RP 2015

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Warszawa

Integer-Complete Parameter Synthesis for Bounded Parametric Timed Automata

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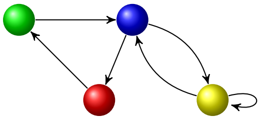
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

Context: Formal verification of timed systems

- Model checking



A model of the system

 is unreachable

A property to be satisfied

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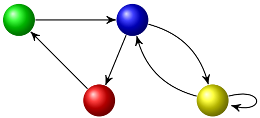

$\overset{?}{\models}$

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A property to be satisfied

- Question: does the model of the system satisfy the property?

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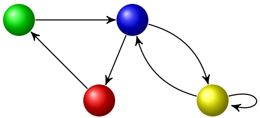

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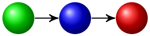
- Question: does the model of the system satisfy the property?

Yes

No



Counterexample

Beyond model checking: parameter synthesis

- Timed systems are characterized by a set of timing constants
  - "The packet transmission lasts for 50 ms"
  - "The sensor reads the value every 10 s"
- Verification for one set of constants does not usually guarantee the correctness for other values
- Challenges
  - Numerous verifications: is the system correct for any value within $[40;60]$?
  - Optimization: until what value can we increase 10?
  - Robustness [Markey, 2011]: What happens if 50 is implemented with 49.99?

Beyond model checking: parameter synthesis

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- Parameter synthesis
  - Consider that timing constants are unknown constants (parameters)
  - Find good values for the parameters

Outline

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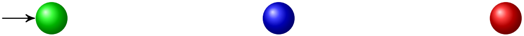
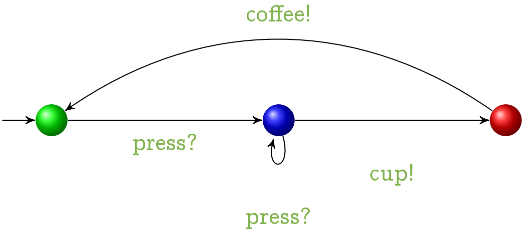
Timed automaton (TA)

- Finite state automaton (sets of locations)



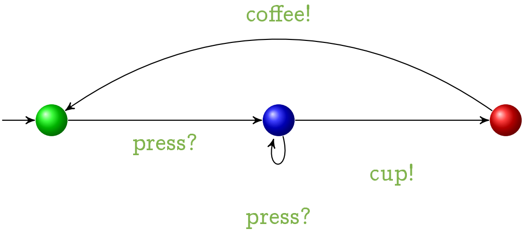
Timed automaton (TA)

- Finite state automaton (sets of locations and actions)



Timed automaton (TA)

- Finite state automaton (sets of locations and actions) augmented with a set X of clocks [Alur and Dill, 1994]
  - Real-valued variables evolving linearly at the same rate



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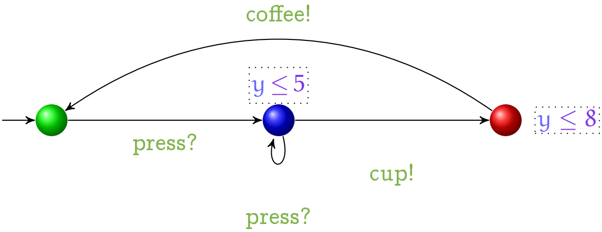
  - Location invariant: property to be verified to stay at a location



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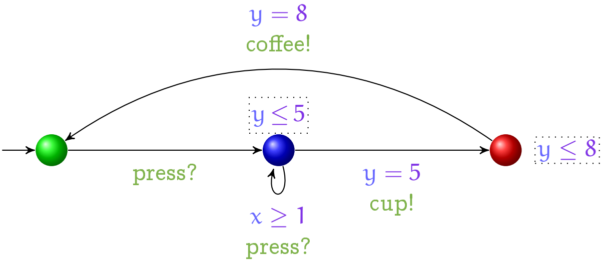

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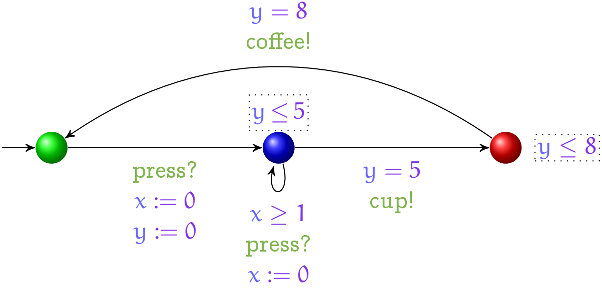
  - Clock reset: some of the clocks can be set to 0 at each transition



Concrete semantics of timed automata

- Concrete state of a TA: pair (l, w), where
  - l is a location,
  - w is a valuation of each clock

- Concrete run: alternating sequence of concrete states and actions or elapsing of time
  - Possible concrete runs for the coffee machine

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x	0
y	0

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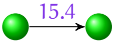

x	0	15.4
y	0	15.4

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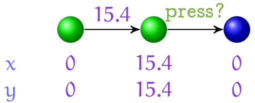

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x	0	15.4	0	5
y	0	15.4	0	5

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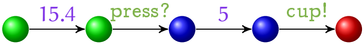

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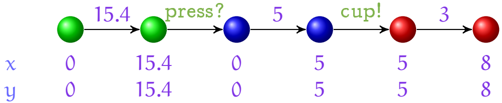

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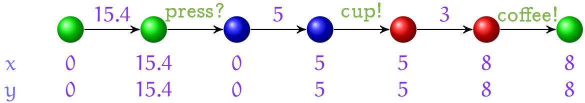

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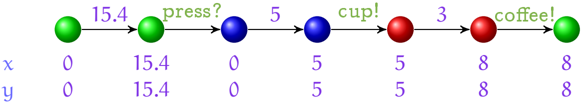

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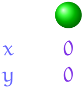

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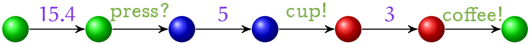

x	0	15.4	0	5	5	8	8
y	0	15.4	0	5	5	8	8

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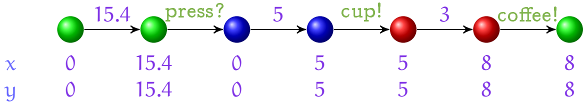

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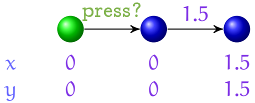

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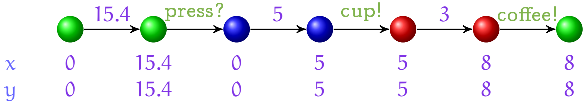

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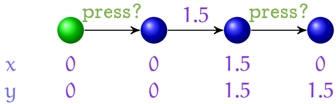

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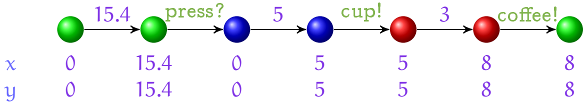

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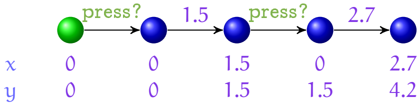

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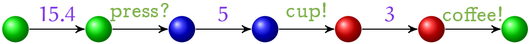

x	0	15.4	0	5	5	8	8
y	0	15.4	0	5	5	8	8

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x	0	0	1.5	0	2.7	0
y	0	0	1.5	1.5	4.2	4.2

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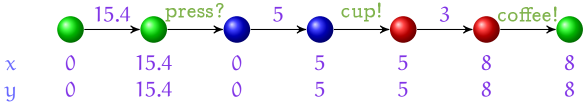

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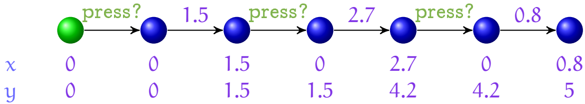

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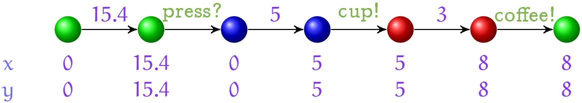

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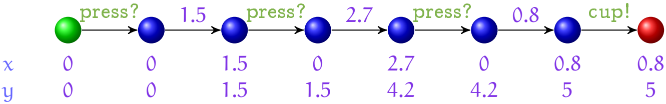

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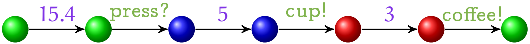

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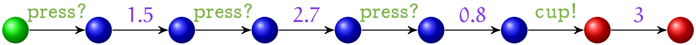

x	0	0	1.5	0	2.7	0	0.8	0.8	3.8
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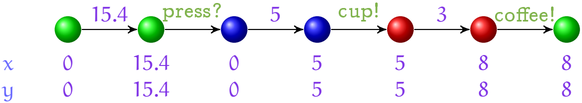

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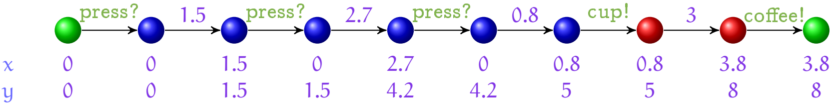
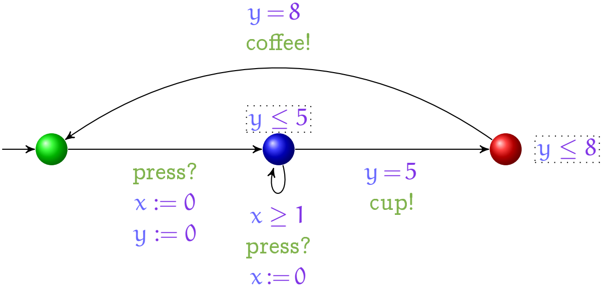


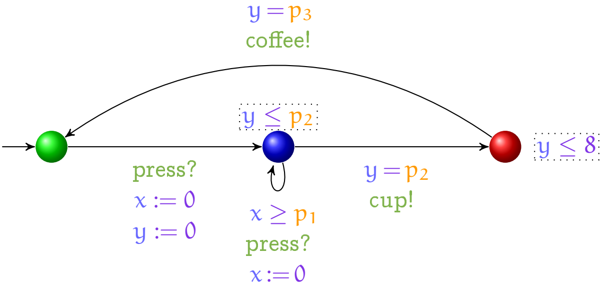
Parametric Timed Automaton (PTA)

- Timed automaton (sets of locations, actions and clocks)



Parametric Timed Automaton (PTA)

- Timed automaton (sets of locations, actions and clocks) augmented with a set P of parameters [Alur et al., 1993]
  - Unknown constants used in guards and invariants



Symbolic semantics of a PTA

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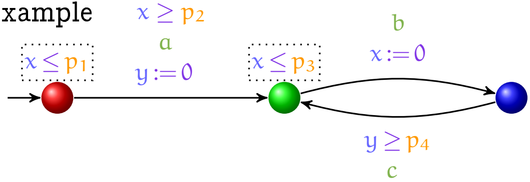
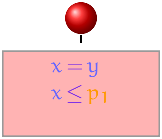


  - Possible symbolic run for this PTA



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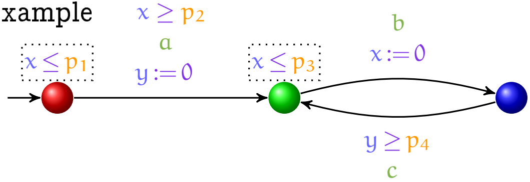

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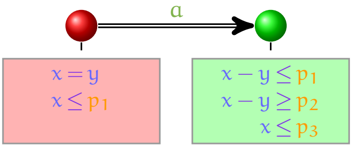

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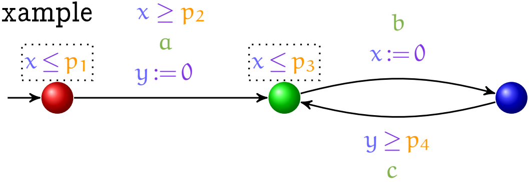

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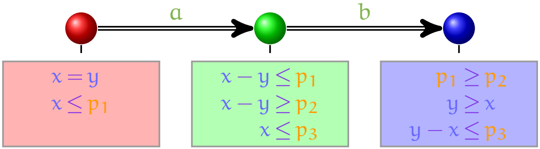

Valuation of a PTA

- Given a PTA $\mathcal{A}$ and a parameter valuation v, we denote by $v(\mathcal{A})$ the (non-parametric) timed automaton where all parameters are valuated by v

Objective: Computation problems

Definition (reachability synthesis (EF))

Input: a PTA $\mathcal{A}$ and a set of locations G

Problem: Synthesize all parameter valuations v such that there exists a run of $v(\mathcal{A})$ reaching a location $l \in G$

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Definition (reachability synthesis (EF))

Input: a PTA $\mathcal{A}$ and a set of locations G
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Definition (unavoidability synthesis (AF))

Input: a PTA $\mathcal{A}$ and a set of locations G
Problem: Synthesize all parameter valuations v such that all runs of $v(\mathcal{A})$ eventually reach a location $l \in G$

Outline

Decidability results: reachability

Reachability emptiness

Reachability emptiness ("does there exist at least one parameter valuation reaching a given location l?") is undecidable for PTA [Alur et al., 1993]

- even with a single parametric clock [Miller, 2000]
- even with only strict constraints [Doyen, 2007]
- even with a single integer-valued parameter [Beneš et al., 2015]

Decidability results: unavoidability

Reachability emptiness

Unavoidability emptiness ("does there exist at least one parameter valuation such that all runs reach a given location l?") is undecidable for PTA, even with a single bounded parameter

[Jovanović et al., 2015]

Synthesis of bounded integers

What if parameters are bounded integers. . . ?

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Bounded integers

Reachability and unavoidability emptiness are decidable (and PSPACE-complete) for PTA with bounded integers [Jovanović et al., 2015]

Synthesis of bounded integers

What if parameters are bounded integers. . . ?

Bounded integers

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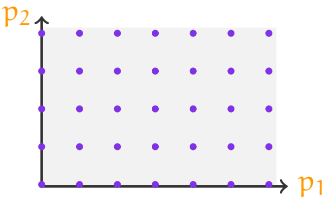
Two algorithms:

- IEF: reachability synthesis
- IAF: unavoidability synthesis

Synthesis of bounded integers: How?

Naive idea: enumerate all integers, and check the TA (which is PSPACE-complete [Alur and Dill, 1994])



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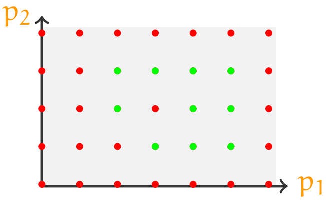

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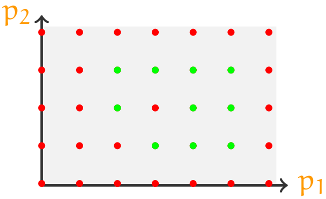

Smarter: symbolic algorithm [Jovanović et al., 2015]

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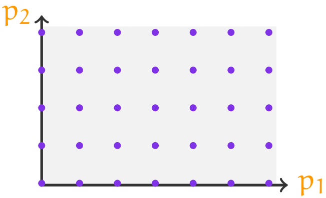

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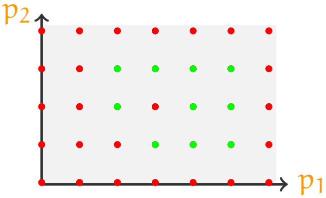

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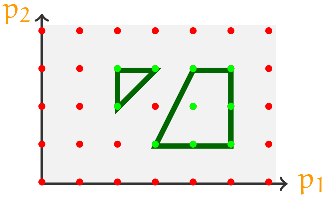

Integer hull of a polyhedron

Definition (integer hull)

Let C be a polyhedron.

The integer hull of C is

$$\mathsf{IH}(C) = \mathsf{Conv}(\mathsf{IV}(C))$$

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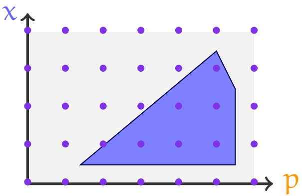

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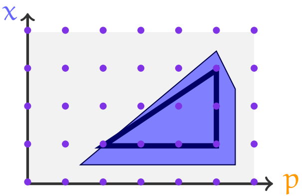

Reachability synthesis

Algorithm $\mathsf{EF}(\mathcal{A}, G)$

$K \leftarrow \bot$
Add the initial state to the waiting list

while the waiting list is not empty
 Pick a symbolic state (l, C) from the waiting list
 if $l \in G$ **then** $K \leftarrow K \vee \quad C \downarrow_P$
 else if $(l, \quad C \ ) = (l', \quad C' \ )$, for some (l', C') met before
  then do not explore further this branch
 else store $(l, \quad C \ )$ and add its successors to the waiting list

return K

Reachability synthesis of bounded integers using IH

Algorithm $\mathsf{IEF}(\mathcal{A}, G)$ [Jovanović et al., 2015]

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Add the initial state to the waiting list

while the waiting list is not empty

Pick a symbolic state (l, C) from the waiting list

if $l \in G$ **then** $K \leftarrow K \vee \mathsf{IH}(C)\downarrow_P$

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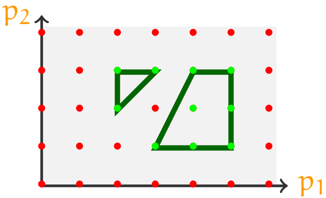
return K

Outline

What about the dense result?

IEF and IAF return symbolic sets of integer valuations



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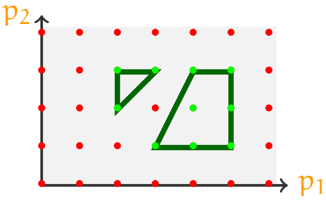

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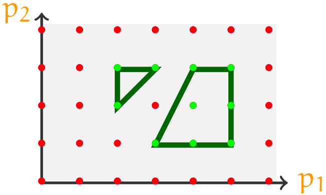

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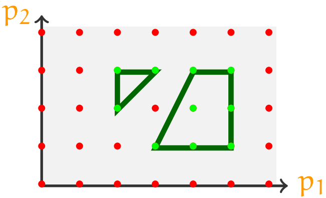

Can we interpret the result of IEF and IAF over dense parameter valuations?

- ☹ For IEF: yes! ...but it may not terminate

  (example in paper)

- ☹ For IAF: no! May yield incorrect valuations

  (counter-example in paper)

A parametric extrapolation for PTA

Definition (M-extrapolation)

Let M be the largest constant in $\mathcal{A}$ (including the bounds on the parameters), let x be a clock.
The (M, x)-extrapolation is

$$\mathsf{Ext}_x^M(C) = \big(C \cap (x \leq M)\big) \cup \mathsf{Cyl}_x\big(C \cap (x > M)\big) \cap (x > M).$$

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Generalized to (M, X)-extrapolation by applying to all clocks.

Integer reachability synthesis

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return K

Integer complete reachability synthesis RIEF

Algorithm $\mathsf{RIEF}(\mathcal{A}, G)$

$K \leftarrow \bot$

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while the waiting list is not empty

Pick a symbolic state (l, C) from the waiting list

if $l \in G$ **then** $K \leftarrow K \vee \quad C \downarrow_P$

else if $\big(l, \mathsf{IH}\big(\mathsf{Ext}_X^M(C)\big)\big) = \big(l', \mathsf{IH}\big(\mathsf{Ext}_X^M(C')\big)\big)$,

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else store $\big(l, \mathsf{IH}(\mathsf{Ext}_X^M(C))\big)$ and add its successors to the waiting list

return K

Termination of RIEF

Theorem

For any PTA $\mathcal{A}$ with bounded parameters, the computation of RIEF$(\mathcal{A}, G)$ *terminates.*

Proof (hint).

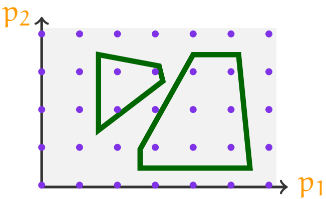
From the finiteness of the number of integer hulls of (M, X)-extrapolations of possible states. □

Characterization of RIEF

Theorem

Given a PTA $\mathcal{A}$ *with bounded parameters,* $\mathsf{RIEF}(\mathcal{A}, G)$ *contains*

1. *no valuation that is not a solution of* $\mathsf{EF}(\mathcal{A}, G)$ *[correctness]*



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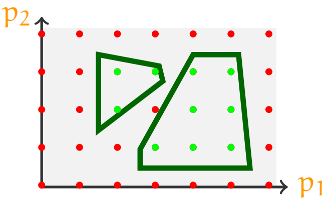

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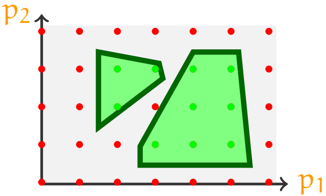
3. *all the rational valuations in the parametric zones computed by the symbolic exploration* *[?]*



Unavoidability

Algorithm RIAF computing parameter valuations such that a set of locations is unavoidable

Similar principle and similar results

(see paper)

Outline

Roméo

Model checker for parametric time Petri nets and PTA [Lime et al., 2009]

Uses the Parma Polyhedra Library (PPL) for operations on polyhedra [Bagnara et al., 2008]

Available in the open source CeCILL license

www.ROMEO.xxx

Case study: scheduling example

Three tasks τ_1, τ_2, τ_3 scheduled using static priorities ($\tau_1 > \tau_2 > \tau_3$) in a non-preemptive manner [Jovanović et al., 2015]

Task τ_1: periodic with period a and a non-deterministic duration in $[10, b]$

Task τ_2: minimal activation time of $2a$ and a non-deterministic duration in $[18, 28]$

Task τ_3: periodic with period $3a$ and a non-deterministic duration in $[20, 28]$.

Each task: deadline equal to its period

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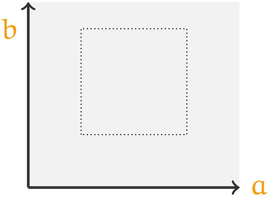
Each task: deadline equal to its period

Goal: synthesize parameter valuations ensuring that the system does not reach a deadline violation.

Experiments

Bounded parameters: $a \in [0, 50]$ and $b \in [0, 50]$



Algorithm	Result	Time
IEF	discrete	7.4 s
RIEF	dense	12.7 s

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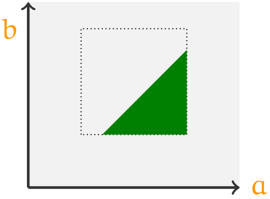
Result obtained by IEF: $a \geq 34, b \geq 10, a - b \geq 24$



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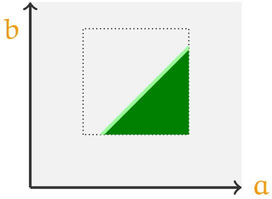

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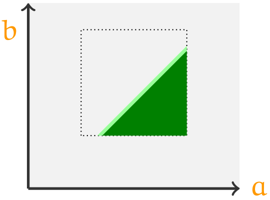

Algorithm	Result	Time
IEF	discrete	7.4 s
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- ☺ Slightly better result by RIEF
- ☹ Longer computation time (IH is expensive)
- ☺ Most important: RIEF is dense

Outline

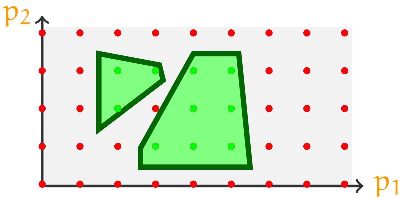
Summary

- Two synthesis algorithms for PTA with guaranteed termination and dense result
  - Dense valuations are important for robustness

- First terminating algorithms over dense valuations with guarantee on the results

Perspectives

- Exact characterization of the result of RIEF and RIAF
  - What part of the result may be missing?



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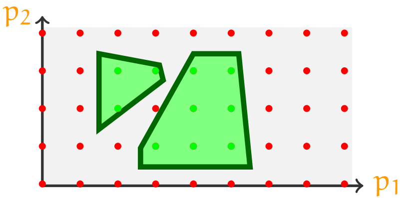

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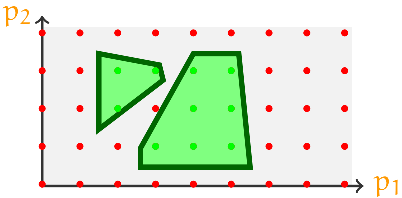

- Extension of this principle to further algorithms
  - Inverse method (trace or language preservation) [A., Chatain, Encrenaz, Fribourg, 2009] and implementation in IMITATOR
- Use multi-core processors
  - E.g., some cores to compute successor states, and some to check the equality of integer hulls

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