Journées des GT CLAP, HiFi et LVP

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Execution-time opacity problems in (parametric) timed automata

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

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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

A simple example of timing attack

```
1 # input pwd     : Real password
2 # input attempt: Tentative password
3 for i = 0 to min(len(pwd), len(attempt)) - 1 do
4     if pwd[i] =/= attempt[i] then
5         return false
6 done
7 return true
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pwd	c	h	i	c	k	e	n
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`

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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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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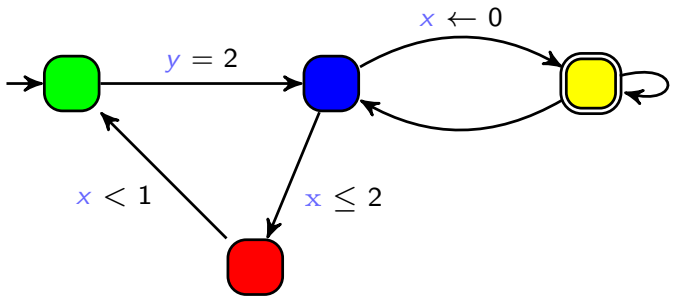
Timed model checking

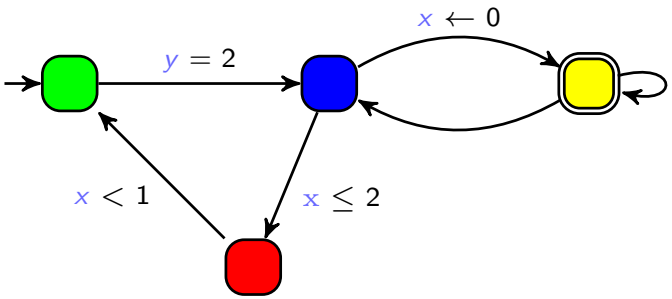


A model of the system

is unreachable

A property to be satisfied

Timed model checking



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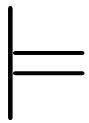

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- Question: does the model of the system satisfy the property?

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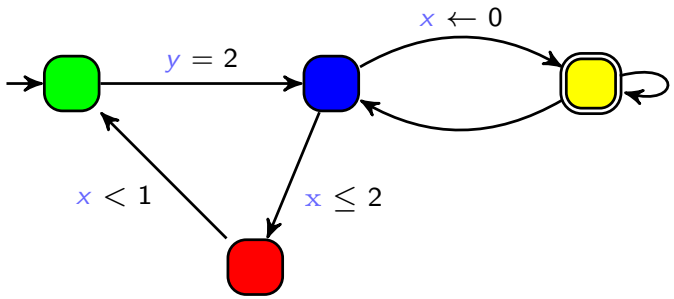

A model of the system

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$\models$

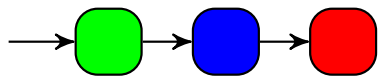
is unreachable

A property to be satisfied

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

Yes

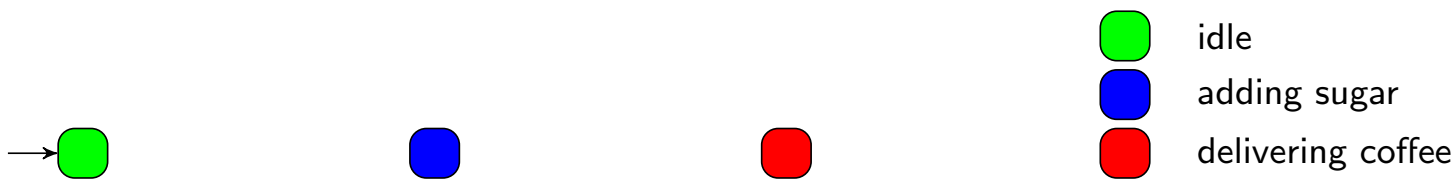
No



Counterexample

Timed automaton (TA)

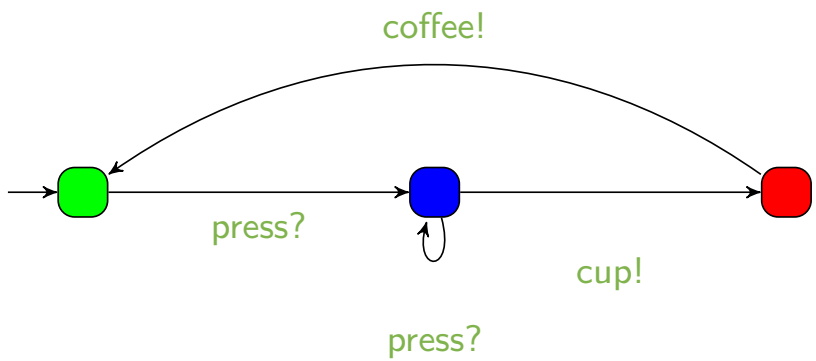
- Finite state automaton (sets of locations)

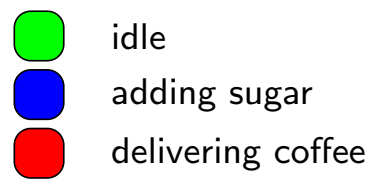


[AD94] Rajeev Alur and David L. Dill. "A theory of timed automata". In: *Theoretical Computer Science* 126.2 (Apr. 1994), pp. 183–235. DOI: 10.1016/0304-3975(94)90010-8

Timed automaton (TA)

- Finite state automaton (sets of locations and actions)





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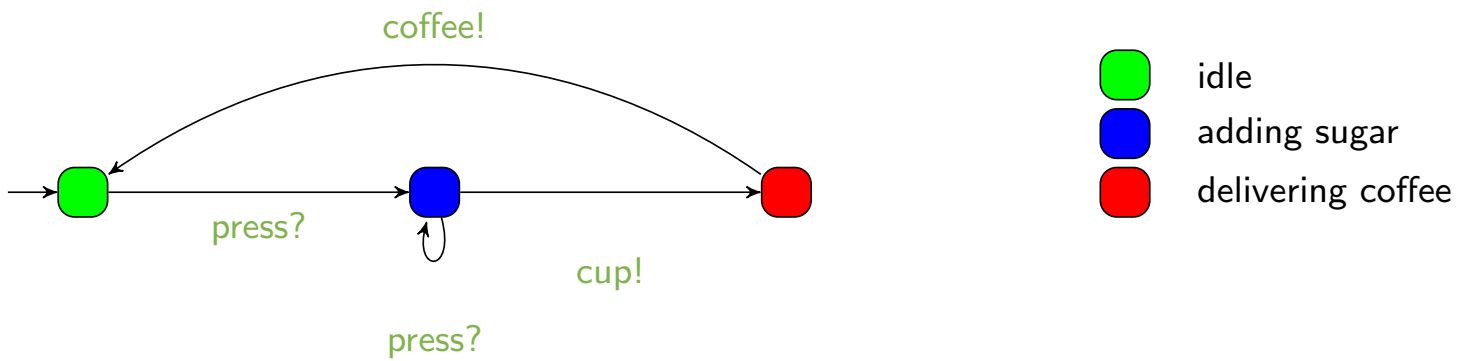
- Finite state automaton (sets of locations and actions) augmented with a set X of clocks [AD94]
  - Real-valued variables evolving linearly at the same rate



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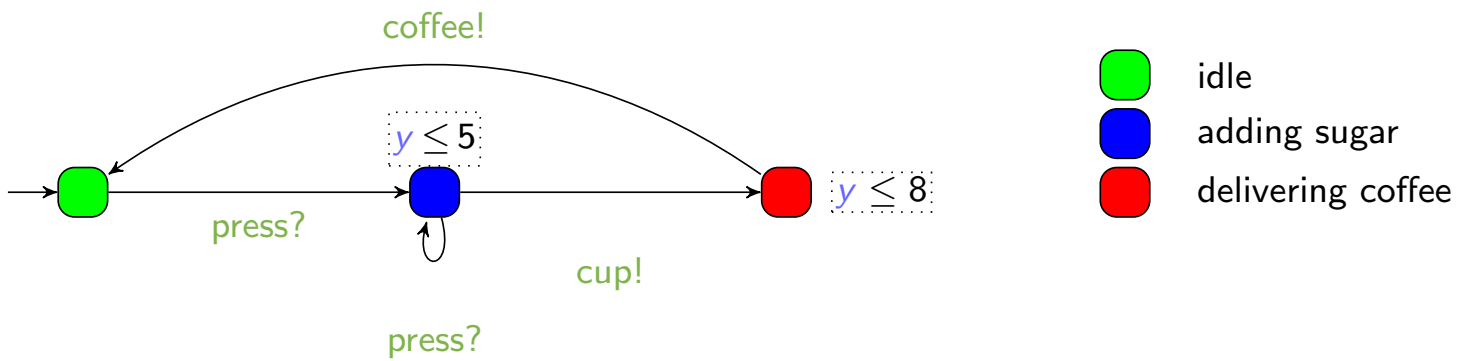
- Features
  - Location invariant: property to be verified to stay at a location



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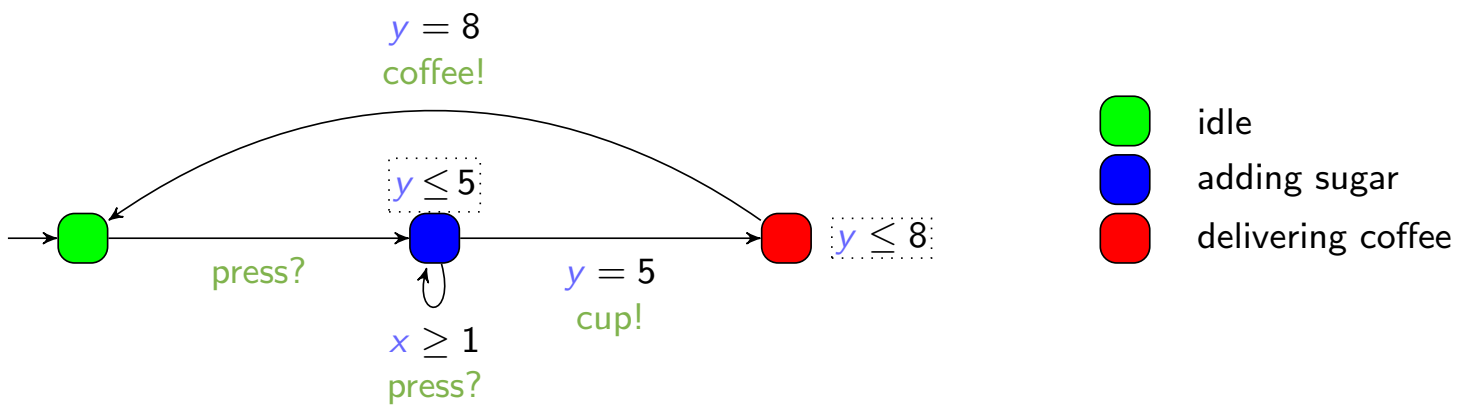

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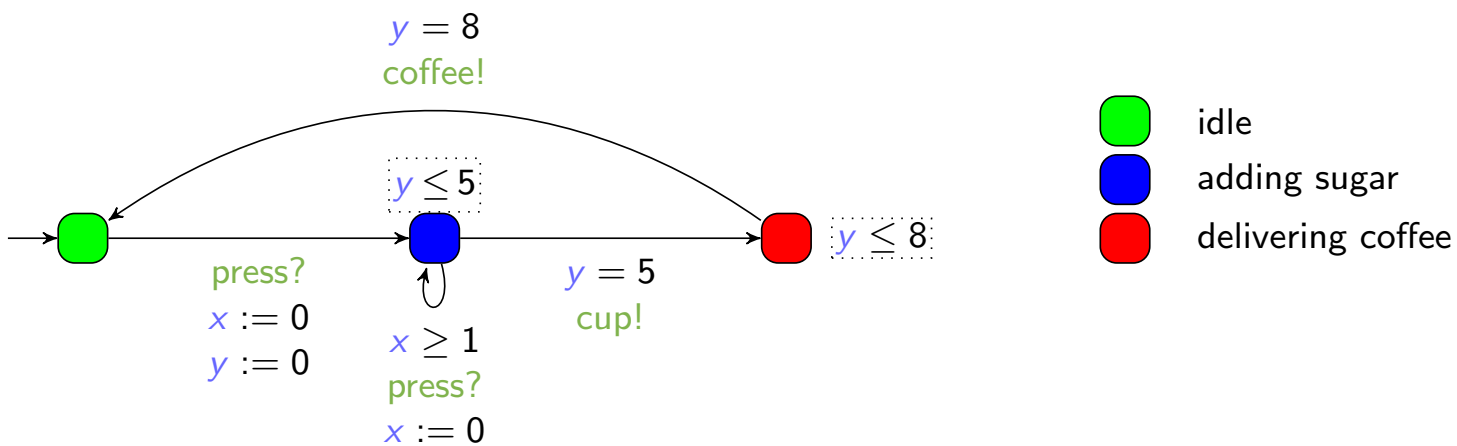
  - Transition guard: property to be verified to enable a transition
  - Clock reset: some of the clocks can be set to 0 along transitions



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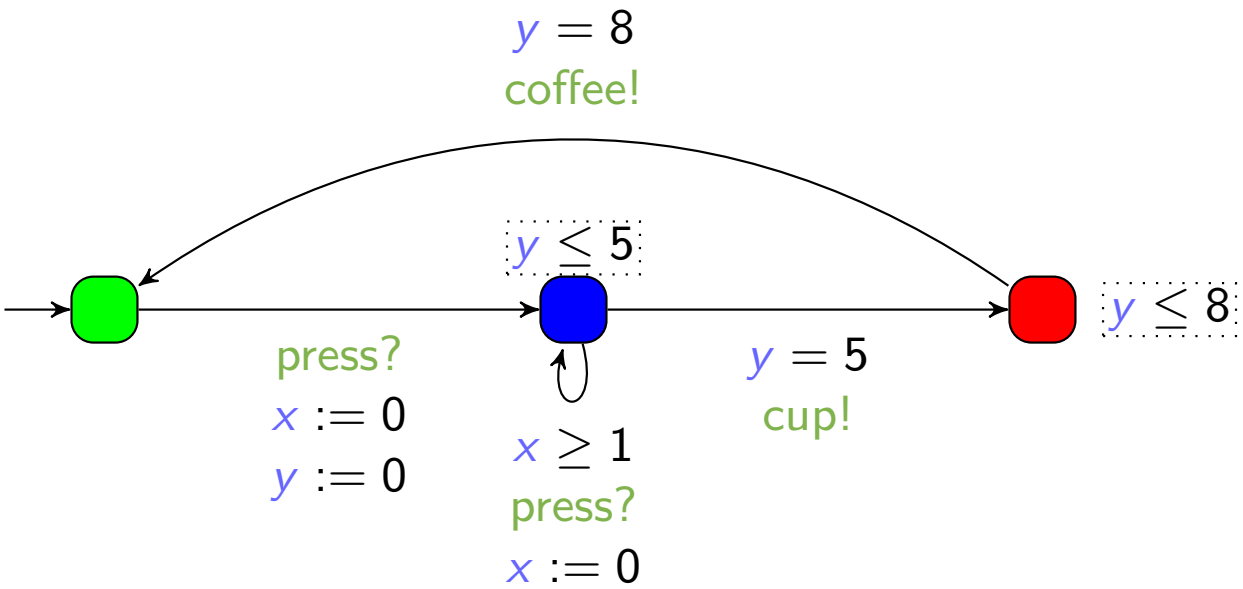
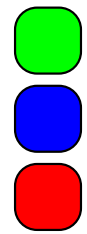
The most critical system: The coffee machine





idle

adding sugar

delivering coffee

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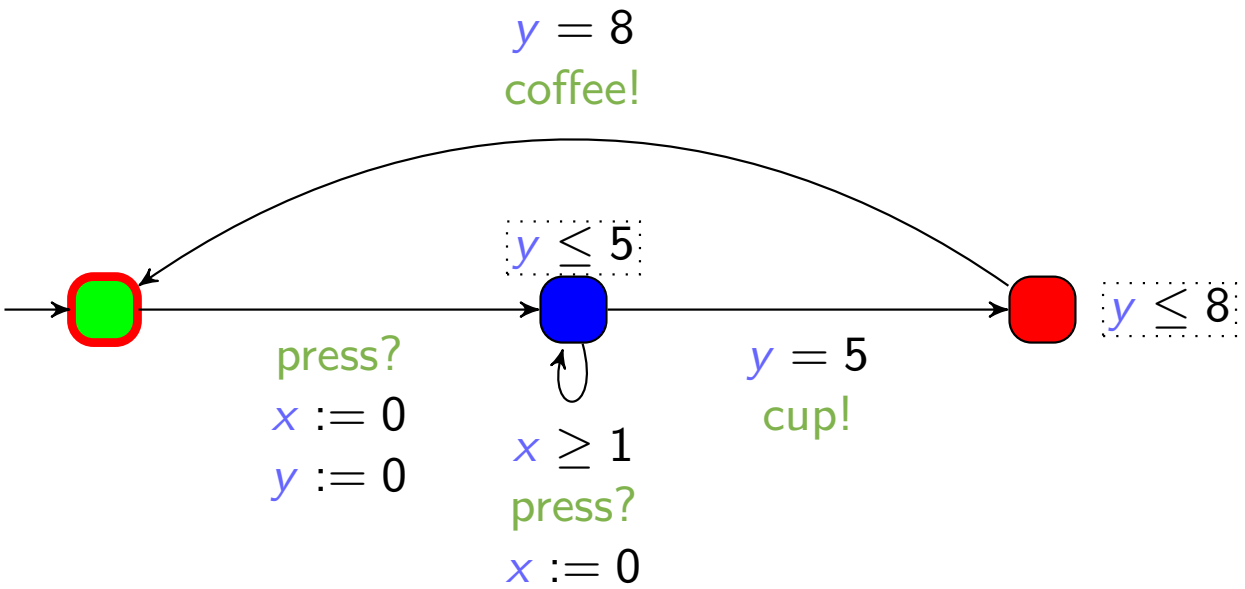
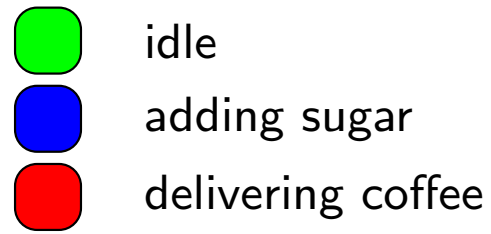
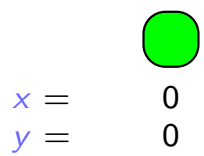




- Example of concrete run for the coffee machine
  - Coffee with 2 doses of sugar



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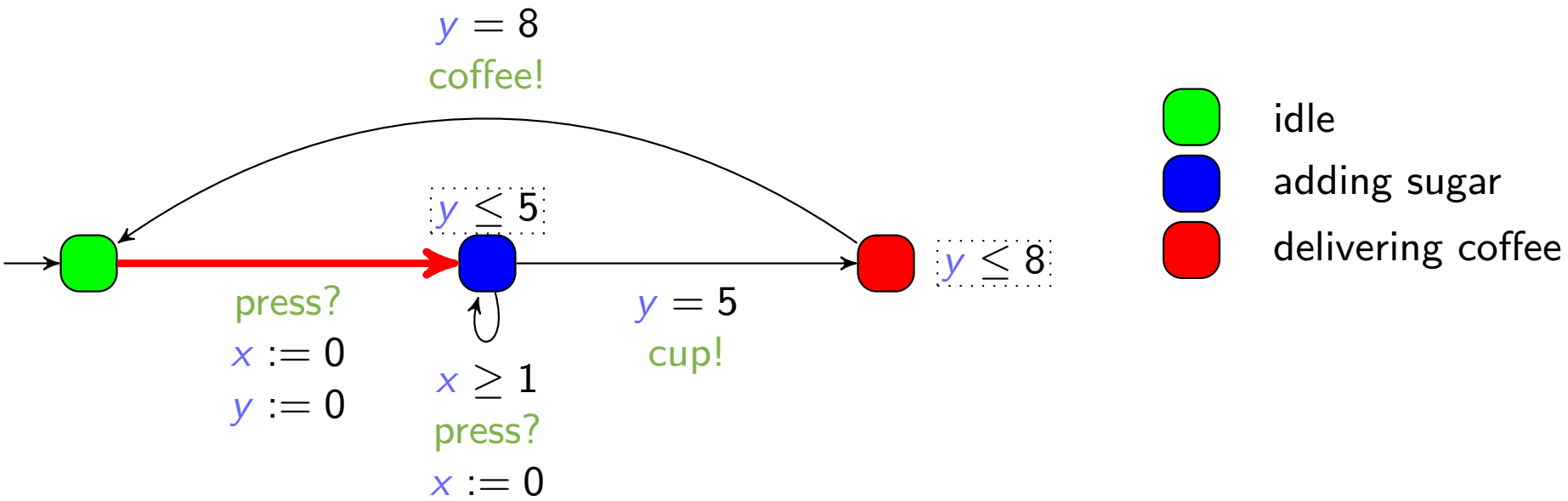

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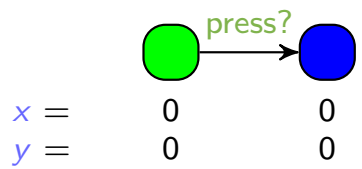

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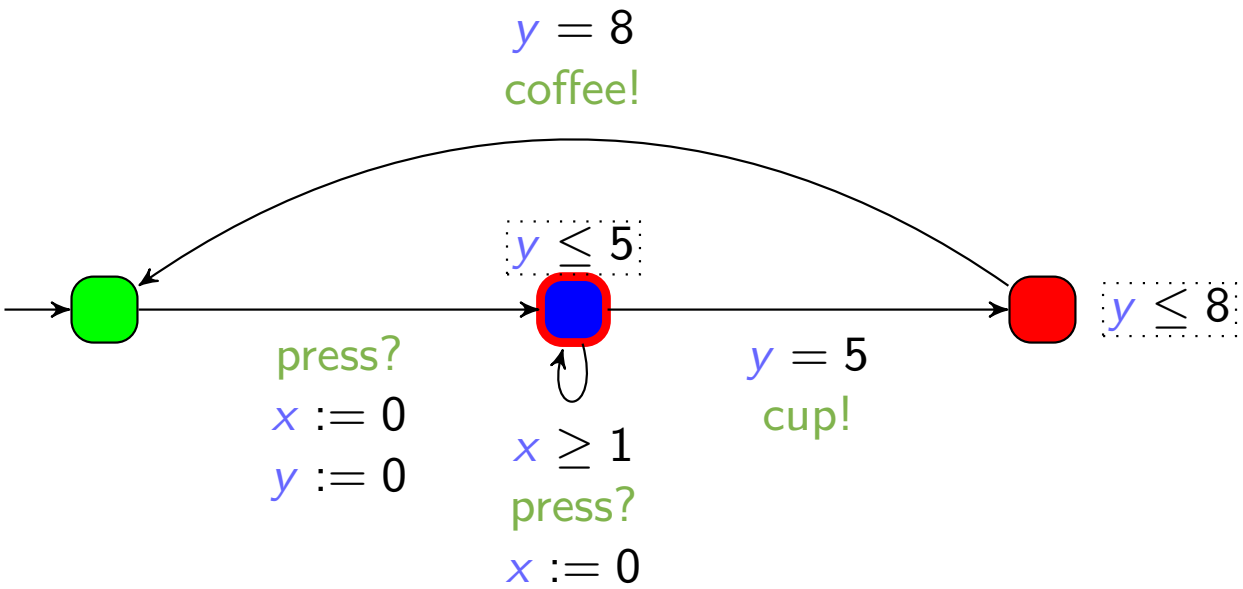

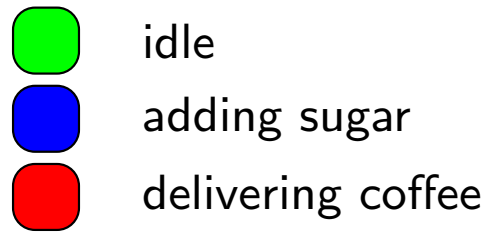

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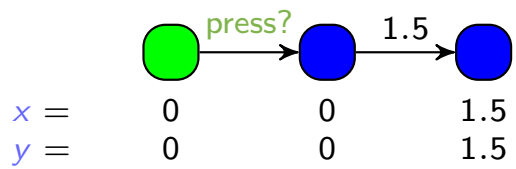

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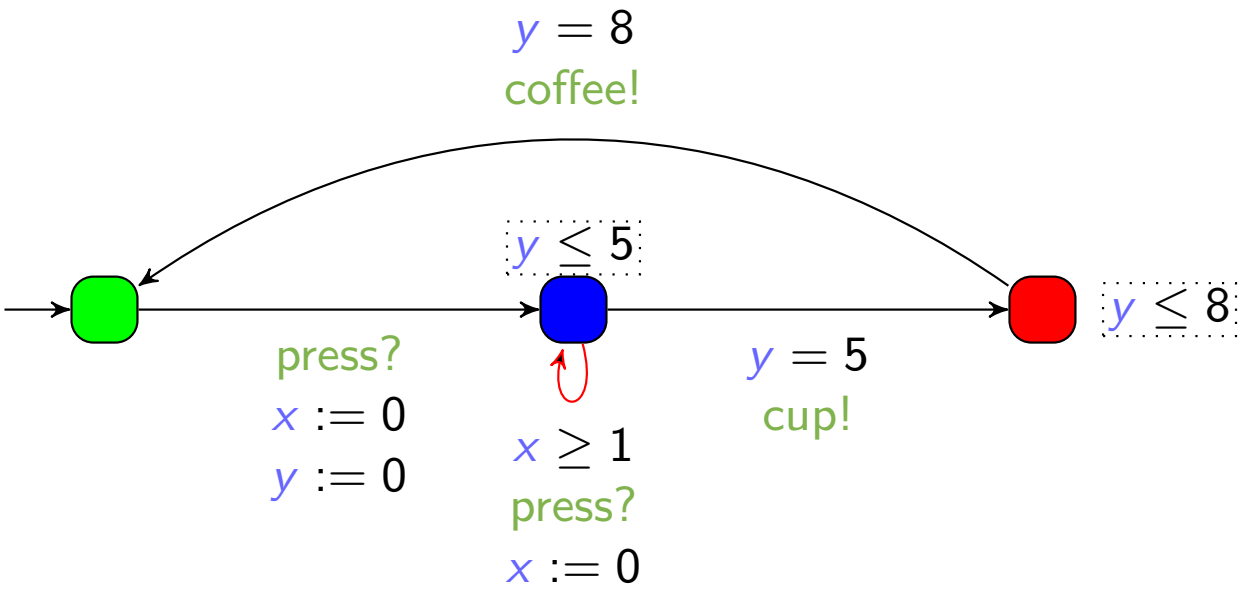

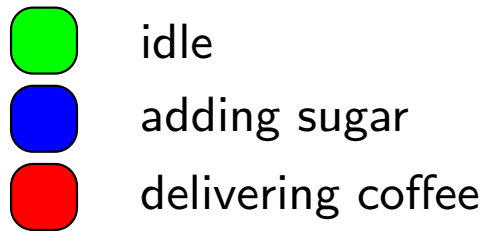

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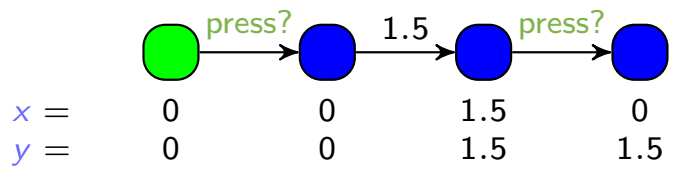

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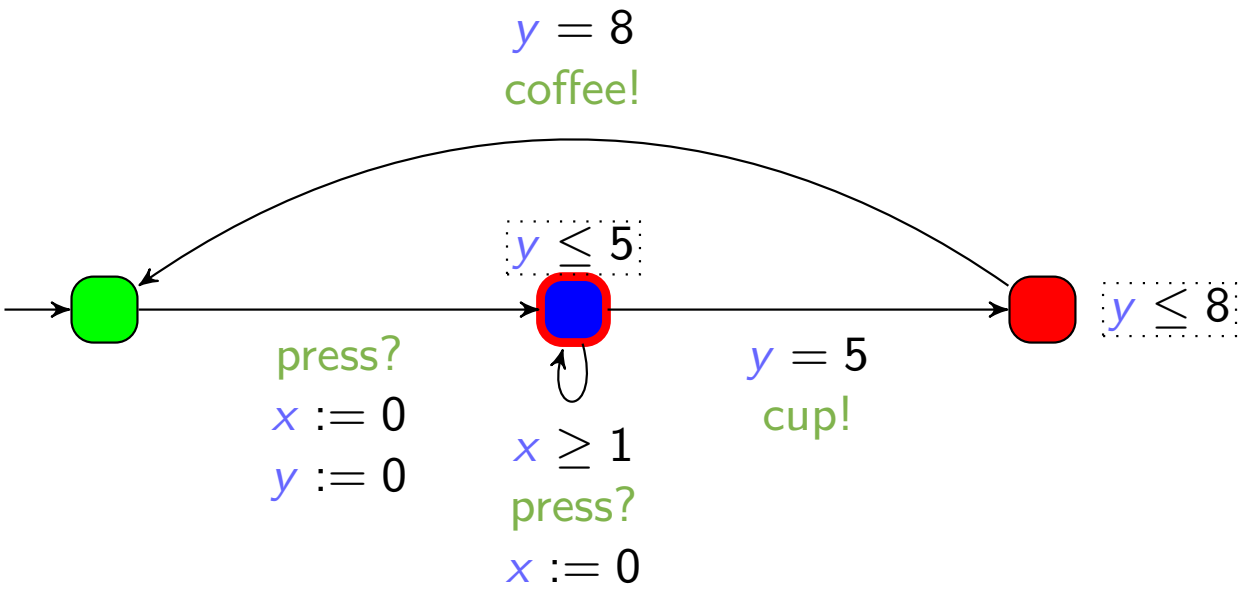

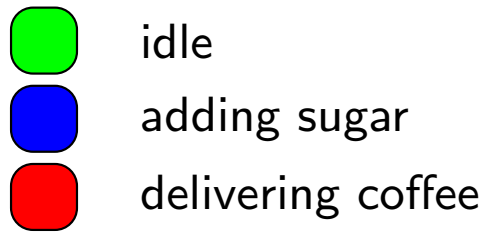

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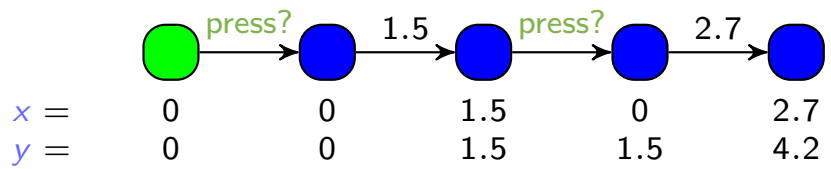

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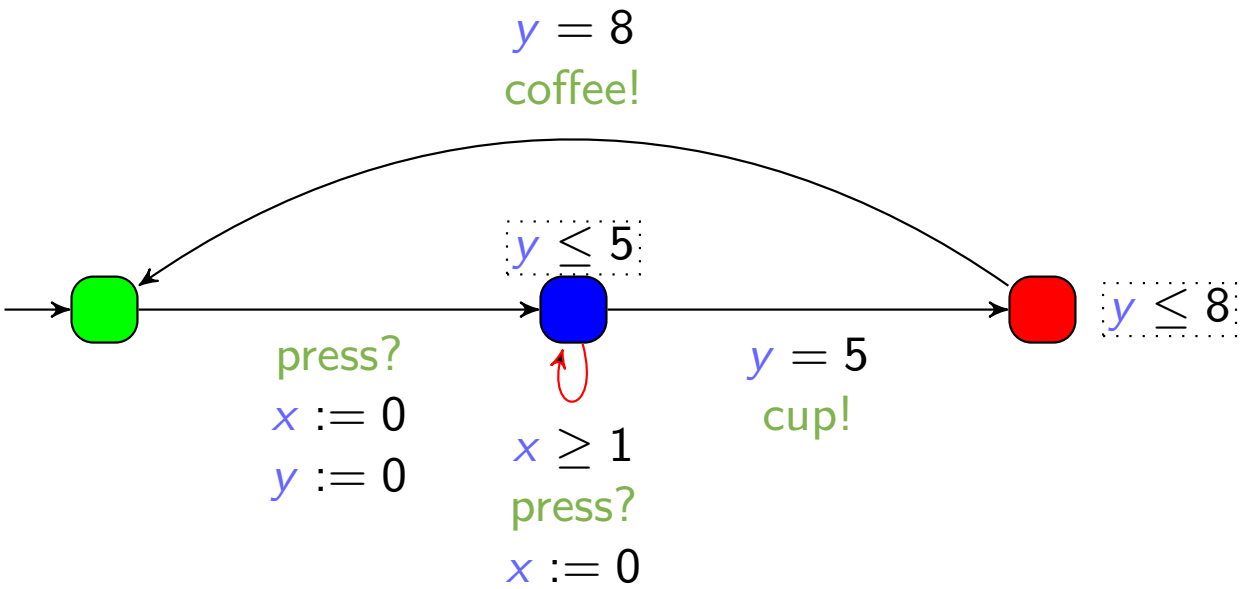

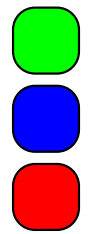

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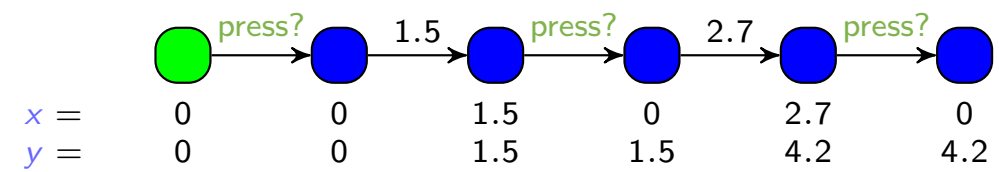

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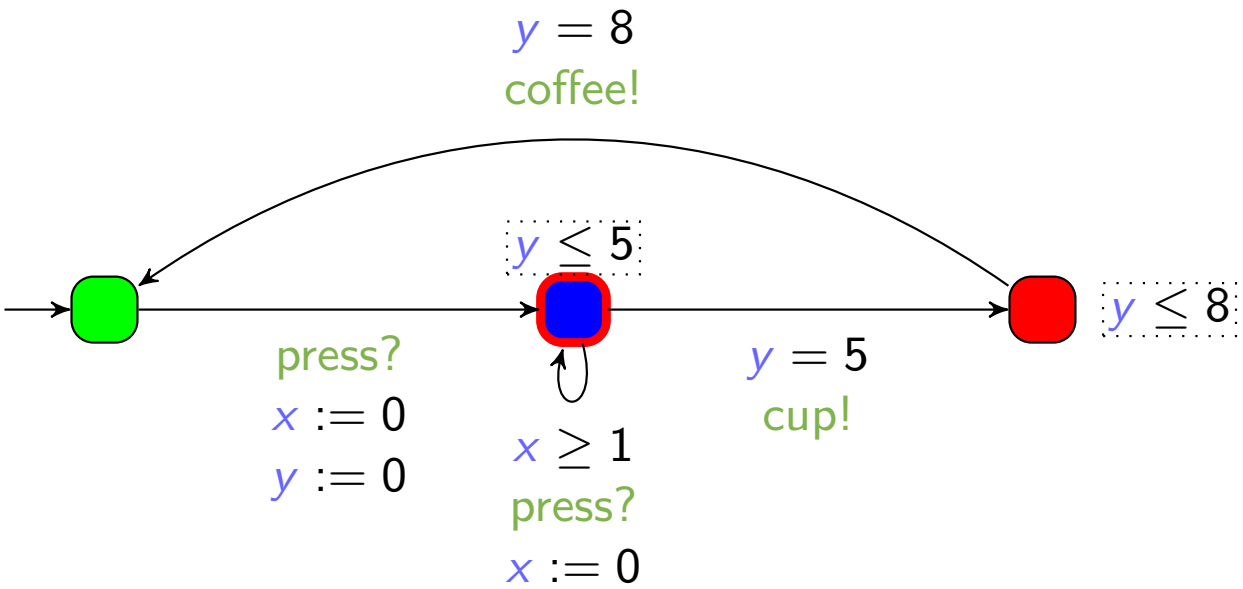

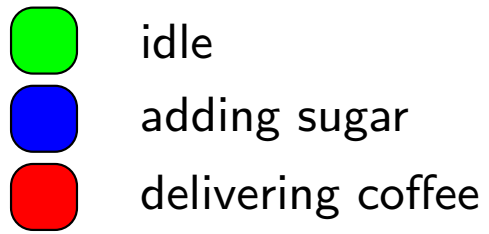

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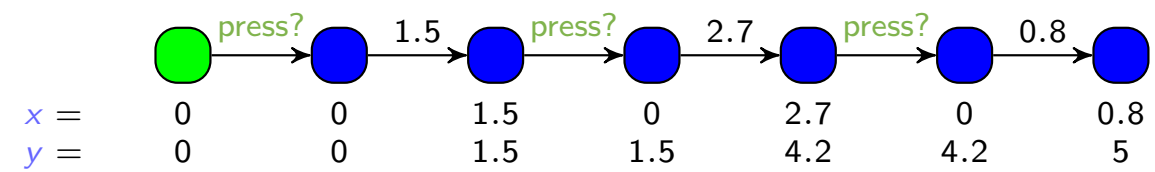

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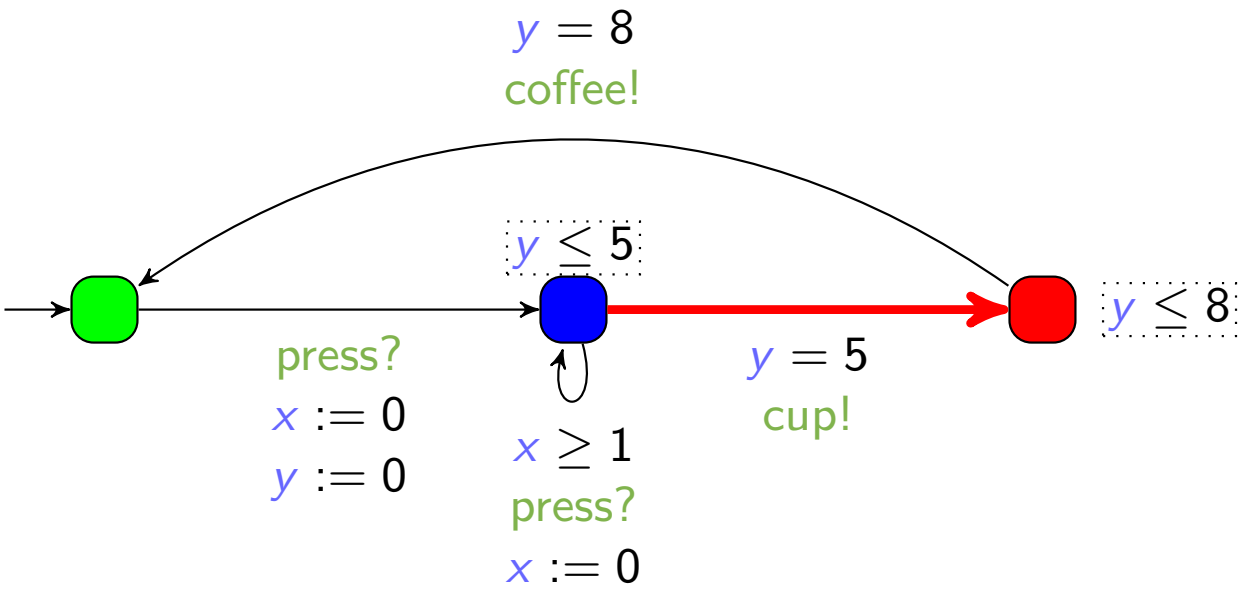

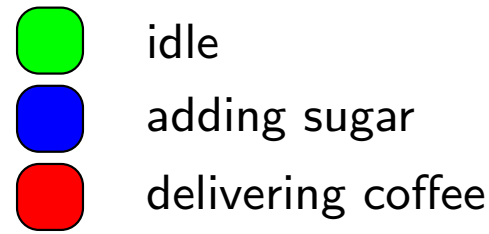

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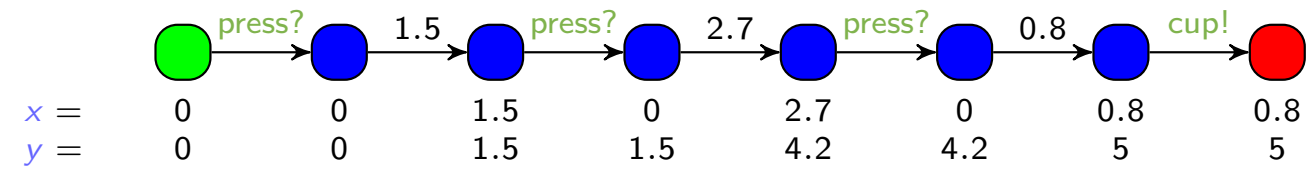

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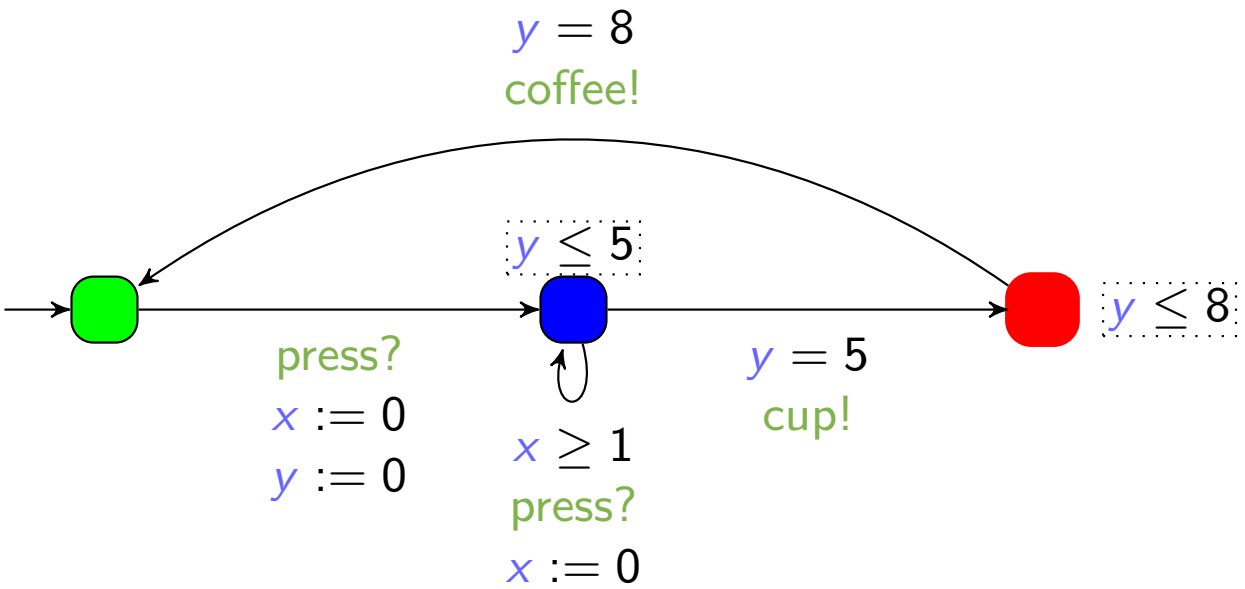

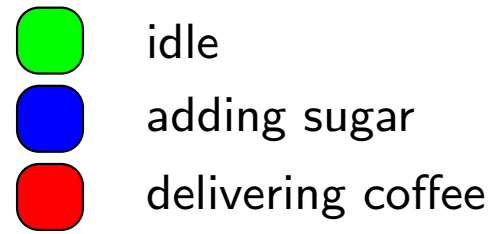

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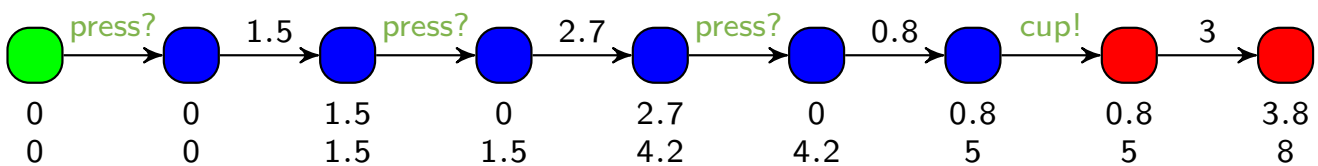

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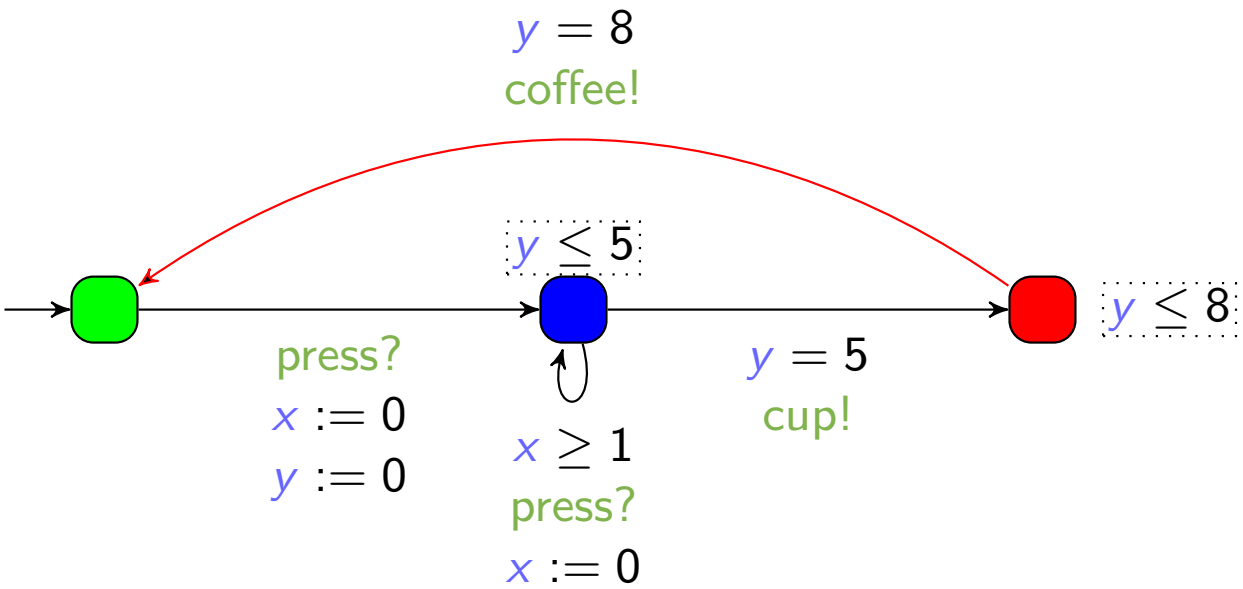

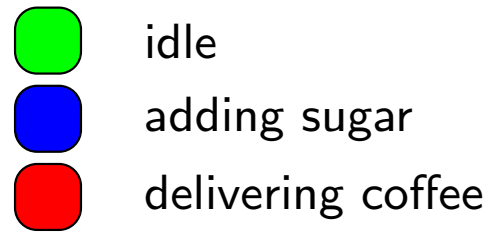

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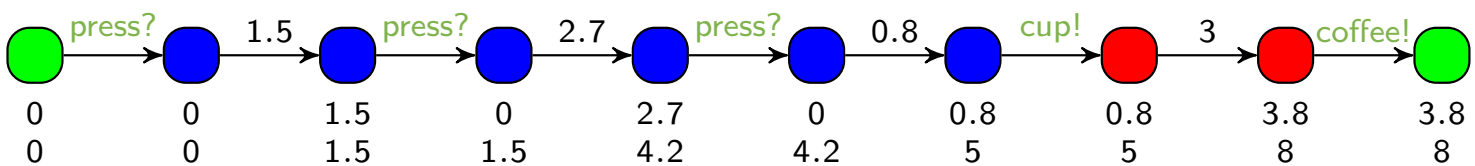
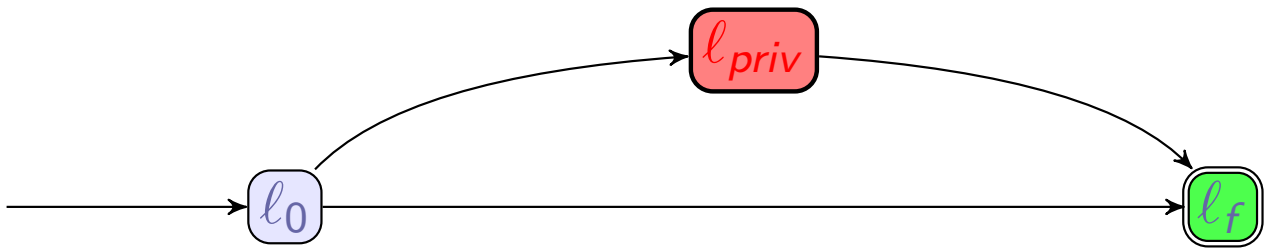


Outline

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 passing by ℓ_{priv}
2. one *not* passing by 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 passing by ℓ_{priv},
one not passing by ℓ_{priv}

Weak

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

Full

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

Three levels of ET-opacity

Existential – $\exists$

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

Weak

For all duration d,
There exists a run passing by ℓ_{priv} of duration d
$\Rightarrow$
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For all duration d,
There exists a run passing by ℓ_{priv} of duration d
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Three levels of ET-opacity

Existential – $\exists$

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

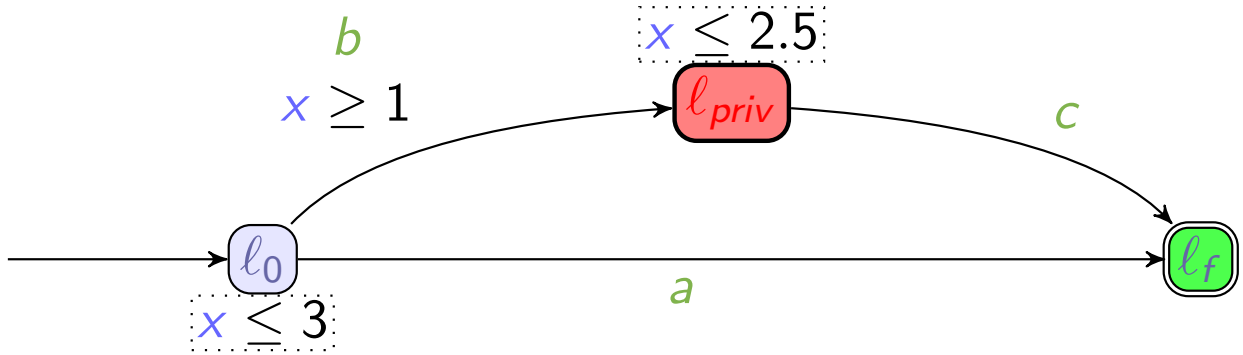
Weak

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

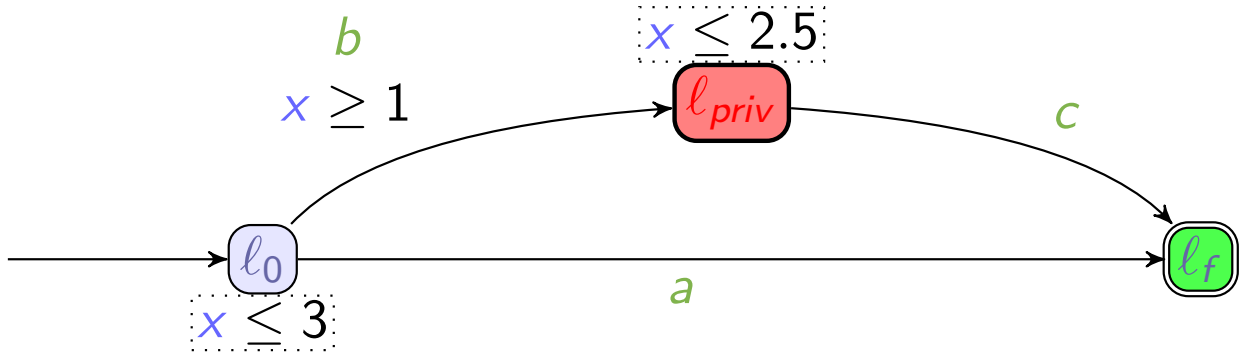
Full

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

Example

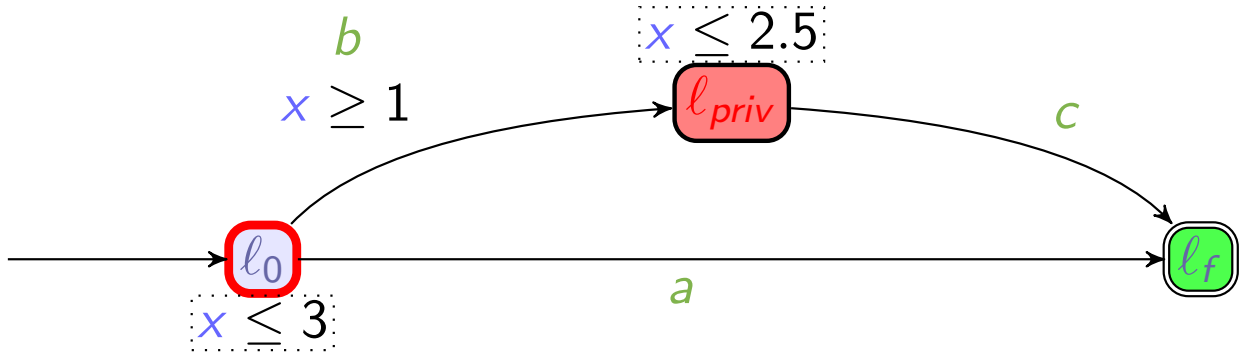


Example



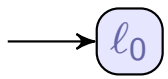
- There exist *(at least)* two runs of duration $d = 2$:

Example

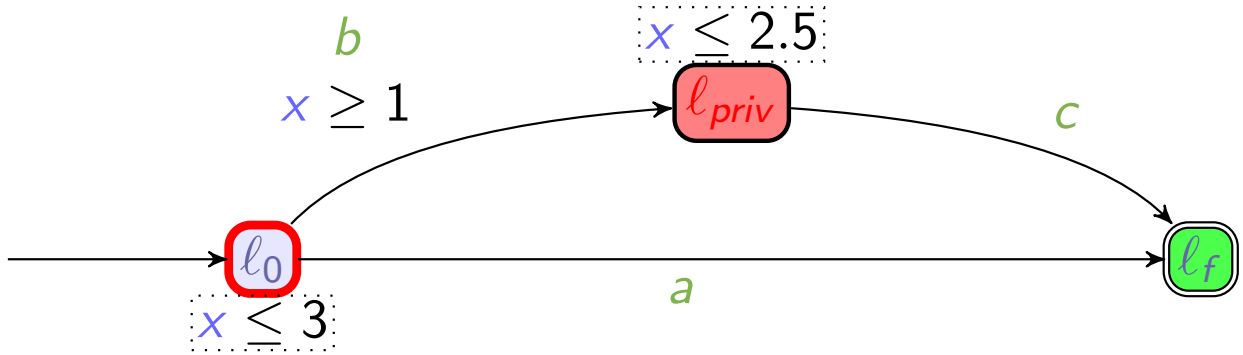


- There exist *(at least)* two runs of duration $d = 2$:

visiting ℓ_{priv}



Example



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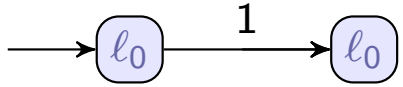
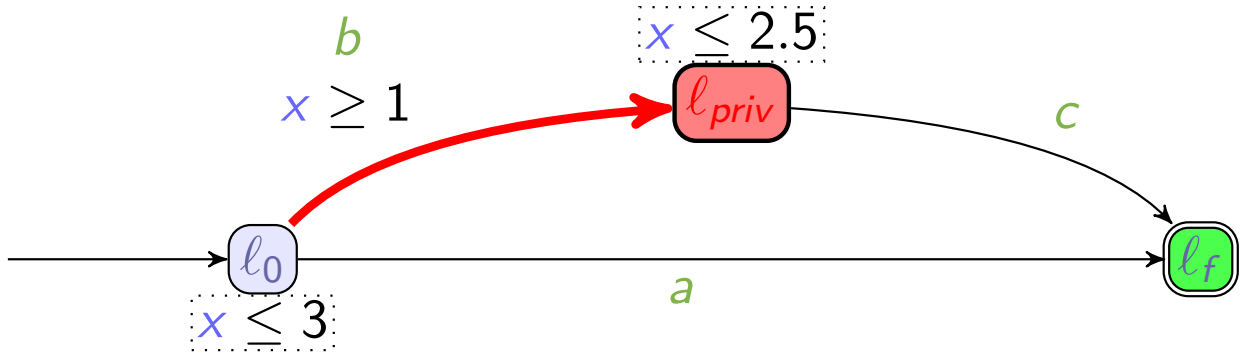


Example



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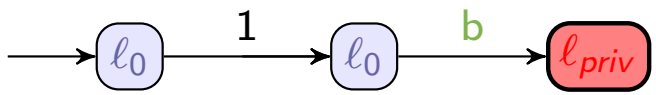
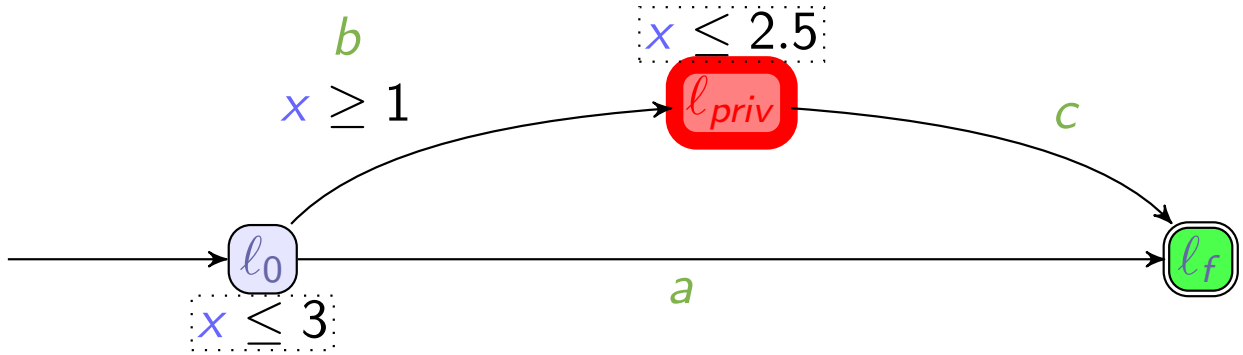


Example



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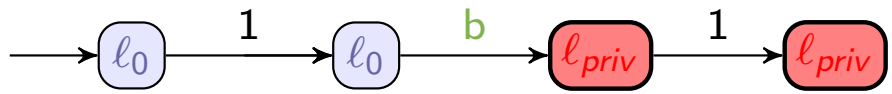

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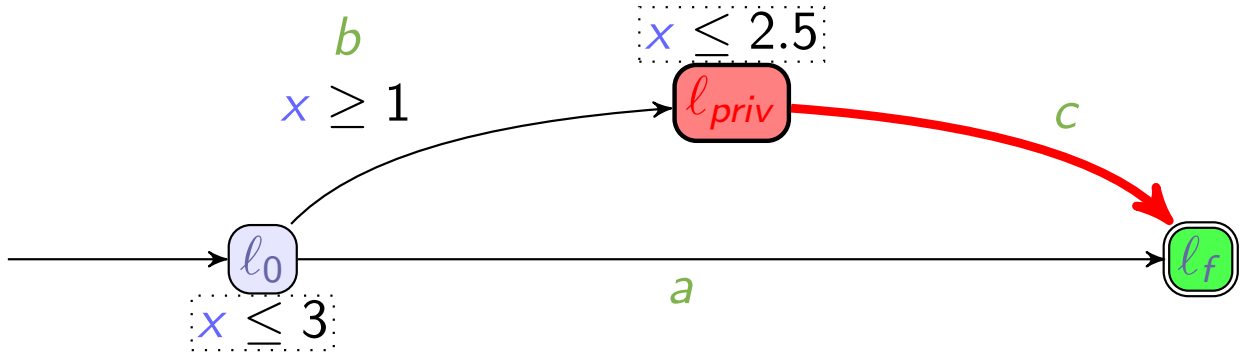

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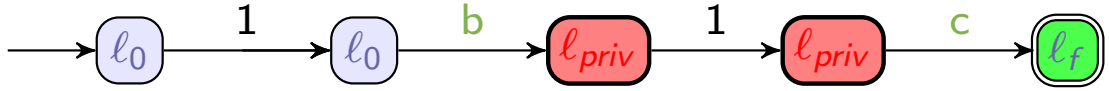
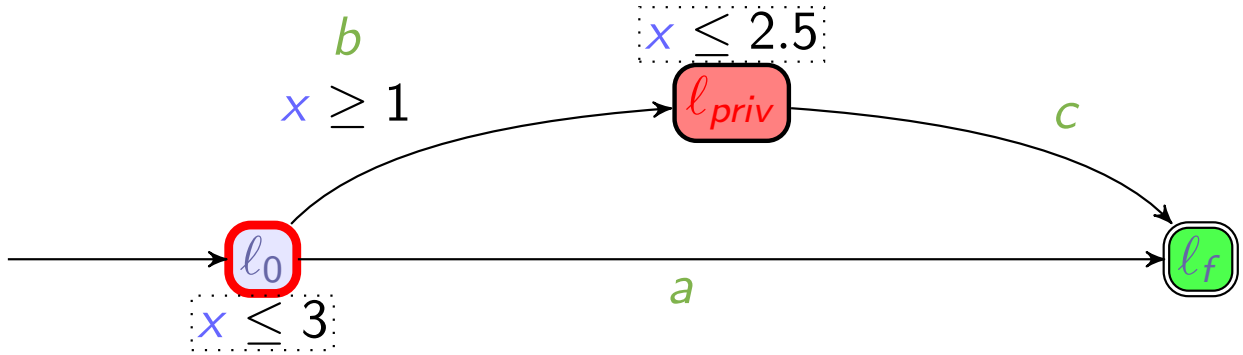


Example



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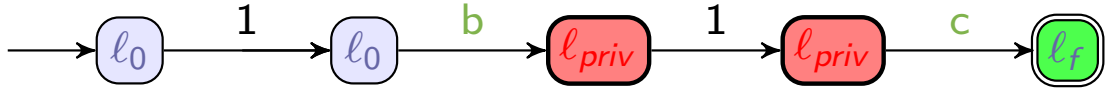
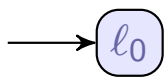
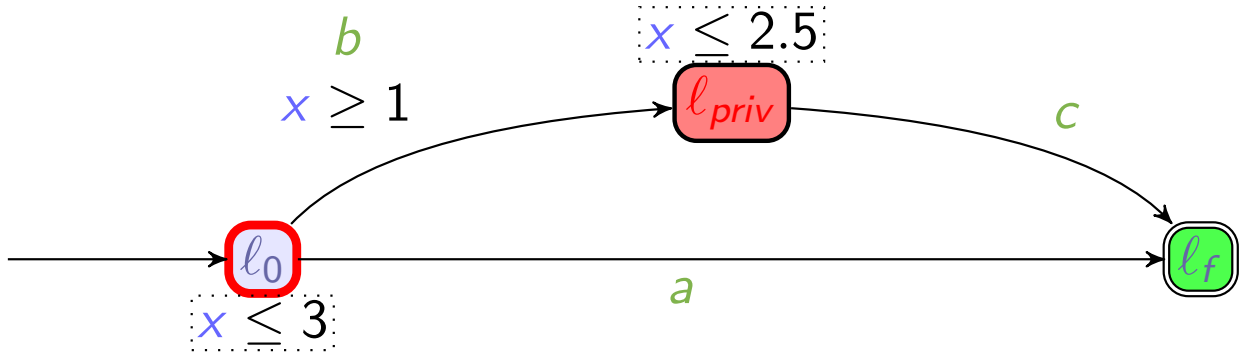


not visiting ℓ_{priv}



Example



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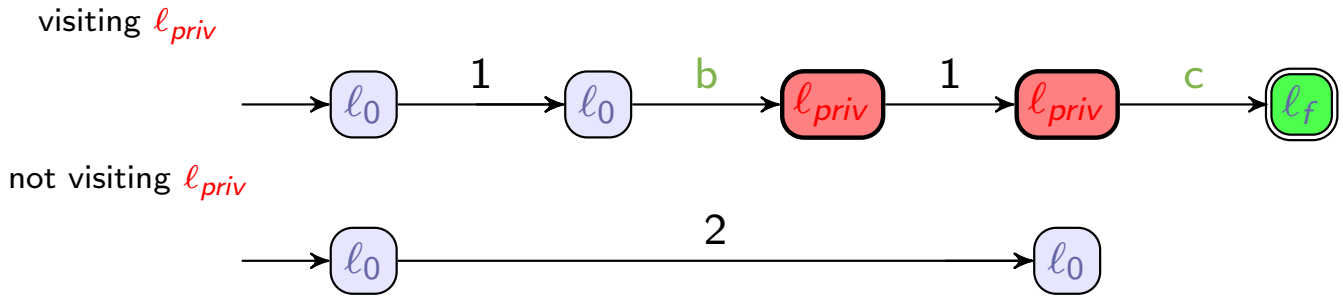
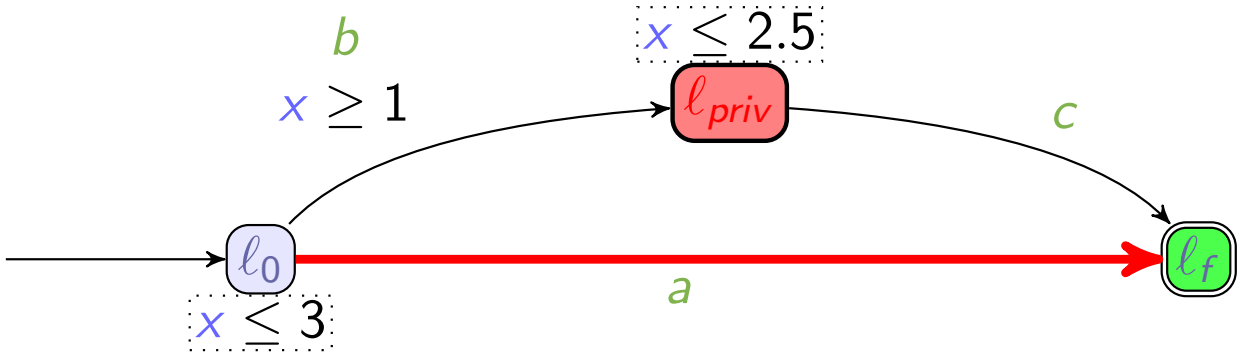


Example



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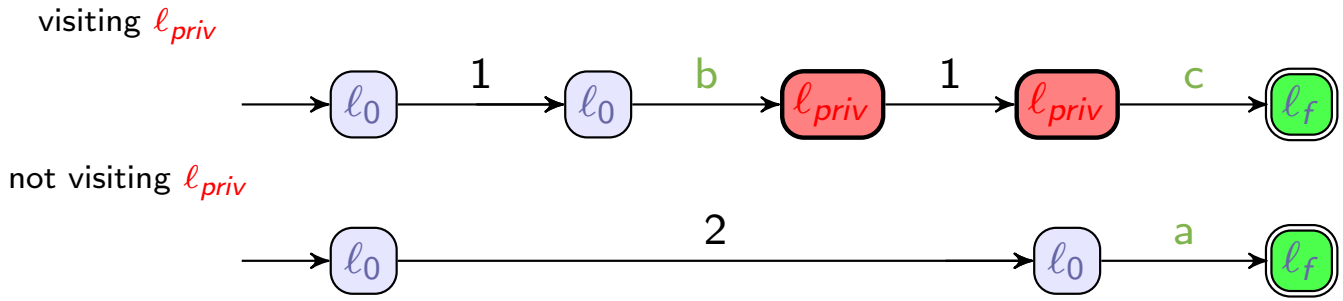
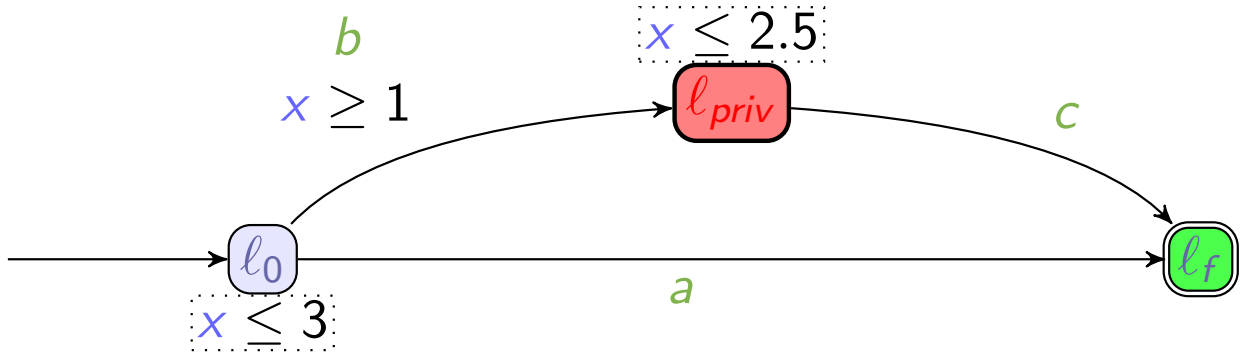


Example



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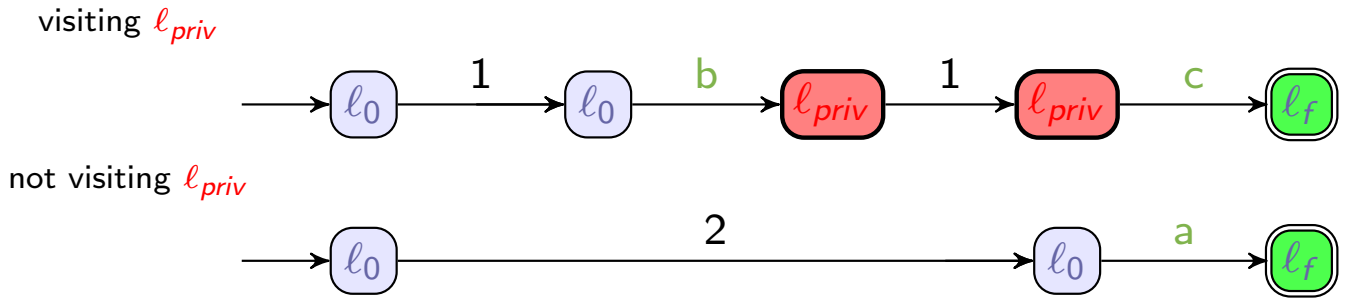
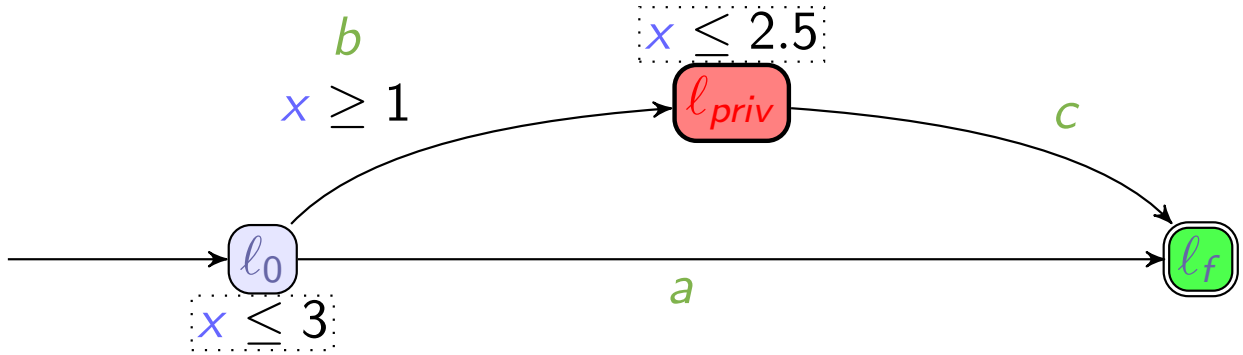


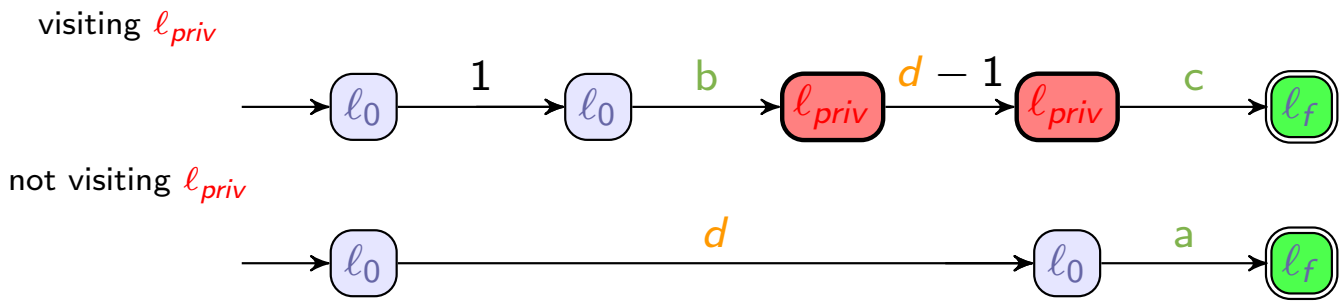
The system is ET-opaque for a duration $d = 2$

The system is $\exists$-ET-opaque

Example



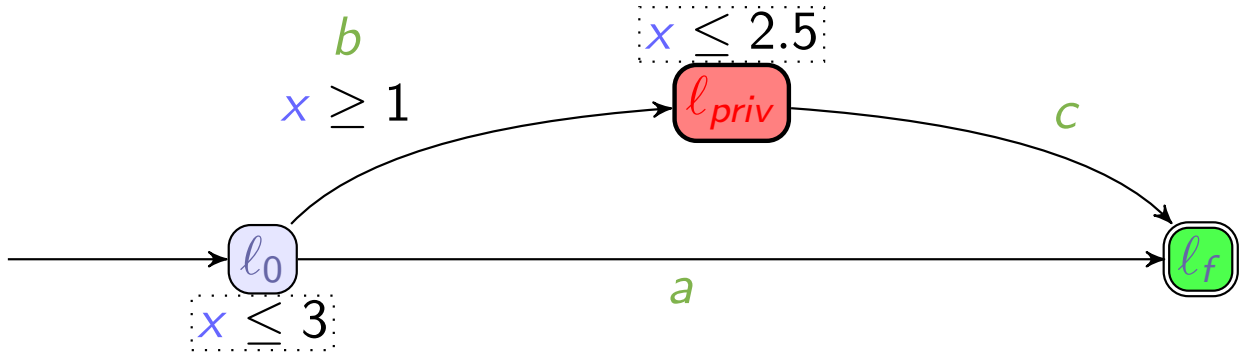
- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$:



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

The system is ∃-ET-opaque

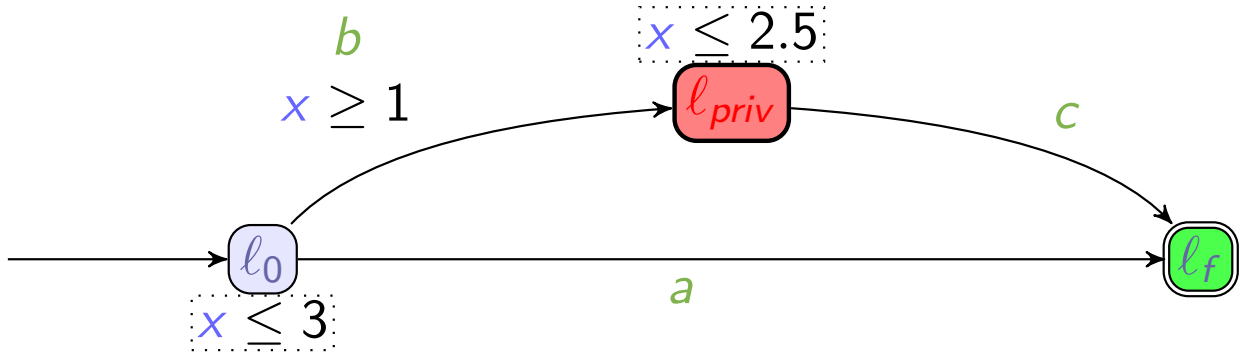
Example



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

The system is $\exists$-ET-opaque

Example

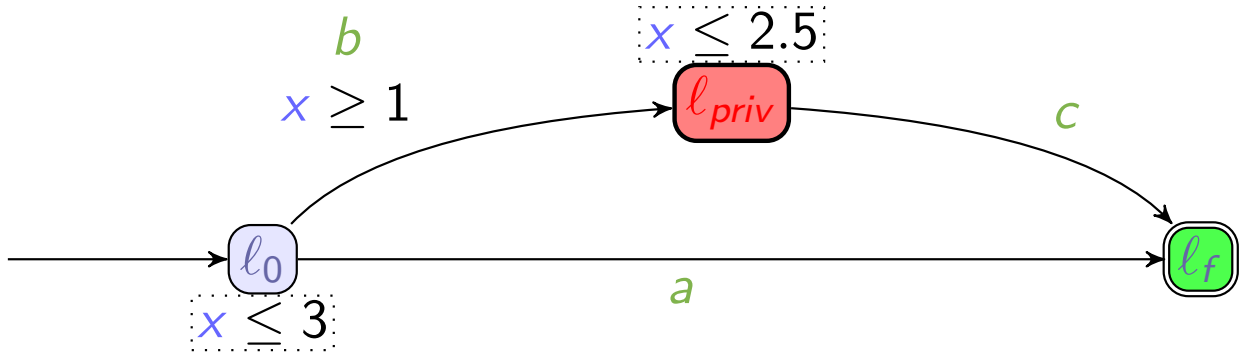


- There exist *(at least)* two runs of duration d for all durations $d \in [1, 2.5]$

The system is ∃-ET-opaque

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

Example



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The system is ∃-ET-opaque

- But,
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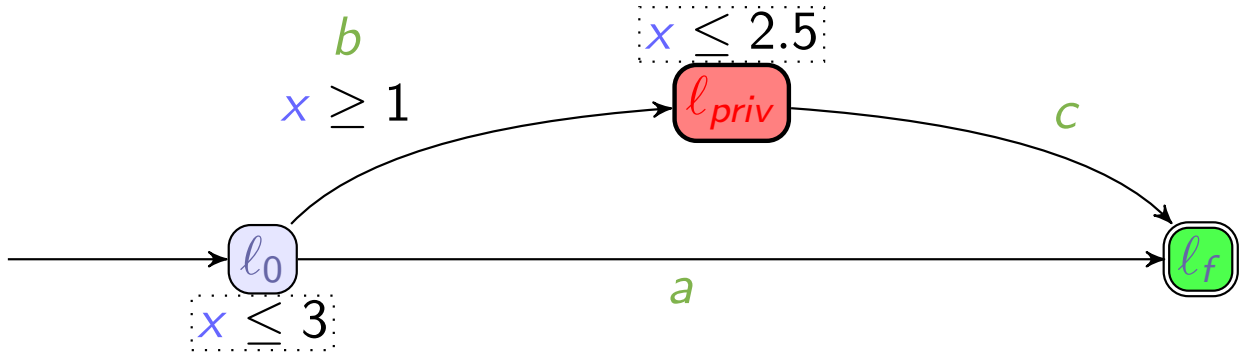
  - private durations $\subseteq$ public durations

Example



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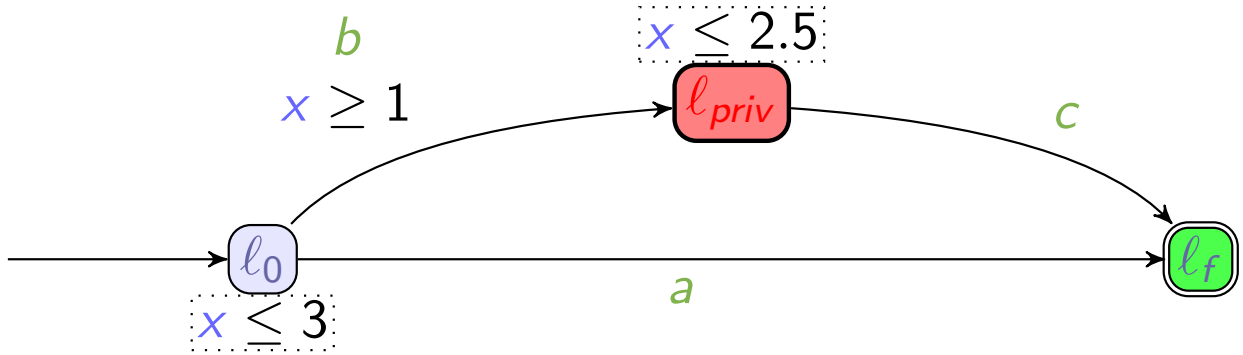
The system is weakly ET-opaque

Example



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The system is ∃-ET-opaque

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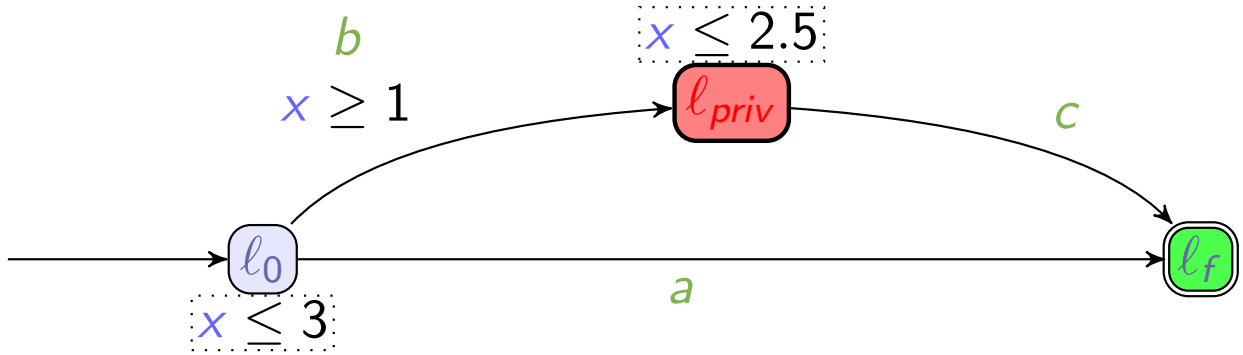
    public execution times are [0,3]
  - private durations $\subseteq$ public durations

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

Expiring ET-opacity

Idea

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

	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

Three levels of ET-opacity

Existential–∃

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

Weak

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

Full

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

Three levels of expiring ET-opacity

Existential–$\exists$ expiring

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

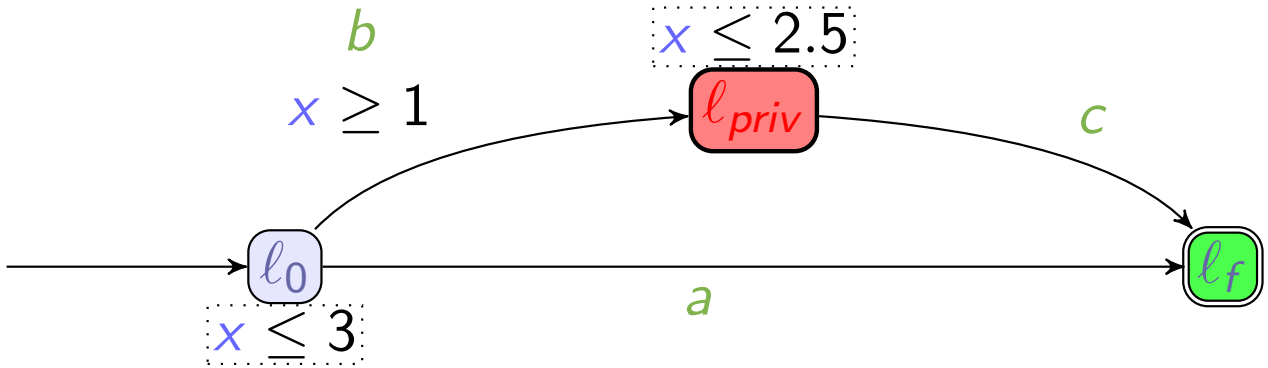
Weak expiring

secret durations $\subseteq$ non-secret durations

Full expiring

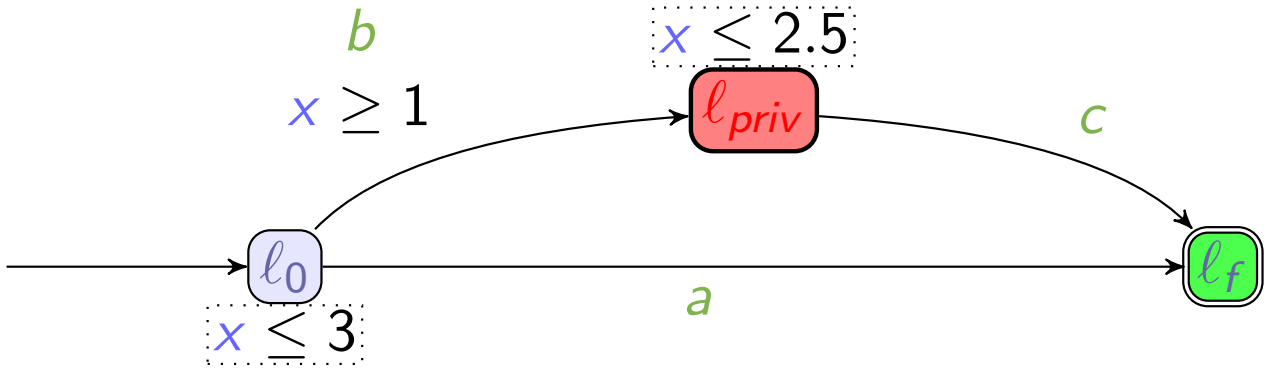
secret durations $=$ non-secret durations

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
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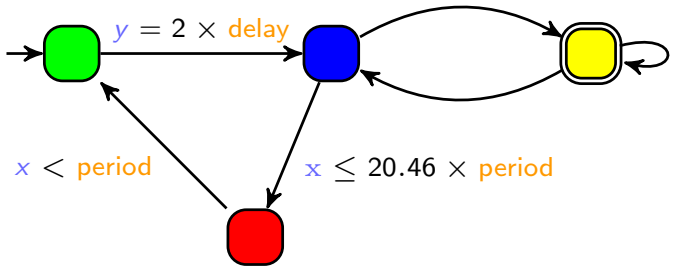
	weak	$[1, 2.5]$	$[0, 3]$	$\surd$
	full			$\times$
	$\exists$-exp.			$\surd$
$\Delta = 1$	weak-exp.	$[1, 2.5]$	$(2, 2.5] \cup [0, 3]$	$\surd$
	full-exp.			$\times$
	$\exists$-exp.			$\surd$
$\Delta = 1.25$	weak-exp.	$[1, 2.5]$	$(2.25, 2.5] \cup [0, 3]$	$\surd$
	full-exp.			$\times$

Outline

Outline

timed model checking



A model of the system

?

$\models$

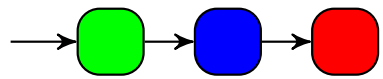
is unreachable

A property to be satisfied

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

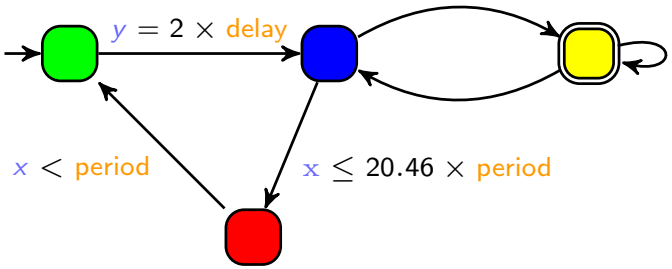
Yes

No



Counterexample

Parametric timed model checking



A model of the system

?

$\models$

 is unreachable

A property to be satisfied

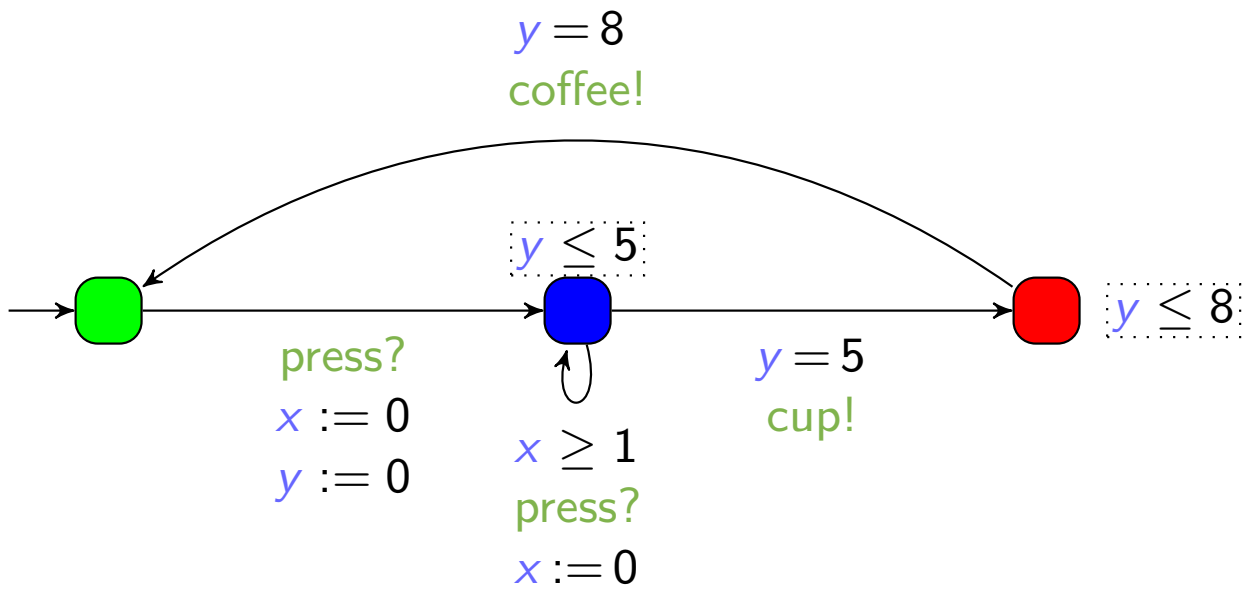
- Question: for what values of the parameters does the model of the system satisfy the property?

Yes if...

$2 \times$ delay $> 20.46 \times$ period

Timed Automaton (PTA)

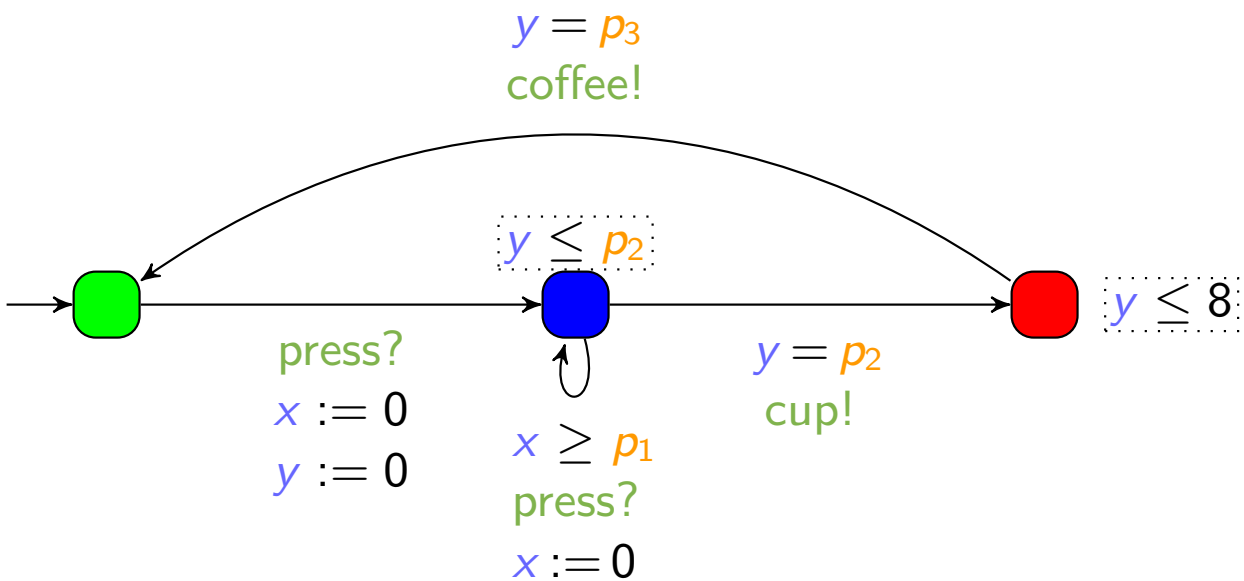
- Timed automaton (sets of locations, actions and clocks)



[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

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 $v(p)$

Valuation of a PTA = TA

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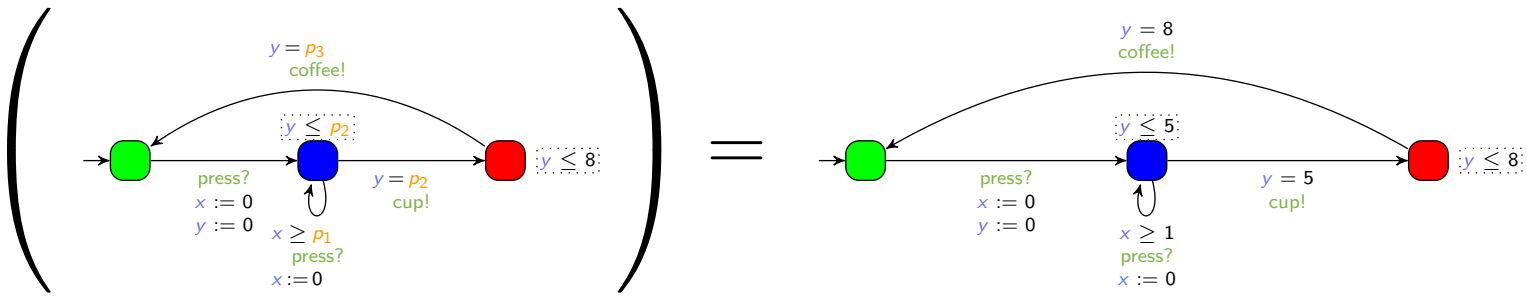
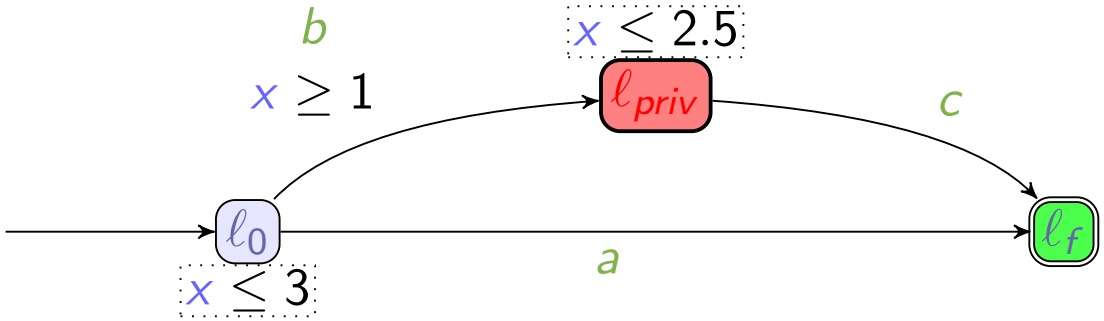
v 

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

Outline

Example



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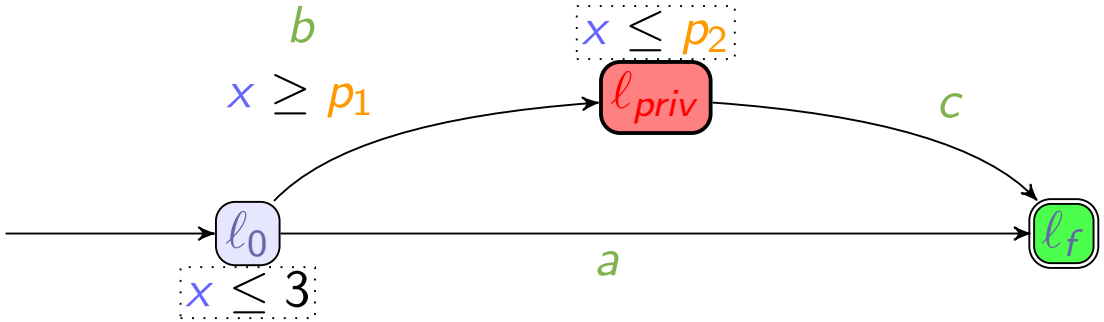
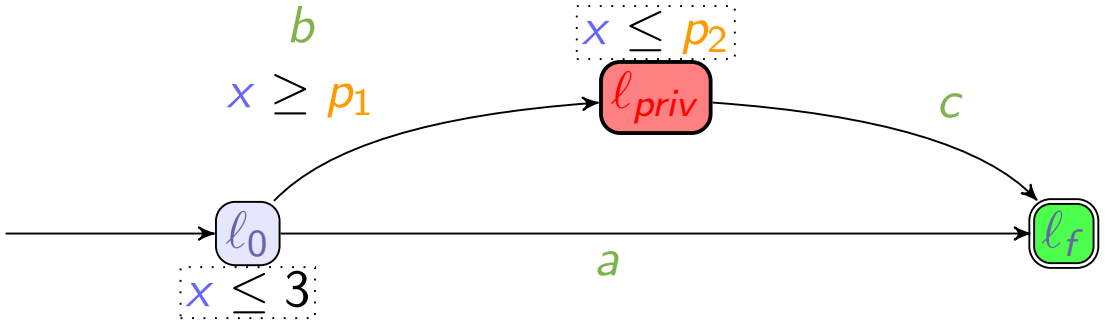
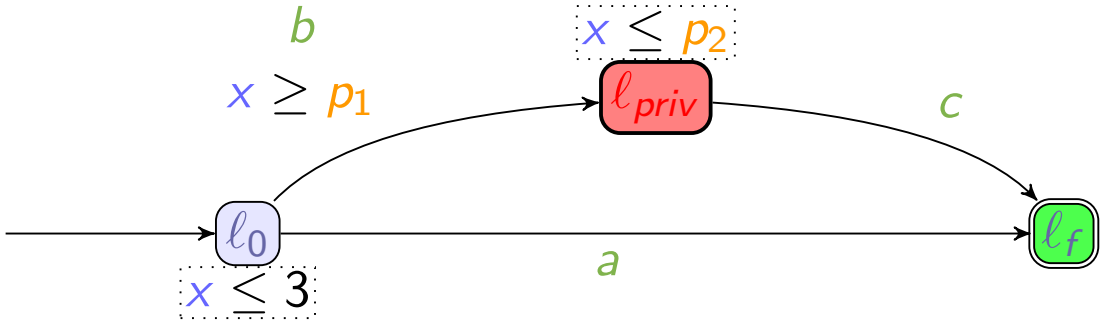


Example



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

Example



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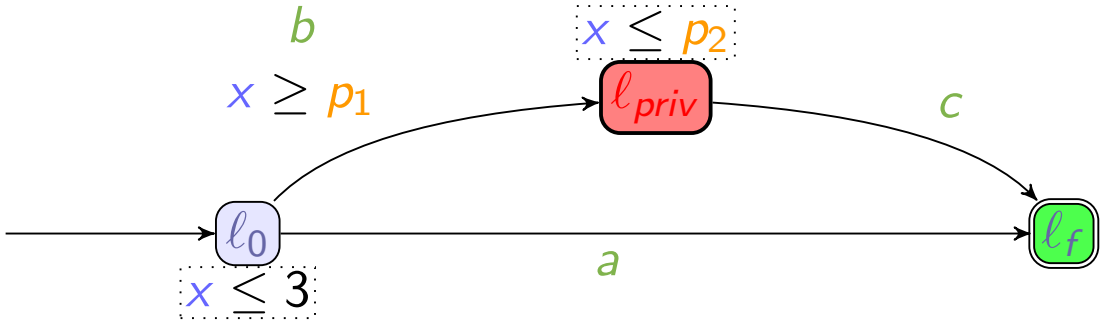
Public	$[0, 3]$

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

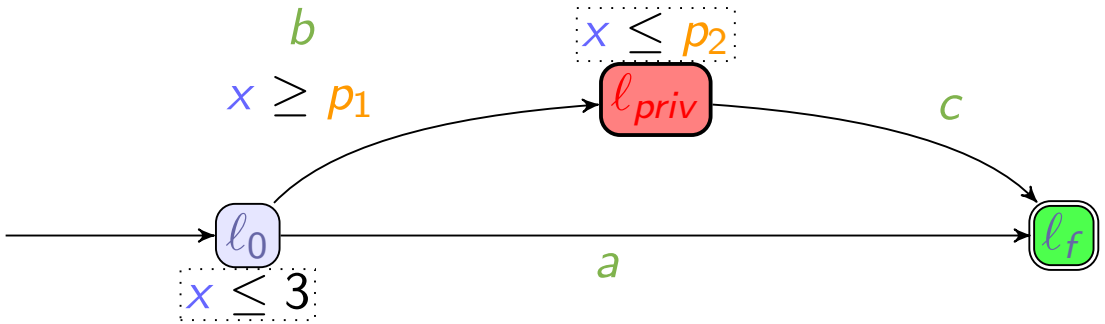
p-Emptiness problem

Is the set of parameter valuations ensuring the property empty?

p-Synthesis problem

Synthesize all the parameter valuations ensuring the property

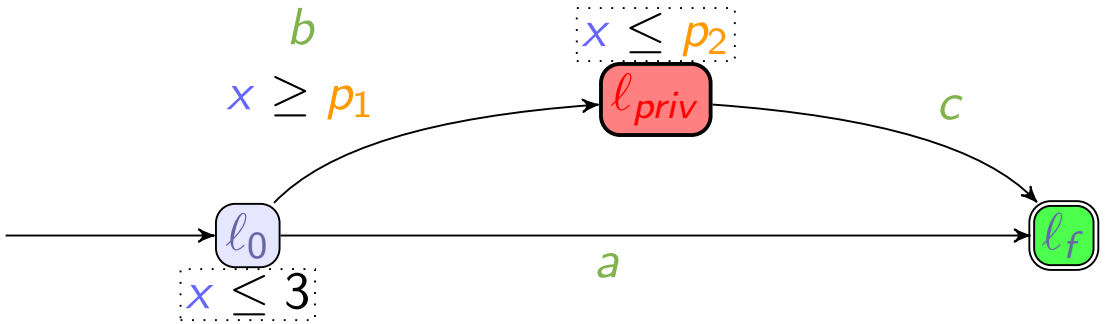
Example



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

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

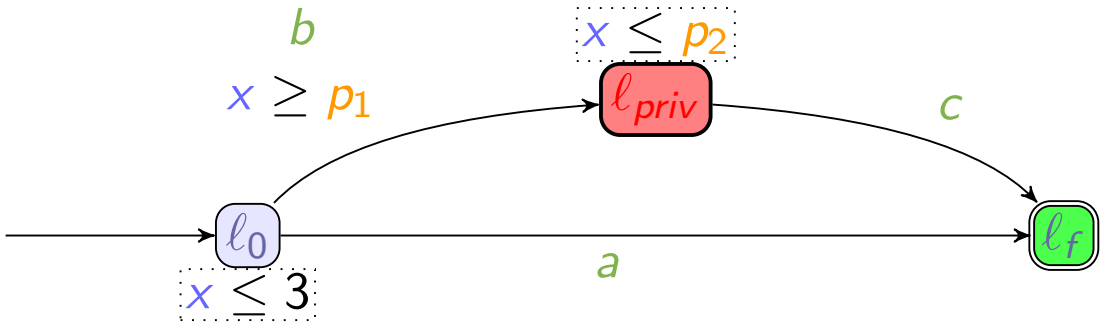
Example



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

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

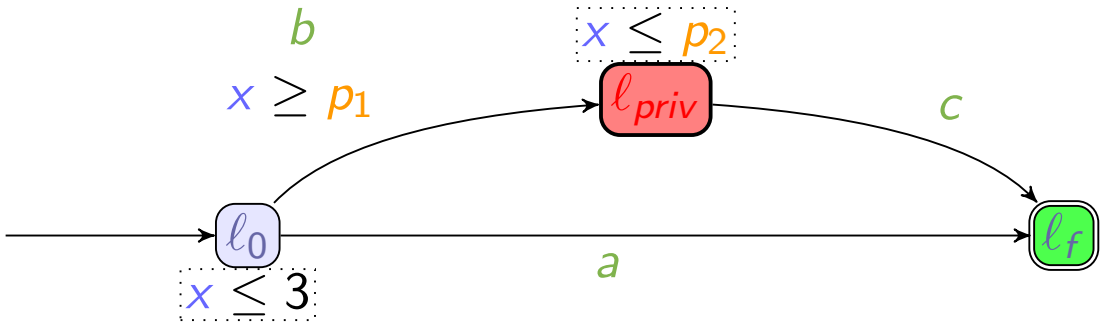
Example



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



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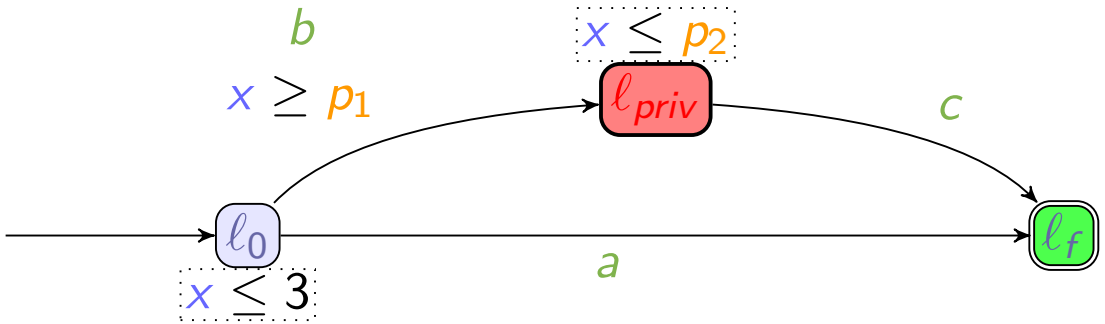
ET-opacity notion	p-Emptiness	p-Synthesis
$\exists$	$\times(\exists v)$	$0 \leq p_1 \leq 3 \quad \wedge \quad p_1 \leq p_2$
weak	$\times(\exists v)$	$0 \leq p_1 \wedge p_2 \leq 3 \quad \wedge \quad p_1 \leq p_2$
full	$\times(\exists v)$	

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

Outline

Summary of the results for ET-opacity [And+22]

		∃-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+22] 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

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

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

[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. Accepted. Toulouse, France, 2023

Outline

Perspectives

Theory

- 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)

Perspectives

Theory

- 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)

Algorithmic and implementation

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

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[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.

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[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.

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[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.