

The Parma Polyhedra Library

User's Manual*

(version 0.7)

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This document describes the Parma Polyhedra Library (PPL).

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For the most up-to-date information see the Parma Polyhedra Library WWW site:

<http://www.cs.unipr.it/ppl/>

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1 General Information on the PPL

1.1 The Main Features

The Parma Polyhedra Library (PPL) is a modern C++ library for the manipulation of numerical information that can be represented by points in some n -dimensional vector space. For instance, one of the key domains the PPL supports is that of rational convex polyhedra (Section **Convex Polyhedra**(p. 2)). Such domains are employed in several systems for the analysis and verification of hardware and software components, with applications spanning imperative, functional and logic programming languages, synchronous languages and synchronization protocols, real-time and hybrid systems. Even though the PPL library is not meant to target a particular problem, the design of its interface has been largely influenced by the needs of the above class of applications. That is the reason why the library implements a few operators that are more or less specific to static analysis applications, while lacking some other operators that might be useful when working, e.g., in the field of computational geometry.

The main features of the library are the following:

- it is user friendly: you write $x + 2*y + 5*z \leq 7$ when you mean it;
- it is fully dynamic: available virtual memory is the only limitation to the dimension of anything;
- it provides full support for the manipulation of convex polyhedra that are not topologically closed;
- it is written in standard C++: meant to be portable;
- it is exception-safe: never leaks resources or leaves invalid object fragments around;
- it is rather efficient: and we hope to make it even more so;
- it is thoroughly documented: perhaps not literate programming but close enough;
- it has interfaces to other programming languages: including C and a number of Prolog systems;
- it is free software: distributed under the terms of the GNU General Public License.

In addition to the basic domains, we also provide generic support for constructing new domains from pre-existing domains. The following domains and domain constructors are provided by the PPL:

- the domain of topologically closed, rational convex polyhedra;
- the domain of rational convex polyhedra that are not necessarily closed;
- the powerset construction;
- the powerset construction, instantiated for rational convex polyhedra.

In the following sections we describe these domains and domain constructors together with their representations and operations that are available to the PPL user.

In the final section of this chapter (Section **Using the Library**(p. 14)), we provide some additional advice on the use of the library.

1.2 Convex Polyhedra

In this section we introduce convex polyhedra, as considered by the library, in more detail. For more information about the definitions and results stated here see [BRZH02b](p. 16), [Fuk98](p. 17), [NW88](p. 18), and [Wil93](p. 19).

Vectors, Matrices and Scalar Products

We denote by \mathbb{R}^n the n -dimensional vector space on the field of real numbers \mathbb{R} , endowed with the standard topology. The set of all non-negative reals is denoted by \mathbb{R}_+ . For each $i \in \{0, \dots, n-1\}$, v_i denotes the i -th component of the (column) vector $\mathbf{v} = (v_0, \dots, v_{n-1})^T \in \mathbb{R}^n$. We denote by $\mathbf{0}$ the vector of \mathbb{R}^n , called *the origin*, having all components equal to zero. A vector $\mathbf{v} \in \mathbb{R}^n$ can be also interpreted as a matrix in $\mathbb{R}^{n \times 1}$ and manipulated accordingly using the usual definitions for addition, multiplication (both by a scalar and by another matrix), and transposition, denoted by \mathbf{v}^T .

The *scalar product* of $\mathbf{v}, \mathbf{w} \in \mathbb{R}^n$, denoted $\langle \mathbf{v}, \mathbf{w} \rangle$, is the real number

$$\mathbf{v}^T \mathbf{w} = \sum_{i=0}^{n-1} v_i w_i.$$

For any $S_1, S_2 \subseteq \mathbb{R}^n$, the *Minkowski's sum* of S_1 and S_2 is: $S_1 + S_2 = \{ \mathbf{v}_1 + \mathbf{v}_2 \mid \mathbf{v}_1 \in S_1, \mathbf{v}_2 \in S_2 \}$.

Affine Hyperplanes and Half-spaces

For each vector $\mathbf{a} \in \mathbb{R}^n$ and scalar $b \in \mathbb{R}$, where $\mathbf{a} \neq \mathbf{0}$, and for each relation symbol $\bowtie \in \{=, \geq, >\}$, the linear constraint $\langle \mathbf{a}, \mathbf{x} \rangle \bowtie b$ defines:

- an affine hyperplane if it is an equality constraint, i.e., if $\bowtie \in \{=\}$;
- a topologically closed affine half-space if it is a non-strict inequality constraint, i.e., if $\bowtie \in \{\geq\}$;
- a topologically open affine half-space if it is a strict inequality constraint, i.e., if $\bowtie \in \{>\}$.

Note that each hyperplane $\langle \mathbf{a}, \mathbf{x} \rangle = b$ can be defined as the intersection of the two closed affine half-spaces $\langle \mathbf{a}, \mathbf{x} \rangle \geq b$ and $\langle -\mathbf{a}, \mathbf{x} \rangle \geq -b$. Also note that, when $\mathbf{a} = \mathbf{0}$, the constraint $\langle \mathbf{0}, \mathbf{x} \rangle \bowtie b$ is either a tautology (i.e., always true) or inconsistent (i.e., always false), so that it defines either the whole vector space \mathbb{R}^n or the empty set \emptyset .

Convex Polyhedra

The set $\mathcal{P} \subseteq \mathbb{R}^n$ is a *not necessarily closed convex polyhedron* (*NNC polyhedron*, for short) if and only if either \mathcal{P} can be expressed as the intersection of a finite number of (open or closed) affine half-spaces of \mathbb{R}^n or $n = 0$ and $\mathcal{P} = \emptyset$. The set of all NNC polyhedra on the vector space \mathbb{R}^n is denoted \mathbb{P}_n .

The set $\mathcal{P} \in \mathbb{P}_n$ is a *closed convex polyhedron* (*closed polyhedron*, for short) if and only if either \mathcal{P} can be expressed as the intersection of a finite number of closed affine half-spaces of \mathbb{R}^n or $n = 0$ and $\mathcal{P} = \emptyset$. The set of all closed polyhedra on the vector space \mathbb{R}^n is denoted \mathbb{CP}_n .

When ordering NNC polyhedra by the set inclusion relation, the empty set \emptyset and the vector space \mathbb{R}^n are, respectively, the smallest and the biggest elements of both \mathbb{P}_n and \mathbb{CP}_n . The vector space \mathbb{R}^n is also called the *universe polyhedron*.

In theoretical terms, \mathbb{P}_n is a *lattice* under set inclusion and \mathbb{CP}_n is a *sub-lattice* of \mathbb{P}_n .

Note:

In the following, we will usually specify operators on the domain \mathbb{P}_n of NNC polyhedra. Unless an explicit distinction is made, these operators are provided with the same specification when applied to the domain \mathbb{CP}_n of topologically closed polyhedra. The implementation maintains a clearer separation between the two domains of polyhedra (see **Topologies and Topological-compatibility**(p.5)): while computing polyhedra in \mathbb{P}_n may provide more precise results, polyhedra in \mathbb{CP}_n can be represented and manipulated more efficiently. As a rule of thumb, if your application will only manipulate polyhedra that are topologically closed, then it should use the simpler domain \mathbb{CP}_n . Using NNC polyhedra is only recommended if you are going to actually benefit from the increased accuracy.

Bounded Polyhedra

An NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ is *bounded* if there exists a $\lambda \in \mathbb{R}_+$ such that

$$\mathcal{P} \subseteq \{ \mathbf{x} \in \mathbb{R}^n \mid -\lambda \leq x_j \leq \lambda \text{ for } j = 0, \dots, n-1 \}.$$

A bounded polyhedron is also called a *polytope*.

1.3 Representations of Convex Polyhedra

NNC polyhedra can be specified by using two possible representations, the constraints (or implicit) representation and the generators (or parametric) representation.

Constraints representation

In the sequel, we will simply write “equality” and “inequality” to mean “linear equality” and “linear inequality”, respectively; also, we will refer to either an equality or an inequality as a *constraint*.

By definition, each polyhedron $\mathcal{P} \in \mathbb{P}_n$ is the set of solutions to a *constraint system*, i.e., a finite number of constraints. By using matrix notation, we have

$$\mathcal{P} \stackrel{\text{def}}{=} \{ \mathbf{x} \in \mathbb{R}^n \mid A_1 \mathbf{x} = \mathbf{b}_1, A_2 \mathbf{x} \geq \mathbf{b}_2, A_3 \mathbf{x} > \mathbf{b}_3 \},$$

where, for all $i \in \{1, 2, 3\}$, $A_i \in \mathbb{R}^{m_i} \times \mathbb{R}^n$ and $\mathbf{b}_i \in \mathbb{R}^{m_i}$, and $m_1, m_2, m_3 \in \mathbb{N}$ are the number of equalities, the number of non-strict inequalities, and the number of strict inequalities, respectively.

Combinations and Hulls

Let $S = \{\mathbf{x}_1, \dots, \mathbf{x}_k\} \subseteq \mathbb{R}^n$ be a finite set of vectors. For all scalars $\lambda_1, \dots, \lambda_k \in \mathbb{R}$, the vector $\mathbf{v} = \sum_{j=1}^k \lambda_j \mathbf{x}_j$ is said to be a *linear* combination of the vectors in S . Such a combination is said to be

- a *positive* (or *conic*) combination, if $\forall j \in \{1, \dots, k\} : \lambda_j \in \mathbb{R}_+$;
- an *affine* combination, if $\sum_{j=1}^k \lambda_j = 1$;
- a *convex* combination, if it is both positive and affine.

We denote by $\text{linear.hull}(S)$ (resp., $\text{conic.hull}(S)$, $\text{affine.hull}(S)$, $\text{convex.hull}(S)$) the set of all the linear (resp., positive, affine, convex) combinations of the vectors in S .

Let $P, C \subseteq \mathbb{R}^n$, where $P \cup C = S$. We denote by $\text{nnc.hull}(P, C)$ the set of all convex combinations of the vectors in S such that $\lambda_j > 0$ for some $\mathbf{x}_j \in P$ (informally, we say that there exists a vector of P that plays an active role in the convex combination). Note that $\text{nnc.hull}(P, C) = \text{nnc.hull}(P, P \cup C)$ so that, if $C \subseteq P$,

$$\text{convex.hull}(P) = \text{nnc.hull}(P, \emptyset) = \text{nnc.hull}(P, P) = \text{nnc.hull}(P, C).$$

It can be observed that $\text{linear.hull}(S)$ is an affine space, $\text{conic.hull}(S)$ is a topologically closed convex cone, $\text{convex.hull}(S)$ is a topologically closed polytope, and $\text{nnc.hull}(P, C)$ is an NNC polytope.

Points, Closure Points, Rays and Lines

Let $\mathcal{P} \in \mathbb{P}_n$ be an NNC polyhedron. Then

- a vector $\mathbf{p} \in \mathcal{P}$ is called a *point* of \mathcal{P} ;
- a vector $\mathbf{c} \in \mathbb{R}^n$ is called a *closure point* of \mathcal{P} if it is a point of the topological closure of \mathcal{P} ;
- a vector $\mathbf{r} \in \mathbb{R}^n$, where $\mathbf{r} \neq \mathbf{0}$, is called a *ray* (or *direction of infinity*) of \mathcal{P} if $\mathcal{P} \neq \emptyset$ and $\mathbf{p} + \lambda \mathbf{r} \in \mathcal{P}$, for all points $\mathbf{p} \in \mathcal{P}$ and all $\lambda \in \mathbb{R}_+$;
- a vector $\mathbf{l} \in \mathbb{R}^n$ is called a *line* of \mathcal{P} if both \mathbf{l} and $-\mathbf{l}$ are rays of \mathcal{P} .

A point of an NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ is a *vertex* if and only if it cannot be expressed as a convex combination of any other pair of distinct points in \mathcal{P} . A ray r of a polyhedron \mathcal{P} is an *extreme ray* if and only if it cannot be expressed as a positive combination of any other pair r_1 and r_2 of rays of \mathcal{P} , where $r \neq \lambda r_1$, $r \neq \lambda r_2$ and $r_1 \neq \lambda r_2$ for all $\lambda \in \mathbb{R}_+$ (i.e., rays differing by a positive scalar factor are considered to be the same ray).

Generators Representation

Each NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ can be represented by finite sets of lines L , rays R , points P and closure points C of \mathcal{P} . The 4-tuple $\mathcal{G} = (L, R, P, C)$ is said to be a *generator system* for \mathcal{P} , in the sense that

$$\mathcal{P} = \text{linear.hull}(L) + \text{conic.hull}(R) + \text{nnc.hull}(P, C),$$

where the symbol '+' denotes the Minkowski's sum.

When $\mathcal{P} \in \mathbb{CP}_n$ is a closed polyhedron, then it can be represented by finite sets of lines L , rays R and points P of \mathcal{P} . In this case, the 3-tuple $\mathcal{G} = (L, R, P)$ is said to be a *generator system* for \mathcal{P} since we have

$$\mathcal{P} = \text{linear.hull}(L) + \text{conic.hull}(R) + \text{convex.hull}(P).$$

Thus, in this case, every closure point of \mathcal{P} is a point of \mathcal{P} .

For any $\mathcal{P} \in \mathbb{P}_n$ and generator system $\mathcal{G} = (L, R, P, C)$ for \mathcal{P} , we have $\mathcal{P} = \emptyset$ if and only if $P = \emptyset$. Also P must contain all the vertices of \mathcal{P} although \mathcal{P} can be non-empty and have no vertices. In this case, as P is necessarily non-empty, it must contain points of \mathcal{P} that are *not* vertices. For instance, the half-space of \mathbb{R}^2 corresponding to the single constraint $y \geq 0$ can be represented by the generator system $\mathcal{G} = (L, R, P, C)$ such that $L = \{(1, 0)^T\}$, $R = \{(0, 1)^T\}$, $P = \{(0, 0)^T\}$, and $C = \emptyset$. It is also worth noting that the only ray in R is *not* an extreme ray of \mathcal{P} .

Minimized Representations

A constraints system \mathcal{C} for an NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ is said to be *minimized* if no proper subset of \mathcal{C} is a constraint system for \mathcal{P} .

Similarly, a generator system $\mathcal{G} = (L, R, P, C)$ for an NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ is said to be *minimized* if there does not exist a generator system $\mathcal{G}' = (L', R', P', C') \neq \mathcal{G}$ for \mathcal{P} such that $L' \subseteq L$, $R' \subseteq R$, $P' \subseteq P$ and $C' \subseteq C$.

Double Description

Any NNC polyhedron \mathcal{P} can be described by using a constraint system \mathcal{C} , a generator system \mathcal{G} , or both by means of the *double description pair (DD pair)* $(\mathcal{C}, \mathcal{G})$. The *double description method* is a collection of well-known as well as novel theoretical results showing that, given one kind of representation, there are algorithms for computing a representation of the other kind and for minimizing both representations by removing redundant constraints/generators.

Such changes of representation form a key step in the implementation of many operators on NNC polyhedra: this is because some operators, such as intersections and poly-hulls, are provided with a natural and efficient implementation when using one of the representations in a DD pair, while being rather cumbersome when using the other.

Topologies and Topological-compatibility

As indicated above, when an NNC polyhedron \mathcal{P} is necessarily closed, we can ignore the closure points contained in its generator system $\mathcal{G} = (L, R, P, C)$ (as every closure point is also a point) and represent \mathcal{P} by the triple (L, R, P) . Similarly, \mathcal{P} can be represented by a constraint system that has no strict inequalities. Thus a necessarily closed polyhedron can have a smaller representation than one that is not necessarily closed. Moreover, operators restricted to work on closed polyhedra only can be implemented more efficiently. For this reason the library provides two alternative “topological kinds” for a polyhedron, *NNC* and *C*. We shall abuse terminology by referring to the topological kind of a polyhedron as its *topology*.

In the library, the topology of each polyhedron object is fixed once for all at the time of its creation and must be respected when performing operations on the polyhedron.

Unless it is otherwise stated, all the polyhedra, constraints and/or generators in any library operation must obey the following *topological-compatibility* rules:

- polyhedra are topologically-compatible if and only if they have the same topology;
- all constraints except for strict inequality constraints and all generators except for closure points are topologically-compatible with both C and NNC polyhedra;
- strict inequality constraints and closure points are topologically-compatible with a polyhedron if and only if it is NNC.

Wherever possible, the library provides methods that, starting from a polyhedron of a given topology, build the corresponding polyhedron having the other topology.

Space Dimensions and Dimension-compatibility

The *space dimension* of an NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ (resp., a C polyhedron $\mathcal{P} \in \mathbb{CP}_n$) is the dimension $n \in \mathbb{N}$ of the corresponding vector space \mathbb{R}^n . The space dimension of constraints, generators and other objects of the library is defined similarly.

Unless it is otherwise stated, all the polyhedra, constraints and/or generators in any library operation must obey the following (space) *dimension-compatibility* rules:

- polyhedra are dimension-compatible if and only if they have the same space dimension;
- the constraint $\langle \mathbf{a}, \mathbf{x} \rangle \bowtie b$ where $\bowtie \in \{=, \geq, >\}$ and $\mathbf{a}, \mathbf{x} \in \mathbb{R}^m$, is dimension-compatible with a polyhedron having space dimension n if and only if $m \leq n$;
- the generator $\mathbf{x} \in \mathbb{R}^m$ is dimension-compatible with a polyhedron having space dimension n if and only if $m \leq n$;
- a system of constraints (resp., generators) is dimension-compatible with a polyhedron if and only if all the constraints (resp., generators) in the system are dimension-compatible with the polyhedron.

While the space dimension of a constraint, a generator or a system thereof is automatically adjusted when needed, the space dimension of a polyhedron can only be changed by explicit calls to operators provided for that purpose.

Affine Independence and Affine Dimension

A finite set of points $\{\mathbf{x}_1, \dots, \mathbf{x}_k\} \subseteq \mathbb{R}^n$ is *affinely independent* if, for all $\lambda_1, \dots, \lambda_k \in \mathbb{R}$, the system of equations

$$\sum_{i=1}^k \lambda_i \mathbf{x}_i = \mathbf{0}, \quad \sum_{i=1}^k \lambda_i = 0$$

implies that, for each $i = 1, \dots, k$, $\lambda_i = 0$.

The maximum number of affinely independent points in \mathbb{R}^n is $n + 1$.

A *non-empty* NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ has *affine dimension* $k \in \mathbb{N}$, denoted by $\dim(\mathcal{P}) = k$, if the maximum number of affinely independent points in \mathcal{P} is $k + 1$.

We remark that the above definition only applies to polyhedra that are not empty, so that $0 \leq \dim(\mathcal{P}) \leq n$. By convention, the affine dimension of an empty polyhedron is 0 (even though the “natural” generalization of the definition above would imply that the affine dimension of an empty polyhedron is -1).

Note:

The affine dimension $k \leq n$ of an NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$ must not be confused with the space dimension n of \mathcal{P} , which is the dimension of the enclosing vector space \mathbb{R}^n . In particular, we can have $\dim(\mathcal{P}) \neq \dim(\mathcal{Q})$ even though \mathcal{P} and \mathcal{Q} are dimension-compatible; and vice versa, \mathcal{P} and \mathcal{Q} may be dimension-incompatible polyhedra even though $\dim(\mathcal{P}) = \dim(\mathcal{Q})$.

Rational Polyhedra

An NNC polyhedron is called *rational* if it can be represented by a constraint system where all the constraints have rational coefficients. It has been shown that an NNC polyhedron is rational if and only if it can be represented by a generator system where all the generators have rational coefficients.

The library only supports rational polyhedra. The restriction to rational numbers applies not only to polyhedra, but also to the other numeric arguments that may be required by the operators considered, such as the coefficients defining (rational) affine transformations and (rational) bounding boxes.

1.4 Operations on Convex Polyhedra

In this section we briefly describe operations on NNC polyhedra that are provided by the library.

Intersection and Convex Polyhedral Hull

For any pair of NNC polyhedra $\mathcal{P}_1, \mathcal{P}_2 \in \mathbb{P}_n$, the *intersection* of \mathcal{P}_1 and \mathcal{P}_2 , defined as the set intersection $\mathcal{P}_1 \cap \mathcal{P}_2$, is the biggest NNC polyhedron included in both \mathcal{P}_1 and \mathcal{P}_2 ; similarly, the *convex polyhedral hull* (or *poly-hull*) of \mathcal{P}_1 and \mathcal{P}_2 , denoted by $\mathcal{P}_1 \uplus \mathcal{P}_2$, is the smallest NNC polyhedron that includes both \mathcal{P}_1 and \mathcal{P}_2 . The intersection and poly-hull of any pair of closed polyhedra in \mathbb{CP}_n is also closed.

In theoretical terms, the intersection and poly-hull operators defined above are the binary *meet* and the binary *join* operators on the lattices \mathbb{P}_n and \mathbb{CP}_n .

Convex Polyhedral Difference

For any pair of NNC polyhedra $\mathcal{P}_1, \mathcal{P}_2 \in \mathbb{P}_n$, the *convex polyhedral difference* (or *poly-difference*) of \mathcal{P}_1 and \mathcal{P}_2 is defined as the smallest convex polyhedron containing the set-theoretic difference of \mathcal{P}_1 and \mathcal{P}_2 .

In general, even though $\mathcal{P}_1, \mathcal{P}_2 \in \mathbb{CP}_n$ are topologically closed polyhedra, their poly-difference may be a convex polyhedron that is not topologically closed. For this reason, when computing the poly-difference of two C polyhedra, the library will enforce the topological closure of the result.

Concatenating Polyhedra

Viewing a polyhedron as a set of tuples (its points), it is sometimes useful to consider the set of tuples obtained by concatenating an ordered pair of polyhedra. Formally, the *concatenation* of the polyhedra $\mathcal{P} \in \mathbb{P}_n$ and $\mathcal{Q} \in \mathbb{P}_m$ (taken in this order) is the polyhedron $\mathcal{R} \in \mathbb{P}_{n+m}$ such that

$$\mathcal{R} \stackrel{\text{def}}{=} \left\{ (x_0, \dots, x_{n-1}, y_0, \dots, y_{m-1})^T \in \mathbb{R}^{n+m} \mid (x_0, \dots, x_{n-1})^T \in \mathcal{P}, (y_0, \dots, y_{m-1})^T \in \mathcal{Q} \right\}.$$

Another way of seeing it is as follows: first embed polyhedron \mathcal{P} into a vector space of dimension $n + m$ and then add a suitably renamed-apart version of the constraints defining \mathcal{Q} .

Adding New Dimensions to the Vector Space

The library provides two operators for adding a number i of space dimensions to an NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$, therefore transforming it into a new NNC polyhedron $\mathcal{Q} \in \mathbb{P}_{n+i}$. In both cases, the added dimensions of the vector space are those having the highest indices.

The operator `add_space_dimensions_and_embed` *embeds* the polyhedron \mathcal{P} into the new vector space of dimension $i + n$ and returns the polyhedron \mathcal{Q} defined by all and only the constraints defining \mathcal{P} (the variables corresponding to the added dimensions are unconstrained). For instance, when starting from a polyhedron $\mathcal{P} \subseteq \mathbb{R}^2$ and adding a third space dimension, the result will be the polyhedron

$$\mathcal{Q} = \left\{ (x_0, x_1, x_2)^T \in \mathbb{R}^3 \mid (x_0, x_1)^T \in \mathcal{P} \right\}.$$

In contrast, the operator `add_space_dimensions_and_project` *projects* the polyhedron \mathcal{P} into the new vector space of dimension $i + n$ and returns the polyhedron \mathcal{Q} whose constraint system, besides

the constraints defining \mathcal{P} , will include additional constraints on the added dimensions. Namely, the corresponding variables are all constrained to be equal to 0. For instance, when starting from a polyhedron $\mathcal{P} \subseteq \mathbb{R}^2$ and adding a third space dimension, the result will be the polyhedron

$$\mathcal{Q} = \{ (x_0, x_1, 0)^T \in \mathbb{R}^3 \mid (x_0, x_1)^T \in \mathcal{P} \}.$$

Removing Dimensions from the Vector Space

The library provides two operators for removing space dimensions from an NNC polyhedron $\mathcal{P} \in \mathbb{P}_n$, therefore transforming it into a new NNC polyhedron $\mathcal{Q} \in \mathbb{P}_m$ where $m \leq n$.

Given a set of variables, the operator `remove_space_dimensions` removes all the space dimensions specified by the variables in the set. For instance, letting $\mathcal{P} \in \mathbb{P}_4$ be the singleton set $\{(3, 1, 0, 2)^T\} \subseteq \mathbb{R}^4$, then after invoking this operator with the set of variables $\{x_1, x_2\}$ the resulting polyhedron is

$$\mathcal{Q} = \{(3, 2)^T\} \subseteq \mathbb{R}^2.$$

Given a space dimension m less than or equal to that of the polyhedron, the operator `remove_higher_space_dimensions` removes the space dimensions having indices greater than or equal to m . For instance, letting $\mathcal{P} \in \mathbb{P}_4$ defined as before, by invoking this operator with $m = 2$ the resulting polyhedron will be

$$\mathcal{Q} = \{(3, 1)^T\} \subseteq \mathbb{R}^2.$$

Mapping the Dimensions of the Vector Space

The operator `map_space_dimensions` provided by the library maps the dimensions of the vector space \mathbb{R}^n according to a partial injective function $\rho: \{0, \dots, n-1\} \mapsto \mathbb{N}$ such that $\rho(\{0, \dots, n-1\}) = \{0, \dots, m-1\}$ with $m \leq n$. Dimensions corresponding to indices that are not mapped by ρ are removed.

If $m = 0$, i.e., if the function ρ is undefined everywhere, then the operator projects the argument polyhedron $\mathcal{P} \in \mathbb{P}_n$ onto the zero-dimension space \mathbb{R}^0 ; otherwise the result is $\mathcal{Q} \in \mathbb{P}_m$ given by

$$\mathcal{Q} \stackrel{\text{def}}{=} \left\{ (v_{\rho^{-1}(0)}, \dots, v_{\rho^{-1}(m-1)})^T \mid (v_0, \dots, v_{n-1})^T \in \mathcal{P} \right\}.$$

Expanding One Dimension of the Vector Space to Multiple Dimensions

The operator `expand_space_dimension` provided by the library adds m new space dimensions to a polyhedron $\mathcal{P} \in \mathbb{P}_n$, with $n > 0$, so that dimensions $n, n+1, \dots, n+m-1$ of the result \mathcal{Q} are exact copies of the i -th space dimension of \mathcal{P} . More formally,

$$\mathcal{Q} \stackrel{\text{def}}{=} \left\{ \mathbf{u} \in \mathbb{R}^{n+m} \mid \begin{array}{l} \exists \mathbf{v}, \mathbf{w} \in \mathcal{P} . u_i = v_i \\ \wedge \forall j = n, n+1, \dots, n+m-1 : u_j = w_i \\ \wedge \forall k = 0, \dots, n-1 : k \neq i \implies u_k = v_k = w_k \end{array} \right\}.$$

This operation has been proposed in [GDMDRS04](p. 17).

Folding Multiple Dimensions of the Vector Space into One Dimension

The operator `fold_space_dimensions` provided by the library, given a polyhedron $\mathcal{P} \in \mathbb{P}_n$, with $n > 0$, folds a set of space dimensions $J = \{j_0, \dots, j_{m-1}\}$, with $m < n$ and $j < n$ for each $j \in J$, into space dimension $i < n$, where $i \notin J$. The result is given by

$$\mathcal{Q} \stackrel{\text{def}}{=} \bigoplus_{d=0}^m \mathcal{Q}_d$$

where

$$\mathcal{Q}_m \stackrel{\text{def}}{=} \left\{ \mathbf{u} \in \mathbb{R}^{n-m} \mid \begin{array}{l} \exists \mathbf{v} \in \mathcal{P} . u_{i'} = v_i \\ \wedge \forall k = 0, \dots, n-1 : k \neq i \implies u_{k'} = v_k \end{array} \right\}$$

and, for $d = 0, \dots, m-1$,

$$\mathcal{Q}_d \stackrel{\text{def}}{=} \left\{ \mathbf{u} \in \mathbb{R}^{n-m} \mid \begin{array}{l} \exists \mathbf{v} \in \mathcal{P} . u_{i'} = v_{j_d} \\ \wedge \forall k = 0, \dots, n-1 : k \neq i \implies u_{k'} = v_k \end{array} \right\},$$

and, finally, for $k = 0, \dots, n-1$,

$$k' \stackrel{\text{def}}{=} k - \#\{j \in J \mid k > j\},$$

($\# S$ denotes the cardinality of the finite set S).

This operation has been proposed in [GDMDRS04](p. 17).

Affine Images and Preimages

For each function mapping $\phi: \mathbb{R}^n \rightarrow \mathbb{R}^m$, we denote by $\phi(S) \subseteq \mathbb{R}^m$ the *image* under ϕ of the set $S \subseteq \mathbb{R}^n$; formally,

$$\phi(S) \stackrel{\text{def}}{=} \{ \phi(\mathbf{v}) \in \mathbb{R}^m \mid \mathbf{v} \in S \}.$$

Similarly, we denote by $\phi^{-1}(S') \subseteq \mathbb{R}^n$ the *preimage* under ϕ of $S' \subseteq \mathbb{R}^m$, that is the largest set $S \subseteq \mathbb{R}^n$ such that $\phi(S) \subseteq S'$; formally,

$$\phi^{-1}(S') \stackrel{\text{def}}{=} \{ \mathbf{v} \in \mathbb{R}^n \mid \phi(\mathbf{v}) \in S' \}.$$

The function mapping $\phi: \mathbb{R}^n \rightarrow \mathbb{R}^m$ is an *affine transformation* if there exist a matrix $A \in \mathbb{R}^m \times \mathbb{R}^n$ and a vector $\mathbf{b} \in \mathbb{R}^m$ such that, for all $\mathbf{x} \in \mathbb{R}^n$, we have $\phi(\mathbf{x}) = A\mathbf{x} + \mathbf{b}$. If $n = m$, then the function ϕ is said to be *space dimension preserving*.

Both \mathbb{P}_n and \mathbb{CP}_n are closed under the application of any space dimension preserving affine image and preimage operators.

The library provides two operators, one computes an affine image and the other an affine preimage of a polyhedron $\mathcal{P} \in \mathbb{P}_n$ for a given variable x_k and linear expression $\text{expr} = \sum_{i=0}^{n-1} a_i x_i + b$. This variable and expression determine the affine transformation ϕ that is to be used by the operator. That is, ϕ is the transformation defined by the matrix and vector

$$A = \begin{pmatrix} 1 & & 0 & 0 & \cdots & \cdots & 0 \\ & \ddots & & \vdots & & & \vdots \\ 0 & & 1 & 0 & \cdots & \cdots & 0 \\ a_0 & \cdots & a_{k-1} & a_k & a_{k+1} & \cdots & a_{n-1} \\ 0 & \cdots & \cdots & 0 & 1 & \cdots & 0 \\ \vdots & & & \vdots & & \ddots & \\ 0 & \cdots & \cdots & 0 & 0 & & 1 \end{pmatrix}, \quad \mathbf{b} = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ b \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

where the a_i (resp., b) occurs in the $(k+1)$ st row in A (resp., position in \mathbf{b}). Thus ϕ transforms any point $(x_0, \dots, x_{n-1})^T$ in the polyhedron \mathcal{P} to

$$\left(x_0, \dots, \left(\sum_{i=0}^{n-1} a_i x_i + b \right), \dots, x_{n-1} \right)^T.$$

The affine image operator computes the affine image of \mathcal{P} under ϕ . For instance, suppose the polyhedron \mathcal{P} to be transformed is the square in \mathbb{R}^2 generated by the set of points $\{(0, 0)^T, (0, 3)^T, (3, 0)^T, (3, 3)^T\}$. Then, for example if the considered variable is x_0 and the linear expression $x_0 + 2x_1 + 4$ (so that $k = 0$, $a_0 = 1, a_1 = 2, b = 4$), the affine image operator will translate \mathcal{P} to the parallelogram \mathcal{P}_1 generated by the set of points $\{(4, 0)^T, (10, 3)^T, (7, 0)^T, (13, 3)^T\}$ with height equal to the side of the square and oblique sides parallel to the line $x_0 - 2x_1$. If the considered variable is as before (i.e., $k = 0$) but the linear

expression is x_1 (so that $a_0 = 0, a_1 = 1, b = 0$), then the resulting polyhedron \mathcal{P}_2 is the positive diagonal of the square.

The affine preimage operator computes the affine preimage of \mathcal{P} under ϕ . For instance, suppose now that we apply the affine preimage operator as given in the first example using variable x_0 and linear expression $x_0 + 2x_1 + 4$ to the parallelogram \mathcal{P}_1 ; then we get the original square \mathcal{P} back. If, on the other hand, we apply the affine preimage operator as given in the second example using variable x_0 and linear expression x_1 to \mathcal{P}_2 , then the resulting polyhedron is a line that corresponds to the x_1 axes.

Observe that provided the coefficient a_k of the considered variable in the linear expression is non-zero, the affine transformation is invertible.

Generalized Affine Images

The library provides another operator which is a generalization of the affine image operator. Given a polyhedron $\mathcal{P} \in \mathbb{P}_n$, an affine expression $\text{lhs} = \sum_{i=0}^{n-1} a'_i x_i + b'$, a relation symbol $\bowtie \in \{<, \leq, =, \geq, >\}$, and an affine expression $\text{rhs} = \sum_{i=0}^{n-1} a_i x_i + b$, the image of \mathcal{P} with respect to the transfer function $\text{lhs} \bowtie \text{rhs}$ is defined as

$$\left\{ (w_0, \dots, w_{n-1})^T \in \mathbb{R}^n \mid \begin{array}{l} (v_0, \dots, v_{n-1})^T \in \mathcal{P}, \\ (i \in \{0, \dots, n-1\} \wedge a'_i = 0 \implies w_i = v_i), \\ \sum_{i=0}^{n-1} a'_i w_i + b' \bowtie \sum_{i=0}^{n-1} a_i v_i + b \end{array} \right\}.$$

Note that, when $\text{lhs} = x_k$ and $\bowtie \in \{=\}$, then the above operator is equivalent to the application of the standard affine image of \mathcal{P} with respect to the variable x_k and the affine expression rhs (hence the name given to this operator).

Time-Elapse Operator

The *time-elapse* operator has been defined in [HPR97](p. 18). Actually, the time-elapse operator provided by the library is a slight generalization of that one, since it also works on NNC polyhedra. For any two NNC polyhedra $\mathcal{P}, \mathcal{Q} \in \mathbb{P}_n$, the time-elapse between \mathcal{P} and \mathcal{Q} , denoted $\mathcal{P} \nearrow \mathcal{Q}$, is the smallest NNC polyhedron containing the set

$$\{ \mathbf{p} + \lambda \mathbf{q} \in \mathbb{R}^n \mid \mathbf{p} \in \mathcal{P}, \mathbf{q} \in \mathcal{Q}, \lambda \in \mathbb{R}_+ \}.$$

Note that, if $\mathcal{P}, \mathcal{Q} \in \mathbb{CP}_n$ are closed polyhedra, the above set is also a closed polyhedron. In contrast, when \mathcal{Q} is not topologically closed, the above set might not be an NNC polyhedron.

Relation-with Operators

The library provides operators for checking the relation holding between an NNC polyhedron and either a constraint or a generator.

Suppose \mathcal{P} is an NNC polyhedron and \mathcal{C} an arbitrary constraint system representing \mathcal{P} . Suppose also that $c = (\langle \mathbf{a}, \mathbf{x} \rangle \bowtie b)$ is a constraint with $\bowtie \in \{=, \geq, >\}$ and \mathcal{Q} the set of points that satisfy c . The possible relations between \mathcal{P} and c are as follows.

- \mathcal{P} is *disjoint* from c if $\mathcal{P} \cap \mathcal{Q} = \emptyset$; that is, adding c to \mathcal{C} gives us the empty polyhedron.
- \mathcal{P} *strictly intersects* c if $\mathcal{P} \cap \mathcal{Q} \neq \emptyset$ and $\mathcal{P} \cap \mathcal{Q} \subset \mathcal{P}$; that is, adding c to \mathcal{C} gives us a non-empty polyhedron strictly smaller than \mathcal{P} .
- \mathcal{P} is *included* in c if $\mathcal{P} \subseteq \mathcal{Q}$; that is, adding c to \mathcal{C} leaves \mathcal{P} unchanged.
- \mathcal{P} *saturates* c if $\mathcal{P} \subseteq \mathcal{H}$, where \mathcal{H} is the hyperplane induced by constraint c , i.e., the set of points satisfying the equality constraint $\langle \mathbf{a}, \mathbf{x} \rangle = b$; that is, adding the constraint $\langle \mathbf{a}, \mathbf{x} \rangle = b$ to \mathcal{C} leaves \mathcal{P} unchanged.

The polyhedron \mathcal{P} *subsumes* the generator g if adding g to any generator system representing \mathcal{P} does not change \mathcal{P} .

Intervals, boxes and bounding boxes

An *interval* in \mathbb{R} is a pair of *bounds*, called *lower* and *upper*. Each bound can be either (1) *closed and bounded*, (2) *open and bounded*, or (3) *open and unbounded*. If the bound is *bounded*, then it has a value in \mathbb{R} . An n -dimensional *box* \mathcal{B} in \mathbb{R}^n is a sequence of n intervals in \mathbb{R} .

The polyhedron \mathcal{P} represents a box \mathcal{B} in \mathbb{R}^n if \mathcal{P} is described by a constraint system in \mathbb{R}^n that consists of one constraint for each bounded bound (lower and upper) in an interval in \mathcal{B} : Letting $e_i = (0, \dots, 1, \dots, 0)^T$ be the vector in \mathbb{R}^n with 1 in the i 'th position and zeroes in every other position; if the lower bound of the i 'th interval in \mathcal{B} is bounded, the corresponding constraint is defined as $\langle e_i, x \rangle \bowtie b$, where b is the value of the bound and \bowtie is \geq if it is a closed bound and $>$ if it is an open bound. Similarly, if the upper bound of the i 'th interval in \mathcal{B} is bounded, the corresponding constraint is defined as $\langle e_i, x \rangle \bowtie b$, where b is the value of the bound and \bowtie is \leq if it is a closed bound and $<$ if it is an open bound.

If every bound in the intervals defining a box \mathcal{B} is either closed and bounded or open and unbounded, then \mathcal{B} represents a closed polyhedron.

The *bounding box* of an NNC polyhedron \mathcal{P} is the smallest n -dimensional box containing \mathcal{P} .

The library provides operations for computing the bounding box of an NNC polyhedron and conversely, for obtaining the NNC polyhedron representing a given bounding box.

Widening Operators

The library provides two widening operators for the domain of polyhedra. The first one, that we call *H79-widening*, mainly follows the specification provided in the PhD thesis of N. Halbwachs [Hal79](p. 17), also described in [HPR97](p. 18). The main difference between the H79-widening and the widening described in the cited paper is that the H79-widening $\mathcal{P} \nabla \mathcal{Q}$ of two polyhedra $\mathcal{P}, \mathcal{Q} \in \mathbb{CP}_n$ requires as a precondition that $\mathcal{P} \subseteq \mathcal{Q}$ (other differences at the implementation level are transparent to the user of the library).

The second widening operator, that we call *BHRZ03-widening*, is an instance of the specification provided in [BHRZ03a](p. 16). This operator also requires as a precondition that $\mathcal{P} \subseteq \mathcal{Q}$ and it is guaranteed to provide a result which is at least as precise as the H79-widening.

Both widening operators can be applied to NNC polyhedra. The user is warned that, in such a case, the results may not closely match the geometric intuition which is at the base of the specification of the two widenings. The reason is that, in the current implementation, the widenings are not directly applied to the NNC polyhedra, but rather to their internal representations. Implementation work is in progress and future versions of the library may provide an even better integration of the two widenings with the domain of NNC polyhedra.

Note:

As is the case for the other operators on polyhedra, the implementation overwrites one of the two polyhedra arguments with the result of the widening application. To avoid trivial misunderstandings, it is worth stressing that if polyhedra \mathcal{P} and \mathcal{Q} (where $\mathcal{P} \subseteq \mathcal{Q}$) are identified by program variables p and q , respectively, then the call `q.H79_widening_assign(p)` will assign the polyhedron $\mathcal{P} \nabla \mathcal{Q}$ to variable q . Namely, it is the bigger polyhedron \mathcal{Q} which is overwritten by the result of the widening. The smaller polyhedron is not modified, so as to lead to an easier coding of the usual convergence test ($\mathcal{P} \supseteq \mathcal{P} \nabla \mathcal{Q}$ can be coded as `p.contains(q)`). Note that, in the above context, a call such as `p.H79_widening_assign(q)` is likely to result in undefined behavior, since the precondition $\mathcal{Q} \subseteq \mathcal{P}$ will be missed (unless it happens that $\mathcal{P} = \mathcal{Q}$). The same observation holds for all flavors of widenings and extrapolation operators that are implemented in the library and for all the foreign language interfaces.

Widening with Tokens

When approximating a fixpoint computation using widening operators, a common tactic to improve the precision of the final result is to delay the application of widening operators. The usual approach is to fix a parameter k and only apply widenings starting from the k -th iteration.

The library also supports an improved widening delay strategy, that we call *widening with tokens* [BHRZ03a](p. 16). A token is a sort of wildcard allowing for the replacement of the widening application by the exact upper bound computation: the token is used (and thus consumed) only when the widening would have resulted in an actual precision loss (as opposed to the *potential* precision loss of the classical delay strategy). Thus, all widening operators can be supplied with an optional argument, recording the number of available tokens, which is decremented when tokens are used. The approximated fixpoint computation will start with a fixed number k of tokens, which will be used if and when needed. When there are no tokens left, the widening is always applied.

Extrapolation Operators

Besides the two widening operators, the library also implements several *extrapolation* operators, which differ from widenings in that their use along an upper iteration sequence does not ensure convergence in a finite number of steps.

In particular, for each of the two widenings there is a corresponding *limited* extrapolation operator, which can be used to implement the *widening “up to”* technique as described in [HPR97](p. 18). Each limited extrapolation operator takes a constraint system as an additional parameter and uses it to improve the approximation yielded by the corresponding widening operator. Note that a convergence guarantee can only be obtained by suitably restricting the set of constraints that can occur in this additional parameter. For instance, in [HPR97](p. 18) this set is fixed once and for all before starting the computation of the upward iteration sequence.

The *bounded* extrapolation operators further enhance each one of the limited extrapolation operators described above, by ensuring that their results cannot be worse than the smallest **bounding box**(p. 10) enclosing the two argument polyhedra.

1.5 The Powerset Construction

The PPL provides the finite powerset construction; this takes a pre-existing domain and upgrades it to one that can represent disjunctive information (by using a *finite* number of disjuncts). The construction follows the approach described in [Bag98](p. 15), also summarised in [BHZ04](p. 16) where there is an account of generic widenings for the powerset domain (some of which are supported in the instantiation of this construction by the domain of convex polyhedra and described in Section **The Polyhedra Powerset Domain**(p. 13)).

The Powerset Domain

The domain is built from a pre-existing base-level domain D which must include an entailment relation ‘ \vdash ’, a meet operation ‘ \otimes ’, a top element ‘ $\mathbf{1}$ ’ and bottom element ‘ $\mathbf{0}$ ’.

As the intended semantics of an element of the powerset of the base-level domain is that of disjunction, elements of the powerset are always *reduced* to semantically-equivalent non-redundant elements.

A set $\mathcal{S} \in \wp(D)$ is called *non-redundant* with respect to ‘ \vdash ’ if and only if $\mathbf{0} \notin \mathcal{S}$ and $\forall d_1, d_2 \in \mathcal{S} : d_1 \vdash d_2 \implies d_1 = d_2$. The set of finite non-redundant subsets of D (with respect to ‘ \vdash ’) is denoted by $\wp_{\text{fn}}^+(D)$. The reduction function $\Omega_D^+ : \wp_{\text{f}}(D) \rightarrow \wp_{\text{fn}}^+(D)$ mapping a finite set into its non-redundant counterpart, also called *Omega-reduction*, is defined, for each $\mathcal{S} \in \wp_{\text{f}}(D)$, by

$$\Omega_D^+(\mathcal{S}) \stackrel{\text{def}}{=} \mathcal{S} \setminus \{d \in \mathcal{S} \mid d = \mathbf{0} \text{ or } \exists d' \in \mathcal{S} . d \vdash d'\}.$$

The restriction to the finite subsets reflects the fact that here disjunctions are implemented by explicit collections of elements of the base-level abstract domain. As a consequence of this restriction, for any $\mathcal{S} \in \wp_{\text{f}}(D)$ such that $\mathcal{S} \neq \{\mathbf{0}\}$, $\Omega_D^+(\mathcal{S})$ is the (finite) set of the maximal elements of \mathcal{S} .

The *finite powerset domain* over a domain D is the set of all finite reduced sets of D and denoted by D_{p} .

The domain includes an approximation ordering ‘ \vdash_P ’ defined so that $\mathcal{S}_1 \vdash_P \mathcal{S}_2$ if and only if

$$\forall d_1 \in \mathcal{S}_1 : \exists d_2 \in \mathcal{S}_2 . d_1 \vdash d_2.$$

Therefore the top element is $\{1\}$ and the bottom element is the emptyset.

Note:

As far as Omega-reduction is concerned, the library adopts a *lazy* approach: an element of the powerset domain is represented by a potentially redundant sequence of disjuncts. Redundancies can be eliminated by explicitly invoking the operator `omega_reduce()`, e.g., before performing the output of a powerset element. Note that all the documented operators automatically perform reductions on their arguments, when needed or appropriate.

1.6 Operations on the Powerset Construction

In this section we briefly describe the generic operations on Powerset Domains that are provided by the library for any given base-level domain D .

Meet and Upper Bound

Given the sets \mathcal{S}_1 and $\mathcal{S}_2 \in D_P$, the *meet* and *upper bound* operators provided by the library returns the set $\Omega_D^+(\{d_1 \otimes d_2 \mid d_1 \in \mathcal{S}_1, d_2 \in \mathcal{S}_2\})$ and reduced set union $\Omega_D^+(\mathcal{S}_1 \cup \mathcal{S}_2)$ respectively.

Adding a Disjunct

Given the powerset element $\mathcal{S} \in D_P$ and the base-level element $d \in D$, the *add disjunct* operator provided by the library returns the powerset element $\Omega_D^+(\mathcal{S} \cup \{d\})$.

Collapsing a Powerset Element

If the given powerset element is not empty, then the *collapse* operator returns the singleton powerset consisting of an upper-bound of all the disjuncts.

1.7 The Polyhedra Powerset Domain

The Polyhedra powerset domain $(\mathbb{P}_n)_P$ provided by the PPL is the finite powerset domain (defined in Section **The Powerset Construction**(p. 12)) over the domain of NNC polyhedra \mathbb{P}_n .

In addition to the operations described for the generic powerset domain in Section **Operations on the Powerset Construction**(p. 13), we provide some operations that are specific to this instantiation. Of these, most correspond to the application of the equivalent operation on each of the NNC polyhedra that are in the given set. Here we just describe those operations that are particular to the polyhedra powerset domain.

Geometric Comparisons

Given the sets $\mathcal{S}_1, \mathcal{S}_2 \in (\mathbb{P}_n)_P$, then we say that \mathcal{S}_1 *geometrically covers* \mathcal{S}_2 if every point (in some element) in a polyhedron in \mathcal{S}_2 is also a point in a polyhedron in \mathcal{S}_1 . If \mathcal{S}_1 geometrically covers \mathcal{S}_2 and \mathcal{S}_2 geometrically covers \mathcal{S}_1 , then we say that they are *geometrically equal*.

Pairwise Merge

Given the powerset $\mathcal{S} \in (\mathbb{P}_n)_P$, then the *pairwise merge* operator takes pairs of distinct elements in \mathcal{S} whose poly-hull is the same as their set-theoretical union and replaces them by their union. This replacement is done recursively so that, for each pair \mathcal{P}, \mathcal{Q} of distinct polyhedra in the result set, we have $\mathcal{P} \uplus \mathcal{Q} \neq \mathcal{P} \cup \mathcal{Q}$.

Extrapolation Operators

The library implements a generalization of the extrapolation operator for powerset domains proposed in [BGP99](p. 15). The operator `BGP99_extrapolation_assign` is made parametric by allowing for

the specification of a base-level extrapolation operator different from the H79 widening (e.g., the BHRZ03 widening can be used). Note that, in the general case, this operator cannot guarantee the convergence of the iteration sequence in a finite number of steps (for a counter-example, see [BHZ04](p. 16)).

Certificate-Based Widenings

The PPL library provides support for the specification of proper widening operators on the powerset domain of convex polyhedra. In particular, this version of the library implements an instance of the *certificate-based widening framework* proposed in [BHZ03b](p. 16).

A *finite convergence certificate* for an extrapolation operator is a formal way of ensuring that such an operator is indeed a widening on the considered domain. Given a widening operator on the base-level domain, together with the corresponding convergence certificate, the BHZ03 framework shows how it is possible to lift this widening so as to work on the finite powerset domain, while still ensuring convergence in a finite number of iterations.

Being highly parametric, the BHZ03 widening framework can be instantiated in many ways. The current implementation provides the templatic operator `BHZ03_widening_assign<Certificate, Widening>` which only exploits a fraction of this generality, by allowing the user to specify the base-level widening function and the corresponding certificate. The widening strategy is fixed and uses two extrapolation heuristics: first, the least upper bound is tried; second, the **BGP99 extrapolation operator**(p. 13) is tried, possibly applying **pairwise merging**(p. 13). If both heuristics fail to converge according to the convergence certificate, then an attempt is made to apply the base-level widening to the poly-hulls of the two arguments, possibly improving the result obtained by means of the **poly-difference**(p. 7) operator. For more details and a justification of the overall approach, see [BHZ03b](p. 16) and [BHZ04](p. 16).

The library provides two convergence certificates: while **BHRZ03_Certificate**(p. 76) is compatible with both the BHRZ03 and the H79 widenings, **H79_Certificate**(p. 100) is only compatible with the latter. Note that using different certificates will change the results obtained, even when using the same base-level widening operator. It is also worth stressing that it is up to the user to see that the widening operator is actually compatible with a given convergence certificate. If such a requirement is not met, then an extrapolation operator will be obtained.

1.8 Using the Library

A Note on the Implementation of the Operators

When adopting the double description method for the representation of convex polyhedra, the implementation of most of the operators may require an explicit conversion from one of the two representations into the other one, leading to algorithms having a worst-case exponential complexity. However, thanks to the adoption of lazy and incremental computation techniques, the library turns out to be rather efficient in many practical cases.

In earlier versions of the library, a number of operators were introduced in two flavors: a *lazy* version and an *eager* version, the latter having the operator name ending with `_and_minimize`. In principle, only the lazy versions should be used. The eager versions were added to help a knowledgeable user obtain better performance in particular cases. Basically, by invoking the eager version of an operator, the user is trading laziness to better exploit the incrementality of the inner library computations. Starting from version 0.5, the lazy and incremental computation techniques have been refined to achieve a better integration: as a consequence, the lazy versions of the operators are now almost always more efficient than the eager versions.

One of the cases when an eager computation still makes sense is when the well-known *fail-first* principle comes into play. For instance, if you have to compute the intersection of several polyhedra and you strongly suspect that the result will become empty after a few of these intersections, then you may obtain a better performance by calling the eager version of the intersection operator, since the minimization process also enforces an emptiness check. Note anyway that the same effect can be obtained by interleaving the calls of

the lazy operator with explicit emptiness checks.

On Object-Orientation and Polymorphism: A Disclaimer

The PPL library is mainly a collection of so-called “concrete data types”: while providing the user with a clean and friendly interface, these types are not meant to — i.e., they should not — be used polymorphically (since, e.g., most of the destructors are not declared `virtual`). In practice, this restriction means that the library types should not be used as *public base classes* to be derived from. A user willing to extend the library types, adding new functionalities, often can do so by using *containment* instead of inheritance; even when there is the need to override a `protected` method, non-public inheritance should suffice.

On Const-Correctness: A Warning about the Use of References and Iterators

Most operators of the library depend on one or more parameters that are declared “const”, meaning that they will not be changed by the application of the considered operator. Due to the adoption of lazy computation techniques, in many cases such a const-correctness guarantee only holds at the semantic level, whereas it does not necessarily hold at the implementation level. For a typical example, consider the extraction from a polyhedron of its constraint system representation. While this operation is not going to change the polyhedron, it might actually invoke the internal conversion algorithm and modify the generators representation of the polyhedron object, e.g., by reordering the generators and removing those that are detected as redundant. Thus, any previously computed reference to the generators of the polyhedron (be it a direct reference object or an indirect one, such as an iterator) will no longer be valid. For this reason, code fragments such as the following should be avoided, as they may result in undefined behavior:

```
// Find a reference to the first point of the non-empty polyhedron 'ph'.
const Generator_System& gs = ph.generators();
Generator_System::const_iterator i = gs.begin();
for (Generator_System::const_iterator gs_end = gs.end(); i != gs_end; ++i)
    if (i->is_point())
        break;
const Generator& p = *i;
// Get the constraints of 'ph'.
const Constraint_System& cs = ph.constraints();
// Both the const iterator 'i' and the reference 'p'
// are no longer valid at this point.
cout << p.divisor() << endl; // Undefined behavior!
++i;                          // Undefined behavior!
```

As a rule of thumb, if a polyhedron plays any role in a computation (even as a const parameter), then any previously computed reference to parts of the polyhedron may have been invalidated. Note that, in the example above, the computation of the constraint system could have been placed after the uses of the iterator `i` and the reference `p`. Anyway, if really needed, it is always possible to take a copy of, instead of a reference to, the parts of interest of the polyhedron; in the case above, one may have taken a copy of the generator system by replacing the second line of code with the following:

```
Generator_System gs = ph.generators();
```

The same observations, modulo syntactic sugar, apply to the operators defined in the C interface of the library.

1.9 Bibliography

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3.1 PPL Directories

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4.1 PPL Namespace List

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5.1 PPL Class Hierarchy

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6 PPL Class Index

6.1 PPL Class List

Here are the classes, structs, unions and interfaces with brief descriptions:

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Parma_Polyhedra_Library::BHRZ03_Certificate::Compare (A total ordering on BHRZ03 certificates)	77
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7.1 PPL Related Pages

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GNU General Public License	154
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8 PPL Module Documentation

8.1 The Library

The core implementation of the Parma Polyhedra Library is written in C++. See Namespace, Hierarchical and Compound indexes for additional information about each single data type.

8.2 Library Defines

Defines

- **#define PPL_VERSION_MAJOR 0**
The major number of the PPL version.
- **#define PPL_VERSION_MINOR 7**
The minor number of the PPL version.
- **#define PPL_VERSION_REVISION 0**
The revision number of the PPL version.
- **#define PPL_VERSION_BETA 0**
The beta number of the PPL version. This is zero for official releases and nonzero for development snapshots.
- **#define PPL_VERSION "0.7"**
A string containing the PPL version.

8.2.1 Define Documentation

8.2.1.1 #define PPL_VERSION "0.7"

A string containing the PPL version.

Let M and m denote the numbers associated to `PPL_VERSION_MAJOR` and `PPL_VERSION_MINOR`, respectively. The format of `PPL_VERSION` is M "." m if both `PPL_VERSION_REVISION` (r) and `PPL_VERSION_BETA` (b) are zero, M "." m "pre" b if `PPL_VERSION_REVISION` is zero and `PPL_VERSION_BETA` is not zero, M "." m "." r if `PPL_VERSION_REVISION` is not zero and `PPL_VERSION_BETA` is zero, M "." m "." r "pre" b if neither `PPL_VERSION_REVISION` nor `PPL_VERSION_BETA` are zero.

8.3 C Language Interface

Some details about the C Interface(p. 42).

Version Checking

- **#define PPL_VERSION_MAJOR 0**
The major number of the PPL version.
- **#define PPL_VERSION_MINOR 7**
The minor number of the PPL version.
- **#define PPL_VERSION_REVISION 0**
The revision number of the PPL version.
- **#define PPL_VERSION_BETA 0**
The beta number of the PPL version. This is zero for official releases and nonzero for development snapshots.
- **#define PPL_VERSION "0.7"**
A string containing the PPL version.
- **int ppl_version_major (void)**
Returns the major number of the PPL version.
- **int ppl_version_minor (void)**
Returns the minor number of the PPL version.
- **int ppl_version_revision (void)**
Returns the revision number of the PPL version.
- **int ppl_version_beta (void)**
Returns the beta number of the PPL version.
- **int ppl_version (const char **p)**
Writes to `p` a pointer to a character string containing the PPL version.
- **int ppl_banner (const char **p)**
Writes to `p` a pointer to a character string containing the PPL banner.

Simple I/O Functions

- **typedef const char * ppl_io_variable_output_function_type (ppl_dimension_type var)**
The type of output functions used for printing variables.
- **int ppl_io_print_variable (ppl_dimension_type var)**
Pretty-prints `x` to `stdout`.
- **int ppl_io_fprint_variable (FILE *stream, ppl_dimension_type var)**
Pretty-prints `var` to the given output `stream`.
- **int ppl_io_print_Coefficient (ppl_const_Coefficient_t x)**
Prints `x` to `stdout`.

- **int ppl_io_fprint_Coefficient** (FILE *stream, **ppl_const_Coefficient_t** x)
Prints x to the given output stream.
- **int ppl_io_print_Linear_Expression** (**ppl_const_Linear_Expression_t** x)
Prints x to stdout.
- **int ppl_io_fprint_Linear_Expression** (FILE *stream, **ppl_const_Linear_Expression_t** x)
Prints x to the given output stream.
- **int ppl_io_print_Constraint** (**ppl_const_Constraint_t** x)
Prints x to stdout.
- **int ppl_io_fprint_Constraint** (FILE *stream, **ppl_const_Constraint_t** x)
Prints x to the given output stream.
- **int ppl_io_print_Constraint_System** (**ppl_const_Constraint_System_t** x)
Prints x to stdout.
- **int ppl_io_fprint_Constraint_System** (FILE *stream, **ppl_const_Constraint_System_t** x)
Prints x to the given output stream.
- **int ppl_io_print_Generator** (**ppl_const_Generator_t** x)
Prints x to stdout.
- **int ppl_io_fprint_Generator** (FILE *stream, **ppl_const_Generator_t** x)
Prints x to the given output stream.
- **int ppl_io_print_Generator_System** (**ppl_const_Generator_System_t** x)
Prints x to stdout.
- **int ppl_io_fprint_Generator_System** (FILE *stream, **ppl_const_Generator_System_t** x)
Prints x to the given output stream.
- **int ppl_io_print_Polyhedron** (**ppl_const_Polyhedron_t** x)
Prints x to stdout.
- **int ppl_io_fprint_Polyhedron** (FILE *stream, **ppl_const_Polyhedron_t** x)
Prints x to the given output stream.
- **int ppl_io_set_variable_output_function** (**ppl_io_variable_output_function_type** *p)
Sets the output function to be used for printing variables to p.
- **int ppl_io_get_variable_output_function** (**ppl_io_variable_output_function_type** **pp)
Writes a pointer to the current variable output function to pp.

Initialization, Error Handling and Auxiliary Functions

- **int ppl_max_space_dimension (ppl_dimension_type *m)**
Writes to m the maximum space dimension this library can handle.
- **int ppl_not_a_dimension (ppl_dimension_type *m)**
Writes to m a value that does not designate a valid dimension.
- **int ppl_initialize (void)**
Initializes the Parma Polyhedra Library. This function must be called before any other function.
- **int ppl_finalize (void)**
Finalizes the Parma Polyhedra Library. This function must be called after any other function.
- **int ppl_set_error_handler (void(*h)(enum ppl_enum_error_code code, const char *description))**
Installs the user-defined error handler pointed at by h.

Functions Related to Coefficients

- **int ppl_new_Coefficient (ppl_Coefficient_t *pc)**
Creates a new coefficient with value 0 and writes a handle for the newly created coefficient at address pc.
- **int ppl_new_Coefficient_from_mpz_t (ppl_Coefficient_t *pc, mpz_t z)**
Creates a new coefficient with the value given by the GMP integer z and writes a handle for the newly created coefficient at address pc.
- **int ppl_new_Coefficient_from_Coefficient (ppl_Coefficient_t *pc, ppl_const_Coefficient_t c)**
Builds a coefficient that is a copy of c; writes a handle for the newly created coefficient at address pc.
- **int ppl_assign_Coefficient_from_mpz_t (ppl_Coefficient_t dst, mpz_t z)**
Assign to dst the value given by the GMP integer z.
- **int ppl_assign_Coefficient_from_Coefficient (ppl_Coefficient_t dst, ppl_const_Coefficient_t src)**
Assigns a copy of the coefficient src to dst.
- **int ppl_delete_Coefficient (ppl_const_Coefficient_t c)**
Invalidates the handle c: this makes sure the corresponding resources will eventually be released.
- **int ppl_Coefficient_to_mpz_t (ppl_const_Coefficient_t c, mpz_t z)**
Sets the value of the GMP integer z to the value of c.
- **int ppl_Coefficient_OK (ppl_const_Coefficient_t c)**
Returns a positive integer if c is well formed, i.e., if it satisfies all its implementation invariants; returns 0 and perhaps make some noise if c is broken. Useful for debugging purposes.

Functions Related to Linear Expressions

- **int ppl_new_Linear_Expression (ppl_Linear_Expression_t *ple)**
Creates a new linear expression corresponding to the constant 0 in a zero-dimensional space; writes a handle for the new linear expression at address ple.
- **int ppl_new_Linear_Expression_with_dimension (ppl_Linear_Expression_t *ple, ppl_dimension_type d)**
Creates a new linear expression corresponding to the constant 0 in a d-dimensional space; writes a handle for the new linear expression at address ple.
- **int ppl_new_Linear_Expression_from_Linear_Expression (ppl_Linear_Expression_t *ple, ppl_const_Linear_Expression_t le)**
Builds a linear expression that is a copy of le; writes a handle for the newly created linear expression at address ple.
- **int ppl_new_Linear_Expression_from_Constraint (ppl_Linear_Expression_t *ple, ppl_const_Constraint_t c)**
Builds a linear expression corresponding to constraint c; writes a handle for the newly created linear expression at address ple.
- **int ppl_new_Linear_Expression_from_Generator (ppl_Linear_Expression_t *ple, ppl_const_Generator_t g)**
Builds a linear expression corresponding to generator g; writes a handle for the newly created linear expression at address ple.
- **int ppl_delete_Linear_Expression (ppl_const_Linear_Expression_t le)**
Invalidates the handle le: this makes sure the corresponding resources will eventually be released.
- **int ppl_assign_Linear_Expression_from_Linear_Expression (ppl_Linear_Expression_t dst, ppl_const_Linear_Expression_t src)**
Assigns a copy of the linear expression src to dst.
- **int ppl_Linear_Expression_add_to_coefficient (ppl_Linear_Expression_t le, ppl_dimension_type var, ppl_const_Coefficient_t n)**
Adds n to the coefficient of variable var in the linear expression le. The space dimension is set to be the maximum between var + 1 and the old space dimension.
- **int ppl_Linear_Expression_add_to_inhomogeneous (ppl_Linear_Expression_t le, ppl_const_Coefficient_t n)**
Adds n to the inhomogeneous term of the linear expression le.
- **int ppl_add_Linear_Expression_to_Linear_Expression (ppl_Linear_Expression_t dst, ppl_const_Linear_Expression_t src)**
Adds the linear expression src to dst.
- **int ppl_subtract_Linear_Expression_from_Linear_Expression (ppl_Linear_Expression_t dst, ppl_const_Linear_Expression_t src)**
Subtracts the linear expression src from dst.
- **int ppl_multiply_Linear_Expression_by_Coefficient (ppl_Linear_Expression_t le, ppl_const_Coefficient_t n)**

Multiply the linear expression `dst` by `n`.

- **int ppl_Linear_Expression_space_dimension** (**ppl_const_Linear_Expression_t** `le`, **ppl_dimension_type** `*m`)

Writes to `m` the space dimension of `le`.

- **int ppl_Linear_Expression_coefficient** (**ppl_const_Linear_Expression_t** `le`, **ppl_dimension_type** `var`, **ppl_Coefficient_t** `n`)

Copies into `n` the coefficient of variable `var` in the linear expression `le`.

- **int ppl_Linear_Expression_inhomogeneous_term** (**ppl_const_Linear_Expression_t** `le`, **ppl_Coefficient_t** `n`)

Copies into `n` the inhomogeneous term of linear expression `le`.

- **int ppl_Linear_Expression_OK** (**ppl_const_Linear_Expression_t** `le`)

Returns a positive integer if `le` is well formed, i.e., if it satisfies all its implementation invariants; returns 0 and perhaps make some noise if `le` is broken. Useful for debugging purposes.

Functions Related to Constraints

- **int ppl_new_Constraint** (**ppl_Constraint_t** `*pc`, **ppl_const_Linear_Expression_t** `le`, **enum ppl_enum_Constraint_Type** `rel`)

Creates the new constraint '`le rel 0`' and writes a handle for it at address `pc`. The space dimension of the new constraint is equal to the space dimension of `le`.

- **int ppl_new_Constraint_zero_dim_false** (**ppl_Constraint_t** `*pc`)

Creates the unsatisfiable (zero-dimension space) constraint $0 = 1$ and writes a handle for it at address `pc`.

- **int ppl_new_Constraint_zero_dim_positivity** (**ppl_Constraint_t** `*pc`)

Creates the true (zero-dimension space) constraint $0 \leq 1$, also known as positivity constraint. a handle for the newly created constraint is written at address `pc`.

- **int ppl_new_Constraint_from_Constraint** (**ppl_Constraint_t** `*pc`, **ppl_const_Constraint_t** `c`)

Builds a constraint that is a copy of `c`; writes a handle for the newly created constraint at address `pc`.

- **int ppl_delete_Constraint** (**ppl_const_Constraint_t** `c`)

Invalidates the handle `c`: this makes sure the corresponding resources will eventually be released.

- **int ppl_assign_Constraint_from_Constraint** (**ppl_Constraint_t** `dst`, **ppl_const_Constraint_t** `src`)

Assigns a copy of the constraint `src` to `dst`.

- **int ppl_Constraint_space_dimension** (**ppl_const_Constraint_t** `c`, **ppl_dimension_type** `*m`)

Writes to `m` the space dimension of `c`.

- **int ppl_Constraint_type** (**ppl_const_Constraint_t** `c`)

Returns the type of constraint `c`.

- **int ppl_Constraint_coefficient** (**ppl_const_Constraint_t** `c`, **ppl_dimension_type** `var`, **ppl_Coefficient_t** `n`)

Copies into n the coefficient of variable var in constraint c .

- **int ppl_Constraint_inhomogeneous_term (ppl_const_Constraint_t c, ppl_Coefficient_t n)**
Copies into n the inhomogeneous term of constraint c .
- **int ppl_Constraint_OK (ppl_const_Constraint_t c)**
Returns a positive integer if c is well formed, i.e., if it satisfies all its implementation invariants; returns 0 and perhaps make some noise if c is broken. Useful for debugging purposes.

Functions Related to Constraint Systems

- **int ppl_new_Constraint_System (ppl_Constraint_System_t *pcs)**
Builds an empty system of constraints and writes a handle to it at address pcs .
- **int ppl_new_Constraint_System_zero_dim_empty (ppl_Constraint_System_t *pcs)**
Builds a zero-dimensional, unsatisfiable constraint system and writes a handle to it at address pcs .
- **int ppl_new_Constraint_System_from_Constraint (ppl_Constraint_System_t *pcs, ppl_const_Constraint_t c)**
Builds the singleton constraint system containing only a copy of constraint c ; writes a handle for the newly created system at address pcs .
- **int ppl_new_Constraint_System_from_Constraint_System (ppl_Constraint_System_t *pcs, ppl_const_Constraint_System_t cs)**
Builds a constraint system that is a copy of cs ; writes a handle for the newly created system at address pcs .
- **int ppl_delete_Constraint_System (ppl_const_Constraint_System_t cs)**
Invalidates the handle cs : this makes sure the corresponding resources will eventually be released.
- **int ppl_assign_Constraint_System_from_Constraint_System (ppl_Constraint_System_t dst, ppl_const_Constraint_System_t src)**
Assigns a copy of the constraint system src to dst .
- **int ppl_Constraint_System_space_dimension (ppl_const_Constraint_System_t cs, ppl_dimension_type *m)**
Writes to m the dimension of the vector space enclosing cs .
- **int ppl_Constraint_System_clear (ppl_Constraint_System_t cs)**
Removes all the constraints from the constraint system cs and sets its space dimension to 0.
- **int ppl_Constraint_System_insert_Constraint (ppl_Constraint_System_t cs, ppl_const_Constraint_t c)**
Inserts a copy of the constraint c into cs ; the space dimension is increased, if necessary.
- **int ppl_Constraint_System_OK (ppl_const_Constraint_System_t cs)**
Returns a positive integer if cs is well formed, i.e., if it satisfies all its implementation invariants; returns 0 and perhaps make some noise if cs is broken. Useful for debugging purposes.

- **int ppl_new_Constraint_System_const_iterator** (**ppl_Constraint_System_const_iterator_t** *pcit)
Builds a new 'const iterator' and writes a handle to it at address pcit.
- **int ppl_new_Constraint_System_const_iterator_from_Constraint_System_const_iterator** (**ppl_Constraint_System_const_iterator_t** *pcit, **ppl_const_Constraint_System_const_iterator_t** cit)
Builds a const iterator that is a copy of cit; writes an handle for the newly created const iterator at address pcit.
- **int ppl_delete_Constraint_System_const_iterator** (**ppl_const_Constraint_System_const_iterator_t** cit)
Invalidates the handle cit: this makes sure the corresponding resources will eventually be released.
- **int ppl_assign_Constraint_System_const_iterator_from_Constraint_System_const_iterator** (**ppl_Constraint_System_const_iterator_t** dst, **ppl_const_Constraint_System_const_iterator_t** src)
Assigns a copy of the const iterator src to dst.
- **int ppl_Constraint_System_begin** (**ppl_const_Constraint_System_t** cs, **ppl_Constraint_System_const_iterator_t** cit)
Assigns to cit a const iterator "pointing" to the beginning of the constraint system cs.
- **int ppl_Constraint_System_end** (**ppl_const_Constraint_System_t** cs, **ppl_Constraint_System_const_iterator_t** cit)
Assigns to cit a const iterator "pointing" past the end of the constraint system cs.
- **int ppl_Constraint_System_const_iterator_dereference** (**ppl_const_Constraint_System_const_iterator_t** cit, **ppl_const_Constraint_t** *pc)
Dereference cit writing a const handle to the resulting constraint at address pc.
- **int ppl_Constraint_System_const_iterator_increment** (**ppl_Constraint_System_const_iterator_t** cit)
Increment cit so that it "points" to the next constraint.
- **int ppl_Constraint_System_const_iterator_equal_test** (**ppl_const_Constraint_System_const_iterator_t** x, **ppl_const_Constraint_System_const_iterator_t** y)
Returns a positive integer if the iterators corresponding to x and y are equal; return 0 if they are different.

Functions Related to Generators

- **int ppl_new_Generator** (**ppl_Generator_t** *pg, **ppl_const_Linear_Expression_t** le, **enum ppl_enum_Generator_Type** t, **ppl_const_Coefficient_t** d)
Creates a new generator of direction le and type t. If the generator to be created is a point or a closure point, the divisor d is applied to le. For other types of generators d is simply disregarded. A handle for the new generator is written at address pg. The space dimension of the new generator is equal to the space dimension of le.
- **int ppl_new_Generator_zero_dim_point** (**ppl_Generator_t** *pg)

Creates the point that is the origin of the zero-dimensional space \mathbb{R}^0 . Writes a handle for the new generator at address `pg`.

- **int `ppl_new_Generator_zero_dim_closure_point` (`ppl_Generator_t` *pg)**
Creates, as a closure point, the point that is the origin of the zero-dimensional space \mathbb{R}^0 . Writes a handle for the new generator at address `pg`.
- **int `ppl_new_Generator_from_Generator` (`ppl_Generator_t` *pg, `ppl_const_Generator_t` g)**
Builds a generator that is a copy of `g`; writes a handle for the newly created generator at address `pg`.
- **int `ppl_delete_Generator` (`ppl_const_Generator_t` g)**
Invalidates the handle `g`: this makes sure the corresponding resources will eventually be released.
- **int `ppl_assign_Generator_from_Generator` (`ppl_Generator_t` dst, `ppl_const_Generator_t` src)**
Assigns a copy of the generator `src` to `dst`.
- **int `ppl_Generator_space_dimension` (`ppl_const_Generator_t` g, `ppl_dimension_type` *m)**
Writes to `m` the space dimension of `g`.
- **int `ppl_Generator_type` (`ppl_const_Generator_t` g)**
Returns the type of generator `g`.
- **int `ppl_Generator_coefficient` (`ppl_const_Generator_t` g, `ppl_dimension_type` var, `ppl_Coefficient_t` n)**
Copies into `n` the coefficient of variable `var` in generator `g`.
- **int `ppl_Generator_divisor` (`ppl_const_Generator_t` g, `ppl_Coefficient_t` n)**
If `g` is a point or a closure point assigns its divisor to `n`.
- **int `ppl_Generator_OK` (`ppl_const_Generator_t` g)**
Returns a positive integer if `g` is well formed, i.e., if it satisfies all its implementation invariants; returns 0 and perhaps make some noise if `g` is broken. Useful for debugging purposes.

Functions Related to Generator Systems

- **int `ppl_new_Generator_System` (`ppl_Generator_System_t` *pgs)**
Builds an empty system of generators and writes a handle to it at address `pgs`.
- **int `ppl_new_Generator_System_from_Generator` (`ppl_Generator_System_t` *pgs, `ppl_const_Generator_t` g)**
Builds the singleton generator system containing only a copy of generator `g`; writes a handle for the newly created system at address `pgs`.
- **int `ppl_new_Generator_System_from_Generator_System` (`ppl_Generator_System_t` *pgs, `ppl_const_Generator_System_t` gs)**
Builds a generator system that is a copy of `gs`; writes a handle for the newly created system at address `pgs`.
- **int `ppl_delete_Generator_System` (`ppl_const_Generator_System_t` gs)**
Invalidates the handle `gs`: this makes sure the corresponding resources will eventually be released.

- **int ppl_assign_Generator_System_from_Generator_System** (**ppl_Generator_System_t** dst, **ppl_const_Generator_System_t** src)
Assigns a copy of the generator system src to dst.
- **int ppl_Generator_System_space_dimension** (**ppl_const_Generator_System_t** gs, **ppl_dimension_type** *m)
Writes to m the dimension of the vector space enclosing gs.
- **int ppl_Generator_System_clear** (**ppl_Generator_System_t** gs)
Removes all the generators from the generator system gs and sets its space dimension to 0.
- **int ppl_Generator_System_insert_Generator** (**ppl_Generator_System_t** gs, **ppl_const_Generator_t** g)
Inserts a copy of the generator g into gs; the space dimension is increased, if necessary.
- **int ppl_Generator_System_OK** (**ppl_const_Generator_System_t** c)
Returns a positive integer if gs is well formed, i.e., if it satisfies all its implementation invariants; returns 0 and perhaps make some noise if gs is broken. Useful for debugging purposes.
- **int ppl_new_Generator_System_const_iterator** (**ppl_Generator_System_const_iterator_t** *pgit)
Builds a new 'const iterator' and writes a handle to it at address pgit.
- **int ppl_new_Generator_System_const_iterator_from_Generator_System_const_iterator** (**ppl_Generator_System_const_iterator_t** *pgit, **ppl_const_Generator_System_const_iterator_t** git)
Builds a const iterator that is a copy of git; writes an handle for the newly created const iterator at address pgit.
- **int ppl_delete_Generator_System_const_iterator** (**ppl_const_Generator_System_const_iterator_t** git)
Invalidates the handle git: this makes sure the corresponding resources will eventually be released.
- **int ppl_assign_Generator_System_const_iterator_from_Generator_System_const_iterator** (**ppl_Generator_System_const_iterator_t** dst, **ppl_const_Generator_System_const_iterator_t** src)
Assigns a copy of the const iterator src to dst.
- **int ppl_Generator_System_begin** (**ppl_const_Generator_System_t** gs, **ppl_Generator_System_const_iterator_t** git)
Assigns to git a const iterator "pointing" to the beginning of the generator system gs.
- **int ppl_Generator_System_end** (**ppl_const_Generator_System_t** gs, **ppl_Generator_System_const_iterator_t** git)
Assigns to git a const iterator "pointing" past the end of the generator system gs.
- **int ppl_Generator_System_const_iterator_dereference** (**ppl_const_Generator_System_const_iterator_t** git, **ppl_const_Generator_t** *pg)
Dereference git writing a const handle to the resulting generator at address pg.

- **int ppl_Generator_System_const_iterator_increment (ppl_Generator_System_const_iterator_t git)**

Increment git so that it "points" to the next generator.

- **int ppl_Generator_System_const_iterator_equal_test (ppl_const_Generator_System_const_iterator_t x, ppl_const_Generator_System_const_iterator_t y)**

Return a positive integer if the iterators corresponding to x and y are equal; return 0 if they are different.

Functions Related to Polyhedra

- **int ppl_new_C_Polyhedron_from_dimension (ppl_Polyhedron_t *pph, ppl_dimension_type d)**

Builds an universe closed polyhedron of dimension d and writes an handle to it at address pph.

- **int ppl_new_NNC_Polyhedron_from_dimension (ppl_Polyhedron_t *pph, ppl_dimension_type d)**

Builds an universe NNC polyhedron of dimension d and writes an handle to it at address pph.

- **int ppl_new_C_Polyhedron_empty_from_dimension (ppl_Polyhedron_t *pph, ppl_dimension_type d)**

Builds an empty closed polyhedron of space dimension d and writes an handle to it at address pph.

- **int ppl_new_NNC_Polyhedron_empty_from_dimension (ppl_Polyhedron_t *pph, ppl_dimension_type d)**

Builds an empty NNC polyhedron of space dimension d and writes an handle to it at address pph.

- **int ppl_new_C_Polyhedron_from_C_Polyhedron (ppl_Polyhedron_t *pph, ppl_const_Polyhedron_t ph)**

Builds a closed polyhedron that is a copy of ph; writes a handle for the newly created polyhedron at address pph.

- **int ppl_new_C_Polyhedron_from_NNC_Polyhedron (ppl_Polyhedron_t *pph, ppl_const_Polyhedron_t ph)**

Builds a closed polyhedron that is a copy of of the NNC polyhedron ph; writes a handle for the newly created polyhedron at address pph.

- **int ppl_new_NNC_Polyhedron_from_C_Polyhedron (ppl_Polyhedron_t *pph, ppl_const_Polyhedron_t ph)**

Builds an NNC polyhedron that is a copy of of the closed polyhedron ph; writes a handle for the newly created polyhedron at address pph.

- **int ppl_new_NNC_Polyhedron_from_NNC_Polyhedron (ppl_Polyhedron_t *pph, ppl_const_Polyhedron_t ph)**

Builds an NNC polyhedron that is a copy of ph; writes a handle for the newly created polyhedron at address pph.

- **int ppl_new_C_Polyhedron_from_Constraint_System (ppl_Polyhedron_t *pph, ppl_const_Constraint_System_t cs)**

Builds a new closed polyhedron from the system of constraints cs and writes a handle for the newly created polyhedron at address pph.

- **int ppl_new_C_Polyhedron_recycle_Constraint_System (ppl_Polyhedron_t *pph, ppl_Constraint_System_t cs)**
Builds a new closed polyhedron recycling the system of constraints cs and writes a handle for the newly created polyhedron at address pph.
- **int ppl_new_NNC_Polyhedron_from_Constraint_System (ppl_Polyhedron_t *pph, ppl_Constraint_System_t cs)**
Builds a new NNC polyhedron from the system of constraints cs and writes a handle for the newly created polyhedron at address pph.
- **int ppl_new_NNC_Polyhedron_recycle_Constraint_System (ppl_Polyhedron_t *pph, ppl_Constraint_System_t cs)**
Builds a new NNC polyhedron recycling the system of constraints cs and writes a handle for the newly created polyhedron at address pph.
- **int ppl_new_C_Polyhedron_from_Generator_System (ppl_Polyhedron_t *pph, ppl_Generator_System_t gs)**
Builds a new closed polyhedron from the system of generators gs and writes a handle for the newly created polyhedron at address pph.
- **int ppl_new_C_Polyhedron_recycle_Generator_System (ppl_Polyhedron_t *pph, ppl_Generator_System_t gs)**
Builds a new closed polyhedron recycling the system of generators gs and writes a handle for the newly created polyhedron at address pph.
- **int ppl_new_NNC_Polyhedron_from_Generator_System (ppl_Polyhedron_t *pph, ppl_Generator_System_t gs)**
Builds a new NNC polyhedron from the system of generators gs and writes a handle for the newly created polyhedron at address pph.
- **int ppl_new_NNC_Polyhedron_recycle_Generator_System (ppl_Polyhedron_t *pph, ppl_Generator_System_t gs)**
Builds a new NNC polyhedron recycling the system of generators gs and writes a handle for the newly created polyhedron at address pph.
- **int ppl_new_C_Polyhedron_from_bounding_box (ppl_Polyhedron_t *pph, ppl_dimension_type(*space_dimension)(void), int(*is_empty)(void), int(*get_lower_bound)(ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d), int(*get_upper_bound)(ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d))**
Builds a new C polyhedron corresponding to an interval-based bounding box, writing a handle for the newly created polyhedron at address pph.
- **int ppl_new_NNC_Polyhedron_from_bounding_box (ppl_Polyhedron_t *pph, ppl_dimension_type(*space_dimension)(void), int(*is_empty)(void), int(*get_lower_bound)(ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d), int(*get_upper_bound)(ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d))**
Builds a new C polyhedron corresponding to an interval-based bounding box, writing a handle for the newly created polyhedron at address pph.
- **int ppl_assign_C_Polyhedron_from_C_Polyhedron (ppl_Polyhedron_t dst, ppl_Const_Polyhedron_t src)**
Assigns a copy of the closed polyhedron src to the closed polyhedron dst.

- **int ppl_assign_NNC_Polyhedron_from_NNC_Polyhedron** (ppl_Polyhedron_t dst, ppl_const_Polyhedron_t src)
Assigns a copy of the NNC polyhedron src to the NNC polyhedron dst.
- **int ppl_delete_Polyhedron** (ppl_const_Polyhedron_t ph)
Invalidates the handle ph: this makes sure the corresponding resources will eventually be released.
- **int ppl_Polyhedron_space_dimension** (ppl_const_Polyhedron_t ph, ppl_dimension_type *m)
Writes to m the dimension of the vector space enclosing ph.
- **int ppl_Polyhedron_affine_dimension** (ppl_const_Polyhedron_t ph)
Writes to m the affine dimension of ph (not to be confused with the dimension of its enclosing vector space) or 0, if ph is empty.
- **int ppl_Polyhedron_constraints** (ppl_const_Polyhedron_t ph, ppl_const_Constraint_System_t *pcs)
Writes a const handle to the constraint system defining the polyhedron ph at address pcs.
- **int ppl_Polyhedron_minimized_constraints** (ppl_const_Polyhedron_t ph, ppl_const_Constraint_System_t *pcs)
Writes a const handle to the minimized constraint system defining the polyhedron ph at address pcs.
- **int ppl_Polyhedron_generators** (ppl_const_Polyhedron_t ph, ppl_const_Generator_System_t *pgs)
Writes a const handle to the generator system defining the polyhedron ph at address pgs.
- **int ppl_Polyhedron_minimized_generators** (ppl_const_Polyhedron_t ph, ppl_const_Generator_System_t *pgs)
Writes a const handle to the minimized generator system defining the polyhedron ph at address pgs.
- **int ppl_Polyhedron_relation_with_Constraint** (ppl_const_Polyhedron_t ph, ppl_const_Constraint_t c)
Checks the relation between the polyhedron ph with the constraint c.
- **int ppl_Polyhedron_relation_with_Generator** (ppl_const_Polyhedron_t ph, ppl_const_Generator_t g)
Checks the relation between the polyhedron ph with the generator g.
- **int ppl_Polyhedron_shrink_bounding_box** (ppl_const_Polyhedron_t ph, unsigned int complexity, void(*set_empty)(void), void(*raise_lower_bound)(ppl_dimension_type k, int closed, ppl_const_Coefficient_t n, ppl_const_Coefficient_t d), void(*lower_upper_bound)(ppl_dimension_type k, int closed, ppl_const_Coefficient_t n, ppl_const_Coefficient_t d))
Use ph to shrink a generic, interval-based bounding box. The bounding box is abstractly provided by means of the parameters.
- **int ppl_Polyhedron_is_empty** (ppl_const_Polyhedron_t ph)
Returns a positive integer if ph is empty; returns 0 if ph is not empty.
- **int ppl_Polyhedron_is_universe** (ppl_const_Polyhedron_t ph)
Returns a positive integer if ph is a universe polyhedron; returns 0 if it is not.

- **int ppl_Polyhedron_is_bounded (ppl_const_Polyhedron_t ph)**
Returns a positive integer if ph is bounded; returns 0 if ph is unbounded.
- **int ppl_Polyhedron_bounds_from_above (ppl_const_Polyhedron_t ph, ppl_const_Linear_Expression_t le)**
Returns a positive integer if le is bounded from above in ph ; returns 0 otherwise.
- **int ppl_Polyhedron_bounds_from_below (ppl_const_Polyhedron_t ph, ppl_const_Linear_Expression_t le)**
Returns a positive integer if le is bounded from below in ph ; returns 0 otherwise.
- **int ppl_Polyhedron_maximize (ppl_const_Polyhedron_t ph, ppl_const_Linear_Expression_t le, ppl_Coefficient_t sup_n, ppl_Coefficient_t sup_d, int *pmaximum, ppl_const_Generator_t *ppoint)**
Returns a positive integer if ph is not empty and le is bounded from above in ph , in which case the supremum value and a point where le reaches it are computed.
- **int ppl_Polyhedron_minimize (ppl_const_Polyhedron_t ph, ppl_const_Linear_Expression_t le, ppl_Coefficient_t inf_n, ppl_Coefficient_t inf_d, int *pminimum, ppl_const_Generator_t *ppoint)**
Returns a positive integer if ph is not empty and le is bounded from above in ph , in which case the infimum value and a point where le reaches it are computed.
- **int ppl_Polyhedron_is_topologically_closed (ppl_const_Polyhedron_t ph)**
Returns a positive integer if ph is topologically closed; returns 0 if ph is not topologically closed.
- **int ppl_Polyhedron_contains_Polyhedron (ppl_const_Polyhedron_t x, ppl_const_Polyhedron_t y)**
Returns a positive integer if x contains or is equal to y ; returns 0 if it does not.
- **int ppl_Polyhedron_strictly_contains_Polyhedron (ppl_const_Polyhedron_t x, ppl_const_Polyhedron_t y)**
Returns a positive integer if x strictly contains y ; returns 0 if it does not.
- **int ppl_Polyhedron_is_disjoint_from_Polyhedron (ppl_const_Polyhedron_t x, ppl_const_Polyhedron_t y)**
Returns a positive integer if x and y are disjoint; returns 0 if they are not.
- **int ppl_Polyhedron_equals_Polyhedron (ppl_const_Polyhedron_t x, ppl_const_Polyhedron_t y)**
Returns a positive integer if x and y are the same polyhedron; return 0 if they are different.
- **int ppl_Polyhedron_OK (ppl_const_Polyhedron_t ph)**
Returns a positive integer if ph is well formed, i.e., if it satisfies all its implementation invariants; returns 0 and perhaps make some noise if ph is broken. Useful for debugging purposes.
- **int ppl_Polyhedron_add_constraint (ppl_Polyhedron_t ph, ppl_const_Constraint_t c)**
Adds a copy of the constraint c to the system of constraints of ph .

- **int ppl_Polyhedron_add_constraint_and_minimize** (ppl_Polyhedron_t ph, ppl_const_Constraint_t c)
Adds a copy of the constraint c to the system of constraints of ph. Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.
- **int ppl_Polyhedron_add_generator** (ppl_Polyhedron_t ph, ppl_const_Generator_t g)
Adds a copy of the generator g to the system of generators of ph.
- **int ppl_Polyhedron_add_generator_and_minimize** (ppl_Polyhedron_t ph, ppl_const_Generator_t g)
Adds a copy of the generator g to the system of generators of ph. Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.
- **int ppl_Polyhedron_add_constraints** (ppl_Polyhedron_t ph, ppl_const_Constraint_System_t cs)
Adds a copy of the system of constraints cs to the system of constraints of ph.
- **int ppl_Polyhedron_add_constraints_and_minimize** (ppl_Polyhedron_t ph, ppl_const_Constraint_System_t cs)
Adds a copy of the system of constraints cs to the system of constraints of ph. Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.
- **int ppl_Polyhedron_add_generators** (ppl_Polyhedron_t ph, ppl_const_Generator_System_t gs)
Adds a copy of the system of generators gs to the system of generators of ph.
- **int ppl_Polyhedron_add_generators_and_minimize** (ppl_Polyhedron_t ph, ppl_const_Generator_System_t gs)
Adds a copy of the system of generators gs to the system of generators of ph. Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.
- **int ppl_Polyhedron_add_recycled_constraints** (ppl_Polyhedron_t ph, ppl_Constraint_System_t cs)
Adds the system of constraints cs to the system of constraints of ph.
- **int ppl_Polyhedron_add_recycled_constraints_and_minimize** (ppl_Polyhedron_t ph, ppl_Constraint_System_t cs)
Adds the system of constraints cs to the system of constraints of ph. Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.
- **int ppl_Polyhedron_add_recycled_generators** (ppl_Polyhedron_t ph, ppl_Generator_System_t gs)
Adds the system of generators gs to the system of generators of ph.
- **int ppl_Polyhedron_add_recycled_generators_and_minimize** (ppl_Polyhedron_t ph, ppl_Generator_System_t gs)
Adds the system of generators gs to the system of generators of ph. Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.
- **int ppl_Polyhedron_intersection_assign** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y)

Intersects x with polyhedron y and assigns the result x .

- **int ppl_Polyhedron_intersection_assign_and_minimize** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y)
Intersects x with polyhedron y and assigns the result x . Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, x is also guaranteed to be minimized.
- **int ppl_Polyhedron_poly_hull_assign** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y)
Assigns to x the poly-hull of x and y .
- **int ppl_Polyhedron_poly_hull_assign_and_minimize** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y)
Assigns to x the poly-hull of x and y . Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, x is also guaranteed to be minimized.
- **int ppl_Polyhedron_poly_difference_assign** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y)
Assigns to x the poly-difference(p. 7) of x and y .
- **int ppl_Polyhedron_affine_image** (ppl_Polyhedron_t ph , ppl_dimension_type var , ppl_const_Linear_Expression_t le , ppl_const_Coefficient_t d)
Transforms the polyhedron ph , assigning an affine expression to the specified variable.
- **int ppl_Polyhedron_affine_preimage** (ppl_Polyhedron_t ph , ppl_dimension_type var , ppl_const_Linear_Expression_t le , ppl_const_Coefficient_t d)
Transforms the polyhedron ph , substituting an affine expression to the specified variable.
- **int ppl_Polyhedron_generalized_affine_image** (ppl_Polyhedron_t ph , ppl_dimension_type var , enum ppl_enum_Constraint_Type $relsym$, ppl_const_Linear_Expression_t le , ppl_const_Coefficient_t d)
*Assigns to ph the image of ph with respect to the **generalized affine transfer function**(p. 10) $var' \bowtie \frac{expr}{denominator}$, where \bowtie is the relation symbol encoded by $relsym$.*
- **int ppl_Polyhedron_generalized_affine_image_lhs_rhs** (ppl_Polyhedron_t ph , ppl_const_Linear_Expression_t lhs , enum ppl_enum_Constraint_Type $relsym$, ppl_const_Linear_Expression_t rhs)
*Assigns to ph the image of ph with respect to the **generalized affine transfer function**(p. 10) $lhs' \bowtie rhs$, where \bowtie is the relation symbol encoded by $relsym$.*
- **int ppl_Polyhedron_time_elapse_assign** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y)
*Assigns to x the **time-elapse**(p. 10) between the polyhedra x and y .*
- **int ppl_Polyhedron_BHRZ03_widening_assign_with_tokens** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y , unsigned * tp)
*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **BHRZ03-widening**(p. 11) of x and y . If tp is not the null pointer, the **widening with tokens**(p. 11) delay technique is applied with * tp available tokens.*
- **int ppl_Polyhedron_BHRZ03_widening_assign** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y)
*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **BHRZ03-widening**(p. 11) of x and y .*

- **int ppl_Polyhedron_limited_BHRZ03_extrapolation_assign_with_tokens** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, ppl_const_Constraint_System_t cs, unsigned *tp)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **BHRZ03-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x . If tp is not the null pointer, the **widening with tokens**(p. 11) delay technique is applied with $*tp$ available tokens.*
- **int ppl_Polyhedron_limited_BHRZ03_extrapolation_assign** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, ppl_const_Constraint_System_t cs)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **BHRZ03-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x .*
- **int ppl_Polyhedron_bounded_BHRZ03_extrapolation_assign_with_tokens** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, ppl_const_Constraint_System_t cs, unsigned *tp)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **BHRZ03-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x , further intersected with all the constraints of the form $\pm v \leq r$ and $\pm v < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of x . If tp is not the null pointer, the **widening with tokens**(p. 11) delay technique is applied with $*tp$ available tokens.*
- **int ppl_Polyhedron_bounded_BHRZ03_extrapolation_assign** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, ppl_const_Constraint_System_t cs)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **BHRZ03-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x , further intersected with all the constraints of the form $\pm v \leq r$ and $\pm v < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of x .*
- **int ppl_Polyhedron_H79_widening_assign_with_tokens** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, unsigned *tp)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **H79-widening**(p. 11) of x and y . If tp is not the null pointer, the **widening with tokens**(p. 11) delay technique is applied with $*tp$ available tokens.*
- **int ppl_Polyhedron_H79_widening_assign** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **H79-widening**(p. 11) of x and y .*
- **int ppl_Polyhedron_limited_H79_extrapolation_assign_with_tokens** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, ppl_const_Constraint_System_t cs, unsigned *tp)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **H79-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x . If tp is not the null pointer, the **widening with tokens**(p. 11) delay technique is applied with $*tp$ available tokens.*
- **int ppl_Polyhedron_limited_H79_extrapolation_assign** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, ppl_const_Constraint_System_t cs)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **H79-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x .*
- **int ppl_Polyhedron_bounded_H79_extrapolation_assign_with_tokens** (ppl_Polyhedron_t x, ppl_const_Polyhedron_t y, ppl_const_Constraint_System_t cs, unsigned *tp)

*If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **H79-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x , further intersected*

with all the constraints of the form $\pm v \leq r$ and $\pm v < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of x . If τ_p is not the null pointer, the **widening with tokens**(p. 11) delay technique is applied with $*\tau_p$ available tokens.

- **int ppl_Polyhedron_bounded_H79_extrapolation_assign** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y , ppl_const_Constraint_System_t cs)

If the polyhedron y is contained in (or equal to) the polyhedron x , assigns to x the **H79-widening**(p. 11) of x and y intersected with the constraints in cs that are satisfied by all the points of x , further intersected with all the constraints of the form $\pm v \leq r$ and $\pm v < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of x .

- **int ppl_Polyhedron_topological_closure_assign** (ppl_Polyhedron_t ph)

Assigns to ph its topological closure.

- **int ppl_Polyhedron_add_space_dimensions_and_embed** (ppl_Polyhedron_t ph , ppl_dimension_type d)

Adds d new dimensions to the space enclosing the polyhedron ph and to ph itself.

- **int ppl_Polyhedron_add_space_dimensions_and_project** (ppl_Polyhedron_t ph , ppl_dimension_type d)

Adds d new dimensions to the space enclosing the polyhedron ph .

- **int ppl_Polyhedron_concatenate_assign** (ppl_Polyhedron_t x , ppl_const_Polyhedron_t y)

Seeing a polyhedron as a set of tuples (its points), assigns to x all the tuples that can be obtained by concatenating, in the order given, a tuple of x with a tuple of y .

- **int ppl_Polyhedron_remove_space_dimensions** (ppl_Polyhedron_t ph , ppl_dimension_type $ds[]$, size_t n)

Removes from the vector space enclosing ph the space dimensions that are specified in first n positions of the array ds . The presence of duplicates in ds is a waste but an innocuous one.

- **int ppl_Polyhedron_remove_higher_space_dimensions** (ppl_Polyhedron_t ph , ppl_dimension_type d)

Removes the higher dimensions from the vector space enclosing ph so that, upon successful return, the new space dimension is d .

- **int ppl_Polyhedron_map_space_dimensions** (ppl_Polyhedron_t ph , ppl_dimension_type $maps[]$, size_t n)

Remaps the dimensions of the vector space according to a **partial function**(p. 8). This function is specified by means of the $maps$ array, which has n entries.

- **int ppl_Polyhedron_expand_space_dimension** (ppl_Polyhedron_t ph , ppl_dimension_type d , ppl_dimension_type m)

Expands(p. 8) the d -th dimension of the vector space enclosing ph to m new space dimensions.

- **int ppl_Polyhedron_fold_space_dimensions** (ppl_Polyhedron_t ph , ppl_dimension_type $ds[]$, size_t n , ppl_dimension_type d)

Modifies ph by **folding**(p. 8) the space dimensions contained in the first n positions of the array ds into dimension d . The presence of duplicates in ds is a waste but an innocuous one.

Typedefs

- typedef size_t **ppl_dimension_type**
An unsigned integral type for representing space dimensions.
- typedef ppl_Coefficient_tag * **ppl_Coefficient_t**
Opaque pointer.
- typedef ppl_Coefficient_tag const * **ppl_const_Coefficient_t**
Opaque pointer to const object.
- typedef ppl_Linear_Expression_tag * **ppl_Linear_Expression_t**
Opaque pointer.
- typedef ppl_Linear_Expression_tag const * **ppl_const_Linear_Expression_t**
Opaque pointer to const object.
- typedef ppl_Constraint_tag * **ppl_Constraint_t**
Opaque pointer.
- typedef ppl_Constraint_tag const * **ppl_const_Constraint_t**
Opaque pointer to const object.
- typedef ppl_Constraint_System_tag * **ppl_Constraint_System_t**
Opaque pointer.
- typedef ppl_Constraint_System_tag const * **ppl_const_Constraint_System_t**
Opaque pointer to const object.
- typedef ppl_Constraint_System_const_iterator_tag * **ppl_Constraint_System_const_iterator_t**
Opaque pointer.
- typedef ppl_Constraint_System_const_iterator_tag const * **ppl_const_Constraint_System_const_iterator_t**
Opaque pointer to const object.
- typedef ppl_Generator_tag * **ppl_Generator_t**
Opaque pointer.
- typedef ppl_Generator_tag const * **ppl_const_Generator_t**
Opaque pointer to const object.
- typedef ppl_Generator_System_tag * **ppl_Generator_System_t**
Opaque pointer.
- typedef ppl_Generator_System_tag const * **ppl_const_Generator_System_t**
Opaque pointer to const object.
- typedef ppl_Generator_System_const_iterator_tag * **ppl_Generator_System_const_iterator_t**
Opaque pointer.

- `typedef ppl_Generator_System_const_iterator_tag const * ppl_const_Generator_System_const_iterator_t`
Opaque pointer to const object.
- `typedef ppl_Polyhedron_tag * ppl_Polyhedron_t`
Opaque pointer.
- `typedef ppl_Polyhedron_tag const * ppl_const_Polyhedron_t`
Opaque pointer to const object.

Enumerations

- `enum ppl_enum_error_code {`
`PPL_ERROR_OUT_OF_MEMORY, PPL_ERROR_INVALID_ARGUMENT, PPL_ERROR_LENGTH_ERROR, PPL_ARITHMETIC_OVERFLOW,`
`PPL_STDIO_ERROR, PPL_ERROR_INTERNAL_ERROR, PPL_ERROR_UNKNOWN_STANDARD_EXCEPTION, PPL_ERROR_UNEXPECTED_ERROR }`
Defines the error codes that any function may return.
- `enum ppl_enum_Constraint_Type {`
`PPL_CONSTRAINT_TYPE_LESS_THAN, PPL_CONSTRAINT_TYPE_LESS_THAN_OR_EQUAL,`
`PPL_CONSTRAINT_TYPE_EQUAL, PPL_CONSTRAINT_TYPE_GREATER_THAN_OR_EQUAL,`
`PPL_CONSTRAINT_TYPE_GREATER_THAN }`
Describes the relations represented by a constraint.
- `enum ppl_enum_Generator_Type { PPL_GENERATOR_TYPE_LINE, PPL_GENERATOR_TYPE_RAY,`
`PPL_GENERATOR_TYPE_POINT, PPL_GENERATOR_TYPE_CLOSURE_POINT }`
Describes the different kinds of generators.

Variables

- unsigned int `PPL_COMPLEXITY_CLASS_POLYNOMIAL`
Code of the worst-case polynomial complexity class.
- unsigned int `PPL_COMPLEXITY_CLASS_SIMPLEX`
Code of the worst-case exponential but typically polynomial complexity class.
- unsigned int `PPL_COMPLEXITY_CLASS_ANY`
Code of the universal complexity class.
- unsigned int `PPL_POLY_CON_RELATION_IS_DISJOINT`
Individual bit saying that the polyhedron and the set of points satisfying the constraint are disjoint.
- unsigned int `PPL_POLY_CON_RELATION_STRICTLY_INTERSECTS`

Individual bit saying that the polyhedron intersects the set of points satisfying the constraint, but it is not included in it.

- unsigned int **PPL_POLY_CON_RELATION_IS_INCLUDED**

Individual bit saying that the polyhedron is included in the set of points satisfying the constraint.

- unsigned int **PPL_POLY_CON_RELATION_SATURATES**

Individual bit saying that the polyhedron is included in the set of points saturating the constraint.

- unsigned int **PPL_POLY_GEN_RELATION_SUBSUMES**

Individual bit saying that adding the generator would not change the polyhedron.

8.3.1 Detailed Description

Some details about the C Interface(p. 42).

All the declarations needed for using the PPL's C interface (preprocessor symbols, data types, variables and functions) are collected in the header file `ppl_c.h`. This file, which is designed to work with pre-ANSI and ANSI C compilers as well as C99 and C++ compilers, should be included, either directly or via some other header file, with the directive

```
#include <ppl_c.h>
```

If this directive does not work, then your compiler is unable to find the file `ppl_c.h`. So check that the library is installed (if it is not installed, you may want to make `install`, perhaps with root privileges) in the right place (if not you may want to reconfigure the library using the appropriate pathname for the `-prefix` option); and that your compiler knows where it is installed (if not you should add the path to the directory where `ppl_c.h` is located to the compiler's include file search path; this is usually done with the `-I` option).

The name space of the PPL's C interface is `PPL_*` for preprocessor symbols, enumeration values and variables; and `ppl_*` for data types and function names. The interface systematically uses *opaque data types* (generic pointers that completely hide the internal representations from the client code) and provides all required access functions. By using just the interface, the client code can exploit all the functionalities of the library yet avoid directly manipulating the library's data structures. The advantages are that (1) applications do not depend on the internals of the library (these may change from release to release), and (2) the interface invariants can be thoroughly checked (by the access functions).

The PPL's C interface is initialized by means of the `ppl_initialize` function. This function must be called *before using any other interface of the library*. The application can release the resources allocated by the library by calling the `ppl_finalize` function. After this function is called *no other interface of the library may be used* until the interface is re-initialized using `ppl_initialize`.

Any application using the PPL should make sure that only the intended version(s) of the library are ever used. The version used can be checked at compile-time thanks to the macros `PPL_VERSION_MAJOR`, `PPL_VERSION_MINOR`, `PPL_VERSION_REVISION` and `PPL_VERSION_BETA`, which give, respectively major, minor, revision and beta numbers of the PPL version. This is an example of their use:

```
#if PPL_VERSION_MAJOR == 0 && PPL_VERSION_MINOR < 6
# error "PPL version 0.6 or following is required"
#endif
```

Compile-time checking, however, is not normally enough, particularly in an environment where there is dynamic linking. Run-time checking can be performed by means of the functions `ppl_version_major`,

`ppl_version_minor`, `ppl_version_revision`, and `ppl_version_beta`. The PPL's C interface also provides functions `ppl_version`, returning character string containing the full version number, and `ppl_banner`, returning a string that, in addition, provides (pointers to) other useful information for the library user.

All programs using the PPL's C interface must link with the following libraries: `libppl_c` (PPL's C interface), `libppl` (PPL's core), `libgmpxx` (GMP's C++ interface), and `libgmp` (GMP's library core). On most Unix-like systems, this is done by adding `-lppl_c`, `-lppl`, `-lgmpxx`, and `-lgmp` to the compiler's or linker's command line. For example:

```
gcc myprogram.o -lppl_c -lppl -lgmpxx -lgmp
```

If this does not work, it means that your compiler/linker is not finding the libraries where it expects. Again, this could be because you forgot to install the library or you installed it in a non-standard location. In the latter case you will need to use the appropriate options (usually `-L`) and, if you use shared libraries, some sort of run-time path selection mechanisms. Consult your compiler's documentation for details. Notice that the PPL is built using `Libtool` and an application can exploit this fact to significantly simplify the linking phase. See `Libtool`'s documentation for details. Those working under Linux can find a lot of useful information on how to use program libraries (including static, shared, and dynamically loaded libraries) in the `Program Library HOWTO`.

For examples on how to use the functions provided by the C interface, you are referred to the `interfaces/C/lpenum/` directory in the source distribution. It contains a toy *Linear Programming* solver written in C. In order to use this solver you will need to install GLPK (the GNU Linear Programming Kit): this is used to read linear programs in MPS format.

8.3.2 Define Documentation

8.3.2.1 `#define PPL_VERSION "0.7"`

A string containing the PPL version.

Let `M` and `m` denote the numbers associated to `PPL_VERSION_MAJOR` and `PPL_VERSION_MINOR`, respectively. The format of `PPL_VERSION` is `M "." m` if both `PPL_VERSION_REVISION` (`r`) and `PPL_VERSION_BETA` (`b`) are zero, `M "." m "pre" b` if `PPL_VERSION_REVISION` is zero and `PPL_VERSION_BETA` is not zero, `M "." m "." r` if `PPL_VERSION_REVISION` is not zero and `PPL_VERSION_BETA` is zero, `M "." m "." r "pre" b` if neither `PPL_VERSION_REVISION` nor `PPL_VERSION_BETA` are zero.

8.3.3 Typedef Documentation

8.3.3.1 `typedef const char* ppl_io_variable_output_function_type(ppl_dimension_type var)`

The type of output functions used for printing variables.

An output function for variables must write a textual representation for `var` to a character buffer, null-terminate it, and return a pointer to the beginning of the buffer. In case the operation fails, 0 should be returned and perhaps `errno` should be set in a meaningful way. The library does nothing with the buffer, besides printing its contents.

8.3.4 Enumeration Type Documentation

8.3.4.1 `enum ppl_enum_error_code`

Defines the error codes that any function may return.

Enumeration values:

PPL_ERROR_OUT_OF_MEMORY The virtual memory available to the process has been exhausted.

PPL_ERROR_INVALID_ARGUMENT A function has been invoked with an invalid argument.

PPL_ERROR_LENGTH_ERROR The construction of an object that would exceed its maximum permitted size was attempted.

PPL_ARITHMETIC_OVERFLOW An arithmetic overflow occurred and the computation was consequently interrupted. This can *only* happen in library's incarnations using bounded integers as coefficients.

PPL_STDIO_ERROR An error occurred during a C input/output operation. A more precise indication of what went wrong is available via `errno`.

PPL_ERROR_INTERNAL_ERROR An internal error that was diagnosed by the PPL itself. This indicates a bug in the PPL.

PPL_ERROR_UNKNOWN_STANDARD_EXCEPTION A standard exception has been raised by the C++ run-time environment. This indicates a bug in the PPL.

PPL_ERROR_UNEXPECTED_ERROR A totally unknown, totally unexpected error happened. This indicates a bug in the PPL.

8.3.4.2 enum ppl_enum_Constraint_Type

Describes the relations represented by a constraint.

Enumeration values:

PPL_CONSTRAINT_TYPE_LESS_THAN The constraint is of the form $e < 0$.

PPL_CONSTRAINT_TYPE_LESS_THAN_OR_EQUAL The constraint is of the form $e \leq 0$.

PPL_CONSTRAINT_TYPE_EQUAL The constraint is of the form $e = 0$.

PPL_CONSTRAINT_TYPE_GREATER_THAN_OR_EQUAL The constraint is of the form $e \geq 0$.

PPL_CONSTRAINT_TYPE_GREATER_THAN The constraint is of the form $e > 0$.

8.3.4.3 enum ppl_enum_Generator_Type

Describes the different kinds of generators.

Enumeration values:

PPL_GENERATOR_TYPE_LINE The generator is a line.

PPL_GENERATOR_TYPE_RAY The generator is a ray.

PPL_GENERATOR_TYPE_POINT The generator is a point.

PPL_GENERATOR_TYPE_CLOSURE_POINT The generator is a closure point.

8.3.5 Function Documentation**8.3.5.1 int ppl_banner (const char ** p)**

Writes to `m` a pointer to a character string containing the PPL banner.

The banner provides information about the PPL version, the licensing, the lack of any warranty whatsoever, the C++ compiler used to build the library, where to report bugs and where to look for further information.

8.3.5.2 int ppl_initialize (void)

Initializes the Parma Polyhedra Library. This function must be called before any other function.

Returns:

PPL_ERROR_INVALID_ARGUMENT if the library was already initialized.

8.3.5.3 int ppl_finalize (void)

Finalizes the Parma Polyhedra Library. This function must be called after any other function.

Returns:

PPL_ERROR_INVALID_ARGUMENT if the library was already finalized.

8.3.5.4 int ppl_set_error_handler (void(*)(enum ppl_enum_error_code code, const char *description) h)

Installs the user-defined error handler pointed at by *h*.

The error handler takes an error code and a textual description that gives further information about the actual error. The C string containing the textual description is read-only and its existence is not guaranteed after the handler has returned.

8.3.5.5 int ppl_new_C_Polyhedron_from_Constraint_System (ppl_Polyhedron_t * pph, ppl_Const_Constraint_System_t cs)

Builds a new closed polyhedron from the system of constraints *cs* and writes a handle for the newly created polyhedron at address *pph*.

The new polyhedron will inherit the space dimension of *cs*.

8.3.5.6 int ppl_new_C_Polyhedron_recycle_Constraint_System (ppl_Polyhedron_t * pph, ppl_Const_Constraint_System_t cs)

Builds a new closed polyhedron recycling the system of constraints *cs* and writes a handle for the newly created polyhedron at address *pph*.

Since *cs* will be *the* system of constraints of the new polyhedron, the space dimension is also inherited.

Warning:

This function modifies the constraint system referenced by *cs*: upon return, no assumption can be made on its value.

8.3.5.7 int ppl_new_NNC_Polyhedron_from_Constraint_System (ppl_Polyhedron_t * pph, ppl_Const_Constraint_System_t cs)

Builds a new NNC polyhedron from the system of constraints *cs* and writes a handle for the newly created polyhedron at address *pph*.

The new polyhedron will inherit the space dimension of *cs*.

8.3.5.8 `int ppl_new_NNC_Polyhedron_recycle_Constraint_System (ppl_Polyhedron_t * pph, ppl_Constraint_System_t cs)`

Builds a new NNC polyhedron recycling the system of constraints *cs* and writes a handle for the newly created polyhedron at address *pph*.

Since *cs* will be *the* system of constraints of the new polyhedron, the space dimension is also inherited.

Warning:

This function modifies the constraint system referenced by *cs*: upon return, no assumption can be made on its value.

8.3.5.9 `int ppl_new_C_Polyhedron_from_Generator_System (ppl_Polyhedron_t * pph, ppl_const_Generator_System_t gs)`

Builds a new closed polyhedron from the system of generators *gs* and writes a handle for the newly created polyhedron at address *pph*.

The new polyhedron will inherit the space dimension of *gs*.

8.3.5.10 `int ppl_new_C_Polyhedron_recycle_Generator_System (ppl_Polyhedron_t * pph, ppl_Generator_System_t gs)`

Builds a new closed polyhedron recycling the system of generators *gs* and writes a handle for the newly created polyhedron at address *pph*.

Since *gs* will be *the* system of generators of the new polyhedron, the space dimension is also inherited.

Warning:

This function modifies the generator system referenced by *gs*: upon return, no assumption can be made on its value.

8.3.5.11 `int ppl_new_NNC_Polyhedron_from_Generator_System (ppl_Polyhedron_t * pph, ppl_const_Generator_System_t gs)`

Builds a new NNC polyhedron from the system of generators *gs* and writes a handle for the newly created polyhedron at address *pph*.

The new polyhedron will inherit the space dimension of *gs*.

8.3.5.12 `int ppl_new_NNC_Polyhedron_recycle_Generator_System (ppl_Polyhedron_t * pph, ppl_Generator_System_t gs)`

Builds a new NNC polyhedron recycling the system of generators *gs* and writes a handle for the newly created polyhedron at address *pph*.

Since *gs* will be *the* system of generators of the new polyhedron, the space dimension is also inherited.

Warning:

This function modifies the generator system referenced by *gs*: upon return, no assumption can be made on its value.

8.3.5.13 `int ppl_new_C_Polyhedron_from_bounding_box (ppl_Polyhedron_t * pph, ppl_dimension_type(*) (void) space_dimension, int(*) (void) is_empty, int(*) (ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d) get_lower_bound, int(*) (ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d) get_upper_bound)`

Builds a new C polyhedron corresponding to an interval-based bounding box, writing a handle for the newly created polyhedron at address pph.

If an interval of the bounding box is provided with any finite but open bound, then the polyhedron is not built and the value `PPL_ERROR_INVALID_ARGUMENT` is returned. The bounding box is accessed by using the following functions, passed as arguments:

```
ppl_dimension_type space_dimension()
```

returns the dimension of the vector space enclosing the polyhedron represented by the bounding box.

```
int is_empty()
```

returns 0 if and only if the bounding box describes a non-empty set. The function `is_empty()` will always be called before the other functions. However, if `is_empty()` does not return 0, none of the functions below will be called.

```
int get_lower_bound(ppl_dimension_type k, int closed,
                    ppl_Coefficient_t n, ppl_Coefficient_t d)
```

Let I the interval corresponding to the k -th space dimension. If I is not bounded from below, simply return 0. Otherwise, set `closed`, `n` and `d` as follows: `closed` is set to 0 if the lower boundary of I is open and is set to a value different from zero otherwise; `n` and `d` are assigned the integers n and d such that the canonical fraction n/d corresponds to the greatest lower bound of I . The fraction n/d is in canonical form if and only if n and d have no common factors and d is positive, $0/1$ being the unique representation for zero.

```
int get_upper_bound(ppl_dimension_type k, int closed,
                    ppl_Coefficient_t n, ppl_Coefficient_t d)
```

Let I the interval corresponding to the k -th space dimension. If I is not bounded from above, simply return 0. Otherwise, set `closed`, `n` and `d` as follows: `closed` is set to 0 if the upper boundary of I is open and is set to a value different from 0 otherwise; `n` and `d` are assigned the integers n and d such that the canonical fraction n/d corresponds to the least upper bound of I .

8.3.5.14 `int ppl_new_NNC_Polyhedron_from_bounding_box (ppl_Polyhedron_t * pph, ppl_dimension_type(*) (void) space_dimension, int(*) (void) is_empty, int(*) (ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d) get_lower_bound, int(*) (ppl_dimension_type k, int closed, ppl_Coefficient_t n, ppl_Coefficient_t d) get_upper_bound)`

Builds a new C polyhedron corresponding to an interval-based bounding box, writing a handle for the newly created polyhedron at address pph.

The bounding box is accessed by using the following functions, passed as arguments:

```
ppl_dimension_type space_dimension()
```

returns the dimension of the vector space enclosing the polyhedron represented by the bounding box.

```
int is_empty()
```


returns 0 if and only if the bounding box describes a non-empty set. The function `is_empty()` will always be called before the other functions. However, if `is_empty()` does not return 0, none of the functions below will be called.

```
int get_lower_bound(ppl_dimension_type k, int closed,
                   ppl_Coefficient_t n, ppl_Coefficient_t d)
```

Let I the interval corresponding to the k -th space dimension. If I is not bounded from below, simply return 0. Otherwise, set `closed`, `n` and `d` as follows: `closed` is set to 0 if the lower boundary of I is open and is set to a value different from zero otherwise; `n` and `d` are assigned the integers n and d such that the canonical fraction n/d corresponds to the greatest lower bound of I . The fraction n/d is in canonical form if and only if n and d have no common factors and d is positive, 0/1 being the unique representation for zero.

```
int get_upper_bound(ppl_dimension_type k, int closed,
                   ppl_Coefficient_t n, ppl_Coefficient_t d)
```

Let I the interval corresponding to the k -th space dimension. If I is not bounded from above, simply return 0. Otherwise, set `closed`, `n` and `d` as follows: `closed` is set to 0 if the upper boundary of I is open and is set to a value different from 0 otherwise; `n` and `d` are assigned the integers n and d such that the canonical fraction n/d corresponds to the least upper bound of I .

8.3.5.15 `int ppl_Polyhedron_relation_with_Constraint (ppl_const_Polyhedron_t ph, ppl_const_Constraint_t c)`

Checks the relation between the polyhedron `ph` with the constraint `c`.

If successful, returns a non-negative integer that is obtained as the bitwise or of the bits (chosen among `PPL_POLY_CON_RELATION_IS_DISJOINT`, `PPL_POLY_CON_RELATION_STRICTLY_INTERSECTS`, `PPL_POLY_CON_RELATION_IS_INCLUDED`, and `PPL_POLY_CON_RELATION_SATURATES`) that describe the relation between `ph` and `c`.

8.3.5.16 `int ppl_Polyhedron_relation_with_Generator (ppl_const_Polyhedron_t ph, ppl_const_Generator_t g)`

Checks the relation between the polyhedron `ph` with the generator `g`.

If successful, returns a non-negative integer that is obtained as the bitwise or of the bits (only `PPL_POLY_GEN_RELATION_SUBSUMES`, at present) that describe the relation between `ph` and `g`.

8.3.5.17 `int ppl_Polyhedron_shrink_bounding_box (ppl_const_Polyhedron_t ph, unsigned int complexity, void(*) (void) set_empty, void(*) (ppl_dimension_type k, int closed, ppl_const_Coefficient_t n, ppl_const_Coefficient_t d) raise_lower_bound, void(*) (ppl_dimension_type k, int closed, ppl_const_Coefficient_t n, ppl_const_Coefficient_t d) lower_upper_bound)`

Use `ph` to shrink a generic, interval-based bounding box. The bounding box is abstractly provided by means of the parameters.

Parameters:

ph The polyhedron that is used to shrink the bounding box;

complexity The code of the complexity class of the algorithm to be used. Must be one of `PPL_COMPLEXITY_CLASS_POLYNOMIAL`, `PPL_COMPLEXITY_CLASS_SIMPLEX`, or `PPL_COMPLEXITY_CLASS_ANY`;

set_empty A pointer to a void function with no arguments that causes the bounding box to become empty, i.e., to represent the empty set;

raise_lower_bound A pointer to a void function with arguments (`ppl_dimension_type k`, `int closed`, `ppl_const_Coefficient_t n`, `ppl_const_Coefficient_t d`) that intersects the interval corresponding to the k -th space dimension with $[n/d, +\infty)$ if `closed` is non-zero, with $(n/d, +\infty)$ if `closed` is zero. The fraction n/d is in canonical form, that is, n and d have no common factors and d is positive, $0/1$ being the unique representation for zero;

lower_upper_bound a pointer to a void function with argument (`ppl_dimension_type k`, `int closed`, `ppl_const_Coefficient_t n`, `ppl_const_Coefficient_t d`) that intersects the interval corresponding to the k -th space dimension with $(-\infty, n/d]$ if `closed` is non-zero, with $(-\infty, n/d)$ if `closed` is zero. The fraction n/d is in canonical form.

8.3.5.18 `int ppl_Polyhedron_maximize (ppl_const_Polyhedron_t ph, ppl_const_Linear_Expression_t le, ppl_Coefficient_t sup_n, ppl_Coefficient_t sup_d, int * pmaximum, ppl_const_Generator_t * ppoint)`

Returns a positive integer if `ph` is not empty and `le` is bounded from above in `ph`, in which case the supremum value and a point where `le` reaches it are computed.

Parameters:

ph The polyhedron constraining `le`;

le The linear expression to be maximized subject to `ph`;

sup_n Will be assigned the numerator of the supremum value;

sup_d Will be assigned the denominator of the supremum value;

pmaximum Will store 1 in this location if the supremum is also the maximum, will store 0 otherwise;

ppoint When nonzero, a point or closure point where `le` reaches the extremum value will be stored here. If `ph` is empty or `le` is not bounded from above, 0 is returned and `sup_n`, `sup_d`, `*pmaximum` and `*ppoint` are left untouched.

8.3.5.19 `int ppl_Polyhedron_minimize (ppl_const_Polyhedron_t ph, ppl_const_Linear_Expression_t le, ppl_Coefficient_t inf_n, ppl_Coefficient_t inf_d, int * pminimum, ppl_const_Generator_t * ppoint)`

Returns a positive integer if `ph` is not empty and `le` is bounded from above in `ph`, in which case the infimum value and a point where `le` reaches it are computed.

Parameters:

ph The polyhedron constraining `le`;

le The linear expression to be minimized subject to `ph`;

inf_n Will be assigned the numerator of the infimum value;

inf_d Will be assigned the denominator of the infimum value;

pminimum Will store 1 in this location if the infimum is also the minimum, will store 0 otherwise;

ppoint When nonzero, a point or closure point where `le` reaches the extremum value will be stored here. If `ph` is empty or `le` is not bounded from below, 0 is returned and `inf_n`, `inf_d`, `*pminimum` and `*ppoint` are left untouched.

8.3.5.20 `int ppl_Polyhedron_equals_Polyhedron (ppl_const_Polyhedron_t x, ppl_const_Polyhedron_t y)`

Returns a positive integer if x and y are the same polyhedron; return 0 if they are different.

Note that x and y may be topology- and/or dimension-incompatible polyhedra: in those cases, the value 0 is returned.

8.3.5.21 `int ppl_Polyhedron_add_recycled_constraints (ppl_Polyhedron_t ph, ppl_Constraint_System_t cs)`

Adds the system of constraints cs to the system of constraints of ph .

Warning:

This function modifies the constraint system referenced by cs : upon return, no assumption can be made on its value.

8.3.5.22 `int ppl_Polyhedron_add_recycled_constraints_and_minimize (ppl_Polyhedron_t ph, ppl_Constraint_System_t cs)`

Adds the system of constraints cs to the system of constraints of ph . Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.

Warning:

This function modifies the constraint system referenced by cs : upon return, no assumption can be made on its value.

8.3.5.23 `int ppl_Polyhedron_add_recycled_generators (ppl_Polyhedron_t ph, ppl_Generator_System_t gs)`

Adds the system of generators gs to the system of generators of ph .

Warning:

This function modifies the generator system referenced by gs : upon return, no assumption can be made on its value.

8.3.5.24 `int ppl_Polyhedron_add_recycled_generators_and_minimize (ppl_Polyhedron_t ph, ppl_Generator_System_t gs)`

Adds the system of generators gs to the system of generators of ph . Returns a positive integer if the resulting polyhedron is non-empty; returns 0 if it is empty. Upon successful return, ph is guaranteed to be minimized.

Warning:

This function modifies the generator system referenced by gs : upon return, no assumption can be made on its value.

8.3.5.25 `int ppl_Polyhedron_affine_image (ppl_Polyhedron_t ph, ppl_dimension_type var, ppl_const_Linear_Expression_t le, ppl_const_Coefficient_t d)`

Transforms the polyhedron *ph*, assigning an affine expression to the specified variable.

Parameters:

- ph* The polyhedron that is transformed;
- var* The variable to which the affine expression is assigned;
- le* The numerator of the affine expression;
- d* The denominator of the affine expression.

8.3.5.26 `int ppl_Polyhedron_affine_preimage (ppl_Polyhedron_t ph, ppl_dimension_type var, ppl_const_Linear_Expression_t le, ppl_const_Coefficient_t d)`

Transforms the polyhedron *ph*, substituting an affine expression to the specified variable.

Parameters:

- ph* The polyhedron that is transformed;
- var* The variable to which the affine expression is substituted;
- le* The numerator of the affine expression;
- d* The denominator of the affine expression.

8.3.5.27 `int ppl_Polyhedron_generalized_affine_image (ppl_Polyhedron_t ph, ppl_dimension_type var, enum ppl_enum_Constraint_Type relsym, ppl_const_Linear_Expression_t le, ppl_const_Coefficient_t d)`

Assigns to *ph* the image of *ph* with respect to the **generalized affine transfer function**(p. 10) $\text{var}' \bowtie \frac{\text{expr}}{\text{denominator}}$, where \bowtie is the relation symbol encoded by *relsym*.

Parameters:

- ph* The polyhedron that is transformed;
- var* The left hand side variable of the generalized affine transfer function;
- relsym* The relation symbol;
- le* The numerator of the right hand side affine expression;
- d* The denominator of the right hand side affine expression.

8.3.5.28 `int ppl_Polyhedron_generalized_affine_image_lhs_rhs (ppl_Polyhedron_t ph, ppl_const_Linear_Expression_t lhs, enum ppl_enum_Constraint_Type relsym, ppl_const_Linear_Expression_t rhs)`

Assigns to *ph* the image of *ph* with respect to the **generalized affine transfer function**(p. 10) $\text{lhs}' \bowtie \text{rhs}$, where \bowtie is the relation symbol encoded by *relsym*.

Parameters:

- ph* The polyhedron that is transformed;
- lhs* The left hand side affine expression;
- relsym* The relation symbol;
- rhs* The right hand side affine expression.

8.3.5.29 `int ppl_Polyhedron_map_space_dimensions (ppl_Polyhedron_t ph, ppl_dimension_type maps[], size_t n)`

Remaps the dimensions of the vector space according to a **partial function**(p. 8). This function is specified by means of the `maps` array, which has `n` entries.

The partial function is defined on dimension `i` if `i < n` and `maps[i] != ppl_not_a_dimension`; otherwise it is undefined on dimension `i`. If the function is defined on dimension `i`, then dimension `i` is mapped onto dimension `maps[i]`.

The result is undefined if `maps` does not encode a partial function with the properties described in the **specification of the mapping operator**(p. 8).

8.4 Prolog Language Interface

The Parma Polyhedra Library comes equipped with a Prolog interface. Despite the lack of standardization of Prolog's foreign language interfaces, the PPL Prolog interface supports several Prolog systems and, to the extent this is possible, provides a uniform view of the library from each such systems.

The system-independent features of the library are described in Section **System-Independent Features**(p. 52). Section **Compilation and Installation**(p. 68) explains how the various incarnations of the Prolog interface are compiled and installed. Section **System-Dependent Features**(p. 68) illustrates the system-dependent features of the interface for all the supported systems.

System-Independent Features

The Prolog interface provides access to the PPL polyhedra. A general introduction to convex polyhedra, their representation in the PPL and the operations provided by the PPL is given in Sections **The Main Features**(p. 2), **Convex Polyhedra**(p. 2), **Representations of Convex Polyhedra**(p. 4) and **Operations on Convex Polyhedra**(p. 7) of this manual. Here we just describe those aspects that are specific to the Prolog interface.

Overview First, here is a list of notes with general information and advice on the use of the interface.

- The Prolog interface to the PPL is initialized and finalized by the predicates `ppl_initialize/0` and `ppl_finalize/0`. Thus the only interface predicates callable after `ppl_finalize/0` are `ppl_finalize/0` itself (this further call has no effect) and `ppl_initialize/0`, after which the interface's services are usable again. Some Prolog systems allow the specification of initialization and deinitialization functions in their foreign language interfaces. The corresponding incarnations of the PPL-Prolog interface have been written so that `ppl_initialize/0` and/or `ppl_finalize/0` are called automatically. Section **System-Dependent Features**(p. 68) will detail in which cases initialization and finalization is automatically performed or is left to the Prolog programmer's responsibility. However, for portable applications, it is best to invoke `ppl_initialize/0` and `ppl_finalize/0` explicitly: since they can be called multiple times without problems, this will result in enhanced portability at a cost that is, by all means, negligible.
- A PPL polyhedron can only be accessed by means of a Prolog term called a *handle*. Note, however, that the data structure of a handle, is implementation-dependent, system-dependent and version-dependent, and, for this reason, deliberately left unspecified. What we do guarantee is that the handle requires very little memory.
- A Prolog term can be bound to a valid handle by using:

```
ppl_new_Polyhedron_from_space_dimension/4,
ppl_new_Polyhedron_from_Polyhedron/4,
ppl_new_Polyhedron_from_constraints/3,
ppl_new_Polyhedron_from_generators/3.
ppl_new_Polyhedron_from_bounding_box/3.
```

These predicates will create or copy a PPL polyhedron and construct a valid handle for referencing it. The first argument (in the case of `ppl_new_Polyhedron_from_Polyhedron/4`, the first and third arguments) denotes the topology and can be either `c` or `nnc` indicating a C or NNC polyhedron, respectively. The third argument (in the case of `ppl_new_Polyhedron_from_Polyhedron/4` and `ppl_new_Polyhedron_from_Dimension/4`, the fourth argument) is a Prolog term that is unified with a new valid handle for accessing this polyhedron.

- As soon as a PPL polyhedron is no longer required, the memory occupied by it should be released using the PPL predicate `ppl_delete_Polyhedron/1`. To understand why this is important, consider a Prolog program and a variable that is bound to a Herbrand term. When the variable dies (goes out of scope) or is uninstantiated (on backtracking) the term it is bound to is amenable to garbage collection. But this only applies for the standard domain of the language: Herbrand terms. In Prolog+PPL, when a variable bound to a handle for a PPL Polyhedron dies or is uninstantiated, the handle can be garbage-collected, but the polyhedra to which the handle refers will not be released. Once a handle has been used as an argument in `ppl_delete_Polyhedron/1`, it becomes invalid.
- For a PPL polyhedron with space dimension k , the identifiers used for the PPL variables must lie between 0 and $k - 1$ and correspond to the indices of the associated Cartesian axes. When using the predicates that combine PPL polyhedra or add constraints or generators to a representation of a PPL polyhedron, the polyhedra referenced and any constraints or generators in the call should follow all the (space) dimension-compatibility rules stated in Section **Representations of Convex Polyhedra**(p. 4).
- As explained above, a polyhedron has a fixed topology C or NNC, that is determined at the time of its initialization. All subsequent operations on the polyhedron must respect all the topological compatibility rules stated in Section **Representations of Convex Polyhedra**(p. 4).
- Any application using the PPL should make sure that only the intended version(s) of the library are ever used. Predicates

```
ppl_version_major/1,
ppl_version_minor/1,
ppl_version_revision/1,
ppl_version_beta/1,
ppl_version/1,
ppl_banner.
```

allow run-time checking of information about the version being used.

PPL Predicate List Here is a list of all the PPL predicates provided by the Prolog interface.

```
ppl_version_major(?C_int)
ppl_version_minor(?C_int)
ppl_version_revision(?C_int)
ppl_version_beta(?C_int)
ppl_version(?Atom)
```

```
ppl_banner(?Atom)
ppl_max_space_dimension(?Dimension_Type)
ppl_initialize
ppl_finalize
ppl_set_timeout_exception_atom(+Atom)
ppl_set_timeout(+C_unsigned)
ppl_reset_timeout
ppl_new_Polyhedron_from_space_dimension(+Topology, +Dimension_Type,
+Universe_or_Empty, -Handle)
ppl_new_Polyhedron_from_Polyhedron(+Topology_1, +Handle_1, +Topology_-
2, -Handle_2)
ppl_new_Polyhedron_from_constraints(+Topology, +Constraint_System,
-Handle)
ppl_new_Polyhedron_from_generators(+Topology, +Generator_System,
-Handle)
ppl_new_Polyhedron_from_bounding_box(+Topology, +Box, -Handle)
ppl_Polyhedron_swap(+Handle1, +Handle2)
ppl_delete_Polyhedron(+Handle)
ppl_Polyhedron_space_dimension(+Handle, ?Dimension_Type)
ppl_Polyhedron_affine_dimension(+Handle, ?Dimension_Type)
ppl_Polyhedron_get_constraints(+Handle, -Constraint_System)
ppl_Polyhedron_get_minimized_constraints(+Handle, -Constraint_System)
ppl_Polyhedron_get_generators(+Handle, -Generator_System)
ppl_Polyhedron_get_minimized_generators(+Handle, -Generator_System)
ppl_Polyhedron_relation_with_constraint(+Handle, +Constraint,
-Relation)
ppl_Polyhedron_relation_with_generator(+Handle, +Generator,
-Relation)
ppl_Polyhedron_get_bounding_box(+Handle, +Complexity, -Box)
ppl_Polyhedron_is_empty(+Handle)
ppl_Polyhedron_is_universe(+Handle)
ppl_Polyhedron_is_bounded(+Handle)
ppl_Polyhedron_bounds_from_above(+Handle, +Lin_Expr)
ppl_Polyhedron_bounds_from_below(+Handle, +Lin_Expr)
ppl_Polyhedron_maximize(+Handle, +Lin_Expr, ?Coefficient_1,
?Coefficient_2, ?Boolean)
ppl_Polyhedron_maximize_with_point(+Handle, +Lin_Expr, ?Coefficient_1,
?Coefficient_2, ?Boolean, ?Point)
```

```

ppl_Polyhedron_minimize(+Handle, +Lin_Expr, ?Coefficient_1,
?Coefficient_2, ?Boolean)

ppl_Polyhedron_minimize_with_point(+Handle, +Lin_Expr, ?Coefficient_1,
?Coefficient_2, ?Boolean, ?Point)

ppl_Polyhedron_is_topologically_closed(+Handle)

ppl_Polyhedron_contains_Polyhedron(+Handle_1, +Handle_2)

ppl_Polyhedron_strictly_contains_Polyhedron(+Handle_1, +Handle_2)

ppl_Polyhedron_is_disjoint_from_Polyhedron(+Handle_1, +Handle_2)

ppl_Polyhedron_equals_Polyhedron(+Handle_1, +Handle_2)

ppl_Polyhedron_OK(+Handle)

ppl_Polyhedron_add_constraint(+Handle, +Constraint)

ppl_Polyhedron_add_constraint_and_minimize(+Handle, +Constraint)

ppl_Polyhedron_add_generator(+Handle, +Generator)

ppl_Polyhedron_add_generator_and_minimize(+Handle, +Generator)

ppl_Polyhedron_add_constraints(+Handle, +Constraint_System)

ppl_Polyhedron_add_constraints_and_minimize(+Handle, +Constraint_-
System)

ppl_Polyhedron_add_generators(+Handle, +Generator_System)

ppl_Polyhedron_add_generators_and_minimize(+Handle, +Generator_-
System)

ppl_Polyhedron_intersection_assign(+Handle_1, +Handle_2)

ppl_Polyhedron_intersection_assign_and_minimize(+Handle_1, +Handle_2)

ppl_Polyhedron_poly_hull_assign(+Handle_1, +Handle_2)

ppl_Polyhedron_poly_hull_assign_and_minimize(+Handle_1, +Handle_2)

ppl_Polyhedron_poly_difference_assign(+Handle_1, +Handle_2)

ppl_Polyhedron_affine_image(+Handle, +PPL_Var, +Lin_Expr,
+Coefficient)

ppl_Polyhedron_affine_preimage(+Handle, +PPL_Var, +Lin_Expr,
+Coefficient)

ppl_Polyhedron_generalized_affine_image(+Handle, +PPL_Var, +Relation_-
Symbol, +Lin_Expr, +Coefficient)

ppl_Polyhedron_generalized_affine_image_lhs_rhs(+Handle, +Lin_Expr1,
+Relation_Symbol, +Lin_Expr2)

ppl_Polyhedron_time_elapse_assign(+Handle_1, +Handle_2)

ppl_Polyhedron_BHRZ03_widening_assign_with_token(+Handle_1, +Handle_2,
?C_unsigned)

ppl_Polyhedron_BHRZ03_widening_assign(+Handle_1, +Handle_2)

ppl_Polyhedron_limited_BHRZ03_extrapolation_assign_with_-
token(+Handle_1, +Handle_2, +Constraint_System, ?C_unsigned)

```



```

ppl_Polyhedron_limited_BHRZ03_extrapolation_assign(+Handle_1,
+Handle_2, +Constraint_System)

ppl_Polyhedron_bounded_BHRZ03_extrapolation_assign_with_-
token(+Handle_1, +Handle_2, +Constraint_System, ?C_unsigned)

ppl_Polyhedron_bounded_BHRZ03_extrapolation_assign(+Handle_1,
+Handle_2, +Constraint_System)

ppl_Polyhedron_H79_widening_assign_with_token(+Handle_1, +Handle_2,
?C_unsigned)

ppl_Polyhedron_H79_widening_assign(+Handle_1, +Handle_2)

ppl_Polyhedron_limited_H79_extrapolation_assign_with_token(+Handle_1,
+Handle_2, +Constraint_System, ?C_unsigned)

ppl_Polyhedron_limited_H79_extrapolation_assign(+Handle_1, +Handle_2,
+Constraint_System)

ppl_Polyhedron_bounded_H79_extrapolation_assign_with_token(+Handle_1,
+Handle_2, +Constraint_System, ?C_unsigned)

ppl_Polyhedron_bounded_H79_extrapolation_assign(+Handle_1, +Handle_2,
+Constraint_System)

ppl_Polyhedron_topological_closure_assign(+Handle)

ppl_Polyhedron_add_space_dimensions_and_embed(+Handle, +Dimension_-
Type)

ppl_Polyhedron_add_space_dimensions_and_project(+Handle, +Dimension_-
Type)

ppl_Polyhedron_concatenate_assign(+Handle1, +Handle2)

ppl_Polyhedron_remove_space_dimensions(+Handle, +List_of_PPL_Vars)

ppl_Polyhedron_remove_higher_space_dimensions(+Handle, +Dimension_-
Type))

ppl_Polyhedron_expand_space_dimension(+Handle, +PPL_Var, +Dimension_-
Type))

ppl_Polyhedron_fold_space_dimensions(+Handle, +List_of_PPL_Vars,
+PPL_Var))

ppl_Polyhedron_map_space_dimensions(+Handle, +P_Func))

```

PPL Predicate Specifications The PPL predicates provided by the Prolog interface are specified below. The specification uses the following grammar rules:

Number	--> unsigned integer	ranging from 0 to an upper bound depending on the actual Prolog system.
C_int	--> Number - Number	C integer
C_unsigned	--> Number	C unsigned integer
Coefficient	--> Number	used in linear expressions; the upper bound will depend on how the PPL has been configured
Dimension_Type		

	--> Number	used for the number of affine and space dimensions and the names of the dimensions; the upper bound will depend on the maximum number of dimensions allowed by the PPL (see <code>ppl_max_space_dimensions/1</code>)
Boolean	--> true false	
Handle	--> Prolog term	used to identify a Polyhedron
Topology	--> c nnc	Polyhedral kind; c is closed and nnc is NNC
VarId	--> Dimension_Type	variable identifier
PPL_Var	--> '\$VAR'(VarId)	PPL variable
Lin_Expr	--> PPL_Var Coefficient Lin_Expr - Lin_Expr Lin_Expr + Lin_Expr Lin_Expr - Lin_Expr Coefficient * Lin_Expr Lin_Expr * Coefficient	PPL variable unary plus unary minus addition subtraction multiplication multiplication
Relation_Symbol	--> = <= >= < >	equals less than or equal greater than or equal strictly less than strictly greater than
Constraint	--> Lin_Expr Relation_Symbol Lin_Expr	constraint
Constraint_System	--> [] [Constraint Constraint_System]	list of constraints
Generator_Denominator	--> Coefficient Coefficient - Coefficient	must be non-zero
Generator	--> point(Lin_Expr) point(Lin_Expr, Generator_Denominator) closure_point(Lin_Expr) closure_point(Lin_Expr, Generator_Denominator) ray(Lin_Expr) line(Lin_Expr)	point point point closure point closure point closure point ray line
Generator_System	--> [] [Generator Generator_System]	list of generators
Atom	--> Prolog atom	
Universe_or_Empty	--> universe empty	polyhedron
Poly_Relation	--> is_disjoint	polyhedron relation: with a constraint

```

| strictly_intersects      with a constraint
| is_included              with a constraint
| saturates                with a constraint
| subsumes                 with a generator

Poly_Relation_List          list of polyhedron relations
--> []
| [Poly_Relation | Poly_Relation_List]

Complexity --> polynomial | simplex | any

Rational_Numerator
--> Coefficient | - Coefficient

Rational_Denominator
--> Coefficient          must be non-zero

Rational --> Rational_Numerator    rational number
| Rational_Numerator/Rational_Denominator

Bound --> c(Rational)      closed rational limit
| o(Rational)             open rational limit
| o(pinf)                 unbounded in the positive direction
| o(minf)                 unbounded in the negative direction

Interval --> i(Bound, Bound)    rational interval

Box --> []                 list of intervals
| [Interval | Box]

Vars_Pair --> PPLVar - PPLVar    map relation

P_Func --> []              list of map relations
| [Vars_Pair | P_Func].

```

Below is a short description of each of the interface predicates. For full definitions of terminology used here, see Sections **The Main Features**(p. 2), **Convex Polyhedra**(p. 2), **Representations of Convex Polyhedra**(p. 4) and **Operations on Convex Polyhedra**(p. 7) of this manual.

`ppl_version_major(?C_int)` Unifies `C_int` with the major number of the PPL version.

`ppl_version_minor(?C_int)` Unifies `C_int` with the minor number of the PPL version.

`ppl_version_revision(?C_int)` Unifies `C_int` with the revision number of the PPL version.

`ppl_version_beta(?C_int)` Unifies `C_int` with the beta number of the PPL version.

`ppl_version(?Atom)` Unifies `Atom` with the PPL version.

`ppl_banner(?Atom)` Unifies `Atom` with information about the PPL version, the licensing, the lack of any warranty whatsoever, the C++ compiler used to build the library, where to report bugs and where to look for further information.

`ppl_max_space_dimension(?Dimension_Type)` Unifies `Dimension_Type` with the maximum space dimension this library can handle.

`ppl_initialize` Initializes the PPL interface. Multiple calls to `ppl_initialize` does no harm.

`ppl_finalize` Finalizes the PPL interface. Once this is executed, the next call to an interface predicate must either be to `ppl_initialize` or to `ppl_finalize`. Multiple calls to `ppl_finalize` does no harm.

`ppl_set_timeout_exception_atom(+Atom)` Sets the atom to be thrown by timeout exceptions to `Atom`. The default value is `time_out`.

`ppl_timeout_exception_atom(?Atom)` The atom to be thrown by timeout exceptions is unified with `Atom`.

`ppl_set_timeout(+C_unsigned)` Computations taking exponential time will be interrupted some time after `C_unsigned` ms after that call. If the computation is interrupted that way, the current timeout exception atom will be thrown. `C_unsigned` must be strictly greater than zero.

`ppl_reset_timeout` Resets the timeout time so that the computation is not interrupted.

`ppl_new_Polyhedron_from_space_dimension(+Topology, +Dimension_Type, +Universe_or_Empty, -Handle)` Creates a C or NNC polyhedron \mathcal{P} , depending on the value of `Topology`, with `Dimension_Type` dimensions; it is empty or the universe polyhedron depending on whether `Atom` is empty or universe, respectively. `Handle` is unified with the handle for \mathcal{P} . Thus the query

```
?- ppl_new_Polyhedron_from_space_dimension(nnc, 3, empty, X).
```

creates an empty NNC polyhedron embedded in \mathbb{R}^3 with `X` bound to a valid handle for accessing it.

Also the query

```
?- ppl_new_Polyhedron_from_space_dimension(c, 3, universe, X).
```

creates the C polyhedron defining the 3-dimensional vector space \mathbb{R}^3 with `X` bound to a valid handle for accessing it.

`ppl_new_Polyhedron_from_Polyhedron(+Topology_1, +Handle_1, +Topology_2, -Handle_2)` If `Handle_1` refers to a C or NNC polyhedron \mathcal{P}_1 (depending on the value of `Topology_1`), then this creates a copy \mathcal{P}_2 of \mathcal{P}_1 with topology C or NNC, depending on the value of `Topology_2`. `Handle_2` is unified with the handle for \mathcal{P}_2 . Thus the query

```
?- ppl_new_Polyhedron_from_space_dimension(nnc, 3, empty, X),
   ppl_new_Polyhedron_from_Polyhedron(c, X, nnc, Y).
```

creates an empty C polyhedron embedded in \mathbb{R}^3 referenced by `X` and then makes a copy, converting the topology to an NNC polyhedron. with `Y` bound to a valid handle for accessing it.

When using `ppl_new_Polyhedron_from_Polyhedron/2`, when the source polyhedron is NNC and the copy is C, care must be taken that the source polyhedron referenced by `Handle1` is topologically closed.

`ppl_new_Polyhedron_from_constraints(+Topology, +Constraint_System, -Handle)` Creates a polyhedron \mathcal{P} represented by `Constraint_System` with topology `C` or `NNC`, depending on the value of `Topology`. `Handle` is unified with the handle for \mathcal{P} .

`ppl_new_Polyhedron_from_generators(+Topology, +Generator_System, -Handle)` Creates a polyhedron \mathcal{P} represented by `Generator_System` with topology `C` or `NNC`, depending on the value of `Topology`. `Handle` is unified with the handle for \mathcal{P} .

`ppl_new_Polyhedron_from_bounding_box(+Topology, +Box, -Handle)` Creates a polyhedron \mathcal{P} represented by `Box` with topology `C` or `NNC`, depending on the value of `Topology`, and `Handle` is unified with the handle for \mathcal{P} . A bound of the form `o(Rational)` can be included in an interval in `Box` only if `Topology` is `nnc`.

`ppl_Polyhedron_swap(+Handle1, +Handle2)` Swaps the polyhedron referenced by `Handle1` with the one referenced by `Handle2`. The polyhedra \mathcal{P} and \mathcal{Q} must have the same topology.

`ppl_delete_Polyhedron(+Handle)` Deletes the polyhedron referenced by `Handle`. After execution, `Handle` is no longer a valid handle for a PPL polyhedron.

`ppl_Polyhedron_space_dimension(+Handle, ?Dimension_Type)` Unifies the dimension of the vector space in which the polyhedron referenced by `Handle` is embedded with `Dimension_Type`.

`ppl_Polyhedron_affine_dimension(+Handle, ?Dimension_Type)` Unifies the actual dimension of the polyhedron referenced by `Handle` with `Dimension_Type`.

`ppl_Polyhedron_get_constraints(+Handle, ?Constraint_System)` Unifies `Constraint_System` with a list of the constraints in the constraints system representing the polyhedron referenced by `Handle`.

`ppl_Polyhedron_get_minimized_constraints(+Handle, ?Constraint_System)` Unifies `Constraint_System` with a minimized list of the constraints in the constraints system representing the polyhedron referenced by `Handle`.

`ppl_Polyhedron_get_generators(+Handle, ?Generator_System)` Unifies `Generator_System` with a list of the generators in the generators system representing the polyhedron referenced by `Handle`.

`ppl_Polyhedron_get_minimized_generators(+Handle, ?Generator_System)` Unifies `Generator_System` with a minimized list of the generators in the generators system representing the polyhedron referenced by `Handle`.

`ppl_Polyhedron_relation_with_constraint(+Handle, +Constraint, ?Poly_Relation_List)` Unifies `Poly_Relation_List` with the list of relations the polyhedron referenced by `Handle` has with `Constraint`. The possible relations are listed in the grammar rules above; their meaning is given in the paragraph **specifying the relation_with operations**(p. 10) in Section **Operations on Convex Polyhedra**(p. 7).

`ppl_Polyhedron_relation_with_generator(+Handle, +Generator, ?Poly_Relation_List)` Unifies `Poly_Relation_List` with the list of relations the polyhedron referenced by `Handle` has with `Generator`. The possible relations are listed in the grammar rules above; their meaning is given in the paragraph **specifying the relation_with operations**(p. 10) in Section **Operations on Convex Polyhedra**(p. 7).

`ppl_Polyhedron_get_bounding_box(+Handle, +Complexity, ?Box)` Succeeds if and only if the bounding box of the polyhedron referenced by `Handle` unifies with the box defined by `Box`. E.g.,

```
?- A = '$VAR'(0), B = '$VAR'(1),
    ppl_new_Polyhedron_from_constraints(nnc, [B > 0, 4*A =< 2], X),
    ppl_Polyhedron_get_bounding_box(X, any, Box).

Box = [i(o(minf), c(1/2)), i(o(0), o(pinf))].
```

Note that the rational numbers in `Box` are in canonical form. E.g., the following will fail:

```
?- A = '$VAR'(0), B = '$VAR'(1),
    ppl_new_Polyhedron_from_constraints(nnc, [B > 0, 4*A =< 2], X),
    ppl_Polyhedron_get_bounding_box(X, any, Box),
    Box = [i(o(minf), c(2/4)), i(o(0), o(pinf))].
```

The complexity class `Complexity` determining the algorithm to be used has the following meaning:

- `polynomial` allows code of the worst-case polynomial complexity class;
- `simplex` allows code of the worst-case exponential but typically polynomial complexity class;
- `any` allows code of the universal complexity class.

`ppl_Polyhedron_is_empty(+Handle)` Succeeds if and only if the polyhedron referenced by `Handle` is empty.

`ppl_Polyhedron_is_universe(+Handle)` Succeeds if and only if the polyhedron referenced by `Handle` is the universe.

`ppl_Polyhedron_is_bounded(+Handle)` Succeeds if and only if the polyhedron referenced by `Handle` is bounded.

`ppl_Polyhedron_bounds_from_above(+Handle, +Lin_Expr)` Succeeds if and only if `Lin_Expr` is bounded from above in the polyhedron referenced by `Handle`.

`ppl_Polyhedron_bounds_from_below(+Handle, +Lin_Expr)` Succeeds if and only if `Lin_Expr` is bounded from below in the polyhedron referenced by `Handle`.

`ppl_Polyhedron_maximize(+Handle, +Lin_Expr, ?Coefficient1, ?Coefficient2, ?Boolean)` Succeeds if and only if the polyhedron P referenced by `Handle` is not empty and `Lin_Expr` is bounded from above in P .

`Coefficient1` is unified with the numerator of the supremum value and `Coefficient2` with the denominator of the supremum value. If the supremum is also the maximum, `Boolean` is unified with the atom `true` and, otherwise, unified with the atom `false`.

`ppl_Polyhedron_maximize_with_point(+Handle, +Lin_Expr, ?Coefficient1, ?Coefficient2, ?Boolean, ?Point)` Succeeds if and only if the polyhedron P referenced by `Handle` is not empty and `Lin_Expr` is bounded from above in P .

`Coefficient1` is unified with the numerator of the supremum value, `Coefficient2` with the denominator of the supremum value, and `Point` with a point or closure point where `Lin_Expr` reaches this value. If the supremum is also the maximum, `Boolean` is unified with the atom `true` and, otherwise, unified with the atom `false`.

`ppl_Polyhedron_minimize(+Handle, +Lin_Expr, ?Coefficient1, ?Coefficient2, ?Boolean)` Succeeds if and only if the polyhedron P referenced by `Handle` is not empty and `Lin_Expr` is bounded from below in P .

`Coefficient1` is unified with the numerator of the infimum value and `Coefficient2` with the denominator of the infimum value. If the infimum is also the minimum, `Boolean` is unified with the atom `true` and, otherwise, unified with the atom `false`.

`ppl_Polyhedron_minimize_with_point(+Handle, +Lin_Expr, ?Coefficient1, ?Coefficient2, ?Boolean, ?Point)` Succeeds if and only if the polyhedron P referenced by `Handle` is not empty and `Lin_Expr` is bounded from below in P .

`Coefficient1` is unified with the numerator of the infimum value, `Coefficient2` with the denominator of the infimum value, and `Point` with a point or closure point where `Lin_Expr` reaches this value. If the infimum is also the minimum, `Boolean` is unified with the atom `true` and, otherwise, unified with the atom `false`.

`ppl_Polyhedron_is_topologically_closed(+Handle)` Succeeds if and only if the polyhedron referenced by `Handle` is topologically closed.

`ppl_Polyhedron_contains_Polyhedron(+Handle_1, +Handle_2)` Succeeds if and only if the polyhedron referenced by `Handle_1` is included in or equal to the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_strictly_contains_Polyhedron(+Handle_1, +Handle_2)` Succeeds if and only if the polyhedron referenced by `Handle_1` is included in but not equal to the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_is_disjoint_from_Polyhedron(+Handle_1, +Handle_2)` Succeeds if and only if the polyhedron referenced by `Handle_1` is disjoint from the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_equals_Polyhedron(+Handle_1, +Handle_2)` Succeeds if and only if the polyhedron referenced by `Handle_1` is equal to the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_OK(+Handle)` Succeeds only if the polyhedron referenced by `Handle` is well formed, i.e., if it satisfies all its implementation invariants. Useful for debugging purposes.

`ppl_Polyhedron_add_constraint(+Handle, +Constraint)`

`ppl_Polyhedron_add_constraint_and_minimize(+Handle, +Constraint)` Updates the polyhedron referenced by `Handle` to one obtained by adding `Constraint` to its constraint system. Thus, the query

```
?- ppl_new_Polyhedron_from_space_dimension(c, 3, universe, X),
   A = '$VAR'(0), B = '$VAR'(1), C = '$VAR'(2),
   ppl_Polyhedron_add_constraint(X, 4*A + B - 2*C >= 5).
```

will update the polyhedron with handle `X` to consist of the set of points in the vector space \mathbb{R}^3 satisfying the constraint $4x + y - 2z \geq 5$.

Note that `ppl_Polyhedron_add_constraint_and_minimize/2` will fail if, after adding the constraint, the polyhedron is empty.

`ppl_Polyhedron_add_generator(+Handle, +Generator)`

`ppl_Polyhedron_add_generator_and_minimize(+Handle, +Generator)` Updates the polyhedron referenced by `Handle` to one obtained by adding `Generator` to its generator system. Thus, after the query

```
?- ppl_new_Polyhedron_from_space_dimension(c, 3, universe, X),
   A = '$VAR'(0), B = '$VAR'(1), C = '$VAR'(2),
   ppl_Polyhedron_add_generator(X, point(-100*A - 5*B, 8)).
```

will update the polyhedron with handle `X` to be the single point $(-12.5, -0.625, 0)^T$ in the vector space \mathbb{R}^3 .

`ppl_Polyhedron_add_constraints(+Handle, +Constraint_System)` Updates the polyhedron referenced by `Handle` to one obtained by adding to its constraint system the constraints in `Constraint_System`. E.g.,

```
| ?- ppl_new_Polyhedron_from_space_dimension(c, 2, universe, X),
   A = '$VAR'(0), B = '$VAR'(1),
   ppl_Polyhedron_add_constraints(X, [4*A + B >= 3, A = 1]),
   ppl_Polyhedron_get_constraints(X, CS).

CS = [4*A+1*B>=3,1*A=1] ?
```

The updated polyhedron referenced by `Handle` can be empty and a query will succeed even when `Constraint_System` is unsatisfiable.

`ppl_Polyhedron_add_constraints_and_minimize(+Handle, +Constraint_System)` Updates the polyhedron referenced by `Handle` to one obtained by adding to its constraint system the constraints in `Constraint_System`. E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(c, 2, universe, X),
   A = '$VAR'(0), B = '$VAR'(1),
   ppl_Polyhedron_add_constraints_and_minimize(X, [4*A + B >= 3, A = 1]),
   ppl_Polyhedron_get_constraints(X, CS).

CS = [1*B>= -1,1*A=1]
```

This will fail if, after adding the constraints, the polyhedron is empty. E.g., the following will fail,


```
?- A = '$VAR'(0), B = '$VAR'(1),
   ppl_new_Polyhedron_from_space_dimension(c, 2, universe, X),
   ppl_Polyhedron_add_constraints_and_minimize(X,
       [4*A + B >= 3, A = 0, B <= 0]),
   ppl_Polyhedron_get_constraints(X, CS).
```

`ppl_Polyhedron_add_generators(+Handle, +Generator_System)` Updates the polyhedron referenced by `Handle` to one obtained by adding to its generator system the generators in `Generator_System`.

If the system of generators representing a polyhedron is non-empty, then it must include a point (see the paragraph on generator representation in Section **Representations of Convex Polyhedra**(p. 4)). Thus care must be taken to ensure that, before calling this predicate, either the polyhedron referenced by `Handle` is non-empty or that whenever `Generator_System` is non-empty the first element defines a point. E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(c, 3, empty, X),
   A='$VAR'(0), B = '$VAR'(1), C = '$VAR'(2),
   ppl_Polyhedron_add_generators(X,
       [point(1*A + 1*B + 1*C, 1), ray(1*A), ray(2*A)]),
   ppl_Polyhedron_get_generators(X, GS).

GS = [ray(2*A), point(1*A+1*B+1*C), ray(1*A)]
```

`ppl_Polyhedron_add_generators_and_minimize(+Handle, +Generator_System)` Updates the polyhedron referenced by `Handle` to one obtained by adding to its generator system the generators in `Generator_System`.

Unlike the predicate `ppl_add_generators`, the order of the generators in `Generator_System` is not important. E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(c, 3, empty, X),
   A='$VAR'(0), B = '$VAR'(1), C = '$VAR'(2),
   ppl_Polyhedron_add_generators_and_minimize(X,
       [ray(1*A), ray(2*A), point(1*A + 1*B + 1*C, 1)]),
   ppl_Polyhedron_get_generators(X, GS).

GS = [point(1*A+1*B+1*C), ray(1*A)]
```

`ppl_Polyhedron_intersection_assign(+Handle_1, +Handle_2)`

`ppl_Polyhedron_intersection_assign_and_minimize(+Handle_1, +Handle_2)` Assigns to the polyhedron referenced by `Handle_1` its intersection with the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_poly_hull_assign(+Handle_1, +Handle_2)`

`ppl_Polyhedron_poly_hull_assign_and_minimize(+Handle_1, +Handle_2)` Assigns to the polyhedron referenced by `Handle_1` its poly-hull with the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_poly_difference_assign(+Handle_1, +Handle_2)` Assigns to the polyhedron referenced by `Handle_1` its poly-difference with the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_affine_image(+Handle, +PPL_Var, +Lin_Expr, +Coefficient)` Transforms the polyhedron referenced by `Handle` assigning the affine expression `Lin_Expr/Coefficient` to `PPL_Var`.

`ppl_Polyhedron_affine_preimage(+Handle, +PPL_Var, +Lin_Expr, +Coefficient)` This is the inverse transformation to that for `ppl_affine_image`.

`ppl_Polyhedron_generalized_affine_image(+Handle, +PPL_Var, +Relation_Symbol +Lin_Expr, +Coefficient)` Transforms the polyhedron referenced by `Handle` assigning the generalized affine image with respect to the transfer function `PPL_Var Relation_Symbol Lin_Expr/Coefficient`.

`ppl_Polyhedron_generalized_affine_image_lhs_rhs(+Handle, +Lin_Expr1, +Relation_Symbol +Lin_Expr2)` Transforms the polyhedron referenced by `Handle` assigning the generalized affine image with respect to the transfer function `Lin_Expr1 Relation_Symbol Lin_Expr2`.

`ppl_Polyhedron_time_elapse_assign(+Handle_1, +Handle_2)` Assigns to the polyhedron \mathcal{P} referenced by `Handle_1` the time-elapse ($\mathcal{P} \nearrow \mathcal{Q}$) with the polyhedron \mathcal{Q} referenced by `Handle_2`.

`ppl_Polyhedron_BHRZ03_widening_assign_with_token(+Handle_1, +Handle_2, ?C_unsigned)` The polyhedra referenced by `Handle_1` and `Handle_2` are unaltered. The token `C_unsigned` is 0 if a BHRZ03 widening would have changed the polyhedron referenced by `Handle_1` and is 1 otherwise.

`ppl_Polyhedron_BHRZ03_widening_assign(+Handle_1, +Handle_2)` Assigns to the polyhedron referenced by `Handle_1` its BHRZ03-widening with the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_limited_BHRZ03_extrapolation_assign_with_token(+Handle_1, +Handle_2, +Constraint_System, ?C_unsigned)` The polyhedra referenced by `Handle_1` and `Handle_2` are unaltered. The token `C_unsigned` is 0 if a BHRZ03-widening with the polyhedron referenced by `Handle_2`, improved by enforcing those constraints in `Constraint_System` would have changed the polyhedron referenced by `Handle_1` and is 1 otherwise.

`ppl_Polyhedron_limited_BHRZ03_extrapolation_assign(+Handle_1, +Handle_2, +Constraint_System)` Assigns to the polyhedron \mathcal{P} referenced by `Handle_1` the result of its BHRZ03-widening with the polyhedron referenced by `Handle_2`, improved by enforcing those constraints in `Constraint_System`.

`ppl_Polyhedron_bounded_BHRZ03_extrapolation_assign_with_token(+Handle_1, +Handle_2, +Constraint_System, ?C_unsigned)` The polyhedra \mathcal{P}_1 and \mathcal{P}_2 referenced by `Handle_1` and `Handle_2`, respectively are unaltered. The token `C_unsigned` is 0 if a BHRZ03-widening with \mathcal{P}_2 , improved by enforcing all the constraints of the form $\pm x \leq r$ and $\pm x < r$ that are satisfied by all the points of \mathcal{P}_1 together with the constraints in `Constraint_System` would have changed the polyhedron referenced by `Handle_1` and is 1 otherwise.

`ppl_Polyhedron_bounded_BHRZ03_extrapolation_assign(+Handle_1, +Handle_2, +Constraint_System)` Assigns to the polyhedron \mathcal{P} referenced by `Handle_1` the result of its BHRZ03-widening with the polyhedron referenced by `Handle_2` improved by enforcing all the constraints of the form $\pm x \leq r$ and $\pm x < r$ that are satisfied by all the points of \mathcal{P} together with the constraints in `Constraint_System`.

`ppl_Polyhedron_H79_widening_assign_with_token(+Handle_1, +Handle_2, ?C_unsigned)` The polyhedra referenced by `Handle_1` and `Handle_2` are unaltered. The token `C_unsigned` is 0 if an H79 widening would have changed the polyhedron referenced by `Handle_1` and is 1 otherwise.

`ppl_Polyhedron_H79_widening_assign(+Handle_1, +Handle_2)` Assigns to the polyhedron referenced by `Handle_1` its H79-widening with the polyhedron referenced by `Handle_2`.

`ppl_Polyhedron_limited_H79_extrapolation_assign_with_token(+Handle_1, +Handle_2, +Constraint_System, ?C_unsigned)` The polyhedra referenced by `Handle_1` and `Handle_2` are unaltered. The token `C_unsigned` is 0 if a H79-widening with the polyhedron referenced by `Handle_2`, improved by enforcing those constraints in `Constraint_System` would have changed the polyhedron referenced by `Handle_1` and is 1 otherwise.

`ppl_Polyhedron_limited_H79_extrapolation_assign(+Handle_1, +Handle_2, +Constraint_System)` Assigns to the polyhedron \mathcal{P} referenced by `Handle_1` its H79-widening with the polyhedron referenced by `Handle_2`, improved by enforcing those constraints in `Constraint_System`.

`ppl_Polyhedron_bounded_H79_extrapolation_assign_with_token(+Handle_1, +Handle_2, +Constraint_System, ?C_unsigned)` The polyhedra \mathcal{P}_1 and \mathcal{P}_2 referenced by `Handle_1` and `Handle_2`, respectively are unaltered. The token `C_unsigned` is 0 if a H79-widening with \mathcal{P}_2 , improved by enforcing all the constraints of the form $\pm x \leq r$ and $\pm x < r$ that are satisfied by all the points of \mathcal{P}_1 together with the constraints in `Constraint_System` would have changed the polyhedron referenced by `Handle_1` and is 1 otherwise.

`ppl_Polyhedron_bounded_H79_extrapolation_assign(+Handle_1, +Handle_2, +Constraint_System)` Assigns to the polyhedron \mathcal{P} referenced by `Handle_1` the result of its H79-widening with the polyhedron referenced by `Handle_2` improved by enforcing all the constraints of the form $\pm x \leq r$ and $\pm x < r$ that are satisfied by all the points of \mathcal{P} together with the constraints in `Constraint_System`.

`ppl_Polyhedron_topological_closure_assign(+Handle)` Assigns to the polyhedron referenced by `Handle` its topological closure.

`ppl_Polyhedron_add_space_dimensions_and_embed(+Handle, +Dimension_Type)` Embeds the polyhedron referenced by `Handle` in a space that is enlarged by `Dimension_Type` dimensions, E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(c, 0, empty, X),
   ppl_Polyhedron_add_space_dimensions_and_embed(X, 2),
   ppl_Polyhedron_get_constraints(X, CS),
   ppl_Polyhedron_get_generators(X, GS).
```

```
CS = [],
GS = [point(0),line(1*A),line(1*B)]
```

`ppl_Polyhedron_concatenate_assign(+Handle1, +Handle2)` Updates the polyhedron \mathcal{P}_1 referenced by `Handle1` by first embedding \mathcal{P}_1 in a new space enlarged by the space dimensions of the polyhedron \mathcal{P}_2 referenced by `Handle2`, and then adds to its system of constraints a renamed-apart version of the constraints of \mathcal{P}_2 .

E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(nnc, 2, universe, X),
   A = '$VAR'(0), B = '$VAR'(1), C = '$VAR'(2),
   D = '$VAR'(3), E = '$VAR'(4),
   ppl_new_Polyhedron_from_constraints(nnc, [A > 1, B >= 0, C >= 0], Y),
   ppl_Polyhedron_concatenate_assign(X, Y),
   ppl_Polyhedron_get_constraints(X, CS).

CS = [1*C > 1, 1*D >= 0, 1*E >= 0]
```

`ppl_Polyhedron_add_space_dimensions_and_project(+Handle, +Dimension_Type)` Projects the polyhedron referenced by `Handle` onto a space that is enlarged by `Dimension_Type` dimensions, E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(c, 0, empty, X),
   ppl_Polyhedron_add_space_dimensions_and_project(X, 2),
   ppl_Polyhedron_get_constraints(X, CS),
   ppl_Polyhedron_get_generators(X, GS).

CS = [1*A = 0, 1*B = 0],
GS = [point(0)]
```

`ppl_Polyhedron_remove_space_dimensions(+Handle, +List_of_PPL_Vars)` Removes the space dimensions given by the identifiers of the PPL variables in list `List_of_PPL_Vars` from the polyhedron referenced by `Handle`. The identifiers for the remaining PPL variables are renumbered so that they are consecutive and the maximum index is less than the number of dimensions. E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(c, 3, empty, X),
   A = '$VAR'(0), B = '$VAR'(1), C = '$VAR'(2),
   ppl_Polyhedron_remove_space_dimensions(X, [B]),
   ppl_Polyhedron_space_dimension(X, K),
   ppl_Polyhedron_get_generators(X, GS).

K = 2,
GS = [point(0),line(1*A),line(1*B),line(0)]
```

`ppl_Polyhedron_remove_higher_space_dimensions(+Handle, +Dimension_Type)` Projects the polyhedron referenced to by `Handle` onto the first `Dimension_Type` dimension. E.g.,

```
?- ppl_new_Polyhedron_from_space_dimension(c, 5, empty, X),
   ppl_Polyhedron_remove_higher_space_dimensions(X, 3),
   ppl_Polyhedron_space_dimension(X, K).
```

`ppl_Polyhedron_expand_space_dimension(+Handle, +PPL_Var, +Dimension_Type))` `Dimension_Type` copies of the space dimension referenced by `PPL_Var` are added to the polyhedron referenced to by `Handle`.

`ppl_Polyhedron_fold_space_dimensions(+Handle, +List_of_PPL_Vars, +PPL_Var))` The space dimensions referenced by the PPL variables in list `List_of_PPL_Vars` are folded into the dimension referenced by `PPL_Var` and removed. The result is undefined if `List_of_PPL_Vars` does not have the properties described in the paragraph **specifying the fold_space_dimensions operator**(p. 8) in Section **Operations on Convex Polyhedra**(p. 7).

`ppl_Polyhedron_map_space_dimensions(+Handle, +P_Func))` Maps the space dimensions of the polyhedron referenced by `Handle` using the partial function defined by `P_Func`. The result is undefined if `P_Func` does not encode a partial function with the properties described in the paragraph **specifying the map_space_dimensions operator**(p. 8) in Section **Operations on Convex Polyhedra**(p. 7).

Compilation and Installation

When the Parma Polyhedra Library is configured, it tests for the existence of each supported Prolog system. If a supported Prolog system is correctly installed in a standard location, things are arranged so that the corresponding interface is built and installed.

In the sequel, `prefix` is the prefix under which you have installed the library (typically `/usr` or `/usr/local`).

As an option, the Prolog interface can track the creation and disposal of polyhedra. In fact, differently from native Prolog data, PPL polyhedra must be explicitly disposed and forgetting to do so is a very common mistake. To enable this option, configure the library adding `-DPROLOG_TRACK_ALLOCATION` to the options passed to the C++ compiler. Your configure command would then look like

```
path/to/configure --with-cxxflags="-DPROLOG_TRACK_ALLOCATION" ...
```

System-Dependent Features

CIAO Prolog The Ciao Prolog interface to the PPL is available both as a statically linked module and as a dynamically linked one. Only Ciao Prolog versions 1.10 #5 and later are supported.

The Ciao Prolog interface to the PPL is available both as “PPL enhanced” Ciao Prolog interpreter and as a library that can be linked to Ciao Prolog programs. Only Ciao Prolog versions 1.10 #5 and later are supported.

So that it can be used with the Ciao Prolog PPL interface, the Ciao Prolog installation must be configured with the `-disable-regs` option.

The `ppl_ciao` Executable If an appropriate version of Ciao Prolog is installed on the machine on which you compiled the library, the command `make install` will install the executable `ppl_ciao` in the directory `prefix/bin`. The `ppl_ciao` executable is simply the Ciao Prolog interpreter with the Parma Polyhedra library linked in. The only thing you should do to use the library is to call `ppl_initialize/0` before any other PPL predicate and to call `ppl_finalize/0` when you are done with the library.

Linking the Library To Ciao Prolog Programs In order to allow linking Ciao Prolog programs to the PPL, the following files are installed in the directory `prefix/lib/ppl`: `ppl_ciao.pl` contains the required foreign declarations; `libppl_ciao.*` contain the executable code for the Ciao Prolog interface in various formats (static library, shared library, libtool library). If your Ciao Prolog program is constituted by, say, `source1.pl` and `source2.pl` and you want to create the executable `myprog`, your compilation command may look like

```
ciaoc -o myprog prefix/lib/ppl/ppl_ciao.pl ciao_pl_check.pl \
-L '-Lprefix/lib/ppl -lppl_ciao -Lprefix/lib -lppl -lgmpxx -lgmp -lstdc++'
```

GNU Prolog The GNU Prolog interface to the PPL is available both as “PPL enhanced” GNU Prolog interpreter and as a library that can be linked to GNU Prolog programs. Only GNU Prolog versions 1.2.18 and later are supported.

So that it can be used with the GNU Prolog PPL interface (and, for that matter, with any foreign code), the GNU Prolog installation must be configured with the `-disable-regs` option.

The `ppl_gprolog` Executable If an appropriate version of GNU Prolog is installed on the machine on which you compiled the library, the command `make install` will install the executable `ppl_gprolog` in the directory `prefix/bin`. The `ppl_gprolog` executable is simply the GNU Prolog interpreter with the Parma Polyhedra library linked in. The only thing you should do to use the library is to call `ppl_initialize/0` before any other PPL predicate and to call `ppl_finalize/0` when you are done with the library.

Linking the Library To GNU Prolog Programs In order to allow linking GNU Prolog programs to the PPL, the following files are installed in the directory `prefix/lib/ppl`: `ppl_gprolog.pl` contains the required foreign declarations; `libppl_gprolog.*` contain the executable code for the GNU Prolog interface in various formats (static library, shared library, libtool library). If your GNU Prolog program is constituted by, say, `source1.pl` and `source2.pl` and you want to create the executable `myprog`, your compilation command may look like

```
gplc -o myprog prefix/lib/ppl/ppl_gprolog.pl source1.pl source2.pl \
-L '-Lprefix/lib/ppl -lppl_gprolog -Lprefix/lib -lppl -lgmpxx -lgmp -lstdc++'
```

SICStus Prolog The SICStus Prolog interface to the PPL is available both as a statically linked module or as a dynamically linked one. Only SICStus Prolog versions 3.9.0 and later are supported.

The Statically Linked `ppl_sicstus` Executable If an appropriate version of SICStus Prolog is installed on the machine on which you compiled the library, the command `make install` will install the executable `ppl_sicstus` in the directory `prefix/bin`. The `ppl_sicstus` executable is simply the SICStus Prolog system with the Parma Polyhedra library statically linked. The only thing you should do to use the library is to load `prefix/lib/ppl/ppl_sicstus.pl`.

Loading the SICStus Interface Dynamically In order to dynamically load the library from SICStus Prolog you should simply load `prefix/lib/ppl/ppl_sicstus.pl`. Notice that, for dynamic linking to work, you should have configured the library with the `-enable-shared` option.

SWI-Prolog The SWI-Prolog interface to the PPL is available both as a statically linked module or as a dynamically linked one. Only SWI-Prolog versions 5.0 and later are supported.

The `ppl_pl` Executable If an appropriate version of SWI-Prolog is installed on the machine on which you compiled the library, the command `make install` will install the executable `ppl_pl` in the directory `prefix/bin`. The `ppl_pl` executable is simply the SWI-Prolog shell with the Parma Polyhedra library statically linked: from within `ppl_pl` all the services of the library are available without further action.

Loading the SWI-Prolog Interface Dynamically In order to dynamically load the library from SWI-Prolog you should simply load `prefix/lib/ppl/ppl_swiprolog.pl`. This will invoke `ppl_initialize/0` automatically but, at least for SWI-Prolog versions up to 5.0.7, it is the programmer's responsibility to call `ppl_finalize/0`. Alternatively, you can load the library directly with

```
:- load_foreign_library('prefix/lib/ppl/libppl_swiprolog').
```

This will call `ppl_initialize/0` automatically. Analogously,

```
:- unload_foreign_library('prefix/lib/ppl/libppl_swiprolog').
```

will, as part of the unload process, invoke `ppl_finalize/0`.

Notice that, for dynamic linking to work, you should have configured the library with the `-enable-shared` option.

XSB The XSB Prolog interface to the PPL is available as a dynamically linked module. Only XSB versions 2.6 and later are supported.

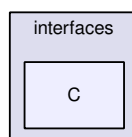
In order to dynamically load the library from XSB you should load the `ppl_xsb` module and import the predicates you need. For things to work, you may have to copy the files `prefix/lib/ppl/ppl_xsb.xwam` and `prefix/lib/ppl/ppl_xsb.so` in your current directory or in one of the XSB library directories.

YAP The YAP Prolog interface to the PPL is available as a dynamically linked module. Only YAP versions 4.4 and later are supported.

In order to dynamically load the library from YAP you should simply load `prefix/lib/ppl/ppl_yap.pl`. This will invoke `ppl_initialize/0` automatically; it is the programmer's responsibility to call `ppl_finalize/0` when the PPL library is no longer needed. Notice that, for dynamic linking to work, you should have configured the library with the `-enable-shared` option.

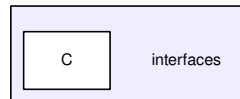
9 PPL Directory Documentation

9.1 `/home/roberto/ppl-0.7/ppl-0.7/interfaces/C/` Directory Reference

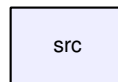


Files

- file `ppl_c.h`

9.2 /home/roberto/ppl-0.7/ppl-0.7/interfaces/ Directory Reference**Directories**

- directory `C`

9.3 /home/roberto/ppl-0.7/ppl-0.7/src/ Directory Reference**Files**

- file `ppl.hh`

10 PPL Namespace Documentation**10.1 Parma_Polyhedra_Library Namespace Reference**

The entire library is confined to this namespace.

Classes

- class **Checked_Number**
A wrapper for native numeric types implementing a given policy.
- class **Native_Integer**
A wrapper for unchecked native integer types.
- class **Variable**
A dimension of the vector space.
- class **Linear_Expression**
A linear expression.

- class **Constraint**
A linear equality or inequality.
- class **Generator**
A line, ray, point or closure point.
- class **Poly_Con_Relation**
The relation between a polyhedron and a constraint.
- class **Poly_Gen_Relation**
The relation between a polyhedron and a generator.
- class **BHRZ03_Certificate**
The convergence certificate for the BHRZ03 widening operator.
- class **H79_Certificate**
A convergence certificate for the H79 widening operator.
- class **Polyhedron**
The base class for convex polyhedra.
- class **C_Polyhedron**
A closed convex polyhedron.
- class **NNC_Polyhedron**
A not necessarily closed convex polyhedron.
- class **Determinate**
Wraps a PPL class into a determinate constraint system interface.
- class **Powerset**
The powerset construction on constraint systems.
- class **Polyhedra_Powerset**
The powerset construction instantiated on PPL polyhedra.

Namespaces

- namespace **IO_Operators**
All input/output operators are confined to this namespace.

Functions Operating on Unbounded Integer Coefficients

- void **negate** (**GMP_Integer** &x)
Assigns to x its negation.
- void **gcd_assign** (**GMP_Integer** &x, const **GMP_Integer** &y)

Assigns to x the greatest common divisor of x and y .

- **void gcd_assign (GMP_Integer &x, const GMP_Integer &y, const GMP_Integer &z)**
Assigns to x the greatest common divisor of y and z .
- **void lcm_assign (GMP_Integer &x, const GMP_Integer &y)**
Assigns to x the least common multiple of x and y .
- **void lcm_assign (GMP_Integer &x, const GMP_Integer &y, const GMP_Integer &z)**
Assigns to x the least common multiple of y and z .
- **void add_mul_assign (GMP_Integer &x, const GMP_Integer &y, const GMP_Integer &z)**
*Assigns to x the value $x + y * z$.*
- **void sub_mul_assign (GMP_Integer &x, const GMP_Integer &y, const GMP_Integer &z)**
*Assigns to x the value $x - y * z$.*
- **void exact_div_assign (GMP_Integer &x, const GMP_Integer &y)**
Assigns to x the quotient of the integer division of x by y .
- **void exact_div_assign (GMP_Integer &x, const GMP_Integer &y, const GMP_Integer &z)**
Assigns to x the quotient of the integer division of y by z .
- **void sqrt_assign (GMP_Integer &x)**
Assigns to x its integer square root.
- **void sqrt_assign (GMP_Integer &x, const GMP_Integer &y)**
Assigns to x the integer square root of y .
- **int cmp (const GMP_Integer &x, const GMP_Integer &y)**
Returns a negative, zero or positive value depending on whether x is lower than, equal to or greater than y , respectively.
- **const mpz_class & raw_value (const GMP_Integer &x)**
Returns a const reference to x .
- **mpz_class & raw_value (GMP_Integer &x)**
Returns a reference to x .
- **size_t total_memory_in_bytes (const GMP_Integer &x)**
Returns the total size in bytes of the memory occupied by x .
- **size_t external_memory_in_bytes (const GMP_Integer &x)**
Returns the size in bytes of the memory managed by x .

Typedefs

- typedef mpz_class **GMP_Integer**
Unbounded integers are implemented using the GMP library.
- typedef COEFFICIENT_TYPE **Coefficient**
An alias for easily naming the type of PPL coefficients.
- typedef std::set< **Variable**, **Variable::Compare** > **Variables_Set**
An std::set containing variables in increasing order of dimension index.

Functions

- unsigned **version_major** ()
Returns the major number of the PPL version.
- unsigned **version_minor** ()
Returns the minor number of the PPL version.
- unsigned **version_revision** ()
Returns the revision number of the PPL version.
- unsigned **version_beta** ()
Returns the beta number of the PPL version.
- const char * **version** ()
Returns a character string containing the PPL version.
- const char * **banner** ()
Returns a character string containing the PPL banner.

10.1.1 Detailed Description

The entire library is confined to this namespace.

10.1.2 Typedef Documentation

10.1.2.1 typedef mpz_class Parma_Polyhedra_Library::GMP_Integer

Unbounded integers are implemented using the GMP library.

GMP_Integer is an alias for the mpz_class type defined in the C++ interface of the GMP library. For more information, see <http://www.swox.com/gmp/>

10.1.2.2 typedef COEFFICIENT_TYPE Parma_Polyhedra_Library::Coefficient

An alias for easily naming the type of PPL coefficients.

Objects of type `Coefficient` are used to implement the integral valued coefficients occurring in linear expressions, constraints, generators, intervals, bounding boxes and so on. Depending on the chosen configuration options (see file `README.configure`), a `Coefficient` may actually be:

- The `GMP_Integer` type, which in turn is an alias for the `mpz_class` type implemented by the C++ interface of the GMP library (this is the default configuration);
- An instance of the `Checked_Number`(p. 80) class template, implementing overflow detection on top of a native integral type (available template instances include checked integers having 8, 16, 32 or 64 bits);
- An instance of the `Native_Integer`(p. 105) class template, simply wrapping a native integral types with no overflow detection (available template instances include native integers having 8, 16, 32 or 64 bits).

10.1.3 Function Documentation

10.1.3.1 const char* banner ()

Returns a character string containing the PPL banner.

The banner provides information about the PPL version, the licensing, the lack of any warranty whatsoever, the C++ compiler used to build the library, where to report bugs and where to look for further information.

10.2 Parma_Polyhedra_Library::IO_Operators Namespace Reference

All input/output operators are confined to this namespace.

10.2.1 Detailed Description

All input/output operators are confined to this namespace.

This is done so that the library's input/output operators do not interfere with those the user might want to define. In fact, it is highly unlikely that any pre-defined I/O operator will suit the needs of a client application. On the other hand, those applications for which the PPL I/O operator are enough can easily obtain access to them. For example, a directive like

```
using namespace Parma_Polyhedra_Library::IO_Operators;
```

would suffice for most uses. In more complex situations, such as

```
const Constraint_System& cs = ...;
copy(cs.begin(), cs.end(),
      ostream_iterator<Constraint>(cout, "\n"));
```

the `Parma_Polyhedra_Library`(p. 71) namespace must be suitably extended. This can be done as follows:

```
namespace Parma_Polyhedra_Library {
    // Import all the output operators into the main PPL namespace.
    using IO_Operators::operator<<;
}
```

10.3 std Namespace Reference

The standard C++ namespace.

Functions

- `void swap (Parma_Polyhedra_Library::GMP_Integer &x, Parma_Polyhedra_Library::GMP_Integer &y)`
Specializes std::swap.

10.3.1 Detailed Description

The standard C++ namespace.

The Parma Polyhedra Library conforms to the C++ standard and, in particular, as far as reserved names are concerned (17.4.3.1, [lib.reserved.names]). The PPL, however, defines several template specializations for the standard library templates `swap()` (p. 76) and `iter_swap()` (25.2.2, [lib.alg.swap]).

11 PPL Class Documentation

11.1 Parma_Polyhedra_Library::BHRZ03_Certificate Class Reference

The convergence certificate for the BHRZ03 widening operator.

Public Member Functions

- **BHRZ03_Certificate ()**
Default constructor.
- **BHRZ03_Certificate (const Polyhedron &ph)**
Constructor: computes the certificate for ph.
- **BHRZ03_Certificate (const BHRZ03_Certificate &y)**
Copy constructor.
- **~BHRZ03_Certificate ()**
Destructor.
- **int compare (const BHRZ03_Certificate &y) const**
The comparison function for certificates.
- **int compare (const Polyhedron &ph) const**
*Compares *this with the certificate for polyhedron ph.*

Classes

- struct **Compare**

A total ordering on BHRZ03 certificates.

11.1.1 Detailed Description

The convergence certificate for the BHRZ03 widening operator.

Convergence certificates are used to instantiate the BHZ03 framework so as to define widening operators for the finite powerset domain.

Note:

Each convergence certificate has to be used together with a compatible widening operator. In particular, **BHRZ03_Certificate**(p. 76) can certify the convergence of both the BHRZ03 and the H79 widenings.

11.1.2 Member Function Documentation

11.1.2.1 `int Parma_Polyhedra_Library::BHRZ03_Certificate::compare (const BHRZ03_Certificate &y) const`

The comparison function for certificates.

Returns:

−1, 0 or 1 depending on whether `*this` is smaller than, equal to, or greater than `y`, respectively.

Compares `*this` with `y`, using a total ordering which is a refinement of the limited growth ordering relation for the BHRZ03 widening.

11.2 Parma_Polyhedra_Library::BHRZ03_Certificate::Compare Struct Reference

A total ordering on BHRZ03 certificates.

Public Member Functions

- `bool operator() (const BHRZ03_Certificate &x, const BHRZ03_Certificate &y) const`

Returns true if and only if x comes before y.

11.2.1 Detailed Description

A total ordering on BHRZ03 certificates.

This binary predicate defines a total ordering on BHRZ03 certificates which is used when storing information about sets of polyhedra.

11.3 Parma_Polyhedra_Library::C_Polyhedron Class Reference

A closed convex polyhedron.

Inherits **Parma_Polyhedra_Library::Polyhedron**.

Public Member Functions

- **C_Polyhedron** (dimension_type num_dimensions=0, **Degenerate_Kind** kind=UNIVERSE)
Builds either the universe or the empty C polyhedron.
- **C_Polyhedron** (const Constraint_System &cs)
Builds a C polyhedron from a system of constraints.
- **C_Polyhedron** (Constraint_System &cs)
Builds a C polyhedron recycling a system of constraints.
- **C_Polyhedron** (const Generator_System &gs)
Builds a C polyhedron from a system of generators.
- **C_Polyhedron** (Generator_System &gs)
Builds a C polyhedron recycling a system of generators.
- **C_Polyhedron** (const NNC_Polyhedron &y)
Builds a C polyhedron representing the topological closure of the NNC polyhedron y.
- template<typename Box> **C_Polyhedron** (const Box &box, From_Bounding_Box dummy)
Builds a C polyhedron out of a generic, interval-based bounding box.
- **C_Polyhedron** (const C_Polyhedron &y)
Ordinary copy-constructor.
- **C_Polyhedron & operator=** (const C_Polyhedron &y)
*The assignment operator. (*this and y can be dimension-incompatible.).*
- **C_Polyhedron & operator=** (const NNC_Polyhedron &y)
*Assigns to *this the topological closure of the NNC polyhedron y.*
- **~C_Polyhedron** ()
Destructor.

11.3.1 Detailed Description

A closed convex polyhedron.

An object of the class **C_Polyhedron**(p. 78) represents a *topologically closed* convex polyhedron in the vector space \mathbb{R}^n .

When building a closed polyhedron starting from a system of constraints, an exception is thrown if the system contains a *strict inequality* constraint. Similarly, an exception is thrown when building a closed polyhedron starting from a system of generators containing a *closure point*.

Note:

Such an exception will be obtained even if the system of constraints (resp., generators) actually defines a topologically closed subset of the vector space, i.e., even if all the strict inequalities (resp., closure points) in the system happen to be redundant with respect to the system obtained by removing all the strict inequality constraints (resp., all the closure points). In contrast, when building a closed polyhedron starting from an object of the class `NNC_Polyhedron` (p. 110), the precise topological closure test will be performed.

11.3.2 Constructor & Destructor Documentation**11.3.2.1 Parma_Polyhedra_Library::C_Polyhedron::C_Polyhedron (dimension_type num_dimensions = 0, Degenerate_Kind kind = UNIVERSE) [explicit]**

Builds either the universe or the empty C polyhedron.

Parameters:

num_dimensions The number of dimensions of the vector space enclosing the C polyhedron;
kind Specifies whether a universe or an empty C polyhedron should be built.

Exceptions:

std::length_error Thrown if *num_dimensions* exceeds the maximum allowed space dimension.

Both parameters are optional: by default, a 0-dimension space universe C polyhedron is built.

11.3.2.2 Parma_Polyhedra_Library::C_Polyhedron::C_Polyhedron (const Constraint_System & cs) [explicit]

Builds a C polyhedron from a system of constraints.

The polyhedron inherits the space dimension of the constraint system.

Parameters:

cs The system of constraints defining the polyhedron.

Exceptions:

std::invalid_argument Thrown if the system of constraints contains strict inequalities.

11.3.2.3 Parma_Polyhedra_Library::C_Polyhedron::C_Polyhedron (Constraint_System & cs) [explicit]

Builds a C polyhedron recycling a system of constraints.

The polyhedron inherits the space dimension of the constraint system.

Parameters:

cs The system of constraints defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

Exceptions:

std::invalid_argument Thrown if the system of constraints contains strict inequalities.

11.3.2.4 Parma_Polyhedra_Library::C_Polyhedron::C_Polyhedron (const Generator_System & gs) [explicit]

Builds a C polyhedron from a system of generators.

The polyhedron inherits the space dimension of the generator system.

Parameters:

gs The system of generators defining the polyhedron.

Exceptions:

std::invalid_argument Thrown if the system of generators is not empty but has no points, or if it contains closure points.

11.3.2.5 Parma_Polyhedra_Library::C_Polyhedron::C_Polyhedron (Generator_System & gs) [explicit]

Builds a C polyhedron recycling a system of generators.

The polyhedron inherits the space dimension of the generator system.

Parameters:

gs The system of generators defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

Exceptions:

std::invalid_argument Thrown if the system of generators is not empty but has no points, or if it contains closure points.

11.3.2.6 template<typename Box> Parma_Polyhedra_Library::C_Polyhedron::C_Polyhedron (const Box & box, From_Bounding_Box dummy)

Builds a C polyhedron out of a generic, interval-based bounding box.

For a description of the methods that should be provided by the template class `Box`, see the documentation of the protected method: `template <typename Box> Polyhedron::Polyhedron(Topology topol, const Box& box)(p. 133);`

Parameters:

box The bounding box representing the polyhedron to be built;

dummy A dummy tag to syntactically differentiate this one from the other constructors.

Exceptions:

std::length_error Thrown if the space dimension of `box` exceeds the maximum allowed space dimension.

std::invalid_argument Thrown if `box` has intervals that are not topologically closed (i.e., having some finite but open bounds).

11.4 Parma_Polyhedra_Library::Checked_Number< T, Policy > Class Template Reference

A wrapper for native numeric types implementing a given policy.

Public Member Functions

- **void swap (Checked_Number &y)**

*Swaps *this with y.*

Constructors

- **Checked_Number ()**

Default constructor.

- **Checked_Number (const signed char y)**

Direct initialization from a signed char value.

- **Checked_Number (const short y)**

Direct initialization from a signed short value.

- **Checked_Number (const int y)**

Direct initialization from a signed int value.

- **Checked_Number (const long y)**

Direct initialization from a signed long value.

- **Checked_Number (const long long y)**

Direct initialization from a signed long long value.

- **Checked_Number (const unsigned char y)**

Direct initialization from an unsigned char value.

- **Checked_Number (const unsigned short y)**

Direct initialization from an unsigned short value.

- **Checked_Number (const unsigned int y)**

Direct initialization from an unsigned int value.

- **Checked_Number (const unsigned long y)**

Direct initialization from an unsigned long value.

- **Checked_Number (const unsigned long long y)**

Direct initialization from an unsigned long long value.

- **Checked_Number (const float32_t y)**

Direct initialization from a 32 bits floating-point value.

- **Checked_Number (const float64_t y)**

Direct initialization from a 64 bits floating-point value.

- **Checked_Number (const mpq_class &y)**

Direct initialization from a GMP unbounded rational value.

- **Checked_Number (const mpz_class &y)**

Direct initialization from a GMP unbounded integer value.

- **Checked_Number** (const char *y)
Direct initialization from a C string value.

Accessors and Conversions

- **operator T ()** const
Conversion operator: returns a copy of the underlying native integer value.
- **T & raw_value ()**
Returns a reference to the underlying native integer value.
- **const T & raw_value ()** const
Returns a const reference to the underlying native integer value.

Assignment Operators

- **Checked_Number & operator=** (const **Checked_Number** &y)
Assignment operator.
- **Checked_Number & operator+=** (const **Checked_Number** &y)
Add and assign operator.
- **Checked_Number & operator-=** (const **Checked_Number** &y)
Subtract and assign operator.
- **Checked_Number & operator *=** (const **Checked_Number** &y)
Multiply and assign operator.
- **Checked_Number & operator/=** (const **Checked_Number** &y)
Divide and assign operator.
- **Checked_Number & operator%=** (const **Checked_Number** &y)
Compute modulus and assign operator.

Increment and Decrement Operators

- **Checked_Number & operator++ ()**
Pre-increment operator.
- **Checked_Number operator++ (int)**
Post-increment operator.
- **Checked_Number & operator-- ()**
Pre-decrement operator.
- **Checked_Number operator-- (int)**
Post-decrement operator.

Related Functions

(Note that these are not member functions.)

Accessor Functions

- **const T & raw_value** (const **Checked_Number**< T, Policy > &x)
Returns a const reference to the underlying native integer value.
- **T & raw_value** (**Checked_Number**< T, Policy > &x)
Returns a reference to the underlying native integer value.

Memory Size Inspection Functions

- **size_t total_memory_in_bytes** (const **Checked_Number**< T, Policy > &x)
Returns the total size in bytes of the memory occupied by x.
- **size_t external_memory_in_bytes** (const **Checked_Number**< T, Policy > &x)
Returns the size in bytes of the memory managed by x.

Arithmetic Operators

- **Checked_Number**< T, Policy > **operator+** (const **Checked_Number**< T, Policy > &x)
Unary plus operator.
- **Checked_Number**< T, Policy > **operator-** (const **Checked_Number**< T, Policy > &x)
Unary minus operator.
- **Checked_Number**< T, Policy > **operator+** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Addition operator.
- **Checked_Number**< T, Policy > **operator-** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Subtraction operator.
- **Checked_Number**< T, Policy > **operator*** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Multiplication operator.
- **Checked_Number**< T, Policy > **operator/** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Integer division operator.
- **Checked_Number**< T, Policy > **operator%** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Modulus operator.
- **void negate** (**Checked_Number**< T, Policy > &x)
Assigns to x its negation.

- void **add_mul_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y, const Checked_Number< T, Policy > &z)
*Assigns to x the value $x + y * z$.*
- void **sub_mul_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y, const Checked_Number< T, Policy > &z)
*Assigns to x the value $x - y * z$.*
- void **gcd_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y)
Assigns to x the greatest common divisor of x and y.
- void **gcd_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y, const Checked_Number< T, Policy > &z)
Assigns to x the greatest common divisor of y and z.
- void **lcm_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y)
Assigns to x the least common multiple of x and y.
- void **lcm_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y, const Checked_Number< T, Policy > &z)
Assigns to x the least common multiple of y and z.
- void **exact_div_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y)
Assigns to x the integer division of x and y.
- void **exact_div_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y, const Checked_Number< T, Policy > &z)
Assigns to x the integer division of y and z.
- void **sqrt_assign** (Checked_Number< T, Policy > &x)
Assigns to x its integer square root.
- void **sqrt_assign** (Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y)
Assigns to x the integer square root of y.

Relational Operators and Comparison Functions

- bool **operator==** (const Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y)
Equality operator.
- bool **operator!=** (const Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y)
Disequality operator.
- bool **operator>=** (const Checked_Number< T, Policy > &x, const Checked_Number< T, Policy > &y)
Greater than or equal to operator.

- **bool operator>** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Greater than operator.
- **bool operator<=** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Less than or equal to operator.
- **bool operator<** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Less than operator.
- **int sgn** (const **Checked_Number**< T, Policy > &x)
Returns -1, 0 or 1 depending on whether the value of x is negative, zero or positive, respectively.
- **int cmp** (const **Checked_Number**< T, Policy > &x, const **Checked_Number**< T, Policy > &y)
Returns a negative, zero or positive value depending on whether x is lower than, equal to or greater than y, respectively.

Input-Output Operators

- **std::ostream & operator<<** (std::ostream &os, const **Checked_Number**< T, Policy > &x)
Output operator.
- **std::istream & operator>>** (std::istream &is, **Checked_Number**< T, Policy > &x)
Input operator.

11.4.1 Detailed Description

template<typename T, typename Policy> class Parma_Polyhedra_Library::Checked_Number< T, Policy >

A wrapper for native numeric types implementing a given policy.

The wrapper and related functions implement an interface which is common to all kinds of coefficient types, therefore allowing for a uniform coding style. This class also implements the policy encoded by the second template parameter. The default policy is to perform the detection of overflow errors.

11.5 Parma_Polyhedra_Library::Constraint Class Reference

A linear equality or inequality.

Public Types

- **enum Type { EQUALITY, NONSTRICT_INEQUALITY, STRICT_INEQUALITY }**
The constraint type.

Public Member Functions

- **Constraint** (const **Constraint** &c)
Ordinary copy-constructor.
- **~Constraint** ()
Destructor.
- **Constraint & operator=** (const **Constraint** &c)
Assignment operator.
- dimension_type **space_dimension** () const
*Returns the dimension of the vector space enclosing *this.*
- **Type** **type** () const
*Returns the constraint type of *this.*
- bool **is_equality** () const
*Returns true if and only if *this is an equality constraint.*
- bool **is_inequality** () const
*Returns true if and only if *this is an inequality constraint (either strict or non-strict).*
- bool **is_nonstrict_inequality** () const
*Returns true if and only if *this is a non-strict inequality constraint.*
- bool **is_strict_inequality** () const
*Returns true if and only if *this is a strict inequality constraint.*
- Coefficient_traits::const_reference **coefficient** (**Variable** v) const
*Returns the coefficient of v in *this.*
- Coefficient_traits::const_reference **inhomogeneous_term** () const
*Returns the inhomogeneous term of *this.*
- memory_size_type **total_memory_in_bytes** () const
*Returns a lower bound to the total size in bytes of the memory occupied by *this.*
- memory_size_type **external_memory_in_bytes** () const
*Returns the size in bytes of the memory managed by *this.*
- bool **OK** () const
Checks if all the invariants are satisfied.

Static Public Member Functions

- dimension_type **max_space_dimension** ()
*Returns the maximum space dimension a **Constraint**(p. 85) can handle.*

- **const Constraint & zero_dim_false ()**
The unsatisfiable (zero-dimension space) constraint $0 = 1$.
- **const Constraint & zero_dim_positivity ()**
The true (zero-dimension space) constraint $0 \leq 1$, also known as positivity constraint.

Related Functions

(Note that these are not member functions.)

- **std::ostream & operator<< (std::ostream &s, const Constraint &c)**
Output operator.
- **Constraint operator== (const Linear_Expression &e1, const Linear_Expression &e2)**
Returns the constraint $e1 = e2$.
- **Constraint operator== (const Linear_Expression &e, Coefficient_traits::const_reference n)**
Returns the constraint $e = n$.
- **Constraint operator== (Coefficient_traits::const_reference n, const Linear_Expression &e)**
Returns the constraint $n = e$.
- **Constraint operator<= (const Linear_Expression &e1, const Linear_Expression &e2)**
Returns the constraint $e1 \leq e2$.
- **Constraint operator<= (const Linear_Expression &e, Coefficient_traits::const_reference n)**
Returns the constraint $e \leq n$.
- **Constraint operator<= (Coefficient_traits::const_reference n, const Linear_Expression &e)**
Returns the constraint $n \leq e$.
- **Constraint operator>= (const Linear_Expression &e1, const Linear_Expression &e2)**
Returns the constraint $e1 \geq e2$.
- **Constraint operator>= (const Linear_Expression &e, Coefficient_traits::const_reference n)**
Returns the constraint $e \geq n$.
- **Constraint operator>= (Coefficient_traits::const_reference n, const Linear_Expression &e)**
Returns the constraint $n \geq e$.
- **Constraint operator< (const Linear_Expression &e1, const Linear_Expression &e2)**
Returns the constraint $e1 < e2$.
- **Constraint operator< (const Linear_Expression &e, Coefficient_traits::const_reference n)**
Returns the constraint $e < n$.
- **Constraint operator< (Coefficient_traits::const_reference n, const Linear_Expression &e)**
Returns the constraint $n < e$.

- **Constraint operator>** (const **Linear_Expression** &e1, const **Linear_Expression** &e2)
Returns the constraint $e1 > e2$.
- **Constraint operator>** (const **Linear_Expression** &e, Coefficient_traits::const_reference n)
Returns the constraint $e > n$.
- **Constraint operator>** (Coefficient_traits::const_reference n, const **Linear_Expression** &e)
Returns the constraint $n > e$.
- void **swap** (**Parma_Polyhedra_Library::Constraint** &x, **Parma_Polyhedra_Library::Constraint** &y)
Specializes `std::swap`.

11.5.1 Detailed Description

A linear equality or inequality.

An object of the class **Constraint**(p. 85) is either:

- an equality: $\sum_{i=0}^{n-1} a_i x_i + b = 0$;
- a non-strict inequality: $\sum_{i=0}^{n-1} a_i x_i + b \geq 0$; or
- a strict inequality: $\sum_{i=0}^{n-1} a_i x_i + b > 0$;

where n is the dimension of the space, a_i is the integer coefficient of variable x_i and b is the integer inhomogeneous term.

How to build a constraint

Constraints are typically built by applying a relation symbol to a pair of linear expressions. Available relation symbols are equality (`==`), non-strict inequalities (`>=` and `<=`) and strict inequalities (`<` and `>`). The space dimension of a constraint is defined as the maximum space dimension of the arguments of its constructor.

In the following examples it is assumed that variables `x`, `y` and `z` are defined as follows:

```
Variable x(0);
Variable y(1);
Variable z(2);
```

Example 1

The following code builds the equality constraint $3x + 5y - z = 0$, having space dimension 3:

```
Constraint eq_c(3*x + 5*y - z == 0);
```

The following code builds the (non-strict) inequality constraint $4x \geq 2y - 13$, having space dimension 2:

```
Constraint ineq_c(4*x >= 2*y - 13);
```

The corresponding strict inequality constraint $4x > 2y - 13$ is obtained as follows:

```
Constraint strict_ineq_c(4*x > 2*y - 13);
```

An unsatisfiable constraint on the zero-dimension space \mathbb{R}^0 can be specified as follows:

```
Constraint false_c = Constraint::zero_dim_false();
```

Equivalent, but more involved ways are the following:

```
Constraint false_c1(Linear_Expression::zero() == 1);
Constraint false_c2(Linear_Expression::zero() >= 1);
Constraint false_c3(Linear_Expression::zero() > 0);
```

In contrast, the following code defines an unsatisfiable constraint having space dimension 3:

```
Constraint false_c(0*z == 1);
```

How to inspect a constraint

Several methods are provided to examine a constraint and extract all the encoded information: its space dimension, its type (equality, non-strict inequality, strict inequality) and the value of its integer coefficients.

Example 2

The following code shows how it is possible to access each single coefficient of a constraint. Given an inequality constraint (in this case $x - 5y + 3z \leq 4$), we construct a new constraint corresponding to its complement (thus, in this case we want to obtain the strict inequality constraint $x - 5y + 3z > 4$).

```
Constraint c1(x - 5*y + 3*z <= 4);
cout << "Constraint c1: " << c1 << endl;
if (c1.is_equality())
    cout << "Constraint c1 is not an inequality." << endl;
else {
    Linear_Expression e;
    for (int i = c1.space_dimension() - 1; i >= 0; i--)
        e += c1.coefficient(Variable(i)) * Variable(i);
    e += c1.inhomogeneous_term();
    Constraint c2 = c1.is_strict_inequality() ? (e <= 0) : (e < 0);
    cout << "Complement c2: " << c2 << endl;
}
```

The actual output is the following:

```
Constraint c1: -A + 5*B - 3*C >= -4
Complement c2: A - 5*B + 3*C > 4
```

Note that, in general, the particular output obtained can be syntactically different from the (semantically equivalent) constraint considered.

11.5.2 Member Enumeration Documentation

11.5.2.1 enum Parma_Polyhedra_Library::Constraint::Type

The constraint type.

Enumeration values:

EQUALITY The constraint is an equality.

NONSTRICT_INEQUALITY The constraint is a non-strict inequality.

STRICT_INEQUALITY The constraint is a strict inequality.

11.5.3 Member Function Documentation

11.5.3.1 Coefficient_traits::const_reference Parma_Polyhedra_Library::Constraint::coefficient (Variable v) const

Returns the coefficient of v in `*this`.

Exceptions:

std::invalid_argument thrown if the index of v is greater than or equal to the space dimension of `*this`.

11.6 Parma_Polyhedra_Library::Determinate< PH > Class Template Reference

Wraps a PPL class into a determinate constraint system interface.

Public Member Functions

Constructors and Destructor

- **Determinate** (dimension_type num_dimensions=0, bool universe=true)
Builds either the top or the bottom of the determinate constraint system defined on the vector space having num_dimensions dimensions.
- **Determinate** (const PH &p)
Injection operator: builds the determinate constraint system element corresponding to the base-level element p.
- **Determinate** (const Constraint_System &cs)
Injection operator: builds the determinate constraint system element corresponding to the base-level element represented by cs.
- **Determinate** (const Determinate &y)
Copy constructor.
- **~Determinate** ()
Destructor.

Member Functions that Do Not Modify the Domain Element

- dimension_type **space_dimension** () const
*Returns the dimension of the vector space enclosing *this.*
- const Constraint_System & **constraints** () const
Returns the system of constraints.
- const Constraint_System & **minimized_constraints** () const
Returns the system of constraints, with no redundant constraint.
- const PH & **element** () const
Returns a const reference to the embedded element.
- PH & **element** ()

Returns a reference to the embedded element.

- **bool is_top () const**
*Returns true if and only if *this is the top of the determinate constraint system (i.e., the whole vector space).*
- **bool is_bottom () const**
*Returns true if and only if *this is the bottom of the determinate constraint system.*
- **bool definitely_entails (const Determinate &y) const**
*Returns true if and only if *this entails y.*
- **bool is_definitely_equivalent_to (const Determinate &y) const**
*Returns true if and only if *this and y are equivalent.*
- **memory_size_type total_memory_in_bytes () const**
*Returns a lower bound to the total size in bytes of the memory occupied by *this.*
- **memory_size_type external_memory_in_bytes () const**
*Returns a lower bound to the size in bytes of the memory managed by *this.*
- **bool OK () const**
Checks if all the invariants are satisfied.

Space Dimension Preserving Member Functions that May Modify the Domain Element

- **void upper_bound_assign (const Determinate &y)**
*Assigns to *this the upper bound of *this and y.*
- **void meet_assign (const Determinate &y)**
*Assigns to *this the meet of *this and y.*
- **void add_constraint (const Constraint &c)**
*Assigns to *this the meet of *this and the element represented by constraint c.*
- **void add_constraints (Constraint_System &cs)**
*Assigns to *this the meet of *this and the element represented by the constraints in cs.*

Member Functions that May Modify the Dimension of the Vector Space

- **Determinate & operator= (const Determinate &y)**
Assignment operator.
- **void swap (Determinate &y)**
*Swaps *this with y.*
- **void add_space_dimensions_and_embed (dimension_type m)**
Adds m new space dimensions and embeds the old domain element in the new vector space.
- **void add_space_dimensions_and_project (dimension_type m)**
Adds m new space dimensions to the domain element and does not embed it in the new vector space.

- void **concatenate_assign** (const **Determinate** &y)
*Assigns to *this the concatenation(p. 7) of *this and y, taken in this order.*
- void **remove_space_dimensions** (const **Variables_Set** &to_be_removed)
Removes all the specified space dimensions.
- void **remove_higher_space_dimensions** (dimension_type new_dimension)
Removes the higher space dimensions so that the resulting space will have dimension new_dimension.
- template<typename Partial_Function> void **map_space_dimensions** (const Partial_Function &pfunc)
Remaps the dimensions of the vector space according to a partial function.

Friends

- bool **operator==** (const **Determinate**< PH > &x, const **Determinate**< PH > &y)
Returns true if and only if x and y are the same domain element.
- bool **operator!=** (const **Determinate**< PH > &x, const **Determinate**< PH > &y)
Returns true if and only if x and y are different domain elements.

Related Functions

(Note that these are not member functions.)

- std::ostream & **operator<<** (std::ostream &, const **Determinate**< PH > &)
Output operator.
- void **swap** (Parma_Polyhedra_Library::Determinate< PH > &x, Parma_Polyhedra_Library::Determinate< PH > &y)
Specializes std::swap.

11.6.1 Detailed Description

template<typename PH> class Parma_Polyhedra_Library::Determinate< PH >

Wraps a PPL class into a determinate constraint system interface.

11.6.2 Constructor & Destructor Documentation

11.6.2.1 template<typename PH> Parma_Polyhedra_Library::Determinate< PH >::Determinate (dimension_type num_dimensions = 0, bool universe = true) [explicit]

Builds either the top or the bottom of the determinate constraint system defined on the vector space having num_dimensions dimensions.

The top element, corresponding to the whole vector space, is built if `universe` is `true`; otherwise the bottom element, corresponding to the emptyset, is built. By default, the top of a zero-dimension vector space is built.

11.6.3 Member Function Documentation

11.6.3.1 `template<typename PH> void Parma_Polyhedra_Library::Determinate< PH >::add_constraint (const Constraint & c)`

Assigns to `*this` the meet of `*this` and the element represented by constraint `c`.

Exceptions:

std::invalid_argument Thrown if `*this` and constraint `c` are topology-incompatible or dimension-incompatible.

11.6.3.2 `template<typename PH> void Parma_Polyhedra_Library::Determinate< PH >::add_constraints (Constraint_System & cs)`

Assigns to `*this` the meet of `*this` and the element represented by the constraints in `cs`.

Parameters:

`cs` The constraints to intersect with. This parameter is not declared `const` because it can be modified.

Exceptions:

std::invalid_argument Thrown if `*this` and `cs` are topology-incompatible or dimension-incompatible.

11.6.3.3 `template<typename PH> void Parma_Polyhedra_Library::Determinate< PH >::remove_space_dimensions (const Variables_Set & to_be_removed)`

Removes all the specified space dimensions.

Parameters:

`to_be_removed` The set of `Variable`(p. 152) objects corresponding to the space dimensions to be removed.

Exceptions:

std::invalid_argument Thrown if `*this` is dimension-incompatible with one of the `Variable`(p. 152) objects contained in `to_be_removed`.

11.6.3.4 `template<typename PH> void Parma_Polyhedra_Library::Determinate< PH >::remove_higher_space_dimensions (dimension_type new_dimension)`

Removes the higher space dimensions so that the resulting space will have dimension `new_dimension`.

Exceptions:

std::invalid_argument Thrown if `new_dimensions` is greater than the space dimension of `*this`.

11.6.3.5 `template<typename PH> template<typename Partial_Function> void Parma_Polyhedra_Library::Determinate< PH >::map_space_dimensions (const Partial_Function & pfunc)`

Remaps the dimensions of the vector space according to a partial function.

See `Polyhedron::map_space_dimensions`.

11.6.4 Friends And Related Function Documentation

11.6.4.1 `template<typename PH> bool operator== (const Determinate< PH > & x, const Determinate< PH > & y) [friend]`

Returns `true` if and only if `x` and `y` are the same domain element.

Exceptions:

`std::invalid_argument` Thrown if `x` and `y` are topology-incompatible or dimension-incompatible.

11.6.4.2 `template<typename PH> bool operator!= (const Determinate< PH > & x, const Determinate< PH > & y) [friend]`

Returns `true` if and only if `x` and `y` are different domain elements.

Exceptions:

`std::invalid_argument` Thrown if `x` and `y` are topology-incompatible or dimension-incompatible.

11.7 Parma_Polyhedra_Library::Generator Class Reference

A line, ray, point or closure point.

Public Types

- `enum Type { LINE, RAY, POINT, CLOSURE_POINT }`
The generator type.

Public Member Functions

- `Generator (const Generator &g)`
Ordinary copy-constructor.
- `~Generator ()`
Destructor.
- `Generator & operator= (const Generator &g)`
Assignment operator.
- `dimension_type space_dimension () const`
*Returns the dimension of the vector space enclosing *this.*

- **Type type () const**
*Returns the generator type of *this.*
- **bool is_line () const**
*Returns true if and only if *this is a line.*
- **bool is_ray () const**
*Returns true if and only if *this is a ray.*
- **bool is_point () const**
*Returns true if and only if *this is a point.*
- **bool is_closure_point () const**
*Returns true if and only if *this is a closure point.*
- **Coefficient_traits::const_reference coefficient (Variable v) const**
*Returns the coefficient of v in *this.*
- **Coefficient_traits::const_reference divisor () const**
*If *this is either a point or a closure point, returns its divisor.*
- **memory_size_type total_memory_in_bytes () const**
*Returns a lower bound to the total size in bytes of the memory occupied by *this.*
- **memory_size_type external_memory_in_bytes () const**
*Returns the size in bytes of the memory managed by *this.*
- **bool OK () const**
Checks if all the invariants are satisfied.

Static Public Member Functions

- **Generator line (const Linear_Expression &e)**
Shorthand for Generator(p. 94) Generator::line(const Linear_Expression& e)(p. 99).
- **Generator ray (const Linear_Expression &e)**
Shorthand for Generator(p. 94) Generator::ray(const Linear_Expression& e)(p. 99).
- **Generator point (const Linear_Expression &e=Linear_Expression::zero(), Coefficient_traits::const_reference d=Coefficient_one())**
Shorthand for Generator(p. 94) Generator::point(const Linear_Expression& e, Coefficient_traits::const_reference d)(p. 99).
- **Generator closure_point (const Linear_Expression &e=Linear_Expression::zero(), Coefficient_traits::const_reference d=Coefficient_one())**
Shorthand for Generator(p. 94) Generator::closure_point(const Linear_Expression& e, Coefficient_traits::const_reference d)(p. 99).
- **dimension_type max_space_dimension ()**

Returns the maximum space dimension a **Generator**(p. 94) can handle.

- `const Generator & zero_dim_point ()`

Returns the origin of the zero-dimensional space \mathbb{R}^0 .

- `const Generator & zero_dim_closure_point ()`

Returns, as a closure point, the origin of the zero-dimensional space \mathbb{R}^0 .

Related Functions

(Note that these are not member functions.)

- `std::ostream & operator<< (std::ostream &s, const Generator &g)`

Output operator.

- `void swap (Parma_Polyhedra_Library::Generator &x, Parma_Polyhedra_Library::Generator &y)`

Specializes `std::swap`.

11.7.1 Detailed Description

A line, ray, point or closure point.

An object of the class **Generator**(p. 94) is one of the following:

- a line $l = (a_0, \dots, a_{n-1})^T$;
- a ray $r = (a_0, \dots, a_{n-1})^T$;
- a point $p = (\frac{a_0}{d}, \dots, \frac{a_{n-1}}{d})^T$;
- a closure point $c = (\frac{a_0}{d}, \dots, \frac{a_{n-1}}{d})^T$;

where n is the dimension of the space and, for points and closure points, $d > 0$ is the divisor.

A note on terminology.

As observed in Section **Representations of Convex Polyhedra**(p. 4), there are cases when, in order to represent a polyhedron \mathcal{P} using the generator system $\mathcal{G} = (L, R, P, C)$, we need to include in the finite set P even points of \mathcal{P} that are *not* vertices of \mathcal{P} . This situation is even more frequent when working with NNC polyhedra and it is the reason why we prefer to use the word ‘point’ where other libraries use the word ‘vertex’.

How to build a generator.

Each type of generator is built by applying the corresponding function (line, ray, point or closure_point) to a linear expression, representing a direction in the space; the space dimension of the generator is defined as the space dimension of the corresponding linear expression. Linear expressions used to define a generator should be homogeneous (any constant term will be simply ignored). When defining points and closure points, an optional Coefficient argument can be used as a common *divisor* for all the coefficients occurring in the provided linear expression; the default value for this argument is 1.

In all the following examples it is assumed that variables x , y and z are defined as follows:

```
Variable x(0);
Variable y(1);
Variable z(2);
```

Example 1

The following code builds a line with direction $x - y - z$ and having space dimension 3:

```
Generator l = line(x - y - z);
```

As mentioned above, the constant term of the linear expression is not relevant. Thus, the following code has the same effect:

```
Generator l = line(x - y - z + 15);
```

By definition, the origin of the space is not a line, so that the following code throws an exception:

```
Generator l = line(0*x);
```

Example 2

The following code builds a ray with the same direction as the line in Example 1:

```
Generator r = ray(x - y - z);
```

As is the case for lines, when specifying a ray the constant term of the linear expression is not relevant; also, an exception is thrown when trying to build a ray from the origin of the space.

Example 3

The following code builds the point $p = (1, 0, 2)^T \in \mathbb{R}^3$:

```
Generator p = point(1*x + 0*y + 2*z);
```

The same effect can be obtained by using the following code:

```
Generator p = point(x + 2*z);
```

Similarly, the origin $0 \in \mathbb{R}^3$ can be defined using either one of the following lines of code:

```
Generator origin3 = point(0*x + 0*y + 0*z);
Generator origin3_alt = point(0*z);
```

Note however that the following code would have defined a different point, namely $0 \in \mathbb{R}^2$:

```
Generator origin2 = point(0*y);
```

The following two lines of code both define the only point having space dimension zero, namely $0 \in \mathbb{R}^0$. In the second case we exploit the fact that the first argument of the function `point` is optional.

```
Generator origin0 = Generator::zero_dim_point();
Generator origin0_alt = point();
```

Example 4

The point p specified in Example 3 above can also be obtained with the following code, where we provide a non-default value for the second argument of the function `point` (the divisor):

```
Generator p = point(2*x + 0*y + 4*z, 2);
```

Obviously, the divisor can be usefully exploited to specify points having some non-integer (but rational) coordinates. For instance, the point $q = (-1.5, 3.2, 2.1)^T \in \mathbb{R}^3$ can be specified by the following code:

```
Generator q = point(-15*x + 32*y + 21*z, 10);
```

If a zero divisor is provided, an exception is thrown.

Example 5

Closures points are specified in the same way we defined points, but invoking their specific constructor function. For instance, the closure point $c = (1, 0, 2)^T \in \mathbb{R}^3$ is defined by

```
Generator c = closure_point(1*x + 0*y + 2*z);
```

For the particular case of the (only) closure point having space dimension zero, we can use any of the following:

```
Generator closure_origin0 = Generator::zero_dim_closure_point();
Generator closure_origin0_alt = closure_point();
```

How to inspect a generator

Several methods are provided to examine a generator and extract all the encoded information: its space dimension, its type and the value of its integer coefficients.

Example 6

The following code shows how it is possible to access each single coefficient of a generator. If g_1 is a point having coordinates $(a_0, \dots, a_{n-1})^T$, we construct the closure point g_2 having coordinates $(a_0, 2a_1, \dots, (i+1)a_i, \dots, na_{n-1})^T$.

```
if (g1.is_point()) {
    cout << "Point g1: " << g1 << endl;
    Linear_Expression e;
    for (int i = g1.space_dimension() - 1; i >= 0; i--)
        e += (i + 1) * g1.coefficient(Variable(i)) * Variable(i);
    Generator g2 = closure_point(e, g1.divisor());
    cout << "Closure point g2: " << g2 << endl;
}
else
    cout << "Generator g1 is not a point." << endl;
```

Therefore, for the point

```
Generator g1 = point(2*x - y + 3*z, 2);
```

we would obtain the following output:

```
Point g1: p((2*A - B + 3*C)/2)
Closure point g2: cp((2*A - 2*B + 9*C)/2)
```

When working with (closure) points, be careful not to confuse the notion of *coefficient* with the notion of *coordinate*: these are equivalent only when the divisor of the (closure) point is 1.

11.7.2 Member Enumeration Documentation

11.7.2.1 enum Parma_Polyhedra_Library::Generator::Type

The generator type.

Enumeration values:

LINE The generator is a line.

RAY The generator is a ray.

POINT The generator is a point.

CLOSURE_POINT The generator is a closure point.

11.7.3 Member Function Documentation

11.7.3.1 Generator line (const Linear_Expression & e) [static]

Shorthand for `Generator(p. 94) Generator::line(const Linear_Expression& e)(p. 99)`.

Exceptions:

std::invalid_argument Thrown if the homogeneous part of e represents the origin of the vector space.

11.7.3.2 Generator ray (const Linear_Expression & e) [static]

Shorthand for `Generator(p. 94) Generator::ray(const Linear_Expression& e)(p. 99)`.

Exceptions:

std::invalid_argument Thrown if the homogeneous part of e represents the origin of the vector space.

11.7.3.3 Generator point (const Linear_Expression & e = Linear_Expression::zero(), Coefficient_traits::const_reference d = Coefficient_one()) [static]

Shorthand for `Generator(p. 94) Generator::point(const Linear_Expression& e, Coefficient_traits::const_reference d)(p. 99)`.

Both e and d are optional arguments, with default values `Linear_Expression::zero()(p. 102)` and `Coefficient_one()`, respectively.

Exceptions:

std::invalid_argument Thrown if d is zero.

11.7.3.4 Generator closure_point (const Linear_Expression & e = Linear_Expression::zero(), Coefficient_traits::const_reference d = Coefficient_one()) [static]

Shorthand for `Generator(p. 94) Generator::closure_point(const Linear_Expression& e, Coefficient_traits::const_reference d)(p. 99)`.

Both e and d are optional arguments, with default values `Linear_Expression::zero()(p. 102)` and `Coefficient_one()`, respectively.

Exceptions:

std::invalid_argument Thrown if d is zero.

11.7.3.5 Coefficient_traits::const_reference Parma_Polyhedra_Library::Generator::coefficient (Variable v) const

Returns the coefficient of v in *this.

Exceptions:

std::invalid_argument Thrown if the index of v is greater than or equal to the space dimension of *this.

11.7.3.6 Coefficient_traits::const_reference Parma_Polyhedra_Library::Generator::divisor () const

If `*this` is either a point or a closure point, returns its divisor.

Exceptions:

std::invalid_argument Thrown if `*this` is neither a point nor a closure point.

11.8 Parma_Polyhedra_Library::H79_Certificate Class Reference

A convergence certificate for the H79 widening operator.

Public Member Functions

- **H79_Certificate** ()
Default constructor.
- **H79_Certificate** (const **Polyhedron** &ph)
Constructor: computes the certificate for ph.
- **H79_Certificate** (const **H79_Certificate** &y)
Copy constructor.
- **~H79_Certificate** ()
Destructor.
- int **compare** (const **H79_Certificate** &y) const
The comparison function for certificates.
- int **compare** (const **Polyhedron** &ph) const
*Compares *this with the certificate for polyhedron ph.*

Classes

- struct **Compare**
A total ordering on H79 certificates.

11.8.1 Detailed Description

A convergence certificate for the H79 widening operator.

Convergence certificates are used to instantiate the BHZ03 framework so as to define widening operators for the finite powerset domain.

Note:

The convergence of the H79 widening can also be certified by **BHRZ03_Certificate**(p. 76).

11.8.2 Member Function Documentation

11.8.2.1 `int Parma_Polyhedra_Library::H79_Certificate::compare (const H79_Certificate & y) const`

The comparison function for certificates.

Returns:

−1, 0 or 1 depending on whether `*this` is smaller than, equal to, or greater than `y`, respectively.

Compares `*this` with `y`, using a total ordering which is a refinement of the limited growth ordering relation for the H79 widening.

11.9 Parma_Polyhedra_Library::H79_Certificate::Compare Struct Reference

A total ordering on H79 certificates.

Public Member Functions

- `bool operator() (const H79_Certificate &x, const H79_Certificate &y) const`
Returns true if and only if x comes before y.

11.9.1 Detailed Description

A total ordering on H79 certificates.

This binary predicate defines a total ordering on H79 certificates which is used when storing information about sets of polyhedra.

11.10 Parma_Polyhedra_Library::Linear_Expression Class Reference

A linear expression.

Public Member Functions

- `Linear_Expression ()`
Default constructor: returns a copy of `Linear_Expression::zero()` (p. 102).
- `Linear_Expression (const Linear_Expression &e)`
Ordinary copy-constructor.
- `~Linear_Expression ()`
Destructor.
- `Linear_Expression (Coefficient_traits::const_reference n)`
Builds the linear expression corresponding to the inhomogeneous term `n`.
- `Linear_Expression (const Constraint &c)`

Builds the linear expression corresponding to constraint c .

- **Linear_Expression** (const **Generator** &g)

Builds the linear expression corresponding to generator g (for points and closure points, the divisor is not copied).

- dimension_type **space_dimension** () const

*Returns the dimension of the vector space enclosing $*this$.*

- Coefficient_traits::const_reference **coefficient** (**Variable** v) const

*Returns the coefficient of v in $*this$.*

- Coefficient_traits::const_reference **inhomogeneous_term** () const

*Returns the inhomogeneous term of $*this$.*

- memory_size_type **total_memory_in_bytes** () const

*Returns a lower bound to the total size in bytes of the memory occupied by $*this$.*

- memory_size_type **external_memory_in_bytes** () const

*Returns the size in bytes of the memory managed by $*this$.*

- bool **OK** () const

Checks if all the invariants are satisfied.

Static Public Member Functions

- dimension_type **max_space_dimension** ()

*Returns the maximum space dimension a **Linear_Expression**(p. 101) can handle.*

- const **Linear_Expression** & **zero** ()

Returns the (zero-dimension space) constant 0.

Related Functions

(Note that these are not member functions.)

- **Linear_Expression** (const **Variable** v)

Builds the linear expression corresponding to the variable v .

- **Linear_Expression** operator+ (const **Linear_Expression** &e1, const **Linear_Expression** &e2)

Returns the linear expression $e1 + e2$.

- **Linear_Expression** operator+ (Coefficient_traits::const_reference n, const **Linear_Expression** &e)

Returns the linear expression $n + e$.

- **Linear_Expression** operator+ (const **Linear_Expression** &e, Coefficient_traits::const_reference n)

Returns the linear expression $e + n$.

- **Linear_Expression operator+** (const **Linear_Expression** &e)
Returns the linear expression e .
- **Linear_Expression operator-** (const **Linear_Expression** &e)
Returns the linear expression $-e$.
- **Linear_Expression operator-** (const **Linear_Expression** &e1, const **Linear_Expression** &e2)
Returns the linear expression $e1 - e2$.
- **Linear_Expression operator-** (Coefficient_traits::const_reference n, const **Linear_Expression** &e)
Returns the linear expression $n - e$.
- **Linear_Expression operator-** (const **Linear_Expression** &e, Coefficient_traits::const_reference n)
Returns the linear expression $e - n$.
- **Linear_Expression operator *** (Coefficient_traits::const_reference n, const **Linear_Expression** &e)
*Returns the linear expression $n * e$.*
- **Linear_Expression operator *** (const **Linear_Expression** &e, Coefficient_traits::const_reference n)
*Returns the linear expression $e * n$.*
- **Linear_Expression & operator+=** (**Linear_Expression** &e1, const **Linear_Expression** &e2)
Returns the linear expression $e1 + e2$ and assigns it to $e1$.
- **Linear_Expression & operator+=** (**Linear_Expression** &e, const **Variable** v)
Returns the linear expression $e + v$ and assigns it to e .
- **Linear_Expression & operator+=** (**Linear_Expression** &e, Coefficient_traits::const_reference n)
Returns the linear expression $e + n$ and assigns it to e .
- **Linear_Expression & operator-=** (**Linear_Expression** &e1, const **Linear_Expression** &e2)
Returns the linear expression $e1 - e2$ and assigns it to $e1$.
- **Linear_Expression & operator-=** (**Linear_Expression** &e, const **Variable** v)
Returns the linear expression $e - v$ and assigns it to e .
- **Linear_Expression & operator-=** (**Linear_Expression** &e, Coefficient_traits::const_reference n)
Returns the linear expression $e - n$ and assigns it to e .
- **Linear_Expression & operator*=** (**Linear_Expression** &e, Coefficient_traits::const_reference n)
*Returns the linear expression $n * e$ and assigns it to e .*
- **std::ostream & operator<<** (std::ostream &s, const **Linear_Expression** &e)
Output operator.
- **void swap** (**Parma_Polyhedra_Library::Linear_Expression** &x, **Parma_Polyhedra_Library::Linear_Expression** &y)

Specializes std::swap.

11.10.1 Detailed Description

A linear expression.

An object of the class **Linear_Expression**(p. 101) represents the linear expression

$$\sum_{i=0}^{n-1} a_i x_i + b$$

where n is the dimension of the vector space, each a_i is the integer coefficient of the i -th variable x_i and b is the integer for the inhomogeneous term.

How to build a linear expression.

Linear expressions are the basic blocks for defining both constraints (i.e., linear equalities or inequalities) and generators (i.e., lines, rays, points and closure points). A full set of functions is defined to provide a convenient interface for building complex linear expressions starting from simpler ones and from objects of the classes **Variable**(p. 152) and **Coefficient**: available operators include unary negation, binary addition and subtraction, as well as multiplication by a **Coefficient**. The space dimension of a linear expression is defined as the maximum space dimension of the arguments used to build it: in particular, the space dimension of a **Variable**(p. 152) x is defined as $x.id() + 1$, whereas all the objects of the class **Coefficient** have space dimension zero.

Example

The following code builds the linear expression $4x - 2y - z + 14$, having space dimension 3:

```
Linear_Expression e = 4*x - 2*y - z + 14;
```

Another way to build the same linear expression is:

```
Linear_Expression e1 = 4*x;
Linear_Expression e2 = 2*y;
Linear_Expression e3 = z;
Linear_Expression e = Linear_Expression(14);
e += e1 - e2 - e3;
```

Note that $e1$, $e2$ and $e3$ have space dimension 1, 2 and 3, respectively; also, in the fourth line of code, e is created with space dimension zero and then extended to space dimension 3 in the fifth line.

11.10.2 Constructor & Destructor Documentation

11.10.2.1 Parma_Polyhedra_Library::Linear_Expression::Linear_Expression (const Constraint & c) [explicit]

Builds the linear expression corresponding to constraint c .

Given the constraint $c = (\sum_{i=0}^{n-1} a_i x_i + b \bowtie 0)$, where $\bowtie \in \{=, \geq, >\}$, this builds the linear expression $\sum_{i=0}^{n-1} a_i x_i + b$. If c is an inequality (resp., equality) constraint, then the built linear expression is unique up to a positive (resp., non-zero) factor.

11.10.2.2 Parma_Polyhedra_Library::Linear_Expression::Linear_Expression (const Generator & g) [explicit]

Builds the linear expression corresponding to generator g (for points and closure points, the divisor is not copied).

Given the generator $g = (\frac{a_0}{d}, \dots, \frac{a_{n-1}}{d})^T$ (where, for lines and rays, we have $d = 1$), this builds the linear expression $\sum_{i=0}^{n-1} a_i x_i$. The inhomogeneous term of the linear expression will always be 0. If g is a ray, point or closure point (resp., a line), then the linear expression is unique up to a positive (resp., non-zero) factor.

11.10.3 Friends And Related Function Documentation

11.10.3.1 Linear_Expression (const Variable v) [related]

Builds the linear expression corresponding to the variable v .

Exceptions:

std::length_error Thrown if the space dimension of v exceeds **Linear_Expression::max_space_dimension()**(p. 102).

11.10.3.2 Linear_Expression & operator+= (Linear_Expression & e, const Variable v) [related]

Returns the linear expression $e + v$ and assigns it to e .

Exceptions:

std::length_error Thrown if the space dimension of v exceeds **Linear_Expression::max_space_dimension()**(p. 102).

11.10.3.3 Linear_Expression & operator-= (Linear_Expression & e, const Variable v) [related]

Returns the linear expression $e - v$ and assigns it to e .

Exceptions:

std::length_error Thrown if the space dimension of v exceeds **Linear_Expression::max_space_dimension()**(p. 102).

11.11 Parma_Polyhedra_Library::Native_Integer< T > Class Template Reference

A wrapper for unchecked native integer types.

Public Member Functions

Constructors

- **Native_Integer ()**
Default constructor.

- **Native_Integer** (const signed char y)
Direct initialization from a signed char value.
- **Native_Integer** (const short y)
Direct initialization from a signed short value.
- **Native_Integer** (const int y)
Direct initialization from an signed int value.
- **Native_Integer** (const long y)
Direct initialization from a signed long value.
- **Native_Integer** (const long long y)
Direct initialization from a signed long long value.
- **Native_Integer** (const unsigned char y)
Direct initialization from an unsigned char value.
- **Native_Integer** (const unsigned short y)
Direct initialization from an unsigned short value.
- **Native_Integer** (const unsigned int y)
Direct initialization from an unsigned int value.
- **Native_Integer** (const unsigned long y)
Direct initialization from an unsigned long value.
- **Native_Integer** (const unsigned long long y)
Direct initialization from an unsigned long long value.
- **Native_Integer** (const float32_t y)
Direct initialization from a 32 bits floating-point value.
- **Native_Integer** (const float64_t y)
Direct initialization from a 64 bits floating-point value.
- **Native_Integer** (const mpq_class &y)
Direct initialization from a GMP unbounded rational value.
- **Native_Integer** (const mpz_class &y)
Direct initialization from a GMP unbounded integer value.
- **Native_Integer** (const char *y)
Direct initialization from a C string value.

Accessors and Conversions

- **operator T ()** const
Conversion operator: returns a copy of the underlying native integer value.
- **T & raw_value ()**
Returns a reference to the underlying native integer value.

- **const T & raw_value () const**
Returns a const reference to the underlying native integer value.

Assignment Operators

- **Native_Integer & operator= (const Native_Integer &y)**
Assignment operator.
- **Native_Integer & operator+= (const Native_Integer &y)**
Add and assign operator.
- **Native_Integer & operator-= (const Native_Integer &y)**
Subtract and assign operator.
- **Native_Integer & operator *= (const Native_Integer &y)**
Multiply and assign operator.
- **Native_Integer & operator /= (const Native_Integer &y)**
Divide and assign operator.
- **Native_Integer & operator %= (const Native_Integer &y)**
Compute modulus and assign operator.

Increment and Decrement Operators

- **Native_Integer & operator++ ()**
Pre-increment operator.
- **Native_Integer operator++ (int)**
Post-increment operator.
- **Native_Integer & operator-- ()**
Pre-decrement operator.
- **Native_Integer operator-- (int)**
Post-decrement operator.

Related Functions

(Note that these are not member functions.)

Accessor Functions

- **const T & raw_value (const Native_Integer< T > &x)**
Returns a const reference to the underlying native integer value.
- **T & raw_value (Native_Integer< T > &x)**
Returns a reference to the underlying native integer value.

Memory Size Inspection Functions

- **size_t total_memory_in_bytes** (const Native_Integer< T > &x)
Returns the total size in bytes of the memory occupied by x.
- **size_t external_memory_in_bytes** (const Native_Integer< T > &x)
Returns the size in bytes of the memory managed by x.

Arithmetic Operators

- **Native_Integer< T > operator+** (const Native_Integer< T > &x)
Unary plus operator.
- **Native_Integer< T > operator-** (const Native_Integer< T > &x)
Unary minus operator.
- **Native_Integer< T > operator+** (const Native_Integer< T > &x, const Native_Integer< T > &y)
Addition operator.
- **Native_Integer< T > operator-** (const Native_Integer< T > &x, const Native_Integer< T > &y)
Subtraction operator.
- **Native_Integer< T > operator *** (const Native_Integer< T > &x, const Native_Integer< T > &y)
Multiplication operator.
- **Native_Integer< T > operator/** (const Native_Integer< T > &x, const Native_Integer< T > &y)
Integer division operator.
- **Native_Integer< T > operator%** (const Native_Integer< T > &x, const Native_Integer< T > &y)
Modulus operator.
- **void negate** (Native_Integer< T > &x)
Assigns to x its negation.
- **void add_mul_assign** (Native_Integer< T > &x, const Native_Integer< T > &y, const Native_Integer< T > &z)
*Assigns to x the value $x + y * z$.*
- **void sub_mul_assign** (Native_Integer< T > &x, const Native_Integer< T > &y, const Native_Integer< T > &z)
*Assigns to x the value $x - y * z$.*
- **void gcd_assign** (Native_Integer< T > &x, const Native_Integer< T > &y)
Assigns to x the greatest common divisor of x and y.
- **void gcd_assign** (Native_Integer< T > &x, const Native_Integer< T > &y, const Native_Integer< T > &z)

Assigns to x the greatest common divisor of y and z.

- **void lcm_assign (Native_Integer< T > &x, const Native_Integer< T > &y)**
Assigns to x the least common multiple of x and y.
- **void lcm_assign (Native_Integer< T > &x, const Native_Integer< T > &y, const Native_Integer< T > &z)**
Assigns to x the least common multiple of y and z.
- **void exact_div_assign (Native_Integer< T > &x, const Native_Integer< T > &y)**
Assigns to x the integer division of x and y.
- **void exact_div_assign (Native_Integer< T > &x, const Native_Integer< T > &y, const Native_Integer< T > &z)**
Assigns to x the integer division of y and z.
- **void sqrt_assign (Native_Integer< T > &x)**
Assigns to x its integer square root.
- **void sqrt_assign (Native_Integer< T > &x, const Native_Integer< T > &y)**
Assigns to x the integer square root of y.

Relational Operators and Comparison Functions

- **bool operator== (const Native_Integer< T > &x, const Native_Integer< T > &y)**
Equality operator.
- **bool operator!= (const Native_Integer< T > &x, const Native_Integer< T > &y)**
Disequality operator.
- **bool operator>= (const Native_Integer< T > &x, const Native_Integer< T > &y)**
Greater than or equal to operator.
- **bool operator> (const Native_Integer< T > &x, const Native_Integer< T > &y)**
Greater than operator.
- **bool operator<= (const Native_Integer< T > &x, const Native_Integer< T > &y)**
Less than or equal to operator.
- **bool operator< (const Native_Integer< T > &x, const Native_Integer< T > &y)**
Less than operator.
- **int sgn (const Native_Integer< T > &x)**
Returns -1, 0 or 1 depending on whether the value of x is negative, zero or positive, respectively.
- **int cmp (const Native_Integer< T > &x, const Native_Integer< T > &y)**
Returns a negative, zero or positive value depending on whether x is lower than, equal to or greater than y, respectively.

Input-Output Operators

- **std::ostream & operator<< (std::ostream &os, const Native_Integer< T > &x)**
Output operator.
- **std::istream & operator>> (std::istream &is, Native_Integer< T > &x)**
Input operator.

11.11.1 Detailed Description

template<typename T> class Parma_Polyhedra_Library::Native_Integer< T >

A wrapper for unchecked native integer types.

The wrapper and related functions implement an interface which is common to all kinds of coefficient types, therefore allowing for a uniform coding style.

Warning:

Native integer coefficients do not check for overflows and therefore are likely to produce unreliable results. We are currently using them as a tool to estimate the overhead incurred by the *checked* integral types.

11.12 Parma_Polyhedra_Library::NNC_Polyhedron Class Reference

A not necessarily closed convex polyhedron.

Inherits **Parma_Polyhedra_Library::Polyhedron**.

Public Member Functions

- **NNC_Polyhedron** (dimension_type num_dimensions=0, **Degenerate_Kind** kind=UNIVERSE)
Builds either the universe or the empty NNC polyhedron.
- **NNC_Polyhedron** (const Constraint_System &cs)
Builds an NNC polyhedron from a system of constraints.
- **NNC_Polyhedron** (Constraint_System &cs)
Builds an NNC polyhedron recycling a system of constraints.
- **NNC_Polyhedron** (const Generator_System &gs)
Builds an NNC polyhedron from a system of generators.
- **NNC_Polyhedron** (Generator_System &gs)
Builds an NNC polyhedron recycling a system of generators.
- **NNC_Polyhedron** (const C_Polyhedron &y)
Builds an NNC polyhedron from the C polyhedron y.
- **template<typename Box> NNC_Polyhedron** (const Box &box, From_Bounding_Box dummy)
Builds an NNC polyhedron out of a generic, interval-based bounding box.
- **NNC_Polyhedron** (const NNC_Polyhedron &y)
Ordinary copy-constructor.
- **NNC_Polyhedron & operator=** (const NNC_Polyhedron &y)
*The assignment operator. (*this and y can be dimension-incompatible.).*
- **NNC_Polyhedron & operator=** (const C_Polyhedron &y)
*Assigns to *this the C polyhedron y.*

- `~NNC_Polyhedron()`

Destructor.

11.12.1 Detailed Description

A not necessarily closed convex polyhedron.

An object of the class **NNC_Polyhedron**(p. 110) represents a *not necessarily closed* (NNC) convex polyhedron in the vector space \mathbb{R}^n .

Note:

Since NNC polyhedra are a generalization of closed polyhedra, any object of the class **C_Polyhedron**(p. 78) can be (explicitly) converted into an object of the class **NNC_Polyhedron**(p. 110). The reason for defining two different classes is that objects of the class **C_Polyhedron**(p. 78) are characterized by a more efficient implementation, requiring less time and memory resources.

11.12.2 Constructor & Destructor Documentation

11.12.2.1 Parma_Polyhedra_Library::NNC_Polyhedron::NNC_Polyhedron (dimension_type num_dimensions = 0, Degenerate_Kind kind = UNIVERSE) [explicit]

Builds either the universe or the empty NNC polyhedron.

Parameters:

num_dimensions The number of dimensions of the vector space enclosing the NNC polyhedron;
kind Specifies whether a universe or an empty NNC polyhedron should be built.

Exceptions:

std::length_error Thrown if num_dimensions exceeds the maximum allowed space dimension.

Both parameters are optional: by default, a 0-dimension space universe NNC polyhedron is built.

11.12.2.2 Parma_Polyhedra_Library::NNC_Polyhedron::NNC_Polyhedron (const Constraint_System & cs) [explicit]

Builds an NNC polyhedron from a system of constraints.

The polyhedron inherits the space dimension of the constraint system.

Parameters:

cs The system of constraints defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

11.12.2.3 Parma_Polyhedra_Library::NNC_Polyhedron::NNC_Polyhedron (Constraint_System & cs) [explicit]

Builds an NNC polyhedron recycling a system of constraints.

The polyhedron inherits the space dimension of the constraint system.

Parameters:

cs The system of constraints defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

11.12.2.4 Parma_Polyhedra_Library::NNC_Polyhedron::NNC_Polyhedron (const Generator_System & *gs*) [explicit]

Builds an NNC polyhedron from a system of generators.

The polyhedron inherits the space dimension of the generator system.

Parameters:

gs The system of generators defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

Exceptions:

std::invalid_argument Thrown if the system of generators is not empty but has no points.

11.12.2.5 Parma_Polyhedra_Library::NNC_Polyhedron::NNC_Polyhedron (Generator_System & *gs*) [explicit]

Builds an NNC polyhedron recycling a system of generators.

The polyhedron inherits the space dimension of the generator system.

Parameters:

gs The system of generators defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

Exceptions:

std::invalid_argument Thrown if the system of generators is not empty but has no points.

11.12.2.6 template<typename Box> Parma_Polyhedra_Library::NNC_Polyhedron::NNC_Polyhedron (const Box & *box*, From_Bounding_Box *dummy*)

Builds an NNC polyhedron out of a generic, interval-based bounding box.

For a description of the methods that should be provided by the template class `Box`, see the documentation of the protected method: `template <typename Box> Polyhedron::Polyhedron(Topology topol, const Box& box)(p. 133);`

Parameters:

box The bounding box representing the polyhedron to be built;

dummy A dummy tag to syntactically differentiate this one from the other constructors.

Exceptions:

std::length_error Thrown if the space dimension of `box` exceeds the maximum allowed space dimension.

11.13 Parma_Polyhedra_Library::Poly_Con_Relation Class Reference

The relation between a polyhedron and a constraint.

Public Member Functions

- **bool implies** (const **Poly_Con_Relation** &y) const
*True if and only if *this implies y.*
- **bool OK** () const
Checks if all the invariants are satisfied.

Static Public Member Functions

- **Poly_Con_Relation nothing** ()
The assertion that says nothing.
- **Poly_Con_Relation is_disjoint** ()
The polyhedron and the set of points satisfying the constraint are disjoint.
- **Poly_Con_Relation strictly_intersects** ()
The polyhedron intersects the set of points satisfying the constraint, but it is not included in it.
- **Poly_Con_Relation is_included** ()
The polyhedron is included in the set of points satisfying the constraint.
- **Poly_Con_Relation saturates** ()
The polyhedron is included in the set of points saturating the constraint.

Related Functions

(Note that these are not member functions.)

- **bool operator==** (const **Poly_Con_Relation** &x, const **Poly_Con_Relation** &y)
True if and only if x and y are logically equivalent.
- **bool operator!=** (const **Poly_Con_Relation** &x, const **Poly_Con_Relation** &y)
True if and only if x and y are not logically equivalent.
- **Poly_Con_Relation operator &&** (const **Poly_Con_Relation** &x, const **Poly_Con_Relation** &y)
Yields the logical conjunction of x and y.
- **Poly_Con_Relation operator-** (const **Poly_Con_Relation** &x, const **Poly_Con_Relation** &y)
Yields the assertion with all the conjuncts of x that are not in y.
- **std::ostream & operator<<** (std::ostream &s, const **Poly_Con_Relation** &r)
Output operator.

11.13.1 Detailed Description

The relation between a polyhedron and a constraint.

This class implements conjunctions of assertions on the relation between a polyhedron and a constraint.

11.14 Parma_Polyhedra_Library::Poly_Gen_Relation Class Reference

The relation between a polyhedron and a generator.

Public Member Functions

- **bool implies** (const **Poly_Gen_Relation** &y) const
*True if and only if *this implies y.*
- **bool OK** () const
Checks if all the invariants are satisfied.

Static Public Member Functions

- **Poly_Gen_Relation nothing** ()
The assertion that says nothing.
- **Poly_Gen_Relation subsumes** ()
Adding the generator would not change the polyhedron.

Related Functions

(Note that these are not member functions.)

- **bool operator==** (const **Poly_Gen_Relation** &x, const **Poly_Gen_Relation** &y)
True if and only if x and y are logically equivalent.
- **bool operator!=** (const **Poly_Gen_Relation** &x, const **Poly_Gen_Relation** &y)
True if and only if x and y are not logically equivalent.
- **Poly_Gen_Relation operator &&** (const **Poly_Gen_Relation** &x, const **Poly_Gen_Relation** &y)
Yields the logical conjunction of x and y.
- **Poly_Gen_Relation operator-** (const **Poly_Gen_Relation** &x, const **Poly_Gen_Relation** &y)
Yields the assertion with all the conjuncts of x that are not in y.
- **std::ostream & operator<<** (std::ostream &s, const **Poly_Gen_Relation** &r)
Output operator.

11.14.1 Detailed Description

The relation between a polyhedron and a generator.

This class implements conjunctions of assertions on the relation between a polyhedron and a generator.

11.15 Parma_Polyhedra_Library::Polyhedra_Powerset< PH > Class Template Reference

The powerset construction instantiated on PPL polyhedra.

Inherits **Parma_Polyhedra_Library::Powerset< Parma_Polyhedra_Library::Determinate< PH >**.

Public Member Functions

Constructors

- **Polyhedra_Powerset** (dimension_type num_dimensions=0, **Polyhedron::Degenerate_Kind** kind=**Polyhedron::UNIVERSE**)
*Builds a universe (top) or empty (bottom) **Polyhedra_Powerset**(p. 115).*
- **Polyhedra_Powerset** (const **Polyhedra_Powerset** &y)
Ordinary copy-constructor.
- **Polyhedra_Powerset** (const PH &ph)
If ph is nonempty, builds a powerset containing only ph. Builds the empty powerset otherwise.
- template<typename QH> **Polyhedra_Powerset** (const **Polyhedra_Powerset**< QH > &y)
Copy-constructor allowing a source powerset with elements of a different polyhedron kind.
- **Polyhedra_Powerset** (const Constraint_System &cs)

Member Functions that Do Not Modify the Powerset of Polyhedra

- dimension_type **space_dimension** () const
*Returns the dimension of the vector space enclosing *this.*
- bool **geometrically_covers** (const **Polyhedra_Powerset** &y) const
*Returns true if and only if *this geometrically covers y, i.e., if any point (in some element) of y is also a point (of some element) of *this.*
- bool **geometrically_equals** (const **Polyhedra_Powerset** &y) const
*Returns true if and only if *this is geometrically equal to y, i.e., if (the elements of) *this and y contain the same set of points.*
- memory_size_type **total_memory_in_bytes** () const
*Returns a lower bound to the total size in bytes of the memory occupied by *this.*
- memory_size_type **external_memory_in_bytes** () const
*Returns a lower bound to the size in bytes of the memory managed by *this.*
- bool **OK** () const

Checks if all the invariants are satisfied.

Space Dimension Preserving Member Functions that May Modify the Powerset of Polyhedra

- void **add_constraint** (const **Constraint** &c)
*Intersects *this with constraint c.*
- bool **add_constraint_and_minimize** (const **Constraint** &c)
*Intersects *this with the constraint c, minimizing the result.*
- void **add_constraints** (const **Constraint_System** &cs)
*Intersects *this with the constraints in cs.*
- bool **add_constraints_and_minimize** (const **Constraint_System** &cs)
*Intersects *this with the constraints in cs, minimizing the result.*
- void **pairwise_reduce** ()
*Assign to *this the result of (recursively) merging together the pairs of polyhedra whose poly-hull is the same as their set-theoretical union.*
- template<typename Widening> void **BGP99_extrapolation_assign** (const **Polyhedra_Powerset** &y, Widening wf, unsigned max_disjuncts)
*Assigns to *this the result of applying the **BGP99 extrapolation operator**(p. 13) to *this and y, using the widening function wf and the cardinality threshold max_disjuncts.*
- template<typename Cert, typename Widening> void **BHZ03_widening_assign** (const **Polyhedra_Powerset** &y, Widening wf)
*Assigns to *this the result of computing the **BHZ03-widening**(p. 14) between *this and y, using the widening function wf certified by the convergence certificate Cert.*
- template<typename Widening> void **BHZ03_widening_assign** (const **Polyhedra_Powerset** &y, Widening wf)
*An instance of the BHZ03 framework using the widening function wf certified by **BHRZ03-Certificate**(p. 76).*

Member Functions that May Modify the Dimension of the Vector Space

- **Polyhedra_Powerset & operator=** (const **Polyhedra_Powerset** &y)
*The assignment operator (*this and y can be dimension-incompatible).*
- template<typename QH> **Polyhedra_Powerset & operator=** (const **Polyhedra_Powerset**<QH> &y)
*Assignment operator allowing a source powerset with elements of a different polyhedron kind (*this and y can be dimension-incompatible).*
- void **swap** (**Polyhedra_Powerset** &y)
*Swaps *this with y.*
- void **add_space_dimensions_and_embed** (dimension_type m)
*Adds m new dimensions to the vector space containing *this and embeds each polyhedron in *this in the new space.*
- void **add_space_dimensions_and_project** (dimension_type m)

Adds m new dimensions to the vector space containing **this* without embedding the polyhedra in **this* in the new space.

- void **intersection_assign** (const **Polyhedra_Powerset** &y)
Assigns to **this* the intersection of **this* and *y*.
- void **poly_difference_assign** (const **Polyhedra_Powerset** &y)
Assigns to **this* the difference of **this* and *y*.
- void **concatenate_assign** (const **Polyhedra_Powerset** &y)
Assigns to **this* the concatenation of **this* and *y*.
- void **time_elapse_assign** (const **Polyhedra_Powerset** &y)
Assigns to **this* the result of computing the **time-elapse**(p. 10) between **this* and *y*.
- void **remove_space_dimensions** (const **Variables_Set** &to_be_removed)
Removes all the specified space dimensions.
- void **remove_higher_space_dimensions** (dimension_type new_dimension)
Removes the higher space dimensions so that the resulting space will have dimension *new_dimension*.
- template<typename Partial_Function> void **map_space_dimensions** (const Partial_Function &pfunc)
Remaps the dimensions of the vector space according to a partial function.

Static Public Member Functions

- dimension_type **max_space_dimension** ()
Returns the maximum space dimension a **Polyhedra_Powerset**<PH> can handle.

Related Functions

(Note that these are not member functions.)

- Widening_Function< PH > **widen_fun_ref** (void(PH::*wm)(const PH &, unsigned *))
Wraps a widening method into a function object.
- Limited_Widening_Function< PH > **widen_fun_ref** (void(PH::*lwm)(const PH &, const Constraint_System &, unsigned *), const Constraint_System &cs)
Wraps a limited widening method into a function object.
- std::pair< PH, **Polyhedra_Powerset**< **NNC_Polyhedron** > > **linear_partition** (const PH &p, const PH &q)
Partitions \mathcal{Q} with respect to \mathcal{P} .
- void **swap** (**Parma_Polyhedra_Library::Polyhedra_Powerset**< PH > &x, **Parma_Polyhedra_Library::Polyhedra_Powerset**< PH > &y)
Specializes `std::swap`.

11.15.1 Detailed Description

template<typename PH> class Parma_Polyhedra_Library::Polyhedra_Powerset< PH >

The powerset construction instantiated on PPL polyhedra.

11.15.2 Constructor & Destructor Documentation

11.15.2.1 template<typename PH> Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::Polyhedra_Powerset (dimension_type *num_dimensions* = 0, Polyhedron::Degenerate_Kind *kind* = Polyhedron::UNIVERSE) [explicit]

Builds a universe (top) or empty (bottom) **Polyhedra_Powerset**(p. 115).

Parameters:

num_dimensions The number of dimensions of the vector space enclosing the powerset;

kind Specifies whether the universe or the empty powerset has to be built.

11.15.2.2 template<typename PH> Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::Polyhedra_Powerset (const Constraint_System & *cs*) [explicit]

Creates a **Polyhedra_Powerset**(p. 115) with a single polyhedron with the same information contents as *cs*.

11.15.3 Member Function Documentation

11.15.3.1 template<typename PH> bool Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::geometrically_covers (const Polyhedra_Powerset< PH > & *y*) const

Returns `true` if and only if **this* geometrically covers *y*, i.e., if any point (in some element) of *y* is also a point (of some element) of **this*.

Exceptions:

std::invalid_argument Thrown if **this* and *y* are topology-incompatible or dimension-incompatible.

Warning:

This may be *really* expensive!

11.15.3.2 template<typename PH> bool Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::geometrically_equals (const Polyhedra_Powerset< PH > & *y*) const

Returns `true` if and only if **this* is geometrically equal to *y*, i.e., if (the elements of) **this* and *y* contain the same set of points.

Exceptions:

std::invalid_argument Thrown if **this* and *y* are topology-incompatible or dimension-incompatible.

Warning:

This may be *really* expensive!

11.15.3.3 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::add_constraint (const Constraint & c)`

Intersects **this* with constraint *c*.

Exceptions:

std::invalid_argument Thrown if **this* and constraint *c* are topology-incompatible or dimension-incompatible.

11.15.3.4 `template<typename PH> bool Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::add_constraint_and_minimize (const Constraint & c)`

Intersects **this* with the constraint *c*, minimizing the result.

Returns:

false if and only if the result is empty.

Exceptions:

std::invalid_argument Thrown if **this* and *c* are topology-incompatible or dimension-incompatible.

11.15.3.5 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::add_constraints (const Constraint_System & cs)`

Intersects **this* with the constraints in *cs*.

Parameters:

cs The constraints to intersect with.

Exceptions:

std::invalid_argument Thrown if **this* and *cs* are topology-incompatible or dimension-incompatible.

11.15.3.6 `template<typename PH> bool Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::add_constraints_and_minimize (const Constraint_System & cs)`

Intersects **this* with the constraints in *cs*, minimizing the result.

Returns:

false if and only if the result is empty.

Parameters:

cs The constraints to intersect with.

Exceptions:

std::invalid_argument Thrown if **this* and *cs* are topology-incompatible or dimension-incompatible.

11.15.3.7 template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::pairwise_reduce ()

Assign to `*this` the result of (recursively) merging together the pairs of polyhedra whose poly-hull is the same as their set-theoretical union.

On exit, for all the pairs \mathcal{P}, \mathcal{Q} of different polyhedra in `*this`, we have $\mathcal{P} \uplus \mathcal{Q} \neq \mathcal{P} \cup \mathcal{Q}$.

11.15.3.8 template<typename PH> template<typename Widening> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::BGP99_extrapolation_assign (const Polyhedra_Powerset< PH > & y, Widening wf, unsigned max_disjuncts)

Assigns to `*this` the result of applying the **BGP99 extrapolation operator**(p. 13) to `*this` and `y`, using the widening function `wf` and the cardinality threshold `max_disjuncts`.

Parameters:

- `y` A finite powerset of polyhedra. It *must* definitely entail `*this`;
- `wf` The widening function to be used on polyhedra objects. It is obtained from the corresponding widening method by using the helper function `Parma_Polyhedra_Library::widen_fun_ref`. Legal values are, e.g., `widen_fun_ref(&Polyhedron::H79_widening_assign)` and `widen_fun_ref(&Polyhedron::limited_H79_extrapolation_assign, cs)`;
- `max_disjuncts` The maximum number of disjuncts occurring in the powerset `*this` *before* starting the computation. If this number is exceeded, some of the disjuncts in `*this` are collapsed (i.e., joined together).

Exceptions:

- `std::invalid_argument` Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

For a description of the extrapolation operator, see [BGP99](p. 15) and [BHZ03b](p. 16).

11.15.3.9 template<typename PH> template<typename Cert, typename Widening> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::BHZ03_widening_assign (const Polyhedra_Powerset< PH > & y, Widening wf)

Assigns to `*this` the result of computing the **BHZ03-widening**(p. 14) between `*this` and `y`, using the widening function `wf` certified by the convergence certificate `Cert`.

Parameters:

- `y` The finite powerset of polyhedra computed in the previous iteration step. It *must* definitely entail `*this`;
- `wf` The widening function to be used on polyhedra objects. It is obtained from the corresponding widening method by using the helper function `widen_fun_ref`. Legal values are, e.g., `widen_fun_ref(&Polyhedron::H79_widening_assign)` and `widen_fun_ref(&Polyhedron::limited_H79_extrapolation_assign, cs)`.

Exceptions:

- `std::invalid_argument` Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

Warning:

In order to obtain a proper widening operator, the template parameter `Cert` should be a finite convergence certificate for the base-level widening function `wf`; otherwise, an extrapolation operator

is obtained. For a description of the methods that should be provided by Cert, see **BHRZ03_-Certificate**(p. 76) or **H79_Certificate**(p. 100).

11.15.3.10 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::intersection_assign (const Polyhedra_Powerset< PH > & y)`

Assigns to `*this` the intersection of `*this` and `y`.

The result is obtained by intersecting each polyhedron in `*this` with each polyhedron in `y` and collecting all these intersections.

11.15.3.11 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::poly_difference_assign (const Polyhedra_Powerset< PH > & y)`

Assigns to `*this` the difference of `*this` and `y`.

The result is obtained by computing the **poly-difference**(p. 7) of each polyhedron in `*this` with each polyhedron in `y` and collecting all these differences.

11.15.3.12 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::concatenate_assign (const Polyhedra_Powerset< PH > & y)`

Assigns to `*this` the concatenation of `*this` and `y`.

The result is obtained by computing the pairwise **concatenate**(p. 7) "concatenation" of each polyhedron in `*this` with each polyhedron in `y`.

11.15.3.13 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::time_elapse_assign (const Polyhedra_Powerset< PH > & y)`

Assigns to `*this` the result of computing the **time-elapse**(p. 10) between `*this` and `y`.

The result is obtained by computing the pairwise **time_elapse**(p. 10) "time elapse" of each polyhedron in `*this` with each polyhedron in `y`.

11.15.3.14 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::remove_space_dimensions (const Variables_Set & to_be_removed)`

Removes all the specified space dimensions.

Parameters:

to_be_removed The set of **Variable**(p. 152) objects corresponding to the space dimensions to be removed.

Exceptions:

std::invalid_argument Thrown if `*this` is dimension-incompatible with one of the **Variable**(p. 152) objects contained in `to_be_removed`.

11.15.3.15 `template<typename PH> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::remove_higher_space_dimensions (dimension_type new_dimension)`

Removes the higher space dimensions so that the resulting space will have dimension `new_dimension`.

Exceptions:

std::invalid_argument Thrown if `new_dimensions` is greater than the space dimension of `*this`.

11.15.3.16 `template<typename PH> template<typename Partial_Function> void Parma_Polyhedra_Library::Polyhedra_Powerset< PH >::map_space_dimensions (const Partial_Function & pfunc)`

Remaps the dimensions of the vector space according to a partial function.

See also `Polyhedron::map_space_dimensions`.

11.15.4 Friends And Related Function Documentation

11.15.4.1 `template<typename PH> Widening_Function< PH > widen_fun_ref (void(PH::*)(const PH &, unsigned *) wm) [related]`

Wraps a widening method into a function object.

Parameters:

wm The widening method.

11.15.4.2 `template<typename PH> Limited_Widening_Function< PH > widen_fun_ref (void(PH::*)(const PH &, const Constraint_System &, unsigned *) lwm, const Constraint_System & cs) [related]`

Wraps a limited widening method into a function object.

Parameters:

lwm The limited widening method.

cs The constraint system limiting the widening.

11.15.4.3 `template<typename PH> std::pair< PH, Polyhedra_Powerset< NNC_Polyhedron > > linear_partition (const PH & p, const PH & q) [related]`

Partitions *q* with respect to *p*.

Let *p* and *q* be two polyhedra. The function returns an object *r* of type `std::pair<PH, Polyhedra_Powerset(p. 115)<NNC_Polyhedron(p. 110)> >` such that

- *r.first* is the intersection of *p* and *q*;
- *r.second* has the property that all its elements are pairwise disjoint and disjoint from *p*;
- the union of *r.first* with all the elements of *r.second* gives *q* (i.e., *r* is the representation of a partition of *q*).

11.16 Parma_Polyhedra_Library::Polyhedron Class Reference

The base class for convex polyhedra.

Inherited by `Parma_Polyhedra_Library::C_Polyhedron`, and `Parma_Polyhedra_Library::NNC_Polyhedron`.

Public Types

- enum `Degenerate_Kind` { `UNIVERSE`, `EMPTY` }
- Kinds of degenerate polyhedra.*

Public Member Functions

Member Functions that Do Not Modify the Polyhedron

- dimension_type **space_dimension** () const
*Returns the dimension of the vector space enclosing *this.*
- dimension_type **affine_dimension** () const
*Returns 0, if *this is empty; otherwise, returns the **affine dimension**(p. 6) of *this.*
- const Constraint_System & **constraints** () const
Returns the system of constraints.
- const Constraint_System & **minimized_constraints** () const
Returns the system of constraints, with no redundant constraint.
- const Generator_System & **generators** () const
Returns the system of generators.
- const Generator_System & **minimized_generators** () const
Returns the system of generators, with no redundant generator.
- **Poly_Con_Relation relation_with** (const **Constraint** &c) const
*Returns the relations holding between the polyhedron *this and the constraint c.*
- **Poly_Gen_Relation relation_with** (const **Generator** &g) const
*Returns the relations holding between the polyhedron *this and the generator g.*
- bool **is_empty** () const
*Returns true if and only if *this is an empty polyhedron.*
- bool **is_universe** () const
*Returns true if and only if *this is a universe polyhedron.*
- bool **is_topologically_closed** () const
*Returns true if and only if *this is a topologically closed subset of the vector space.*
- bool **is_disjoint_from** (const **Polyhedron** &y) const
*Returns true if and only if *this and y are disjoint.*
- bool **is_bounded** () const
*Returns true if and only if *this is a bounded polyhedron.*
- bool **bounds_from_above** (const **Linear_Expression** &expr) const
*Returns true if and only if expr is bounded from above in *this.*
- bool **bounds_from_below** (const **Linear_Expression** &expr) const
*Returns true if and only if expr is bounded from below in *this.*
- bool **maximize** (const **Linear_Expression** &expr, **Coefficient** &sup_n, **Coefficient** &sup_d, bool &maximum) const
*Returns true if and only if *this is not empty and expr is bounded from above in *this, in which case the supremum value is computed.*

- **bool maximize** (const **Linear_Expression** &expr, **Coefficient** &sup_n, **Coefficient** &sup_d, bool &maximum, const **Generator** **const pppoint) const
*Returns true if and only if *this is not empty and expr is bounded from above in *this, in which case the supremum value and a point where expr reaches it are computed.*
- **bool minimize** (const **Linear_Expression** &expr, **Coefficient** &inf_n, **Coefficient** &inf_d, bool &minimum) const
*Returns true if and only if *this is not empty and expr is bounded from below in *this, in which case the infimum value is computed.*
- **bool minimize** (const **Linear_Expression** &expr, **Coefficient** &inf_n, **Coefficient** &inf_d, bool &minimum, const **Generator** **const pppoint) const
*Returns true if and only if *this is not empty and expr is bounded from below in *this, in which case the infimum value and a point where expr reaches it are computed.*
- **bool contains** (const **Polyhedron** &y) const
*Returns true if and only if *this contains y.*
- **bool strictly_contains** (const **Polyhedron** &y) const
*Returns true if and only if *this strictly contains y.*
- **template<typename Box> void shrink_bounding_box** (Box &box, Complexity_Class complexity=ANY_COMPLEXITY) const
*Uses *this to shrink a generic, interval-based bounding box.*
- **bool OK** (bool check_not_empty=false) const
Checks if all the invariants are satisfied.

Space Dimension Preserving Member Functions that May Modify the Polyhedron

- **void add_constraint** (const **Constraint** &c)
*Adds a copy of constraint c to the system of constraints of *this (without minimizing the result).*
- **bool add_constraint_and_minimize** (const **Constraint** &c)
*Adds a copy of constraint c to the system of constraints of *this, minimizing the result.*
- **void add_generator** (const **Generator** &g)
*Adds a copy of generator g to the system of generators of *this (without minimizing the result).*
- **bool add_generator_and_minimize** (const **Generator** &g)
*Adds a copy of generator g to the system of generators of *this, minimizing the result.*
- **void add_constraints** (const **Constraint_System** &cs)
*Adds a copy of the constraints in cs to the system of constraints of *this (without minimizing the result).*
- **void add_recycled_constraints** (**Constraint_System** &cs)
*Adds the constraints in cs to the system of constraints of *this (without minimizing the result).*
- **bool add_constraints_and_minimize** (const **Constraint_System** &cs)
*Adds a copy of the constraints in cs to the system of constraints of *this, minimizing the result.*
- **bool add_recycled_constraints_and_minimize** (**Constraint_System** &cs)
*Adds the constraints in cs to the system of constraints of *this, minimizing the result.*

- void **add_generators** (const Generator_System &gs)
*Adds a copy of the generators in gs to the system of generators of *this (without minimizing the result).*
- void **add_recycled_generators** (Generator_System &gs)
*Adds the generators in gs to the system of generators of *this (without minimizing the result).*
- bool **add_generators_and_minimize** (const Generator_System &gs)
*Adds a copy of the generators in gs to the system of generators of *this, minimizing the result.*
- bool **add_recycled_generators_and_minimize** (Generator_System &gs)
*Adds the generators in gs to the system of generators of *this, minimizing the result.*
- void **intersection_assign** (const Polyhedron &y)
*Assigns to *this the intersection of *this and y. The result is not guaranteed to be minimized.*
- bool **intersection_assign_and_minimize** (const Polyhedron &y)
*Assigns to *this the intersection of *this and y, minimizing the result.*
- void **poly_hull_assign** (const Polyhedron &y)
*Assigns to *this the poly-hull of *this and y. The result is not guaranteed to be minimized.*
- bool **poly_hull_assign_and_minimize** (const Polyhedron &y)
*Assigns to *this the poly-hull of *this and y, minimizing the result.*
- void **poly_difference_assign** (const Polyhedron &y)
*Assigns to *this the poly-difference(p. 7) of *this and y. The result is not guaranteed to be minimized.*
- void **affine_image** (Variable var, const Linear_Expression &expr, Coefficient_traits::const_reference denominator=Coefficient_one())
*Assigns to *this the affine image(p. 9) of *this under the function mapping variable var to the affine expression specified by expr and denominator.*
- void **affine_preimage** (Variable var, const Linear_Expression &expr, Coefficient_traits::const_reference denominator=Coefficient_one())
*Assigns to *this the affine preimage(p. 9) of *this under the function mapping variable var to the affine expression specified by expr and denominator.*
- void **generalized_affine_image** (Variable var, const Relation_Symbol relsym, const Linear_Expression &expr, Coefficient_traits::const_reference denominator=Coefficient_one())
*Assigns to *this the image of *this with respect to the generalized affine transfer function(p. 10) $\text{var}' \bowtie \frac{\text{expr}}{\text{denominator}}$, where \bowtie is the relation symbol encoded by relsym.*
- void **generalized_affine_image** (const Linear_Expression &lhs, const Relation_Symbol relsym, const Linear_Expression &rhs)
*Assigns to *this the image of *this with respect to the generalized affine transfer function(p. 10) $\text{lhs}' \bowtie \text{rhs}$, where \bowtie is the relation symbol encoded by relsym.*
- void **time_elapse_assign** (const Polyhedron &y)
*Assigns to *this the result of computing the time-elapse(p. 10) between *this and y.*
- void **topological_closure_assign** ()
*Assigns to *this its topological closure.*
- void **BHRZ03_widening_assign** (const Polyhedron &y, unsigned *tp=0)

Assigns to `*this` the result of computing the **BHRZ03-widening**(p. 11) between `*this` and `y`.

- void **limited_BHRZ03_extrapolation_assign** (const **Polyhedron** &y, const **Constraint_System** &cs, unsigned *tp=0)
*Improves the result of the **BHRZ03-widening**(p. 11) computation by also enforcing those constraints in `cs` that are satisfied by all the points of `*this`.*
- void **bounded_BHRZ03_extrapolation_assign** (const **Polyhedron** &y, const **Constraint_System** &cs, unsigned *tp=0)
*Improves the result of the **BHRZ03-widening**(p. 11) computation by also enforcing those constraints in `cs` that are satisfied by all the points of `*this`, plus all the constraints of the form $\pm x \leq r$ and $\pm x < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of `*this`.*
- void **H79_widening_assign** (const **Polyhedron** &y, unsigned *tp=0)
*Assigns to `*this` the result of computing the **H79-widening**(p. 11) between `*this` and `y`.*
- void **limited_H79_extrapolation_assign** (const **Polyhedron** &y, const **Constraint_System** &cs, unsigned *tp=0)
*Improves the result of the **H79-widening**(p. 11) computation by also enforcing those constraints in `cs` that are satisfied by all the points of `*this`.*
- void **bounded_H79_extrapolation_assign** (const **Polyhedron** &y, const **Constraint_System** &cs, unsigned *tp=0)
*Improves the result of the **H79-widening**(p. 11) computation by also enforcing those constraints in `cs` that are satisfied by all the points of `*this`, plus all the constraints of the form $\pm x \leq r$ and $\pm x < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of `*this`.*

Member Functions that May Modify the Dimension of the Vector Space

- void **add_space_dimensions_and_embed** (dimension_type m)
Adds `m` new space dimensions and embeds the old polyhedron in the new vector space.
- void **add_space_dimensions_and_project** (dimension_type m)
Adds `m` new space dimensions to the polyhedron and does not embed it in the new vector space.
- void **concatenate_assign** (const **Polyhedron** &y)
*Assigns to `*this` the **concatenation**(p. 7) of `*this` and `y`, taken in this order.*
- void **remove_space_dimensions** (const **Variables_Set** &to_be_removed)
Removes all the specified dimensions from the vector space.
- void **remove_higher_space_dimensions** (dimension_type new_dimension)
Removes the higher dimensions of the vector space so that the resulting space will have dimension `new_dimension`.
- template<typename Partial_Function> void **map_space_dimensions** (const Partial_Function &pfunc)
*Remaps the dimensions of the vector space according to a **partial function**(p. 8).*
- void **expand_space_dimension** (**Variable** var, dimension_type m)
Creates `m` copies of the space dimension corresponding to `var`.
- void **fold_space_dimensions** (const **Variables_Set** &to_be_folded, **Variable** var)
Folds the space dimensions in `to_be_folded` into `var`.

Miscellaneous Member Functions

- **~Polyhedron ()**
Destructor.
- **void swap (Polyhedron &y)**
*Swaps *this with polyhedron y. (*this and y can be dimension-incompatible.).*
- **memory_size_type total_memory_in_bytes () const**
*Returns the total size in bytes of the memory occupied by *this.*
- **memory_size_type external_memory_in_bytes () const**
*Returns the size in bytes of the memory managed by *this.*

Static Public Member Functions

- **dimension_type max_space_dimension ()**
*Returns the maximum space dimension all kinds of **Polyhedron**(p. 122) can handle.*

Protected Member Functions

- **Polyhedron** (Topology *topol*, dimension_type *num_dimensions*, **Degenerate_Kind** *kind*)
Builds a polyhedron having the specified properties.
- **Polyhedron** (const **Polyhedron** &y)
Ordinary copy-constructor.
- **Polyhedron** (Topology *topol*, const Constraint_System &cs)
Builds a polyhedron from a system of constraints.
- **Polyhedron** (Topology *topol*, Constraint_System &cs)
Builds a polyhedron recycling a system of constraints.
- **Polyhedron** (Topology *topol*, const Generator_System &gs)
Builds a polyhedron from a system of generators.
- **Polyhedron** (Topology *topol*, Generator_System &gs)
Builds a polyhedron recycling a system of generators.
- **template<typename Box> Polyhedron** (Topology *topol*, const Box &box)
Builds a polyhedron out of a generic, interval-based bounding box.
- **Polyhedron & operator=** (const **Polyhedron** &y)
*The assignment operator. (*this and y can be dimension-incompatible.).*

Related Functions

(Note that these are not member functions.)

- `std::ostream & operator<< (std::ostream &s, const Polyhedron &ph)`
Output operator.
- `bool operator==(const Polyhedron &x, const Polyhedron &y)`
Returns true if and only if x and y are the same polyhedron.
- `bool operator!=(const Polyhedron &x, const Polyhedron &y)`
Returns true if and only if x and y are different polyhedra.
- `void swap (Parma_Polyhedra_Library::Polyhedron &x, Parma_Polyhedra_Library::Polyhedron &y)`
Specializes std::swap.
- `template<typename PH> bool poly_hull_assign_if_exact (PH &p, const PH &q)`
If the poly-hull between p and q is exact it is assigned to p.

11.16.1 Detailed Description

The base class for convex polyhedra.

An object of the class **Polyhedron**(p. 122) represents a convex polyhedron in the vector space \mathbb{R}^n .

A polyhedron can be specified as either a finite system of constraints or a finite system of generators (see Section **Representations of Convex Polyhedra**(p. 4)) and it is always possible to obtain either representation. That is, if we know the system of constraints, we can obtain from this the system of generators that define the same polyhedron and vice versa. These systems can contain redundant members: in this case we say that they are not in the minimal form. Most operators on polyhedra are provided with two implementations: one of these, denoted `<operator-name>_and_minimize`, also enforces the minimization of the representations, and returns the Boolean value `false` whenever the resulting polyhedron turns out to be empty.

Two key attributes of any polyhedron are its topological kind (recording whether it is a **C_Polyhedron**(p. 78) or an **NNC_Polyhedron**(p. 110) object) and its space dimension (the dimension $n \in \mathbb{N}$ of the enclosing vector space):

- all polyhedra, the empty ones included, are endowed with a specific topology and space dimension;
- most operations working on a polyhedron and another object (i.e., another polyhedron, a constraint or generator, a set of variables, etc.) will throw an exception if the polyhedron and the object are not both topology-compatible and dimension-compatible (see Section **Representations of Convex Polyhedra**(p. 4));
- the topology of a polyhedron cannot be changed; rather, there are constructors for each of the two derived classes that will build a new polyhedron with the topology of that class from another polyhedron from either class and any topology;
- the only ways in which the space dimension of a polyhedron can be changed are:
 - *explicit* calls to operators provided for that purpose;

- standard copy, assignment and swap operators.

Note that four different polyhedra can be defined on the zero-dimension space: the empty polyhedron, either closed or NNC, and the universe polyhedron R^0 , again either closed or NNC.

In all the examples it is assumed that variables x and y are defined (where they are used) as follows:

```
Variable x(0);
Variable y(1);
```

Example 1

The following code builds a polyhedron corresponding to a square in \mathbb{R}^2 , given as a system of constraints:

```
Constraint_System cs;
cs.insert(x >= 0);
cs.insert(x <= 3);
cs.insert(y >= 0);
cs.insert(y <= 3);
C_Polyhedron ph(cs);
```

The following code builds the same polyhedron as above, but starting from a system of generators specifying the four vertices of the square:

```
Generator_System gs;
gs.insert(point(0*x + 0*y));
gs.insert(point(0*x + 3*y));
gs.insert(point(3*x + 0*y));
gs.insert(point(3*x + 3*y));
C_Polyhedron ph(gs);
```

Example 2

The following code builds an unbounded polyhedron corresponding to a half-strip in \mathbb{R}^2 , given as a system of constraints:

```
Constraint_System cs;
cs.insert(x >= 0);
cs.insert(x - y <= 0);
cs.insert(x - y + 1 >= 0);
C_Polyhedron ph(cs);
```

The following code builds the same polyhedron as above, but starting from the system of generators specifying the two vertices of the polyhedron and one ray:

```
Generator_System gs;
gs.insert(point(0*x + 0*y));
gs.insert(point(0*x + y));
gs.insert(ray(x - y));
C_Polyhedron ph(gs);
```

Example 3

The following code builds the polyhedron corresponding to a half-plane by adding a single constraint to the universe polyhedron in \mathbb{R}^2 :

```
C_Polyhedron ph(2);
ph.add_constraint(y >= 0);
```

The following code builds the same polyhedron as above, but starting from the empty polyhedron in the space \mathbb{R}^2 and inserting the appropriate generators (a point, a ray and a line).

```
C_Polyhedron ph(2, Polyhedron::EMPTY);
ph.add_generator(point(0*x + 0*y));
ph.add_generator(ray(y));
ph.add_generator(line(x));
```

Note that, although the above polyhedron has no vertices, we must add one point, because otherwise the result of the Minkowsky's sum would be an empty polyhedron. To avoid subtle errors related to the minimization process, it is required that the first generator inserted in an empty polyhedron is a point (otherwise, an exception is thrown).

Example 4

The following code shows the use of the function `add_space_dimensions_and_embed`:

```
C_Polyhedron ph(1);
ph.add_constraint(x == 2);
ph.add_space_dimensions_and_embed(1);
```

We build the universe polyhedron in the 1-dimension space \mathbb{R} . Then we add a single equality constraint, thus obtaining the polyhedron corresponding to the singleton set $\{2\} \subseteq \mathbb{R}$. After the last line of code, the resulting polyhedron is

$$\{(2, y)^T \in \mathbb{R}^2 \mid y \in \mathbb{R}\}.$$

Example 5

The following code shows the use of the function `add_space_dimensions_and_project`:

```
C_Polyhedron ph(1);
ph.add_constraint(x == 2);
ph.add_space_dimensions_and_project(1);
```

The first two lines of code are the same as in Example 4 for `add_space_dimensions_and_embed`. After the last line of code, the resulting polyhedron is the singleton set $\{(2, 0)^T\} \subseteq \mathbb{R}^2$.

Example 6

The following code shows the use of the function `affine_image`:

```
C_Polyhedron ph(2, Polyhedron::EMPTY);
ph.add_generator(point(0*x + 0*y));
ph.add_generator(point(0*x + 3*y));
ph.add_generator(point(3*x + 0*y));
ph.add_generator(point(3*x + 3*y));
Linear_Expression coeff = x + 4;
ph.affine_image(x, coeff);
```

In this example the starting polyhedron is a square in \mathbb{R}^2 , the considered variable is x and the affine expression is $x + 4$. The resulting polyhedron is the same square translated to the right. Moreover, if the affine transformation for the same variable x is $x + y$:

```
Linear_Expression coeff = x + y;
```

the resulting polyhedron is a parallelogram with the height equal to the side of the square and the oblique sides parallel to the line $x - y$. Instead, if we do not use an invertible transformation for the same variable; for example, the affine expression y :

```
Linear_Expression coeff = y;
```

the resulting polyhedron is a diagonal of the square.

Example 7

The following code shows the use of the function `affine_preimage`:

```

C_Polyhedron ph(2);
ph.add_constraint(x >= 0);
ph.add_constraint(x <= 3);
ph.add_constraint(y >= 0);
ph.add_constraint(y <= 3);
Linear_Expression coeff = x + 4;
ph.affine_preimage(x, coeff);

```

In this example the starting polyhedron, var and the affine expression and the denominator are the same as in Example 6, while the resulting polyhedron is again the same square, but translated to the left. Moreover, if the affine transformation for x is $x + y$

```
Linear_Expression coeff = x + y;
```

the resulting polyhedron is a parallelogram with the height equal to the side of the square and the oblique sides parallel to the line $x + y$. Instead, if we do not use an invertible transformation for the same variable x , for example, the affine expression y :

```
Linear_Expression coeff = y;
```

the resulting polyhedron is a line that corresponds to the y axis.

Example 8

For this example we use also the variables:

```

Variable z(2);
Variable w(3);

```

The following code shows the use of the function `remove_space_dimensions`:

```

Generator_System gs;
gs.insert(point(3*x + y + 0*z + 2*w));
C_Polyhedron ph(gs);
set<Variable> to_be_removed;
to_be_removed.insert(y);
to_be_removed.insert(z);
ph.remove_space_dimensions(to_be_removed);

```

The starting polyhedron is the singleton set $\{(3, 1, 0, 2)^T\} \subseteq \mathbb{R}^4$, while the resulting polyhedron is $\{(3, 2)^T\} \subseteq \mathbb{R}^2$. Be careful when removing space dimensions *incrementally*: since dimensions are automatically renamed after each application of the `remove_space_dimensions` operator, unexpected results can be obtained. For instance, by using the following code we would obtain a different result:

```

set<Variable> to_be_removed1;
to_be_removed1.insert(y);
ph.remove_space_dimensions(to_be_removed1);
set<Variable> to_be_removed2;
to_be_removed2.insert(z);
ph.remove_space_dimensions(to_be_removed2);

```

In this case, the result is the polyhedron $\{(3, 0)^T\} \subseteq \mathbb{R}^2$: when removing the set of dimensions `to_be_removed2` we are actually removing variable w of the original polyhedron. For the same reason, the operator `remove_space_dimensions` is not idempotent: removing twice the same non-empty set of dimensions is never the same as removing them just once.

11.16.2 Member Enumeration Documentation

11.16.2.1 enum Parma_Polyhedra_Library::Polyhedron::Degenerate_Kind

Kinds of degenerate polyhedra.

Enumeration values:

UNIVERSE The universe polyhedron, i.e., the whole vector space.

EMPTY The empty polyhedron, i.e., the empty set.

11.16.3 Constructor & Destructor Documentation

11.16.3.1 Parma_Polyhedra_Library::Polyhedron::Polyhedron (Topology *topol*, dimension_type *num_dimensions*, Degenerate_Kind *kind*) [protected]

Builds a polyhedron having the specified properties.

Parameters:

topol The topology of the polyhedron;

num_dimensions The number of dimensions of the vector space enclosing the polyhedron;

kind Specifies whether the universe or the empty polyhedron has to be built.

11.16.3.2 Parma_Polyhedra_Library::Polyhedron::Polyhedron (Topology *topol*, const Constraint_System & *cs*) [protected]

Builds a polyhedron from a system of constraints.

The polyhedron inherits the space dimension of the constraint system.

Parameters:

topol The topology of the polyhedron;

cs The system of constraints defining the polyhedron.

Exceptions:

std::invalid_argument Thrown if the topology of *cs* is incompatible with *topol*.

11.16.3.3 Parma_Polyhedra_Library::Polyhedron::Polyhedron (Topology *topol*, Constraint_System & *cs*) [protected]

Builds a polyhedron recycling a system of constraints.

The polyhedron inherits the space dimension of the constraint system.

Parameters:

topol The topology of the polyhedron;

cs The system of constraints defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

Exceptions:

std::invalid_argument Thrown if the topology of *cs* is incompatible with *topol*.

11.16.3.4 Parma_Polyhedra_Library::Polyhedron::Polyhedron (Topology *topol*, const Generator_System & *gs*) [protected]

Builds a polyhedron from a system of generators.

The polyhedron inherits the space dimension of the generator system.

Parameters:

topol The topology of the polyhedron;

gs The system of generators defining the polyhedron.

Exceptions:

std::invalid_argument Thrown if if the topology of *gs* is incompatible with *topol*, or if the system of generators is not empty but has no points.

11.16.3.5 Parma_Polyhedra_Library::Polyhedron::Polyhedron (Topology *topol*, Generator_System & *gs*) [protected]

Builds a polyhedron recycling a system of generators.

The polyhedron inherits the space dimension of the generator system.

Parameters:

topol The topology of the polyhedron;

gs The system of generators defining the polyhedron. It is not declared `const` because its data-structures will be recycled to build the polyhedron.

Exceptions:

std::invalid_argument Thrown if if the topology of *gs* is incompatible with *topol*, or if the system of generators is not empty but has no points.

11.16.3.6 template<typename Box> Parma_Polyhedra_Library::Polyhedron::Polyhedron (Topology *topol*, const Box & *box*) [protected]

Builds a polyhedron out of a generic, interval-based bounding box.

Parameters:

topol The topology of the polyhedron;

box The bounding box representing the polyhedron to be built.

Exceptions:

std::invalid_argument Thrown if *box* has intervals that are incompatible with *topol*.

The template class Box must provide the following methods.

```
dimension_type space_dimension() const
```

returns the dimension of the vector space enclosing the polyhedron represented by the bounding box.

```
bool is_empty() const
```

returns `true` if and only if the bounding box describes the empty set. The `is_empty()`(p. 123) method will always be called before the methods below. However, if `is_empty()`(p. 123) returns `true`, none of the functions below will be called.

```
bool get_lower_bound(dimension_type k, bool closed,
                    Coefficient& n, Coefficient& d) const
```

Let I the interval corresponding to the k -th space dimension. If I is not bounded from below, simply return `false`. Otherwise, set `closed`, n and d as follows: `closed` is set to `true` if the the lower boundary of I is closed and is set to `false` otherwise; n and d are assigned the integers n and d such that the canonical fraction n/d corresponds to the greatest lower bound of I . The fraction n/d is in canonical form if and only if n and d have no common factors and d is positive, $0/1$ being the unique representation for zero.

```
bool get_upper_bound(dimension_type k, bool closed,
                    Coefficient& n, Coefficient& d) const
```

Let I the interval corresponding to the k -th space dimension. If I is not bounded from above, simply return `false`. Otherwise, set `closed`, n and d as follows: `closed` is set to `true` if the the upper boundary of I is closed and is set to `false` otherwise; n and d are assigned the integers n and d such that the canonical fraction n/d corresponds to the least upper bound of I .

11.16.4 Member Function Documentation

11.16.4.1 Poly_Con_Relation Parma_Polyhedra_Library::Polyhedron::relation_with (const Constraint & c) const

Returns the relations holding between the polyhedron **this* and the constraint *c*.

Exceptions:

std::invalid_argument Thrown if **this* and constraint *c* are dimension-incompatible.

11.16.4.2 Poly_Gen_Relation Parma_Polyhedra_Library::Polyhedron::relation_with (const Generator & g) const

Returns the relations holding between the polyhedron **this* and the generator *g*.

Exceptions:

std::invalid_argument Thrown if **this* and generator *g* are dimension-incompatible.

11.16.4.3 bool Parma_Polyhedra_Library::Polyhedron::is_disjoint_from (const Polyhedron & y) const

Returns true if and only if **this* and *y* are disjoint.

Exceptions:

std::invalid_argument Thrown if *x* and *y* are topology-incompatible or dimension-incompatible.

11.16.4.4 bool Parma_Polyhedra_Library::Polyhedron::bounds_from_above (const Linear_Expression & expr) const

Returns true if and only if *expr* is bounded from above in **this*.

Exceptions:

std::invalid_argument Thrown if *expr* and **this* are dimension-incompatible.

11.16.4.5 bool Parma_Polyhedra_Library::Polyhedron::bounds_from_below (const Linear_Expression & expr) const

Returns true if and only if *expr* is bounded from below in **this*.

Exceptions:

std::invalid_argument Thrown if *expr* and **this* are dimension-incompatible.

11.16.4.6 bool Parma_Polyhedra_Library::Polyhedron::maximize (const Linear_Expression & expr, Coefficient & sup_n, Coefficient & sup_d, bool & maximum) const

Returns true if and only if **this* is not empty and *expr* is bounded from above in **this*, in which case the supremum value is computed.

Parameters:

expr The linear expression to be maximized subject to **this*;

sup_n The numerator of the supremum value;
sup_d The denominator of the supremum value;
maximum true if and only if the supremum is also the maximum value.

Exceptions:

std::invalid_argument Thrown if *expr* and **this* are dimension-incompatible.

If **this* is empty or *expr* is not bounded from above, *false* is returned and *sup_n*, *sup_d* and *maximum* are left untouched.

11.16.4.7 bool Parma_Polyhedra_Library::Polyhedron::maximize (const Linear_Expression & *expr*, Coefficient & *sup_n*, Coefficient & *sup_d*, bool & *maximum*, const Generator **const *pppoint*) const

Returns true if and only if **this* is not empty and *expr* is bounded from above in **this*, in which case the supremum value and a point where *expr* reaches it are computed.

Parameters:

expr The linear expression to be maximized subject to **this*;
sup_n The numerator of the supremum value;
sup_d The denominator of the supremum value;
maximum true if and only if the supremum is also the maximum value;
pppoint When nonzero and maximization succeeds, a pointer to a point or closure point where *expr* reaches its supremum value will be written at this address.

Exceptions:

std::invalid_argument Thrown if *expr* and **this* are dimension-incompatible.

If **this* is empty or *expr* is not bounded from above, *false* is returned and *sup_n*, *sup_d*, *maximum* and *pppoint* are left untouched.

11.16.4.8 bool Parma_Polyhedra_Library::Polyhedron::minimize (const Linear_Expression & *expr*, Coefficient & *inf_n*, Coefficient & *inf_d*, bool & *minimum*) const

Returns true if and only if **this* is not empty and *expr* is bounded from below in **this*, in which case the infimum value is computed.

Parameters:

expr The linear expression to be minimized subject to **this*;
inf_n The numerator of the infimum value;
inf_d The denominator of the infimum value;
minimum true if and only if the infimum is also the minimum value.

Exceptions:

std::invalid_argument Thrown if *expr* and **this* are dimension-incompatible.

If **this* is empty or *expr* is not bounded from below, *false* is returned and *inf_n*, *inf_d* and *minimum* are left untouched.

11.16.4.9 `bool Parma_Polyhedra_Library::Polyhedron::minimize (const Linear_Expression & expr, Coefficient & inf_n, Coefficient & inf_d, bool & minimum, const Generator **const pppoint) const`

Returns `true` if and only if `*this` is not empty and `expr` is bounded from below in `*this`, in which case the infimum value and a point where `expr` reaches it are computed.

Parameters:

- expr* The linear expression to be minimized subject to `*this`;
- inf_n* The numerator of the infimum value;
- inf_d* The denominator of the infimum value;
- minimum* `true` if and only if the infimum is also the minimum value;
- pppoint* When nonzero and minimization succeeds, a pointer to a point or closure point where `expr` reaches its infimum value will be written at this address.

Exceptions:

- std::invalid_argument* Thrown if `expr` and `*this` are dimension-incompatible.

If `*this` is empty or `expr` is not bounded from below, `false` is returned and `inf_n`, `inf_d`, `minimum` and `pppoint` are left untouched.

11.16.4.10 `bool Parma_Polyhedra_Library::Polyhedron::contains (const Polyhedron & y) const`

Returns `true` if and only if `*this` contains `y`.

Exceptions:

- std::invalid_argument* Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.11 `bool Parma_Polyhedra_Library::Polyhedron::strictly_contains (const Polyhedron & y) const`

Returns `true` if and only if `*this` strictly contains `y`.

Exceptions:

- std::invalid_argument* Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.12 `template<typename Box> void Parma_Polyhedra_Library::Polyhedron::shrink_bounding_box (Box & box, Complexity_Class complexity = ANY_COMPLEXITY) const`

Uses `*this` to shrink a generic, interval-based bounding box.

Parameters:

- box* The bounding box to be shrunk;
- complexity* The complexity class of the algorithm to be used.

The template class `Box` must provide the following methods, whose return value, if any, is simply ignored.

```
set_empty()
```

causes the box to become empty, i.e., to represent the empty set.

```
raise_lower_bound(dimension_type k, bool closed,
                  Coefficient_traits::const_reference n,
                  Coefficient_traits::const_reference d)
```

intersects the interval corresponding to the k -th space dimension with $[n/d, +\infty)$ if `closed` is true, with $(n/d, +\infty)$ if `closed` is false.

```
lower_upper_bound(dimension_type k, bool closed,
                  Coefficient_traits::const_reference n,
                  Coefficient_traits::const_reference d)
```

intersects the interval corresponding to the k -th space dimension with $(-\infty, n/d]$ if `closed` is true, with $(-\infty, n/d)$ if `closed` is false.

The function `raise_lower_bound(k, closed, n, d)` will be called at most once for each possible value for k and for all such calls the fraction n/d will be in canonical form, that is, n and d have no common factors and d is positive, $0/1$ being the unique representation for zero. The same guarantee is offered for the function `lower_upper_bound(k, closed, n, d)`.

11.16.4.13 `bool Parma_Polyhedra_Library::Polyhedron::OK (bool check_not_empty = false) const`

Checks if all the invariants are satisfied.

Returns:

true if and only if `*this` satisfies all the invariants and either `check_not_empty` is false or `*this` is not empty.

Parameters:

check_not_empty true if and only if, in addition to checking the invariants, `*this` must be checked to be not empty.

The check is performed so as to intrude as little as possible. If the library has been compiled with run-time assertions enabled, error messages are written on `std::cerr` in case invariants are violated. This is useful for the purpose of debugging the library.

11.16.4.14 `void Parma_Polyhedra_Library::Polyhedron::add_constraint (const Constraint & c)`

Adds a copy of constraint `c` to the system of constraints of `*this` (without minimizing the result).

Exceptions:

std::invalid_argument Thrown if `*this` and constraint `c` are topology-incompatible or dimension-incompatible.

11.16.4.15 `bool Parma_Polyhedra_Library::Polyhedron::add_constraint_and_minimize (const Constraint & c)`

Adds a copy of constraint `c` to the system of constraints of `*this`, minimizing the result.

Returns:

false if and only if the result is empty.

Exceptions:

std::invalid_argument Thrown if **this* and constraint *c* are topology-incompatible or dimension-incompatible.

11.16.4.16 void Parma_Polyhedra_Library::Polyhedron::add_generator (const Generator & g)

Adds a copy of generator *g* to the system of generators of **this* (without minimizing the result).

Exceptions:

std::invalid_argument Thrown if **this* and generator *g* are topology-incompatible or dimension-incompatible, or if **this* is an empty polyhedron and *g* is not a point.

11.16.4.17 bool Parma_Polyhedra_Library::Polyhedron::add_generator_and_minimize (const Generator & g)

Adds a copy of generator *g* to the system of generators of **this*, minimizing the result.

Returns:

false if and only if the result is empty.

Exceptions:

std::invalid_argument Thrown if **this* and generator *g* are topology-incompatible or dimension-incompatible, or if **this* is an empty polyhedron and *g* is not a point.

11.16.4.18 void Parma_Polyhedra_Library::Polyhedron::add_constraints (const Constraint_System & cs)

Adds a copy of the constraints in *cs* to the system of constraints of **this* (without minimizing the result).

Parameters:

cs Contains the constraints that will be added to the system of constraints of **this*.

Exceptions:

std::invalid_argument Thrown if **this* and *cs* are topology-incompatible or dimension-incompatible.

11.16.4.19 void Parma_Polyhedra_Library::Polyhedron::add_recycled_constraints (Constraint_System & cs)

Adds the constraints in *cs* to the system of constraints of **this* (without minimizing the result).

Parameters:

cs The constraint system that will be recycled, adding its constraints to the system of constraints of **this*.

Exceptions:

std::invalid_argument Thrown if **this* and *cs* are topology-incompatible or dimension-incompatible.

Warning:

The only assumption that can be made on *cs* upon successful or exceptional return is that it can be safely destroyed.

11.16.4.20 bool Parma_Polyhedra_Library::Polyhedron::add_constraints_and_minimize (const Constraint_System & cs)

Adds a copy of the constraints in `cs` to the system of constraints of `*this`, minimizing the result.

Returns:

`false` if and only if the result is empty.

Parameters:

`cs` Contains the constraints that will be added to the system of constraints of `*this`.

Exceptions:

std::invalid_argument Thrown if `*this` and `cs` are topology-incompatible or dimension-incompatible.

11.16.4.21 bool Parma_Polyhedra_Library::Polyhedron::add_recycled_constraints_and_minimize (Constraint_System & cs)

Adds the constraints in `cs` to the system of constraints of `*this`, minimizing the result.

Returns:

`false` if and only if the result is empty.

Parameters:

`cs` The constraint system that will be recycled, adding its constraints to the system of constraints of `*this`.

Exceptions:

std::invalid_argument Thrown if `*this` and `cs` are topology-incompatible or dimension-incompatible.

Warning:

The only assumption that can be made on `cs` upon successful or exceptional return is that it can be safely destroyed.

11.16.4.22 void Parma_Polyhedra_Library::Polyhedron::add_generators (const Generator_System & gs)

Adds a copy of the generators in `gs` to the system of generators of `*this` (without minimizing the result).

Parameters:

`gs` Contains the generators that will be added to the system of generators of `*this`.

Exceptions:

std::invalid_argument Thrown if `*this` and `gs` are topology-incompatible or dimension-incompatible, or if `*this` is empty and the system of generators `gs` is not empty, but has no points.

11.16.4.23 void Parma_Polyhedra_Library::Polyhedron::add_recycled_generators (Generator_System & gs)

Adds the generators in `gs` to the system of generators of `*this` (without minimizing the result).

Parameters:

`gs` The generator system that will be recycled, adding its generators to the system of generators of `*this`.

Exceptions:

std::invalid_argument Thrown if `*this` and `gs` are topology-incompatible or dimension-incompatible, or if `*this` is empty and the system of generators `gs` is not empty, but has no points.

Warning:

The only assumption that can be made on `gs` upon successful or exceptional return is that it can be safely destroyed.

11.16.4.24 bool Parma_Polyhedra_Library::Polyhedron::add_generators_and_minimize (const Generator_System & gs)

Adds a copy of the generators in `gs` to the system of generators of `*this`, minimizing the result.

Returns:

`false` if and only if the result is empty.

Parameters:

`gs` Contains the generators that will be added to the system of generators of `*this`.

Exceptions:

std::invalid_argument Thrown if `*this` and `gs` are topology-incompatible or dimension-incompatible, or if `*this` is empty and the the system of generators `gs` is not empty, but has no points.

11.16.4.25 bool Parma_Polyhedra_Library::Polyhedron::add_recycled_generators_and_minimize (Generator_System & gs)

Adds the generators in `gs` to the system of generators of `*this`, minimizing the result.

Returns:

`false` if and only if the result is empty.

Parameters:

`gs` The generator system that will be recycled, adding its generators to the system of generators of `*this`.

Exceptions:

std::invalid_argument Thrown if `*this` and `gs` are topology-incompatible or dimension-incompatible, or if `*this` is empty and the the system of generators `gs` is not empty, but has no points.

Warning:

The only assumption that can be made on `gs` upon successful or exceptional return is that it can be safely destroyed.

11.16.4.26 void Parma_Polyhedra_Library::Polyhedron::intersection_assign (const Polyhedron & y)

Assigns to `*this` the intersection of `*this` and `y`. The result is not guaranteed to be minimized.

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.27 bool Parma_Polyhedra_Library::Polyhedron::intersection_assign_and_minimize (const Polyhedron & y)

Assigns to `*this` the intersection of `*this` and `y`, minimizing the result.

Returns:

`false` if and only if the result is empty.

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.28 void Parma_Polyhedra_Library::Polyhedron::poly_hull_assign (const Polyhedron & y)

Assigns to `*this` the poly-hull of `*this` and `y`. The result is not guaranteed to be minimized.

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.29 bool Parma_Polyhedra_Library::Polyhedron::poly_hull_assign_and_minimize (const Polyhedron & y)

Assigns to `*this` the poly-hull of `*this` and `y`, minimizing the result.

Returns:

`false` if and only if the result is empty.

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.30 void Parma_Polyhedra_Library::Polyhedron::poly_difference_assign (const Polyhedron & y)

Assigns to `*this` the **poly-difference**(p. 7) of `*this` and `y`. The result is not guaranteed to be minimized.

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.31 `void Parma_Polyhedra_Library::Polyhedron::affine_image (Variable var, const Linear_Expression & expr, Coefficient_traits::const_reference denominator = Coefficient_one())`

Assigns to **this* the **affine image**(p. 9) of **this* under the function mapping variable *var* to the affine expression specified by *expr* and *denominator*.

Parameters:

- var* The variable to which the affine expression is assigned;
- expr* The numerator of the affine expression;
- denominator* The denominator of the affine expression (optional argument with default value 1.)

Exceptions:

- std::invalid_argument* Thrown if *denominator* is zero or if *expr* and **this* are dimension-incompatible or if *var* is not a space dimension of **this*.

11.16.4.32 `void Parma_Polyhedra_Library::Polyhedron::affine_preimage (Variable var, const Linear_Expression & expr, Coefficient_traits::const_reference denominator = Coefficient_one())`

Assigns to **this* the **affine preimage**(p. 9) of **this* under the function mapping variable *var* to the affine expression specified by *expr* and *denominator*.

Parameters:

- var* The variable to which the affine expression is substituted;
- expr* The numerator of the affine expression;
- denominator* The denominator of the affine expression (optional argument with default value 1.)

Exceptions:

- std::invalid_argument* Thrown if *denominator* is zero or if *expr* and **this* are dimension-incompatible or if *var* is not a space dimension of **this*.

11.16.4.33 `void Parma_Polyhedra_Library::Polyhedron::generalized_affine_image (Variable var, const Relation_Symbol relsym, const Linear_Expression & expr, Coefficient_traits::const_reference denominator = Coefficient_one())`

Assigns to **this* the image of **this* with respect to the **generalized affine transfer function**(p. 10) $\text{var}' \bowtie \frac{\text{expr}}{\text{denominator}}$, where \bowtie is the relation symbol encoded by *relsym*.

Parameters:

- var* The left hand side variable of the generalized affine transfer function;
- relsym* The relation symbol;
- expr* The numerator of the right hand side affine expression;
- denominator* The denominator of the right hand side affine expression (optional argument with default value 1.)

Exceptions:

- std::invalid_argument* Thrown if *denominator* is zero or if *expr* and **this* are dimension-incompatible or if *var* is not a space dimension of **this* or if **this* is a **C_Polyhedron**(p. 78) and *relsym* is a strict relation symbol.

11.16.4.34 void Parma_Polyhedra_Library::Polyhedron::generalized_affine_image (const Linear_Expression & lhs, const Relation_Symbol relsym, const Linear_Expression & rhs)

Assigns to `*this` the image of `*this` with respect to the **generalized affine transfer function**(p. 10) $lhs' \bowtie rhs$, where \bowtie is the relation symbol encoded by `relsym`.

Parameters:

lhs The left hand side affine expression;
relsym The relation symbol;
rhs The right hand side affine expression.

Exceptions:

std::invalid_argument Thrown if `*this` is dimension-incompatible with `lhs` or `rhs` or if `*this` is a `C_Polyhedron`(p. 78) and `relsym` is a strict relation symbol.

11.16.4.35 void Parma_Polyhedra_Library::Polyhedron::time_elapse_assign (const Polyhedron & y)

Assigns to `*this` the result of computing the **time-elapse**(p. 10) between `*this` and `y`.

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.36 void Parma_Polyhedra_Library::Polyhedron::BHRZ03_widening_assign (const Polyhedron & y, unsigned * tp = 0)

Assigns to `*this` the result of computing the **BHRZ03-widening**(p. 11) between `*this` and `y`.

Parameters:

y A polyhedron that *must* be contained in `*this`;
tp An optional pointer to an unsigned variable storing the number of available tokens (to be used when applying the **widening with tokens**(p. 11) delay technique).

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible or dimension-incompatible.

11.16.4.37 void Parma_Polyhedra_Library::Polyhedron::limited_BHRZ03_extrapolation_assign (const Polyhedron & y, const Constraint_System & cs, unsigned * tp = 0)

Improves the result of the **BHRZ03-widening**(p. 11) computation by also enforcing those constraints in `cs` that are satisfied by all the points of `*this`.

Parameters:

y A polyhedron that *must* be contained in `*this`;
cs The system of constraints used to improve the widened polyhedron;
tp An optional pointer to an unsigned variable storing the number of available tokens (to be used when applying the **widening with tokens**(p. 11) delay technique).

Exceptions:

std::invalid_argument Thrown if `*this`, `y` and `cs` are topology-incompatible or dimension-incompatible.

11.16.4.38 void Parma_Polyhedra_Library::Polyhedron::bounded_BHRZ03_extrapolation_assign (const Polyhedron & y, const Constraint_System & cs, unsigned * tp = 0)

Improves the result of the **BHRZ03-widening**(p. 11) computation by also enforcing those constraints in *cs* that are satisfied by all the points of **this*, plus all the constraints of the form $\pm x \leq r$ and $\pm x < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of **this*.

Parameters:

- y* A polyhedron that *must* be contained in **this*;
- cs* The system of constraints used to improve the widened polyhedron;
- tp* An optional pointer to an unsigned variable storing the number of available tokens (to be used when applying the **widening with tokens**(p. 11) delay technique).

Exceptions:

- std::invalid_argument* Thrown if **this*, *y* and *cs* are topology-incompatible or dimension-incompatible.

11.16.4.39 void Parma_Polyhedra_Library::Polyhedron::H79_widening_assign (const Polyhedron & y, unsigned * tp = 0)

Assigns to **this* the result of computing the **H79-widening**(p. 11) between **this* and *y*.

Parameters:

- y* A polyhedron that *must* be contained in **this*;
- tp* An optional pointer to an unsigned variable storing the number of available tokens (to be used when applying the **widening with tokens**(p. 11) delay technique).

Exceptions:

- std::invalid_argument* Thrown if **this* and *y* are topology-incompatible or dimension-incompatible.

11.16.4.40 void Parma_Polyhedra_Library::Polyhedron::limited_H79_extrapolation_assign (const Polyhedron & y, const Constraint_System & cs, unsigned * tp = 0)

Improves the result of the **H79-widening**(p. 11) computation by also enforcing those constraints in *cs* that are satisfied by all the points of **this*.

Parameters:

- y* A polyhedron that *must* be contained in **this*;
- cs* The system of constraints used to improve the widened polyhedron;
- tp* An optional pointer to an unsigned variable storing the number of available tokens (to be used when applying the **widening with tokens**(p. 11) delay technique).

Exceptions:

- std::invalid_argument* Thrown if **this*, *y* and *cs* are topology-incompatible or dimension-incompatible.

11.16.4.41 void Parma_Polyhedra_Library::Polyhedron::bounded_H79_extrapolation_assign (const Polyhedron & y, const Constraint_System & cs, unsigned * tp = 0)

Improves the result of the **H79-widening**(p. 11) computation by also enforcing those constraints in `cs` that are satisfied by all the points of `*this`, plus all the constraints of the form $\pm x \leq r$ and $\pm x < r$, with $r \in \mathbb{Q}$, that are satisfied by all the points of `*this`.

Parameters:

- `y` A polyhedron that *must* be contained in `*this`;
- `cs` The system of constraints used to improve the widened polyhedron;
- `tp` An optional pointer to an unsigned variable storing the number of available tokens (to be used when applying the **widening with tokens**(p. 11) delay technique).

Exceptions:

- `std::invalid_argument`** Thrown if `*this`, `y` and `cs` are topology-incompatible or dimension-incompatible.

11.16.4.42 void Parma_Polyhedra_Library::Polyhedron::add_space_dimensions_and_embed (dimension_type m)

Adds `m` new space dimensions and embeds the old polyhedron in the new vector space.

Parameters:

- `m` The number of dimensions to add.

Exceptions:

- `std::length_error`** Thrown if adding `m` new space dimensions would cause the vector space to exceed dimension `max_space_dimension()`(p. 127).

The new space dimensions will be those having the highest indexes in the new polyhedron, which is characterized by a system of constraints in which the variables running through the new dimensions are not constrained. For instance, when starting from the polyhedron $\mathcal{P} \subseteq \mathbb{R}^2$ and adding a third space dimension, the result will be the polyhedron

$$\{ (x, y, z)^T \in \mathbb{R}^3 \mid (x, y)^T \in \mathcal{P} \}.$$

11.16.4.43 void Parma_Polyhedra_Library::Polyhedron::add_space_dimensions_and_project (dimension_type m)

Adds `m` new space dimensions to the polyhedron and does not embed it in the new vector space.

Parameters:

- `m` The number of space dimensions to add.

Exceptions:

- `std::length_error`** Thrown if adding `m` new space dimensions would cause the vector space to exceed dimension `max_space_dimension()`(p. 127).

The new space dimensions will be those having the highest indexes in the new polyhedron, which is characterized by a system of constraints in which the variables running through the new dimensions are all

constrained to be equal to 0. For instance, when starting from the polyhedron $\mathcal{P} \subseteq \mathbb{R}^2$ and adding a third space dimension, the result will be the polyhedron

$$\{ (x, y, 0)^T \in \mathbb{R}^3 \mid (x, y)^T \in \mathcal{P} \}.$$

11.16.4.44 void Parma_Polyhedra_Library::Polyhedron::concatenate_assign (const Polyhedron & y)

Assigns to `*this` the **concatenation**(p. 7) of `*this` and `y`, taken in this order.

Exceptions:

std::invalid_argument Thrown if `*this` and `y` are topology-incompatible.

std::length_error Thrown if the concatenation would cause the vector space to exceed dimension `max_space_dimension()`(p. 127).

11.16.4.45 void Parma_Polyhedra_Library::Polyhedron::remove_space_dimensions (const Variables_Set & to_be_removed)

Removes all the specified dimensions from the vector space.

Parameters:

to_be_removed The set of **Variable**(p. 152) objects corresponding to the space dimensions to be removed.

Exceptions:

std::invalid_argument Thrown if `*this` is dimension-incompatible with one of the **Variable**(p. 152) objects contained in `to_be_removed`.

11.16.4.46 void Parma_Polyhedra_Library::Polyhedron::remove_higher_space_dimensions (dimension_type new_dimension)

Removes the higher dimensions of the vector space so that the resulting space will have dimension `new_dimension`.

Exceptions:

std::invalid_argument Thrown if `new_dimensions` is greater than the space dimension of `*this`.

11.16.4.47 template<typename Partial_Function> void Parma_Polyhedra_Library::Polyhedron::map_space_dimensions (const Partial_Function & pfunc)

Remaps the dimensions of the vector space according to a **partial function**(p. 8).

Parameters:

pfunc The partial function specifying the destiny of each space dimension.

The template class **Partial_Function** must provide the following methods.

```
bool has_empty_codomain() const
```

returns `true` if and only if the represented partial function has an empty codomain (i.e., it is always undefined). The `has_empty_codomain()` method will always be called before the methods below. However, if `has_empty_codomain()` returns `true`, none of the functions below will be called.

```
dimension_type max_in_codomain() const
```

returns the maximum value that belongs to the codomain of the partial function. The `max_in_codomain()` method is called at most once.

```
bool maps(dimension_type i, dimension_type& j) const
```

Let f be the represented function and k be the value of i . If f is defined in k , then $f(k)$ is assigned to j and `true` is returned. If f is undefined in k , then `false` is returned. This method is called at most n times, where n is the dimension of the vector space enclosing the polyhedron.

The result is undefined if `pfunc` does not encode a partial function with the properties described in the [specification of the mapping operator](#)(p. 8).

11.16.4.48 void Parma_Polyhedra_Library::Polyhedron::expand_space_dimension (Variable var, dimension_type m)

Creates m copies of the space dimension corresponding to `var`.

Parameters:

- var** The variable corresponding to the space dimension to be replicated;
- m** The number of replica to be created.

Exceptions:

- std::invalid_argument** Thrown if `var` does not correspond to a dimension of the vector space.
- std::length_error** Thrown if adding m new space dimensions would cause the vector space to exceed dimension `max_space_dimension()`(p. 127).

If `*this` has space dimension n , with $n > 0$, and `var` has space dimension $k \leq n$, then the k -th space dimension is **expanded**(p. 8) to m new space dimensions $n, n + 1, \dots, n + m - 1$.

11.16.4.49 void Parma_Polyhedra_Library::Polyhedron::fold_space_dimensions (const Variables_Set & to_be_folded, Variable var)

Folds the space dimensions in `to_be_folded` into `var`.

Parameters:

- to_be_folded** The set of [Variable](#)(p. 152) objects corresponding to the space dimensions to be folded;
- var** The variable corresponding to the space dimension that is the destination of the folding operation.

Exceptions:

- std::invalid_argument** Thrown if `*this` is dimension-incompatible with `var` or with one of the [Variable](#)(p. 152) objects contained in `to_be_folded`. Also thrown if `var` is contained in `to_be_folded`.

If `*this` has space dimension n , with $n > 0$, `var` has space dimension $k \leq n$, `to_be_folded` is a set of variables whose maximum space dimension is also less than or equal to n , and `var` is not a member of `to_be_folded`, then the space dimensions corresponding to variables in `to_be_folded` are **folded**(p. 8) into the k -th space dimension.

11.16.4.50 void Parma_Polyhedra_Library::Polyhedron::swap (Polyhedron & y)

Swaps `*this` with polyhedron `y`. (`*this` and `y` can be dimension-incompatible.).

Exceptions:

`std::invalid_argument` Thrown if `x` and `y` are topology-incompatible.

11.16.5 Friends And Related Function Documentation**11.16.5.1 std::ostream & operator<< (std::ostream & s, const Polyhedron & ph) [related]**

Output operator.

Writes a textual representation of `ph` on `s`: `false` is written if `ph` is an empty polyhedron; `true` is written if `ph` is a universe polyhedron; a minimized system of constraints defining `ph` is written otherwise, all constraints in one row separated by ", ".

11.16.5.2 bool operator== (const Polyhedron & x, const Polyhedron & y) [related]

Returns `true` if and only if `x` and `y` are the same polyhedron.

Note that `x` and `y` may be topology- and/or dimension-incompatible polyhedra: in those cases, the value `false` is returned.

11.16.5.3 bool operator!= (const Polyhedron & x, const Polyhedron & y) [related]

Returns `true` if and only if `x` and `y` are different polyhedra.

Note that `x` and `y` may be topology- and/or dimension-incompatible polyhedra: in those cases, the value `true` is returned.

11.17 Parma_Polyhedra_Library::Powerset< CS > Class Template Reference

The powerset construction on constraint systems.

Public Member Functions

- `const_iterator begin () const`
A const_iterator pointing to the first element in the sequence.
- `const_iterator end () const`
The past-the-end const_iterator.
- `void omega_reduce () const`
Erase from the sequence of disjuncts all the non-maximal elements.

Constructors and Destructor

- `Powerset ()`
- `Powerset (const Powerset &y)`
Copy constructor.

- **Powerset** (const CS &d)
If d is not bottom, builds a powerset containing only d. Builds the empty powerset otherwise.
- **~Powerset** ()
Destructor.

Member Functions that Do Not Modify the Powerset Element

- bool **definitely_entails** (const Powerset &y) const
*Returns true if *this definitely entails y. Returns false if *this may not entail y (i.e., if *this does not entail y or if entailment could not be decided).*
- bool **is_top** () const
*Returns true if and only if *this is the top element of the powerset constraint system (i.e., it represents the universe).*
- bool **is_bottom** () const
*Returns true if and only if *this is the bottom element of the powerset constraint system (i.e., it represents the empty set).*
- memory_size_type **total_memory_in_bytes** () const
*Returns a lower bound to the total size in bytes of the memory occupied by *this.*
- memory_size_type **external_memory_in_bytes** () const
*Returns a lower bound to the size in bytes of the memory managed by *this.*
- bool **OK** (bool disallow_bottom=false) const
Checks if all the invariants are satisfied.

Member Functions that May Modify the Powerset Element

- **Powerset & operator=** (const Powerset &y)
The assignment operator.
- void **swap** (Powerset &y)
*Swaps *this with y.*
- void **add_disjunct** (const CS &d)
*Adds to *this the disjunct d.*
- void **least_upper_bound_assign** (const Powerset &y)
*Assigns to *this the least upper bound of *this and y.*
- void **upper_bound_assign** (const Powerset &y)
*Assigns to *this an upper bound of *this and y.*
- void **meet_assign** (const Powerset &y)
*Assigns to *this the meet of *this and y.*
- void **collapse** ()
*If *this is not empty (i.e., it is not the bottom element), it is reduced to a singleton obtained by computing an upper-bound of all the disjuncts.*

Protected Types

- typedef std::list< CS > **Sequence**

A powerset is implemented as a sequence of elements.

Protected Member Functions

- bool **is_omega_reduced** () const

*Returns true if and only if *this does not contain non-maximal elements.*

- void **collapse** (unsigned max_disjuncts)

*Upon return, *this will contain max_disjuncts elements at most, by replacing all the exceeding disjuncts, if any, with their upper-bound.*

- template<typename Binary_Operator_Assign> void **pairwise_apply_assign** (const **Powerset** &y, Binary_Operator_Assign op_assign)

*Assigns to *this the result of applying op_assign pairwise to the elements in *this and y.*

Static Protected Member Functions

- void **add_non_bottom_disjunct** (**Sequence** &s, const CS &d, iterator &first, iterator last)

*Adds to *this the disjunct d, assuming d is not the bottom element and ensuring partial omega-reduction.*

- void **add_non_bottom_disjunct** (**Sequence** &s, const CS &d)

*Adds to *this the disjunct d, assuming d is not the bottom element.*

Protected Attributes

- **Sequence** **sequence**

The sequence container holding powerset's elements.

- bool **reduced**

*If true, *this is omega-reduced.*

Related Functions

(Note that these are not member functions.)

- bool **operator==** (const **Powerset**< CS > &x, const **Powerset**< CS > &y)

Returns true if and only if x and y are equivalent.

- bool **operator!=** (const **Powerset**< CS > &x, const **Powerset**< CS > &y)

Returns true if and only if x and y are not equivalent.

- std::ostream & **operator<<** (std::ostream &s, const **Powerset**< CS > &x)

Output operator.

- `void swap (Parma_Polyhedra_Library::Powerset< CS > &x, Parma_Polyhedra_Library::Powerset< CS > &y)`

Specializes std::swap.

11.17.1 Detailed Description

`template<typename CS> class Parma_Polyhedra_Library::Powerset< CS >`

The powerset construction on constraint systems.

This class offers a generic implementation of *powerset constraint systems* as defined in [Bag98](p. 15). See also the description in Section **The Powerset Construction**(p. 12).

11.17.2 Member Typedef Documentation

11.17.2.1 `template<typename CS> typedef std::list<CS> Parma_Polyhedra_Library::Powerset< CS >::Sequence` [protected]

A powerset is implemented as a sequence of elements.

The particular sequence employed must support efficient deletion in any position and efficient back insertion.

11.17.3 Constructor & Destructor Documentation

11.17.3.1 `template<typename CS> Parma_Polyhedra_Library::Powerset< CS >::Powerset ()`

Default constructor: builds the bottom of the powerset constraint system (i.e., the empty powerset).

11.17.4 Member Function Documentation

11.17.4.1 `template<typename CS> void Parma_Polyhedra_Library::Powerset< CS >::upper_bound_assign (const Powerset< CS > &y)`

Assigns to **this* an upper bound of **this* and *y*.

The result will be the least upper bound of **this* and *y*.

11.17.4.2 `template<typename CS> void Parma_Polyhedra_Library::Powerset< CS >::add_non_bottom_disjunct (Sequence &s, const CS &d, iterator &first, iterator last)` [static, protected]

Adds to **this* the disjunct *d*, assuming *d* is not the bottom element and ensuring partial omega-reduction.

If *d* is not the bottom element and is not redundant with respect to the elements in positions between *first* and *last*, adds to **this* the disjunct *d*, erasing all the elements in the above mentioned positions that are made omega-redundant by the addition of *d*.

11.17.4.3 `template<typename CS> template<typename Binary_Operator_Assign> void Parma_Polyhedra_Library::Powerset< CS >::pairwise_apply_assign (const Powerset< CS > &y, Binary_Operator_Assign op_assign)` [protected]

Assigns to `*this` the result of applying `op_assign` pairwise to the elements in `*this` and `y`.

The elements of the powerset result are obtained by applying `op_assign` to each pair of elements whose components are drawn from `*this` and `y`, respectively.

11.18 Parma_Polyhedra_Library::Variable Class Reference

A dimension of the vector space.

Public Types

- typedef void **output_function_type** (std::ostream &s, const **Variable** &v)
Type of output functions.

Public Member Functions

- **Variable** (dimension_type i)
Builds the variable corresponding to the Cartesian axis of index i.
- dimension_type **id** () const
Returns the index of the Cartesian axis associated to the variable.
- dimension_type **space_dimension** () const
*Returns the dimension of the vector space enclosing *this.*
- memory_size_type **total_memory_in_bytes** () const
*Returns the total size in bytes of the memory occupied by *this.*
- memory_size_type **external_memory_in_bytes** () const
*Returns the size in bytes of the memory managed by *this.*
- bool **OK** () const
Checks if all the invariants are satisfied.

Static Public Member Functions

- dimension_type **max_space_dimension** ()
*Returns the maximum space dimension a **Variable**(p. 152) can handle.*
- void **set_output_function** (output_function_type *p)
*Sets the output function to be used for printing **Variable**(p. 152) objects.*
- output_function_type * **get_output_function** ()
Returns the pointer to the current output function.

Related Functions

(Note that these are not member functions.)

- `std::ostream & operator<< (std::ostream &s, const Variable &v)`
Output operator.
- `bool less (Variable v, Variable w)`
Defines a total ordering on variables.

Classes

- struct **Compare**
Binary predicate defining the total ordering on variables.

11.18.1 Detailed Description

A dimension of the vector space.

An object of the class **Variable**(p. 152) represents a dimension of the space, that is one of the Cartesian axes. Variables are used as base blocks in order to build more complex linear expressions. Each variable is identified by a non-negative integer, representing the index of the corresponding Cartesian axis (the first axis has index 0). The space dimension of a variable is the dimension of the vector space made by all the Cartesian axes having an index less than or equal to that of the considered variable; thus, if a variable has index i , its space dimension is $i + 1$.

Note that the “meaning” of an object of the class **Variable**(p. 152) is completely specified by the integer index provided to its constructor: be careful not to be misled by C++ language variable names. For instance, in the following example the linear expressions `e1` and `e2` are equivalent, since the two variables `x` and `z` denote the same Cartesian axis.

```
Variable x(0);
Variable y(1);
Variable z(0);
Linear_Expression e1 = x + y;
Linear_Expression e2 = y + z;
```

11.18.2 Constructor & Destructor Documentation

11.18.2.1 Parma_Polyhedra_Library::Variable::Variable (dimension_type i) [explicit]

Builds the variable corresponding to the Cartesian axis of index `i`.

Exceptions:

`std::length_error` Thrown if the `i+1` exceeds **Variable::max_space_dimension()**(p. 152).

11.18.3 Member Function Documentation

11.18.3.1 dimension_type Parma_Polyhedra_Library::Variable::space_dimension () const

Returns the dimension of the vector space enclosing `*this`.

The returned value is **id()**(p. 152)+1.

11.19 Parma_Polyhedra_Library::Variable::Compare Struct Reference

Binary predicate defining the total ordering on variables.

Public Member Functions

- **bool operator() (Variable x, Variable y) const**
Returns true if and only if x comes before y.

11.19.1 Detailed Description

Binary predicate defining the total ordering on variables.

12 PPL Page Documentation

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