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A Benchmarks Library for Extended Parametric Timed Automata

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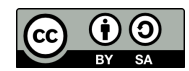

Motivation

- Real-time systems:
  - Systems for which not only the functional correctness but also the time answer is important

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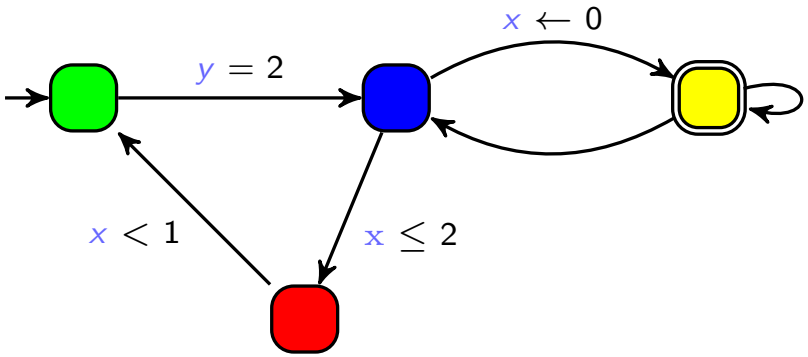
- Critical Real-time systems:
  - Systems for which not only the functional correctness but also the time answer is important
  - Failures (in correctness or timing) may result in dramatic consequences

Outline

Timed model checking

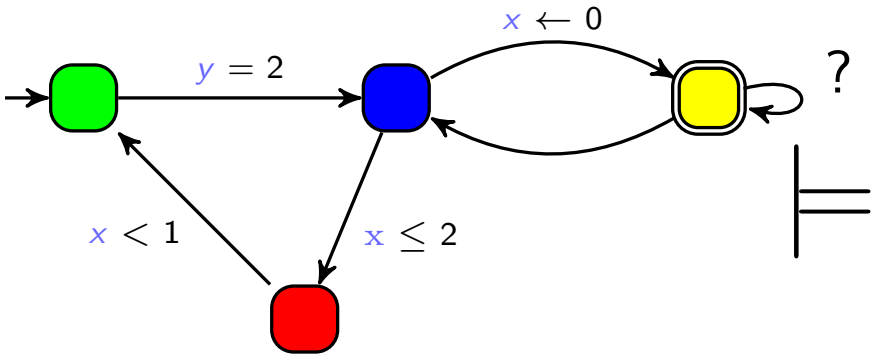


A model of the system

is unreachable

A property to be satisfied

Timed model checking



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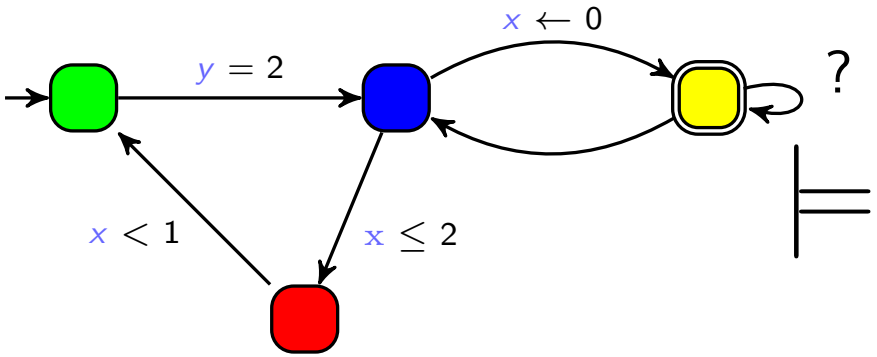

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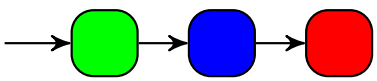
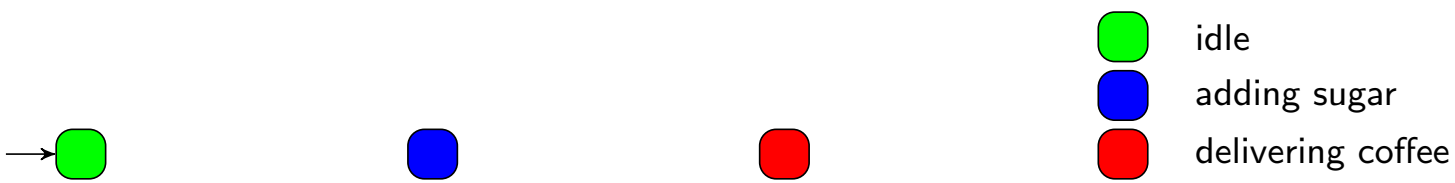


Counterexample

Timed automaton (TA)

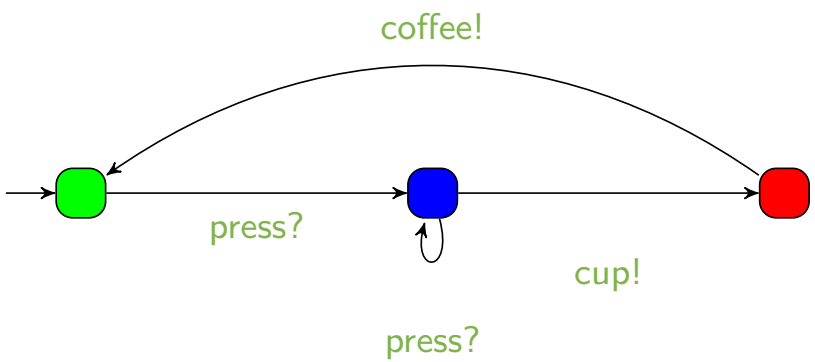
- Finite state automaton (sets of locations)

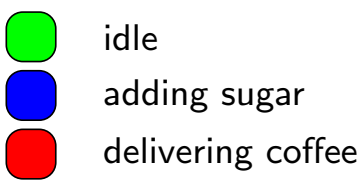


[AD94] Rajeev Alur and David L. Dill. "A theory of timed automata". In: *Theoretical Computer Science* 126.2 (Apr. 1994), pp. 183–235. ISSN: 0304-3975

Timed automaton (TA)

- Finite state automaton (sets of locations and actions)





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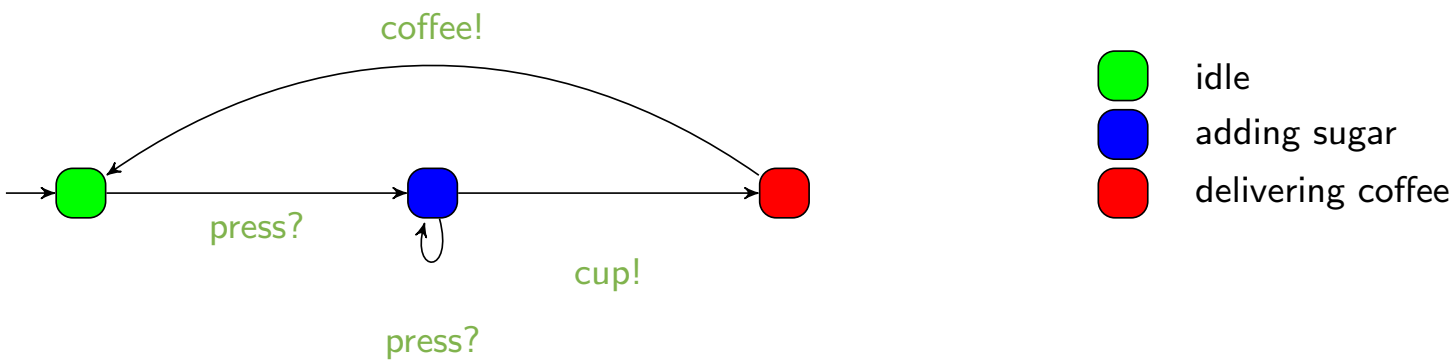
Timed automaton (TA)

- Finite state automaton (sets of locations and actions) augmented with a set X of clocks [AD94]
  - Real-valued variables evolving linearly at the same rate
  - Can be compared to integer constants



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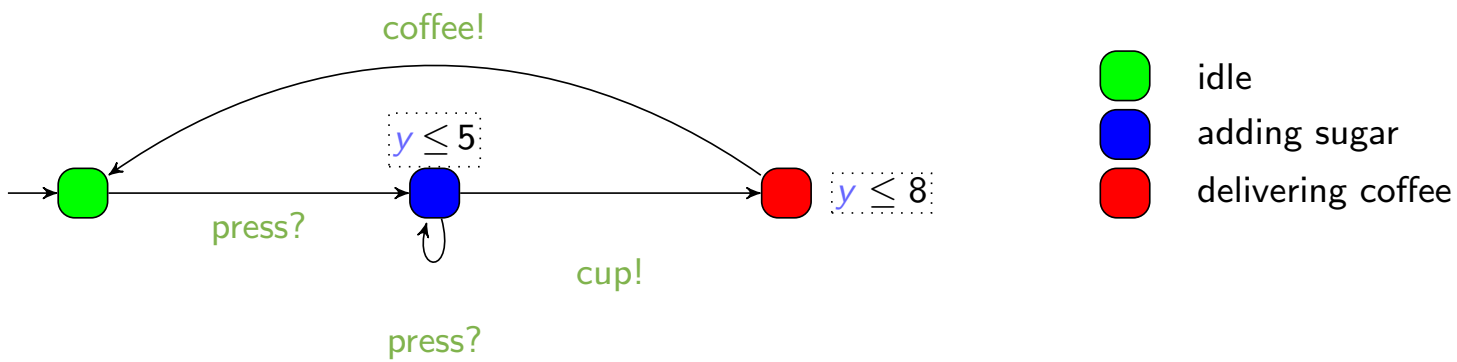
- Finite state automaton (sets of locations and actions) augmented with a set X of clocks [AD94]
  - Real-valued variables evolving linearly at the same rate
  - Can be compared to integer constants in invariants
- Features
  - Location invariant: property to be verified to stay at a location



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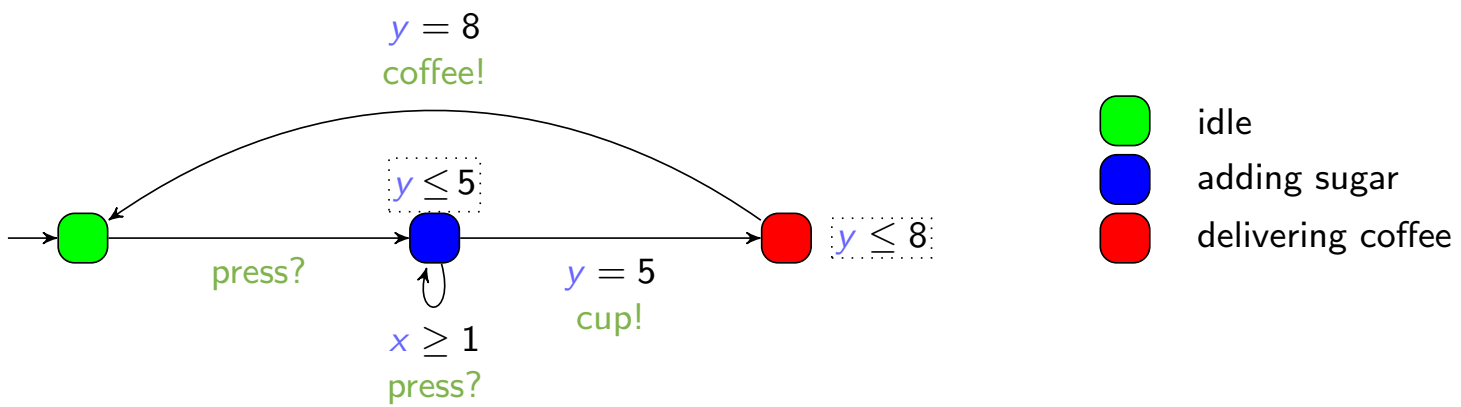
  - Transition guard: property to be verified to enable a transition



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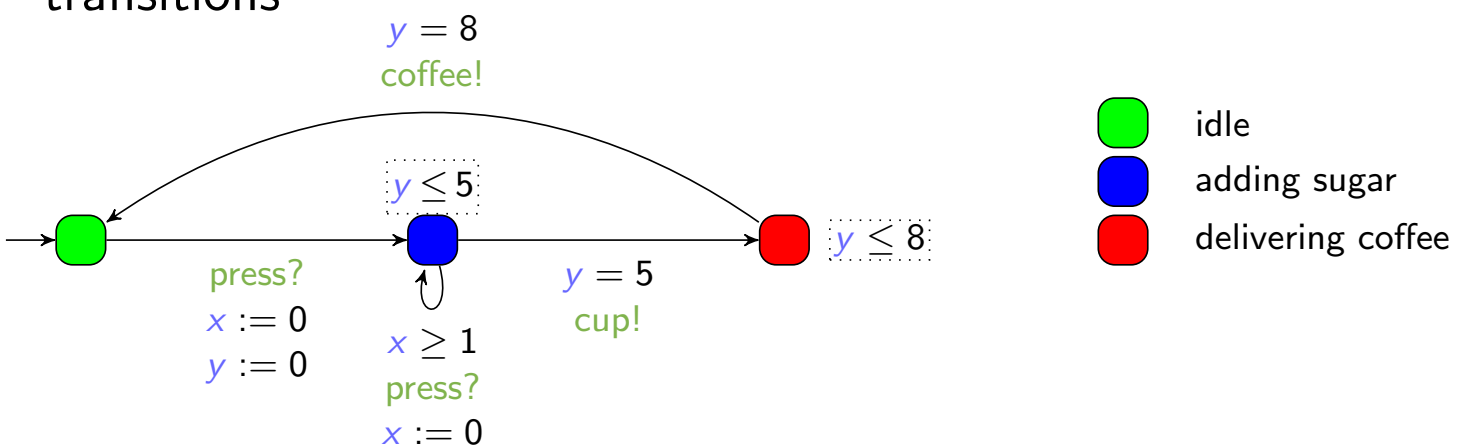
  - Location invariant: property to be verified to stay at a location
  - Transition guard: property to be verified to enable a transition
  - Clock reset: some of the clocks can be set to 0 along transitions



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Timed automata: a useful formalism for verification and testing

- Timed automata are a common formalism to reason about systems involving timing and concurrency
- Nice decidability results [AD94]
- Many interesting applications
  - Notably testing [Lut+17] and monitoring [AHW18]

[AD94] Rajeev Alur and David L. Dill. "A theory of timed automata". In: *Theoretical Computer Science* 126.2 (Apr. 1994), pp. 183–235. ISSN: 0304-3975

[Lut+17] Lars Luthmann et al. "Modeling and Testing Product Lines with Unbounded Parametric Real-Time Constraints". In: *SPLC, Volume A*. ACM, 2017, pp. 104–113

[AHW18] Étienne André, Ichiro Hasuo, and Masaki Waga. "Offline timed pattern matching under uncertainty". In: *ICECCS*. IEEE Computer Society, 2018, pp. 10–20

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 a given constant while preserving correctness?
  - Robustness [BMS13]: 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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  - System incompletely specified: Can I verify my system even if I don't know the period value with full certainty?
- Parameter synthesis
  - Consider that timing constants are unknown constants (parameters)

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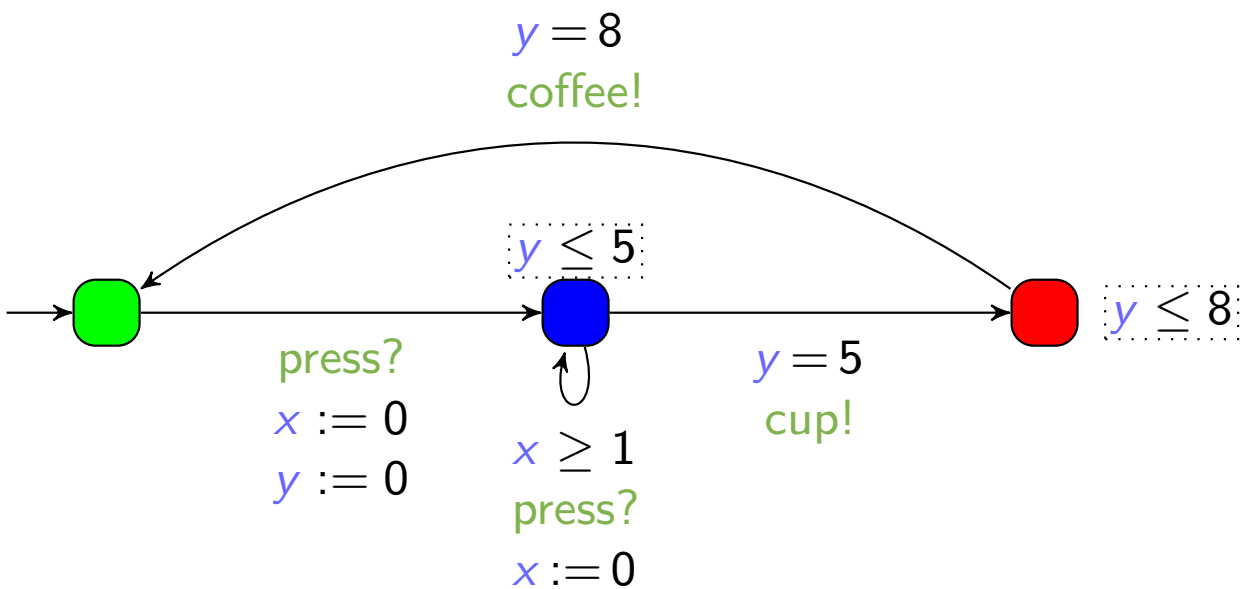
Parametric Timed Automaton (PTA)

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



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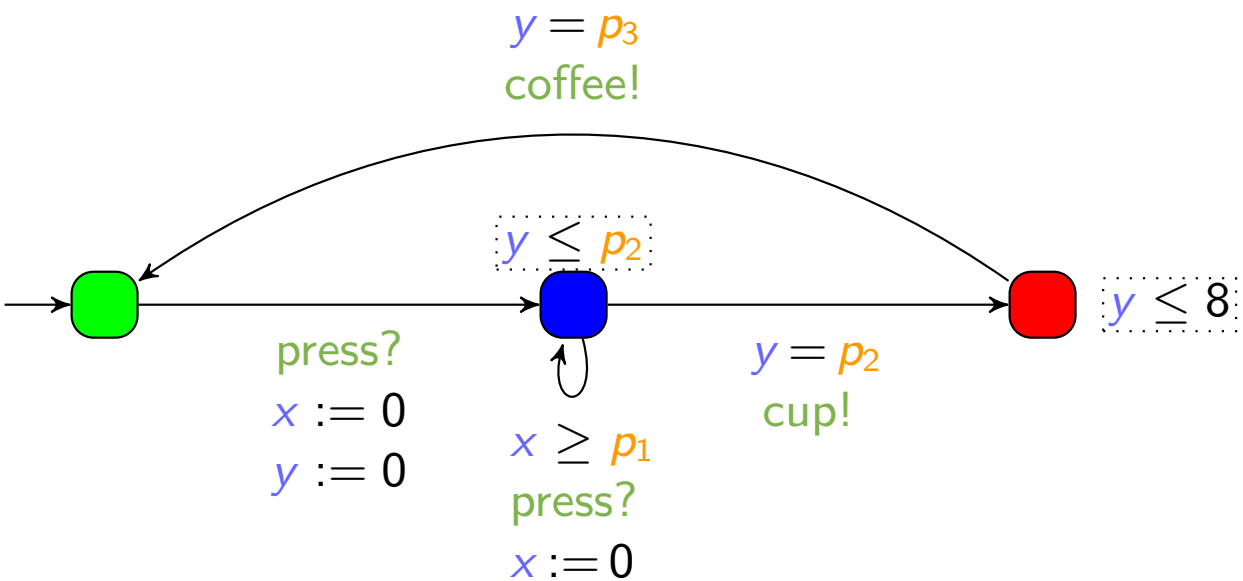
Parametric Timed Automaton (PTA)

- Timed automaton (sets of locations, actions and clocks) augmented with a set P of parameters [AHV93]
  - Unknown rational constants compared to a clock in guards and invariants



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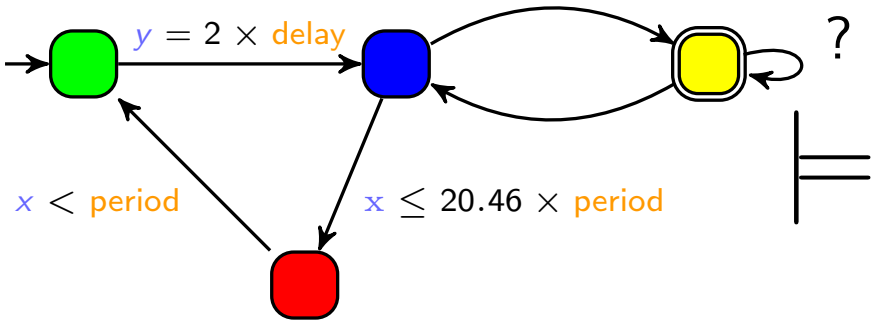

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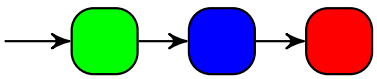
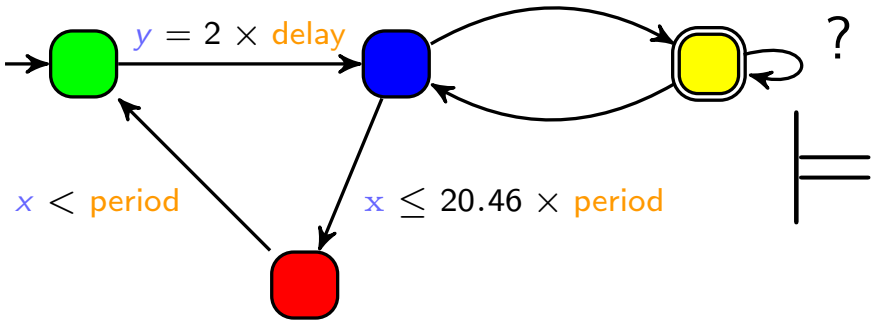


Counterexample

Parametric timed model checking



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A property to be satisfied

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

Yes if...

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

An undecidable formalism

- Parametric timed automata are very expressive
  - Most interesting problems are undecidable [AHV93]
  - Exact parameter synthesis is out of reach
    - . . . but approximated algorithms, or exact algorithms without guarantee of termination, can be proposed
  - In practice: many interesting problems can still be solved (exactly)

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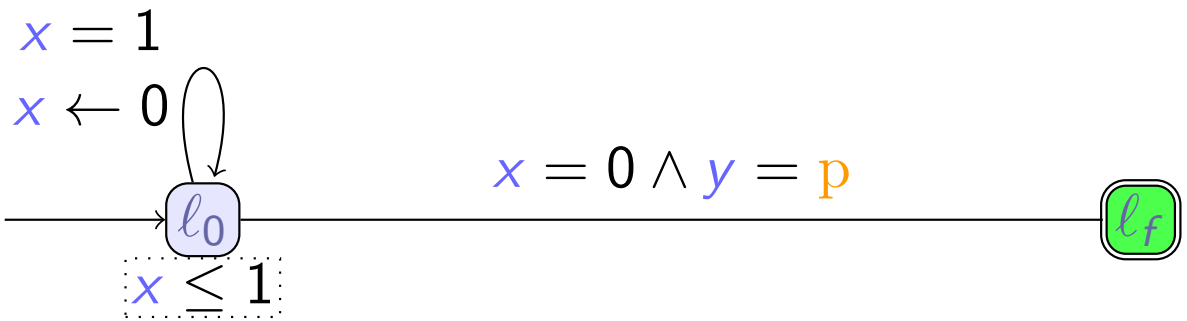
Outline

Motivation

- Test new algorithms for TAs or PTAs and check their efficiency by comparing them with existing techniques
- Improve existing techniques and tools
- Provide a set of "unsolvable" (yet very simple) benchmarks:
  - Emphasize the limits of state-of-the-art algorithms to encourage the community to address these cases

Motivation

Example of an "unsolvable" model



ℓ_f is reachable iff $\mathrm{p} \in \mathbb{N}$

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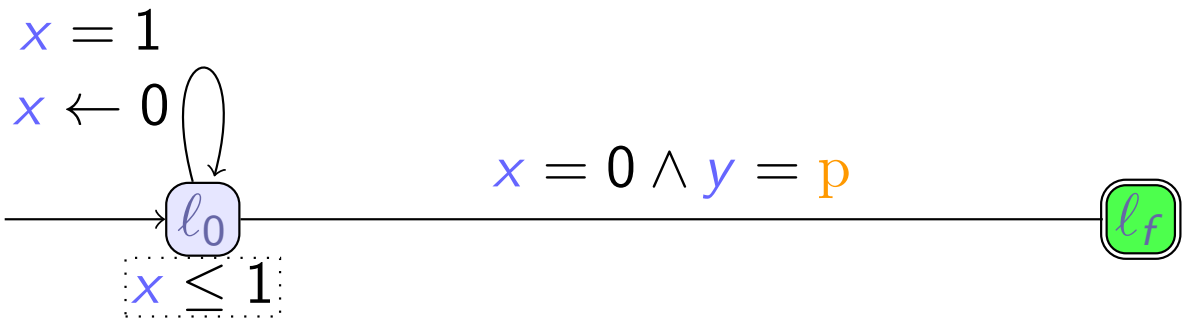

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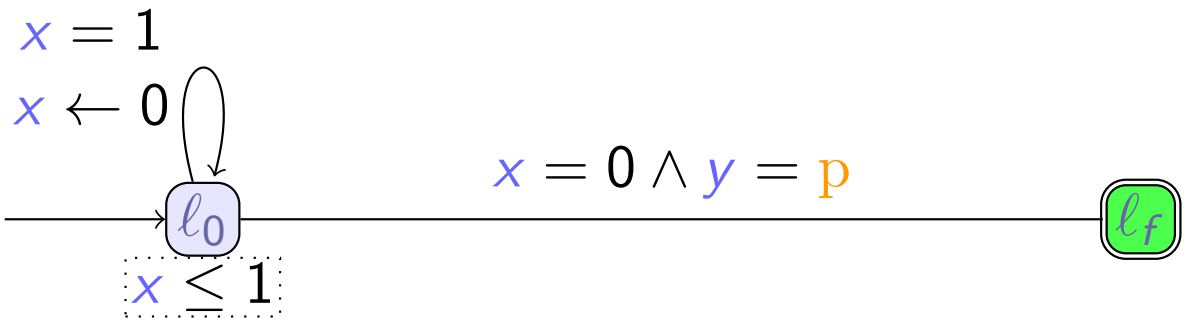

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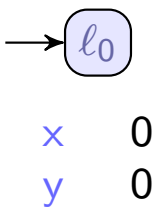

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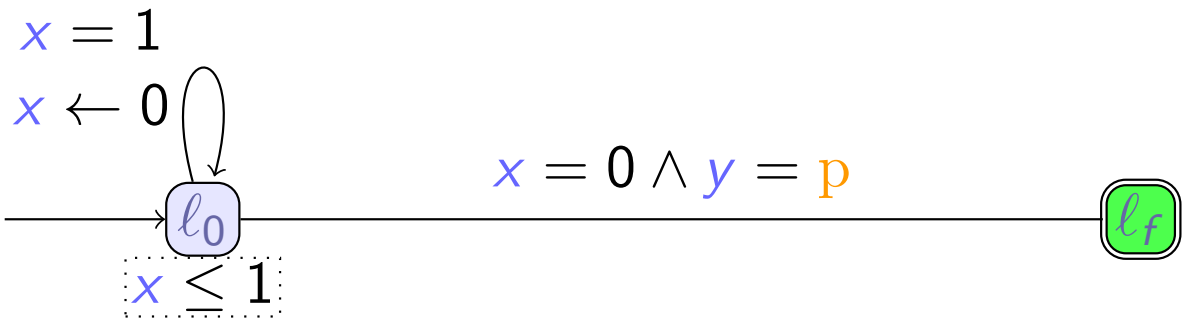

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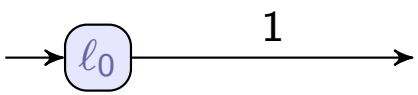

x	0
y	0

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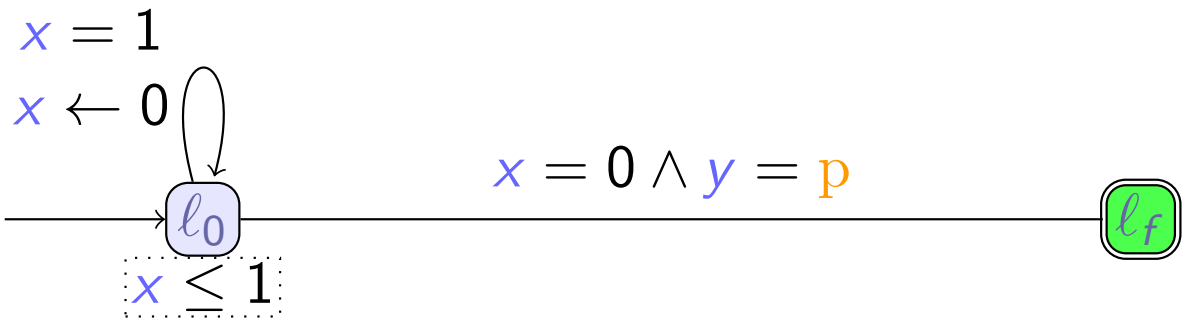

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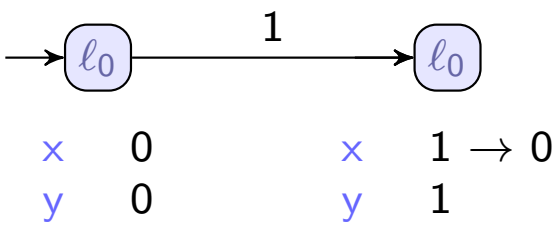

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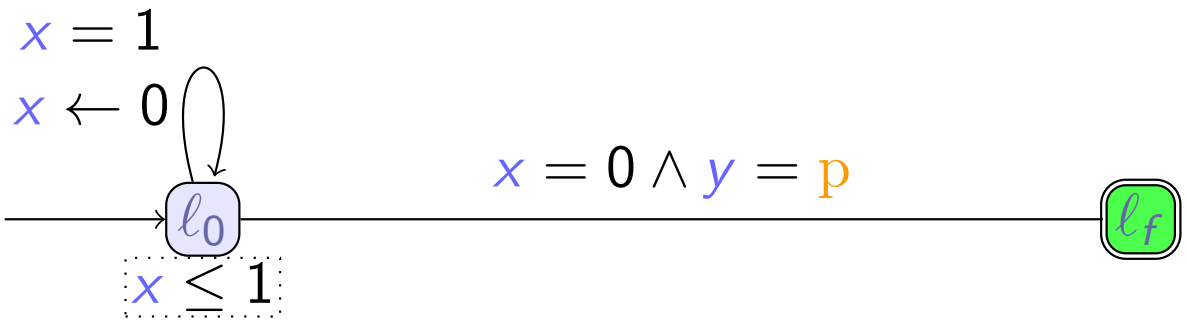

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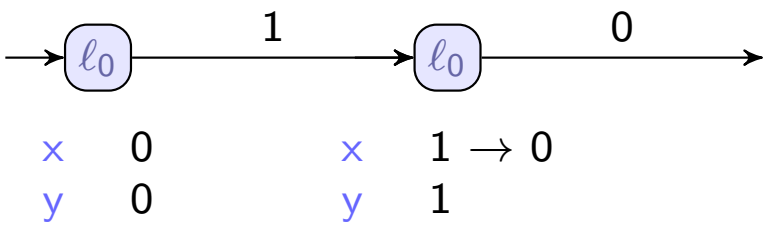

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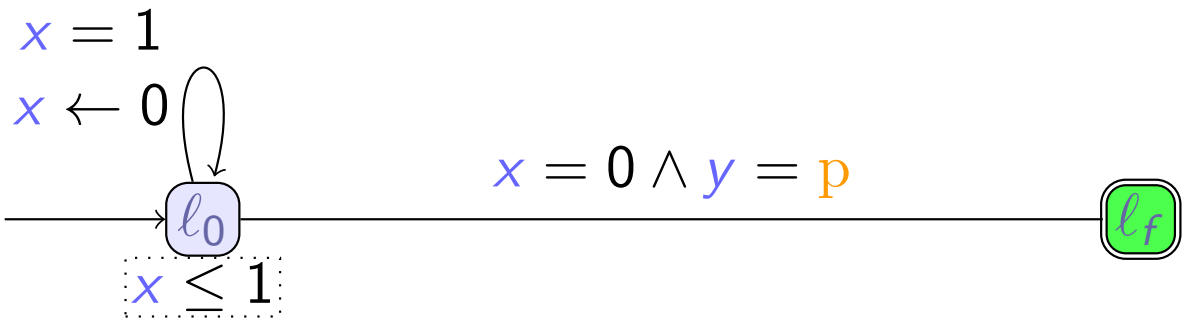

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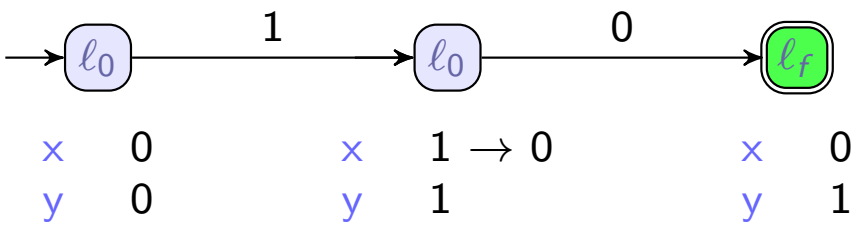

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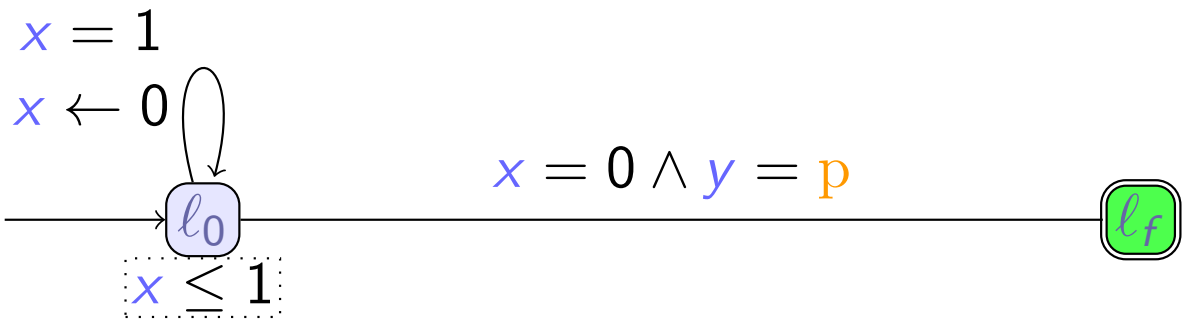

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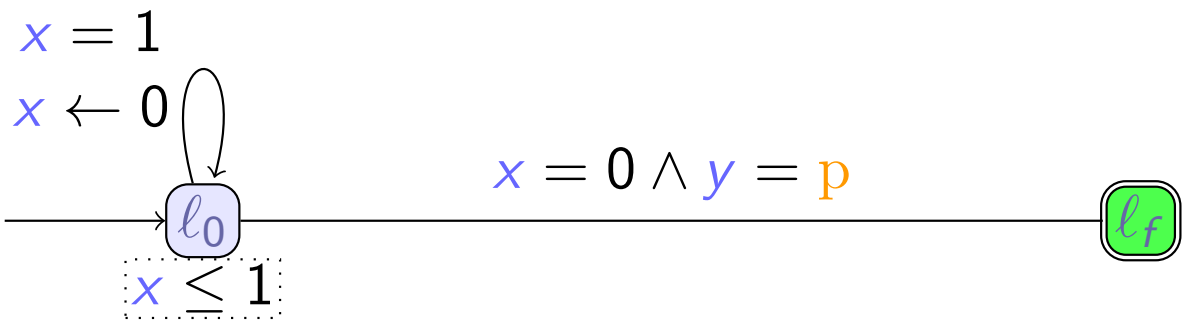

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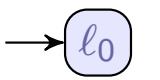

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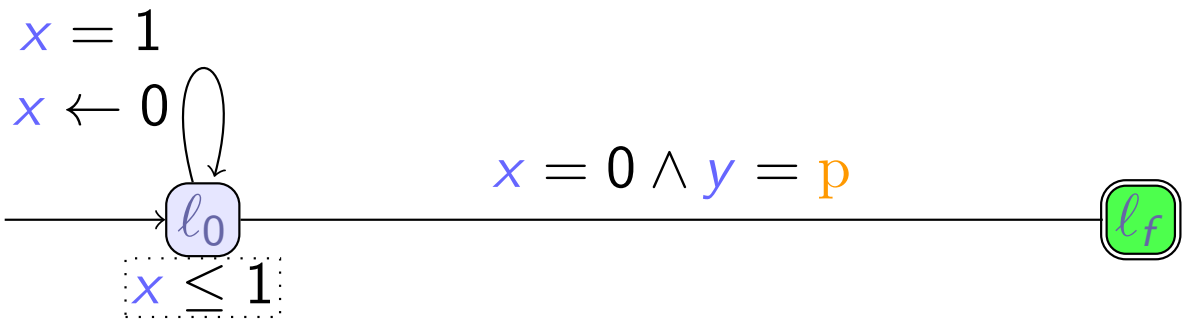

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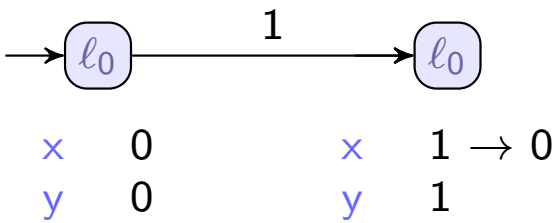

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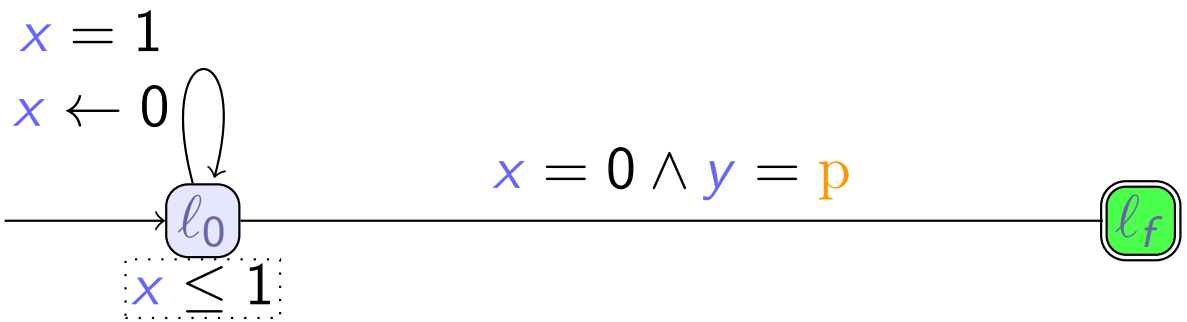

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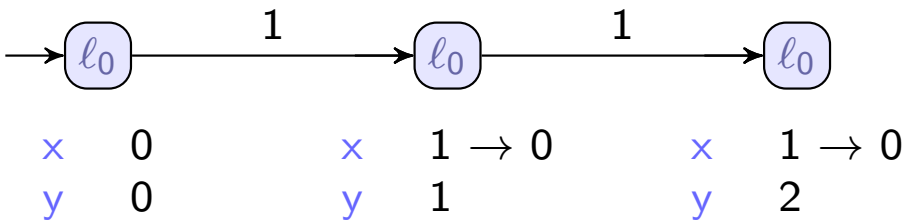

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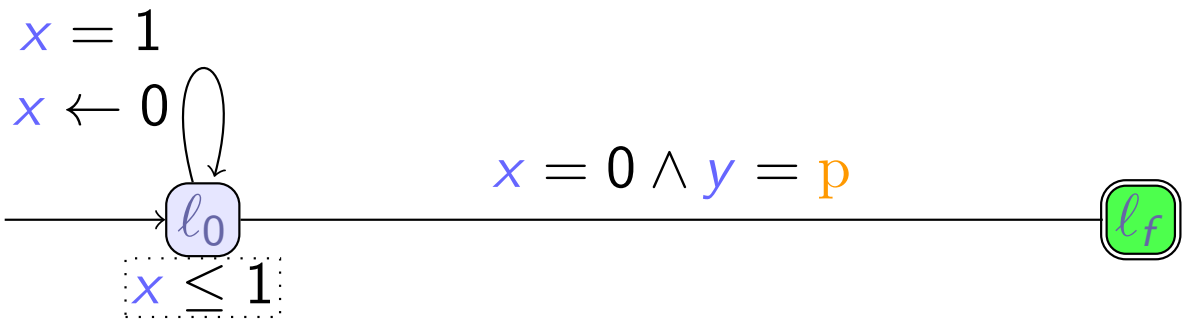

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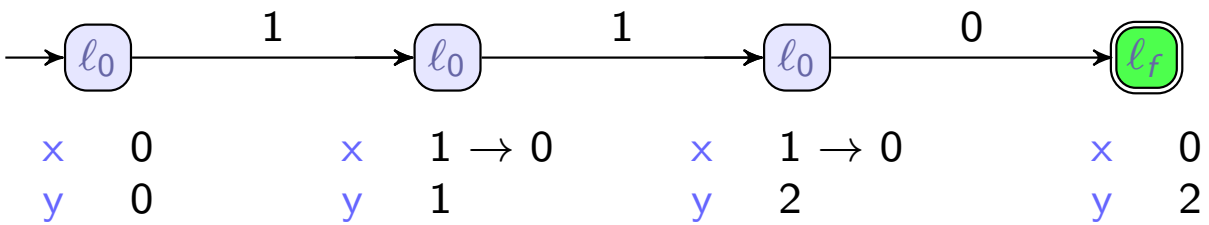

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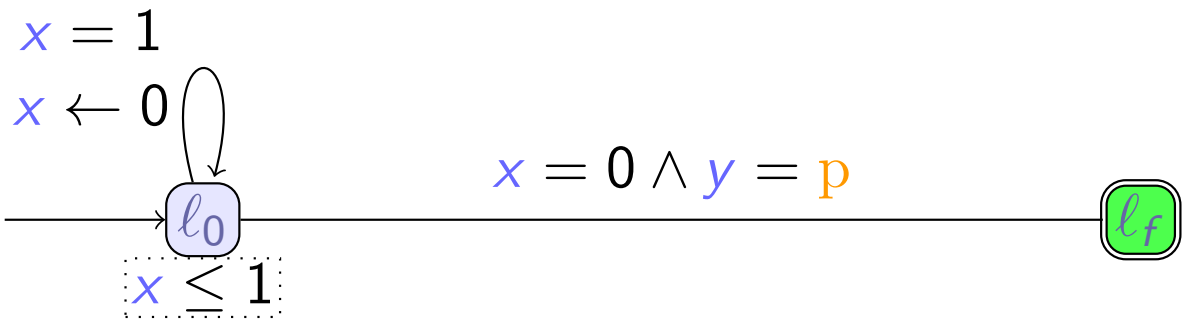

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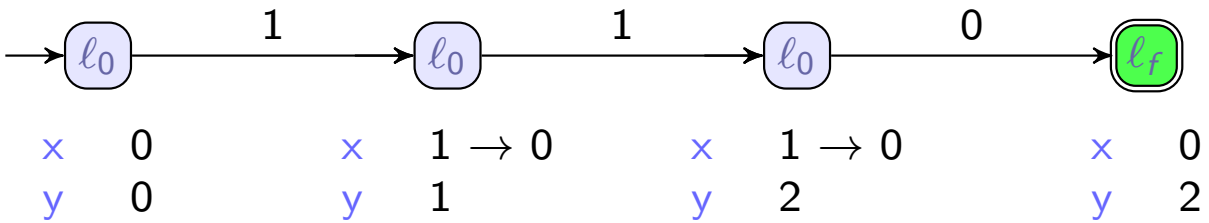

Exact synthesis (i. e., inferring $\mathrm{p} = i, i \in \mathbb{N}$) is not solvable by any existing parametric timed model checker (to the best of our knowledge)

Why a new version?

- A first library [And18] exists, but
  - the syntax is only compatible with the previous version of IMITATOR, and the former calling paradigm
  - it contains exclusively safety/reachability properties
  - only syntactic information is provided
    - No expected result

[And18] Étienne André. *The IMITATOR benchmarks library v1.0*. 2018. URL: https://www.imitator.fr/library1.html

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  - it contains exclusively safety/reachability properties
  - only syntactic information is provided
    - No expected result
- New version:
  - More benchmarks
  - Focus on liveness properties
  - Focus on unsolvable benchmarks
  - Semantic information (computation time, expected result...)

[And18] Étienne André. *The IMITATOR benchmarks library v1.0*. 2018. URL: https://www.imitator.fr/library1.html

The IMITATOR library v2

Library	Size			Metrics		Properties		
Vers.	Bench.	Models	Prop.	Static	Semantic	EF	TPS	liveness
1.0	34	80	122	√	×	√	√	×
2.0 [AMP21b]	56	119	216	√	√	√	√	√

Library	Format		Categories	Analysis
Vers.	`.imi`	Jani [Bud+17]	Unsolvable	Results
1.0	2.12	×	×	×
2.0	3.0	√	√	√

[AMP21b] Étienne André, Dylan Marinho, and Jaco van de Pol. *The IMITATOR benchmarks library v2.0*. 2021. URL: https://www.imitator.fr/static/library2/

[Bud+17] Carlos E. Budde et al. *JANI specification*. 2017. URL: https://jani-spec.org/

Origins and Provided formats

- Benchmarks come from industrial collaborations, from academic papers (from different communities), and from our experience in the field (toys, unsolvable)

- Two formats are provided:
  - The IMITATOR 3 syntax (`.imi`) [And21]
  - The `JANI Specification` translation [Bud+17]
    - A new interchange format for automata-based formalisms

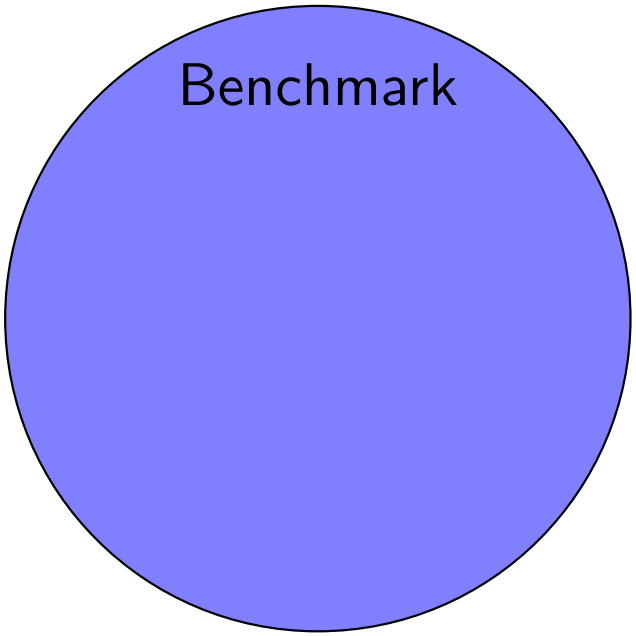
[And21] Étienne André. "IMITATOR 3: Synthesis of timing parameters beyond decidability". In: *CAV*. 2021

[Bud+17] Carlos E. Budde et al. *JANI specification*. 2017. URL: https://jani-spec.org/

Tagging our models

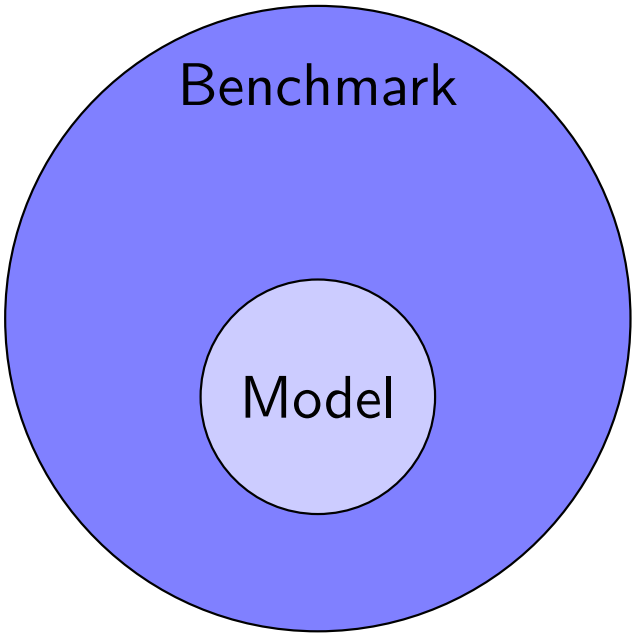
- All the benchmarks are tagged with one or more categories
- So far:
  - Academic,
  - Automotive,
  - Education,
  - Hardware,
  - Industrial,
  - Monitoring,
  - Producer-consumer,
  - Protocol,
  - Real-time system,
  - Scheduling,
  - Toy,
  - Unsolvable.

Structure of the library



Benchmark `FischerPS08`

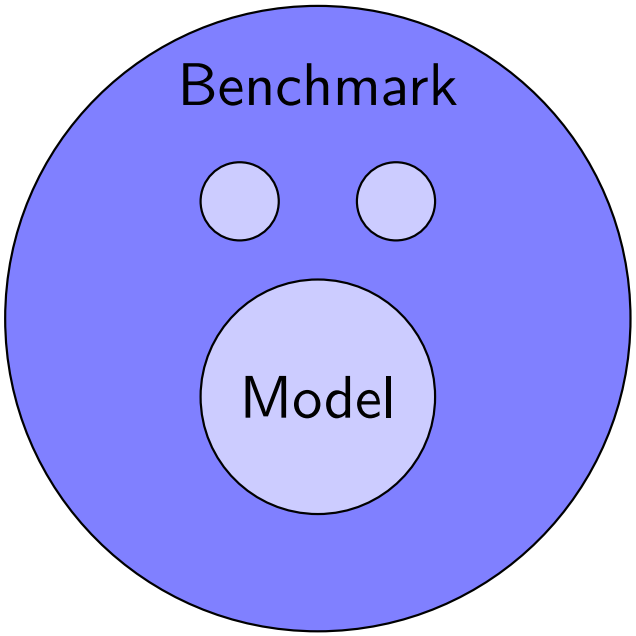
Structure of the library



Benchmark `FischerPS08`

Model `FischerPS08:2`

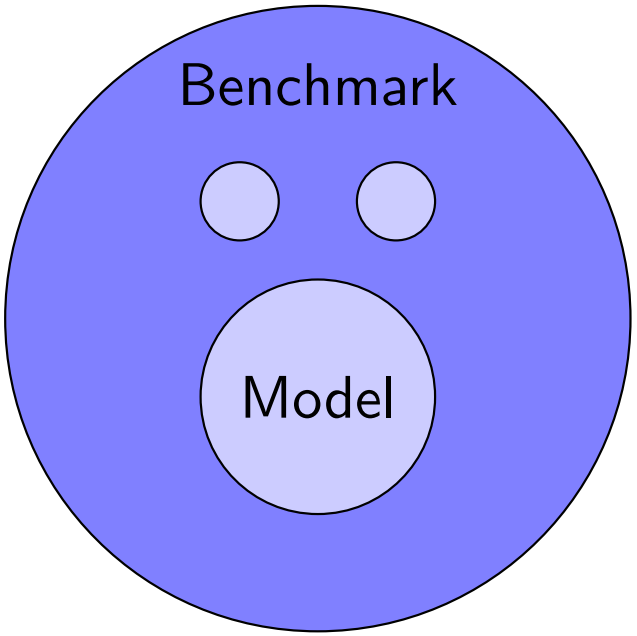
Structure of the library



Benchmark `FischerPS08`

Models `FischerPS08:2`, `FischerPS08:3`, ...

Structure of the library



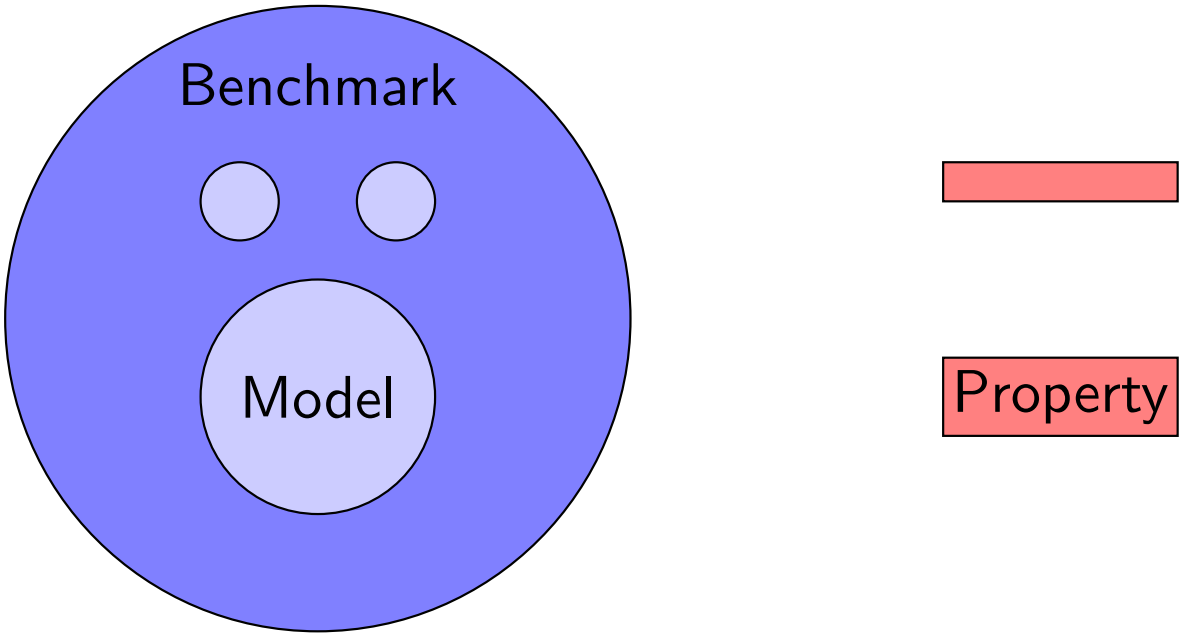
Property

Benchmark `FischerPS08`

Models `FischerPS08:2`, `FischerPS08:3`, ...

Property `FischerPS08:AGnot`

Structure of the library

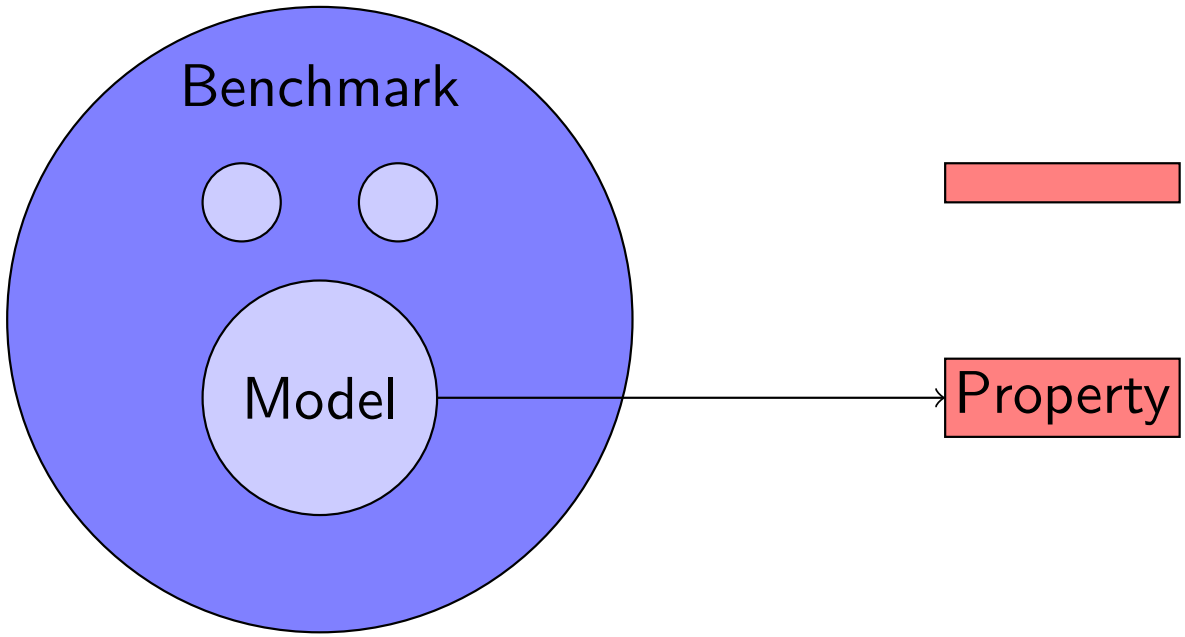


Benchmark `FischerPS08`

Models `FischerPS08:2`, `FischerPS08:3`, ...

Properties `FischerPS08:AGnot`, `FischerPS08:IM`, ...

Structure of the library



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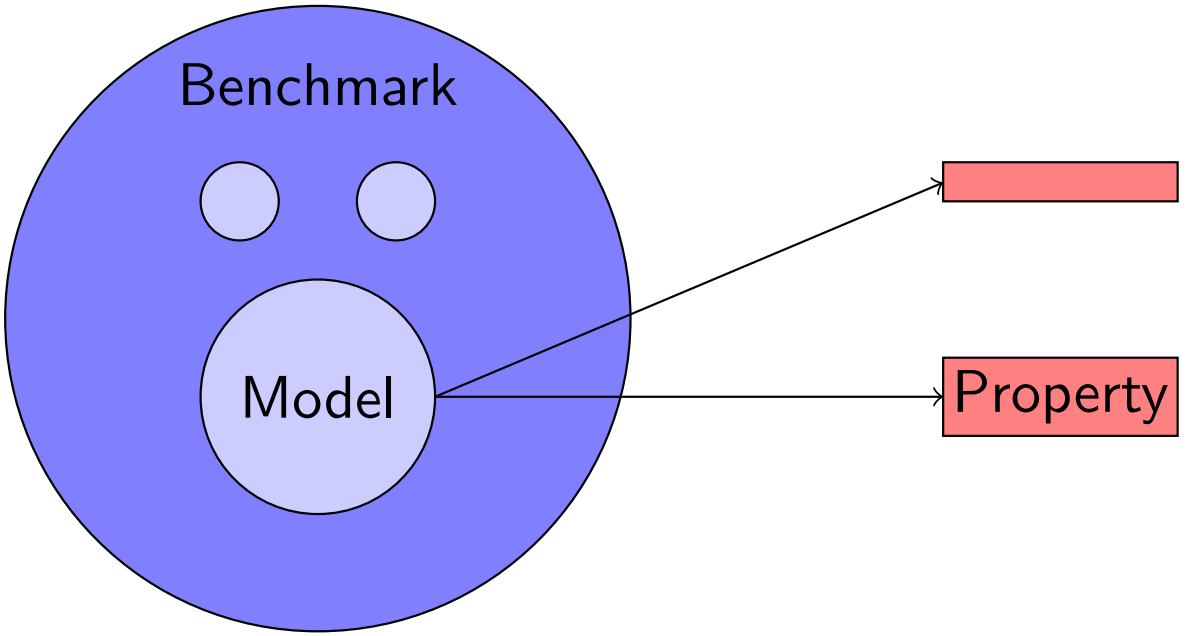

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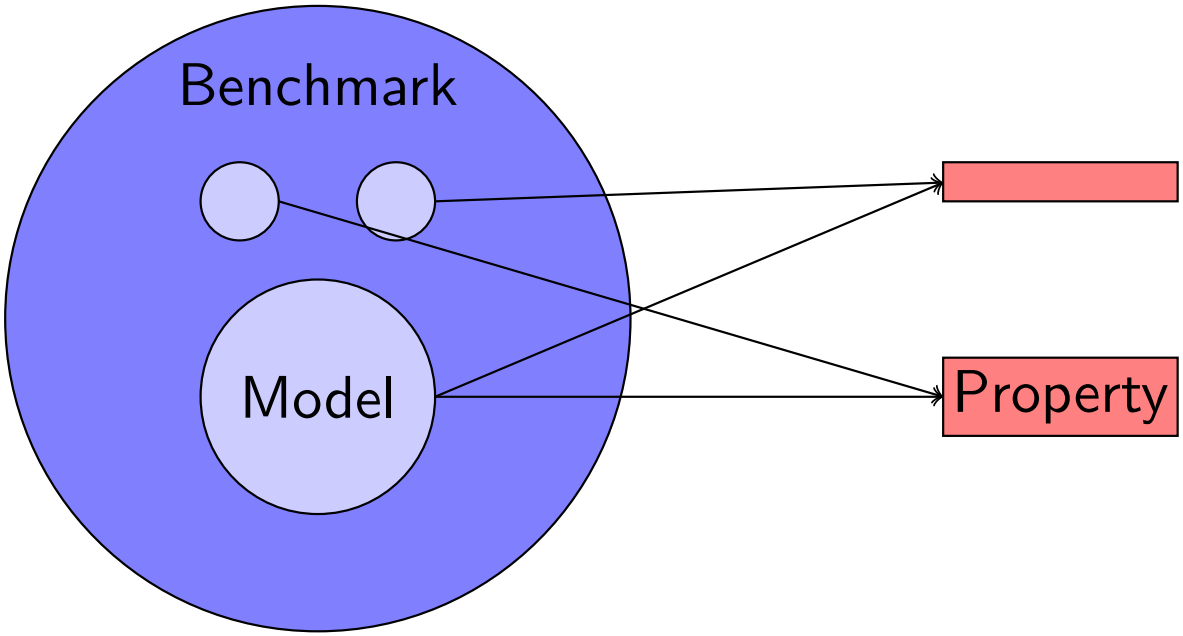

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Models `FischerPS08:2`, `FischerPS08:3`, ...

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How to select a subset of our benchmarks?

Classification	Static	Semantic
categorization	number of clocks	size of the state space
generation method	silent actions?	total computation time
scalability	...	...

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scalability	...	...

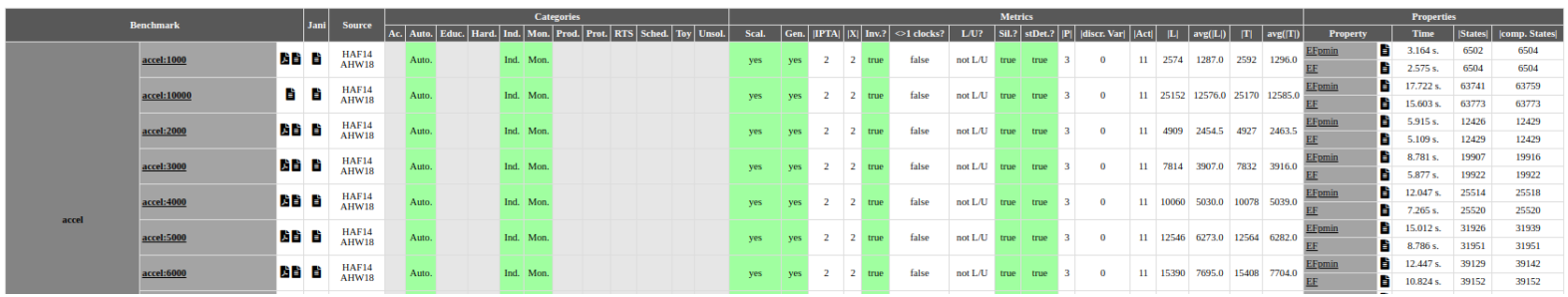
For example

Get all benchmarks

- that are scalable,
- that feature no invariant nor unobservable actions
- and for which the synthesis time is (approximately) between 10 and 60 seconds

Where to find it?

- Initial version DOI [AMP21a]
- A webpage (updated version) [AMP21b]



Benchmark		Jani	Source	Categories												Metrics														Properties			
				Ac.	Auto.	Educ.	Hard.	Ind.	Mon.	Prod.	Prot.	RTS	Sched.	Toy	Unsol.	Scal.	Gen.	|IPTA|	|X|	Inv.?	<>1 clocks?	L/U?	Sil.?	stDet.?	|P|	|discr. Var|	|Act|	|L|	avg(|L|)	|T|	avg(|T|)	Property	Time	|States|	|comp. States|
accel	accel:1000		HAF14 AHW18		Auto.			Ind.	Mon.							yes	yes	2	2	true	false	not L/U	true	true	3	0	11	2574	1287.0	2592	1296.0	EFomin	3.164 s.	6502	6504
																																EF	2.575 s.	6504	6504
	accel:10000		HAF14 AHW18		Auto.			Ind.	Mon.							yes	yes	2	2	true	false	not L/U	true	true	3	0	11	25152	12576.0	25170	12585.0	EFomin	17.722 s.	63741	63759
																																EF	15.603 s.	63773	63773
	accel:2000		HAF14 AHW18		Auto.			Ind.	Mon.							yes	yes	2	2	true	false	not L/U	true	true	3	0	11	4909	2454.5	4927	2463.5	EFomin	5.915 s.	12426	12429
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	accel:3000		HAF14 AHW18		Auto.			Ind.	Mon.							yes	yes	2	2	true	false	not L/U	true	true	3	0	11	7814	3907.0	7832	3916.0	EFomin	8.781 s.	19907	19916
																																EF	5.877 s.	19922	19922
	accel:4000		HAF14 AHW18		Auto.			Ind.	Mon.							yes	yes	2	2	true	false	not L/U	true	true	3	0	11	10060	5030.0	10078	5039.0	EFomin	12.047 s.	25514	25518
																																EF	7.265 s.	25520	25520
	accel:5000		HAF14 AHW18		Auto.			Ind.	Mon.							yes	yes	2	2	true	false	not L/U	true	true	3	0	11	12546	6273.0	12564	6282.0	EFomin	15.012 s.	31926	31939
																																EF	8.786 s.	31951	31951
	accel:6000		HAF14 AHW18		Auto.			Ind.	Mon.							yes	yes	2	2	true	false	not L/U	true	true	3	0	11	15390	7695.0	15408	7704.0	EFomin	12.447 s.	39129	39142
																																EF	10.824 s.	39152	39152

- with the static and semantic metrics
- with expected results (if exist)

[AMP21a] Étienne André, Dylan Marinho, and Jaco van de Pol. *The IMITATOR benchmarks library 2.0: A benchmarks library for extended parametric timed automata*. Apr. 2021. DOI: 10.5281/zenodo.4730980

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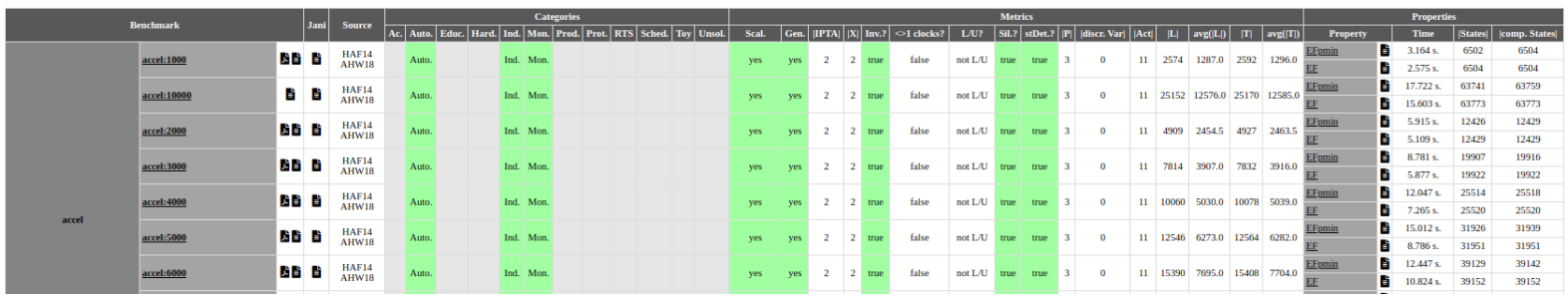

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We are open to new model submissions!

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Future work

- Keep enlarging the library using future benchmarks, and future synthesis algorithms
  - Add "difficulty" score to benchmarks (from easy to unsolvable)
- Bindings with other libraries, e. g.,
  - share a non-parametric version of PTAs to TAs libraries
  - integrate benchmarks from hybrid automata libraries to ours when the expressiveness is compatible
- Develop translations to other model checkers: e. g.,
  - `Uppaal` [LPY97] (non-parametric timed automata)
  - `SpaceEx` [Fre+11] (hybrid systems)
  - `Roméo` [Lim+09] (parametric time Petri nets)

[LPY97] Kim Guldstrand Larsen, Paul Pettersson, and Wang Yi. "UPPAAL in a Nutshell". In: *International Journal on Software Tools for Technology Transfer* 1.1-2 (1997), pp. 134–152

[Fre+11] Goran Frehse et al. "SpaceEx: Scalable Verification of Hybrid Systems". In: *CAV*. vol. 6806. Lecture Notes in Computer Science. Springer, 2011, pp. 379–395

[Lim+09] Didier Lime et al. "Romeo: A Parametric Model-Checker for Petri Nets with Stopwatches". In: *TACAS*. vol. 5505. Lecture Notes in Computer Science. Springer, Mar. 2009, pp. 54–57

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