PhD defense

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Nancy, France

Theoretical and algorithmic contributions to the analysis of safety and security properties in timed systems under uncertainty

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Motivation

- Real-time systems:
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Execution time: $\epsilon + \epsilon + \epsilon$

- Problem: The execution time is proportional to the number of consecutive correct characters from the beginning of `attempt`

Timing attacks

- Principle: deduce private information from timing data (execution time)

Issues:

- May depend on the implementation (or, even worse, be introduced by the compiler)
- A relatively trivial solution: make the program last always its maximum execution time
  Drawback: loss of efficiency

$\rightsquigarrow$ Non-trivial problem

Detection

Need to detect timing-leak vulnerabilities

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- Various methods:
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  - Static analysis
  - Model checking
  - Theorem proving

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Methodology

A program

A specification

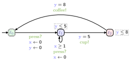
“The program must be secure”

Methodology

A program

→

A model



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A property

"Is the program secure?"

Methodology

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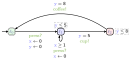

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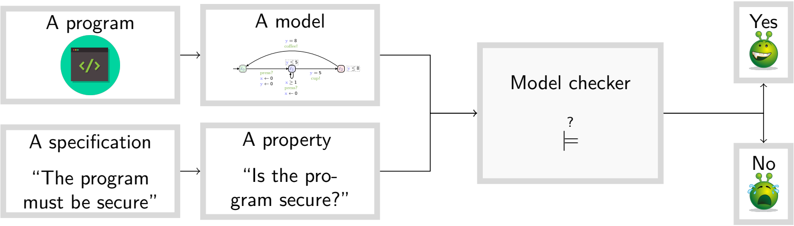
Model checker

$\stackrel{?}{\models}$

Methodology



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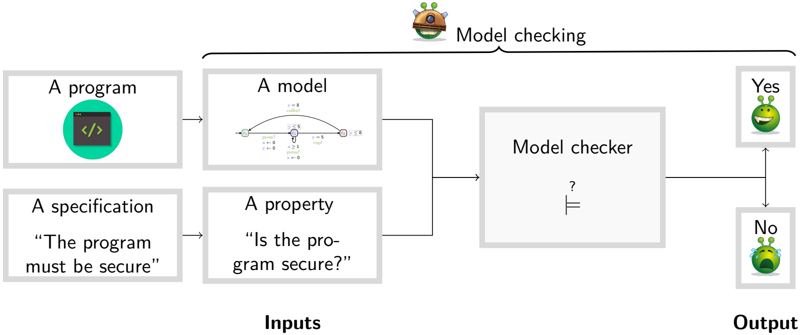

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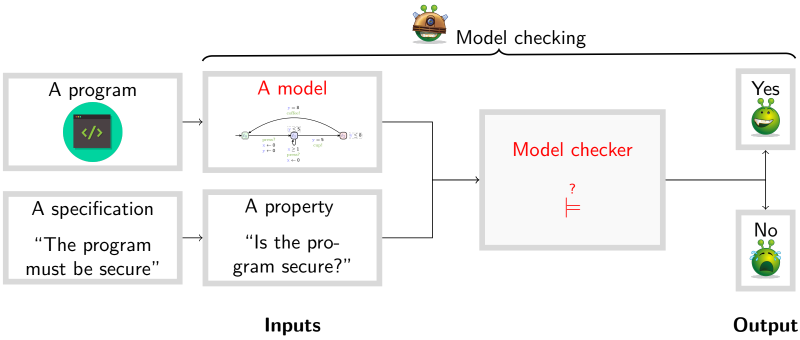

Outline

1. Preliminaries: Timed model checking

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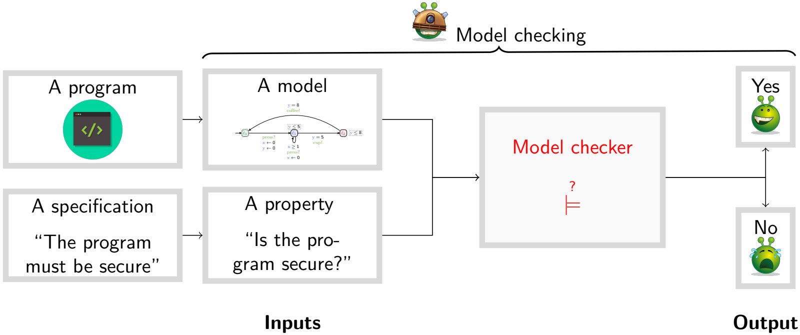

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2. Contribution: Efficient verification (Manuscript, Part I)

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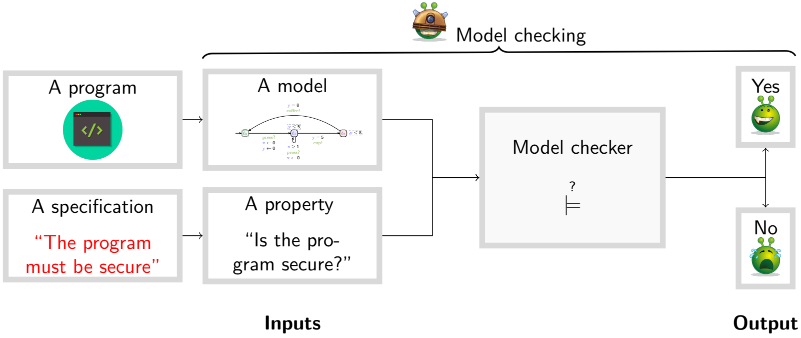

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2. Contribution: Efficient verification (Manuscript, Part I)
3. Contribution: Execution-time opacity (Manuscript, Part II)

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Preliminaries: (Parametric) Timed model checking

Contribution: Efficient verification in Parametric Timed Automata

Contribution: Execution-time opacity

Conclusion & Perspectives

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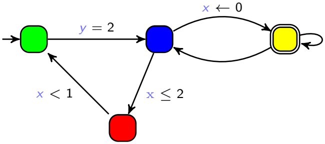
- Preliminaries: (Parametric) Timed model checking
  - Timed model checking and Timed automata
  - Parametric timed model checking and Parametric timed automata
- Contribution: Efficient verification in Parametric Timed Automata
- Contribution: Execution-time opacity
- Conclusion & Perspectives

Timed model checking

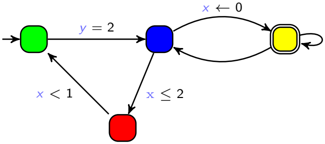


A model of the system

 is unreachable

A property to be satisfied

Timed model checking



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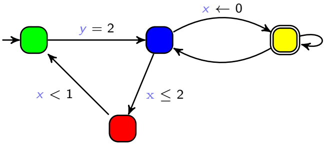

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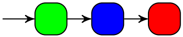
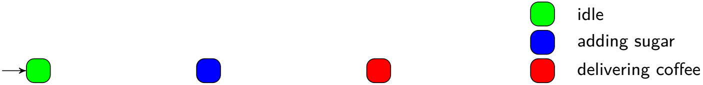


Counterexample

Timed automaton (TA)

[AD94]

- Finite state automaton (sets of locations)



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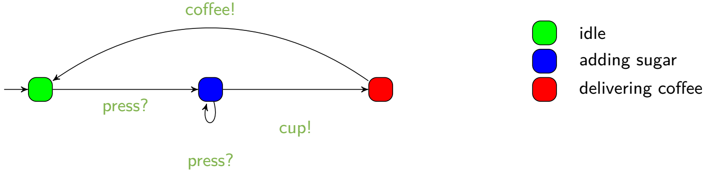

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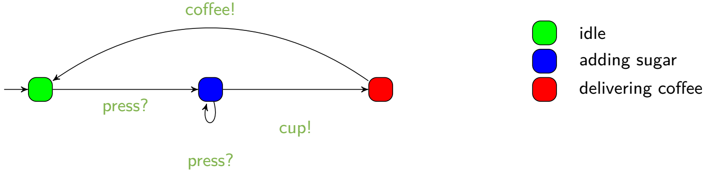

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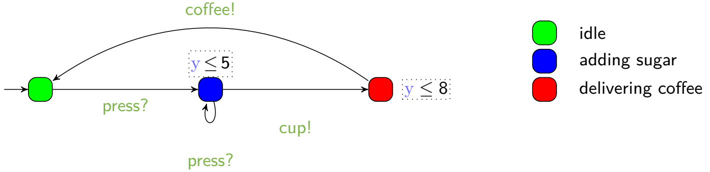

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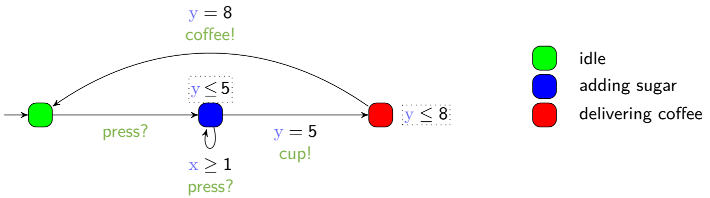

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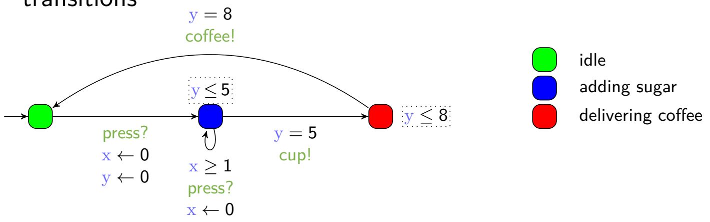
  - Clock reset: some of the clocks can be set to 0 along transitions



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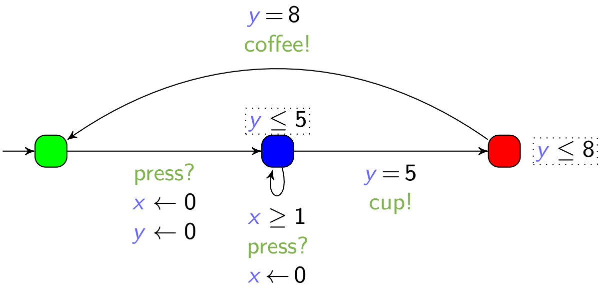
Timed Automaton (PTA)

[AHV93]

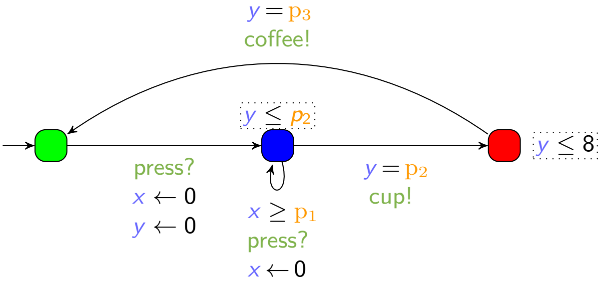
- Timed automaton (sets of locations, actions and clocks)



Parametric Timed Automaton (PTA)

[AHV93]

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



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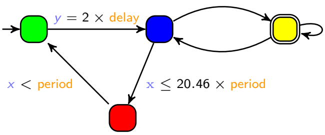

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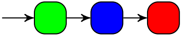
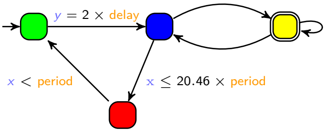


Counterexample

Parametric timed model checking



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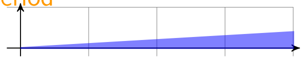
- Question: for what values of the parameters does the model of the system satisfy the property?

Yes if...



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

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- Given a PTA $\mathcal{P}$ and a parameter valuation v,
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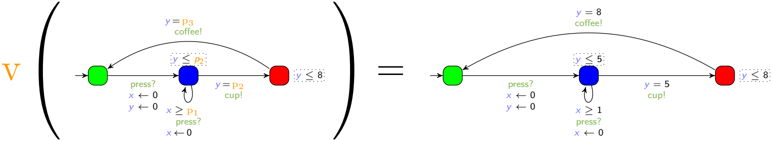

$$\text{with } v : \begin{cases} p_1 & \rightarrow & 1 \\ p_2 & \rightarrow & 5 \\ p_3 & \rightarrow & 8 \end{cases}$$

Parametric Zone Graph (PZG)

- Parametric extension zone graph of TAs
- **Symbolic state**: a pair with
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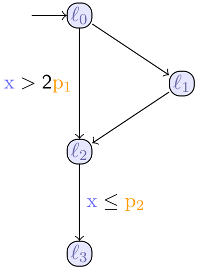

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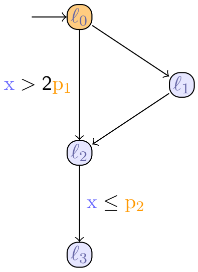

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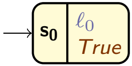

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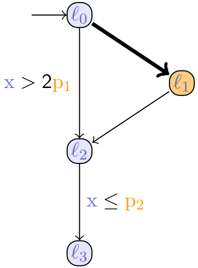

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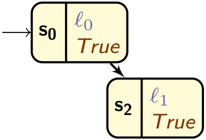

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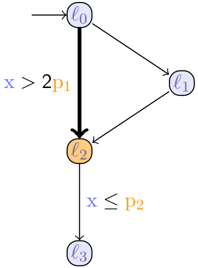

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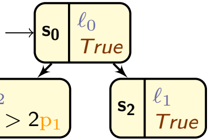

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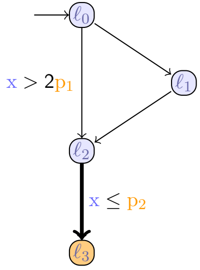

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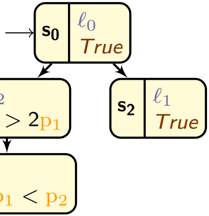

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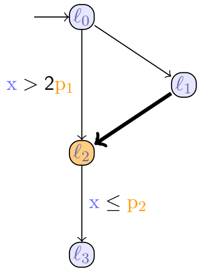

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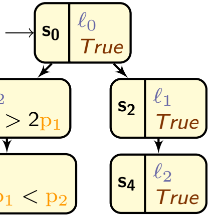

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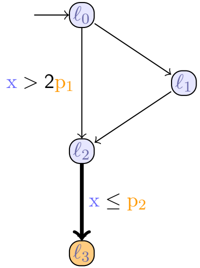

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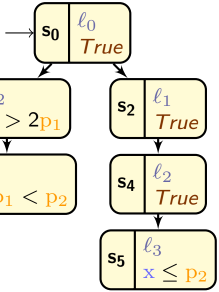

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Contribution: Efficient verification of PTA models

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- Efficient verification
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Contributions

- Benchmark library [TAP21]
- Zone merging algorithm [FORMATS22]

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Merging states

Definition

Two states (, $\mathbf{C}_1$) and (, $\mathbf{C}_2$) are mergeable if:

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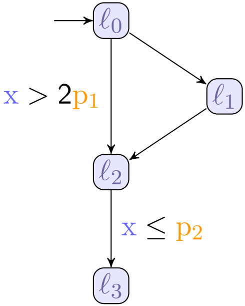
$\rightarrow$ Contribution: Extension to reachability properties

Constructing the PZG with merging algorithm

When constructing a new state, check if it can be merged



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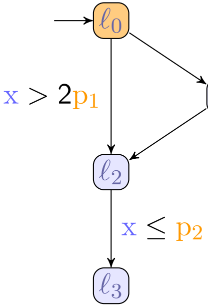

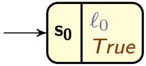

Constructing the PZG with merging algorithm

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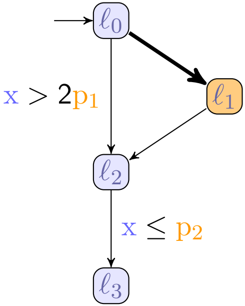

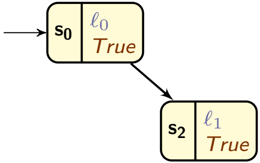

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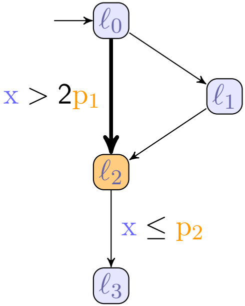

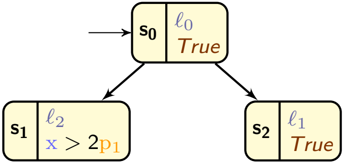

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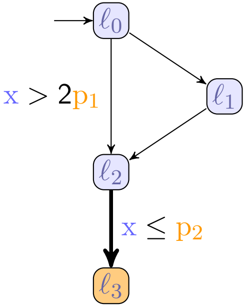

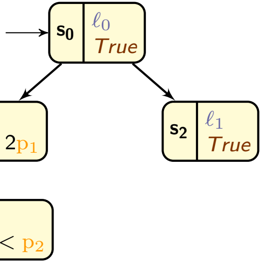

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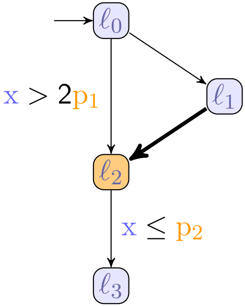

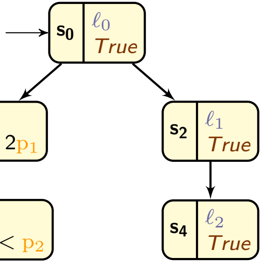

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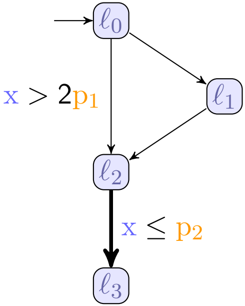

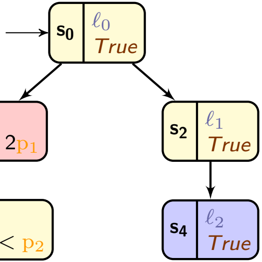

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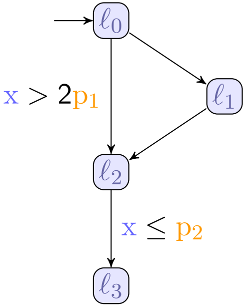

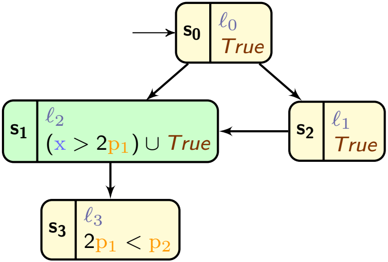

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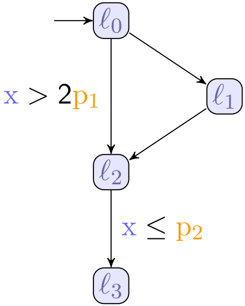

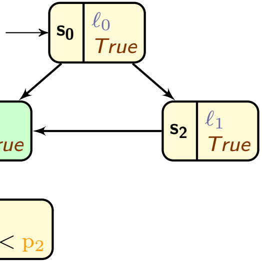

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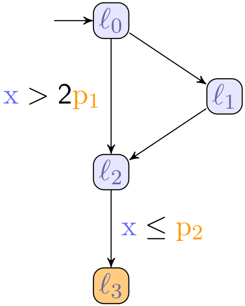

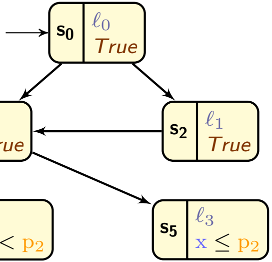

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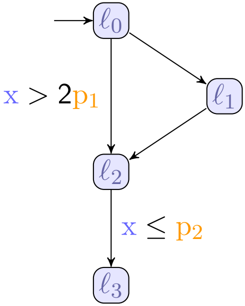

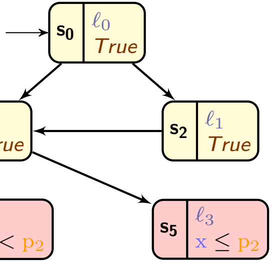

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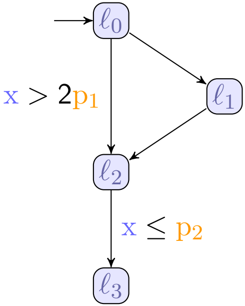
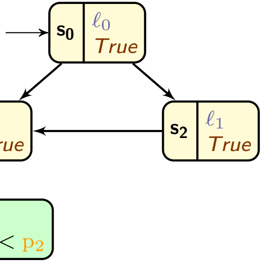
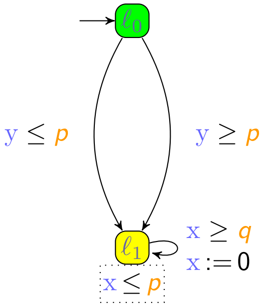
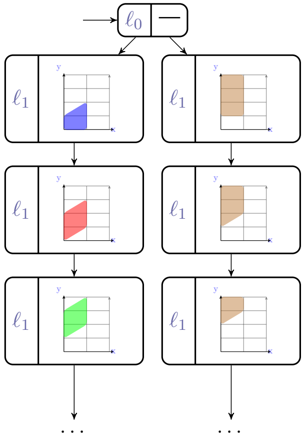




Merging can make difference for termination!

PZG without any heuristic





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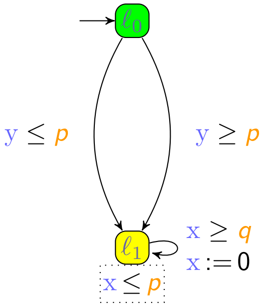
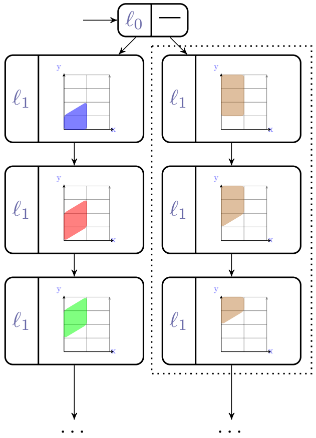
PZG with inclusion





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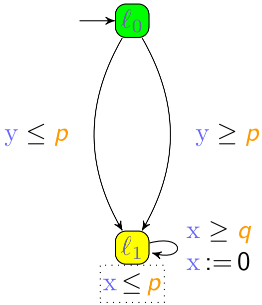

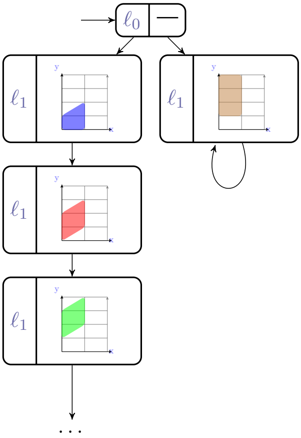

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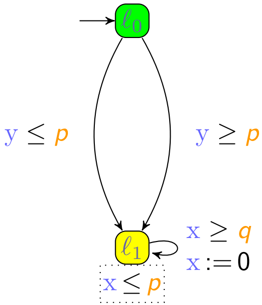
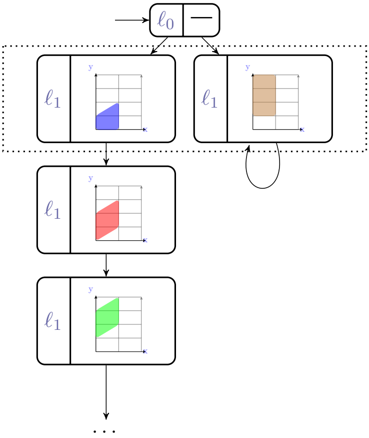
PZG with merging





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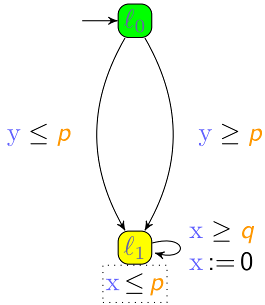
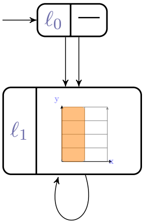
PZG with merging





Preservation of properties

Theorem

Merging states while computing the PZG is correct for reachability properties

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Implementation

In a model-checker with heuristics

Heuristics for merging

What to merge with what? Queue, Visited, Ordered

Restart after merge?

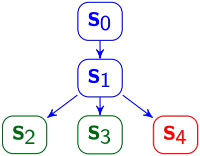
When to update the state space?

- After each merge
- After exploring the candidates list
- After exploring a level

How to update the state space?

- Reconstruction of the state-space
- *In situ*

Illustration of the merging options



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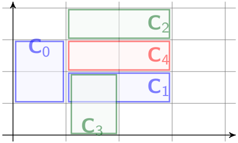

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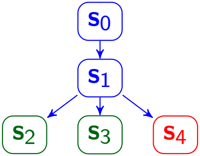

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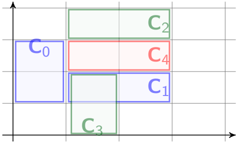

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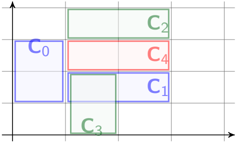

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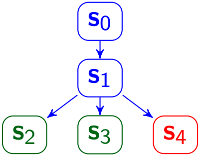

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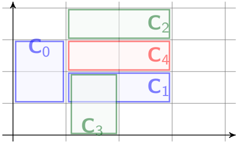

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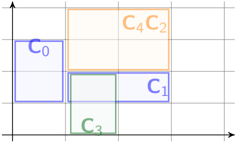

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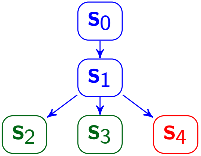

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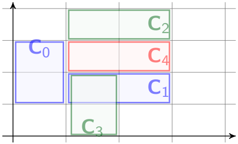

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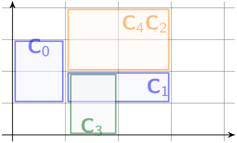

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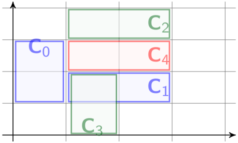

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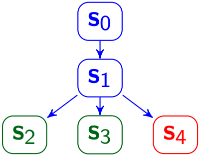

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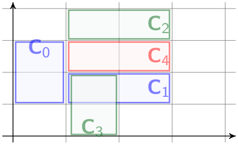

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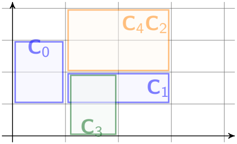

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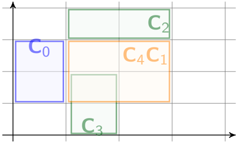

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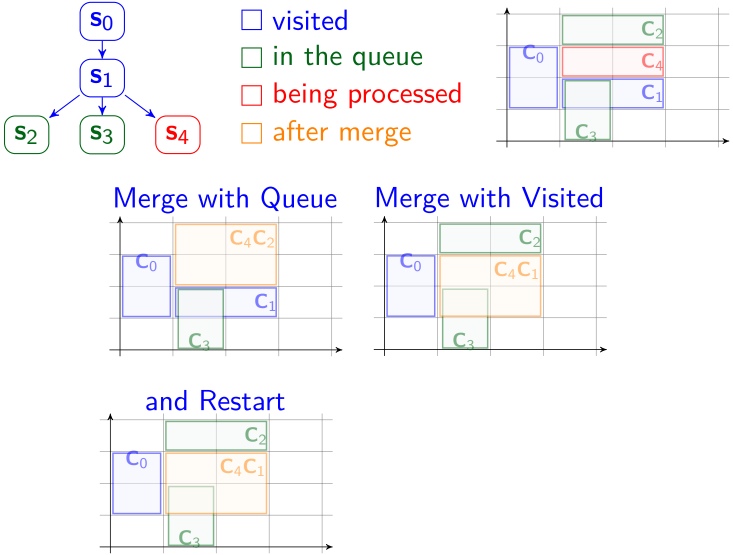

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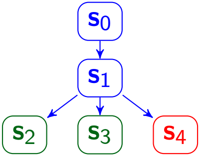

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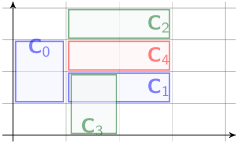

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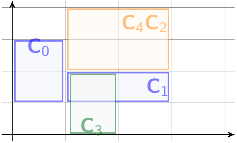

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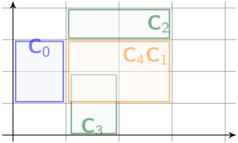
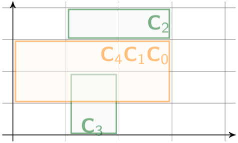


and Restart



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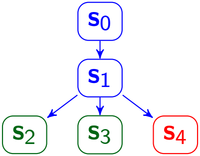

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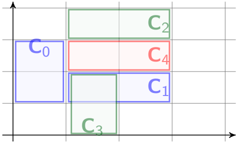

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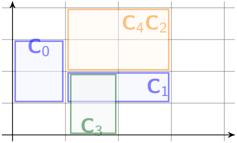

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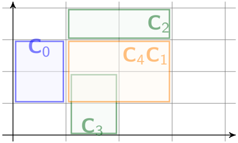

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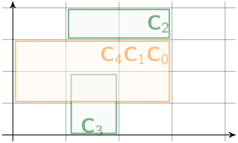

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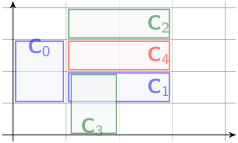

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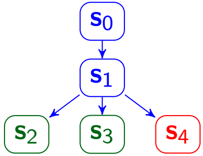

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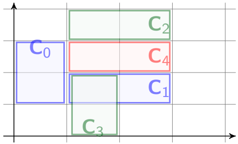

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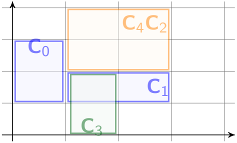

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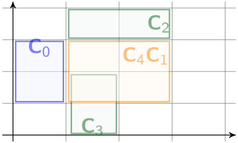

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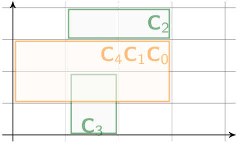

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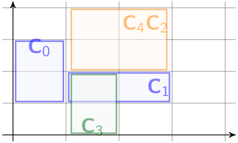

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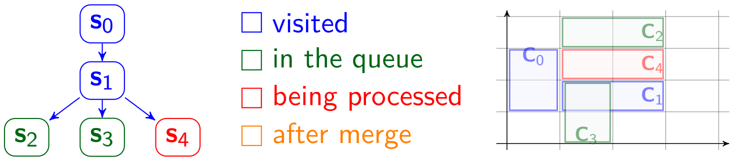

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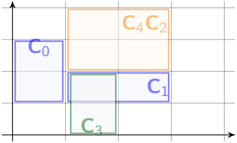

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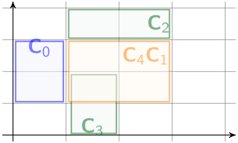
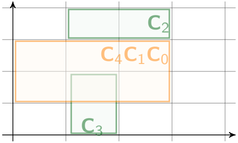
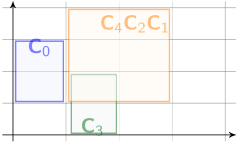


and Restart



Queue ; Visited



Outline

Preliminaries: (Parametric) Timed model checking

Contribution: Efficient verification in Parametric Timed Automata

- Merging Zones
- Experiments & Results

Contribution: Execution-time opacity

Conclusion & Perspectives

Experiments

- Comparison of all the combinations of heuristics
- Use of the IMITATOR library, restricted to reachability-based properties [TAP21]:
  - 124 executions (model, reachability property)
  - 42 executions perform at least one merge

[TAP21] Étienne André, Dylan Marinho, and Jaco van de Pol. "A Benchmarks Library for Extended Parametric Timed Automata". In: *TAP* (2021). LNCS. Springer, 2021

The IMITATOR benchmark library

Overview of Chapter 4 of the manuscript

Library	Size		
Vers.	Bench.	Models	Prop.
1.0	34	80	122
2.0	56	119	216

Contribution

- More benchmarks (publications, industrial collaborations, …)
- Inclusion of liveness properties, unsolvable benchmarks
- Export to JANI
- Semantic information (computation time, expected result…)
- Published as long-term access

imitator.fr/library2
DOI 10.5281/zenodo.4730980

[TAP21] Étienne André, Dylan Marinho, and Jaco van de Pol. "A Benchmarks Library for Extended Parametric Timed Automata". In: *TAP* (2021). LNCS. Springer, 2021

Comparing merging heuristics: Results

		Nomerge	RVMr	OQM
Time	# wins	24	22	**42**
	Avg (s)	10.0	4.56	**3.77**
	Avg (merge) (s)	18.8	5.57	**3.63**
	Avg (no merge) (s)	3.83	3.85	3.88
	Median (s)	1.39	1.14	**1.12**
States	# wins	0	**37**	16
	Avg	11443.08	**11064.37**	11120.79
	Avg (merge)	1512.02	**592.31**	729.33
	Median	2389.5	**604.5**	905.0

Gain of 62% of the average computation time

Outline

Contribution: Execution-time opacity

- How to detect timing-leak vulnerabilities?

Contribution: Execution-time opacity

- How to detect timing-leak vulnerabilities?

Goal

- Propose a formalization of the private information and attacker model
- Check whether a model is secure or not

Contribution: Execution-time opacity

- How to detect timing-leak vulnerabilities?

Goal

- Propose a formalization of the private information and attacker model
- Check whether a model is secure or not

Contributions

- ET-opacity definition, decidability results and experiments [TOSEM22]
- Expiring ET-opacity definition and decidability results [ICECCS23]
- Untimed control [FTSCS22]

Our attacker model

Attacker capabilities

- Has access to the model (white box)
- Can only observe the total execution time

Our attacker model

Attacker capabilities

- Has access to the model (white box)
- Can only observe the total execution time

Attacker goal

- Wants to deduce some private information based on these observations
  $\rightarrow$ visit of a private location

Outline

Preliminaries: (Parametric) Timed model checking

Contribution: Efficient verification in Parametric Timed Automata

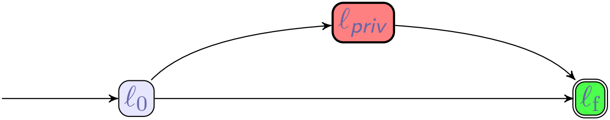
Contribution: Execution-time opacity
- ET-opacity problems in TAs
- ET-opacity problems in PTAs
- Expiring ET-opacity problems
- Untimed control

Conclusion & Perspectives

Formalization

Hypotheses: [AS19][TOSEM22]

- A start location ℓ_0 and an end location ℓ_f
- A special private location ℓ_{priv}



[TOSEM22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun. "Guaranteeing Timed Opacity using Parametric Timed Model Checking". In: *ACM TOSEM* (2022)

Formalization

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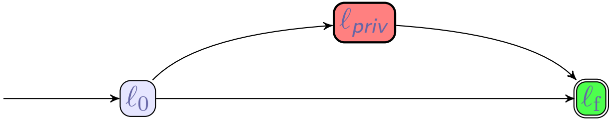


Definition (execution-time opacity)

The system is ET-opaque for a duration d if there exist two runs to ℓ_f of duration d

1. one visiting ℓ_{priv}
2. one *not* visiting ℓ_{priv}

[TOSEM22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun. "Guaranteeing Timed Opacity using Parametric Timed Model Checking". In: *ACM TOSEM* (2022)

Three levels of ET-opacity

Existential (∃)

There exist a duration d and two runs of duration d,
one visiting ℓ_{priv},
one not visiting ℓ_{priv}

Three levels of ET-opacity

Existential (∃)

private durations $\cap$ public durations $\neq \emptyset$

Three levels of ET-opacity

Existential (∃)

private durations $\cap$ public durations $\neq \emptyset$

Weak

For all durations d,
There exists a run of duration d visiting ℓ_{priv}
$\Rightarrow$
There exists a run of duration d not visiting ℓ_{priv}

Three levels of ET-opacity

Existential (∃)

private durations ∩ public durations $\neq \emptyset$

Weak

For all durations d,
There exists a run of duration d visiting ℓ_{priv}
$\Rightarrow$
There exists a run of duration d not visiting ℓ_{priv}

Full

For all durations d,
There exists a run of duration d visiting ℓ_{priv}
$\Leftrightarrow$
There exists a run of duration d not visiting ℓ_{priv}

Three levels of ET-opacity

Existential ($\exists$)

private durations $\cap$ public durations $\neq \emptyset$

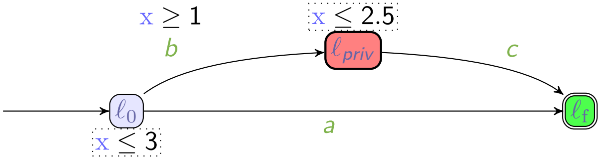
Weak

private durations $\subseteq$ public durations

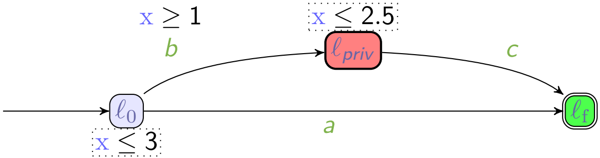
Full

private durations $=$ public durations

Example

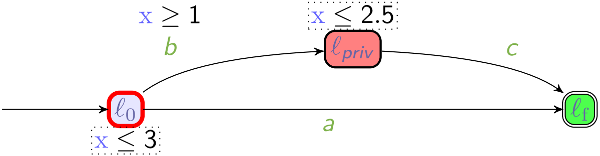


Example



- There exist *(at least)* two runs of duration $d = 2$:

Example



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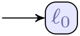
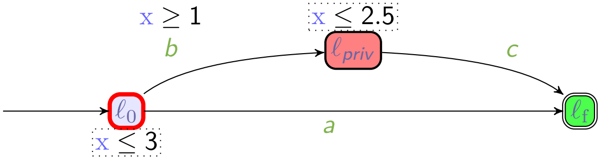
visiting ℓ_{priv}



Example



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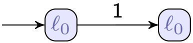

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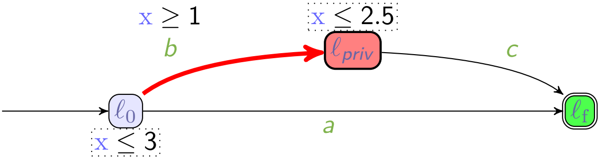

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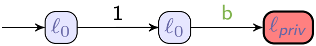

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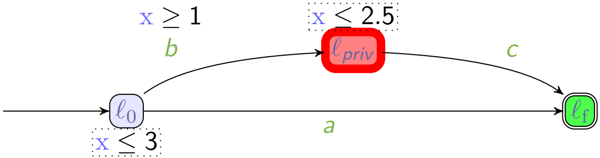

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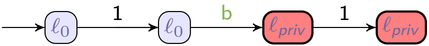

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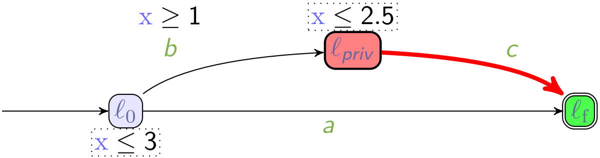
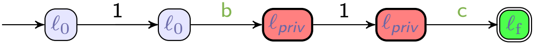


- There exist *(at least)* two runs of duration $\mathrm{d} = 2$:

visiting ℓ_{priv}



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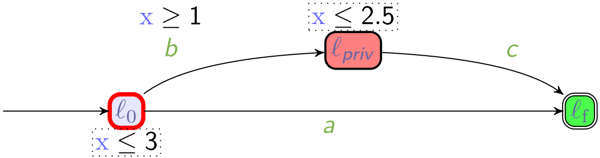

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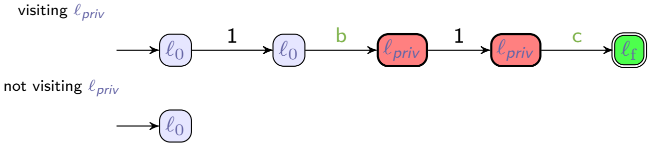

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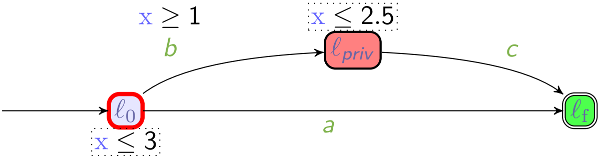

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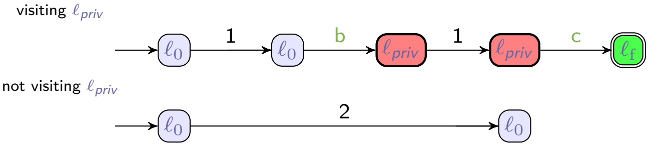
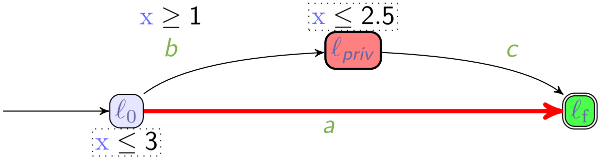


Example



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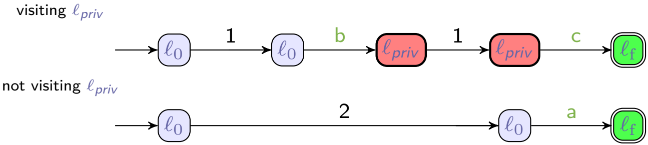

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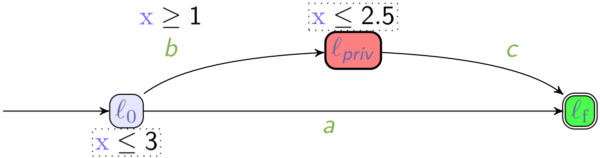
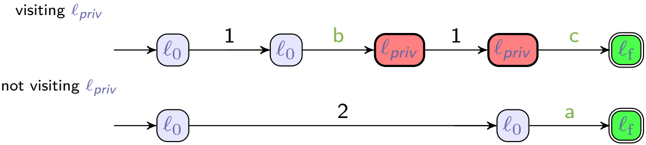


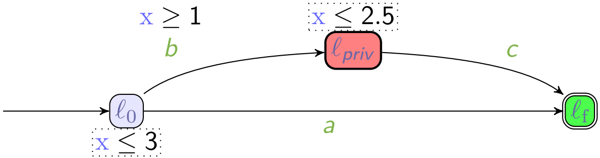
- There exist *(at least)* two runs of duration $\mathrm{d} = 2$:



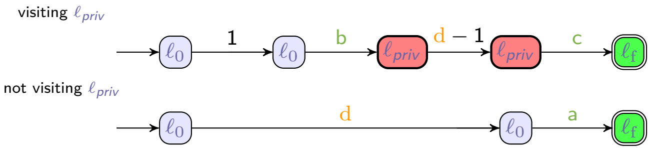
The system is ET-opaque for a duration $\mathrm{d} = 2$

The system is ∃-ET-opaque

Example



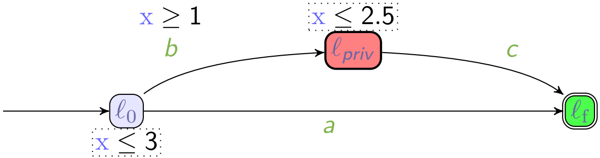
- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$:



The system is ET-opaque for all durations in $[1, 2.5]$

The system is ∃-ET-opaque

Example



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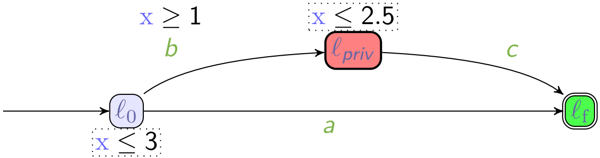
The system is ∃-ET-opaque

Example

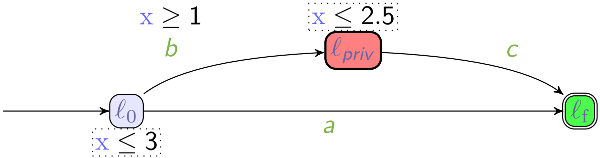


- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is ∃-ET-opaque

- private durations are $[1, 2.5]$
  public durations are $[0, 3]$

Example



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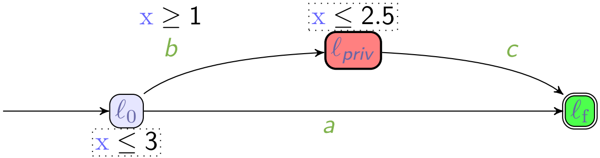
The system is ∃-ET-opaque

- private durations are $[1, 2.5]$
  public durations are $[0, 3]$
- private durations $\subseteq$ public durations

Example



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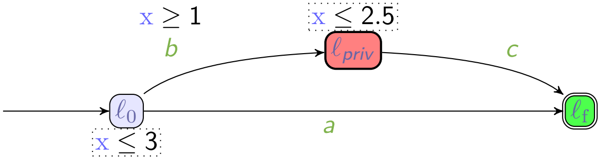
The system is weakly ET-opaque

Example



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The system is weakly ET-opaque

- private durations $\neq$ public durations

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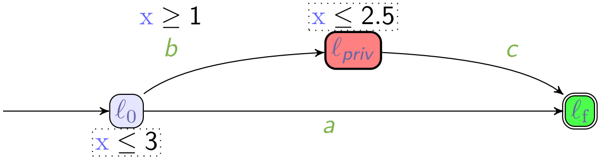

- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is ∃-ET-opaque

- private durations are $[1, 2.5]$
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- private durations $\subseteq$ public durations

The system is weakly ET-opaque

- private durations $\neq$ public durations

The system is *not* fully ET-opaque

Outline

Preliminaries: (Parametric) Timed model checking

Contribution: Efficient verification in Parametric Timed Automata

Contribution: Execution-time opacity
- ET-opacity problems in TAs
- ET-opacity problems in PTAs
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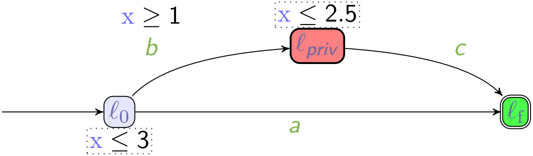
Conclusion & Perspectives

Example



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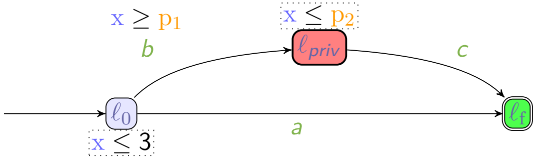
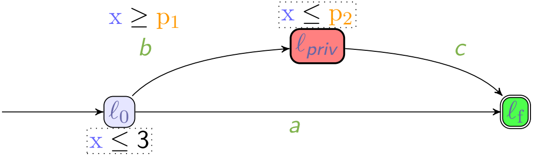
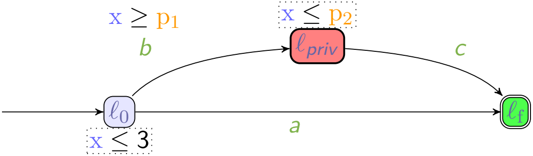


Example



Private	$[p_1, p_2]$
Public	$[0, 3]$

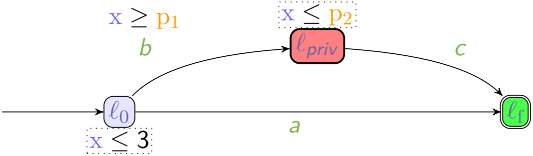
Example



Private	$[p_1, p_2]$
Public	$[0, 3]$

ET-opacity notion	Private	Public	Answer
$p_1 = 1 \wedge p_2 = 2.5$			
∃			√
weak	$[1, 2.5]$	$[0, 3]$	√
full			×

Example



Private	$[p_1, p_2]$
Public	$[0, 3]$

ET-opacity notion	Private	Public	Answer
$p_1 = 1 \wedge p_2 = 2.5$			
$\exists$			$\surd$
weak	$[1, 2.5]$	$[0, 3]$	$\surd$
full			$\times$
$p_1 = 0 \wedge p_2 = 3$			
$\exists$			$\surd$
weak	$[0, 3]$	$[0, 3]$	$\surd$
full			$\surd$

Two classes of parametric problems

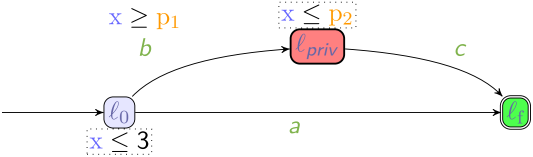
p-Emptiness problem

Decide the emptiness of the set of parameter valuations v s. t. $\mathrm{v}(\mathcal{P})$ is ET-opaque

p-Synthesis problem

Synthesize the set of parameter valuations v s. t. $\mathrm{v}(\mathcal{P})$ is ET-opaque

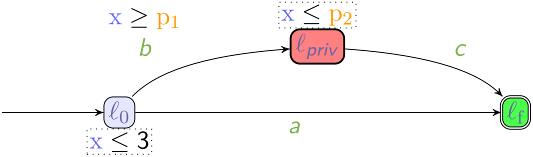
Example



Private	$[p_1, p_2]$
Public	$[0, 3]$

ET-opacity notion	∃	Weak	Full
p-Emptiness			
p-Synthesis			

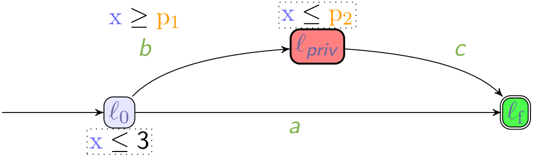
Example



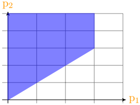
Private	$[p_1, p_2]$
Public	$[0, 3]$

ET-opacity notion	∃	Weak	Full
p-Emptiness	$\times (\exists v)$	$\times (\exists v)$	$\times (\exists v)$
p-Synthesis			

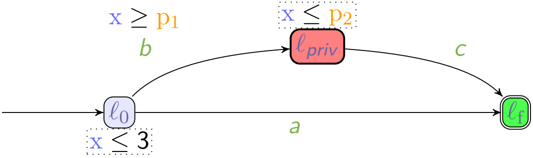
Example



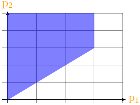
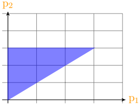
Private	$[p_1, p_2]$
Public	$[0, 3]$

ET-opacity notion	∃	Weak	Full
p-Emptiness	×(∃v)	×(∃v)	×(∃v)
p-Synthesis	$0 \leq p_1 \leq 3$ $\land\ p_1 \leq p_2$ 		

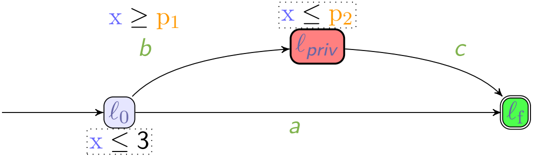
Example



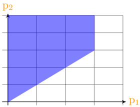
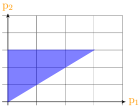
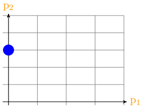
Private	$[p_1, p_2]$
Public	$[0, 3]$

ET-opacity notion	$\exists$	**Weak**	**Full**
p-Emptiness	$\times(\exists v)$	$\times(\exists v)$	$\times(\exists v)$
p-Synthesis	$0 \leq p_1 \leq 3$ $\wedge\ p_1 \leq p_2$ 	$0 \leq p_1 \wedge p_2 \leq 3$ $\wedge\ p_1 \leq p_2$ 	

Example



Private	$[p_1, p_2]$
Public	$[0, 3]$

ET-opacity notion	$\exists$	Weak	Full
p-Emptiness	$\times (\exists v)$	$\times (\exists v)$	$\times (\exists v)$
p-Synthesis	$0 \leq p_1 \leq 3 \wedge p_1 \leq p_2$ 	$0 \leq p_1 \wedge p_2 \leq 3 \wedge p_1 \leq p_2$ 	$p_1 = 0 \wedge p_2 = 3$ 

Decidability results for ET-opacity

		∃-ET-opaque	weakly ET-opaque	fully ET-opaque
Decision	TA	√	√	√
p-emptiness	L/U-PTA	√	×	×
	PTA	×	×	×
p-synthesis	L/U-PTA	×	×	×
	PTA	×	×	×

- L/U-PTA (*Lower/Upper-PTA*): subclass of PTA where the parameters are partitioned into two sets (either compared to clocks as upperbound, or as lower bound) [Hun+02]
- *Proofs are based on the region automaton (for TAs) and by reduction from EF-emptiness (for PTAs). (see formal proofs in Manuscript, Chapter 7)*

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Decidability results for ET-opacity

		∃-ET-opaque	weakly ET-opaque	fully ET-opaque
Decision	TA	√	√	√
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	PTA	×	×	×
p-synthesis	L/U-PTA	×	×	×
	PTA	×	×	×

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- *Proofs are based on the region automaton (for TAs) and by reduction from EF-emptiness (for PTAs). (see formal proofs in Manuscript, Chapter 7)*

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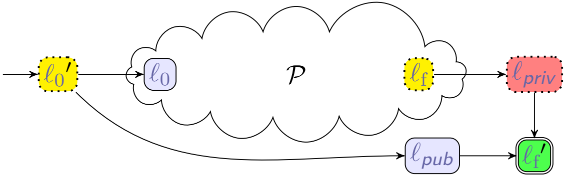
ET-opacity synthesis is (very) difficult

Theorem (Undecidability of ∃-ET-opacity p-emptiness)

Given $\mathcal{P}$, the mere existence of a parameter valuation v s. t. $\mathrm{v}(\mathcal{P})$ ∃-ET-opacity is undecidable.

Proof idea: reduction from reachability-emptiness for PTAs



Remark: L/U-PTA is a decidable subclass

Outline

Preliminaries: (Parametric) Timed model checking

Contribution: Efficient verification in Parametric Timed Automata

Contribution: Execution-time opacity

- ET-opacity problems in TAs
- ET-opacity problems in PTAs
- Expiring ET-opacity problems
- Untimed control

Conclusion & Perspectives

Expiring ET-opacity

- How to deal with outdated secrets?
  e. g., cache values, status of the memory, ...

Idea

The secret can expire: beyond a certain duration, knowing the secret is useless to the attacker (e. g., a cache value) [Amm+21]

Expiring ET-opacity

Assumption

Knowing an expired secret is equivalent to not knowing a secret

	Secret runs	**Non-secret runs**
ET-opacity	Runs visiting the private location (= private runs)	Runs not visiting the private location (= public runs)
expiring-ET-opacity	Private runs with ℓ_{priv} visit $\leq \Delta$ before the system completion	(i) Public runs and (ii) Private runs with ℓ_{priv} visit $> \Delta$ before the system completion

[ICECCS23] Étienne André, Engel Lefaucheux, and Dylan Marinho. "Expiring opacity problems in parametric timed automata". In: *ICECCS* (2023). To appear. Springer, 2023

Three levels of ET-opacity

Existential (∃)

private durations $\cap$ public durations $\neq \emptyset$

Weak

private durations $\subseteq$ public durations

Full

private durations $=$ public durations

Three levels of expiring ET-opacity

Existential (∃) expiring

secret durations $\cap$ non-secret durations $\neq \emptyset$

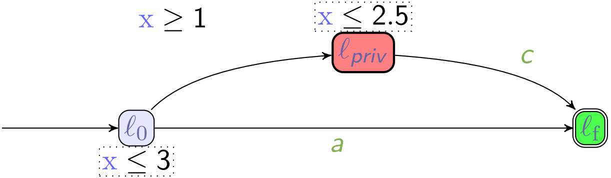
Weak expiring

secret durations $\subseteq$ non-secret durations

Full expiring

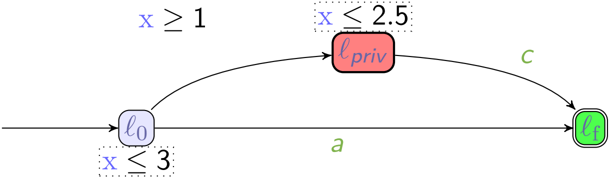
secret durations $=$ non-secret durations

Example



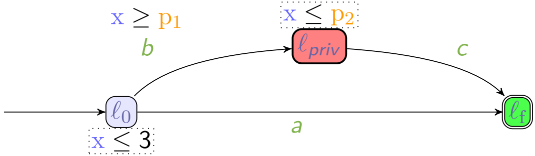
ET-opacity notion		Secret	Non-secret	Answer
	∃			√
	weak	$[1, 2.5]$	$[0, 3]$	√
	full			×
	∃-exp.			√
$\Delta = 1$	weak-exp.	$[1, 2.5]$	$(2, 2.5] \cup [0, 3]$	√
	full-exp.			×

Example



ET-opacity notion		Secret	Non-secret	Answer
	∃	$[1, 2.5]$	$[0, 3]$	√
	weak			√
	full			×
$\Delta = 1$	∃-exp.	$[1, 2.5]$	$(2, 2.5] \cup [0, 3]$	√
	weak-exp.			√
	full-exp.			×
$\Delta = 1.25$	∃-exp.	$[1, 2.5]$	$(2.25, 2.5] \cup [0, 3]$	√
	weak-exp.			√
	full-exp.			×

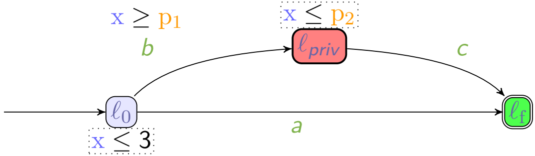
Example



	if $p_1 \leq 3$	otherwise
Secret	$[p_1, \min(\Delta + 3, p_2)]$	$\emptyset$
Non-secret	$(p_1 + \Delta, p_2] \cup [0, 3]$	$\emptyset \cup [0, 3]$

ET-opacity notion	Weak	Full
(p+Δ)-Emptiness		
(p+Δ)-Synthesis		

Example



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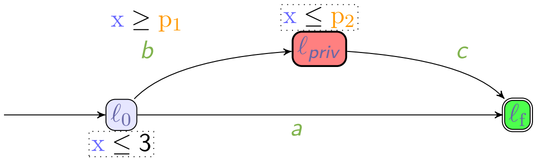
Non-secret	$(p_1 + \Delta, p_2] \cup [0, 3]$	$\emptyset \cup [0, 3]$

ET-opacity notion	**Weak**	**Full**
(p+Δ)-Emptiness	$\times (\exists v)$	$\times (\exists v)$
(p+Δ)-Synthesis		

Example



	if $p_1 \leq 3$	otherwise
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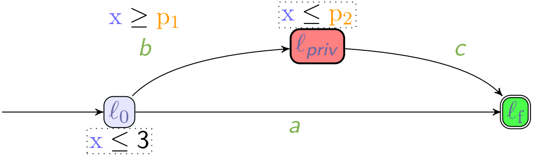
ET-opacity notion	**Weak**	**Full**
(p+Δ)-Emptiness	$\times(\exists v)$	$\times(\exists v)$
(p+Δ)-Synthesis	$p_1 > 3 \lor \Delta = 0 \lor p_2 \leq 3 \lor p_1 + \Delta <= 3$	

Example



	if $p_1 \leq 3$	otherwise
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Non-secret	$(p_1 + \Delta, p_2] \cup [0, 3]$	$\emptyset \cup [0, 3]$

ET-opacity notion	**Weak**	**Full**
(p+Δ)-Emptiness	$\times(\exists v)$	$\times(\exists v)$
(p+Δ)-Synthesis	$p_1 > 3 \vee \Delta = 0 \vee p_2 \leq 3 \vee p_1 + \Delta <= 3$	$p_1 = 0 \wedge ((\Delta \leq 3 \wedge 3 \leq p_2 \leq \Delta + 3) \vee (p_2 = 3))$

Decidability results for expiring-ET-opacity

		weakly expiring-ET-opaque	fully expiring-ET-opaque
Δ-emptiness	TA	√	√
Δ-synthesis	TA	√	?
$(p + \Delta)$-emptiness	L/U-PTA	×	×
$(p + \Delta)$-emptiness	PTA	×	×
$(p + \Delta)$-synthesis	L/U-PTA	×	×
$(p + \Delta)$-synthesis	PTA	×	×

- ∃-expiring ET-opacity was left as a future work.
- L/U-PTA (*Lower/Upper-PTA*): subclass of PTA where the parameters are partitioned into two sets (either compared to clocks as upperbound, or as lower bound) [Hun+02]

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Δ-emptiness	TA	√	√
Δ-synthesis	TA	√	?
$(p + \Delta)$-emptiness	L/U-PTA	×	×
	PTA	×	×
$(p + \Delta)$-synthesis	L/U-PTA	×	×
	PTA	×	×

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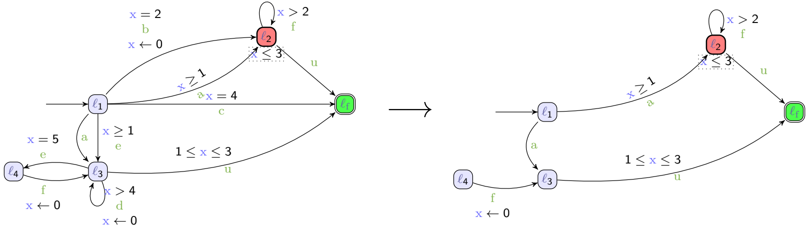
Conclusion & Perspectives

Untimed control

Overview of Chapter 9 of the manuscript



- Restrict the behavior of the system to ensure ET-opacity
- Development of an open-source tool strategFTO (≈ 1200 lines of code, Java)
  - Enumeration of transition sets

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Outline

Preliminaries: (Parametric) Timed model checking

Contribution: Efficient verification in Parametric Timed Automata

Contribution: Execution-time opacity

Conclusion & Perspectives

Conclusion

Efficient verification

- A new benchmark library (119 models, 216 properties) [TAP21]
- Zone merging algorithm for PTA verification [FORMATS22]

Execution-time opacity

- Formalization and decidability results of ET-opacity [TOSEM22]
- Extension with secrets with expiration date [ICECCS23]
- Untimed control, implementation of strategFTO [FTSCS22]

Perspectives

Merging states in PZG

- Merge more than 2 states, “best” merge
- Compatibility of merging and liveness properties

Execution-time opacity

- Extension of the definition to another formalism
- Automatic translation of programs to PTAs

  → Preliminary translation with Petri nets including cache system

Other kind of parameters

- Parametric systems: probabilities, costs
- Parameterized systems: number of components

Publications

[FORMATS22] Étienne André, Dylan Marinho, Laure Petrucci, and Jaco van de Pol. "Efficient Convex Zone Merging in Parametric Timed Automata". In: *FORMATS* (2022). LNCS. Springer, 2022.

[FTSCS22] Étienne André, Shapagat Bolat, Engel Lefaucheux, and Dylan Marinho. "strategFTO: Untimed control for timed opacity". In: *FTSCS* (2022). ACM, 2022.

[ICECCS23] Étienne André, Engel Lefaucheux, and Dylan Marinho. "Expiring opacity problems in parametric timed automata". In: *ICECCS* (2023). To appear. Springer, 2023.

[TAP21] Étienne André, Dylan Marinho, and Jaco van de Pol. "A Benchmarks Library for Extended Parametric Timed Automata". In: *TAP* (2021). LNCS. Springer, 2021.

[TICSA23] Étienne André, Engel Lefaucheux, Didier Lime, Dylan Marinho, and Jun Sun. "Configuring Timing Parameters to Ensure Execution-Time Opacity in Timed Automata". In: *TICSA*. 2023.

[TOSEM22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun. "Guaranteeing Timed Opacity using Parametric Timed Model Checking". In: *ACM TOSEM* 31 (2022).

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[Amm+21] Ikhlass Ammar, Yamen El Touati, Moez Yeddes, and John Mullins. "Bounded opacity for timed systems". In: *Journal of Information Security and Applications* 61 (Sept. 2021).

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[AS19] Étienne André and Jun Sun. "Parametric Timed Model Checking for Guaranteeing Timed Opacity". In: *ATVA* (2019). LNCS. Springer, 2019.

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[FORMATS22] Étienne André, Dylan Marinho, Laure Petrucci, and Jaco van de Pol. "Efficient Convex Zone Merging in Parametric Timed Automata". In: *FORMATS* (2022). LNCS. Springer, 2022.

References III

[FTSCS22] Étienne André, Shapagat Bolat, Engel Lefaucheux, and Dylan Marinho. "strategFTO: Untimed control for timed opacity". In: *FTSCS* (2022). ACM, 2022.

[HT15] Frédéric Herbreteau and Thanh-Tung Tran. "Improving Search Order for Reachability Testing in Timed Automata". In: *FORMATS* (2015). LNCS. Springer, 2015.

[Hun+02] Thomas Hune, Judi Romijn, Mariëlle Stoelinga, and Frits W. Vaandrager. "Linear parametric model checking of timed automata". In: *Journal of Logic and Algebraic Programming* 52-53 (2002).

References IV

[ICECCS23] Étienne André, Engel Lefaucheux, and Dylan Marinho. "Expiring opacity problems in parametric timed automata". In: *ICECCS* (2023). To appear. Springer, 2023.

[TAP21] Étienne André, Dylan Marinho, and Jaco van de Pol. "A Benchmarks Library for Extended Parametric Timed Automata". In: *TAP* (2021). LNCS. Springer, 2021.

[TOSEM22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun. "Guaranteeing Timed Opacity using Parametric Timed Model Checking". In: *ACM TOSEM* 31 (2022).

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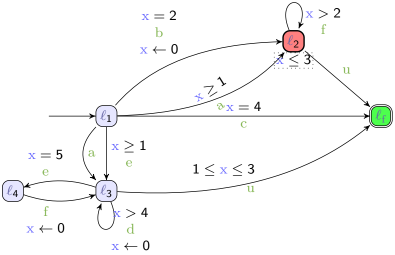
Results

		Nomerge	M2.12	RVMr	OQM
Time	# wins	24	20	22	**42**
	Avg (s)	10.0	5.47	4.56	**3.77**
	Avg (merge) (s)	18.8	7.83	5.57	**3.63**
	Avg (no merge) (s)	3.83	**3.82**	3.85	3.88
	Median (s)	1.39	1.2	1.14	**1.12**
	Norm. avg	1.0	0.91	0.91	**0.87**
	Norm. avg (merge)	1.0	0.75	0.74	**0.64**
	Norm. avg (no merge)	**1.0**	1.02	1.03	1.03
States	# wins	0	19	**37**	16
	Avg	11443.08	11096.54	**11064.37**	11120.79
	Avg (merge)	1512.02	670.43	**592.31**	729.33
	Median	2389.5	703.5	**604.5**	905.0
	Norm. avg	1.0	0.86	**0.84**	0.88

Gain of 62% of the average computation time

An example

[FTSCS22]



Uncontrollable u

Controllable a, b, c, d, e, f

Is the system fully ET-opaque?

- Visiting ℓ_2: $[1, 5]$
- Not visiting ℓ_2: $[1, 3] \cup [4, 4] \cup [5, +\inf)$

$\Rightarrow$ Not fully ET-opaque

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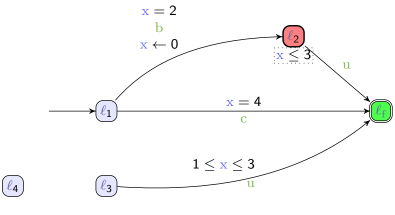


Uncontrollable u

Controllable a, b, c, d, e, f

Allowed u + b, c

Disabled a, d, e, f

Is the system fully ET-opaque?

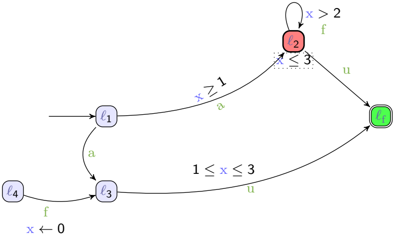
- Visiting ℓ_2: $[2, 5]$
- Not visiting ℓ_2: $[4, 4]$

$\Rightarrow$ Not fully ET-opaque

[FTSCS22] Étienne André, Shapagat Bolat, Engel Lefaucheux, and Dylan Marinho. "strategFTO: Untimed control for timed opacity". In: *FTSCS* (2022). ACM, 2022

An example

[FTSCS22]



Uncontrollable u

Controllable a, b, c, d, e, f

Allowed u + a, f

Disabled b, c, d, e

Is the system fully ET-opaque?

- Visiting ℓ_2: $[1, 3]$
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Untimed control

Overview of Chapter 9 of the manuscript

- Restrict the behavior of the system to ensure ET-opacity
- Development of an open-source tool strategFTO ($\approx$ 1200 lines of code, Java)
  - Enumeration of transition sets

Experiments

- Proof of concept
- Scalability of the tool

Publication

https://github.com/DylanMarinho/Controlling-TA

DOI 10.5281/zenodo.7181848

[FTSCS22] Étienne André, Shapagat Bolat, Engel Lefaucheux, and Dylan Marinho. "strategFTO: Untimed control for timed opacity". In: *FTSCS* (2022). ACM, 2022