Université Grenoble Alpes

Modern System On Chips Security Against Physical Attacks

Phd. defense

Slides available at `https://thomas.trouchkine.com/assets/pdf/defense.pdf`

Defended by Thomas Trouchkine on March 24, 2021

Introduction - Handling sensitive operations

Sensitive operations

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Sensitive operations

Payment

Healthcare

Identification

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Historically

- handled by smartcards
- security designed devices
- high level security evaluation

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- handled by smartphones or laptops
- performance designed devices
- security added recently
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Introduction - Handling sensitive operations

Sensitive operations

Payment Healthcare Identification

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Nowadays

- handled by smartphones or laptops
- performance designed devices
- security added recently
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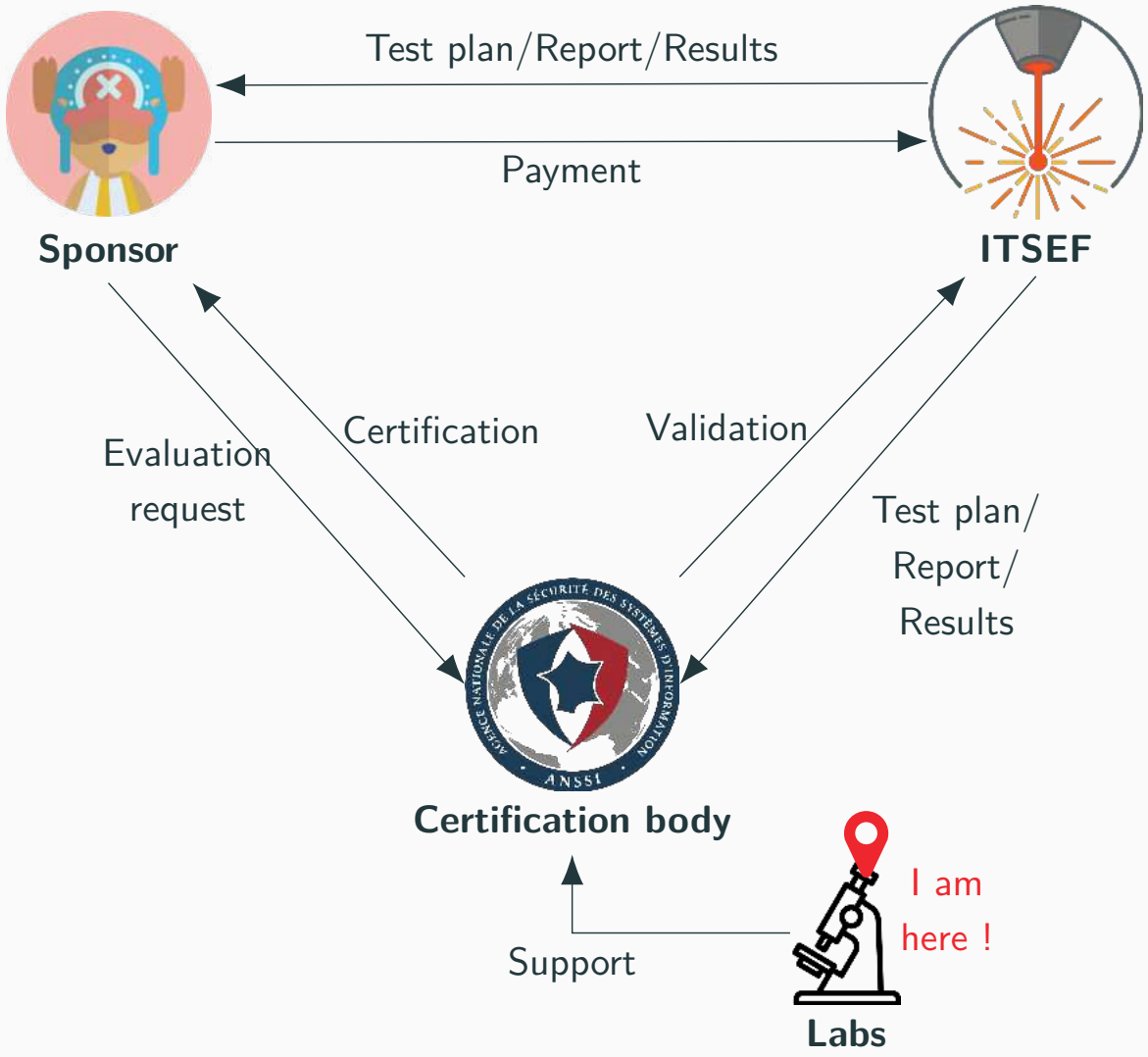
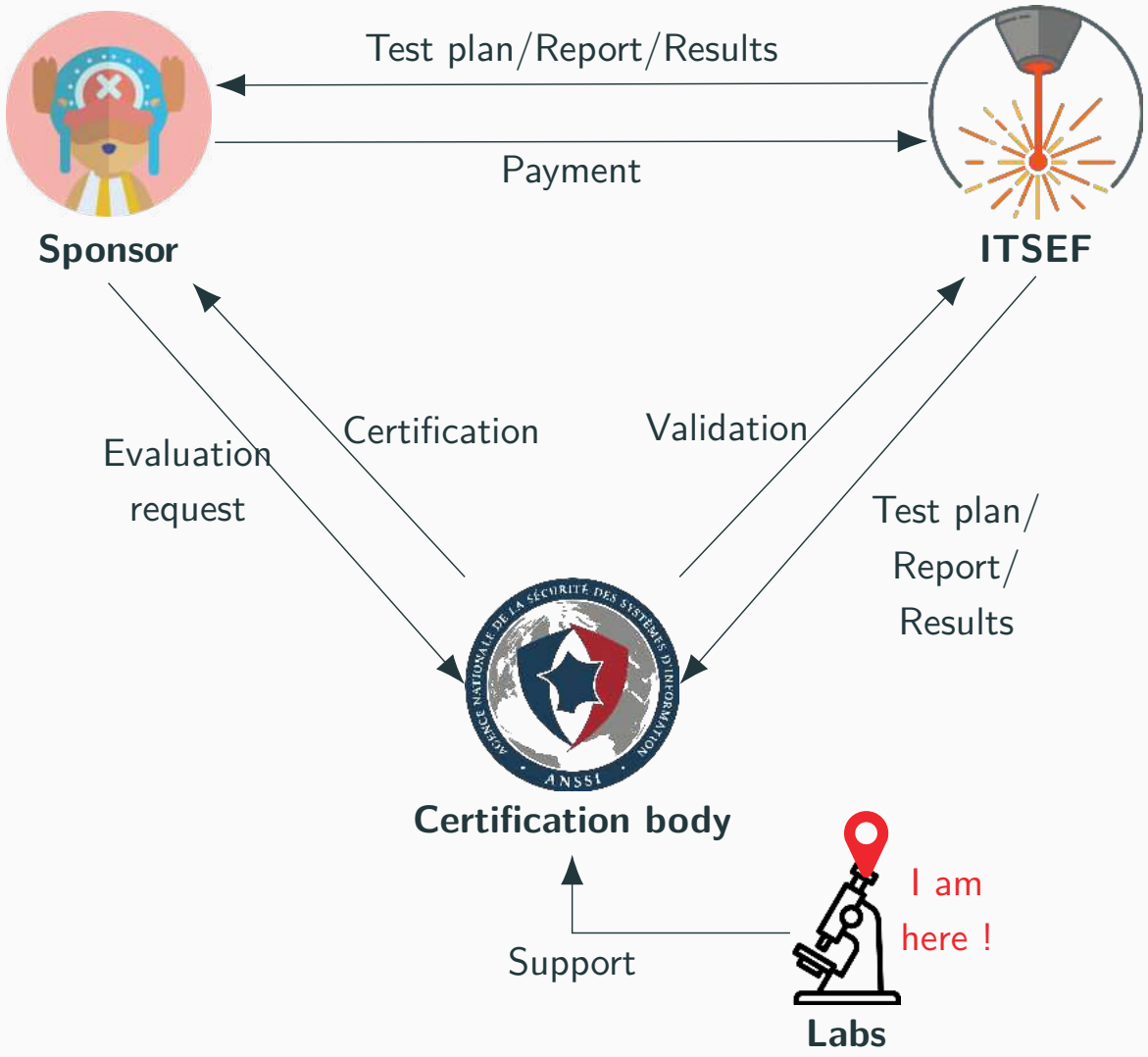
We want to evaluate smartphones' security !

Introduction - Security Evaluation



Introduction - Security Evaluation



Hardware evaluations mainly focus on **smartcards**

Introduction - SEs vs SoCs

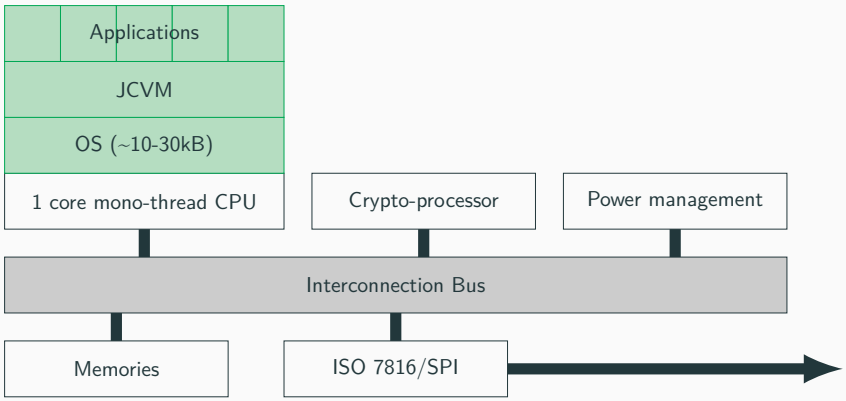
Smartcards

Smartphones

Introduction - SEs vs SoCs

Smartcards

- secure elements (SEs)

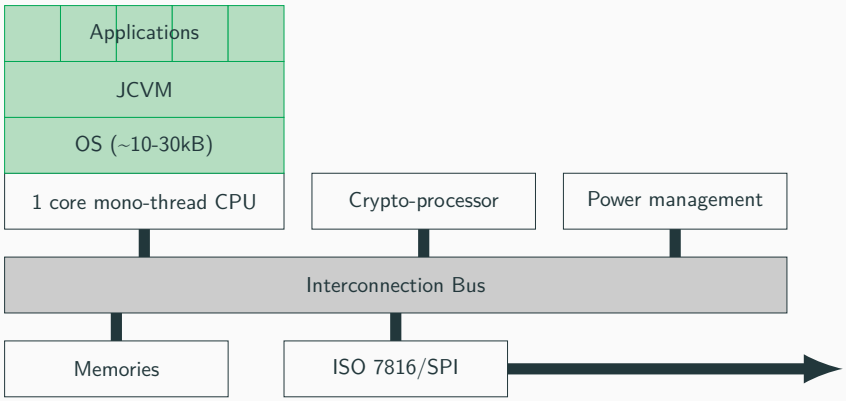


Smartphones

Introduction - SEs vs SoCs

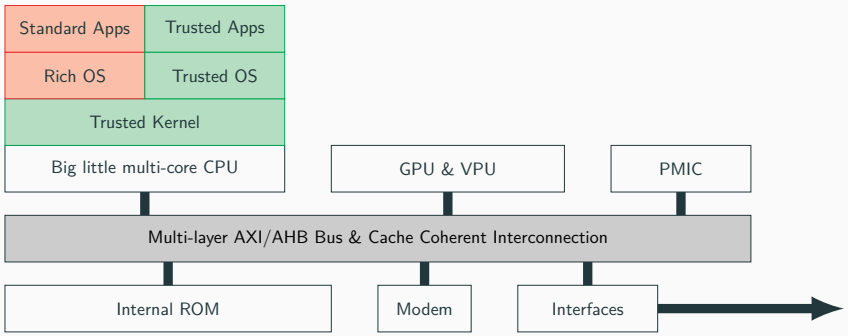
Smartcards

- secure elements (SEs)

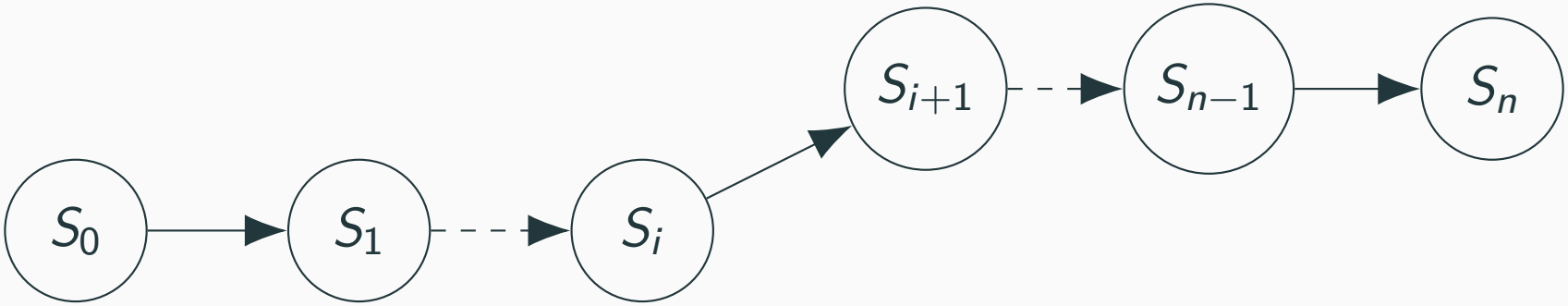


Smartphones

- complex systems on chip (SoCs)



Introduction - Perturbation attacks



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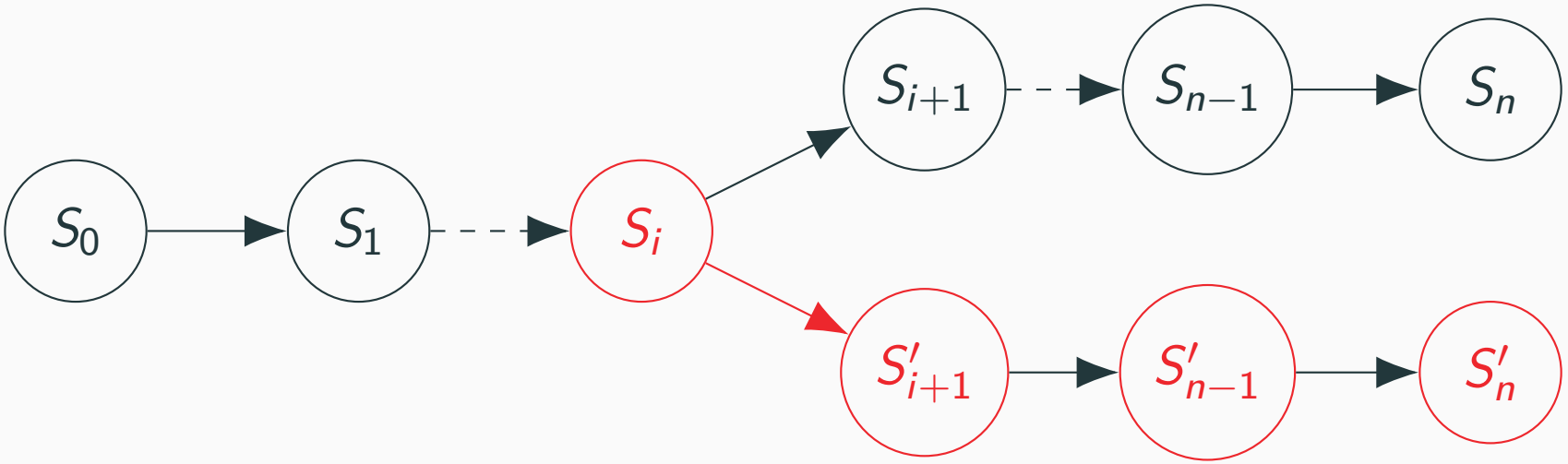


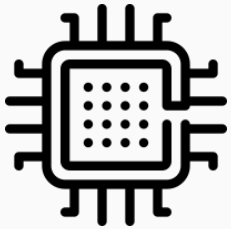
Introduction - Perturbation attacks

Electromagnetic waves

Temperature

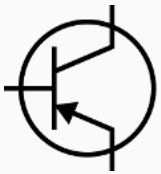
Voltage

Light



Clock

X-ray



Body biasing

Software

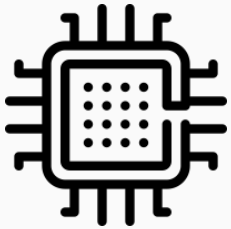
Introduction - Perturbation attacks

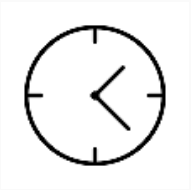
Electromagnetic waves [OGM15; DLM19]

Temperature

Voltage

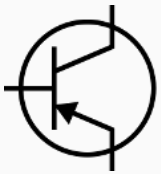
Light [Sam+02; SHP09]





Clock

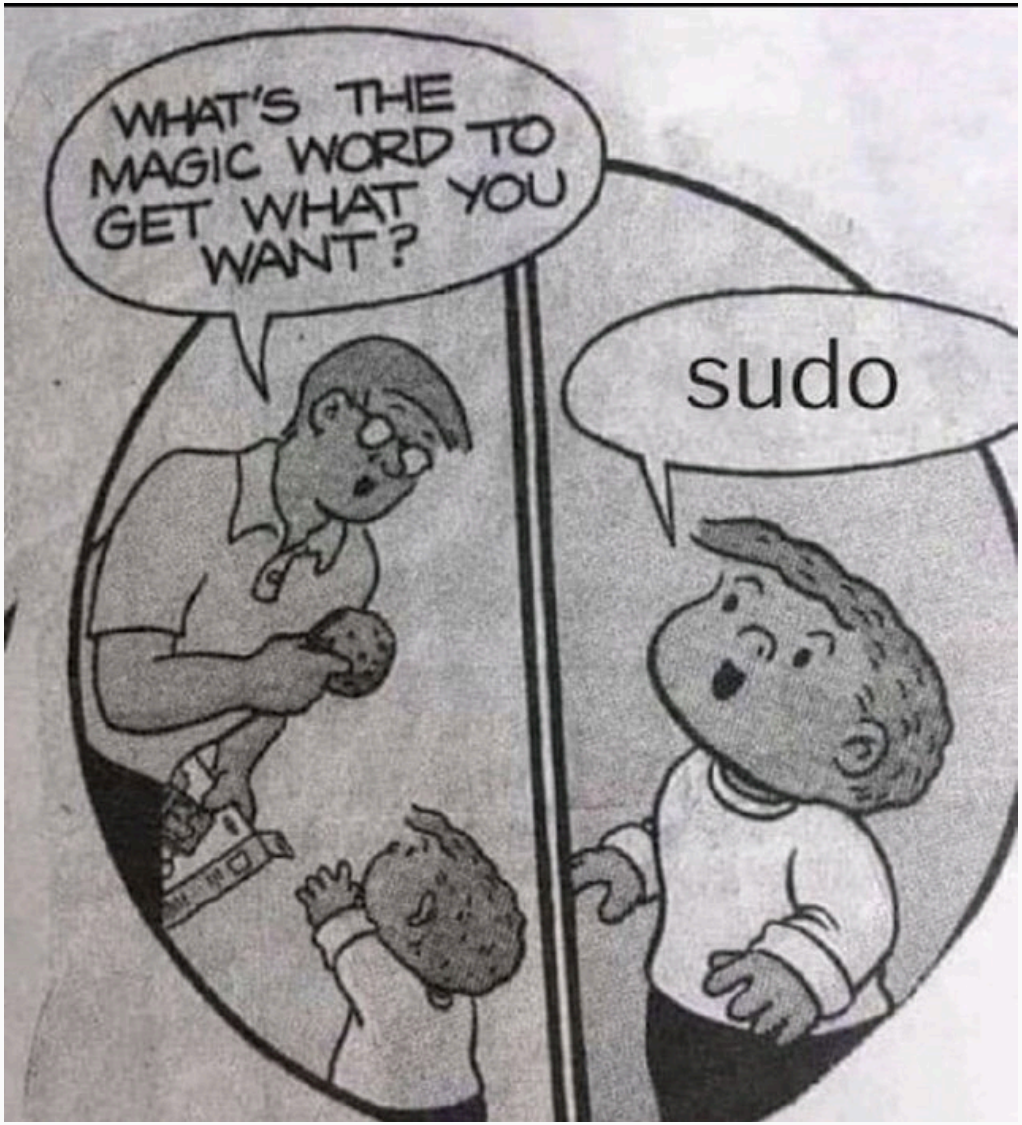
X-ray



Body biasing

Software

Case study - User authentication on Linux



Case study - User authentication on Linux

Password authentication of the `sudo` program on Debian 9

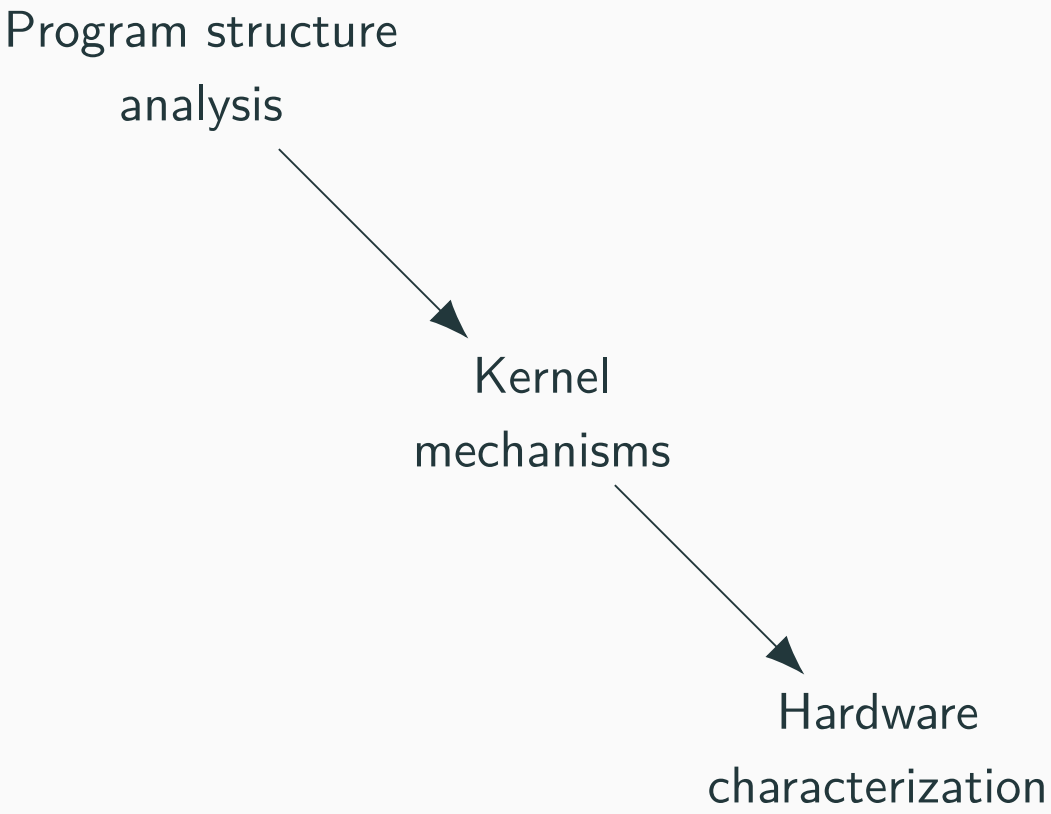
Targets

BCM2837
(Raspberry Pi 3 B)

Intel Core i3-6100T
(Custom motherboard)

BCM2711b0
(Raspberry Pi 4)

Case study - Evaluation methodology



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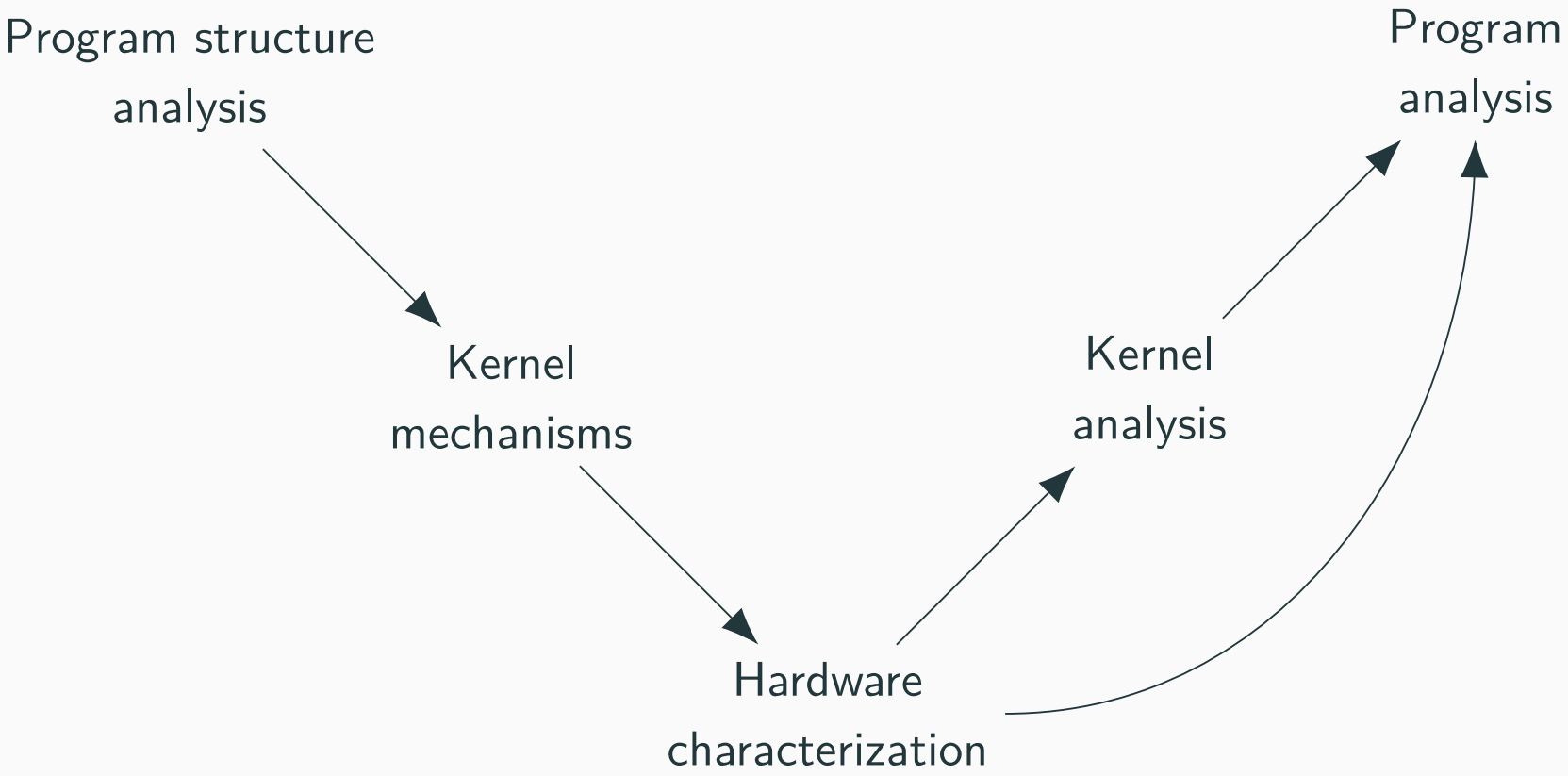
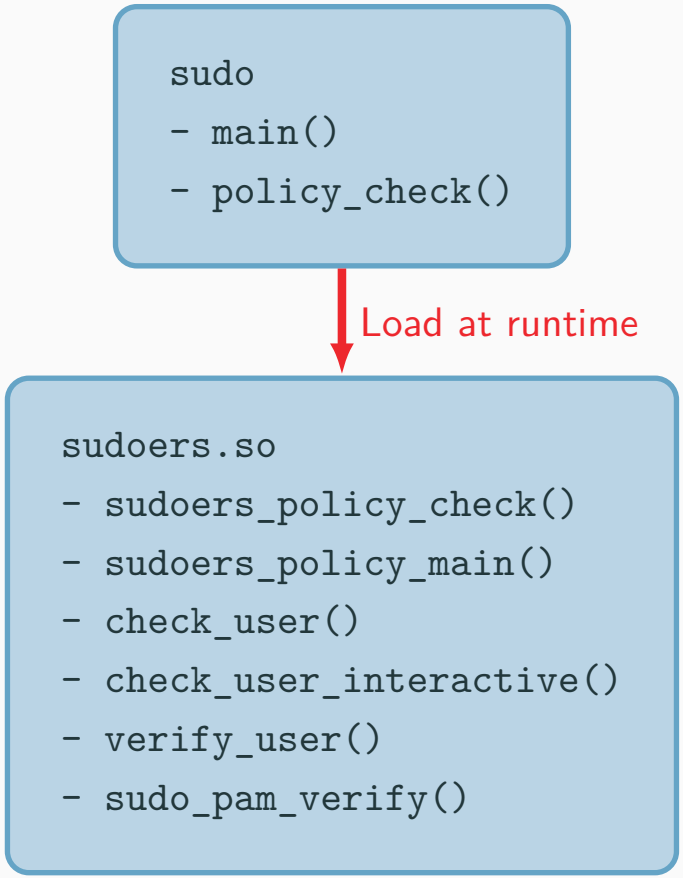


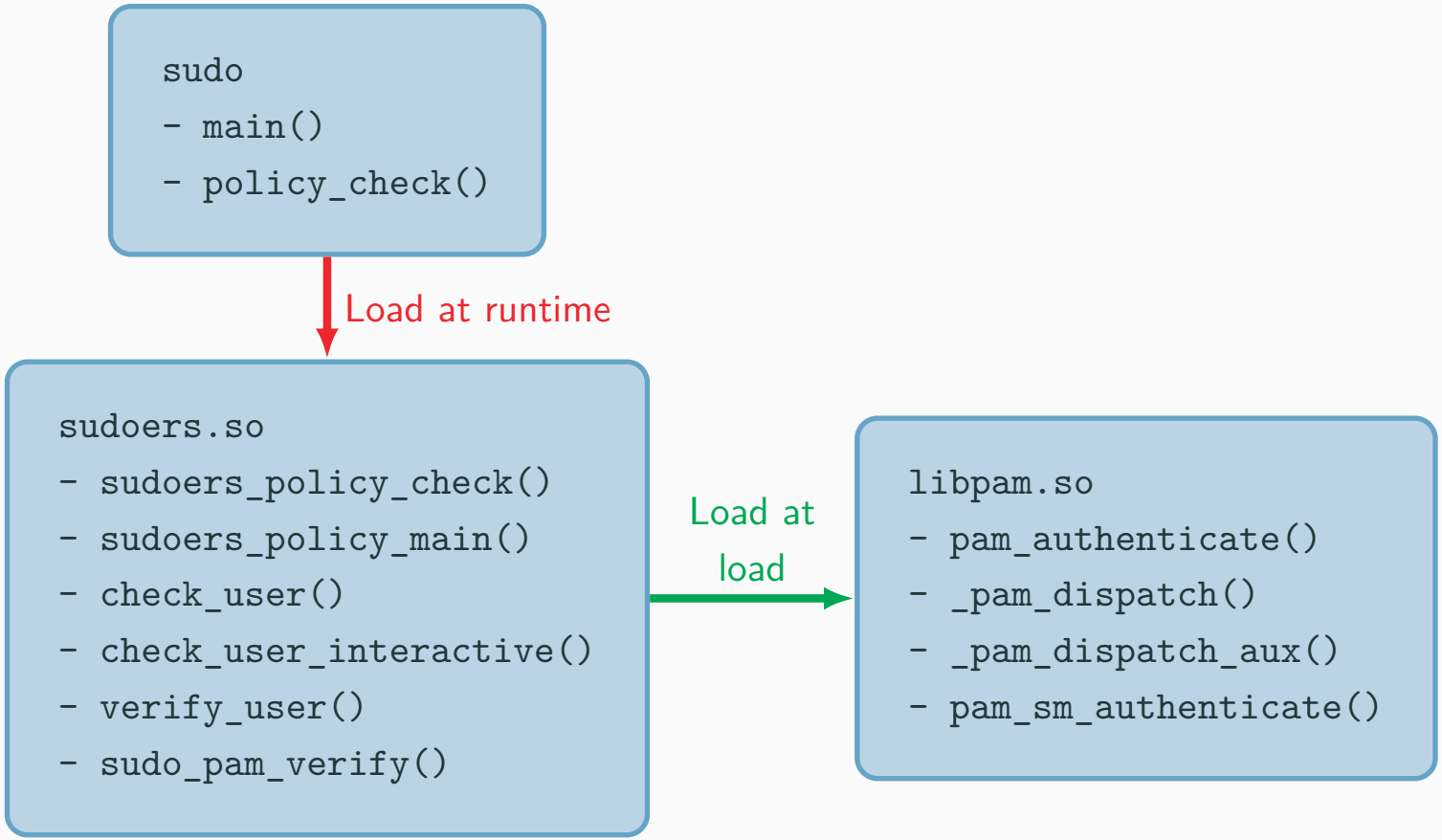
Case study - `sudo` program life

```
sudo
- main()
- policy_check()
```

Case study - sudo program life



Case study - sudo program life



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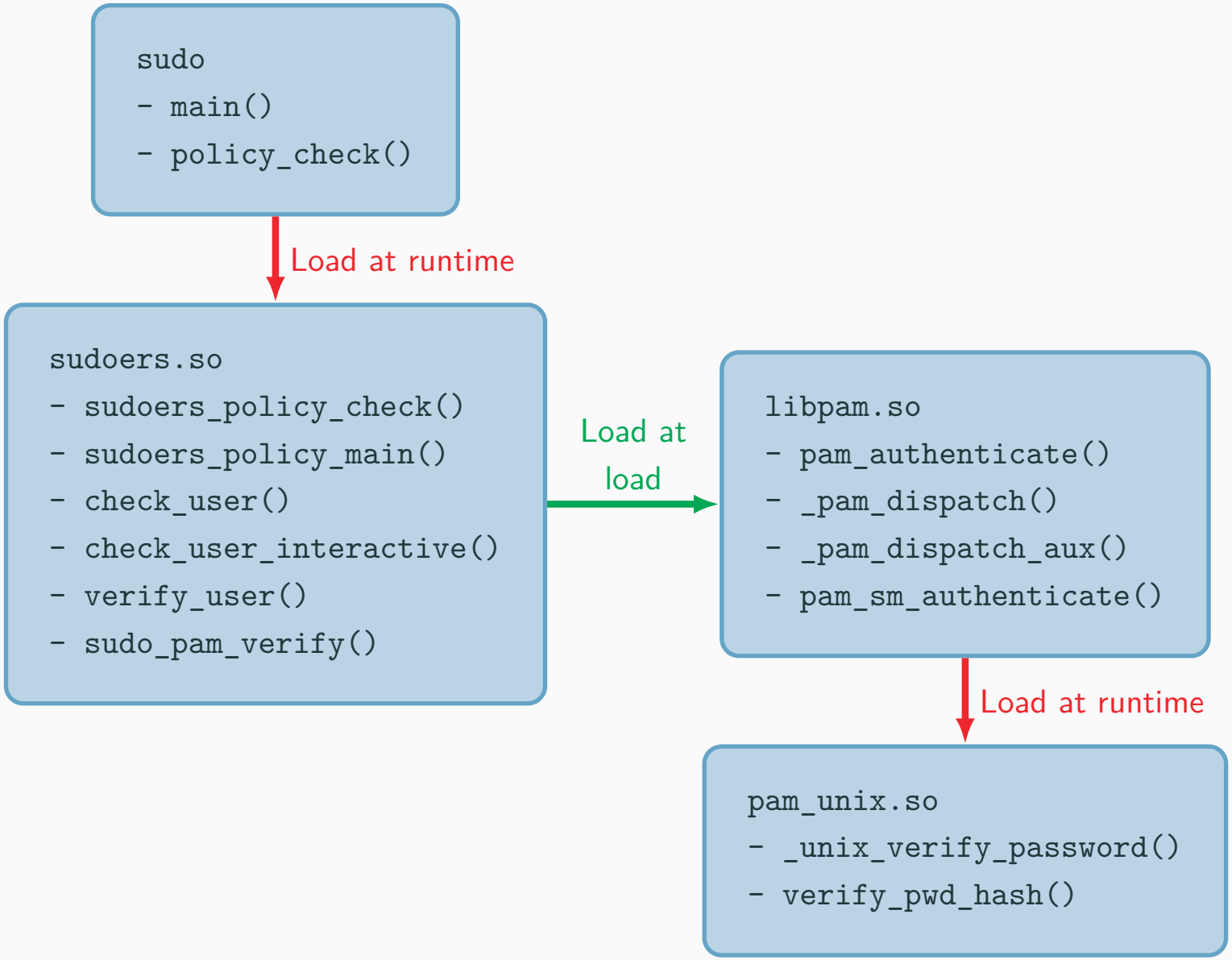
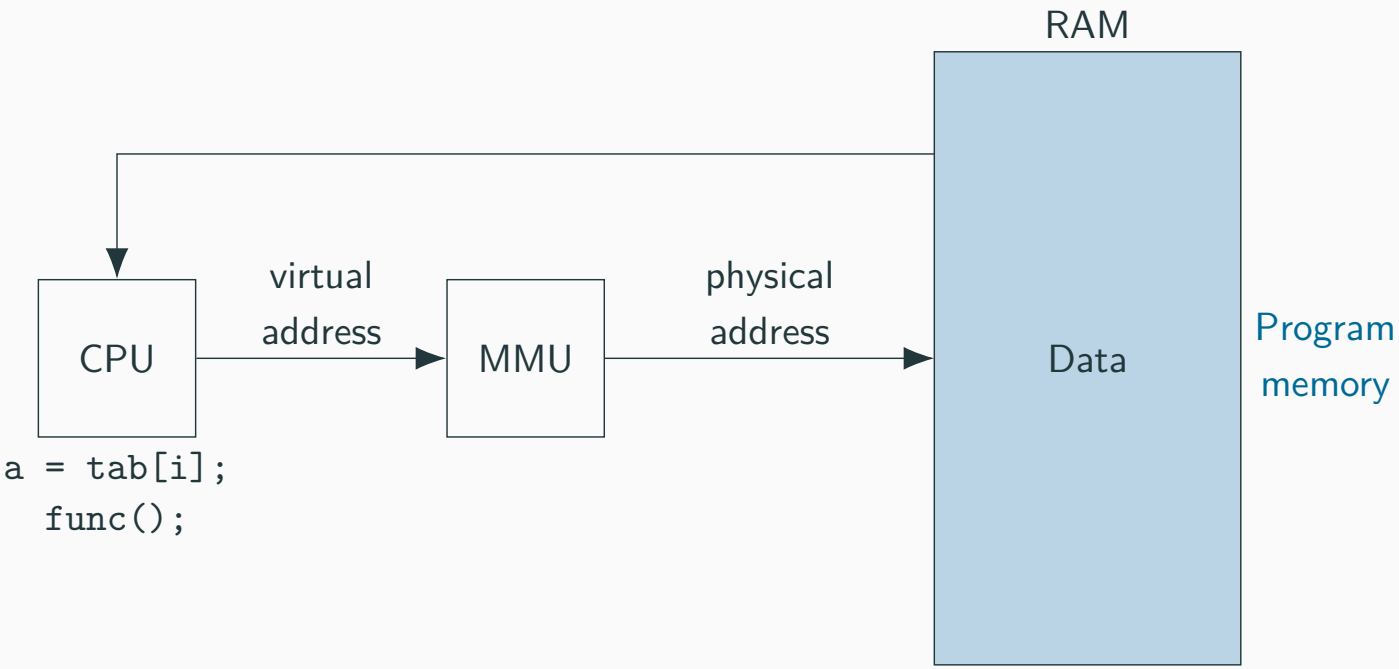


Case study - Address resolution



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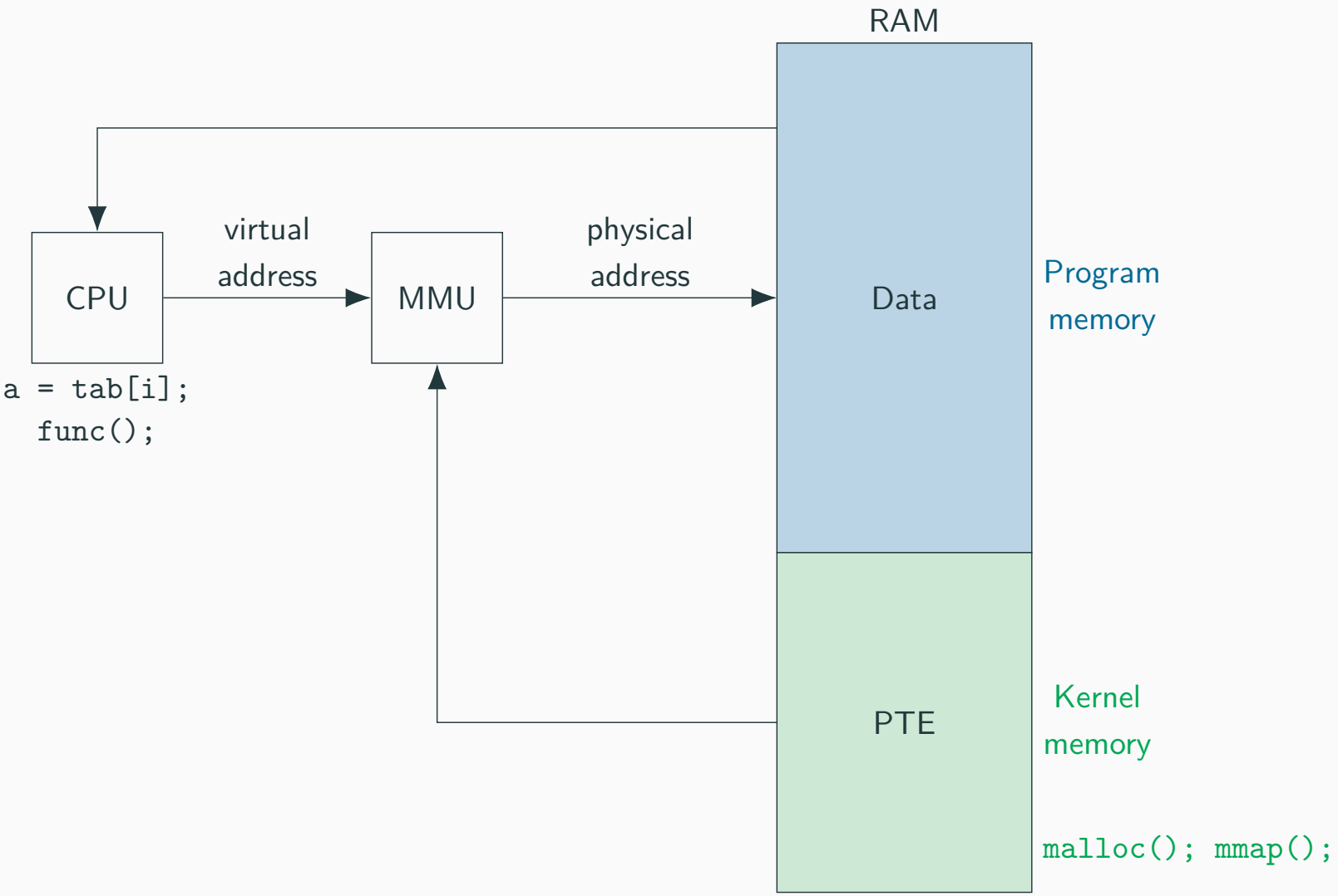

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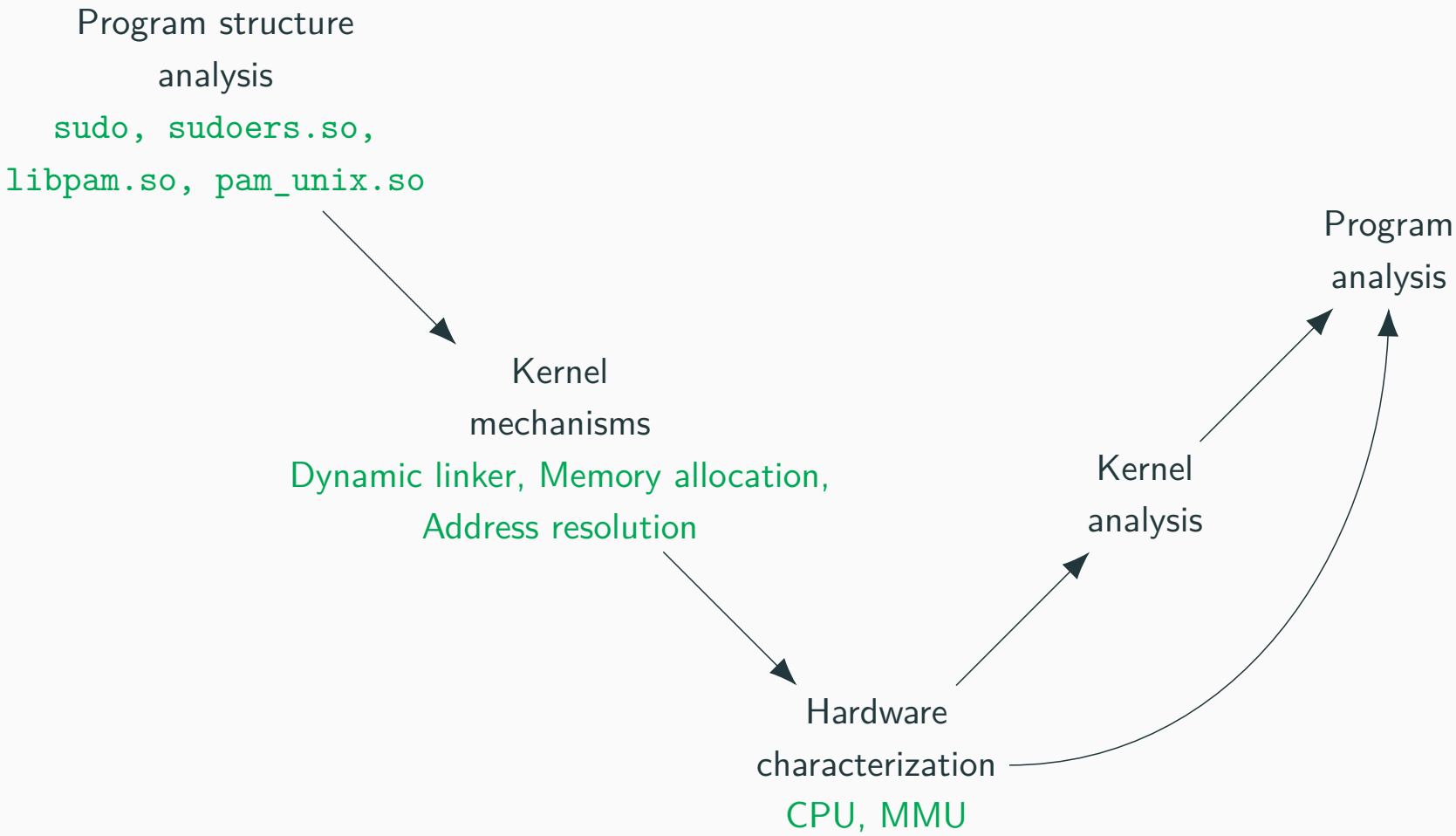
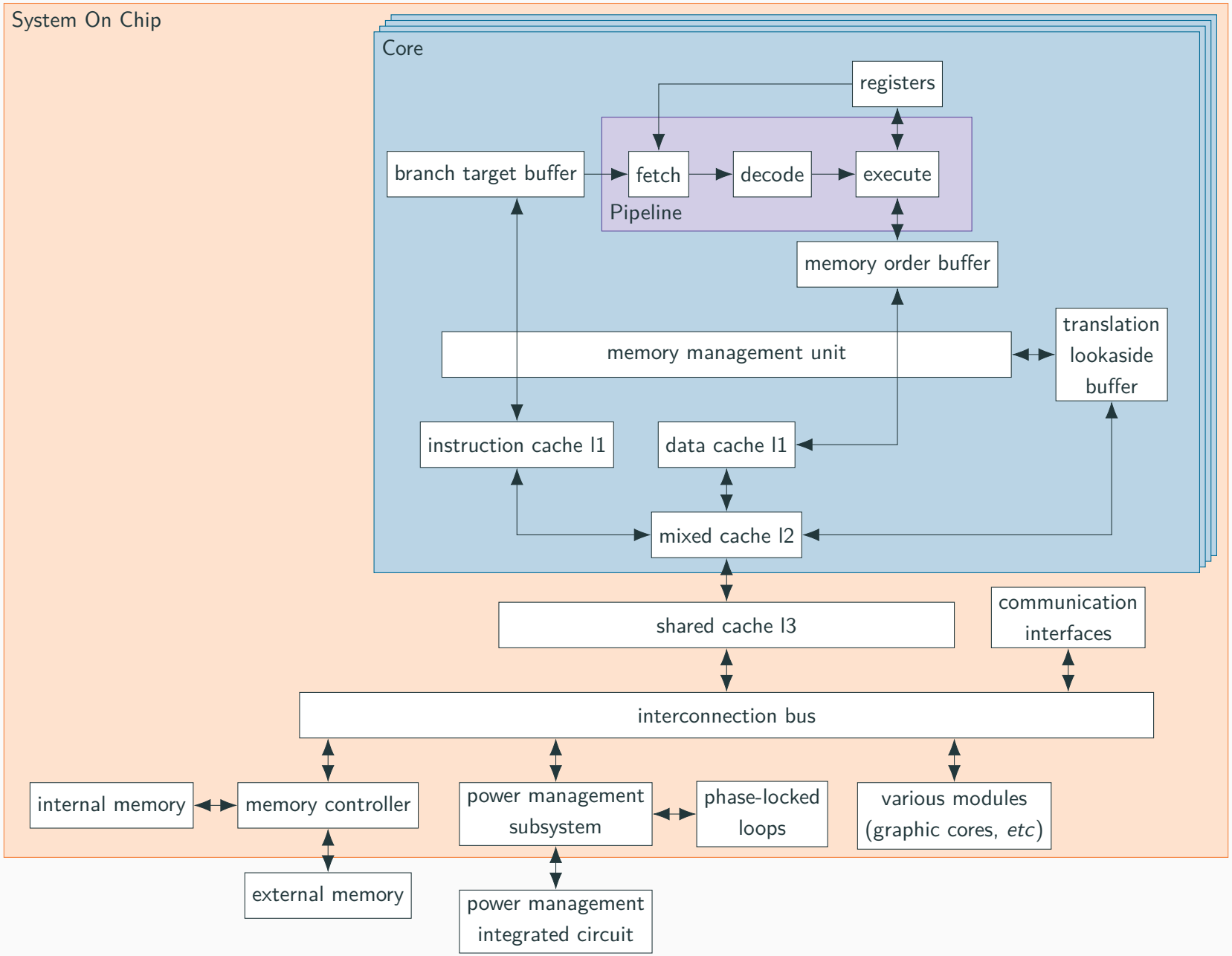


Case study - SoC architecture



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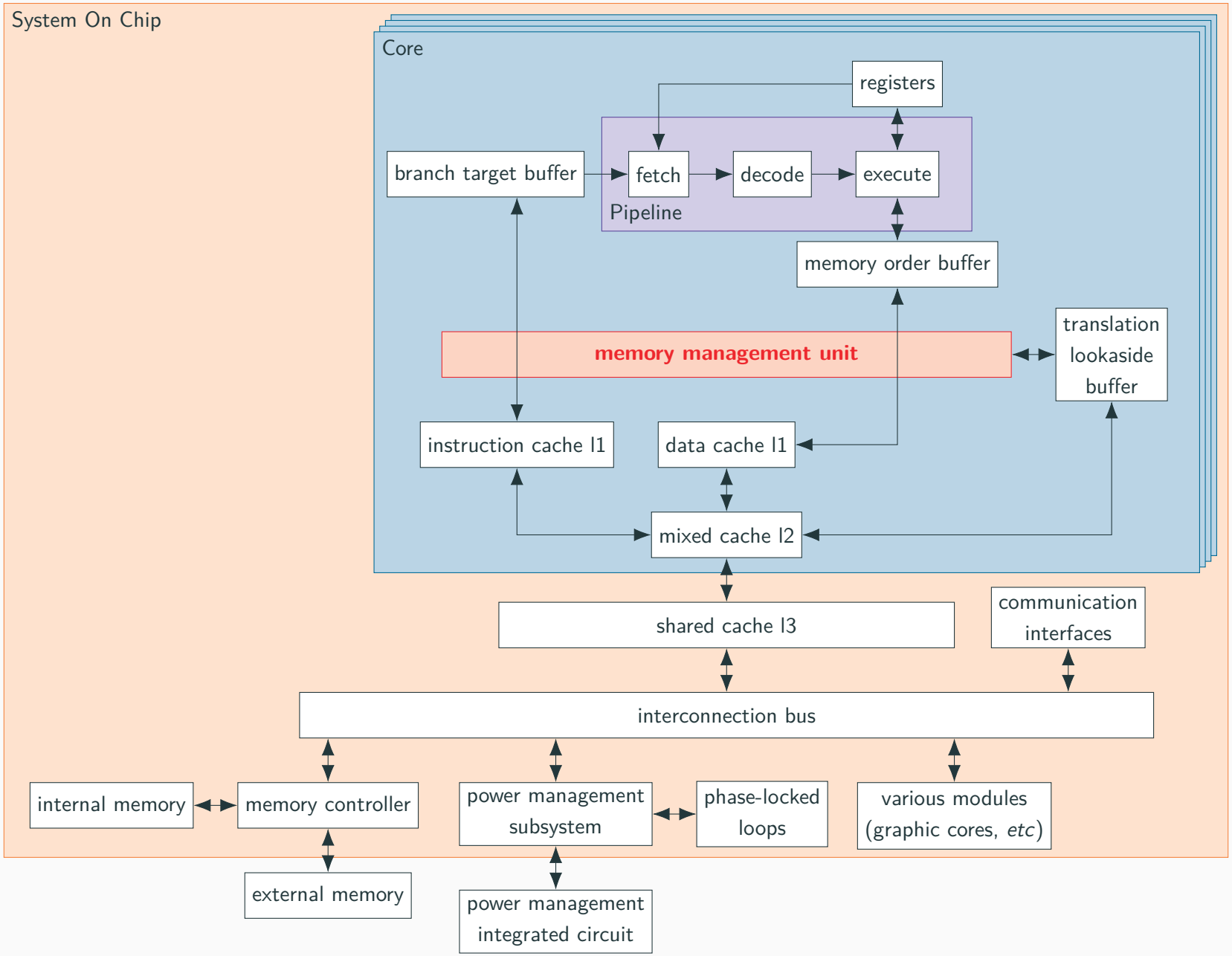

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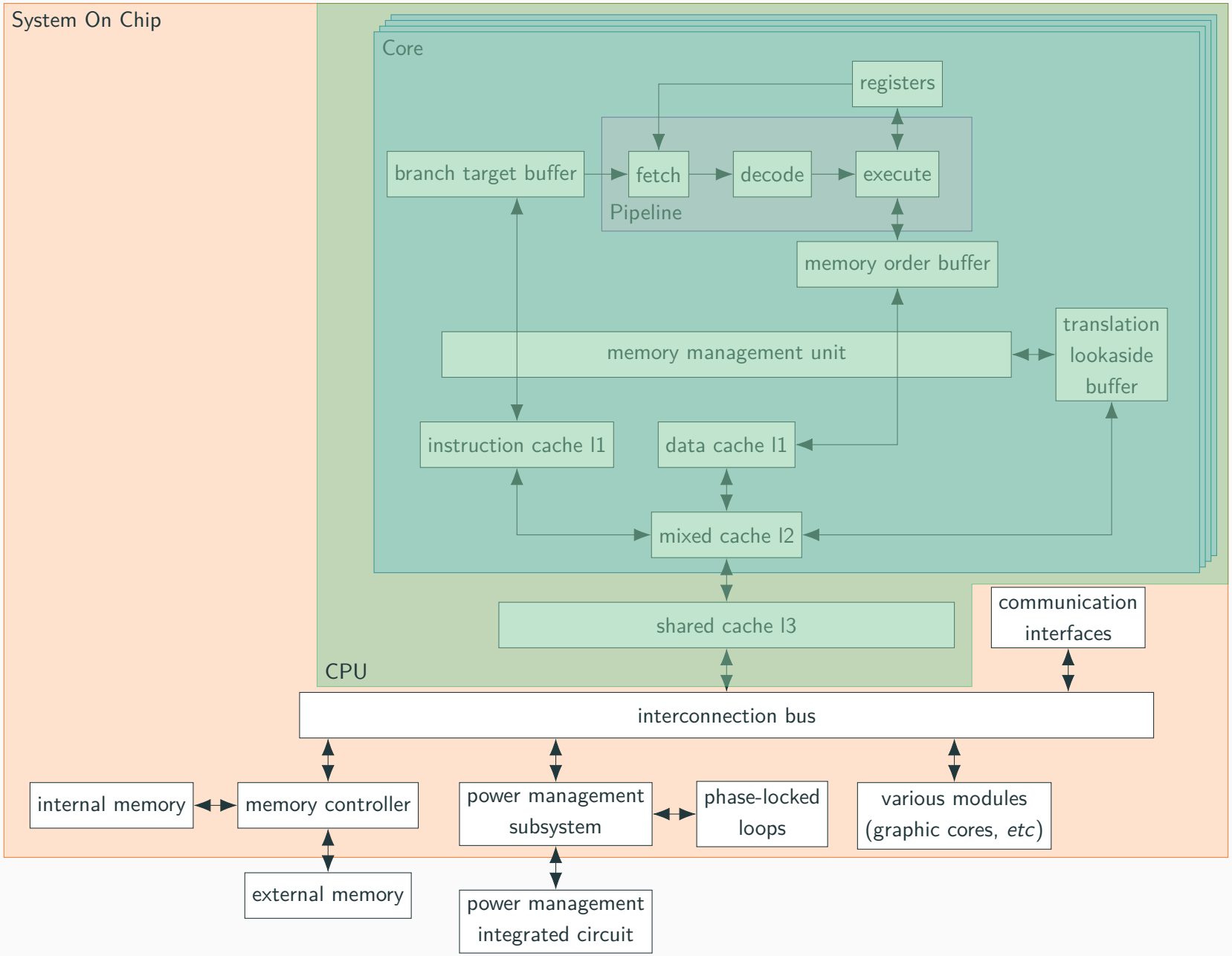
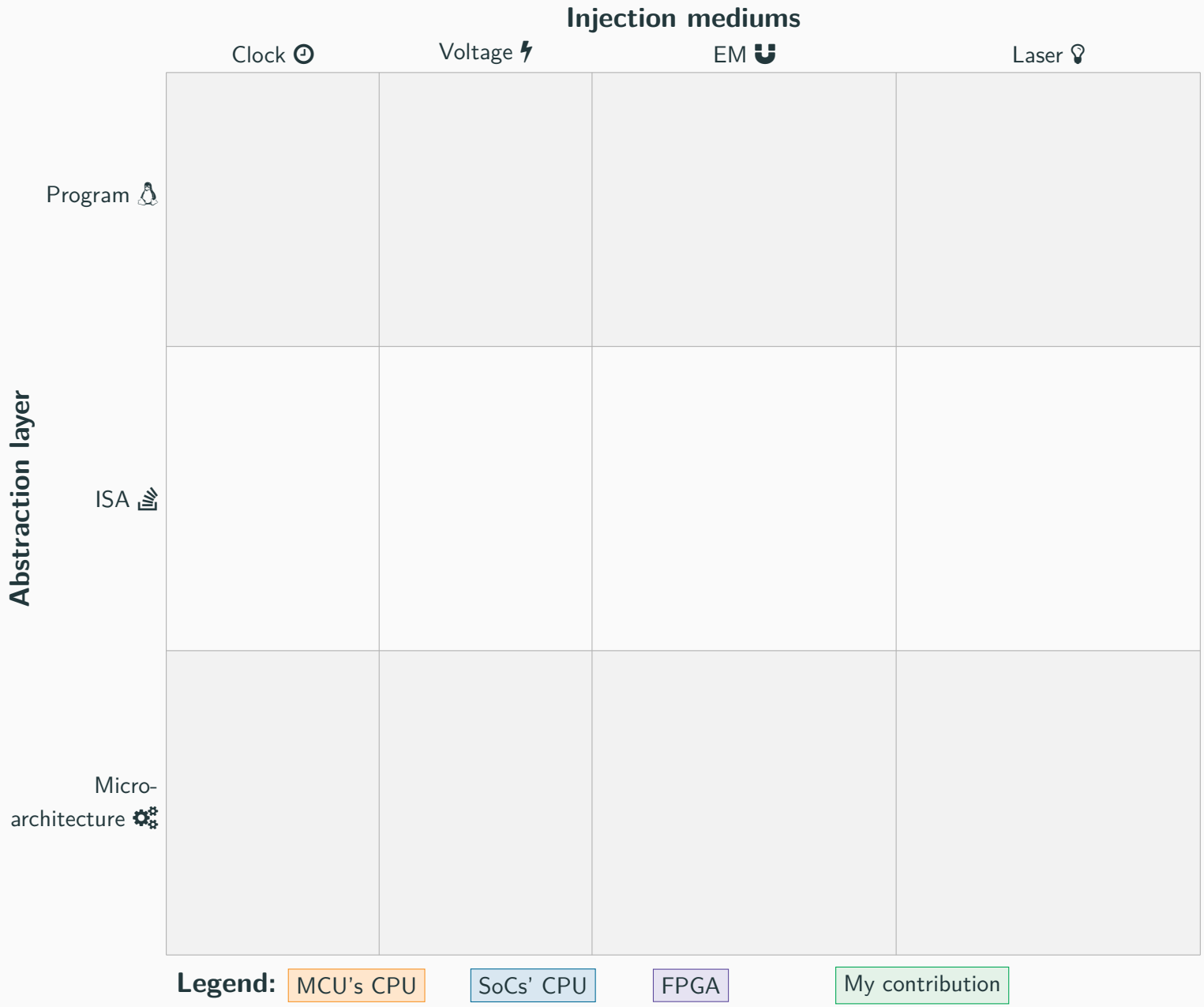


Characterization - State of the art



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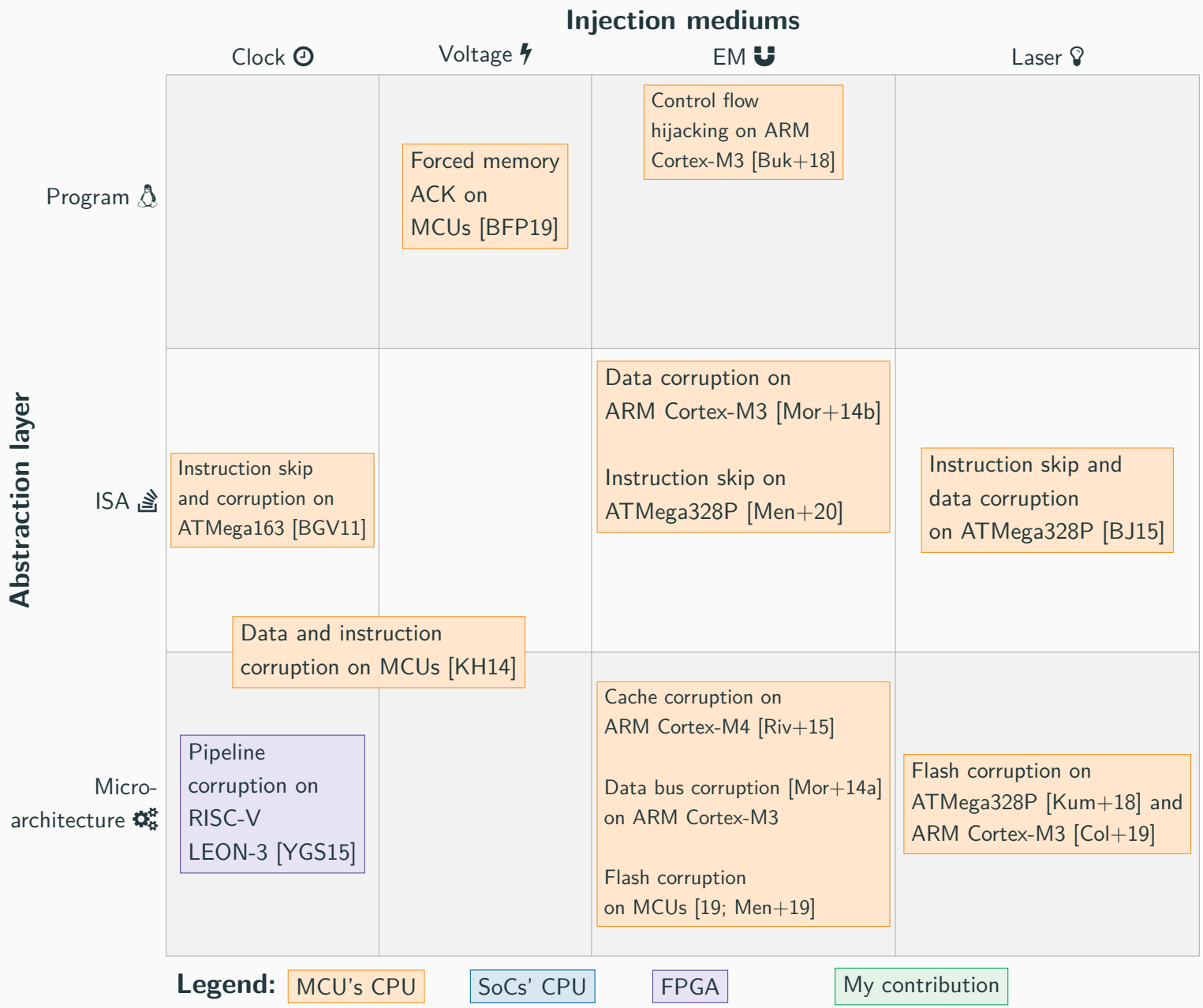

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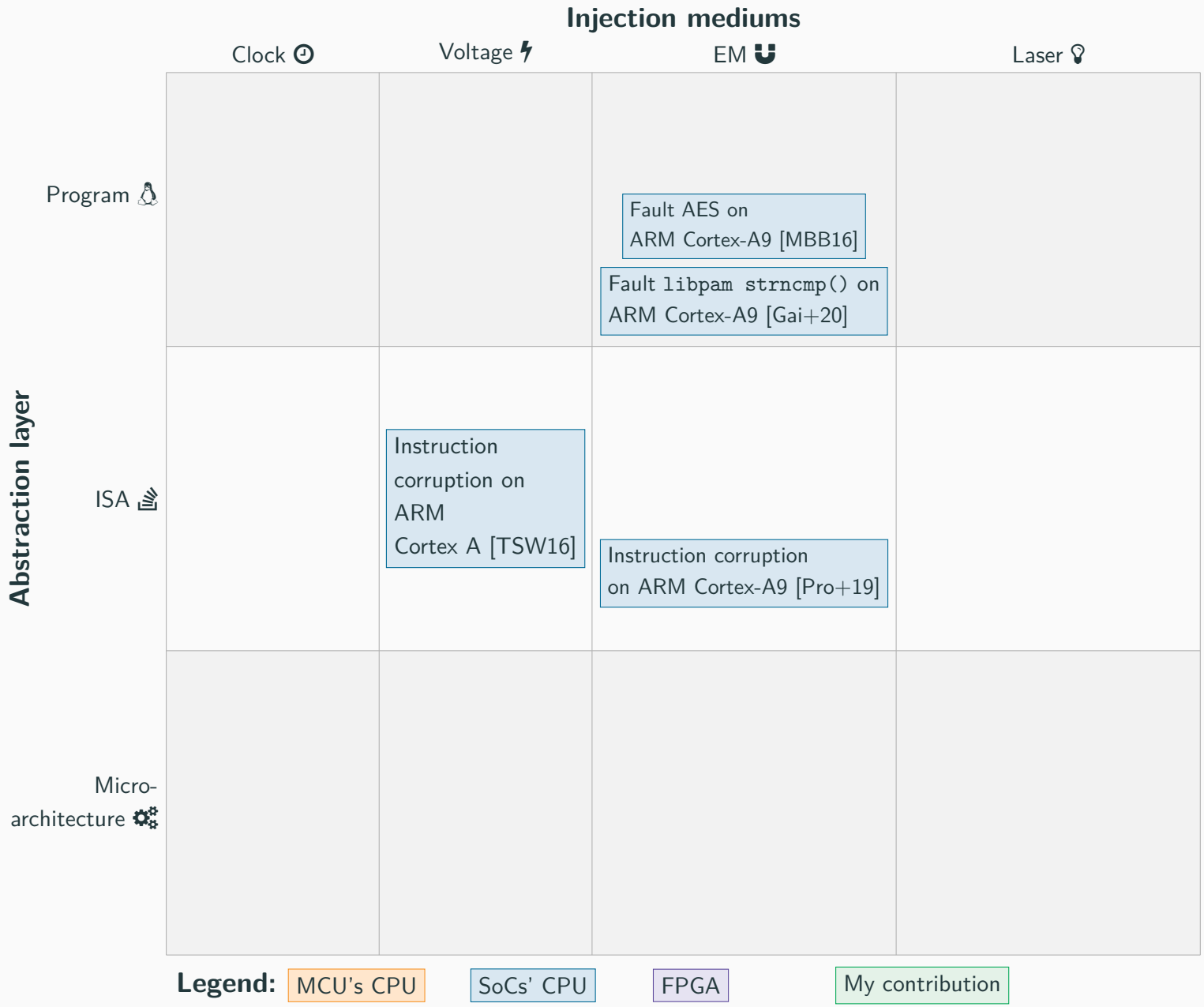

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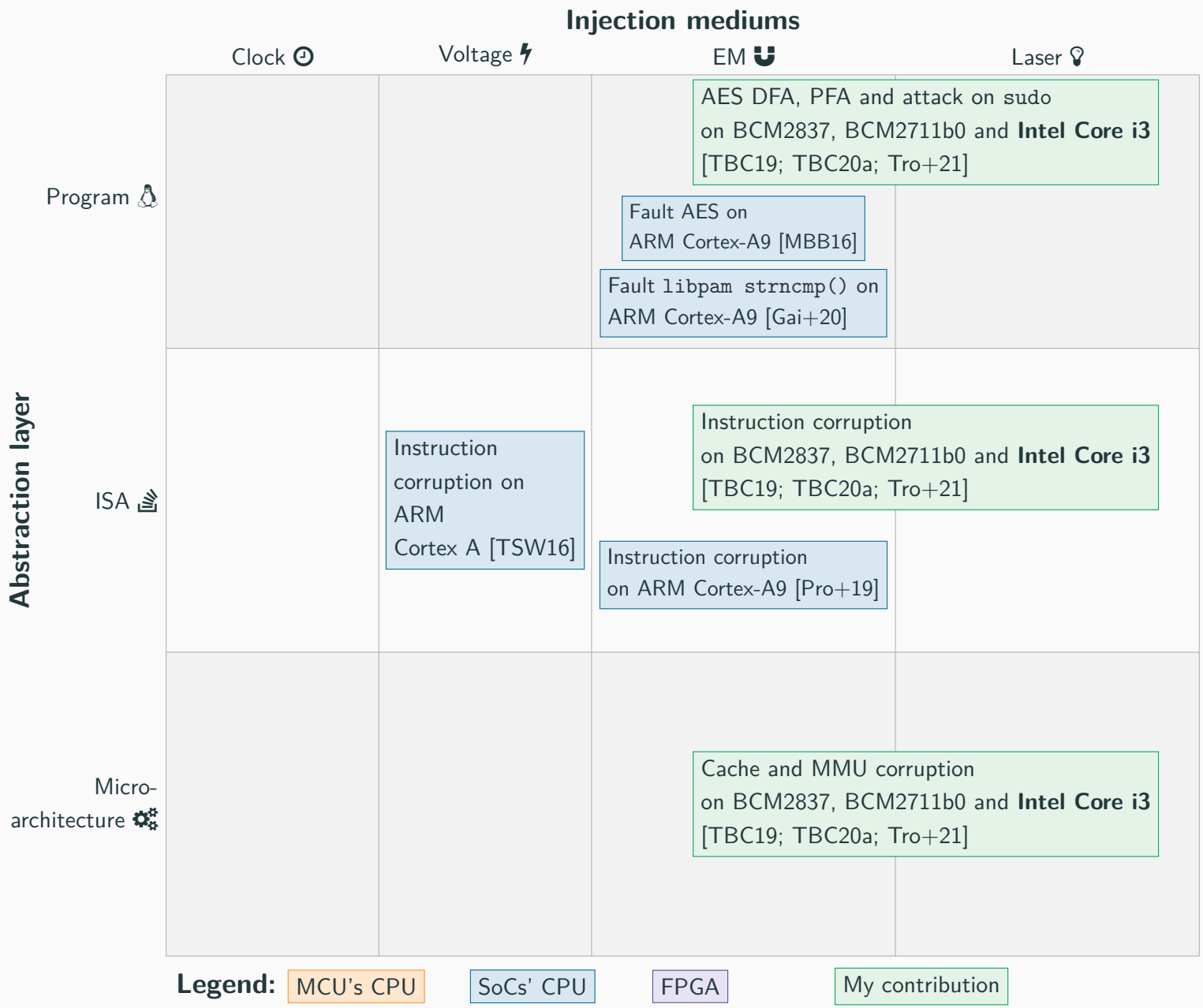

Case study - Characterization Method

Test program

```
orr r5, r5;
/*
 * Arbitrary number
 * of repetitions
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orr r5, r5;
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Initial values

Register	Initial values
r0	0xfffe0001
r1	0xfffd0002
r2	0xfffb0004
r3	0xfff70008
r4	0xffef0010

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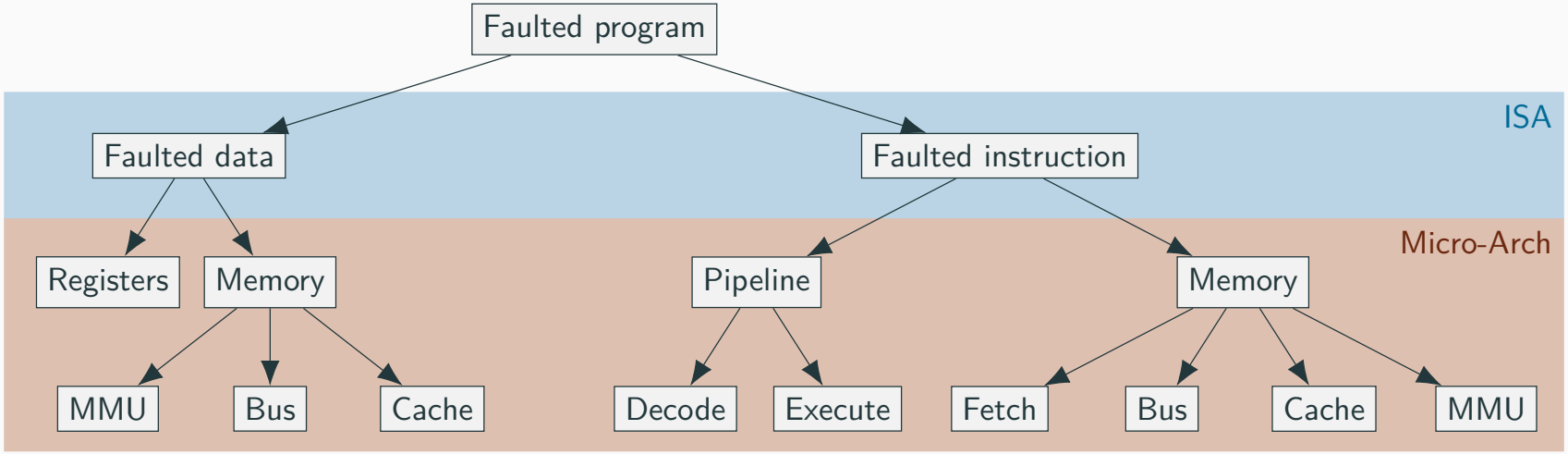
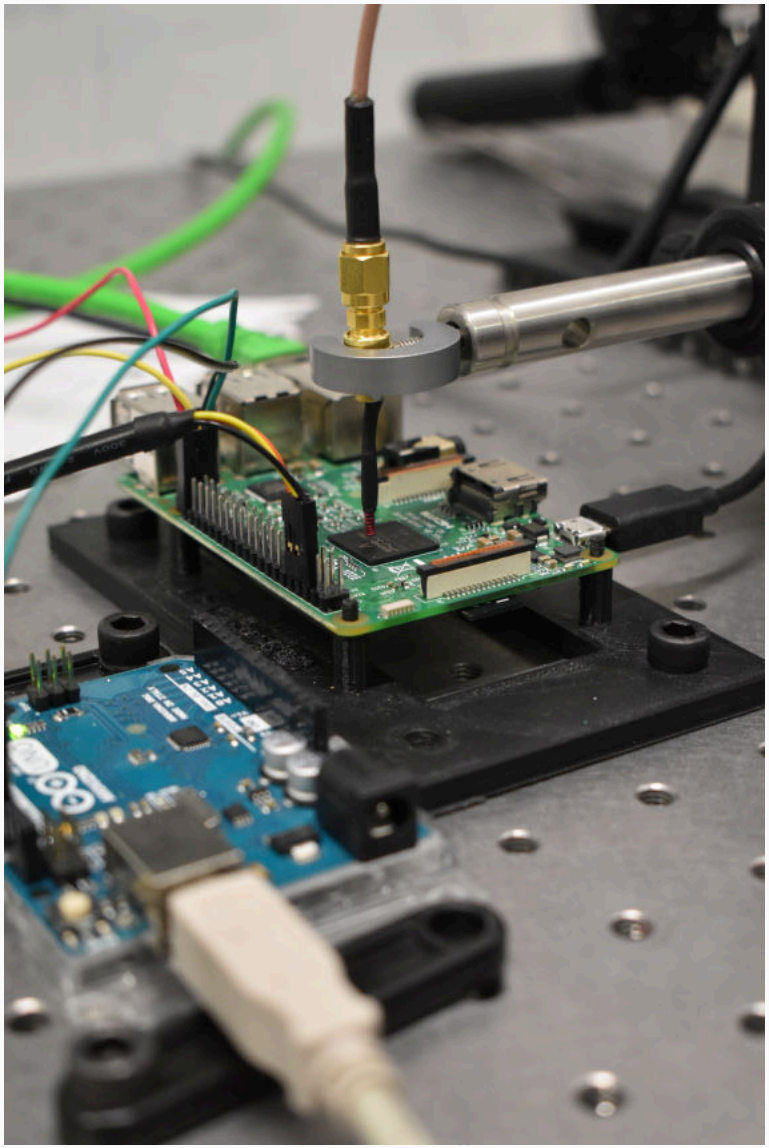
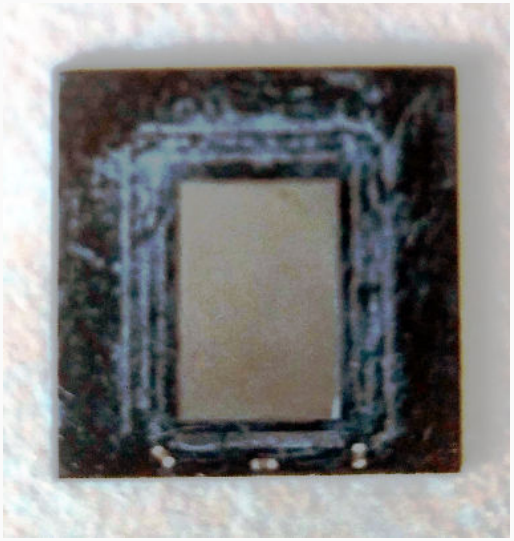
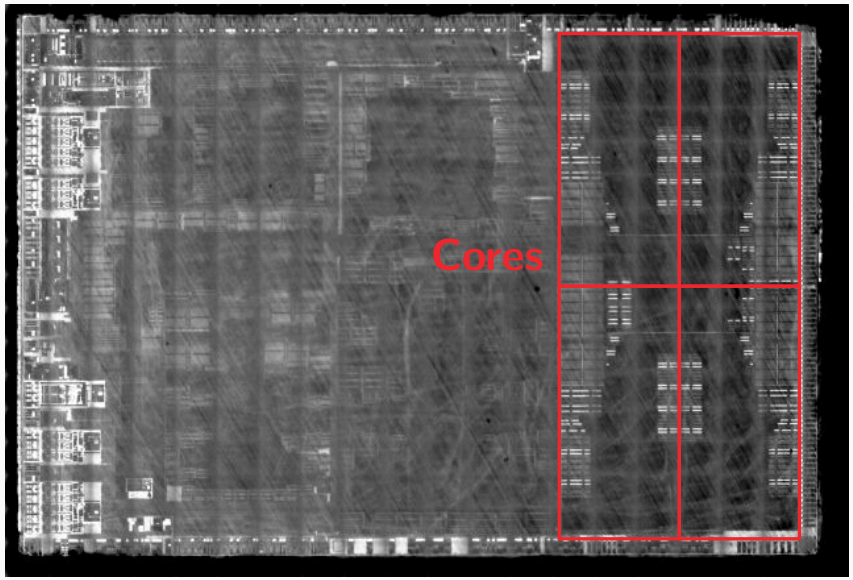
Top down approach



Characterization - BCM2837 (Raspberry Pi 3)







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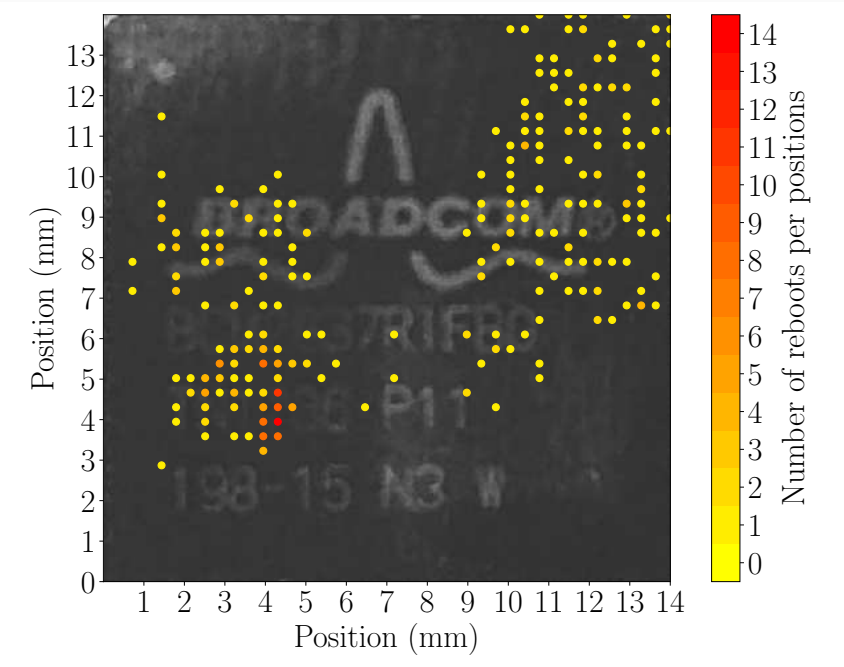
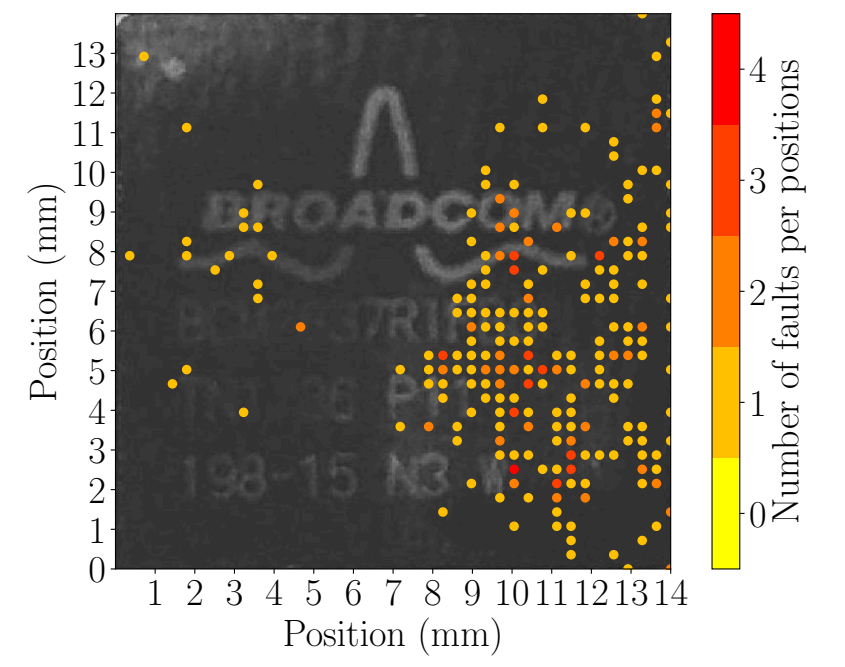


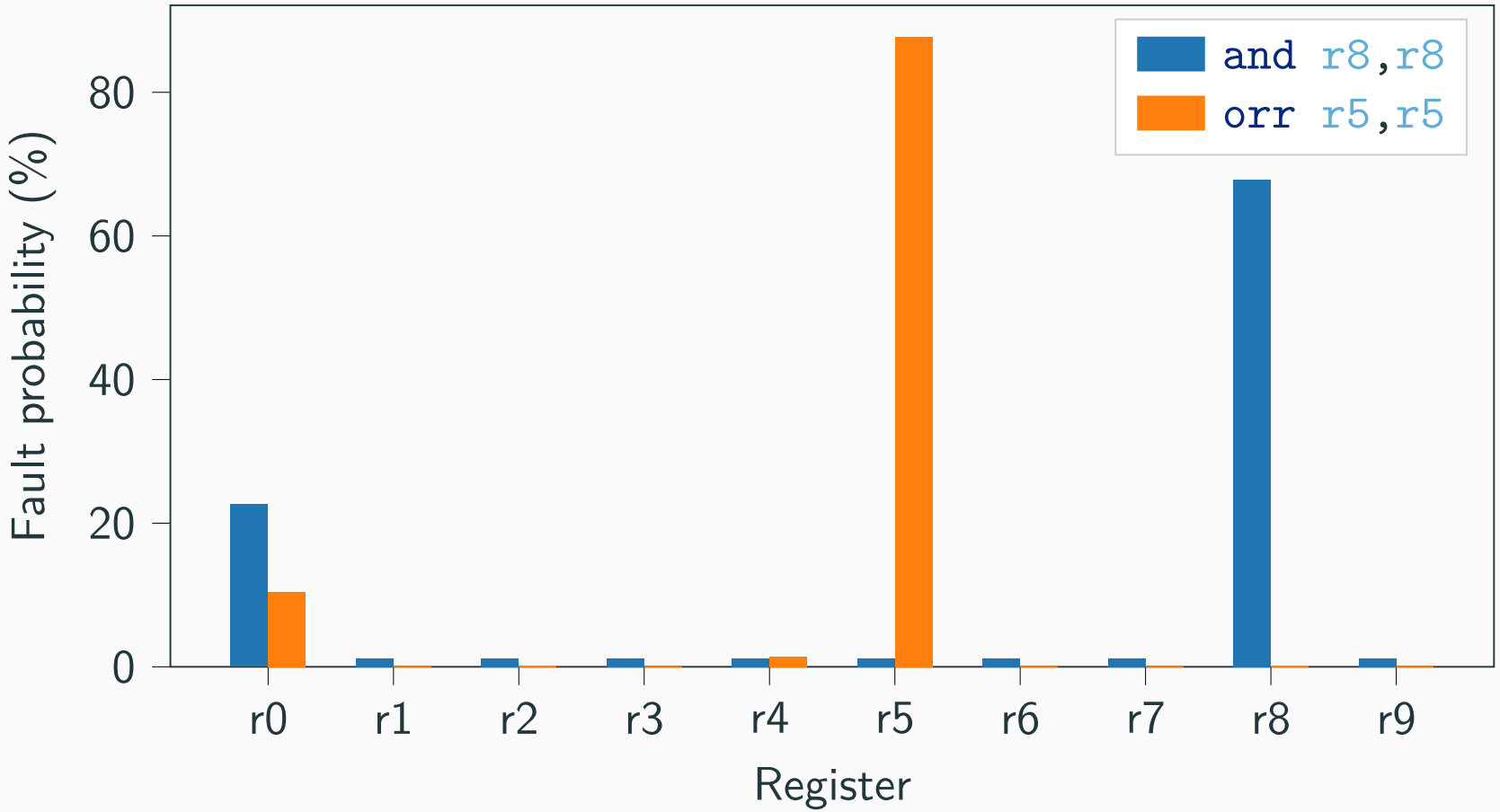
Spots leading to reboots



Spots leading to faults

Characterization - BCM2837

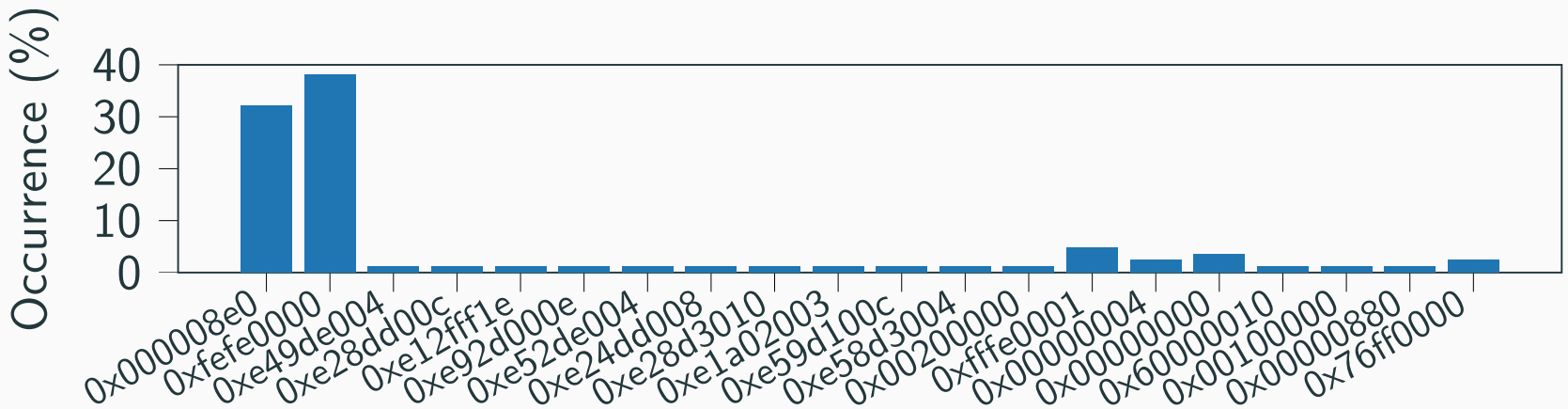
Faulted register distribution regarding the executed instruction



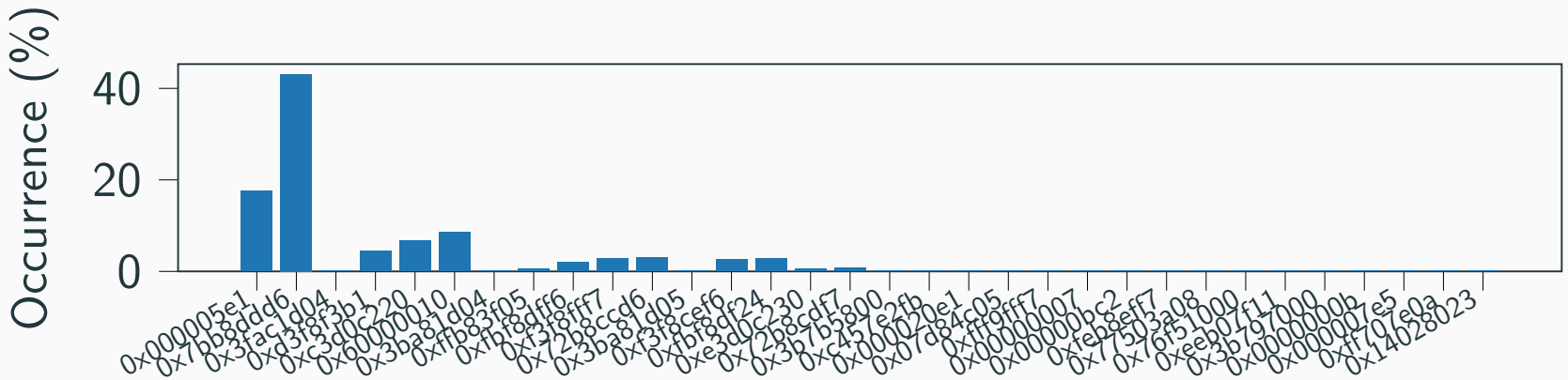
Characterization - BCM2837

Faulted value distribution regarding the executed instruction

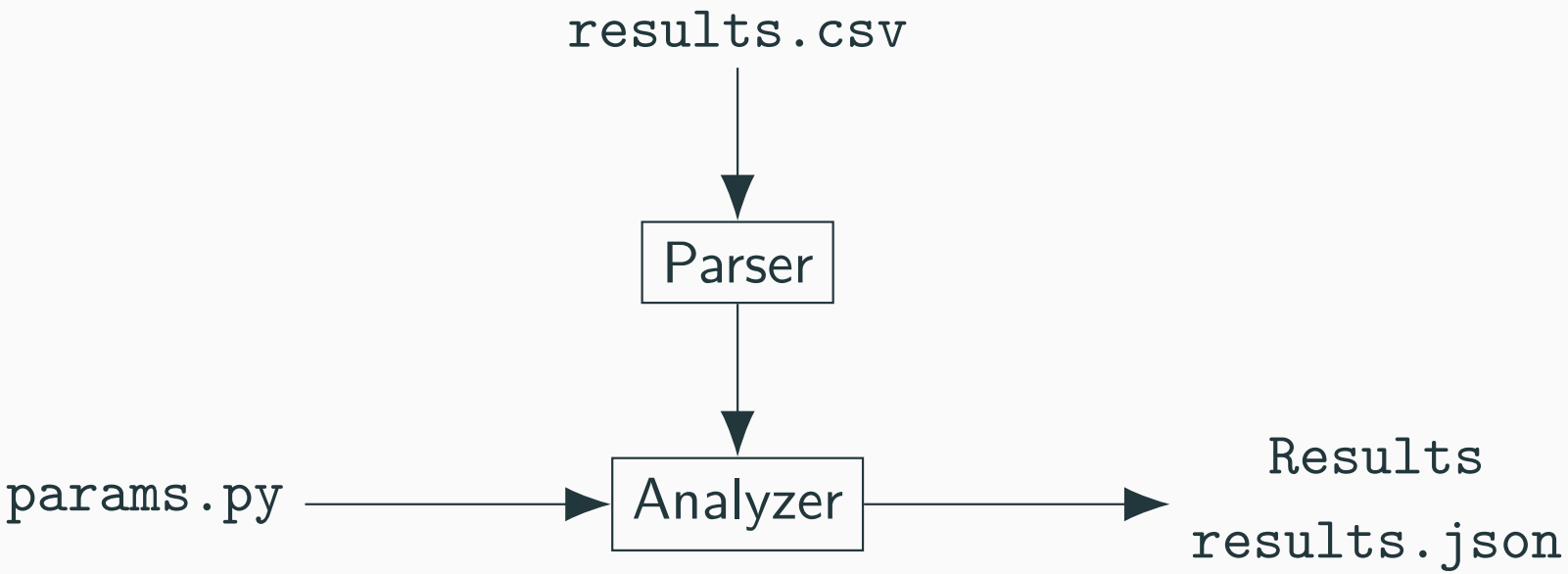
`and r8,r8`



`orr r5,r5`



Characterization - Analysis tool



Characterization - BCM2837

Fault model distribution regarding the executed instruction

Characterization - BCM2837

Instruction matching the "Or with other obs" fault model for the `orr r5,r5` instruction

Faulted instruction	Occurrence (%)
`orr r5,r1`	92.54 %
`orr r5,r0`	6.14 %
`orr r5,r7`	1.32 %

Characterization - BCM2837

Instruction matching the "Or with other obs" fault model for the `orr r5,r5` instruction

Faulted instruction	Occurrence (%)
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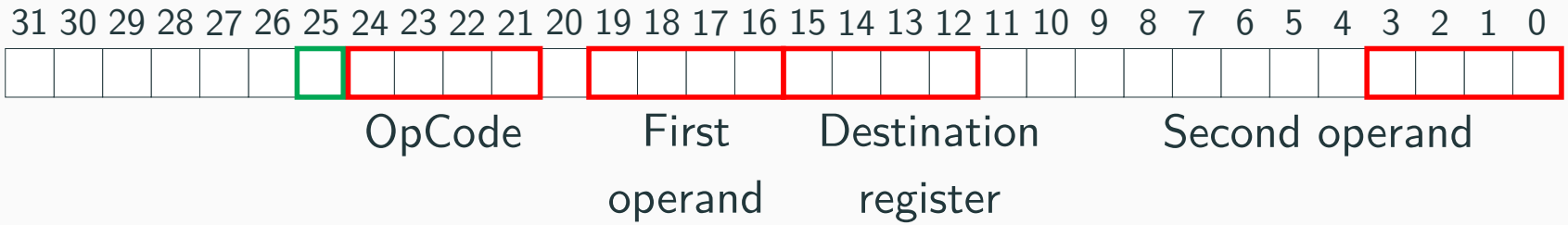
Instruction matching the "And with other obs" fault model for the `and r8,r8` instruction

Faulted instruction	Occurrence (%)
`and r8,r0`	100 %

ARM data processing instruction encoding

If immediate value bit (25) is set to 0



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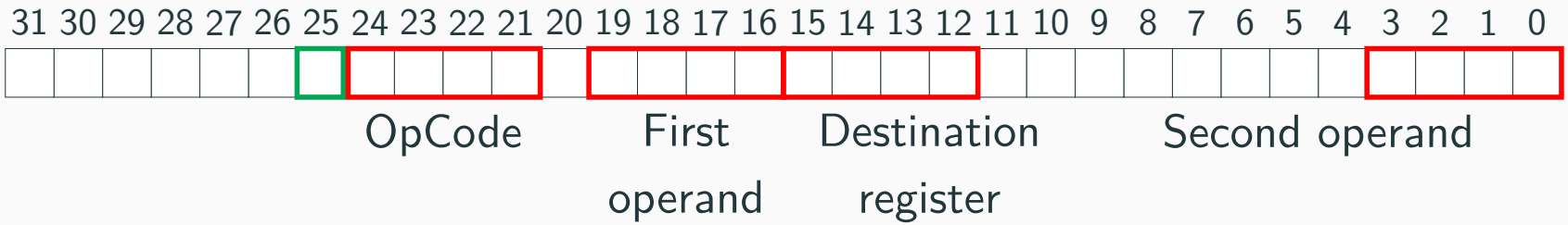
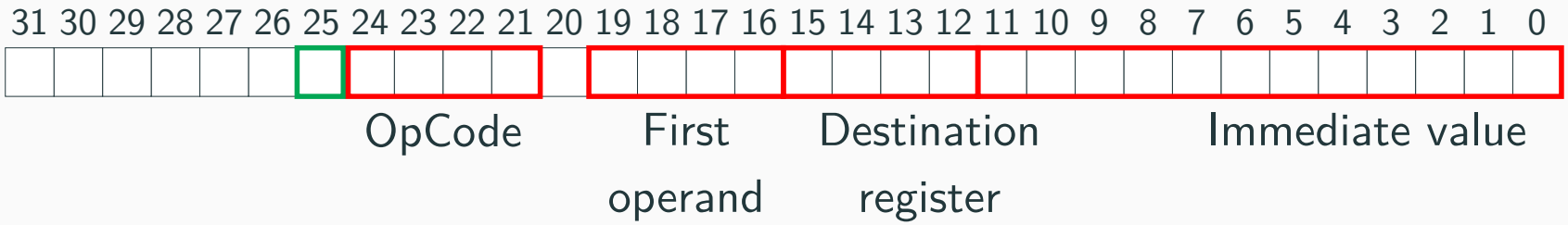
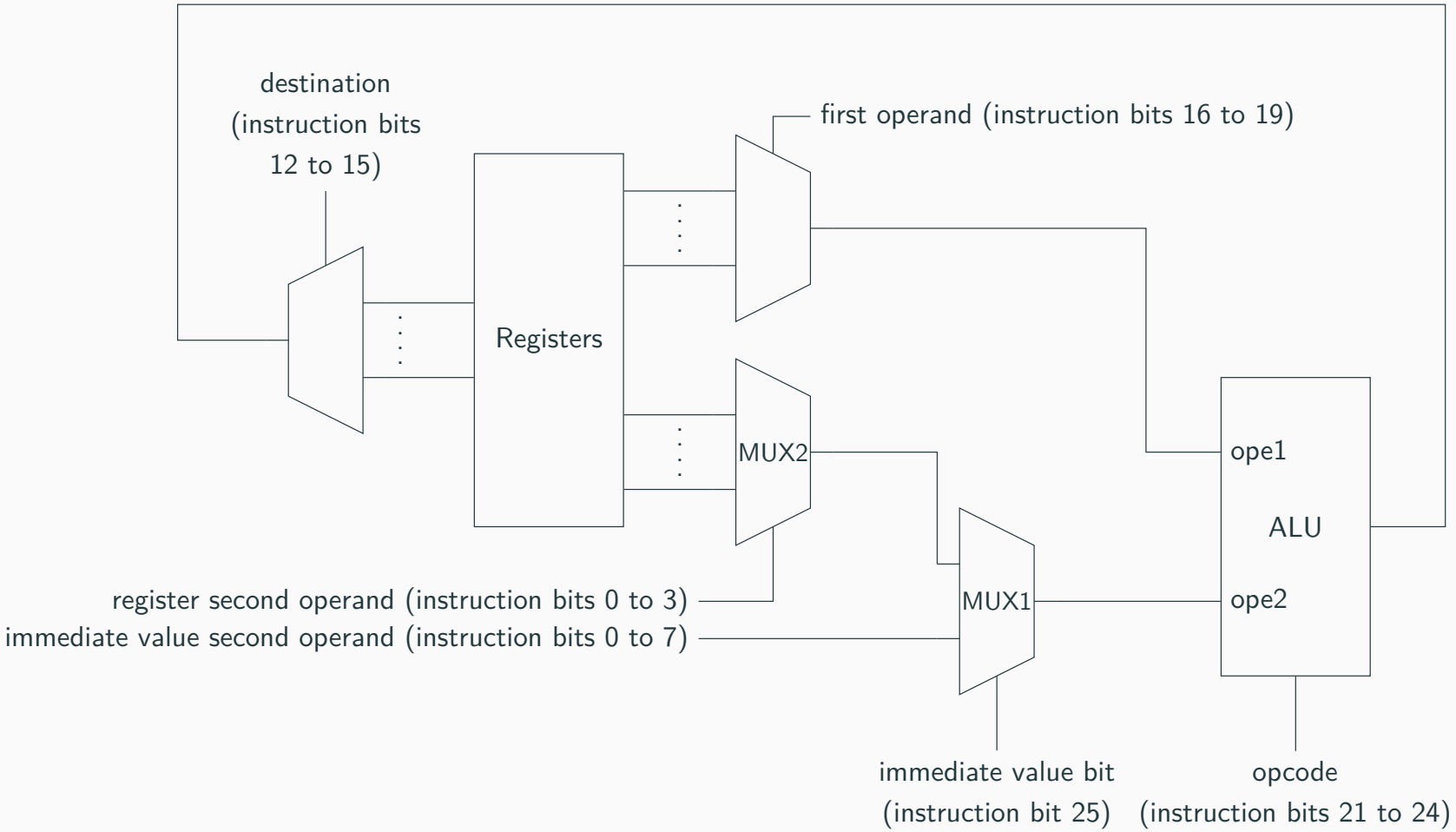


If immediate value bit (25) is set to 1



Characterization - BCM2837



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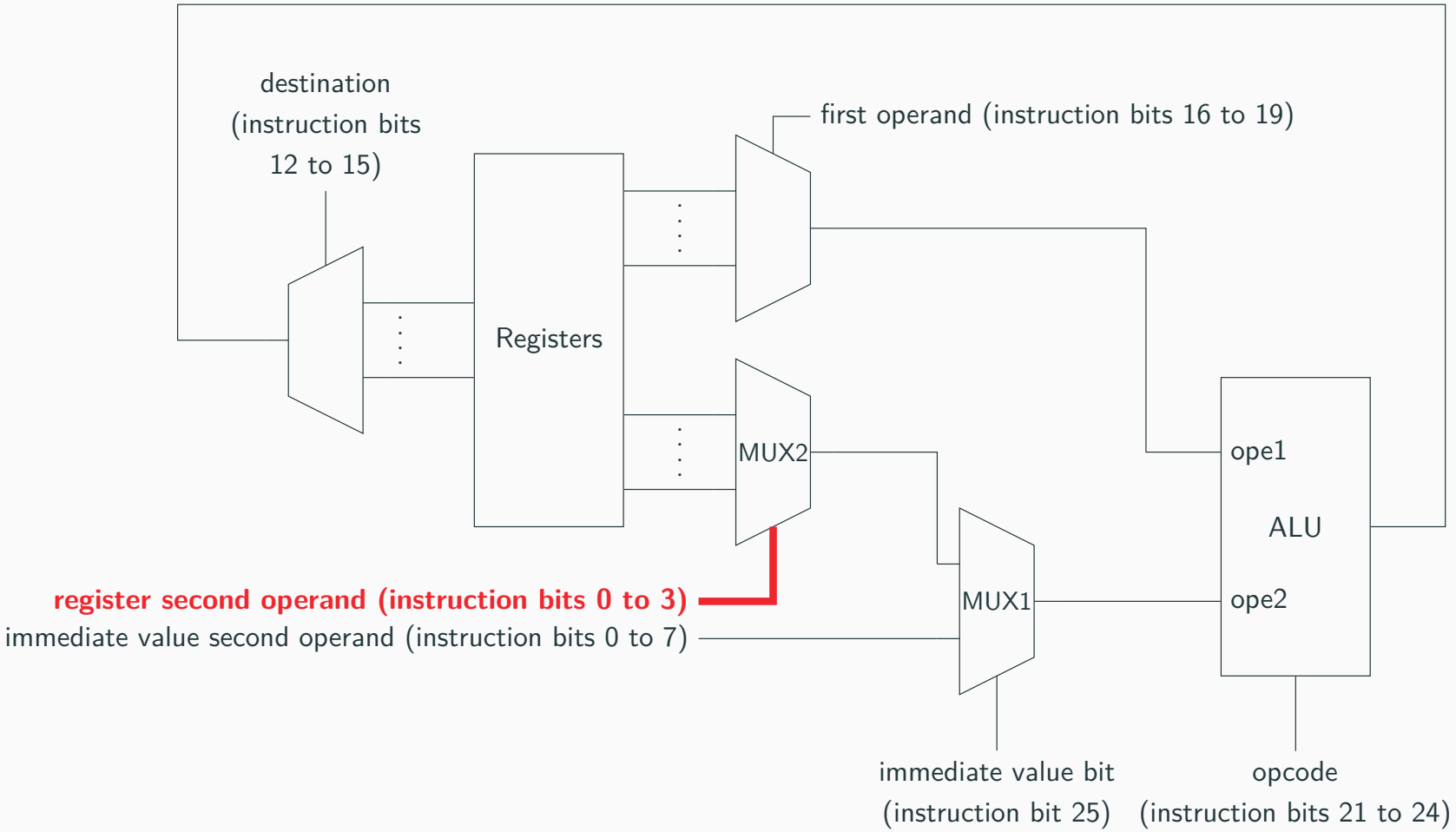


Characterization - BCM2837

Immediate value test code

```
          mov r3, #255
          cmp r3, #255
          bne fault
          b nofault
fault:    mov r9, #170
          b end
nofault:  mov r9, #85
end:      nop
```

Characterization - BCM2837

Immediate value test code

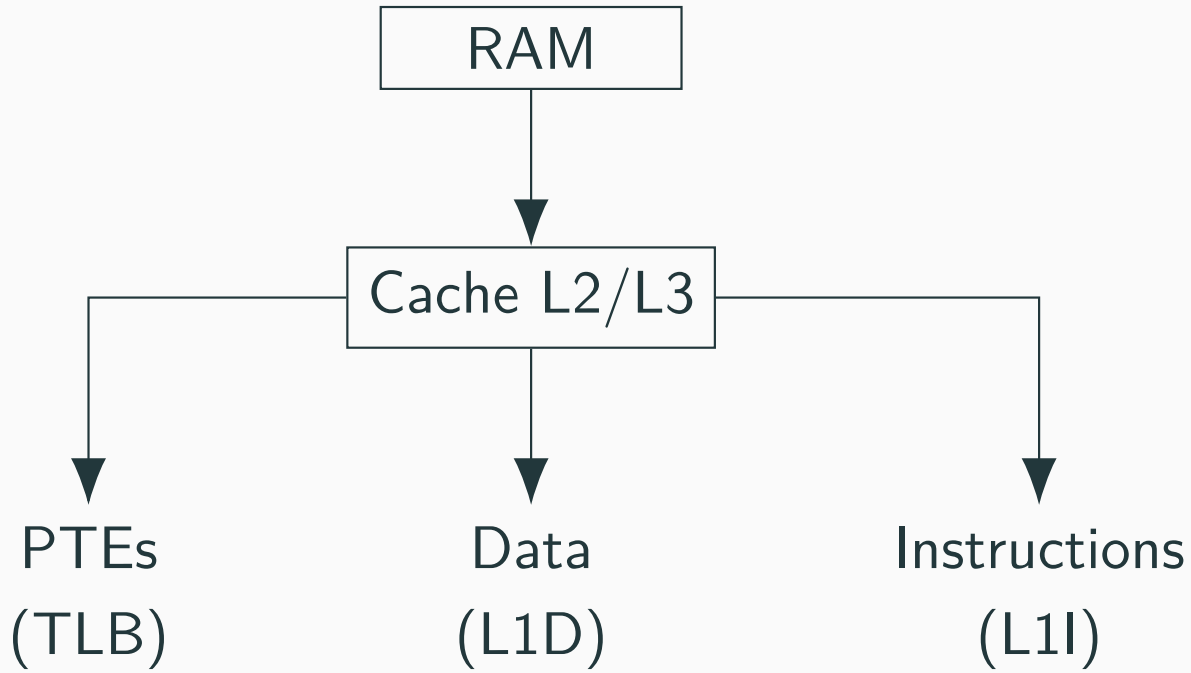
```
          mov r3, #255
          cmp r3, #255
          bne fault
          b nofault
fault:    mov r9, #170
          b end
nofault:  mov r9, #85
end:      nop
```

Results

Fault	r9 = 170	r9 = 0xfffcb924	Unknown
Rate	94%	4%	2%

Characterization - BCM2837

Memory subsystem pathing



Characterization - BCM2837

Memory test code

```
str r8, [r9] // Several
ldr r8, [r9] //      times
```

Initialization

- memory page allocated (4 kB)
- registered initialized to address in the page

Characterization - BCM2837

Memory test code

```
str r8, [r9] // Several
ldr r8, [r9] //     times
```

Initialization

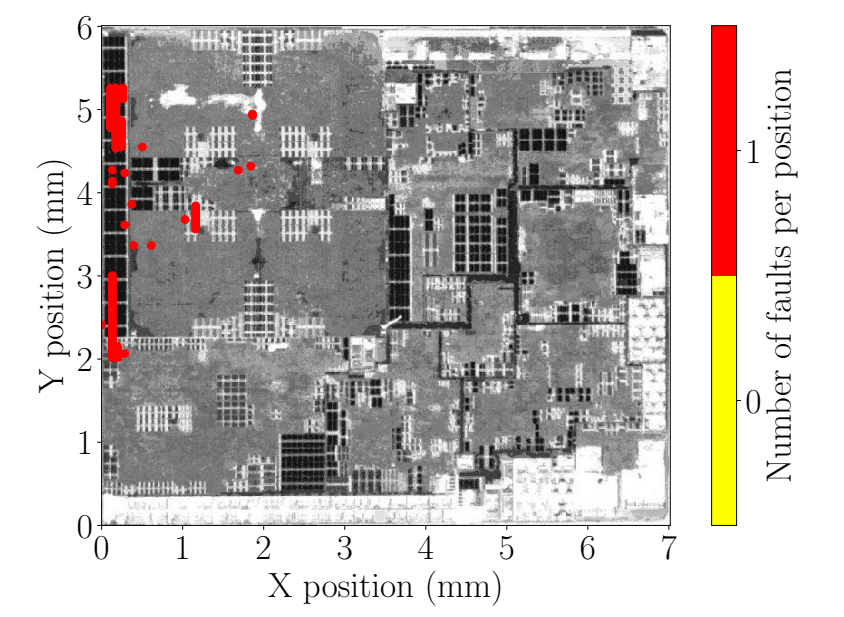
- memory page allocated (4 kB)
- registered initialized to address in the page

Results

- `ldr r8, [r9]` → `ldr r8, [PC]` (25 %)
- `ldr r8, [r9]` → `mov r8, r2` (74.4 %)
- no fault on fetched data

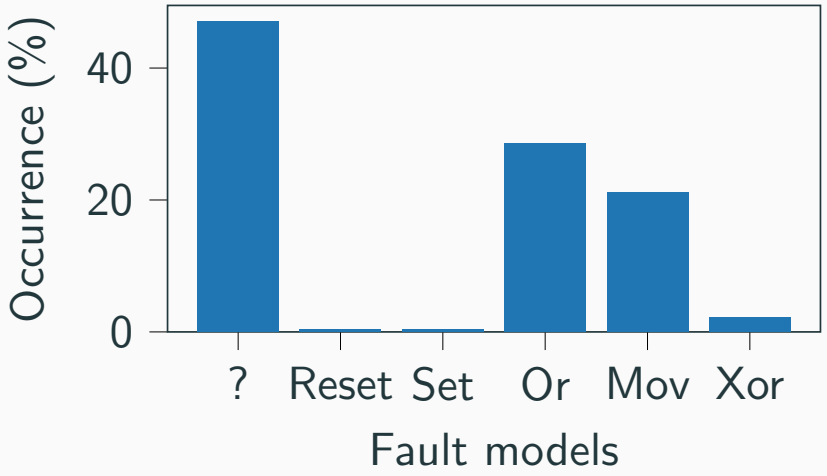
Characterization - BCM2711b0

```
orr r5,r5
```



Spots leading to faults

Fault models

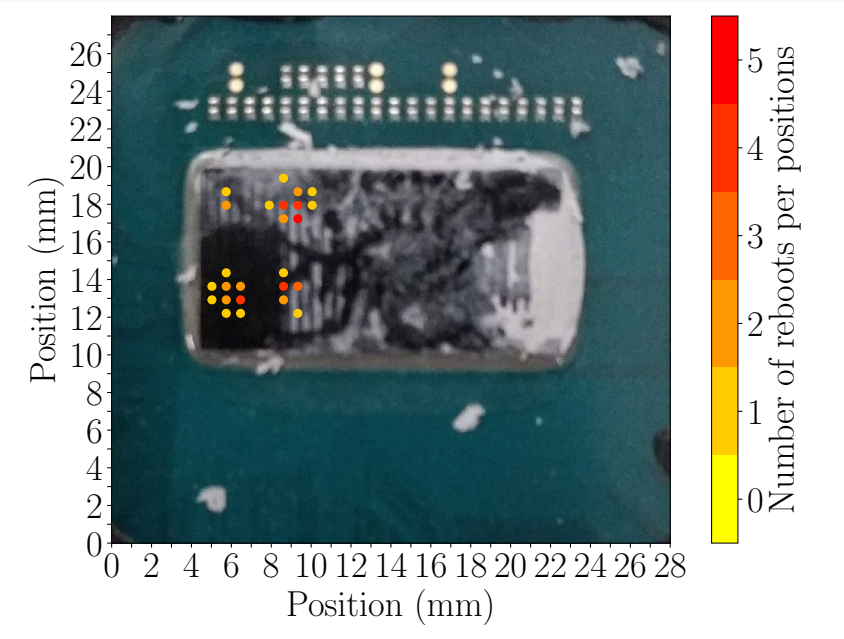


- Instruction corruption
  - Operands corruption
  - Opcode corruption

We mainly target the cache

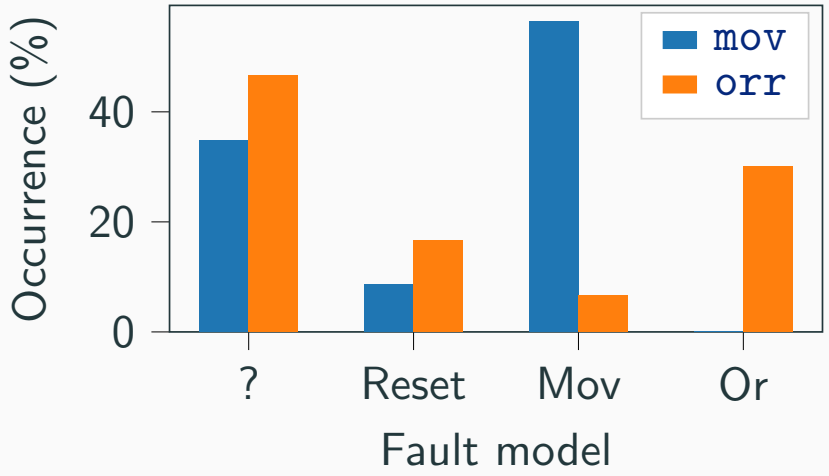
Characterization - Intel Core i3-6100T

`orr r5,r5`



Spots leading to reboots

Fault models



- Instruction corruption
  - Opcode corruption

Characterization - Conclusion

- Classical injection mediums (laser, EMFIs):
  - are efficient on complex CPUs,
  - can be characterized and are understandable

Characterization - Conclusion

- Classical injection mediums (laser, EMFIs):
  - are efficient on complex CPUs,
  - can be characterized and are understandable
- Different injection mediums have shown the similar fault models on different architecture (ARM, x86) and targets:
  - I suppose that there is an **underlying common mechanism** sensitive to perturbation,
  - this mechanism is faulted in the same way independently of the target and medium,
  - the **instruction cache** was identified as faulted on the BCM2837

Conclusion

- modern SoCs are more and more used for sensitive operations
- these SoCs are sensitive to faults
- evaluating modern SoCs is totally new
- security evaluation authorities (JHAS, ANSSI, *etc*) are looking forward modern SoCs evaluation (*cf.* JHAS SoC subgroup)

Conclusion

In my thesis, I provide:

- a method to characterize faults on SoCs CPUs,
- a fault analyzer software,
- perturbation experiment results,
- a fault model on various targets (ARM and x86),
- attacks on AES on Linux,
- an attack path on `sudo`,
- a Linux software analyzer,
- a fault simulator adapted to Linux softwares

Identified research topics and future works

- improvement of the fault analyzer, the software analyzer and the fault simulator
- development of a pattern based trigger generator,
- micro-architectural characterization on remaining targets,
- development of countermeasures to protect the instructions,
- analyzing the Linux kernel and security programs against faults,
- confirming the `sudo` attack path with an actual attack

Contributions i

Publications

- Thomas Trouchkine, Guillaume Bouffard, and Jessy Clediere. "Fault Injection Characterization on modern CPUs – From the ISA to the Micro-Architecture". In: *WISTP 2019, Paris, France*. 2019
- Thomas Trouchkine, Guillaume Bouffard, and Jessy Clediere. "EM Injection Vs. Modern CPU - Fault Characterization And AES Differential Fault Analysis". In: *Comptatibilité électromagnétique France 2020*. 2020

Contributions ii

- Thomas Trouchkine et al. “Electromagnetic Fault Injection against a complex CPU, toward a new micro-architectural fault models”. In: *Journal of Cryptographic Engineering (JCEN)*. 2021

Workshops

- Thomas Trouchkine. “Problems and state of the art of faults injection on Systems on Chip”. In: *PHISIC 2018*. 2018
- Thomas Trouchkine. “EM fault injection on Raspberry Pi 3 and ZedBoard”. In: *GDR SoC2 research group*. 2018

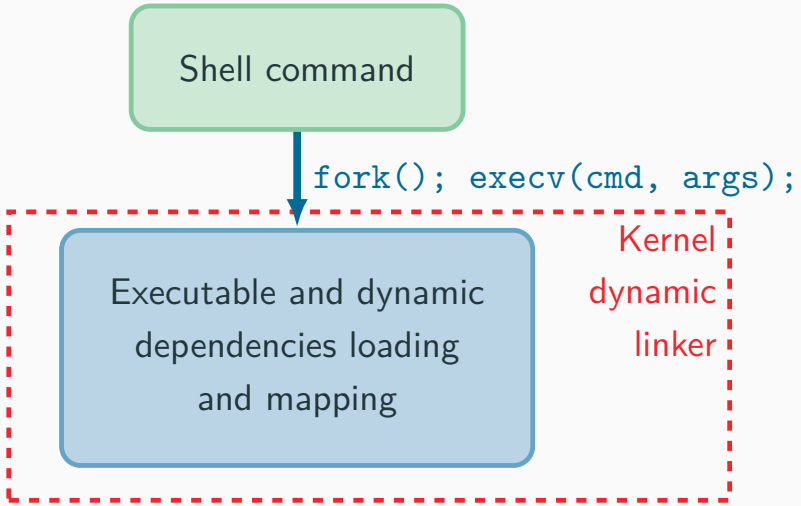
Contributions iii

- Thomas Trouchkine et al. “Do not trust modern System on Chip”. In: *Journée thématique sur les attaques par injection de fautes (JAIF)*. 2019
- Thomas Trouchkine et al. “Do not trust modern System-on-Chips”. In: *PHISIC 2019*. 2019
- Guillaume Bouffard et al. “Radically secure computing”. In: *SILM seminar 2020*. 2020
- Thomas Trouchkine, Guillaume Bouffard, and Jessy Clediere. “Perturbation attack on modern CPUs, from the fault model to the exploitation”. In: *Journée thématique sur les attaques par injection de fautes (JAIF)*. 2020

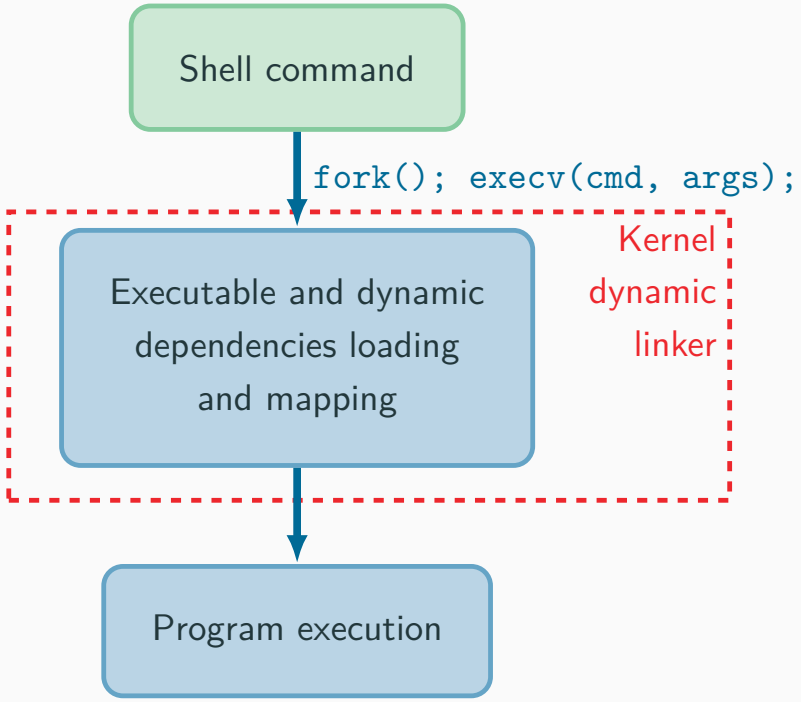
Questions ?

Appendice - Linux program life

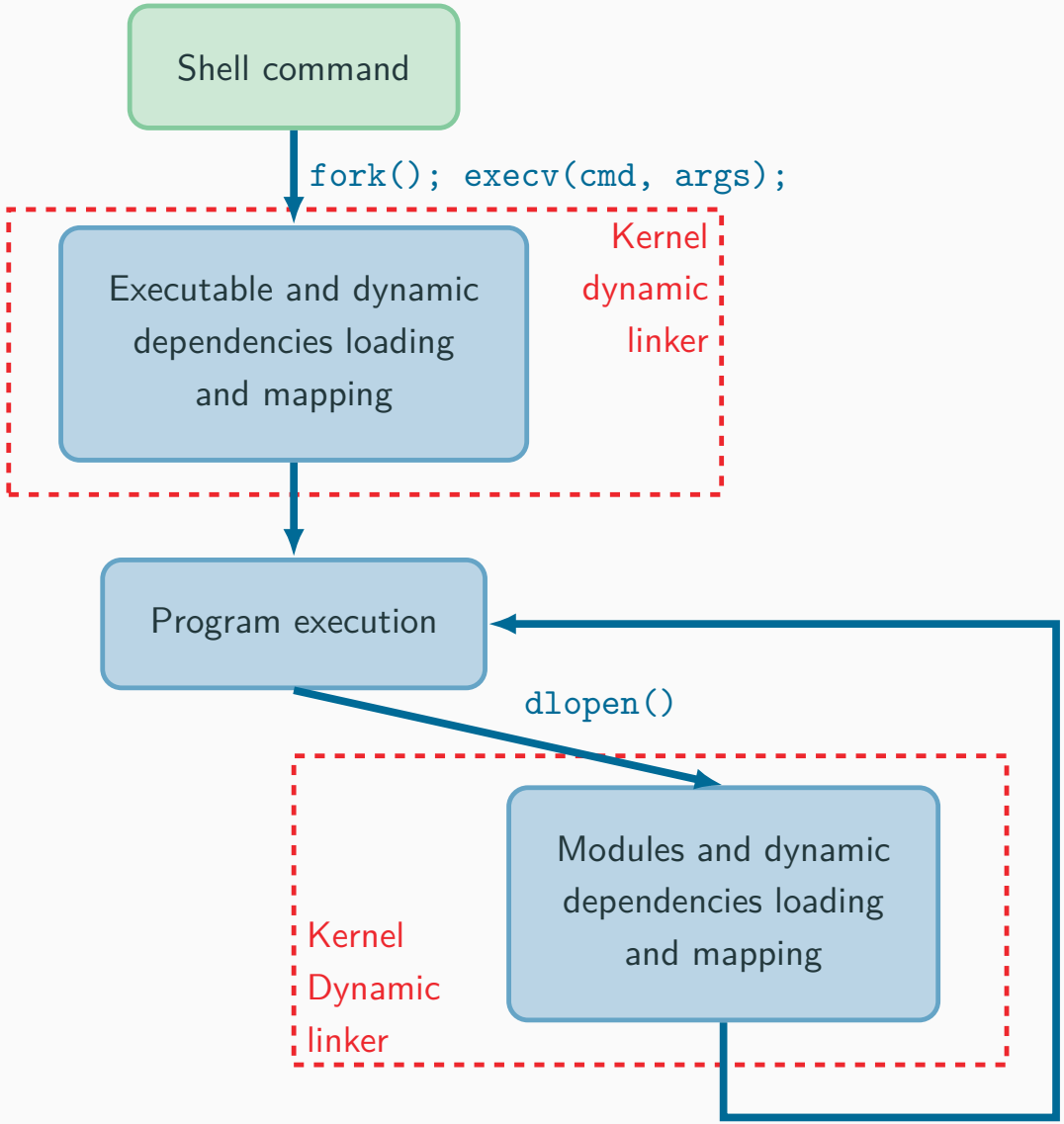
Appendice - Linux program life



Appendice - Linux program life



Appendice - Linux program life



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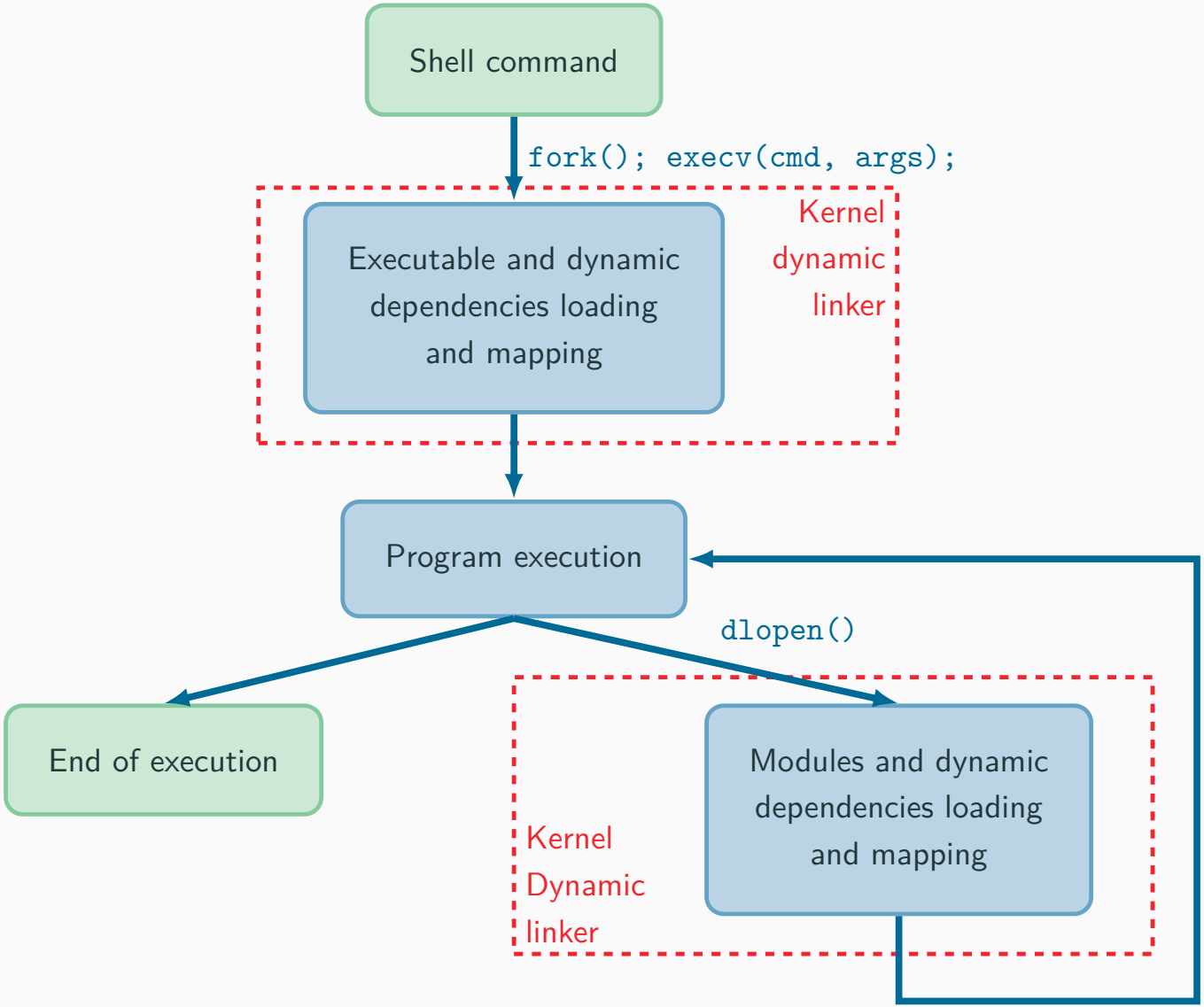


Determining the number of faulted instructions

Test code

```
mov r0,r0
mov r1,r1
mov r2,r2
mov r3,r3
mov r4,r4
mov r5,r5
mov r6,r6
mov r7,r7
mov r8,r8
mov r9,r9
```

Result

On average:

- 1.45 faulted instructions

Appendice - BCM2837 MMU fault

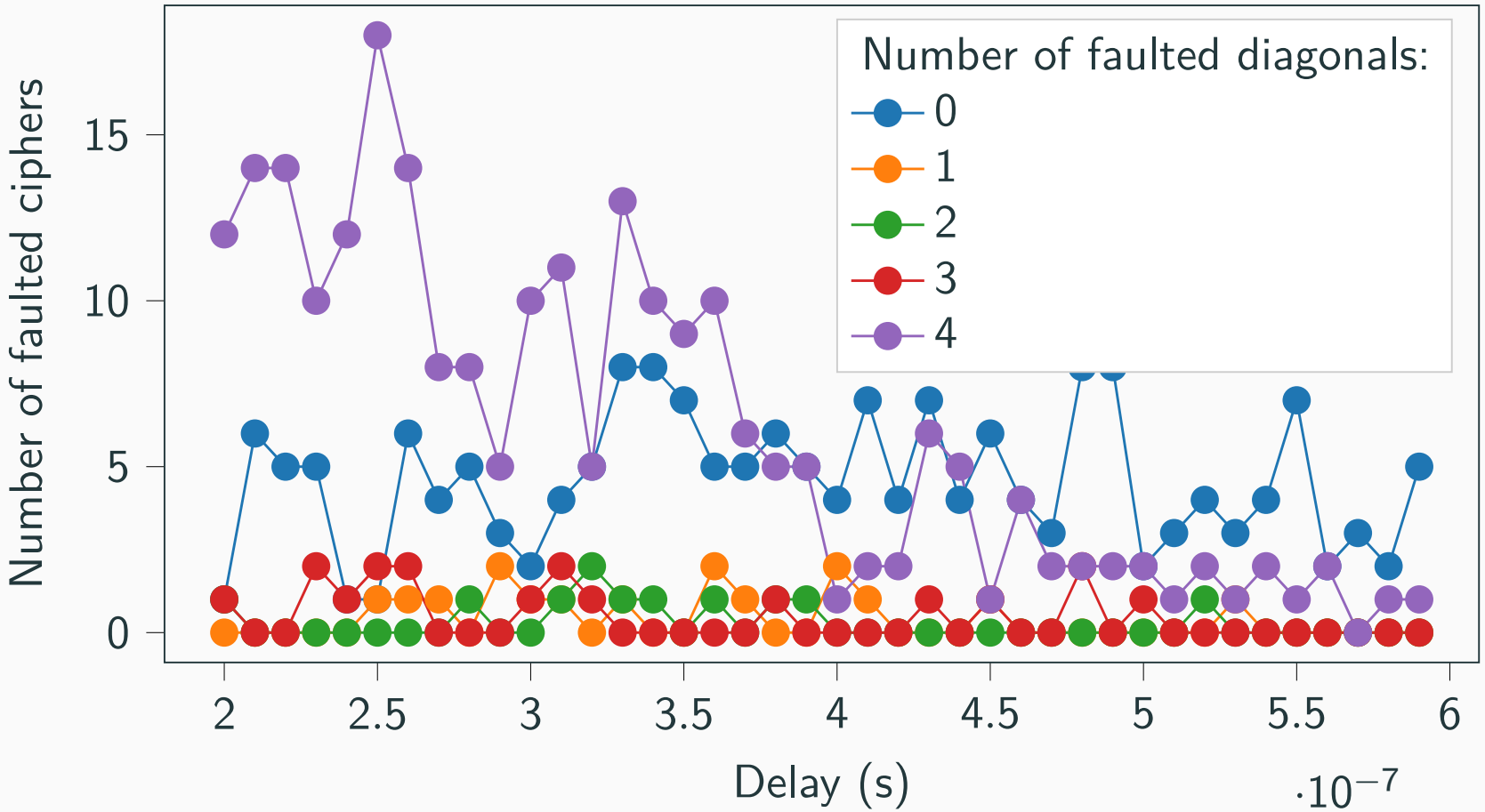
```
VA       -> PA
0x0      -> 0x0       0x80000 -> 0x80000
0x10000  -> 0x10000   0x90000 -> 0x90000
0x20000  -> 0x20000   0xa0000 -> 0xa0000
0x30000  -> 0x30000   0xb0000 -> 0xb0000
0x40000  -> 0x40000   0xc0000 -> 0xc0000
0x50000  -> 0x50000   0xd0000 -> 0xd0000
0x60000  -> 0x60000   0xe0000 -> 0xe0000
0x70000  -> 0x70000   0xf0000 -> 0xf0000
```

Appendice - BCM2837 MMU fault

```
VA       -> PA
0x0      -> 0x0       0x80000 -> 0x0
0x10000  -> 0x10000   0x90000 -> 0x0
0x20000  -> 0x20000   0xa0000 -> 0x0
0x30000  -> 0x30000   0xb0000 -> 0x0
0x40000  -> 0x40000   0xc0000 -> 0x80000
0x50000  -> 0x50000   0xd0000 -> 0x90000
0x60000  -> 0x60000   0xe0000 -> 0xa0000
0x70000  -> 0x70000   0xf0000 -> 0xb0000
```

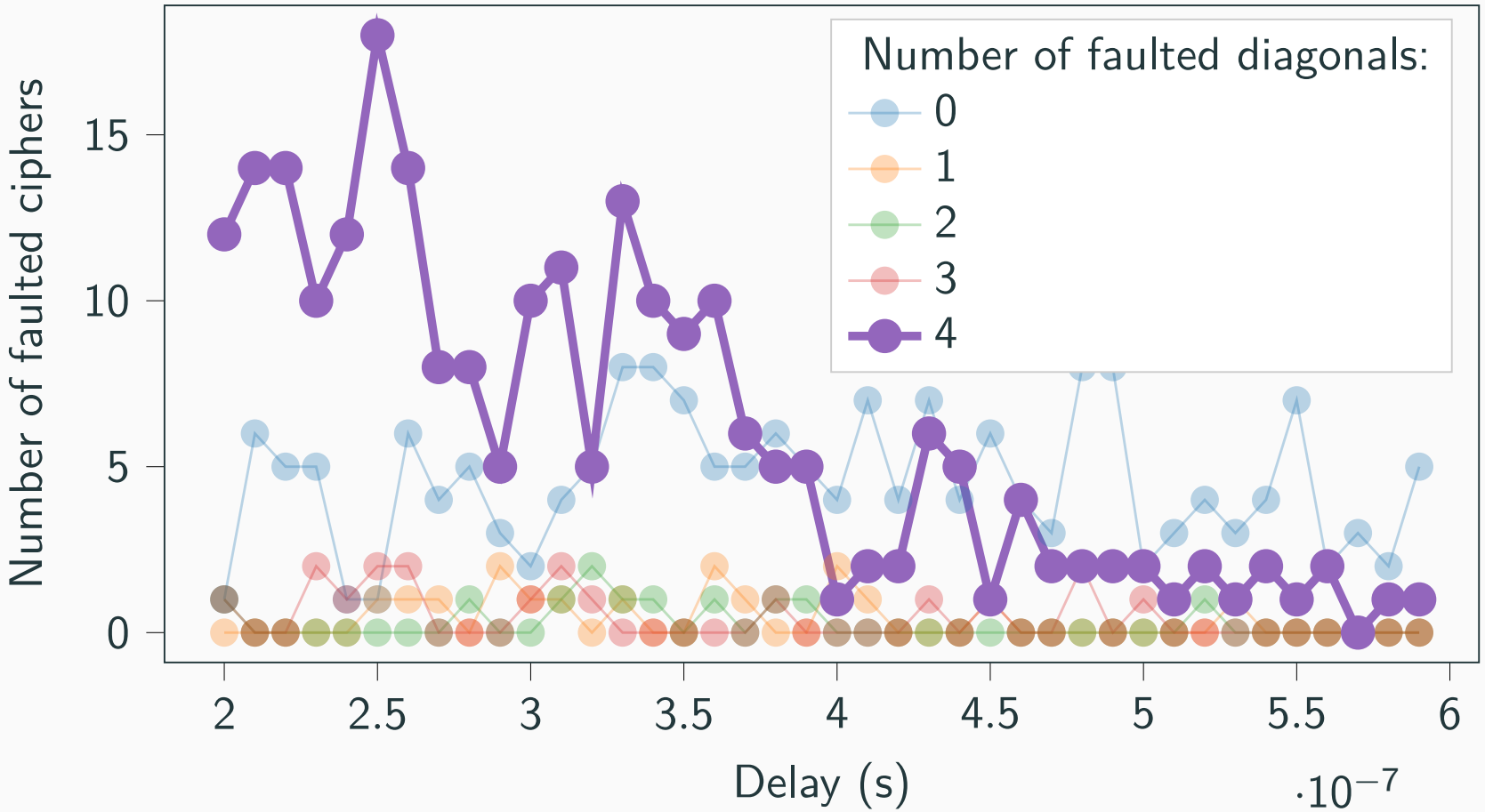
Appendice - OpenSSL AES

Number of faulted ciphers with a specific number of faulted diagonals regarding the delay of injection

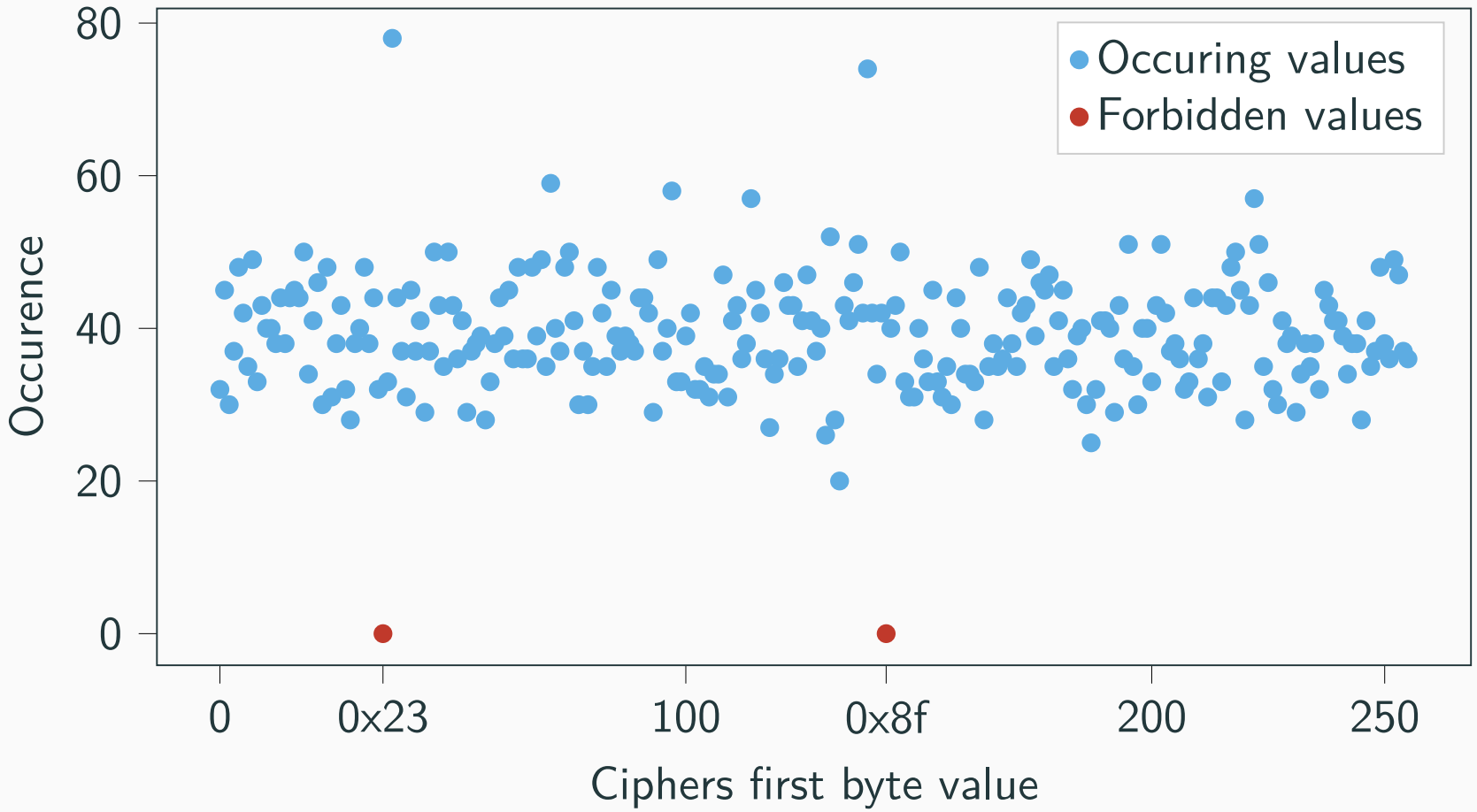


Appendice - OpenSSL AES

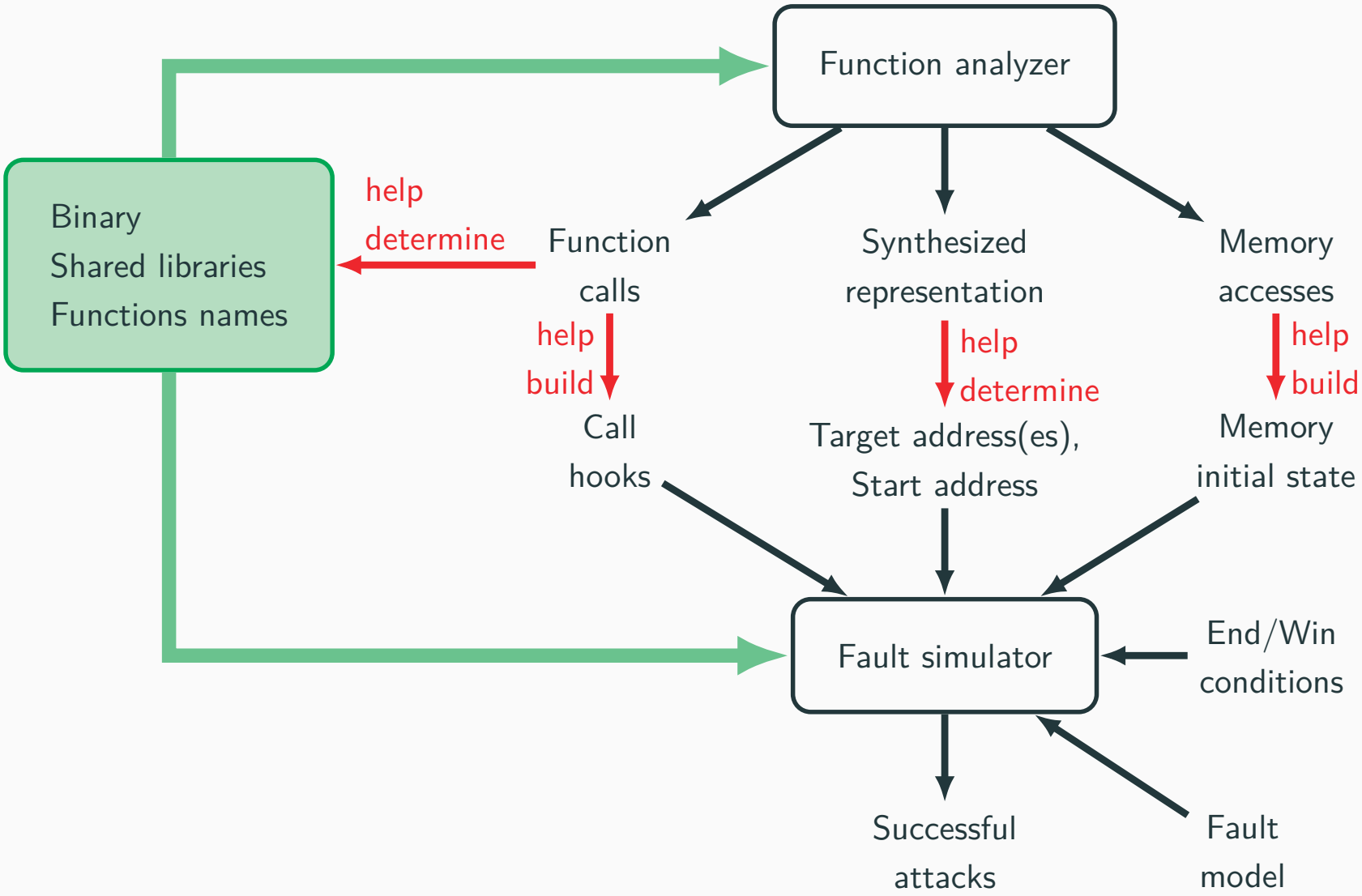
Number of faulted ciphers with a specific number of faulted diagonals regarding the delay of injection



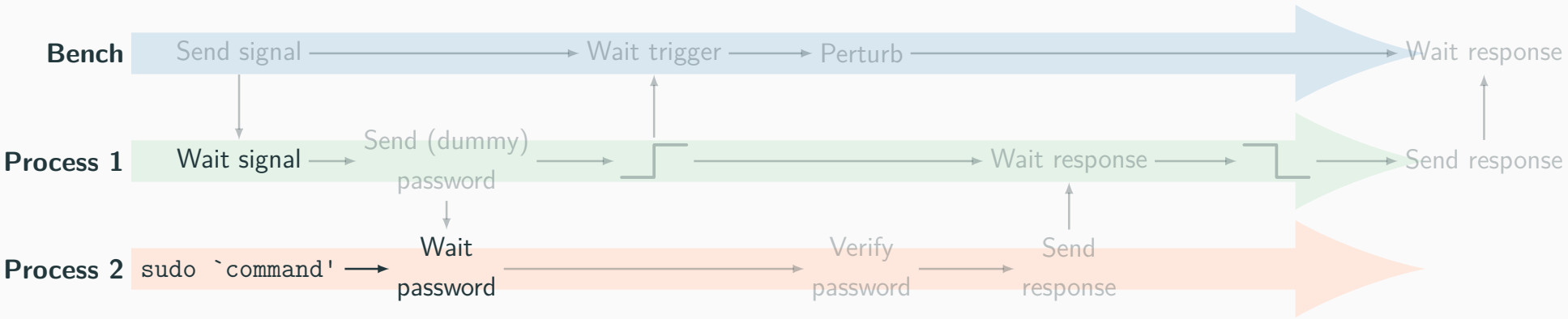
Appendice - AES PFA



Appendice - Analyzer and simulator



Appendice - `sudo` Forced authentication - User program



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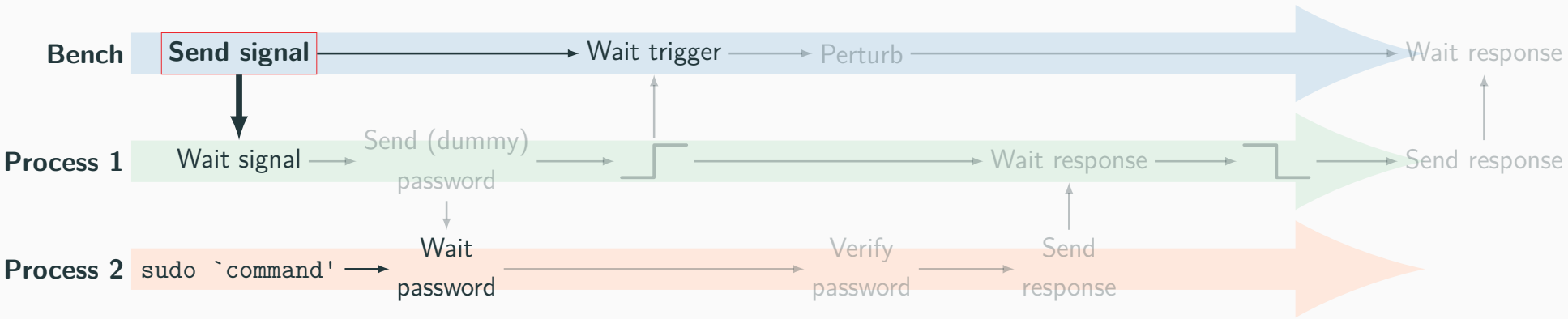

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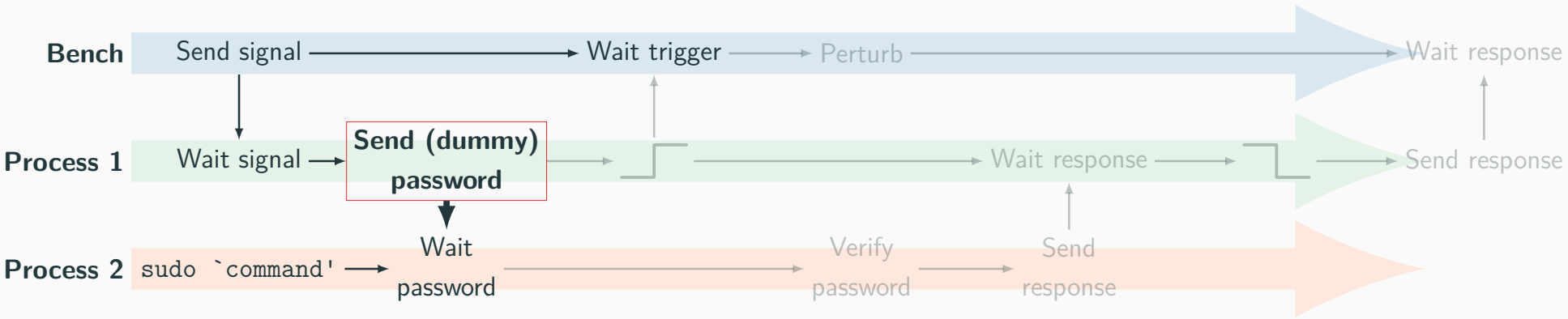

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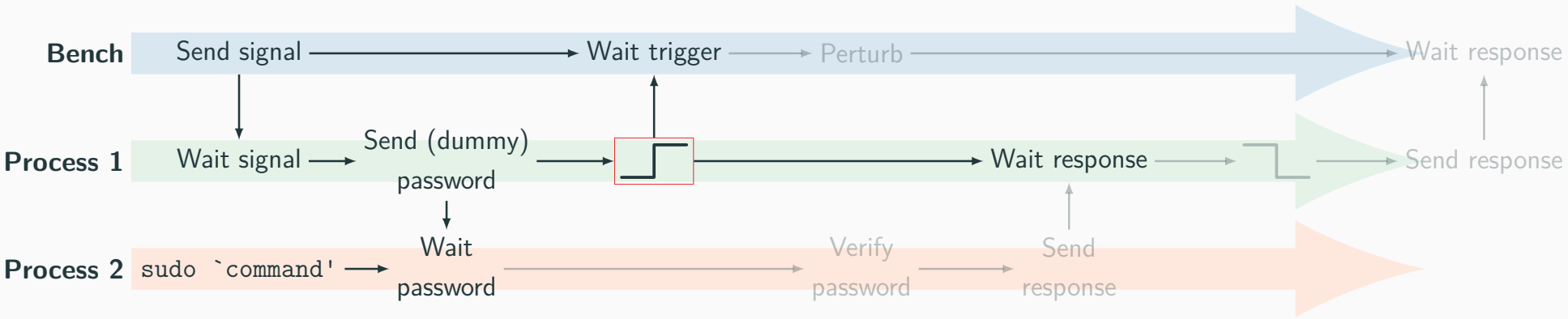

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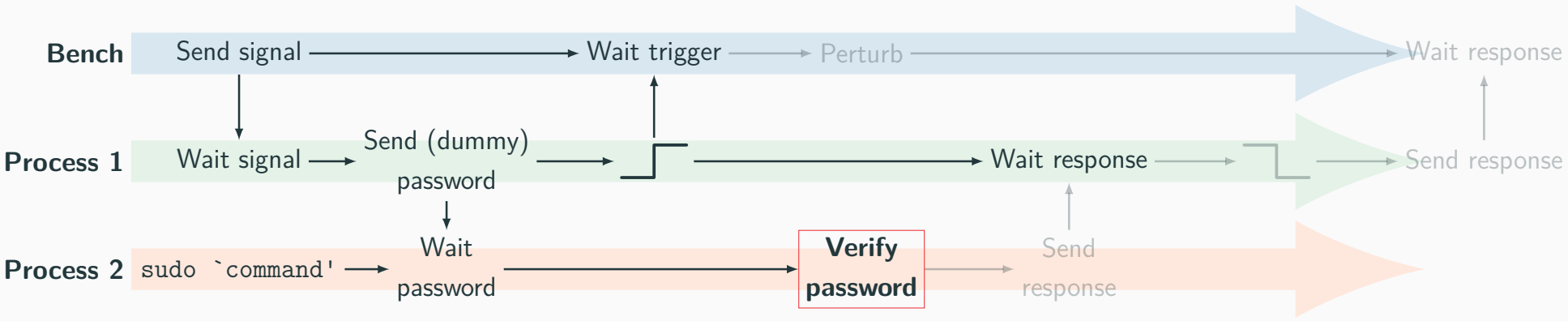

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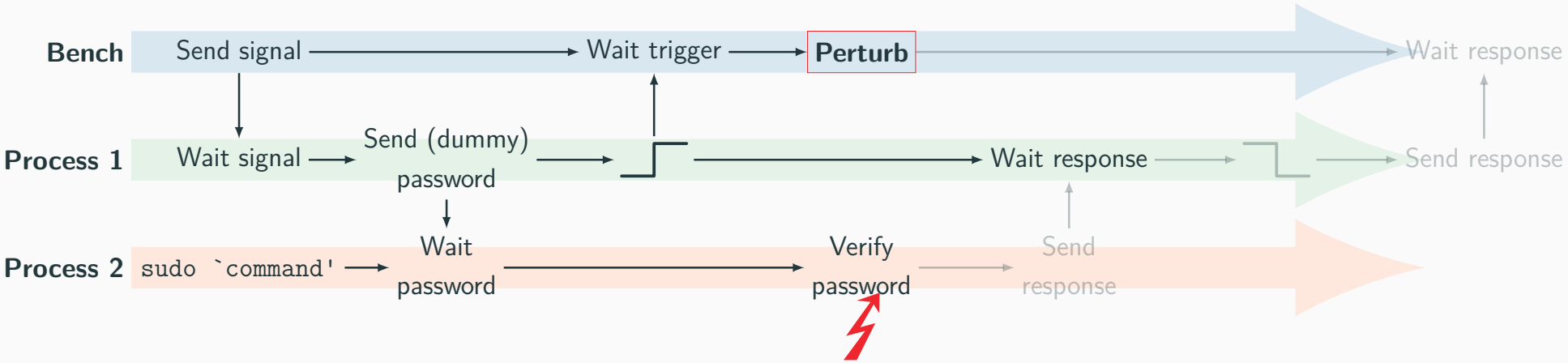

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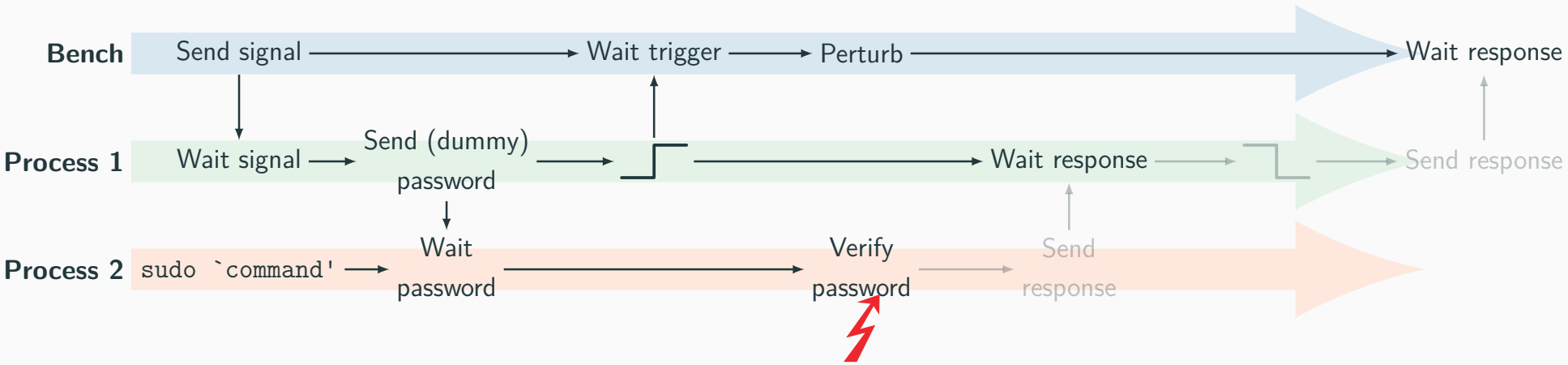

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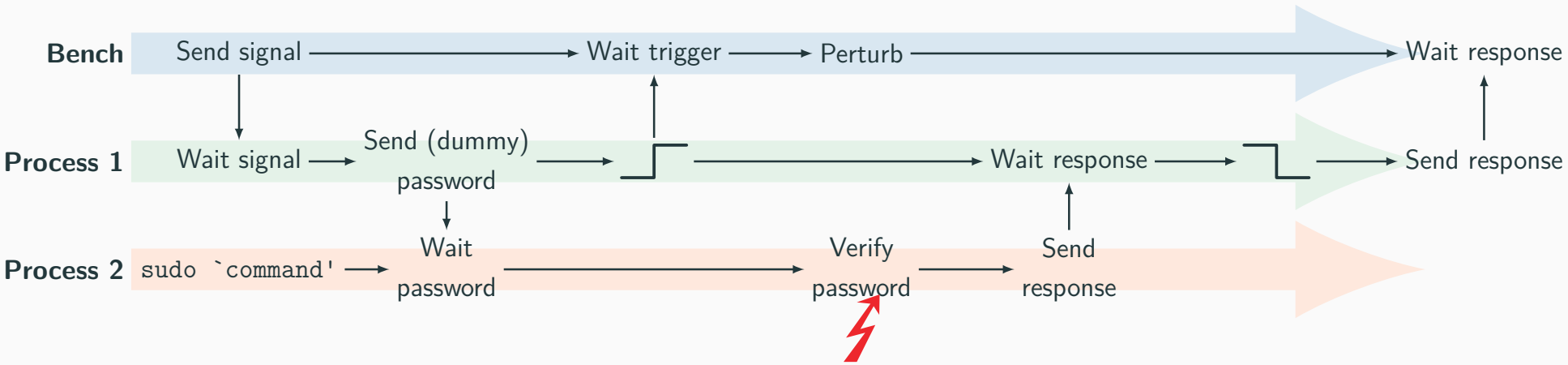
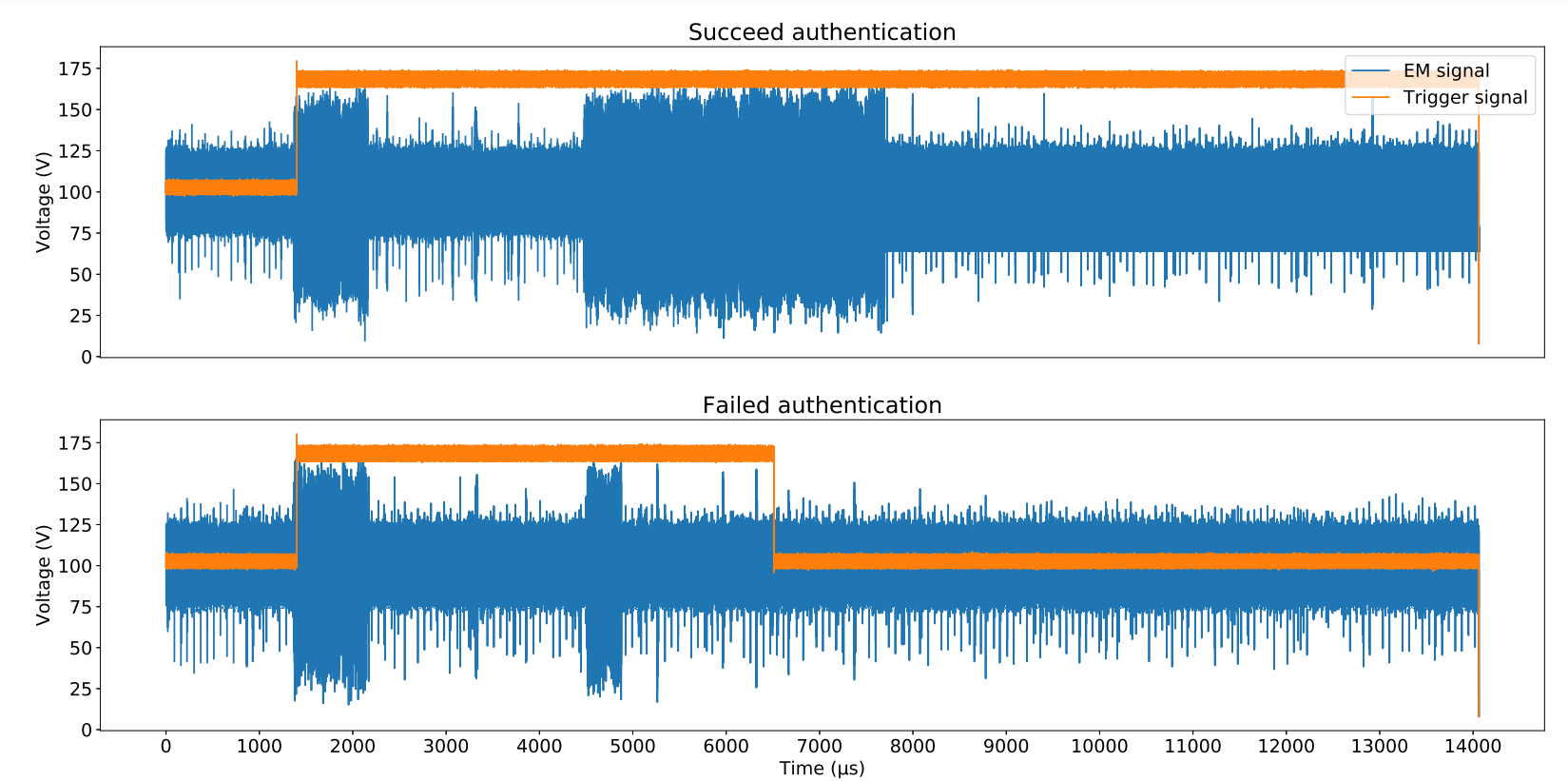


Appendice - `sudo` Forced authentication - EM analysis



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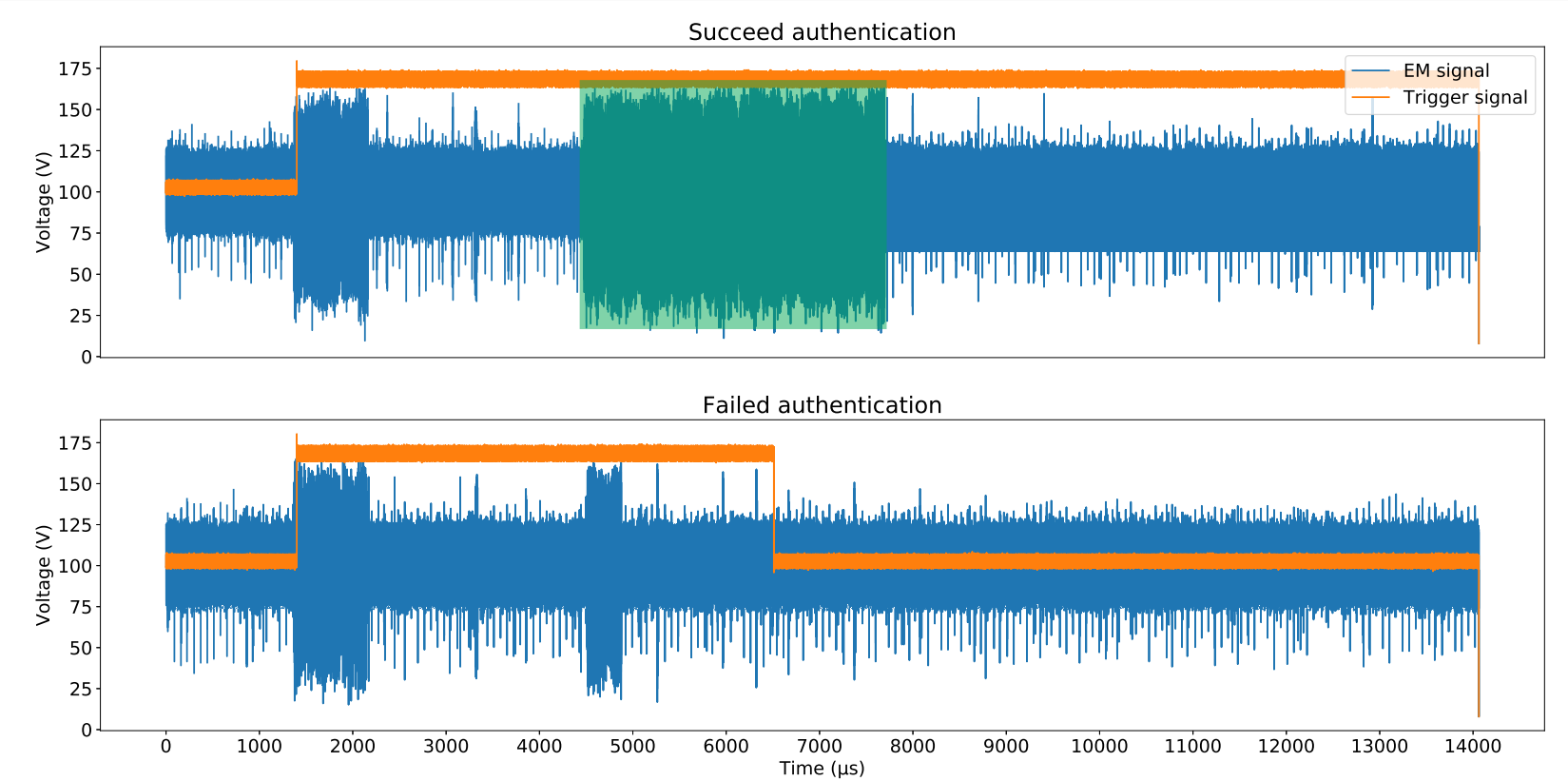


```
$6$hH.15uU5laaxuXHY$wtSOcCKWmY1JmyY2CWlVs/8ixyON36ZxQV2RpMJkITzqkIM18lyXNMICoYNIVDeUVXqHOFs39Onl6Lw8m5ArZ0
```

Appendice - `sudo` Forced authentication - EM analysis


```
$6$hH.15uU5laaxuXHY$wtSOcCKWmY1JmyY2CWlVs/8ixyON36ZxQV2RpMJkITzqkIM18lyXNMICoYNIVDeUVXqHOFs39Onl6Lw8m5ArZ0

$6$hH.15uU5laaxuXHY$4b7acwY3u21L9Wd8TxQeCIkpmasNufgDzIrScjXreP8oFQA4c.0nZmcYJB2zf5p6rDvPdBC0Fo6JWvquBKaVc.
```

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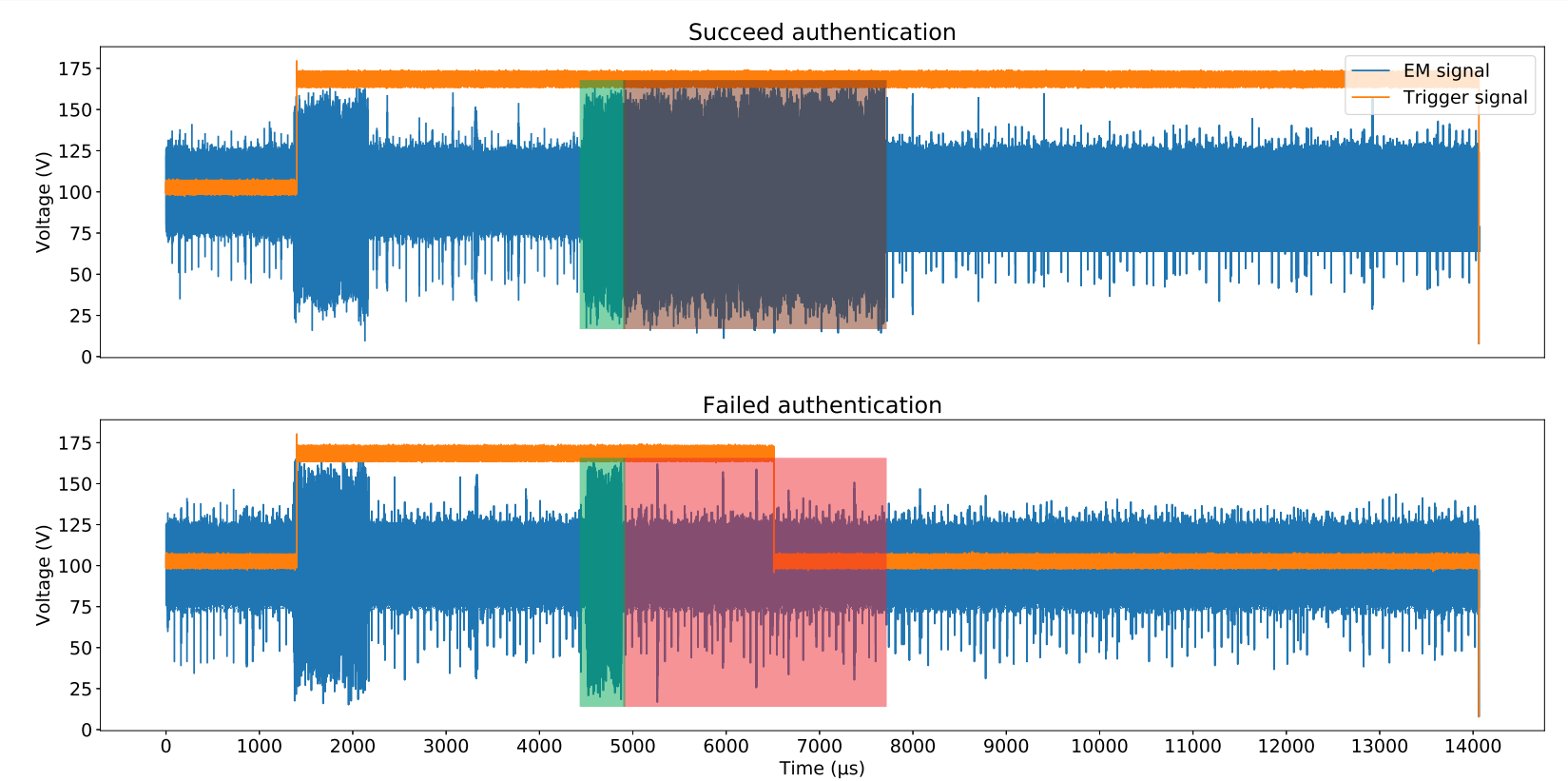


```
$6$hH.15uU5laaxuXHY$wtSOcCKWmY1JmyY2CWlVs/8ixyON36ZxQV2RpMJkITzqkIM18lyXNMICoYNIVDeUVXqHOFs390nl6Lw8m5ArZ0

$6$hH.15uU5laaxuXHY$4b7acwY3u21L9Wd8TxQeCIkpmasNufgDzIrScjXreP8oFQA4c.0nZmcYJB2zf5p6rDvPdBC0Fo6JWvquBKaVc.
```

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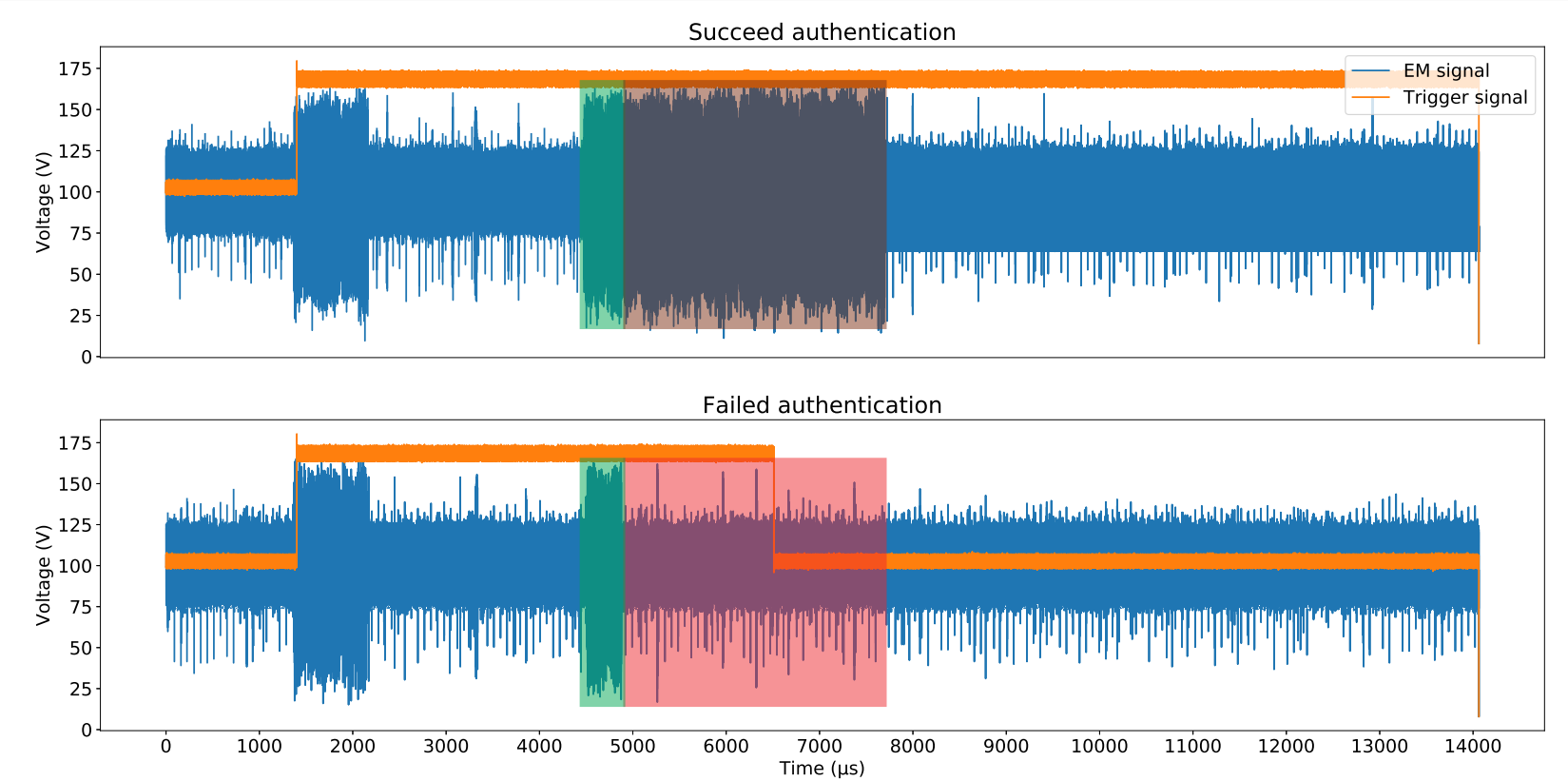


```
$6$hH.15uU5laaxuXHY$wtSOcCKWmY1JmyY2CWlVs/8ixyON36ZxQV2RpMJkITzqkIM18lyXNMICoYNIVDeUVXqHOFs390nl6Lw8m5ArZ0

$6$hH.15uU5laaxuXHY$4b7acwY3u21L9Wd8TxQeCIkpmasNufgDzIrScjXreP8oFQA4c.0nZmcYJB2zf5p6rDvPdBC0Fo6JWvquBKaVc.
```

`strncmp()` in `verify_pwd_hash()` in `pam_unix.so`

PoC of forced authentication done in [Gai+20]

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