NASA Formal Methods 2015

April 27th, 2015
Pasadena, CA, USA

Reachability Preservation Based Parameter Synthesis for Timed Automata

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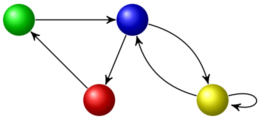
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

Context: Formal Verification of Timed Systems

- Model checking



A model of the system

 is unreachable

A property to be satisfied

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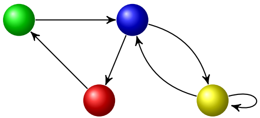

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A model of the system

A property to be satisfied

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

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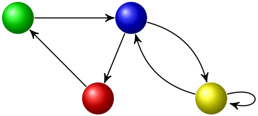

$\overset{?}{\models}$

 is unreachable

A model of the system

A property to be satisfied

- 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?

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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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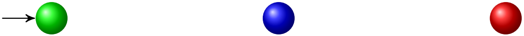
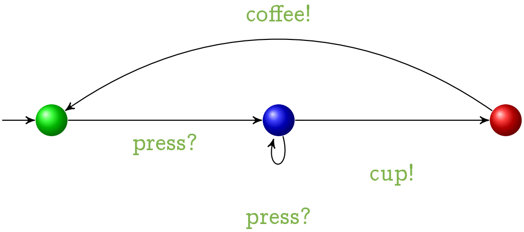
Timed Automaton (TA)

- Finite state automaton (sets of locations)



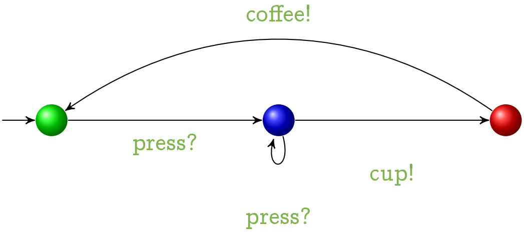
Timed Automaton (TA)

- 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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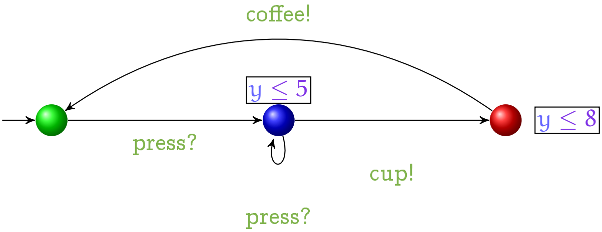

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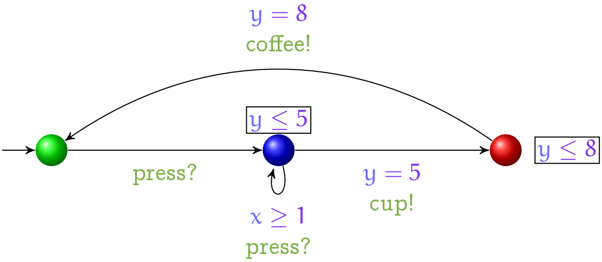

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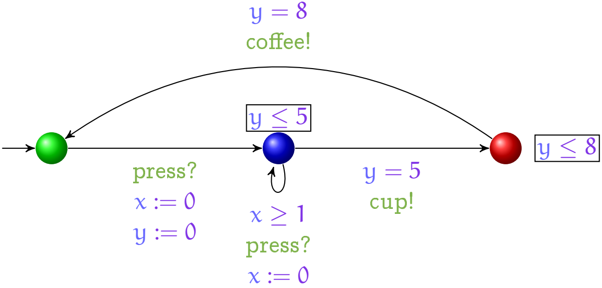
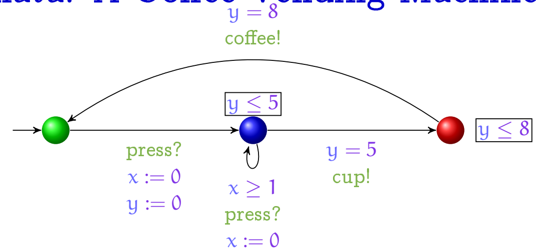
  - Clock reset: some of the clocks can be set to 0 at each transition



Timed Automata: A Coffee Vending Machine



- Examples of concrete runs

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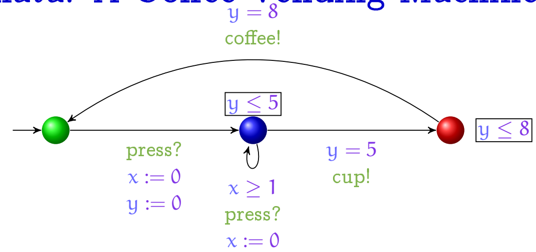

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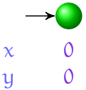

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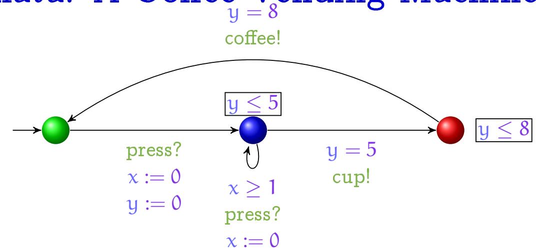

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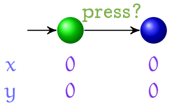

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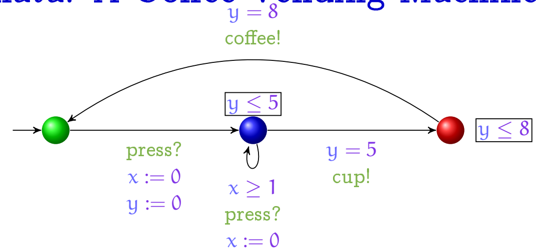

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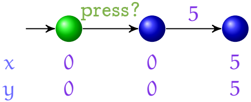

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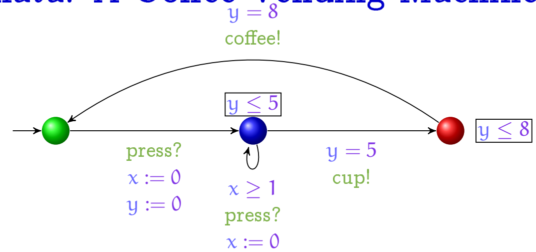

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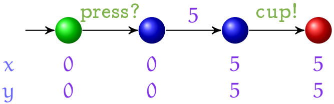

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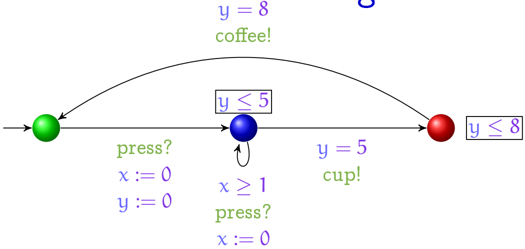

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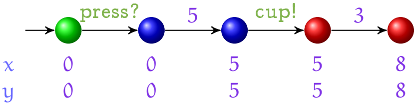

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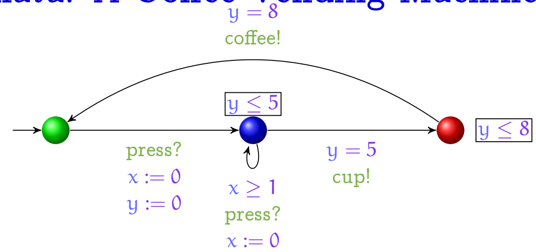

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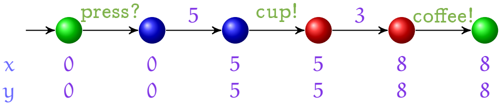

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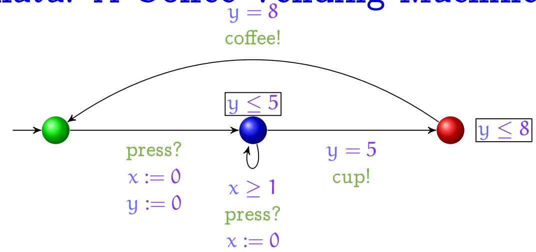

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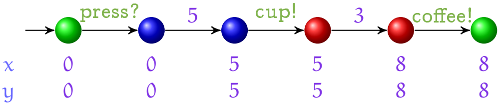
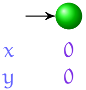


  - Coffee with 2 doses of sugar



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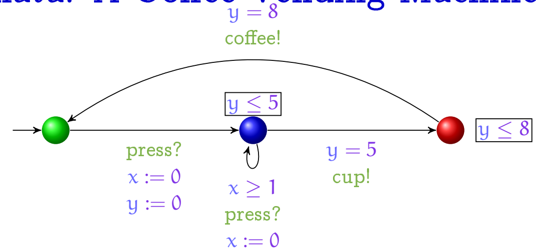

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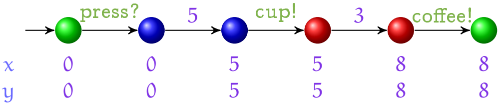

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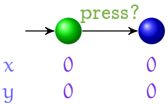

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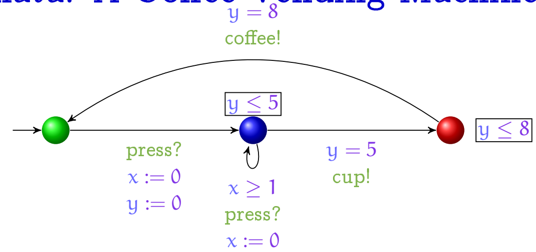

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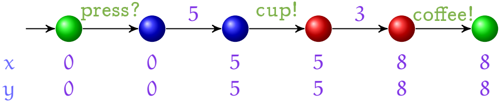

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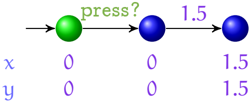

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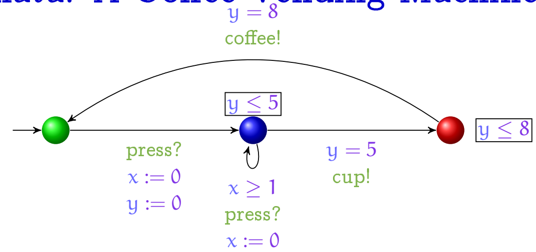

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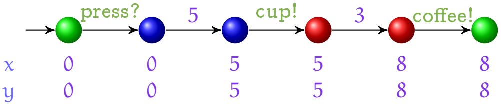

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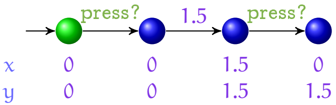

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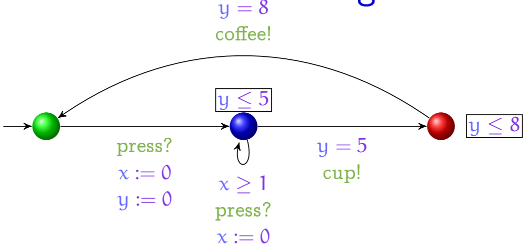

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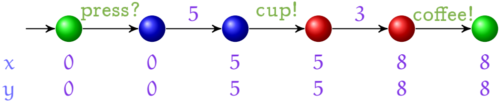

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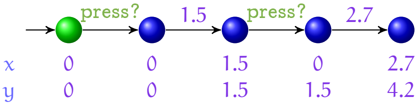

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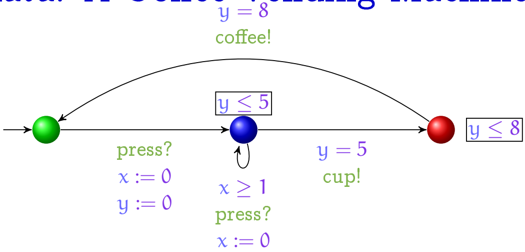

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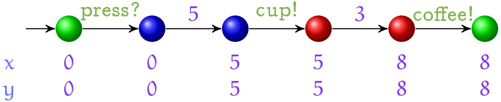

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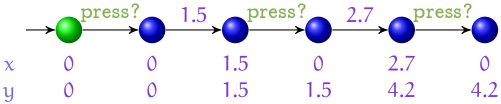

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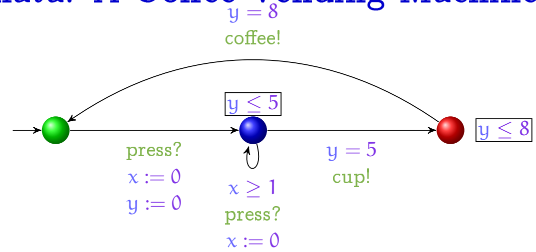

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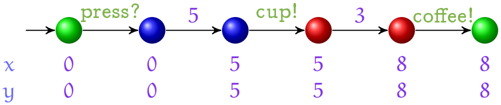

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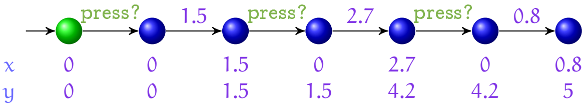

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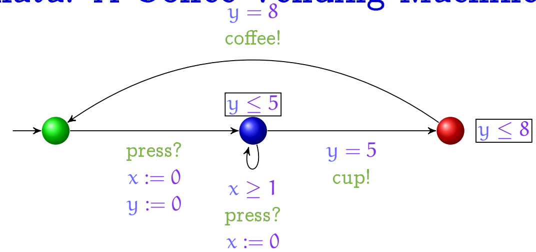

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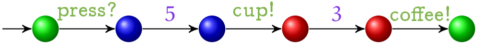

x	0	0	5	5	8	8
y	0	0	5	5	8	8

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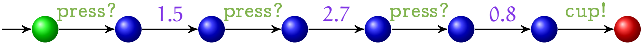
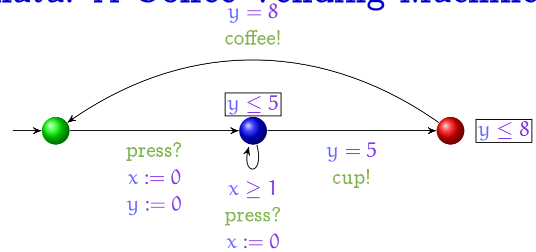


x	0	0	1.5	0	2.7	0	0.8	0.8
y	0	0	1.5	1.5	4.2	4.2	5	5

Timed Automata: A Coffee Vending Machine



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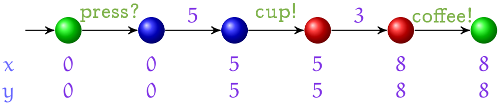

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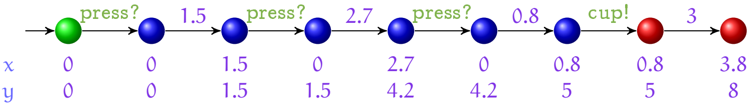

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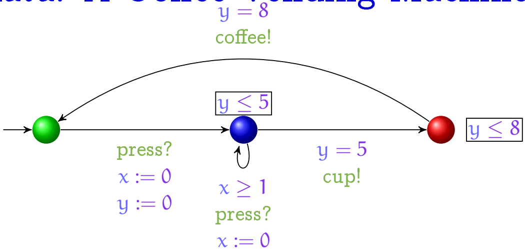

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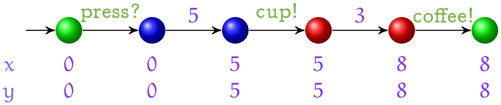

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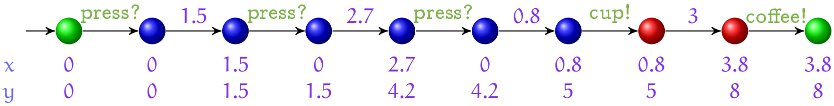
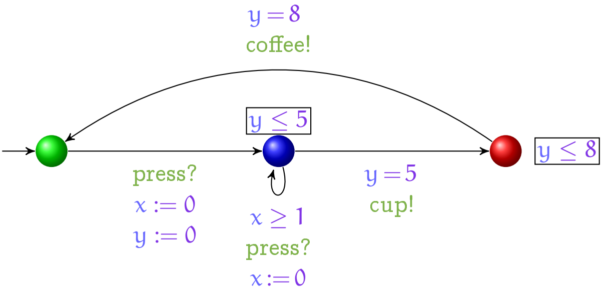


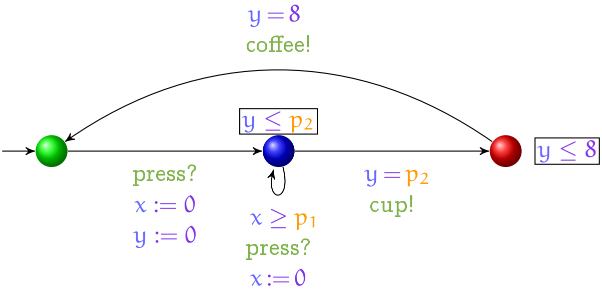
Parametric Timed Automaton (PTA)

- 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



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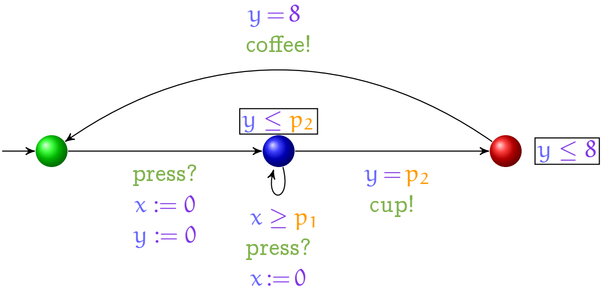

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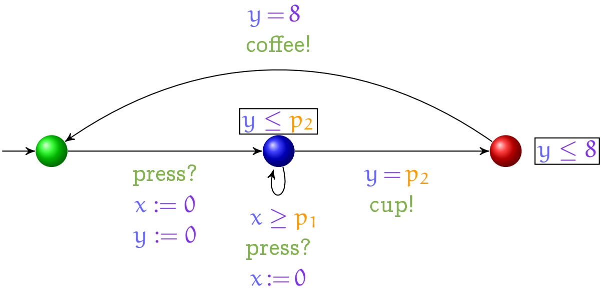

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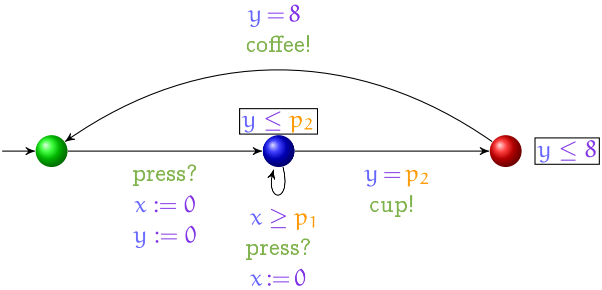

- Examples of problems
  - "Do there exist parameter valuations such that one can never get a coffee?" Yes! e.g.: $p_1 = 2, p_2 = 10$
  - "What are all possible parameter valuations such that one can get a coffee with 3 doses of sugar?"

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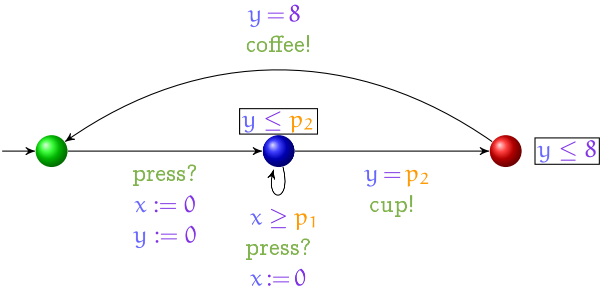

- Examples of problems
  - "Do there exist parameter valuations such that one can never get a coffee?" Yes! e.g.: $p_1 = 2, p_2 = 10$
  - "What are all possible parameter valuations such that one can get a coffee with 3 doses of sugar?" $p_2 \leq 8 \wedge p_2 \geq 3 \times p_1$

Valuation of a PTA

- A valuation π of all the parameters of P is called a point
- Given a PTA $\mathcal{A}$ and a point π, we denote by $\mathcal{A}[\pi]$ the (non-parametric) timed automaton where all parameters are valuated by π

Objective: Reachability Synthesis

Problem (EF-emptiness)

Let $\mathcal{A}$ be a PTA. Is the set of parameter valuations π such that $\mathcal{A}[\pi]$ reaches l_{bad} empty?

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- Semi-algorithm EFsynth proposed in [Alur et al., 1993]
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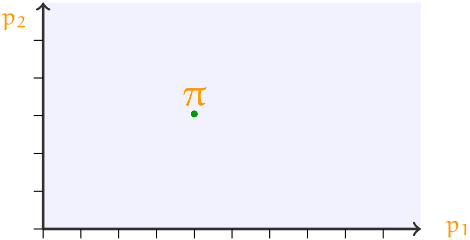
Outline

Reachability Preservation

Key idea

"If we know a parameter valuation π that reaches (resp. does not reach) l_{bad}, can we find other valuations around π that reach (resp. do not reach) l_{bad}?"



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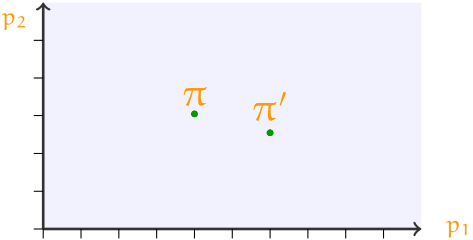

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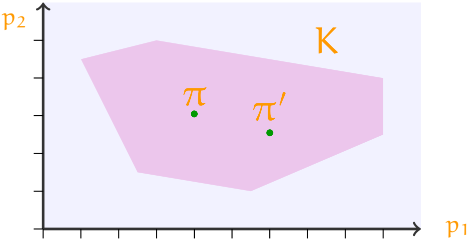

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Let $\mathcal{A}$ be a PTA, and π a parameter valuation. Does there exist $\pi' \neq \pi$ such that $\mathcal{A}[\pi']$ preserves the reachability of l_{bad} in $\mathcal{A}[\pi]$?

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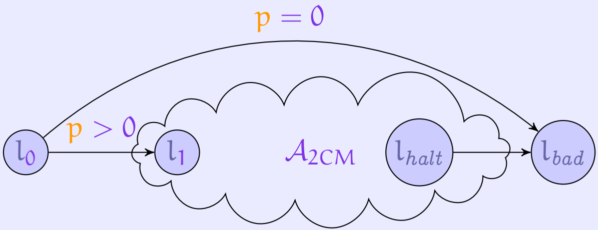

PRP: Parametric Reachability Preservation

Input: parameter valuation π

Output: constraint K such that

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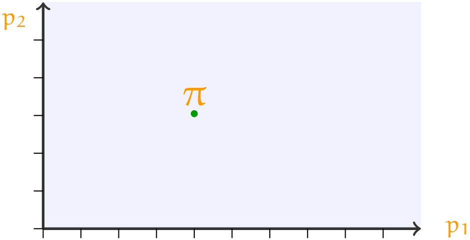

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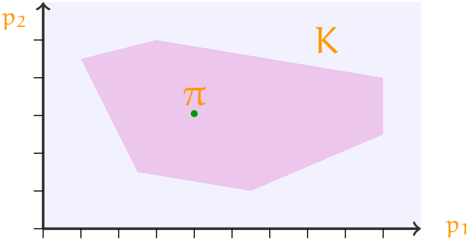

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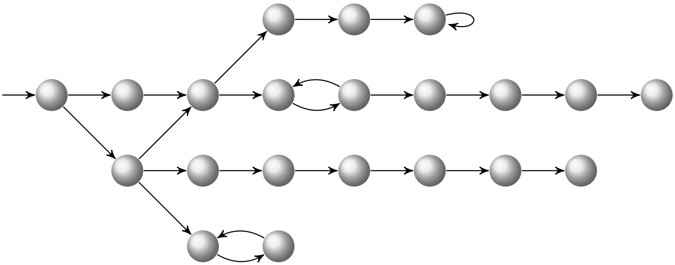

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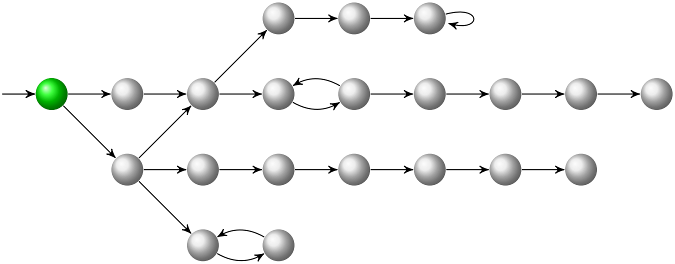

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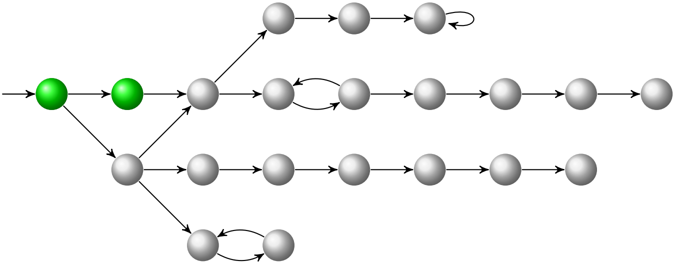

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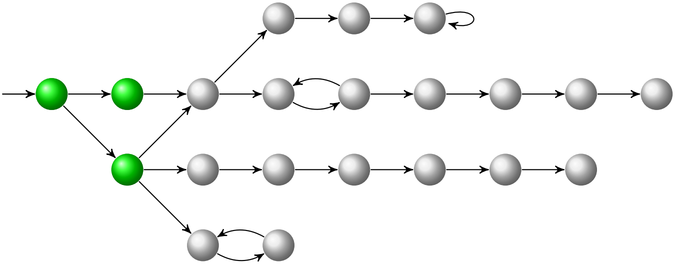

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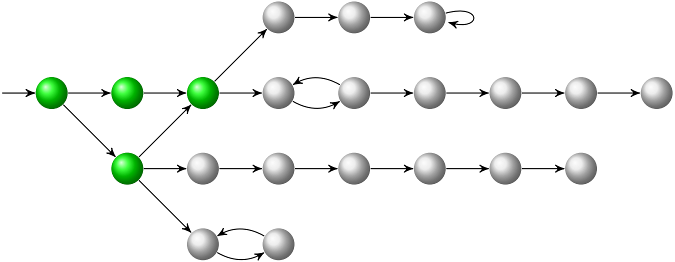

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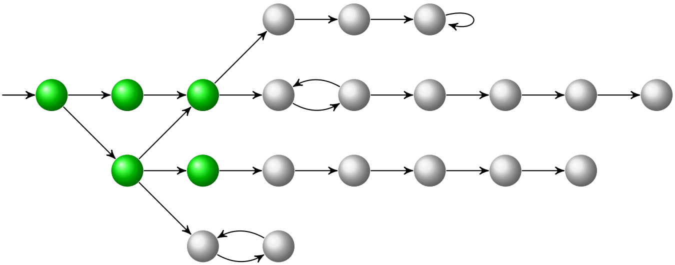

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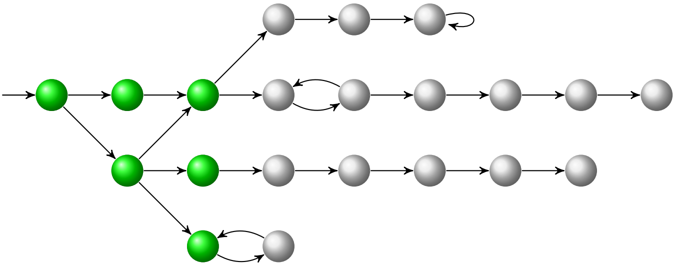

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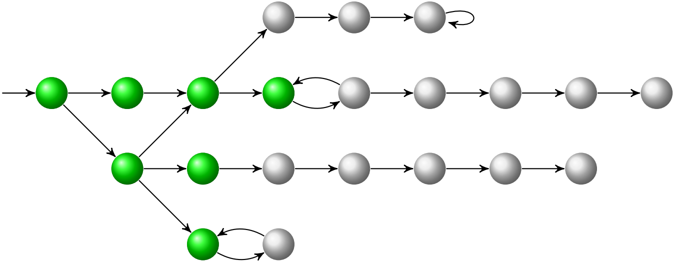

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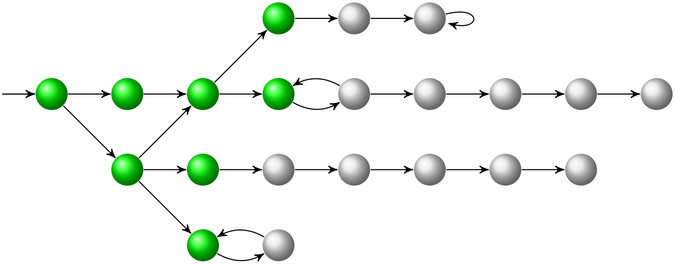

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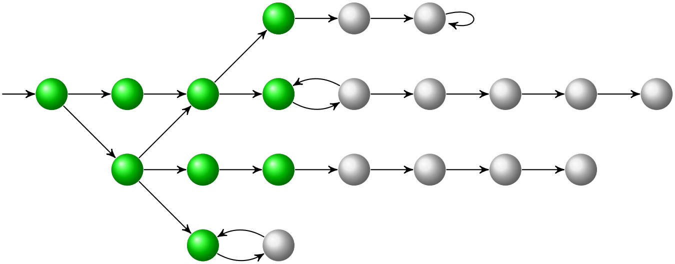

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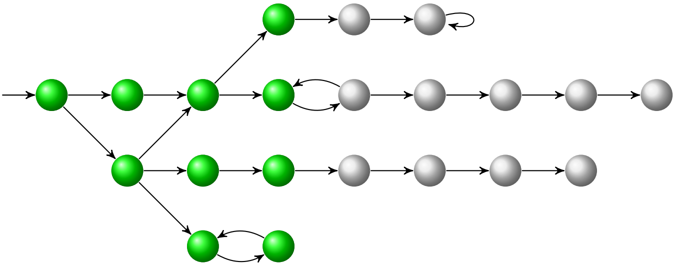

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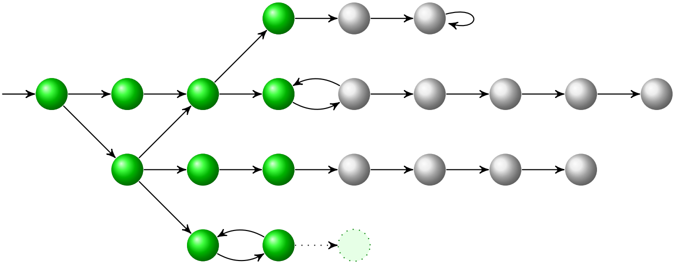

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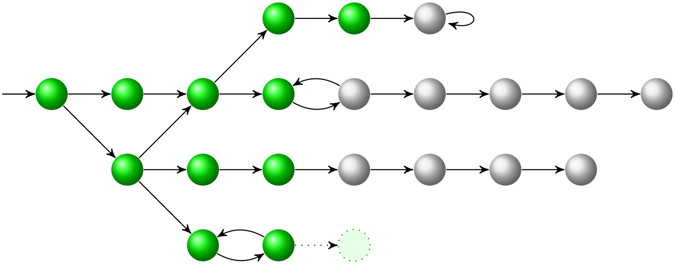

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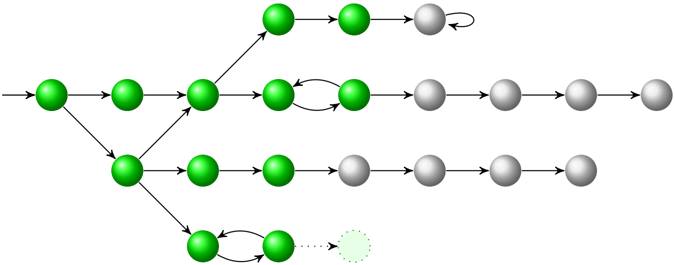

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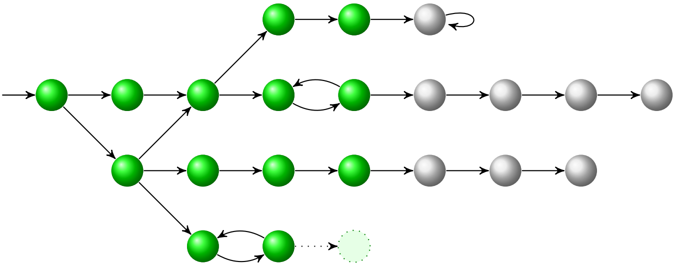

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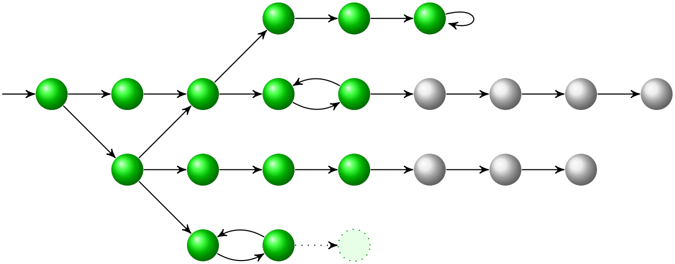

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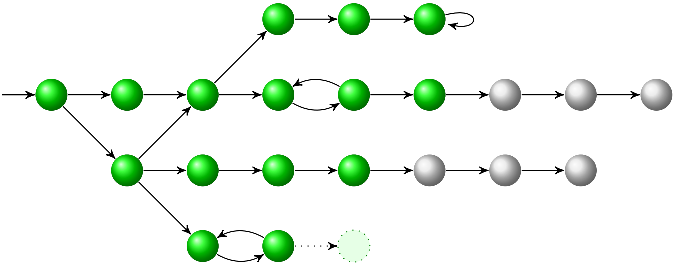

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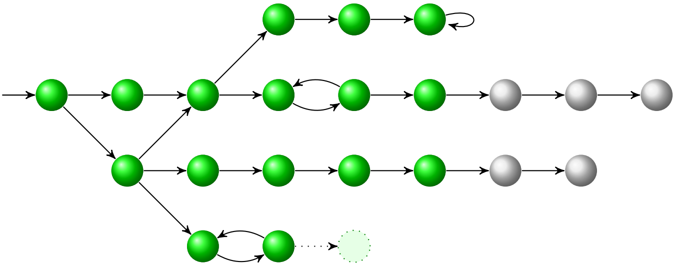

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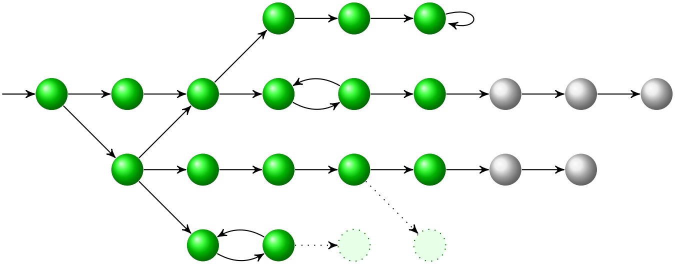

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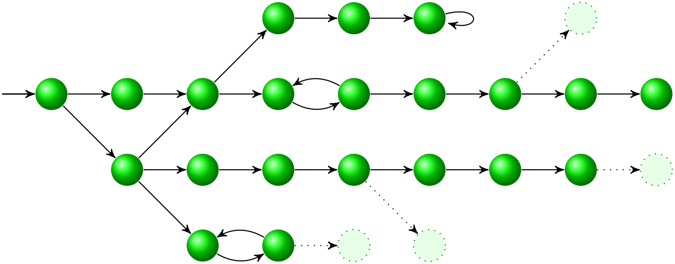

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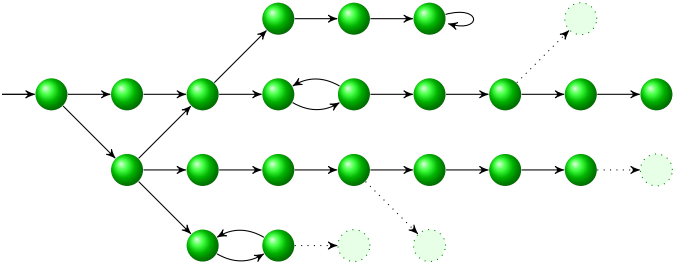

When no successors, and if l_{bad} was never met:

- return $\neg \bigcirc \land \cdots \land \neg \bigcirc$
- Ensures a subset of the behaviors of $\mathcal{A}[\pi]$, and hence guarantees the unreachability of l_{bad}

PRP: Case 1 (Remark)

Questions

How do we know the possible behaviors of $\mathcal{A}[\pi]$?

How do we know that a symbolic state of $\mathcal{A}$ corresponds to a behavior of $\mathcal{A}[\pi]$?

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But this is not necessary.
In fact, we do not even need to know whether $\mathcal{A}[\pi]$ reaches l_{bad} or not.

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Trick

A symbolic state (l, C) corresponds to a behavior of $\mathcal{A}[\pi]$ iff $\pi \models C$.

PRP: Case 2

When l_{bad} is met, switch to an EFsynth-like algorithm. . .

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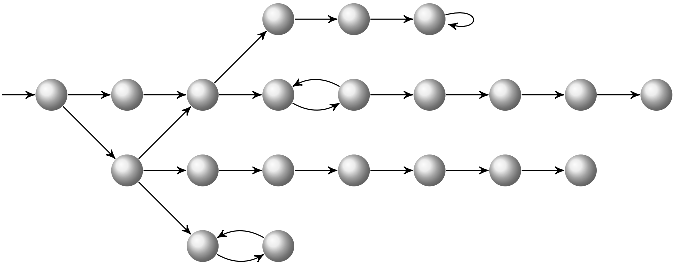

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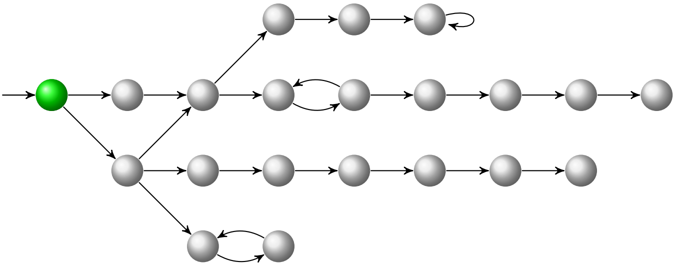

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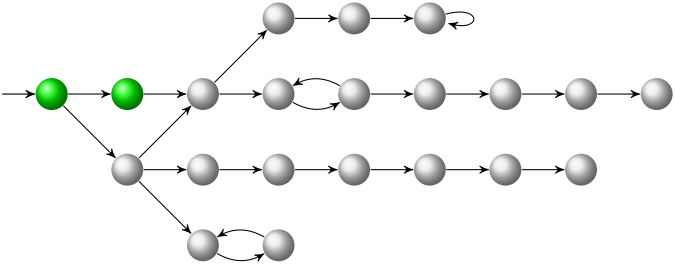

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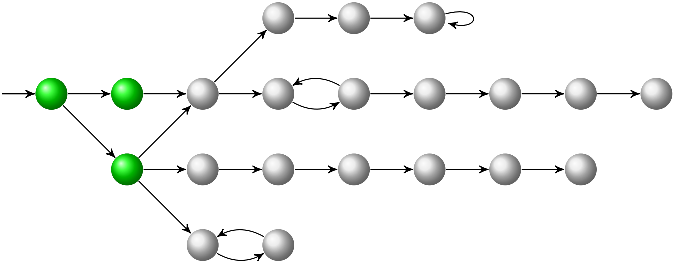

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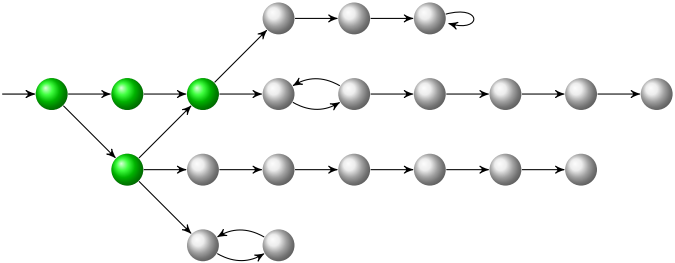

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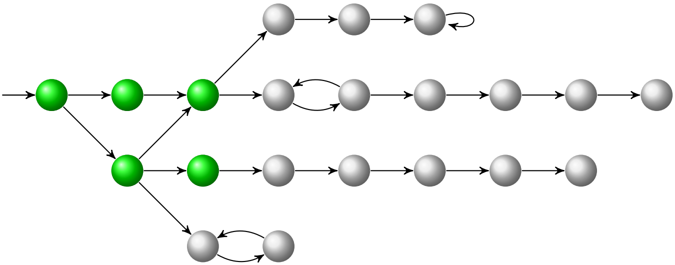

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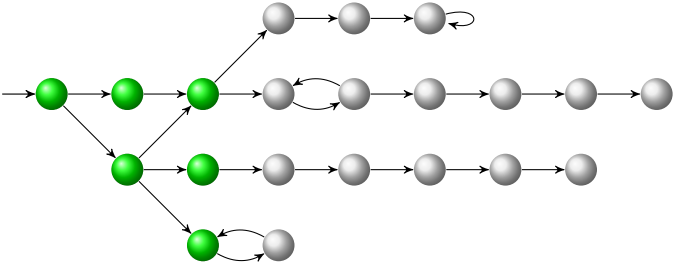

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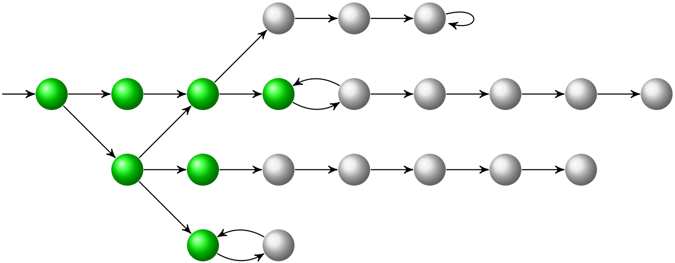

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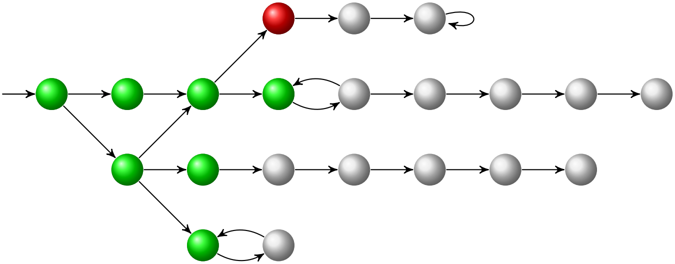

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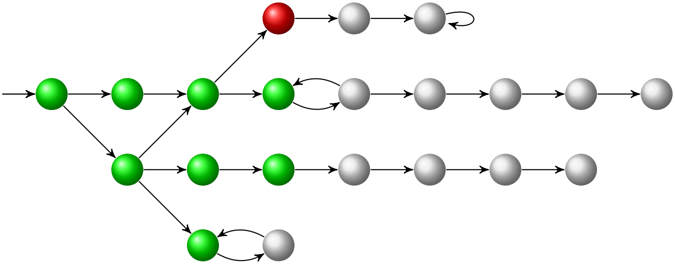

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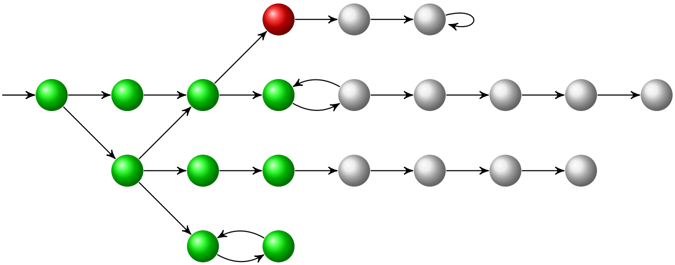

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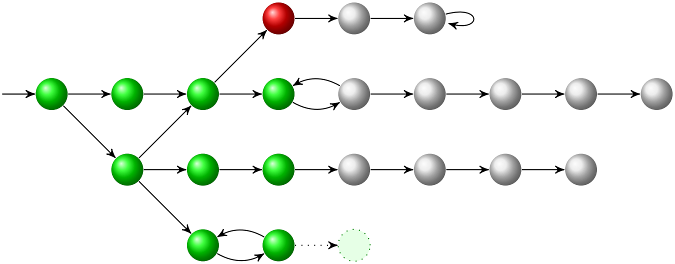

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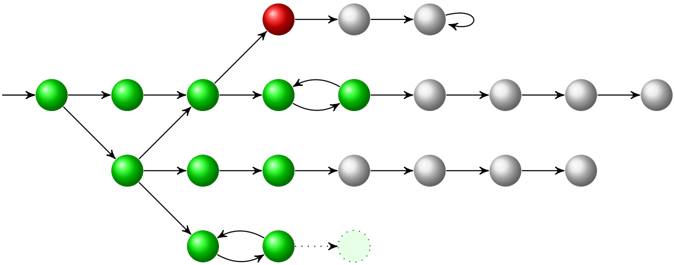

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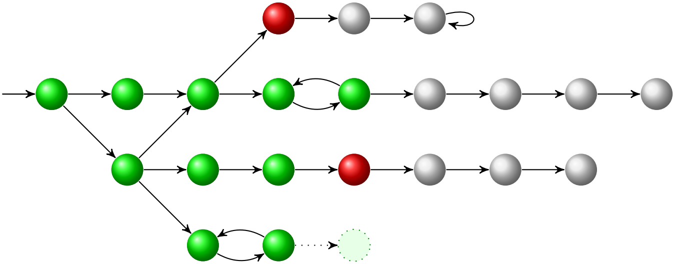

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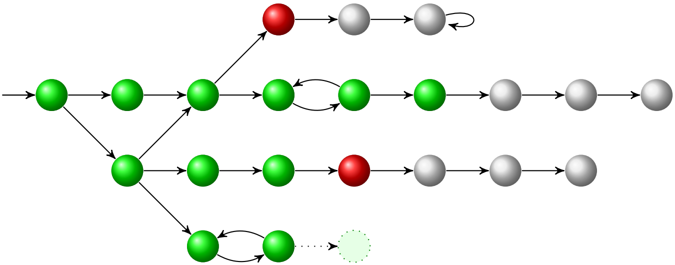

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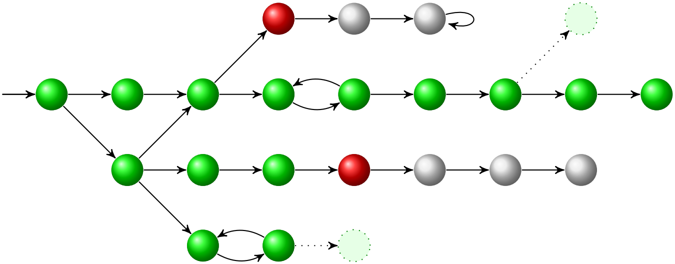
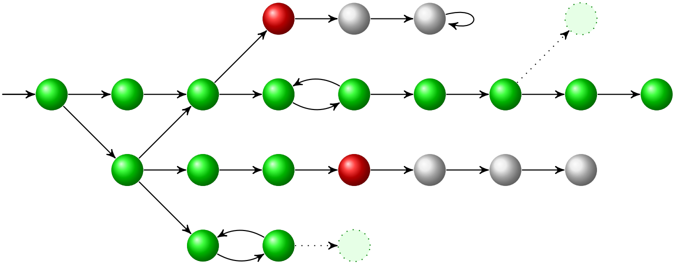


PRP: Case 2

When l_{bad} is met, switch to an EFsynth-like algorithm…

- But still without exploring the behaviors not present in $\mathcal{A}[\pi]$



When no successors, and if l_{bad} was met:

- return  $\vee \cdots \vee$ 
- Guarantees the reachability of l_{bad}

PRP: Early termination

Recall that PREACH-emptiness is undecidable

Hence PRP may not terminate.

PRP: Early termination

Recall that PREACH-emptiness is undecidable
Hence PRP may not terminate.

Proposition (Early termination)

If $\mathsf{PRP}(\mathcal{A}, \pi)$ *does not terminate and is interrupted (e.g., after a timeout), the result is still a valid under-approximation provided* l_{bad} *has been reached.*

This is also true for EFsynth (in any case)

Outline

Perform EF-synthesis using PRP

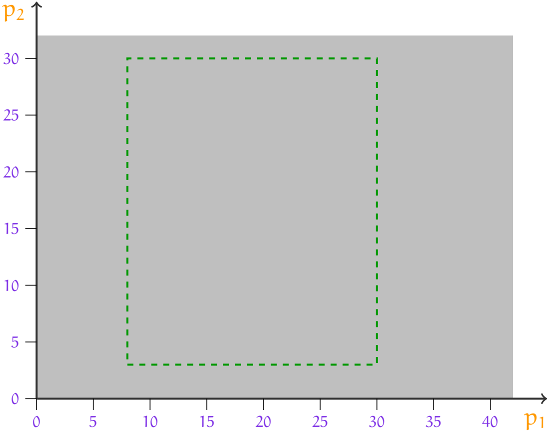
Input: parameter bounded domain V
Output: constraints on the parameter such that l_{bad} is / is not reachable in $\mathcal{A}$

- The idea: reuse the "behavioral cartography" of parametric timed automata [André and Fribourg, 2010]
- Iterate on integer points, and call PRP on each point not covered by a constraint
  - If no termination: break, and keep result if possible (i.e., if l_{bad} is reachable in this analysis)

PRPC: Reusing the Behavioral Cartography

Partition the domain V into constraints where the reachability of l_{bad} is uniform

Method: done by calling PRP on integer points (parameter valuations) sequentially



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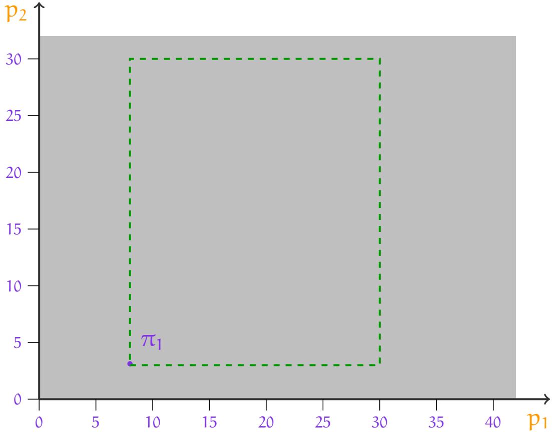

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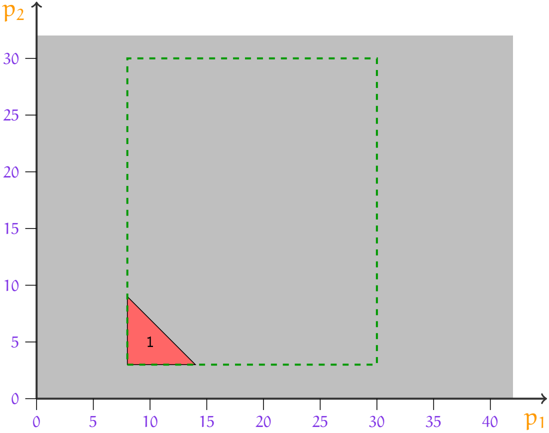

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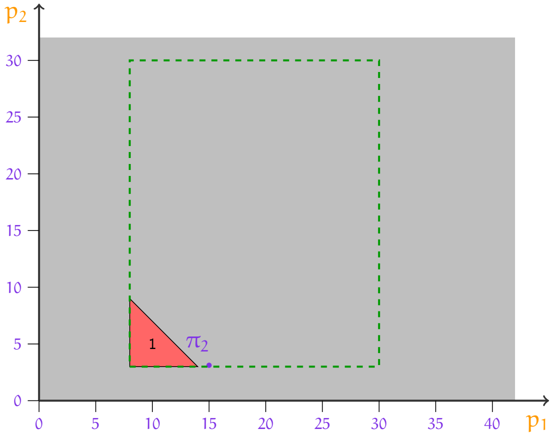

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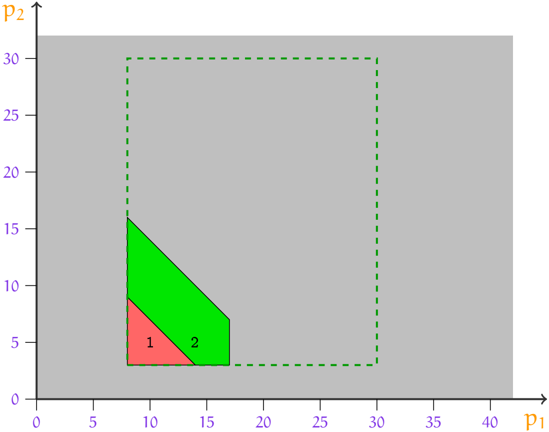

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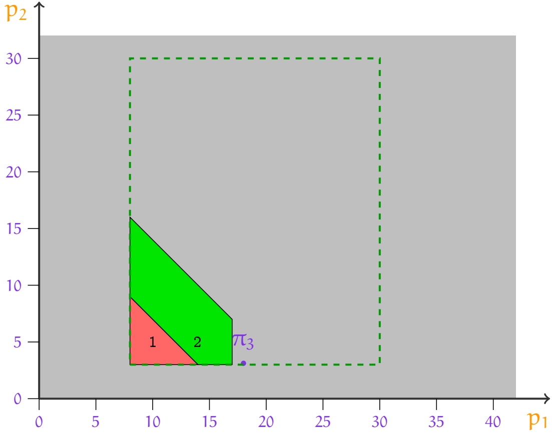

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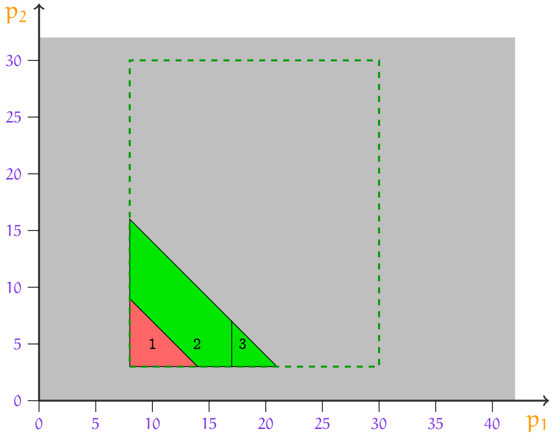

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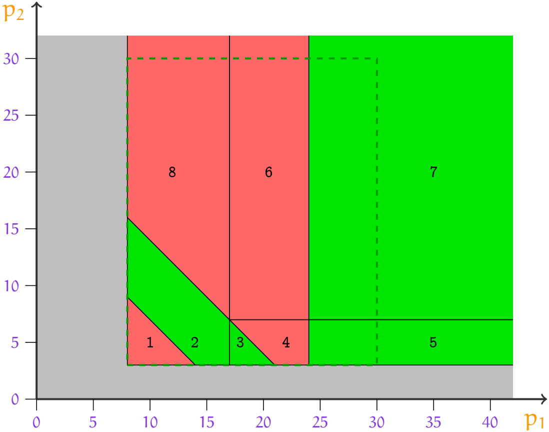
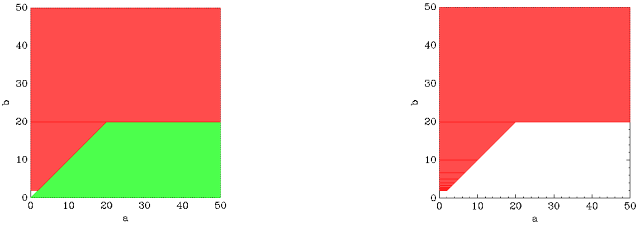


Result: "interval" under-approximation

- PRPC synthesizes:
  - An under-approximation of the bad constraints (reaching l_{bad})
  - An under-approximation of the good constraints (avoiding l_{bad})
- EFsynth synthesizes:
  - An under-approximation of the bad constraints

⇒ The result of PRPC is more valuable than EFsynth, at least when EFsynth does not terminate and is interrupted



PRPC EFsynth

Towards Distributed Parameter Synthesis

Idea

Calling sequentially PRP on various integer points in a bounded parameter domain looks like something that can be easily distributed.

Towards Distributed Parameter Synthesis

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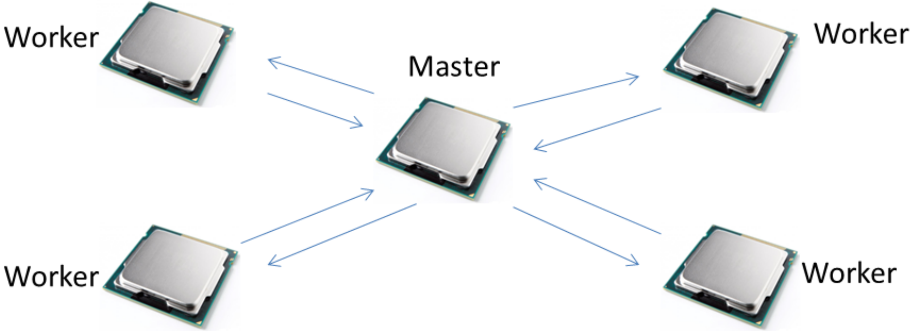
Calling sequentially PRP on various integer points in a bounded parameter domain looks like something that can be easily distributed.

Reuse the distributed algorithms to compute the behavioral cartography of parametric timed automata [A., Coti, Evangelista, 2014]

Master Worker Scheme



Master-Worker distribution scheme:

- Workers: ask the master for a point, calls PRP on that point, and send the result (constraint) to the master
- Master: is responsible for smart repartition of data between the workers
  - (Note: not trivial at all)

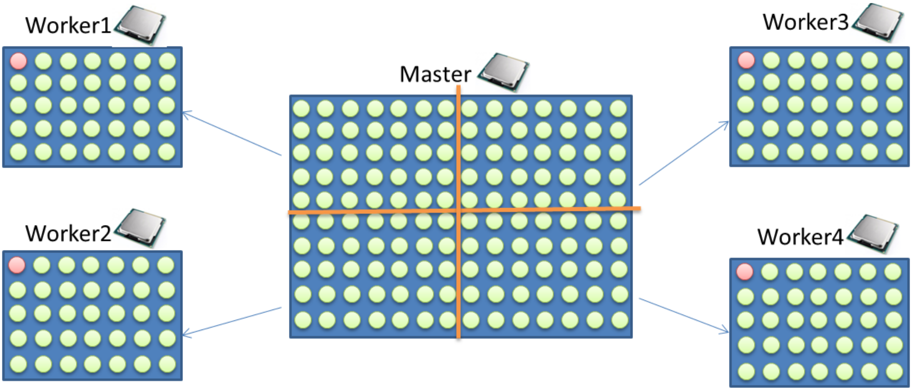
Dynamic Decomposition of BC

Most efficient distributed algorithm for BC (so far!):
"Domain decomposition" scheme [work in progress]

- Master
  1. initially splits the parameter domain into subdomains and send them to the workers
  2. when a worker has completed its subdomain, the master splits another subdomain, and sends it to the idle worker

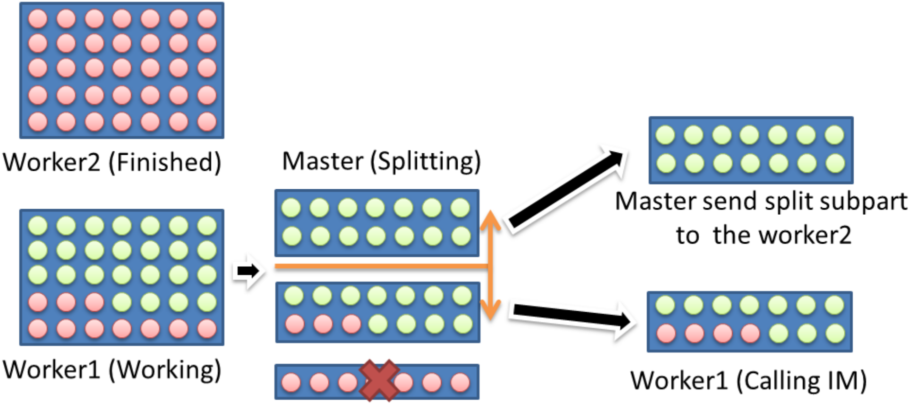
- Workers
  1. receives the subdomain from the master
  2. calls PRP on the points of this subdomain
  3. sends the results (list of constraints) back to the master
  4. asks for more work

Domain Decomposition: Initial Splitting



- Prevent to choose close points
- Prevent bottleneck phenomenon at the master side
  - Master only responsible for gathering constraints and splitting subdomains

Domain Decomposition: Dynamic Splitting



- Master can balance workload between workers

Outline

Implementation in IMITATOR

- IMITATOR [A., Fribourg, Kühne, Soulat, 2012]
  - 26,000 lines of OCaml code
    - Development started in 2009... in Hilton Pasadena!
  - Relies on the PPL library for operations on polyhedra [Bagnara et al., 2008]
  - Available under the GNU-GPL license
  - Latest version (2.7) implements distributed algorithms

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http://www.imitator.fr/

PRPC: experiments

Case study	$\|X\|$	$\|V\|$	EFsynth	BC	PRPC	PRPC distr(12)
$\mathcal{A}_1$	2	2,601	0.401*	TO	0.078*	0.050*
Sched1	13	6,561	TO	TO	1,595	219
Sched2.50.0	6	3,321	9.25	990	14.55	4.77
Sched2.50.2	6	3,321	662	TO	213	84
Sched2.100.0	6	972,971	21.4	2,093	116	10.1
Sched2.100.2	6	972,971	3,757	TO	4,557	1,543
Sched5	21	1,681	352	TO	TO	917
SPSMALL	11	3,082	7.49	587	118	11.2

IMITATOR version: 2.6.2, build 845
* experiment run using -depth-limit 10 (does not terminate in general)
Experiments available at http://www.imitator.fr/static/NFM15/

Outline

Summary

PRP

- Given a parameter valuation π and a location l_{bad}, outputs a dense set of parameter valuations around π that preserve the (un)reachability of l_{bad}

PRPC

- Computes an under-approximated set of parameter valuations reaching / not reaching l_{bad}
- Can be distributed
- Often outperforms EFsynth, especially when distributed

Perspectives

- Improvement: always return both good and bad constraints (for both PRP and EFsynth)
- Combine with integer hull to ensure termination [Jovanović et al., 2014]
  - At least for integer valuations
- Combine with multi-core techniques [Laarman et al., 2013]
- Verify the communication scheme in the distributed IMITATOR for an arbitrary number of nodes
  - Using parametric verification techniques?

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- Verify the communication scheme in the distributed IMITATOR for an arbitrary number of nodes
  - Using parametric verification techniques?
- Extend to compositional verification

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Additional explanation

PRP: The Algorithm

Algorithm 1: PRP$(\mathcal{A}, \pi)$

input : PTA $\mathcal{A}$ of initial state s_0, parameter valuation π

output : Constraint over the parameters

$S \leftarrow \emptyset$; $S_{new} \leftarrow \{s_0\}$; $Bad \leftarrow \texttt{false}$; $K_{good} \leftarrow \top$; $K_{bad} \leftarrow \bot$; $i \leftarrow 0$

while $\texttt{true}$ **do**

  foreach π-*incompatible state* (l, C) *in* S_{new} **do**

    $S_{new} \leftarrow S_{new} \setminus \{(l, C)\}$

    if $Bad = \texttt{false}$ **then**

      Select a π-incompatible inequality J in $C\downarrow_P$ (i.e., s.t. $\pi \not\models J$)

      $K_{good} \leftarrow K_{good} \wedge \neg J$

  foreach *bad state* (l_{bad}, C) *in* S_{new} **do**

    $Bad \leftarrow \texttt{true}$; $K_{bad} \leftarrow K_{bad} \vee C\downarrow_P$; $S_{new} \leftarrow S_{new} \setminus \{(l_{bad}, C)\}$

  if $S_{new} \subseteq S$ **then**

    if $Bad = \texttt{true}$ **then return** K_{bad} **else return** K_{good} ;

  $S \leftarrow S \cup S_{new}$; $S_{new} \leftarrow Succ(S_{new})$; $i \leftarrow i + 1$

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