation of the Thurston-Hubbard-Schleicher "spider algorithm" [HS94] that constructs a rational map from an IMG recursion. This implementation does not give rigorous results, but relies of floating-point approximation. In particular, various floating-point parameters control the proper functioning of the algorithm. They are stored in a record, `EPS@fr`. Their meaning and default values are:

`EPS@fr.mesh := 10-1`

If points on the unit sphere are that close, the triangulation mesh should be refined.

`EPS@fr.prec := 10-6`

If points on the unit sphere are that close, they are considered equal.

`EPS@fr.obst := 10-1`

If points on the unit sphere are that close, they are suspected to form a Thurston obstruction.

`EPS@fr.juliaiter := 103`

In computing images of the Julia set, never recur deeper than that.

`EPS@fr.fast := 10-1`

If the spider moved less than that amount in the last iteration, try speeding up by only wiggling the spider's legs, without recomputing it.

`EPS@fr.ratprec := 10-10`

The desired precision on the coefficients of the rational function.

..... (a) there is a concept of "marked sphere". It is made of an  $N$ -generated group, a collection of  $N$  elements of  $P^1(C)$  called "feet", a triangulation of the sphere that includes these elements among its vertices, and a marking of the edges by elements of the group in such a manner that a loop around

point  $i$  is conjugate to generator  $i$ . To keep track of "loops around things", the triangulation also remembers its dual graph. (b) given a marked sphere and a rational map (given by coefficients), a procedure computes the "lifted marked sphere" and a wreath recursion between their respective groups, i.e. a homomorphism  $G_{\text{below}} \rightarrow G_{\text{above}} \wr \text{sym}(d)$ . The procedure will probably fail unless the critical values are close to the feet. There, the algorithm is already subtle: edges of the dual graph are represented by arcs of great circles. One first computes the full preimage of the feet, and a triangulation spanning them on a sphere "above" the original marked sphere. Then, for each edge of the "down" dual graph, its preimage on the "up" sphere is an algebraic curve. One computes its intersections with all edges of the "up" dual graph, by finding zeroes of real polynomials, to determine from which triangle to which one the lifted edges go. Because of rounding errors, one has to be careful as to when a real polynomial is supposed to have a zero, or when a point is supposed to be in a triangle. E.g., if  $T$  is a triangle and its sides are given by arcs of great circles, represented as  $\gamma_i([0,1])$  for Moebius maps  $\gamma_i$ ,  $i=1,2,3$ , then the test " $\text{Im}(\gamma_i(z)) > 0$  for all  $i$ " determines whether  $z$  is in the triangle. This test is really coded as " $\text{Im}(\gamma_i(z)) / (1 + |\gamma_i(z)|^2) > -\text{IMG.p1eps}$ " to take care of rounding errors. (c) given a marked sphere and a permutation representation of its group, a procedure computes a rational map with that monodromy. If the representation has degree 2, or is bicritical, or a few other cases easily coded by hand, then the rational map is computed algebraically. Otherwise, the "hard" part of the algorithm comes into play. A fresh marked sphere is constructed with only the feet with non-trivial permutation. The triangulation is then combinatorially lifted, using the permutation representation. In particular, the feet are now labeled by cycles of the permutations. It is a purely combinatorial triangulation, at this point; but one remembers that its edges have a length inherited from the sphere metric. The triangulation is then refined by repeatedly adding circumcentres of triangles, till every edge (say from  $v$  to  $w$ ) has length  $\leq \text{IMG.hurwitzmesh} \cdot \text{Maximum}(\text{cycle length at } v, \text{cycle length at } w)$ . Now an external C program, "layout", is called. It seeks a discrete conformal map, given by a function  $u: \{\text{feet}\} \rightarrow \mathbb{R}$ , such that if edge  $e$  (from  $v$  to  $w$ ) has its length scaled by  $u(v) \cdot u(w)$  then the sum-of-angles  $= 2\pi$  condition holds at each vertex (with special treatment for a vertex at infinity; I skip details). Then the triangulation can be laid out on the plane, and projected back stereographically to the sphere. In this manner, we got good approximations of where the feet should be. Now we run Newton's method on the feet positions, using as variables the lifted-feet positions. This is the external program "hsolve". It is assumed that the down-feet contain 0 and infinity, so that the rational map we are looking for is of the form  $f(z) = \text{const} \cdot \prod ((z - c_i)^{-d_i})$  for known integers  $d_i$ . The  $c_i$  are the lifted-feet above 0 and infinity, and the equations in Newton's method say that the log-derivative of  $f$  must vanish at appropriate lifted-feet, and that  $f$  must map these lifted-feet to the down-feet. (d) For Thurston's algorithm, one starts by an arbitrary marked sphere (I chose its feet on the real axis, at equal small angles); computes a rational map using (c), computes  $[*]$  its biset using (b), and matches the original biset with the lifted one. This tells us which feet of the lifted biset we should keep. One then computes a normalized position for the sub-marked sphere: its last foot is at infinity, another one (chosen cleverly) is on the positive real axis, and the center of mass of all feet (in  $\mathbb{R}^3$ ) is  $(0,0,0)$ . This is much more stable, numerically, than putting 3 points at  $0,1,\infty$ . One has a Moebius transformation that puts the sub-marked sphere in normalized position, and by (b) computes its biset. One then composes the bisets, and compares it again to the original biset to determine the marking of the edges of the new marked sphere by group elements. Then, one searches for all quadruples with large cross-ratio, and computes group-theoretically the curve separating the post-critical set in two parts that are well separated. One saturates the resulting curve into an invariant multicurve (aborting if there is an intersection between lifts), computes the Thurston matrix, and finds out (again algebraically) if there is an eigenvalue  $\geq 1$ . There is no

parameter in this part of the code, all quadruples are examined; this is a weakness of the current implementation, sometimes most of the computational time is spent on searching for obstructions when it's "clear" there are none. The distance between two marked spheres (marked by the same group) is computed as follows: if their feet are close in the sense that the sum of the spherical distances between them is less than @IMG.fast, then wiggle one of the spiders to make its feet match that of the other; and check that the identity map gives, by (b), the identity biset. In that case, the sum of the feet distances is the distance between the spheres. Otherwise, add to it some formula involving the entries in the biset, which gives large integer distances. The Thurston algorithm stops when an obstruction is found or when the marked sphere moved less than @IMG.ratprec. Inside the main iteration of the algorithm, if the spider moved less than @IMG.fast, then skip step [\*], and try guessing which of the lifts should be kept. Check the guess: if it is incorrect, go back to the usual method. This is useful if the biset has low degree but high post-critical set size, and useless if the biset has high degree and low post-critical set size, but I haven't taken care to disable it in that case (yet). Another speedup which I should implement, but haven't gotten to, is in (c) to remember the previously computed rational map and/or triangulated sphere, and to directly try Newton's method without doing the "layout" part. ....

```

DeclareCategory("IsSphereTriangulation", IsObject);
BindGlobal("TRIANGULATION_FAMILY", NewFamily("SphereTriangulations", IsSphereTriangulation));
BindGlobal("TYPE_TRIANGULATION", NewType(TRIANGULATION_FAMILY, IsSphereTriangulation));
DeclareRepresentation("IsTriangulationObjectRep", IsComponentObjectRep and IsAttributeStoringRep, []);
DeclareCategory("IsTriangulationObject", IsTriangulationObjectRep);
DeclareCategory("IsTriangulationVertex", IsTriangulationObject);
DeclareCategory("IsTriangulationEdge", IsTriangulationObject);
DeclareCategory("IsTriangulationFace", IsTriangulationObject);
BindGlobal("TRIANGULATIONOBJECT_FAMILY", NewFamily("TriangulationFamily", IsTriangulationObject, CanEasilySortElements, CanEasilySortElements));
BindGlobal("TYPE_VERTEX", NewType(TRIANGULATIONOBJECT_FAMILY, IsTriangulationVertex));
BindGlobal("TYPE_EDGE", NewType(TRIANGULATIONOBJECT_FAMILY, IsTriangulationEdge));
BindGlobal("TYPE_FACE", NewType(TRIANGULATIONOBJECT_FAMILY, IsTriangulationFace));
DeclareAttribute("Neighbour", IsTriangulationVertex);
DeclareOperation("Neighbours", [IsTriangulationVertex]);
DeclareOperation("Neighbours", [IsTriangulationVertex, IsTriangulationEdge]);
DeclareOperation("Valency", [IsTriangulationVertex]);
DeclareAttribute("Pos", IsTriangulationVertex);
DeclareOperation("ClosestFace", [IsTriangulationObject]);
DeclareOperation("ClosestFaces", [IsTriangulationObject]);
DeclareOperation("ClosestVertex", [IsTriangulationObject]);
DeclareOperation("ClosestVertices", [IsTriangulationObject]);
DeclareProperty("IsFake", IsTriangulationVertex);
DeclareAttribute("Left", IsTriangulationEdge);
DeclareAttribute("Right", IsTriangulationEdge);
DeclareAttribute("To", IsTriangulationEdge);
DeclareAttribute("From", IsTriangulationEdge);
DeclareAttribute("Next", IsTriangulationEdge);
DeclareAttribute("Prevopp", IsTriangulationEdge);
DeclareAttribute("Opposite", IsTriangulationEdge);
DeclareAttribute("Pos", IsTriangulationEdge);
DeclareAttribute("FromPos", IsTriangulationEdge);
DeclareAttribute("ToPos", IsTriangulationEdge);
DeclareAttribute("Length", IsTriangulationEdge);
DeclareAttribute("Map", IsTriangulationEdge);
DeclareAttribute("GroupElement", IsTriangulationEdge, "mutable");
DeclareAttribute("Neighbour", IsTriangulationFace);
DeclareOperation("Neighbours", [IsTriangulationFace]);
DeclareOperation("Neighbours", [IsTriangulationFace, IsTriangulationEdge]);
DeclareAttribute("Pos", IsTriangulationFace);
DeclareAttribute("Radius", IsTriangulationFace);
DeclareAttribute("Centre", IsTriangulationFace);
DeclareOperation("Valency", [IsTriangulationFace]);
DeclareOperation("Draw", [IsSphereTriangulation]);

```



### 3.2.1 IsSphereTriangulation

▷ IsSphereTriangulation

(filter)

The category of triangulated spheres (points in Moduli space).

This triangulation is a collection of vertices, edges and faces. These are new GAP objects. The attributes for vertices are:

Neighbour

any edge starting at the vertex

Neighbours

a list of neighbours, in counterclockwise order (an optional adugument lets one specify the starting edge)

Valency

the number of neighbours

Pos The P1 point where the vertex is located

ClosestVertex

The vertex itself

ClosestVertices

A list containing the vertex itself

ClosestFace

The face left of the first neighbour

ClosestFaces

The faces that contain the vertex

IsFake

whether the vertex was added for refinement

The edges come in opposite pairs, and are thought of as having a face on their left. Their possible attributes are:

Left, Right

The adjacent faces

To, From

The vertices that the edge goes to/from

Next

The edge after on the left face (starting where the present edge ends)

Prevopp

The opposite of the edge before on the left face (starting where the present edge starts)

Opposite

The opposite edge (with reversed orientation)

**Pos** The position of the midpoint. **FromPos** and **ToPos** are shortcuts

**Length**

**Map** A P1 map sending  $[0, 1]$  to the edge

**GroupElement**

A group element describing "crossing through the edge from the left to the right"

**ClosestVertex**

The from vertex

**ClosestVertices**

The two endpoints

**ClosestFace**

The left neighbour

**ClosestFaces**

The two adjacent faces

The faces have the following possible attributes:

**Neighbour**

Some edge with this face on its left

**Neighbours**

The neighbours of the face, in counterclockwise order around the face (an optional argument lets one specify the starting edge)

**Pos** The position of the face's barycentre

**Radius, Centre**

The circumradius and circumcentre of the face (assumed to be a triangle)

**Valency**

The number of neighbouring edges

**ClosestVertex**

The from of the first neighbour

**ClosestVertices**

The vertices that the face contains

**ClosestFace**

The face itself

**ClosestFaces**

A list containing the face itself

A triangulation may be plotted with **Draw**; this requires **appletviewer** to be installed. The command **Draw(t:detach)** detaches the subprocess after it is started. The extra arguments **Draw(t:lower)** or **Draw(t:upper)** stretch the triangulation to the lower, respectively upper, hemisphere.

**DeclareOperation("EdgePath", [IsSphereTriangulation, IsTriangulationFace, IsTriangulationFace]);**

### 3.2.2 EdgePath

▷ `EdgePath(t, f0, f1)` (operation)  
**Returns:** A sequence of edges taking *f0* to *f1*.  
`DeclareOperation("DelaunayTriangulation", [IsList]);` `DeclareOperation("DelaunayTriangulation", [IsList, IsFloat]);`

### 3.2.3 DelaunayTriangulation

▷ `DelaunayTriangulation(points[, quality])` (operation)  
**Returns:** A Delaunay triangulation of the sphere.

If *points* is a list of points on the unit sphere, represented by their 3D coordinates, this function creates a triangulation of the sphere with these points as vertices. This triangulation satisfies the *Delaunay* condition that no point lies in the circumcircle of any face.

If all points are aligned on a great circle, or if all points are in a hemisphere, some points are added so as to make the triangulation simplicial with all edges of length  $< \pi$ . These vertices additionally have the `IsFake` property set to `true`.

If the second argument *quality*, which must be a float, is present, then all triangles in the resulting triangulation are guaranteed to have circumcircle ratio / minimal edge length at most *quality*. Of course, additional vertices may need to be added to ensure that.

Example

```
gap> octagon := Concatenation(IdentityMat(3), -IdentityMat(3))*1.0;;
gap> dt := DelaunayTriangulation(octagon);
<triangulation with 6 vertices, 24 edges and 8 faces>
gap> dt!.v;
[ <vertex 1>, <vertex 2>, <vertex 3>, <vertex 4>, <vertex 5>, <vertex 6> ]
gap> last[1].n;
[ <edge 17>, <edge 1>, <edge 2>, <edge 11> ]
gap> last[1].from;
<vertex 1>
```

`DeclareOperation("AddToTriangulation", [IsSphereTriangulation, IsP1Point]);` `DeclareOperation("AddToTriangulation", [IsSphereTriangulation, IsP1Point, IsBool]);` `DeclareOperation("AddToTriangulation", [IsSphereTriangulation, IsTriangulationFace, IsP1Point]);` `DeclareOperation("AddToTriangulation", [IsSphereTriangulation, IsTriangulationFace, IsP1Point, IsBool]);`

### 3.2.4 AddToTriangulation

▷ `AddToTriangulation(t[, seed], point[, delaunay])` (operation)

This command adds the P1 point *point* to the triangulation *t*. If a face *seed* is provided, it will speed up the search for the triangle in which the point is to be added. The other optional boolean argument *delaunay* specifies whether the Delaunay condition is to be fulfilled (by flipping diagonals of some quadrilaterals made of two neighbouring triangles) after the addition.

`DeclareOperation("RemoveFromTriangulation", [IsSphereTriangulation, IsTriangulationVertex]);`

### 3.2.5 RemoveFromTriangulation

▷ `RemoveFromTriangulation(t, vertex)` (operation)

This command removes the vertex *vertex* from the triangulation *t*.

```
DeclareOperation("LocateFaceInTriangulation", [IsSphereTriangulation,IsP1Point]);
DeclareOperation("LocateFaceInTriangulation", [IsSphereTriangulation,IsObject,IsP1Point]);
DeclareOperation("LocateInTriangulation", [IsSphereTriangulation,IsP1Point]);
DeclareOperation("LocateInTriangulation", [IsSphereTriangulation,IsObject,IsP1Point]);
```

### 3.2.6 LocateFaceInTriangulation

- ▷ `LocateFaceInTriangulation(t[, seed], point)` (operation)
- ▷ `LocateInTriangulation(t[, seed], point)` (operation)

**Returns:** The face(*t*) in *t* containing *point*.

This command locates the face in *t* that contains *point*; in the second form, if *point* lies on an edge or a vertex, it returns that edge or vertex.

The optional second argument specifies a starting vertex, edge, face, or vertex index from which to start the search. Its only effect is to speed up the algorithm.

Example

```
gap> cube := Tuples([-1,1],3)/Sqrt(3.0);
gap> dt := DelaunayTriangulation(cube);
<triangulation with 8 vertices, 36 edges and 12 faces>
gap> LocateInTriangulation(dt,dt!.v[1].pos);
<vertex 1>
gap> LocateInTriangulation(dt,[3/5,0,4/5]*1.0);
<face 9>
```

```
DeclareOperation("WiggledTriangulation", [IsSphereTriangulation,IsObject]);
```

### 3.2.7 WiggledTriangulation (wobble moebius)

- ▷ `WiggledTriangulation(t, moebiusmap)` (operation)
- ▷ `WiggledTriangulation(t, newpoints)` (operation)

**Returns:** A new triangulation, with moved vertices.

This command creates a new triangulation, in which only the P1 coordinates are changed. If the second argument *moebiusmap* is a Möbius transformation, then it is applied to the vertices and barycentres of faces and edges. If the second argument *newpoints* is a list of P1 points, then they are taken as new coordinates of the vertices.

```
DeclareGlobalFunction("EquidistributedP1Points");
```

### 3.2.8 EquidistributedP1Points

- ▷ `EquidistributedP1Points(N)` (function)

**Returns:** A list of *N* P1 points that are reasonably well spaced.

```
DeclareCategory("IsMarkedSphere", IsObject); BindGlobal("MARKEDSPHERES_FAMILY",
NewFamily("MarkedSpheres", IsMarkedSphere)); BindGlobal("TYPE_MARKEDSPHERE", New-
Type(MARKEDSPHERES_FAMILY, IsMarkedSphere)); DeclareAttribute("MarkedSphere", Is-
SphereMachine); DeclareAttribute("MarkedSphere", IsP1Map); undocumented for now DeclareAt-
tribute("VerticesOfMarkedSphere", IsMarkedSphere); DeclareAttribute("SpanningTreeBoundary",
IsMarkedSphere);
```

### 3.2.9 IsMarkedSphere

▷ IsMarkedSphere (filter)

The category of marked, triangulated spheres (points in Teichmüller space).

DeclareOperation("NewMarkedSphere", [IsP1PointCollection, IsSphereGroup]);  
DeclareOperation("NewMarkedSphere", [IsP1PointCollection]);

### 3.2.10 NewMarkedSphere

▷ NewMarkedSphere(*points*[, *group*]) (operation)

**Returns:** A new marked sphere on points *points*.

This function creates a new marked sphere, based on the Delaunay triangulation on *points*. If a sphere group *group* is specified, it is used to mark the sphere; otherwise a new sphere group is created.

DeclareOperation("Draw", [IsMarkedSphere]);

### 3.2.11 Draw (spider)

▷ Draw(*s*) (operation)

This command plots the marked sphere *s* in a separate window. It displays the complex sphere, big dots at the post-critical set (feet of the spider), and the arcs and dual arcs of the triangulation connecting the feet.

If the option `julia:=<gridsize>` (if no grid size is specified, it is 500 by default), then the Julia set of the map associated with the spider is also displayed. Points attracted to attracting cycles are coloured in pastel tones, and unattracted points are coloured black.

If the option `noarcs` is specified, the printing of the arcs and dual arcs is disabled.

The options `upper`, `lower` and `detach` also apply.

DeclareOperation("WiggledMarkedSphere", [IsMarkedSphere, IsObject]);

### 3.2.12 WiggledMarkedSphere

▷ WiggledMarkedSphere(*sphere*, *m*) (operation)

**Returns:** A new marked sphere.

This operation moves the vertices of the marked sphere *sphere*, preserving its marking. The argument *m*, which specifies a movement of the vertices, is either a Möbius transformation (to be applied to all vertices) or a list of new positions for them.

DeclareOperation("SphereMachineOfBranchedCovering", [IsMarkedSphere, IsMarkedSphere, IsP1Map, IsBool]);  
DeclareOperation("SphereMachineOfBranchedCovering", [IsMarkedSphere, IsMarkedSphere, IsP1Map]);  
DeclareOperation("SphereMachineAndSphereOfBranchedCovering", [IsMarkedSphere, IsP1Map, IsBool]);  
DeclareOperation("SphereMachineAndSphereOfBranchedCovering", [IsMarkedSphere, IsP1Map]);

### 3.2.13 SphereMachineOfBranchedCovering

▷ SphereMachineOfBranchedCovering(*down*, *up*, *map*[, *poly*]) (operation)

▷ SphereMachineAndSphereOfBranchedCovering(*down*, *map*[, *poly*]) (operation)

**Returns:** A sphere machine or [machine,marked sphere].

The first function computes, out of a marked sphere *down* in the range of the P1 map *map* and a marked sphere *up* in its domain, the sphere machine representing the monodromy action of the map. Its input stateset is the model group of *down*, while its output stateset is the model group of *up*.

The second function first computes a marked sphere on the full preimage by *map* of the vertices of *down*, then computes the sphere machine, and finally returns a list containing the machine and the sphere at the source of *map*.

The optional parameter *poly* specifies that the map *map* is to be treated as a polynomial, and that the machine is to be normalized so that its last generator is an adding machine in standard form.

```
DeclareOperation("MonodromyOfP1Map", [IsMarkedSphere,IsP1Map]);      Declare-
Operation("MonodromyOfP1Map", [IsP1PointCollection,IsP1Map]);      DeclareOpera-
tion("MonodromyOfP1Map", [IsP1Map]);
```

### 3.2.14 MonodromyOfP1Map

▷ MonodromyOfP1Map([*marking*, *map*]) (operation)

**Returns:** The monodromy action of *map*.

This function computes the monodromy of the P1 map *map*; this is simply the activity of the sphere machine associated with the map.

The optional first argument *marking* may be a marked sphere, in which case the monodromy is returned as a homomorphism from the marked sphere's marking. It may also be a list of P1 points, in which case the monodromy is returned as a list of permutations, one per point. If the first argument is missing, it is assumed to be the list of critical values of *map*.

```
DeclareAttribute("SphereMachine", IsP1Map);
```

### 3.2.15 SphereMachine (rational function)

▷ SphereMachine(*f*) (operation)

**Returns:** A sphere machine.

This function computes a triangulation of the sphere, on the post-critical set of *f*, and lifts it through the map *f*. the action of the fundamental group of the punctured sphere is then read into an sphere machine *m*, which is returned.

This machine has a preset attribute MarkedSphere(*m*).

An approximation of the Julia set of *f* can be computed, and plotted on the spider, with the form IMGMachine(*f*:julia) or IMGMachine(*f*:julia:=gridsize).

Example

```
gap> SphereMachine(P1z^2-1);
<FR machine with alphabet [ 1, 2 ] on Group( [ f1, f2, f3 ] )/[ f2*f1*f3 ]>
gap> Display(last);
G |          1          2
---+-----+-----+
f1 |          f2,2    <id>,1
f2 | f3^-1*f1*f3,1    <id>,2
f3 |          <id>,2    f3,1
---+-----+-----+
Relator: f2*f1*f3
```

```
DeclareOperation("DistanceMarkedSpheres", [IsMarkedSphere, IsMarkedSphere]); DeclareOp-
eration("DistanceMarkedSpheres", [IsMarkedSphere, IsMarkedSphere, IsBool]);
```

### 3.2.16 DistanceMarkedSpheres

▷ DistanceMarkedSpheres(*sphere1*, *sphere2*[, *fast*]) (operation)

**Returns:** The approximate distance between the marked spheres.

This function approximates coarsely the Teichmüller distance between marked spheres with same model group. If the vertices of *sphere1* can be wiggled to the vertices of *sphere2* in such a manner that the markings coincide, then the distance is the sum of the movements of the vertices. Otherwise, it is 1+ the sum of the lengths of the images of a sphere group automorphism that carries the marking of *sphere1* to that of *sphere2*.

DeclareOperation("LiftOfConjugacyClass", [IsGroupFRMachine, IsConjugacyClassGroupRep]);

### 3.2.17 LiftOfConjugacyClass

▷ LiftOfConjugacyClass(*m*, *c*) (operation)

**Returns:** A list of conjugacy classes and multiplicities.

This command computes the preimage of the conjugacy class *c* by the sphere machine *m*, namely, it applies the wreath recursion to a representative of *c* and collects the products on all cycles. It returns then a list of pairs [*cc*, *len*] where *cc* is the conjugacy class of a product on a cycle, and *len* is the length of the cycle.

DeclareAttribute("ComplexConjugate", IsFRMachine); # already declared for arithmetic objects

### 3.2.18 ComplexConjugate

▷ ComplexConjugate(*m*) (operation)

**Returns:** An FR machine with inverted states.

This function constructs an FR machine whose generating states are the inverses of the original states. If *m* came from a complex rational map  $f(z)$ , this would construct the machine of the conjugate map  $f(\bar{z})$ .

Example

```
gap> a := PolynomialSphereMachine(2, [1/7]);
<FR machine with alphabet [ 1, 2 ] and adder FRElement(...,f4) on <object>/[ f4*f3*f2*f1 ]>
gap> Display(a);
  G |          1          2
  ---+-----+-----+
  f1 | f1^-1*f2^-1,2    f3*f2*f1,1
  f2 |          f1,1      <id>,2
  f3 |          f2,1      <id>,2
  f4 |          f4,2      <id>,1
  ---+-----+-----+
Adding element: FRElement(...,f4)
Relator: f4*f3*f2*f1
gap> Display(ComplexConjugate(a));
  G |          1          2
  ---+-----+-----+
  f1 | f1*f2*f3*f4,2    f4^-1*f2^-1*f1^-1,1
  f2 |          f1,1      <identity ...>,2
  f3 |          f2,1      <identity ...>,2
  f4 |          f4,2      <identity ...>,1
  ---+-----+-----+
Adding element: FRElement(...,f4)
```

```

Relator: f1*f2*f3*f4
gap> ExternalAngle(a);
{2/7}
gap> ExternalAngle(ComplexConjugate(a));
{6/7}

```

```

DeclareOperation("RotatedSpider", [IsPolynomialSphereMachine]);
DeclareOperation("RotatedSpider", [IsPolynomialSphereMachine, IsInt]);

```

### 3.2.19 RotatedSpider

▷ `RotatedSpider( $m$ ,  $p$ )` (operation)

**Returns:** A polynomial FR machine with rotated spider at infinity.

This function constructs an isomorphic polynomial FR machine, but with a different numbering of the spider legs at infinity. This rotation is accomplished by conjugating by  $\text{adder}^p$ , where  $\text{adder}$  is the adding element of  $m$ , and  $p$ , the rotation parameter, is 1 by default.

Example

```

gap> a := PolynomialSphereMachine(3,[1/4]);
<FR machine with alphabet [ 1, 2, 3 ] and adder FRElement(...,f3) on <object>/[ f3*f2*f1 ]>
gap> Display(a);
G |      1      2      3
---+-----+-----+-----+
f1 | f1^-1,2  <id>,3  f2*f1,1
f2 |   f1,1   <id>,2  <id>,3
f3 |   f3,3   <id>,1  <id>,2
---+-----+-----+-----+
Adding element: FRElement(...,f3)
Relator: f3*f2*f1
gap> Display(RotatedSpider(a));
G |      1      2      3
---+-----+-----+-----+
f1 | <id>,2   f2*f1*f3,3  f3^-1*f1^-1,1
f2 | <id>,1       <id>,2  f3^-1*f1*f3,3
f3 |   f3,3       <id>,1  <id>,2
---+-----+-----+-----+
Adding element: FRElement(...,f3)
Relator: f3*f2*f1
gap> ExternalAngle(a);
{3/8}
gap> List([1..10],i->ExternalAngle(RotatedSpider(a,i)));
[ {7/8}, {1/4}, {7/8}, {1/4}, {7/8}, {1/4}, {7/8}, {1/4}, {7/8}, {1/4} ]

```

```

DeclareOperation("BranchedCoveringByMonodromy", [IsMarkedSphere,IsGroupHomomorphism]);
DeclareOperation("BranchedCoveringByMonodromy", [IsMarkedSphere,IsGroupHomomorphism,IsRecord]);

```

### 3.2.20 BranchedCoveringByMonodromy

▷ `BranchedCoveringByMonodromy( $sphere$ ,  $monodromy$ ,  $last$ )` (operation)

**Returns:** A record describing a Hurwitz map.



If *sphere* is a marked sphere, marked by a group  $G$ , and *monodromy* is a homomorphism from  $G$  to a permutation group, this function computes a rational map whose critical values are the vertices of *sphere* and whose monodromy about these critical values is given by *monodromy*.

The returned data are in a record with a field *degree*, the degree of the map; two fields *map* and *post*, describing the desired  $\mathbb{P}^1$ -map — *post* is a Möbius transformation, and the composition of *map* and *post* is the desired map; and lists *zeros*, *poles* and *cp* describing the zeros, poles and critical points of the map. Each entry in these lists is a record with entries *degree*, *pos* and *to* giving, for each point in the source of *map*, the local degree and the vertex in *sphere* it maps to.

If a third argument is supplied, it should be a record similar to the return value of the command. If the result is close enough to the supplied record, it will be used to speed up the calculation.

This function requires external programs in the subdirectory "hurwitz" to have been compiled.

#### Example

```
gap> # we'll construct 2d-2 points on the equator, and permutations
gap> # in order (1,2),...,(d-1,d),(d-1,d),...,(1,2) for these points.
gap> # first, the marked sphere
gap> d := 20;;
gap> z := List([0..2*d-3], i->P1Point(Exp(i*PMCOMPLEX.constants.2IPI/(2*d-2))));;
gap> g := SphereGroup(2*d-2);;
gap> sphere := NewMarkedSphere(z,g);;
gap> # next, the permutation representation
gap> perms := List([1..d-1], i->(i,i+1));;
gap> Append(perms,Reversed(perms));;
gap> perms := GroupHomomorphismByImages(g,SymmetricGroup(d),GeneratorsOfGroup(g),perms);;
gap> # now compute the map
gap> BranchedCoveringByMonodromy(sphere,perms);
rec( cp := [ rec( degree := 2, pos := <1.0022-0.0099955i>, to := <vertex 19[ 9, 132, 13, 125 ]> ),
  rec( degree := 2, pos := <1.0022-0.0099939i>, to := <vertex 20[ 136, 128, 129, 11 ]> ),
  rec( degree := 2, pos := <1.0039-0.0027487i>, to := <vertex 10[ 73, 74, 16, 82 ]> ),
  rec( degree := 2, pos := <1.0006-0.0027266i>, to := <vertex 29[ 185, 20, 179, 21 ]> ),
  rec( degree := 2, pos := <1.0045-7.772e-05i>, to := <vertex 9[ 24, 77, 17, 72 ]> ),
  rec( degree := 2, pos := <1.1739+0.33627i>, to := <vertex 2[ 31, 32, 41, 28 ]> ),
  rec( degree := 2, pos := <1.0546+0.12276i>, to := <vertex 3[ 37, 38, 33, 46 ]> ),
  rec( degree := 2, pos := <1.026+0.061128i>, to := <vertex 4[ 43, 39, 52, 45 ]> ),
  rec( degree := 2, pos := <1.0148+0.03305i>, to := <vertex 5[ 49, 44, 58, 51 ]> ),
  rec( degree := 2, pos := <1.0098+0.018122i>, to := <vertex 6[ 55, 50, 64, 57 ]> ),
  rec( degree := 2, pos := <1.0071+0.0093947i>, to := <vertex 7[ 61, 62, 71, 59 ]> ),
  rec( degree := 2, pos := <1.0055+0.0037559i>, to := <vertex 8[ 67, 68, 63, 69 ]> ),
  rec( degree := 2, pos := <1.0035-0.0047633i>, to := <vertex 11[ 79, 75, 88, 81 ]> ),
  rec( degree := 2, pos := <1.0031-0.0062329i>, to := <vertex 12[ 85, 80, 94, 87 ]> ),
  rec( degree := 2, pos := <1.0029-0.0073311i>, to := <vertex 13[ 91, 86, 100, 93 ]> ),
  rec( degree := 2, pos := <1.0027-0.008187i>, to := <vertex 14[ 97, 92, 106, 99 ]> ),
  rec( degree := 2, pos := <1.0026-0.008824i>, to := <vertex 15[ 103, 98, 112, 105 ]> ),
  rec( degree := 2, pos := <1.0025-0.0092966i>, to := <vertex 16[ 109, 104, 118, 111 ]> ),
  rec( degree := 2, pos := <1.0024-0.0096345i>, to := <vertex 17[ 115, 110, 124, 117 ]> ),
  rec( degree := 2, pos := <1.0023-0.0098698i>, to := <vertex 18[ 121, 116, 122, 123 ]> ),
  rec( degree := 2, pos := <1.0021-0.0098672i>, to := <vertex 21[ 133, 127, 142, 135 ]> ),
  rec( degree := 2, pos := <1.002-0.0096298i>, to := <vertex 22[ 139, 134, 148, 141 ]> ),
  rec( degree := 2, pos := <1.002-0.0092884i>, to := <vertex 23[ 145, 140, 154, 147 ]> ),
  rec( degree := 2, pos := <1.0019-0.0088147i>, to := <vertex 24[ 151, 146, 160, 153 ]> ),
  rec( degree := 2, pos := <1.0017-0.008166i>, to := <vertex 25[ 157, 152, 166, 159 ]> ),
  rec( degree := 2, pos := <1.0016-0.0073244i>, to := <vertex 26[ 163, 158, 172, 165 ]> ),
  rec( degree := 2, pos := <1.0014-0.0061985i>, to := <vertex 27[ 169, 164, 178, 171 ]> ),
```

```

rec( degree := 2, pos := <1.0011-0.0047031i>, to := <vertex 28[ 175, 170, 176, 177 ]> ),
rec( degree := 2, pos := <0.99908+0.0038448i>, to := <vertex 31[ 187, 183, 196, 189 ]> ),
rec( degree := 2, pos := <0.99759+0.0094326i>, to := <vertex 32[ 193, 188, 202, 195 ]> ),
rec( degree := 2, pos := <0.99461+0.018114i>, to := <vertex 33[ 199, 194, 208, 201 ]> ),
rec( degree := 2, pos := <0.98944+0.032796i>, to := <vertex 34[ 205, 200, 214, 207 ]> ),
rec( degree := 2, pos := <0.9772+0.058259i>, to := <vertex 35[ 211, 206, 220, 213 ]> ),
rec( degree := 2, pos := <0.94133+0.11243i>, to := <vertex 36[ 217, 212, 226, 219 ]> ),
rec( degree := 2, pos := <0.79629+0.23807i>, to := <vertex 37[ 223, 224, 225, 221 ]> ),
rec( degree := 2, pos := <1+0i>, to := <vertex 30[ 181, 182, 6, 190 ]> ) ], degree := 20,
map := <((-0.32271060393507572-4.3599244721894763i_z)*z^20+(3.8941736874493795+78.415744809040
i_z)*z^19+(-16.808157937605603-665.79436908026275i_z)*z^18+(2.6572296014719168+3545.861245383101
)*z^17+(316.57668022762243-13273.931613611372i_z)*z^16+(-1801.6631038749117+37090.818733740503i_
z^15+(5888.6033008259928-80172.972599556582i_z)*z^14+(-13500.864941314803+137069.10015838256i_z)
z^13+(23251.436304923012-187900.36507913063i_z)*z^12+(-31048.192131502536+208077.63047409133i_z)*z
+(32639.349270133433-186578.17493860485i_z)*z^10+(-27155.791223040047+135145.40893002271i_z)*z^9
7836.343164500577-78489.005444299968i_z)*z^8+(-9153.842142530224+36053.895961137248i_z)*z^7+(359
408777659944-12810.65497539577i_z)*z^6+(-1047.541279063196+3397.470068169695i_z)*z^5+(212.906725
0024-633.29691376653466i_z)*z^4+(-26.989372105307872+74.040615571896637i_z)*z^3+(1.6073346640110
-4.0860733899027055i_z)*z^2)/(z^18+(-18.034645372692019-0.45671993287358581i_z)*z^17+(153.540499
49956+7.7811506405054889i_z)*z^16+(-819.9344323563339-62.384270590463998i_z)*z^15+(3077.71530771
75+312.59552100187739i_z)*z^14+(-8623.1225834872057-1096.4398001099003i_z)*z^13+(18689.343968250
2856.8568878158458i_z)*z^12+(-32038.568184053798-5725.9186424029094i_z)*z^11+(44038.148375498437
17.0162876593004i_z)*z^10+(-48898.555649389084-11295.156285052604i_z)*z^9+(43964.579894637543+11
.997395732025i_z)*z^8+(-31931.403449371515-9074.2344933443364i_z)*z^7+(18595.347261301522+5786.6
424805825i_z)*z^6+(-8565.0823844971637-2899.3353634270734i_z)*z^5+(3051.6919509143086+1117.44496
99487i_z)*z^4+(-811.56293104533825-319.93036282549667i_z)*z^3+(151.69784956523344+64.11787684283
5i_z)*z^2+(-17.785127700028404-8.0311759305108268i_z)*z+(0.98427999507354302+0.47338721325094818
))>, poles := [ rec( degree := 1, pos := <0.99517+0.30343i>, to := <vertex 1[ 26, 27, 1, 34 ]> )
rec( degree := 1, pos := <1.0021+0.11512i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0028+0.05702i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0026+0.030964i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0025+0.016951i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0024+0.0085784i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0024+0.003208i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0023-0.00046905i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0023-0.0030802i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0023-0.0049913i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0023-0.0064163i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0022-0.0074855i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0022-0.0082954i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0022-0.0089048i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0022-0.0093543i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0022-0.0096742i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0022-0.0098869i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 1, pos := <1.0022-0.0099988i>, to := <vertex 1[ 26, 27, 1, 34 ]> ),
rec( degree := 2, pos := <P1infinity>, to := <vertex 1[ 26, 27, 1, 34 ]> ) ],
post := <((-0.91742065452766763+0.99658449300666985i_z)*z+(0.74087581626192234-1.1339948562200
i_z))/((-0.75451451285920013+0.96940026593933015i_z)*z+(0.75451451285920013-0.96940026593933015i
))>, zeros := [ rec( degree := 1, pos := <0.92957+0.28362i>, to := <vertex 38[ 30, 3, 228, 7 ]> )
rec( degree := 1, pos := <0.99173+0.11408i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <0.99985+0.056874i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0014+0.030945i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.002+0.016938i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),

```

```

rec( degree := 1, pos := <1.0022+0.0085785i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022+0.0032076i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.00046827i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0030802i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0049908i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.006416i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0074855i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0082953i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0089047i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0093542i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0096742i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0098869i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 1, pos := <1.0022-0.0099988i>, to := <vertex 38[ 30, 3, 228, 7 ]> ),
rec( degree := 2, pos := <0+0i>, to := <vertex 38[ 30, 3, 228, 7 ]> ) ] )

```

```

DeclareOperation("DessinByPermutations", [IsPerm,IsPerm]);
DeclareOperation("DessinByPermutations", [IsPerm,IsPerm,IsPerm]);

```

### 3.2.21 DessinByPermutations

▷ `DessinByPermutations( $s_0$ ,  $s_1$ [,  $\text{sinf}$ ])` (operation)

**Returns:** A rational map (see `BranchedCoveringByMonodromy` (3.2.20)) with monodromies  $s, t$ .

This command computes the Hurwitz map associated with the spanning tree  $[0, 1] \cup [1, \infty]$ ; the monodromy representation is by the permutation  $s_0$  at 0 and  $s_1$  at 1. The optional third argument  $\text{sinf}$  is the monodromy at  $\infty$ , and must equal  $s_0^{-1}s_1^{-1}$ .

The data is returned as a record, with entries `degree`, `map`, `post`, and lists `poles`, `zeros`, and `above1`. Each entry in the list is a record with entries `pos` and `degree`.

Example

```

gap> DessinByPermutations((1,2),(2,3));
rec( above1 := [ rec( degree := 2, pos := <1+0i> ),
                  rec( degree := 1, pos := <-0.5-1.808e-14i> ) ],
      degree := 3,
      map := <(-1.9999999999946754+2.1696575743432764e-13i_z)*z^3+(2.9999999999946754-2.169657574
      poles := [ rec( degree := 3, pos := <PInfinity> ) ],
      post := <z>,
      zeros := [ rec( degree := 1, pos := <1.5+5.4241e-14i> ),
                  rec( degree := 2, pos := <0+0i> ) ] )
gap> # the Cui example
gap> DessinByPermutations((1,3,12,4)(5,9)(6,7)(10,13,11)(2,8),
                          (1,5,13,6)(7,10)(2,3)(8,11,12)(4,9),
                          (1,7,11,2)(3,8)(4,5)(9,12,13)(6,10));
rec(
  above1 := [ rec( degree := 2, pos := <1.9952-0.79619i> ),
              rec( degree := 2, pos := <0.43236-0.17254i> ), rec( degree := 2, pos := <-0.9863-0.16498i> ),
              rec( degree := 3, pos := <-0.12749-0.99184i> ), rec( degree := 4, pos := <1+0i> ) ],
  degree := 13,
  map := <((-6.9809917616400366e-12+0.13002709490708636i_z)*z^13+(-0.68172329304137969-0.8451761
  2062078i_z)*z^12+(4.0903397584184269+0.30979932084028583i_z)*z^11+(-6.3643009040280925+7.5930410
  99336i_z)*z^10+(-5.1732765988942884-16.738910009700096i_z)*z^9+(21.528087032174511+6.11354599010
  5i_z)*z^8+(-15.258776392407746+13.657687016998921i_z)*z^7+(-1.6403496019814323-13.45331629709422

```

```

z)*z^6+(4.4999999996894351+3.3633290741375781i_z)*z^5+(-0.99999999990279009+2.5538451239904557e-
_z)*z^4)/(z^9+(-4.4999999999400613+3.3633290744267983i_z)*z^8+(1.6403496020557891-13.45331629745
7i_z)*z^7+(15.258776391831654+13.657687016903173i_z)*z^6+(-21.528087030670253+6.1135459892162567
)*z^5+(5.1732765986730511-16.738910007513041i_z)*z^4+(6.3643009027133139+7.593041020468557i_z)*z^
(-4.0903397575324512+0.30979932067785648i_z)*z^2+(0.68172329288354727-0.8451761166966415i_z)*z+
734454343833585e-12+0.13002709487107747i_z))>,
poles := [ rec( degree := 2, pos := <1.6127-0.49018i> ),
            rec( degree := 2, pos := <0.5-0.04153i> ), rec( degree := 2, pos := <-0.61269-0.49018i> ),
            rec( degree := 3, pos := <0.5-0.43985i> ), rec( degree := 4, pos := <PInfinity> ) ],
post := <-z+1._z>,
zeros := [ rec( degree := 2, pos := <1.9863-0.16498i> ),
            rec( degree := 3, pos := <1.1275-0.99184i> ), rec( degree := 2, pos := <0.56764-0.17254i> ),
            rec( degree := 2, pos := <-0.99516-0.79619i> ), rec( degree := 4, pos := <0+0i> ) ] )

```

```

gap> # IV.5.2 in Granboulan's PhD, the automorphism group of the Mathieu group
M_22 gap> autm22 := Group((1,2,3,4,5,6,7,8,9,10,11)(12,13,14,15,16,17,18,19,20,21,22),
(1,9,3,2)(4,8,17,21)(5,20,19,6)(12,22,16,13)(7,18)(10,11)(14,15), (3,8)(4,20)(6,18)(7,17)(9,11)(13,15)(16,21));
gap> IsomorphismGroups(DerivedSubgroup(autm22),MathieuGroup(22))<>fail; true
gap> DessinByPermutations(autm22.1,autm22.2,autm22.3); ... gap> # IV.5.3
in Granboulan's PhD, the "extraterrestrial" dessin with group M_24 gap>
m24_ET := Group((1,2,3)(4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24),
(1,7,5)(2,4,23)(3,22,8)(9,21,19)(10,18,12)(13,17,15), (1,4)(2,22)(3,7)(5,6)(8,21)(9,18)(10,11)(12,17)(13,14)(15,16)(19
gap> IsomorphismGroups(m24_ET,MathieuGroup(24))<>fail; true gap> @IMG.hurwitzmesh :=
0.4;; # need finer precision gap> DessinByPermutations(m24_ET.1,m24_ET.2,m24_ET.3); ...
DeclareAttribute("KneadingSequence", IsRat);

```

### 3.2.22 KneadingSequence (angle)

▷ KneadingSequence(*angle*) (attribute)

**Returns:** The kneading sequence associated with *angle*.

This function converts a rational angle to a kneading sequence, to describe a quadratic polynomial.

If *angle* is in  $[1/7, 2/7]$  and the option marked is set, the kneading sequence is decorated with markings in A,B,C.

Example

```

gap> KneadingSequence(1/7);
[ 1, 1 ]
gap> KneadingSequence(1/5:marked);
[ "A1", "B1", "B0" ]

```

```
DeclareGlobalFunction("AllInternalAddresses");
```

### 3.2.23 AllInternalAddresses

▷ AllInternalAddresses(*n*) (attribute)

**Returns:** Internal addresses of maps with period up to *n*.

This function returns internal addresses for all periodic points of period up to *n* under angle doubling. These internal addresses describe the prominent hyperbolic components along the path from the landing point to the main cardioid in the Mandelbrot set; this is a list of length  $3k$ , with at position  $3i+1, 3i+2$  the left and right angles, respectively, and at position  $3i+3$  the period of that

component. For example,  $[3/7, 4/7, 3, 1/3, 2/3, 2]$  describes the airplane: a polynomial with landing angles  $[3/7, 4/7]$  of period 3; and such that there is a polynomial with landing angles  $[1/3, 2/3]$  and period 2.

Example

```
gap> AllInternalAddresses(3);
[[ ], [ [ 1/3, 2/3, 2 ] ],
 [ [ 1/7, 2/7, 3 ], [ 3/7, 4/7, 3, 1/3, 2/3, 2 ], [ 5/7, 6/7, 3 ] ] ]
```

```
DeclareGlobalFunction("ExternalAnglesRelation");
```

### 3.2.24 ExternalAnglesRelation

▷ `ExternalAnglesRelation(degree, n)` (function)

**Returns:** An equivalence relation on the rationals.

This function returns the equivalence relation on `Rationals` identifying all pairs of external angles that land at a common point of period up to  $n$  under angle multiplication by  $degree$ .

Example

```
gap> ExternalAnglesRelation(2,3);
<equivalence relation on Rationals >
gap> EquivalenceRelationPartition(last);
[ [ 1/7, 2/7 ], [ 1/3, 2/3 ], [ 3/7, 4/7 ], [ 5/7, 6/7 ] ]
```

```
DeclareGlobalFunction("ExternalAngle");
```

### 3.2.25 ExternalAngle

▷ `ExternalAngle(machine)` (function)

**Returns:** The external angle identifying *machine*.

In case *machine* is the sphere machine of a unicritical polynomial, this function computes the external angle landing at the critical value. More precisely, it computes the equivalence class of that external angle under `ExternalAnglesRelation` (3.2.24).

Example

```
gap> ExternalAngle(PolynomialSphereMachine(2,[1/7])); # the rabbit
{2/7}
gap> Elements(last);
[ 1/7, 2/7 ]
```

## Chapter 4

# Examples

IMG predefines a large collection of machines and groups. The groups are, whenever possible, defined as state closures of corresponding Mealy machines.

### 4.1 Examples of groups

```
DeclareGlobalFunction("PoirierExamples");
```

#### 4.1.1 PoirierExamples

```
▷ PoirierExamples(...) (function)
```

The examples from Poirier's paper [\[Poi\]](#). See details under `PolynomialSphereMachine` ([3.1.27](#)); in particular, `PoirierExamples(1)` is the Douady rabbit map.

## Chapter 5

# IMG implementation details

IMG creates new categories for the various objects considered in the package. The first category is ...

### 5.1 Marked spheres

IMG contains algorithms that convert a rational function (with floating-point complex coefficients) to an IMG machine and back.

Consider a rational map  $f$  of degree  $d$ . First, compute the post-critical set  $P_f$ ; this is done by iterating  $f$  on critical points, and considering points at angle at most  $EPS@.prec$  from each other as equal.

Then construct a spherical Delaunay triangulation  $T$  on  $P_f$ ; and choose in it a minimal spanning tree; edges of that tree represent a generating set of the fundamental group  $G$  of  $S^2 \setminus P_f$ .

Lift first through  $f$  the edges of the dual tree in the dual tessellation of  $T$ ; they will form  $d$  connected subgraphs, numbered  $1, \dots, d$ . Lift then the edges crossing the minimal spanning tree, and read the elements of  $F$  that their lifts represent, as well as the subgraphs they start and end in. This data describes an FR machine.

Choose then for each vertex in  $P_f$  an adjacent face in  $T$ . This choice defines a generating family of  $F$  made up, for each vertex, of a path in the dual tree starting at a basepoint, a sequence of edges around a vertex starting at the chosen face, and a path back in the dual tree. The product, in an appropriate order, of these generators describes an IMG machine.

There is an epimorphism from the group  $G$ , generated by these loops around vertices, to  $F$ ; and this epimorphism becomes an isomorphism if one adds to  $G$  the relation "product of generators in an appropriate order". Such a triangulation, with a given group  $G$  and a homomorphism from  $G$  to  $F$ , is called a *spider*.

The inverse algorithm is quite similar. Consider an IMG machine  $M$ , with stateset  $G$ . Start by a "standard" set of points on the sphere, one per generator of  $M$ , and construct a spider  $S$  on them. Find a rational map  $f$  with critical values at the vertices of  $S$  and monodromy given by the activities of  $M$ , and lift  $S$  to a spider  $T$ , marked by a group  $H$ . The lifting gives a homomorphism  $f^* : G \rightarrow H \wr \text{Sym}(d)$ .

By appropriately relabeling the alphabet, one can ensure that this homomorphism coincides with  $M$ 's recursion at the first level. Furthermore, it identifies each vertex  $v_i$  of  $T$  either with a vertex  $w_j$  of  $S$ , if for some  $g \in G$  a state in  $M$  of  $g$  is a conjugate  $g_j$ , while the corresponding entry of  $f^*(g)$  is a conjugate of  $h_i$ .

Construct then a new triangulation  $S'$  by keeping only those vertices of  $T$  that were identified, and mapping them by a Möbius transformation  $\mu$  to "standard position". This means that the barycenter

of the points is  $0 \in \mathbb{R}^3$ , that the last point goes to  $\infty$ , and that the next-to-last goes to  $\mathbb{R}_+$ . Letting  $F$  denote the group on the minimal spanning tree of  $S'$ , there is a homomorphism  $\mu_* : H \rightarrow F$ .

The decomposition  $\phi$  of  $M$  then produces a homomorphism  $m : G \rightarrow F$  such that  $\mu_* f^* = m\phi$ . This turns  $S'$  into a spider on  $G$ . Iterate then this process with  $S'$ .

Either the spiders  $S$  converge, and then  $\mu^{-1}f$  is the desired rational function; or there is a Thurston obstruction, which is a non-contracting multicurve. Seek therefore clusters of vertices that are very close from each other, and compute the curve going around them; this defines a conjugacy class in  $G$ . In  $M$ , compute the iterated decomposition of this curve, and its associated transition matrix. If it has spectrum at least 1, return the multicurve as an obstruction; otherwise, continue.



## Chapter 6

# Miscellanea

### 6.1 Complex numbers

#### 6.1.1 IsPMComplex

▷ IsPMComplex	(filter)
▷ PMCOMPLEX_FAMILY	(family)
▷ PMCOMPLEX_PSEUDOFIELD	(global variable)
▷ PMCOMPLEX	(global variable)

A "poor man's" implementation of complex numbers, based on the underlying 64-bit floating-point numbers in GAP.

Strictly speaking, complex numbers do not form a field in GAP, because associativity etc. do not hold. Still, a field is defined, PMCOMPLEX\_FIELD, making it possible to construct an indeterminate and rational functions, to be passed to FR's routines.

These complex numbers can be made the default floating-point numbers via SetFloats(PMCOMPLEX);. They may then be entered as standard floating-point numbers, with the suffix \_z.

Example

```
gap> z := Indeterminate(PMCOMPLEX_FIELD,"z");
z
gap> (z+1/2)^5/(z-1/2);
(z^5+2.5*z^4+2.5*z^3+1.25*z^2+0.3125*z+0.03125)/(z+(-0.5))
gap> NewFloat(IsPMComplex,1,2);
1+2i
gap> last^2;
-3+4i
gap> RealPart(last);
-3
gap> Norm(last2);
25
gap> NewFloat(IsPMComplex,"1+2*I");
1+2i
gap> RootsFloat(z^2-5);
[ 2.23607, -2.23607 ]
gap> RootsFloat(ListWithIdenticalEntries(80,1.0_z));
[ 0.987688+0.156434i, 0.996917+0.0784591i, 0.996917-0.0784591i, 0.987688-0.156434i, 0.760406+0.6
```

```

0.522499+0.85264i, 0.649448+0.760406i, 0.891007+0.45399i, 0.587785+0.809017i, 0.707107+0.70710
0.382683+0.92388i, 0.85264+0.522499i, -0.59719-0.608203i, -0.867574-0.11552i, -0.186972-0.9902
0.156434+0.987688i, 0.295424-0.953359i, 0.588289-0.808509i, 0.455128-0.893999i, 0.0951213-1.01
0.97237-0.233445i, -0.233486+0.972416i, 0.379514-0.92918i, 3.09131e-07+1.i, 0.182752-0.984684i
0.92388-0.382683i, -0.585832+0.81608i, 0.809018-0.587792i, -0.656055+0.770506i, 0.760385-0.649
-0.15643+0.987703i, -0.307608-0.969002i, 0.649377-0.760134i, -0.382904+0.92328i, -0.857704+0.5
-0.929824-0.488558i, -0.671579-0.790133i, -0.886052-0.560249i, -1.05047-0.0873829i, -0.496236-
-0.585809-0.852796i, -0.518635+0.85364i, -1.04842+0.0255453i, -0.752485-0.724528i, -0.309225+0
]
gap> AsSortedList(List(last,AbsoluteValue));
[ 0.739812, 0.847513, 0.852377, 0.861109, 0.875231, 0.967092, 0.977534, 0.998083, 0.998317, 0.99
1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1., 1.00001, 1.000
1.01509, 1.01665, 1.01814, 1.01834, 1.02033, 1.0238, 1.02796, 1.02881, 1.03169, 1.03462, 1.035
1.05036, 1.05155, 1.0541, 1.05442, 1.0672 ]

```

## 6.2 P1 points

```

DeclareCategory("IsP1Point",IsObject);  DeclareCategoryCollections("IsP1Point");  DeclareCat-
egoryCollections("IsP1PointCollection");  DeclareSynonym("IsP1PointList",IsP1PointCollection
and      IsList);  DeclareCategory("IsIEEE754P1Point",IsP1Point);  Bind-
Global("P1PointsFamily",NewFamily("P1PointsFamily",IsP1Point));  Bind-
Global("TYPE_P1POINT",NewType(P1PointsFamily,IsP1Point  and  IsPositionalObjectRep));
BindGlobal("TYPE_IEEE754P1POINT",NewType(P1PointsFamily,IsIEEE754P1Point  and  Is-
DataObjectRep));  DeclareOperation("P1Point",[IsFloat]);  DeclareOperation("P1Point",[IsRat]);
DeclareOperation("P1Point",[IsInfinity]);  DeclareOperation("P1Point",[IsFloat,IsFloat]);

```

### 6.2.1 IsP1Point

```

▷ IsP1Point (filter)
▷ P1PointsFamily (family)
▷ P1Point(complex) (function)
▷ P1Point(real, imag) (function)
▷ P1Point(string) (function)

```

P1 points are complex numbers or infinity; fast methods are implemented to compute with them, and to apply rational maps to them.

The first filter recognizes these objects. Next, the family they belong to. The next methods create a new P1 point.

```
DeclareAttribute("P1Coordinate",IsP1Point);
```

### 6.2.2 P1Coordinate

```

▷ P1Coordinate(p) (function)
Returns: The complex number represented by p.
DeclareOperation("CleanedP1Point",[IsP1Point,IsFloat]);  DeclareOpera-
tion("CleanedP1Point",[IsP1Point]);

```

### 6.2.3 CleanedP1Point

- ▷ `CleanedP1Point( $p$  [,  $prec$ ])` (function)  
**Returns:**  $p$ , rounded towards 0/1/infinity/real at precision  $prec$ .  
`DeclareGlobalVariable("P1infinity"); DeclareOperation("P1INFINITY@",[IsP1Point]); DeclareGlobalVariable("P1one"); DeclareGlobalVariable("P1zero");`

### 6.2.4 P1infinity

- ▷ `P1infinity` (global variable)  
 ▷ `P1one` (global variable)  
 ▷ `P1zero` (global variable)

The south, north and 'east' poles of the Riemann sphere.  
`DeclareAttribute("P1Antipode",IsP1Point);`

### 6.2.5 P1Antipode

- ▷ `P1Antipode( $p$ )` (function)  
**Returns:** The antipode of  $p$  on the Riemann sphere.  
`DeclareOperation("P1Barycentre",[IsP1PointList]);` `DeclareOperation("P1Barycentre",[IsP1Point]);`  
`DeclareOperation("P1Barycentre",[IsP1Point,IsP1Point]);`  
`DeclareOperation("P1Barycentre",[IsP1Point,IsP1Point,IsP1Point]);`

### 6.2.6 P1Barycentre

- ▷ `P1Barycentre( $points$ , ...)` (function)  
**Returns:** The barycentre of its arguments (which can also be a list of P1 points).  
`DeclareOperation("P1Circumcentre",[IsP1Point,IsP1Point,IsP1Point]);`

### 6.2.7 P1Circumcentre

- ▷ `P1Circumcentre( $p$ ,  $q$ ,  $r$ )` (function)  
**Returns:** The centre of the smallest disk containing  $p, q, r$ .  
`DeclareOperation("P1Distance",[IsP1Point,IsP1Point]);`

### 6.2.8 P1Distance

- ▷ `P1Distance( $p$ ,  $q$ )` (function)  
**Returns:** The spherical distance from  $p$  to  $q$ .  
`DeclareOperation("P1Midpoint",[IsP1Point,IsP1Point]);`

### 6.2.9 P1Midpoint

- ▷ `P1Midpoint( $p$ ,  $q$ )` (function)  
**Returns:** The point between  $p$  to  $q$  (undefined if they are antipodes of each other).  
`DeclareAttribute("P1Sphere",IsList);`

### 6.2.10 P1Sphere

- ▷ `P1Sphere(v)` (function)  
**Returns:** The P1 point corresponding to  $v$  in  $\mathbb{R}^3$ .  
`DeclareAttribute("SphereP1",IsP1Point);`

### 6.2.11 SphereP1

- ▷ `SphereP1(p)` (function)  
**Returns:** The coordinates in  $\mathbb{R}^3$  of  $p$ .  
`DeclareAttribute("SphereP1Y",IsP1Point);`

### 6.2.12 SphereP1Y

- ▷ `SphereP1Y(p)` (function)  
**Returns:** The Y coordinate in  $\mathbb{R}^3$  of  $p$ .  
`DeclareOperation("P1XRatio",[IsP1Point,IsP1Point,IsP1Point,IsP1Point]);`      `DeclareOperation("XRatio",[IsP1Point,IsP1Point,IsP1Point,IsP1Point]);`

### 6.2.13 P1XRatio

- ▷ `P1XRatio(p, q, r, s)` (function)  
▷ `XRatio(p, q, r, s)` (function)  
**Returns:** The cross ratio of  $p, q, r, s$ .  
The cross ratio of four points  $p, q, r, s$  is defined as  $(p-r)(q-s)/(p-s)(q-r)$ . The values `P1zero`, `P1one`, `P1infinity` correspond respectively to the special cases  $(p=r \text{ or } q=s)$ ,  $(p=q \text{ or } r=s)$ ,  $(p=s \text{ or } q=r)$ .  
In the first form, the result is a P1 point. In the second form, it is a complex number.  
`DeclareOperation("CollectedP1Points",[IsP1PointList]);`      `DeclareOperation("CollectedP1Points",[IsP1PointList,IsFloat]);`

### 6.2.14 CollectedP1Points

- ▷ `CollectedP1Points(p1points[, precision])` (operation)  
**Returns:** A list of pairs `[point,multiplicity]`.  
Collects the points in `p1points`; points at distance at most `precision` are considered equal, and the barycentre of the clustered points is returned.  
If the argument `precision` is not supplied, `@IMG.p1eps` is taken.  
`DeclareOperation("MatchP1Points",[IsP1PointList,IsP1PointCollColl,IsFloat]);`      `DeclareOperation("MatchP1Points",[IsP1PointList,IsP1PointCollColl]);`

### 6.2.15 MatchP1Points

- ▷ `MatchP1Points(p1pointsA, p1pointsB[, separation])` (operation)  
**Returns:** A list of giving closest point in `p1pointsB` to points in `p1pointsA`, or fail.  
Finds for each point `p1pointsA[i]` the closest point `p1pointB[p[i]]`. If the next-closest is at least `separation` further away for all  $i$ , then the list `p` is returned. Otherwise, fail is returned.  
If the argument `separation` is not supplied, 2 is taken.  
`DeclareOperation("ClosestP1Point",[IsP1PointList,IsP1Point]);`

### 6.2.16 ClosestP1Point

▷ `ClosestP1Point(p1points, p1point)` (operation)

**Returns:** The point in *p1points* closest to *p1point*.

```
DeclareSynonym("IsP1Map", IsUnivariateRationalFunction and IsFloatRationalFunction);
DeclareCategory("IsIEEE754P1Map", IsP1Map); BindGlobal("TYPE_IEEE754P1MAP", New-
Type(RationalFunctionsFamily(PMCOMPLEX_PSEUDOFIELD), IsIEEE754P1Map and IsDataOb-
jectRep));
```

### 6.2.17 IsP1Map

▷ `IsP1Map` (filter)

P1 maps are stored more efficiently than rational functions, but are otherwise equivalent.

```
DeclareOperation("MoebiusMap", [IsP1Point]);
DeclareOperation("MoebiusMap", [IsP1Point, IsP1Point]);
DeclareOperation("MoebiusMap", [IsP1Point, IsP1Point, IsP1Point, IsP1Point]);
DeclareOperation("MoebiusMap", [IsP1PointList]);
DeclareOperation("MoebiusMap", [IsP1PointList, IsP1PointList]);
```

### 6.2.18 MoebiusMap

▷ `MoebiusMap([sourcelist, destlist])` (function)  
 ▷ `MoebiusMap(p, q, r, s, t, u)` (function)  
 ▷ `MoebiusMap(p, q, r)` (function)  
 ▷ `MoebiusMap(p, q)` (function)  
 ▷ `MoebiusMap(p)` (function)

**Returns:** A new Möbius transformation.

In the first case, this is the Möbius transformation sending  $p, q, r$  to  $P, Q, R$  respectively; in the second case, the map sending  $0, 1, P1infinity$  to  $p, q, r$  respectively; in the third case, the map sending  $0, P1infinity$  to  $p, q$  respectively, and of the form  $(z - p)/(z - q)$ ; and in the fourth case, a rotation sending  $P1infinity$  to  $p$ .

```
DeclareOperation("P1ROTATION@", [IsP1Point, IsP1PointList, IsP1PointList]);
DeclareGlobalFunction("P1MapRotatingP1Points");
```

### 6.2.19 P1MapRotatingP1Points

▷ `P1MapRotatingP1Points(points[], oldpoints[])` (operation)

**Returns:** A Möbius rotation sending the last of *points* to  $P1infinity$ .

A Möbius rotation is computed that sends the last of *points* to  $P1infinity$  and, assuming the last point in *oldpoints* is also  $P1infinity$ , matches the points in *points* and *oldpoints* as closely as possible.

```
DeclareOperation("P1MapNormalizingP1Points", [IsP1PointList]);
DeclareOperation("P1MapNormalizingP1Points", [IsP1PointList, IsP1PointList]);
```

### 6.2.20 P1MapNormalizingP1Points

▷ `P1MapNormalizingP1Points(points[, oldpoints])` (operation)

**Returns:** A Möbius transformation sending the last of *points* to `P1infinity`.

A Möbius transformation is computed that sends the last of *points* to `P1infinity` and makes the barycentre of the points in  $\mathbb{R}^3$  as close as possible to the origin. If a list *oldpoints* is also given, the Möbius transformation computed rotates about infinity so as to match the points in *points* and *oldpoints* as closely as possible; this then determines the transformation uniquely.

`DeclareGlobalVariable("P1z");`

### 6.2.21 P1z

▷ `P1z` (global variable)

The identity Möbius transformation.

`DeclareGlobalFunction("P1Monomial");`

### 6.2.22 P1Monomial

▷ `P1Monomial(n)` (function)

**Returns:** The rational function  $z^n$ .

`DeclareOperation("CleanedP1Map",[IsP1Map,IsFloat]);` `DeclareOperation("CleanedP1Map",[IsP1Map]);`

### 6.2.23 CleanedP1Map

▷ `CleanedP1Map(map[, prec])` (operation)

**Returns:** *map*, with coefficients rounded using *prec*.

`DeclareSynonym("CompositionP1Map",CompositionMapping2);`

### 6.2.24 CompositionP1Map

▷ `CompositionP1Map(map1, ...)` (operation)

**Returns:** The composition of the maps passed as arguments, in the functional (*map1* last) order.

`DeclareSynonym("InverseP1Map",InverseGeneralMapping);`

### 6.2.25 InverseP1Map

▷ `InverseP1Map(map)` (operation)

**Returns:** The functional inverse of the Möbius transformation *map*.

`DeclareAttribute("ComplexConjugate",IsP1Map);` # already there for numerical objects

### 6.2.26 ComplexConjugate (P1 map)

▷ `ComplexConjugate(map)` (operation)

**Returns:** The complex conjugated map.

`DeclareOperation("ConjugatedP1Map",[IsP1Map,IsP1Map]);`

### 6.2.27 ConjugatedP1Map

- ▷ `ConjugatedP1Map(map, mobius)` (operation)  
**Returns:** The map `CompositionP1Map(InverseP1Map(mobius), map, mobius)`.  
`DeclareAttribute("CoefficientsOfP1Map", IsP1Map);`

### 6.2.28 CoefficientsOfP1Map

- ▷ `CoefficientsOfP1Map(map)` (operation)  
**Returns:** Coefficients of numerator and denominator of *map*, lowest degree first.  
`DeclareGlobalFunction("P1MapByCoefficients");` `DeclareOperation("P1MAPBYCOEFFICIENTS2@", [IsObject, IsList, IsList]);`

### 6.2.29 P1MapByCoefficients

- ▷ `P1MapByCoefficients(numer, denom)` (operation)  
**Returns:** The P1 map with numerator coefficients *numer* and denominator *denom*, lowest degree first.  
`DeclareAttribute("NumeratorP1Map", IsP1Map);` `DeclareAttribute("DenominatorP1Map", IsP1Map);`

### 6.2.30 NumeratorP1Map

- ▷ `NumeratorP1Map(map)` (attribute)  
▷ `DenominatorP1Map(map)` (attribute)  
**Returns:** The numerator/denominator of *map*.  
`DeclareOperation("P1MapByZerosPoles", [IsP1PointList, IsP1PointList, IsP1Point, IsP1Point]);`

### 6.2.31 P1MapByZerosPoles

- ▷ `P1MapByZerosPoles(zeros, poles, src, dest)` (operation)  
**Returns:** The P1 map with specified zeros and poles, and sending *src* to *dest*.  
`DeclareOperation("P1Path", [IsP1Point, IsP1Point]);`

### 6.2.32 P1Path

- ▷ `P1Path(p, q)` (operation)  
**Returns:** The P1 map sending 0 to *p* and 1 to *q*.  
`DeclareAttribute("DegreeOfP1Map", IsP1Map);`

### 6.2.33 DegreeOfP1Map

- ▷ `DegreeOfP1Map(map)` (operation)  
**Returns:** The degree of *map*.  
`DeclareSynonym("P1Image", ImageElm);` `DeclareOperation("ImageElm", [IsP1Map, IsP1Point]);`

### 6.2.34 P1Image

▷ `P1Image(map, p1point)` (operation)  
**Returns:** The image of *p1point* under *map*.  
`DeclareSynonym("P1PreImage",PreImageElm);`  
`DeclareOperation("PreImageElm",[IsP1Map,IsP1Point]);` DeclareOpera-

### 6.2.35 P1PreImage

▷ `P1PreImage(map, p1point)` (operation)  
**Returns:** The preimage of *p1point* under *map*.  
`DeclareSynonym("P1PreImages",PreImagesElm);`  
`DeclareOperation("PreImagesElm",[IsP1Map,IsP1Point]);` DeclareOpera-

### 6.2.36 P1PreImages

▷ `P1PreImages(map, p1point)` (operation)  
**Returns:** The preimages of *p1point* under *map*.  
`DeclareAttribute("Primitive",IsP1Map);` `DeclareAttribute("Derivative",IsP1Map);`

### 6.2.37 Primitive

▷ `Primitive(map)` (operation)  
▷ `Derivative(map)` (operation)  
**Returns:** The [anti]derivative of the rational map *map*.  
`DeclareOperation("P1MapScaling",[IsP1Map,IsP1Point]);`

### 6.2.38 P1MapScaling

▷ `P1MapScaling(map, p1point)` (operation)  
**Returns:** The scaling factor from *point* to *map(point)*.  
`DeclareAttribute("CriticalPointsOfP1Map",IsP1Map);`

### 6.2.39 CriticalPointsOfP1Map

▷ `CriticalPointsOfP1Map(map)` (attribute)  
**Returns:** The critical points of *map*.  
`DeclareAttribute("AsP1Map",IsScalar);`

### 6.2.40 AsP1Map

▷ `AsP1Map(rat)` (operation)  
**Returns:** The P1 map given by the rational function *rat*.  
`DeclareOperation("P1MapSL2",[IsMatrix]);`



### 6.2.41 P1MapSL2

- ▷ `P1MapSL2(mat)` (operation)  
**Returns:** The Möbius P1 map given by the 2x2 matrix *mat*.  
`DeclareAttribute("SL2P1Map", IsP1Map);`

### 6.2.42 SL2P1Map

- ▷ `SL2P1Map(map)` (operation)  
**Returns:** The matrix of the Möbius P1 map *map*.  
`DeclareGlobalFunction("SetP1Points");`

### 6.2.43 SetP1Points

- ▷ `SetP1Points(record [, prec])` (function)

Installs a default implementation for P1 points. Fundamentally, a P1 point is a complex number or infinity, with a few extra methods. The argument *record* is the record describing the floating-point implementation.

Currently, one implementation (the default) is based on pairs of IEEE754 floats. It is fast, but is limited to 53 bits of precision. It is loaded via `SetP1Points(PMCOMPLEX);`.

Another implementation, in case the package `Float` is available, is based on MPC complex numbers. It offers unlimited precision, but is much slower. It is loaded via `SetP1Points(MPC);` or `SetP1Points(MPC, prec);`.

## 6.3 Miscellanea

`DeclareGlobalFunction("Mandel");`

### 6.3.1 Mandel

- ▷ `Mandel([map])` (function)

**Returns:** Calls the external program `mandel`.

This function starts the external program `mandel`, by Wolf Jung. The program is searched for along the standard `PATH`; alternatively, its location can be set in the string variable `EXEC@FR.mandel`.

When called with no arguments, this command returns starts `mandel` in its default mode. With a rational map as argument, it starts `mandel` pointing at that rational map.

More information on `mandel` can be found at <http://www.mndynamics.com>.

`DeclareOperation("NonContractingSubmatrix", [IsMatrix]);`

### 6.3.2 NonContractingSubmatrix

- ▷ `NonContractingSubmatrix(mat)` (operation)

**Returns:** `fail` or a list of indices *l* such that `mat{l}{l}` is irreducible and non-contracting

This function computes a minimal submatrix whose spectral radius is  $\geq 1$ . If none exists, it returns `fail`.

Example

```
gap> NonContractingSubmatrix([[2]]);
[ 1 ]
gap> NonContractingSubmatrix([[1/2]]);
fail
gap> NonContractingSubmatrix([[0,1],[1,0]]);
[ 1, 2 ]
gap> NonContractingSubmatrix([[0,1],[0,1]]);
[ 2 ]
```

## 6.4 User settings

### 6.4.1 InfoIMG

▷ InfoIMG

(info class)

This is an Info class for the package IMG. The command `SetInfoLevel(InfoIMG,1);` switches on the printing of some information during the computations of certain IMG functions; in particular all automatic conversions between IMG machines and Mealy machines.

The command `SetInfoLevel(InfoIMG,2);` requests a little more information, and in particular prints intermediate results in potentially long calculations such as...

The command `SetInfoLevel(InfoIMG,3);` ensures that IMG will print information every few seconds or so. This is useful to gain confidence that the program is not stuck due to a programming bug by the author of IMG.

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