FORTE 2017

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Learning-Based Compositional Parameter Synthesis for Event-Recording Automata

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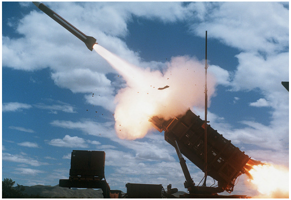
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

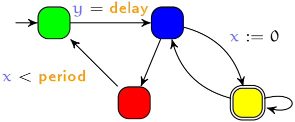
Context: Critical distributed systems

- Need for early bug detection
  - Bugs discovered when final testing: expensive

$\leadsto$ Need for a thorough modeling and verification phase



Timed model checking (1/2)

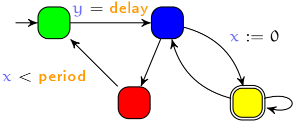


A model of the system

 is unreachable

A property to be satisfied

Timed model checking (1/2)



$\overset{?}{\models}$

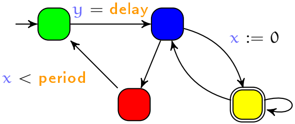
 is unreachable

A model of the system

A property to be satisfied

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

Timed model checking (1/2)



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 is unreachable

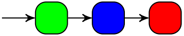
A model of the system

A property to be satisfied

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

Yes

No



Counterexample

Timed model checking (2/2)

- Timed systems are characterized by a set of timing constants
  - "The packet transmission lasts for 50 ms"
  - "The sensor reads the value every 10 s"
- Powerful model checking tools, e.g.:
  - UPPAAL [Larsen et al., 1997]
  - PAT [Sun et al., 2009]

Beyond timed model checking: parameter synthesis

- Verification for one set of constants does not usually guarantee the correctness for other values

- Challenges
  - Numerous verifications: is the system correct for any value within $[40; 60]$?
  - Optimization: until what value can we increase 10?
  - Robustness [Markey, 2011]: What happens if 50 is implemented with 49.99?
  - System incompletely specified: Can I verify my system even if I don't know the period value with full certainty?

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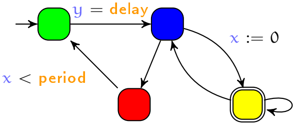
- Parameter synthesis
  - Consider that timing constants are unknown constants (parameters)

timed model checking



$\overset{?}{\models}$

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A model of the system

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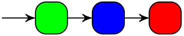
- Question: does the model of the system satisfy the property?

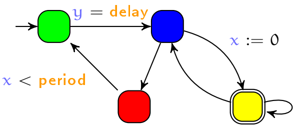
Yes

No



Counterexample

Parametric timed model checking



$\overset{?}{\models}$

 is unreachable

A model of the system

A property to be satisfied

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

Yes if...

$$2\mathsf{delay} > \mathsf{period} \\ \wedge\ \mathsf{period} < 20.46$$

Outline

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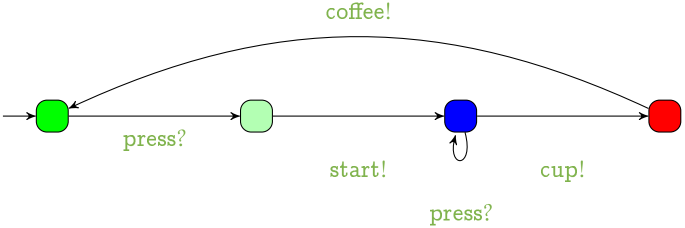
Event-recording automata (ERA)

- Finite state automaton (sets of locations)

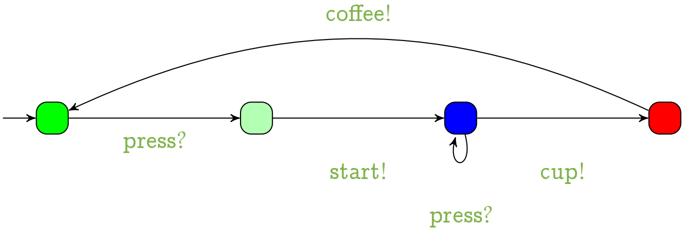
Event-recording automata (ERA)

- Finite state automaton (sets of locations and actions)



Event-recording automata (ERA)

- Finite state automaton (sets of locations and actions) augmented with a set X of clocks, one clock for each action [Alur et al., 1999]
  - Clocks: Real-valued variables evolving linearly at the same rate
  - A (strict) subclass of timed automata [Alur and Dill, 1994]



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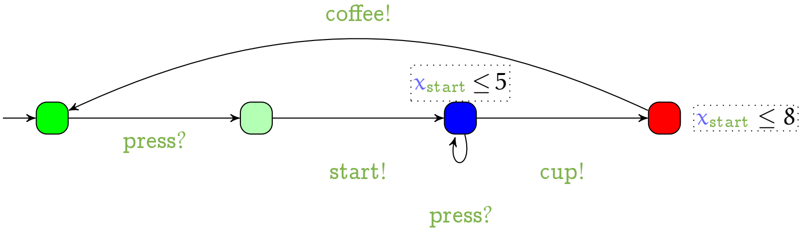
- Features
  - Location invariant: constraint to be verified to stay at a location



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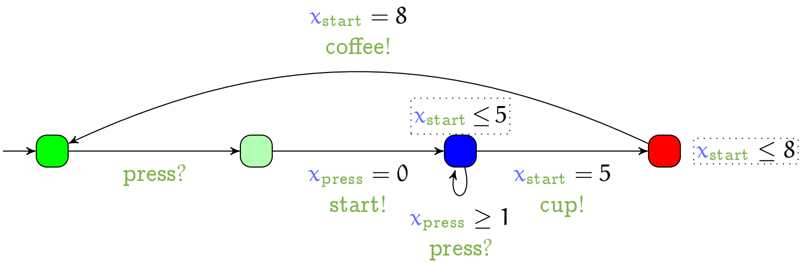
- Features
  - Location invariant: constraint to be verified to stay at a location
  - Transition guard: constraint to be verified to enable a transition



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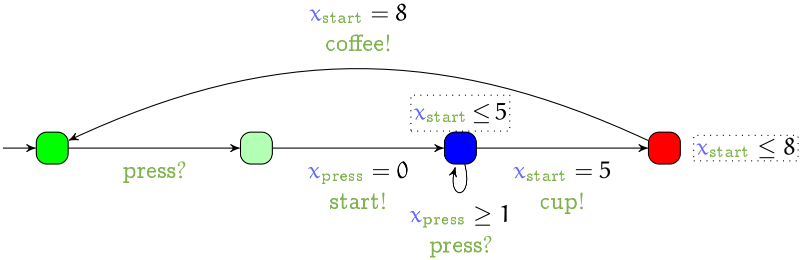
- Features
  - Location invariant: constraint to be verified to stay at a location
  - Transition guard: constraint to be verified to enable a transition
  - For each action a, the corresponding clock x_a is (implicitly) reset

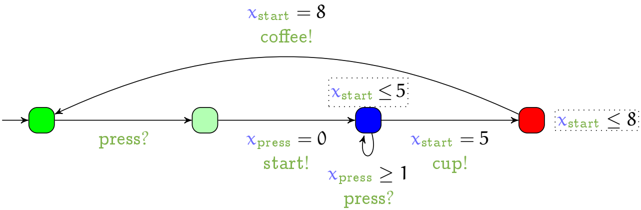


Concrete semantics of event-recording automata

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

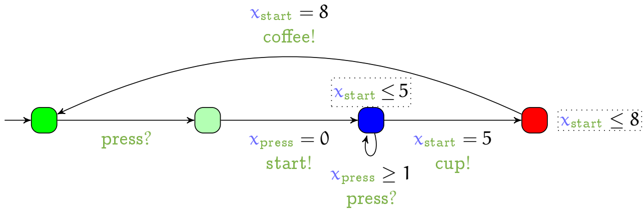
- Concrete run: alternating sequence of concrete states and actions or time elapse

Examples of concrete runs



- Possible concrete runs for the coffee machine

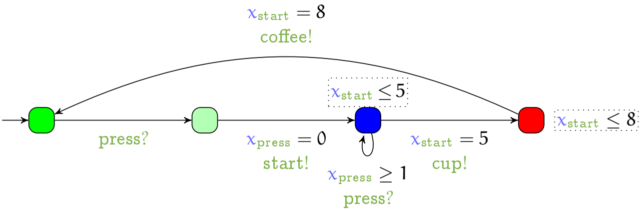
Examples of concrete runs



- Possible concrete runs for the coffee machine
  - Coffee with no sugar

x_{press} 0
x_{start} 0

Examples of concrete runs



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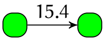
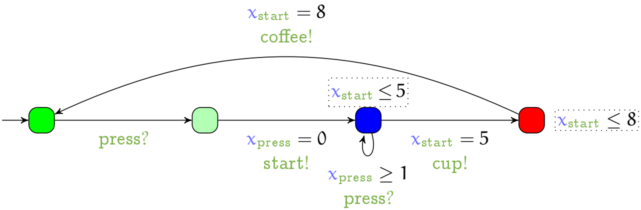


x_{press}	0	15.4
x_{start}	0	15.4

Examples of concrete runs



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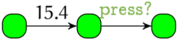
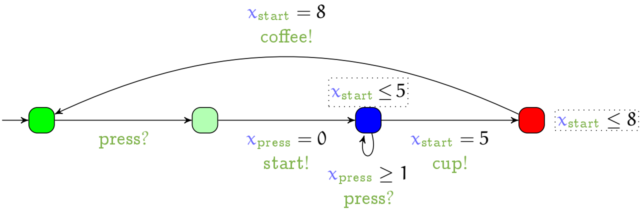


x_{press}	0	15.4	0
x_{start}	0	15.4	15.4

Examples of concrete runs



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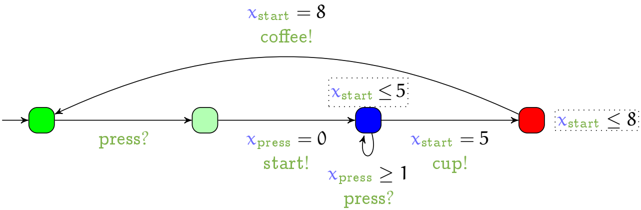
x_{press}	0	15.4	0	0
x_{start}	0	15.4	15.4	0

Examples of concrete runs



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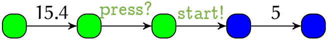
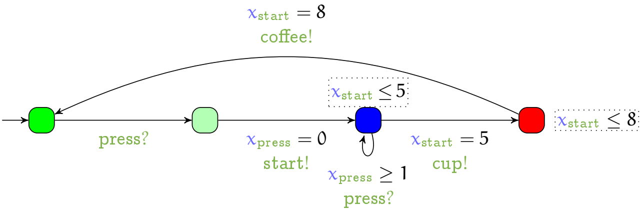


x_{press}	0	15.4	0	0	5
x_{start}	0	15.4	15.4	0	5

Examples of concrete runs



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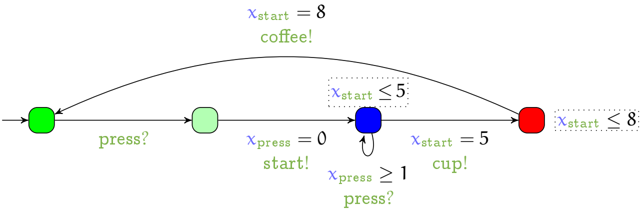
  - Coffee with no sugar

x_{press}	0	15.4	0	0	5	5
x_{start}	0	15.4	15.4	0	5	5

Examples of concrete runs



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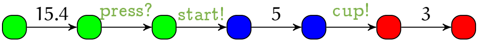
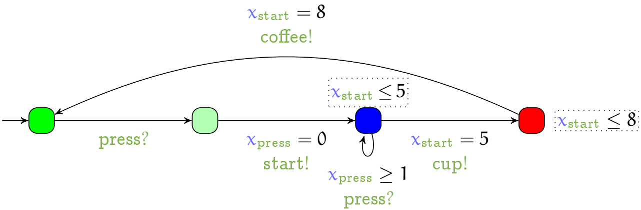


x_{press}	0	15.4	0	0	5	5	8
x_{start}	0	15.4	15.4	0	5	5	8

Examples of concrete runs



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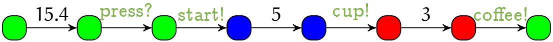

x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

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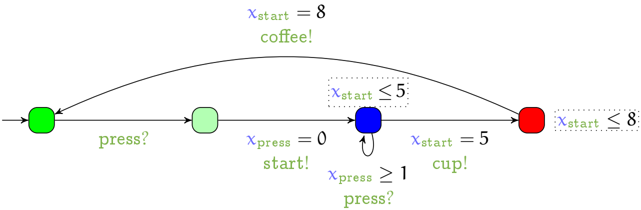

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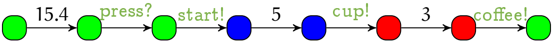
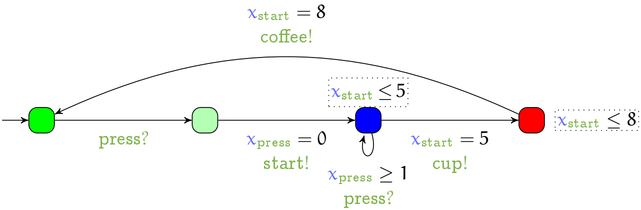


x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

  - Coffee with 2 doses of sugar

x_{press}	0
x_{start}	0

Examples of concrete runs



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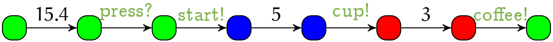

x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

  - Coffee with 2 doses of sugar

x_{press}	0	0
x_{start}	0	0

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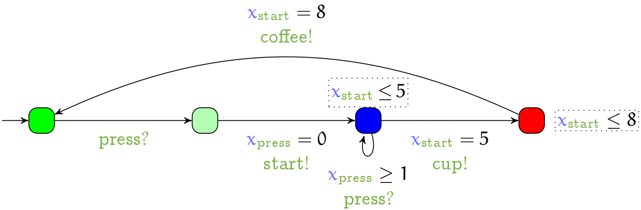

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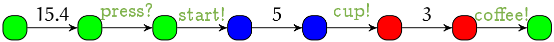

x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

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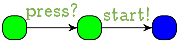
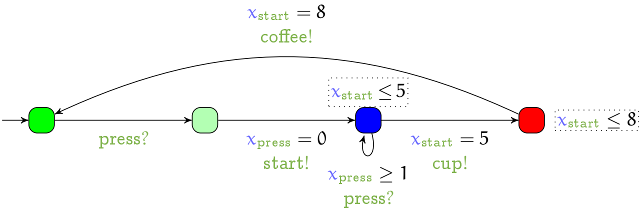


x_{press}	0	0	0
x_{start}	0	0	0

Examples of concrete runs



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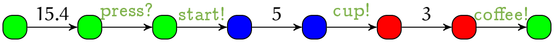
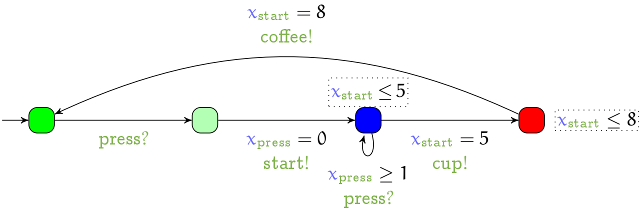


x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

  - Coffee with 2 doses of sugar

x_{press}	0	0	0	1.5
x_{start}	0	0	0	1.5

Examples of concrete runs



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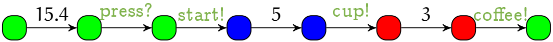

x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

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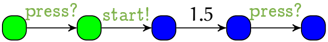
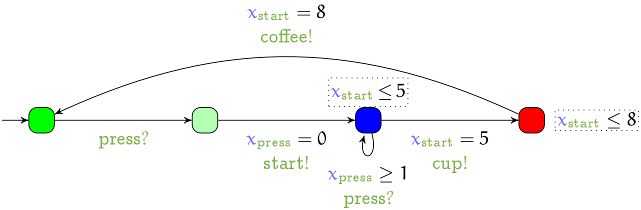


x_{press}	0	0	0	1.5	0
x_{start}	0	0	0	1.5	1.5

Examples of concrete runs



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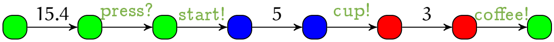

x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

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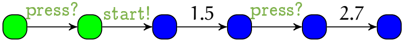
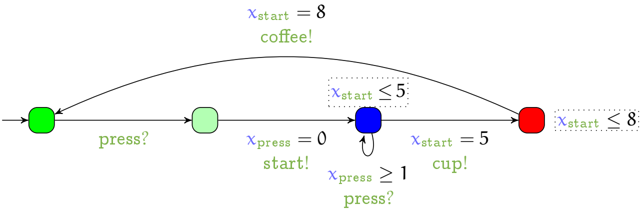
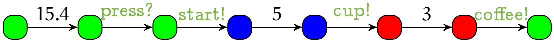


x_{press}	0	0	0	1.5	0	2.7
x_{start}	0	0	0	1.5	1.5	4.2

Examples of concrete runs

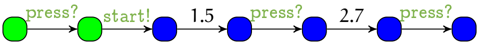


- Possible concrete runs for the coffee machine
  - Coffee with no sugar



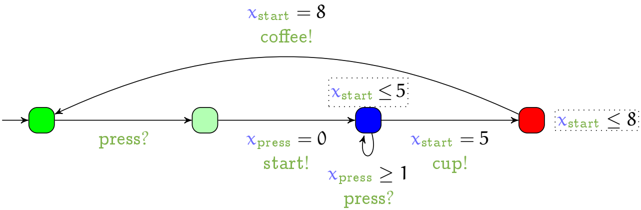
x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

  - Coffee with 2 doses of sugar



x_{press}	0	0	0	1.5	0	2.7	0
x_{start}	0	0	0	1.5	1.5	4.2	4.2

Examples of concrete runs



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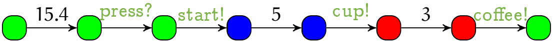
  - Coffee with no sugar

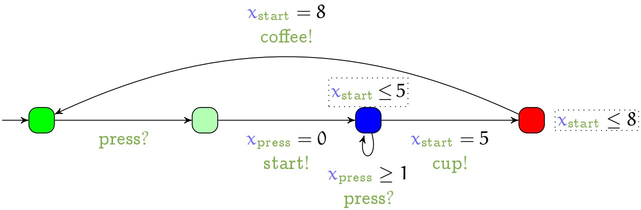


x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

  - Coffee with 2 doses of sugar

x_{press}	0	0	0	1.5	0	2.7	0	0.8
x_{start}	0	0	0	1.5	1.5	4.2	4.2	5

Examples of concrete runs



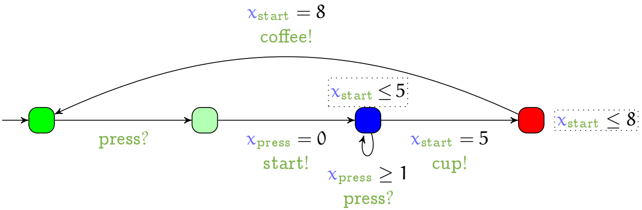
- Possible concrete runs for the coffee machine
  - Coffee with no sugar

		→ 15.4 →		→ press? →		→ start! →		→ 5 →		→ cup! →		→ 3 →		→ coffee! →	
x_{press}	0		15.4		0		0		5		5		8		8
x_{start}	0		15.4		15.4		0		5		5		8		8

  - Coffee with 2 doses of sugar

		→ press? →		→ start! →		→ 1.5 →		→ press? →		→ 2.7 →		→ press? →		→ 0.8 →		→ cup! →	
x_{press}	0		0		0		1.5		0		2.7		0		0.8		0.8
x_{start}	0		0		0		1.5		1.5		4.2		4.2		5		5

Examples of concrete runs



- Possible concrete runs for the coffee machine
  - Coffee with no sugar

		15.4		press?		start!		5		cup!		3		coffee!	
x_{press}	0		15.4		0		0		5		5		8		8
x_{start}	0		15.4		15.4		0		5		5		8		8

  - Coffee with 2 doses of sugar

		press?		start!		1.5		press?		2.7		press?		0.8		cup!		3	
x_{press}	0		0		0		1.5		0		2.7		0		0.8		0.8		3.8
x_{start}	0		0		0		1.5		1.5		4.2		4.2		5		5		8

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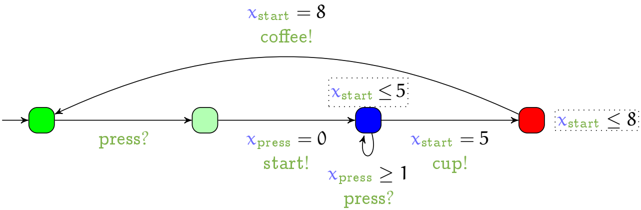

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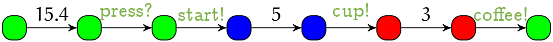
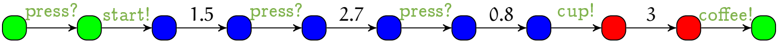


x_{press}	0	15.4	0	0	5	5	8	8
x_{start}	0	15.4	15.4	0	5	5	8	8

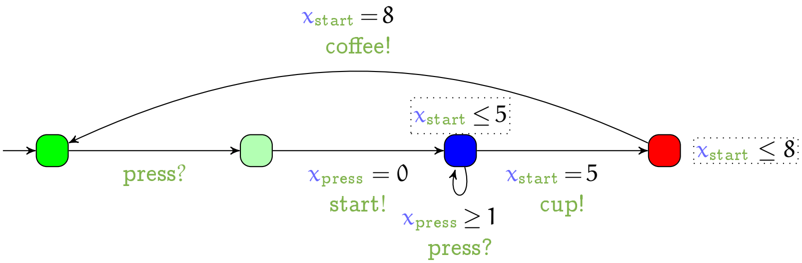
  - Coffee with 2 doses of sugar



x_{press}	0	0	0	1.5	0	2.7	0	0.8	0.8	3.8	3.8
x_{start}	0	0	0	1.5	1.5	4.2	4.2	5	5	8	8

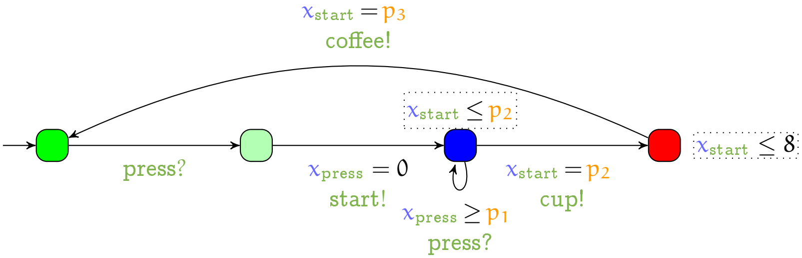
Parametric event-recording automata (PERA)

- Event-recording automata (sets of locations, actions and clocks)



Parametric event-recording automata (PERA)

- Event-recording automata (sets of locations, actions and clocks) augmented with a set P of parameters
  - Parameters: Unknown constants used in guards and invariants
  - Extension in the spirit of parametric timed automata [Alur et al., 1993]



Valuation of a PERA

- Given a PERA A and a parameter valuation v, we denote by $v(A)$ the (non-parametric) event-recording automaton where all parameters are valuated by v

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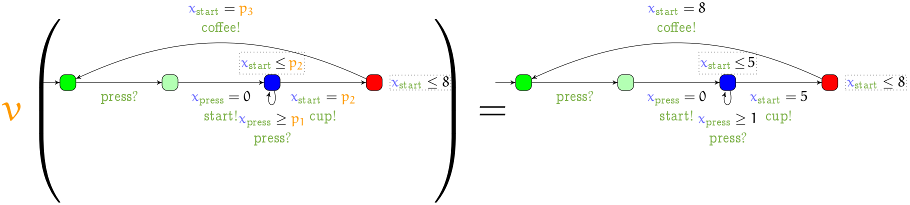

$$\text{with } v : \begin{cases} p_1 & \rightarrow & 1 \\ p_2 & \rightarrow & 5 \\ p_3 & \rightarrow & 8 \end{cases}$$

Problems

Reachability-emptiness

Input: a PERA A, a location l
Question: is the set of valuations v for which a runs reaches l in $v(A)$ empty?

Reachability-synthesis

Input: a PERA A, a location l
Question: synthesize all valuations v for which a runs reaches l in $v(A)$

An undecidability result

Theorem (Undecidability)

The reachability-emptiness problem is undecidable for PERAs

Proof idea.

By encoding a 2-counter machine into a PERA (using a proof of undecidability for parametric timed automata [ICFEM 2016]) □

Consequence: no hope for exact synthesis

An undecidability result

Theorem (Undecidability)

The reachability-emptiness problem is undecidable for PERAs

Proof idea.

By encoding a 2-counter machine into a PERA (using a proof of undecidability for parametric timed automata [ICFEM 2016]) □

Consequence: no hope for exact synthesis… but

- One can design semi-algorithms
- One can design algorithms synthesizing under- or over-approximations

Outline

Goal

- Algorithms for synthesis in parametric timed formalisms are very expensive
  - No efficient data structures (in contrast to BDDs or DBMs)
    - (Even though parametric DBMs were proposed [Annichini et al., 2000, Hune et al., 2002])
  - Expensive operations on polyhedra (e. g., using PPL [Bagnara et al., 2008])

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Goal

Design an efficient (semi-)algorithm for the parameter synthesis for PERAs

Idea

Use learning-based techniques to compute an abstraction of the non-parametric components, so as to speed up the verification

Assume-Guarantee Reasoning (AGR)

$$\frac{\begin{array}{rcl} \mathsf{A} \parallel \widetilde{\mathsf{B}} & \models & \varphi \\ \mathsf{B} & \models & \widetilde{\mathsf{B}} \end{array}}{\mathsf{A} \parallel \mathsf{B} \models \varphi}$$

"If A with an abstraction $\widetilde{\mathsf{B}}$ of B satisfy property φ
then A with B satisfy φ"

Assumption and partitioning heuristics

- The system is modeled using a network of PERAs
  - Some components are parametric (i. e., contains parameters)
  - Some components are non-parametric

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- Partitioning the system into A ∥ B
  1. If a component has timing parameters, it is collected in group A;
  2. If a component shares common action labels with the property, the component is collected in group A.

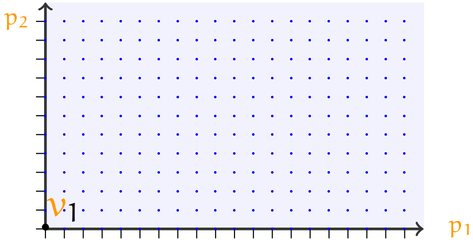
  Other components are collected in group B

Point-based parameter synthesis

In order to apply (non-parametric) AGR abstractions, we use a point-based method

- Iterate on points (parameter valuations) in a bounded parameter domain
  - e. g., integer points
- For each not point by a parameter constraint, generalize the point using the algorithm PRP
  - PRP: Parametric reachability preservation [NFM 2015]
  - Synthesizes a dense constraint around a point that preserves the reachability of a location
    - If the location is reachable for v, then it is for the constraint
    - and vice-versa
- ... until (at least) a certain set of discrete points is covered
  - e. g., all integers

Parametric reachability preservation cartography



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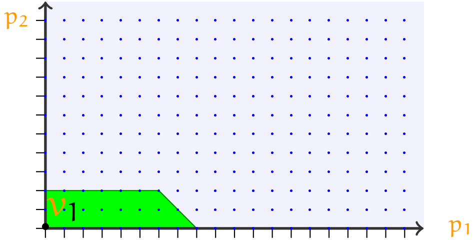

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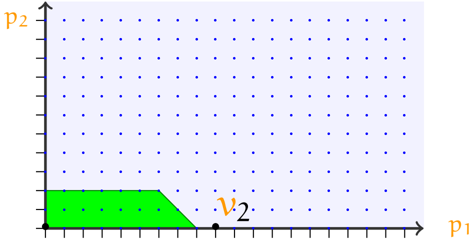

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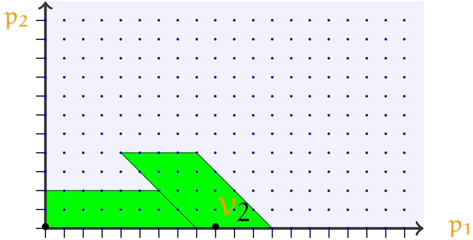

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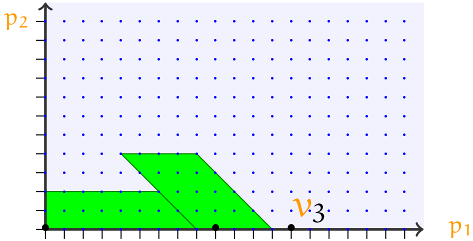

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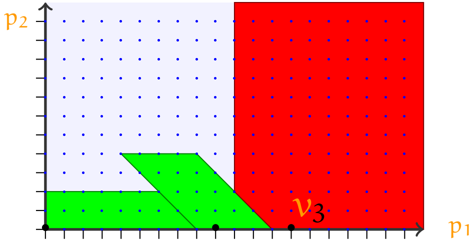

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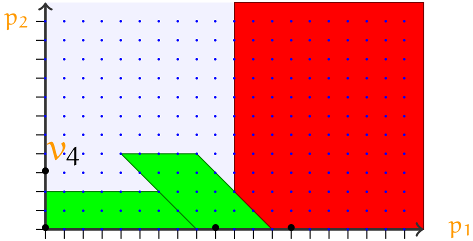

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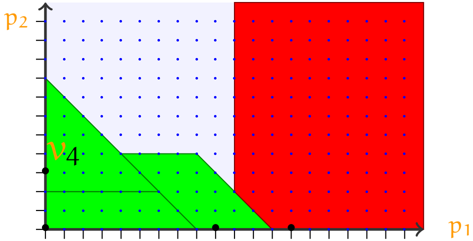

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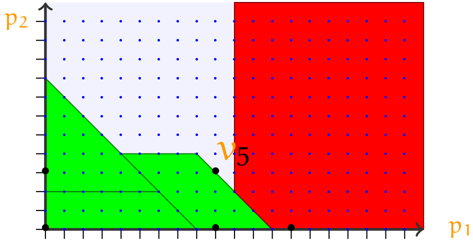

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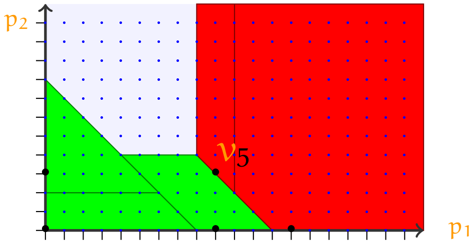

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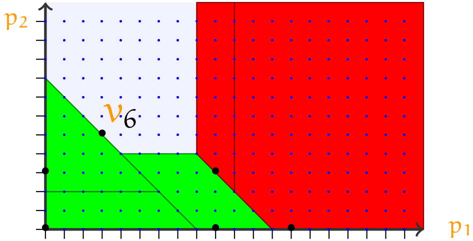

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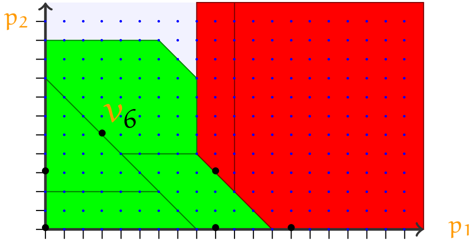

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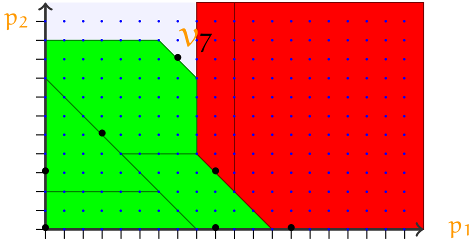

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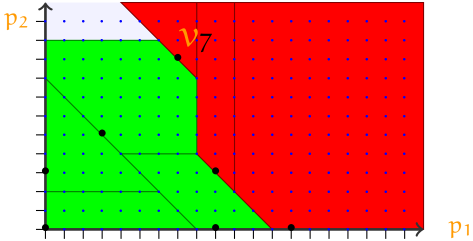

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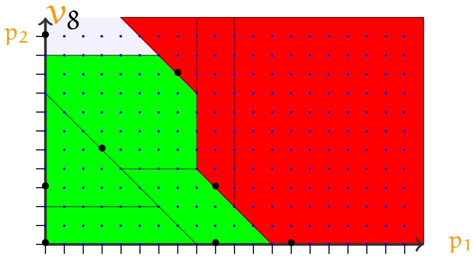

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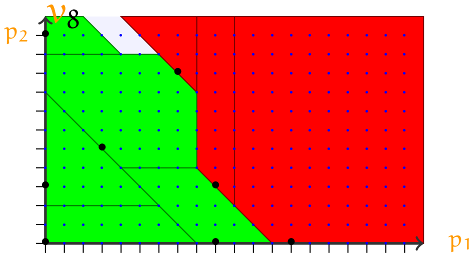

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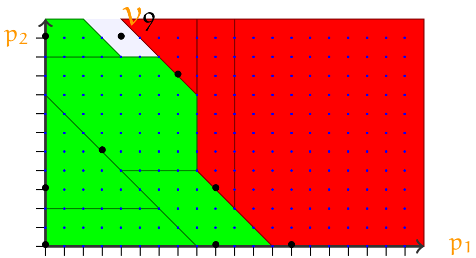

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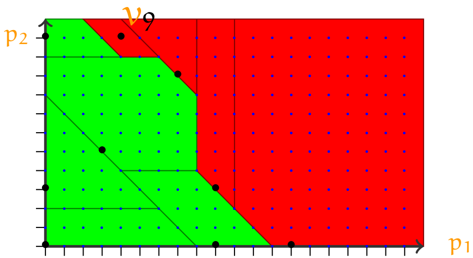

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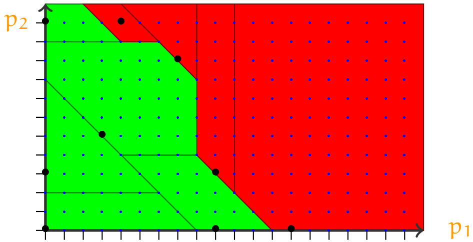

Learning an abstraction: $\mathsf{LearnAbstr}(\mathsf{B}, v(\mathsf{A}), AG\neg L^{☹})$

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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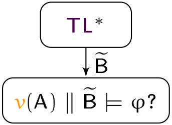

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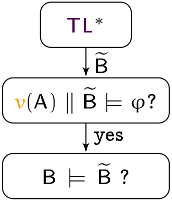

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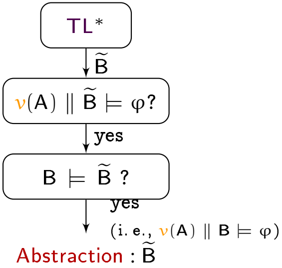

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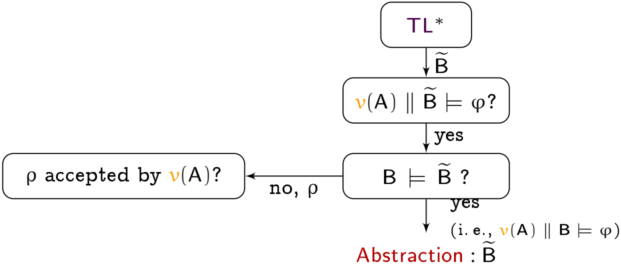

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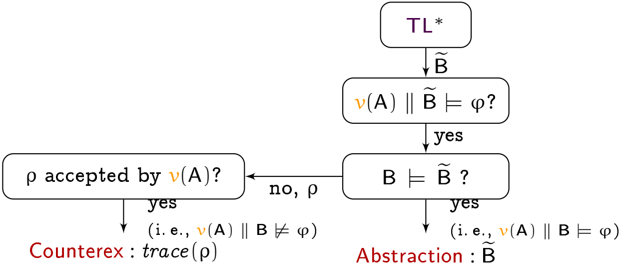

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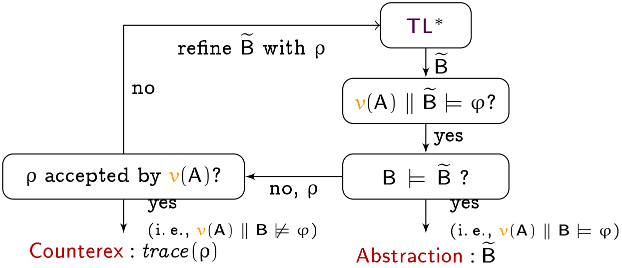

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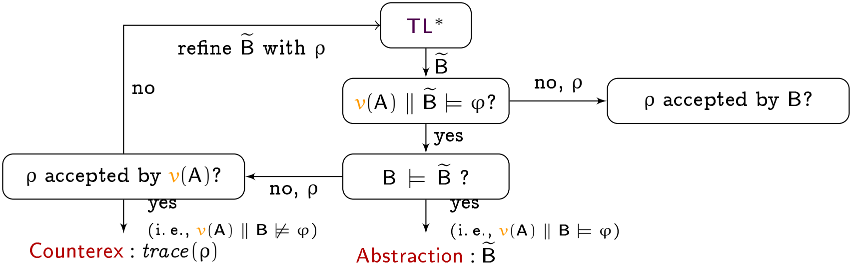

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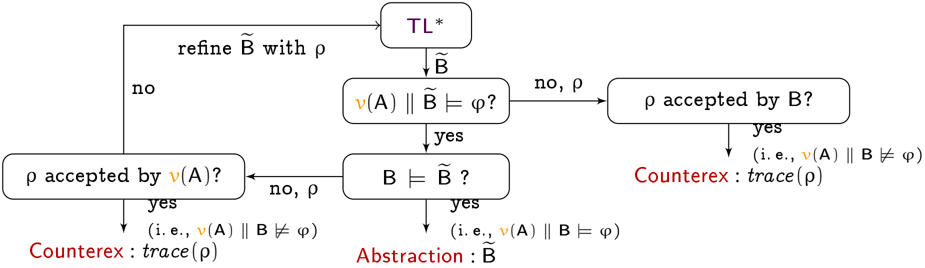

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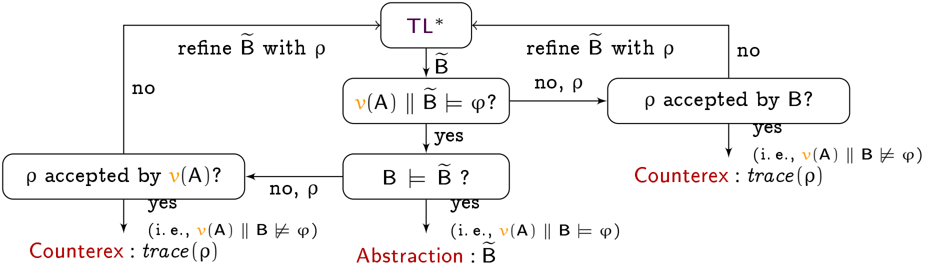

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Refinement: can be performed using learning

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 $\widetilde{B}$ of the non-parametric component w.r.t. $v(A)$ and φ
  - If succeed, synthesize "similar" valuations using PRP on $A \parallel \widetilde{B}$
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$K_{bad} \leftarrow \bot$; $K_{good} \leftarrow \bot$
while *there is an integer point not covered by* K_{bad} *or* K_{good} **do**
  Pick such a point v
  switch $\mathsf{LearnAbstr}(B, v(A), AG\neg L^{☹})$ **do**
    case $\mathsf{Abstraction}(\widetilde{B})$
      $K_{good} \leftarrow K_{good} \cup \mathsf{PRP}(A \parallel \widetilde{B}, v, L^{☹})$
    case $\mathsf{Counterex}(\tau)$
      $K_{bad} \leftarrow K_{bad} \cup \mathsf{ReplayTrace}(A \parallel B, \tau)$
return (K_{good}, K_{bad})

Soundness and termination

Proposition (Soundness)

Assume $\mathsf{CompSynth}(\mathsf{A}, \mathsf{B}, \mathrm{L}^{☹})$ *terminates with result* $(\mathsf{K}_{good}, \mathsf{K}_{bad})$.
Then, for all v

1. *if* $v \models \mathsf{K}_{good}$ *then* $v(\mathsf{A} \parallel \mathsf{B})$ *does not reach* $\mathrm{L}^{☹}$;
2. *if* $v \models \mathsf{K}_{bad}$ *then* $v(\mathsf{A} \parallel \mathsf{B})$ *reaches* $\mathrm{L}^{☹}$.

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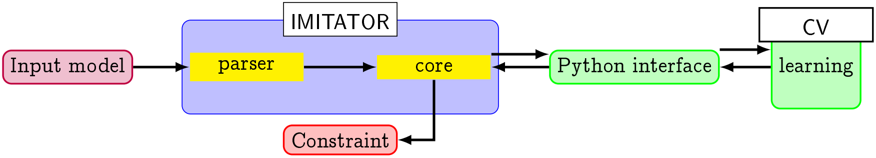
2. *if* $v \models K_{bad}$ *then* $v(A \parallel B)$ *reaches* $L^{☹}$*.*

Proposition (Integer-completeness)

Assume $\mathsf{CompSynth}(A, B, L^{☹})$ *terminates with result* (K_{good}, K_{bad}). *Then any integer point in the bounded parameter domain is either in* K_{good} *or in* K_{bad}*.*

Outline

Our toolkit



- IMITATOR: state-of-the-art tool for parameter synthesis for parametric timed automata [André et al., 2012]
- CV: (new) prototype compositional verifier of the compositional verification framework for ERAs [Lin et al., 2014]
- interface in Python (about 700 lines)

Experiments

Case study	#A	#X	#P	Spec	EFsynth	PRPC		CompSynth			
						#iter	total	#abs	#c.-ex.	learning	total
FMS-1	6	18	2	1	0.299	2	0.654	1	1	0.074	**0.136**
				2	**0.010**	1	0.372	0	1	0.038	0.046
				3	0.282	1	0.309	1	0	0.090	**0.242**
FMS-2	11	37	2	1	T.O.	-	T.O.	1	1	84.2	**88.9**
				2	T.O.	-	T.O.	1	0	81.4	**85.2**
				3	**0.051**	-	T.O.	0	2	1.10	2.44
				4	**0.062**	-	T.O.	0	1	1.42	1.53
				5	T.O.	-	T.O.	1	0	31.4	**40.8**
				6	T.O.	-	T.O.	1	0	37.2	**42.4**
AIP	11	46	2	1	0.551	-	T.O.	0	1	0.086	**0.114**
				2	2.11	-	T.O.	0	1	1.22	**1.25**
				3	**3.91**	-	T.O.	0	1	8.50	8.54
				4	**0.235**	-	T.O.	1	1	8.39	8.42
				5	T.O.	-	T.O.	1	0	0.394	**0.871**
				6	T.O.	-	T.O.	1	0	5.32	**9.58**
				7	T.O.	-	T.O.	1	0	1.76	**3.19**
				8	T.O.	-	T.O.	1	0	1.13	**4.35**
				9	T.O.	-	T.O.	1	1	0.762	**1.84**
				10	**0.022**	-	T.O.	0	1	0.072	0.094
Fischer-3	5	12	2		**2.76**	4	14.0	0	1	-	T.O.
Fischer-4	6	16	2		T.O.	-	T.O.	0	1	-	T.O.

EFsynth: monolithic reachability synthesis

PRPC: point-based synthesis without abstraction

All data (sources, binaries, models, logs) are available at https://www.imitator.fr/static/FORTE17/

Experiments: scalability

Testing the scalability w.r.t. the size of the parameter domain

Case study	#A	#X	#P	Spec	D_0	CompSynth				
						#abs	#c.-ex.	find next point	learning	total
FMS-2	11	37	2	1	2,500	1	1	0.0	81.0	85.7
					10,000	1	1	0.1	82.5	87.3
					250,000	1	1	2.2	82.0	89.0
					1,000,000	1	1	8.9	83.1	96.7
					25,000,000	1	1	221.2	83.1	309.0
					100,000,000	1	1	888.1	83.5	976.4

Gets slower from 10^6 points

- Reason: use exhaustive enumeration

Experiments: scalability

Testing the scalability w.r.t. the size of the parameter domain

Case study	#A	#X	#P	Spec	D_0	CompSynth				
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					100,000,000	1	1	888.1	83.5	976.4

Gets slower from 10^6 points

- Reason: use exhaustive enumeration

Future work: use, e. g., an SMT solver

Outline

Summary

- New method for parameter synthesis for distributed systems, modeled by PERAs
  - PERAs: Strong assumption! Event-recording automata are needed to perform language inclusion in TL^* (undecidable for timed automata)
- Despite undecidability in general, proposed an efficient algorithm
  - Experiments show a dramatic improvement for loosely-synchronized PERAs

Perspectives

- Reuse the distributed point-based synthesis on a cluster
  [A., Coti, Nguyen, ICFEM 2015]
- Beyond PERAs: what can we reuse to perform compositional verification of parametric timed automata?
- Combine our approach with that of [Aştefănoaei et al., 2016]
  - Invariant-based compositional synthesis

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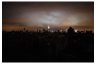
Additional explanation

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)

Error screen on the earliest versions of Macintosh

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)

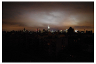
Experiments: partitioning

Test various partitioning heuristics

Case study	#A	#X	#P	Spec	Partitioning A	Partitioning B	CompSynth #abs	CompSynth #c.-ex.	CompSynth learning	CompSynth total
FMS-1	6	18	2	1	CM	R_1R_2A	1	1	1.071	1.137
					CMR_1	R_2A	1	1	0.077	**0.148**
					CMR_2	R_1A	1	1	5.152	5.406
					CMA	R_1R_2	1	1	5.663	5.980
					CMR_1R_2	A	1	1	0.123	0.290
					CMR_1A	R_2	1	1	0.119	0.360
					CMR_2A	R_1	1	1	6.150	6.690
				2	CM	R_1R_2A	0	1	0.133	0.149
					CMR_1	R_2A	0	2	0.077	0.123
					CMR_2	R_1A	0	1	0.040	0.056
					CMA	R_1R_2	0	1	0.824	0.842
					CMR_1R_2	A	0	1	0.034	**0.044**
					CMR_1A	R_2	0	2	0.096	0.144
					CMR_2A	R_1	0	1	0.042	0.051
				3	CM	R_1R_2A	1	0	0.211	0.270
					CMR_1	R_2A	1	0	0.082	**0.186**
					CMR_2	R_1A	1	0	1.094	1.208
					CMA	R_1R_2	1	0	0.729	0.881
					CMR_1R_2	A	1	0	0.119	0.279
					CMR_1A	R_2	1	0	0.314	0.634
					CMR_2A	R_1	1	0	0.104	0.257

Licensing

Source of the graphics used I



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Source of the graphics used II

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