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AUTOMATIC DISCOVERY OF LINEAR RESTRANTS AMONG VARIABLES OF A PROGRAM

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1. INTRODUCTION

The model of abstract interpretation of programs developed by Cousot[1978], Cousot[1977] is applied to the static determination of linear equality or inequality relations among variables of programs.

For example, consider the following sorting procedure (Knuth[1973], p.107):

procedure BUBBLESORT(integer value N;

begin integer B,J,K;

{1} while B+1 do
{2} J:=1; T:=0;
{3} while J<(B-1) do
{4} if K[J]+K[J+1] then
{5} EXCHANGE(J,J+1); {no side effects on N,B,J,T}
{6} T:=3,
{7} J:=J+1;
{8} adj;
{9} if T=0 then return N;
{10} B:=T
{11} end;

Without user provided inductive assertions nor human interaction we have automatically determined (in 1.502 seconds of C.P.U. time) that the following restraints must hold among the variables of the above procedure:

{1} \( B=N \)
{2} \( 1 \leq \text{BN} \)
{3} \( 1 \leq \text{BSN} \), \( J=1 \), \( T=0 \)
{4}, {5}, {6} \( B=0N \), \( T=0 \), \( T=1 \), \( J=1 \)
{7} \( B=0N \), \( J=1 \), \( J=1 \), \( J=1 \)
{8} \( B=0N \), \( J=1 \), \( J=1 \), \( J=1 \)
{9} \( B=0N \), \( J=1 \), \( J=1 \), \( J=1 \)
{10} \( B=0N \), \( J=1 \), \( J=1 \), \( J=1 \)
{11} \( J=1 \), \( J=1 \), \( J=1 \), \( J=1 \)
{12} \( J=1 \), \( J=1 \), \( J=1 \), \( J=1 \)
{13} \( B=0N \)

A certain number of classical data flow analysis techniques are included in or generalized by the determination of linear equality relations among program variables. For example constant propagation can be understood as the discovery of very simple linear equality relations among variables (such as \( x=1 \), \( y=5 \)). However the resolution of the more general problem of determining linear equality relations among variables allows the discovery of symbolic constants (such as \( x=N \), \( y=5N+1 \)). The same way, common subexpressions can be recognized which are not formally identical but are semantically equivalent because of the relationships among variables. Also the loop invariant computations as well as loop induction variables (modified inside the loop by the same loop invariant quantity) can be determined on a basis which is not purely syntactical. The problem of discovering linear equality relations is in fact a particular case of the one of discovering linear inequality relations among the program variables. The main use of these inequality relationships is to determine at compile time whether the value of an expression is within a specified numeric or symbolic subrange of the integers or reals. This includes compile time overflow, integer subrange and array bound checking. In contrast to Suzuki-Ishihata[1977] we do not simply try to verify the legality assertions (such as verifying that array subscripts are within the declared range) but instead we try to discover the assertions (of linear type) that can be deduced from the semantics of the program. The advantage is that we can often discover relations which are never stated explicitely in the program. For example, we can discover that an integer variable lies in a subrange of its declared range or that two references \( A[I] \) and \( A[J] \) to two elements of the same array refer to different storage locations (since e.g. \( I=J+1 \) or that some piece of code is dead.

The problem of determining equality relationships between a linear combination of the variables of the program and a constant was solved by Kerr [1976]. His approach was based on Wegbreit's[1975] algorithm which requires that the properties to be discovered form a lattice every strictly increasing chain of which is of finite length. This assumption is not valid when considering inequality relationships (because of chains such as \( (x-1) \), \( (1\leq x \leq 2) \), \( (1\leq x \leq n) \), \ldots).

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2. APPROXIMATE ANALYSIS OF PROGRAM PROPERTIES, 
Cousot [1976].

For purposes of exposition, a sequential program will be represented by a connected finite flowchart with one entry node and assignment, test, junction and exit nodes. The evaluations of the right-hand side of an assignment and of the boolean expression in a test node are assumed not to affect the values of any variables. Thus all side-effect phenomena must be modeled as assignment statements. The junction nodes contain no computations and represent the merge of program execution paths.

The analysis of a program consists in attaching an assertion $P_i(V_1, ..., V_n)$ to each arc $i$ of the program. These predicates on the variables $V_1, ..., V_n$ are not necessarily the most general form but instead are designed to model a specific aspect of the semantic properties of the program. The assertion on the entry arc to the program represents what is known about the variables at the start of execution. For each other type of program node a transformation specifies the assertion associated with the output arc(s) of the node in terms of the assertions on the input arc(s) to the node and where relevant the content of the node. Hence we have established a system of equations between the local assertions which can be solved by successive approximations (Cousot [1977]). Starting from no information on each arc, this resolution consists in propagating the entry assertion around the program graph by application of the transformation described for each type of node until stabilization. All possible paths are followed sequentially with synchronization on junction nodes. It is assumed that each cycle in the program graph contains a specially marked junction node which is called a loop junction node. In order to ensure stabilization the transformation for a loop junction node will be an approximation of the transformation for ordinary junction nodes. More particularly let $P_{i,j}$ and $P_{i,m}$ be the assertions associated with the input arc of a junction node at step $j$. Let $Q_{i,j}$ be the assertion associated with the output arc $j$ of this node. Then $Q_{i,j} = f(P_{i,j}, ..., P_{i,m})$. For a loop junction node we have $Q_i = 0$ and $Q_{i,j} = f(P_{i,j}, ..., P_{i,m})$ where the widening operation $V$ performs an operation at step $j$ is such that $V(P_{i,j}, P_{i,m})$ and $V(P_{i,j}, P_{i,m})$ for any chain $(P_0 \Rightarrow P_1 \Rightarrow ... \Rightarrow P_j \Rightarrow ...)$ the chain $Q_{i,j} = P_j$. The algorithm performing the global analysis of programs is presented in section 5 by means of simple examples. Section 6 gives more convincing examples and Section 7 discusses the experimental implementation that has been realized.

3. FORMAL REPRESENTATIONS OF LINEAR RESTRAINTS AMONG VARIABLES OF A PROGRAM.

3.1. Linear system of a convex polyhedron.

Let $x_1, ..., x_n$ be the variables of the program.
For simplicity we assume that the values of the variables belong to the set $R$ of reals. The set of solutions to a system of linear equations

$$E_j x = b_j, j = 1, ..., m$$

where $E_j$, $b_j \in R$, if such solutions exist, is a linear variety of $R^n$. A linear variety of dimension $n - 1$ in an hyperplane. The set of solutions to a linear inequality

$$E_j x < b_j$$

is a closed half-space of $R^n$. For simplicity, strict inequalities are not considered. By linear restraint we mean either a linear equality or a linear inequality. In the formal reasoning we often consider that an equation can be viewed as two opposite inequalities.

A subset $C$ of $R^n$ is said to be convex if and only if $(x \in C, \lambda \in [0,1]) \lambda x + (1-\lambda) y \in C$. For example linear varieties and half-spaces are convex. The intersection of two convex sets is convex, but the union of two convex sets is not necessarily convex.

The set of solutions to a finite system of linear inequalities can be interpreted geometrically as the closed convex polyhedron of $R^n$ defined by the intersection of the closed halfspaces corresponding to each inequality.

3.2. The frame of a convex polyhedron, Weyl [1950], Kleene [1959], Church [1953].

Let $V_1, ..., V_p$ be vectors in $R^n$. A vector of the form $\sum_{i=1}^{p} (\lambda_i V_i)$ where for each $i = 1, ..., p$ we have $\lambda_i \in R$ is called a linear combination of the $V_i$. The set of all linear combinations of the $V_i$ is the linear variety generated by the $V_i$. A base of a linear variety $L$ is a minimal set of vectors generating $L$.

A vector of the form $\sum_{i=1}^{p} (\lambda_i V_i)$ where for each $i = 1, ..., p$ we have $\lambda_i \in R^+$ and $\sum_{i=1}^{p} (\lambda_i V_i)$ is called a convex combination of the $V_i$. The set of all convex combinations of the $V_i$ is the convex hull of the $V_i$.

A vertex of a polyhedron $P$ is a point $x$ of $P$ which is not a convex combination of other points of $P$. A polyhedron $P$ has a point $x$ and entirely included in $P$ if $(x \in P$, $\mu \in R^+, \mu x + (1-\mu) y \in P$). Two rays $r$ and $r'$ are equal if and only if $(\mu \in R: \mu r = \mu' r')$. A ray of a polyhedron $P$ is called an extreme ray if and only if it is not a positive combination of other rays $r_1, ..., r_p$ of $P$. A ray of a polyhedron $P$ is a point $x$ such that each half-line parallel to $r$ and entirely included in $P$ is a ray of $P$. A ray of a polyhedron $P$ is an extreme ray if and only if it is a positive combination of other rays $r_1, ..., r_p$. A ray (extreme ray) of a polyhedron is a point (vertex) translated to infinity.

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A line of a polyhedron $P$ is a vector $d$ such that both $d$ and $-d$ are rays of $P$: $(\forall x \in \mathbb{R}^n, \exists y \in \mathbb{R}^m, x+y=d)$. A polyhedron which contains at least one line is called a cylinder. The linear variety generated by all the lines of a cylinder is the greatest linear variety included in the cylinder. A polyhedron that contains no line has only a finite number of vertices and of extreme rays.

A bounded polyhedron has neither lines nor rays. Each point of a bounded polyhedron is a convex combination of the vertices of the polyhedron so that a bounded polyhedron is the convex-hull of its vertices.

Each point $x$ of a polyhedron $P$ which is not a cylinder can be expressed as the sum of a convex combination of the vertices $\{x_1, \ldots, x_p\}$ of $P$ and of a positive combination of the extreme rays $\{r_1, \ldots, r_q\}$ of $P$:

$$x = \sum_{i=1}^{p} \lambda_i x_i + \sum_{j=1}^{q} \mu_j r_j$$

Let $L$ be the greatest linear variety included in a cylinder $P$. Let $L$ be a linear variety orthogonal to $L$. Then the intersection of $L^*$ with $P$ is a convex polyhedron which contains no line and which is called a section of $P$. Each point of a cylinder can be expressed as the sum of a convex combination of the vertices of a section of $P$, a positive combination of the extreme rays of this section and a linear combination of the vectors of a basis of the greatest linear variety included in $P$.

By misuse of words the vertices and rays of a cylinder will be the vertices and rays of a section of that cylinder.

A closed convex polyhedron $P$ can be characterized by three sets $S = \{x_1, \ldots, x_p\}$, $R = \{r_1, \ldots, r_q\}$, $D = \{d_1, \ldots, d_r\}$ of vectors of $\mathbb{R}^n$ called the frame of the polyhedron as follows:

$$(\exists x \in \mathbb{R}^n) \iff \{x = \sum_{i=1}^{p} \lambda_i x_i + \sum_{j=1}^{q} \mu_j r_j : 1 \leq i \leq p, 1 \leq j \leq q, \forall \lambda_i, \mu_j, \in \mathbb{R}^+ \} \cap D = \emptyset.$$ 

We have two equivalent representations of a closed convex polyhedron either as the set of solutions of its system of linear restraints or as the convex hull of its frame.

**Example:** The polyhedron derived by the following system of restraints: $x^1 \geq 2$, $x^2 \geq 2$, $x^1 + 2x^2 \leq 6$, $x^1 - 2x^2 \geq -6$, is spanned by the following frame (see the diagram):

- Vertices: $x_1 = (4, 2)$, $x_2 = (2, 2)$, $x_3 = (4, 0)$
- Extreme rays: $r_1 = (2, 1)$, $r_2 = (2, 3)
- No line.

End of example.

Before looking at the problem of convolution between these representations we need some definitions.

A face of a polyhedron $P$ is a convex polyhedron $F \subseteq P$ such that if a point $x \notin F$ then each segment included in $P$ and containing $x$ is included in $F$; $(\forall \in F, p \in F, \lambda \in [0,1])$ and $x = \lambda p + (1-\lambda)q \Rightarrow (p \in F)$ and $(q \in F)$.

The dimension of a polyhedron $P$ is the dimension of the least linear variety containing $P$.

A face of dimension $k$ is called a $k$-face. An edge is a $1$-face. The vertices of a polyhedron containing no line are its $0$-faces (thus a cylinder has no $0$-faces). Let $\langle a^x x \rangle \leq b^x$ be a linear inequality defining the polyhedron $P$. Then if the intersection of the hyperplane defined by $H = \{x : \langle a^x x \rangle = b^x\}$ with $P$ is non-empty, it is a face of $P$.

We say that a point $a$ satisfies the inequality $\langle a^x x \rangle \leq b^x$ if and only if $\langle a^x x \rangle = b^x$.

We say that the ray $r$ saturates this inequality if and only if $\langle a^x x \rangle = b^x$.

Let $\delta$ be the dimension of the greatest linear variety included in the polyhedron $P$. Two vertices are said to be adjacent if they lie on the same edge (i.e. if $\delta = 0$ we mean the edge of the section). It follows that the number of inequalities saturated at the same time by two adjacent vertices is at least $n - \delta - 2$.

Two extreme rays are said to be adjacent if they belong to the same $2$-face. Therefore they saturate at least $n - \delta - 2$ inequalities simultaneously.

Finally, a vertex $a$ and a ray $r$ are adjacent if $a$ lies on an infinite edge which is parallel to $r$. Therefore a must saturate all the inequalities satisfied by $r$.

3.3. Conversions between the representations of a polyhedron by a system of linear restraints and by a frame.

Some operations that we have to perform on open convex polyhedra are easy when these polyhedra are represented by systems of linear restraints while others are more simple when the frame representation is used. Hence we must be able to make conversions from one representation to the other.

3.3.1. Conversion from the frame to the linear restraints representation.

This conversion consists in finding a system of restraints for the convex hull of the elements (points, rays, line) of a frame. This conversion is followed by a simplification of the system of restraints.

3.3.1.1. Convex hull of a finite frame.

Let $S = \{x_1, \ldots, x_p\}, D = \{d_1, \ldots, d_q\}$ be the frame of a non-empty polyhedron (so that $S \neq \emptyset$). The points $x$ of this polyhedron are characterized by the existence of $\lambda_1, \ldots, \lambda_p, \mu_1, \ldots, \mu_q, \nu_1, \ldots, \nu_q \in \mathbb{R}$ such that:

- $\sum_{i=1}^{p} \lambda_i x_i$ for $1 \leq i \leq p$
- $\sum_{j=1}^{q} \mu_j d_j$ for $1 \leq j \leq q$
- $\sum_{k=q+p+1}^{q+p+q} \nu_k x_k$.

$x = \sum_{i=1}^{p} \lambda_i x_i + \sum_{j=1}^{q} \mu_j d_j + \sum_{k=q+p+1}^{q+p+q} \nu_k x_k$.
Hence this polyhedron is characterized by a system of linear constraints in \( \mathbb{R}^{n+2+d+8} \) upon the variables

\[
  x_i (i=1..n), \quad \lambda_j (j=1..d), \quad \mu_j (j=1..d), \quad \psi_j (k=1..d).
\]

Eliminating the \( \lambda_j, \mu_j, \psi_j \) we get a system of linear constraints in \( \mathbb{R}^n \). This elimination can always be done by the projection operation used in Kuhn[1956].

Let us represent the system of m inequalities by \( A \times x \leq b \) where \( A \) is a real matrix and \( b \) a real vector. In order to eliminate the variable \( x_C \) we project according to the column \( C \) upon \( A \times x \leq b \) in order to get a simplified projected system defined as follows:

- For each row \( i \) such that \( A_C^i A_C^i \leq 0 \), the restraint \( A_C^i x_C \) is part of the projected system.
- For each two rows \( A_C^i, A_C^j \) such that
  
  \[
  A_C^i A_C^j < 0
  \]
  
  the restraint \( A_C^i \times A_C^j \) is part of the projected system.

The projected system contains only zeros in the column \( C \), hence it is independent of \( x_C \).

**Example:** Eliminating \( \lambda \) in the system

\[
  \begin{align*}
  -\lambda & \leq 0 \\
  \lambda & \leq 0 \\
  -x_1 & \leq 0 \\
  x_1 & \leq 0 \\
  x_2 & \leq 0 \\
  x_3 & \leq 0 \\
  x_4 & \leq 0 \\
  x_5 & \leq 0 \\
  & \text{we get:} \\
  -x_3 & \leq 0 \\
  x_1 & \leq 0 \\
  & \text{so:} \\
  x_1 & \leq 2 \\
  x_2 & \leq 2 \\
  x_3 & \leq 2 \\
  4x_4 & \leq 2 \\
  & \text{End of example.}
  \end{align*}
\]

The convex-hull of the frame \( S, R, D \) is computed by successive approximations \( P_1, P_2, \ldots, P_{d+2} \) as follows:

- \( P_1 \) is the point \( s_1 \) so that the corresponding system of restriats is \( (x_1=s_1) \). Then for each \( i=2..d \), \( P_i \) is the convex-hull of \( P_{i-1} \) and the point \( s_i \). Therefore \( (x_i \in P_i) \) if and only if \( (x_i \in P_{i-1}) \).

\( \lambda \geq 0 \) : \( x = x_\lambda \times (1 - \lambda) s_\lambda \). If \( A \times x \leq b \) is the system of constraints describing \( P_{i-1} \) it can be shown that this is equivalent to \( (x \in A \times \lambda \times (1 - \lambda) s_\lambda) \) for each projection according to the column \( \lambda \), \( \lambda \) can be eliminated to get a system of constraints of \( P_i \).

- For each \( j=1..d \), \( P_j \) is obtained by adjunction of the ray \( P_{j-1} \times A_C^j \).

- For each \( k=1..d \), \( P_k \) is built from \( P_{k-1} \) by adjunction of the line \( A_C^k \times (\sigma P) \). If \( P_{k-1} \) is described by \( A \times x \leq b \), this consists in eliminating \( \sigma \) in \( (A_C^k \times (\sigma P) \times b) \). Finally, \( P_{d+2} \) is the convex-hull of \( S, R, D \).

**Example:** The frame of a polyhedron in \( \mathbb{R}^3 \) is given by

\[
  S = \left\{ \begin{pmatrix} 1 \\ -1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \right\}, \quad R = \left\{ \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \right\}, \quad D = \left\{ \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \right\}
\]

The first approximation \( P_1 = (s_1) \) is defined by the system of constraints \( (x_1 \leq 0, x_2 \leq 0, x_3 \leq 0) \). The second approximation \( P_2 \) is the convex-hull of \( P_1 \) and \( (s_2) \) that is \( (D \times s_1, x_1 \leq 2, x_2 \leq 2, x_3 \leq 0) \).

Eliminating \( \lambda \) we get \( (x_1^1 \leq 0, x_1^2 \leq 0, -x_1^3 \leq 1, -x_1^4 \leq 1) \). \( P_3 \) is obtained by adjoining the ray \( (0,0,1) \) to \( P_2 \) that is \( (s_3, x_1 \leq 2, x_2 \leq 2, x_3 \leq 0) \). Eliminating \( \sigma \) we get \( (x_1^1 \leq 0, -x_1^4 \leq 1) \). The last approximation \( P_4 \) is the convex-hull of \( P_3 \) and the line \( (1,0,0) \) that is \( x_1 \leq 2, x_2 \leq 2, x_3 \leq 0 \). Eliminating \( \sigma \) we get the final solution \( (x_1^2 \leq 0, 0 \leq x_2, -x_1^2 \leq 1) \).

End of example.

### 3.3.1.2. Simplification of a system of linear inequalities.

It is often the case that projections lead to projected systems of restraints containing a great number of irrelevant restraints which can be eliminated without changing the polyhedron represented by the system of restraints. For the sake of efficiency these irrelevant restraints must be excluded. Knowing a frame of the polyhedron, the corresponding system of linear inequalities can be simplified according to the following remarks due to Lanery[1968]::

- An inequality which is never saturated by a vertex of the frame is irrelevant.
- An inequality which is saturated by all vertices and all rays of the frame represents an equality. All the equalities are found in that way.

Let \( C_1 := \{a_1, x \in b_1\} \) and \( C_2 := \{a_2, x \in b_2\} \) be two inequalities of the system of restraints which are not equations. Let \( \sigma \) be the quasi-ordering defined by \( \{C_1, C_2\} \Rightarrow \{\forall x \in C_1, (a_1 \leq a_2) \Rightarrow (a_2 \leq a_2)\} \). Hence \( \sigma \leq C_2 \) means that \( C_2 \) is saturated by any vertex or ray saturating \( C_1 \). If \( \sigma \leq C_2 \) but not \( \sigma \leq C_1 \) then \( C_1 \) is irrelevant. If \( \sigma \leq C_2 \) and \( \sigma \leq C_1 \) then one and only one of the inequalities is irrelevant so that one of them can be excluded. Applying these results to a system of restraints we obtain a minimal system of restraints (with no irrelevant inequality) corresponding to the same polyhedron.

### 3.4. Conversion from the linear restriats to the frame representation of the polyhedron

Based on the pivoting method of linear programming, numerous algorithms have been designed to find all vertices of a convex polyhedron (Balinski[1961], Lanery[1968], Mansa-Nedoma[1968], Mattheis[1973], Dyor-Prioli[1975]). We shall give a brief description of Lanery's method which is general enough to find a frame (vertices, extreme rays, lines) of a convex polyhedron. We first recall some elements of linear programming (Simmonds[1973]).
3.4.1. Basic concepts of linear programming

A system of linear inequalities:

\[ \sum_{j=1}^{n} (a_{ij} x_i) + b_j = 0 : j = 1 \ldots n \]

can be written in the equivalent form:

\[ \sum_{j=1}^{n} (a_{ij} x_i) = b_j + y_j^0 \quad y_j^0 = 0 : j = 1 \ldots n \]

Hence a system of constraints can be written in standard form:

\[ [\text{3.4.1.2}] \quad A x = b, \quad x \geq 0 \]

where \( A \) is a \((m \times n)\) matrix, \( b \) is an \( m \)-vector \( \leq \) \( (1 \ldots n, m), F = (1 \ldots n) \). The variables \( x_i : i \in F \) are the initial variables, the \( x_i : i \in E \) are the slack variables.

A basis of the system \([3.4.1.2]\) is a non singular \( m \times m \) submatrix \( A_i \) of \( A \). The system can be written in canonical form with respect to the basis \( A_i \):

\[ x^T (A_i^{-1} A_j) x^T = A_i^{-1} b, \quad x^T \geq 0 \]

\( j = 1 \ldots n \). The variables \( x_i \) such that \( i \in F \) are said to be in basis. The basis \( A_i \) is feasible if and only if \( (A_i^{-1} b)^+ \geq 0 \). Two feasible bases \( A_i \) and \( A_j \) are said to be adjacent if and only if the cardinal of the set \( \text{In} J \) is equal to \( m-1 \). If two bases are adjacent the classical pivot operation transforms the system written in canonical form with respect to \( A_i \) into an equivalent system in canonical form with respect to \( A_j \). The artificial basic method which is the initialization step of the simplex method transforms the system of constraints \([3.4.1.2]\) into an equivalent system in canonical form \([3.4.1.3]\) with respect to a feasible basis of \([3.4.1.2]\) whenever such a basis exists.

3.4.2. Principles of Lanery's method.

The graph of the adjacency relation on the set \( A_i \) of feasible bases containing all initial variables \( i.e., a \) such that \( F = \{1 \} \) is connected. Hence given such a basis we can by successive pivoting operations and an exhaustive traversal technique find all feasible bases of a given system of constraints.

- If \( A_i \) is a feasible basis such that \( F = \{1 \} \) then the vector \( (A_i^{-1} b)^+ \) corresponds to a vertex of the convex polyhedron defined by the system of constraints. To each vertex of a polyhedron containing no line corresponds at least one feasible basis. If two vertices are adjacent then there are two adjacent feasible bases respectively corresponding to them.

- Let \( (A x \geq b, x \geq 0) \) be the canonical form of a system of constraints with respect to the feasible basis \( A_i \) containing all initial variables. Then Lanery shows that if a column \( i \in (E - F) \) satisfies the condition:

\[ [\text{3.4.2.1}] \quad (w_j \in \{1 \ldots m\}, (A_i^{-1} w_j) \supseteq (w_k \in \{n+1 \ldots k\}, A_i^{-1} w_k) \]

then the vector \( x \in R^m \) defined by \( x = A_i^{-1} w_j \) where \( i \in \{n+1 \ldots k\} \), \( j \) is the unique index such that \( A_i^{-1} w_j = 1 \) is an extreme ray of the polyhedron. Applying this result to each column \( i \) verifying \([3.4.2.1]\) in each feasible basis corresponding to a vertex \( v \), we find all extreme rays adjacent to \( v \). Since each extreme ray of a polyhedron that contains no line is adjacent to a vertex we can find all extreme rays of such a polyhedron.

- For polyhedra containing a line there is no feasible bases containing all initial variables.

Hence let \( (A x \geq b, x \geq 0) \) be the canonical form with respect to any feasible basis \( A_i \). Let \( i \in (F - E) \) be a column satisfying the condition:

\[ [\text{3.4.2.2}] \quad (w_j \in \{1 \ldots m\}, (A_i^{-1} w_j) \supseteq (A_i^{-1} w_k = 0 \text{ or } k E) \]

Let \( d_i \) be the vector of \( R^n \) the \( i \)-th component of which is defined by:

\[ d_i = 1 \text{ if } i = 1 \]

\[ \text{else if } i \in I \text{ then } -A_i^{-1} w_j \text{ (where } j \text{ is the unique index such that } A_i^{-1} w_j = 1) \]

\[ \text{else } 0 \]

Then Lanery shows that \( d_i \) corresponds to a line of the polyhedron.

Also if the basis \( A_i \) is such that each \( i \in (F - E) \) verifies the property \([3.4.2.2]\), then the set \( \{d_i \in (F - E)\} \) is a basis of the greatest linear variety contained in the polyhedron.

3.4.3. Algorithm for finding the frame of a convex polyhedron.

Let \( A x \geq b \) be a system of \( m \) linear constraints among the variables \( x \in R^m \).

1. Build the standard form \( A [0] x \geq b [0], x \geq 0 \) where \( x \in R^m \).

2. Apply the first step of the simplex method.

   If there is no feasible bases, the polyhedron is empty. Otherwise we get the system

   \( A [1] x \geq b [1], x \geq 0 \) in canonical form with respect to the feasible basis \( A_1 \) with \( (B [1])^+ \geq 0 \).

3. While there exists an initial variable staying out of the basis and satisfying \([3.4.2.2]\) perform a pivoting which puts this variable in the basis by removing a slack variable from the basis.

4. We get a system \( A [2] x \geq b [2], x \geq 0 \) in canonical form with respect to the basis \( I_2 \). Two subcases must be considered:

   4.1. If all initial variables are in the basis \( (F [1]) \), then the polyhedron contains no line and a vertex has been found. Then traverse exhaustively all feasible bases of the system and note at each step the vertex and the ray that are found. An efficient algorithm for this travel is given by Dyer-Prodl[1971].

   4.2. The initial variables \( x_1, \ldots, x_5 \) possibly remaining out of the basis verify \([3.4.2.2]\). So \( \{d_1, \ldots, d_5\} \) is a basis of the greatest linear variety contained in the polyhedron. Then a system of restraints: 88
\( \{Ax \leq 0, \Sigma_k x_k = 0, \forall k = 1..6\} \) defines a new polyhedron \( P' \) which is a section of the initial polyhedron. Applying the algorithm to this new system of constraints case 4.1 is applicable since \( P' \) contains no lines so that the algorithm terminates.

Example: Let us compute a frame of the polyhedron \( P \) corresponding to the following system of constraints:

\[
\begin{align*}
-x_1 x_2 + x_3 & \leq 0 \\
-x_1 & \leq -1 \\
-x_1 x_2 + x_3 & \leq 0 \\
-x_2 x_3 & \leq 3
\end{align*}
\]

[51]

1-Using the matrix notation for denoting systems of equations the standard form of [51] is:

\[
\begin{array}{cccccccc}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}
\]

[52]

The system [52] is in canonical form with respect to the infeasible basis \( A_{1,4,7,6,5,7} \).

2-The artificial basis method supplies the system [53] in canonical form with respect to the basis \( \{1,4,7,6,5,7\} \), which is feasible:

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}
\]

[53]

Then we put into the basis as many initial variables as we can, we got the basis \( A_{1,4,7,6,5,7} \):

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}
\]

[54]

The initial variable \( x_1 \) remains out of the basis and cannot be put into the basis without getting \( x_2 \) out. The third column verifies [3.4.2.2]. Hence the vector \( d(0,1,1) \) is the only line of the polyhedron \( P \). Let us build the system of restraints of a section \( P' \) of \( P \).

\[
\begin{align*}
-x_1 x_2 - x_3 & \leq 0 \\
-x_1 & \leq -1 \\
-x_1 x_2 - x_3 & \leq 0 \\
-x_2 x_3 & \leq 3
\end{align*}
\]

[55]

Applying (1) and (2) to [55] we get the canonical form with respect to the feasible basis \( A_{1,4,7,6,5,7} \) which contains all initial variables. Thus we have found a first vertex of \( P' \) and we start the traversal of the graph of vertices:

<table>
<thead>
<tr>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( x_3 )</th>
<th>( x_4 )</th>
<th>( x_5 )</th>
<th>( x_6 )</th>
<th>( x_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1/2</td>
<td>1/2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Basis: \( A_{1,2,3,4,7,6} \)

Vertex: \( s_1 = (1,1/2,1/2,1/2) \)

Column 5 satisfies [3.4.2.1]

Rey: \( r_1 = (1/2,1/2,1/2) \)

Adjacent feasible basis: \( A_{1,2,3,4,7,6} \)

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1/2 & 1/2 & 0 & 0 & 1/2 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 2
\end{array}
\]

Basis: \( A_{1,2,3,4,7,6} \)

Vertex: \( s_1 = (1,1/2,1/2,1/2) \)

No column satisfies [3.4.2.1]

Adjacent feasible bases: \( A_{1,2,3,4,7,6} \) already found

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & -1/2 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0
\end{array}
\]

[56] 1 2 3 4 5 6 7 8

Basis: \( A_{1,2,3,4,7,6} \)

Vertex: \( s_2 = (1,1,1,1,1,1,1) \)

Column 6 satisfies [3.4.2.1]

Rey: \( r_2 = (0,0,0,0,0,0,0) \)

Adjacent feasible basis: \( A_{1,2,3,4,7,6} \) already found

All feasible bases that contain initial variables have been found, the algorithm terminates with the following frame for \( P' \):

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & -1/2 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0
\end{array}
\]

Basis: \( A_{1,2,3,4,7,6} \)

Vertex: \( s_2 = (1,1,1,1,1,1,1) \)

3.4.4. Simplification of a frame

Lannery [1966] proposes a method for eliminating all irrelevant members of a frame when a system of restraining the polyhedron is known. This method is the dual of the one given at paragraph 3.3.1.2. For simplifying a system of inequalities. Lannery’s method is based on the following results:

- A vertex or a ray saturating no inequality is irrelevant.
- A ray saturating all constraints corresponds to a line.
- If \( e_1 \) and \( e_2 \) are two vertices or two rays (which are not lines) in the frame the quasi-ordering \( \leq \) is defined by:
  \( e_1 \leq e_2 \) if every inequality satisfied by \( e_1 \) is satisfied by \( e_2 \).

End of example.

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3.5. On the use of two representations for assertions.

The search for the frame of a polyhedron as described above may become very expensive although many important optimizations are possible. The number of vertices of a polyhedron generated in \( \mathbb{R}^n \) by \( m \) inequalities is known to be bounded only by functions increasing very quickly with \( m \) and \( n \), Sooty [1955], Kleo [1964]. So the use of this method should be avoided except when applied to polyhedra which are thought to have very few vertices. However the use of two representations is necessary for the following reasons:

- Some operations like the convex-hull of two polyhedra can only be performed on the frame representation, others like widening require the restraint representation.
- In order to define the inclusion relation between two polyhedra it is very useful to know both representations. Indeed \( P_1 \subseteq P_2 \) if and only if each element of the frame of \( P_1 \) satisfies the restraint of \( P_2 \).
- It appears that it is difficult to simplify one representation without knowing the other one and neither can be used efficiently without simplifications. So we shall build at the same time and in a consistent way the systems of restraints and the frames of the polyhedra. Both representations will be simultaneously used to represent the assertions. Experience shows that this redundant representation is much less expensive than the frequent use of conversions.

4. TRANSFORMATION OF LINEAR ASSERTIONS BY ELEMENTARY LANGUAGE CONSTRUCTS.

Given the flowchart representation of programs we now give for each type of program node a transformation specifying the assertion associated with the output arc(s) of the node in terms of the assertions associated with the input arc(s) of the node and where relevant the content of this node. The conditions of Cousot [1977] guarantee the correctness of these transformations applied to the specific case analyzed here.

4.1. Program entry node.

In some cases (parameters of procedures) the restraints on the input variables may be known. In this case they constitute the assertion associated with the input arc. Otherwise the variables are assumed not to be initialized so that they satisfy no restraints. Hence the vector of their values may be any point of \( \mathbb{R}^n \) where \( n \) is the number of variables involved in the program analysis. The corresponding polyhedron is given by a system with no restraints and equivalently by the frame consisting in:

- The vertex which is the origin of \( \mathbb{R}^n \)
- No ray
- The lines \( \ell_1, \ldots, \ell_n \) such that for every \( 1 \leq i \leq n \),
  \[ d_i \geq 0 \text{ and } d_i \geq 0 \text{ for } j \neq i. \]

4.2. Assignment.

Let \( [A,B,S,R,D] \) be the representation of the input assertion \( P \) corresponding to the polyhedron \( A \times S \) for the frame of which is \( S = \{ d_i : i = 1, \ldots, n \} \).

\[ R = \{ r_j : j = 1, \ldots, p \}, D = \{ d_k : k = 1, \ldots, q \}. \]

Then the representation of the output assertion \( P' \) after the assignment \( X^0_{\text{out}} = E(X) \) is given by

\[ \text{assign } [P', X^0_{\text{out}} = E(X)] = [A', B', S', R', D']. \]

4.2.1. Assignment of a non linear expression.

If the expression \( E(X) \) is not linear it is assumed that any value of \( R \) can be assigned to \( X^0_{\text{out}} \). Hence after the assignment \( X^0_{\text{out}} = E(X) \) nothing is known about the value of \( X^0_{\text{out}} \). Therefore \( X^0_{\text{out}} \) is eliminated from the system of restraints \( A \times S \) by a projection along the column \( i_0 \) (§ 3.1.1.1). For the frame representation this consists in adding the line \( d \) (such that \( d_i = 1 \) and \( d_j = 0 \) for every \( j \neq i \)) different from \( i_0 \) to the set of lines \( D \). Then in general the representation \( [A', B', S', R', D'] \) of \( P' \) is not minimal and must be simplified (§ 3.3.1.2 and § 3.4.4).

Example: Let \( n = 2 \) and \( P' \) be the input assertion represented by the system of restraints:

\[ \begin{align*}
  x_1 - x_2 & \geq -1 \\
  x_2 & \geq 1 \\
  x_1 x_2 & \geq 5
\end{align*} \]

The frame representation is \( S = \{(2,3),(4,1)\} \), \( R = \{(1,1),(1,0)\} \), \( D = \emptyset \). The geometrical interpretation is:

The output assertion \( P' \) after the assignment \( x_2 = x_1 x_2 \) is \( (x_1 \geq 0, x_2 \geq 2) \), the frame of which is \( S' = \{(2,3),(4,1)\} \), \( R' = \{(1,1),(1,0)\} \), \( D' = \{(0,1)\} \).

Simplifying we get \( \{x_2 \geq 2\} \). \( S' = \{(2,3)\} \), \( R' = \{(1,0)\} \), \( D' = \{(0,1)\} \) that is:

\[ \begin{align*}
  x_2 & \geq 2 \\
  x_1 & \geq 0
\end{align*} \]
The approximation is obviously very coarse since the substitution of $x_1x_2$ for $x_2$ in the input system of constraints would lead to:

\[
\begin{cases}
    x_2 \leq x_1^2(x_1) \\
    x_2 \geq x_1 \\
    x_2 \geq 5x_1^2(x_1)
\end{cases}
\]

However, the corresponding domain is not a polyhedron and this situation is hardly manageable:

\[
\begin{array}{c}
\end{array}
\]

Note however that the exact domain is covered by the approximate domain (Cousot[1977]). Also, a more precise analysis is feasible. For example \{$x_2>0$ and $x_3>0$\} implies \{$x_1x_3>0$\} or the assignment $x_1=x_3$ implies that $x_5$ is greater than or equal to zero.

End of example.

4.2.2. Assignment of a linear expression

The assignment is of the form $X^l_0 = \sum_{i=1}^{n} (a_{i1}x_i)^l + b$ where $a_1$ is an $n$-row vector of integers or reals and $b$ is an integer or a real. The transformation consists in an alteration of the basis of the space $R^n$. The output assertion $\beta'$ is defined by the frame \{$S^r,R^r,D^r\}$ computed as follows:

- $S^r = \{s_{11}, \ldots, s_{n1}\}$ where $s_{ij}$ is defined by $y_{1j}^l = a_{ij}y_{1j}$
- $S_{i1} = a_{ij}$ where $i=1..n$ with $l=1$.
- $R^r = \{r_{11}, \ldots, r_{n1}\}$ where $r_{1j}$ is the vector defined by $r_{1j}^l = a_{ij}r_{1j}$
- $D^r = \{d_{11}, \ldots, d'_{n1}\}$ where $d_{1j}'$ is the vector defined

The system of constraints corresponding to $\beta'$ can be obtained as the convex-hull of the frame \{$S^r,R^r,D^r\}$. However, following Karr[1976] this system of restraints can be computed directly.

4.2.2.1. Invertible assignments

The assignment is of the form $X^l_0 = \sum_{i=1}^{n} (a_{i1}x_i)^l + b$ $a_1 \neq 0$. The fact that $a_1 \neq 0$ allows us to carry over our knowledge of the previous value of $X^l$ to the new value of $X^l$. To see this, denote the values of the variables by $X$ before and by $X'$ after the invertible assignment statement. Then for $l=1..n$ and $l=1$ we have $X^l_1 = X^l$ whereas $X^l_2 = X^lX+b$. Therefore $X = MX^k$ as defined by

- $X^l = X^l_1$ for $l \in \{1, n\} - \{1\}$

\[-X^l_1 = (X^l_1)^{l-1}_1(a_1X^l_2)^l/b_1\]

Also \{AX≤B\} is equivalent to \{\{MAX ≤ (B-AX)\} which leads to the output system of restraints satisfied by $X'$.

4.2.2.2. Non-invertible assignments

If $a_1 = 0$ then we cannot solve $X'$ in terms of $X$ so that some information is lost by the assignment. Hence $X^l_0$ is eliminated from the input restraints by a projection operation. The case is similar to the one of the assignment of a non-linear expression except that the restraint $X^l_0 = ax+b$ is adjoined to the resulting system.

Example:

Let $F$ be the input assertion defined by

\[
\begin{cases}
    x_2 \geq 1 \\
    x_1x_2 \geq 5 \\
    x_1-x_2 \geq -1
\end{cases}
\]

The assignment $x_2 = x_1+1$ is not invertible. The elimination of $x_2$ in the input system of restraints leads to \{$x_1,x_2$} so that the output system of restraints is:

\[
\begin{cases}
    x_1 \geq 2 \\
    \frac{x_2-1}{3} \geq 1
\end{cases}
\]

The assignment $x_2 : x_1x_2/2+1$ is invertible so that $x_1=x_1'$ and $x_2 = 2x_2'-2x_1'-3$. Substituting in the input system of restraints we get the output system:

\[
\begin{cases}
    2x_2'-2x_1' \geq 3 \\
    2x_2'-x_1' \geq 7 \\
    -2x_2'+3x_1' \geq -3
\end{cases}
\]

End of example.

4.3. Test Nodes

Let $P(A,B,S,R,D)$ be the assertion associated
with the input arc to a decision mode testing some boolean condition C. Let \( P_t^*(A_t,B_t,S_t,R_t,D_t) \) and \( P_f^*(A_f,B_f,S_f,R_f,D_f) \) be the assertions associated respectively with the true and false exits of the test. Obviously \( P_t^* = P \) and \( C \) whereas \( P_f^* = P \) and \( \neg C \).

The condition \( C \) is said to be linear if and only if it is of the form \( ax+b \) or \( bx+a \), where \( a \) is an \( n \)-row-vector of integers or reals, \( b \) is an \( n \)-column-vector of program variables and \( b \) is an integer or a real.

### 4.3.1. Non-linear tests.

If \( C \) is not a linear condition we "ignore" the test by putting \( P_t^* = P_f^* = P \). This is certainly valid, but it may not be as much information as could be gathered. As for non linear assignments specific studies can be made of how best to handle test conditions which are not linear (for example \( \log(x) \cdot x \) implies \( x \geq 1 \)).

### 4.3.2. Linear equality tests.

When \( C \) is a linear condition let \( H \) be the hyperplane \( \{x \in \mathbb{R} \mid ax+b\} \).

If \( C \) is of the form \( ax+b \) then either \( P \) is included in \( H \) in which case \( P = P_t^* \) or \( P \) is not included in \( H \) in which case \( P = P_f^* \). Note that (\( ax+b \) and \( ax-b \)) is approximated by \( \{ax+b\} \), since the domain \( \{x \in \mathbb{R} \mid ax+b \} \) is not, in general, a closed convex polyhedron.

The frame of \( P_t \) is found thanks to the following results:

1. If each vertex \( s \) of \( P_t \) lies on an edge of \( P \) according to one of the following alternatives:
   - 1.1- \( s \) is a vertex of \( P \) that belongs to \( H \).
   - 1.2- there are two adjacent vertices \( s_1 \) and \( s_2 \) of \( P \) such that \( a = a_1 + (1-\lambda)a_2 \).
     1.2.1- \( \lambda \) is \( \{b-a_1\}/(a_2-a_1) \) belongs to \( [0,1] \).
     1.2.2- there is a vertex \( s_1 \) and a ray \( r \) of \( P \) such that \( s \) is adjacent to \( r \) in \( P \) and \( s = s_1 + \mu r \), where \( \mu = -(b-a_1)/a_2 \), is positive.
   - 1.4- there are a vertex \( s_1 \) and a line \( d \) of \( P \) such that \( s = s_1 + \mu d \), where \( \mu = -(b-a_1)/a_2 \).

2. Each extreme ray \( r \) of \( P_t \) is either an extreme ray of \( r \) of \( P \) that belongs to \( H \).

3. Finally a vertex \( s \) is a line of \( P_t \) if and only if there are two lines \( d_1 \) and \( d_2 \) in \( P \) such that \( \lambda d_1 + (1-\lambda)d_2 \).

### 4.3.3. Linear inequality tests

If \( C \) is of the form \( ax+b \) then \( P_f^* = (P \text{ and } ax+b) \) whereas \( P_f^* = (P \text{ and } ax+b) \). Note that the inequality is not strict since \( P_f^* \) must be a closed polyhedron and that we can write \( ax+b \geq 1 \) for integers.

As above, the determination of the frames of \( P_t \) and \( P_f^* \) makes use of a frame \( (S', R', D') \) of the intersection \( P \times H \) of \( P \) with the hyperplane \( H \). \( a = ax+b \).

The set \( S_t \) of vertices of \( P_t \) is \( \{ax+b \mid ax+b \geq 1 \} \).

If \( S_t \) is empty then \( P_t^* \) is the empty polyhedron whereas \( P_f^* \) equals \( P \). Otherwise \( S_t \) is not empty and TMs set \( S_t \) of extreme rays of \( P_t \) is \( \{ax+b \mid dx+b \geq 1 \} \).

The set of lines \( D_t \) of \( P_t \) is \( \{ax+b \mid dx+b \geq 1 \} \). A symmetric reasoning is used to determine a frame of \( P_f^* \). The resulting frames \( \{ax+b \mid dx+b \geq 1 \} \) and \( \{ax+b \mid dx+b \geq 1 \} \) are not necessarily minimal and must be simplified (3.4.4).

**Example:** Let \( P \) be an input assertion defined by \( \{(x_1 \geq 1, x_2 \geq 2) \} \). Let \( P_t \) and \( P_f^* \) be the output assertions associated respectively with the true and false exits of a test on the condition \( x_1 \geq 2 \) that is \( ax+b \) where \( a = (1,2), b = 8 \) and \( X \) is the 2-column-vector \( (x_1, x_2) \). Let \( H \) be the hyperplane defined by the equation \( x_1 \geq 2 \). The geometrical interpretation is the following:

In order to determine a frame of \( P_t \), it is necessary to know the adjacent elements of the frame of \( P \), \( \{(a_1, b_1), (a_1, b_1), (a_2, b_2), (a_2, b_2) \} \) are adjacent. The vertex \( s' \) of \( H \) corresponds to the case 4.3.2.1.3, that is \( s' = (b-a_1)/a_2 \).

The extreme ray \( r' \) of \( P_t \) corresponds to the case 4.3.2.2.2 that is \( r' = (b-a_1)/a_2 \). A frame of \( P_t^* \) is given by \( s_t = (s', 2) \), \( D_t = (s', 2) \). A frame of \( P_f^* \) is given by \( s_f = (s', 2) \).
\[ R_p = \langle r_2'^r \rangle \quad Q_2 = \emptyset \]

End of example.

4.4. Simple junction nodes.

Simple junction nodes correspond for example to the merge of the "then" and "else" paths in a conditional statement. More generally let \( P_1, P_2, \ldots, P_n \) be the assertions associated with the input arcs \( p_1, p_2, \ldots, p_n \) to the simple junction node and \( P \) the output assertion:

Then the output assertion \( OR_p^{\equiv} \{P_i\} \) does not necessarily correspond to a convex polyhedron so that it must be approximated by the convex-hull of \( P_i \), \( i = 1, 2, \ldots, P \) which is the least polyhedron containing \( P_1, P_2, \ldots, P_n \).

Since the convex-hull operation is associative we can assume without loss of generality that there are two input arcs (p2). Given \( P_1 = (A_1, B_1, \{I_1, D_1\}) \) and \( P_2 = (A_2, B_2, \{I_2, D_2\}) \) the frame of \( P = \text{convex-hull}(P_1, P_2) \) is \( S = S_1 \cup S_2 \cup I \cup U \) where \( D = D_1 \cup D_2 \). The system of constraints \( A \times B \) describing \( P \) is obtained by the convex-hull of the frame \((S, R, D)\) which can be computed by successive approximations (§3.3.1.1). As soon as the system of constraints \((A \times B)\) of \( P \) is known, \( P = \text{convex-hull}(P_1, P_2) \) can be simplified (§4.4).

Notice that \( \text{convex-hull}(P_1, P_2) \) cannot be computed directly from the systems of constraints \( A_1 \times B_1 \) and \( A_2 \times B_2 \). In order to avoid a costly conversion (§3.4) the redundant frame representation has been kept along with the constraints representation. For the output assertion \( P \) the conversion from frame \((S, R, D)\) to constraints \( A \times B \) representation is less expensive (§3.3).

Then the system of constraints of \( P_1 \) (or \( P_2 \) is known. This conversion is optimized as follows:

\[ \text{convex-hull}(P_1, P_2) = \text{convex-hull}(\{S_1 \cup S_2 \cup I \cup U \}, \{R_1 \cup R_2 \} \cup \{D_1 \cup D_2 \}) \]

so that starting from \( A \times B \), we can successively incorporate in the convex-hull the elements of the frame of \( P_2 \).

Example:

\[ P_1 = \{(x_1 \geq 0, x_2 \geq 0, x_1 + x_2 \leq 1)\}, \quad S_1 = \{(0, 0), (1, 0), (0, 1)\}, \quad R_1 = \emptyset, \quad D_1 = \emptyset \]

\[ P_2 = \{(x_1 \geq 1, x_2 \geq 2), \quad S_2 = \{(1, 2)\}, \quad R_2 = \emptyset, \quad D_2 = \emptyset \]

The convex-hull of \( P_1 \) (given by \( A_1 \times B_1 \)) and the vertex \( = (1, 2) \) of \( P_2 \) is obtained (§3.3.1.1) by elimination of \( \lambda \) in \( (0 \lambda x_1, A_1 \lambda x_1, -B_1 \lambda x_1) \) and \( (0 \lambda x_2 + 2 \lambda x_3) \) we get the approximation \( A' \times B' \) given by

\[ (x_1 \geq 1, 0 \lambda x_1, 2 \lambda x_2 + x_2 \leq 0) \]

Example:

Incorporating the ray \( r = (1, 0) \) of \( P_2 \) in \( A' \times B' \) by elimination of \( \mu \) in \( (0 \mu x_1, A' \mu x_1, -B' \mu x_1) \) that is \( (0 \mu x_1, x_2 + x_1, -B' \mu x_1, x_2 \leq 0) \) we get the convex-hull of \( P_1 \) and \( P_2 \) given by \( (0 \lambda x_2 + 2 \lambda x_3, x_2 \geq 0, x_2 \leq 1) \).

End of example.

4.5. Loop junction nodes.

Each cycle in the program graph contains a loop junction node.

The corresponding transformation \( P = \text{convex-hull}(P_1, P_2, \ldots, P_n) \) is defined by the widening operation \( \vee \). Let \( Q_1(A_1, B_1, S_1, R_1, D_1) \) and \( Q_2(A_2, B_2, S_2, R_2, D_2) \) be two convex polyhedra. Then \( Q_1 \vee Q_2 \) is the convex polyhedron consisting in the linear restraints of \( Q_1 \) verified by every element of the frame \((S_2, R_2, D_2)\) of \( Q_2 \).

Example:

\[ Q_1 = \emptyset \]

\[ \{x_1 \geq 1, x_2 \geq 2, x_1 + x_2 \leq 1, x_2 \leq 0\} \]

\[ S = \{(0, 0), (0, 1), (1, 1)\}, \quad R = \emptyset, \quad D = \emptyset \]

\[ Q_2 = \emptyset \]

\[ \{x_1 \geq 1, x_2 \geq 2, x_1 + x_2 \leq 1, x_2 \leq 0\} \]

\[ S = \{(0, 0), (1, 0), (0, 1)\}, \quad R = \emptyset, \quad D = \emptyset \]

\[ Q_1 \vee Q_2 = \emptyset \]

End of example.

In order to compute the frame of \( Q_1 \vee Q_2 \) it is necessary to convert from the linear constraint representation. Lanery's method (§3.4) is known to be expensive. However when applied after a widening operation the cost remains reasonable because of the following arguments:

- In the widening \( Q_1 \vee Q_2 \) by \( Q_2 \) a certain number of vertices of \( Q_1 \) have been replaced by extreme rays. Hence the widening operation eliminates vertices, so that \( Q_1 \vee Q_2 \) can be assumed to have a small number of vertices.
- Now it is the discovery of vertices which is the most costly in Lanery's method.

- A frame of \( Q_1 \) is known and \( Q_1 \) is included in \( Q_1 \vee Q_2 \).

Therefore the initialization of the simplex method needs not to be used. Moreover since any restraint of \( Q_1 \vee Q_2 \) is a restraint of \( Q_1 \) it is highly probable that the frames of \( Q_1 \) and \( Q_1 \vee Q_2 \) have numerous common elements.

The correctness criterion of Cousot[1977] recalled at paragraph 2 is satisfied since \( Q_1 \subseteq Q_1 \vee Q_2 \).

\[ Q_2 \subseteq Q_1 \vee Q_2 \]

and for every chain \( C \subseteq C_1 \subseteq \cdots \subseteq C_n \).

The chain \( S_n = S_1 \subseteq S_2 \subseteq \cdots \subseteq S_n \) is not an infinite strictly increasing chain since at each step the number of restraints describing \( S_n \) is finite and less than or equal to the number of restraints describing \( S_{n-1} \).
The definition of the widening operation must be a balance between compelling the convergence of the global analysis of the program (by throwing away the restraints that do not quickly stabilize in the program cycles) and discovering as much information as possible about the program. Hence it is also not to perform widening operations at loop junction nodes before gathering the information along the program cycles containing that loop junction node. Also the definition of the widening which we have given is a tentative one. The experiments that have been carried out seems to corroborate our choice but further studies are necessary to give a definite conclusion.

6. GLOBAL ANALYSIS OF PROGRAMS.

We illustrate the global analysis of programs on the following ad-hoc skeletal program which is simple enough to allow hand computations:

\[
\begin{align*}
(P_0) & \quad J \mapsto 2, J \mapsto 0, \\
(P_1) & \quad \text{if} \ldots \text{then} \quad I \mapsto I + 4, \\
(P_2) & \quad \text{else} \quad J \mapsto J + 1, I \mapsto I + 2, \\
(P_3) & \quad J \mapsto 1, I \mapsto I + 2, \\
(P_4) & \quad \text{go to } L.
\end{align*}
\]

The text involving some non-linear condition is not taken into account. Each assertion \(P_i, i=0..7\) is initially the empty polyhedron \(\emptyset\) and the input assertion is propagated through the program graph:

\[
\begin{align*}
P_0' & = \mathbb{R}^2, S = \{(0,0)\}, R = \emptyset, D = \{(1,0),(0,1)\}, \\
P_1' & = \text{assign}(P_0', I \mapsto 2), J \mapsto 0) \quad = \{(I=2,J=0), S = \{(1,0),(0,1)\}, R = \emptyset, D = \emptyset \\
P_2' & = \text{convex-hull}(P_1', P_0') \quad = \text{convex-hull}(P_1', \emptyset) = P_1' \\
P_1'' & = \text{assign}(P_1', I \mapsto I + 4) \quad = \{(I=6,J=0), S = \{(0,0)\}, R = \emptyset, D = \emptyset \\
P_2'' & = \text{assign}(P_2', J \mapsto J + 1), I \mapsto I + 2) \quad = \{(I=4,J=1), S = \{(4,1)\}, R = \emptyset, D = \emptyset \\
P_2'' & = \text{convex-hull}(P_2', P_1'') \quad = \{(I=23,J=0,4s156), S = \{(8,0),(4,1)\}, R = \emptyset, D = \emptyset \\
P_2'' & = \text{assign}(P_2', I \mapsto I + 4) \quad = \{(23,5sI,0sJ), S = \{(6,0)\}, R = \{(1,0),(2,1)\}, D = \emptyset \\
P_2'' & = \text{assign}(P_2'', J \mapsto J + 1), I \mapsto I + 2) \quad = \{(23,5sI,1sJ), S = \{(4,1)\}, R = \{(1,0),(2,1)\}, D = \emptyset \\
P_3'' & = \text{convex-hull}(P_3', P_2'') \quad = \{(23,5sI,2sJ), S = \{(6,0), (4,1)\}, R = \{(1,0),(2,1)\}, D = \emptyset \\
\end{align*}
\]

when the loop body has been analyzed a widening operation takes place at the loop junction node \(L\):

\[
P_3'' = P_3' \lor \text{convex-hull}(P_3', P_3')
\]

We have \(P_3'' = \{(23,5sI,2sJ), I \mapsto I + 4\}\) and

\[
\text{convex-hull}(P_3', P_3') = \{(23,5sI,2sJ), I \mapsto I + 4\}
\]

with \(S = \{(2,0), (10,0), (5,0)\}, R = \emptyset, D = \emptyset\), so that \(I \mapsto I + 4\) which is the only constraint of \(P_3''\) not verified by every element of the frame of \(\text{convex-hull}(P_3', P_3')\) is eliminated by the widening operation.
Than \( \text{constr} \) is included in \( P_2 \) so that the program analysis has converged.

The final result shows up linear restraints among the variables of the program that never appear explicitly in the program text and often escape the notice of anyone studying this simple example:

(0) : no information
(1) : i = 2, j = 0
(2), (3), (5) : 2i + z1 = i ≥ 0
(4) : z1 ≥ 0, j ≥ 0
(6) : z1 ≥ 0, j ≥ 0
(7) : 2i + z2 : 1, 1i ≥ 2, j ≥ 0

6. EXAMPLE.

On the next example (HEAPSORT, Knuith[1973,p.148]) it is not possible to trace the details of the analysis so that we directly provide the results produced by our experimental implementation:

procedure HEAPSORT(integer N; real array[1..N] T);
begin integer i, j, k; real K;
  if L := (N div 2) + 1, R := N;
  if L > 2 then
    if L = 1, (K := T[L,]);
  else
    (K := T[R,]; T[R,] := T[L,]); R := R - 1;
  while (R > 1) do
    if (i = 1, j = 2, k = 1);
    while (j > 1) then
      if (j = 1, then
        if (T[i] < T[j]) then
          j := j - 1;
        if (K = T[i]) then
          exit (or the inner loop) fi;
      else
        od;
      end;
end;
end;
end;
end;
end.
end.

The procedure is analyzed with the input specification N = 2 (see Knuith[1973], p.148). This analysis does not take account of the statements involving operations on arrays, these statements such as \( \text{K = T}[L] \) have been bracketed in the text of the procedure. The result of the analysis (taking about 20 seconds of C.P.U. time) is the following:

(1) : N = 2
(2) : N = 2, N ≥ 2; N = 2
(3) : N ≥ 2, N = 2
(4) : N ≥ 2, N ≥ 2
(5) : N = 2, N = 2
(6) : N ≥ 2, N ≥ 2
(7) : N, N ≥ 2
(8) : R = 2, L = 2, L = 2
(9) : R = 2, L = 2, N ≥ 2
(10) : L = 2, N ≥ 2
(11) : R = 2, L = 2
(12), (13) : R = 2, L = 2

7. NOTES ON THE EXPERIMENTAL IMPLEMENTATION.

We have produced an experimental implementation written in PASCAL on the CII/IRIS 80 computer. The length of the program is about 2500 lines.

The systems of equations and inequations have been represented for simplicity by real matrices and this sometimes results in a loss of precision. It seems very difficult to write the program so that this loss of precision is acceptable. It is very often that the relationships have been found correspond to a domain including any value that each real variable can take during any execution of the analyzed program. However, the main applications we have in mind (such as array bound checking) deal with integer variables. In this case the coefficients of the linear restraints are rational, which can be represented as fractions \( p/q \) where \( p \) and \( q \) are integers. Then the operations which are performed on such coefficients \( p/q \) are more costly but introduce no loss of precision.

We have noticed that programs involving numerical constants are better handled when these numerical constants are replaced by the declaration of a symbolic constant. It is often the case that the form of the analysis is faster although the system of restraints remains the same.

It seems to be very difficult to evaluate the cost of the analysis of a program. The cost of the analysis does not only depend on the length (number of lines) of the program but mainly on the complexity of the program graph (number of loops, degree of loop combination, etc.). It seems that the cost of an analysis is almost linear in the length of the program but exponential in the number of variables involved in the analysis. From this point of view nested static scopes (such as ALGOL 68 blocks which authorizes very local declarations or better EUCLID with its import mechanism) is very useful since for example the variables of an outer block can often be analyzed independently of the variables of the inner blocks whereas the variables of the inner block can often be analyzed using only few global variables. In general it can be taken advantage of the scope rules of the usual languages.

We have deliberately taken the point of view not to take account of the legality restraints which must hold on the variables. For example if a program variable is used as an array index which do not take account of the fact that we should try to show that the value of this variable must be within the
array bounds. Taking account of such facts we could propagate this information backward to the loop junction nodes so that we would have a guideline for the widening operation. This would enable us to combine the discovery and verification approaches.

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