Decomposition of Decidable First-Order Logics over Integers and Reals

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Motivation

Initial observation

Lack of efficient means to verify systems with counters and clocks enjoying at the same time :
effective data structure, expressive guards and actions,
exact computation, decidable automated acceleration.

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☞ *This paper only deals with the symbolic representation for integers and reals*

Outline

1. **Symbolic Representations for $\mathbb{R}^n$**
   - Difference Bound Matrices (DBM)
   - Abstractions for DBM
   - Parametric DBM
   - Finite Unions of Sums
2. **Decomposition of Decidable Logics**
   - Presburger extended to reals : $\mathrm{FO}(\mathbb{R}, \mathbb{Z}, +, \leq)$
   - Constrained Parametric DBM (CPDBM)
   - Real Vector Automata (RVA)
3. **Implementation**
   - GENEPI
   - Integer-Decimal Functions (IDF)

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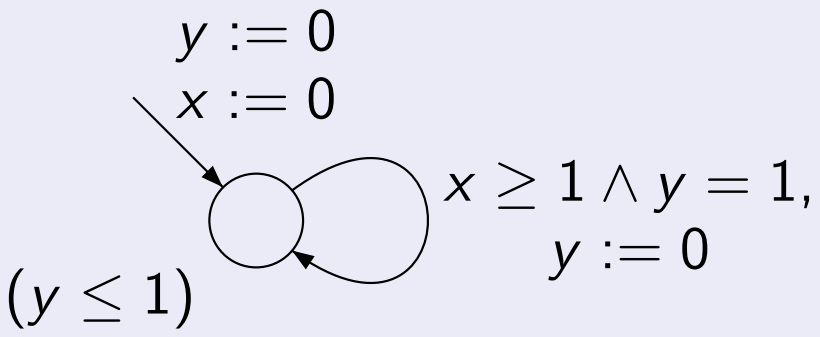
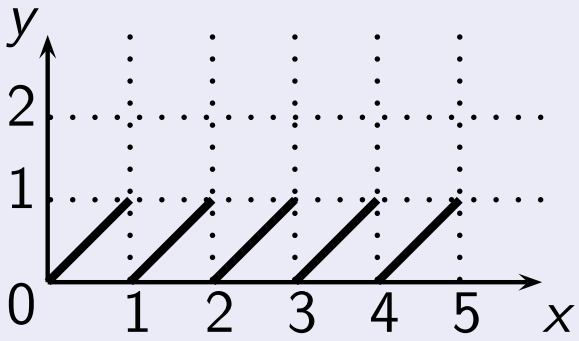
Example

A Timed Automaton from [BBFL03]





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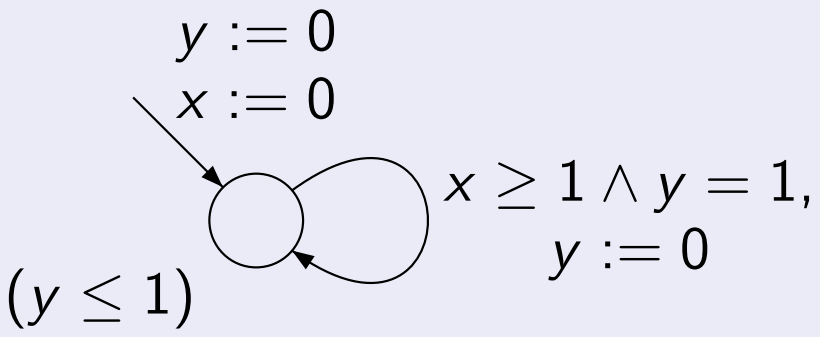

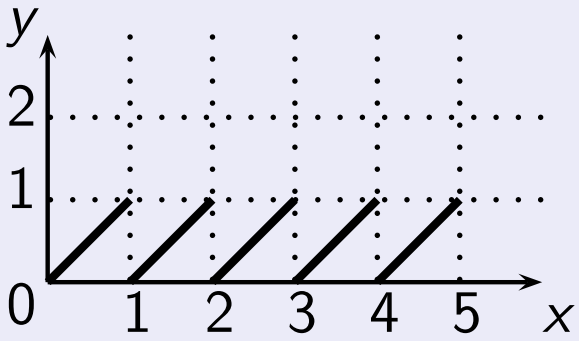

An infinity of associated DBM

$$\left\{ \begin{array}{c} \\ 0 \\ x \\ y \end{array} \begin{array}{c} \begin{array}{ccc} 0 & x & y \end{array} \\ \begin{pmatrix} 0 & -i & 0 \\ i+1 & 0 & i \\ 1 & -i & 0 \end{pmatrix} \end{array} \right\}_{i \geq 0}$$

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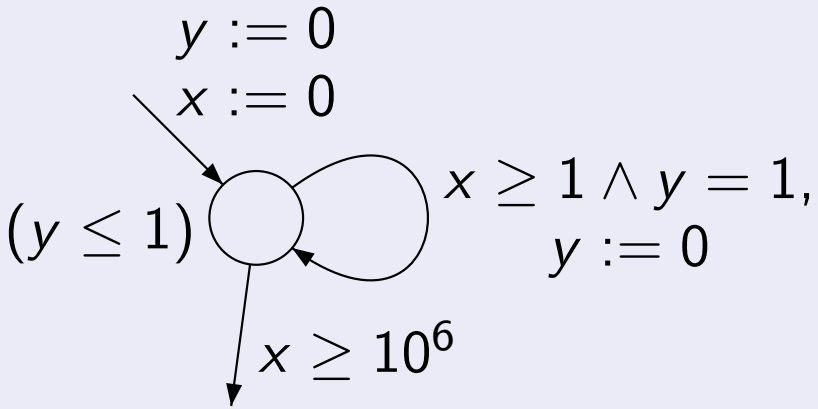
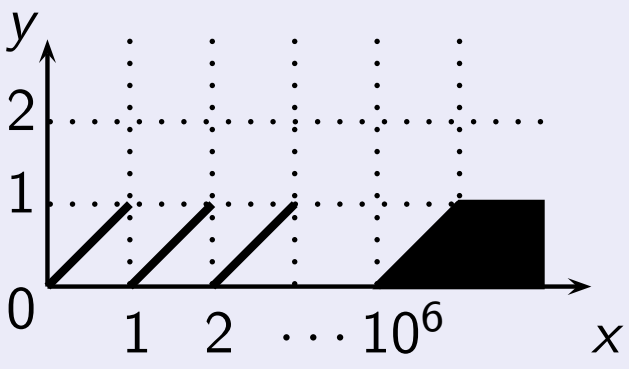
An example abstraction

A slight modification of the automaton





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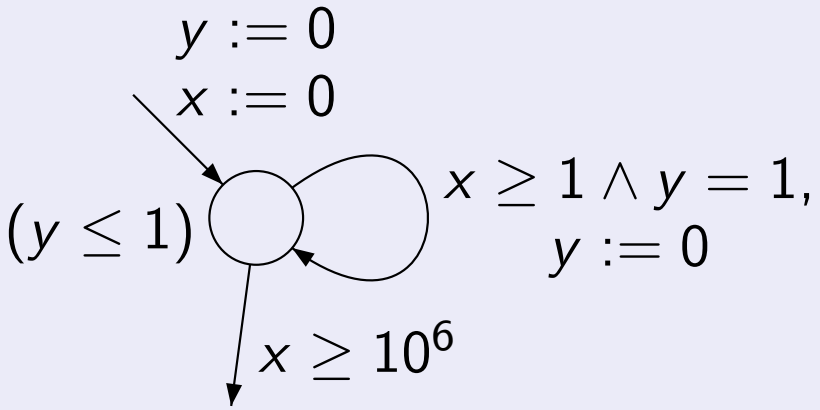

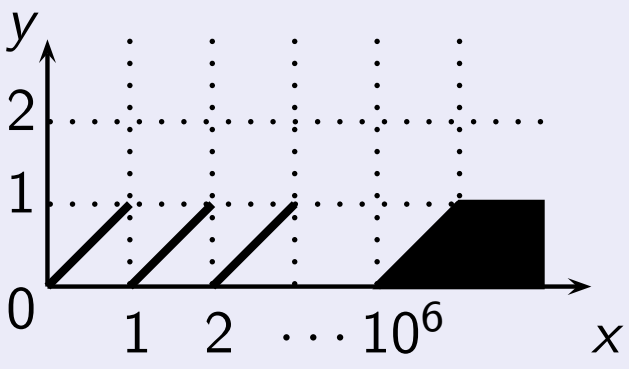

The associated DBM (still too many)

$$\left\{ \left\{ \begin{array}{c} \\ 0 \\ x \\ y \end{array} \begin{array}{c} \begin{array}{ccc} 0 & x & y \end{array} \\ \begin{pmatrix} 0 & -i & 0 \\ i+1 & 0 & i \\ 1 & -i & 0 \end{pmatrix} \end{array} \right\}_{0 \leq i \leq 10^6} , \begin{array}{c} \\ 0 \\ x \\ y \end{array} \begin{array}{c} \begin{array}{ccc} 0 & x & y \end{array} \\ \begin{pmatrix} 0 & \infty & 0 \\ \infty & 0 & \infty \\ 1 & -10^6 & 0 \end{pmatrix} \end{array} \right\}$$

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Parametric DBM

Definition (DBM)

Square matrix composed of elements $(\prec_{i,j}, c_{i,j})$ *in* $\{\leq, <\} \times \mathbb{Z}$ *defining constraints on two clocks* x_i *and* x_j *:* $x_i - x_j \prec_{i,j} c_{i,j}$

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Definition (CPDBM [AAB00])

DBM whose $c_{i,j}$ *are arithmetical terms defined by :*

$$t ::= 0 \mid 1 \mid v \mid t - t \mid t + t \mid t * t, \text{ where } v \in V,\ V \in \{\mathbb{Z}, \mathbb{R}, \dots\}$$

These terms are then constrained by a formula :

$$\phi ::= t \leq t \mid \neg\phi \mid \phi \vee \phi \mid \mathrm{Is\_integer}(t)$$

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Extract the integer component from reals, to use periodicity

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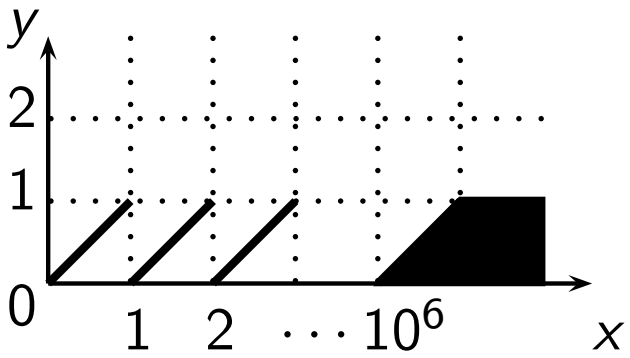

$= \{(x, y) \in [0, 1]^2 \mid x = y\}$

$= \{(x, y) \in [0, 1]^2 \mid x \geq y\}$

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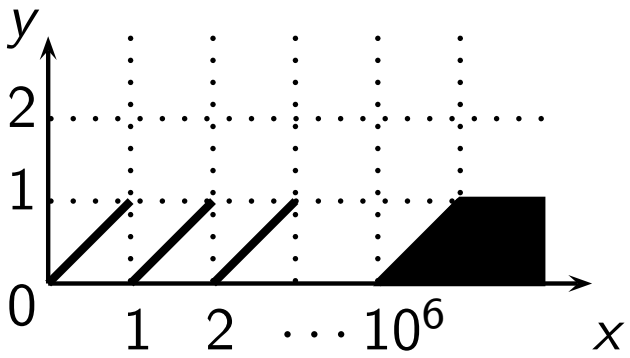

$$\nearrow = \{(x,y) \in [0,1]^2 \mid x = y\}$$
$$\blacktriangle = \{(x,y) \in [0,1]^2 \mid x \geq y\}$$
$$\blacksquare = \{(x,y) \in [0,1]^2\}$$

Finite Unions of Sums "Integer+Decimal"

$$\left(\{0,\ldots,10^6-1\} \times \{0\} + \nearrow\right)$$
$$\bigcup\left(\{10^6\} \times \{0\} + \blacktriangle\right)$$
$$\bigcup\left(\{10^6+1,\ldots,\infty\} \times \{0\} + \blacksquare\right)$$

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- Let $\mathfrak{Z} \uplus \mathfrak{D}$ be the class of every $R \subseteq \mathbb{R}^n$ such that $R = \bigcup_{i=1}^{p} (Z_i + D_i)$, where $(Z_i, D_i) \in \mathfrak{Z} \times \mathfrak{D}$ and $p \geq 1$

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- Note that some R are not representable !

$$\text{Counter-example : } R = \bigcup_{j=1}^{\infty} \left(\{j\} + \left\{ \frac{1}{j+1} \right\} \right)$$

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Definition

A class $\mathfrak{R} \subseteq \bigcup_{n \in \mathbb{N}} P(\mathbb{R}^n)$ is stable if it is closed under union, intersection, difference, cartesian product, quantification/projection, and permutation.

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Proposition (Stability)

The class $\mathfrak{Z} \uplus \mathfrak{D}$ is stable if $\mathfrak{Z}$ and $\mathfrak{D}$ are stable.

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Presburger extended to reals [BRW98, Wei99]

Theorem

$FO(\mathbb{R}, \mathbb{Z}, +, \leq) = FO(\mathbb{Z}, +, \leq) \uplus FO(\mathbb{D}, +, \leq)$

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Proof sketch :

$\boxed{\supseteq :}$ trivial.

$\boxed{\subseteq :}$ just distribute sets and relations over $\uplus$:

- $\mathbb{R}^n$ can be written $\mathbb{Z}^n + \mathbb{D}^n$
- $R_+ = \{\mathbf{r} \in \mathbb{R}^3 \mid r_1 + r_2 = r_3\}$ can be written
  $\bigcup_{c \in \{0,1\}} \{\mathbf{z} \in \mathbb{Z}^3 \mid z_1 + z_2 + c = z_3\} + \{\mathbf{d} \in \mathbb{D}^3 \mid d_1 + d_2 = d_3 + c\}$,
  where c stand for a carry
- similarly, $\emptyset$, $\leq$, $\mathbb{Z}^n$ are easily definable
- then, stability (from the previous Proposition) implies $\subseteq$ $\square$

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Constrained Parametric DBM

Reminder : CPDBM [AAB00]

DBM whose $c_{i,j}$ arithmetical terms defined by

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Proposition

$$\bigcup CP\text{-}DBM_+ = FO(\mathbb{Z}, +, \leq) \uplus \bigcup DBM_{\mathbb{D}}$$

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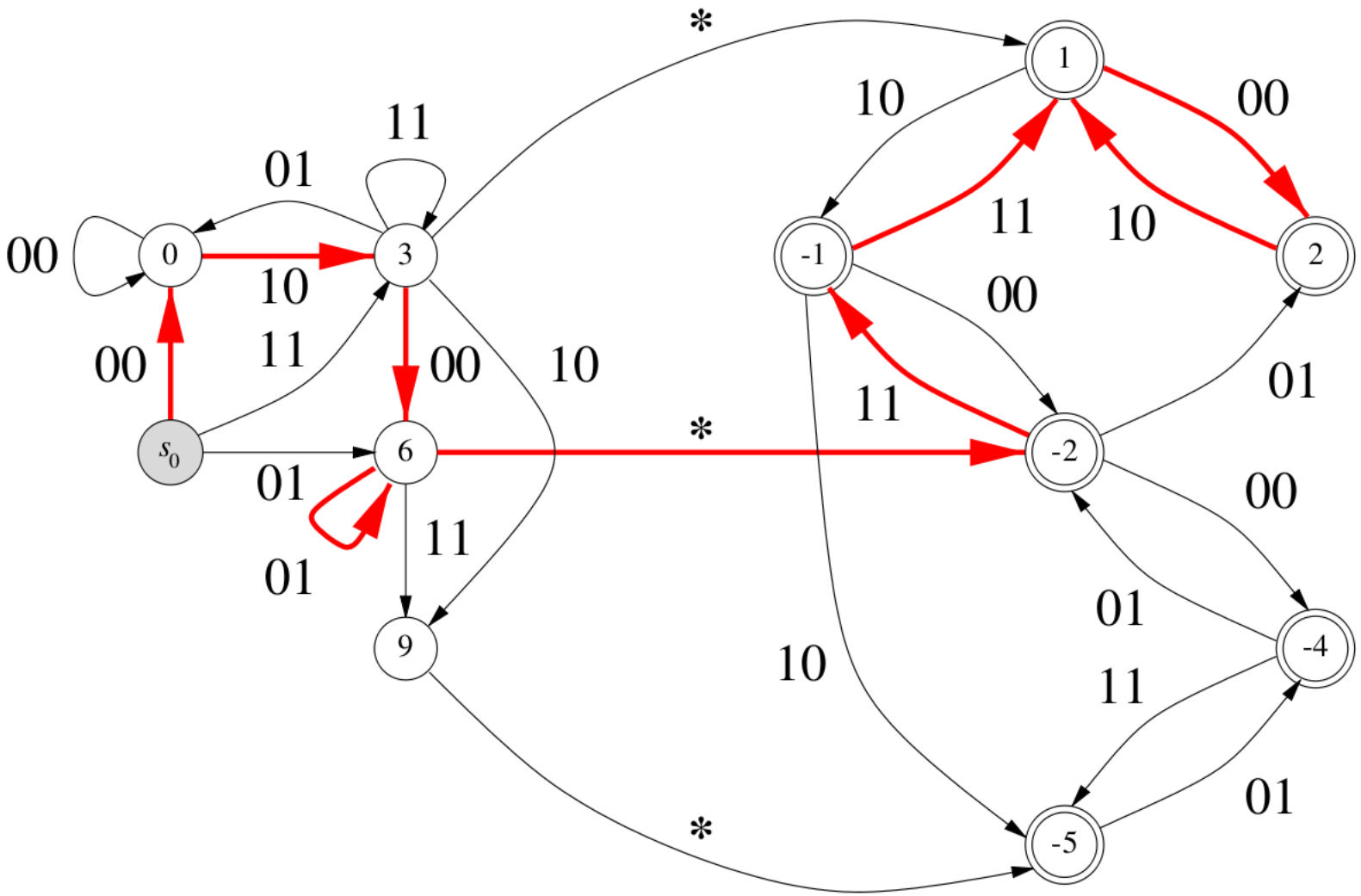
Real Vector Automata (RVA) [BRW98]

$$\{(x, y) \in \mathbb{R}^2 \mid 3x - 6y = 4\}$$



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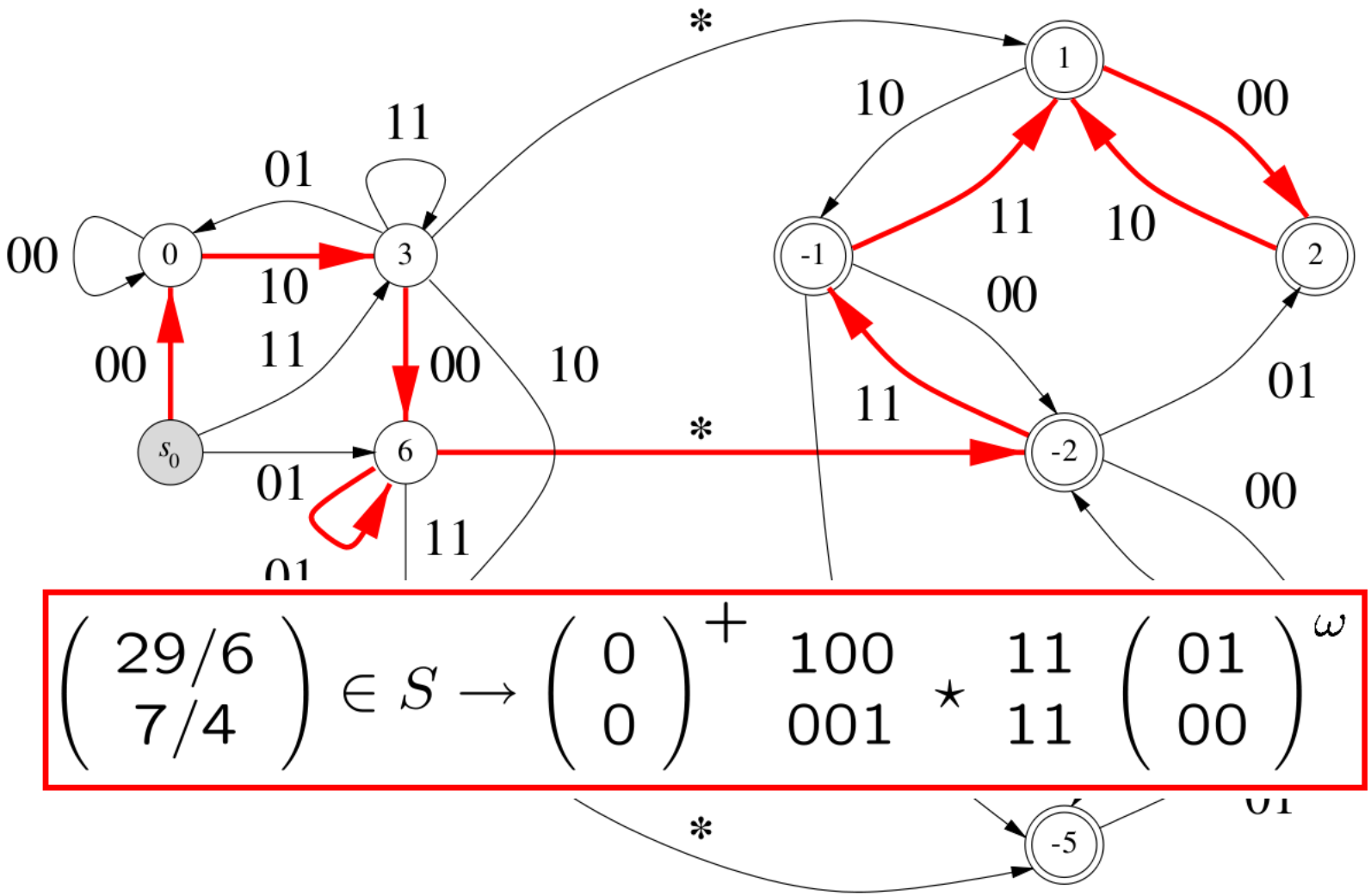

$$\begin{pmatrix} 29/6 \\ 7/4 \end{pmatrix} \in S \rightarrow \begin{pmatrix} 0 \\ 0 \end{pmatrix}^{+} \begin{matrix} 100 \\ 001 \end{matrix} \star \begin{matrix} 11 \\ 11 \end{matrix} \begin{pmatrix} 01 \\ 00 \end{pmatrix}^{\omega}$$

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$FO(\mathbb{R}, \mathbb{Z}, +, \leq, X_b) = FO(\mathbb{Z}, +, \leq, V_b) \uplus FO(\mathbb{D}, +, \leq, W_b)$

Real Vector Automata (RVA) [BRW98]

- $X_b(x, u, a)$ is the predicate being true iff
  - x can be written in basis b as the word $sa_1 \dots a_k \star a_{k+1} \dots$
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- $W_b : \mathbb{D}\backslash\{0\} \to \mathbb{D}$ is the function $W_b(d) = b^j$, where $j \in \mathbb{Z}$ is the least integer such that $b^{-j}d \notin \mathbb{D}$

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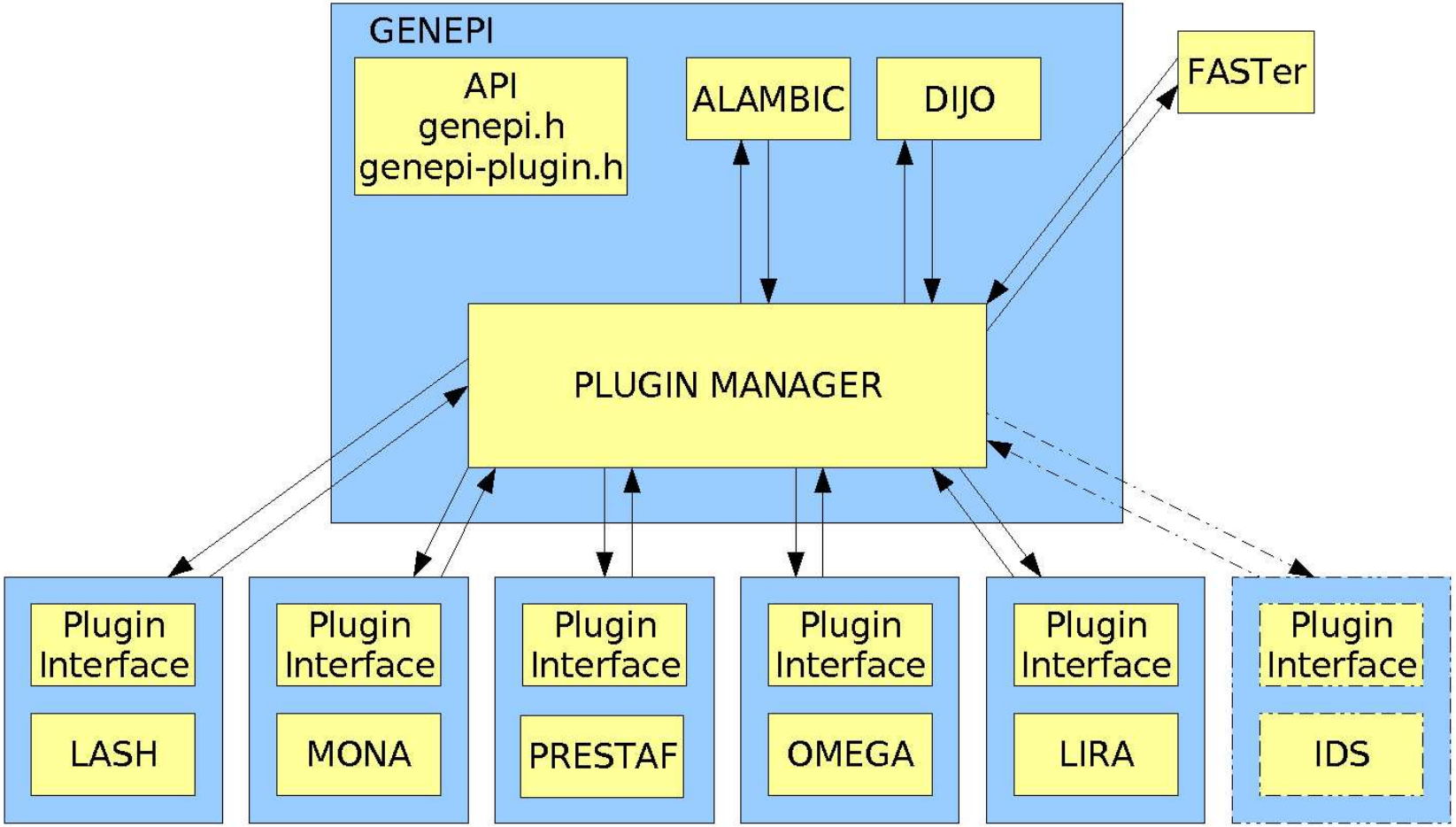
Generic Presburger API [LP06]

GENEPI : A modular framework for solvers and model-checkers



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- We represent a set $R = \bigcup_{i=1}^{p} (Z_i + D_i)$ by a function :

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Definition (interpretation)

$$\forall f \in \mathcal{F}_{\mathfrak{Z} \to \mathfrak{D}},\ [\![f]\!] = \bigcup_{Z \in supp(f)} \Big(Z + f(Z)\Big)$$

Integer-Decimal Functions (IDF)

Definition (IDF)

An IDF is a function $f \in \mathcal{F}_{\mathfrak{Z} \to \mathfrak{D}}$ *such that* $Z \neq Z'$ *implies* $f(Z) \cap f(Z') = \emptyset$

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Let $IDF_{\mathfrak{Z}\to\mathfrak{D}} = \{f \in \mathcal{F}_{\mathfrak{Z}\to\mathfrak{D}} \mid f \text{ is an IDF}\}$
Let $[\![IDF_{\mathfrak{Z}\to\mathfrak{D}}]\!] = \{[\![f]\!] \mid f \in IDF_{\mathfrak{Z}\to\mathfrak{D}}\}$

Proposition (IDF $\equiv$ Finite Unions of Sums)

$\mathfrak{Z} \uplus \mathfrak{D} = [\![IDF_{\mathfrak{Z}\to\mathfrak{D}}]\!]$

Integer-Decimal Functions (IDF)

Definition (IDF)

An IDF is a function $f \in \mathcal{F}_{\mathfrak{Z}\to\mathfrak{D}}$ such that $Z \neq Z'$ implies $f(Z) \cap f(Z') = \emptyset$

Let $IDF_{\mathfrak{Z}\to\mathfrak{D}} = \{f \in \mathcal{F}_{\mathfrak{Z}\to\mathfrak{D}} \mid f \text{ is an IDF}\}$
Let $[\![IDF_{\mathfrak{Z}\to\mathfrak{D}}]\!] = \{[\![f]\!] \mid f \in IDF_{\mathfrak{Z}\to\mathfrak{D}}\}$

Proposition (IDF $\equiv$ Finite Unions of Sums)

$\mathfrak{Z} \uplus \mathfrak{D} = [\![IDF_{\mathfrak{Z}\to\mathfrak{D}}]\!]$

Proposition (Canonicity)

For any $f_1, f_2 \in IDF_{\mathfrak{Z}\to\mathfrak{D}}$, $[\![f_1]\!] = [\![f_2]\!]$ implies $f_1 = f_2$

Conclusion

Contribution

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- Representation of subsets of $\mathbb{R}^n$ as finite unions

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- Representation of subsets of $\mathbb{R}^n$ as finite unions
- Decomposition of 3 decidable logics,
  each into 2 separated fragments (*integer* + *decimal*)
- Bases for an implementation, as a GENEPI plugin

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Future work

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- Implementation/optimisation of the GENEPI plugin

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- Implementation/optimisation of the GENEPI plugin
- Verification of infinite-state systems with counters and clocks

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- Implementation/optimisation of the GENEPI plugin
- Verification of infinite-state systems with counters and clocks
- Extension to other logics decompositions

References

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