Modern System On Chips Security Against Physical Attacks

GDR Sécurité

Thomas Trouchkine

July 1, 2021

Slides available at `https://thomas.trouchkine.com/assets/pdf/gdr_sec_2021.pdf`

Introduction - About me

- Hardware security expert at ANSSI
- Focus on fault attacks on modern SoCs

Introduction - Handling sensitive operations

Sensitive operations

Introduction - Handling sensitive operations

Sensitive operations

Payment

Healthcare

Identification

Introduction - Handling sensitive operations

Sensitive operations

Payment

Healthcare

Identification

Historically

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

Introduction - Handling sensitive operations

Sensitive operations

Payment Healthcare Identification

Historically

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

Nowadays

- handled by smartphones or laptops
- performance designed devices
- security added recently
- no security evaluation

Introduction - SEs vs SoCs

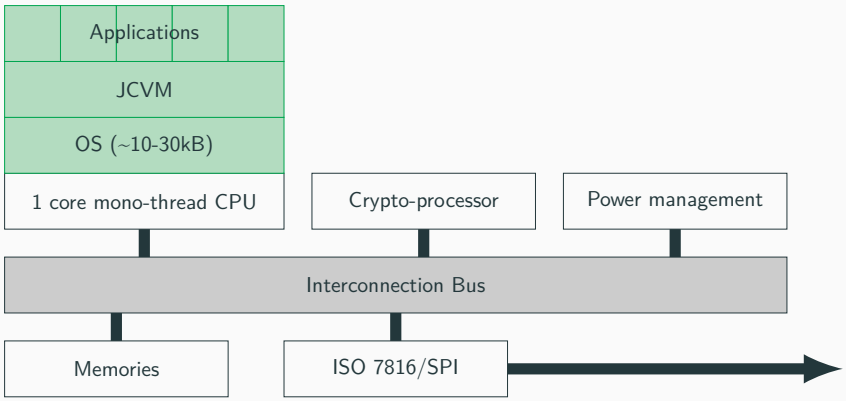
Smartcards

Smartphones

Introduction - SEs vs SoCs

Smartcards

- secure elements (SEs)

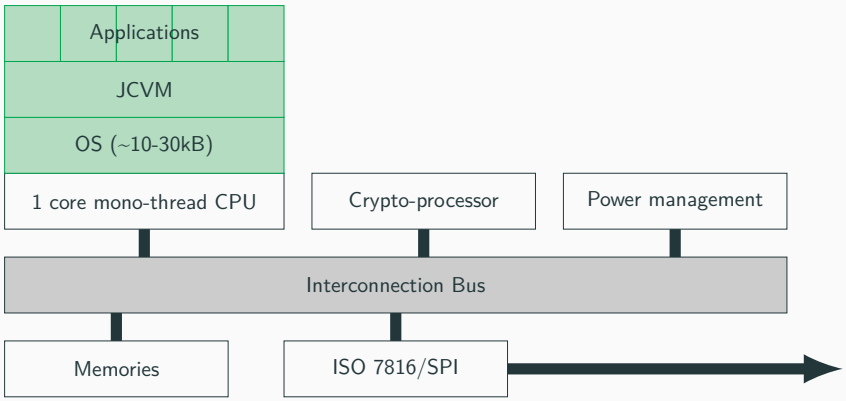


Smartphones

Introduction - SEs vs SoCs

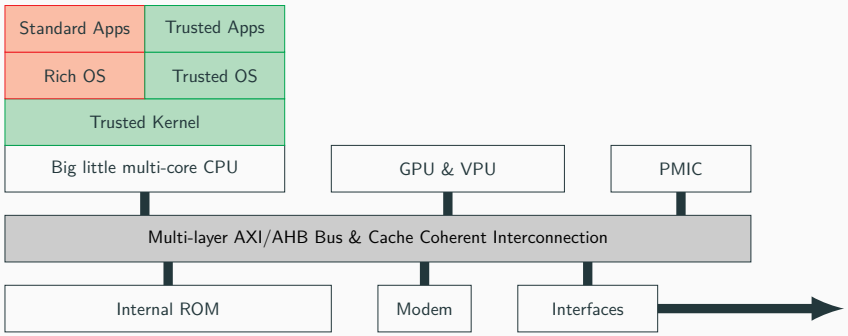
Smartcards

- secure elements (SEs)

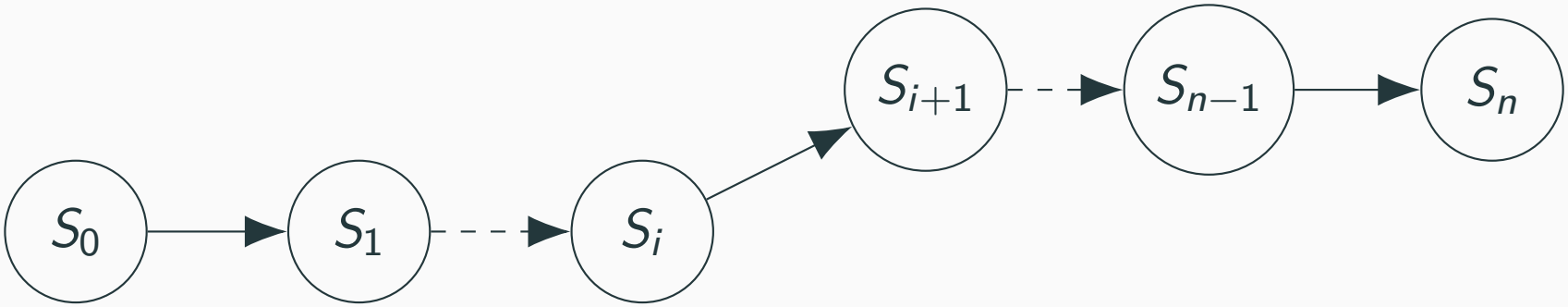


Smartphones

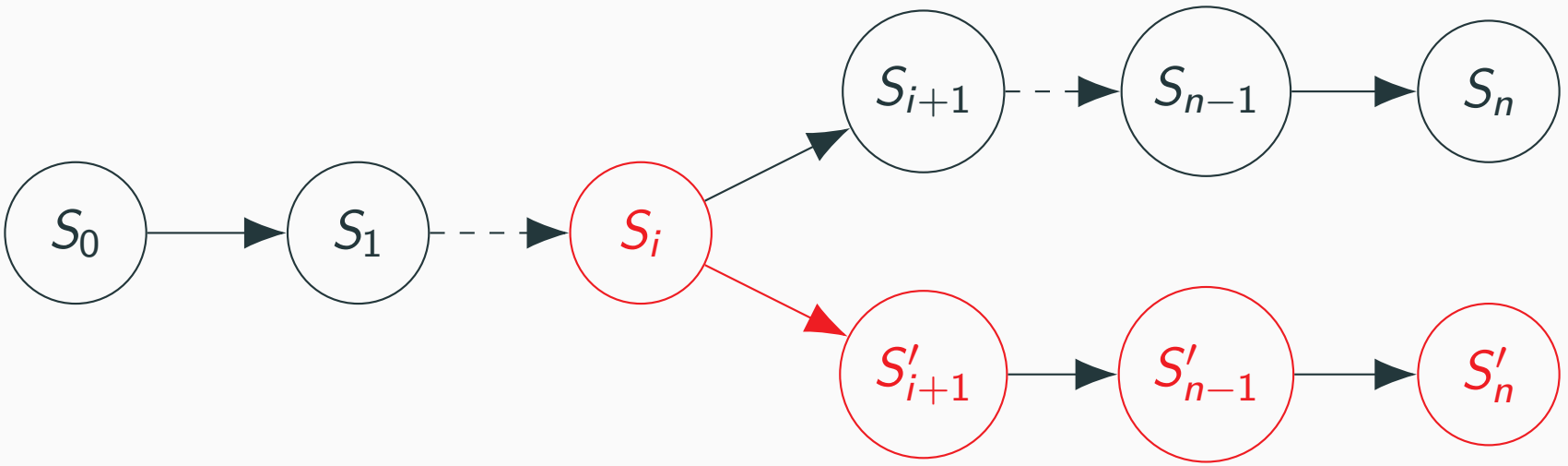
- complex systems on chip (SoCs)



Introduction - Perturbation attacks



Introduction - Perturbation attacks



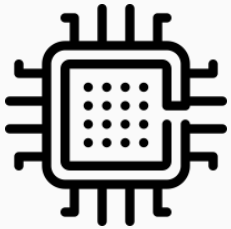
Introduction - Perturbation attacks

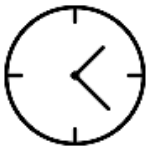
Electromagnetic waves

Temperature

Voltage

Light





Clock

X-ray

Body biasing

Software

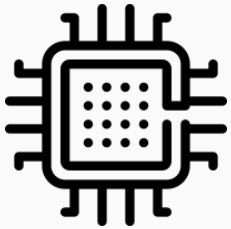
Introduction - Perturbation attacks

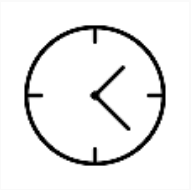
Electromagnetic waves [OGM15; DLM19]

Temperature

Voltage

Light [Sam+02; SHP09]





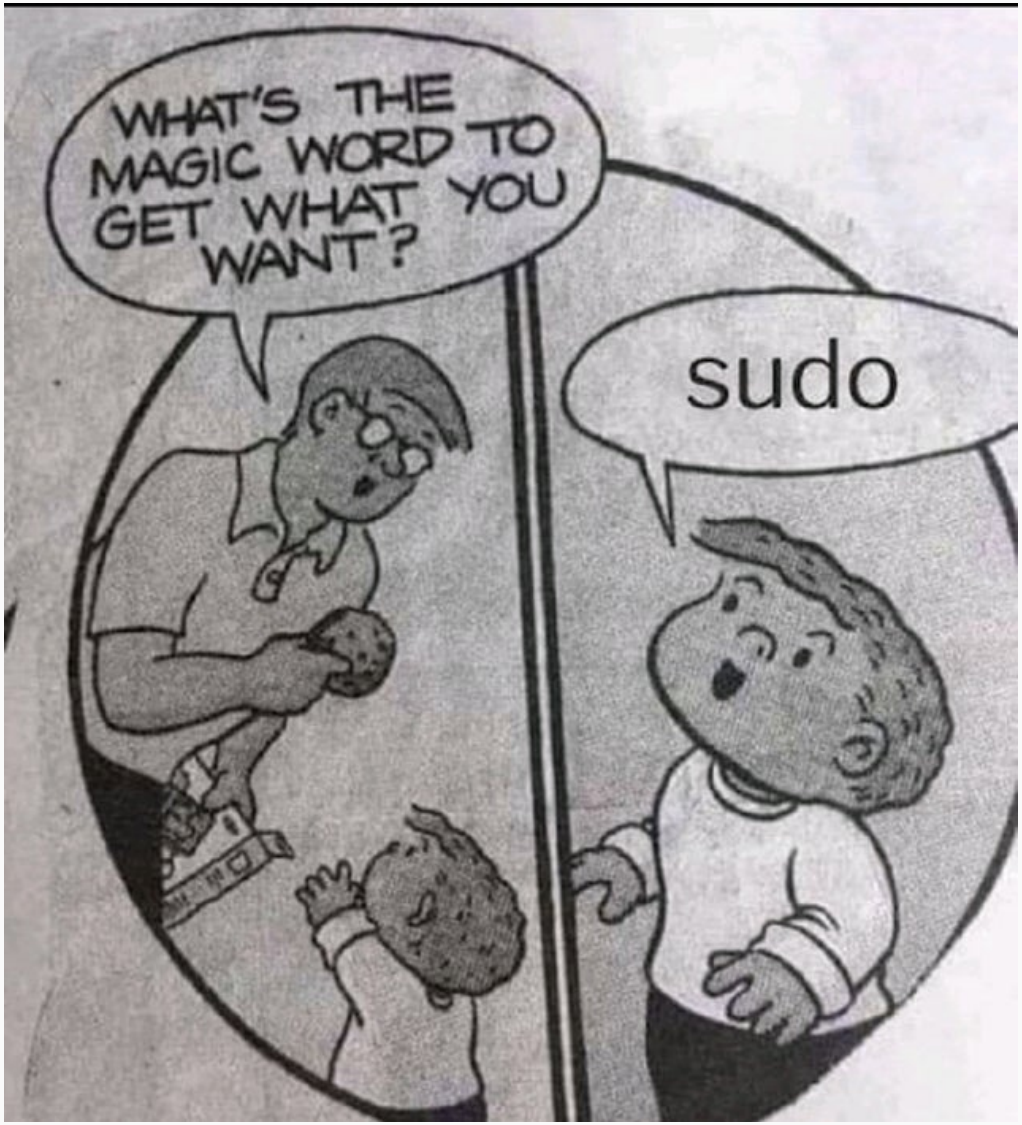
Clock

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

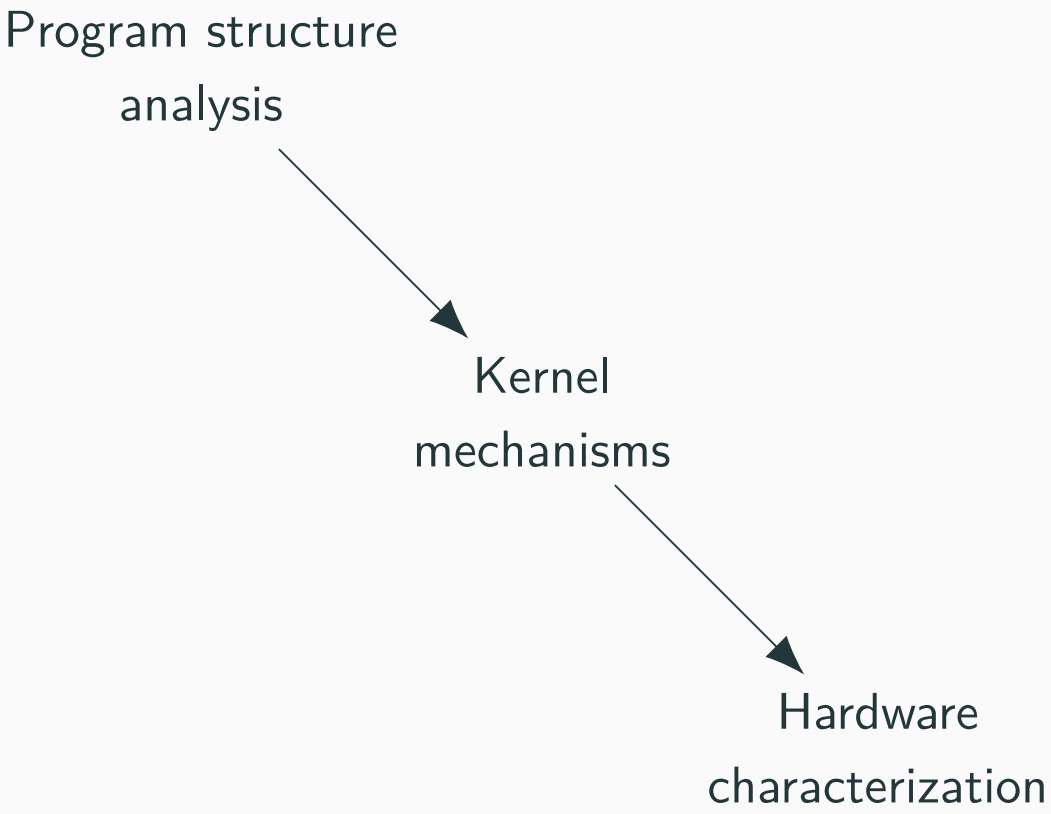
Targets

BCM2837
(Raspberry Pi 3 B)

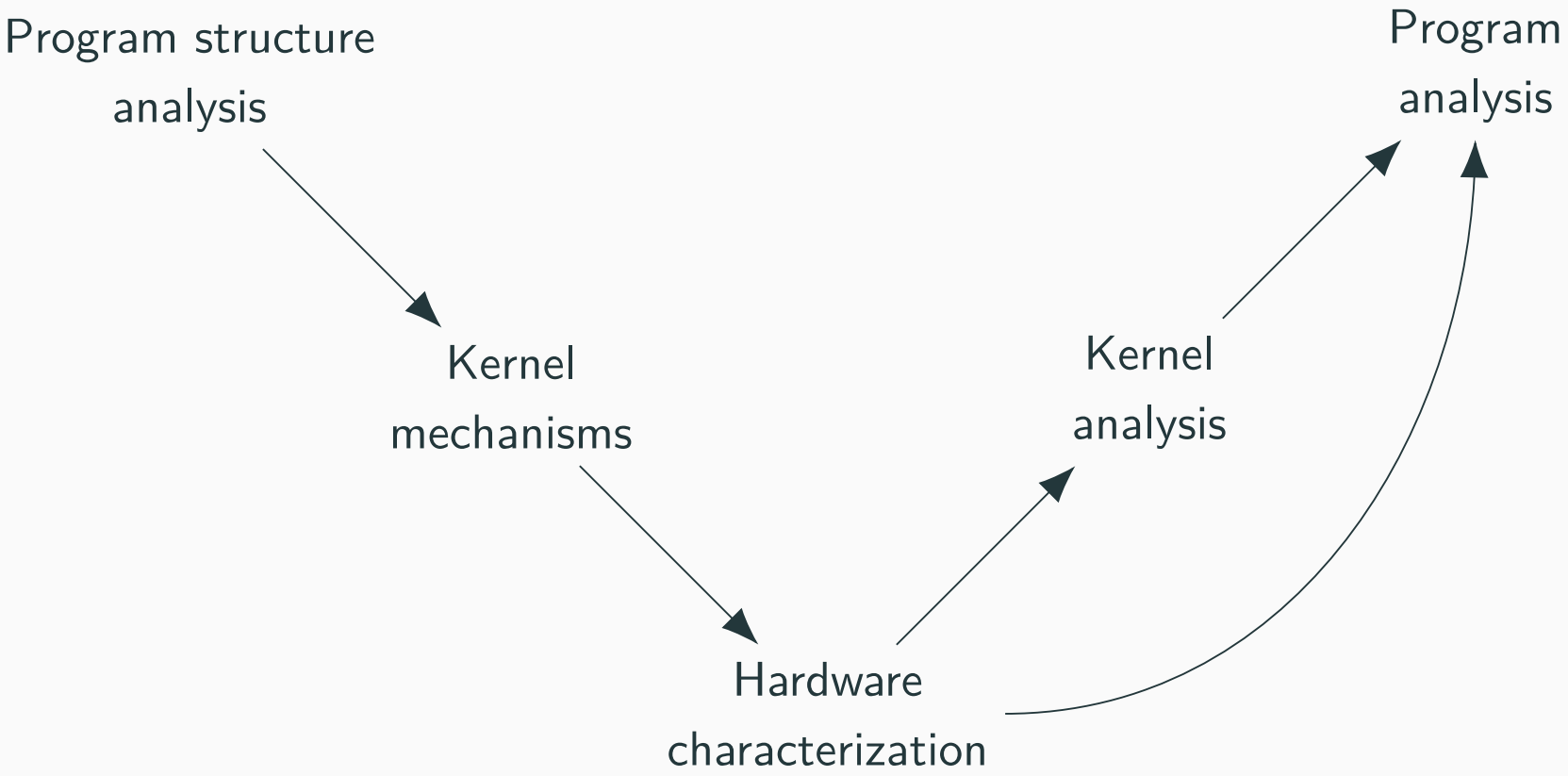
Intel Core i3-6100T
(Custom motherboard)

BCM2711b0
(Raspberry Pi 4)

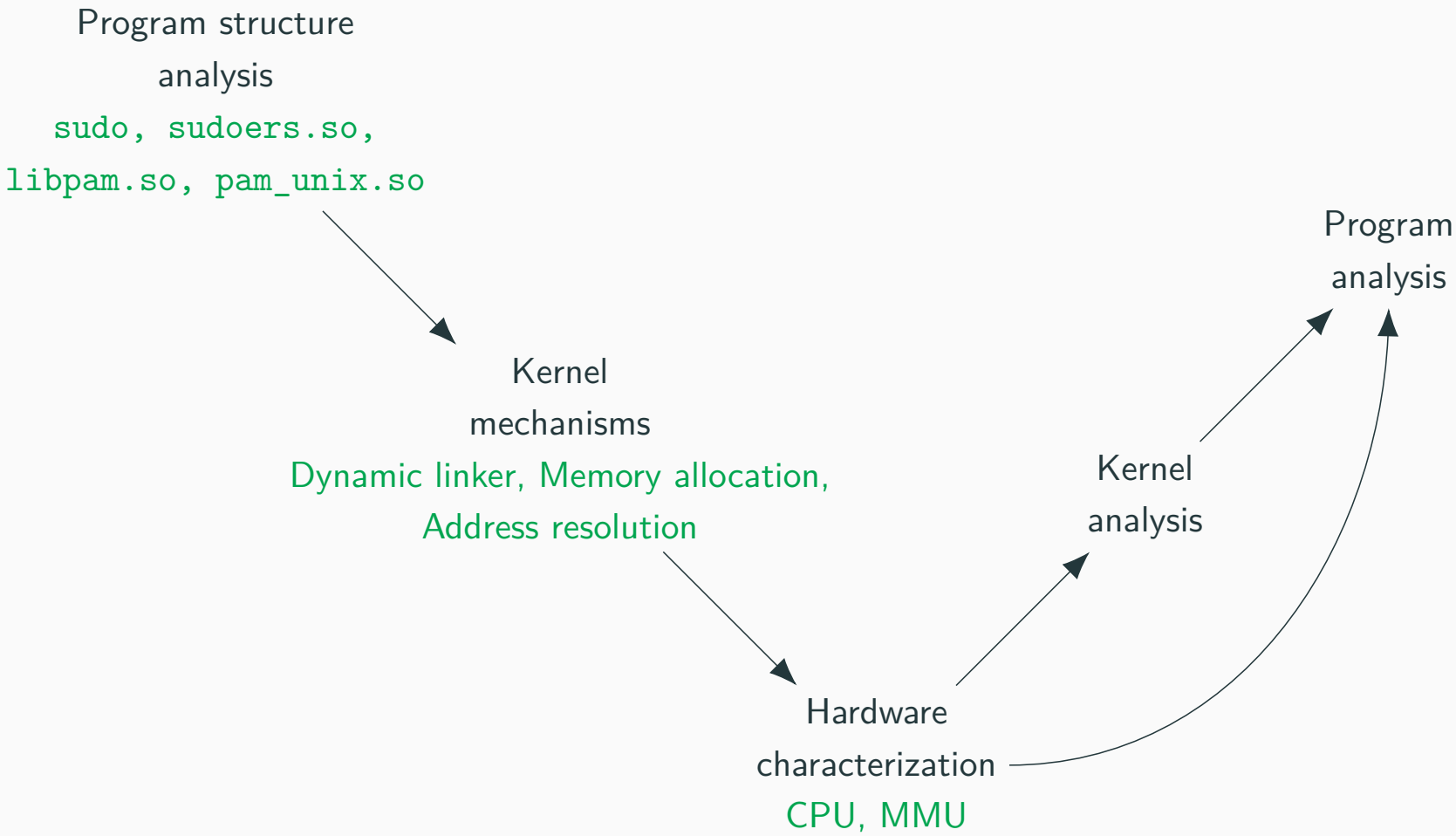
Case study - Evaluation methodology



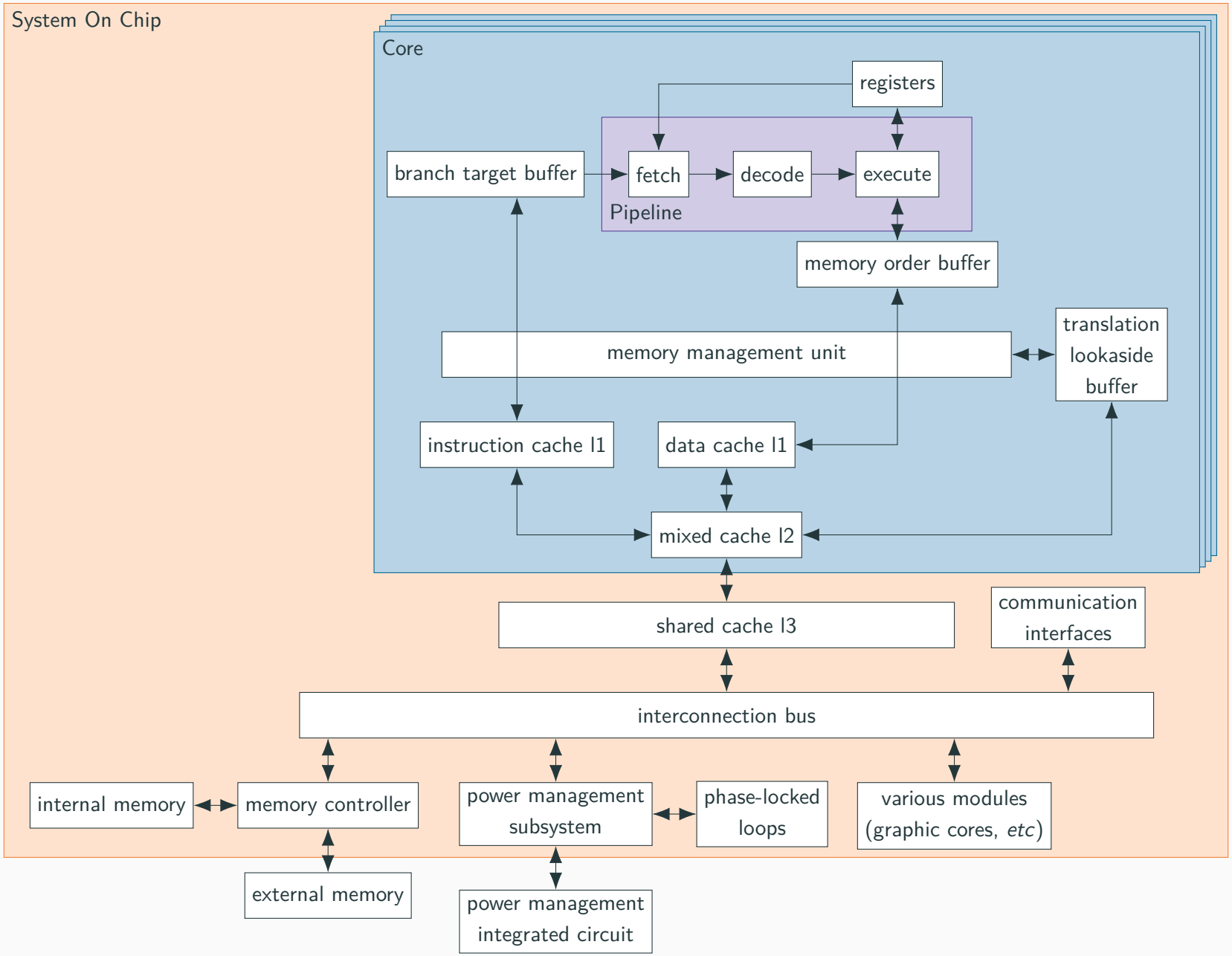
Case study - Evaluation methodology



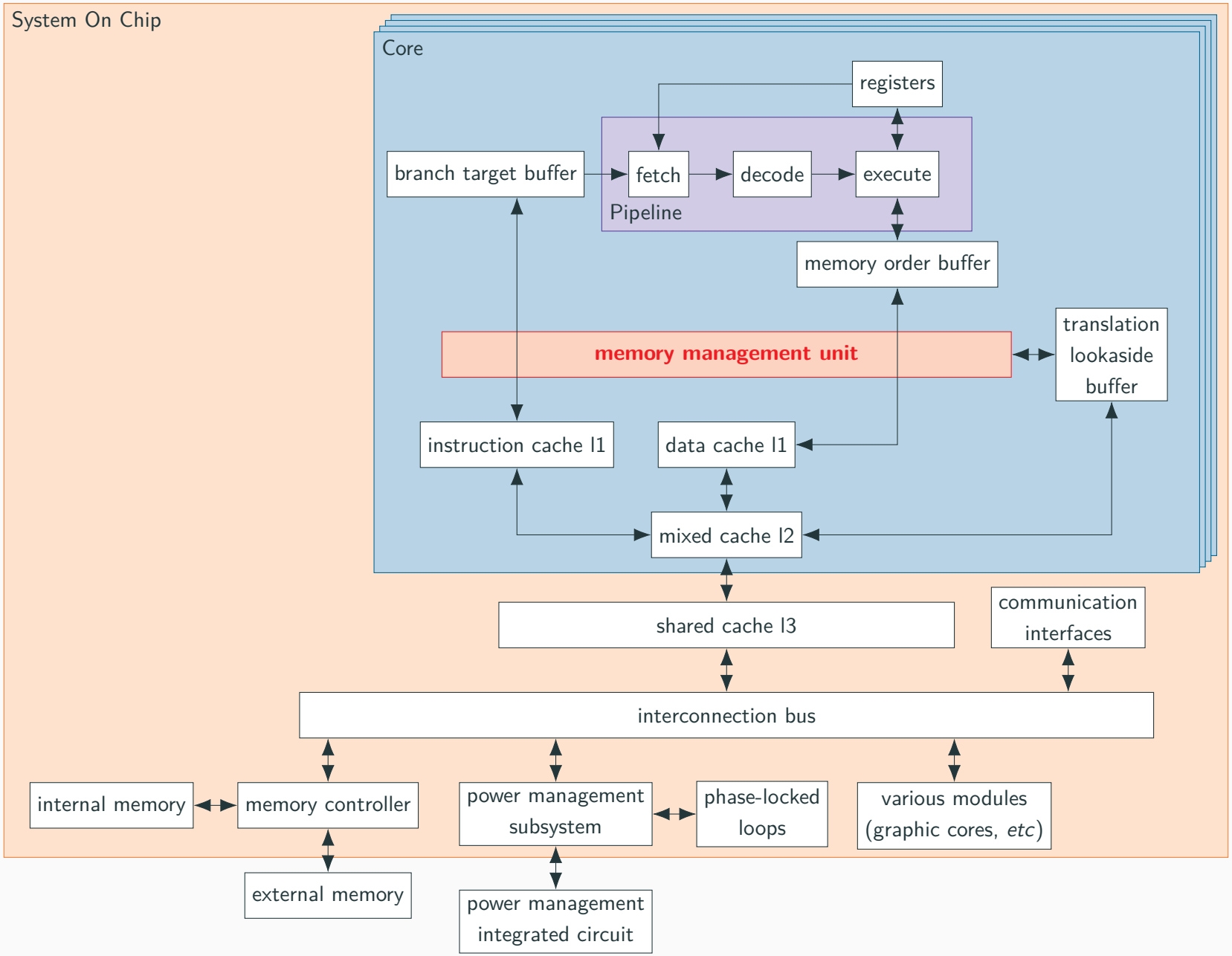
Case study - Evaluation methodology



Case study - SoC architecture



Case study - SoC architecture



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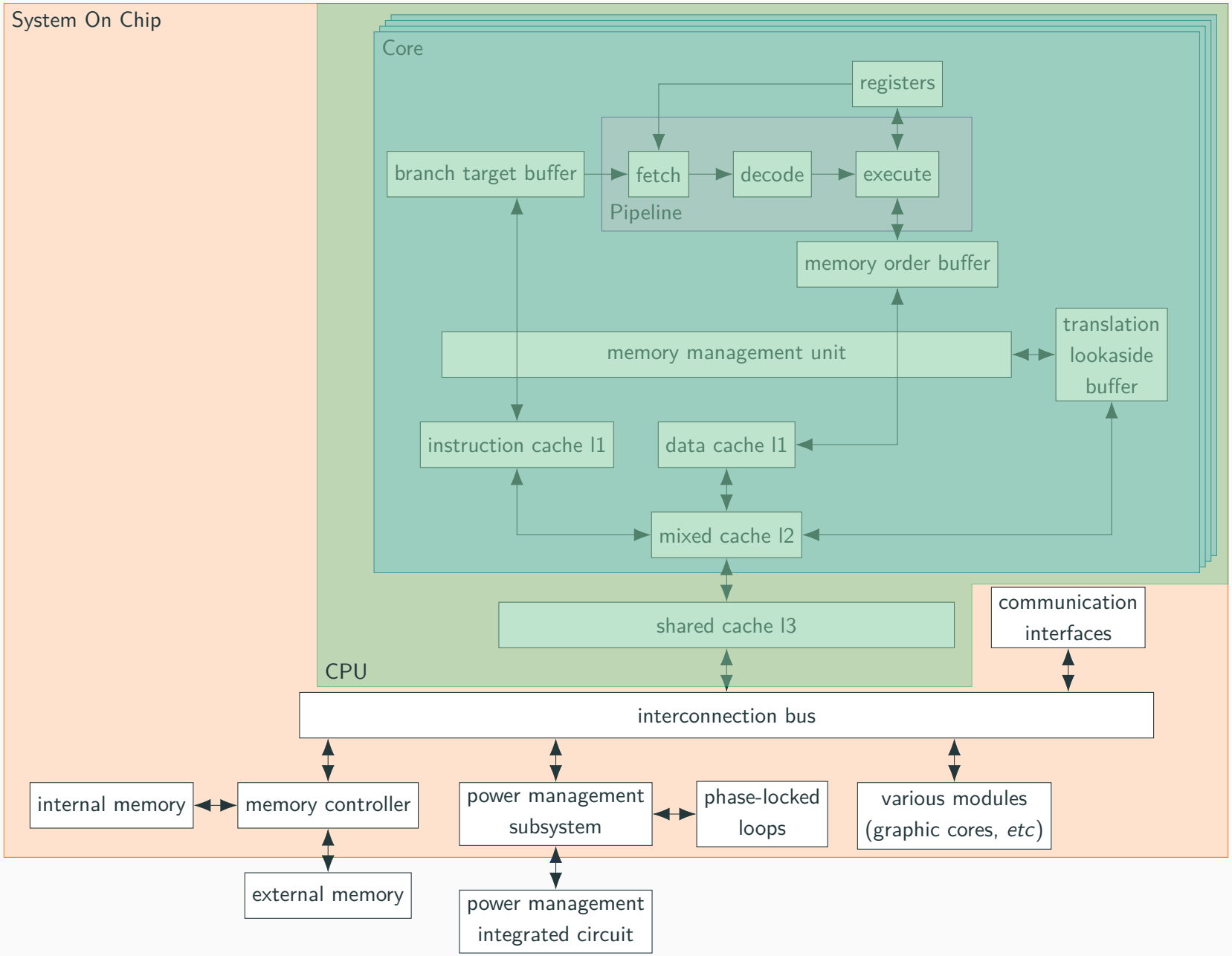
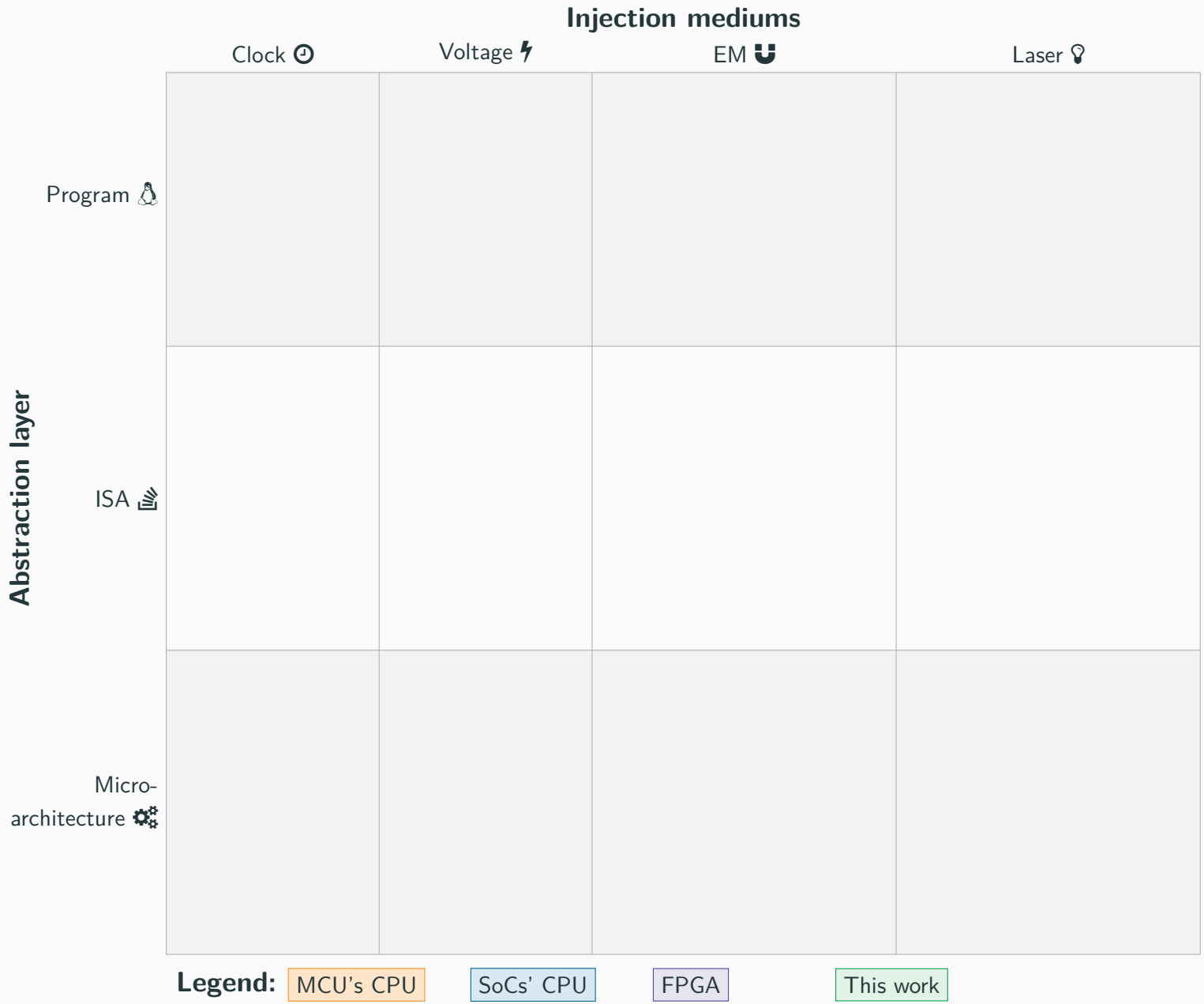


Characterization - State of the art



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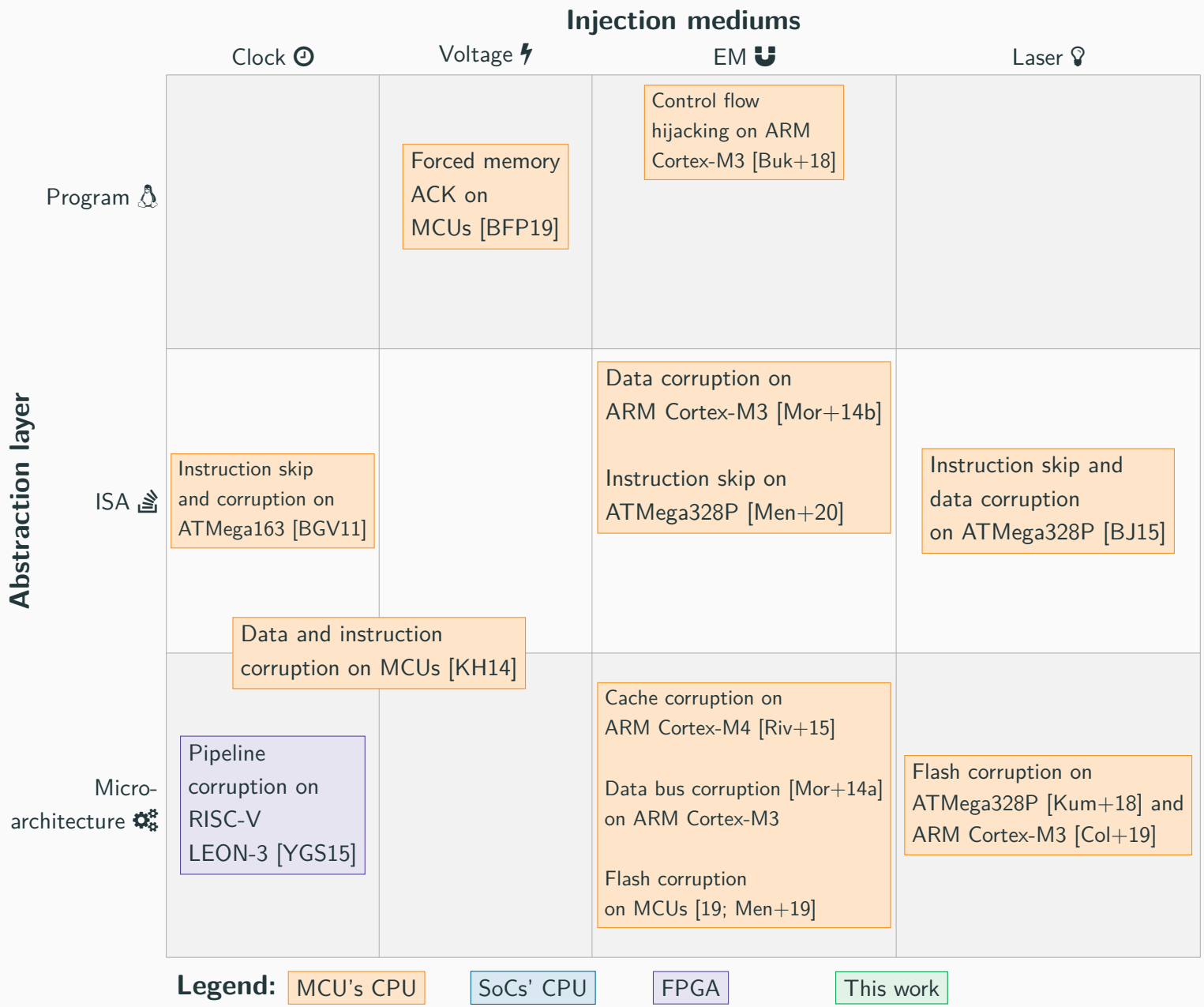

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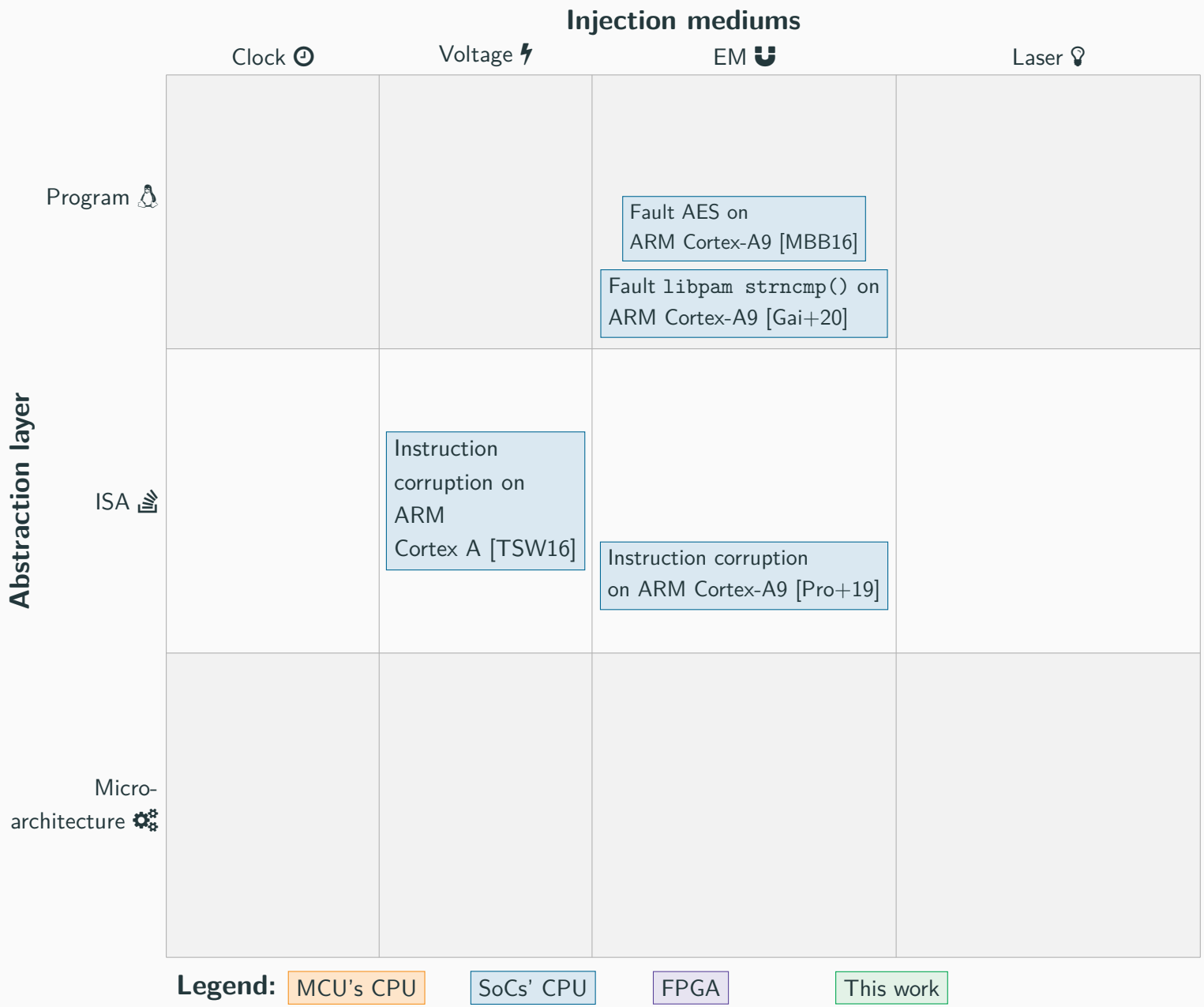

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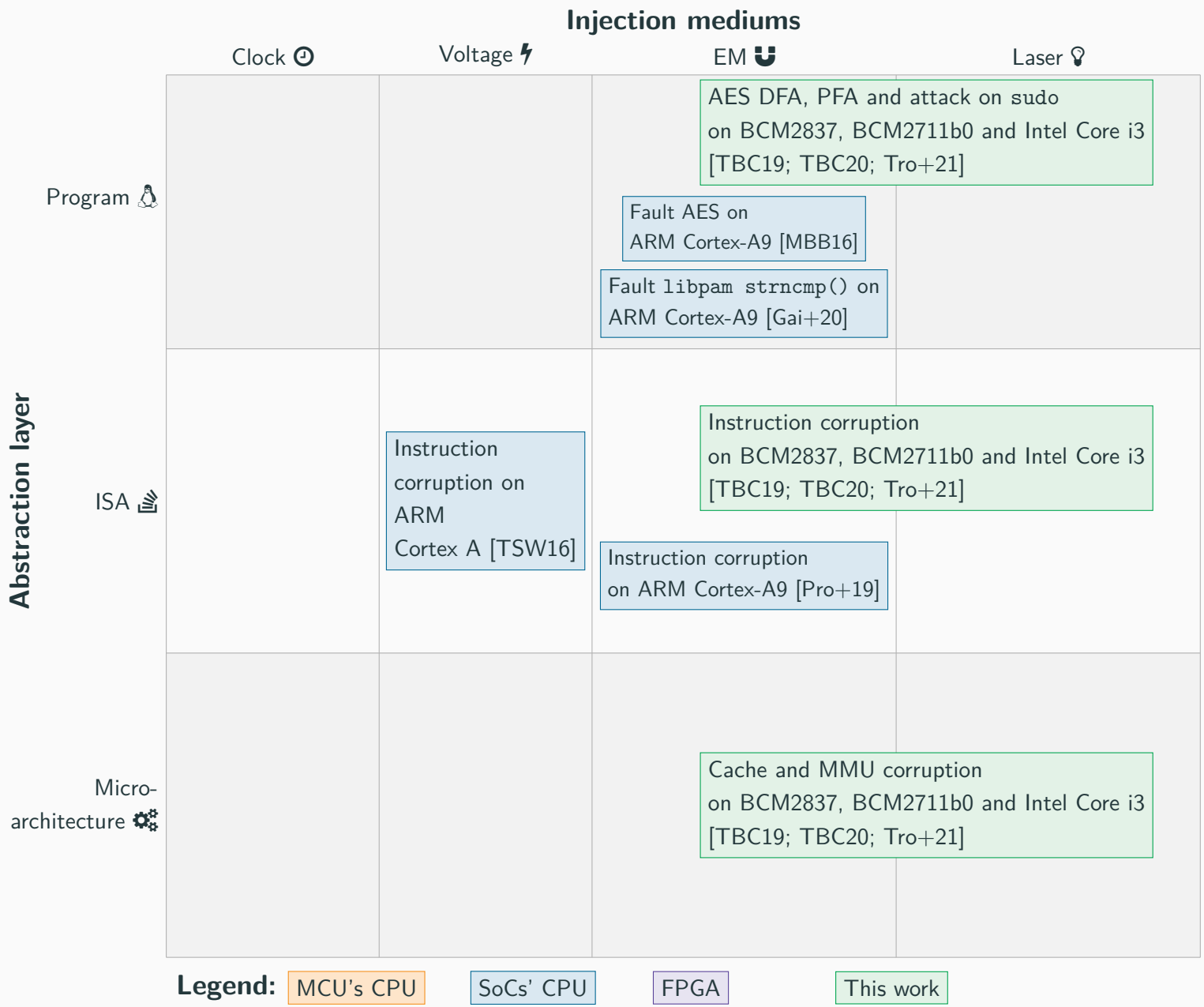

Case study - Characterization Method

Test program

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

Case study - Characterization Method

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Initial values

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

Case study - Characterization Method

Test program

```
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/*
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```

Initial values

Register	Initial values
r0	0xfffe0001
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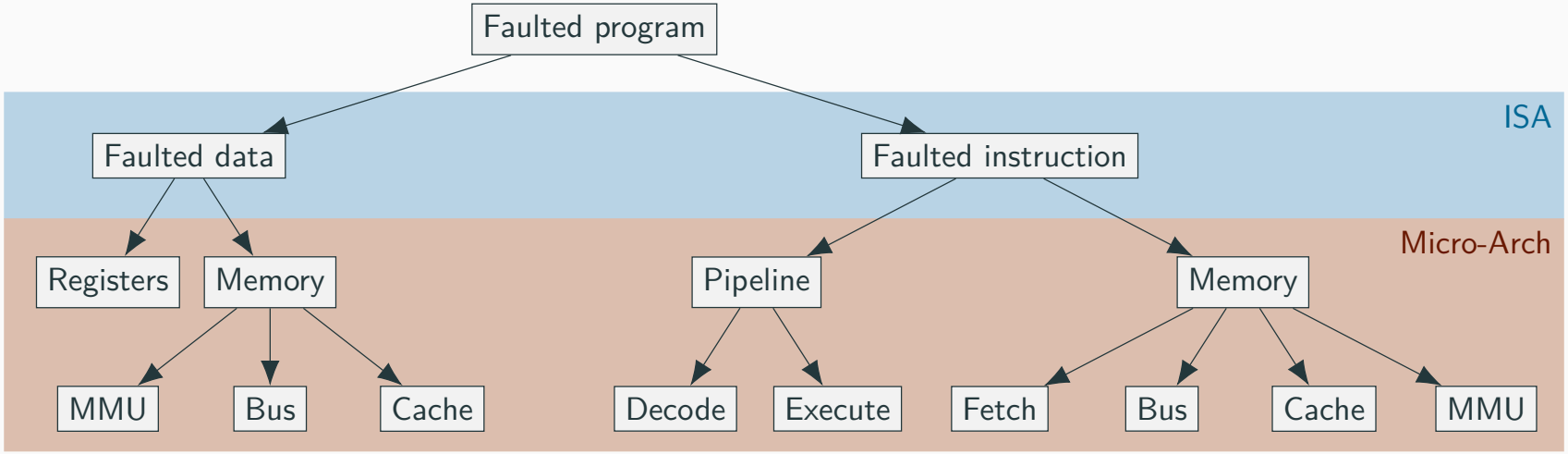
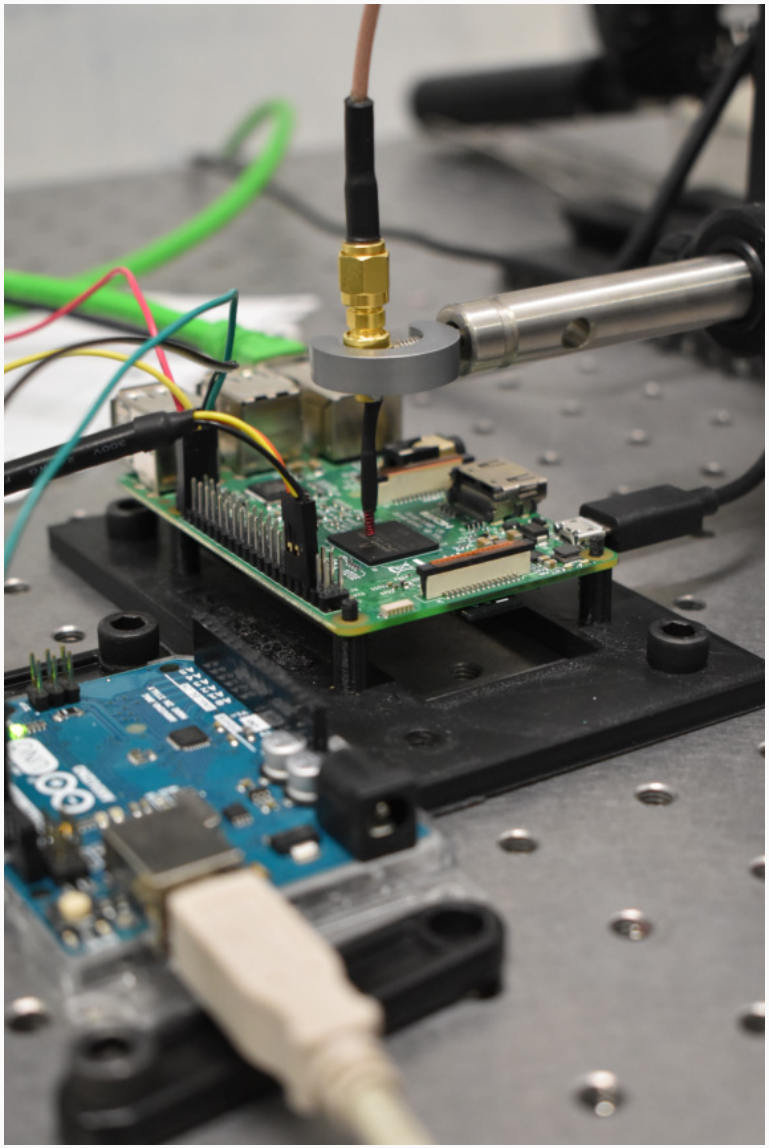
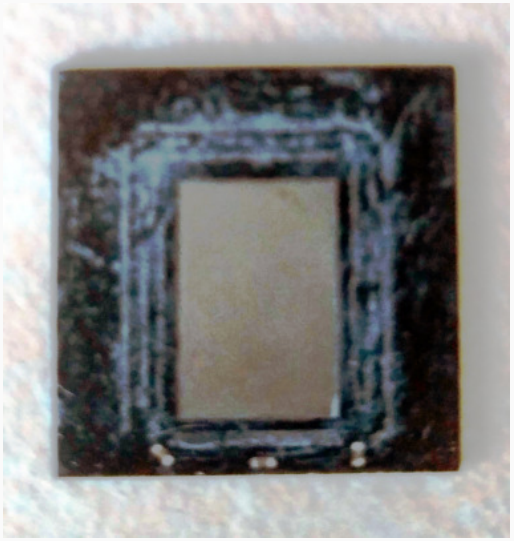
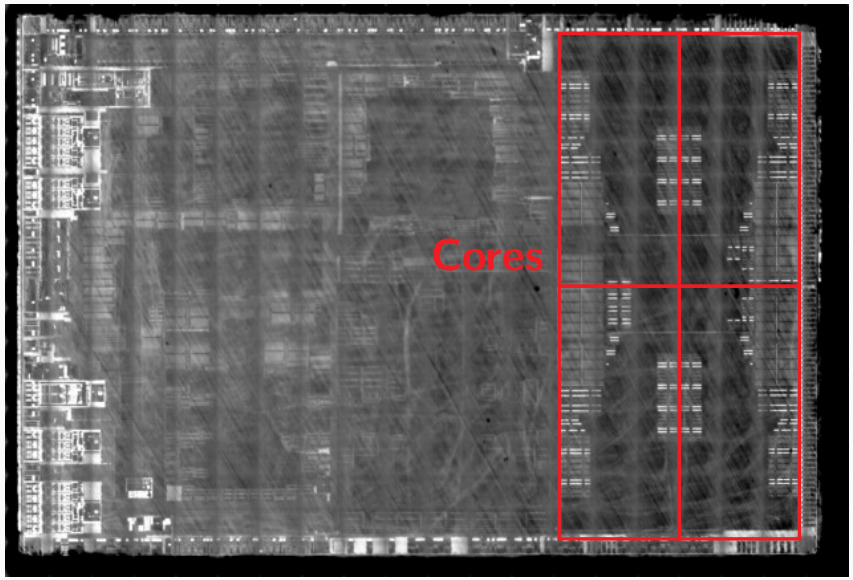
Top down approach



Characterization - BCM2837 (Raspberry Pi 3)







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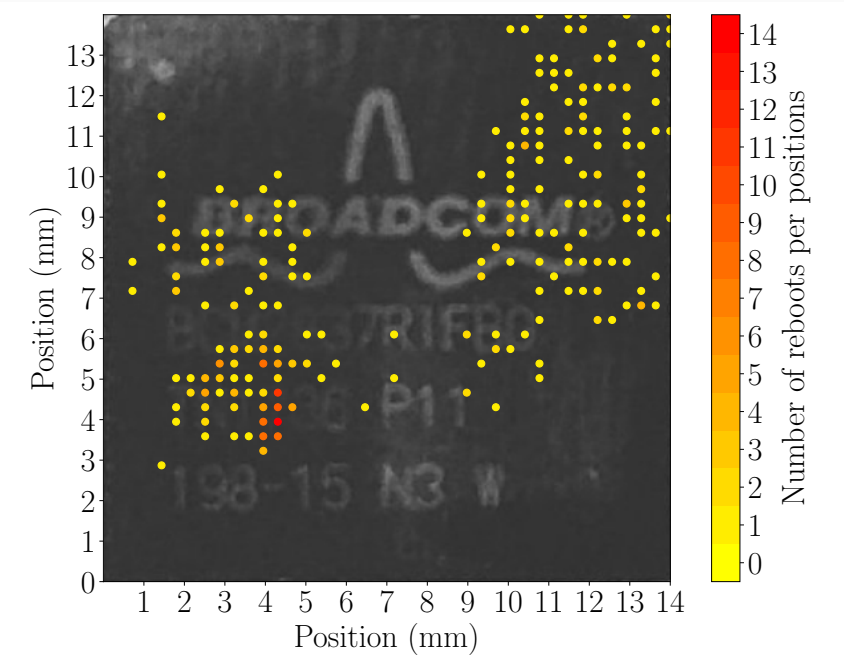
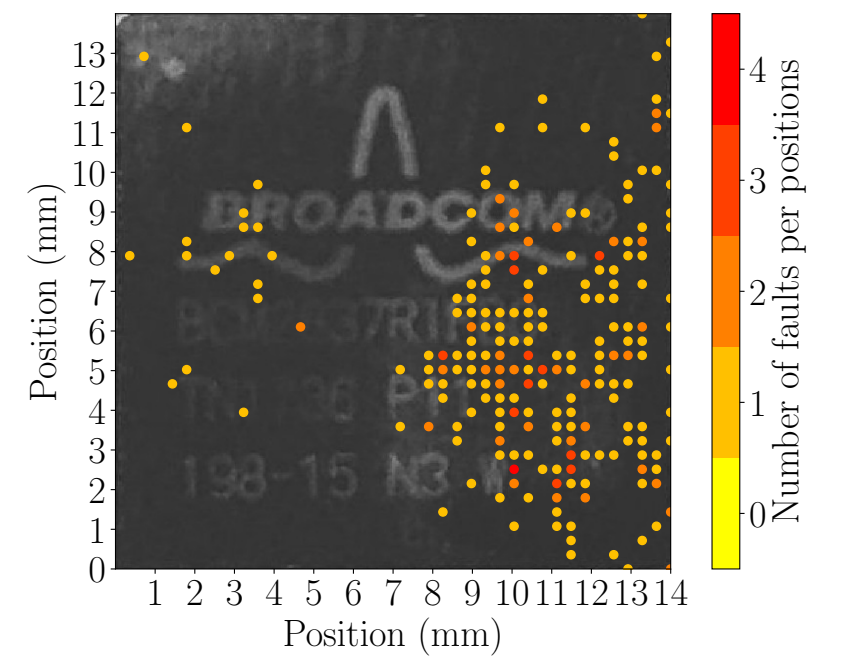


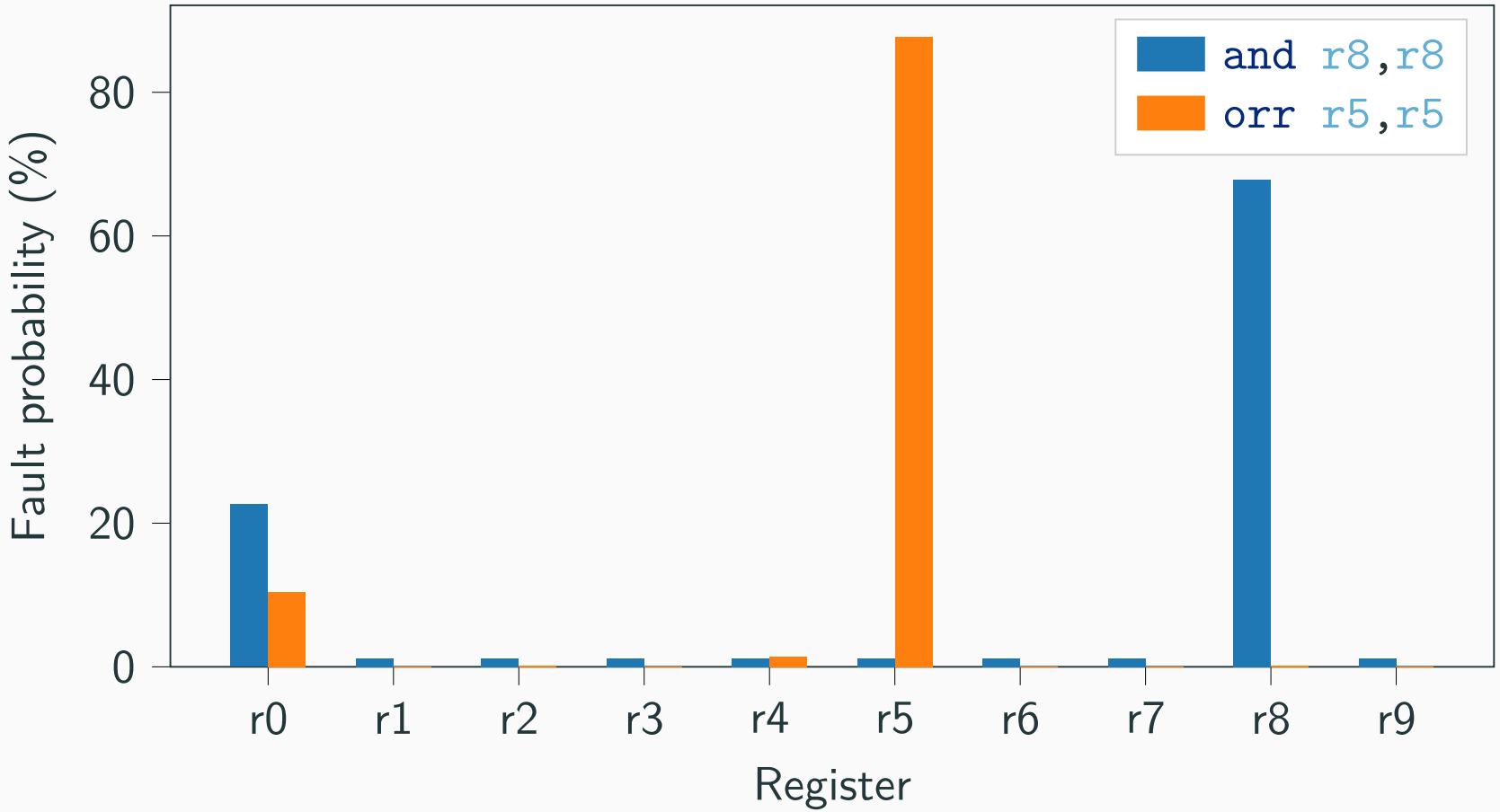
Spots leading to reboots



Spots leading to faults

Characterization - BCM2837

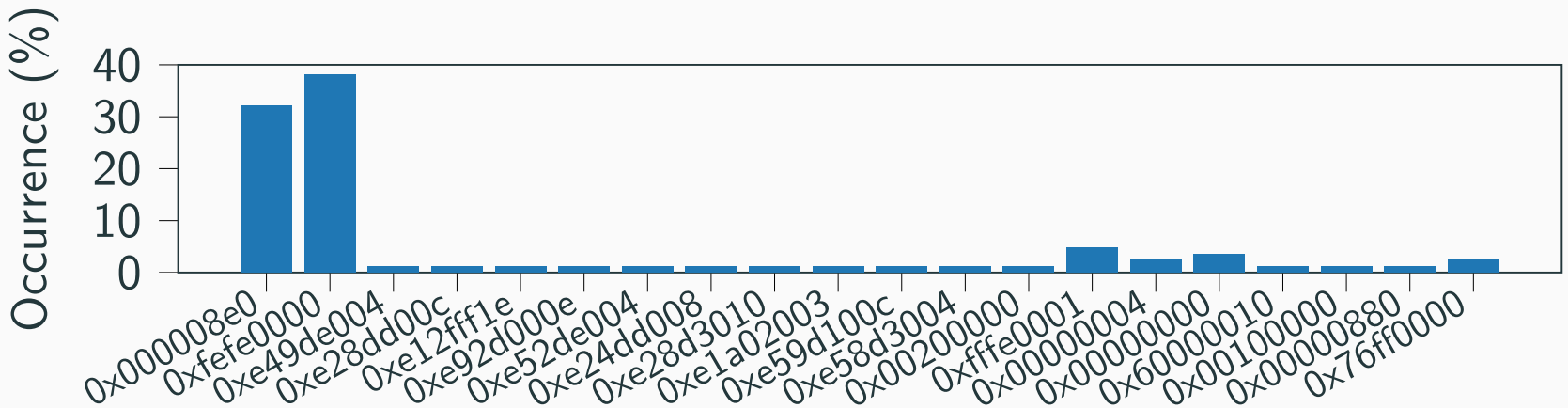
Faulted register distribution regarding the executed instruction



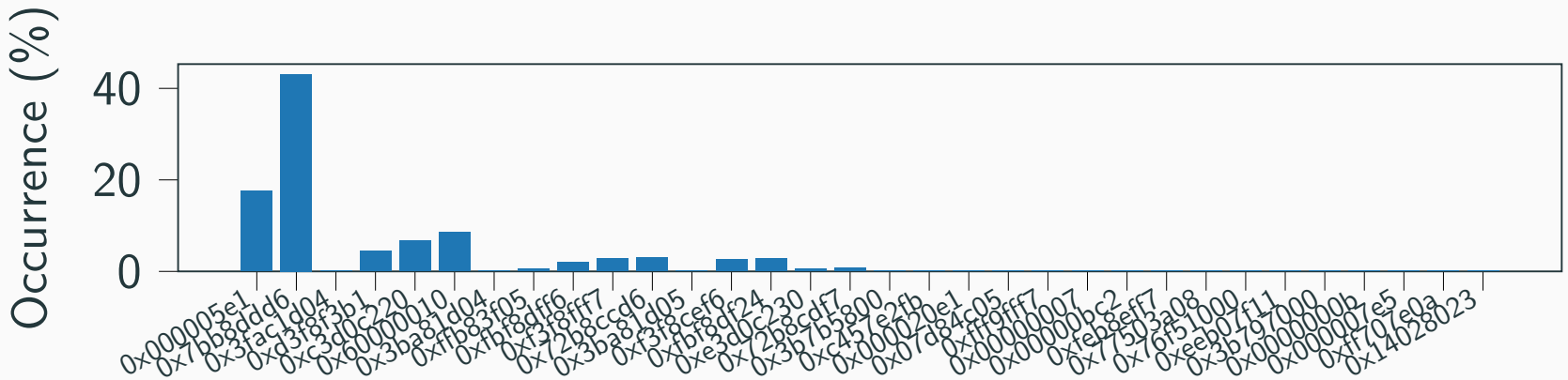
Characterization - BCM2837

Faulted value distribution regarding the executed instruction

`and r8,r8`

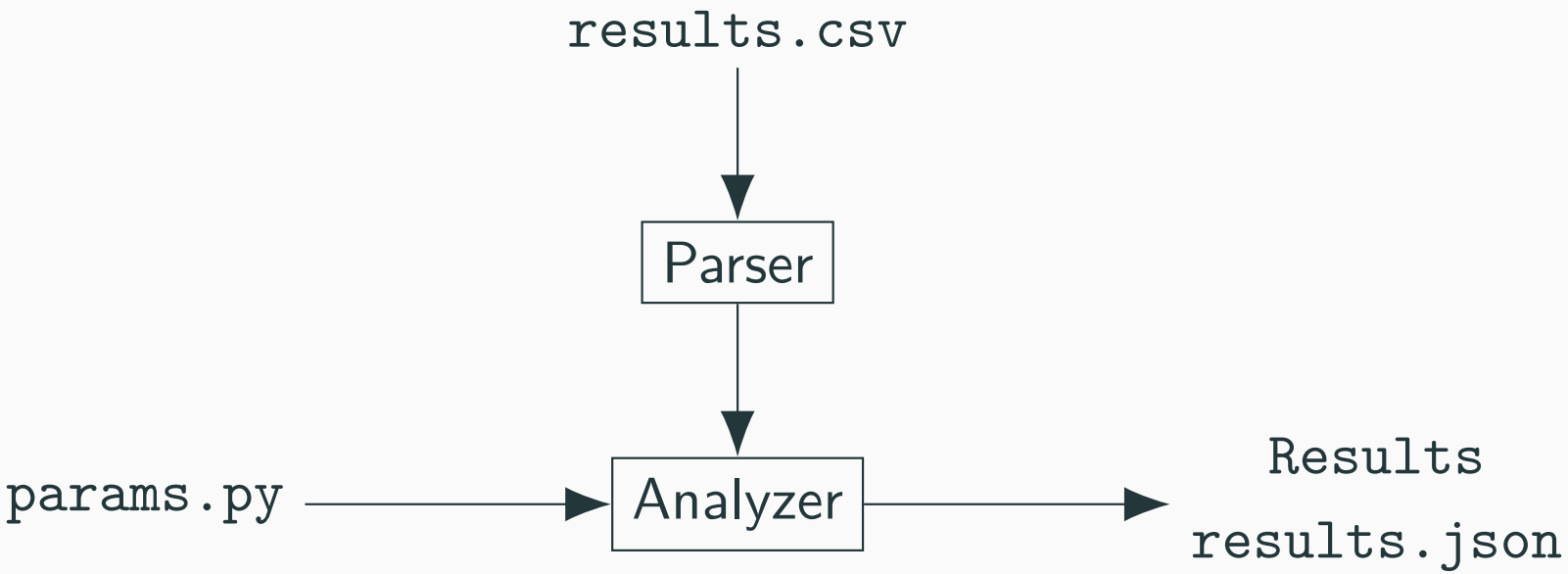


`orr r5,r5`



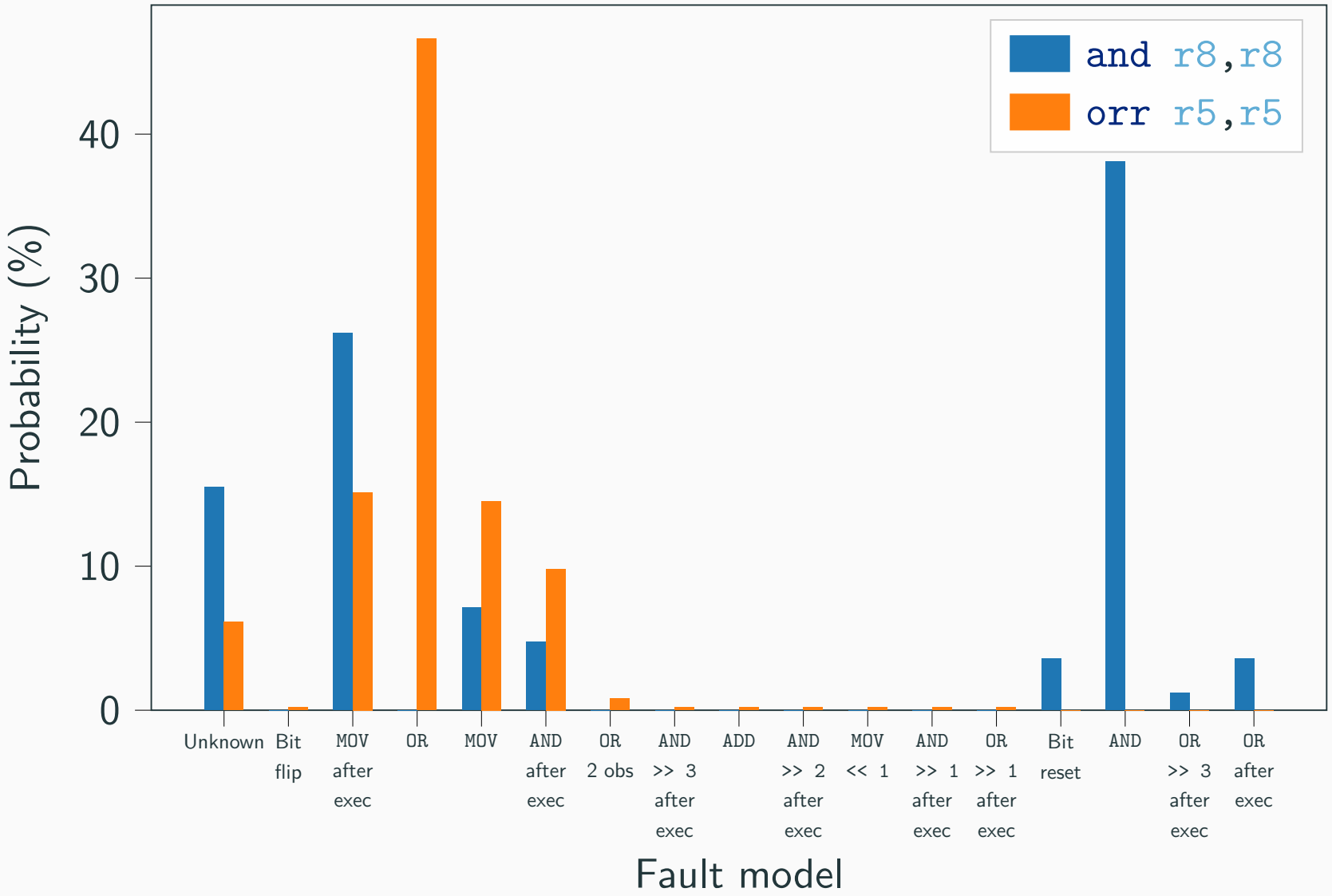
Faulted values

Characterization - Analysis tool



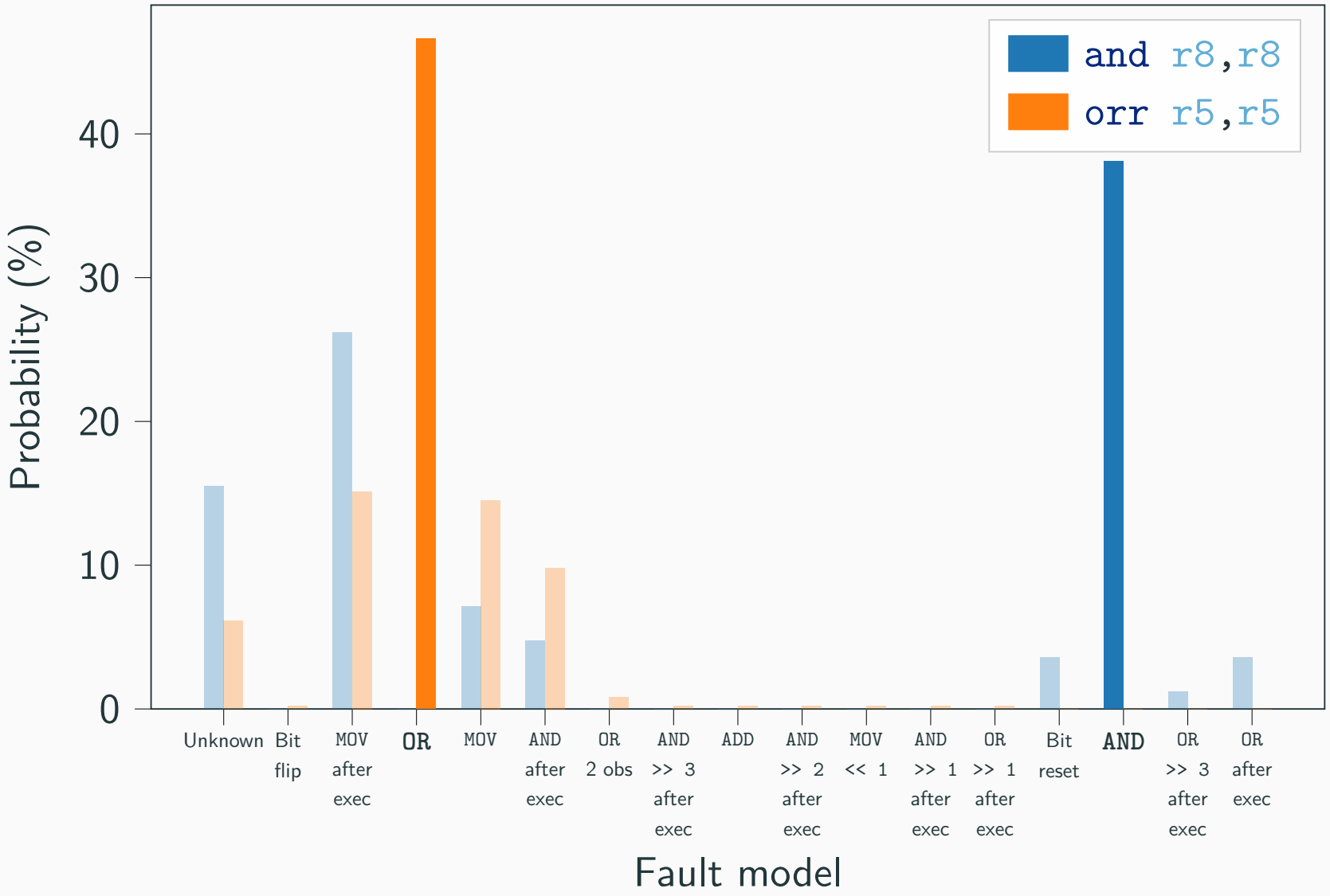
Characterization - BCM2837

Fault model distribution regarding the executed instruction



Characterization - BCM2837

Fault model distribution regarding the executed instruction



Characterization - BCM2837

Instruction matching the `OR` 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

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Faulted instruction	Occurrence (%)
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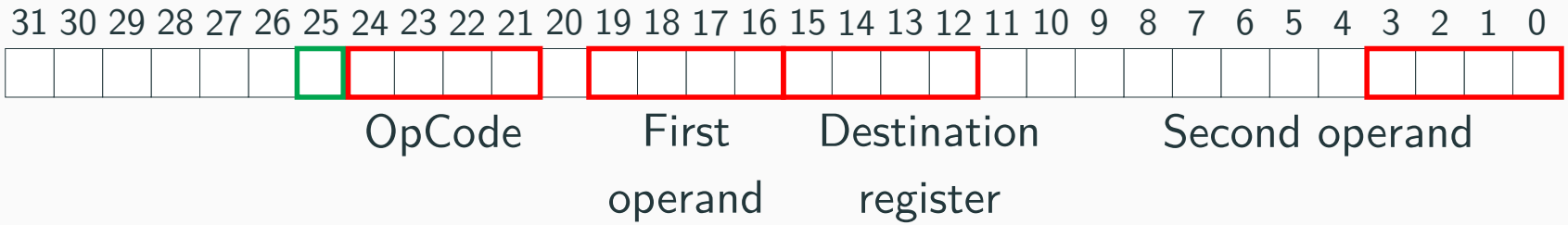
`orr r5,r7`	1.32 %

Instruction matching the `AND` 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



ARM data processing instruction encoding

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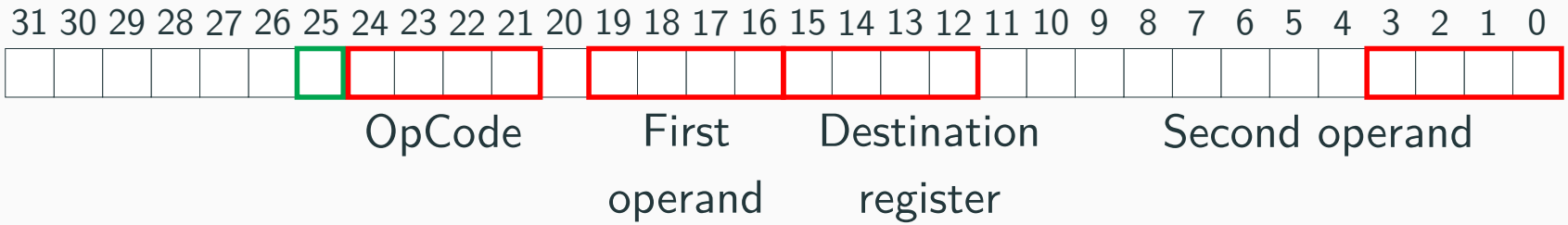
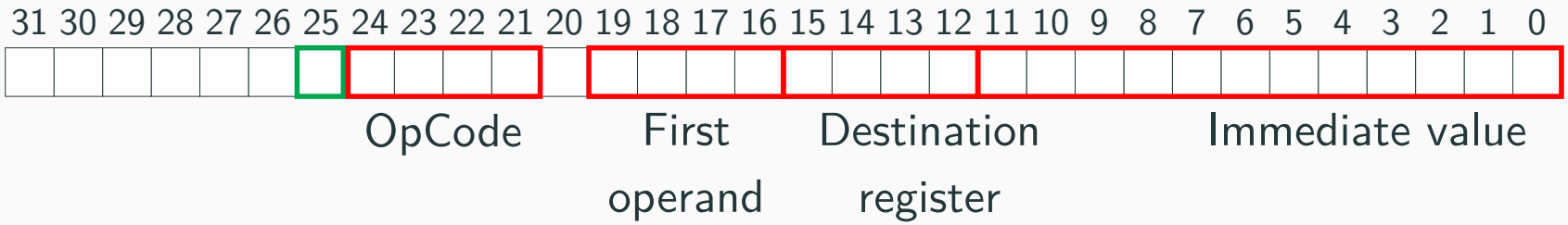
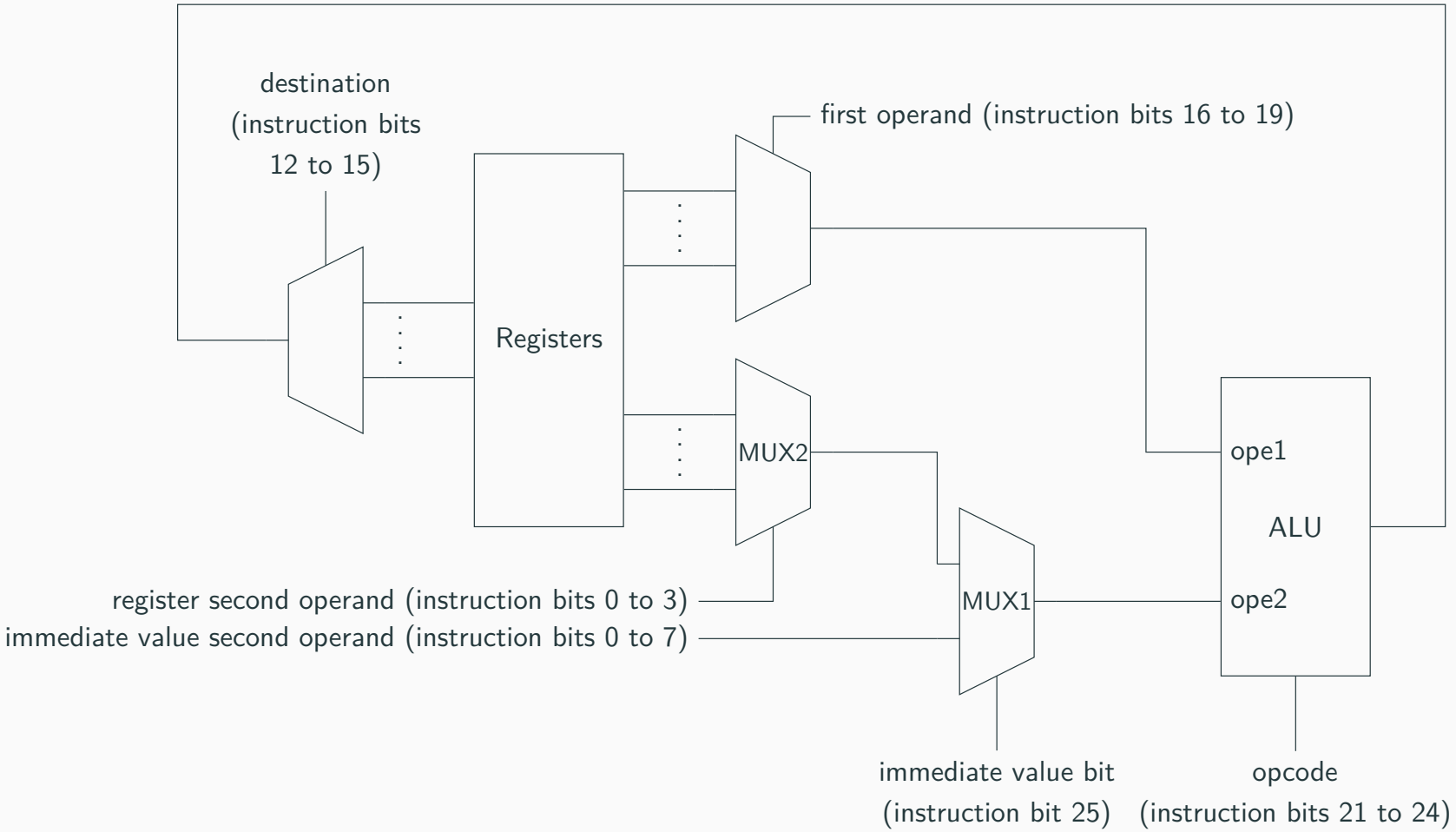


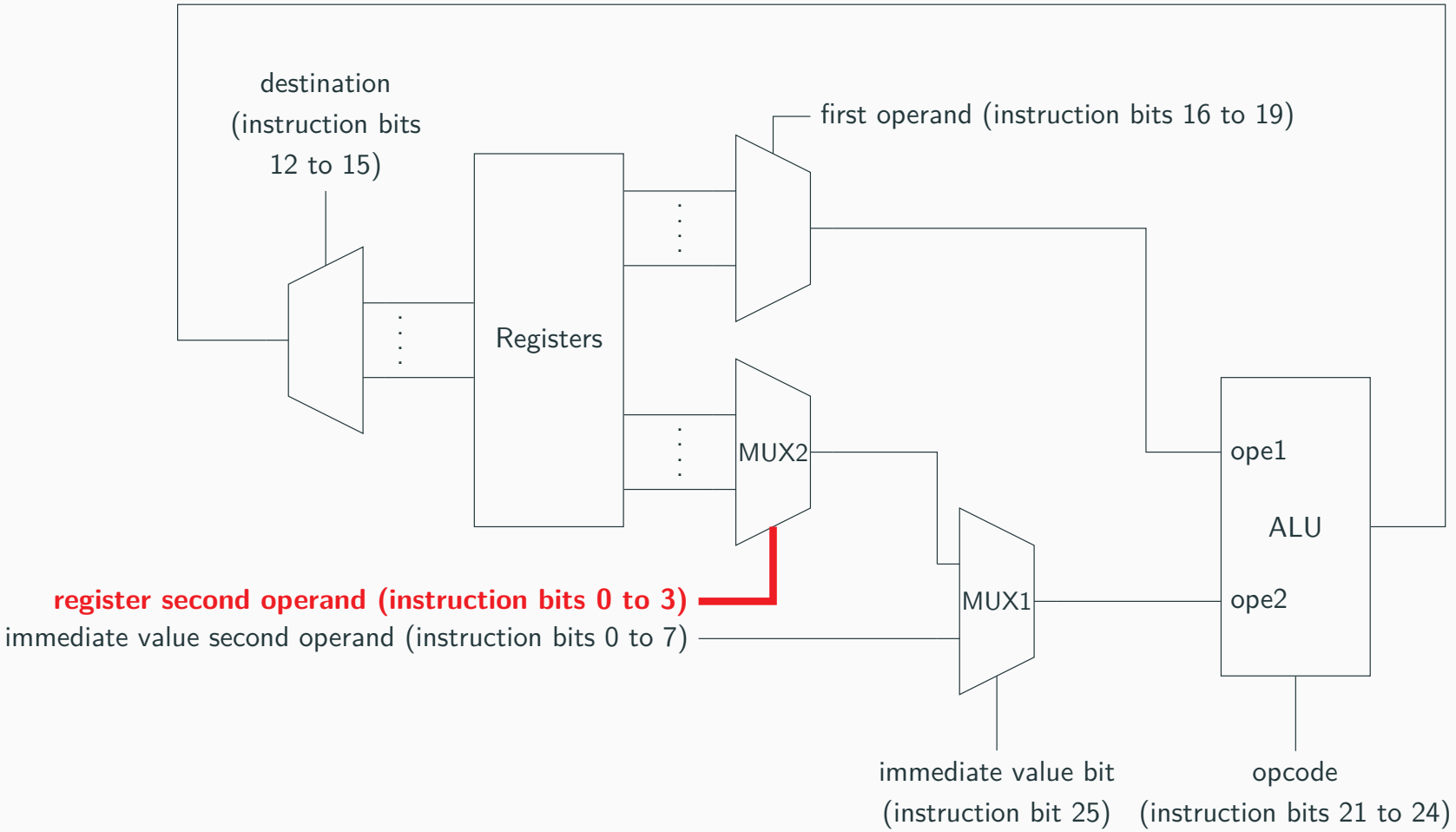
If immediate value bit (25) is set to 1



Characterization - BCM2837



Characterization - BCM2837



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

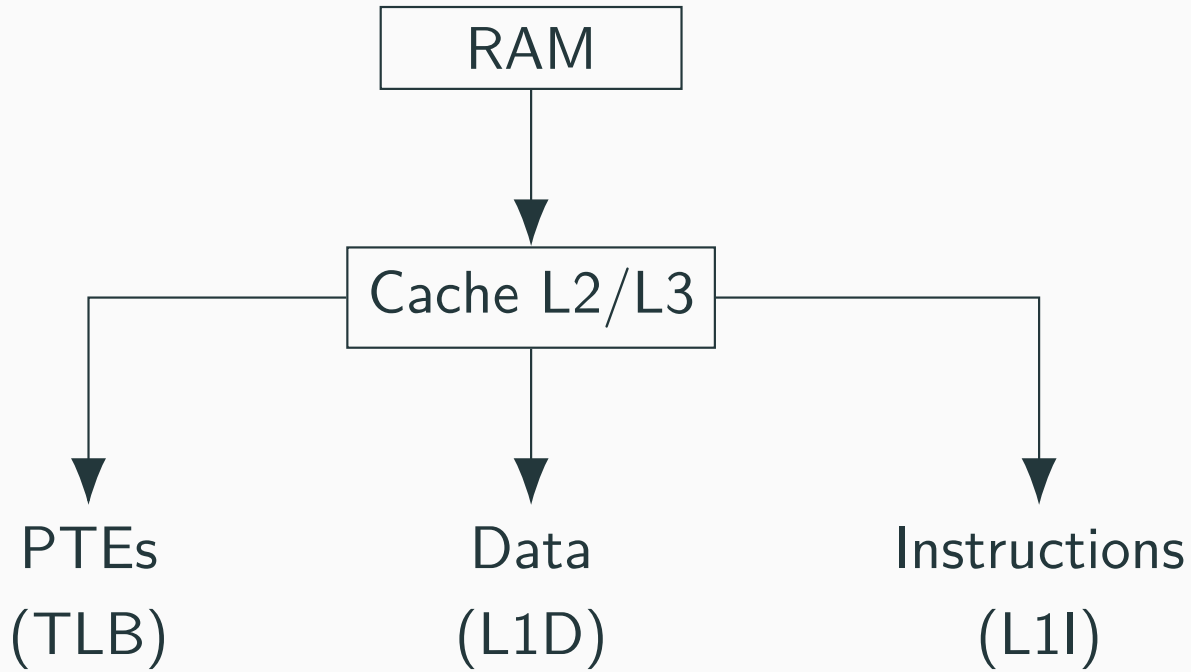
```
          mov r3, #255
          cmp r3, #255
          bne fault
          b nofault
fault:    mov r9, #170
          b end
nofault:  mov r9, #85
end:      nop
```

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

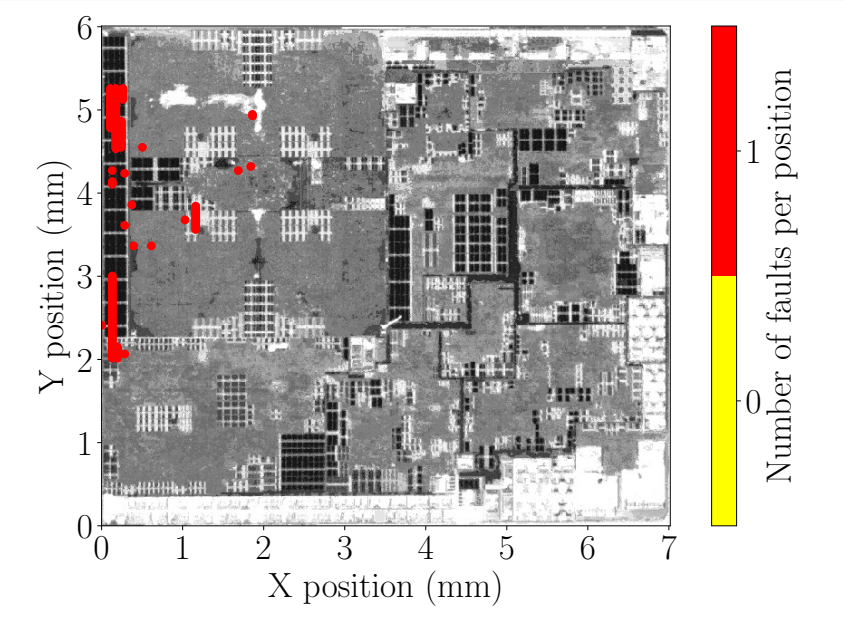
Results

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

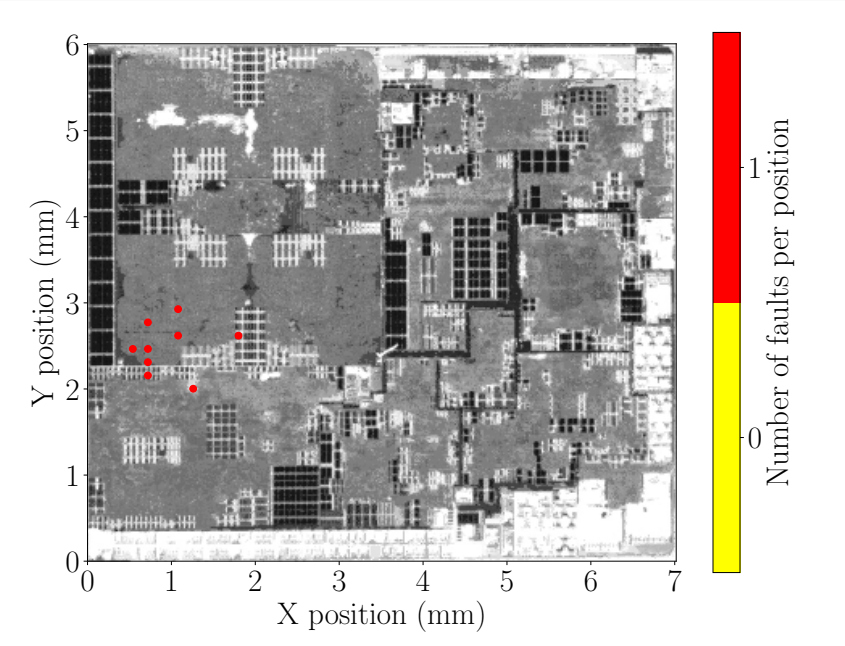
Characterization - BCM2711b0

Spots leading to faults on `orr r5,r5` test code

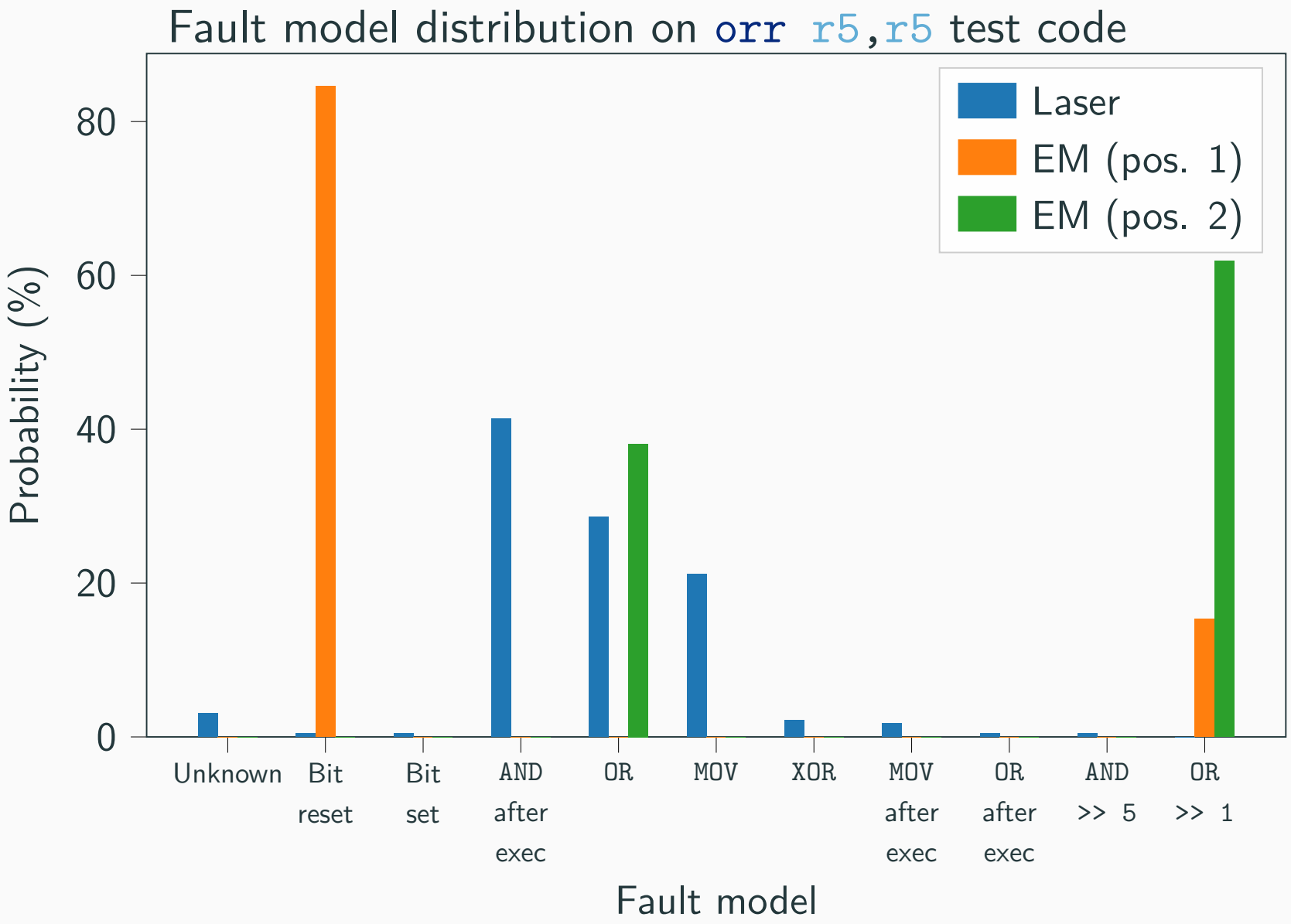
Laser



EM

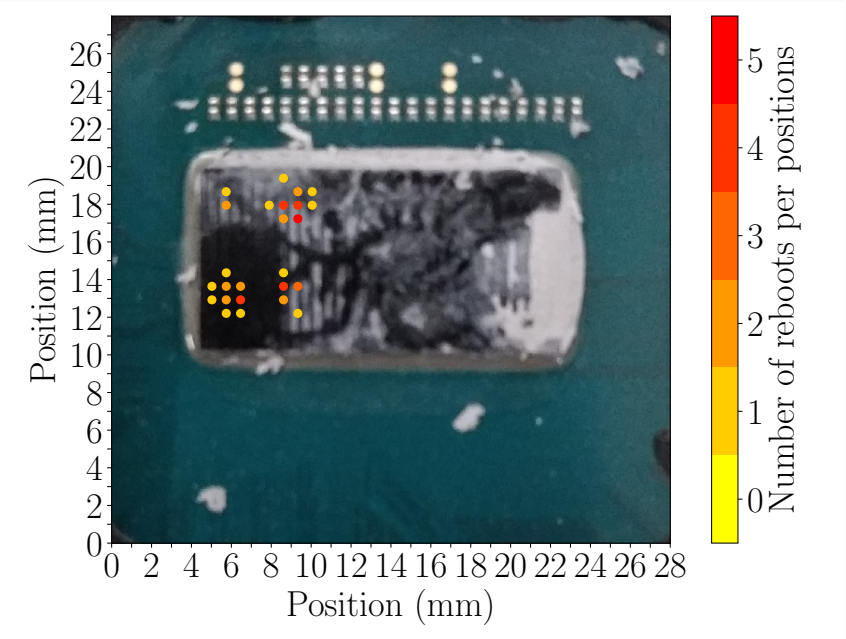


Characterization - BCM2711b0



Characterization - Intel Core i3-6100T

```
or rbx,rbx
```

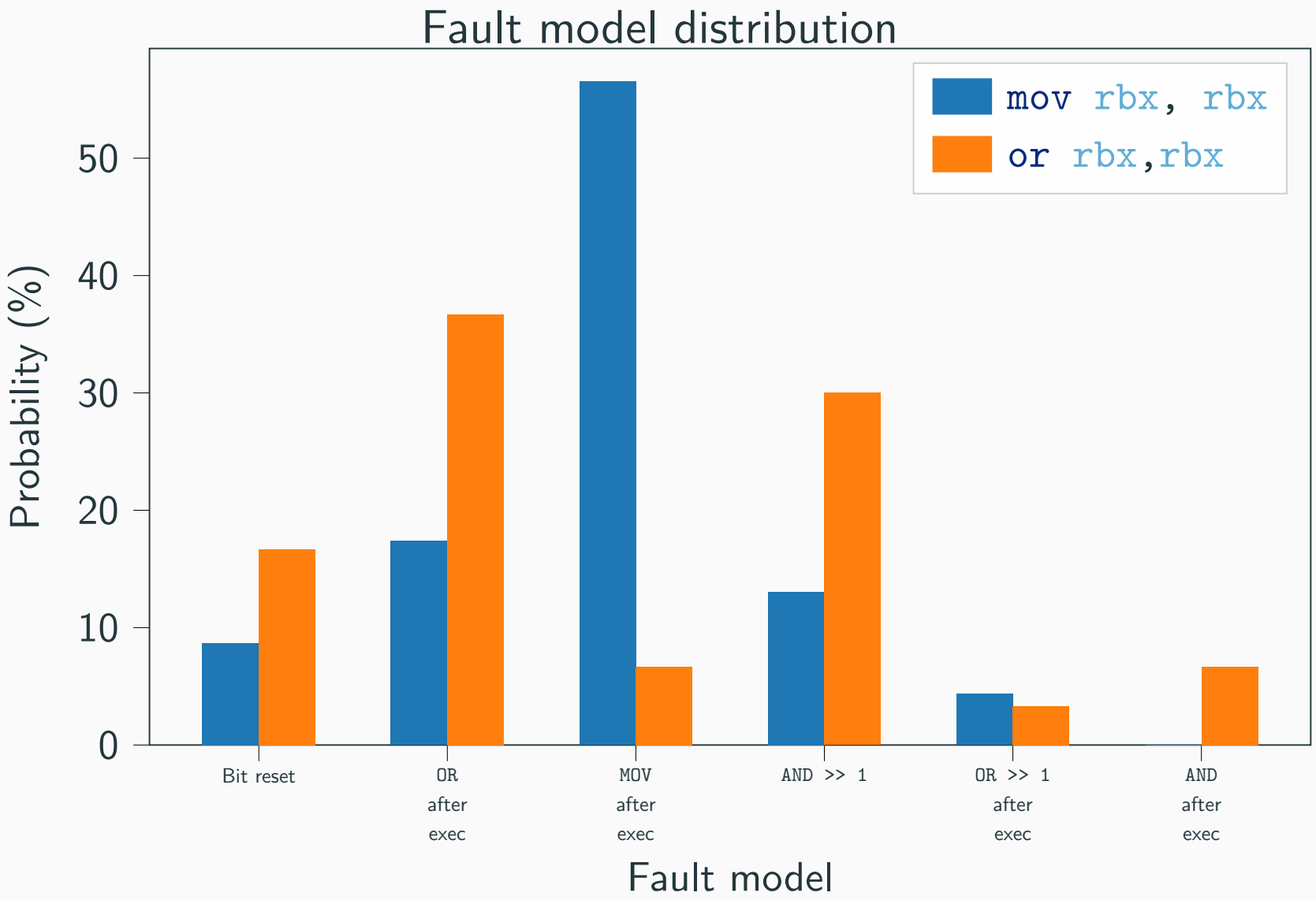


Spots leading to reboots

Faulted register:

- `rbx` in 100% of the cases

Characterization - Intel Core i3-6100T



Conclusion

- Different injection mediums have shown the similar fault models on different architecture (ARM, x86) and targets:
  - we suppose that there is an **underlying common mechanism** sensitive to perturbation„
  - the **instruction cache** was identified as faulted on the BCM2837
  - EM fault injection is less efficient on flip chips

Future works

- improve the fault analyzer
- 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

Questions ?

Appendice - Linux program life

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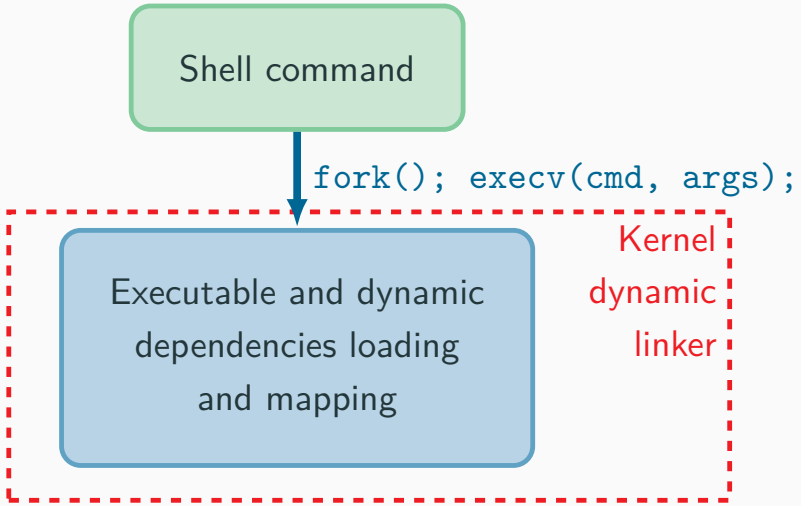
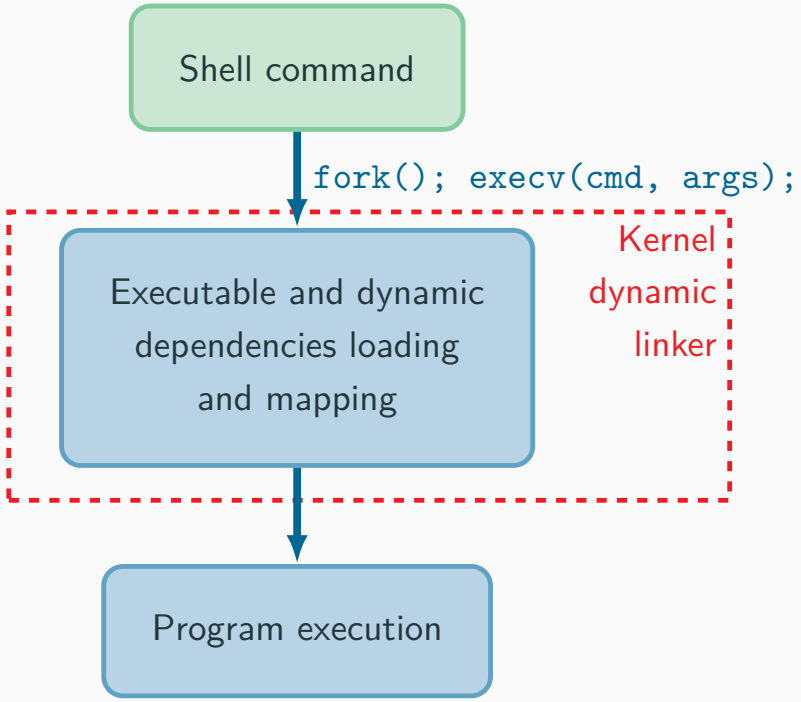
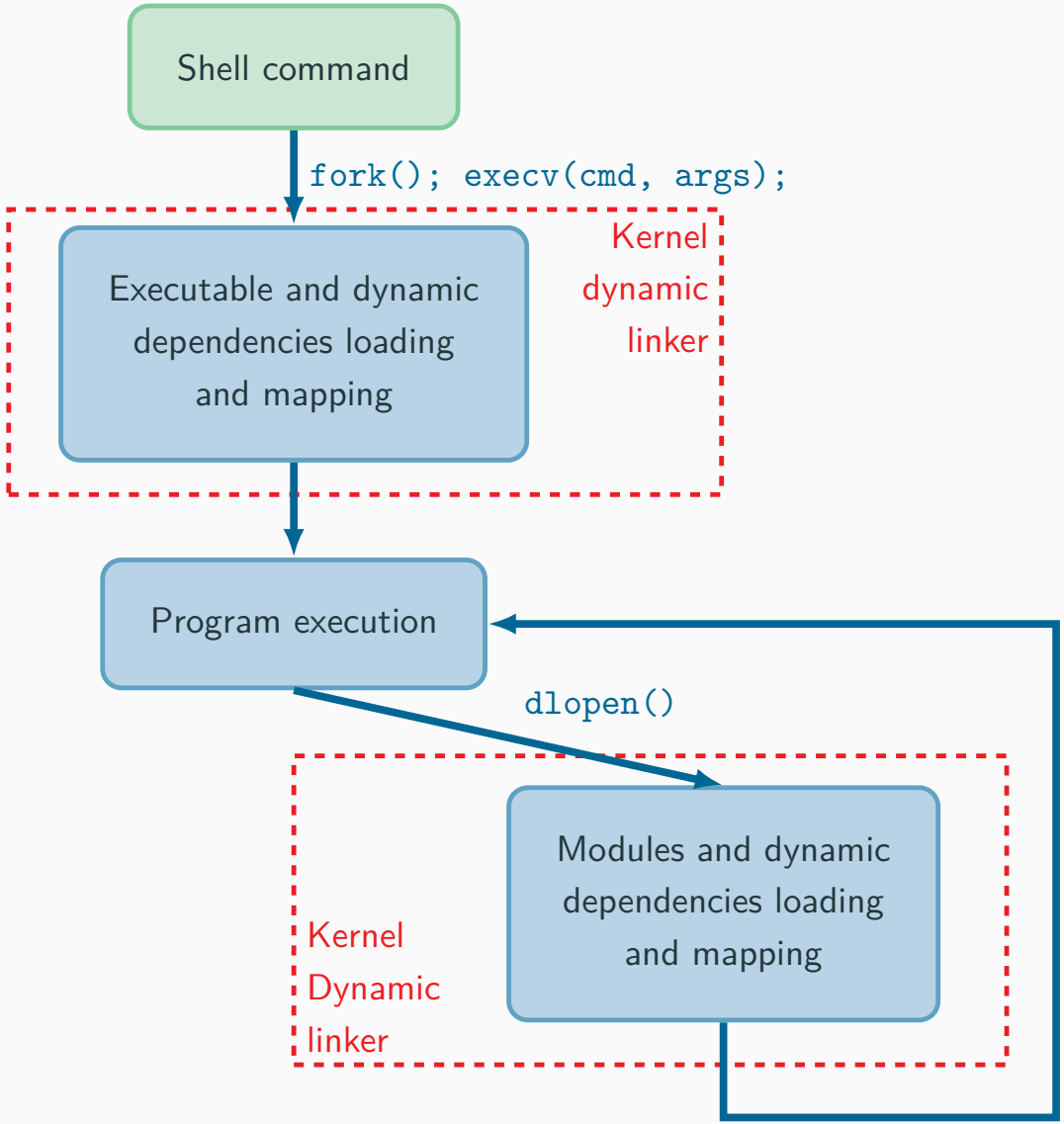


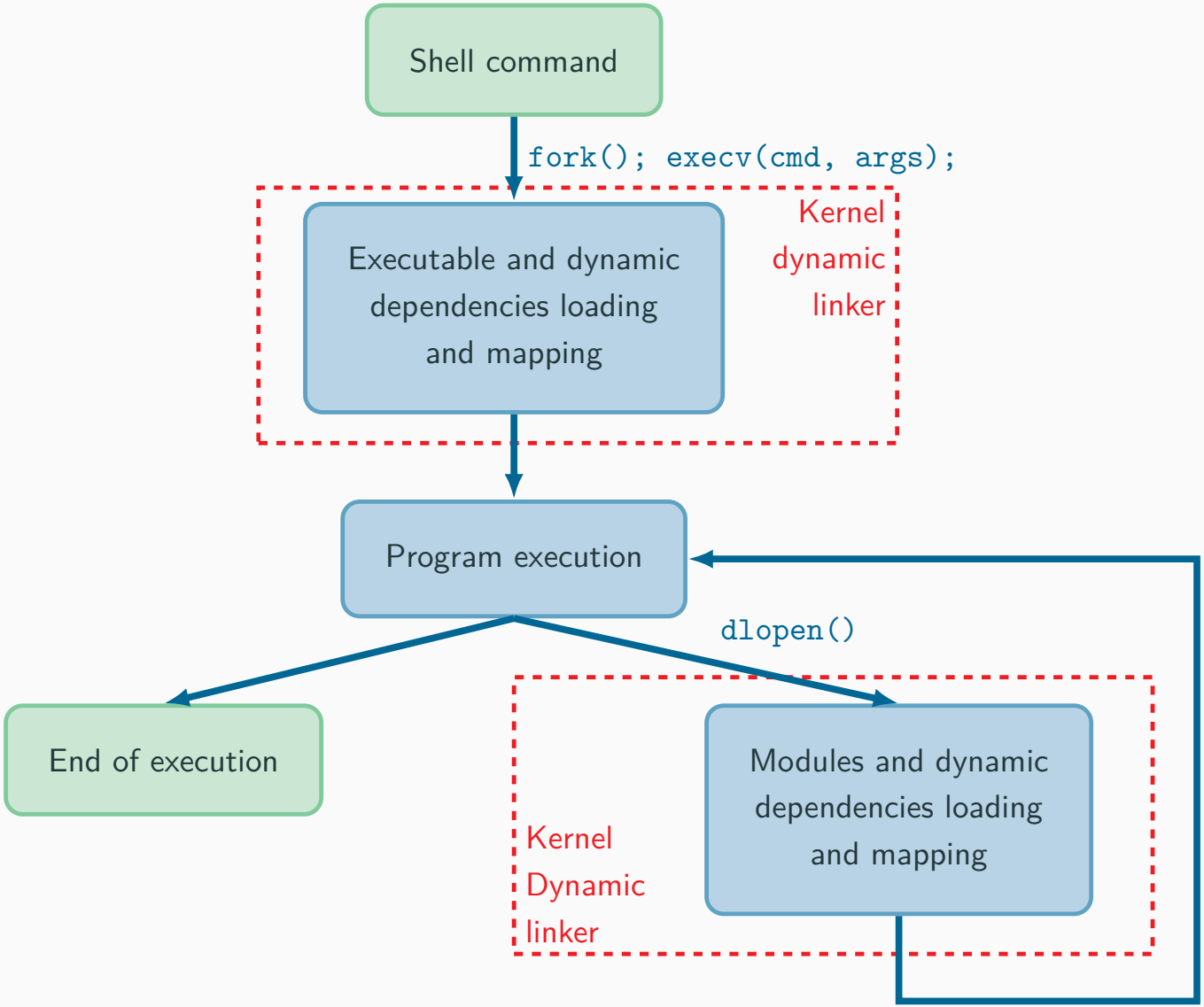
Appendice - Linux program life



Appendice - Linux program life



Appendice - Linux program life



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

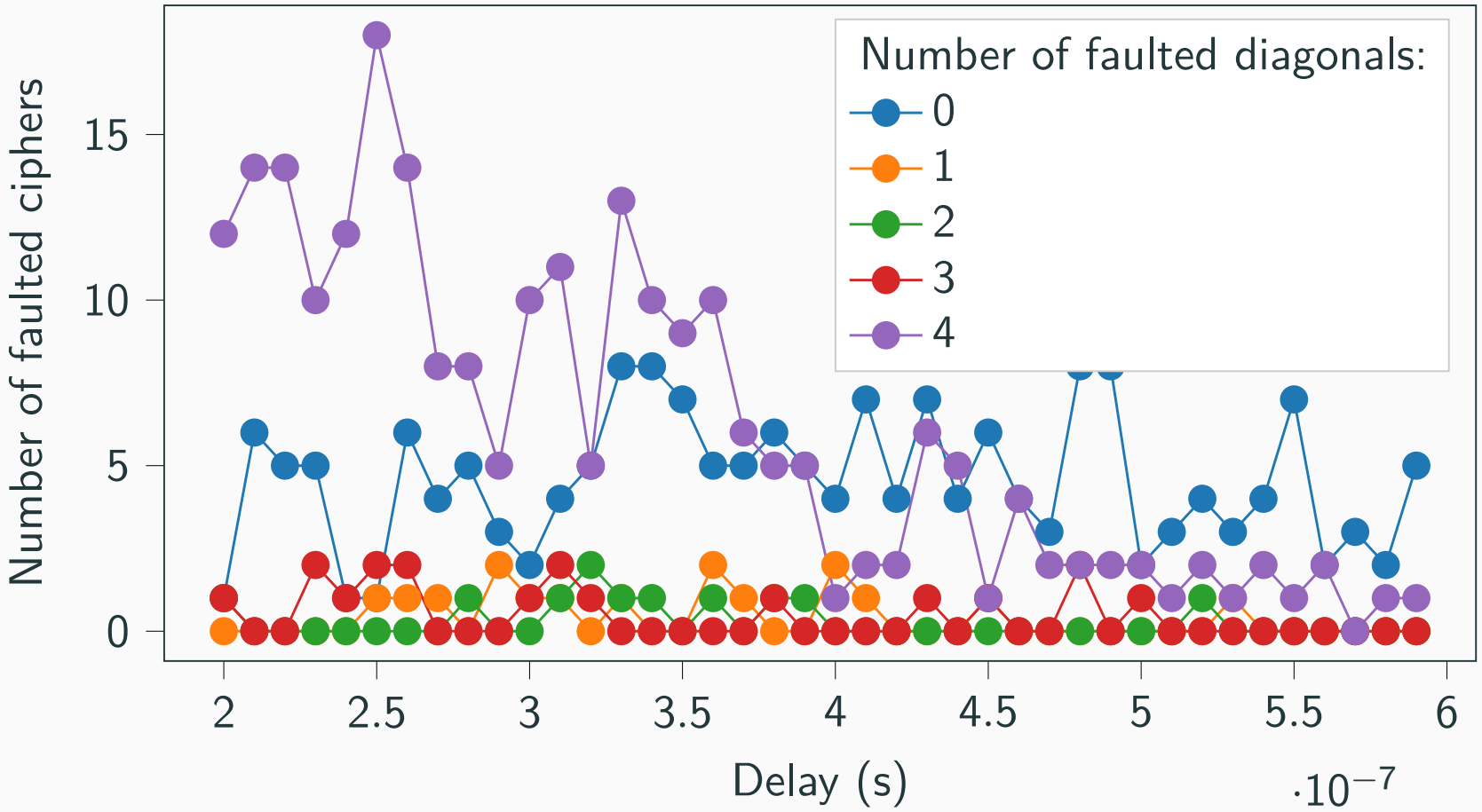
```
VA       -> PA
0x0      -> 0x0       0x80000 -> 0x80000
0x10000  -> 0x10000   0x90000 -> 0x90000
0x20000  -> 0x20000   0xa0000 -> 0xa0000
0x30000  -> 0x30000   0xb0000 -> 0xb0000
0x40000  -> 0x40000   0xc0000 -> 0xc0000
0x50000  -> 0x50000   0xd0000 -> 0xd0000
0x60000  -> 0x60000   0xe0000 -> 0xe0000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

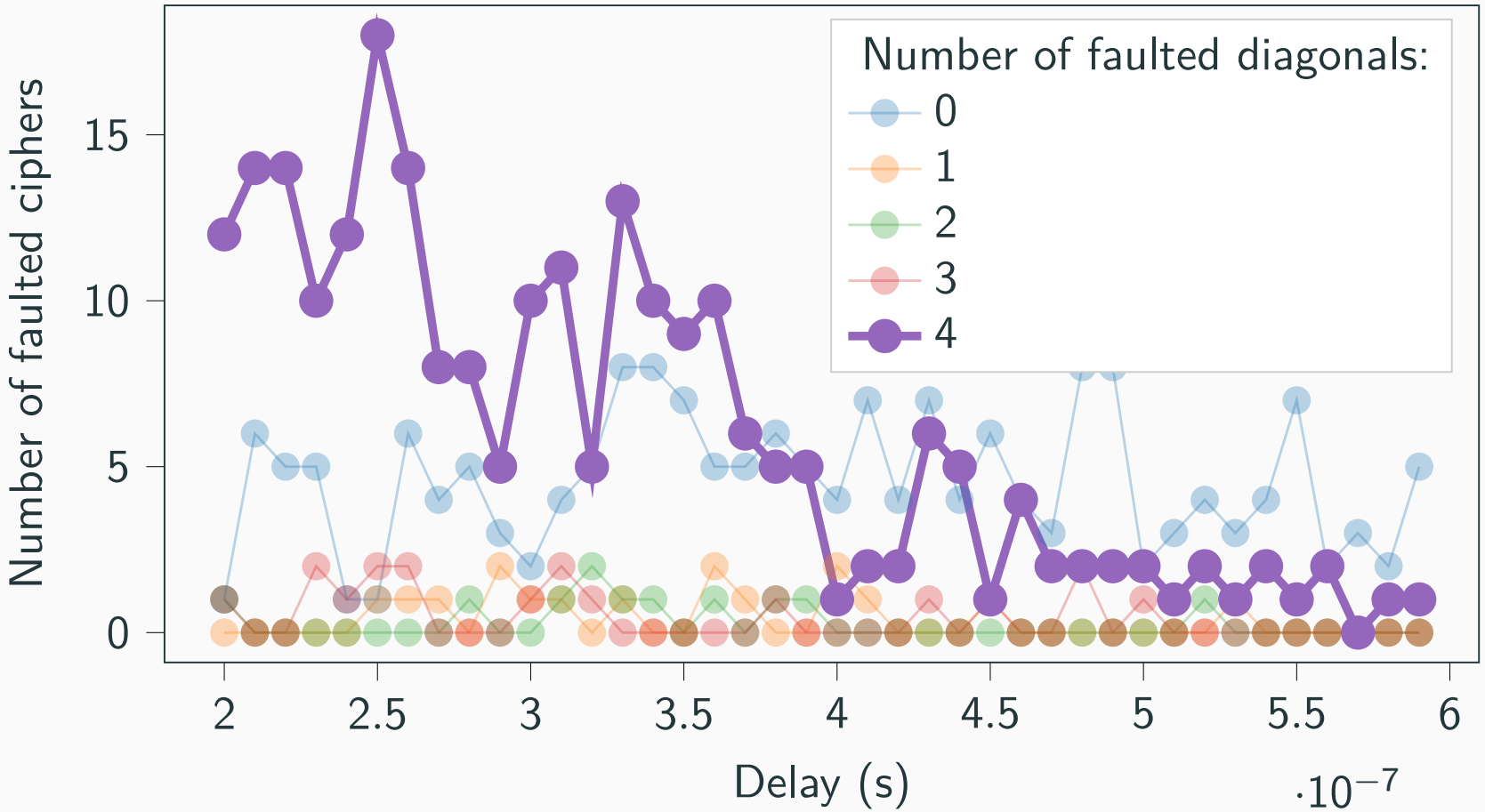
Appendice - OpenSSL AES

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

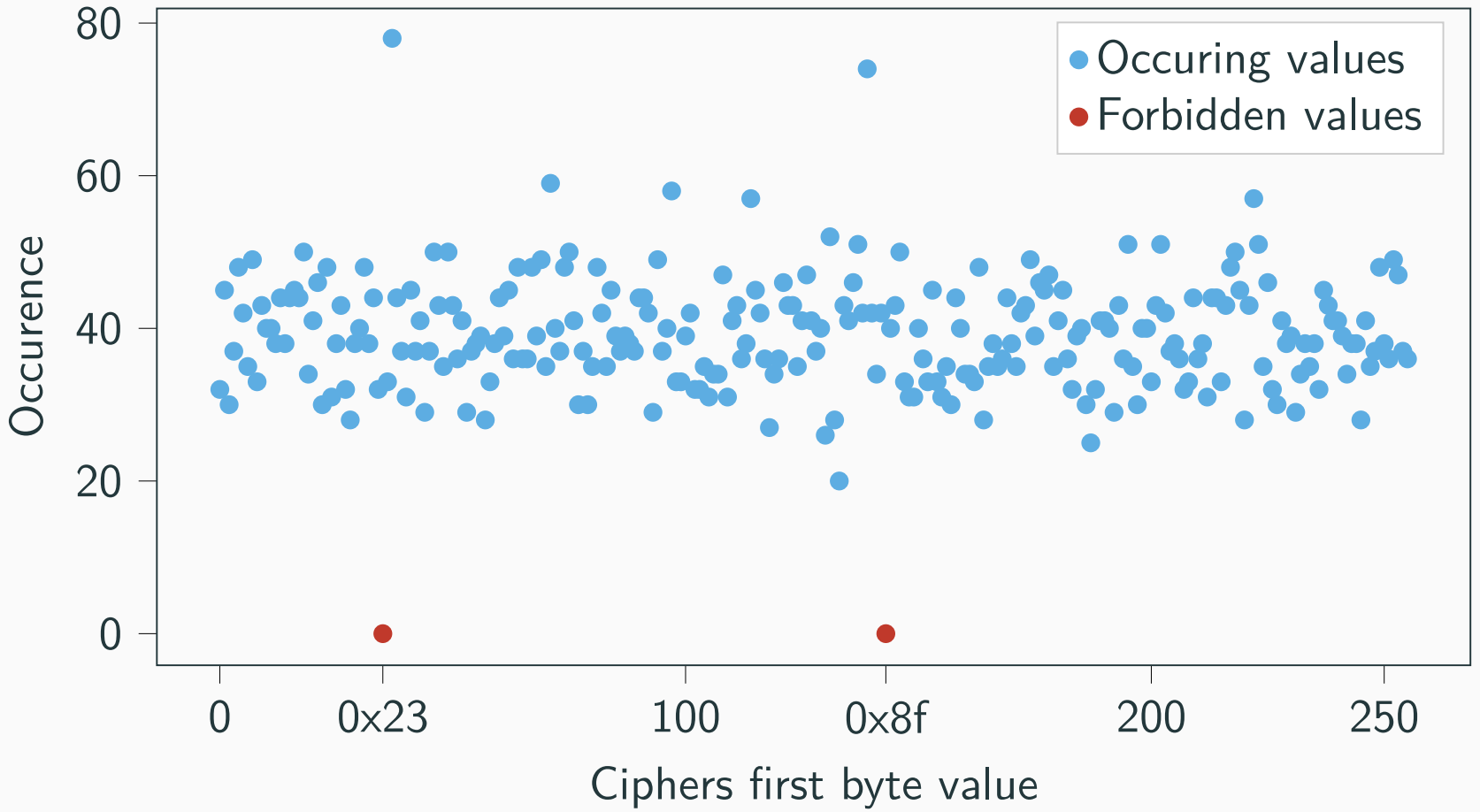


Appendice - OpenSSL AES

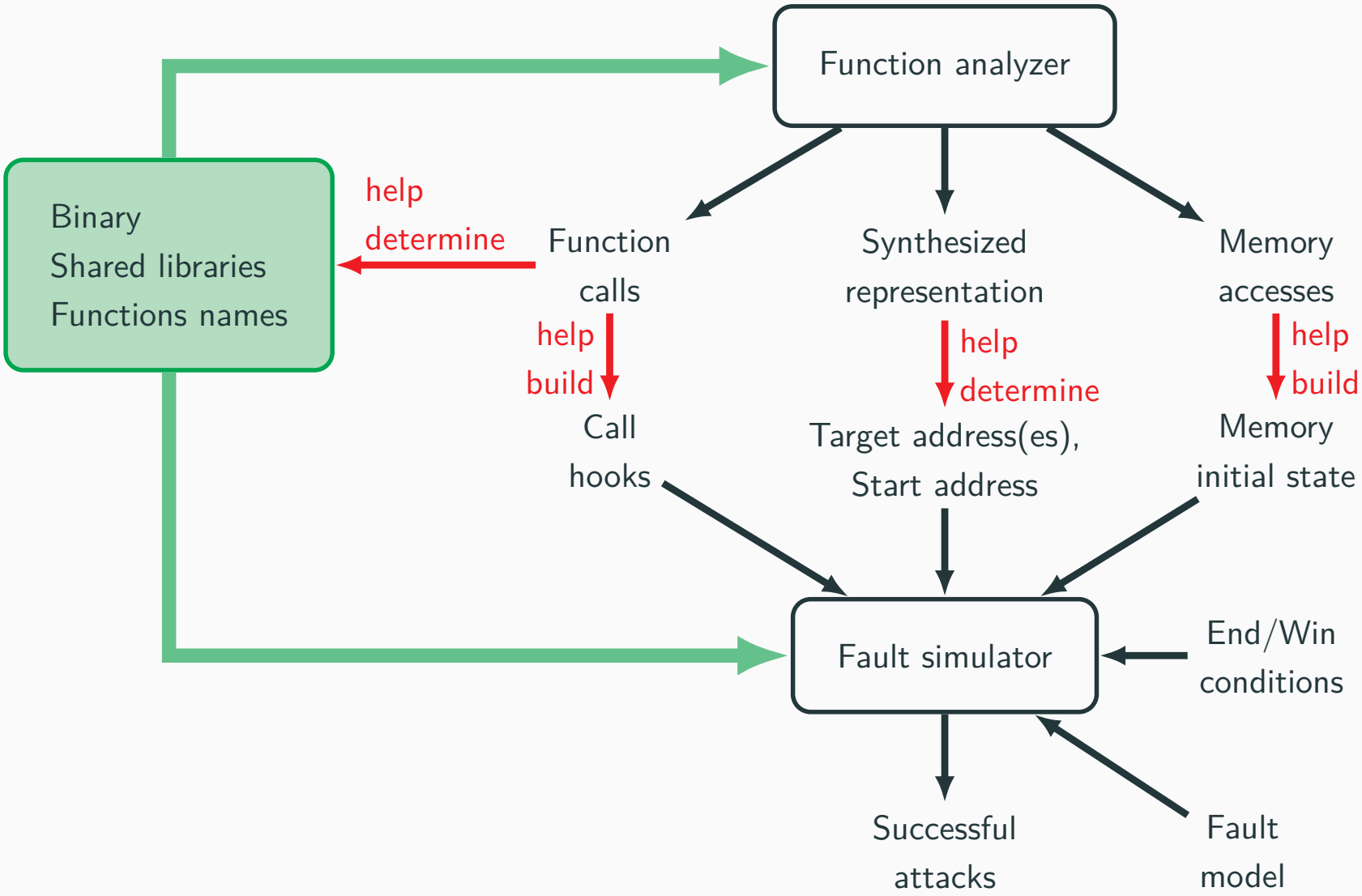
Number of faulted ciphers with a specific number of faulted diagonals regarding the delay of injection



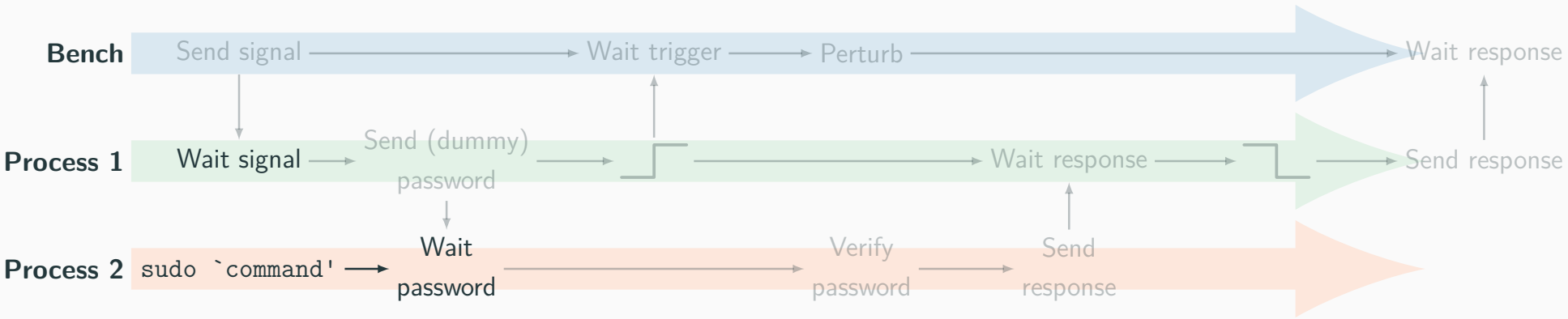
Appendice - AES PFA



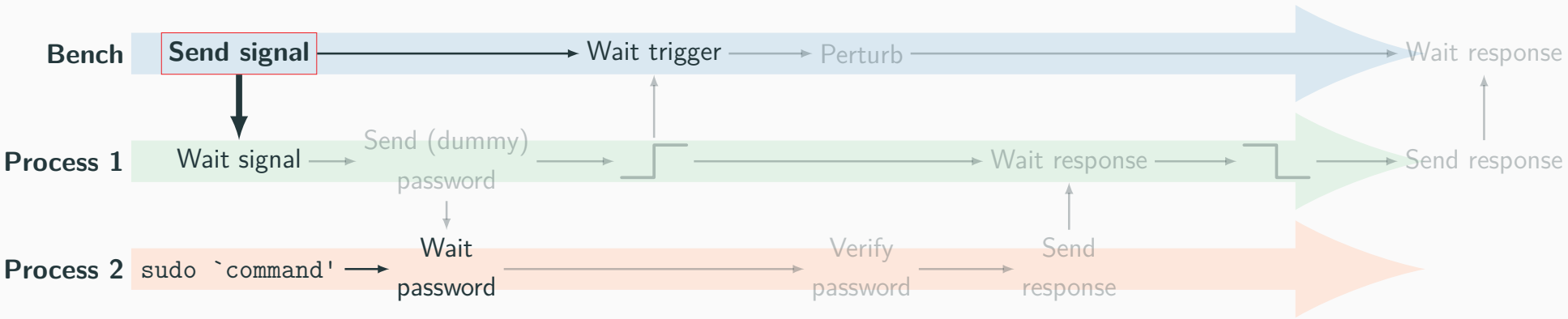
Appendice - Analyzer and simulator



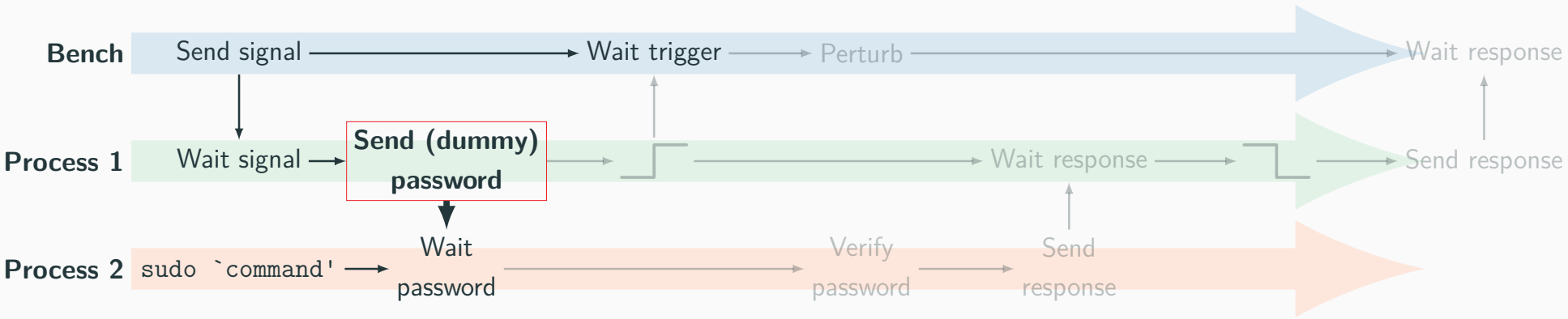
Appendice - `sudo` Forced authentication - User program



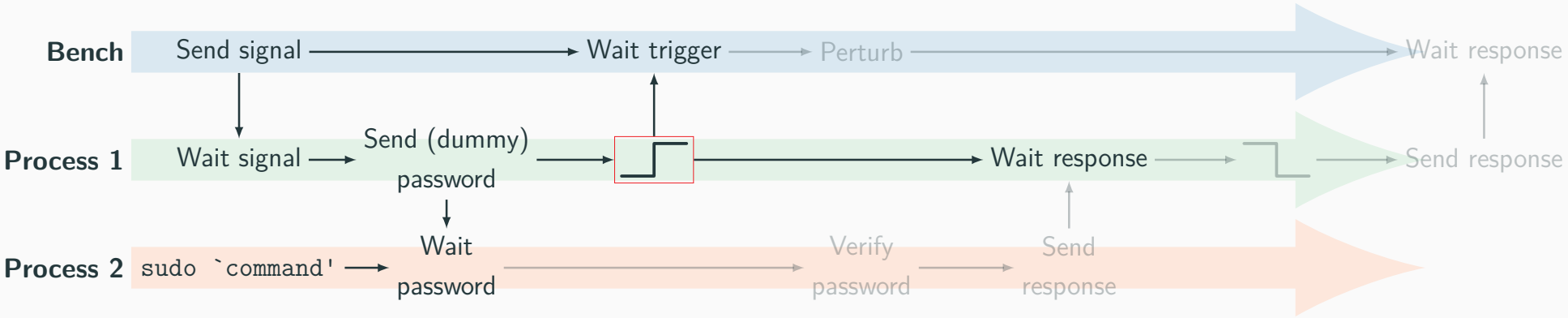
Appendice - `sudo` Forced authentication - User program



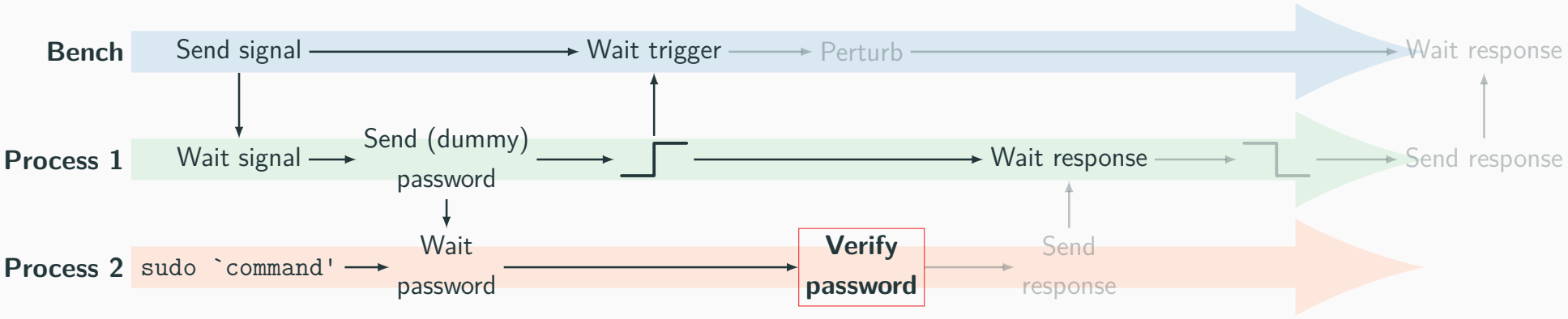
Appendice - `sudo` Forced authentication - User program



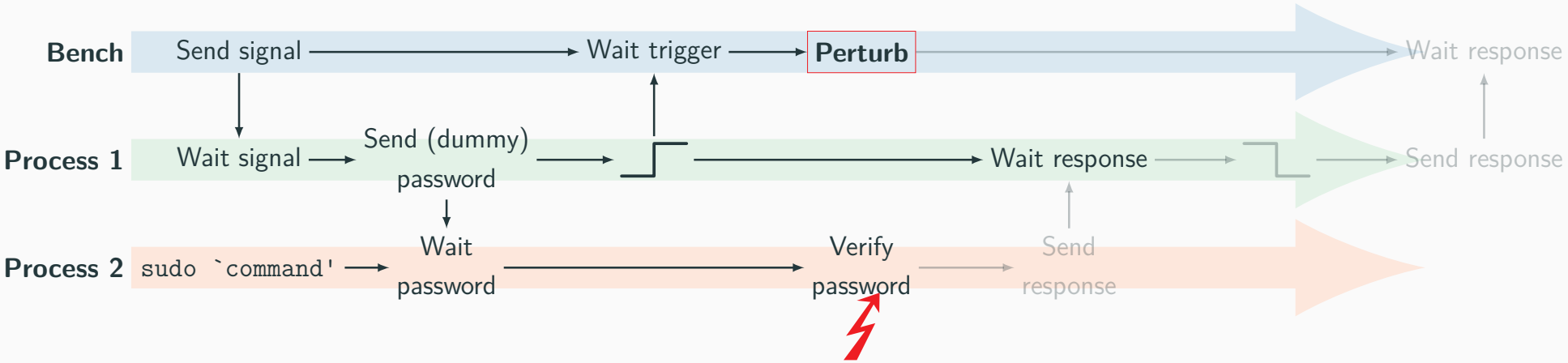
Appendice - `sudo` Forced authentication - User program



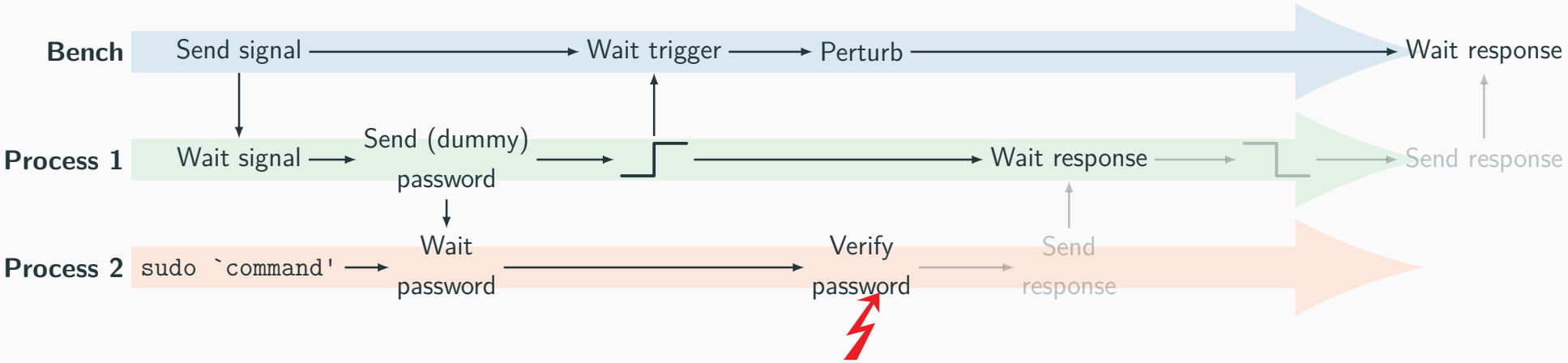
Appendice - `sudo` Forced authentication - User program



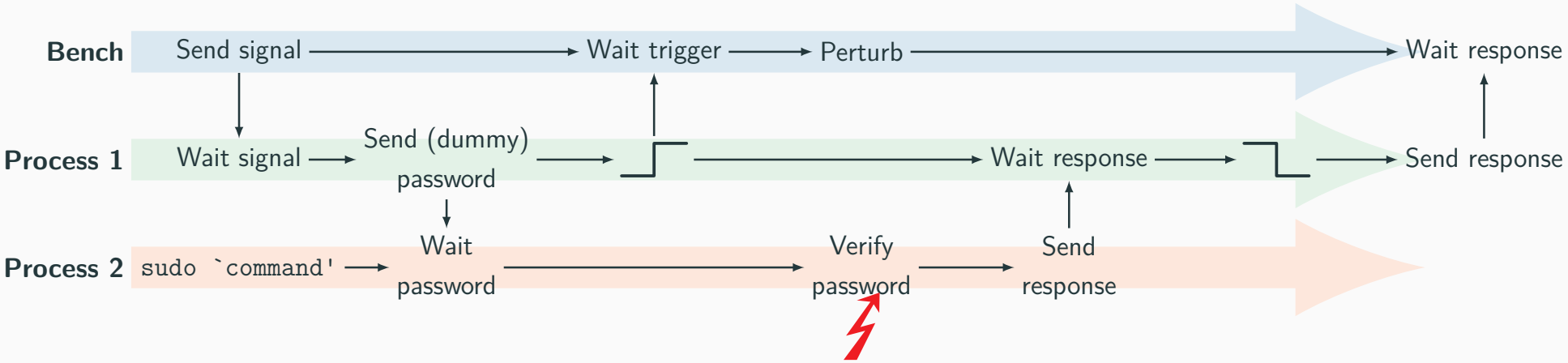
Appendice - `sudo` Forced authentication - User program



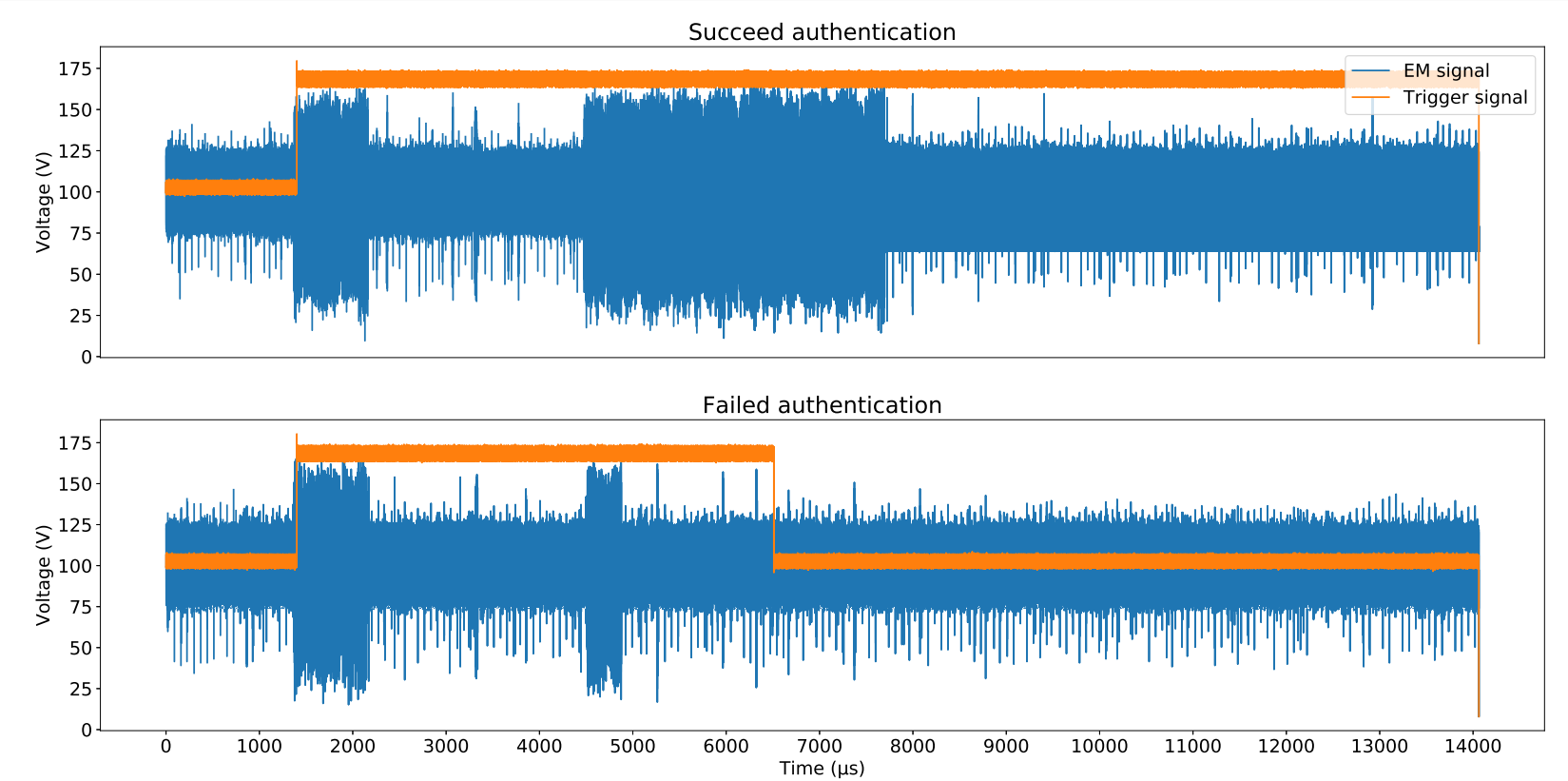
Appendice - `sudo` Forced authentication - User program



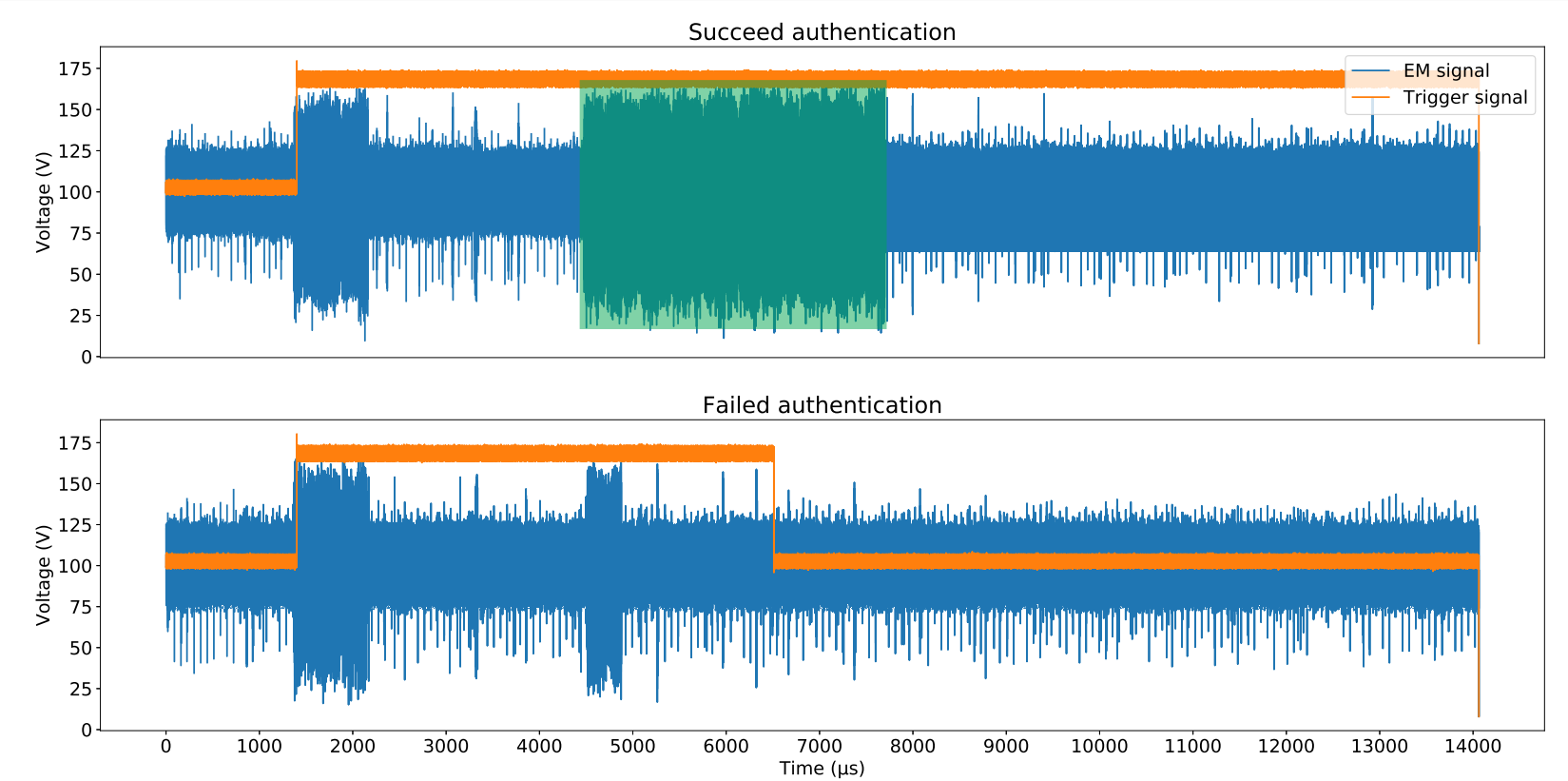
Appendice - `sudo` Forced authentication - User program



Appendice - `sudo` Forced authentication - EM analysis



Appendice - `sudo` Forced authentication - EM analysis



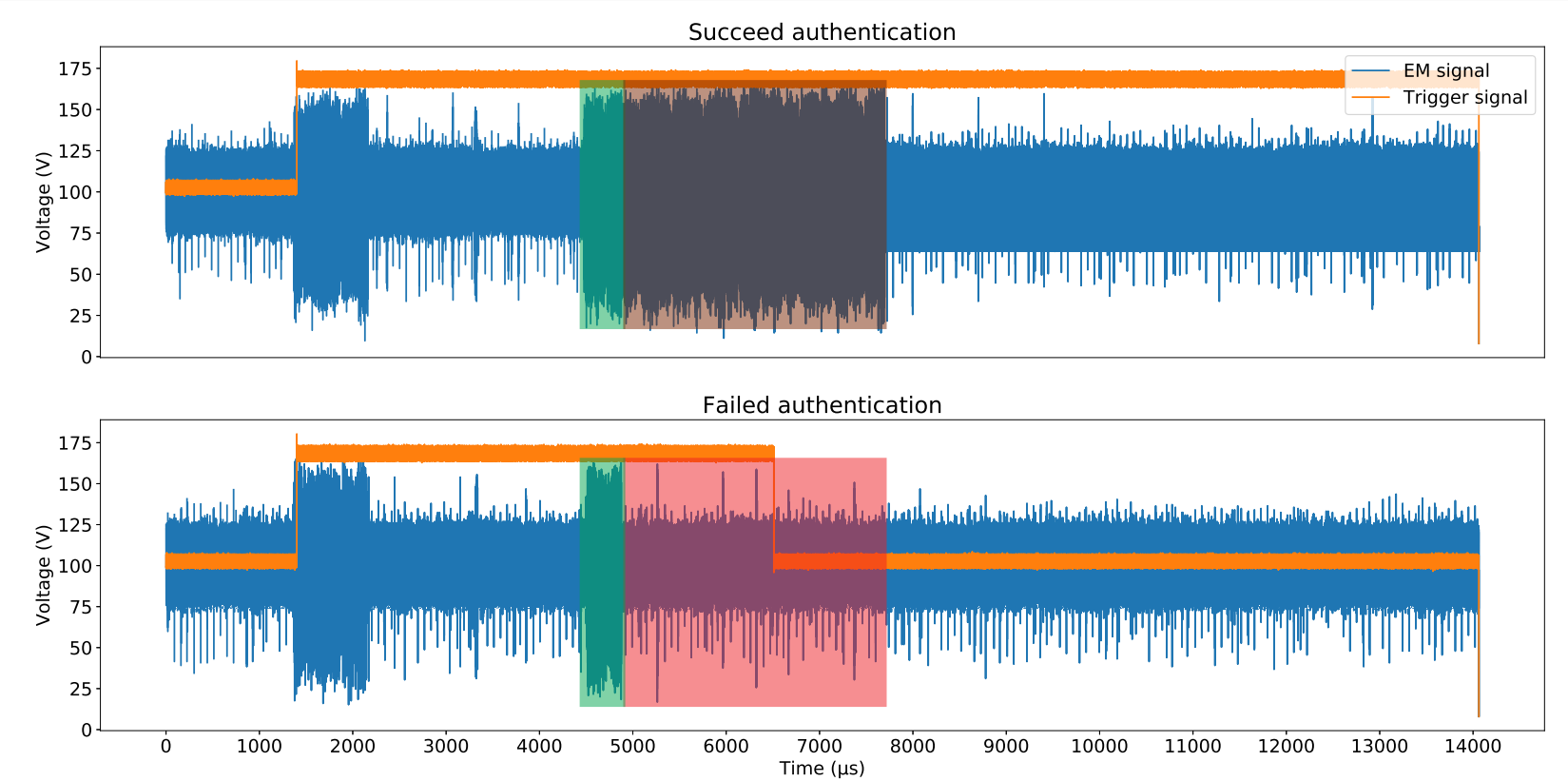

```
$6$hH.15uU5laaxuXHY$wtSOcCKWmY1JmyY2CWlVs/8ixyON36ZxQV2RpMJkITzqkIM18lyXNMICoYNIVDeUVXqHOFs39Onl6Lw8m5ArZ0
```

Appendice - `sudo` Forced authentication - EM analysis


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

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

Appendice - `sudo` Forced authentication - EM analysis




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

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

Appendice - `sudo` Forced authentication - EM analysis


```
$6$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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