01 July 2025 | JAL LIP6 | Paris, France

Verifying Timed Properties of Programs

Using Parametric Time Petri Nets

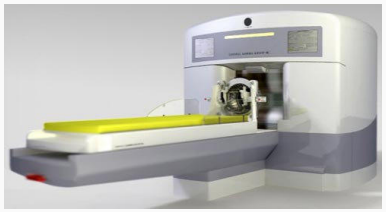
Dylan Marinho

Sorbonne Université, CNRS UMR 7606, LIP6

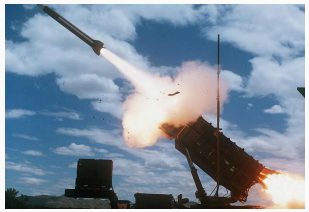
Based on joint work with Étienne André, Jean-Luc Béchennec, Sudipta Chattopadhyay, Sébastien Faucou, Didier Lime, Olivier H. Roux, Jun Sun

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)



MIM-104 Pat. Mis. Fail.
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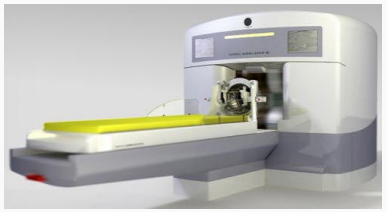

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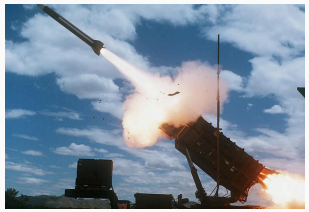

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- Verification is needed to ensure the absence of bugs

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.*

[1] home.xnet.com/~warinner/pizzacites.html (1990s)

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.*

Example

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

[1] home.xnet.com/~warinner/pizzacites.html (1990s)

Context: Side-channel attacks

Side-channel attacks

Thr
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te

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.

Exa

Nun
anno

house prior to major war

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Context: Side-channel attacks

Side-channe

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Exa

Nun

anno

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

Wha

spike

On April 13

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Exa

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anno

Wha

spike

On April 1

that

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But also in Paris (2024) !

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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]){
        return false
    }
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```

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

🕐 Execution time (ET):

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

🕓 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

Context: The use of formal methods

Need to detect **timing-leak** vulnerabilities

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    - Abstract interpretation
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    - **Model checking**
    - Theorem proving

Context: Model checking overview

System

Specification

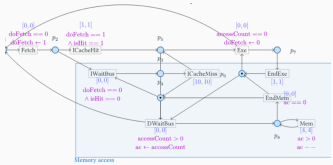
"The system must be safe"

Context: Model checking overview

System

→

Formal model



Specification

"The system must be safe"

→

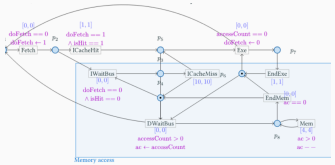
Property

$AG \neg$ ○

Context: Model checking overview

System

Formal model



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Model checking

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$\models$

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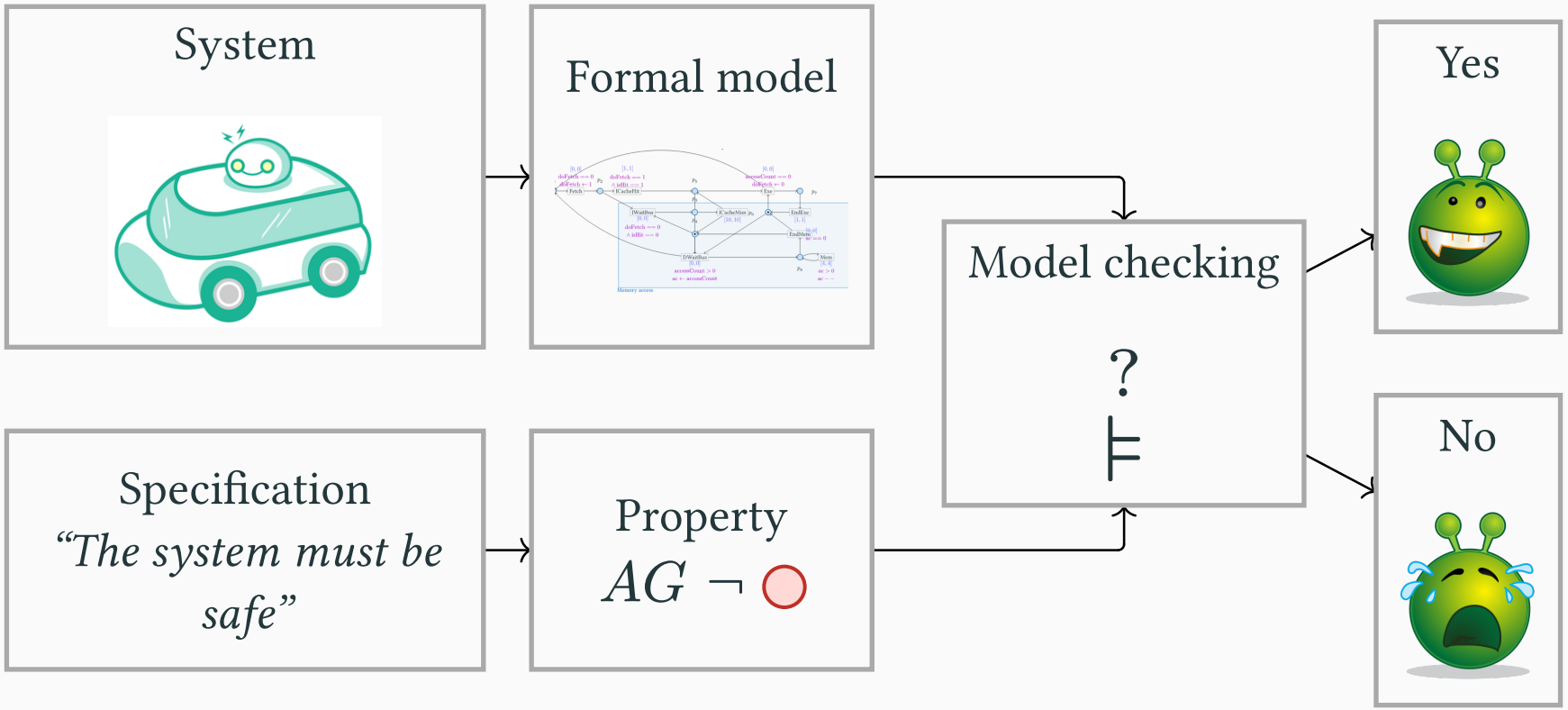


Question: does the model of the system **satisfy** the property?

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

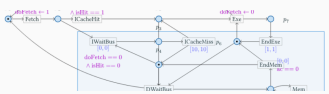
Limitations of existing techniques

- 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

System

Formal model



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"The system must be safe"

Property

$AG \neg \bigcirc$

Model checking

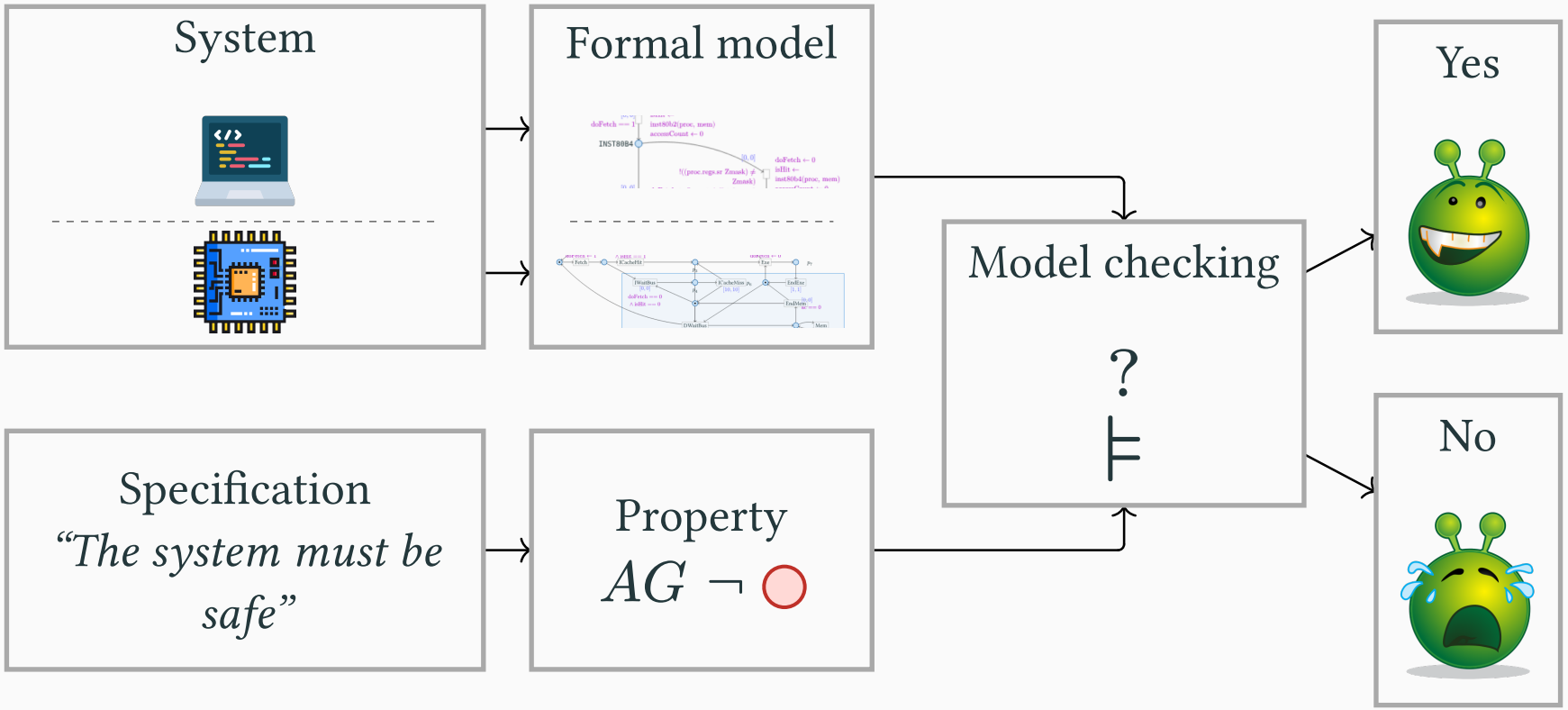
$? \models$

Yes

No

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

Model checking



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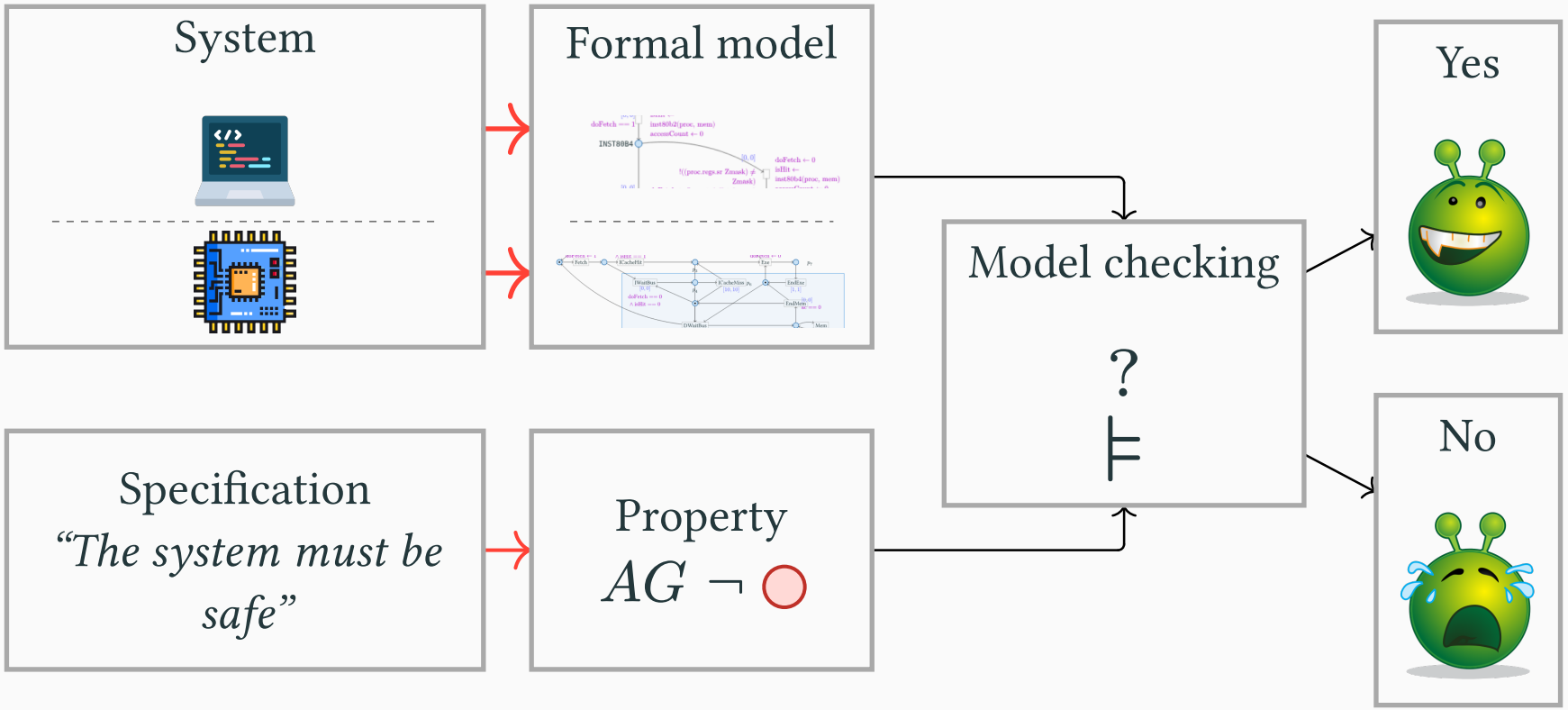

Question: does the model of the system **satisfy** the property?

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

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Methodology

Overall methodology

Inputs

Binary code

Overall methodology

Inputs

01100
10110
11110

Binary code

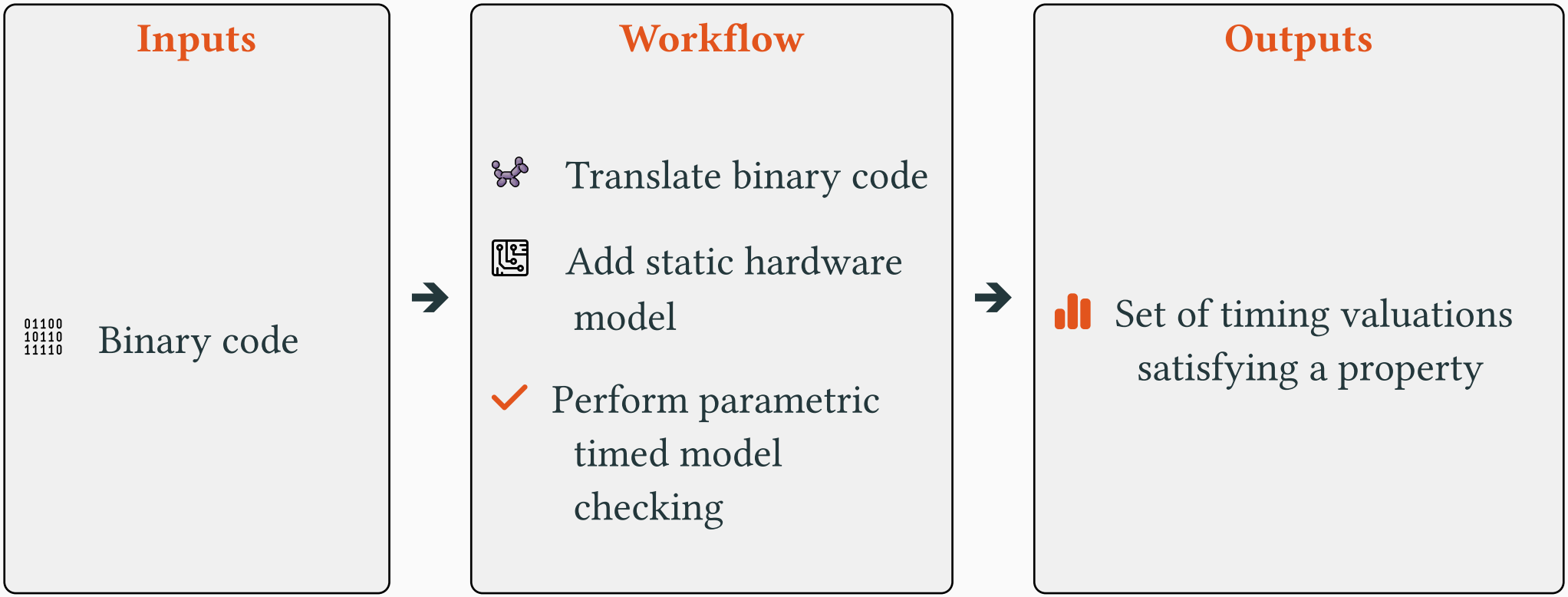
Workflow

Translate binary code

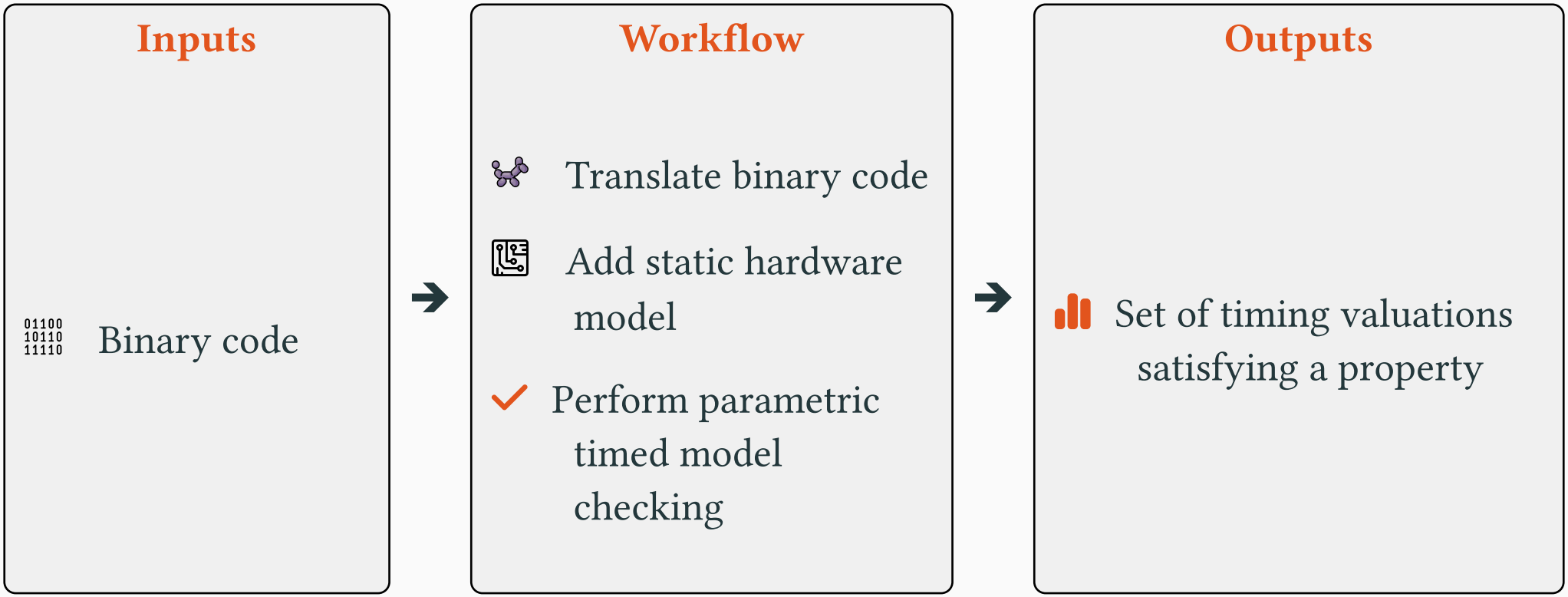
Add static hardware model

✓ Perform parametric timed model checking

Overall methodology



Overall methodology



- *e.g., possible execution times*
- *application: password leak detection*

Parametric time Petri nets with variables

Extension of **Petri nets** with

-
-
-

[TLR09]

[TLR09] Louis-Marie Traonouez, Didier Lime, and Olivier H. Roux, "Parametric Model-Checking of Stopwatch Petri Nets," *Journal of Universal Computer Science*, 2009.

Parametric time Petri nets with variables

Extension of **Petri nets** with

- firing times
- timing parameters
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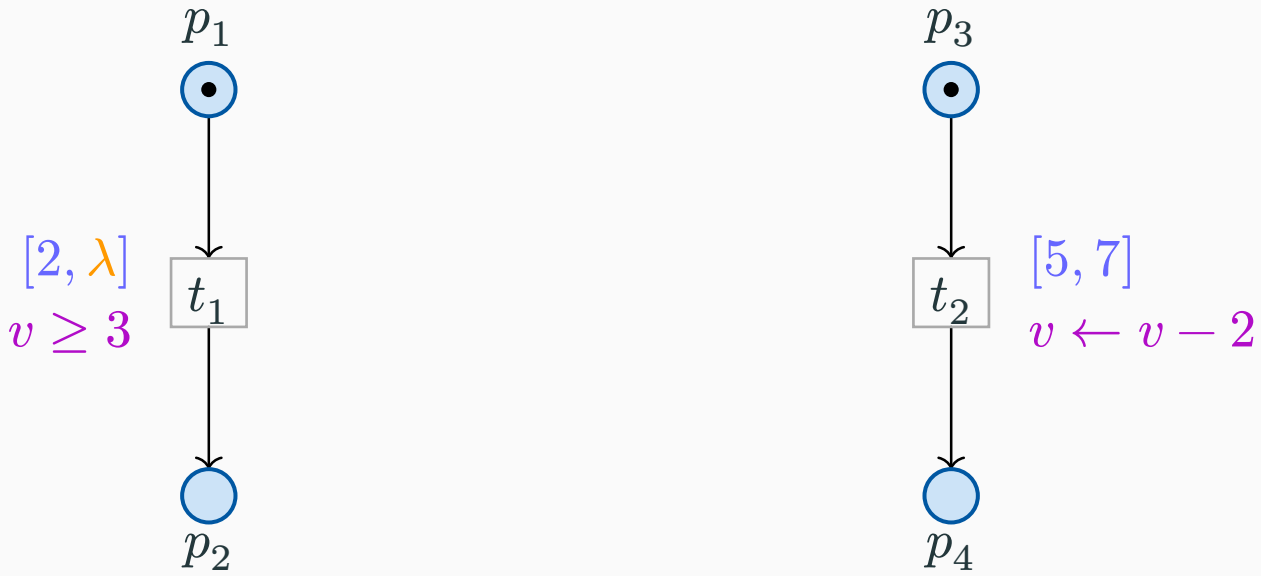
Parametric time Petri nets with variables

Extension of **Petri nets** with

- firing times
- timing parameters
- integer-valued variables (with guards and updates)

[TLR09]



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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*

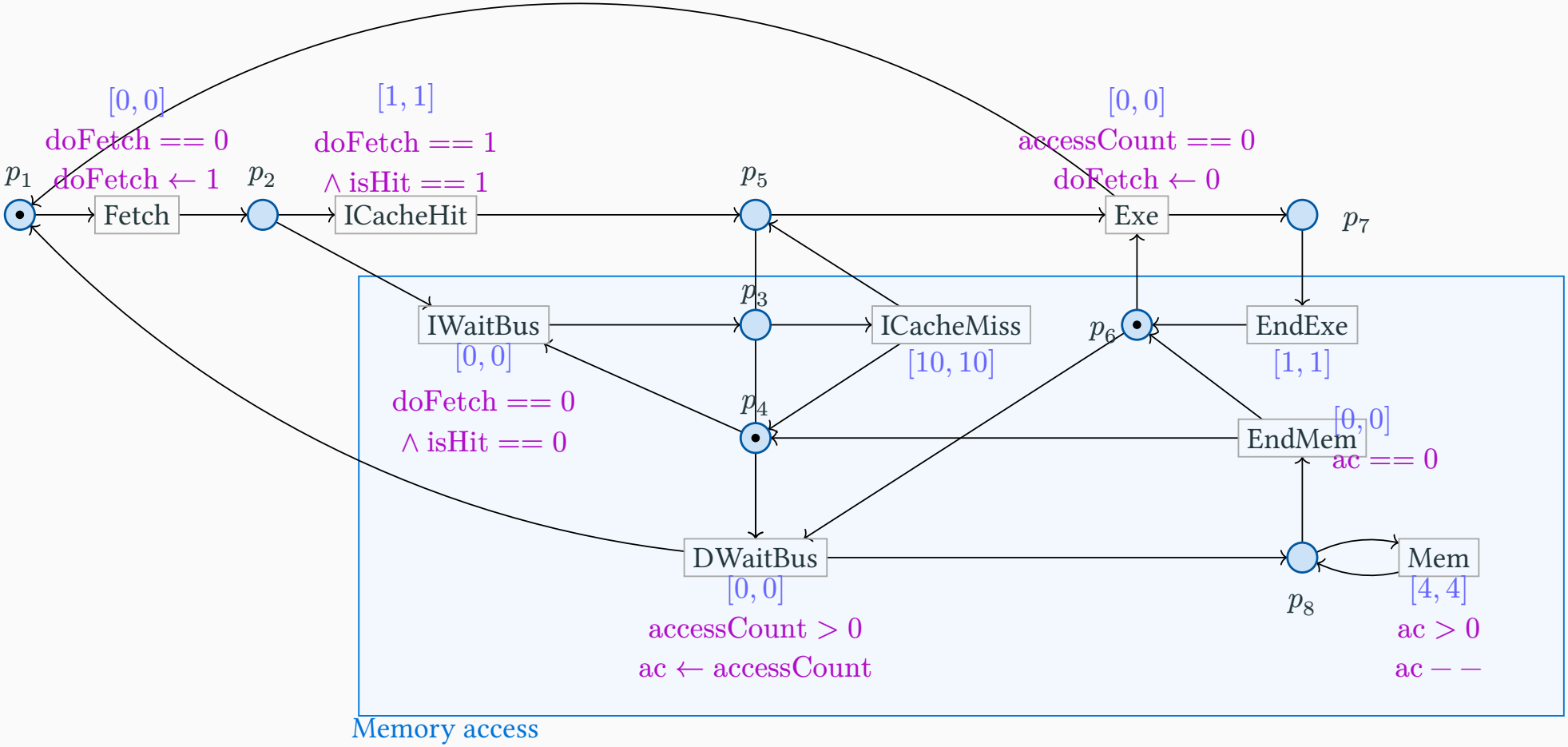
Features

- 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. . .

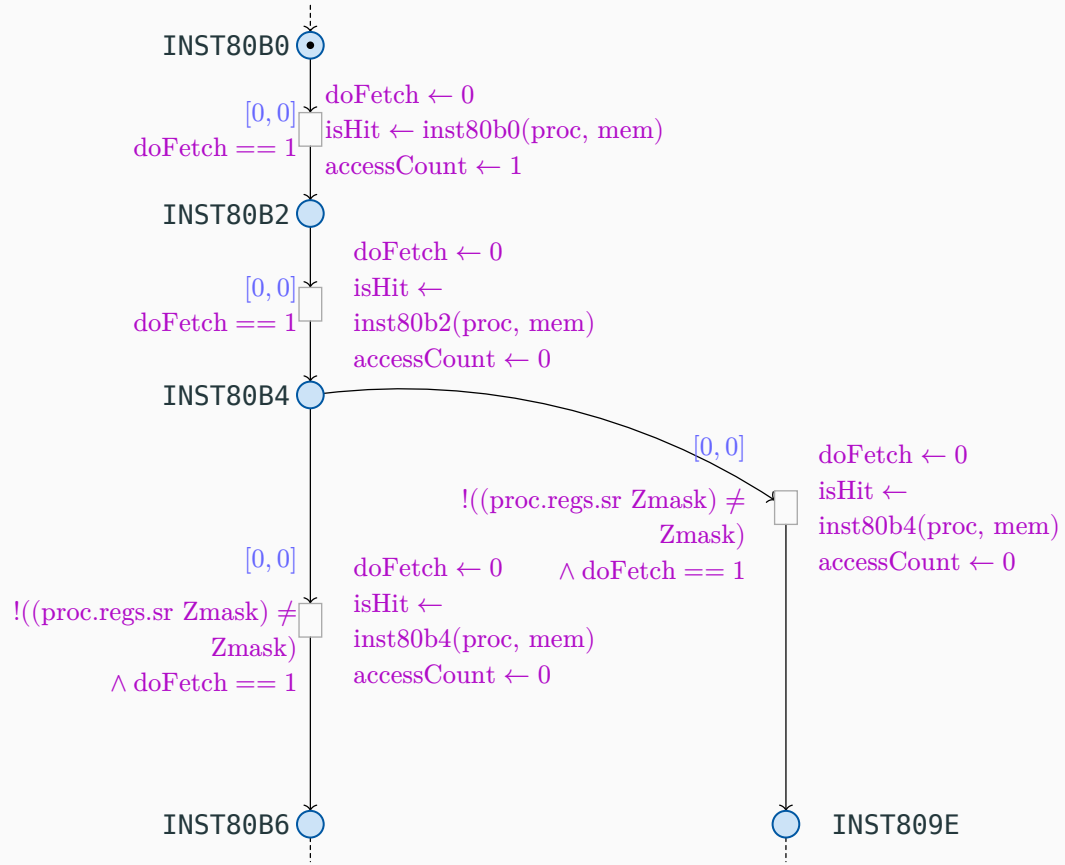
PTPN hardware model

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



PTPN software model

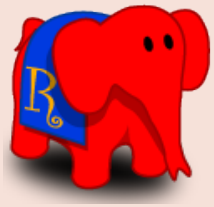
- Captures the **binary code** of the program *(ARMv6-M)*
  - Firing a transition corresponds to executing the instruction
  - Pipeline fetch: doFetch
  - Memory access: accessCount and isHit
- Structurally identical to the **control flow graph**



A fully automated translation

- 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

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[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.

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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

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Which of the following two programs is not secure?

```c
int main() {
    int i;
    int length = 10; // length of the strings
    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
}
```

```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++){
        result &= (ca[i] == cb[i]);
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Unsecure

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Unsecure - ET sensitive

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

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Secure - Constant ET: 876

Is this third program secure?

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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

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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?

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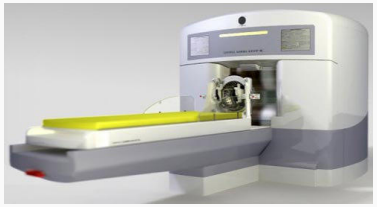
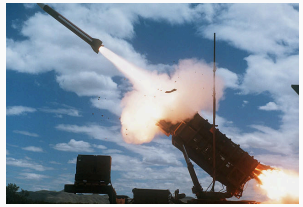
Additional information

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)

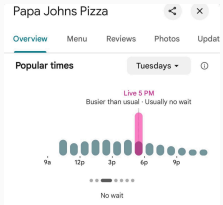
- Allusion to the sinking of the Sleipner A offshore platform (Norway, 1991)
- No fatalities
- Computer bug: inaccurate finite element analysis modeling
- (Picture actually from the Deepwater Horizon Offshore Drilling Platform)

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

Licensing

Sources of the graphics

- Title : Explosion of first Ariane 5 flight, June 4, 1996
- Author : ESA
- Source : https://www.esa.int/ESA_Multimedia/Images/2009/09/Explosion_of_first_Ariane_5_flight_
- License : ESA Standard Licence

- Title : Deepwater Horizon Offshore Drilling Platform on Fire
- Author : ideum
- Source : https://secure.flickr.com/photos/ideum/4711481781/
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- Title : DA-SC-88-01663
- Author : imcomkorea
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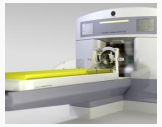
Sources of the graphics



- Title : Therac-25
- Author : ?
- Source : https://arquivonuclear.blogspot.com/2011/03/therac-25.html
- License : unknown

- Title : Autonomous robot vehicle or ADV typically used for food or grocery delivery
- Author : Rlistmedia
- Source : https://commons.wikimedia.org/wiki/File:Autonomous_delivery_robot_vehicles_ADV.png
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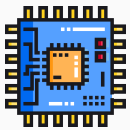

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