FADEX

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Nancy, France

Preventing Timing Leaks using Parametric Timed Model Checking

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Based on join works with Étienne André, Shapagat Bolat, Engel Lefaucheux, Didier Lime, and Sun Jun

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General context: side-channel attacks

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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

$\leadsto$ Non-trivial problem

Detection

Need to detect timing-leak vulnerabilities

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We want formal guarantees → formal methods

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

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Methodology

A program

A specification

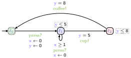
"The program must be secure"

Methodology

A program

→

A model



A specification

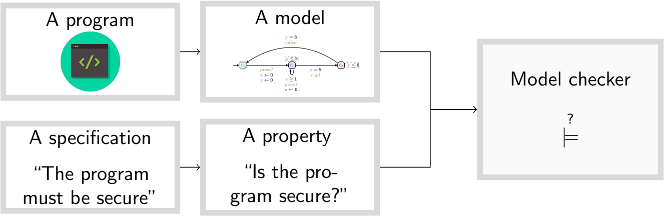
"The program must be secure"

→

A property

"Is the program secure?"

Methodology



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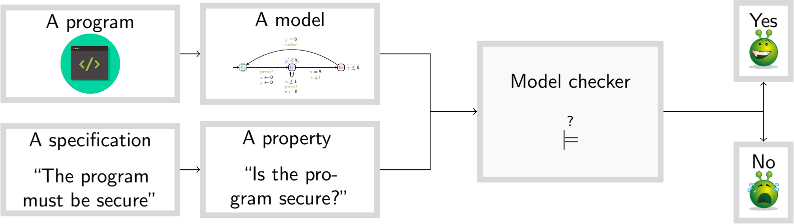

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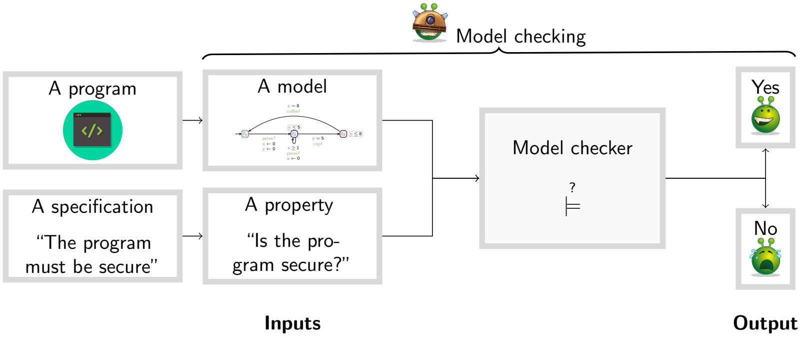
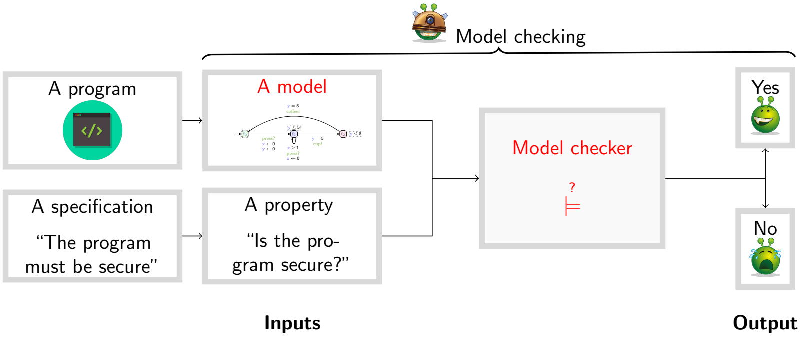


Outline



Outline

1. Preliminaries: Timed model checking

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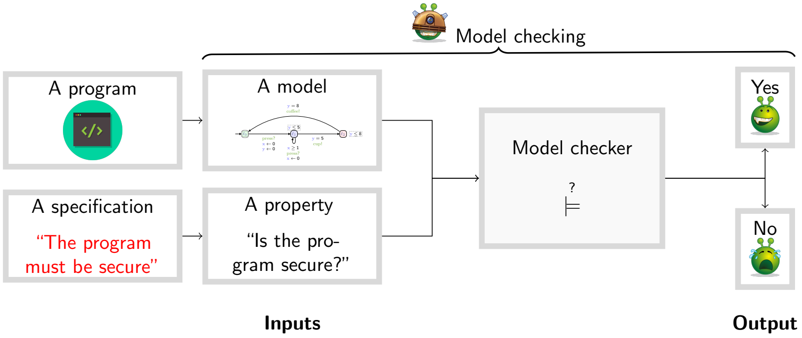


Outline

1. Preliminaries: Timed model checking
2. Execution-time opacity

Outline

Preliminaries: (Parametric) Timed model checking

Execution-time opacity

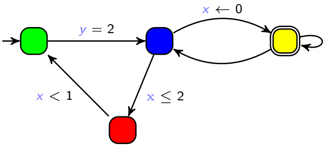
Expiring ET-opacity problems

Untimed control

Conclusion & Perspectives

Outline

Timed model checking

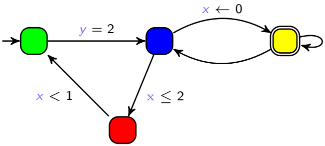


A model of the system

 is unreachable

A property to be satisfied

Timed model checking



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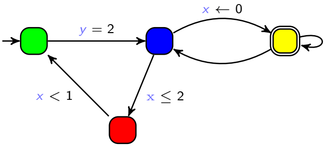

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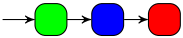
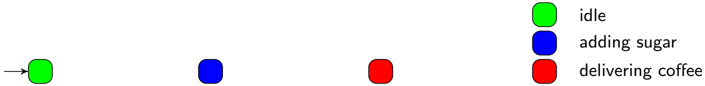


Counterexample

Timed automaton (TA)

[AD94]

- Finite state automaton (sets of locations)



Timed automaton (TA)

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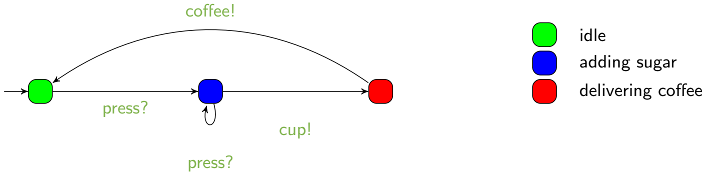

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- Finite state automaton (sets of locations and actions) augmented with a set X of clocks
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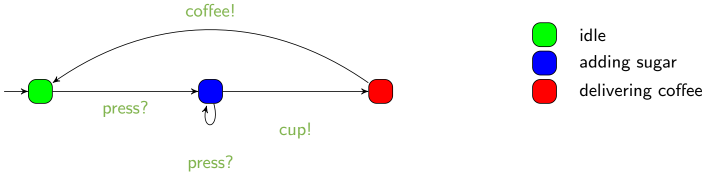

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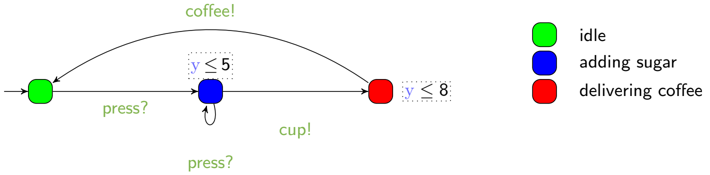

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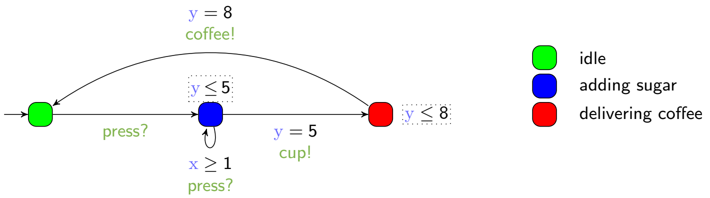

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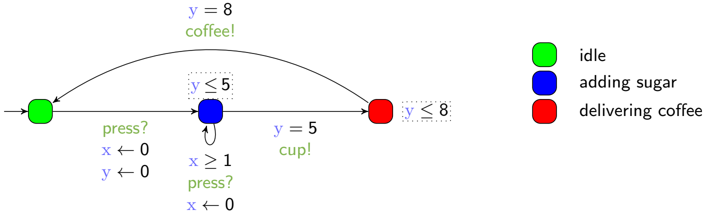
  - Clock reset: some of the clocks can be set to 0 along transitions



Outline

Preliminaries: (Parametric) Timed model checking

Timed model checking and Timed automata

Parametric timed model checking and Parametric timed automata

Execution-time opacity

Expiring ET-opacity problems

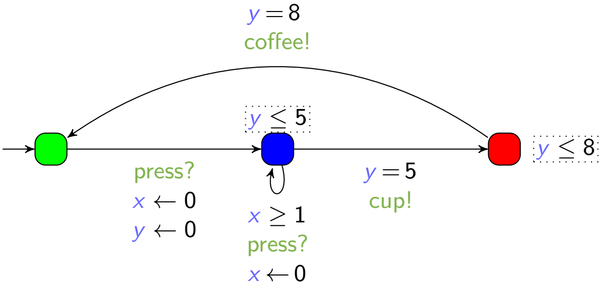
Untimed control

Conclusion & Perspectives

Timed Automaton (PTA)

[AHV93]

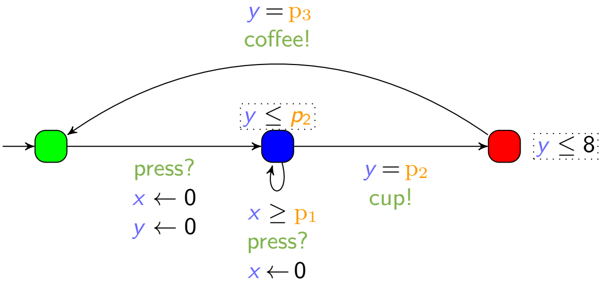
- Timed automaton (sets of locations, actions and clocks)



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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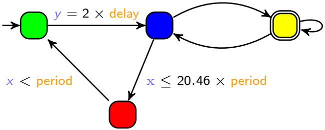

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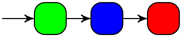
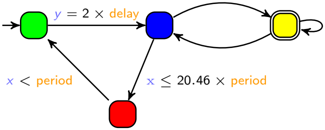


Counterexample

Parametric timed model checking



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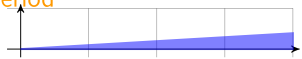
- Question: for what values of the parameters does the model of the system satisfy the property?

Yes if...



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

Valuation of a PTA = TA

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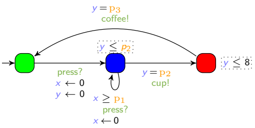
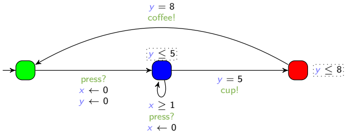
$v\Big($ 

$\Big) =$ 

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

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Execution-time opacity

- How to detect timing-leak vulnerabilities?

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Goal

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

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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

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Attacker goal

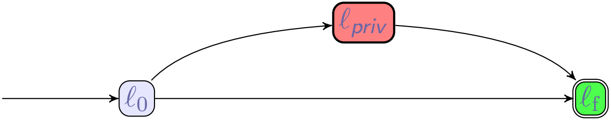
- Wants to deduce some private information based on these observations
  $\rightarrow$ visit of a private location

Outline

Formalization

Hypotheses: [AS19][TOSEM22]

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



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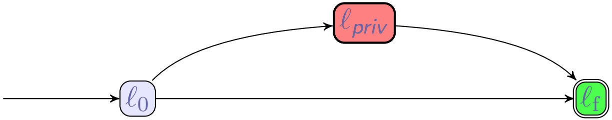

Definition (execution-time opacity)

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}

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Existential ($\exists$)

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

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Weak

For all durations d,
There exists a run of duration d visiting ℓ_{priv}
$\Rightarrow$
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Weak

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Full

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Three levels of ET-opacity

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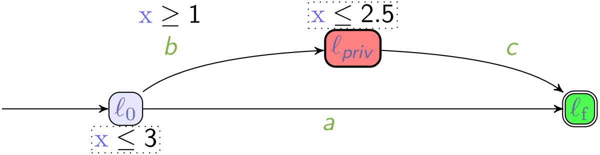
Weak

private durations $\subseteq$ public durations

Full

private durations $=$ public durations

Example



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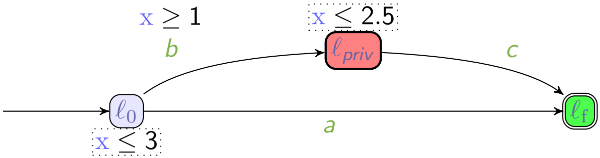
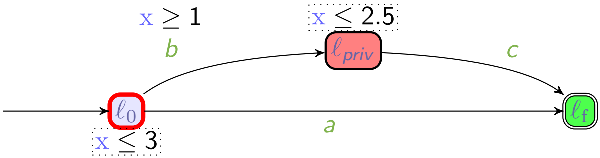


- There exist *(at least)* two runs of duration $d = 2$:

Example



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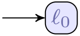

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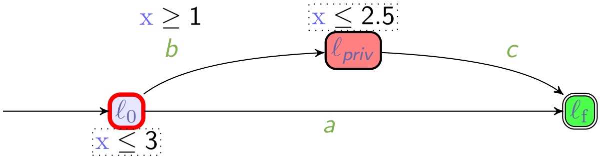

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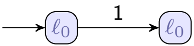

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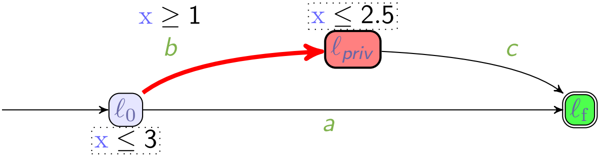

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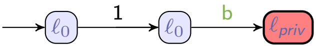

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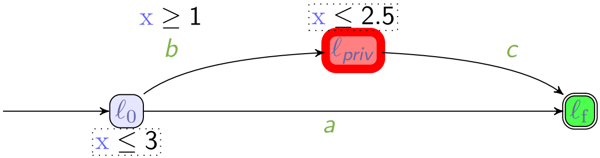

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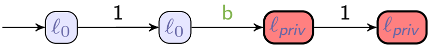

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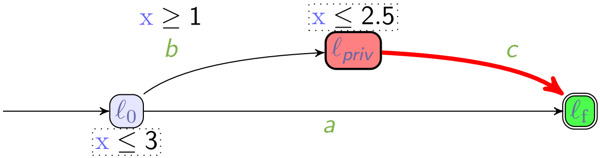

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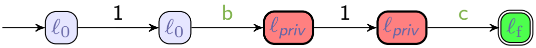

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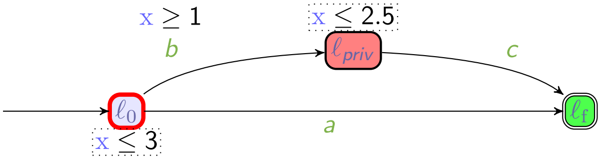

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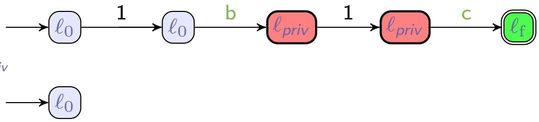
not visiting ℓ_{priv}



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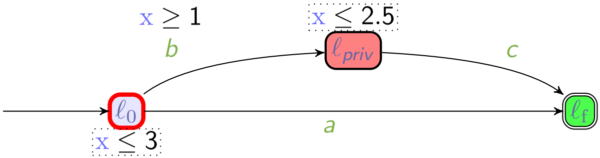

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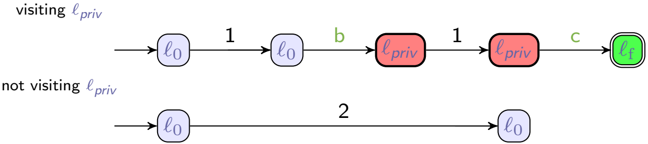
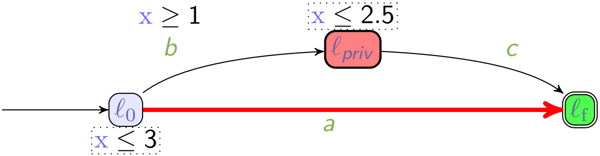
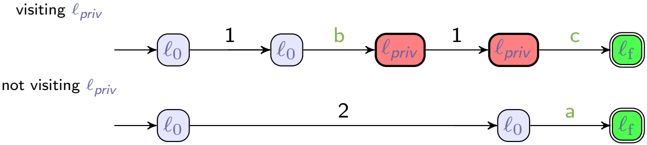


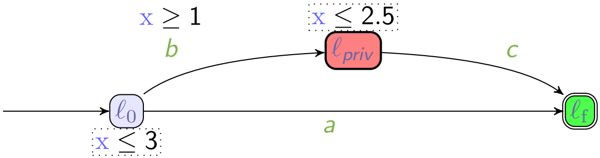
Example



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



Example



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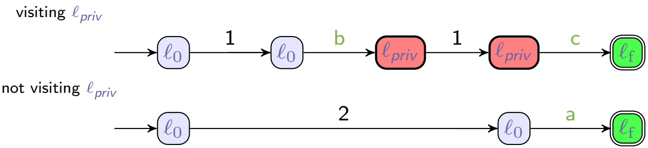
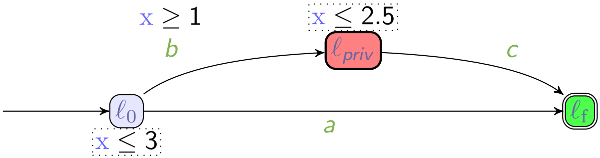


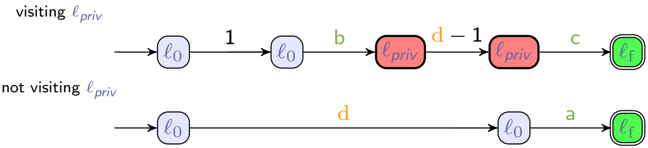
The system is ET-opaque for a duration $d = 2$

The system is $\exists$-ET-opaque

Example



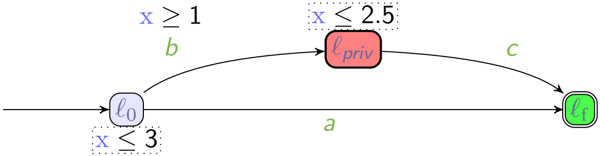
- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$:



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

The system is ∃-ET-opaque

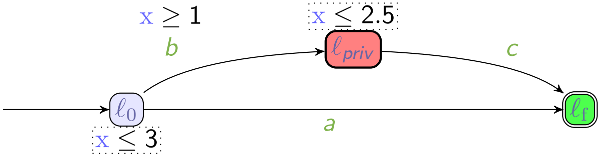
Example



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

The system is ∃-ET-opaque

Example

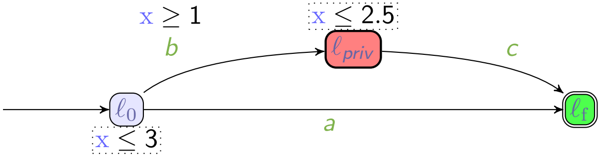


- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is $\exists$-ET-opaque

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

Example

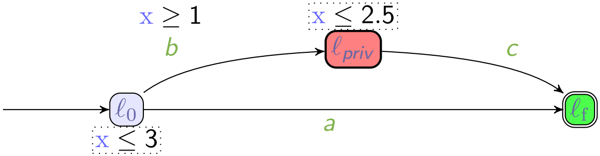


- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is ∃-ET-opaque

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

Example



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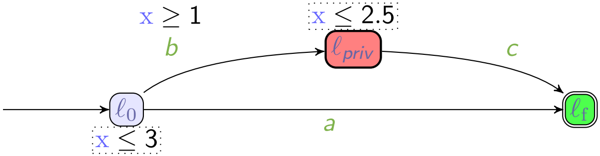
- private durations $\subseteq$ public durations

The system is weakly ET-opaque

Example



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The system is ∃-ET-opaque

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  public durations are $[0, 3]$
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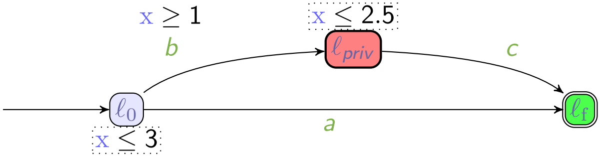
The system is weakly ET-opaque

- private durations $\neq$ public durations

Example



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The system is ∃-ET-opaque

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

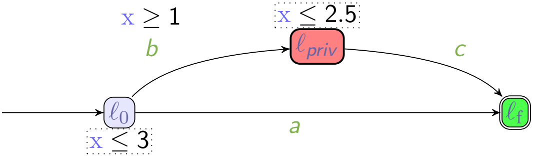
The system is weakly ET-opaque

- private durations $\neq$ public durations

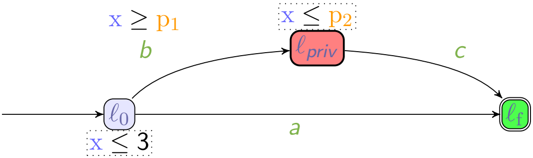
The system is *not* fully ET-opaque

Outline

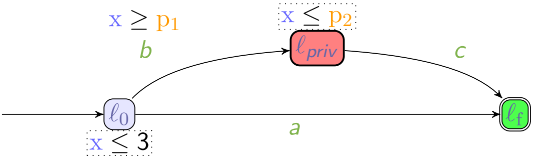
Example



Example

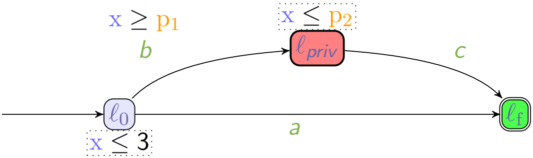


Example



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

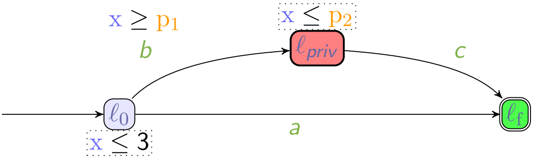
Example



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

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

Example



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$p_1 = 1 \wedge p_2 = 2.5$			
$\exists$			$\surd$
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

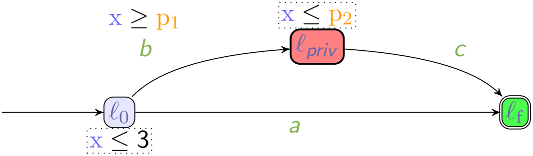
p-Emptiness problem

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

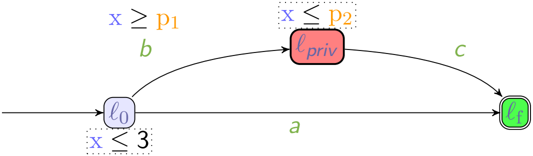
Example



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

ET-opacity notion	$\exists$	Weak	Full
p-Emptiness			
p-Synthesis			

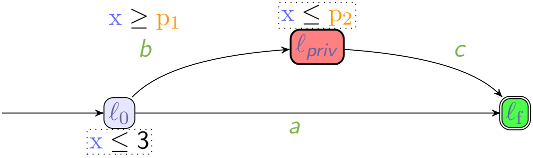
Example



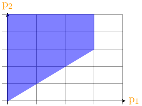
Private	$[p_1, p_2]$
Public	$[0, 3]$

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

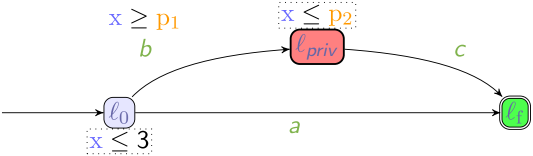
Example



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	$0 \leq p_1 \leq 3$ $\wedge\ p_1 \leq p_2$ 		

Example



Private	$[p_1, p_2]$
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ET-opacity notion	$\exists$	Weak	Full
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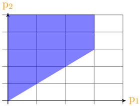
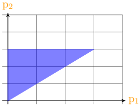
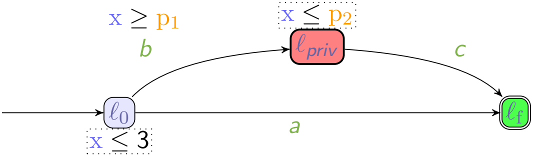
p-Synthesis	$0 \leq p_1 \leq 3 \wedge p_1 \leq p_2$ 	$0 \leq p_1 \wedge p_2 \leq 3 \wedge p_1 \leq p_2$ 	

Example



Private	$[p_1, p_2]$
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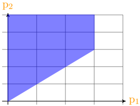
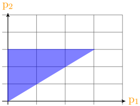
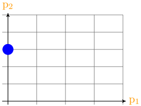
ET-opacity notion	$\exists$	**Weak**	**Full**
p-Emptiness	$\times(\exists v)$	$\times(\exists v)$	$\times(\exists v)$
p-Synthesis	$0 \leq p_1 \leq 3 \land p_1 \leq p_2$ 	$0 \leq p_1 \land p_2 \leq 3 \land p_1 \leq p_2$ 	$p_1 = 0 \land p_2 = 3$ 

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)*

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

Decidability results for ET-opacity

		∃-ET-opaque	weakly ET-opaque	fully ET-opaque
Decision	TA	$\surd$	$\surd$	$\surd$
p-emptiness	L/U-PTA	$\surd$	$\times$	$\times$
	PTA	$\times$	$\times$	$\times$
p-synthesis	L/U-PTA	$\times$	$\times$	$\times$
	PTA	$\times$	$\times$	$\times$

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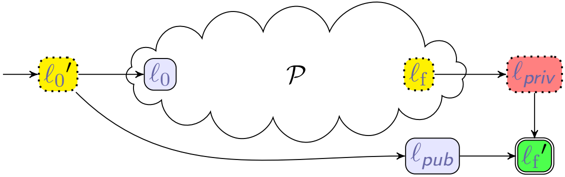
ET-opacity synthesis is (very) difficult

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

Experiments: Computing ET-opaque durations

- Benchmark library + Library of Java programs [2]
  - Manually translated to PTAs
  - User-input variables → (non-timing) parameters
- Algorithms
  1. "Is the TA ET-opaque for all execution times?"
  2. "Synthesize parameter valuations and durations ensuring ET-opacity of a given PTA"

[2] https://github.com/Apogee-Research/STAC/

Experiments: Computing ET-opaque durations

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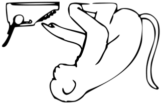
- Algorithms
  1. "Is the TA ET-opaque for all execution times?"
  2. "Synthesize parameter valuations and durations ensuring ET-opacity of a given PTA"

- Problems are undecidable → best-effort approach
- Algorithms based on parameter synthesis



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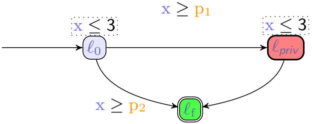
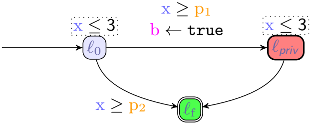
Our transformation of the PTA in 4 overlays



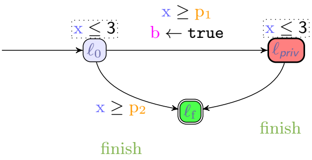
Our transformation of the PTA in 4 overlays

1. Add a Boolean flag b



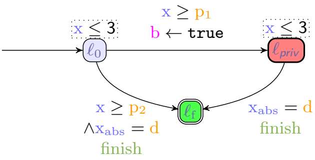
Our transformation of the PTA in 4 overlays

1. Add a Boolean flag b
2. Add a synchronization action finish



Our transformation of the PTA in 4 overlays

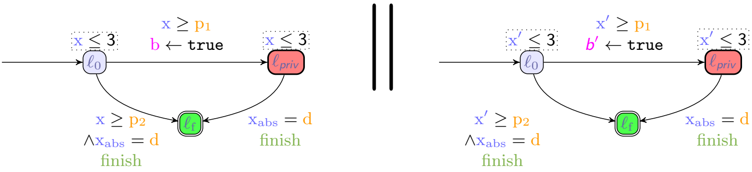
1. Add a Boolean flag b
2. Add a synchronization action finish
3. Measure the (parametric) duration to ℓ_f



Our transformation of the PTA in 4 overlays

1. Add a Boolean flag b
2. Add a synchronization action finish
3. Measure the (parametric) duration to ℓ_f
4. Perform self-composition

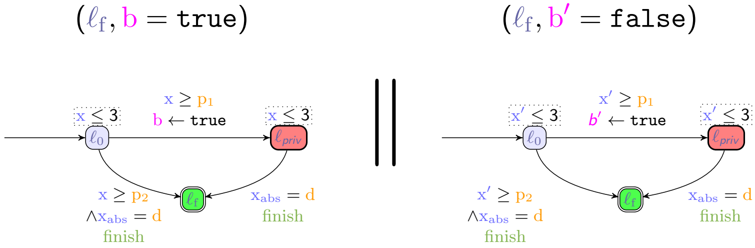
   (a synchronization on shared actions of the PTA with a copy of itself)



Applying reachability-synthesis

Synthesize all parameter valuations (including d) with a particular reachable state:

- ℓ_f with $b = \texttt{true}$
- ℓ_f with $b' = \texttt{false}$



Formal proof of correctness: see [TOSEM22]

Outline

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 ($\exists$)

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 $\neq \emptyset$

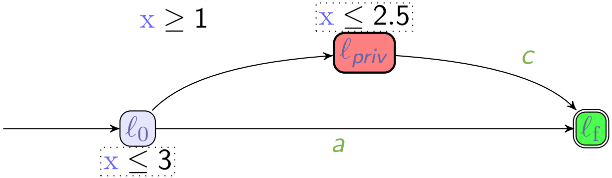
Weak expiring

secret durations $\subseteq$ non-secret durations

Full expiring

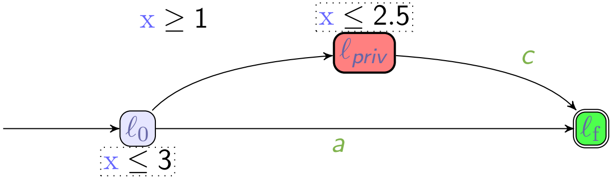
secret durations $=$ non-secret durations

Example



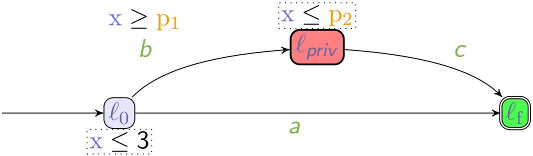
ET-opacity notion		Secret	Non-secret	Answer
	$\exists$	$[1, 2.5]$	$[0, 3]$	√
	weak			√
	full			×
$\Delta = 1$	$\exists$-exp.	$[1, 2.5]$	$(2, 2.5] \cup [0, 3]$	√
	weak-exp.			√
	full-exp.			×

Example



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

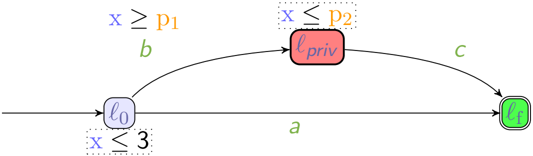
Example



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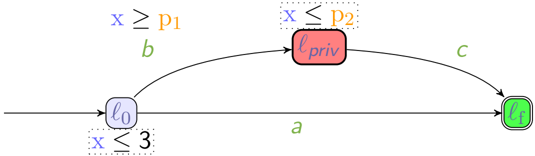
ET-opacity notion	**Weak**	**Full**
(p+Δ)-Emptiness	$\times(\exists v)$	$\times(\exists v)$
(p+Δ)-Synthesis		

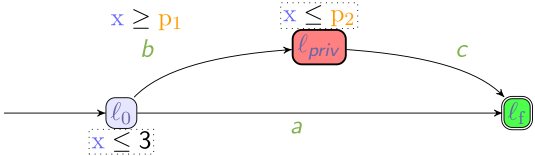
Example



	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	$\times(\exists v)$	$\times(\exists v)$
(p+Δ)-Synthesis	$p_1 > 3 \vee \Delta = 0$ $\vee\ p_2 \leq 3 \vee p_1 + \Delta <= 3$	

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	$\times(\exists v)$	$\times(\exists v)$
(p+Δ)-Synthesis	$p_1 > 3 \quad \vee \quad \Delta = 0$ $\vee \quad p_2 \leq 3 \quad \vee \quad p_1 + \Delta <= 3$	$p_1 = 0 \quad \wedge \quad (\quad (\Delta \leq 3 \wedge 3 \leq p_2 \leq \Delta + 3)$ $\vee (p_2 = 3) \quad)$

Decidability results for expiring-ET-opacity

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

- $\exists$-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]

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

Decidability results for expiring-ET-opacity

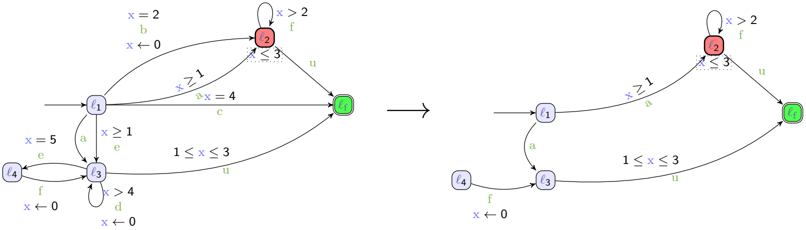
		weakly expiring-ET-opaque	**fully expiring-ET-opaque**
Δ-emptiness	TA	$\surd$	$\surd$
Δ-synthesis	TA	$\surd$	?
$(p + \Delta)$-emptiness	L/U-PTA	$\times$	$\times$
	PTA	$\times$	$\times$
$(p + \Delta)$-synthesis	L/U-PTA	$\times$	$\times$
	PTA	$\times$	$\times$

- $\exists$-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]
- *Proofs are based on the region automaton (for TAs) and by reduction from EF-emptiness (for PTAs). (see formal proofs in Manuscript, Chapter 8)*

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

Outline

Untimed control



- 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

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

Outline

Conclusion

Context: vulnerability by timing-attacks

- Attacker model: observability of the global execution time
- Goal: avoid leaking information on whether some discrete state has been visited

Several problems studied for timed automata

- ☺ Mostly decidable

Extension to parametric timed automata

- ☹ Quickly undecidable
- ☺ One procedure for one synthesis problem
- Toolkit: IMITATOR
- Benchmarks: concurrent systems and Java programs

Perspectives

Theoretical perspectives

- Existential version of expiring ET-opacity
- Δ-synthesis for full expiring ET-opacity

Algorihtmic perspectives

- Synthesis for weak and full ET-opacity
- Synthesis for expiring problems

Automatic translation of programs to PTAs

- Our translation required non-trivial creativity

  $\rightarrow$ Preliminary translation with Petri nets including cache system

References I

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

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