27 January 2026 | APR Seminar | Paris, France

Detecting Timing Leaks of Programs

using Parametric Timed Model Checking

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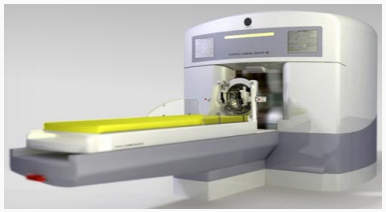
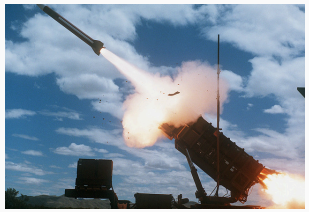
Context: Verifying complex timed systems

- **Critical** systems: Failures may result in **dramatic** consequences
- Need for early bug detection
  - Bugs discovered when final testing: **expensive**
  - Need for a thorough **specification** and **verification** phase



Therac-25
(USA, 1980s)



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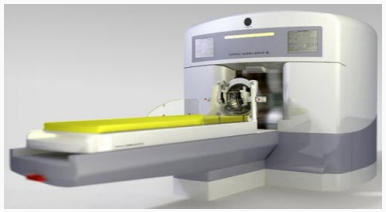

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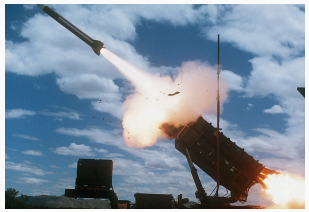

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- Verification is needed to ensure the absence of bugs

Context: Side-channel attacks

Side-channel attacks

Threats to a system using non-algorithmic weaknesses

- *e.g., power consumption, electromagnetic radiation, cache usage, **timing**, accoustic emissions, temperature variations, etc.*

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Example

Number of pizzas (and order time) ordered by the white house prior to major war announcements[1]

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Context: Side-channel attacks

Side-channel attacks

Th

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Example

Nu

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house prior to major war

MIDDLE EAST

What is the Pizza Meter? The signal that spiked on Saturday during Iran's attack on Israel

On April 13 there was a surge in pizza orders from U.S. government buildings such as the White House, the Pentagon, and the Department of Defense.

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Context: Side-channel attacks

Side-channel atta

Example

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Context: Side-channel attacks

Side-channel atta

Example

Papa Johns Pizza

Overv | Overview | Menu | Reviews | Photos | Updat

Popu

Popular times

Tuesdays

Live 5 PM

Busier than usual · Usually no wait

9a 12p 3p 6p 9p

No wait

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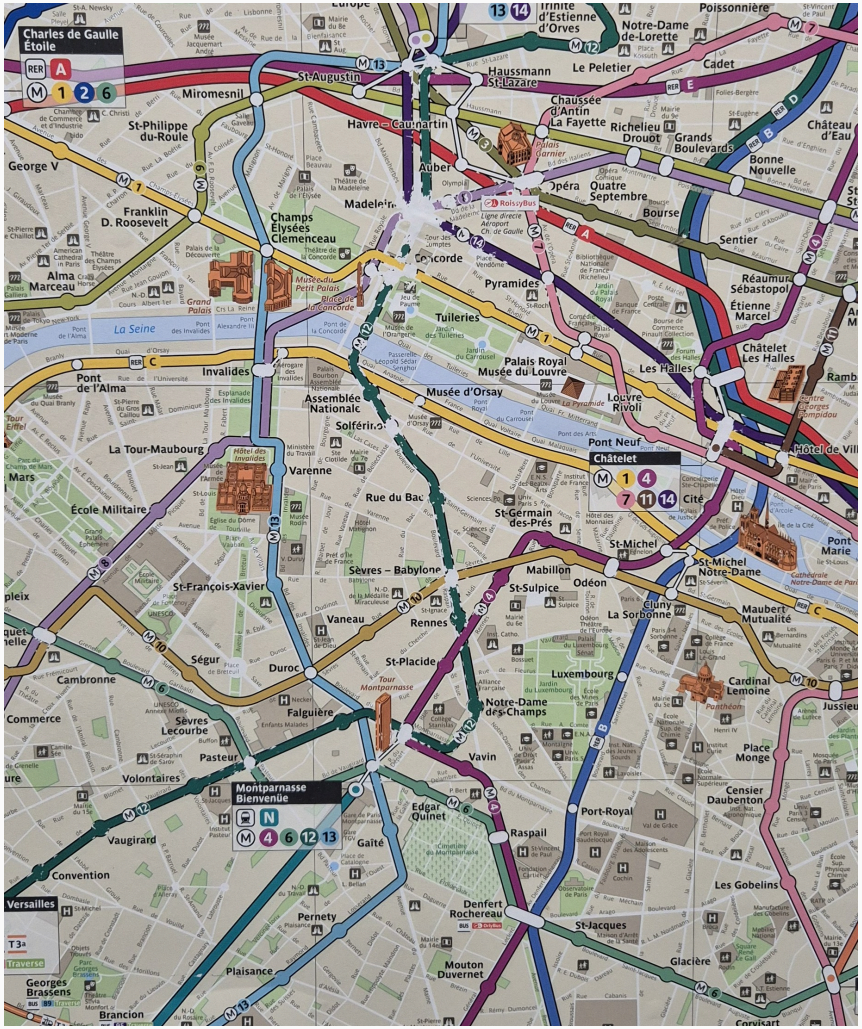
Your turn: where was this picture taken?



Context: Timing attacks over programs

```c
// input pwd    : Real password
// input attempt: Tentative password
for (i = 0; i < min(len(pwd), len(attempt)); i++) {
    if(pwd[i] != attempt[i]){
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    }
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return true
```

pwd	A	L	M	A	S	T	Y
attempt	A	L	S	O	C		

🕑 Execution time (ET):

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🕓 Execution time (ET): $\varepsilon \quad \varepsilon \quad \varepsilon \qquad = 3\varepsilon \quad \Rightarrow$ 2 correct characters

Problem: The ET is proportional to the **number of consecutive correct** characters from the beginning of attempt

Context: The use of formal methods

Need to detect **timing-leak** vulnerabilities

- We want **formal guarantees** → formal methods
  - Various methods:
    - Abstract interpretation
    - Static analysis
    - Model checking
    - Theorem proving

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Context: Model checking overview

System

Specification

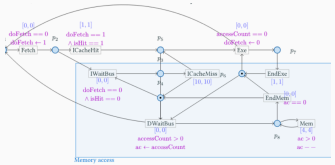
"The system must be safe"

Context: Model checking overview

System

→

Formal model



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Property

$AG \quad \neg$ ○

Context: Model checking overview

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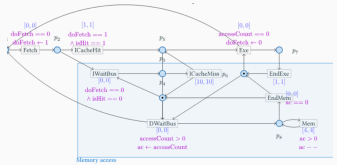

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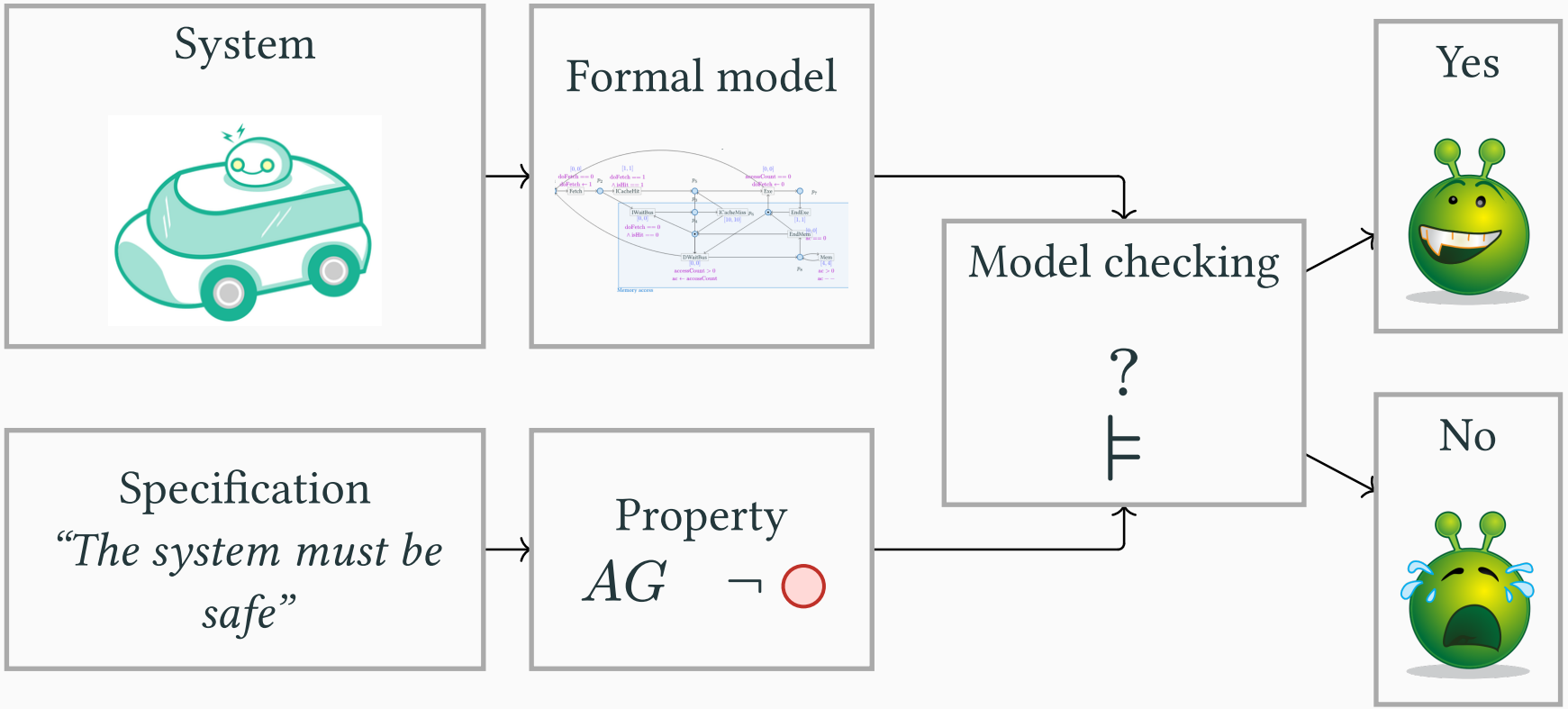


Question: does the model of the system **satisfy** the property?

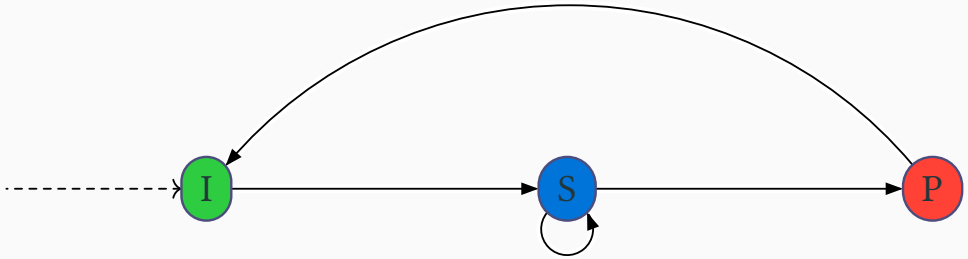
Timed automaton (TA)

- Finite-state automaton (sets of locations,)

[AD94] Rajeev Alur and David L. Dill, "A Theory of Timed Automata," *Theoretical Computer Science*, 1994.

Timed automaton (TA)

- Finite-state automaton (sets of locations, transitions,)



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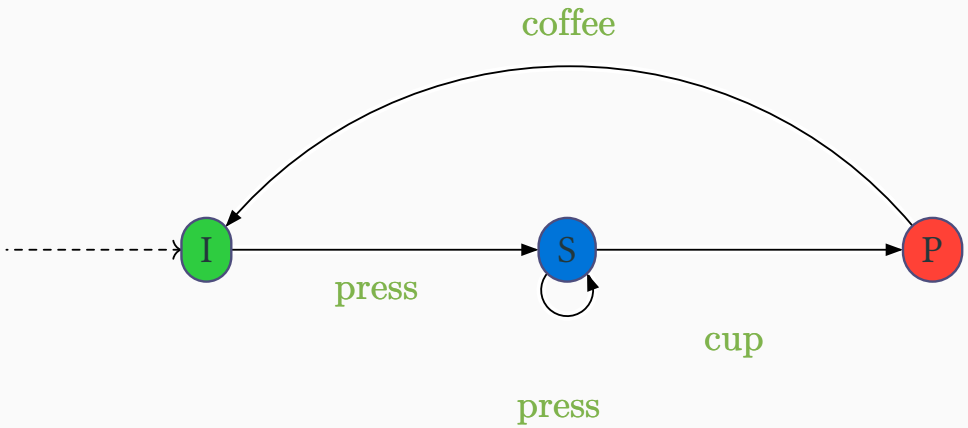

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Timed automaton (TA)

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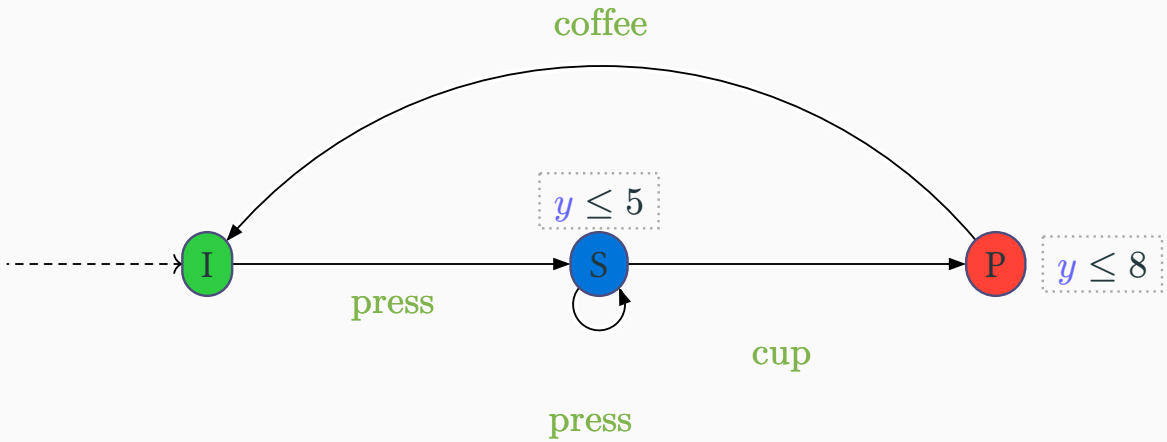
  - Real-valued variables evolving linearly **at the same rate**
- Features:



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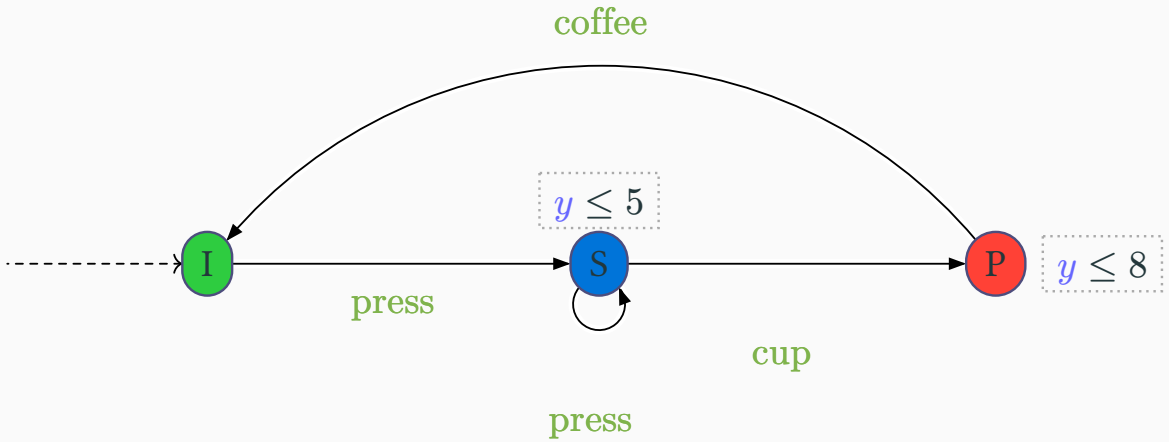

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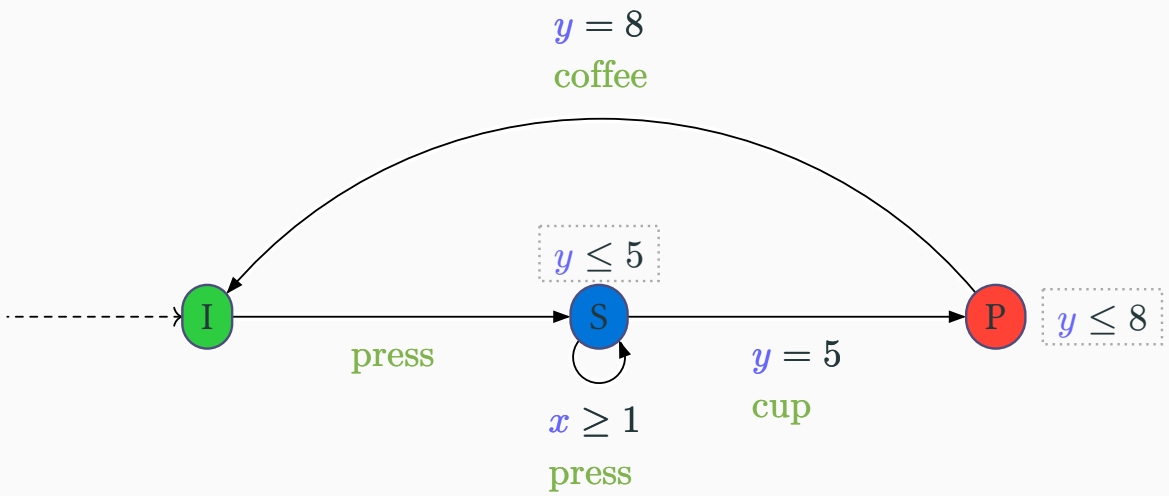

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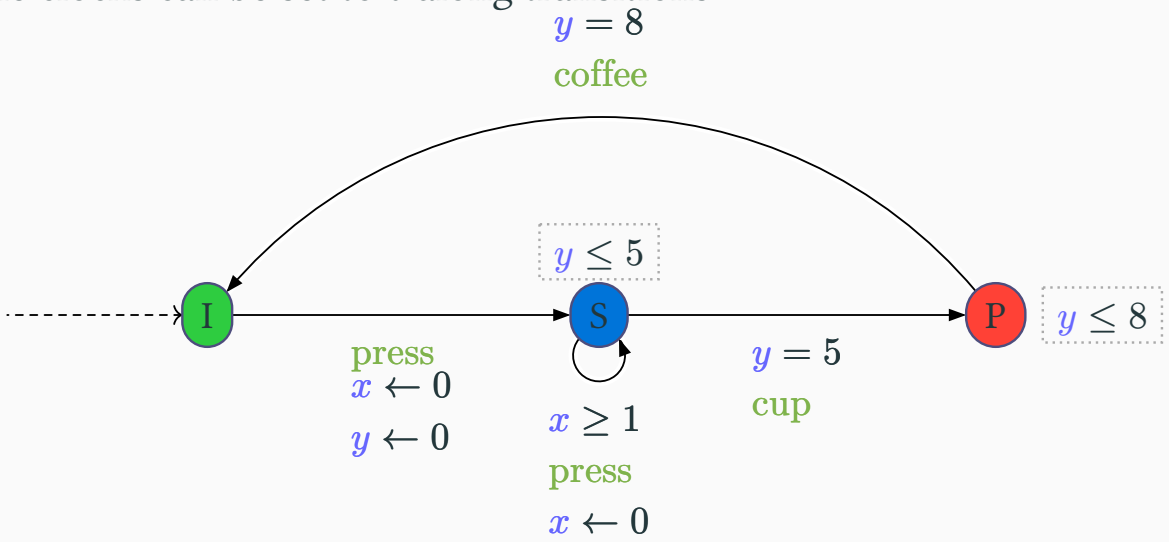
  - Clock **reset**: some of the clocks can be set to 0 along transitions



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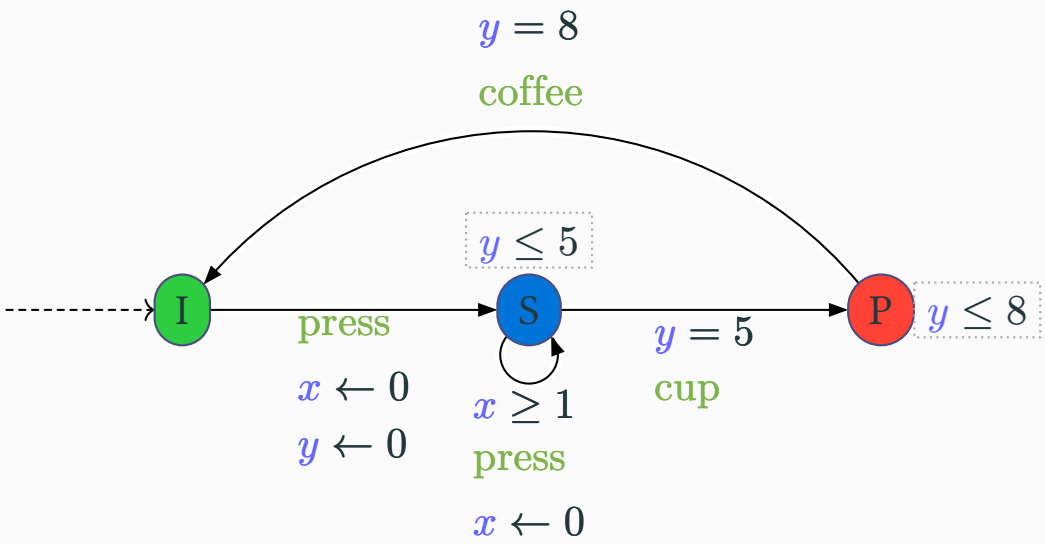
The most critical system: The coffee machine



- Coffee with two doses of sugar

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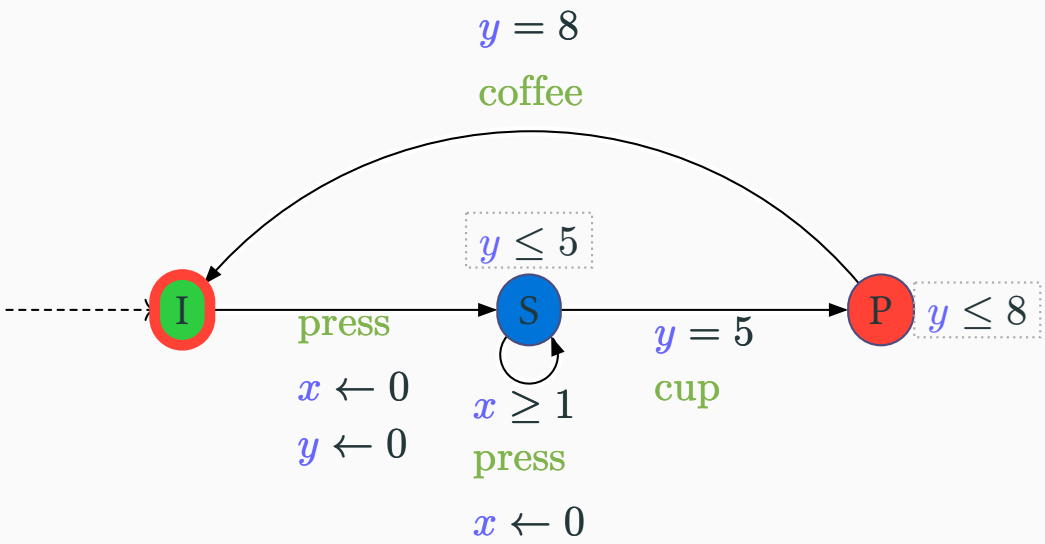

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I

$x = 0$

$y = 0$

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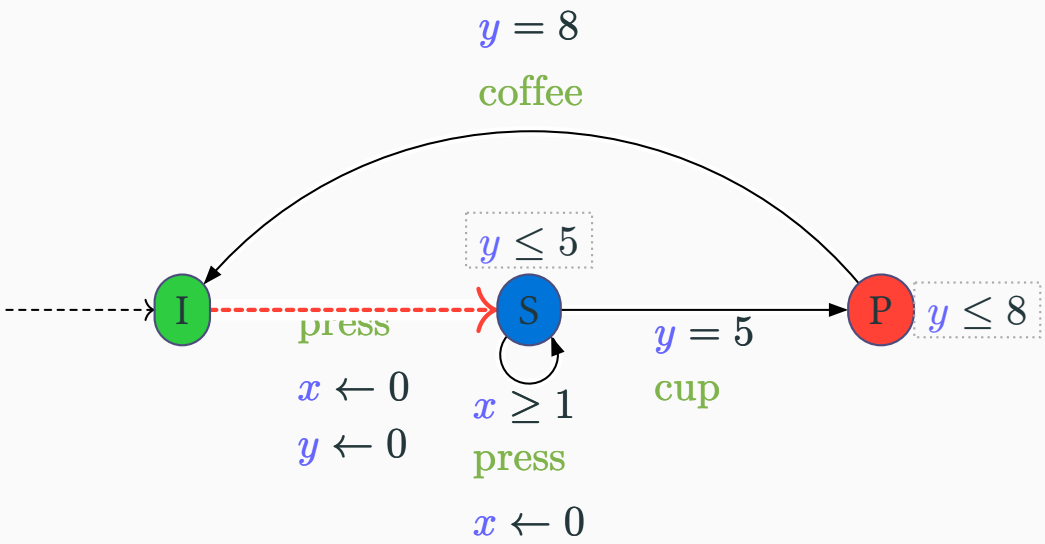

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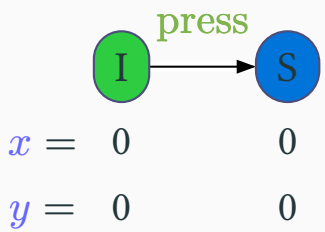

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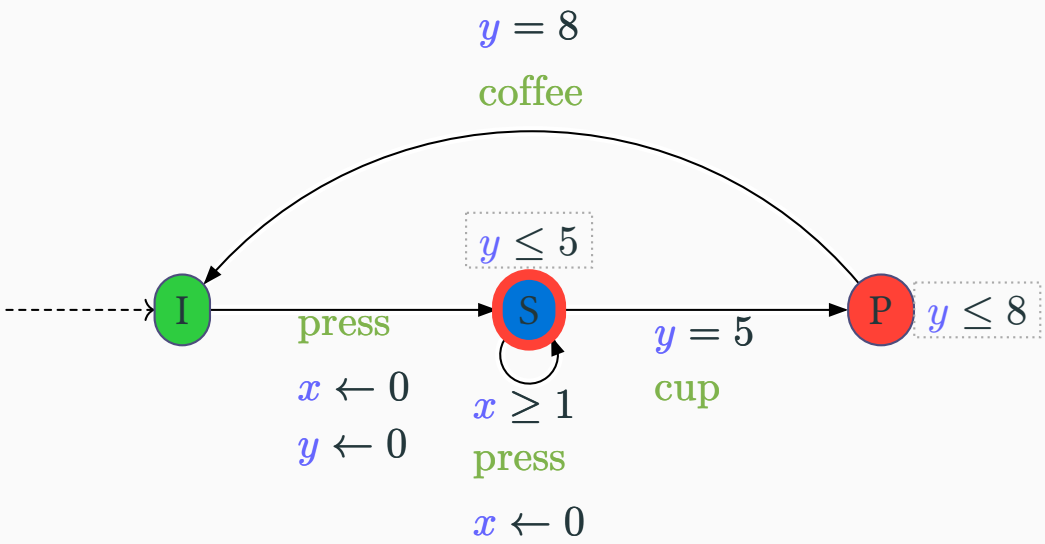

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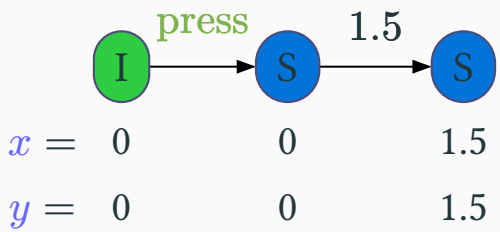

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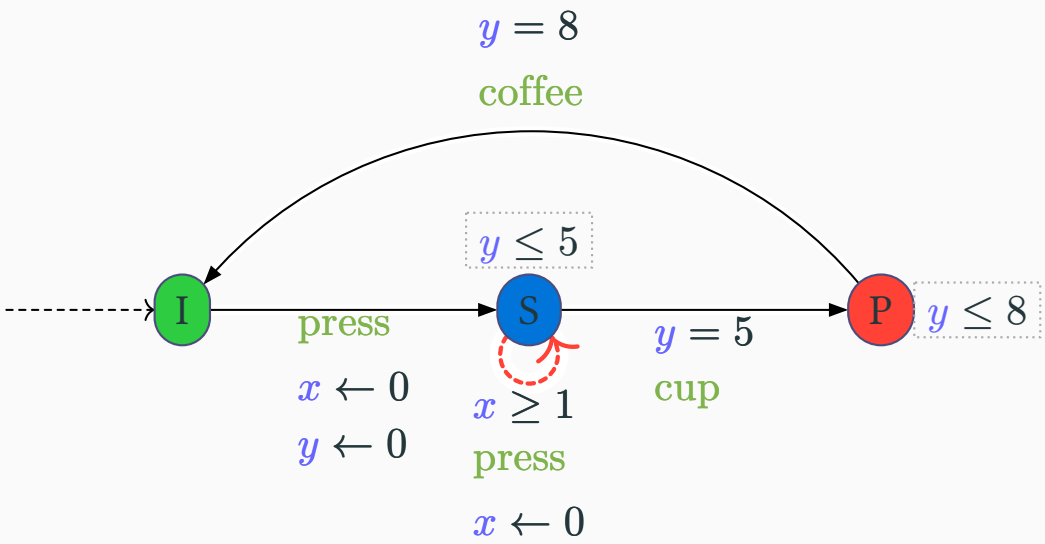

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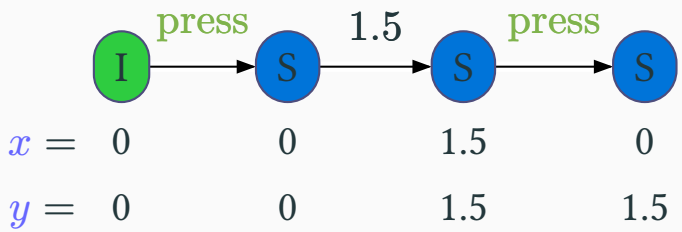

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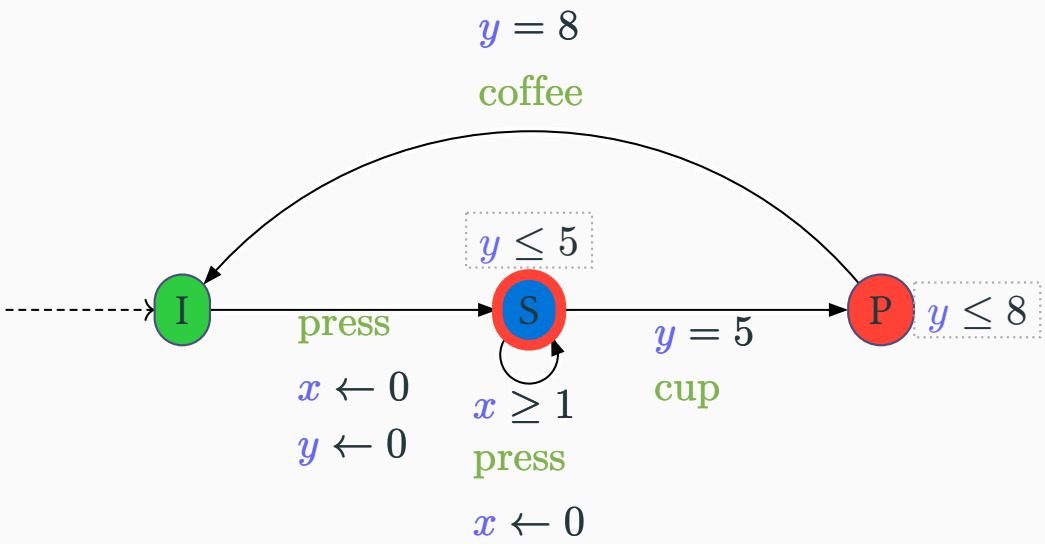

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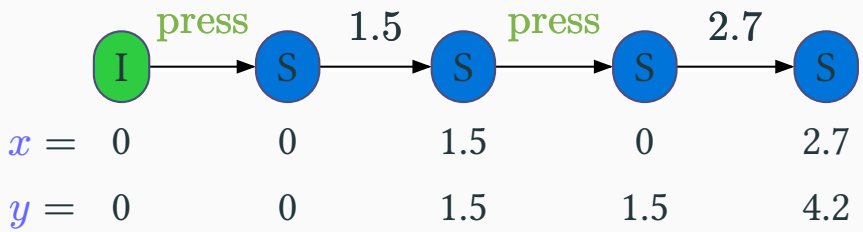

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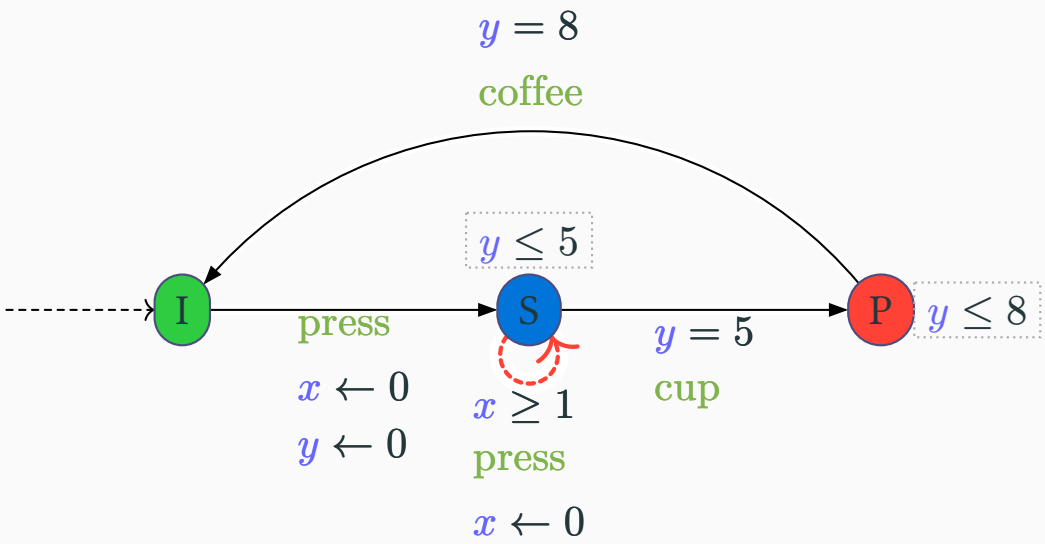

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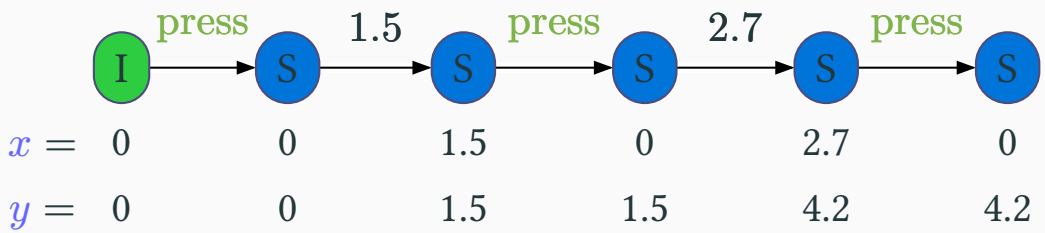

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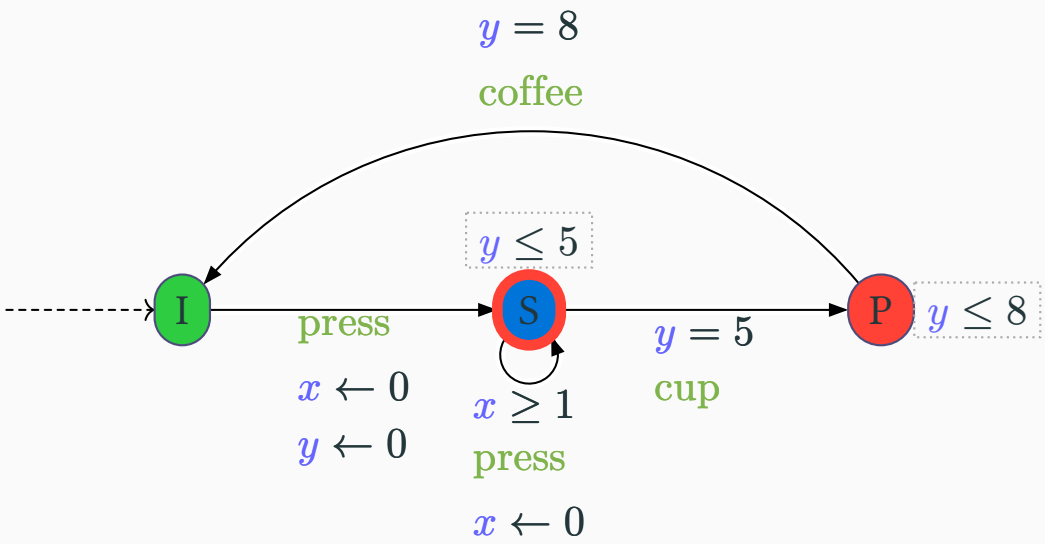

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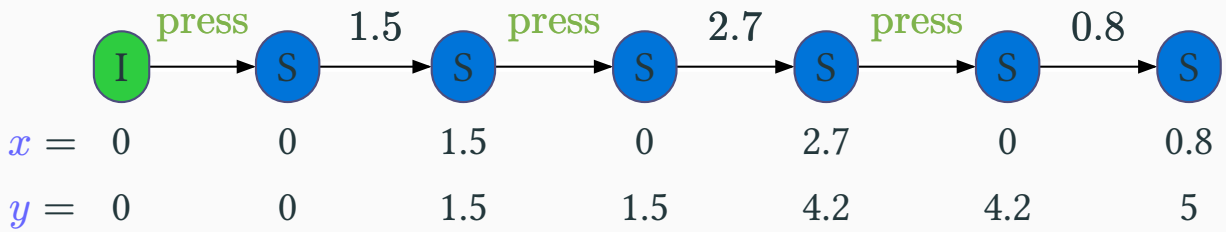

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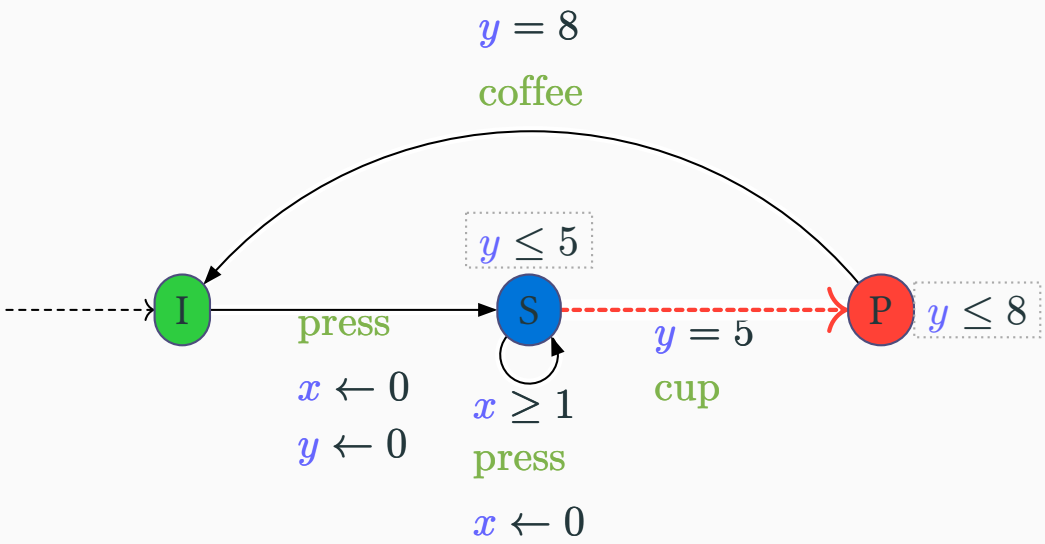

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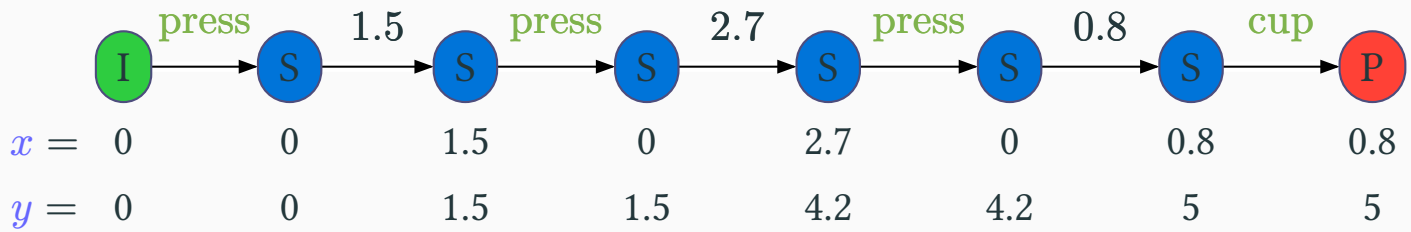

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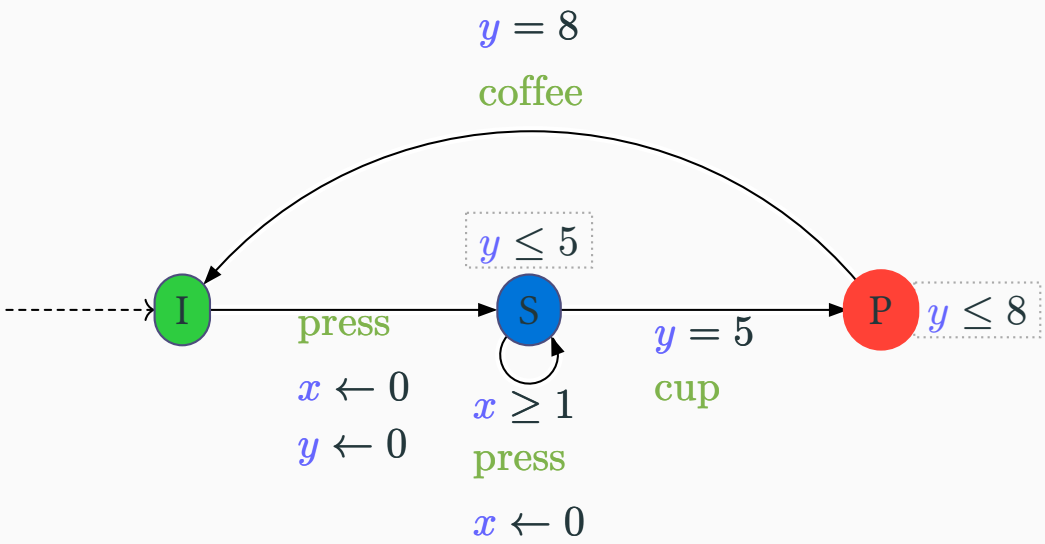

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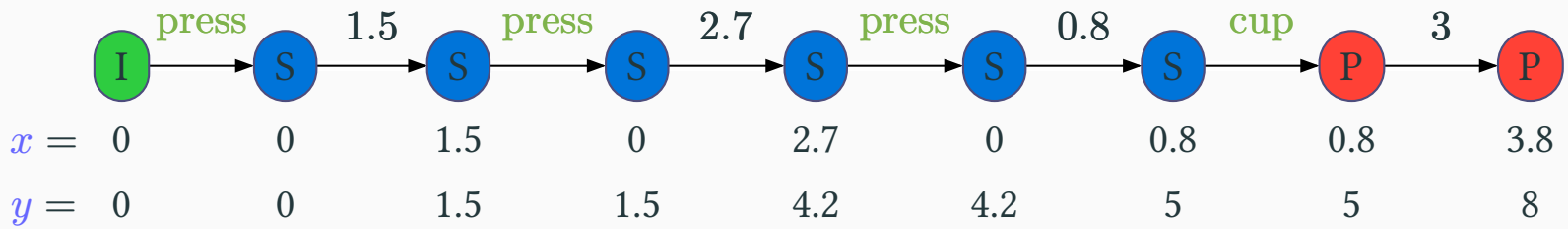

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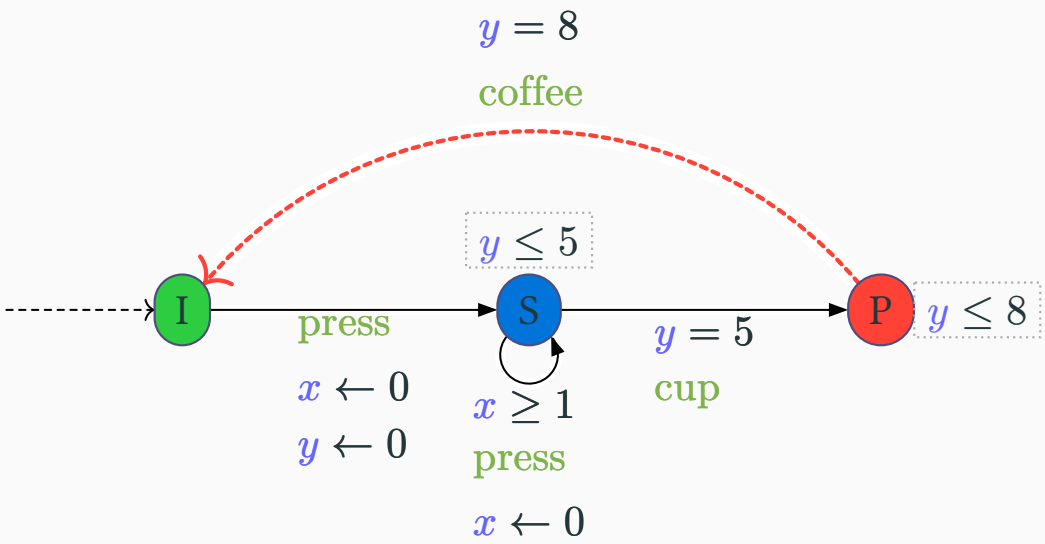

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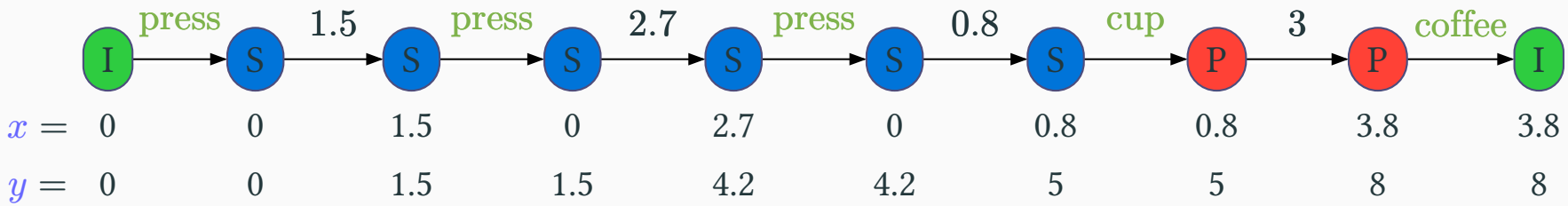

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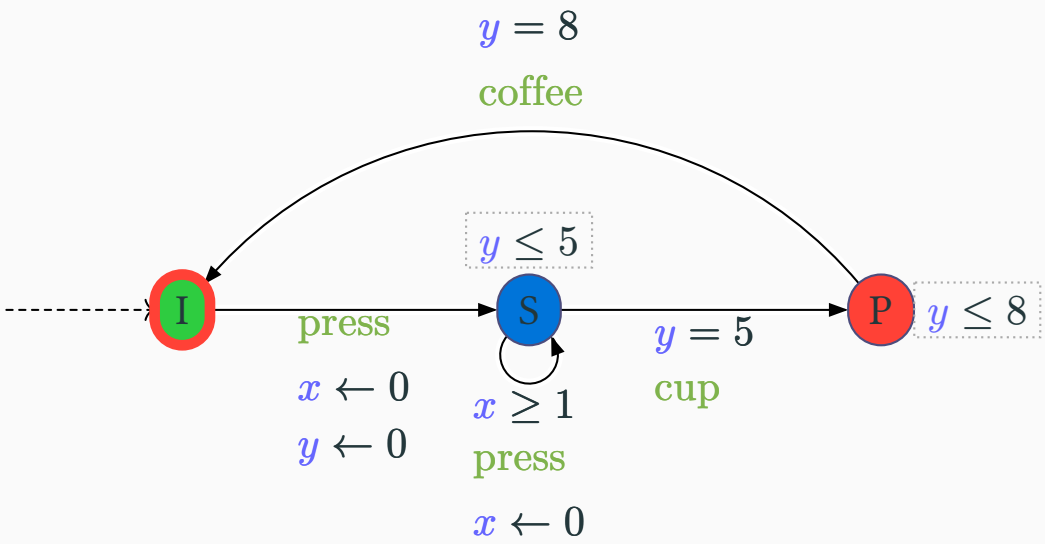

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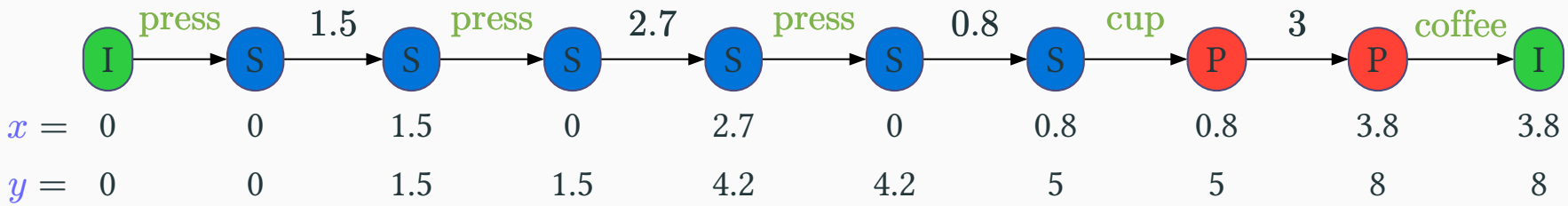

Timed opacity

The attacker model

Attacker capabilities

- Has access to the model (white box)
- Can observe an execution

The attacker model

Attacker capabilities

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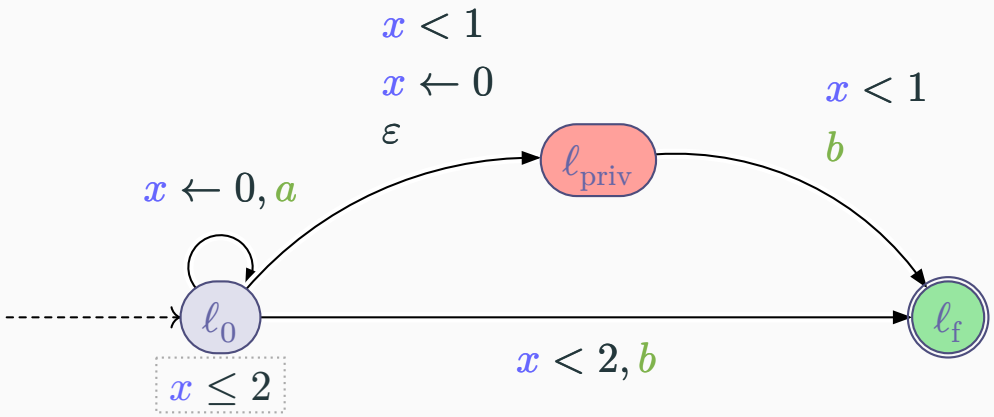
Attacker goal

- Deduce secret information from these observations

  → *visit of a private location*

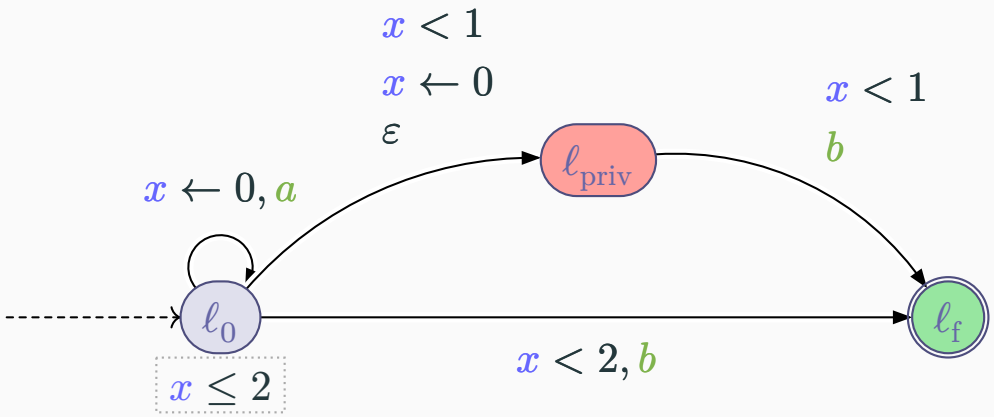
Attacker setting



Observed trace:
$(a, 0.7)(b, 1.3)$

Question: Can the attacker infer if ℓ_{priv} has been visited?

Attacker setting



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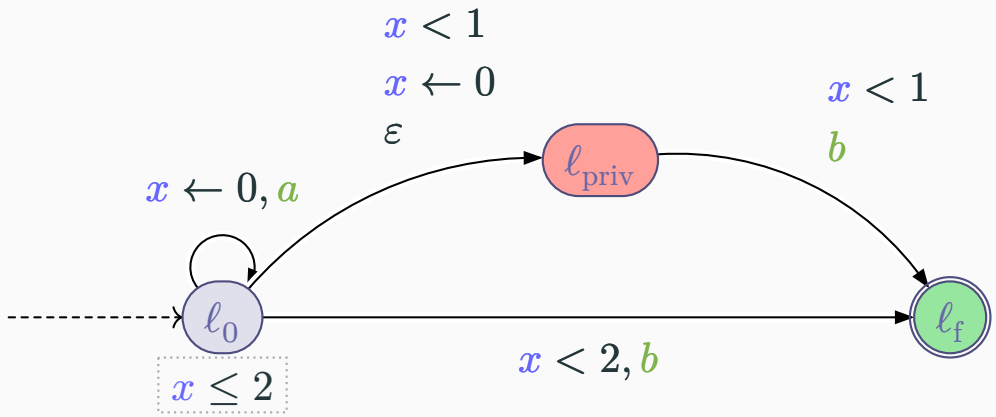

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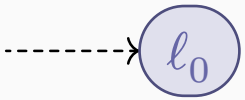

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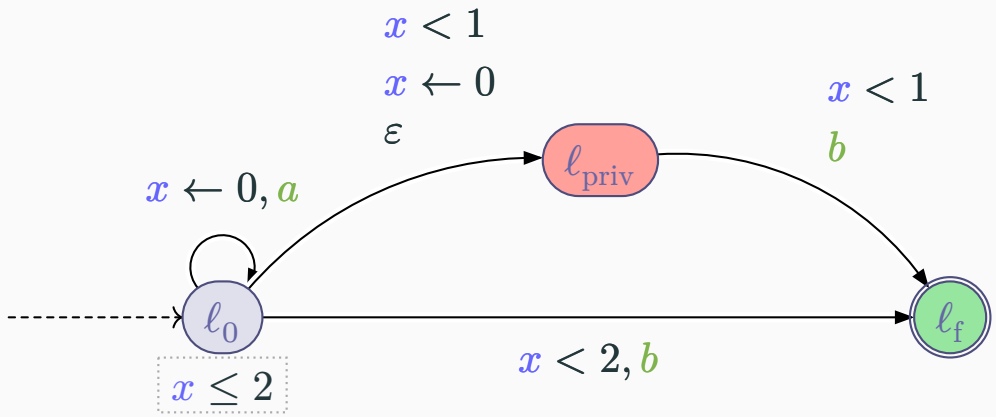

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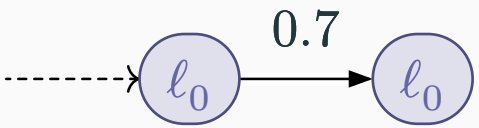

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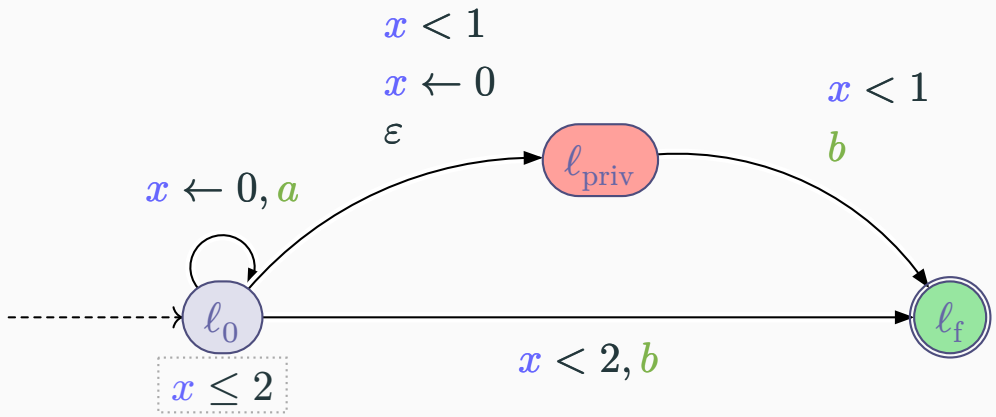

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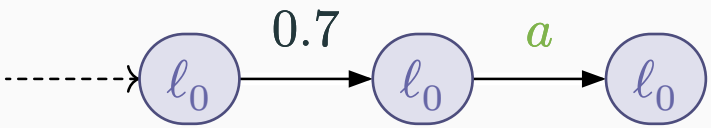

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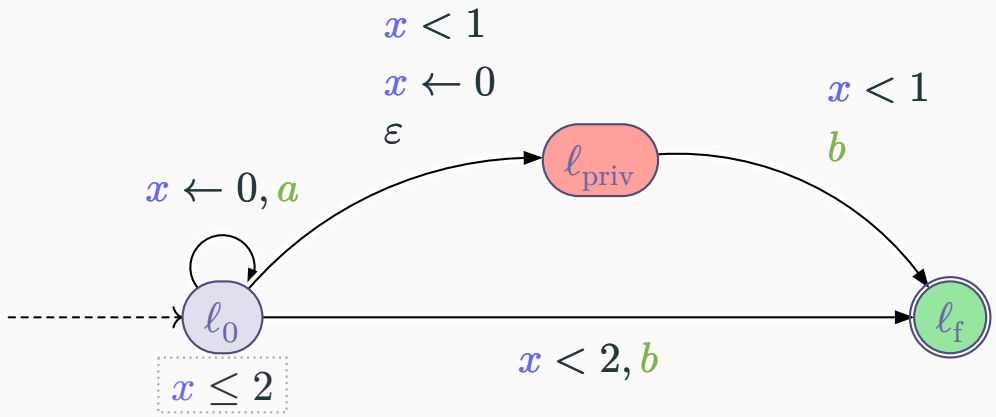

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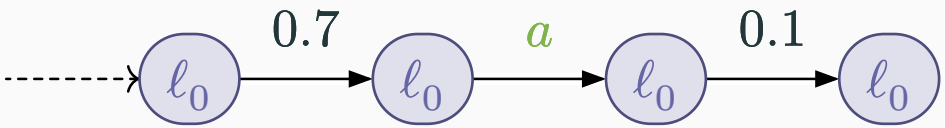

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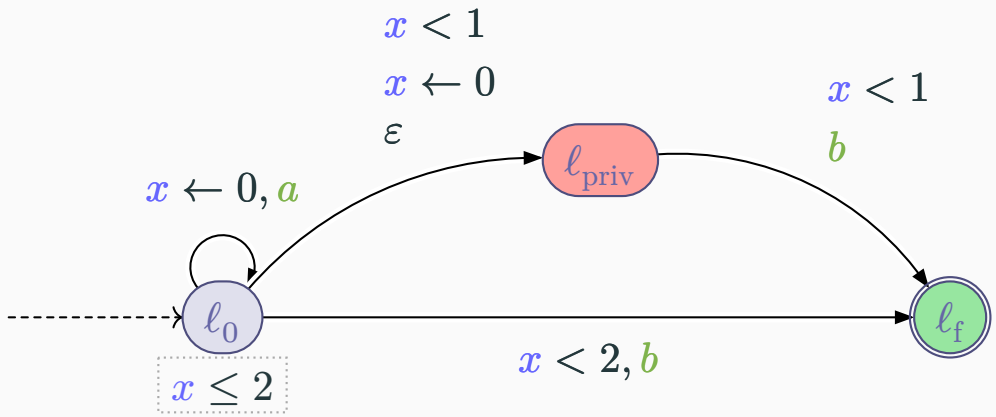

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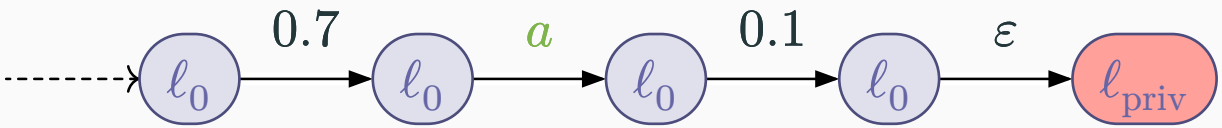

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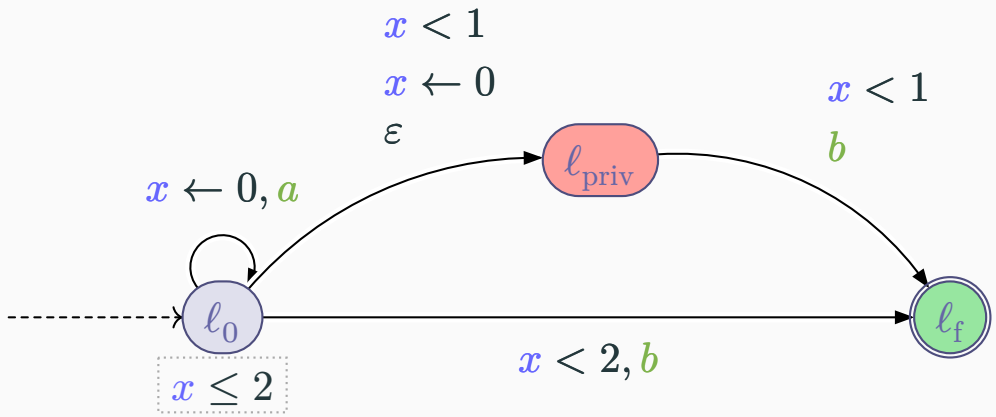

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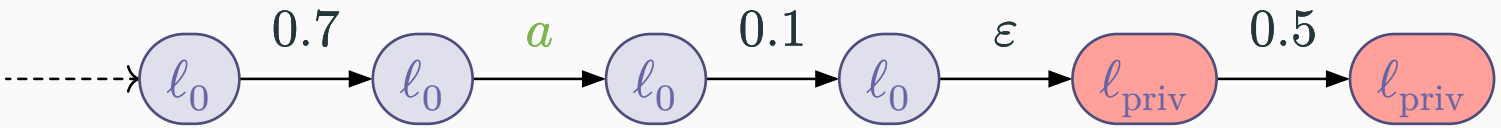

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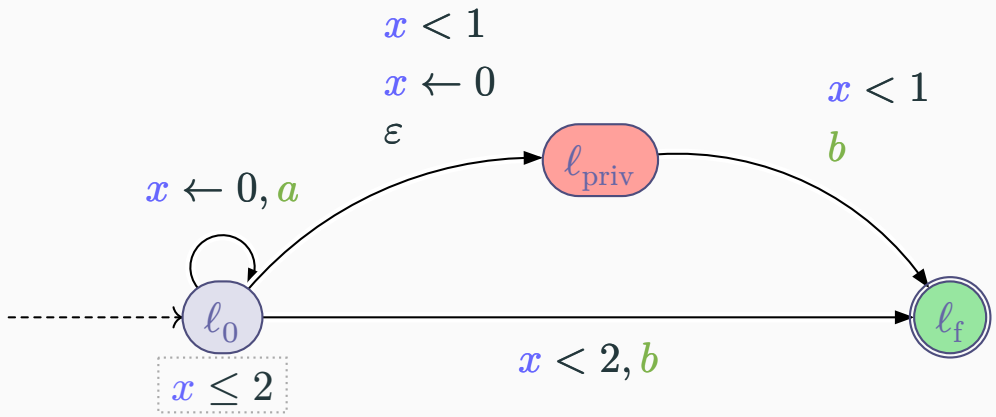

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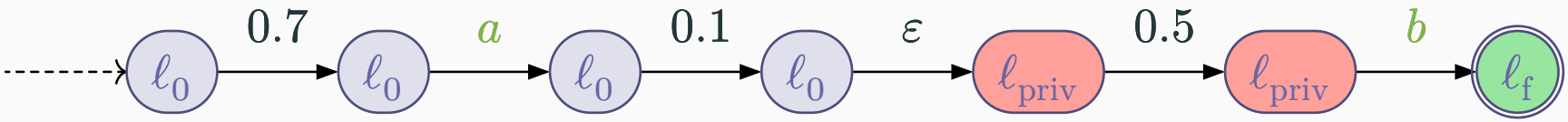

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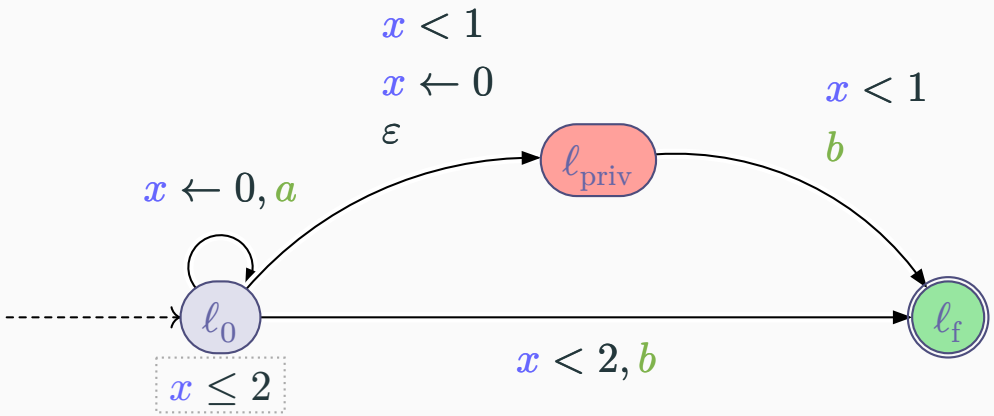

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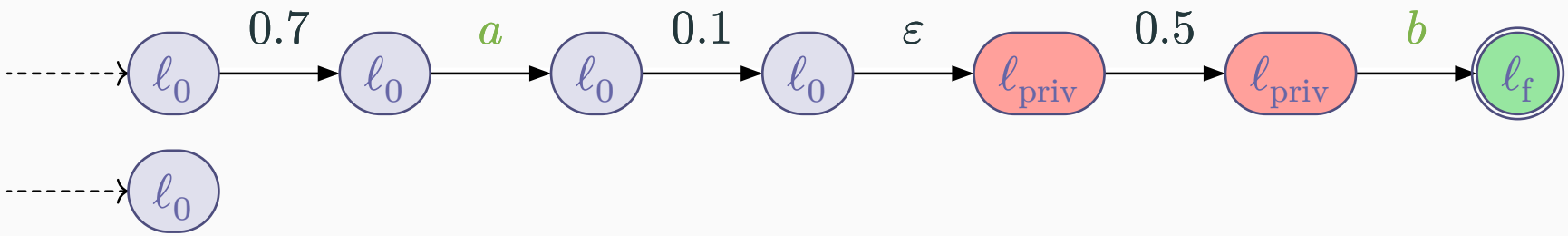

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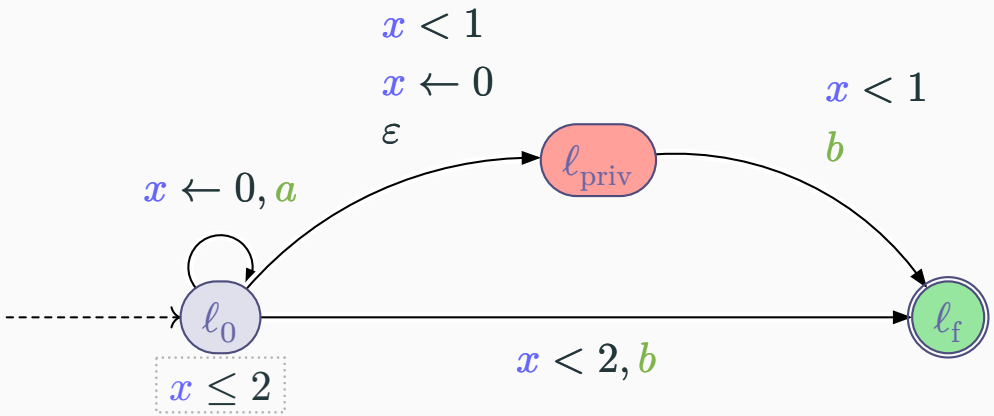

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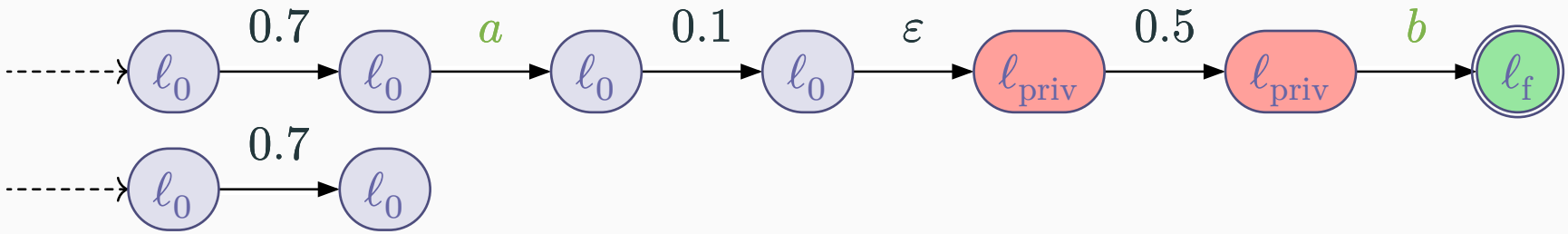

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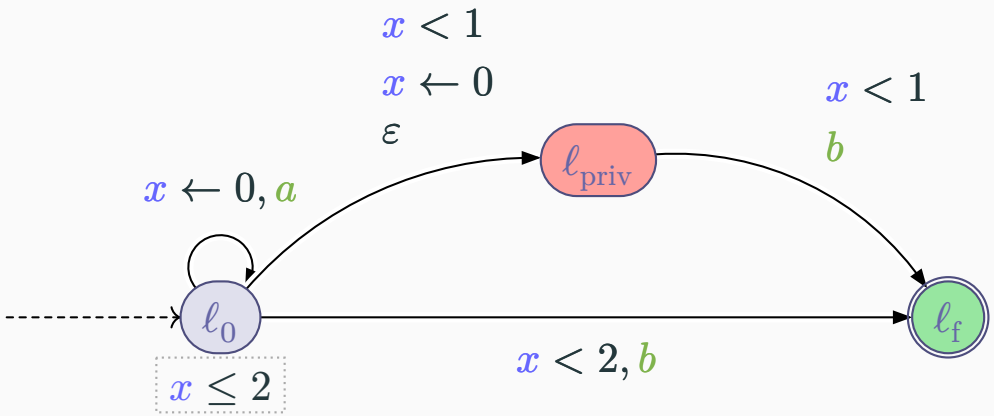

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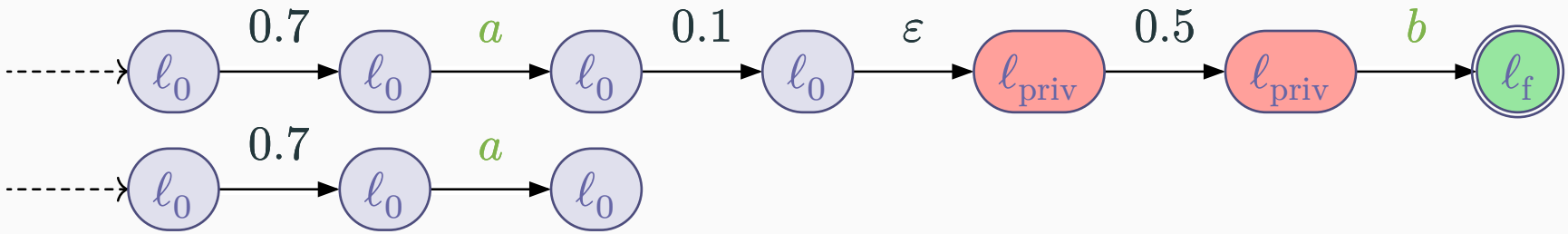

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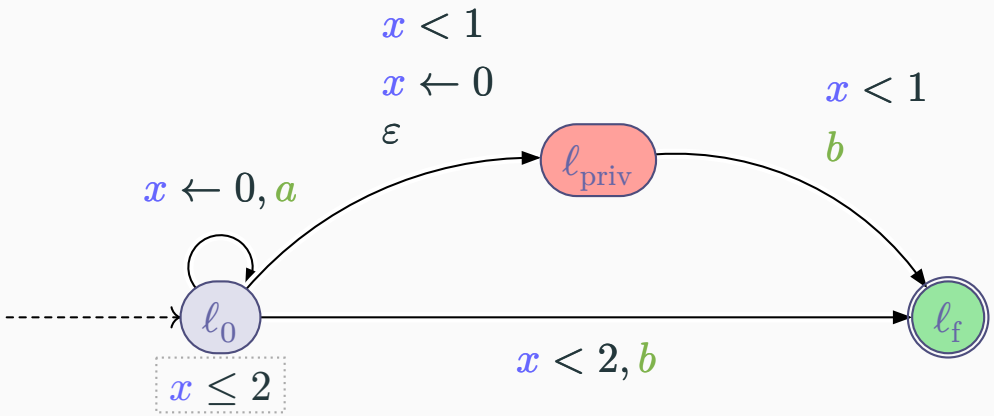

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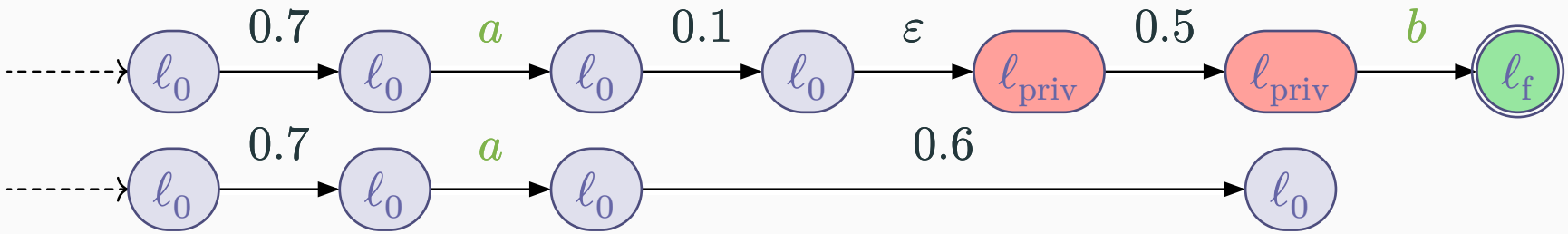

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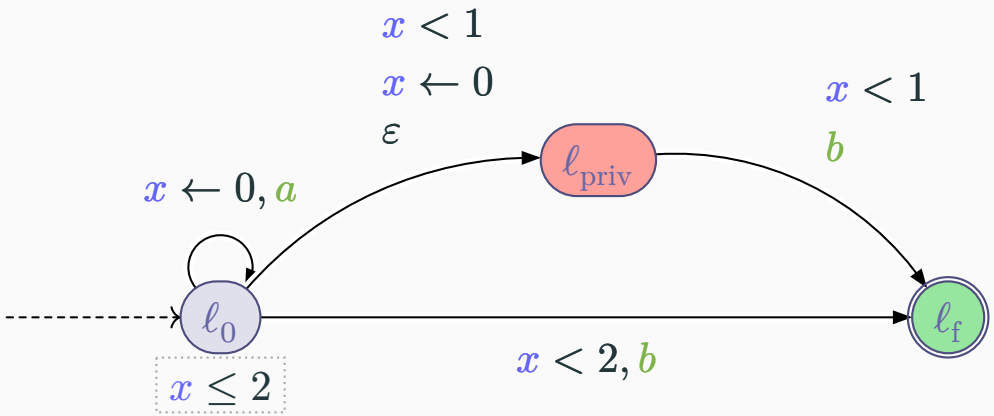

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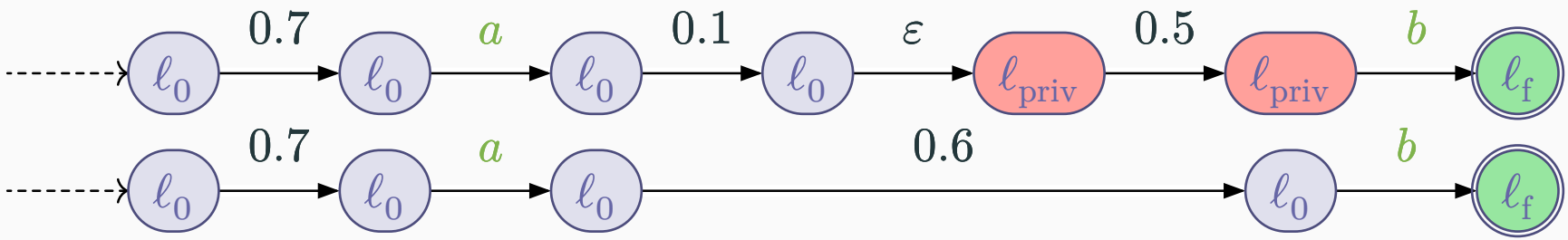

Opacity in timed automata

Definition 1 (Opacity)

A TA is **opaque** iff all *observable* traces can be obtained **both**

- by runs visiting ℓ_{priv}
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So... is it the end?

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Solutions

Proposed solutions

Change the system → Subclasses of TA

- restriction on the number of actions
- restriction on the number of clocks
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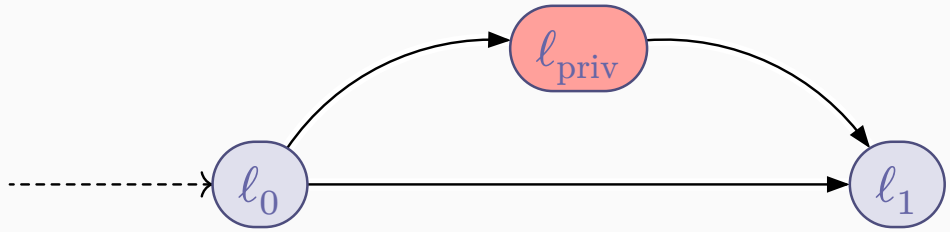
Execution-time opacity

Hypothesis

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



Definition 1 (Execution-time opacity)

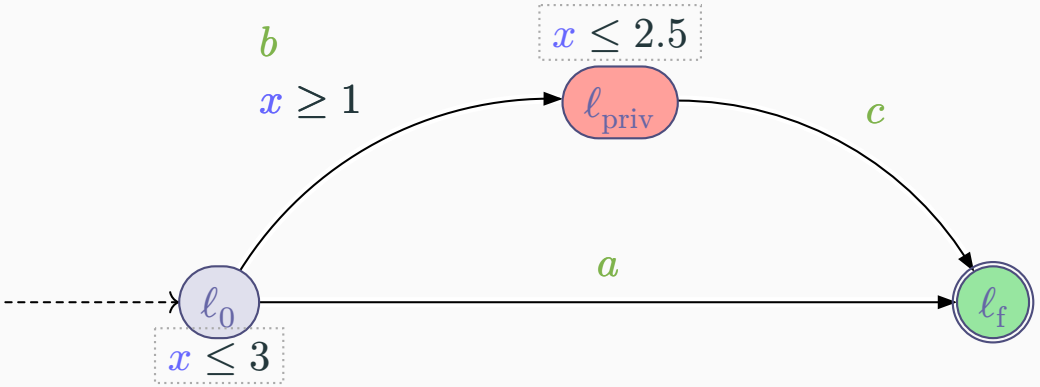
The system is **ET-opaque** for a duration d if there exist two runs of duration d

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

♣

[And+22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun, "Guaranteeing Timed Opacity using Parametric Timed Model Checking," *TOSEM*, 2022.

Example



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

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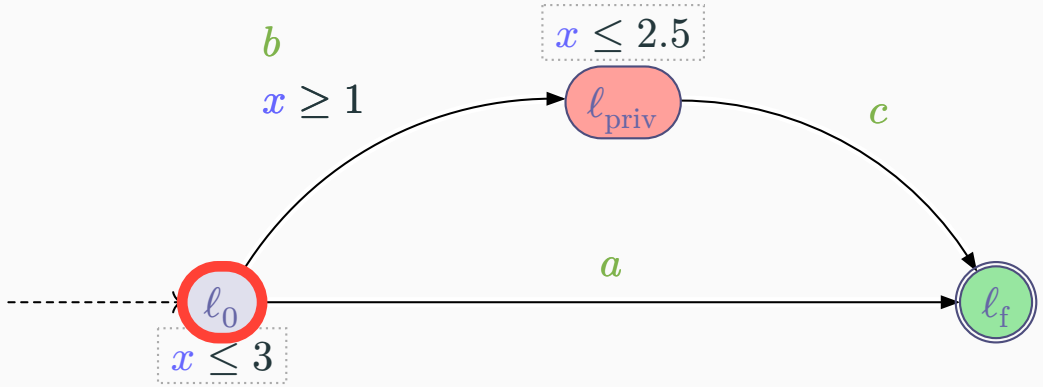

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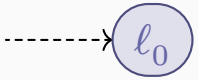

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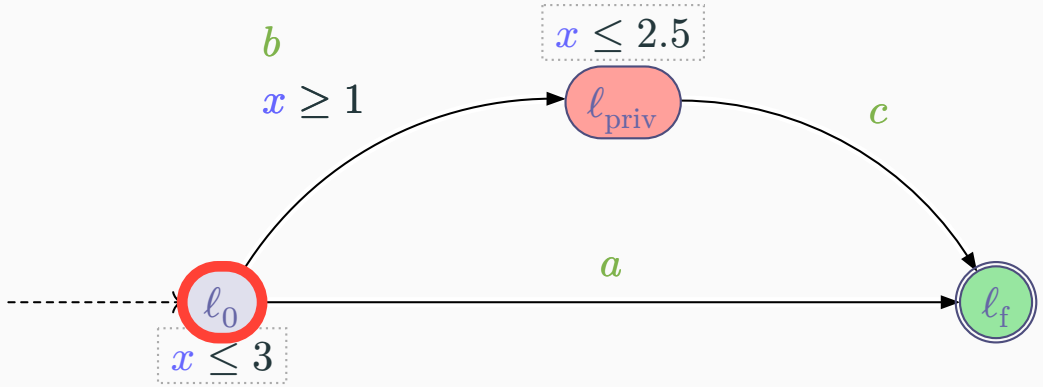

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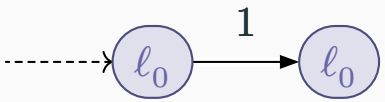

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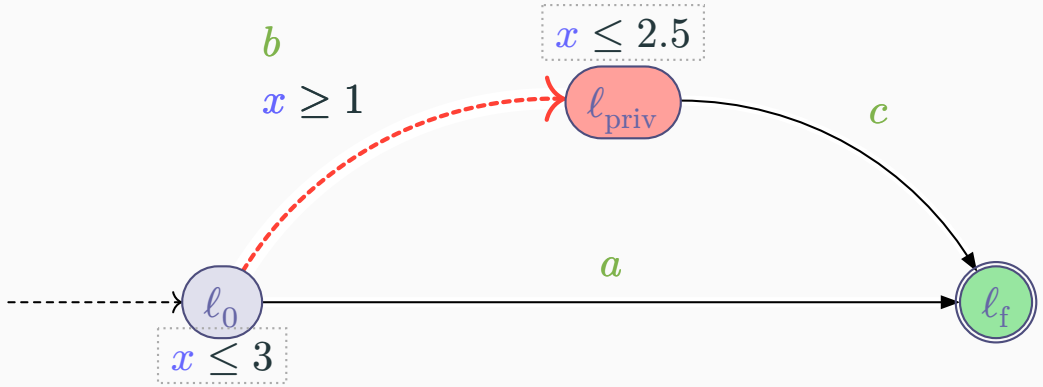

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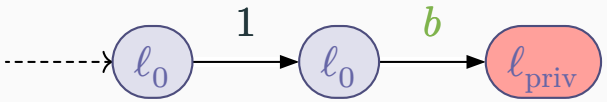

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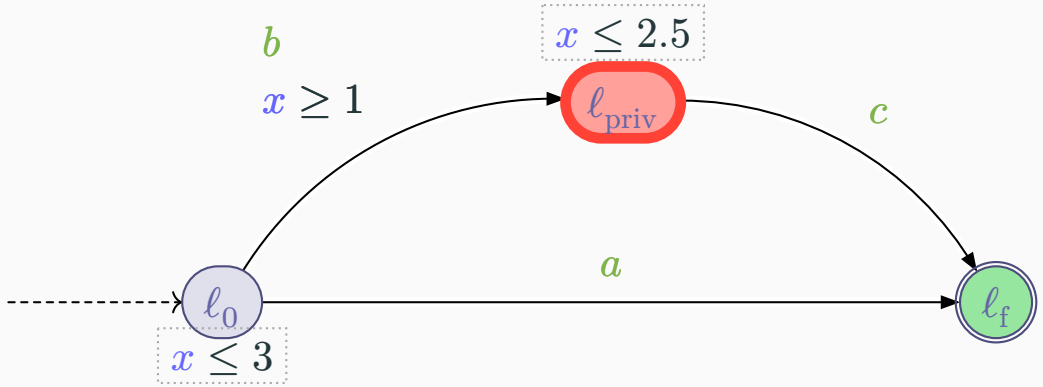

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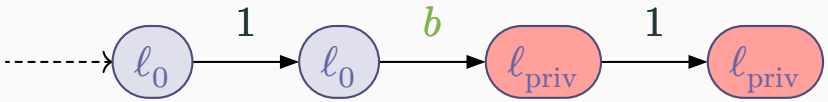

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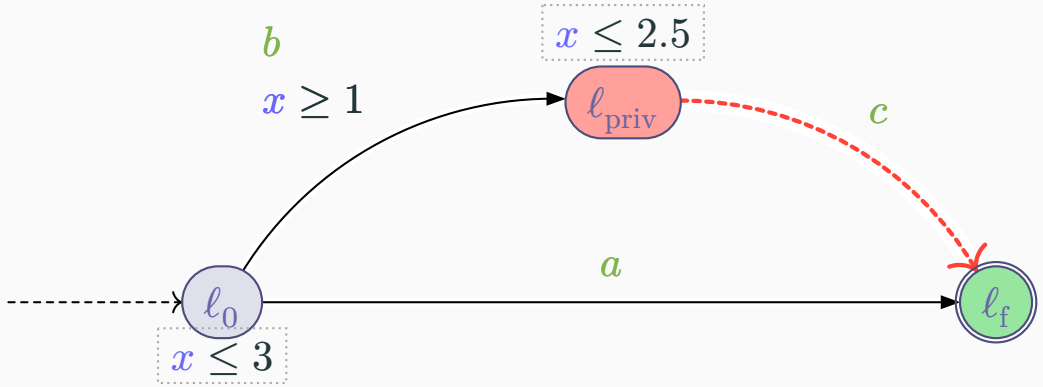

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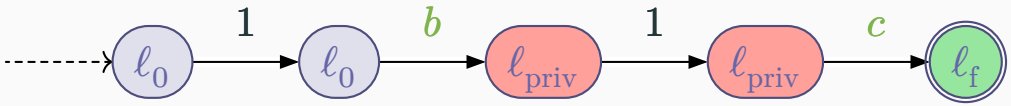

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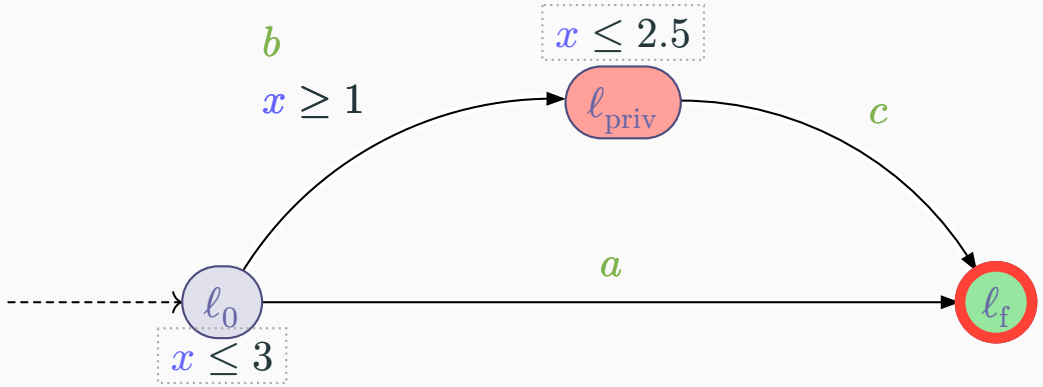

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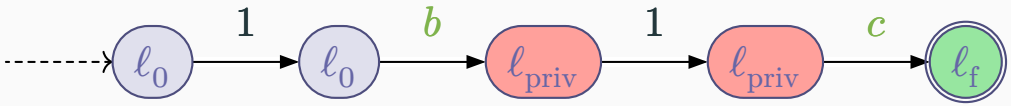

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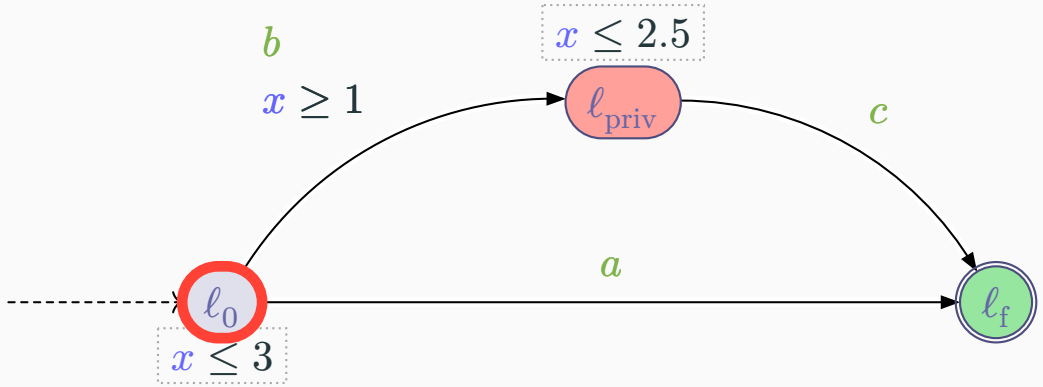

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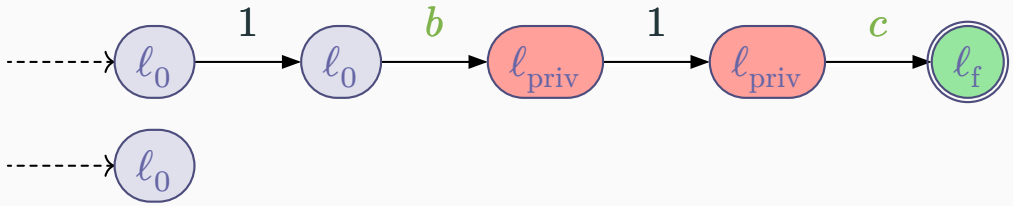

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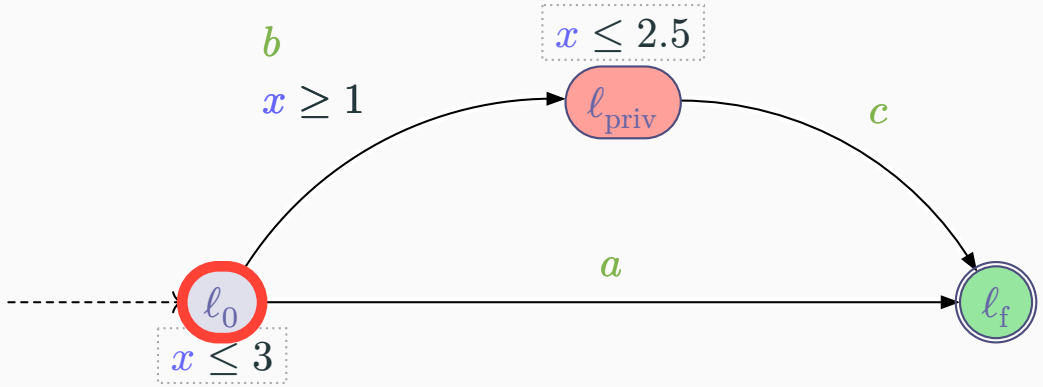

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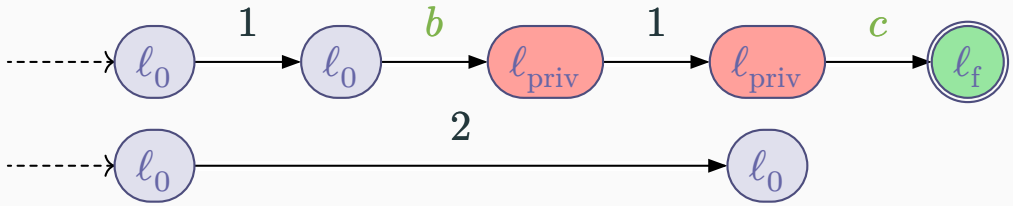

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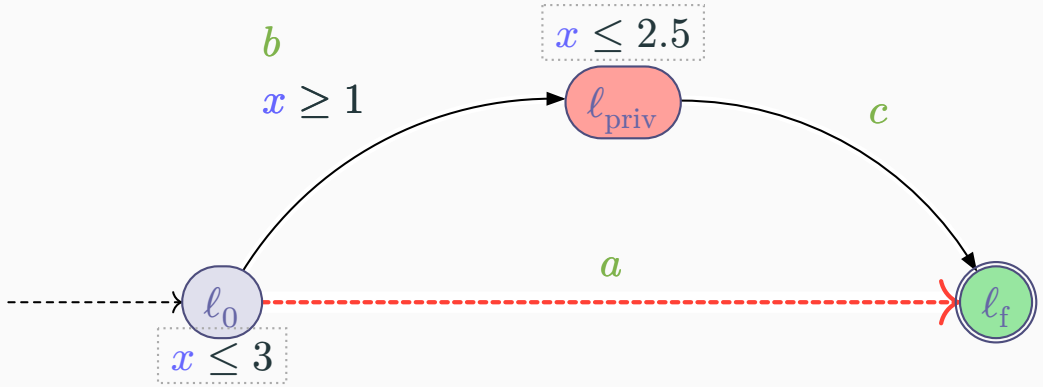

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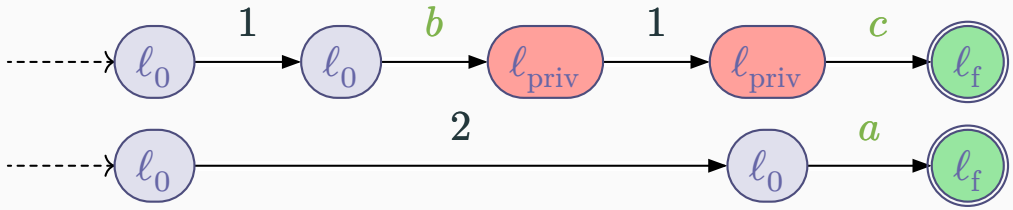

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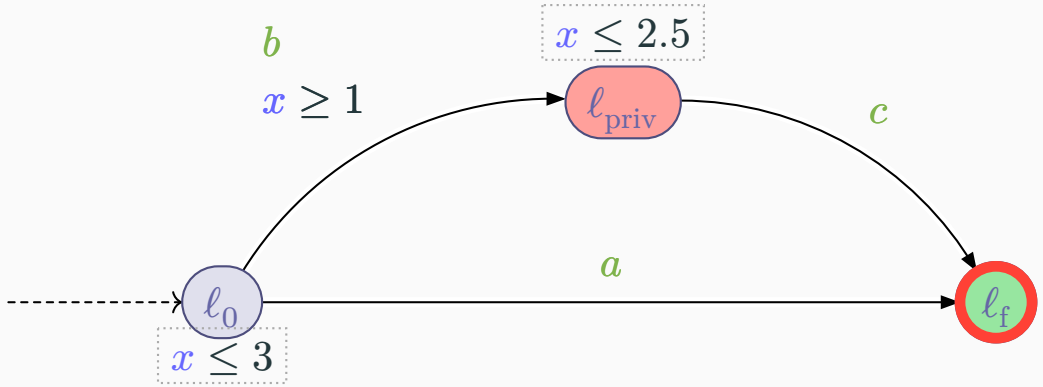

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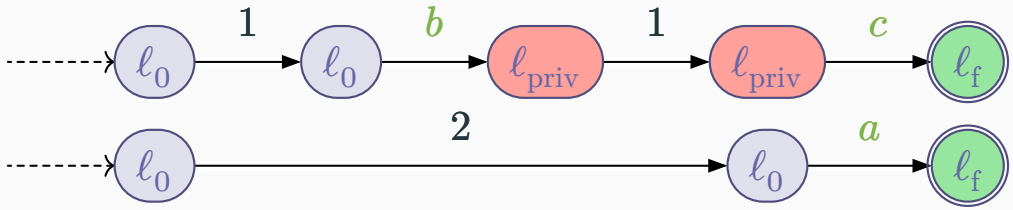

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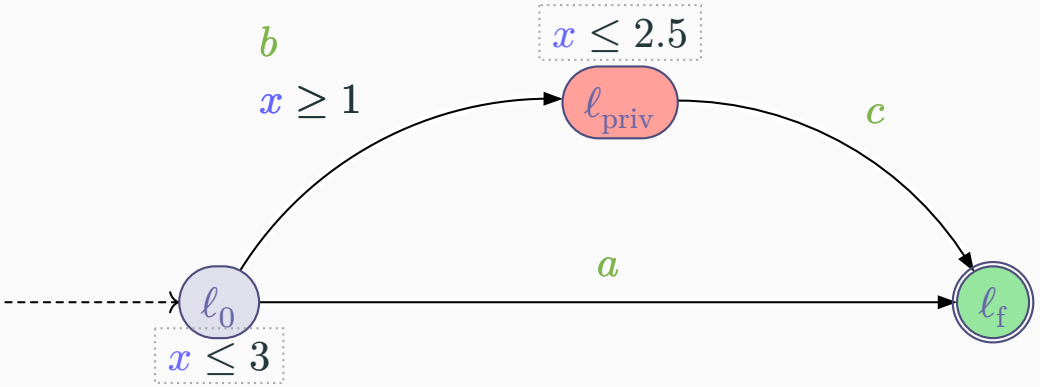

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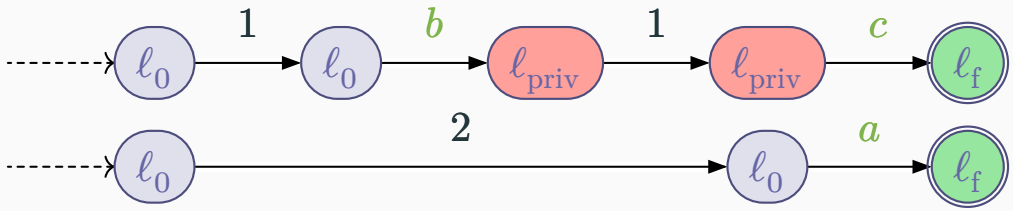

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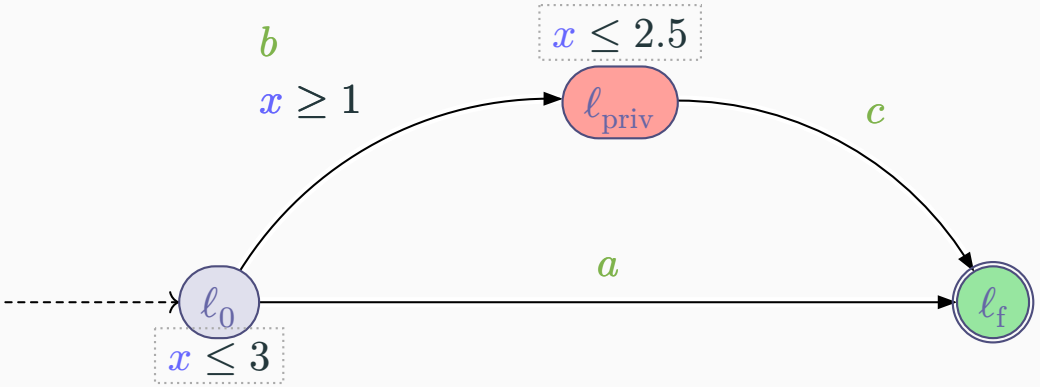

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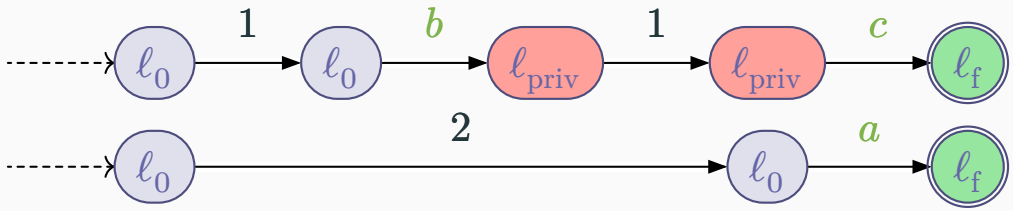

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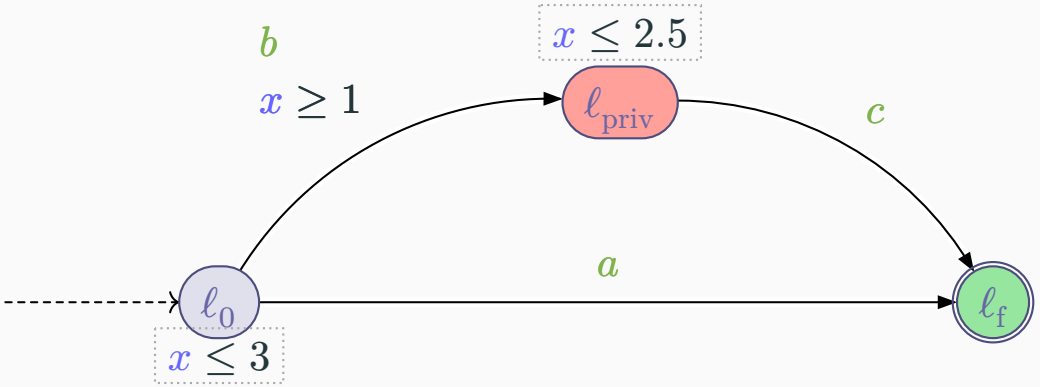
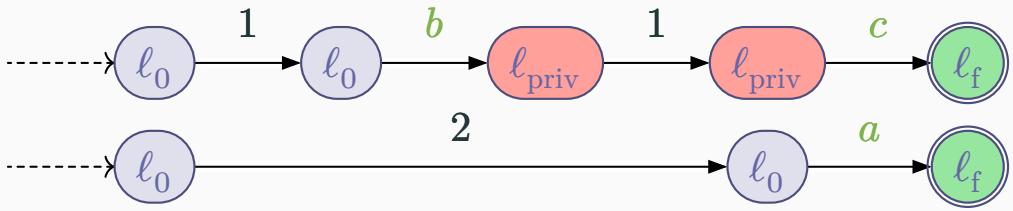
- $D_{\ell_{\text{priv}}} = [1, 2.5] \neq D_{\neg\ell_{\text{priv}}} = [0, 3]$

Example



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



- ET-opaque for $d = 2$
- $\exists$-ET-opaque

- $D_{\ell_{\text{priv}}} = [1, 2.5] \neq D_{\neg\ell_{\text{priv}}} = [0, 3]$

- Not full-ET-opaque

ET-opacity in timed automata

ET-opacity decision problem

Is the given timed automaton ET-opaque?

[And+22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun, "Guaranteeing Timed Opacity using Parametric Timed Model Checking," *TOSEM*, 2022.

ET-opacity in timed automata

ET-opacity decision problem

Is the given timed automaton ET-opaque?

→ ET-opacity is decidable for timed automata!

[And+22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun, "Guaranteeing Timed Opacity using Parametric Timed Model Checking," *TOSEM*, 2022.

Analyzing timing behaviors of programs

Problems

Timing analysis of programs is **hard**: it depends not just on code, but also on **low-level details** of execution

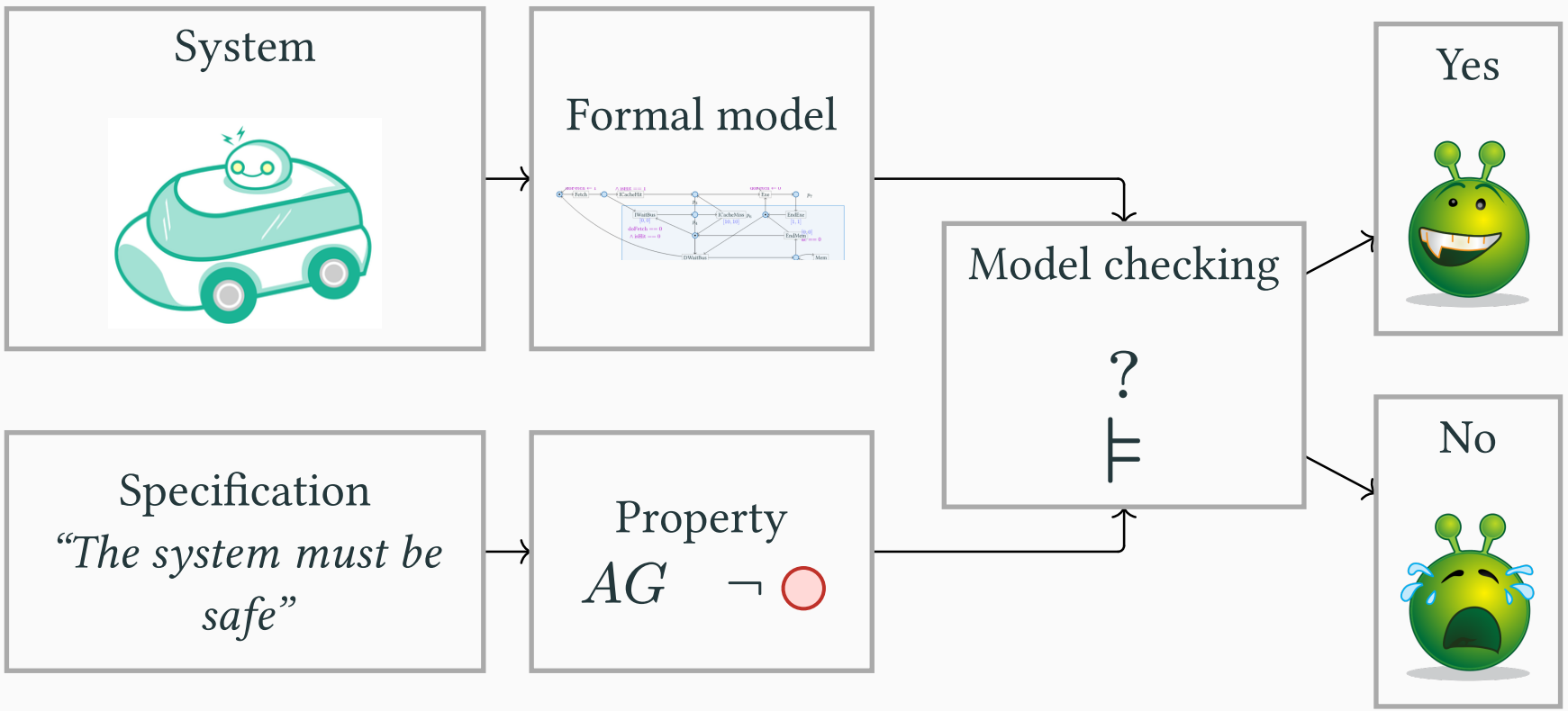
Impact of hardware

- ET is heavily influenced by the **micro-architecture**
  - Especially: pipelines, caches, memory hierarchy

Limitations of existing techniques

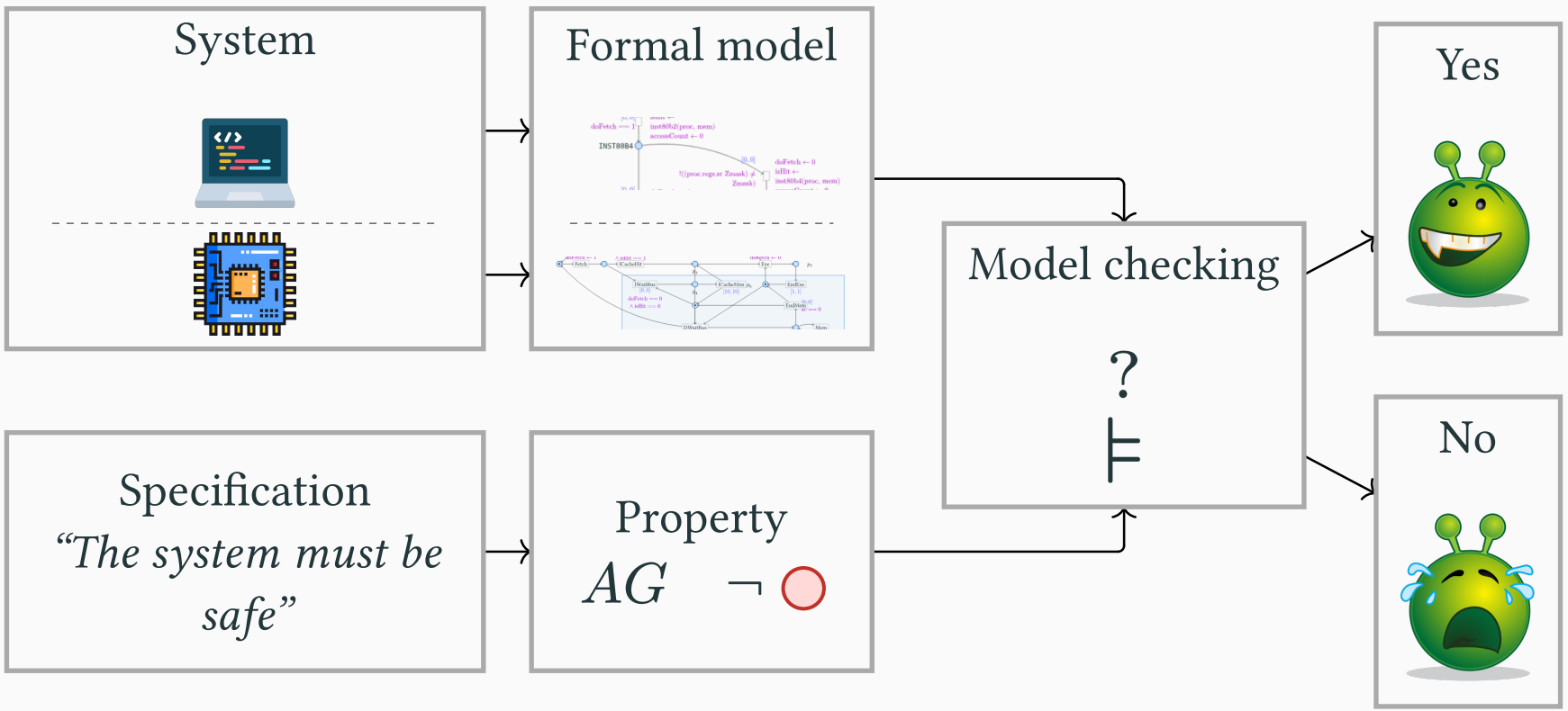
- Most abstract time away or focus on **coarse properties**
  - e.g., schedulability analysis, worst-case execution time (WCET)
- **Insufficient** for fine-grained timing behaviors
  - e.g., detecting or mitigating *timed side-channels*

Model checking



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

Model checking



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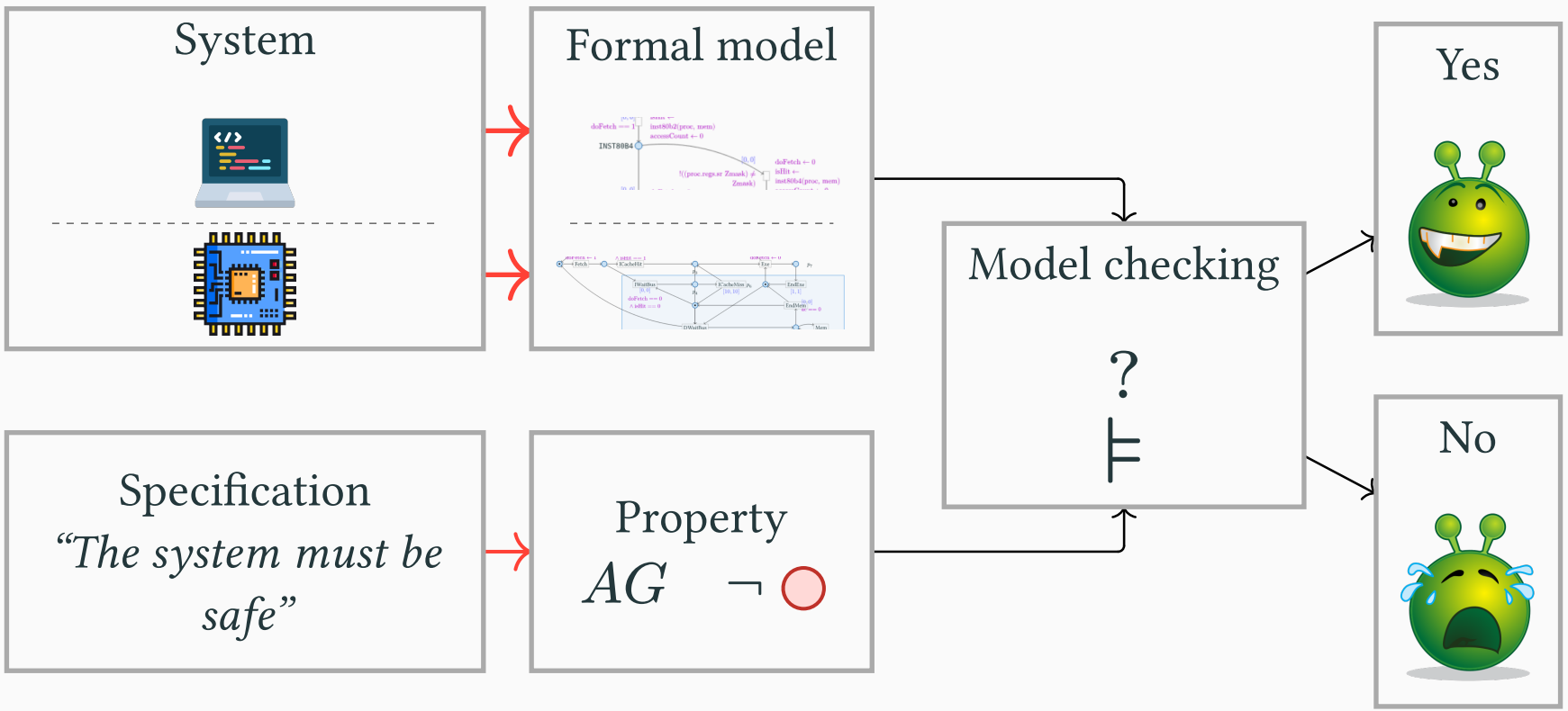

Question: does the model of the system **satisfy** the property?

Our contributions in a nutshell

[And+25]

- A **modular** and **automated** approach to build formal models to analyze **timing behaviors**
  - *binary code with the hardware*

[And+25] Étienne André *et al.*, "Verifying Timed Properties of Programs in IoT nodes using Parametric Time Petri Nets," in *SAC 2025*, 2025.

Our contributions in a nutshell

[And+25]

⚙️ A **modular** and **automated** approach to build formal models to analyze **timing behaviors**

- *binary code with the hardware*

💻 An **implementation**

- *targeting a realistic micro-architecture of a simple micro-controller*
- *producing **time Petri nets** models*

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- *binary code with the hardware*

💻 An **implementation**
- *targeting a realistic micro-architecture of a simple micro-controller*
- *producing **time Petri nets** models*

⚔️ An application to **timing attacks** in **C programs** using the **Roméo** model checker

---

[And+25] Étienne André *et al.*, "Verifying Timed Properties of Programs in IoT nodes using Parametric Time Petri Nets," in *SAC 2025*, 2025.

Modeling hardware

Considered hardware

Our hardware

- Model of the **processor architecture**
  - *relatively simple micro-architecture similar to ARM Cortex M0+ core, with a 2-stage pipeline (Fetch and Execute)*
- Model of the **instruction set** architecture (ISA)
  - *ARMv6-M ISA*

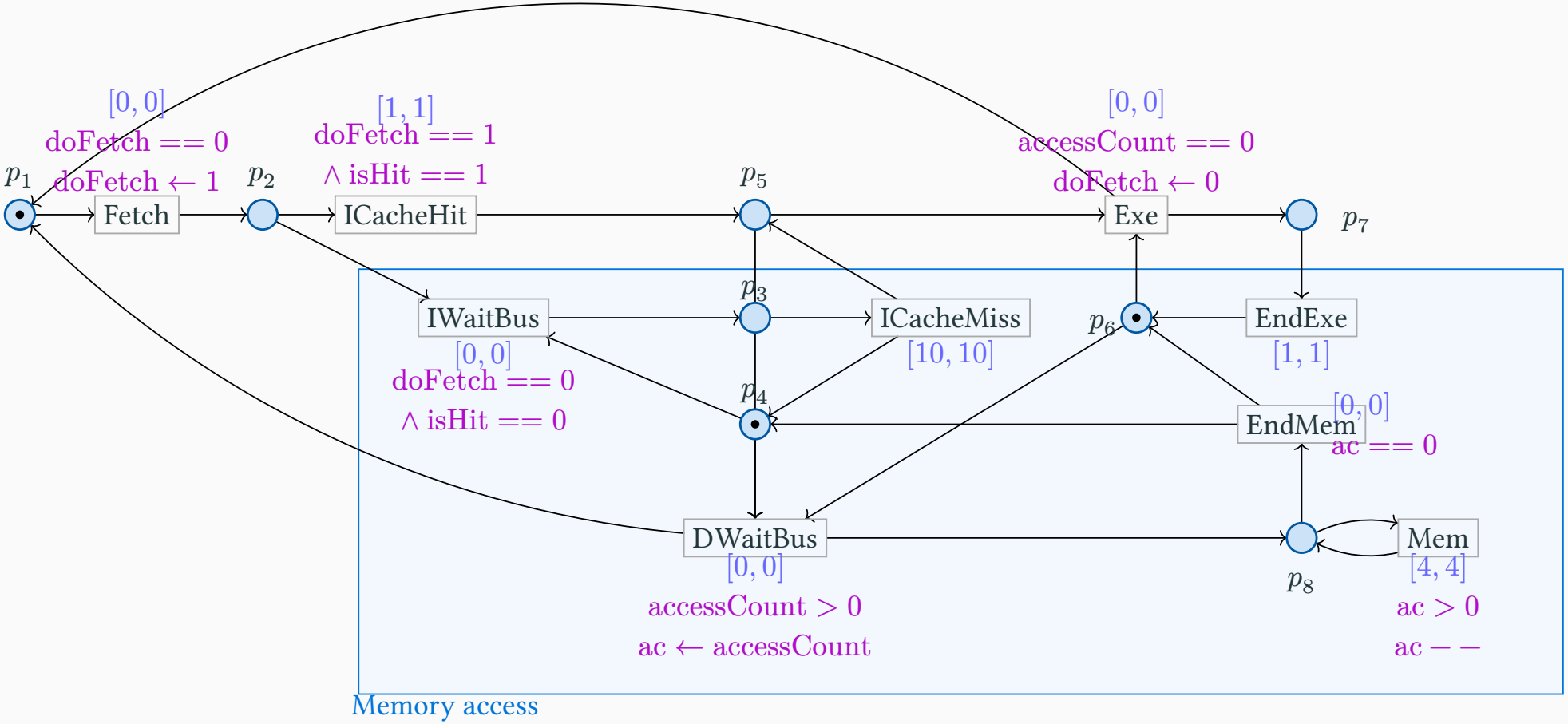
Features

- Execution pipeline of the processor
- Unique memory space
  - *(instructions and data)*
- Bus between the processor and memory
- Direct-mapped **instruction cache**
  - *with 16 lines of 32 bytes*
  - *no actual instructions, but only information about their presence*
- **No data** cache

- Among the limitations: no switch/case, function pointers. . .

PTPN hardware model

- doFetch, isHit and accessCount: variables used to synchronize with the software

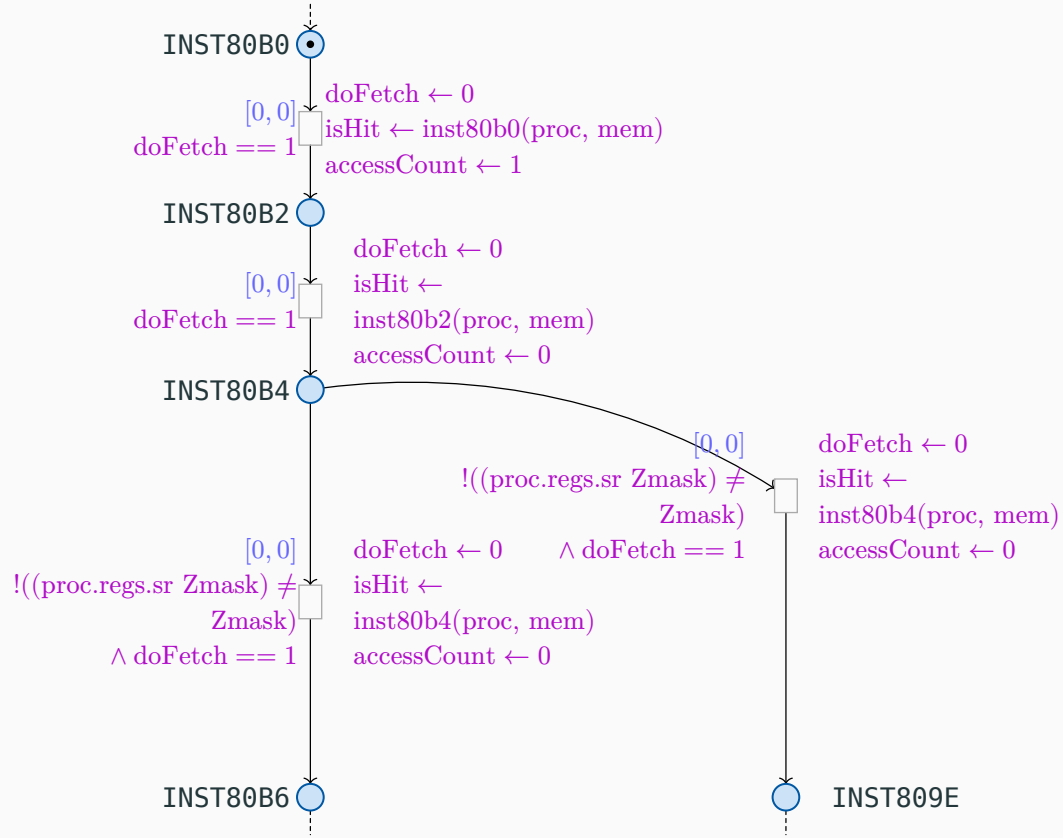


Modeling programs

PTPN software model

Software

- Captures the **binary code** of the program *(ARMv6-M)*
  - Firing a transition corresponds to executing the instruction
  - Pipeline fetch: doFetch
  - Memory access: accessCount and isHit
- Structurally identical to the **control flow graph**

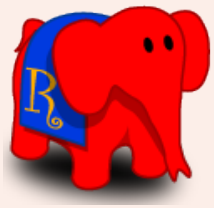


A fully automated translation

A fully automated translation

- Including the hardware and software models
- Written in C and Python
- All the way from the C source code to the PTPN model
- Entirely open source *(github.com/DylanMarinho/codeToPN/)*

Target model checker: Roméo [Lim+09]



- **Parametric timed model checker** supporting (extensions) of PTPNs
- Including **C-like code** to be executed during transitions

[Lim+09] Didier Lime, Olivier H. Roux, Charlotte Seidner, and Louis-Marie Traonouez, "Romeo: A Parametric Model-Checker for Petri Nets with Stopwatches," in *TACAS 2009*, 2009.

Application to security properties

Application to security properties

Timing attacks

- Attacker can **infer information** about the secret key by measuring the **execution time** of the program
  - *e.g., password checking program*

Execution-time opacity [And+23]

"Can the attacker deduce internal behavior by only observing the execution time?"

[And+23] Étienne André, Engel Lefaucheux, Didier Lime, Dylan Marinho, and Jun Sun, "Configuring Timing Parameters to Ensure Execution-Time Opacity in Timed Automata," in *TiCSA@ETAPS 2023*, 2023.

Application to security properties

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Execution-time opacity [And+23]

"Can the attacker deduce internal behavior by only observing the execution time?"

- Use of timing parameters: to measure execution times

[And+23] Étienne André, Engel Lefaucheux, Didier Lime, Dylan Marinho, and Jun Sun, "Configuring Timing Parameters to Ensure Execution-Time Opacity in Timed Automata," in *TiCSA@ETAPS 2023*, 2023.

Which of the following two programs is not secure?

Program 1

C

```c
int main() {
    int i; int length = 10;
    char ca[11] = "patehenaff";
    char cb[11] = "pasta";

    for (i = 0; i < length; i++){
        if (ca[i] != cb[i]) {
            return 0; // false
        }
    }
    return 1; // true
}
```

Program 2

C

```c
int main() {
    int i;  int length = 10;
    char ca[11] = "patehenaff";
    char cb[11] = "pasta";

    int result = 1; // true

    for (i = 0; i < length; i++){
        result &= (ca[i] == cb[i]);
    }
    return result;
}
```

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int main() {
    int i; int length = 10;
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Unsecure

Program 2

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Secure

Which of the following two programs is not secure?

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            return 0; // false
        }
    }
    return 1; // true
}
```

Unsecure - ET sensitive

- 758 for the secret password
- {362, 404, 446, 488, 530, 572, 614, 656, 698, 740} for any other password

Program 2

```c
int main() {
    int i;  int length = 10;
    char ca[11] = "patehenaff";
    char cb[11] = "pasta";

    int result = 1; // true

    for (i = 0; i < length; i++){
        result &= (ca[i] == cb[i]);
    }
    return result;
}
```

Secure - Constant ET: 876

Is this third program secure?

Program 3

```c
int main () {
  int i ;
  int length = 10; // length of the strings
  char ca[11] = " patehenaff " ;
  char cb[11] = " pasta " ;

  int result = 1; // true
  for (i=0; i<length ; i++) {
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      result &= 1;
    } else {
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  }
  return result ;
}
```

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    } else {
      result &= 0;
    }
  }
  return result ;
}
```

- It seems so: very close to the former secure program
- But it is not due to the **instruction cache**
  - 876 for the secret password
  - {816, 822, 828, 834, 840, 846, 852, 858, 864, 870} for any other password

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int main () {
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    }
  }
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```

- It seems so: very close to the former secure program
- But it is not due to the **instruction cache**
  - 876 for the secret password
  - {816, 822, 828, 834, 840, 846, 852, 858, 864, 870} for any other password

We can **reconfigure** the program, by **making it opaque**

- *adding 6 nop instructions at the end of one branch*
- *(see paper)*

Conclusion and perspectives

Conclusion

End-to-end approach on **binary code timing analysis**, subject to micro-architectural constraints

- automated production of **timed formal models** of both the program and the hardware architecture
- using (parametric) time Petri nets

Illustrative case-study: **detection of timing leaks** in C programs

- via parameter synthesis techniques using **Roméo**
- (manual) **reconfiguration** of the program to make it opaque

Perspectives

- Modeling and analysis of programs on **multicore** architectures
- Automatic modification of a program to make it **opaque**

- Handling **more complex attacks**
  - Fault-injection
  - Cache side-channels
    - *flush and reload, prime and probe*
  - Energy-based attacks

- Formal proof of our translation?

27 January 2026 | APR Seminar | Paris, France

Detecting Timing Leaks of Programs

using Parametric Timed Model Checking

Dylan Marinho

Sorbonne Université, CNRS UMR 7606, LIP6

Bibliography

Bibliography

[AD94] Rajeev Alur and David L. Dill, “A Theory of Timed Automata,” *Theoretical Computer Science*, 1994.

[Cas09] Franck Cassez, “The Dark Side of Timed Opacity,” in *ISA*, 2009.

[And+22] Étienne André, Didier Lime, Dylan Marinho, and Jun Sun, “Guaranteeing Timed Opacity using Parametric Timed Model Checking,” *TOSEM*, 2022.

[And+25] Étienne André *et al.*, “Verifying Timed Properties of Programs in IoT nodes using Parametric Time Petri Nets,” in *SAC 2025*, 2025.

[Lim+09] Didier Lime, Olivier H. Roux, Charlotte Seidner, and Louis-Marie Traonouez, “Romeo: A Parametric Model-Checker for Petri Nets with Stopwatches,” in *TACAS 2009*, 2009.

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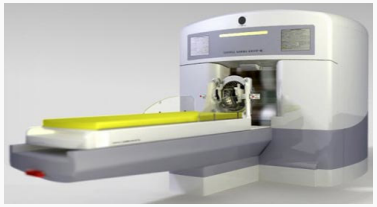
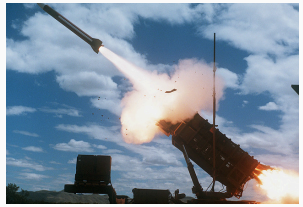
Additional information

Explanation of the pictures



- Therac-25 bug
- Computer bug, race condition
- Consequences: multiple fatalities

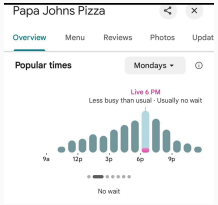


- Allusion to the MIM-104 Patriot Missile Failure (Iraq, 1991)
- 28 fatalities, hundreds of injured
- Computer bug: software error (clock drift)
- (Picture of an actual MIM-104 Patriot Missile, though not the one of 1991)

- Allusion to the sinking of the Sleipner A offshore platform (Norway, 1991)
- No fatalities
- Computer bug: inaccurate finite element analysis modeling
- (Picture actually from the Deepwater Horizon Offshore Drilling Platform)

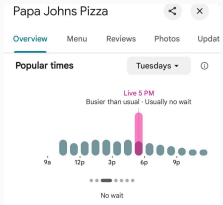
Explanation of the pictures

- Ariane flight V88 (France, 1996)
- Computer bug (notably integer overflow)
- Consequences: US$370 million



- USA, June 2025
- Empty bars during Iran's riposte against US military bases.

(Dr. Dominic Ng)

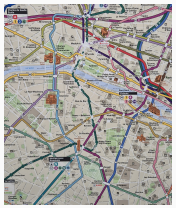


- USA, 24 June 2025
- After the Israel-Iran ceasefire

(Dr. Dominic Ng)

Explanation of the pictures

- Prefecture de Police, Paris (France, 17th July 2024 at 10:10 PM)
- Delivers in front of the Prefecture de Police, Paris
- The day before closing the center of Paris to prepare the 2024 Olympic Games



- Paris Metro map, Madeleine station (Paris, France)

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- Title : Explosion of first Ariane 5 flight, June 4, 1996
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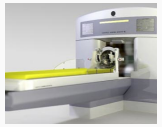

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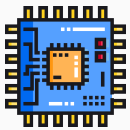

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