UNIVERSITÉ PARIS 13

Habilitation defense

Monday, 25th of June 2018

Contributions to parametric timed model checking: Theory and algorithms

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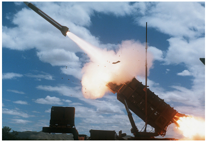
Context: Critical real-time systems

- Real-time systems are everywhere
  - Hard timing constraints and concurrency
  - Criticality: risk for huge damages in case of unexpected behavior (bug)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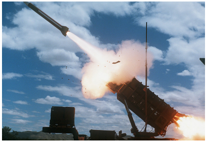


- Verification to ensure absence of bugs is required

- Common techniques
  - Testing
  - Abstract interpretation
  - Theorem proving
  - Model checking

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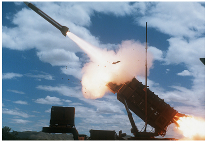


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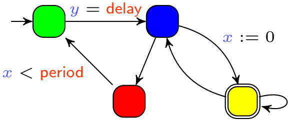
Model checking timed concurrent systems

- Use formal methods [Baier and Katoen, 2008]



A model of the system


is unreachable

A property to be satisfied

Model checking timed concurrent systems

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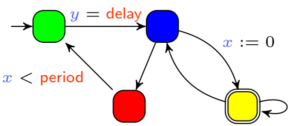

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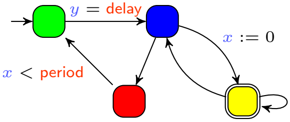

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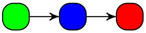
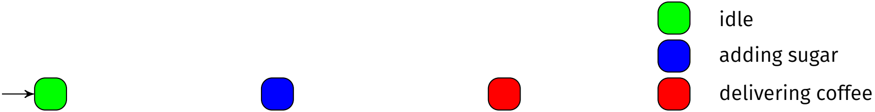


Counterexample

Turing award (2007) to Edmund M. Clarke, Allen Emerson and Joseph Sifakis

Timed automaton (TA)

- Finite state automaton (sets of locations)



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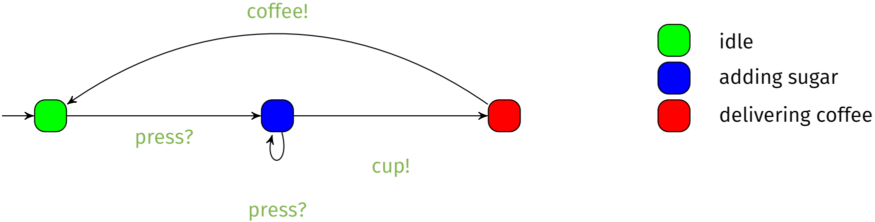

Timed automaton (TA)

- Finite state automaton (sets of locations and actions) augmented with a set X of clocks [Alur and Dill, 1994]
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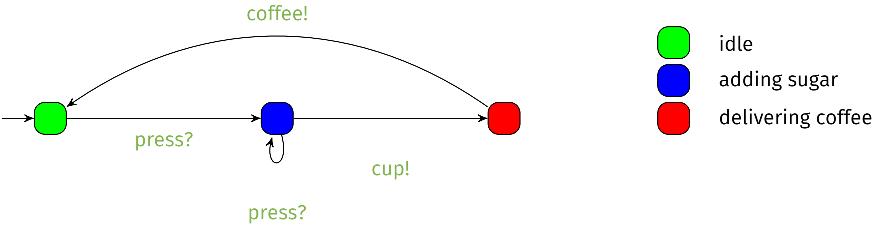

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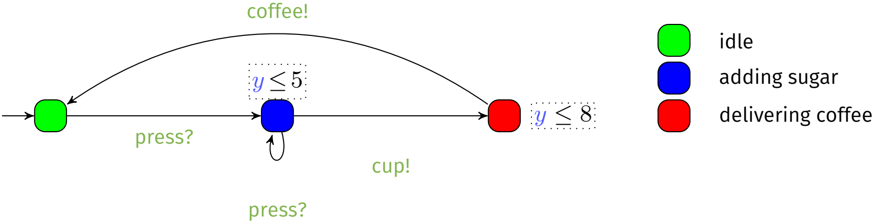

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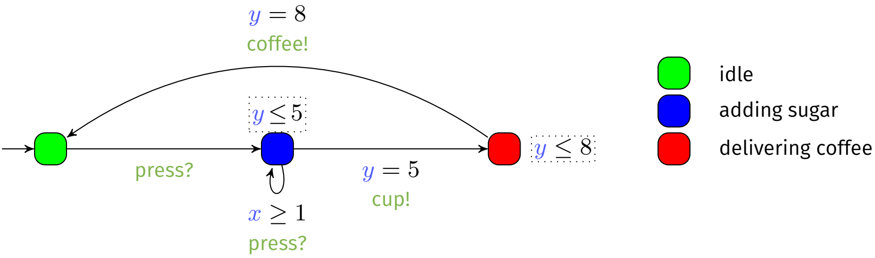

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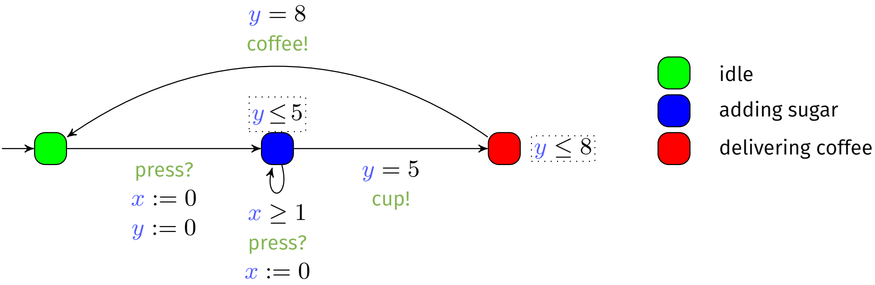
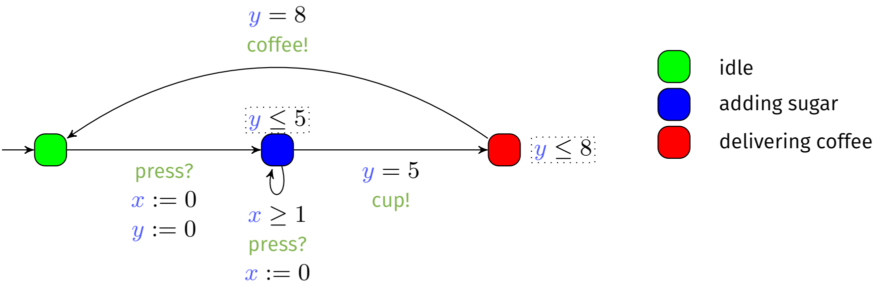
  - Transition guard: property to be verified to enable a transition
  - Clock reset: some of the clocks can be set to 0 along transitions



The most critical system: The coffee machine



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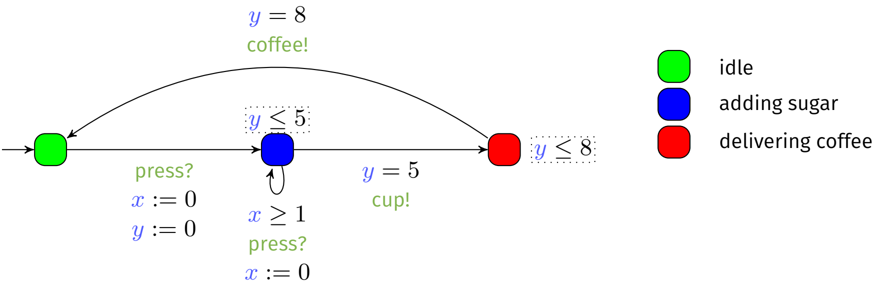

- Example of concrete run for the coffee machine
  - Coffee with 2 doses of sugar

$x = 0$

$y = 0$

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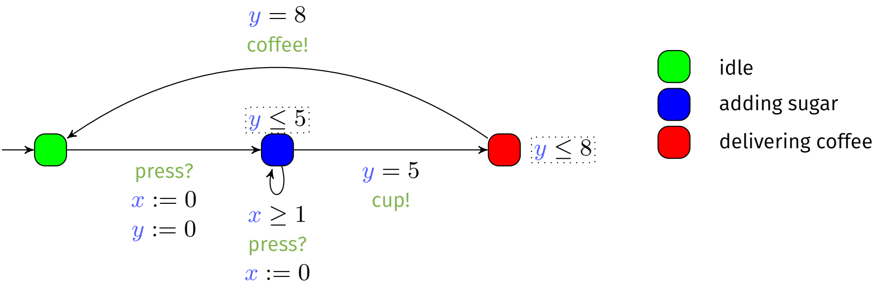

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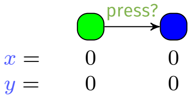

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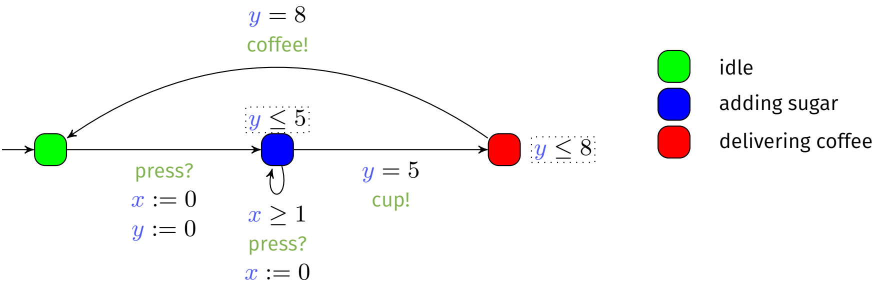

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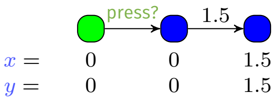

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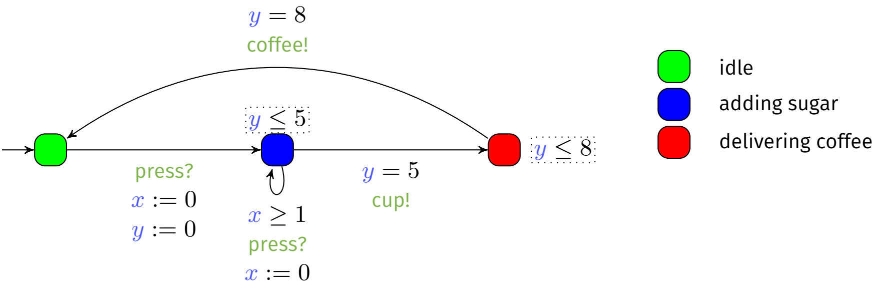

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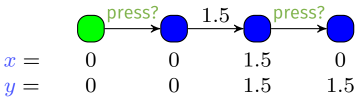

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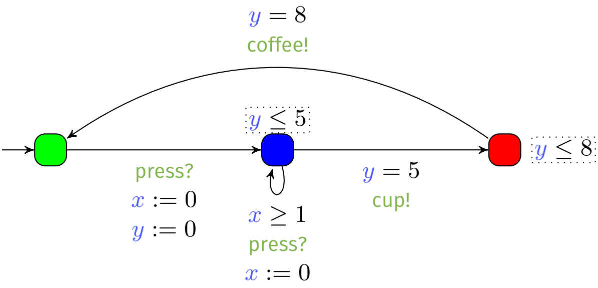

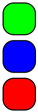

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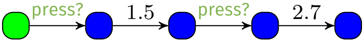

$x =$	0	0	1.5	0	2.7
$y =$	0	0	1.5	1.5	4.2

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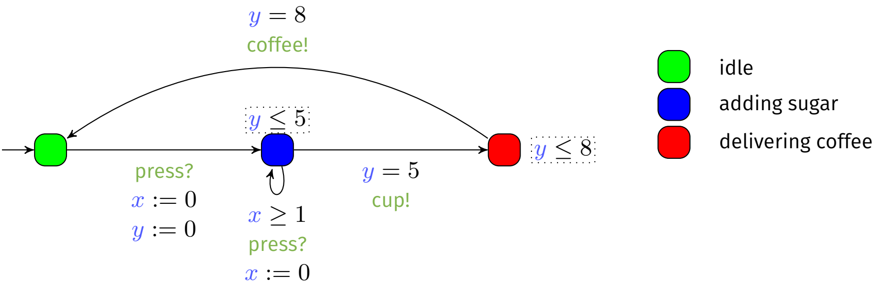

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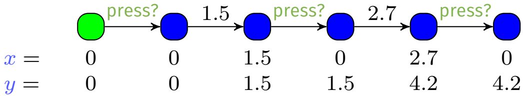

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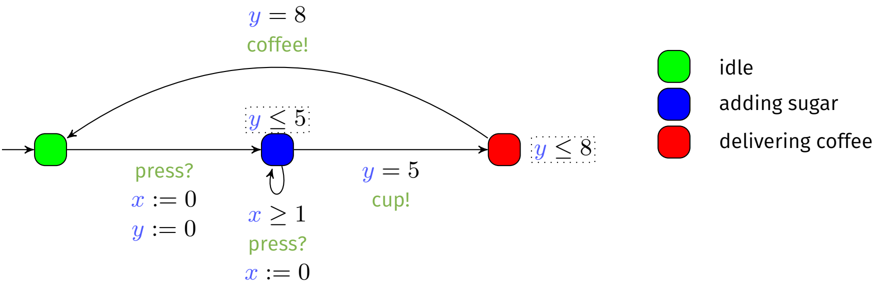

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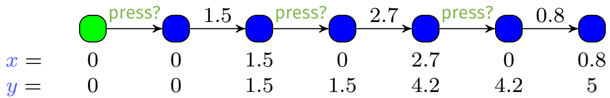

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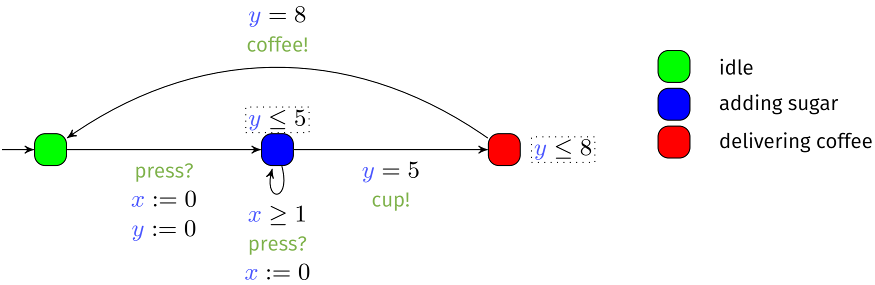

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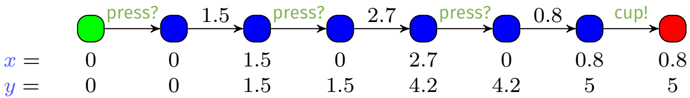

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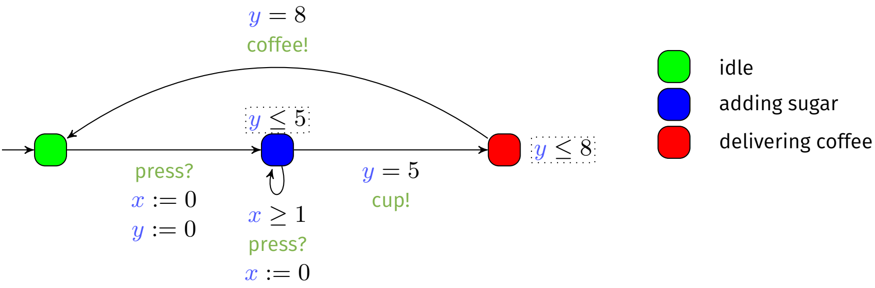

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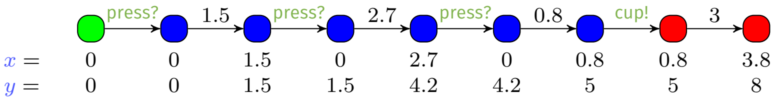

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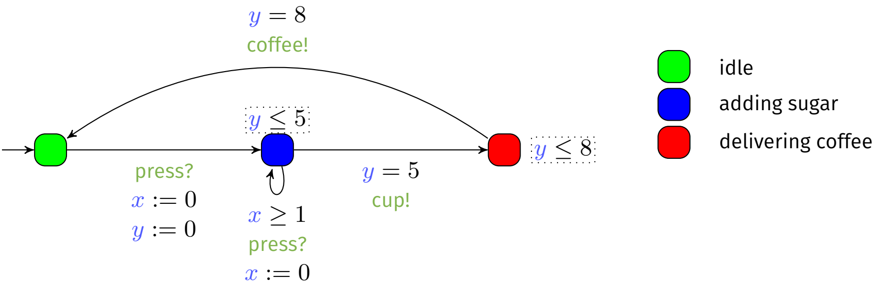

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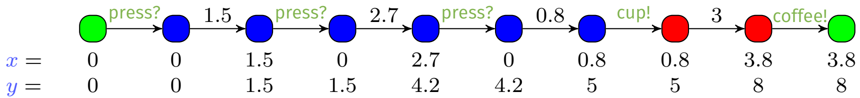

Timed automata: A success story

- An expressive formalism
  - Dense time
  - Concurrency
- A tractable verification in theory
  - Reachability is PSPACE-complete [Alur and Dill, 1994]
- A very efficient verification in practice
  - Symbolic verification: relatively insensitive to constants
  - Several model checkers, notably UPPAAL [Larsen et al., 1997]
  - Long list of successful case studies

Need to allow for abstractions and uncertainty

- Need for abstraction
  - Constants known with limited certainty
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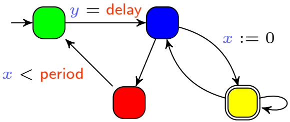
- Challenging problems
  - Existence (dually: emptiness): find one valuation for which a property holds
    - “Can I exhibit a valuation for which I am guaranteed to eventually get a coffee?”
  - Synthesis: find some/all parameter valuations for which a property holds
    - “Synthesize all valuations for which I am guaranteed to eventually get a coffee with 2 sugars”

timed model checking



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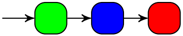
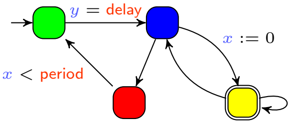


Counterexample

Parametric timed model checking



A model of the system

$\overset{?}{\models}$

 is unreachable

A property to be satisfied

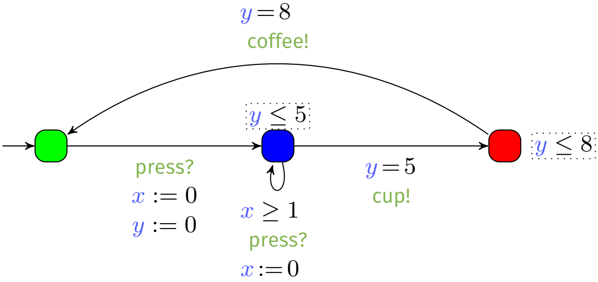
- Question: for what values of the parameters does the model of the system satisfy the property?

Yes if...

$$2 \times \text{delay} > \text{period}$$
$$\wedge\ \text{period} < 20.46$$

Parametric Timed Automaton (PTA)

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



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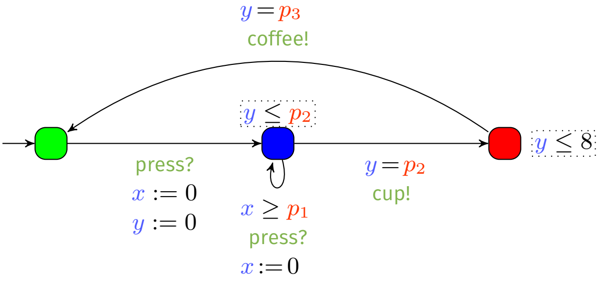

Notation: Valuation of a PTA

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

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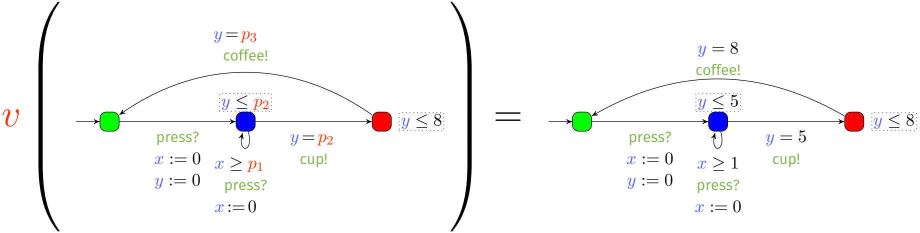

$$\text{with } v : \begin{cases} p_1 & \rightarrow & 1 \\ p_2 & \rightarrow & 5 \\ p_3 & \rightarrow & 8 \end{cases}$$

Objectives

Main objective

Perform efficient parameter synthesis for parametric timed automata

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Before designing algorithms, one shall first study theory

- Decidability
- Complexity
- Syntactic restrictions

Outline

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1 Decidability

2 Efficient synthesis

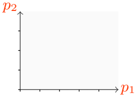
3 Applications to schedulability analysis

4 Perspectives

25 years of (un)decidability results for PTAs

Key problem considered: EF-emptiness

- "given a PTA $\mathcal{A}$ and a location 🟥, is the set of parameter valuations v such that $v(\mathcal{A})$ reaches 🟥 empty"?



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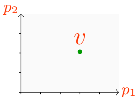

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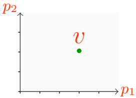

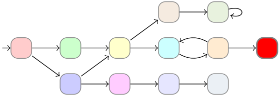

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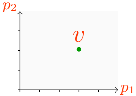

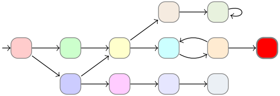

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Survey: **[André, STTT (2017)]**

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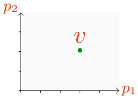

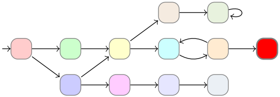

Large collection of results — Survey: **[André, STTT (2017)]**

- Undecidable
  - Undecidable for only 3 clocks [Alur et al., 1993]
  - Undecidable for only 1 clock compared to parameters [Miller, 2000]
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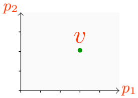

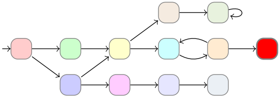

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- Decidable
  - Limiting the number of clocks [Alur et al., 1993, Bundala and Ouaknine, 2014, Beneš et al., 2015]
  - Bounded integer-valued parameters [Jovanović et al., 2015]
  - Restricting the use of parameters [Hune et al., 2002]

Contributions: new (un)decidability results for PTAs

Investigating further problems for parametric timed automata

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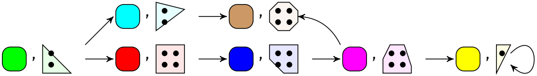
- "Each symbolic state (polyhedron) contains an integer point"



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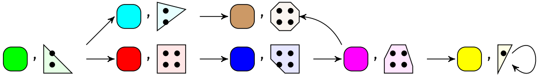

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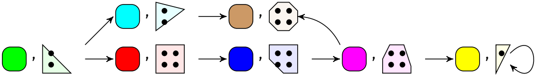

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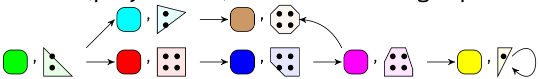

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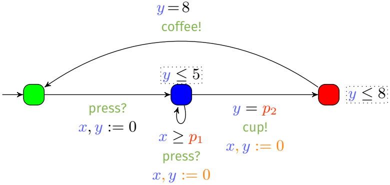
- Good news: syntactic subclass: reset-PTA
  - "Whenever a clock is compared to a parameter, all clocks must be reset"



16 years of (un)decidability results for L/U-PTAs

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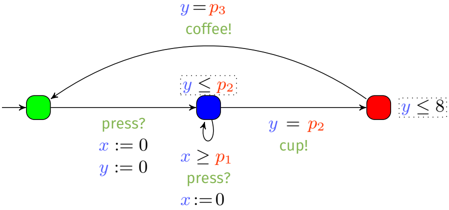

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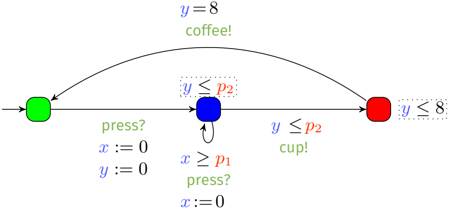

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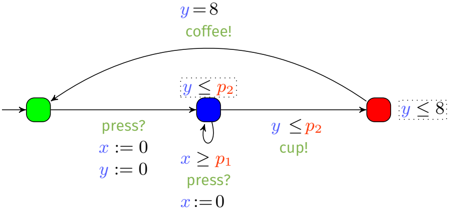

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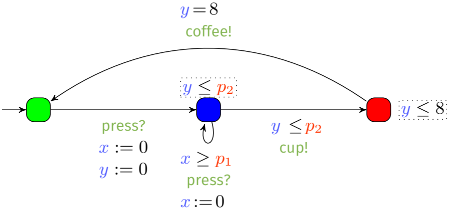

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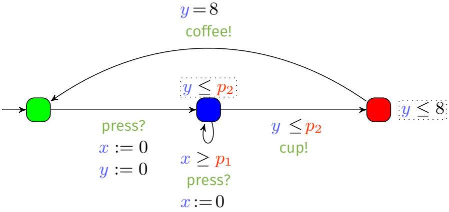

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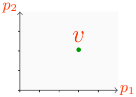

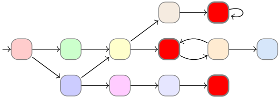

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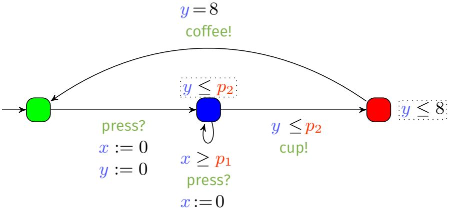

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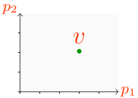
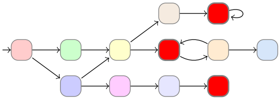
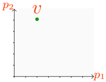


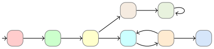


- Seems to allow for interesting applications

Contributions: new (un)decidability results for L/U-PTAs

- Language-preservation problem: undecidable **[FORMATS'15]**





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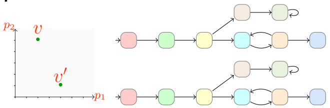

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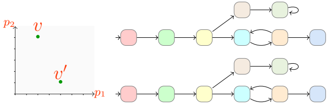

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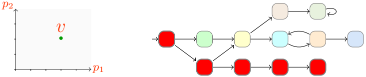

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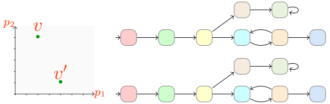

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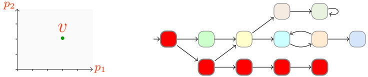

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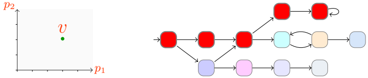

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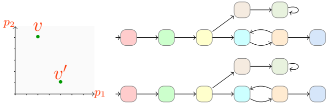

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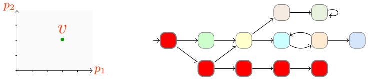

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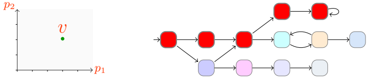
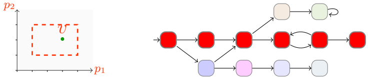


- EG-emptiness: decidable only if the parameters are bounded with closed bounds [ACSD'17]



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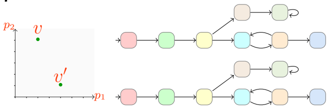

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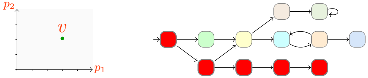

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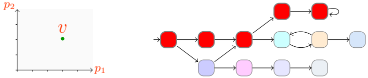

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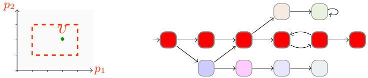

- Full (T)CTL-emptiness: undecidable even for U-PTAs **[FORMATS'18]**

Mathias Ramparison's PhD thesis

Summary of theoretical contributions

<table>
<tr><th>Class</th><th>U-PTAs</th><th colspan="2">bL/U-PTAs</th><th>L/U-PTAs</th><th>bPTAs</th><th>PTAs</th></tr>
<tr><td>emptiness</td><td></td><td>closed</td><td>open</td><td></td><td></td><td></td></tr>
<tr><td>EF</td><td>[Hune et al., 2002]</td><td>[ICFEM’16]</td><td>(WiP)</td><td>[Hune et al., 2002]</td><td>[Miller, 2000]</td><td>[Alur et al., 1993]</td></tr>
<tr><td>AF</td><td>open</td><td colspan="2">[ICFEM’16]</td><td>[Jovanović et al., 2015]</td><td>[ICFEM’16]</td><td>[Jovanović et al., 2015]</td></tr>
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<tr><td>Lg-Pres.</td><td>open</td><td colspan="5">[FORMATS’15]</td></tr>
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</table>

[FORMATS’15]	É. André and N. Markey
[ICTAC’16]	É. André
[ICFEM’16]	É. André, D. Lime and O. H. Roux
[ACSD’17]	É. André and D. Lime
[FORMATS’18]	É. André, D. Lime and M. Ramparison
WiP	Work in progress (decidable)

Decidable
Open
Undecidable

bL/U-PTA: bounded L/U-PTAs

Perspectives

Less expressive classes

- A quite unexplored formalism: U-PTA
  - Still able to model interesting systems

More expressive classes

- Extension to hybrid systems
  - Clocks become variables with arbitrary (and different) rates

Outline

Efficient synthesis: Motivation

- Parametric timed automata are very expressive

  [André, Lime, Roux, FORMATS'16]

- But most problems are undecidable
- Still, they represent an excellent opportunity for pragmatic parametric model checking

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Goal

Design efficient parameter synthesis algorithms

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Goal

Design efficient parameter synthesis algorithms

Two possible directions:

1. Achieving termination without guarantee on the completeness
2. Achieving exact synthesis without guarantee on termination

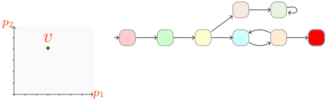
Outline

Parametric reachability preservation

Parametric reachability preservation problem

Input: a PTA $\mathcal{A}$, a goal location 🟥, a parameter valuation v

Problem: synthesize valuations v' such that $v(\mathcal{A})$ reaches 🟥 iff $v'(\mathcal{A})$ reaches 🟥



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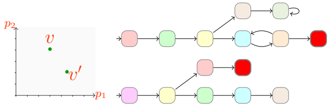

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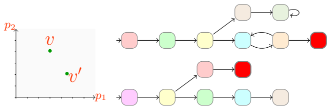
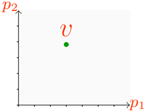


Reachability-preservation-emptiness problem undecidable

[André, Lipari, Nguyen, Sun, NFM'15]

Parametric reachability preservation: An algorithm

A pragmatic procedure: $\mathsf{PRP}(\mathcal{A}, v)$



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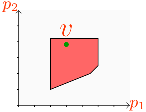

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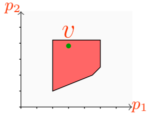
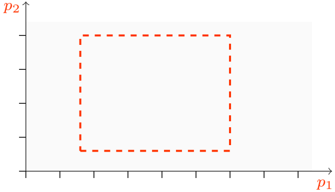


- Built on top of two existing algorithms
  - Reachability synthesis (EFsynth) [Alur et al., 1993, Jovanović et al., 2015]
  - Trace-preservation-synthesis (IM) **[André et al., 2009]**
- Key heuristics: only explore behaviors "similar" to that of $v(\mathcal{A})$

$\rightsquigarrow$ Non-necessarily terminating, incomplete on purpose, but fast in practice

Solving reachability synthesis using PRP

- Idea: select valuations in a bounded parameter domain, and call PRP on these valuations, until a sufficient coverage is reached: algorithm PRPC



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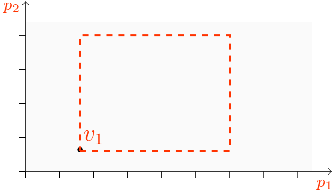

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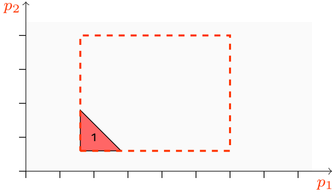

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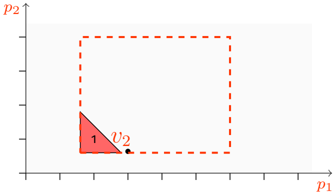

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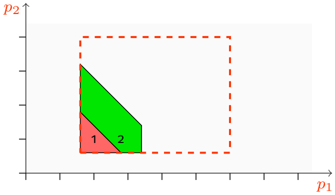

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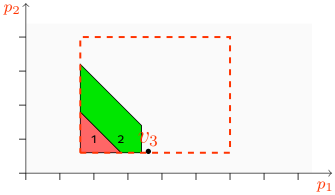

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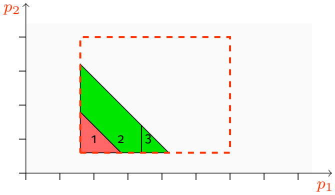

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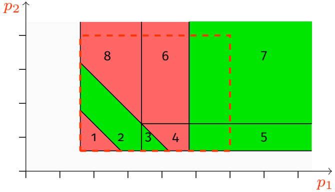

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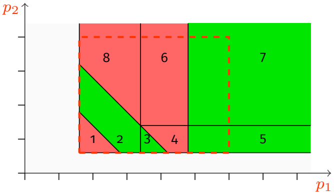

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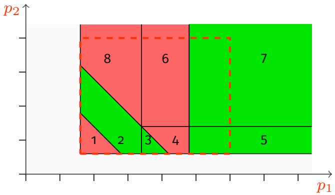

- Principle: “many small analyses rather than one big analysis” $\rightsquigarrow$ memory gain
- Unexpected: time gain in several cases too!

Case study	Clocks	Points	EFsynth	BC	PRPC
toy	2	2 601	0.401	∞	0.078
Sched1	13	6 561	∞	∞	1 595
Sched2.50.0	6	3 321	9.25	990	14.55
Sched2.50.2	6	3 321	662	∞	213
Sched2.100.0	6	972 971	21.4	2 093	116
Sched2.100.2	6	972 971	3 757	∞	4 557
Sched5	21	1 681	352	∞	∞
SPSMALL	11	3 082	7.49	587	118

BC: former algorithm **[André and Fribourg, 2010]**

Towards distributed parameter synthesis

- Point-based algorithms (that iterate on parameter valuations) can obviously be distributed
  - Distribution over a cluster: many computers with their own memory (communication through a network)

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  - Most efficient: dynamic domain decomposition (25 times faster on 128 nodes)

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Nguyễn Hoàng Gia's PhD thesis

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- Application to PRPC

Case study	Clocks	Points	EFsynth	BC	PRPC	PRPC distr(12)
toy	2	2 601	0.401	∞	0.078	0.050
Sched1	13	6 561	∞	∞	1 595	219
Sched2.50.0	6	3 321	9.25	990	14.55	4.77
Sched2.50.2	6	3 321	662	∞	213	84
Sched2.100.0	6	972 971	21.4	2 093	116	10.1
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Outline

Compositional verification of timed systems

Learning an unknown timed system via interactions with a teacher

- Membership queries
- Candidate queries

Extension TL^* of the L^* algorithm [Angluin, 1987]

- Using a subclass of timed automata [Alur et al., 1999]
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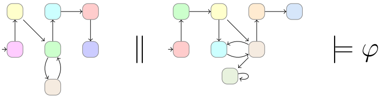
Use TL* to learn an abstraction of a component (assume-guarantee reasoning)



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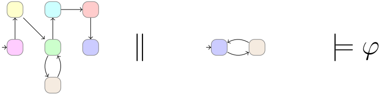

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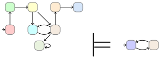

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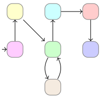
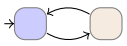
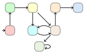
 $\parallel$  $\models \varphi$

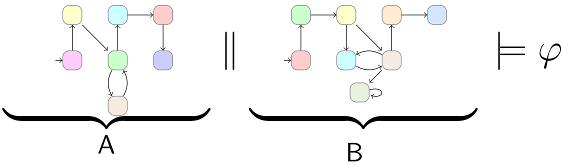
with  $\models$ 

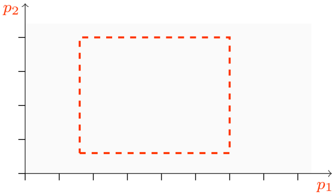
- Membership and candidate queries are performed by model checking
- Much faster than monolithic verification **[Lin, André et al., TSE 2014]**

Compositional parameter synthesis

[André and Lin, FORTE'17]

Given a parametric component A and a non-parametric component B





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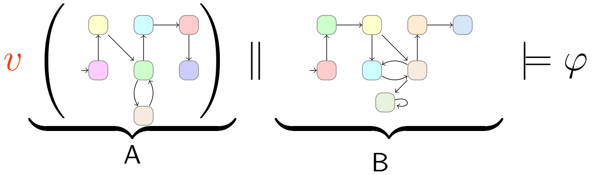

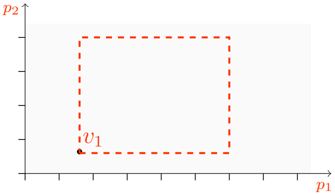

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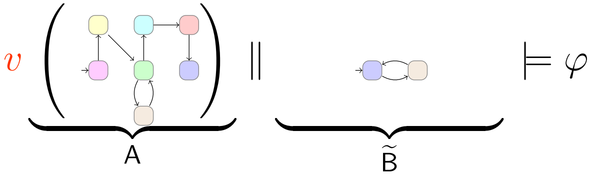

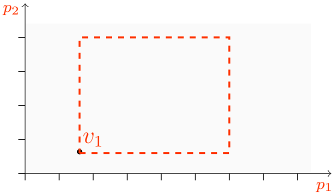

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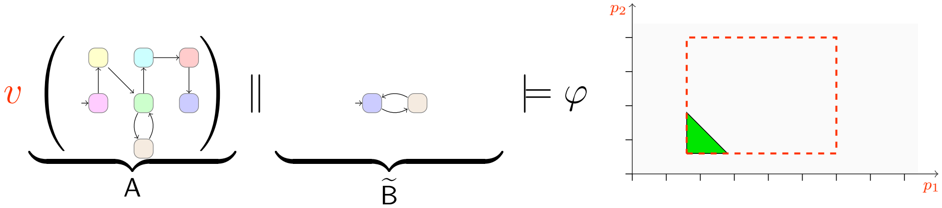

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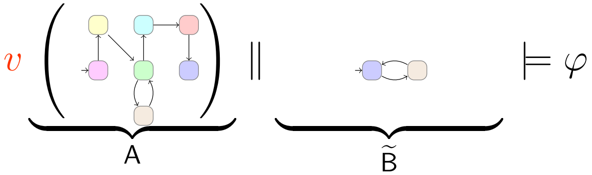

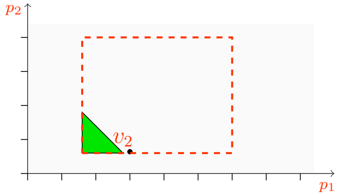

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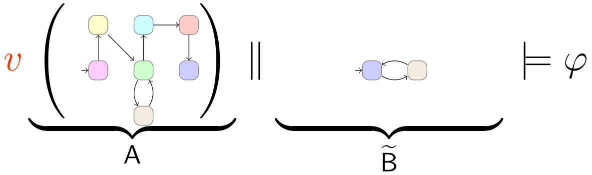

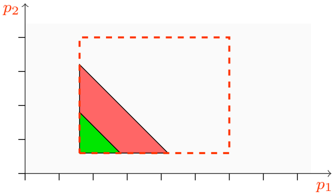

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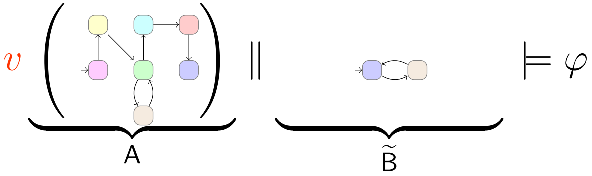
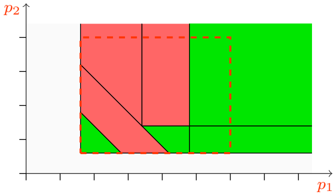




Compositional parameter synthesis: experiments

Toolkit made of IMITATOR and CV, interfaced by a Python script

Case study	$\#\mathcal{A}$	$\#X$	$\#P$	Spec	EFsynth	CompSynth			
						#abs	#c.-ex.	learning	total
FMS-1	6	18	2	1	0.299	1	1	0.074	0.136
				2	0.010	0	1	0.038	0.046
				3	0.282	1	0	0.090	0.242
FMS-2	11	37	2	1	∞	1	1	84.2	88.9
				2	∞	1	0	81.4	85.2
				3	0.051	0	2	1.10	2.44
				4	0.062	0	1	1.42	1.53
				5	∞	1	0	31.4	40.8
				6	∞	1	0	37.2	42.4
AIP	11	46	2	1	0.551	0	1	0.086	0.114
				2	2.11	0	1	1.22	1.25
				3	3.91	0	1	8.50	8.54
				4	0.235	1	1	8.39	8.42
				5	∞	1	0	0.394	0.871
				6	∞	1	0	5.32	9.58
				7	∞	1	0	1.76	3.19
				8	∞	1	0	1.13	4.35
				9	∞	1	1	0.762	1.84
				10	0.022	0	1	0.072	0.094
Fischer-3	5	12	2		2.76	0	1	-	∞
Fischer-4	6	16	2		∞	0	1	-	∞

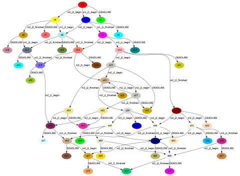
Works well when loosely synchronized and loosely timed

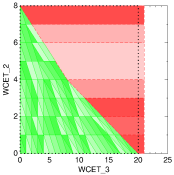
Outline

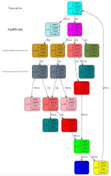
IMITATOR

- A tool for modeling and verifying timed concurrent systems with unknown constants modeled with parametric timed automata
  - Communication through (strong) broadcast synchronization
  - Rational-valued shared discrete variables
  - Stopwatches, to model schedulability problems with preemption

- Synthesis algorithms
  - (non-Zeno) parametric model checking (using a subset of TCTL)
  - Language and trace preservation, and robustness analysis
  - Parametric deadlock-freeness checking







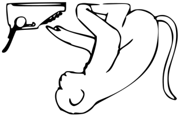
IMITATOR

Under continuous development since 2008 [André et al., FM'12]

A library of benchmarks

- Communication protocols
- Schedulability problems
- Asynchronous circuits
- ...and more

Free and open source software: Available under the GNU-GPL license



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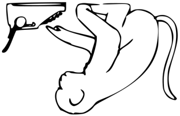

Try it!

www.imitator.fr

Some success stories

- Modeled and verified an asynchronous memory circuit by ST-Microelectronics
  - Project ANR Valmem
- Parametric schedulability analysis of a prospective architecture for the flight control system of the next generation of spacecrafts designed at ASTRIUM Space Transportation [Fribourg et al., 2012]
- Verification of software product lines [Luthmann et al., 2017]
- Formal timing analysis of music scores [Fanchon and Jacquemard, 2013]
- Solution to a challenge related to a distributed video processing system by Thales

Perspectives

- Beyond distributed verification
  - Multicore verification
  - Swarm verification
- Combine non-parametric and parametric analyses
  - Machine learning
    - "Learn" a constraint by repeated call to a non-parametric model checker (much faster)
    - Preliminary works in **[Li, Sun, Gao, André, ICFEM'17]**

Outline

Context: schedulability analysis

Real-time system:

- Set of tasks (with a period, a WCET and a deadline)
- One processor (uniprocessor) or more (multiprocessor)
- Scheduling policies: fixed priority (FPS), earliest deadline first (EDF)...

Definition (Schedulability analysis)

Given a real-time system and a scheduling policy, certify that no deadline miss will ever occur

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In general, schedulability analysis is hard

Outline

Schedulability analysis with parametric model checking

Goal: parametric schedulability analysis

Given a real-time system and a scheduling policy, synthesize valuations (deadlines, periods…) such that the system is schedulable.

Modeling a real-time system with PTAs

- Each task or chain of task: one PTA
- Each scheduler: one PTA
- Use stopwatches to model preemption

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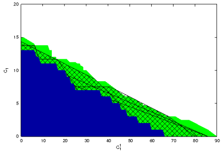
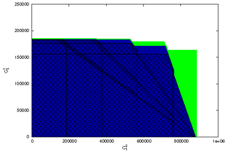
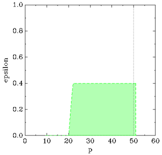
Comparison with analytical methods **[Sun, Soulat, Lipari, André, Fribourg, FTSCS'13]**

- Much better in terms of completeness
- And can evaluate robustness







Romain Soulat's PhD thesis

Outline

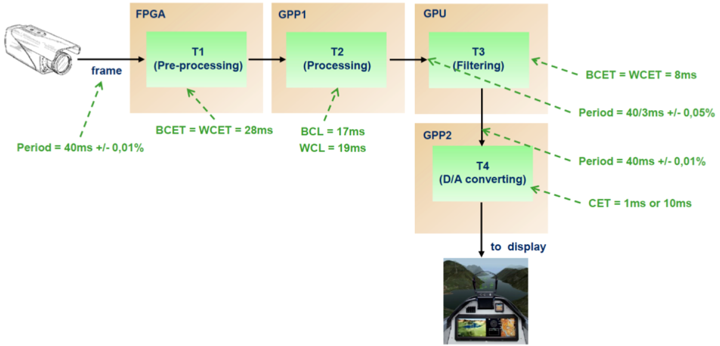
The Thales challenge (1/2)

"FMTV challenge" by Thales proposed during the WATERS 2014 workshop

Solutions presented at WATERS 2015

System: an unmanned aerial video system

- Architecture: 4 processors, 4 tasks, 2 buffers
- ...with uncertain periods
  - Period constant but with a small uncertainty (typically 0.01 %)
  - Not a jitter!



The Thales challenge (2/2)

Goal

Compute the end-to-end BCET and WCET times for a buffer size of 1 and 3

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Compute the end-to-end BCET and WCET times for a buffer size of 1 and 3

Challenging!

- Distributed system (multiprocessor)
- Buffers
- Dependencies between tasks
- Uncertain periods

The Thales challenge (2/2)

Goal

Compute the end-to-end BCET and WCET times for a buffer size of 1 and 3

Challenging!

- Distributed system (multiprocessor)
- Buffers
- Dependencies between tasks
- Uncertain periods

A typical parameter synthesis problem

- The end-to-end time can be set as a parameter… to be synthesized
- The uncertain period is typically a parameter (with some constraint, e. g., $P1 \in [40 - 0.004, 40 + 0.004]$)

Methodology

1. Propose a PTA model with parameters for uncertain periods and the end-to-end time

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Note: not eliminating parameters allows one to know for which values of the periods the best / worst case execution times are obtained.

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6. Exhibit the minimum and the maximum

Note: not eliminating parameters allows one to know for which values of the periods the best / worst case execution times are obtained.

Results obtained by IMITATOR

E2E latency results for the two buffer sizes

Buffer size $\rightarrow$	1	3
min E2E	63 ms	63 ms
max E2E	145.008 ms	225.016 ms

Results obtained using IMITATOR in a few seconds

[André, Lipari, Sun, WATERS'15]

Perspectives

- Better scalability
  - Design dedicated synthesis algorithms
  - Compositional synthesis
- Better integration
  - Parametric task automata **[André, FMICS'17]**
  - Support of existing industrial formalisms in IMITATOR

Outline

Summary of contributions

- Theory
  - New decidable subclasses of parametric timed automata
- Efficient synthesis algorithms
  - Implementation in IMITATOR
- Application to real-time systems
  - Application to industrial case studies

Also (not presented)

- Robustness of timed concurrent systems
- Formal specification of (timed) concurrent systems
  - **Mahdi Benmoussa's PhD thesis**

General perspectives

- Timing parameters in more complex settings
  - Probabilities:
    - preliminary works in **[André and Delahaye, TIME'16]**
  - Hybrid systems
- More parameters
  - Probabilistic parameters
  - Discrete parameters (networks of identical processes)
- Beyond parameter synthesis: controller synthesis
  - More abstraction
  - More uncertainty
- More applications
  - Real-time systems
  - Biological systems
  - Cybersecurity

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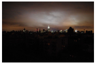
Summary of publications

Summary of publications

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total
Books						1						1
Proceedings							2	1				3
International journals		1				2	2		2	1	1	9
International conferences	1	3	2	2	6	11	8	7	8	7	2	57
Other publications		2	2		2	1	2	1				10
Total	1	6	4	2	8	15	14	9	10	8	3	80

Additional explanation

Explanation for the 4 pictures in the beginning



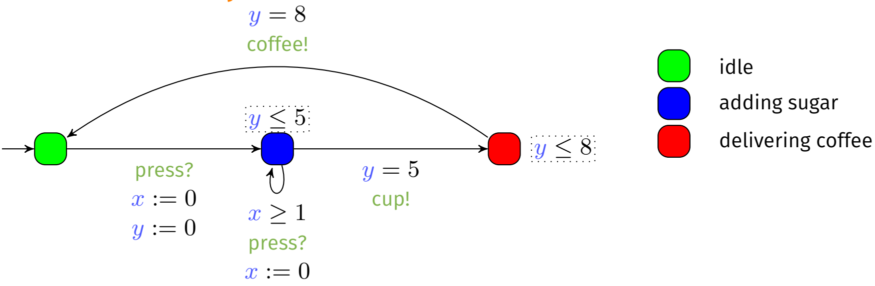
Allusion to the Northeast blackout (USA, 2003)
Computer bug
Consequences: 11 fatalities, huge cost
(Picture actually from the Sandy Hurricane, 2012)

Allusion to the sinking of the Sleipner A offshore platform (Norway, 1991)
No fatalities
Computer bug: inaccurate finite element analysis modeling
(Picture actually from the Deepwater Horizon Offshore Drilling Platform)

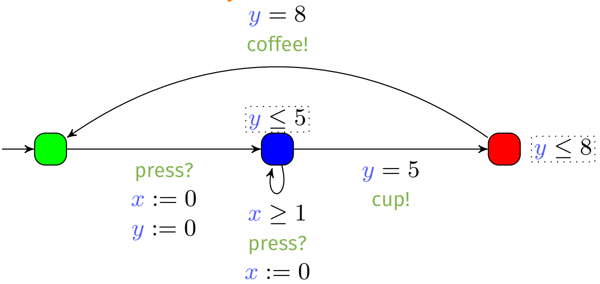
Allusion to the MIM-104 Patriot Missile Failure (Iraq, 1991)
28 fatalities, hundreds of injured
Computer bug: software error (clock drift)
(Picture of an actual MIM-104 Patriot Missile, though not the one of 1991)

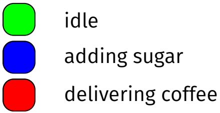
Varying the coffee machine

The most critical system: the coffee machine

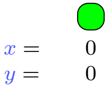


The most critical system: the coffee machine

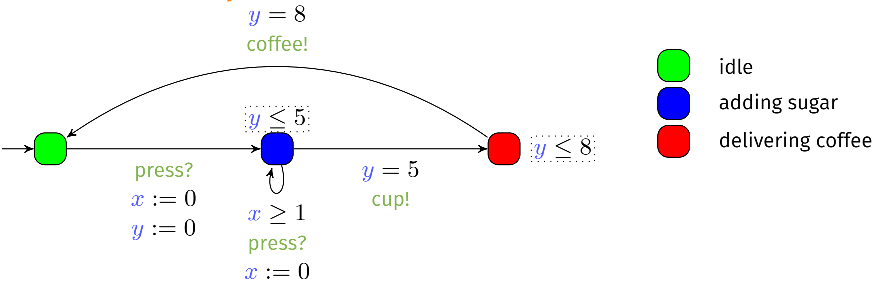




- Example of concrete run for the coffee machine
  - Coffee with no sugar



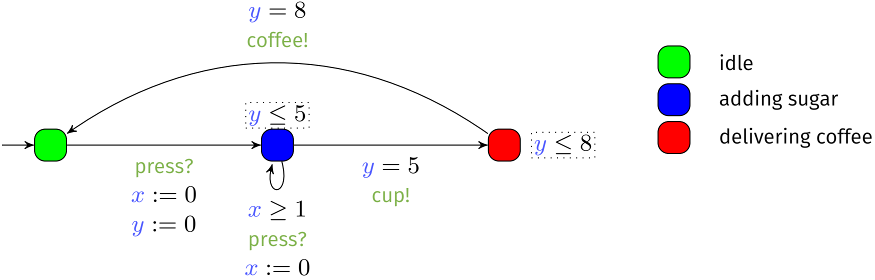
The most critical system: the coffee machine



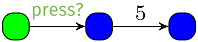
- Example of concrete run for the coffee machine
  - Coffee with no sugar

$x =$	0	0
$y =$	0	0

The most critical system: the coffee machine

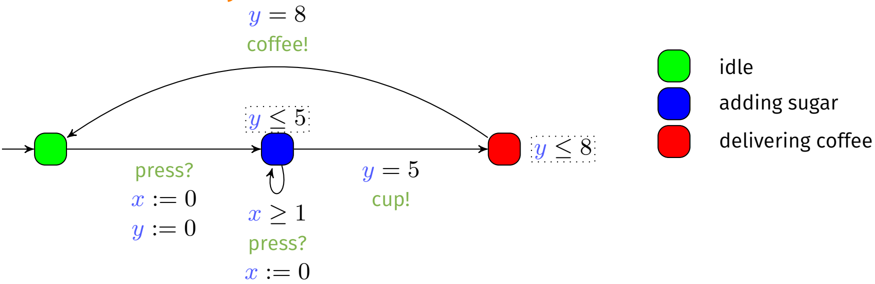


- Example of concrete run for the coffee machine
  - Coffee with no sugar



$x =$	0	0	5
$y =$	0	0	5

The most critical system: the coffee machine



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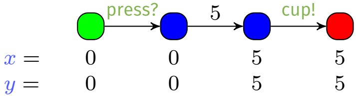
  - Coffee with no sugar



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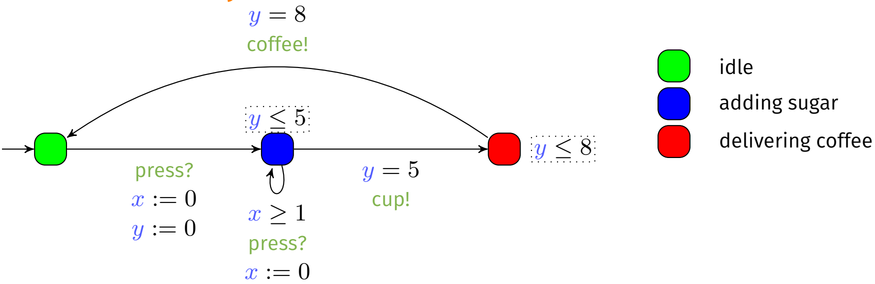

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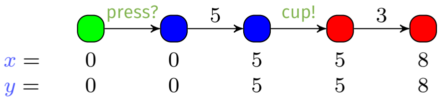

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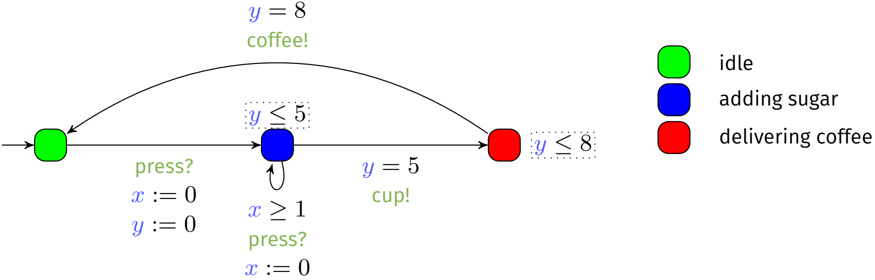

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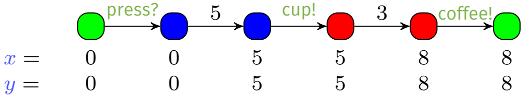

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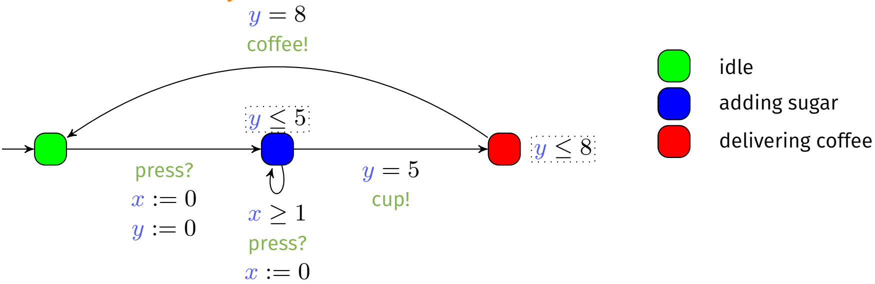

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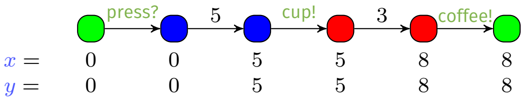
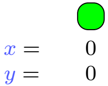


  - Coffee with 2 doses of sugar



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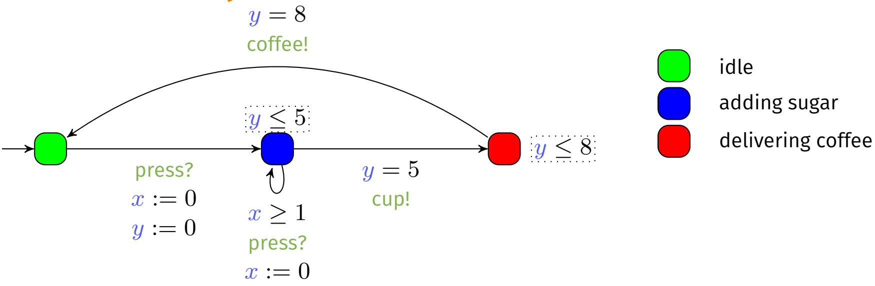

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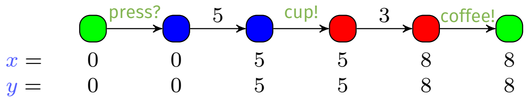

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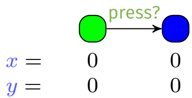

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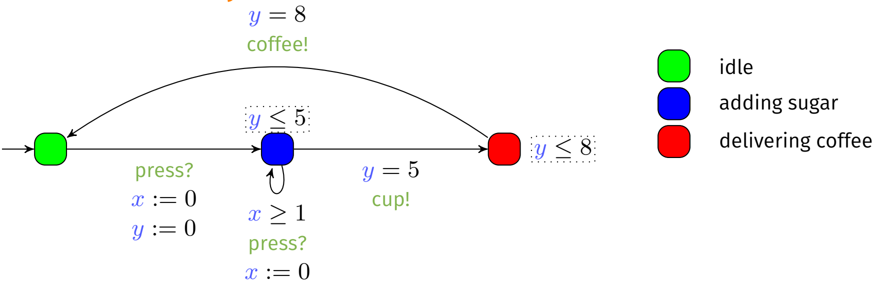

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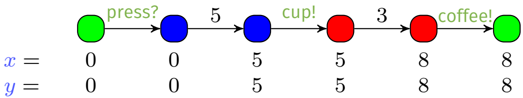

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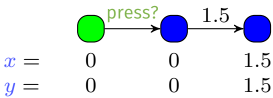

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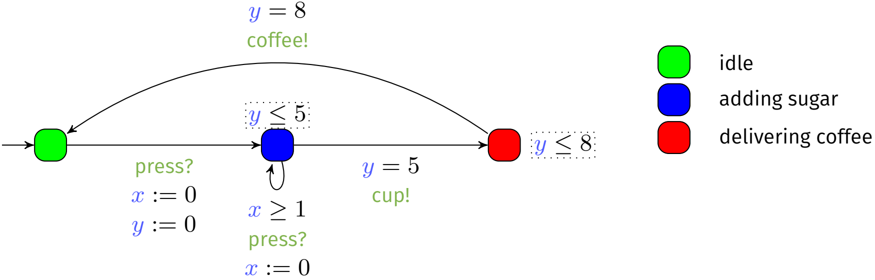

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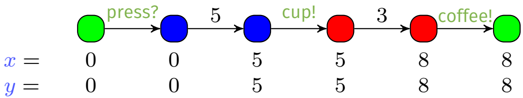
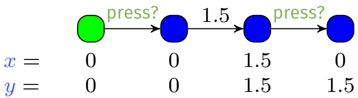


  - Coffee with 2 doses of sugar



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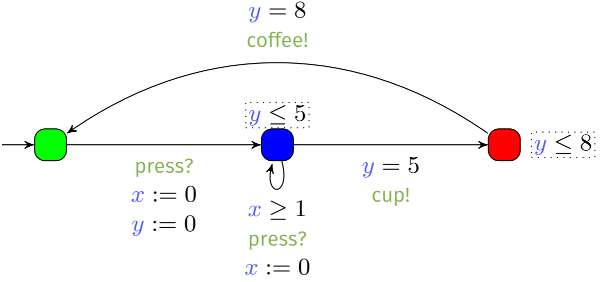

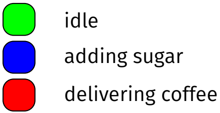

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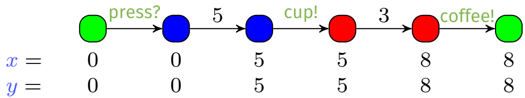
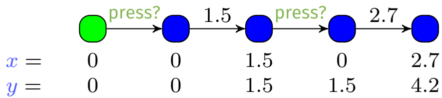


  - Coffee with 2 doses of sugar



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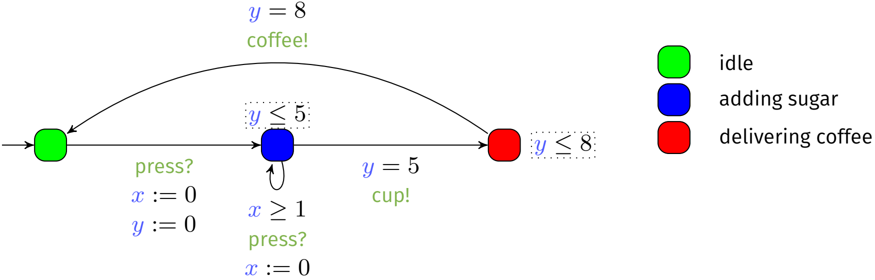


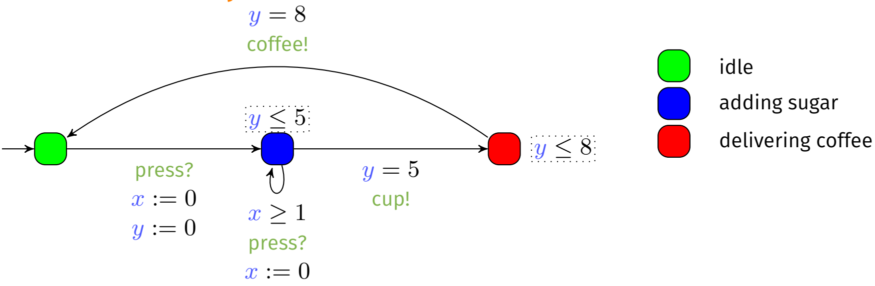
- Example of concrete run for the coffee machine
  - Coffee with no sugar

$x =$	0	0	5	5	8	8
$y =$	0	0	5	5	8	8

  - Coffee with 2 doses of sugar

$x =$	0	0	1.5	0	2.7	0
$y =$	0	0	1.5	1.5	4.2	4.2

The most critical system: the coffee machine



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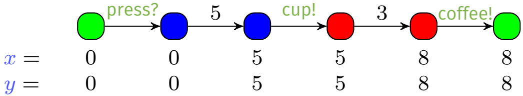
  - Coffee with no sugar



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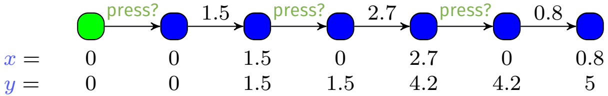

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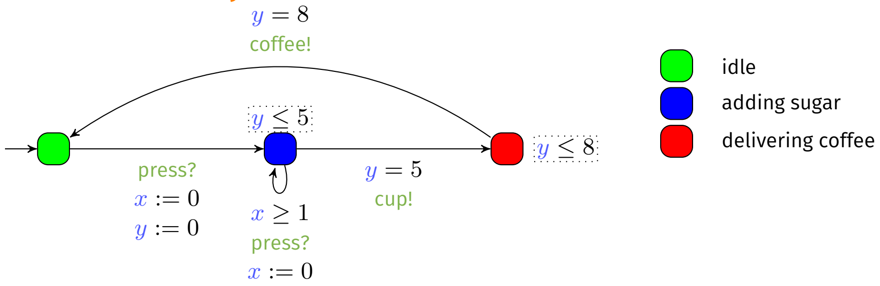

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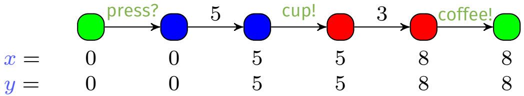

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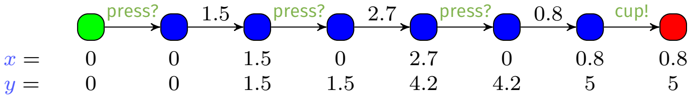

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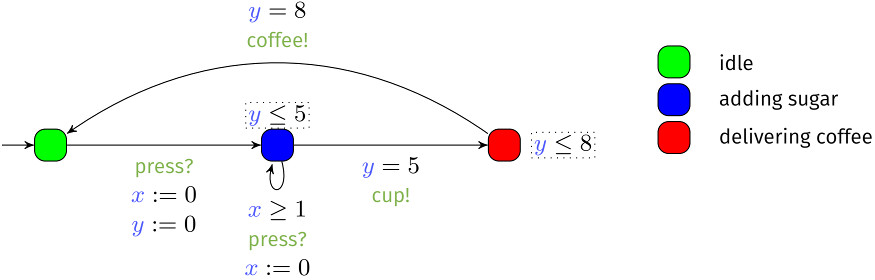

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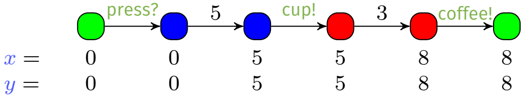
  - Coffee with no sugar



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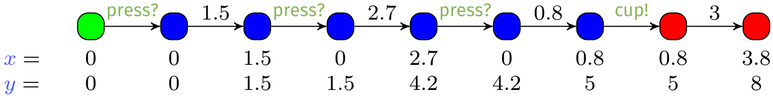
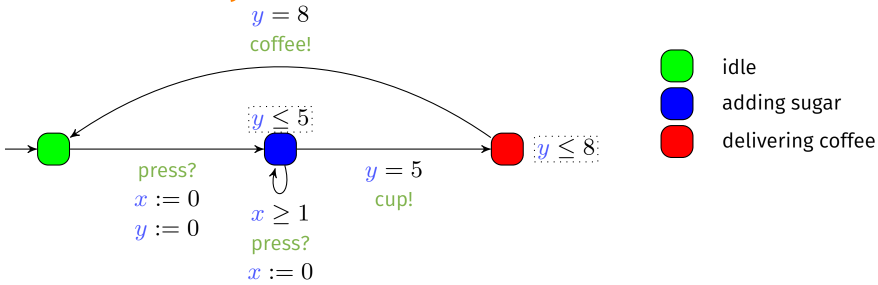


The most critical system: the coffee machine



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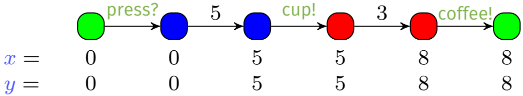

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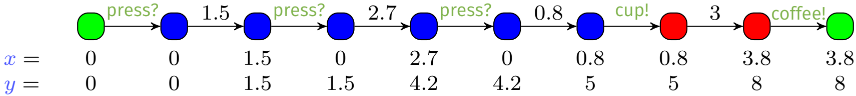
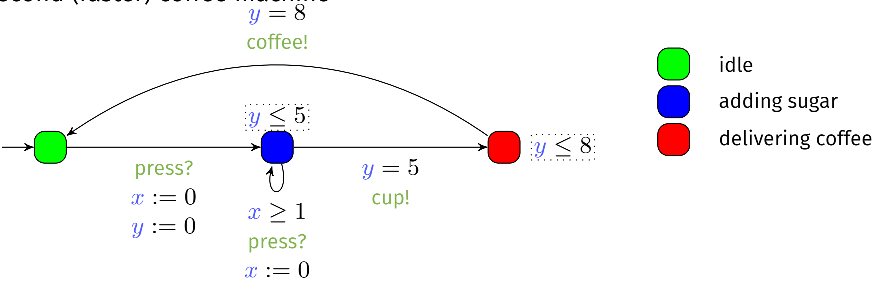


The most critical system: the coffee machine (2/2)

A second (faster) coffee machine



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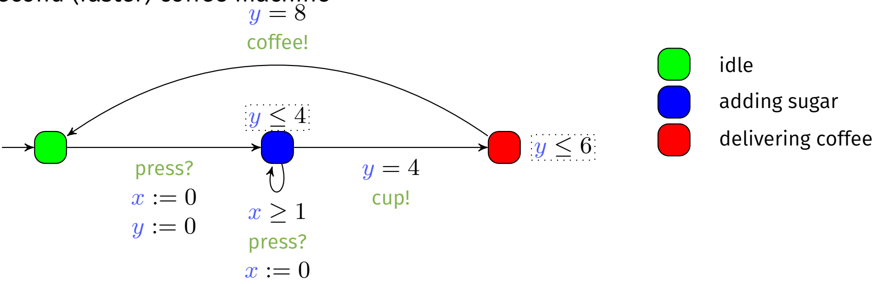

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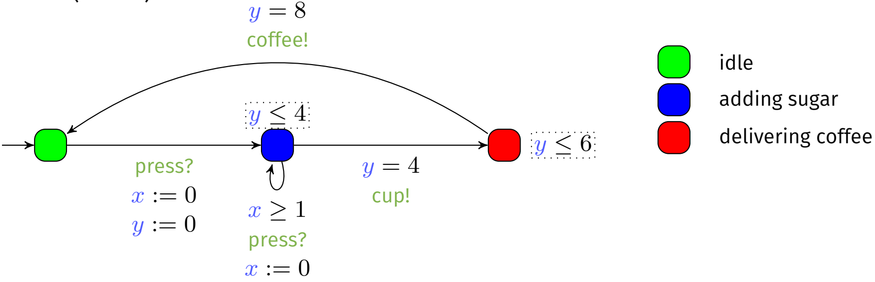

- Example of concrete run for the coffee machine
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$x =$ 0

$y =$ 0

The most critical system: the coffee machine (2/2)

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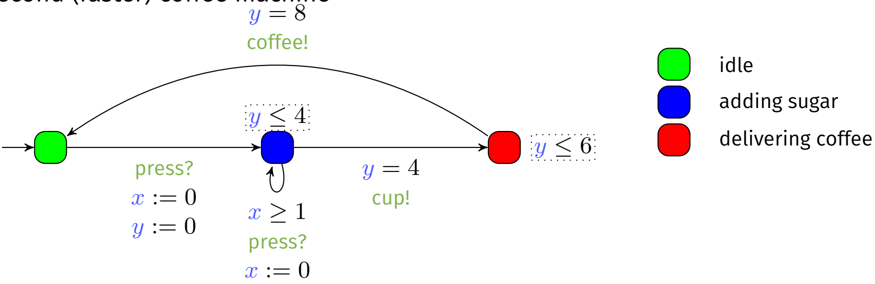

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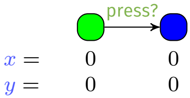

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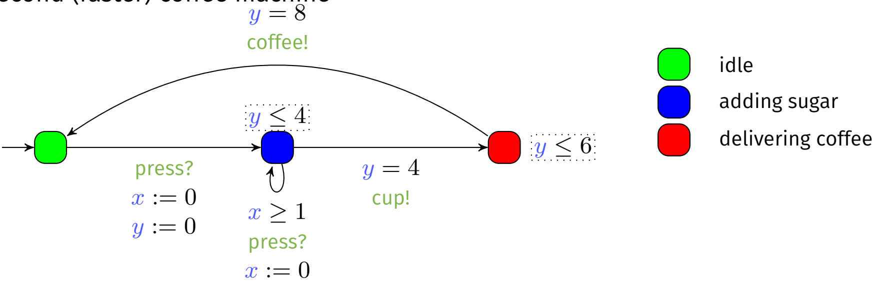

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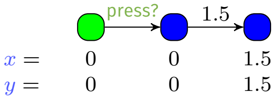

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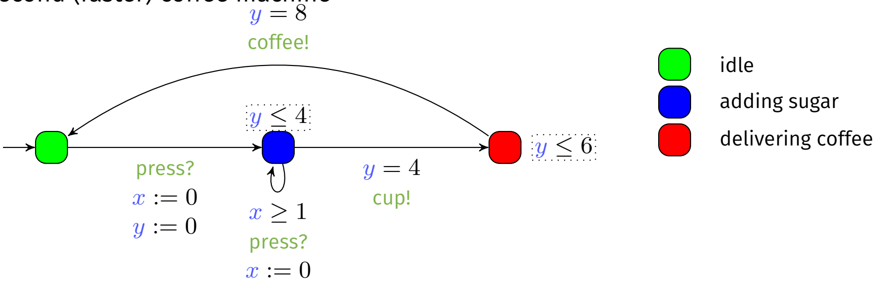

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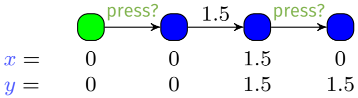

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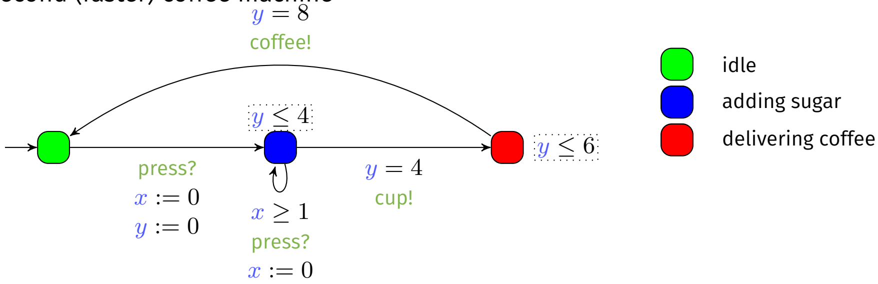

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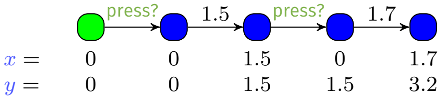

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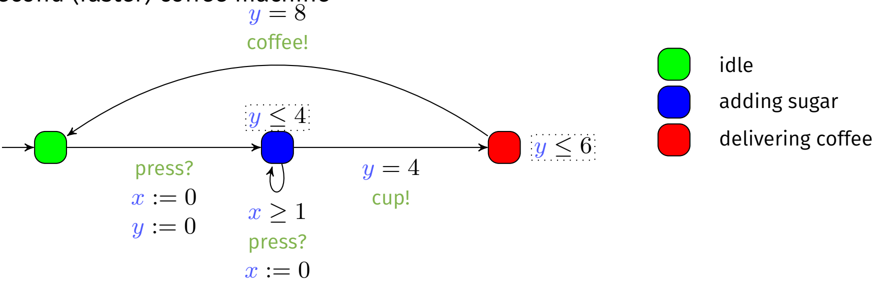

- Example of concrete run for the coffee machine
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$x =$	0	0	1.5	0	1.7	0
$y =$	0	0	1.5	1.5	3.2	3.2

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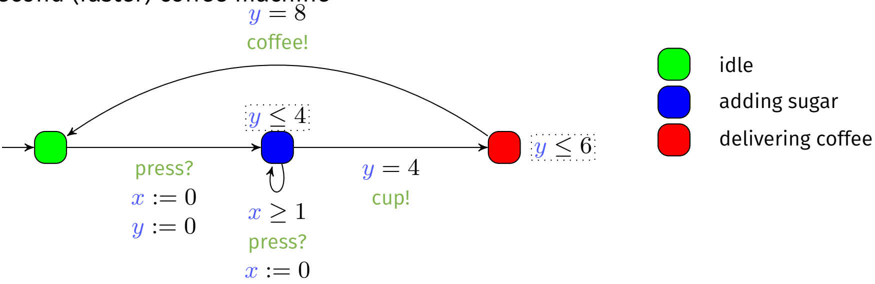

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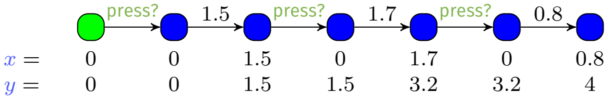

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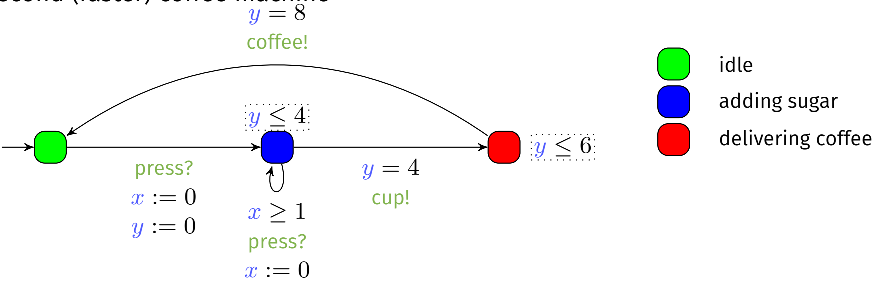

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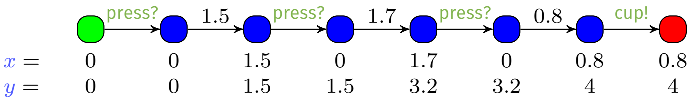

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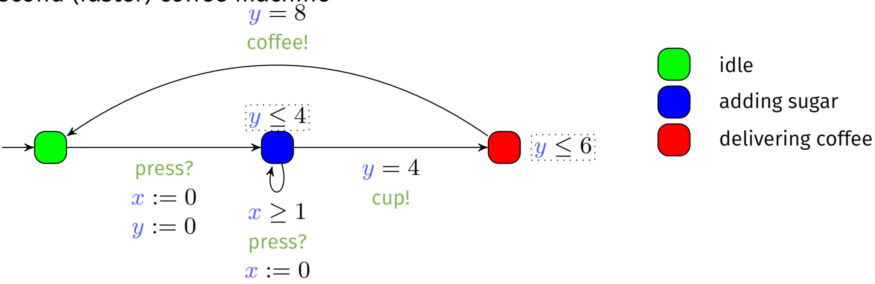

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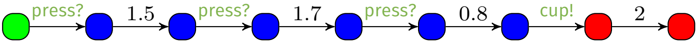

$x =$	0	0	1.5	0	1.7	0	0.8	0.8	2.8
$y =$	0	0	1.5	1.5	3.2	3.2	4	4	6

Decidability of PTAs

Surveying EF-emptiness for PTAs

$\mathbb{T}$	$\mathbb{P}$	**Guards**	**Invariants**	**P-clocks**	**NP-clocks**	**Params**	**Decidability**	**Main ref.**
$\mathbb{N}$	$\mathbb{N}$	$x \bowtie p \mid d$		1	0	fixed	(at most) PTIME	[Miller, 2000] (consequence)
$\mathbb{N}$	$\mathbb{N}$	$x \bowtie p \mid d$		1	0	any	(at most) NP-complete	[Miller, 2000] (consequence)
$\mathbb{N}$	$\mathbb{N}$	$x \leq\geq p \mid d^+$		1	any	any	NEXPTIME-complete	[Bundala and Ouaknine, 2014]
$\mathbb{N}$	$\mathbb{N}$	$x \bowtie p \mid d$	$x \preceq p \mid d^+$	1	any	any	(at most) NEXPTIME	[Beneš et al., 2015] (consequence)
$\mathbb{N}$	$\mathbb{N}$	$x \leq\geq p \mid d^+$		2	any	1	PSPACE$^{\text{NEXP}}$-hard	[Bundala and Ouaknine, 2014]
$\mathbb{N}$	$\mathbb{N}$	any		2	any	> 1	open	
$\mathbb{N}$	$\mathbb{N}$	$x \bowtie p \mid d$	None	3	0	1	undecidable	[Beneš et al., 2015]
$\mathbb{N}$	$\mathbb{N}$	$x = p \mid d$	None	3	0	6	undecidable	[Alur et al., 1993]
$\mathbb{N}$	$\mathbb{N}$	$x <> p$		any	any	any	open	
$\mathbb{N}$	$\mathbb{N}$ bounded	$x \bowtie plt$	$x \preceq plt$	any	any	any	(at most) PSPACE-complete	[Jovanović et al., 2015] (consequence)
$\mathbb{R}^+$	$\mathbb{N}$	$x \bowtie p \mid d$		1	0	fixed	(at most) PTIME	[Miller, 2000] (consequence)
$\mathbb{R}^+$	$\mathbb{N}$	$x \bowtie p \mid d$		1	0	any	(at most) NP-complete	[Miller, 2000] (consequence)
$\mathbb{R}^+$	$\mathbb{N}$	$x \bowtie p \mid d$	$x \preceq p \mid d^+$	1	any	any	NEXPTIME	[Beneš et al., 2015]
$\mathbb{R}^+$	$\mathbb{N}$	any		2	any	any	open	
$\mathbb{R}^+$	$\mathbb{N}$	$x \bowtie p \mid d$	None	3	0	1	undecidable	[Beneš et al., 2015]
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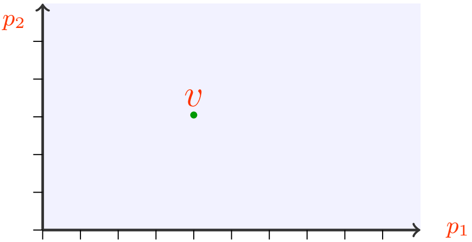
$\mathbb{R}^+$	$\mathbb{N}$	$x <> p$		any	any	any	open	
$\mathbb{R}^+$	$\mathbb{N}$ bounded	$x \bowtie plt$	$x \preceq plt$	any	any	any	PSPACE-complete	[Jovanović et al., 2015]
$\mathbb{R}^+$	$\mathbb{Q}^+$	$x \bowtie p \mid d$		1	0	fixed	PTIME	[Miller, 2000]
$\mathbb{R}^+$	$\mathbb{Q}^+$	$x \bowtie p \mid d$		1	0	any	NP-complete	[Miller, 2000]
$\mathbb{R}^+$	$\mathbb{Q}^+$	any		1	1 or 2	any	open	
$\mathbb{R}^+$	$\mathbb{Q}^+[1;2]$	$x \bowtie p \mid d$		1	3	1	undecidable	[Miller, 2000]
$\mathbb{R}^+$	$\mathbb{Q}^+$	any		2	0 or 1	any	open	
$\mathbb{R}^+$	$\mathbb{Q}^+[1;2]$	$x \bowtie p \mid d$		2	2	1	undecidable	[Miller, 2000] (consequence)
$\mathbb{R}^+$	$\mathbb{Q}^+[1;2]$	$x \bowtie p \mid d$		3	0	1	undecidable	[Miller, 2000]
$\mathbb{R}^+$	$\mathbb{R}^+$	$x = p \mid d$	None	3	0	6	undecidable	[Alur et al., 1993]
$\mathbb{R}^+$	$\mathbb{Q}^+$	$x <> p$		< 2	3	2	open	
$\mathbb{R}^+$	$\mathbb{Q}^+$	$x <> p$		2	< 3	2	open	
$\mathbb{R}^+$	$\mathbb{Q}^+$	$x <> p$		2	3	< 2	open	
$\mathbb{Q}^+/\mathbb{R}^+$	$\mathbb{Q}^+/\mathbb{R}^+$	$x <> p$		2	3	2	undecidable	[Doyen, 2007]

PRP in details

Reachability Preservation

Key idea

"If we know a parameter valuation v that reaches (resp. does not reach) 🟥, can we find other valuations around v that reach (resp. do not reach) 🟥?"



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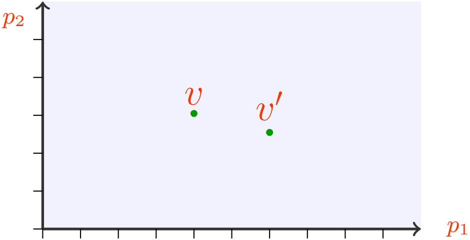

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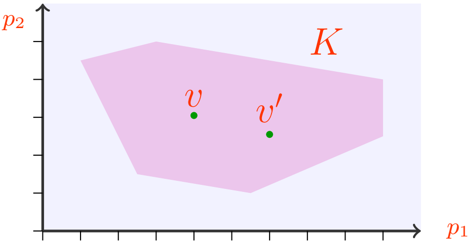

Reachability Preservation: Undecidability

Problem (PREACH-emptiness)

Let $\mathcal{A}$ *be a PTA, and* v *a parameter valuation. Does there exist* $v' \neq v$ *such that* $v'(\mathcal{A})$ *preserves the reachability of* 🟥 *in* $v(\mathcal{A})$*?*

Reachability Preservation: Undecidability

Problem (PREACH-emptiness)

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Theorem ([André, Lipari, Nguyen, Sun, NFM'15])

PREACH-emptiness is undecidable.

Reachability Preservation: Undecidability

Problem (PREACH-emptiness)

Let $\mathcal{A}$ be a PTA, and v a parameter valuation. Does there exist $v' \neq v$ such that $v'(\mathcal{A})$ preserves the reachability of ● *in $v(\mathcal{A})$?*

Theorem ([André, Lipari, Nguyen, Sun, NFM'15])

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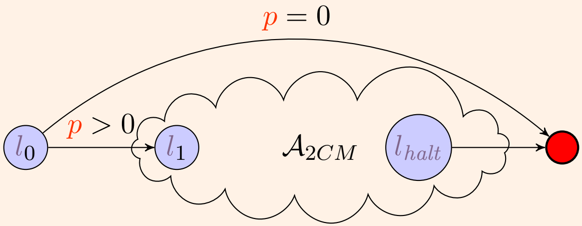
Proof.



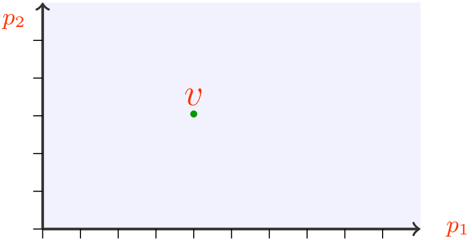
□

PRP: Parametric Reachability Preservation

Input: parameter valuation v

Output: constraint K such that

1. $v \models K$, and
2. $\forall v' \models K$, $v'(\mathcal{A})$ preserves the reachability of ● in $v(\mathcal{A})$



Inspired by EFsynth [Alur et al., 1993, Jovanović et al., 2015] and a variant of IM in [André and Soulat, 2011]

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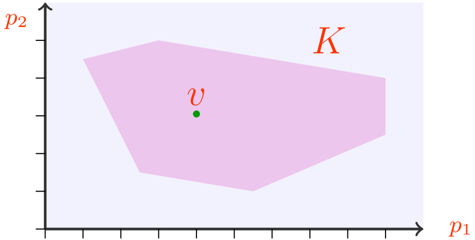

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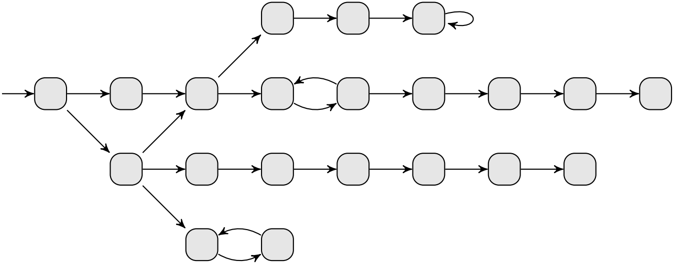
- But do not explore the behaviors not present in $v(\mathcal{A})$!



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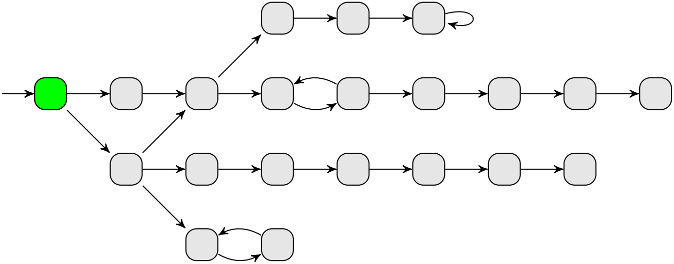

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As long as [red state] is not met…

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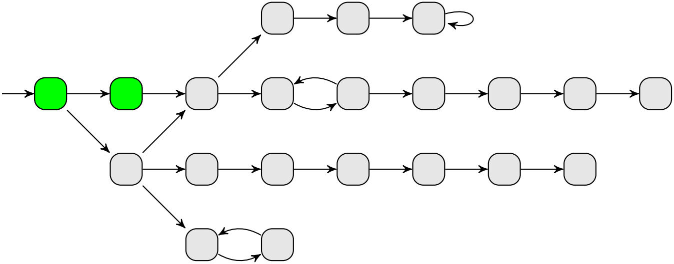

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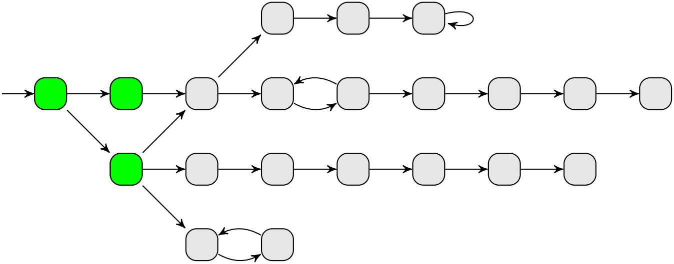

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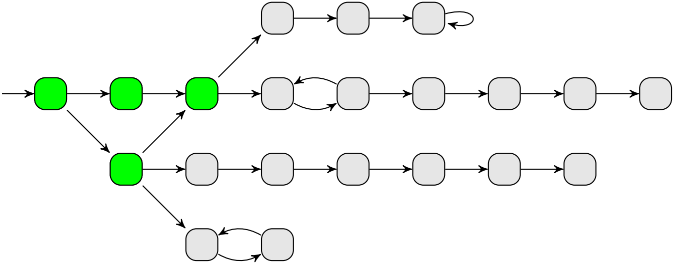

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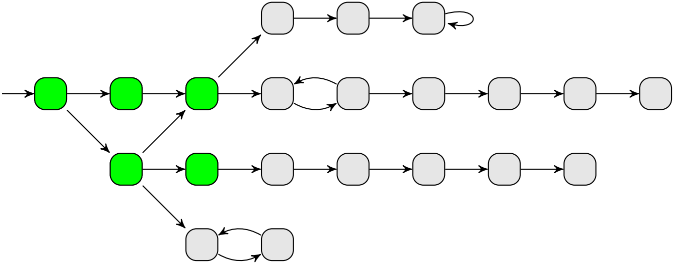

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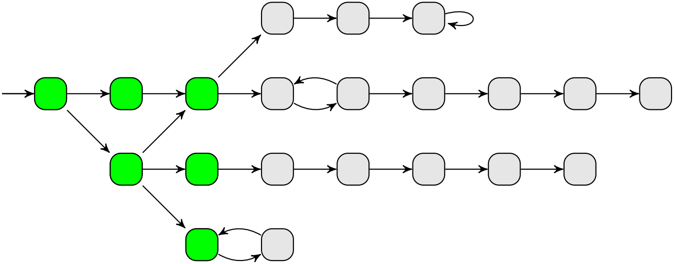

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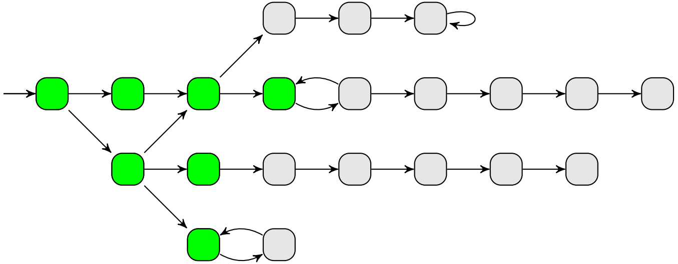

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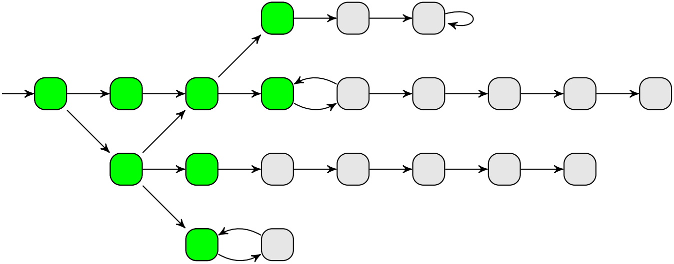

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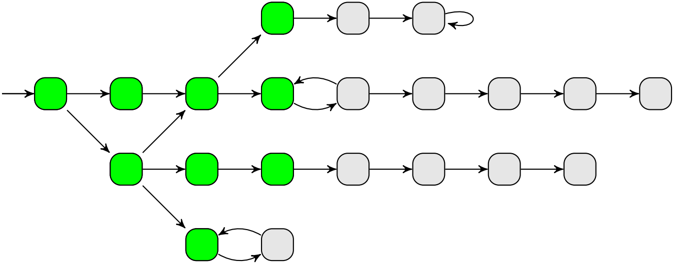

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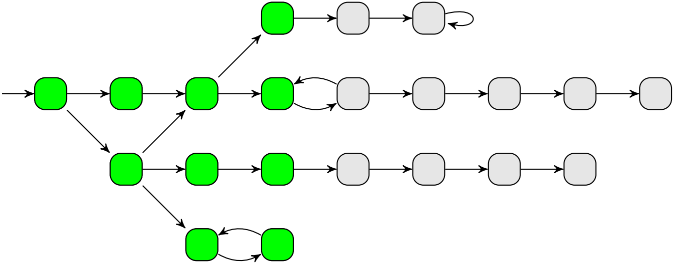

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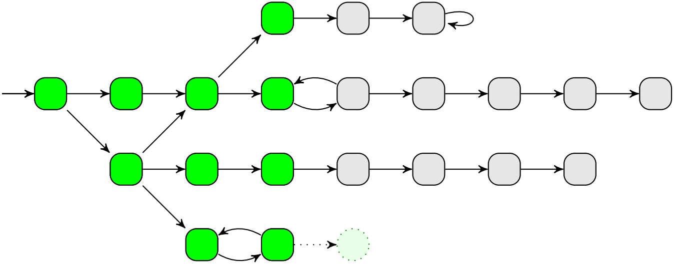

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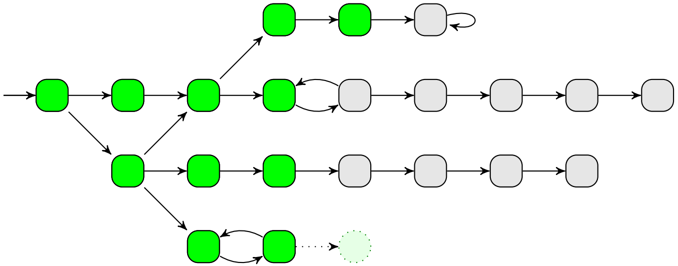

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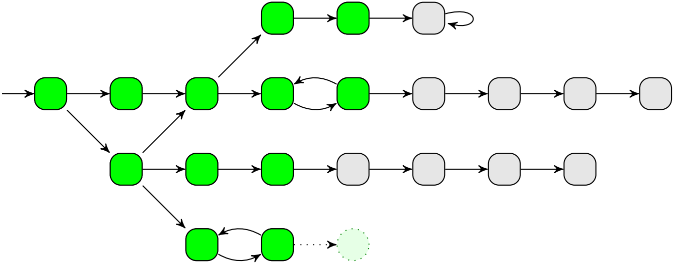

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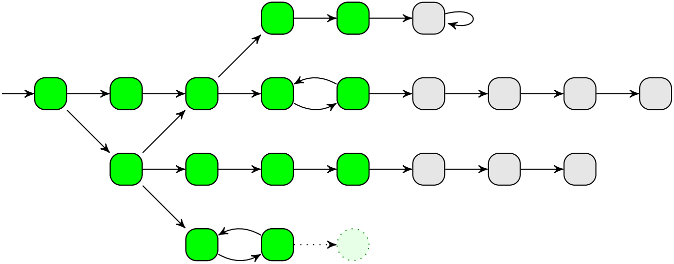

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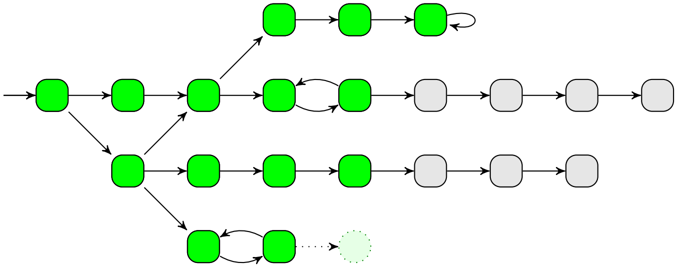

PRP: Case 1

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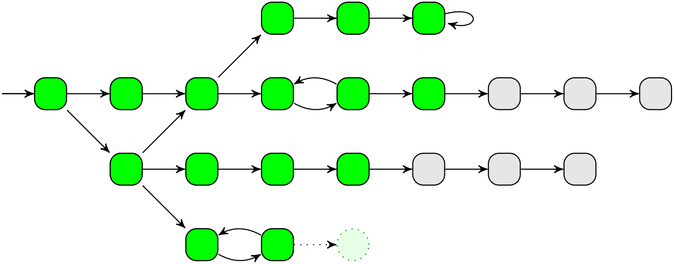

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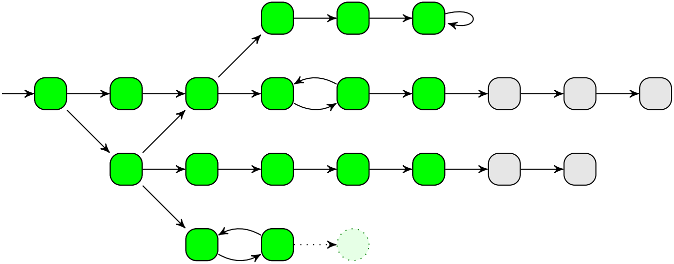

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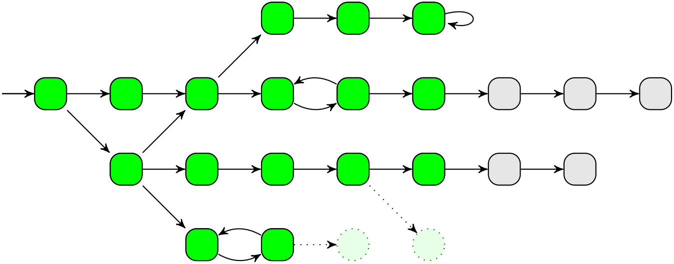

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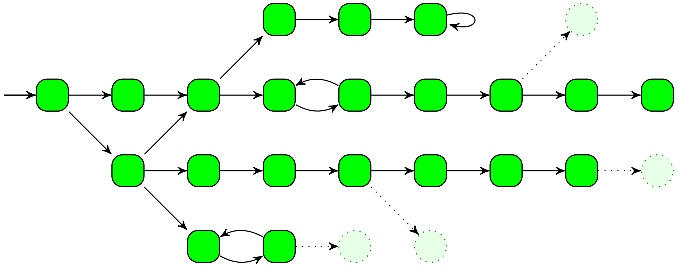

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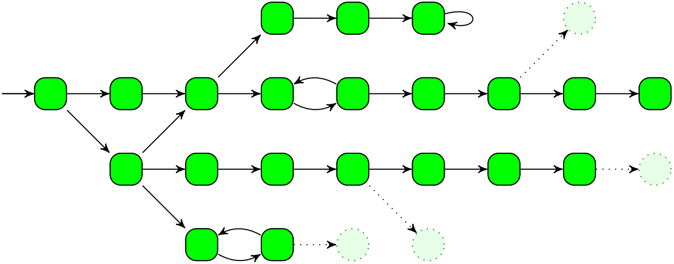

When no successors, and if was never met:

- return $\neg \wedge \cdots \wedge \neg$
- Ensures a subset of the behaviors of $v(\mathcal{A})$, and hence guarantees the unreachability of

PRP: Case 1 (Remark)

Questions

How do we know the possible behaviors of $v(\mathcal{A})$?
How do we know that a symbolic state of $\mathcal{A}$ corresponds to a behavior of $v(\mathcal{A})$?

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But this is not necessary.
In fact, we do not even need to know whether $v(\mathcal{A})$ reaches or not.

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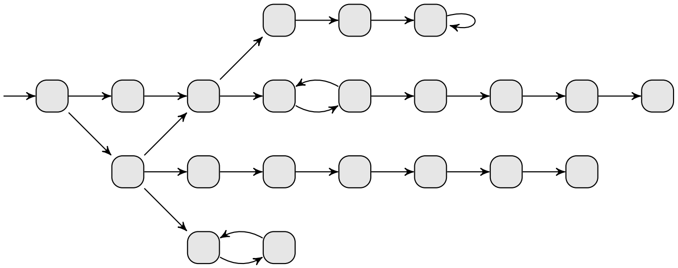
Trick

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

PRP: Case 2

When [red state] is met, switch to an EFsynth-like algorithm…

- But still without exploring the behaviors not present in $v(\mathcal{A})$



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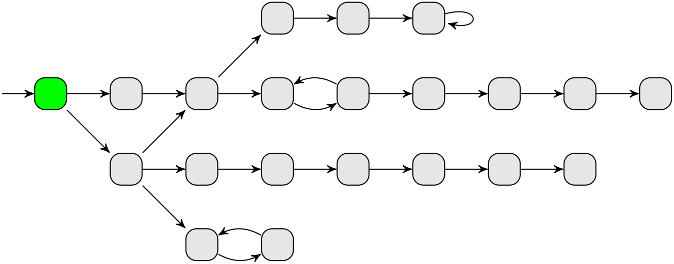

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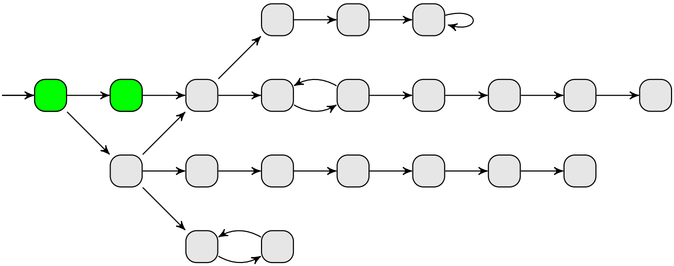

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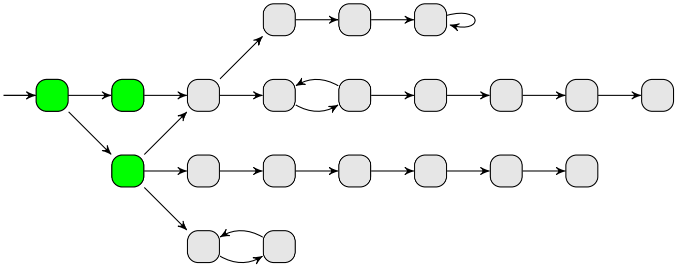

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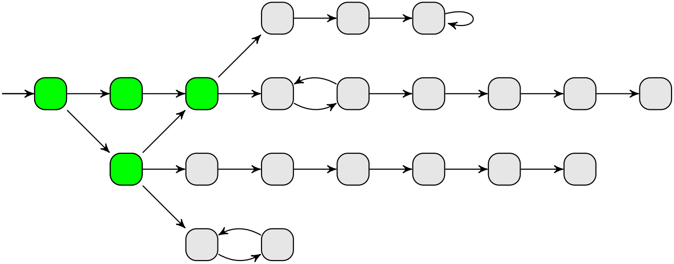

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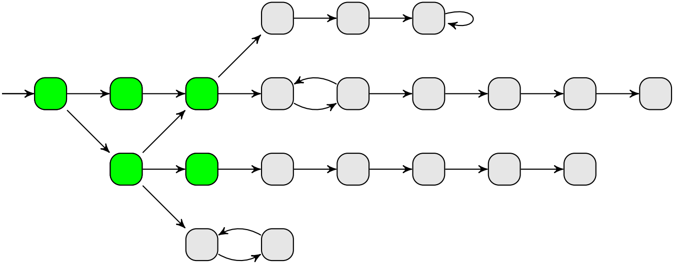

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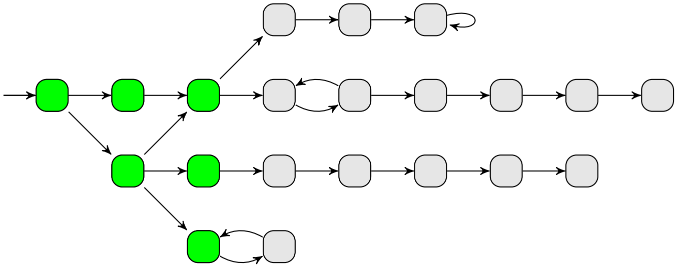

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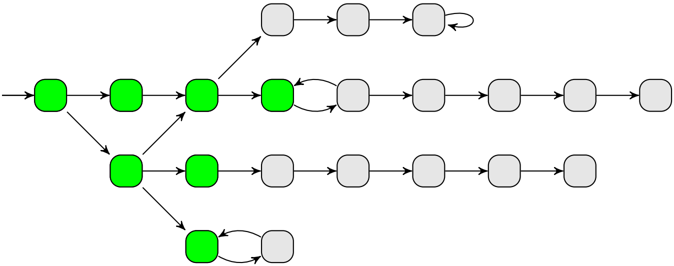

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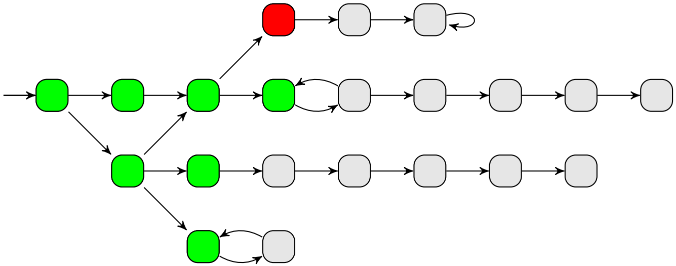

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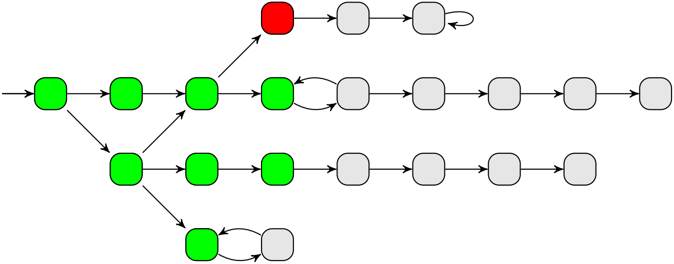

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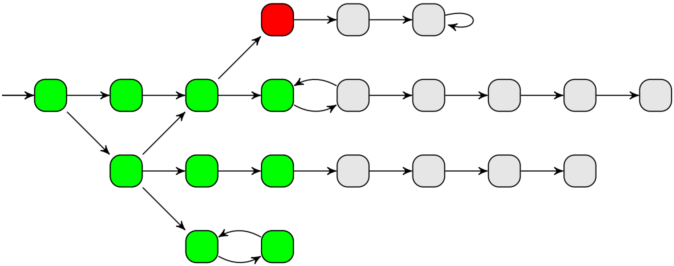

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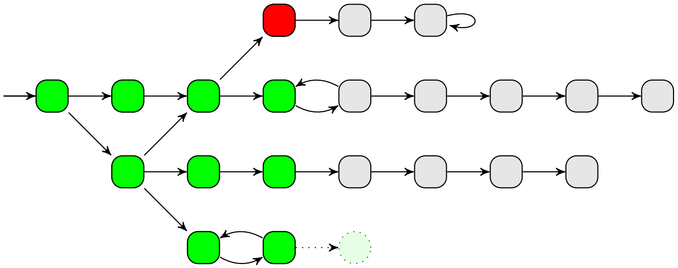

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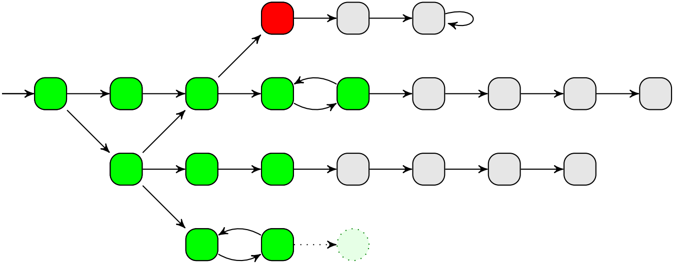

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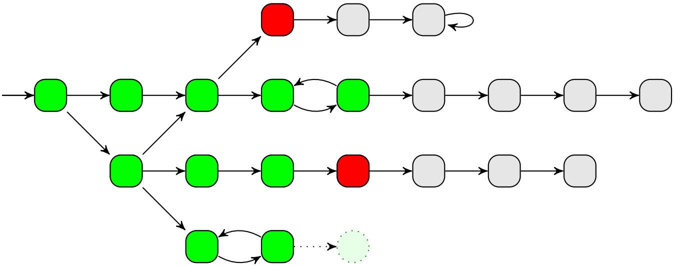

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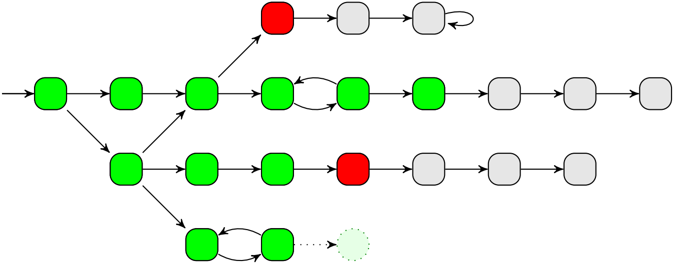

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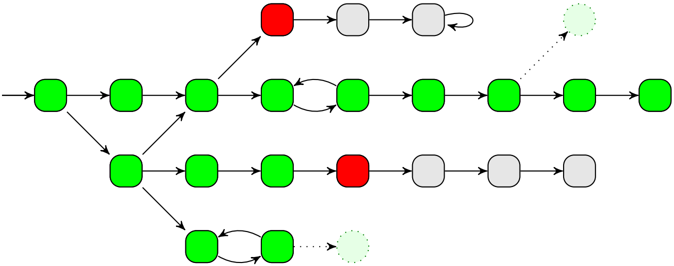

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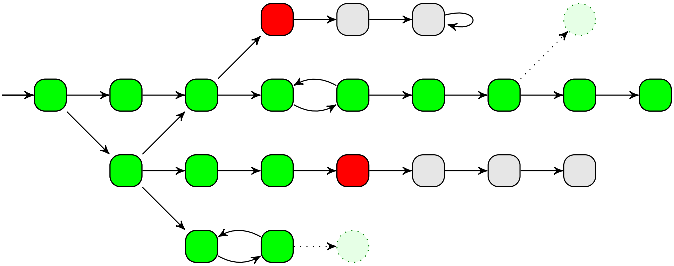

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- Guarantees the reachability of ■

Compositional parameter synthesis

Learning an abstraction: $\mathsf{LearnAbstr}(\mathsf{B}, v(\mathsf{A}), \mathsf{AG}\neg L^{☹})$

Input: $v(\mathsf{A}) \parallel \mathsf{B}$
Output: an abstraction $\widetilde{\mathsf{B}}$ or a counter-example

TL*

TL*: learning algorithm to compute a candidate abstraction $\widetilde{\mathsf{B}}$ of an ERA B
[Lin et al., 2014]

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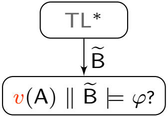

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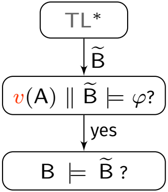

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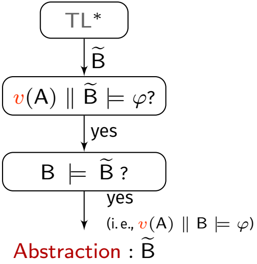

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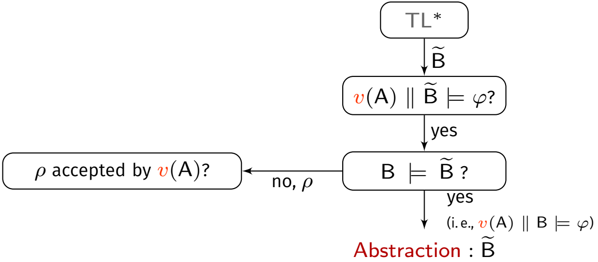

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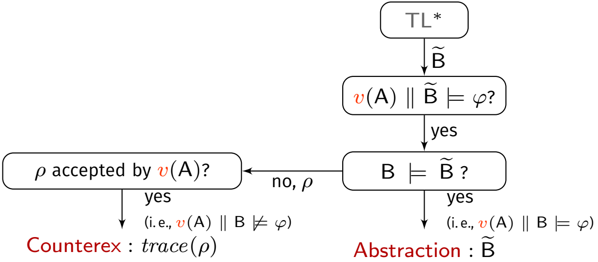

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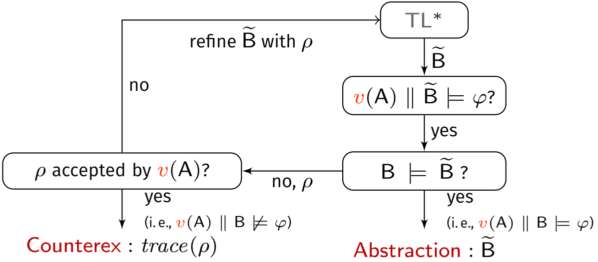

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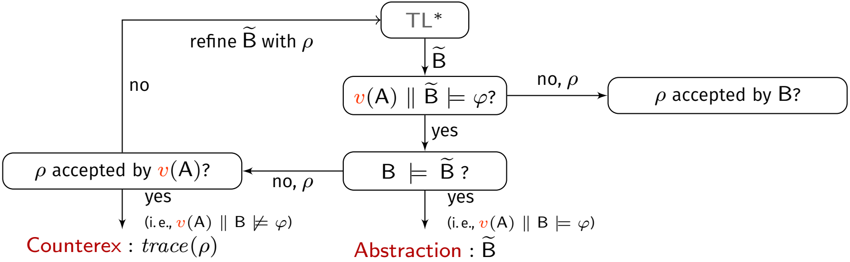

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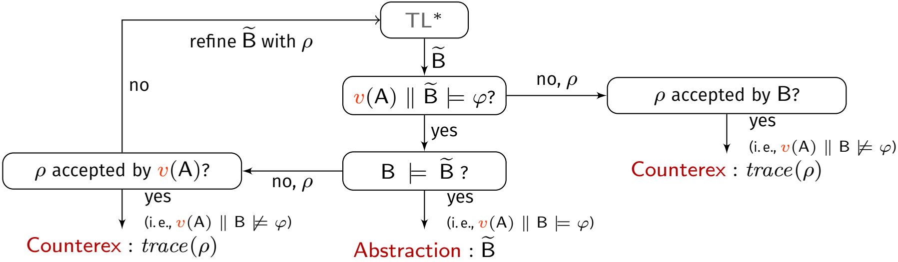

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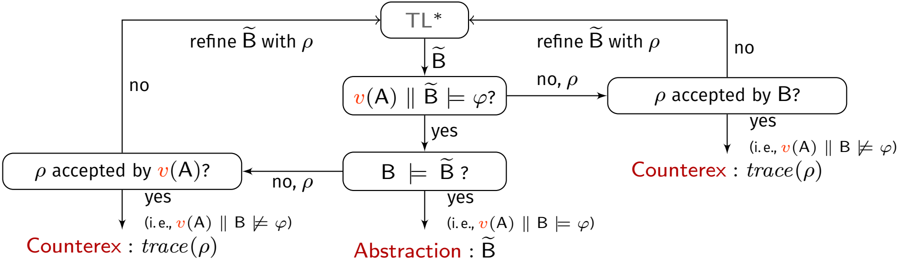

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Replaying a trace

Given a finite trace (i. e., a sequence of actions), we can replay it in the parametric framework

- i. e., find all parameter valuations for which this trace is feasible
- Using a symbolic semantics defined for PERAs (see paper)

☺ Very cheap

Our overall procedure CompSynth

Key ideas:

- Iterate on integer points v
- Try to compute an abstraction $\widetilde{\mathsf{B}}$ of the non-parametric component w.r.t. $v(\mathsf{A})$ and φ
  - If succeed, synthesize "similar" valuations using PRP on $\mathsf{A} \parallel \widetilde{\mathsf{B}}$
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  - If fail, synthesize the valuations corresponding to the counterex.

$K_{bad} \leftarrow \bot$; $K_{good} \leftarrow \bot$

while *there is an integer point not covered by* K_{bad} *or* K_{good} **do**

  Pick such a point v

  switch LearnAbstr$(\mathsf{B}, v(\mathsf{A}), AG\neg L^{☹})$ **do**

    case Abstraction$(\widetilde{\mathsf{B}})$ **do**

      $K_{good} \leftarrow K_{good} \cup \mathrm{PRP}(\mathsf{A} \parallel \widetilde{\mathsf{B}}, v, L^{☹})$

    case Counterex(τ) **do**

      $K_{bad} \leftarrow K_{bad} \cup \mathrm{ReplayTrace}(\mathsf{A} \parallel \mathsf{B}, \tau)$

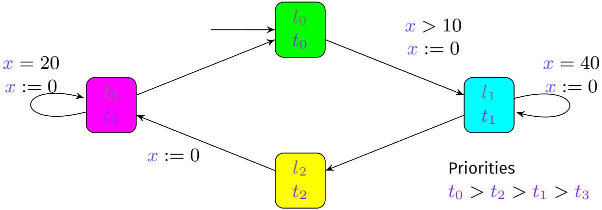
return (K_{good}, K_{bad})

Parametric task automata

A unified formalism: Parametric task automata

Extension of task automata [Norström et al., 1999, Fersman et al., 2007] with parameters

[André, FMICS'17]



Task	B	W	D
t_0	0	1	2
t_1	4	4	20
t_2	0	1	4
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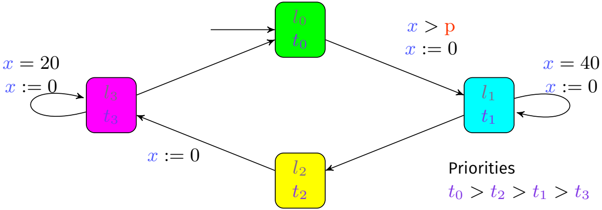

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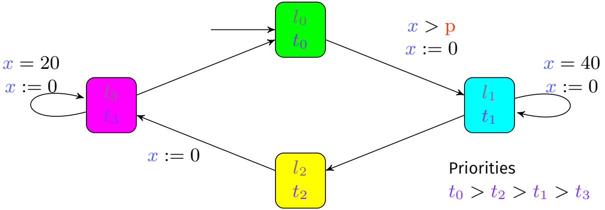

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t_0	0	1	2
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Parametric task automata can model

- Preemption
- Periodic tasks, sporadic tasks, pseudo-periodic tasks...
- Dependencies between tasks
- Offset, jitter
- Uncertainty
- Uniprocessor only

Parametric task automata: theory and practice

Schedulability-emptiness ("is the set of valuations for which the system is schedulable empty?")

- Undecidable in general
- Decidable under some assumptions **[André, FMICS'17]**

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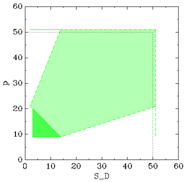
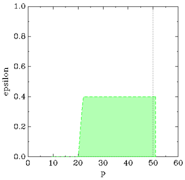
Implementation in IMITATOR

- Translation into a network of parametric stopwatch automata
- Schedulability analysis
- Parametric and/or robust schedulability analysis





The FMTV Challenge in details

To build the PTA model

- Uncertainties in the system:
  - $P1 \in [40 - 0.004, 40 + 0.004]$
  - $P3 \in [\frac{40}{3} - \frac{1}{150}, \frac{40}{3} + \frac{1}{150}]$
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- The end-to-end latency (another parameter): E2E

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- Parameters:
  - P1_uncertain
  - P3_uncertain
  - P4_uncertain
- The end-to-end latency (another parameter): E2E
- Others:
  - the register between task 2 and task 3: discrete variable $\mathrm{reg}_{2,3}$
  - the buffer between task 3 and task 4: $n = 1$ or $n = 3$

Simplification

- T1 and T2 are synchronised; T1, T3 and T4 are asynchronised
  - (exact modeling of the system behaviour is too heavy)

Simplification

- T1 and T2 are synchronised; T1, T3 and T4 are asynchronised
  - (exact modeling of the system behaviour is too heavy)
- We choose a single arbitrary frame, called the target one
- We assume the system is initially in an arbitrary status
  - This is our only uncertain assumption (in other words, can the periods deviate from each other so as to yield any arbitrary deviation?)

Outline

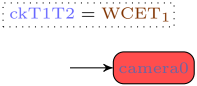
1 Decidability

2 Efficient synthesis

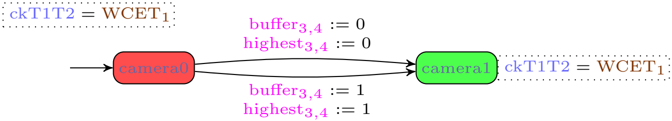
3 Applications to schedulability analysis

4 Perspectives
- The PTA model for $n = 1$

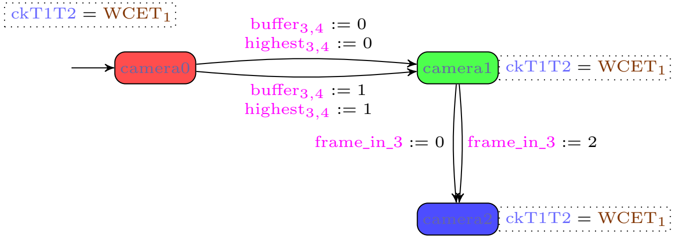
The initialization automaton



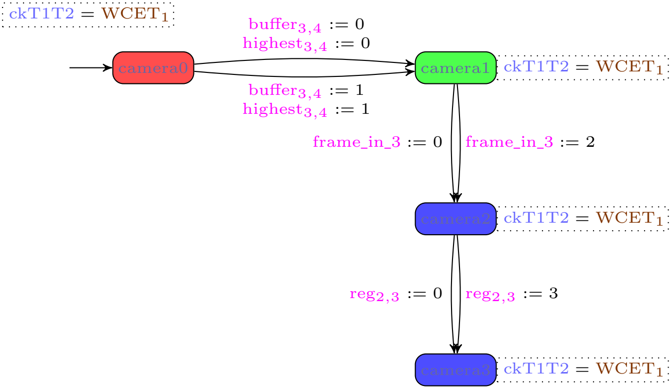
The initialization automaton



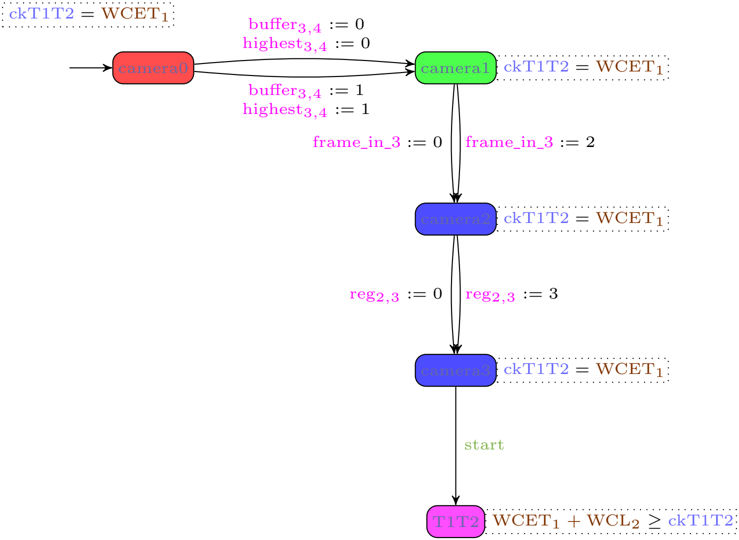
The initialization automaton



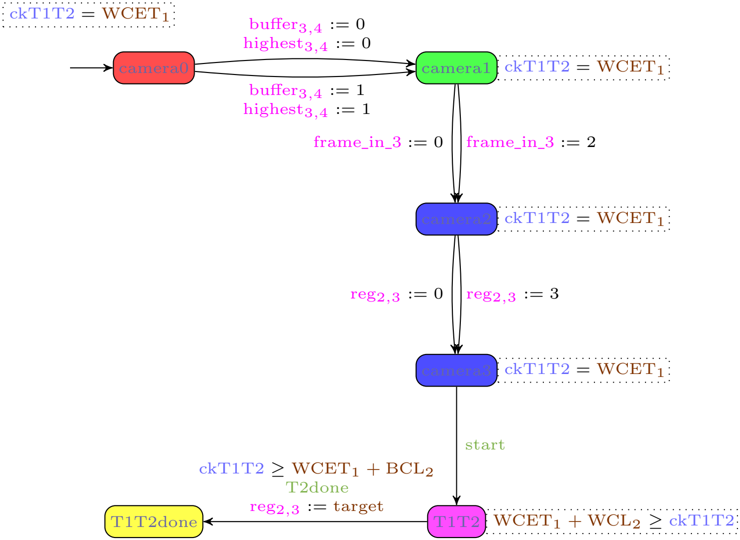
The initialization automaton



The initialization automaton

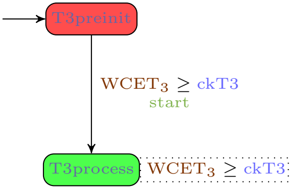


The initialization automaton

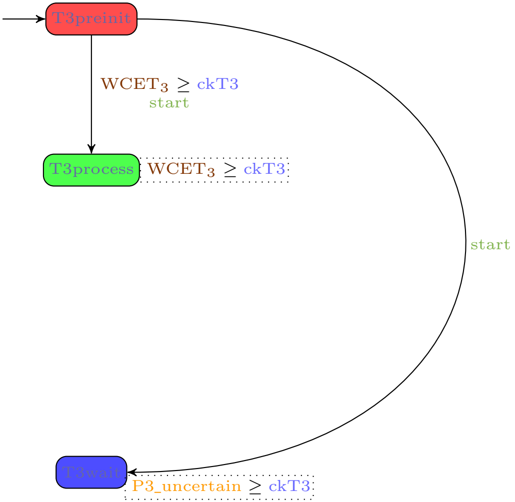


Task T3

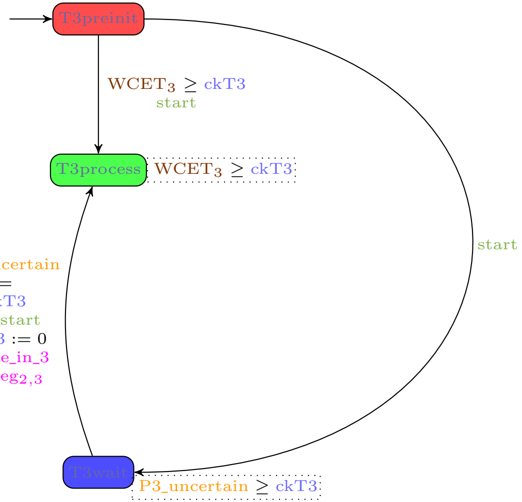
Task T3



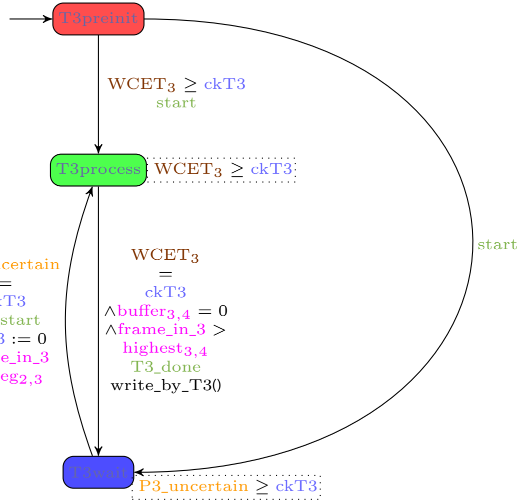
Task T3


T3preinit
WCET₃ ≥ ckT3
start
T3process
WCET₃ ≥ ckT3
start
T3wait
P3_uncertain ≥ ckT3

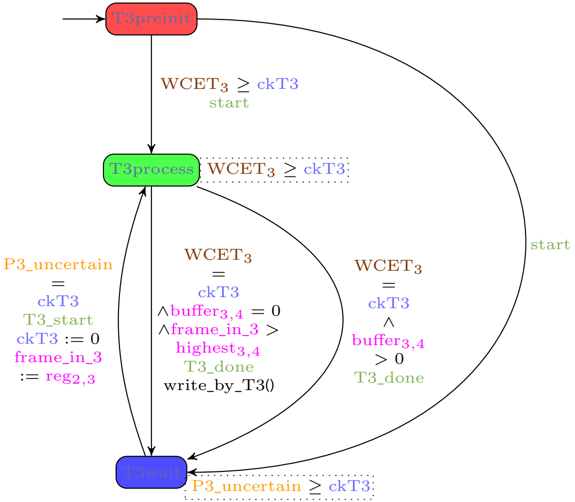
Task T3


T3preinit
WCET$_3$ ≥ ckT3
start
T3process
WCET$_3$ ≥ ckT3
start
P3_uncertain
=
ckT3
T3_start
ckT3 := 0
frame_in_3
:= reg$_{2,3}$
T3wait
P3_uncertain ≥ ckT3

Task T3

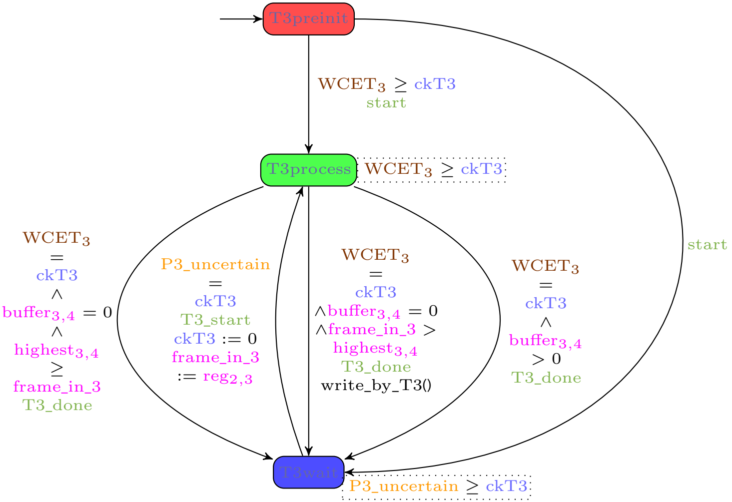

T3preinit
WCET3 ≥ ckT3
start
T3process
WCET3 ≥ ckT3
start
P3_uncertain
=
ckT3
T3_start
ckT3 := 0
frame_in_3
:= reg2,3
WCET3
=
ckT3
∧buffer3,4 = 0
∧frame_in_3 >
highest3,4
T3_done
write_by_T3()
T3wait
P3_uncertain ≥ ckT3

Task T3



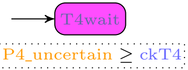
T3preinit
WCET$_3$ ≥ ckT3
start
T3process
WCET$_3$ ≥ ckT3
start
P3_uncertain = ckT3
T3_start
ckT3 := 0
frame_in_3 := reg$_{2,3}$
WCET$_3$ = ckT3 ∧buffer$_{3,4}$ = 0 ∧frame_in_3 > highest$_{3,4}$
T3_done
write_by_T3()
WCET$_3$ = ckT3 ∧ buffer$_{3,4}$ > 0
T3_done
T3wait
P3_uncertain ≥ ckT3

Task T3

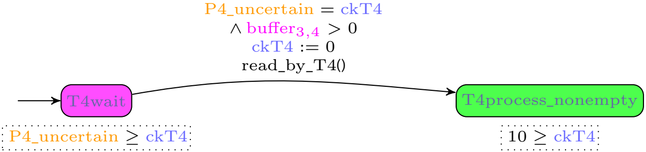


T3preinit
WCET3 ≥ ckT3
start
T3process
WCET3 ≥ ckT3
start
WCET3 = ckT3 ∧ buffer3,4 = 0 ∧ highest3,4 ≥ frame_in_3
T3_done
P3_uncertain = ckT3
T3_start
ckT3 := 0
frame_in_3 := reg2,3
WCET3 = ckT3 ∧buffer3,4 = 0 ∧frame_in_3 > highest3,4
T3_done
write_by_T3()
WCET3 = ckT3 ∧ buffer3,4 > 0
T3_done
T3wait
P3_uncertain ≥ ckT3

Task T4

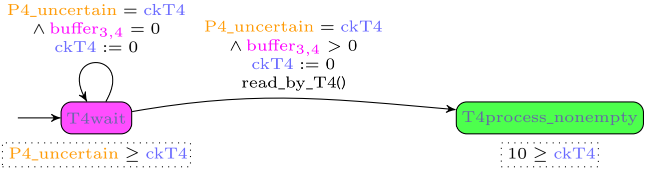


Task T4



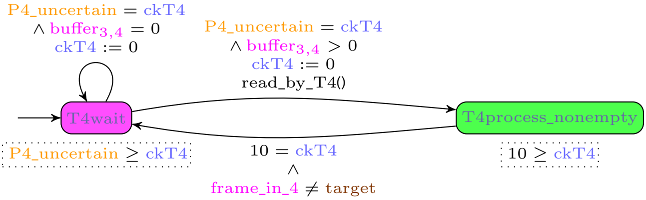
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
P4_uncertain ≥ ckT4
T4process_nonempty
10 ≥ ckT4

Task T4

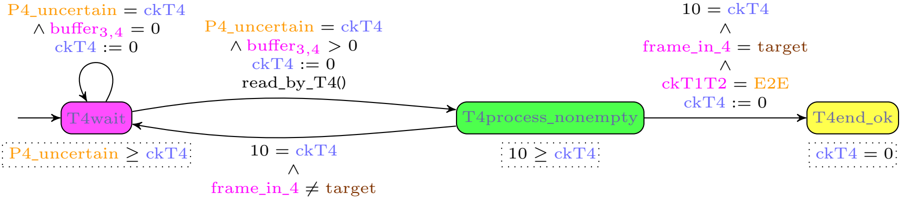


P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 ≥ ckT4

Task T4

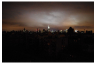

P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 = ckT4
∧
frame_in_4 ≠ target
10 ≥ ckT4

Task T4


P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
10 = ckT4
∧
frame_in_4 = target
∧
ckT1T2 = E2E
ckT4 := 0
T4wait
T4process_nonempty
T4end_ok
P4_uncertain ≥ ckT4
10 = ckT4
∧
frame_in_4 ≠ target
10 ≥ ckT4
ckT4 = 0

Licensing

Source of the graphics used I



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Author: David Shankbone
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Author: imcomkorea
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Title: Smiley green alien big eyes (aaah)
Author: LadyofHats
Source: `https://commons.wikimedia.org/wiki/File:Smiley_green_alien_big_eyes.svg`
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Source of the graphics used II

Title: Smiley green alien big eyes (cry)
Author: LadyofHats
Source: https://commons.wikimedia.org/wiki/File:Smiley_green_alien_big_eyes.svg
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