MTV, LaBRI

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Ensuring opacity in timed systems

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Join works with Étienne André, Shapagat Bolat, Engel Lefaucheux, Didier Lime, and Sun Jun

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A simple example of timing attack

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1 # input pwd     : Real password
2 # input attempt: Tentative password
3 for i = 0 to min(len(pwd), len(attempt)) - 1 do
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attempt	c	h	e	e	s	e	

Execution time:

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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`

Context: 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

Informal problems

Question: can we exhibit secure execution times?

Computation problem: Execution-time opacity computation

Exhibit execution times for which it is not possible to infer information on the internal behavior

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Exhibit execution times for which it is not possible to infer information on the internal behavior

Question: can we make sure all execution times are secure?

Decision problem: Full execution-time opacity

Can we decide whether it is impossible to infer information on the internal behavior, whatever (for all) execution times?

Informal parametric problems

Further question: can we also tune internal timing constants to make the system resisting to timing attacks?

Synthesis problem: Execution-time opacity synthesis

Exhibit execution times and internal timing constants for which it is not possible to infer information on the internal behavior

Outline

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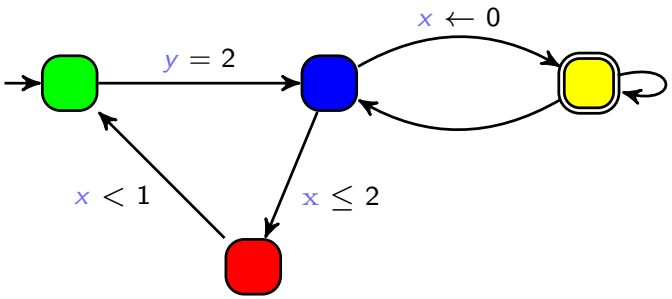
Timed model checking

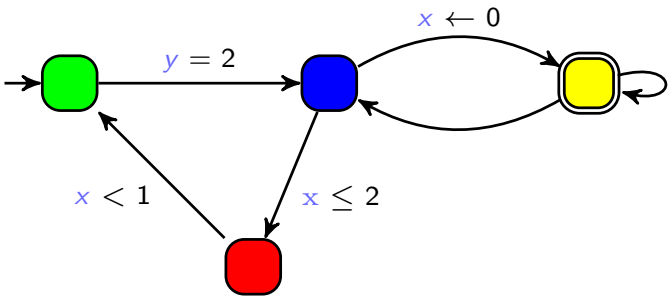


A model of the system

is unreachable

A property to be satisfied

Timed model checking



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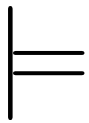

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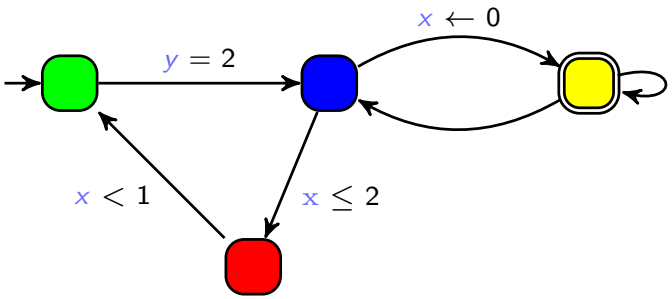

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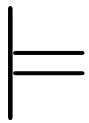

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Yes

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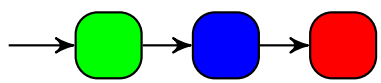
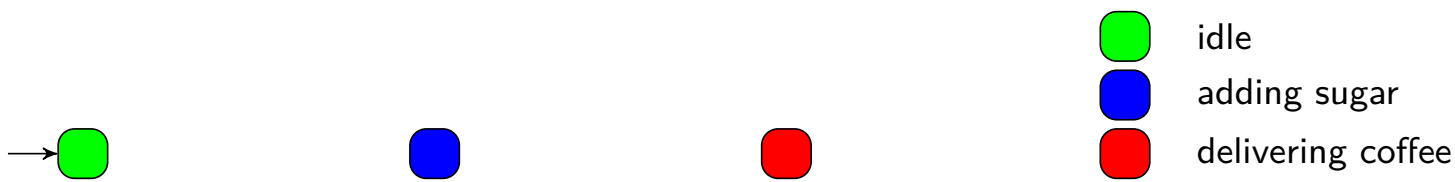


Counterexample

Timed automaton (TA)

- Finite state automaton (sets of locations)



[AD94] Rajeev Alur and David L. Dill. "A theory of timed automata". In: *Theoretical Computer Science* 126.2 (Apr. 1994), pp. 183–235. DOI: 10.1016/0304-3975(94)90010-8

Timed automaton (TA)

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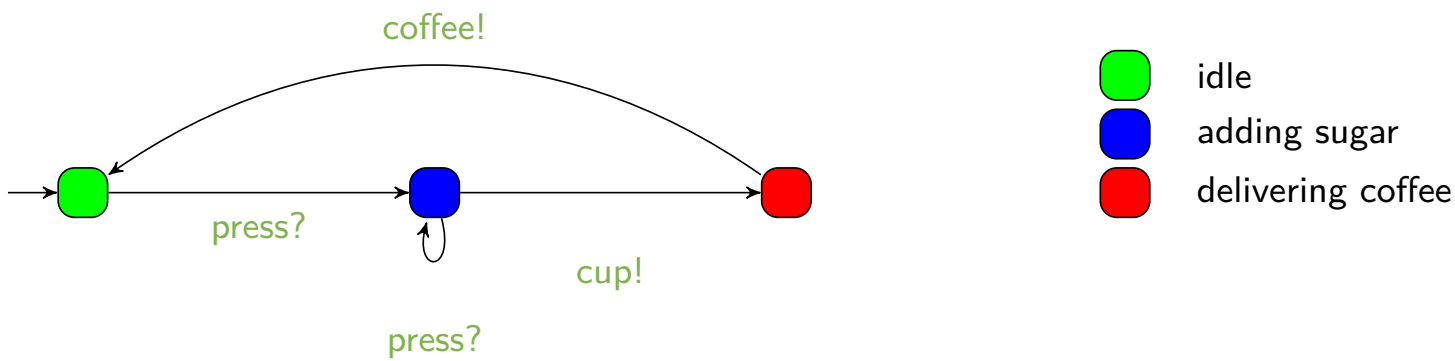

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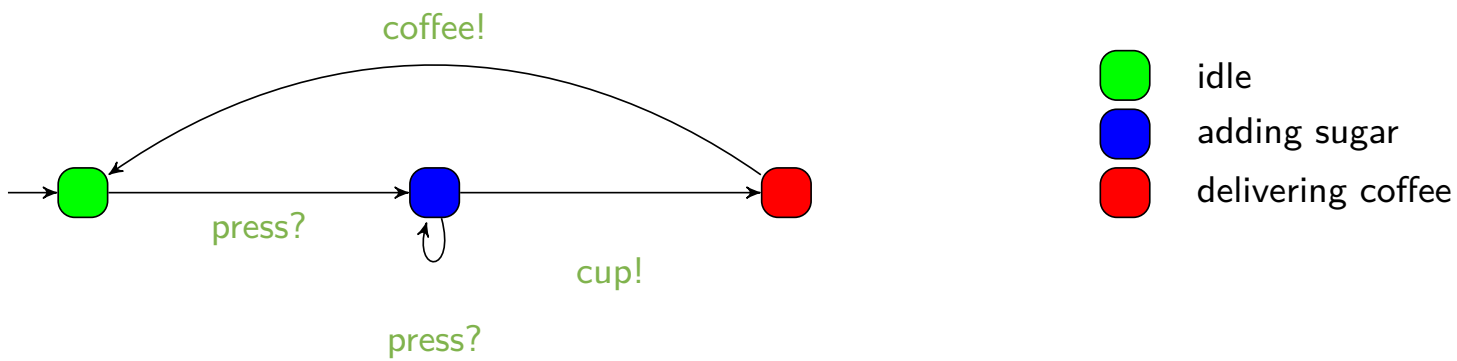

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- Features
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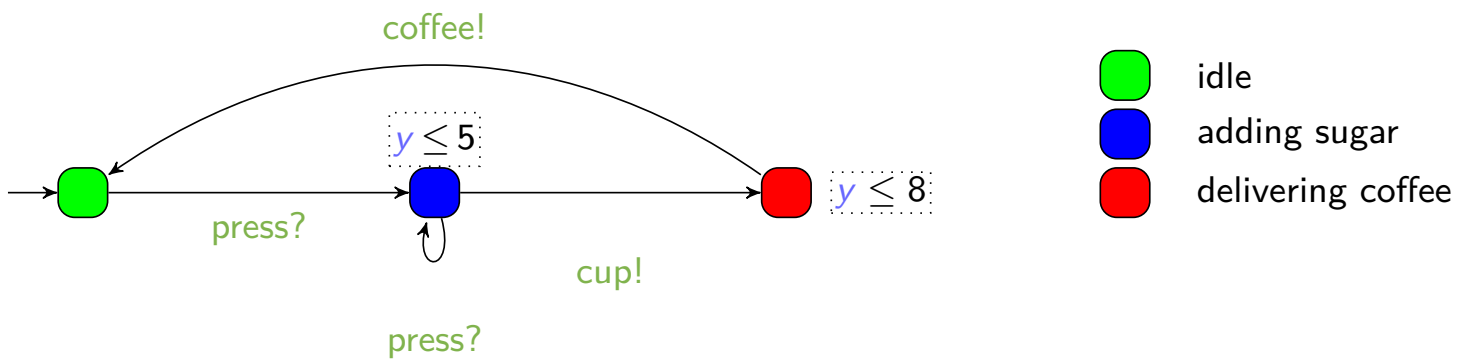

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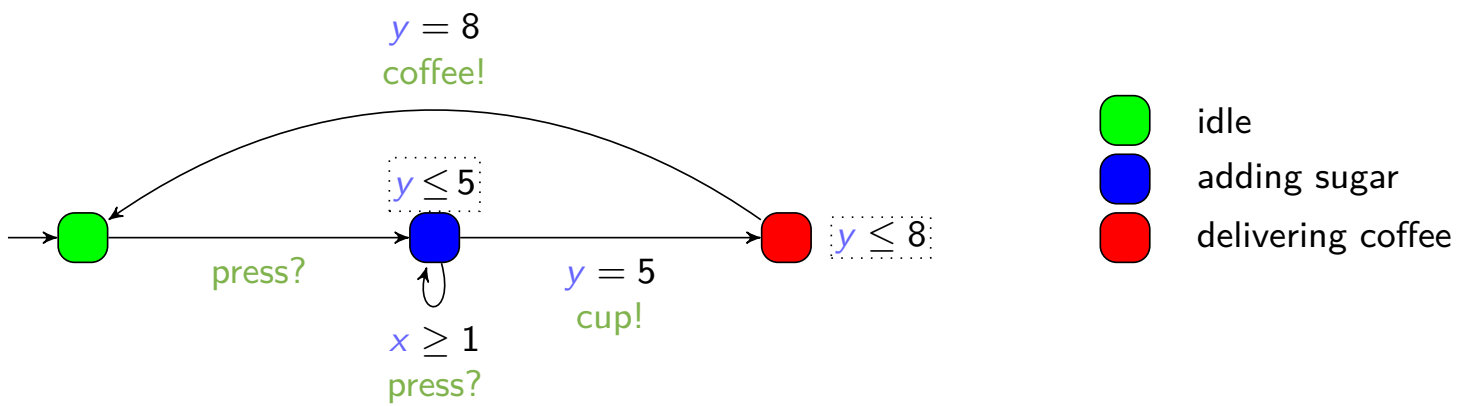

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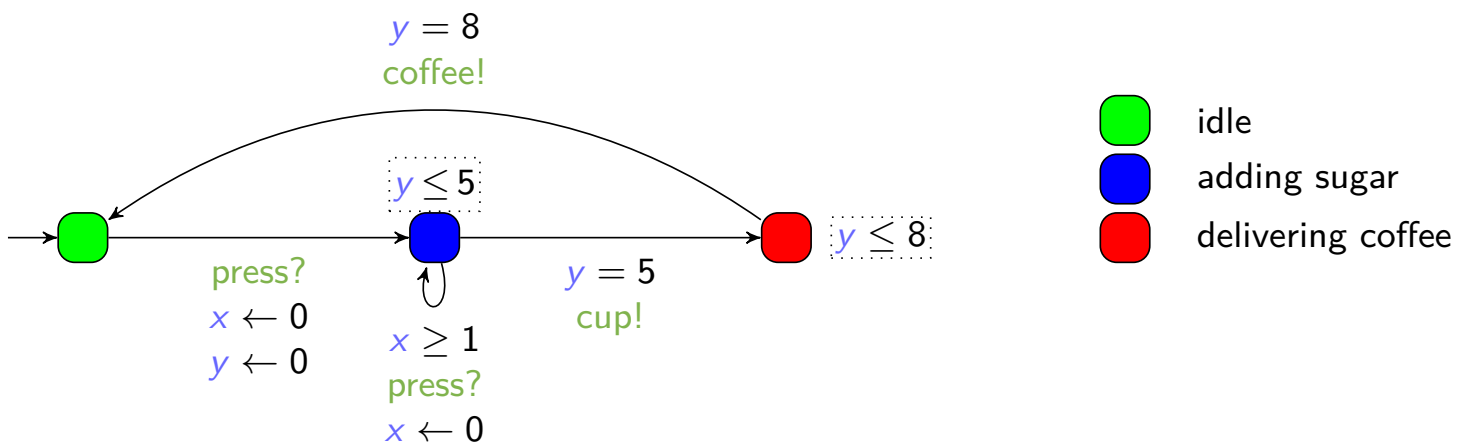
  - Transition guard: property to be verified to enable a transition
  - Clock reset: some of the clocks can be set to 0 along transitions



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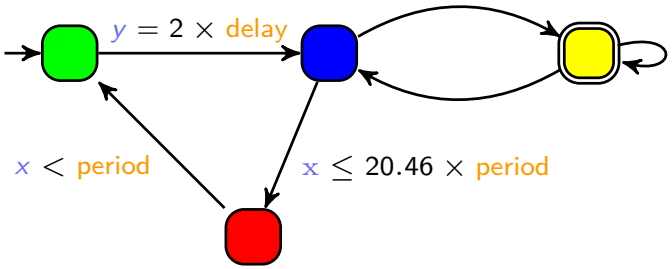

A model of the system

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$\models$

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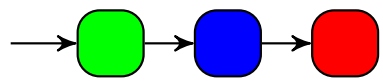
A property to be satisfied

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

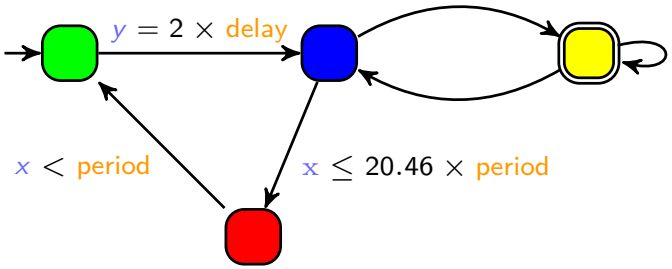
Yes

No



Counterexample

Parametric timed model checking



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A property to be satisfied

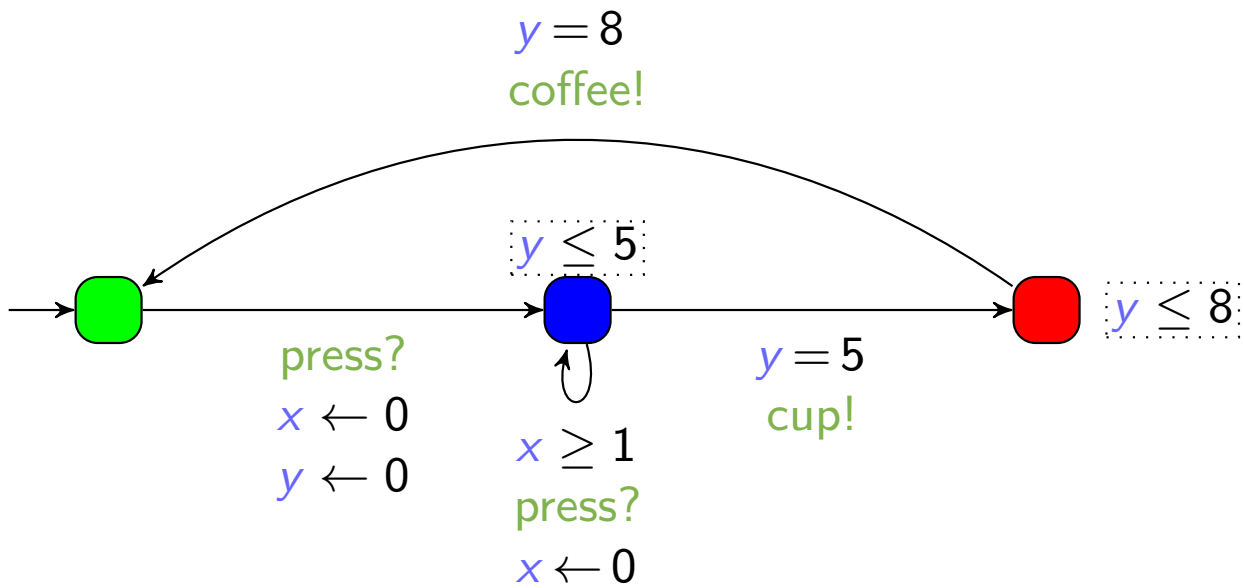
- Question: for what values of the parameters does the model of the system satisfy the property?

Yes if...

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

Timed Automaton (PTA)

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



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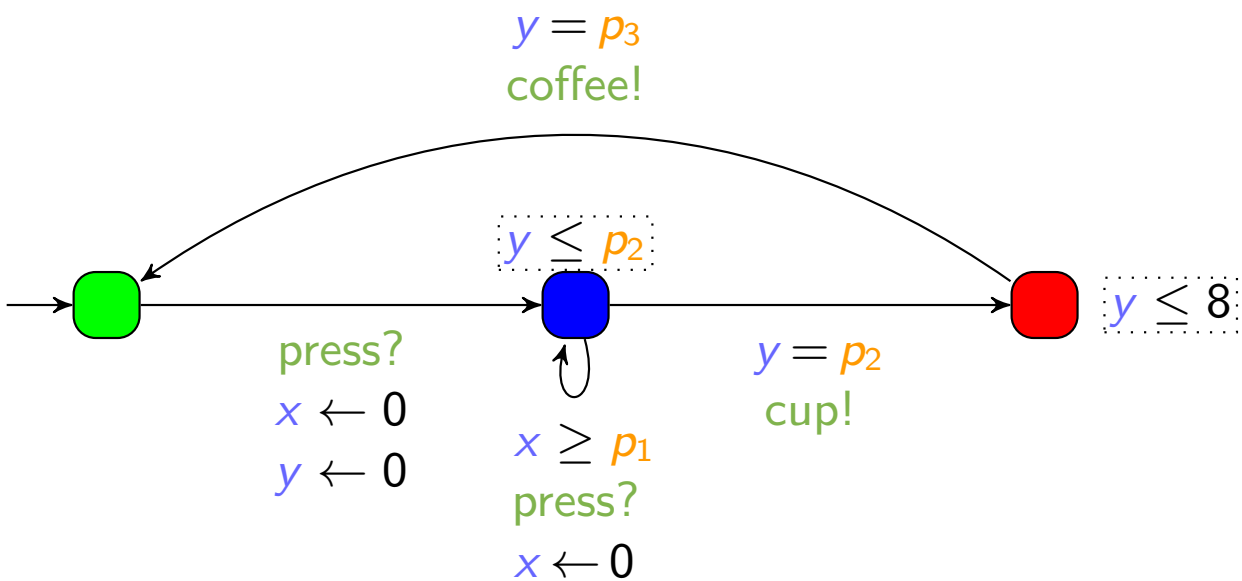
Parametric Timed Automaton (PTA)

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



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Valuation of a PTA = TA

- Given a PTA $\mathcal{A}$ and a parameter valuation v,
  $v(\mathcal{A})$ is the TA where each parameter p is valuated by $v(p)$

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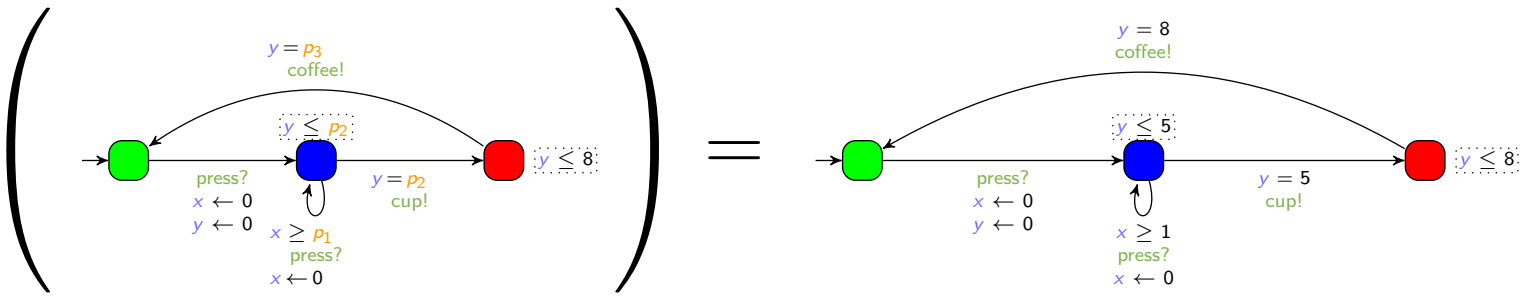
v 

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

Outline

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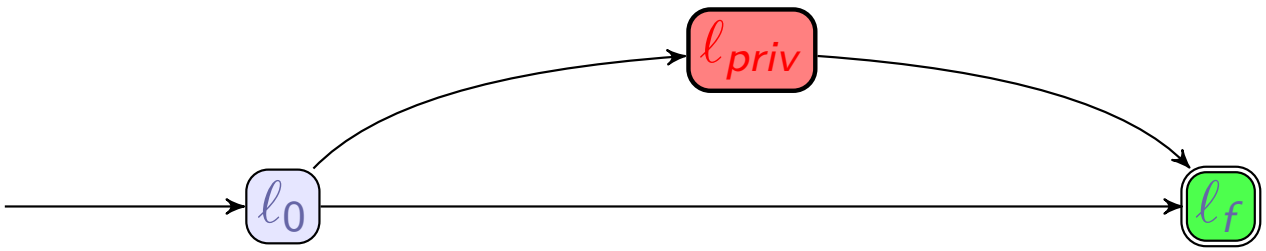
Formalization

Hypotheses: [AS19]

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



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}

[AS19] Étienne André and Jun Sun. "Parametric Timed Model Checking for Guaranteeing Timed Opacity". In: *ATVA* (Oct. 28–31, 2019). Ed. by Yu-Fang Chen, Chih-Hong Cheng, and Javier Esparza. Vol. 11781. Lecture Notes in Computer Science. Taipei, Taiwan: Springer, 2019, pp. 115–130. DOI: 10.1007/978-3-030-31784-3_7

Three levels of ET-opacity

Existential – $\exists$

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

Weak

For all duration 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 duration d,
There exists a run of duration d visiting ℓ_{priv}
$\Leftrightarrow$
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$$\text{private durations} \cap \text{public durations} \neq \emptyset$$

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$$\text{private durations} \cap \text{public durations} \neq \emptyset$$

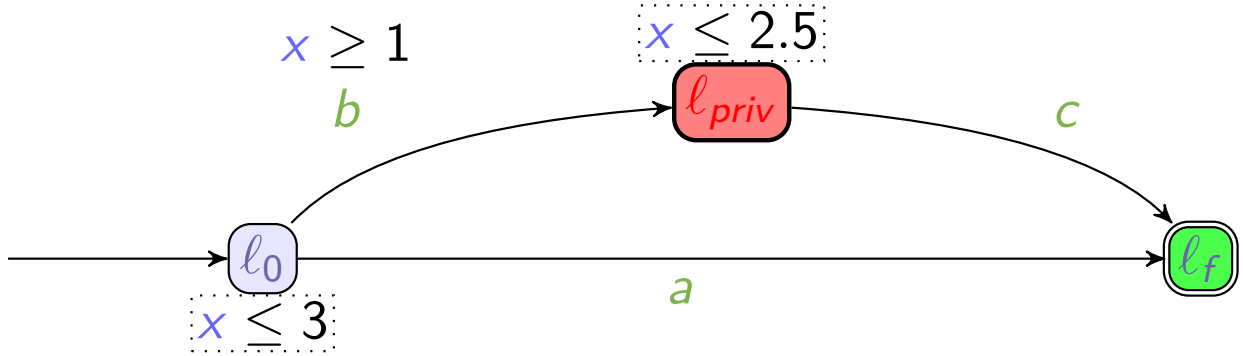
Weak

$$\text{private durations} \subseteq \text{public durations}$$

Full

$$\text{private durations} = \text{public durations}$$

Example



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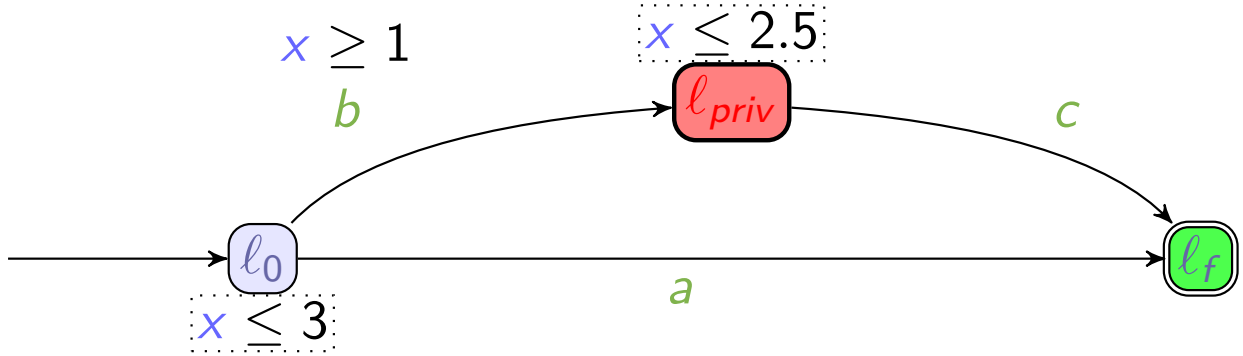
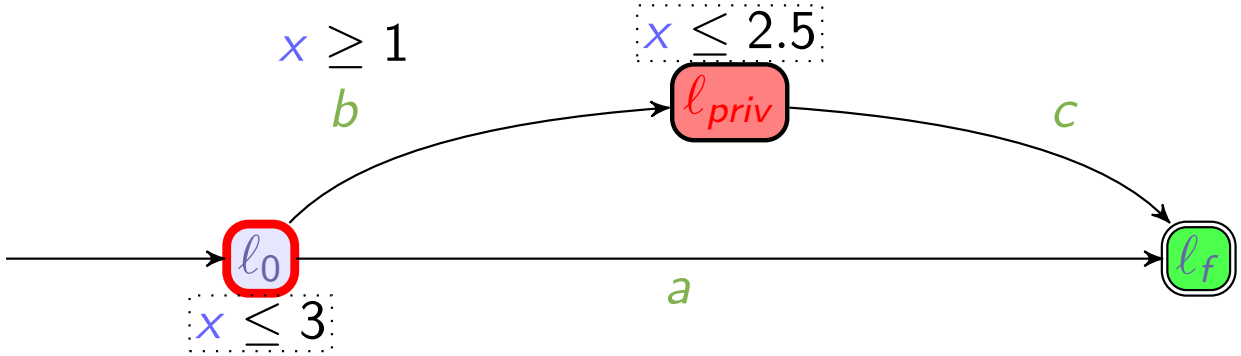


- There exist *(at least)* two runs of duration $d = 2$:

Example



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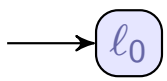
visiting ℓ_{priv}



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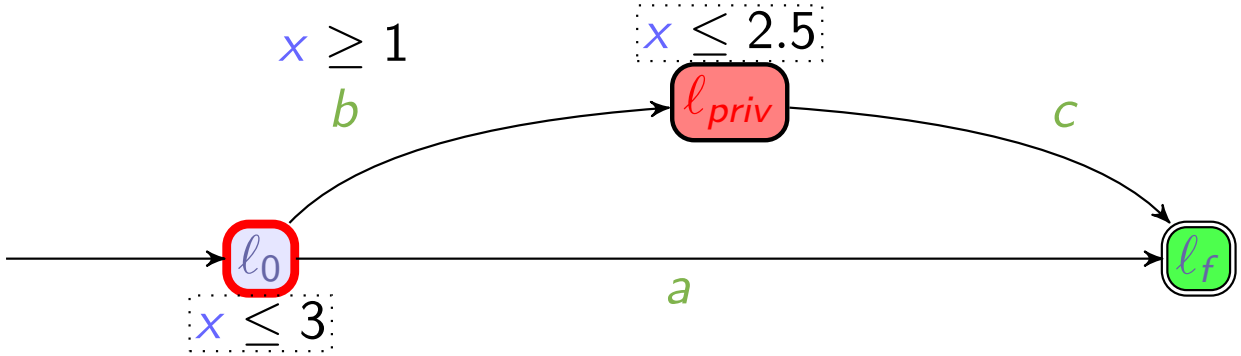

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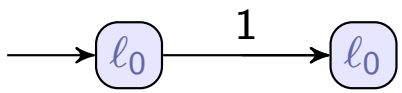

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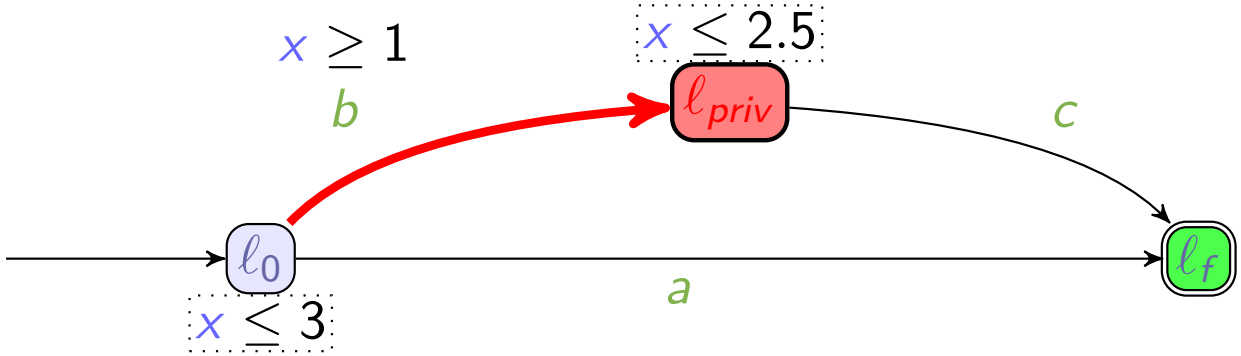

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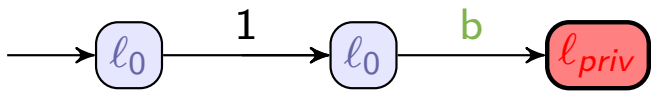

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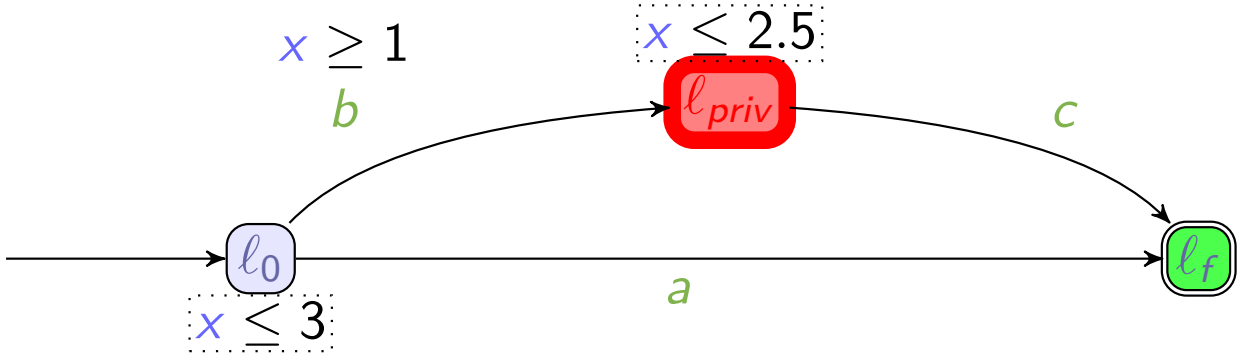

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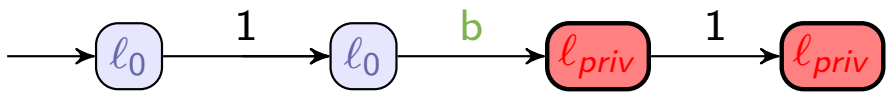

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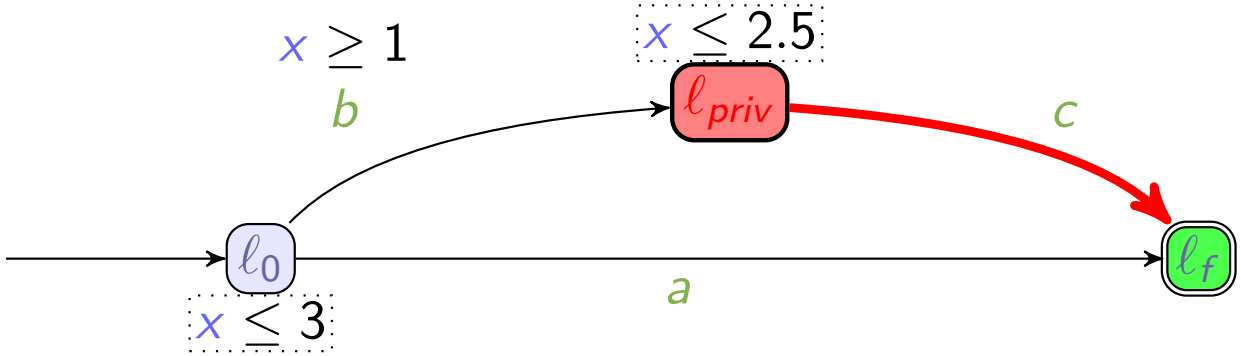

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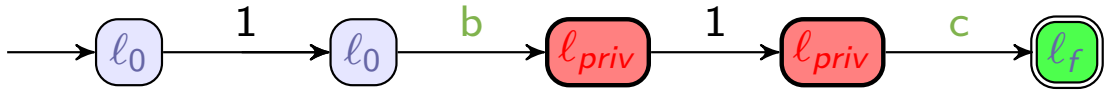

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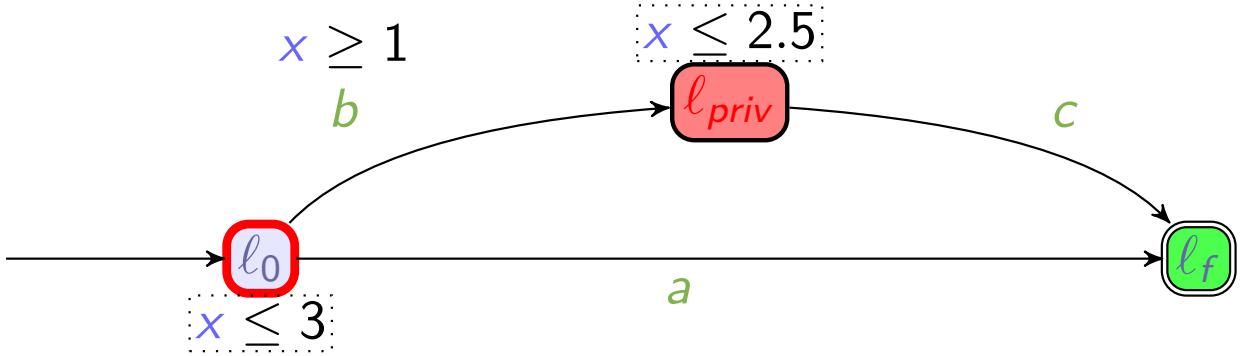

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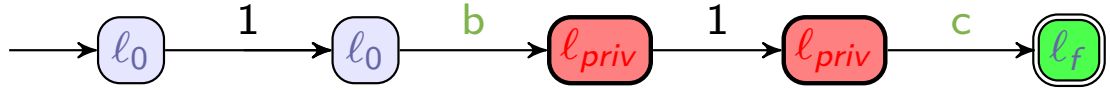
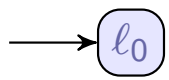


not visiting ℓ_{priv}



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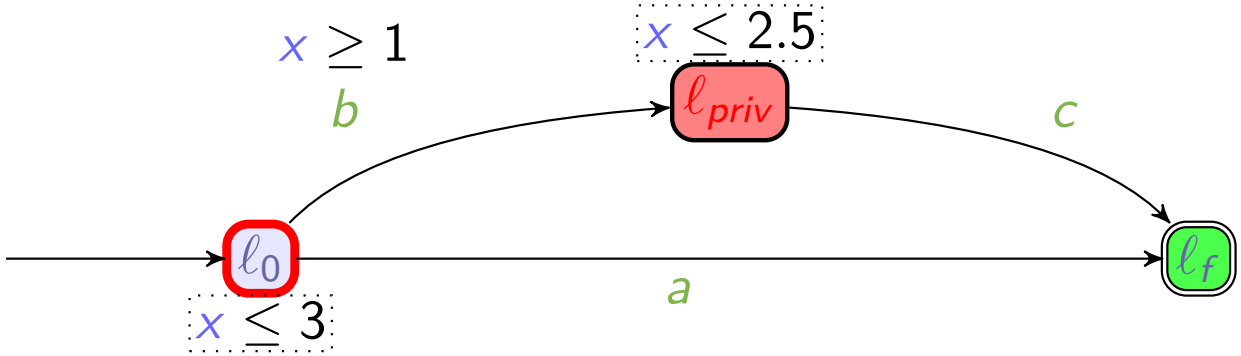

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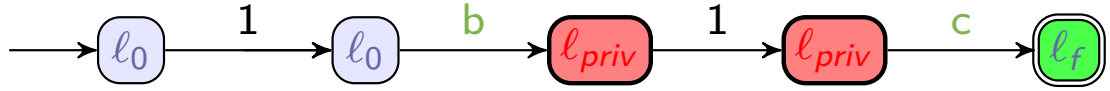
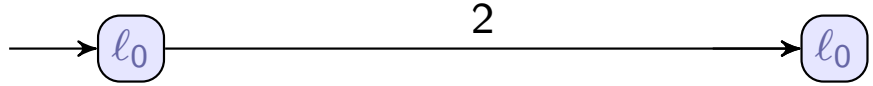
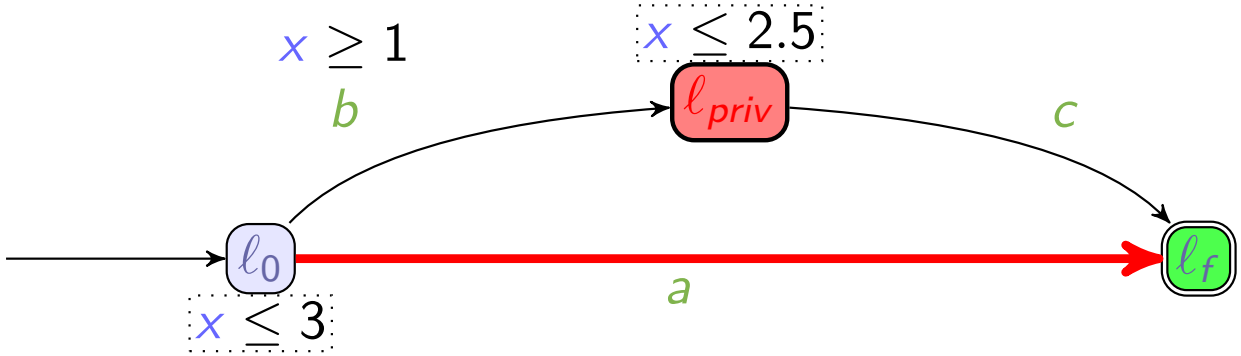
visiting ℓ_{priv}



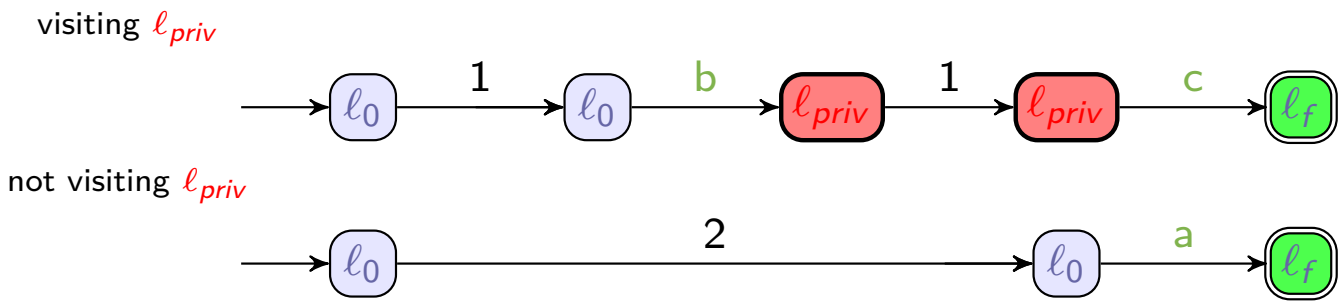
not visiting ℓ_{priv}



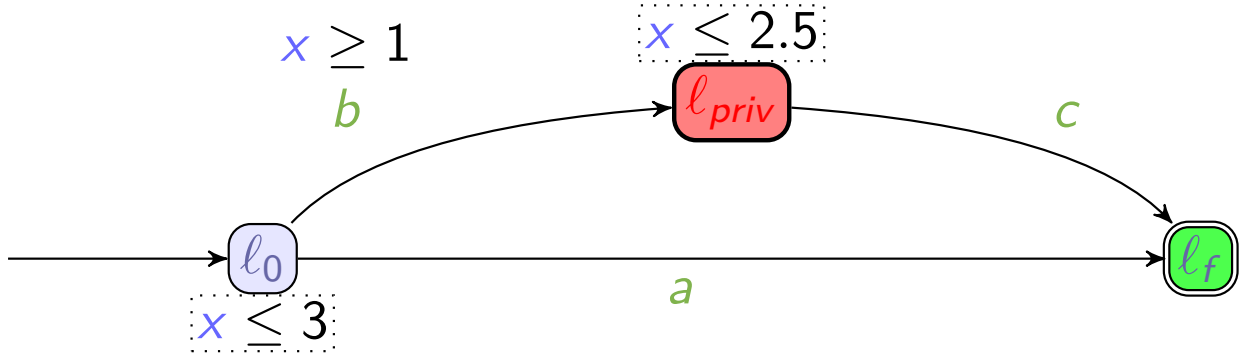
Example



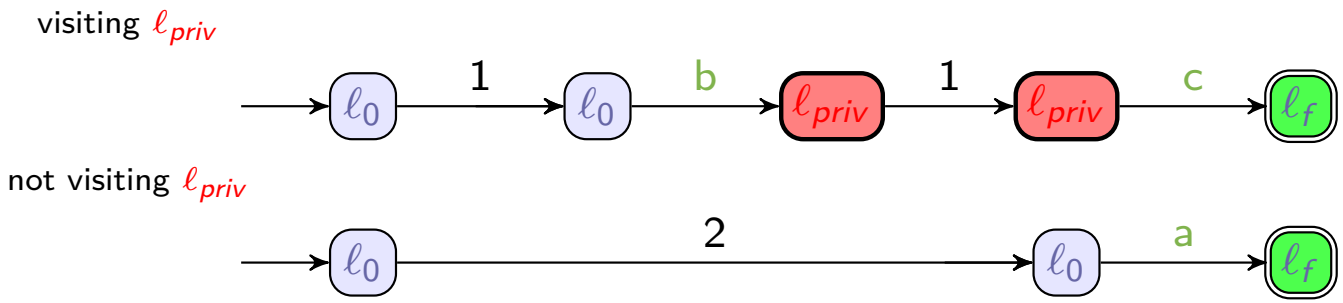
- There exist *(at least)* two runs of duration $d = 2$:



Example



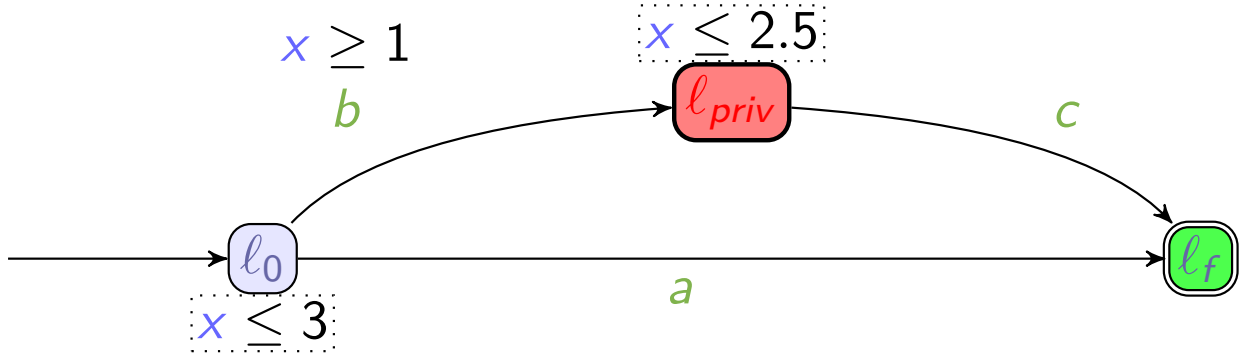
- There exist *(at least)* two runs of duration $d = 2$:



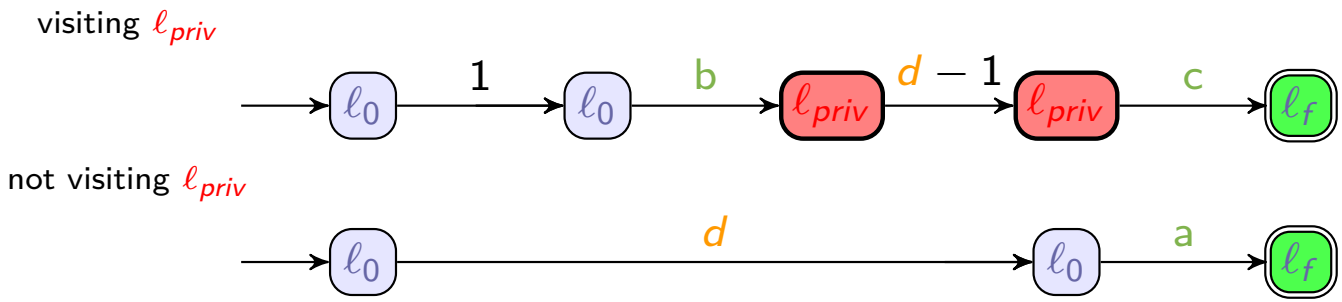
The system is ET-opaque for a duration $d = 2$

The system is $\exists$-ET-opaque

Example



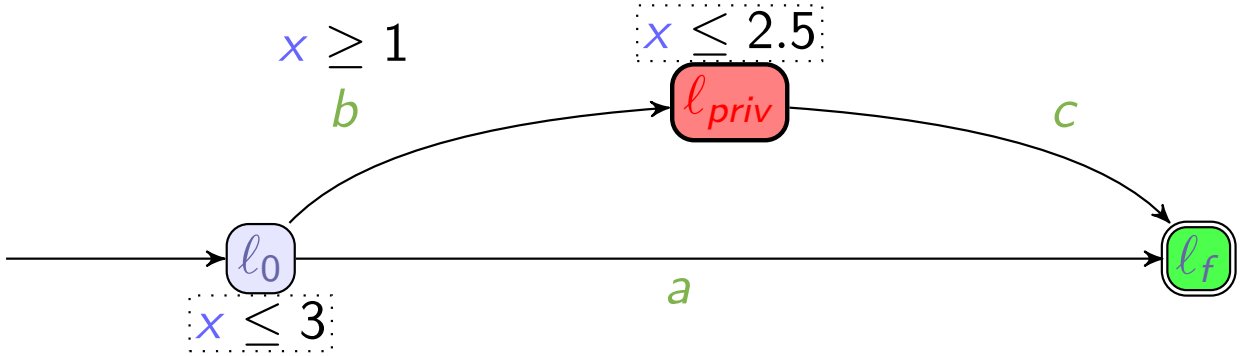
- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$:



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

The system is $\exists$-ET-opaque

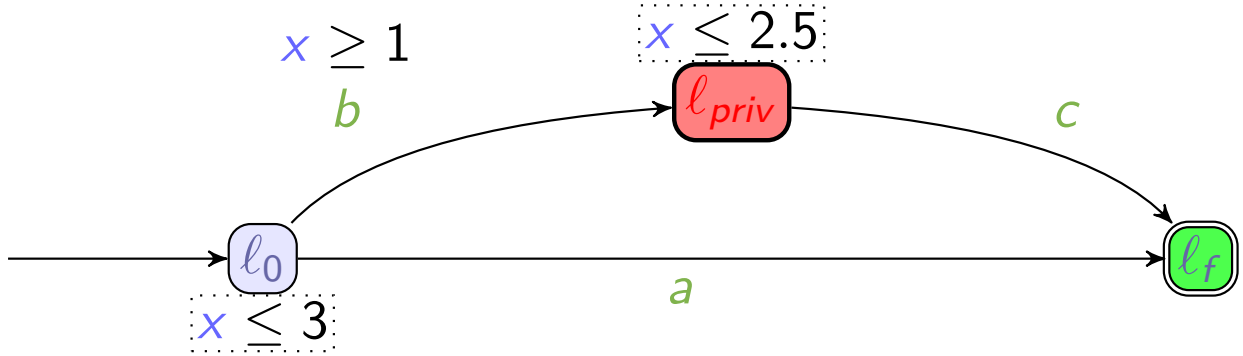
Example



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

The system is $\exists$-ET-opaque

Example

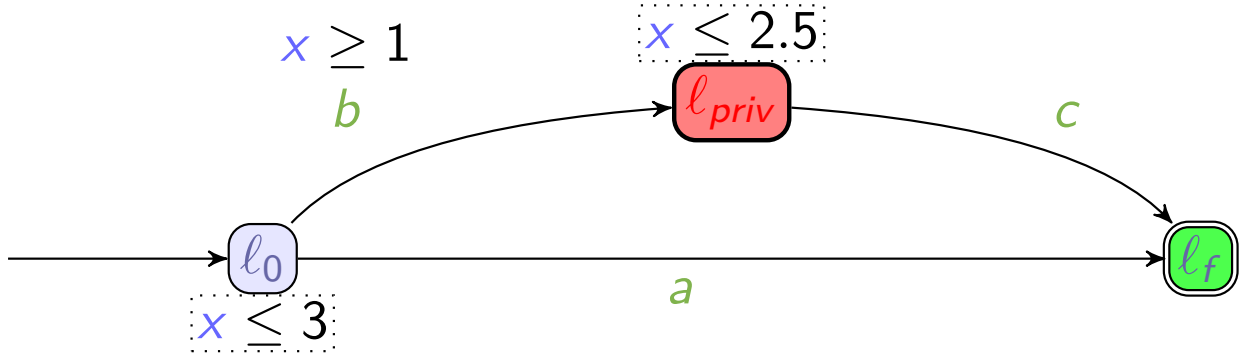


- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is $\exists$-ET-opaque

- But,
  - private execution times are $[1, 2.5]$
    public execution times are $[0, 3]$

Example

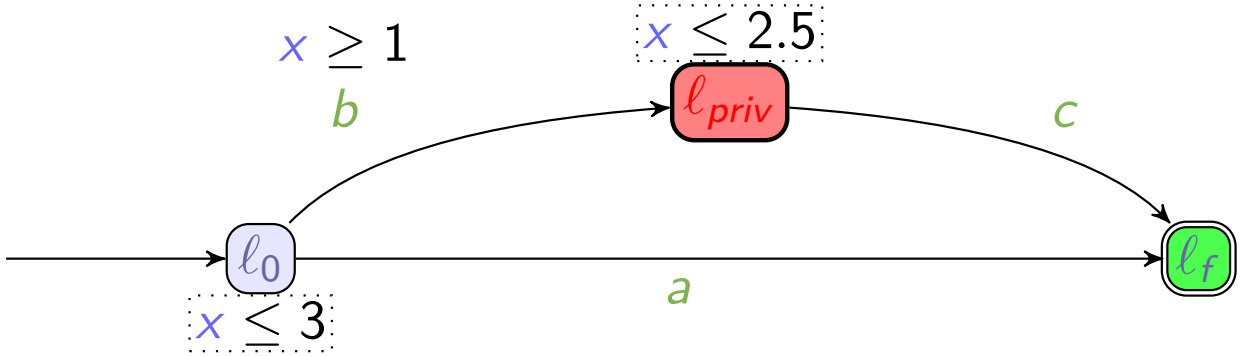


- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is $\exists$-ET-opaque

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

Example



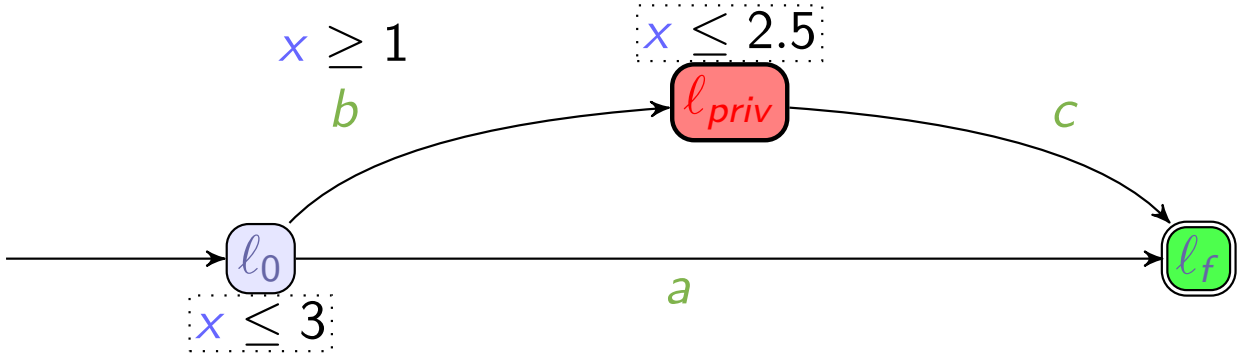
- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is $\exists$-ET-opaque

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

The system is weakly ET-opaque

Example



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

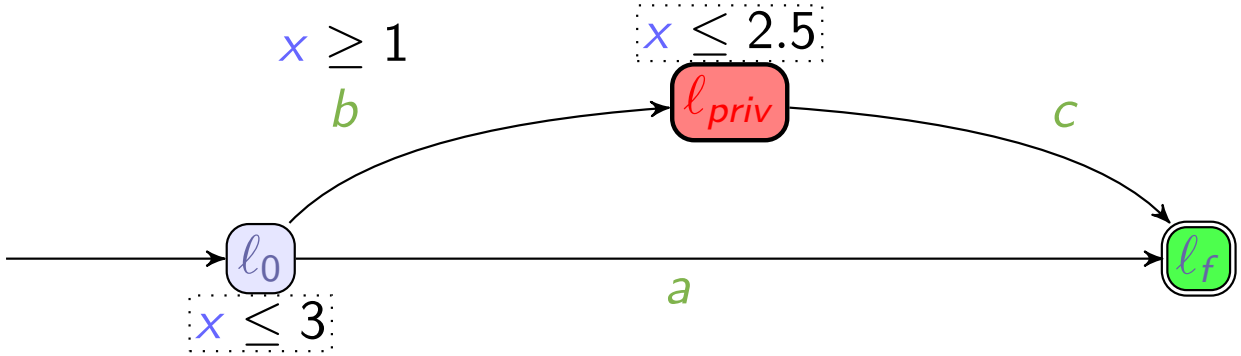
The system is $\exists$-ET-opaque

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

The system is weakly ET-opaque

  - private durations $\neq$ public durations

Example



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

The system is $\exists$-ET-opaque

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

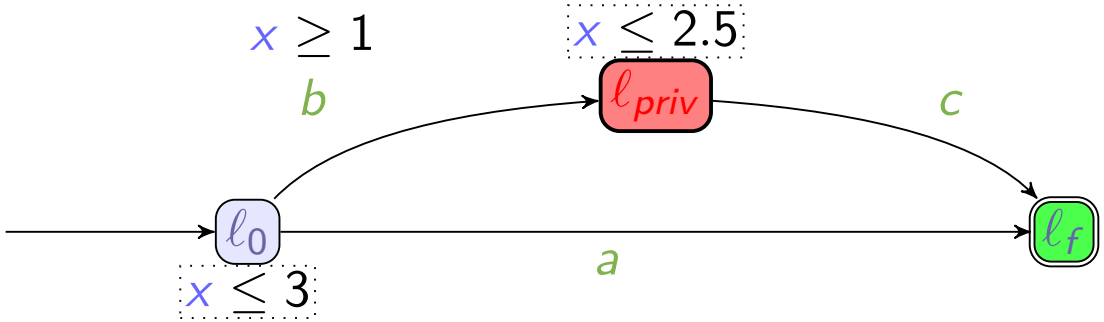
The system is weakly ET-opaque

  - private durations $\neq$ public durations

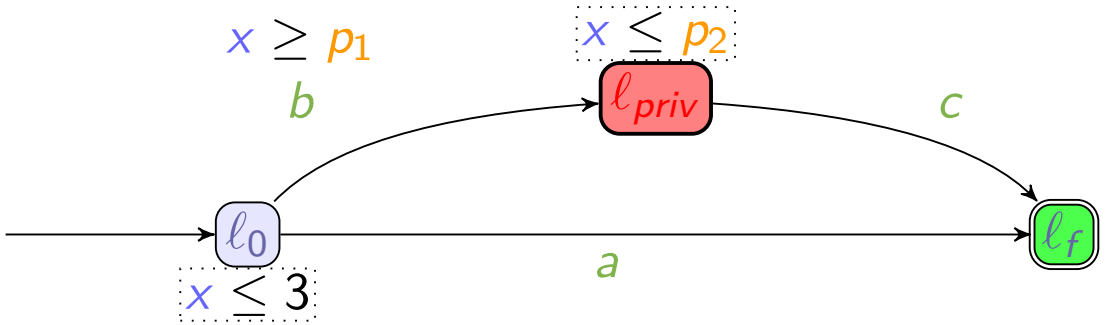
The system is *not* fully ET-opaque

Outline

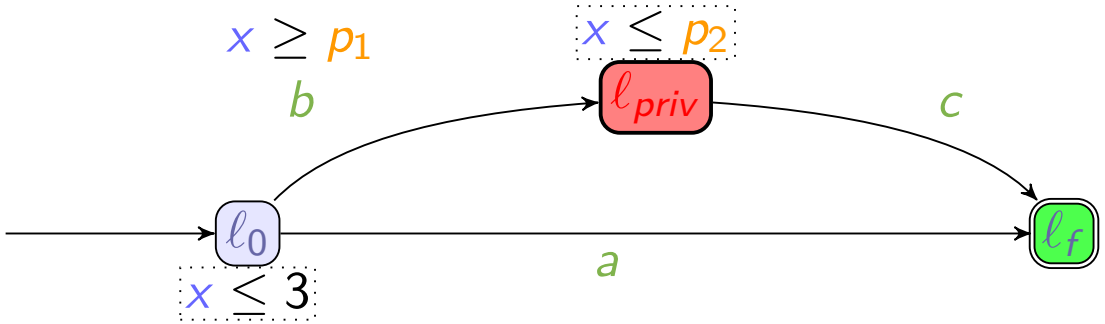
Example



Example

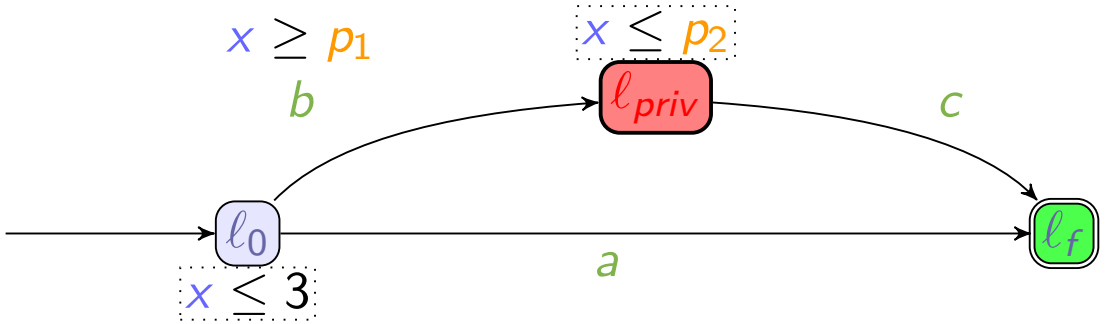


Example



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

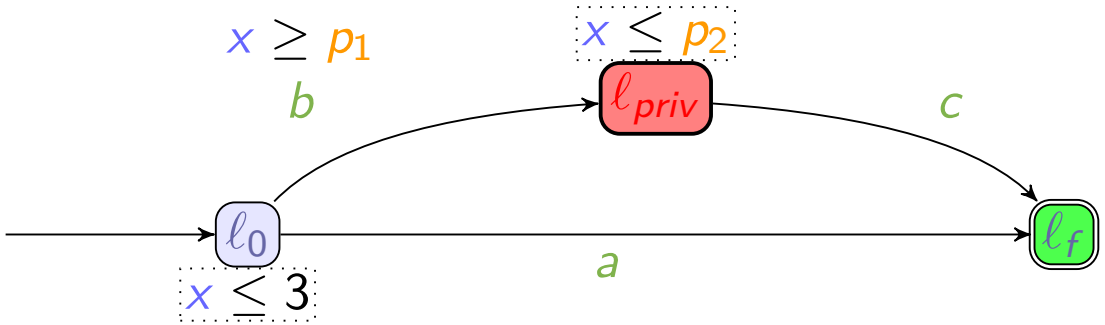
Example



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

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

Example



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

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

Two classes of parametric problems

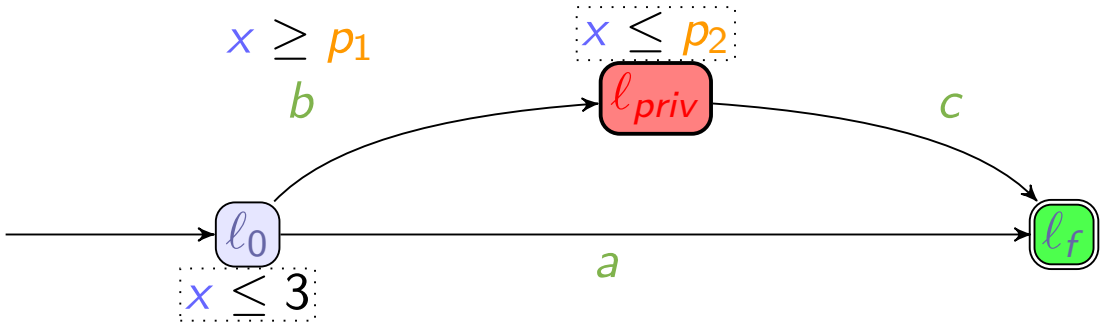
p-Emptiness problem

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

p-Synthesis problem

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

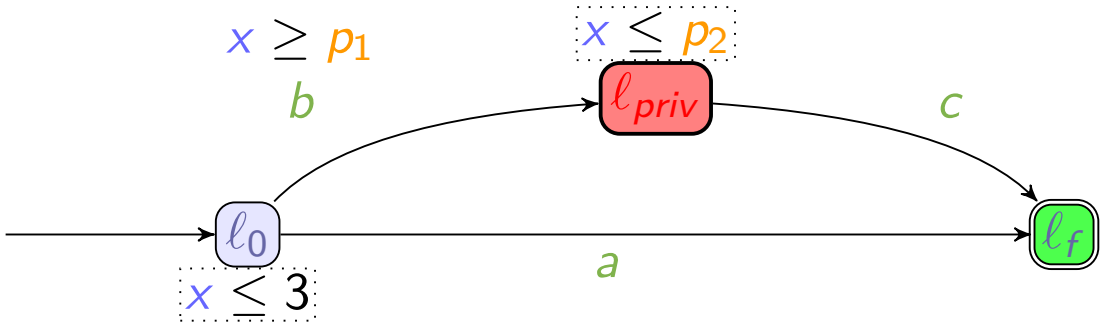
Example



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

ET-opacity notion	p-Emptiness	p-Synthesis
$\exists$		
weak		
full		

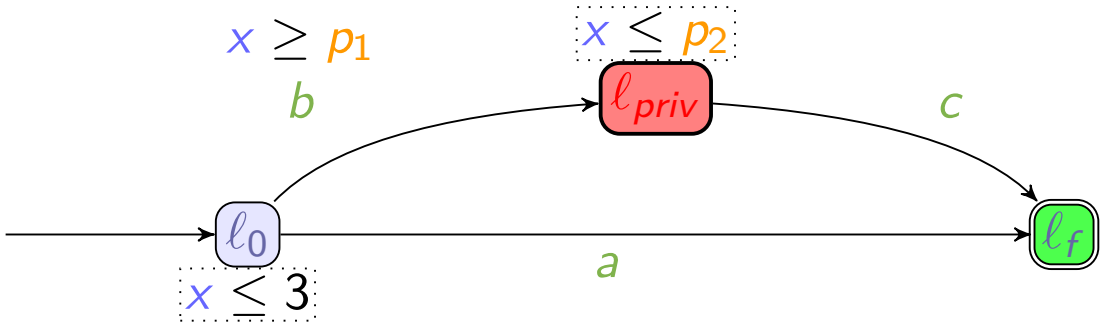
Example



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

ET-opacity notion	p-Emptiness	p-Synthesis
$\exists$	$\times(\exists v)$	
weak	$\times(\exists v)$	
full	$\times(\exists v)$	

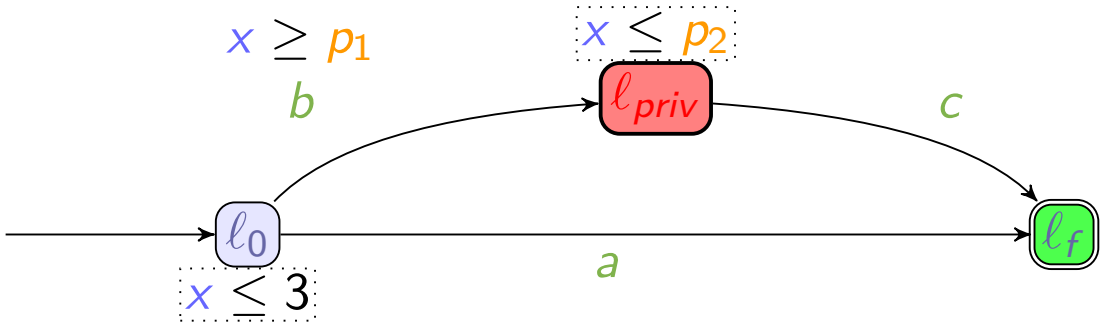
Example



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

ET-opacity notion	p-Emptiness	p-Synthesis
$\exists$	$\times(\exists v)$	$0 \leq p_1 \leq 3 \quad \wedge \quad p_1 \leq p_2$
weak	$\times(\exists v)$	
full	$\times(\exists v)$	

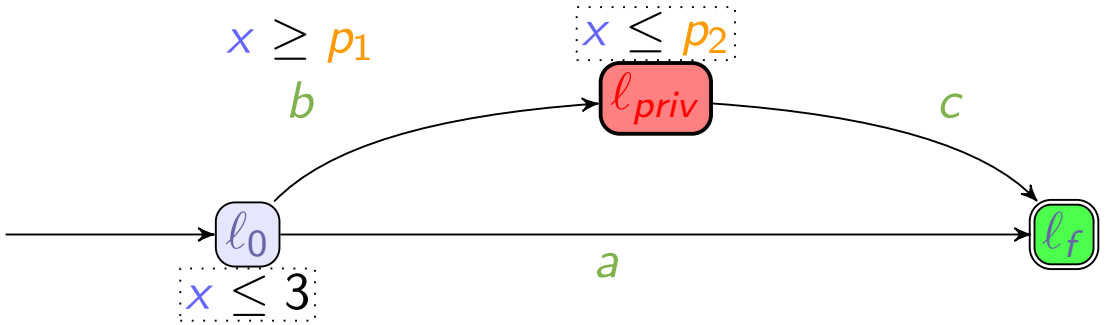
Example



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

ET-opacity notion	p-Emptiness	p-Synthesis
$\exists$	$\times(\exists v)$	$0 \leq p_1 \leq 3 \quad \wedge \quad p_1 \leq p_2$
weak	$\times(\exists v)$	$0 \leq p_1 \wedge p_2 \leq 3 \quad \wedge \quad p_1 \leq p_2$
full	$\times(\exists v)$	

Example



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

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

Outline

Summary of the results for ET-opacity

[And+22b]

		∃-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) [BL09]

[BL09] Laura Bozzelli and Salvatore La Torre. "Decision problems for lower/upper bound parametric timed automata". In: *Formal Methods in System Design* 35.2 (2009), pp. 121–151. DOI: 10.1007/s10703-009-0074-0

[And+22b] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun. "Guaranteeing timed opacity using parametric timed model checking". In: *ACM Transactions on Software Engineering and Methodology* 31.4 (Oct. 2022), pp. 1–36. DOI: 10.1145/3502851

Outline

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][a]

[a] [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), pp. 1–13. DOI: 10.1016/j.jisa.2021.102926

Expiring ET-opacity

[ALM23]

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

[ALM23] Étienne André, Engel Lefaucheux, and Dylan Marinho. "Expiring opacity problems in parametric timed automata". In: *ICECCS* (June 12–16, 2023). Ed. by Yamine Ait-Ameur and Ferhat Khendek. Vol. 13260. Accepted. Toulouse, France: Springer, 2023, pp. 451–469

Two levels of ET-opacity

Existential–∃

$$\text{private durations} \cap \text{public durations} \neq \emptyset$$

Weak

$$\text{private durations} \subseteq \text{public durations}$$

Full

$$\text{private durations} = \text{public durations}$$

Two levels of expiring ET-opacity

Existential–$\exists$ expiring

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

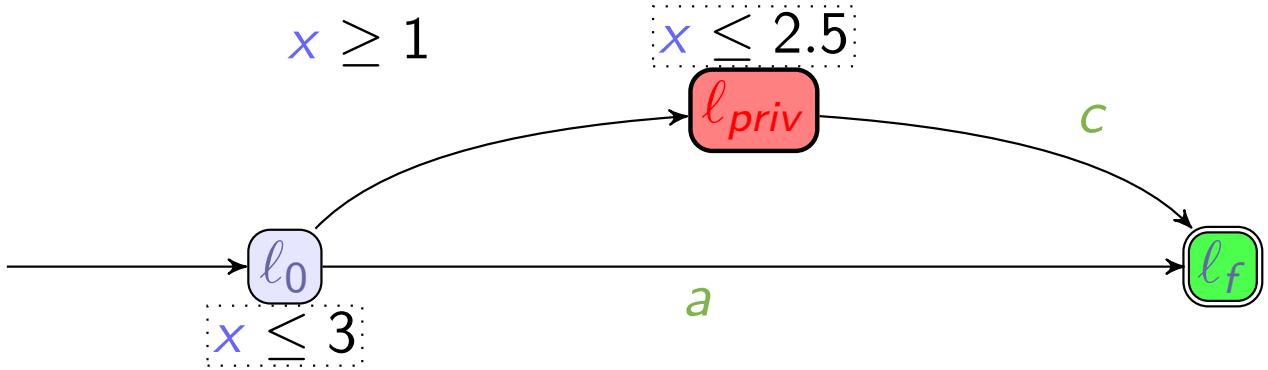
Weak expiring

secret durations $\subseteq$ non-secret durations

Full expiring

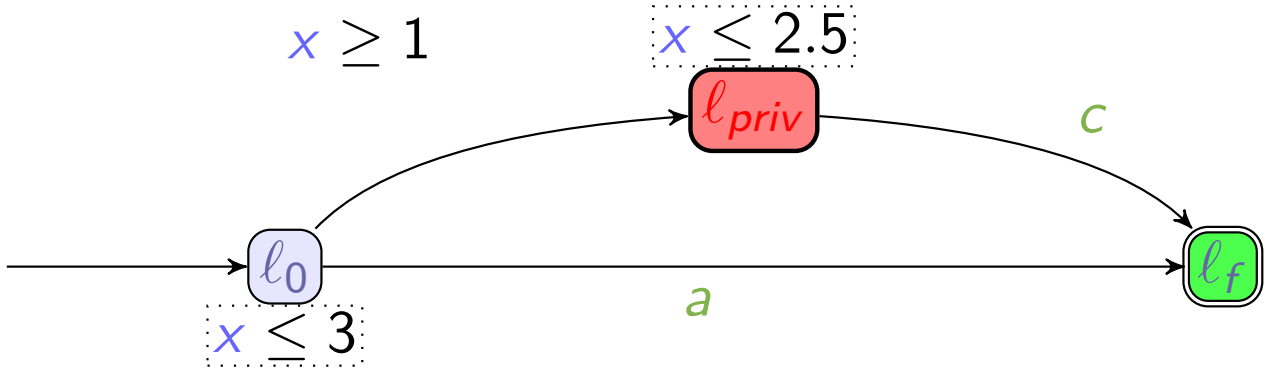
secret durations $=$ non-secret durations

Example



ET-opacity notion		Secret	Non secret	Answer
	$\exists$			$\surd$
	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.			$\times$

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.			$\times$

Outline

Two classes of parametric problems

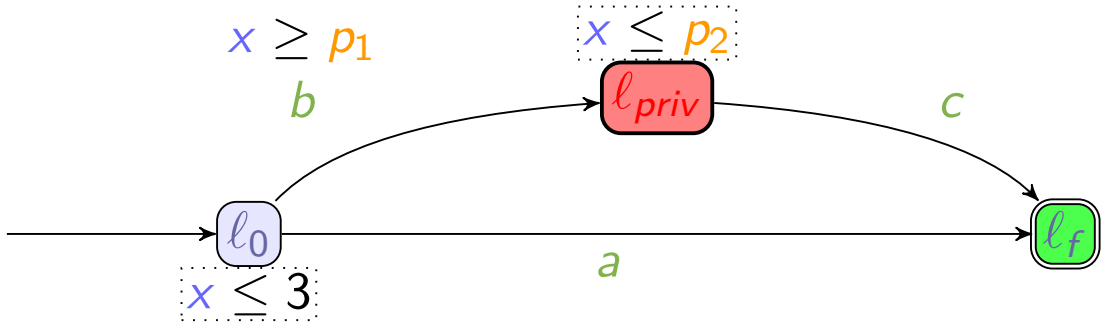
(p+Δ)-Emptiness problem

Decide whether the set of parameter valuations v and Δ s. t. $v(\mathcal{A})$ is expiring-ET-opaque is empty

(p+Δ)-Synthesis problem

Synthesize the set of parameter valuations v and Δ s. t. $v(\mathcal{A})$ is expiring-ET-opaque

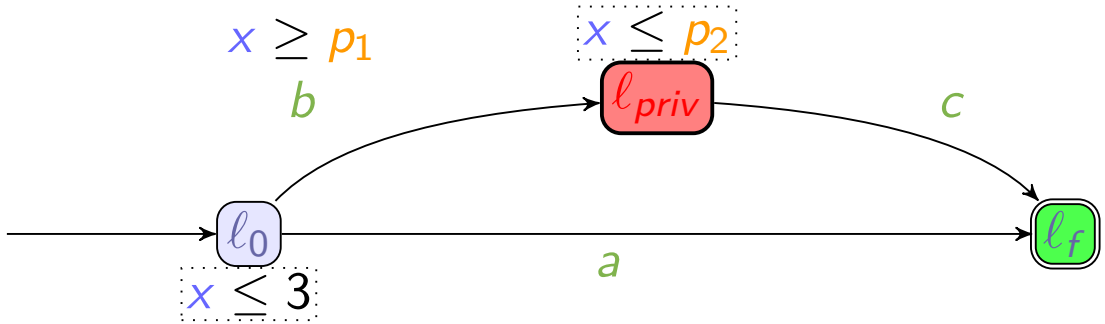
Example



	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	**(p+Δ)-Emptiness**	**(p+Δ)-Synthesis**
weak		
full		

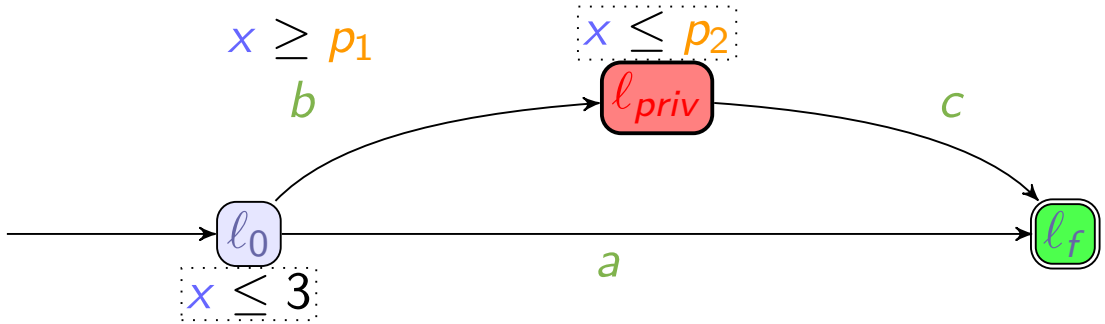
Example



	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	**(p+Δ)-Emptiness**	**(p+Δ)-Synthesis**
weak	$\times_{(\exists \nu)}$	
full	$\times_{(\exists \nu)}$	

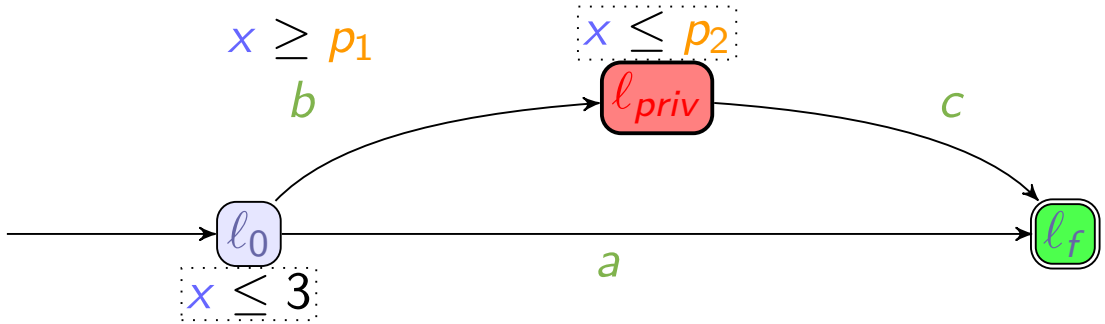
Example



	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	**(p+Δ)-Emptiness**	**(p+Δ)-Synthesis**
weak	$\times_{(\exists \nu)}$	$p_1 > p_2 \quad \vee \quad p_1 > 3 \quad \vee \quad \Delta = 0$ $\vee \quad p_2 \leq 3 \quad \vee \quad p_1 + \Delta <= 3$
full	$\times_{(\exists \nu)}$	

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	**(p+Δ)-Emptiness**	**(p+Δ)-Synthesis**
weak	$\times_{(\exists v)}$	$p_1 > p_2 \quad \vee \quad p_1 > 3 \quad \vee \quad \Delta = 0$ $\vee \quad p_2 \leq 3 \quad \vee \quad p_1 + \Delta <= 3$
full	$\times_{(\exists v)}$	$p_1 = 0 \quad \wedge \quad (\quad (\Delta \leq 3 \wedge 3 \leq p_2 \leq \Delta + 3)$ $\vee (p_2 = 3) \quad)$

Outline

Summary of the results for expiring-ET-opacity [ALM23]

		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	$\times$	$\times$

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) [BL09]

[BL09] Laura Bozzelli and Salvatore La Torre. "Decision problems for lower/upper bound parametric timed automata". In: *Formal Methods in System Design* 35.2 (2009), pp. 121–151. DOI: 10.1007/s10703-009-0074-0

[ALM23] Étienne André, Engel Lefaucheux, and Dylan Marinho. "Expiring opacity problems in parametric timed automata". In: *ICECCS* (June 12–16, 2023). Ed. by Yamine Ait-Ameur and Ferhat Khendek. Vol. 13260. Accepted. Toulouse, France: Springer, 2023, pp. 451–469

Summary of the results for expiring-ET-opacity [ALM23]

		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	$\times$	$\times$

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) [BL09]

$\exists$-expiring ET-opacity was left as a future work.
Proofs are based on the region automaton (for TAs) and by reduction from EF-emptiness (for PTAs).

(see formal proofs in paper)

[BL09] Laura Bozzelli and Salvatore La Torre. "Decision problems for lower/upper bound parametric timed automata". In: *Formal Methods in System Design* 35.2 (2009), pp. 121–151. DOI: 10.1007/s10703-009-0074-0

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Outline

Context & Informal problem

[And+22a]

- ✓ We can decide computation and decision problems for ET-opacity
- × What to do if the model is not (fully) ET-opaque?

[And+22a] Étienne André, Shapagat Bolat, Engel Lefaucheux, and Dylan Marinho. "strategFTO: Untimed control for timed opacity". In: *FTSCS* (Dec. 7, 2022). Ed. by Cyrille Artho and Peter Ölveczky. Auckland, New Zealand: ACM, 2022, pp. 27–33. DOI: 10.1145/3563822.3568013

Context & Informal problem

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- × What to do if the model is not (fully) ET-opaque?

Full ET-opacity control

Is it possible to disable some user actions to make the system fully ET-opaque?

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Untimed control

Goal

Exhibit a controller guaranteeing the system to be fully ET-opaque

i. e., a subset of the actions to be kept, while other controllable actions are disabled

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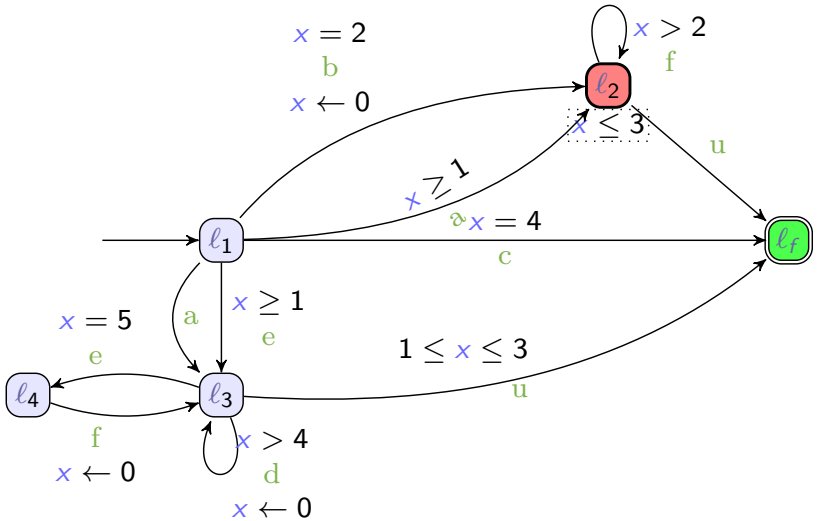
We distinguish two kinds of actions:

- uncontrollable: required by the system or dependent on another agent

  $\rightarrow$ e. g., action dealing with a correct or incorrect password
- controllable: that can be disabled

Outline

A running example



Uncontrollable u

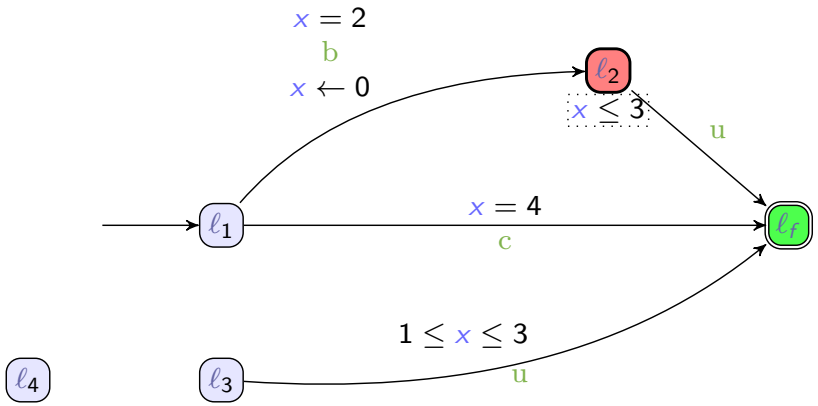
Controllable a, b, c, d, e, f

Is the system fully ET-opaque?

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

$\Rightarrow$ Not fully ET-opaque

A running example



Uncontrollable u

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

Allowed u + b, c

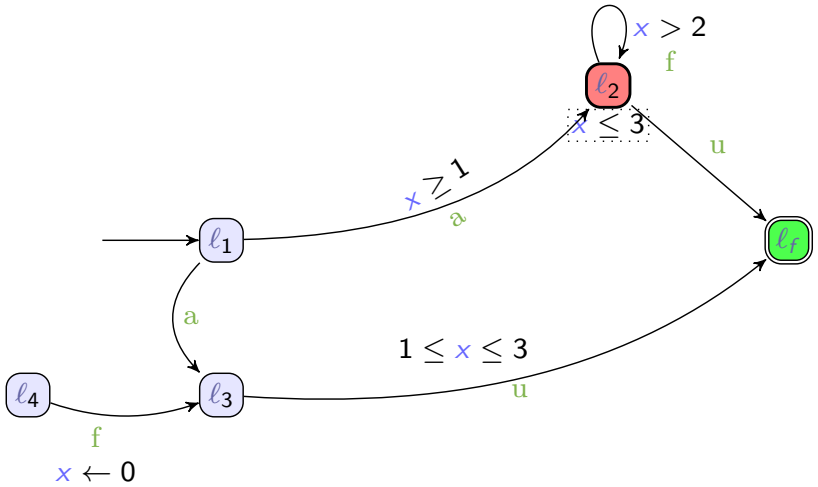
Disabled a, d, e, f

Is the system fully ET-opaque?

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

$\Rightarrow$ Not fully ET-opaque

A running example



Uncontrollable u

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

Allowed u + a, f

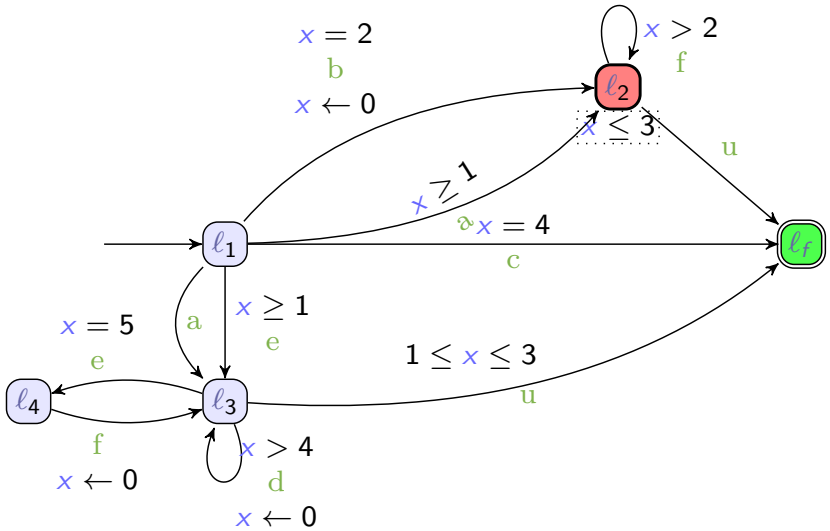
Disabled b, c, d, e

Is the system fully ET-opaque?

- Visiting ℓ_2: $[1, 3]$
- Not visiting ℓ_2: $[1, 3]$

$\Rightarrow$ fully ET-opaque

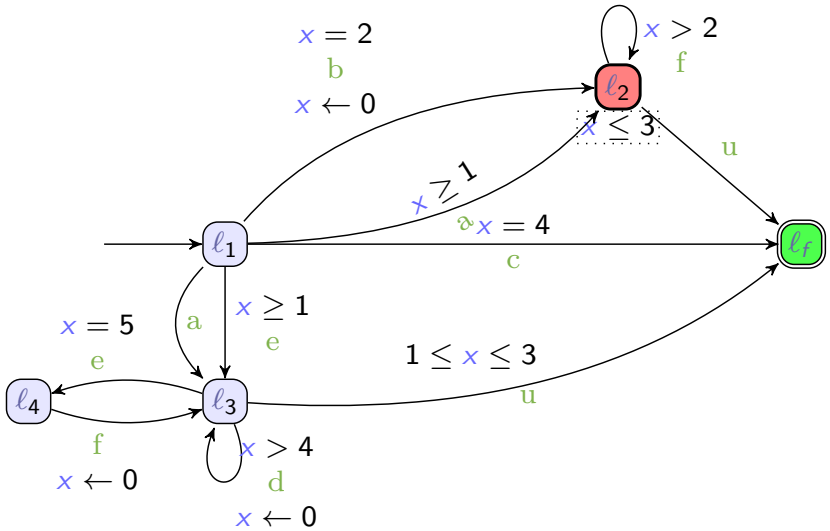
A running example



It can be shown that the set of *sets of actions to allow to ensure full ET-opacity* is

$\{u, a\}$ $\{u, a, e\}$ $\{u, a, f\}$

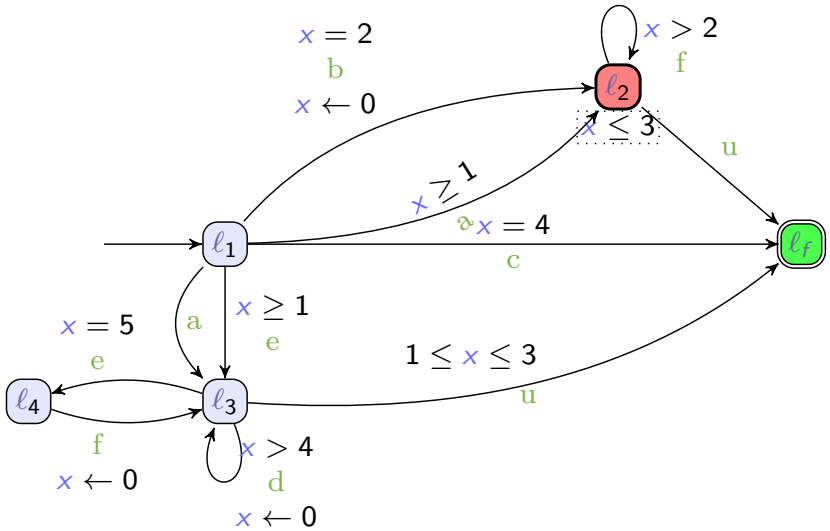
A running example



It can be shown that the set of fully ET-opaque strategies is

$\{u, a\}$ $\{u, a, e\}$ $\{u, a, f\}$

A running example



It can be shown that the set of fully ET-opaque strategies is

$$\underbrace{\{u, a\}}_{\text{minimal}} \qquad \underbrace{\{u, a, e\} \qquad \{u, a, f\}}_{\text{maximal}}$$

Outline

strategFTO

- an automated open-source tool written in Java

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

- iteratively constructs strategies
  - computes the private and public execution times (using IMITATOR[And21])
  - checks full ET-opacity by checking their equality (using PolyOp[1])
    - Method: by considering execution times as a timing parameter, and performing parameter synthesis

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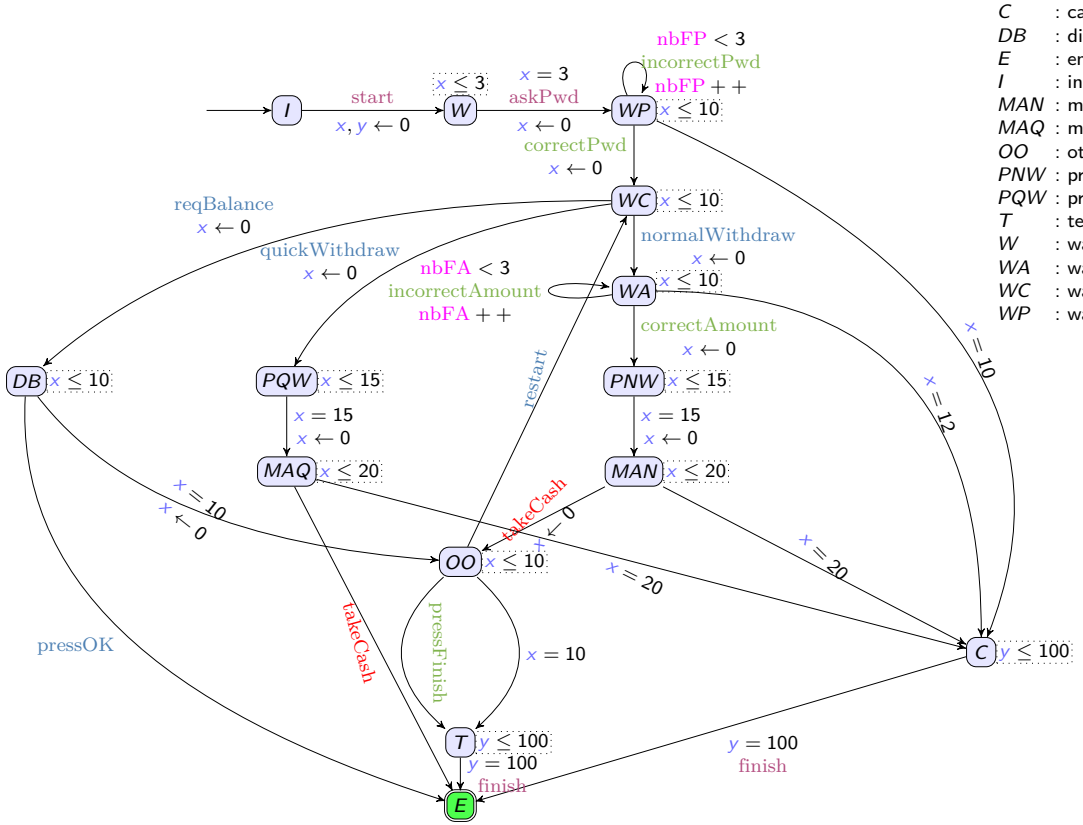
[And21] Étienne André. "IMITATOR 3: Synthesis of timing parameters beyond decidability". In: *CAV* (July 18–23, 2021). Ed. by Rustan Leino and Alexandra Silva. Vol. 12759. Lecture Notes in Computer Science. virtual: Springer, 2021, pp. 1–14. DOI: 10.1007/978-3-030-81685-8_26

[1] https://github.com/etienneandre/PolyOp

Outline

A Proof of concept benchmark: an ATM



Uncontrollable actions	correctAmount, correctPwd, incorrectAmount, incorrectPwd, pressFinish
Controllable system actions	askPwd, finish, start
Controllable user actions	reqBalance, normalWithdraw, pressOK, quickWithdraw, restart
Secret	takeCash

Proof of concept

[And+22a]

Actions to disable **Option**	synthMinControl `-find min`	witnessMinControl `-find min -witness`	synthMaxControl `-find max`	witnessMaxControl `-find max -witness`	synthControl `-find all`
restart, pressOK			√	√	√
restart, reqBalance			√		√
restart, pressOK, quickWithdraw					√
restart, pressOK, reqBalance					√
restart, quickWithdraw, reqBalance					√
restart, pressOK, quickWithdraw, reqBalance	√	√			√

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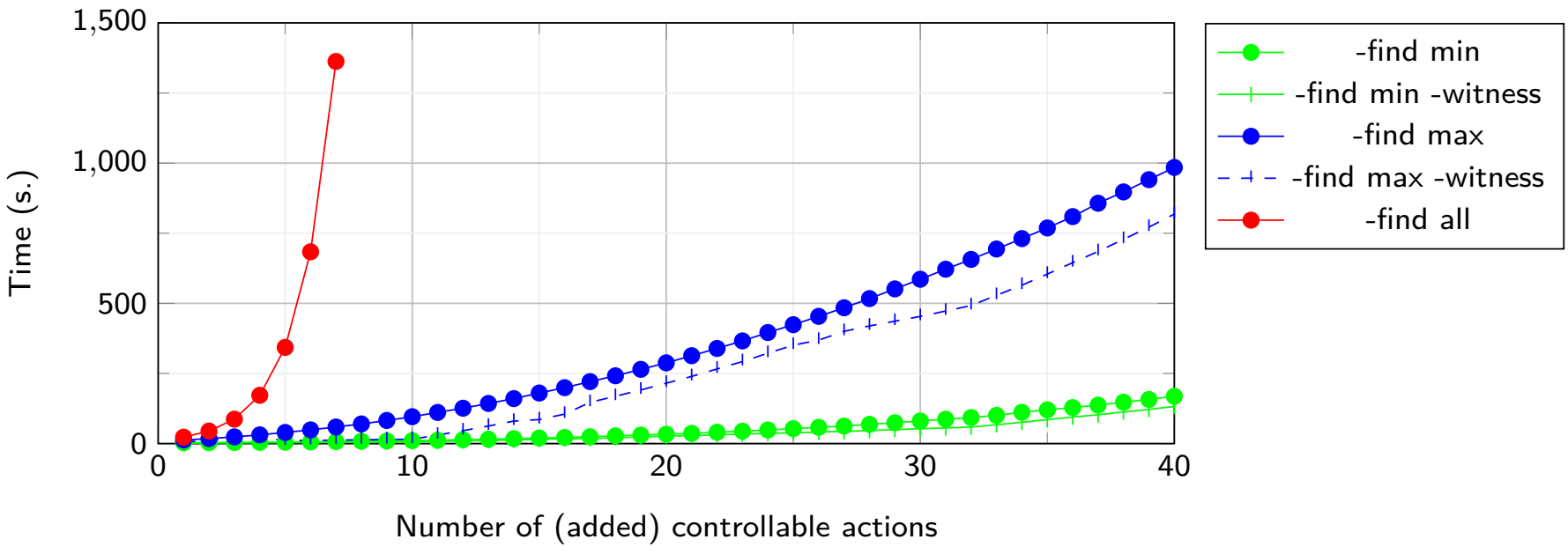
Scalability

Methodology: add to the ATM model an increasing number of self-loop transitions



Outline

Perspectives – Theory

ET-opacity

- Some restricted problems remain open

  e. g., PTA with one clock
- Study more restrictive sub-classes, with the hope to exhibit a decidable one

  Promising subclass: U-PTAs (only upper-bound parameters)

Control

- Use symbolic reasoning

  Instead of a simple enumeration
- Extend the method to timed control

Perspectives – Algorithmic

Algorithmic and implementation

- Automatic translation of programs to timed automata
- Repairing a non ET-opaque system

References I

[AD94] Rajeev Alur and David L. Dill. "A theory of timed automata". In: *Theoretical Computer Science* 126.2 (Apr. 1994), pp. 183–235. DOI: 10.1016/0304-3975(94)90010-8.

[AHV93] Rajeev Alur, Thomas A. Henzinger, and Moshe Y. Vardi. "Parametric real-time reasoning". In: *STOC* (May 16–18, 1993). Ed. by S. Rao Kosaraju, David S. Johnson, and Alok Aggarwal. San Diego, California, United States: ACM, 1993, pp. 592–601. DOI: 10.1145/167088.167242.

References II

[ALM23] Étienne André, Engel Lefaucheux, and Dylan Marinho. "Expiring opacity problems in parametric timed automata". In: *ICECCS* (June 12–16, 2023). Ed. by Yamine Ait-Ameur and Ferhat Khendek. Vol. 13260. Accepted. Toulouse, France: Springer, 2023, pp. 451–469.

[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), pp. 1–13. DOI: 10.1016/j.jisa.2021.102926.

References III

[And+22a] Étienne André, Shapagat Bolat, Engel Lefaucheux, and Dylan Marinho. "strategFTO: Untimed control for timed opacity". In: *FTSCS* (Dec. 7, 2022). Ed. by Cyrille Artho and Peter Ölveczky. Auckland, New Zealand: ACM, 2022, pp. 27–33. DOI: 10.1145/3563822.3568013.

[And+22b] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun. "Guaranteeing timed opacity using parametric timed model checking". In: *ACM Transactions on Software Engineering and Methodology* 31.4 (Oct. 2022), pp. 1–36. DOI: 10.1145/3502851.

References IV

[And21] Étienne André. "IMITATOR 3: Synthesis of timing parameters beyond decidability". In: *CAV* (July 18–23, 2021). Ed. by Rustan Leino and Alexandra Silva. Vol. 12759. Lecture Notes in Computer Science. virtual: Springer, 2021, pp. 1–14. DOI: 10.1007/978-3-030-81685-8_26.

[AS19] Étienne André and Jun Sun. "Parametric Timed Model Checking for Guaranteeing Timed Opacity". In: *ATVA* (Oct. 28–31, 2019). Ed. by Yu-Fang Chen, Chih-Hong Cheng, and Javier Esparza. Vol. 11781. Lecture Notes in Computer Science. Taipei, Taiwan: Springer, 2019, pp. 115–130. DOI: 10.1007/978-3-030-31784-3_7.

References V

[BL09] Laura Bozzelli and Salvatore La Torre. "Decision problems for lower/upper bound parametric timed automata". In: *Formal Methods in System Design* 35.2 (2009), pp. 121–151. DOI: 10.1007/s10703-009-0074-0.