VUSec

riscure

black hat USA 2018

# There Will Be Glitches:

## Extracting and Analyzing Automotive Firmware Efficiently

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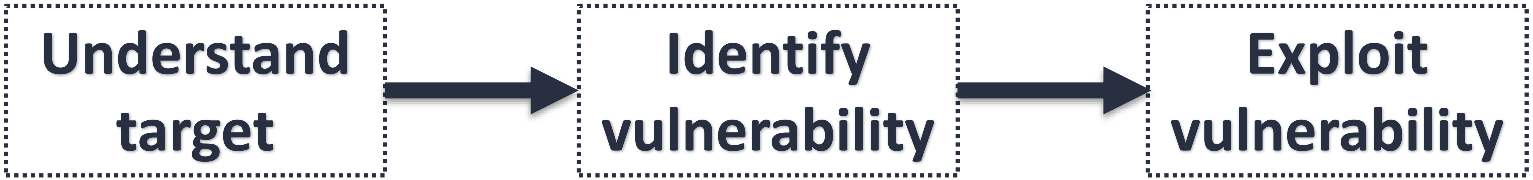
Santiago Cordoba,
Nils Wiersma,
Ramiro Pareja

# Today we are talking about

# Standard approach for breaking embedded systems

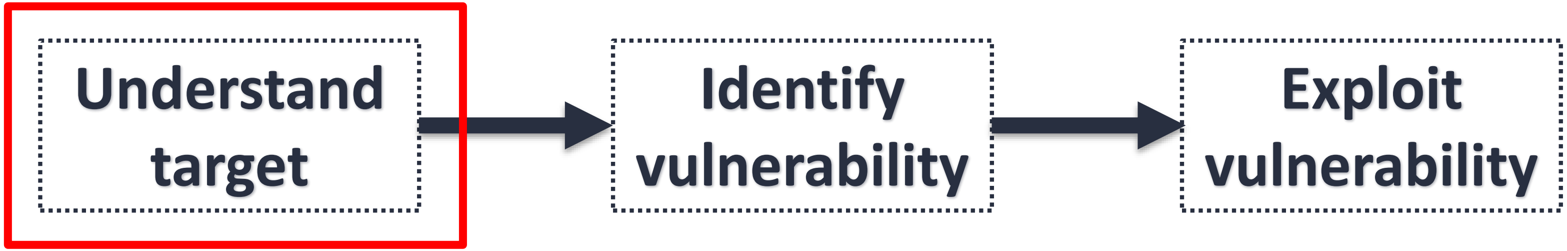


Understand target

Identify vulnerability

Exploit vulnerability

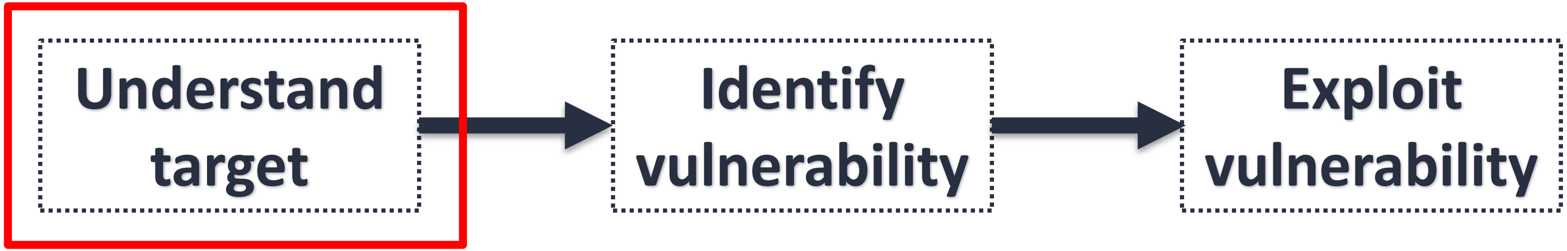
# Standard approach for breaking embedded systems



**Understand target** → **Identify vulnerability** → **Exploit vulnerability**

But to understand, we need the **firmware**!

# Standard approach for breaking ~~embedded systems~~ ECUs found in cars!



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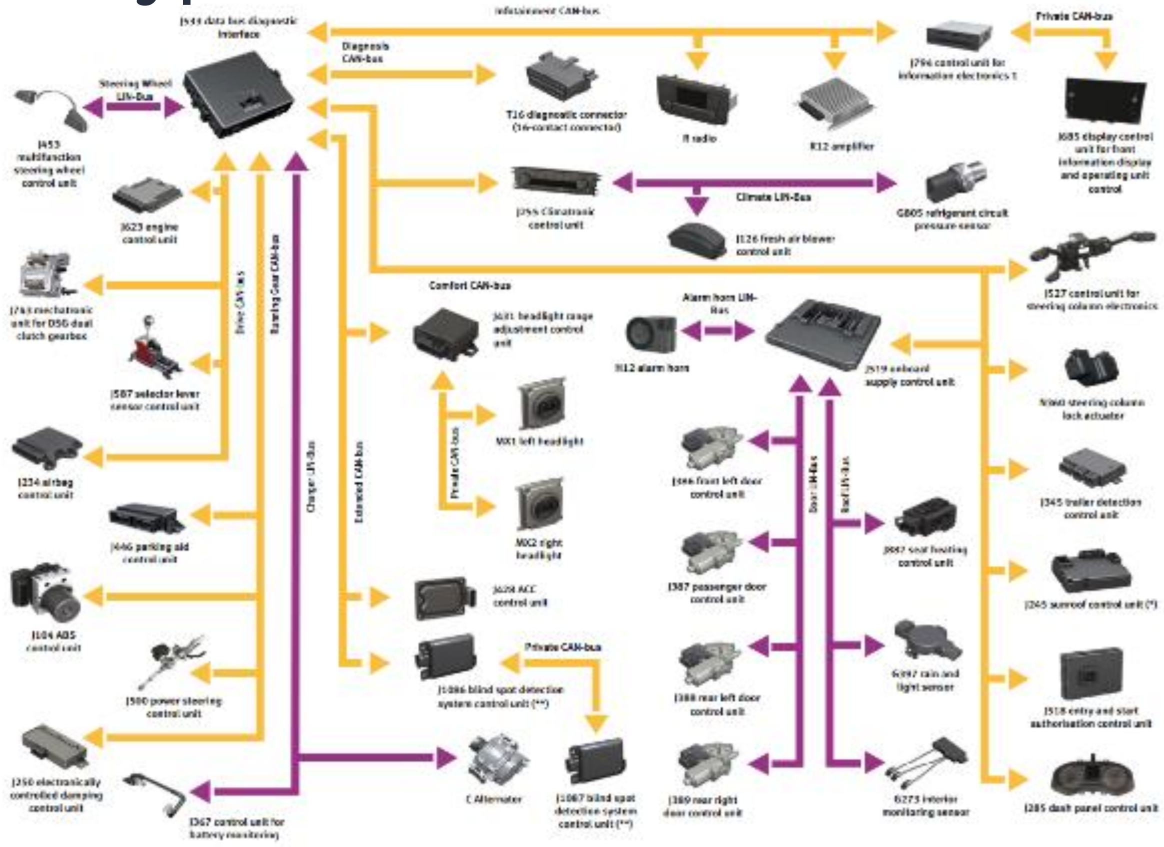
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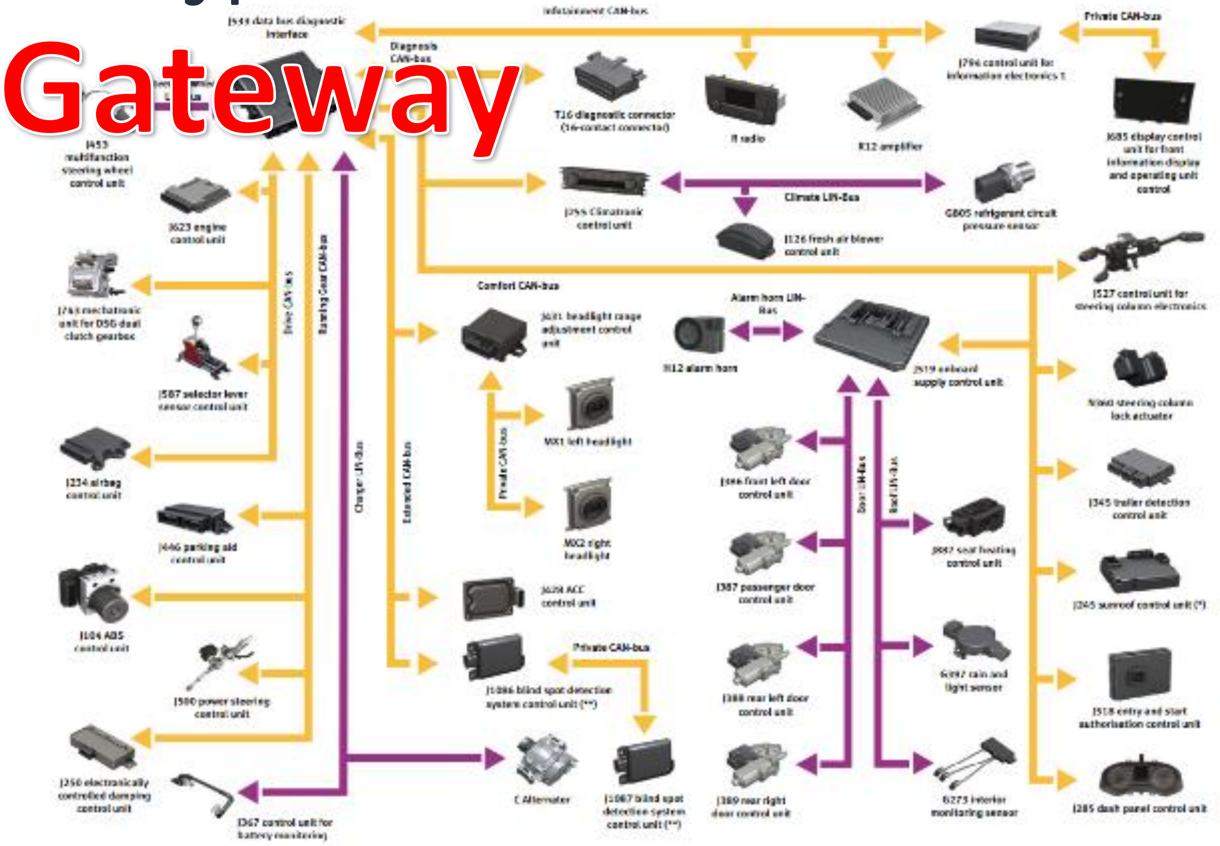

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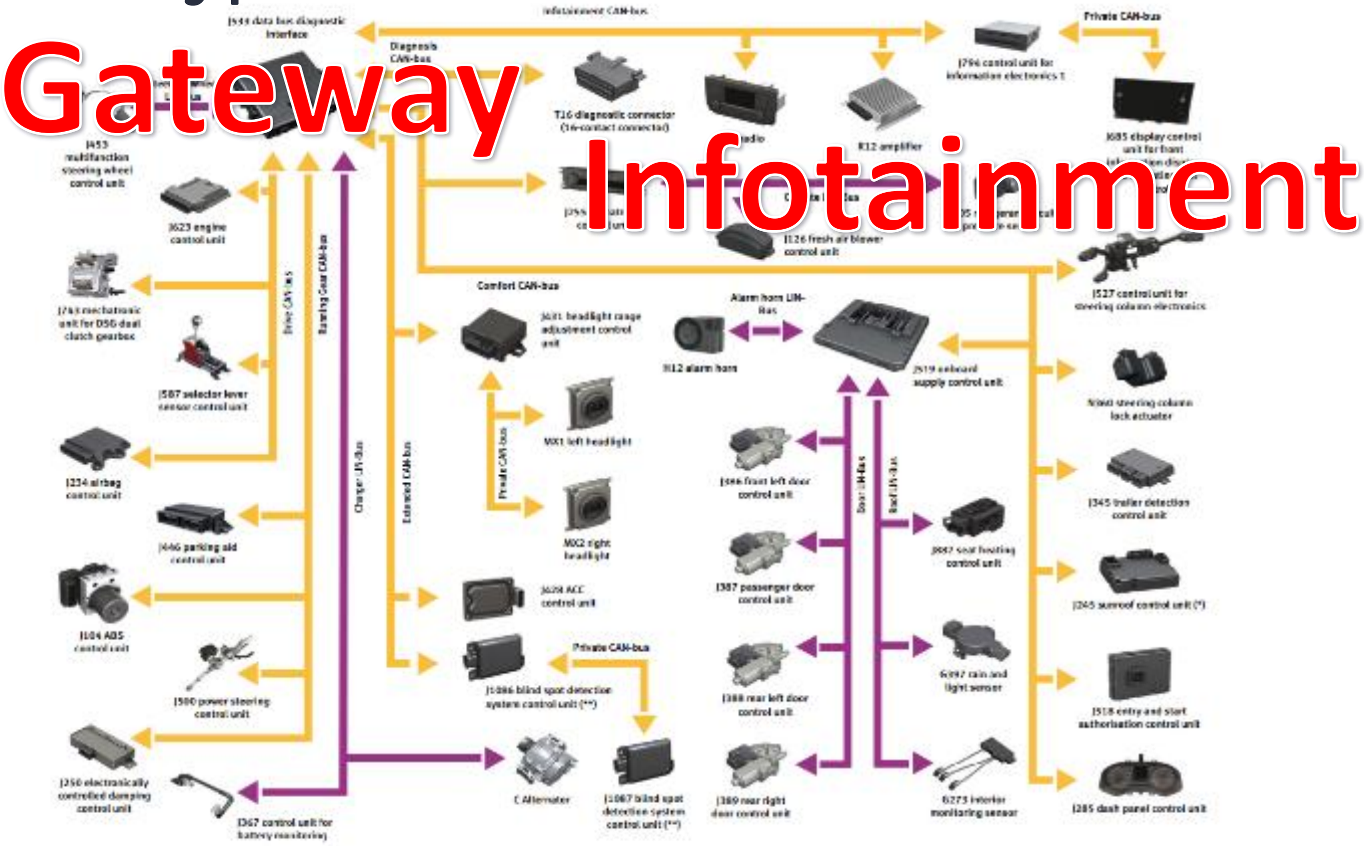
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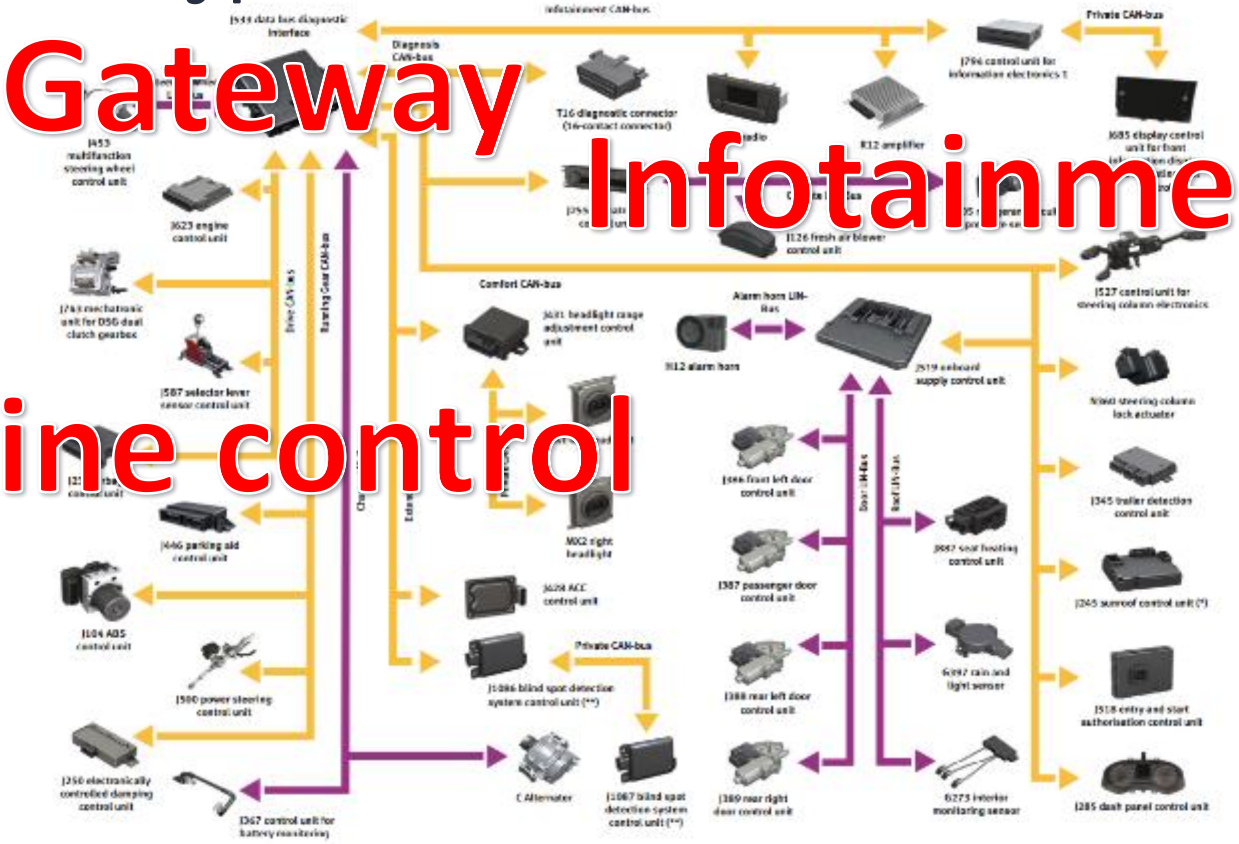
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Gateway

Infotainment

Engine control

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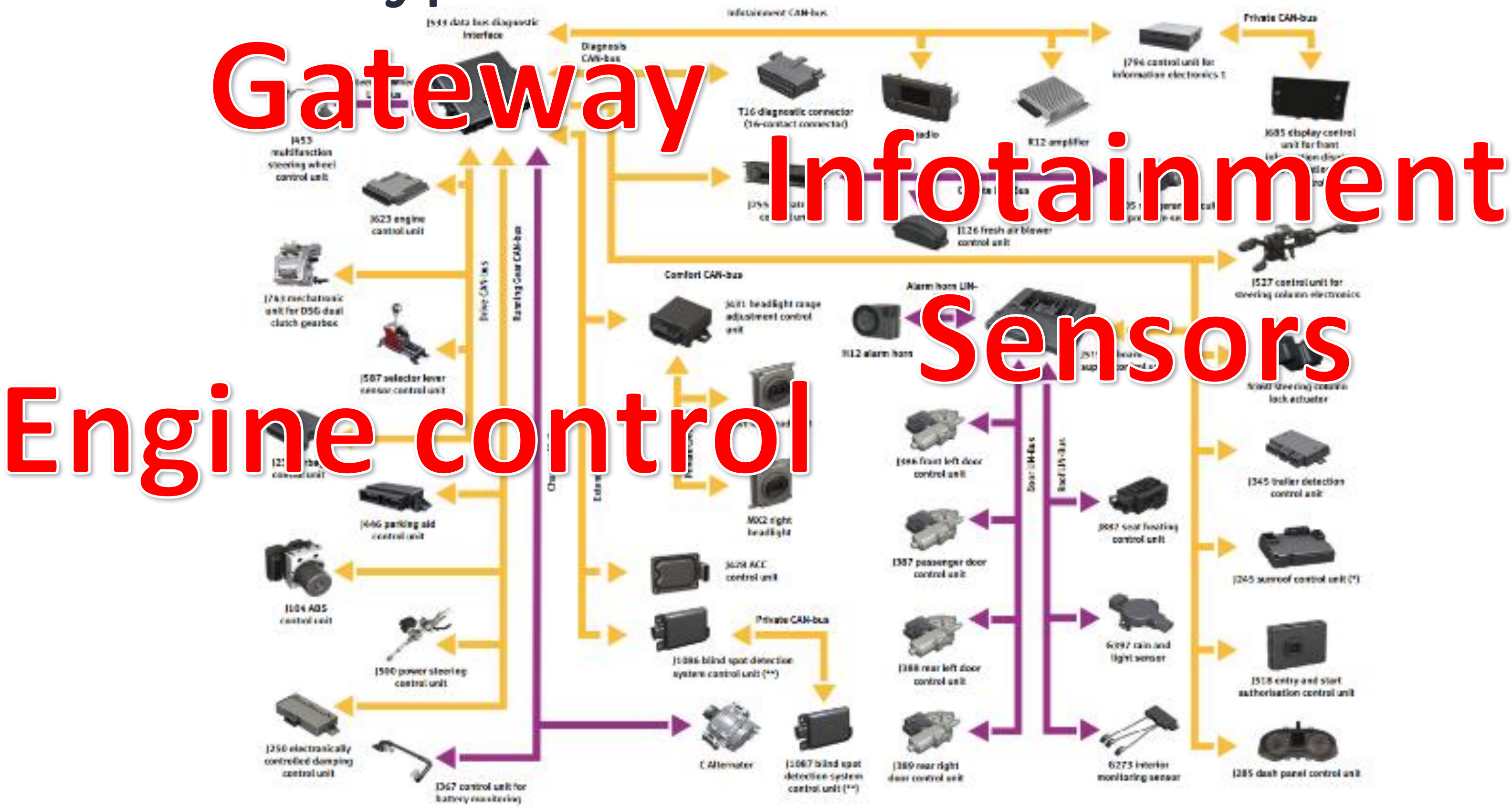

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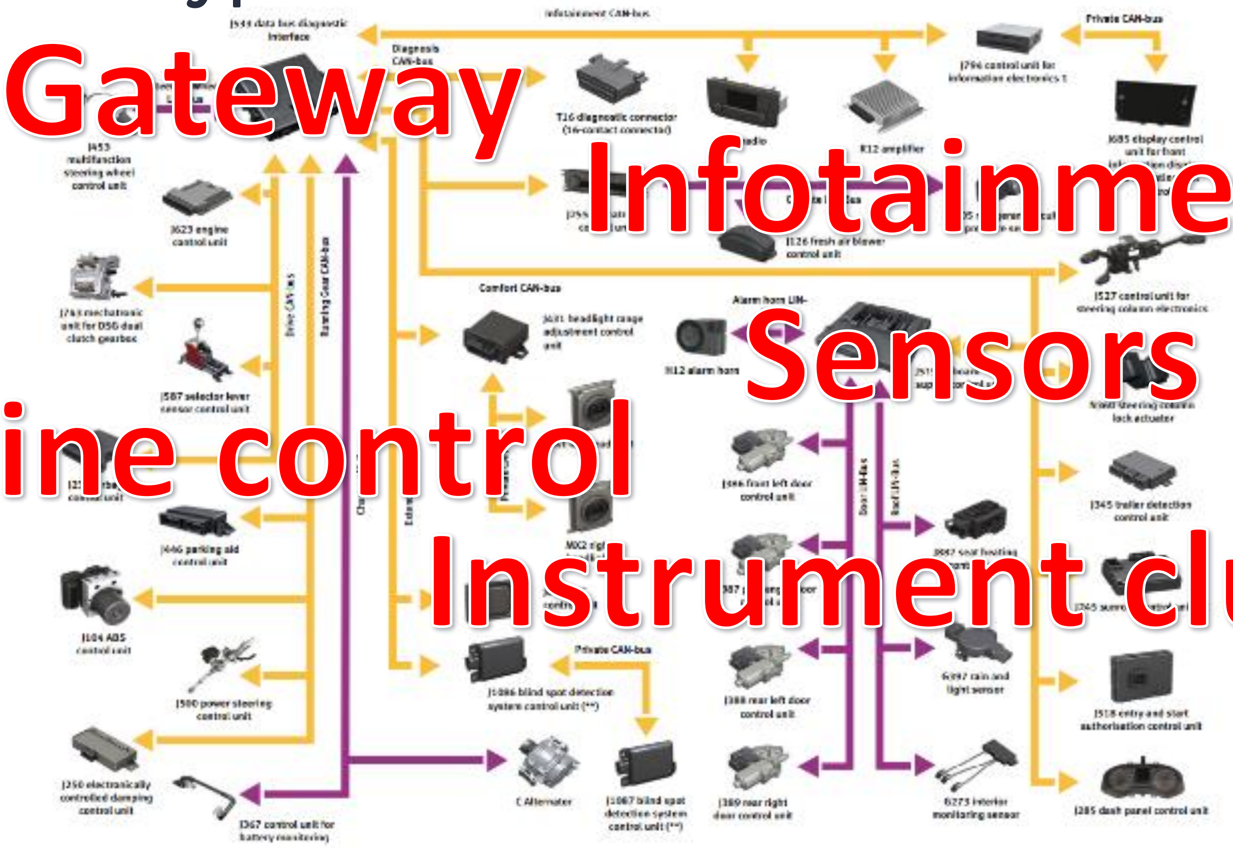
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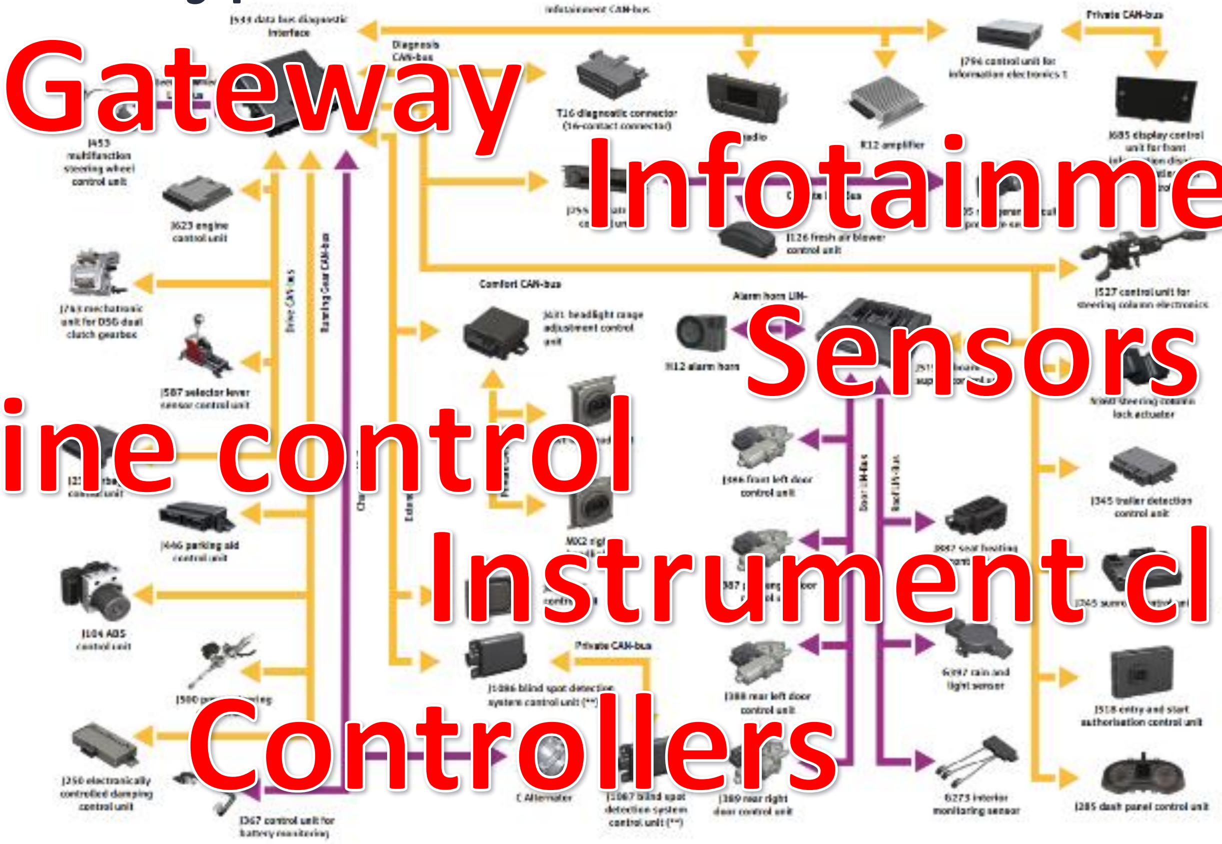
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Controllers

*Just like embedded systems,*

*these ECUs come in all* ***forms****,* ***shapes*** *and* ***sizes****!*

# Lots of them are stuck in cars worldwide…

… and you can buy them cheaply!

ebay

# Today we target an **Instrument Cluster**

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*Why?*

*It has blinky lights!*

*We want to **understand** our target…*

*So we need to its **firmware**!*

# Let’s get our target’s firmware!

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Firmware upgrade

Leaks

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~~Firmware~~ upgrade

~~Leaks~~

# Let’s get our target’s firmware!

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~~Leaks~~

Interfaces

Chips

Software

# Let’s get our target’s firmware!

~~Firmware upgrade~~

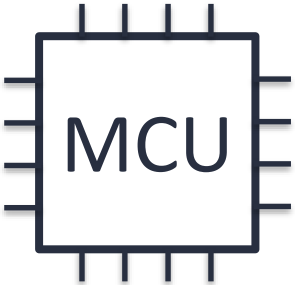
~~Leaks~~

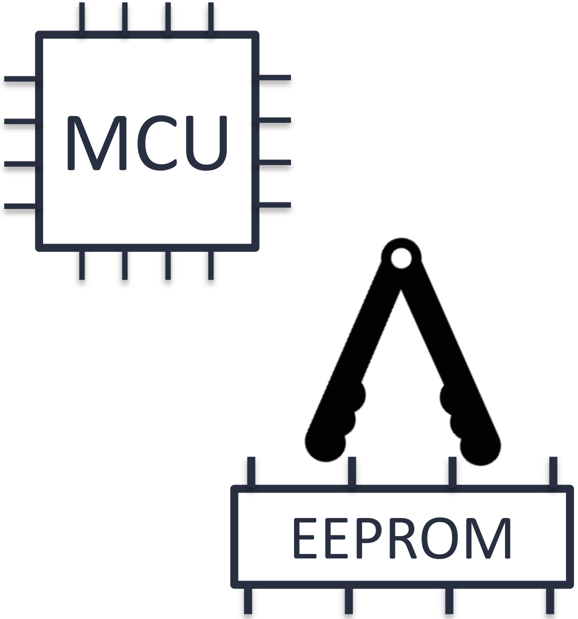
Interfaces

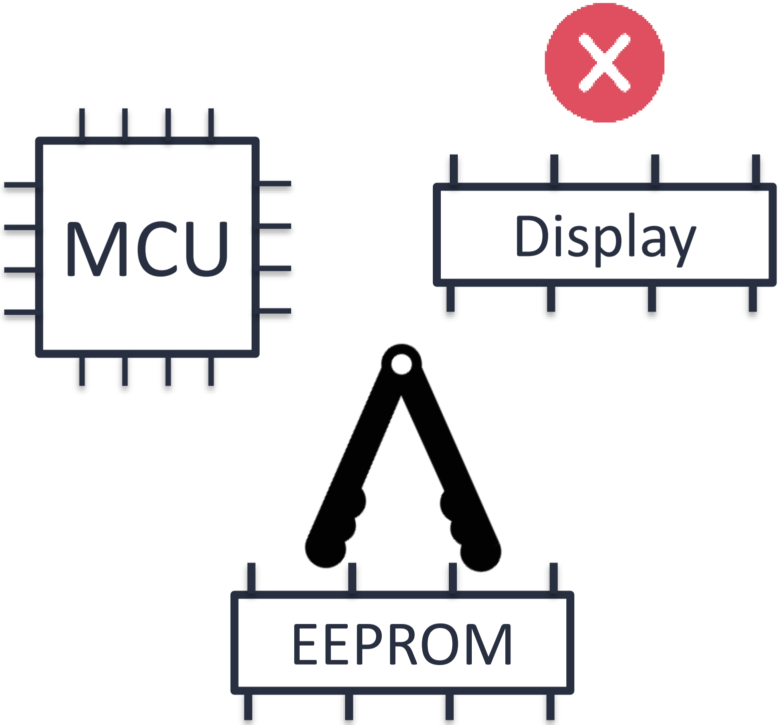
Chips

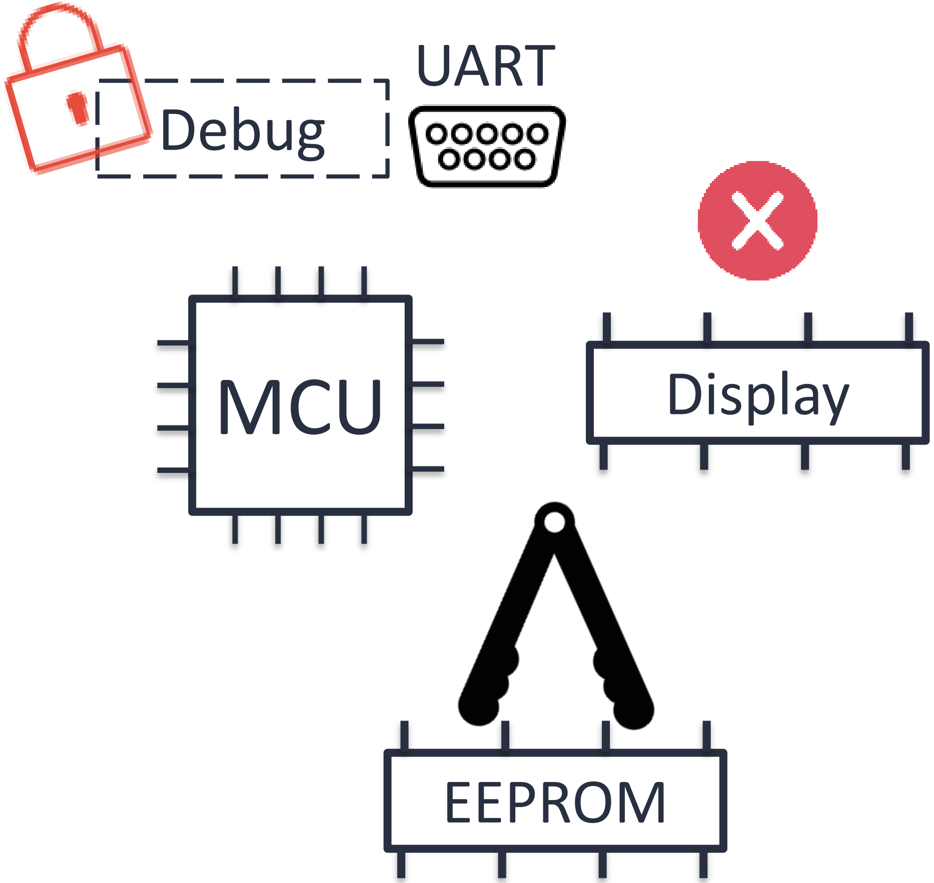
Software

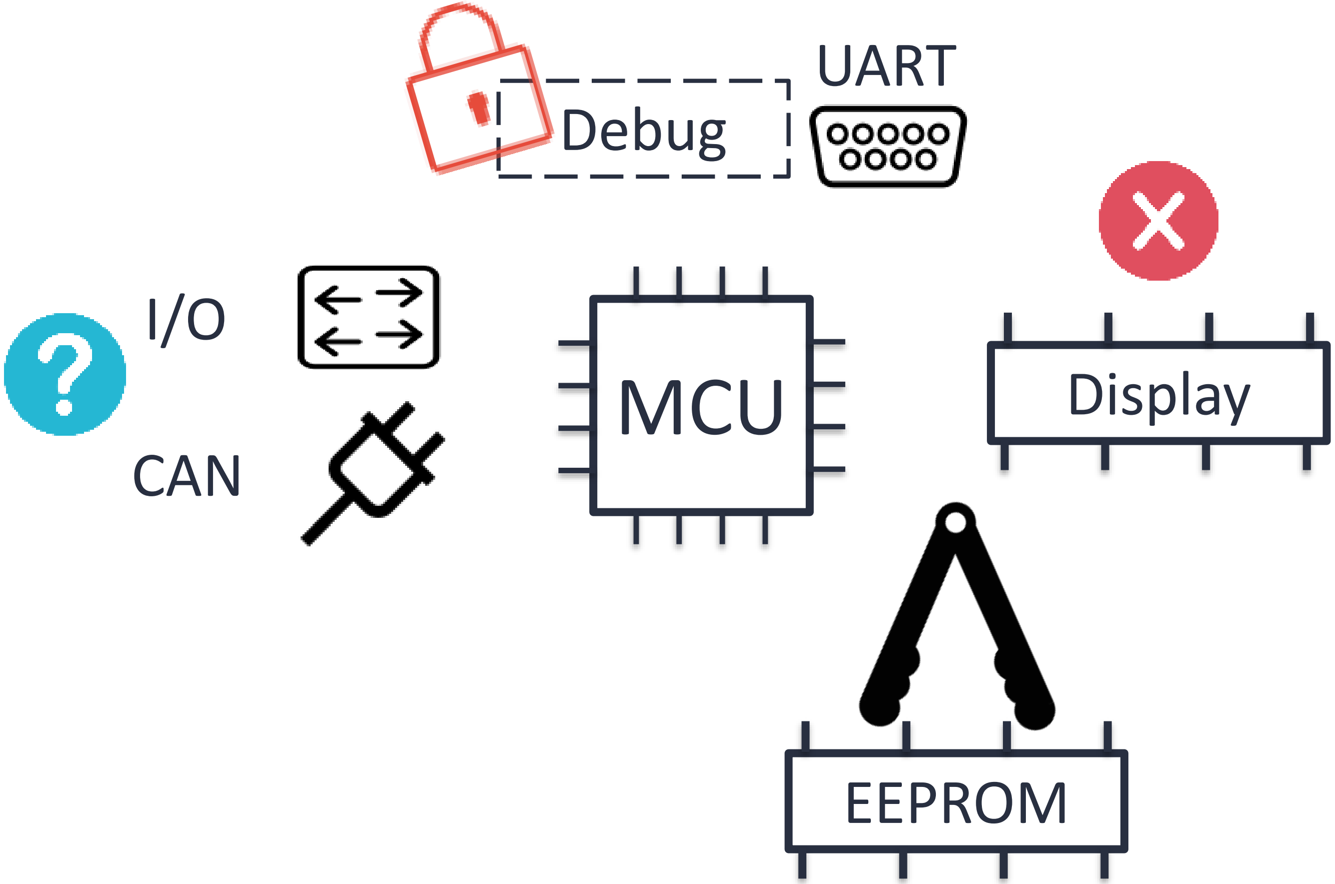
Let’s **open up** our **Instrument Cluster!**


MCU


MCU
EEPROM


MCU
Display
EEPROM


Debug
UART
MCU
Display
EEPROM


Debug
UART
I/O
CAN
MCU
Display
EEPROM

# Most ECUs speak UDS over CAN!

Most ECUs speak UDS over CAN!

Yay, UDS! *Wait… what?*

# Unified Diagnostic Services (UDS)

ISO14229

- Diagnostics
- Data Transmission
  - Read and write memory
- Security Access check
- And loads of more stuff...

# Quick analysis of our dashboard

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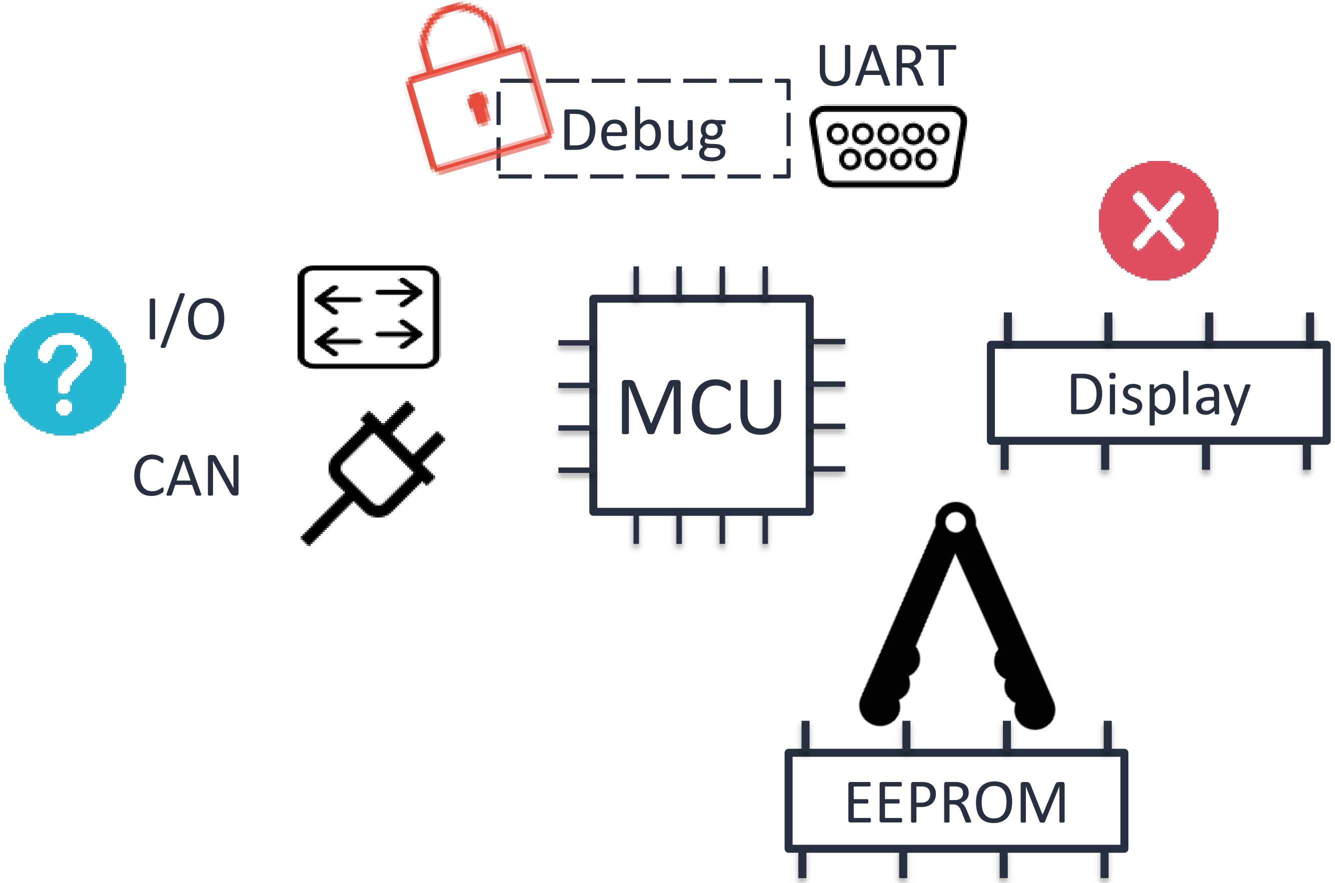
# Quick analysis of our dashboard

- Read/write memory functions
  - **Protected**

- Black-box vulnerability discovery
  - **Possible; but too difficult**

- We want something easy…



Debug

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CAN

MCU

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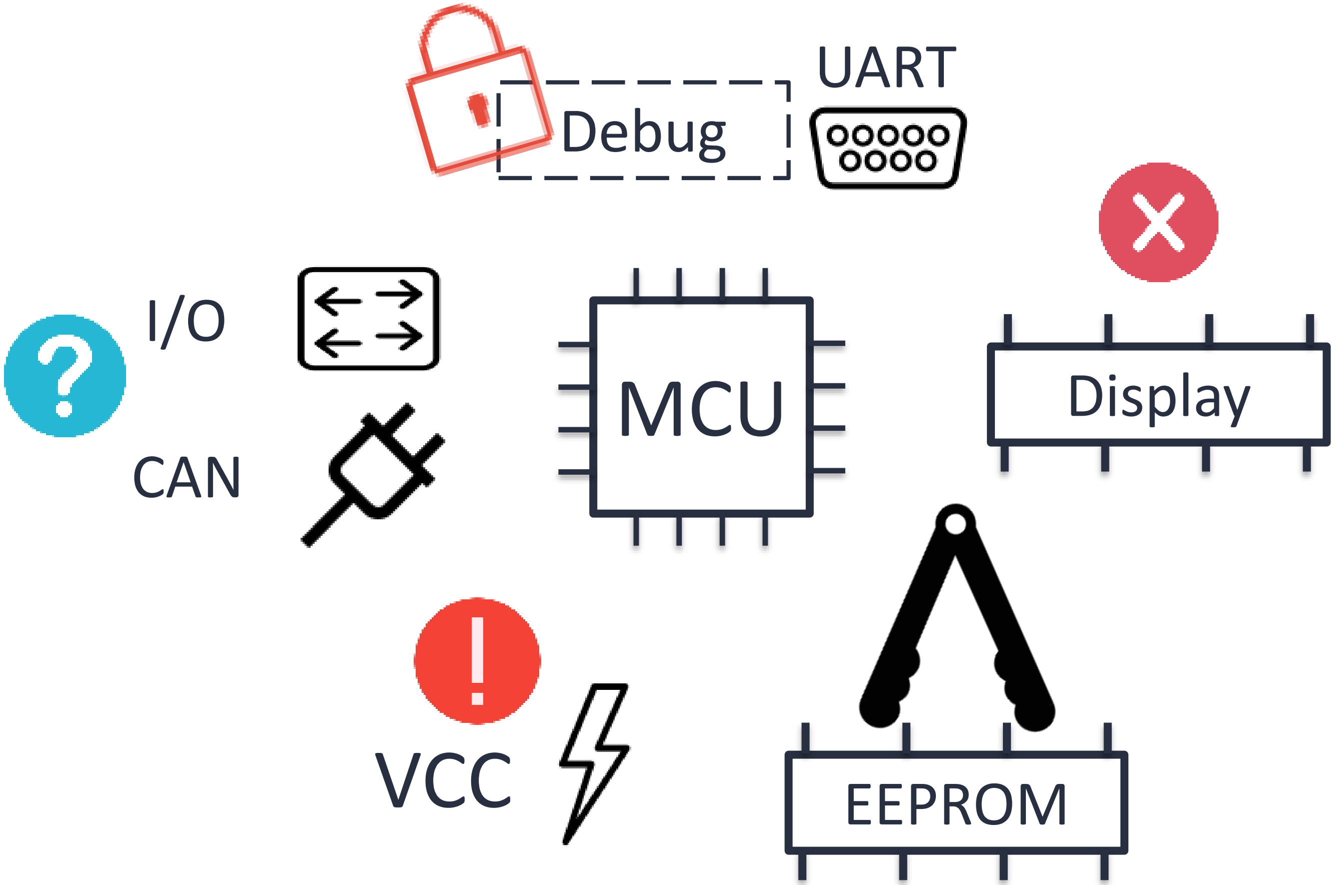
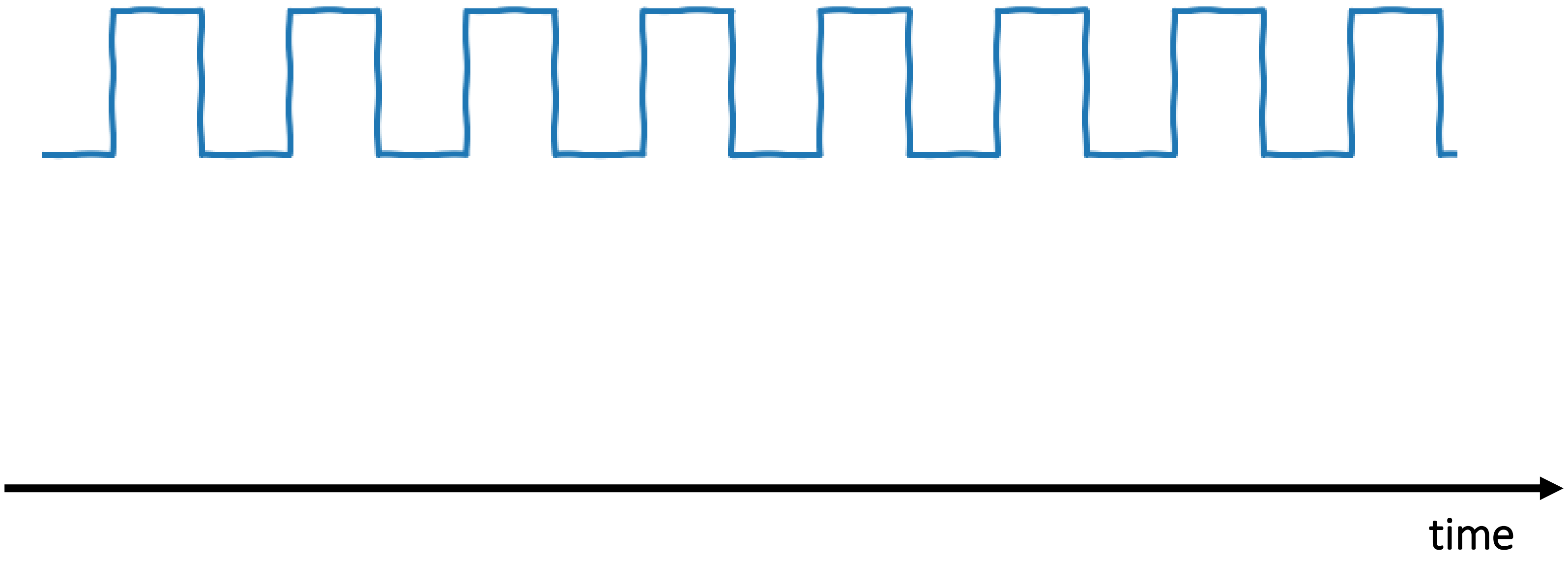
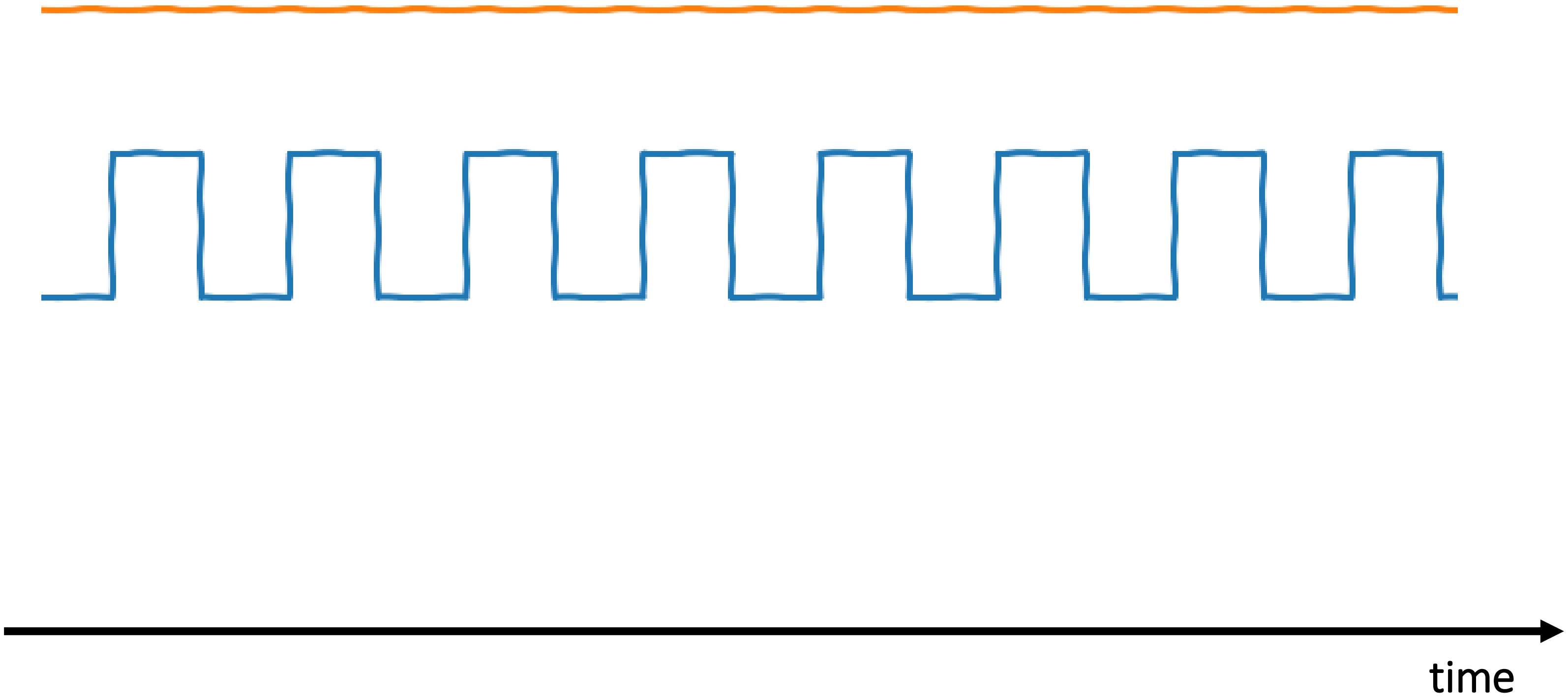

Debug
UART
I/O
CAN
MCU
Display
VCC
EEPROM

# *Voltage Fault Injection !!!*


time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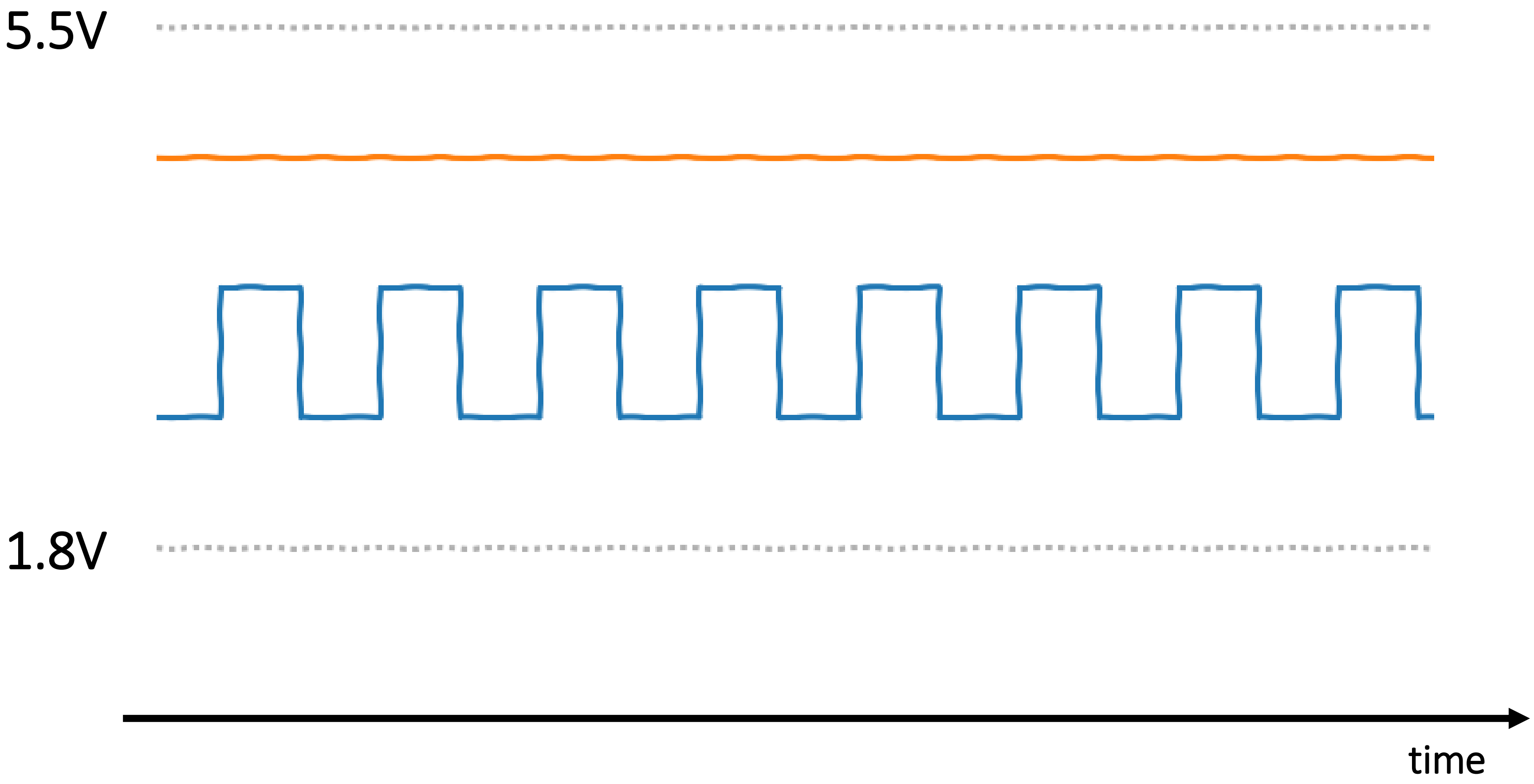
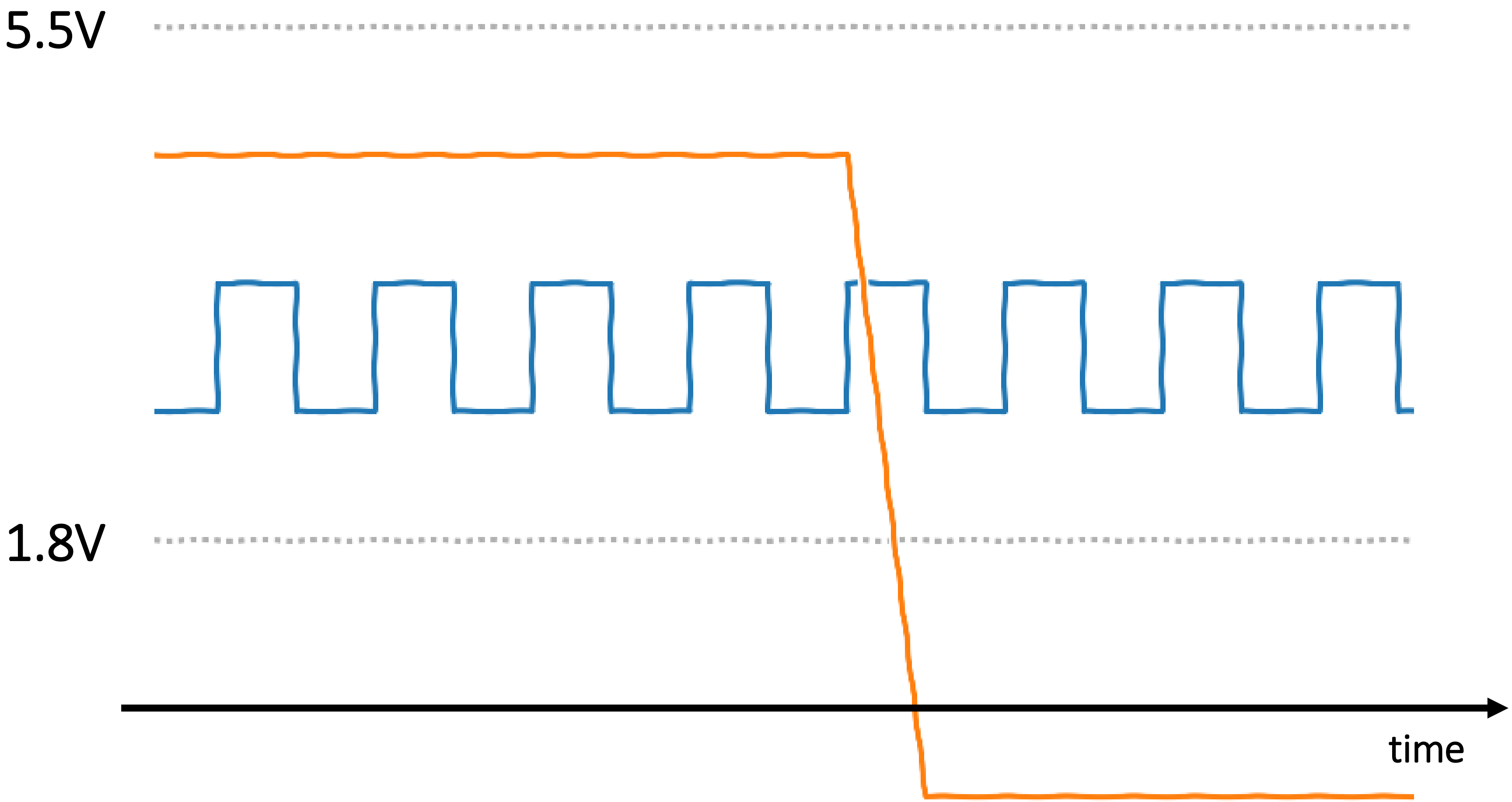

5.5V
1.8V
time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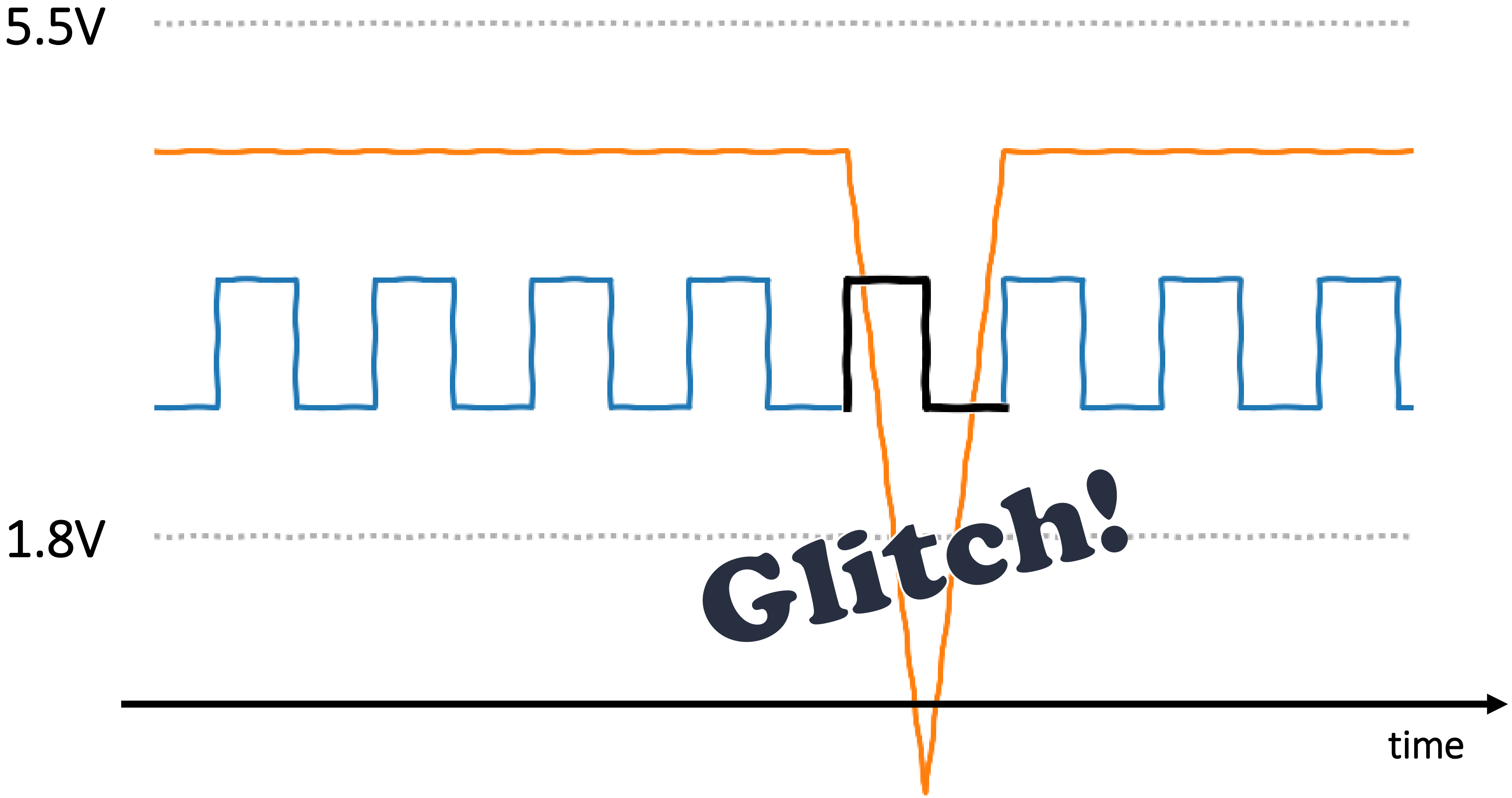
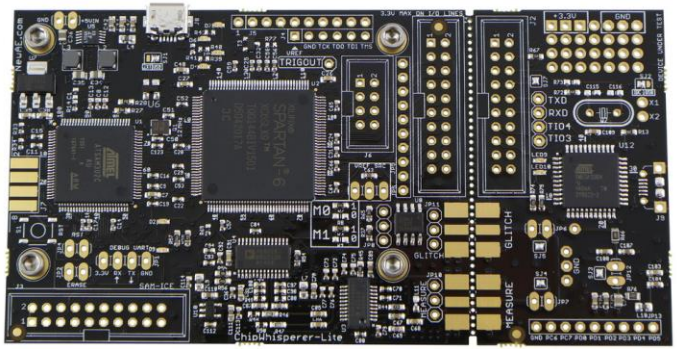

5.5V
1.8V
Glitch!
time

# Fault Injection – Tooling

*Open source*



**ChipWhisperer®**

*Commercial*

**Inspector FI**

***Fault Injection tooling is available to the masses!***

# What happens when we glitch?

## Things go wrong!

# Fault Injection breaks things!

- Memory contents
- Register contents
- Executed instructions

*You cannot trust anything anymore…*

*We can modify instructions and data!*

*We can modify instructions and data!*

*Yes, this also means we can skip instructions!*

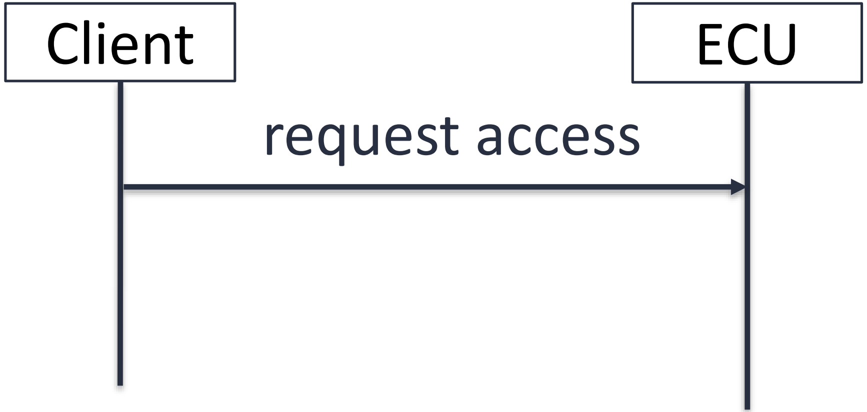
*We can modify instructions and data!*

*Yes, this also means we can <u>skip instructions</u>!*

*This works on all standard architectures:*
***ARM, MIPS, PowerPC, SH4, V850, Intel**, etc.*

*Let’s glitch something…*

# Glitching the Security Access Check



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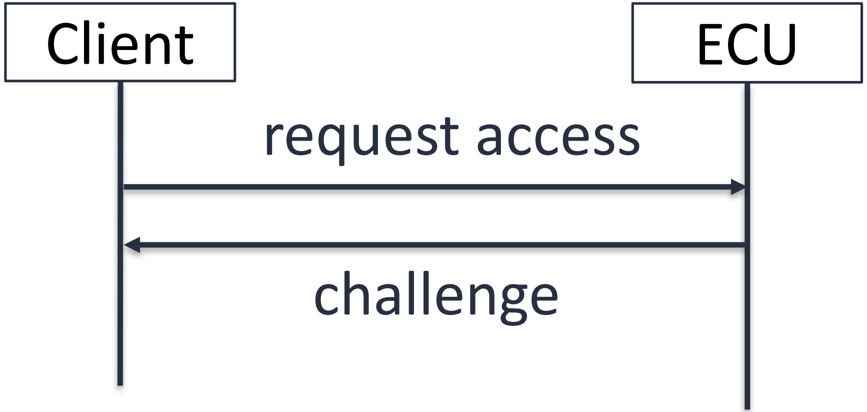

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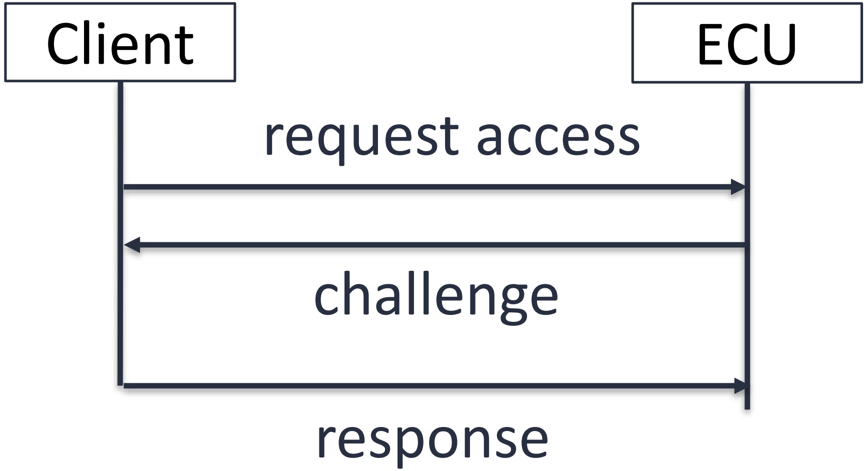


Client

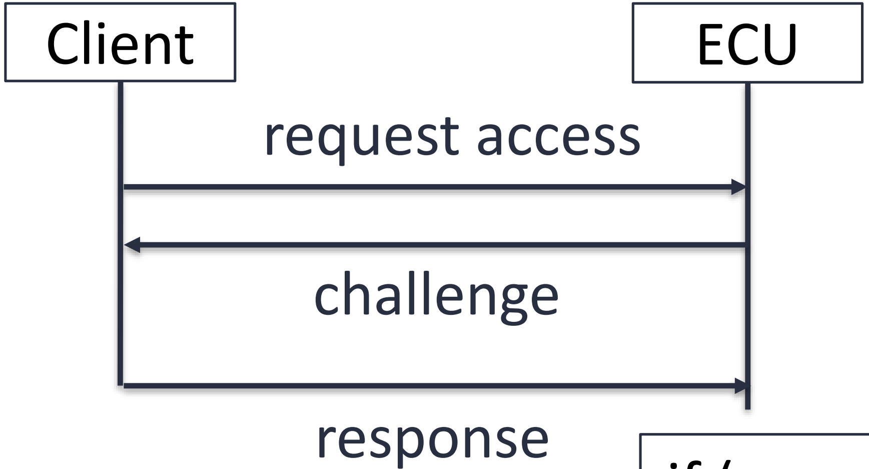
ECU

request access

challenge

response

# Glitching the Security Access Check



```
if (response == correct_response)

        grant_access();
```

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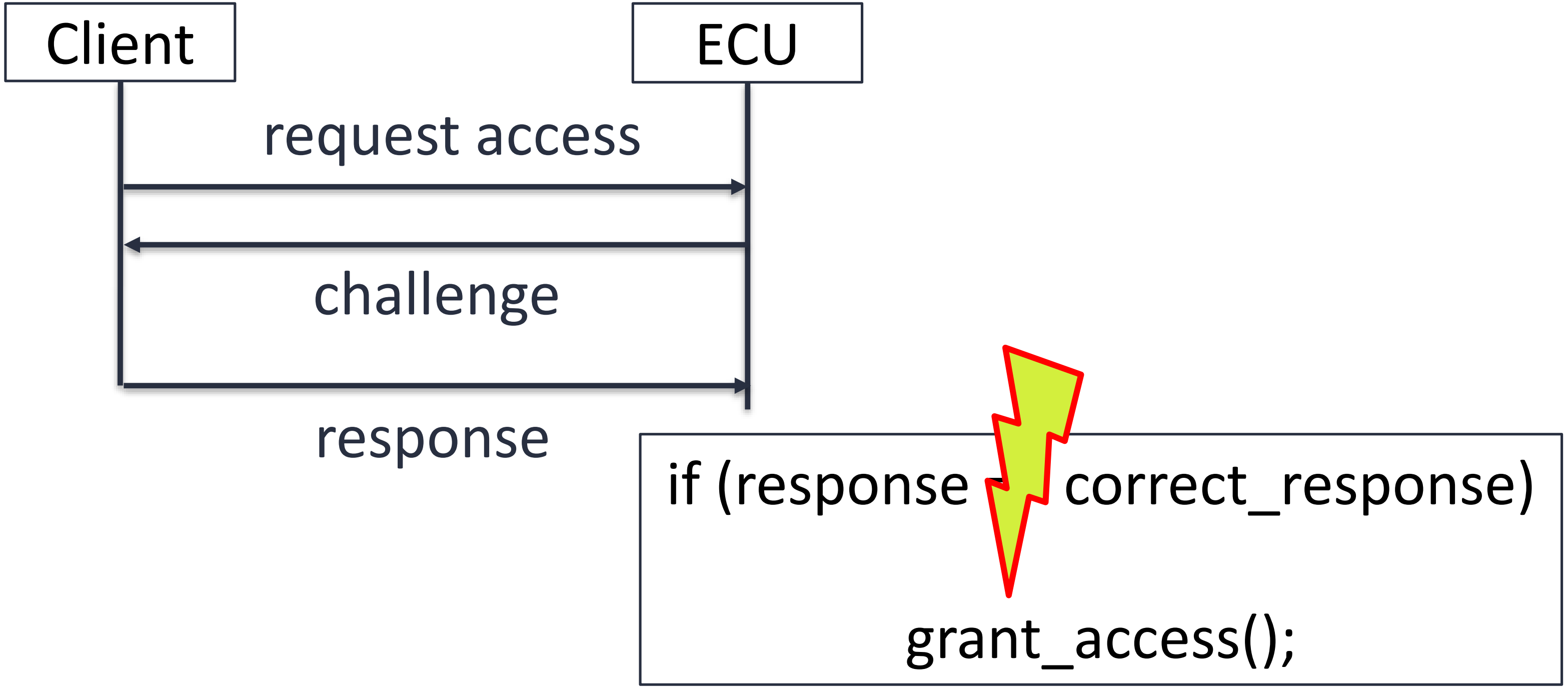

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# Glitching the Security Access Check Results

- Not successful :’(
- There’s a 10 minute timeout after 3 failed attempts
- Simply not practical for us (or an attacker)

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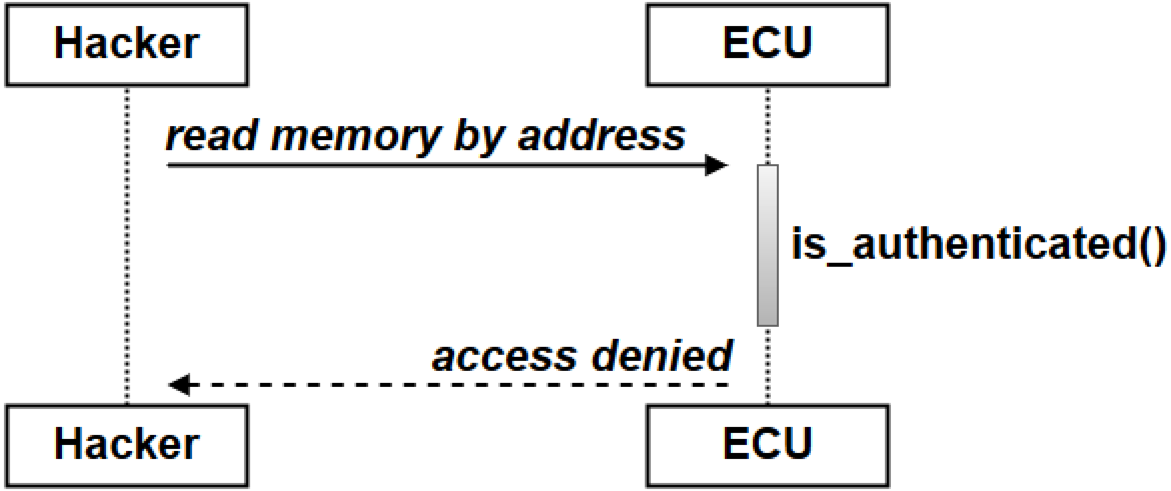
- There’s a 10 minute timeout after 3 failed attempts
- Simply not practical for us (or an attacker)

***You win some, you lose some!***

# Glitching ReadMemoryByAddress



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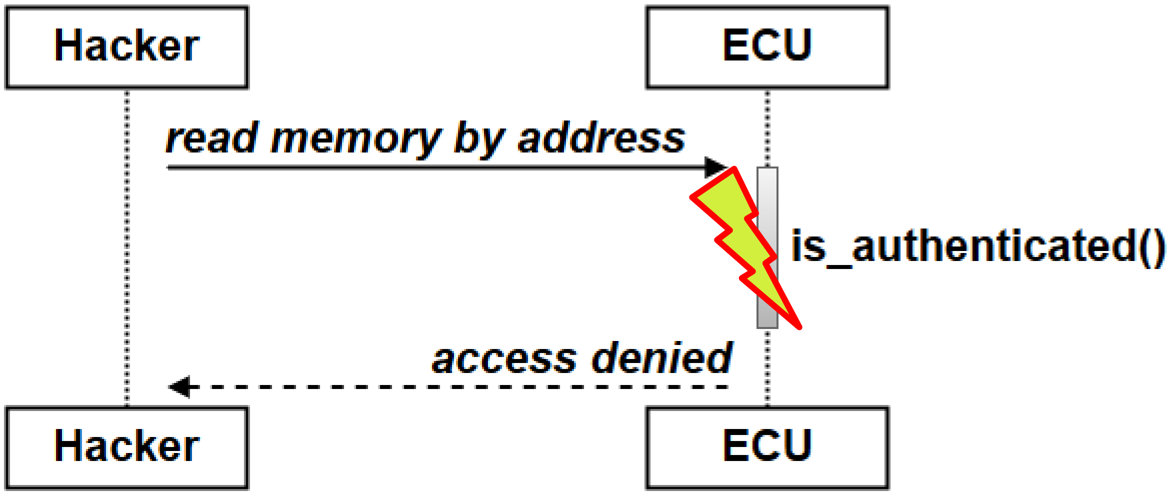

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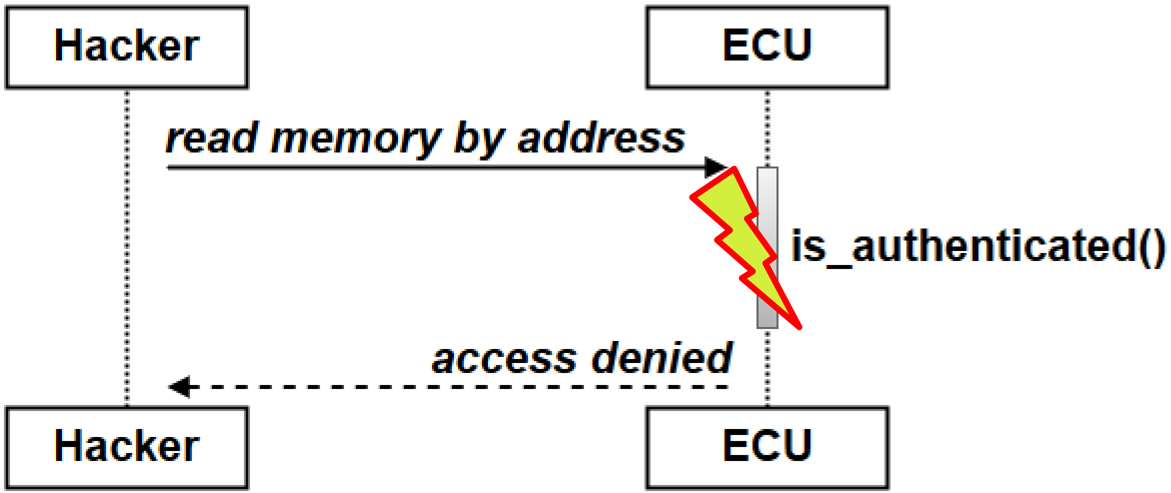


*No restrictions on failed attempts!*

# Glitching ReadMemoryByAddress Results

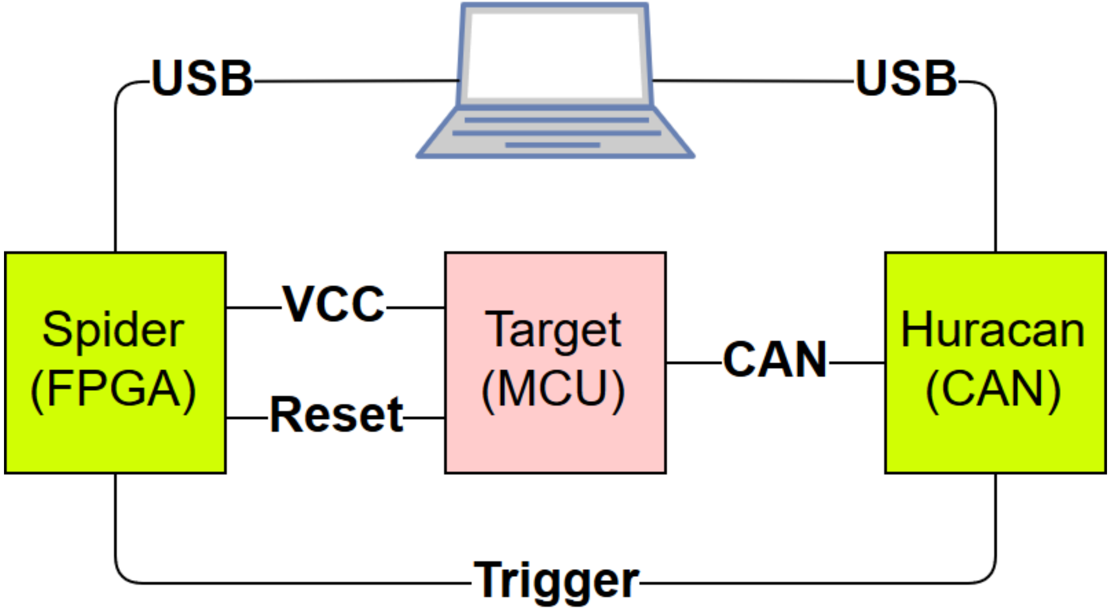
- Successful on several different ECUs
  - Which are designed around different MCUs

- Depending on the target…
  - Allows reading out **N** bytes from an **arbitrary** address

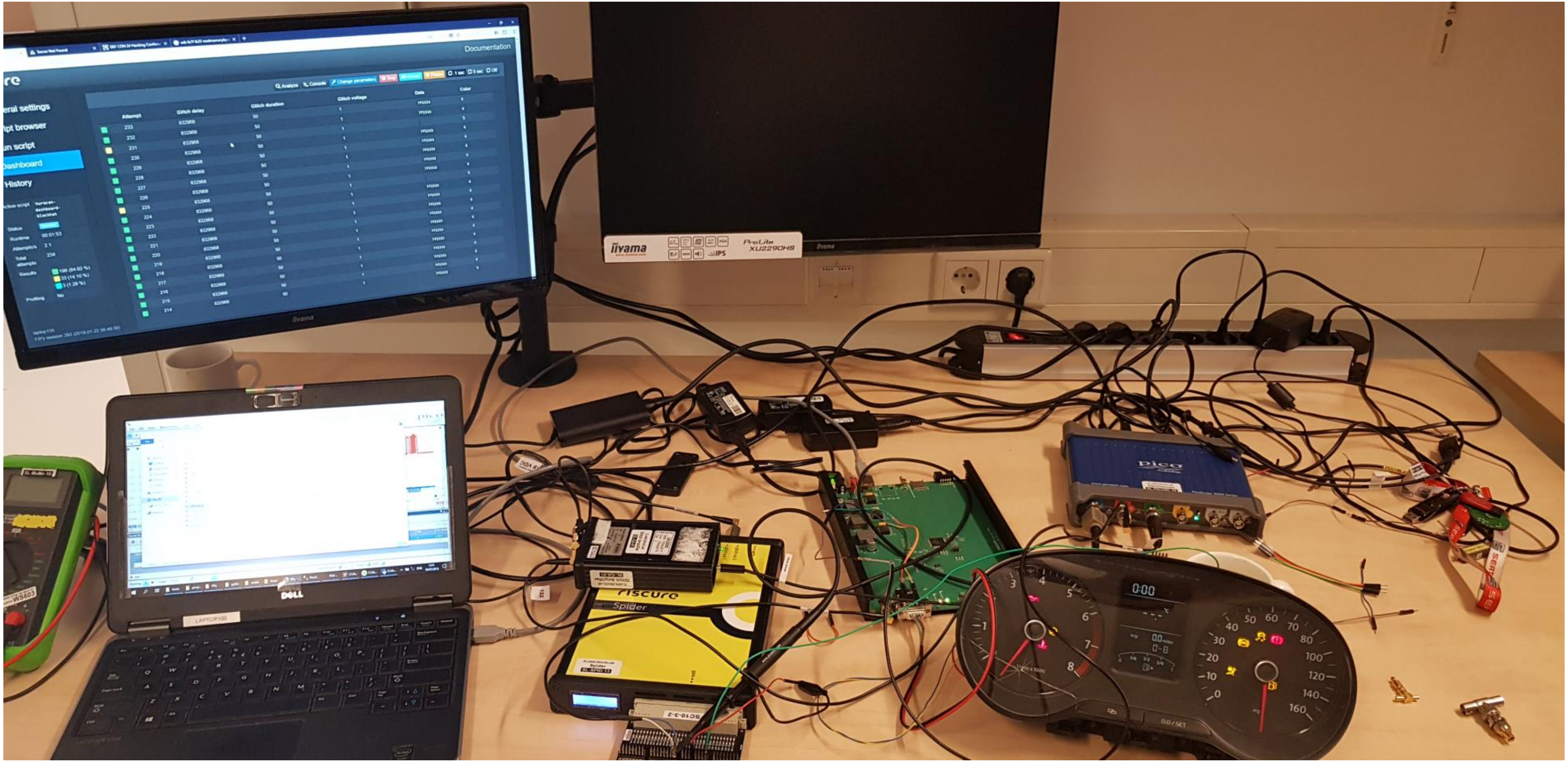
- Complete firmware extracted in the order of days
  - Depended on the size of the internal memory

# *DEMO TIME !!!*

# Fault Injection demo setup



CAN UDS CMD: ReadMemoryByAddress(0x00000000, 0x40)


Documentation
eral settings
ipt browser
un script
Dashboard
History
Attempt
Glitch delay
Glitch duration
Glitch voltage
Data
Color
iiyama
ProLite XU2290HS
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LAPTOP100
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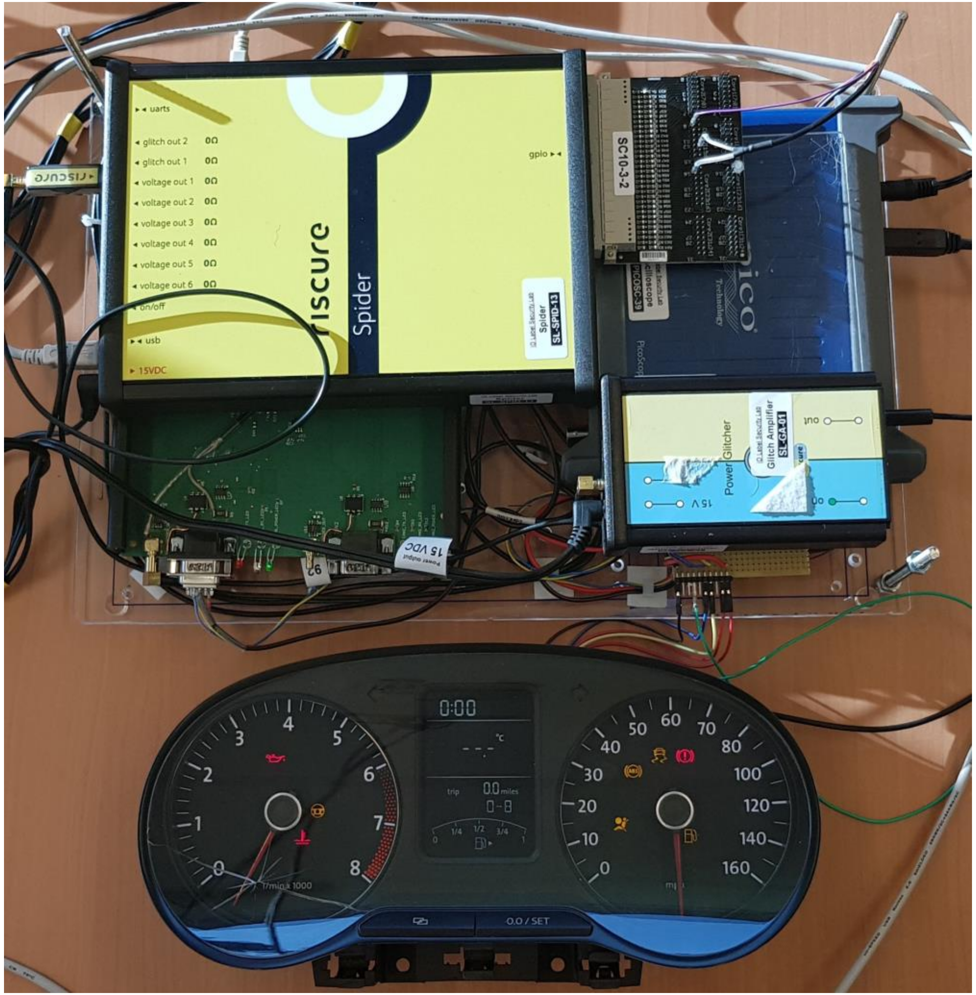
uarts
glitch out 2
glitch out 1
voltage out 1
voltage out 2
voltage out 3
voltage out 4
voltage out 5
voltage out 6
on/off
usb
15VDC
gpio
riscure
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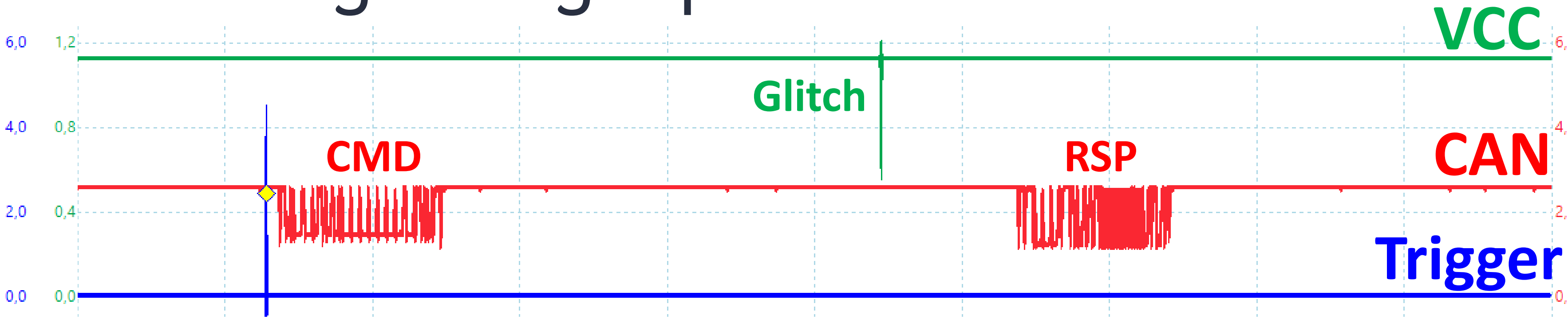
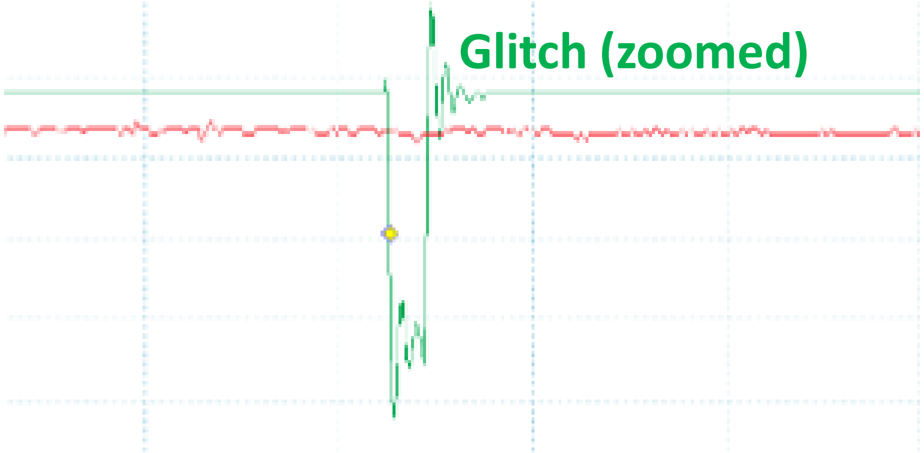
SC10-3-2
PicoScope
pico Technology
Power Glitcher
Glitch Amplifier
SL_GA-01
out
15 V
15 VDC
0:00
trip
0.0 miles
0.0 / SET

# Finding the right parameters: Randomize

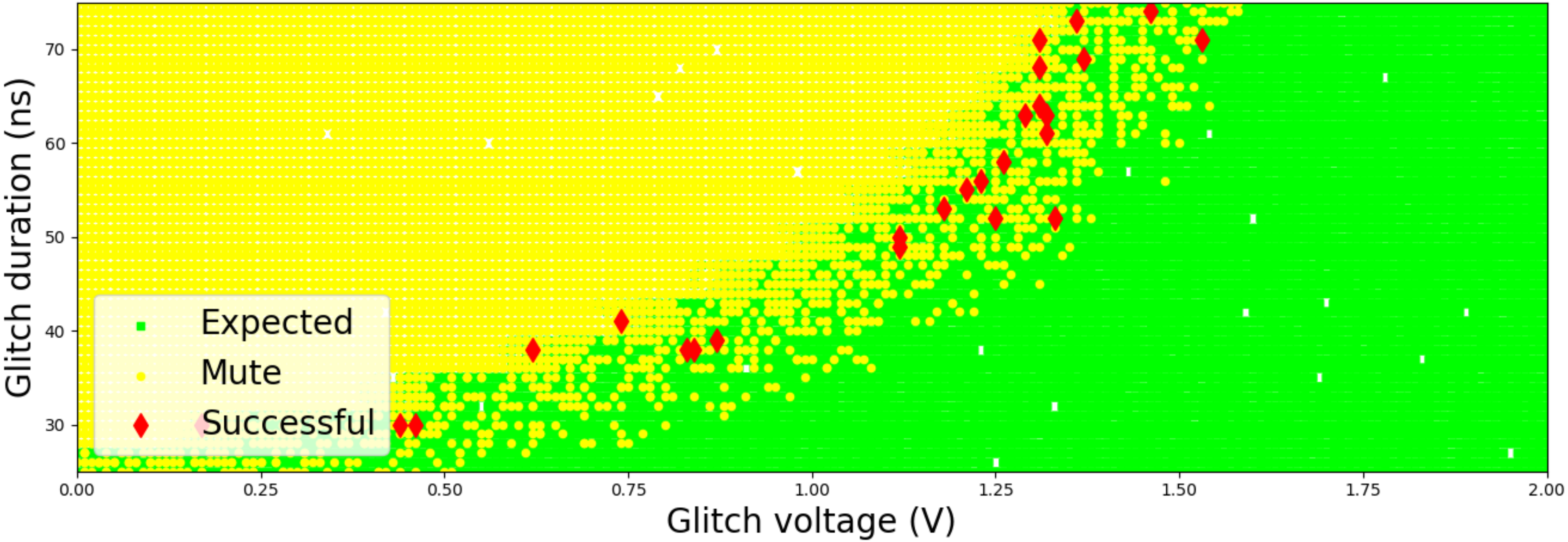




**Glitch Parameters**

- Glitch Delay
- Glitch Duration
- Glitch Voltage

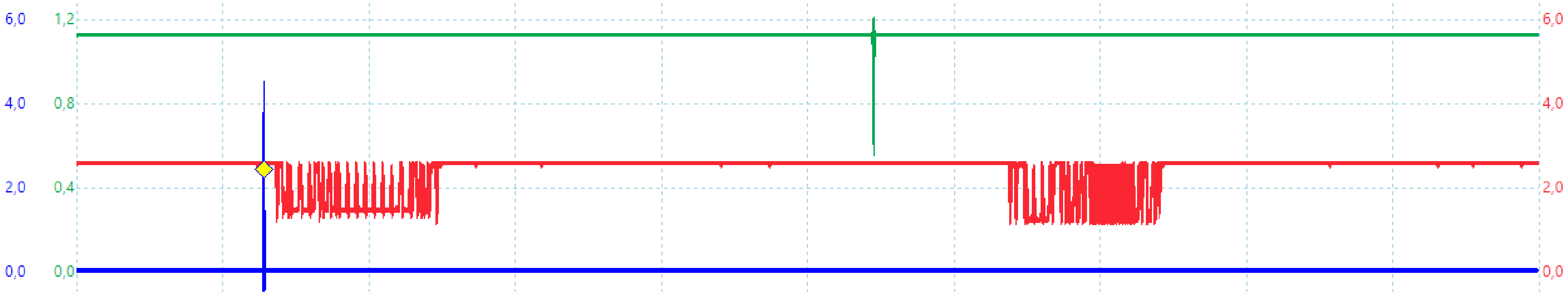
# There is a relationship!



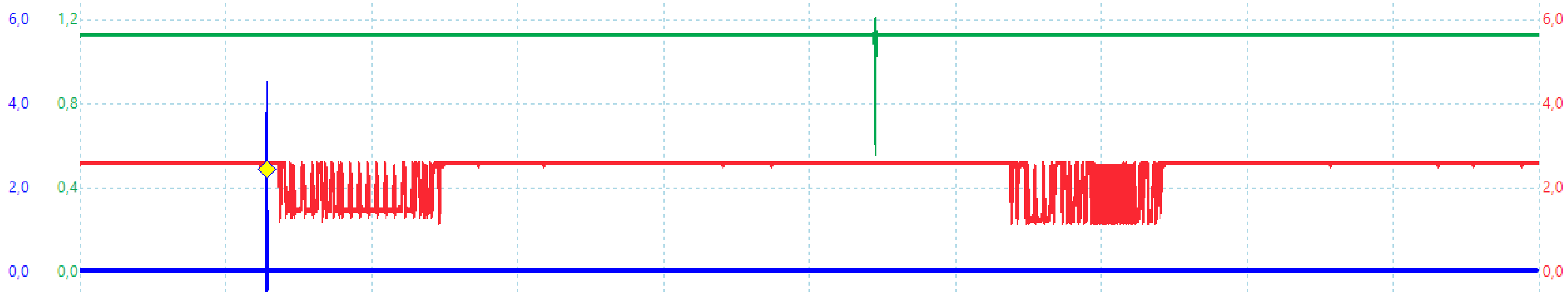
This relationship allows minimizing the parameter search space!

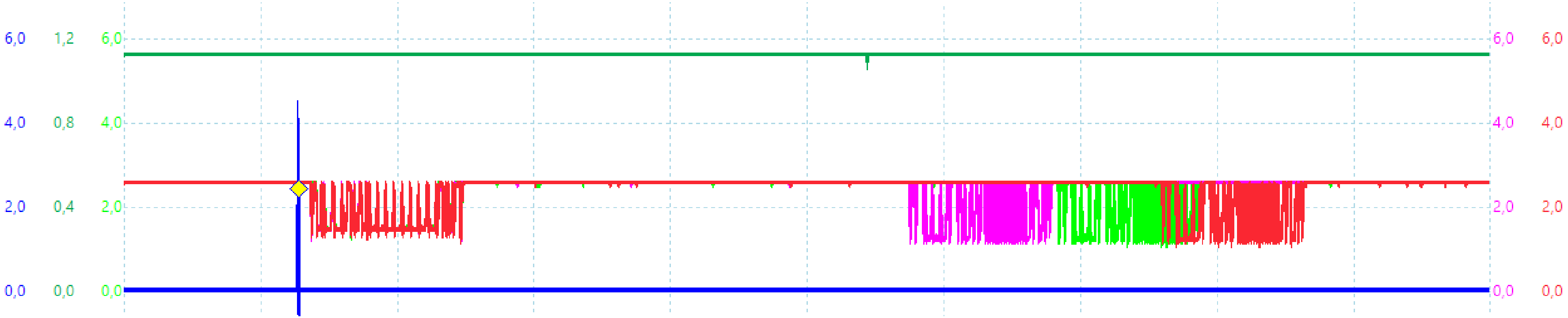
*Let’s switch to the other laptop…*

# Why not a 100% success rate? :’(

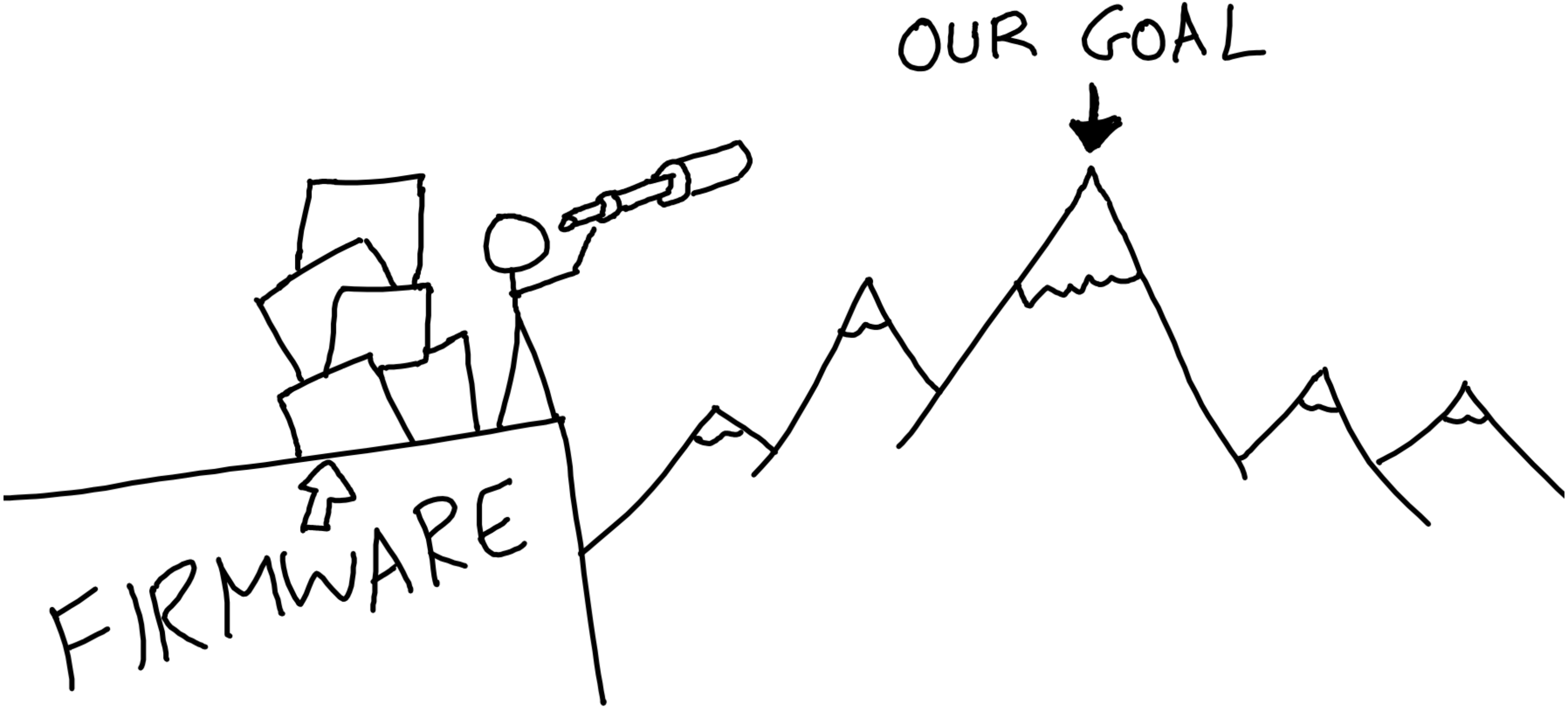


# Why not a 100% success rate? :’(





# *We have the firmware… now what?*


OUR GOAL
FIRMWARE

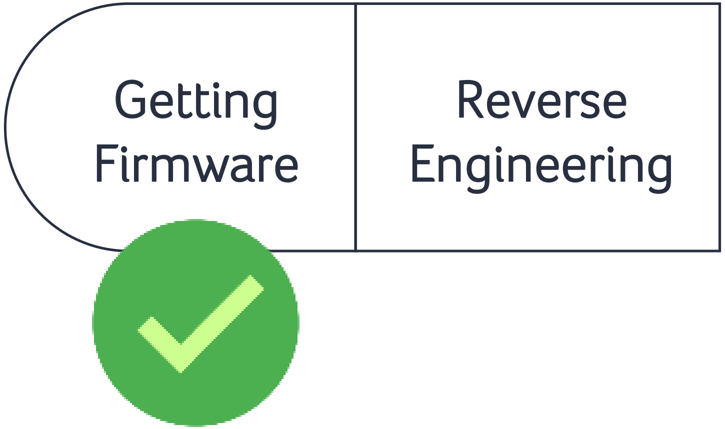
# The Plan

Getting Firmware

# The Plan

Getting Firmware

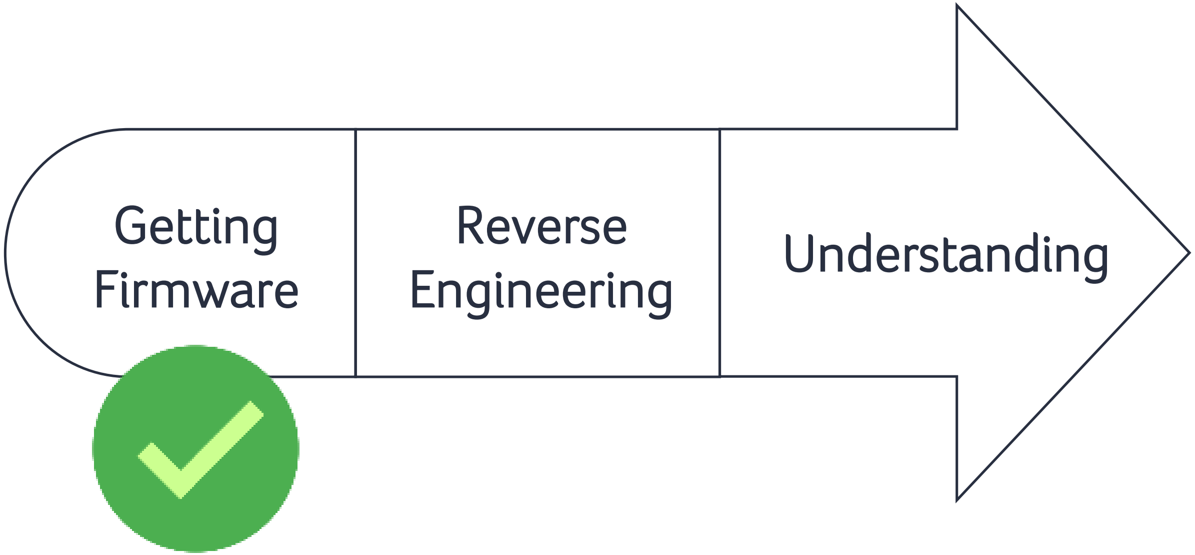
# The Plan



Getting Firmware

Reverse Engineering

# The Plan

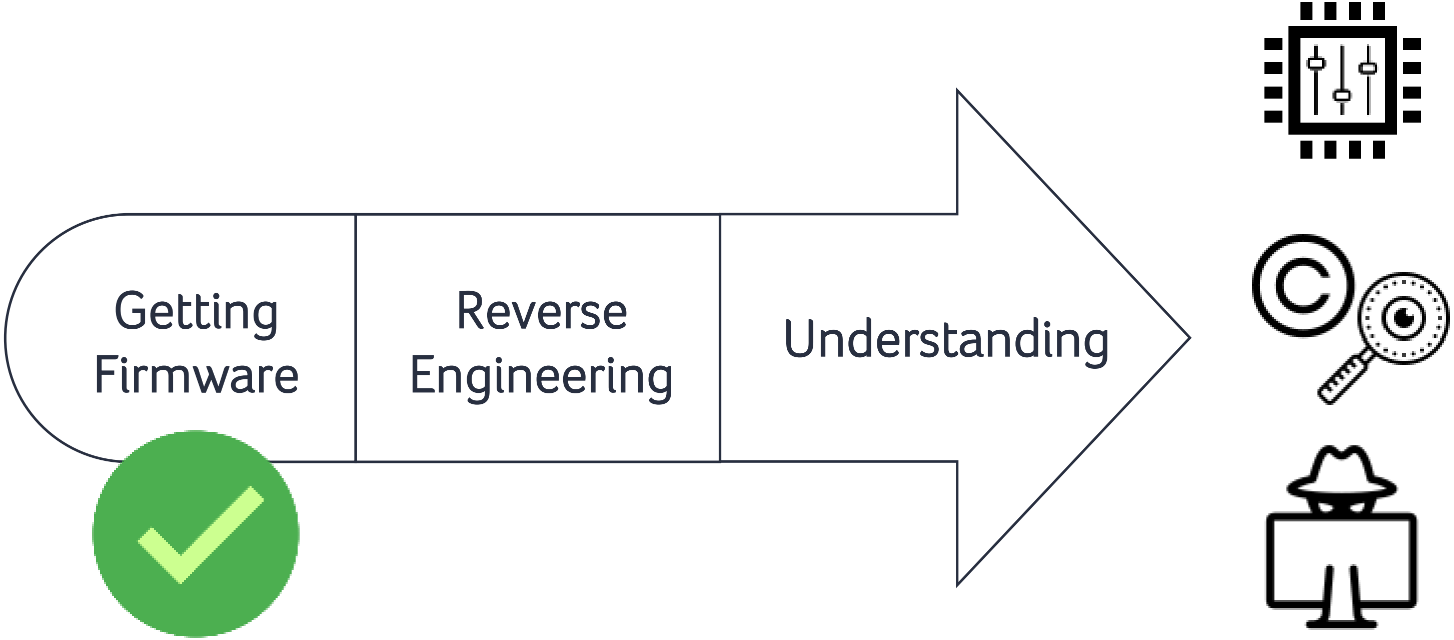


Getting Firmware

Reverse Engineering

Understanding

# The Plan



Getting Firmware ✓

Reverse Engineering

Understanding

Tuning

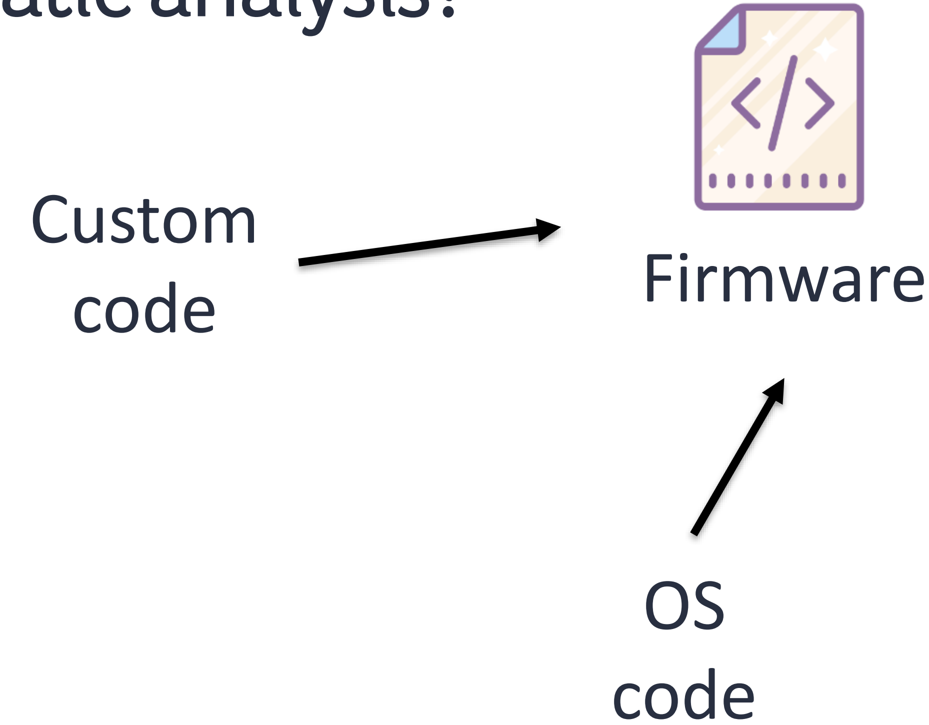
Secrets!

Hacking

# Static analysis?

Firmware

# Static analysis?

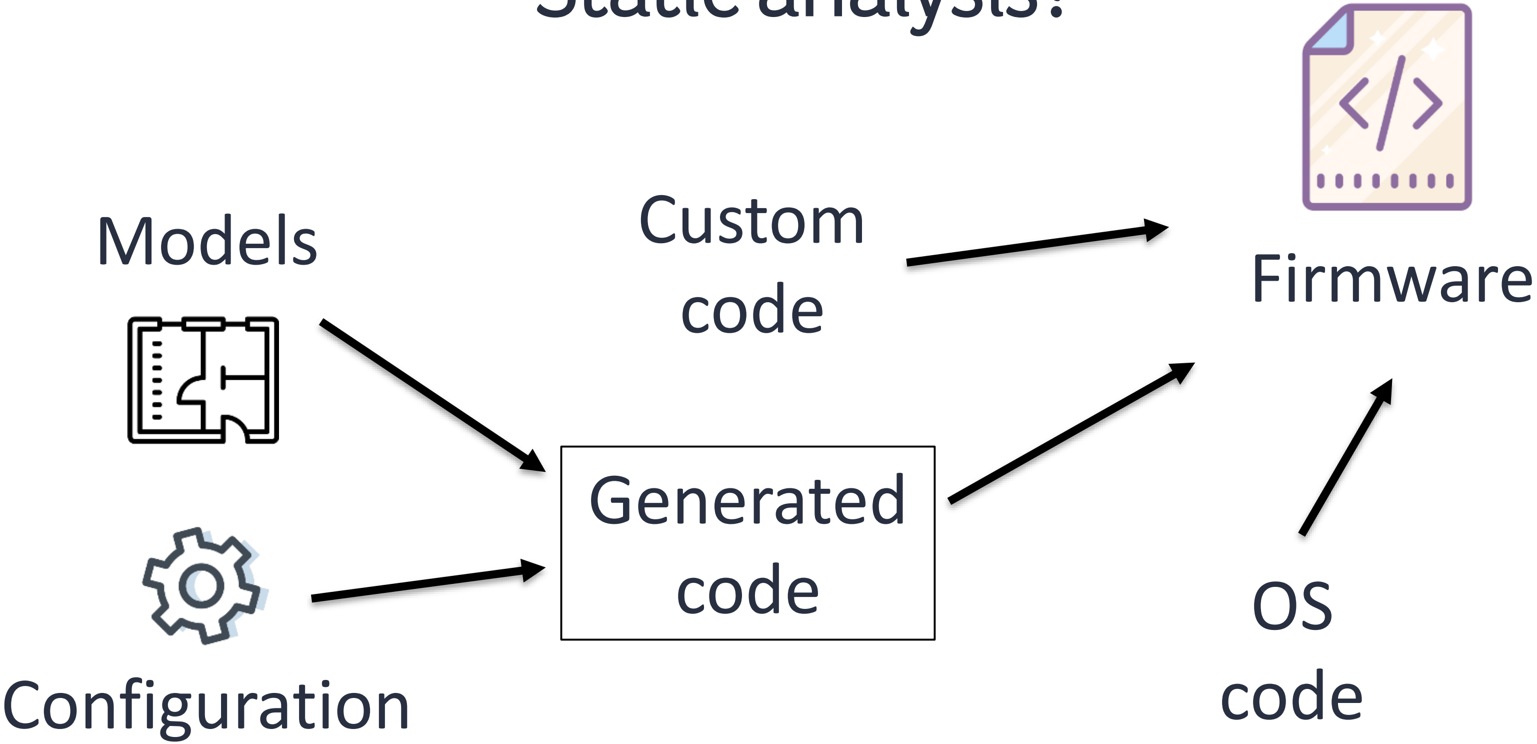


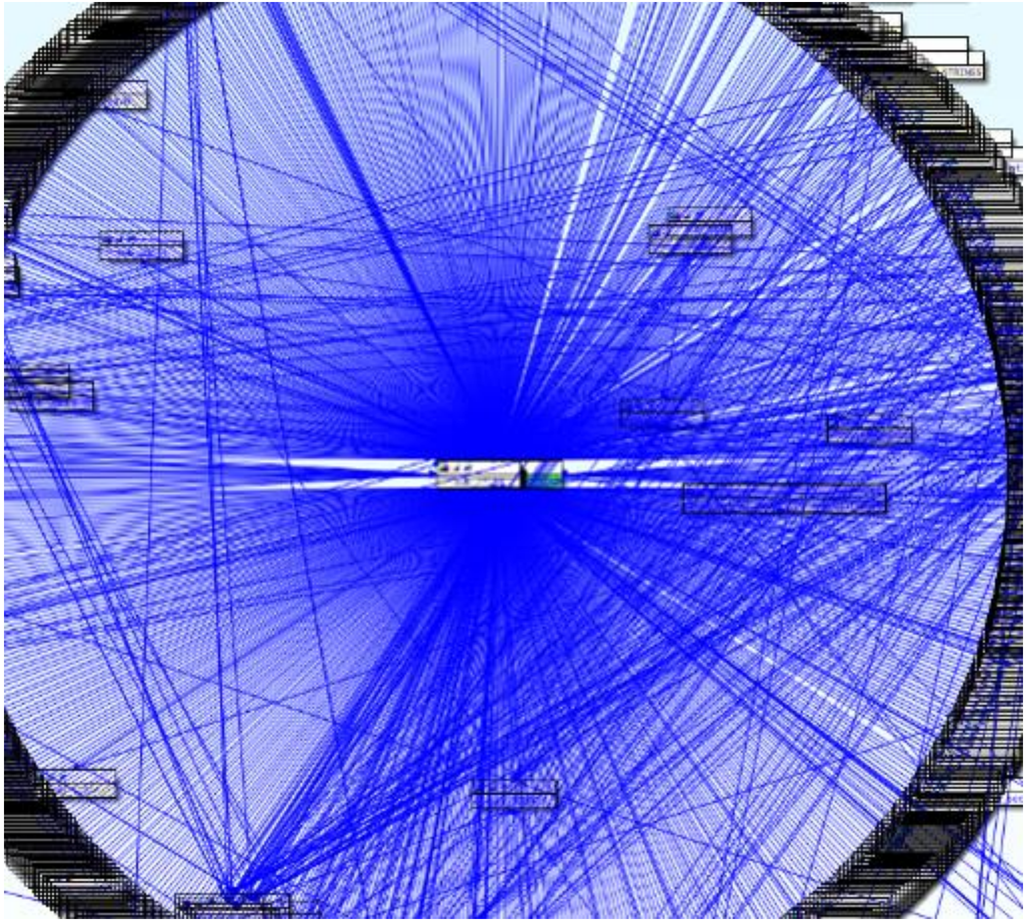
Custom code

Firmware

OS code

# Static analysis?





# Tools?

$ARCH is supported by IDA Pro **and** radare2

# Tools?

Badly ☹

^

$ARCH is supported by IDA Pro **and** radare2

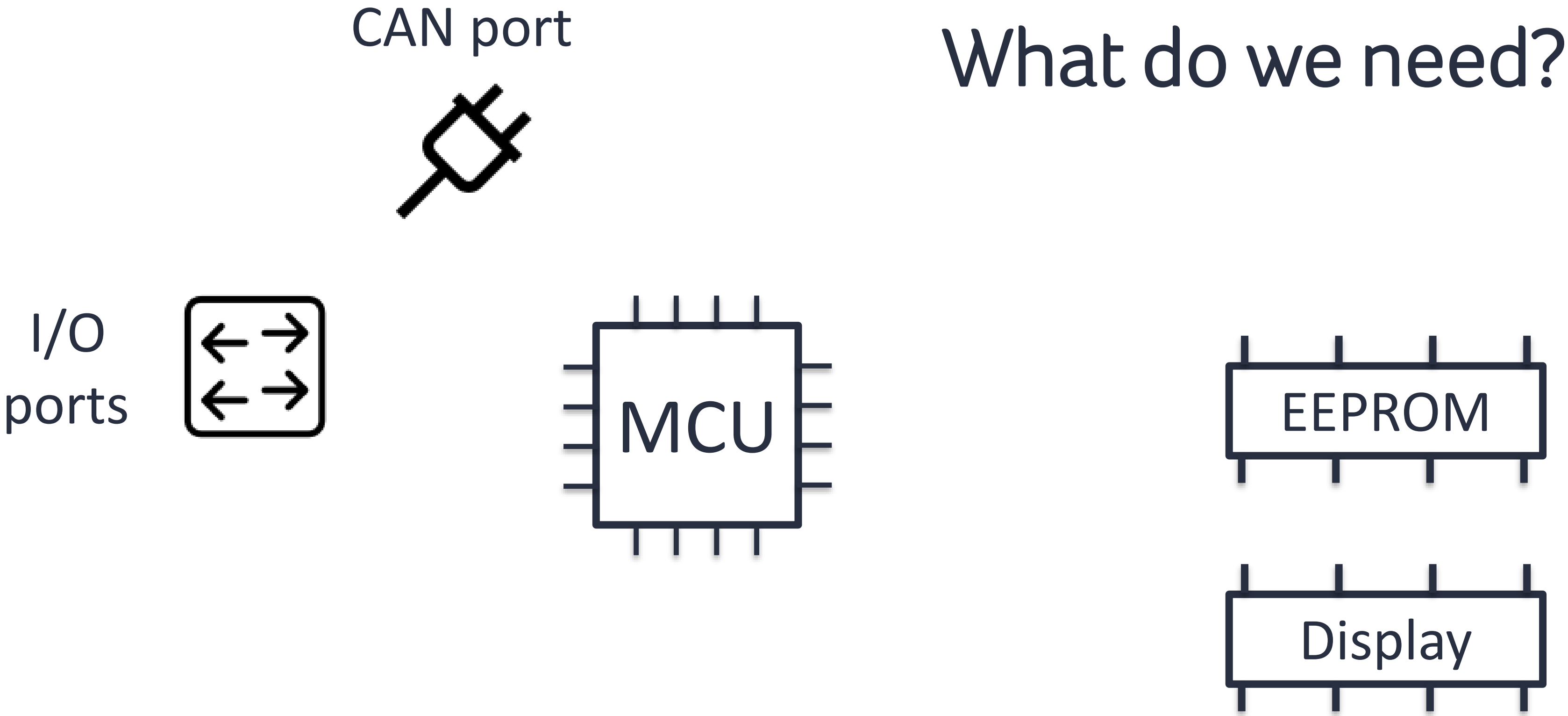
# Tools?

Badly ☹
^
$ARCH is supported by IDA Pro **and** radare2

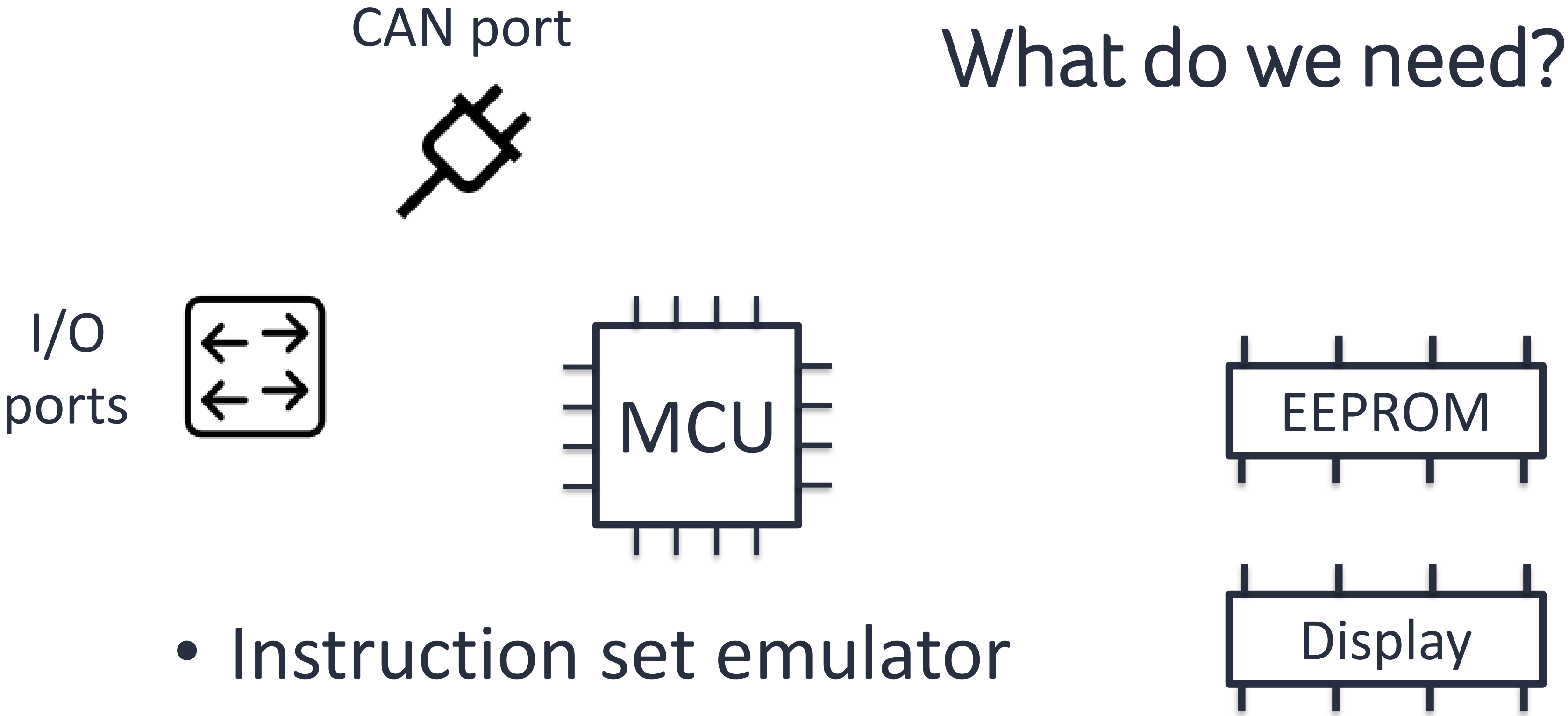
$ARCH is **not** supported by qemu

# *No tools? Let’s make some tools!*

# What do we need?

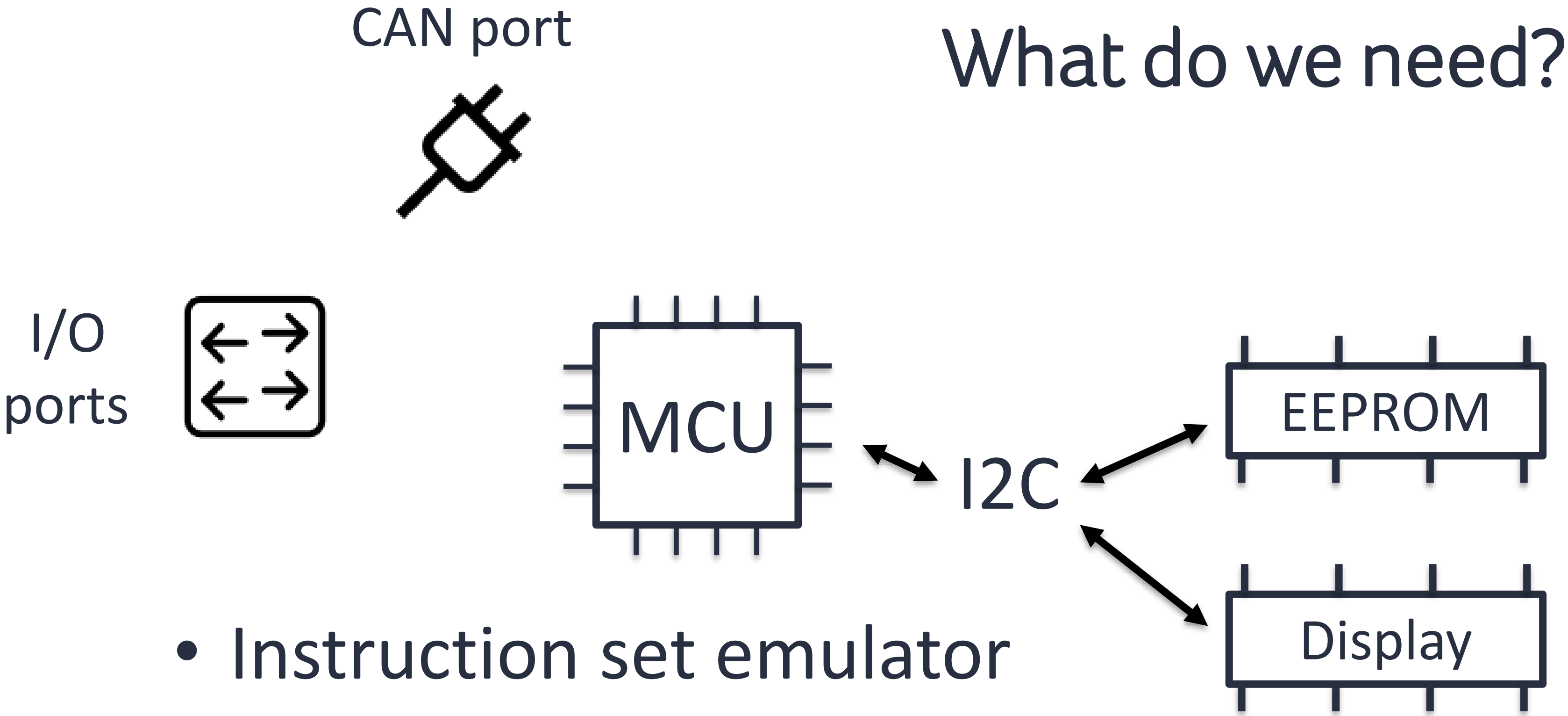


# What do we need?



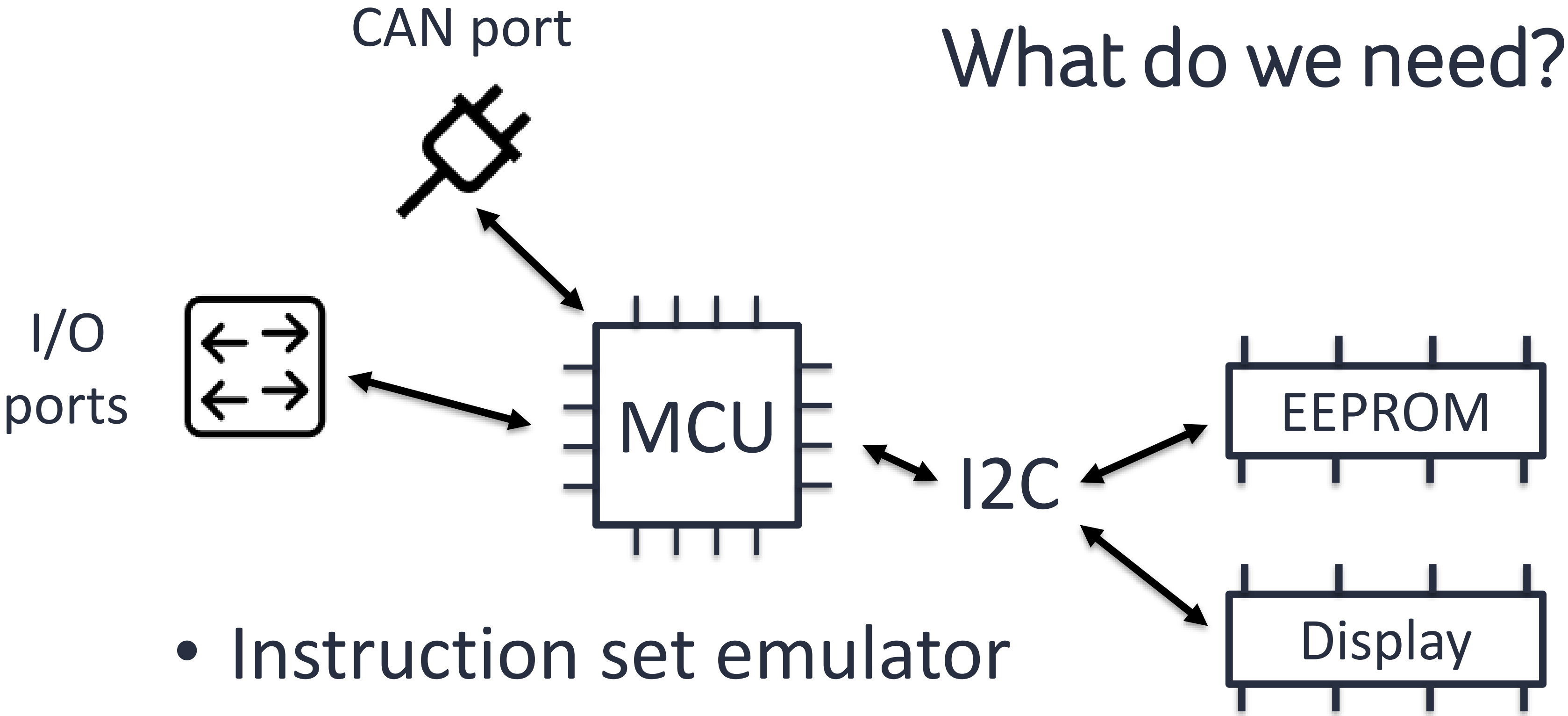
- Instruction set emulator
- Timers, interrupts, ...

# What do we need?



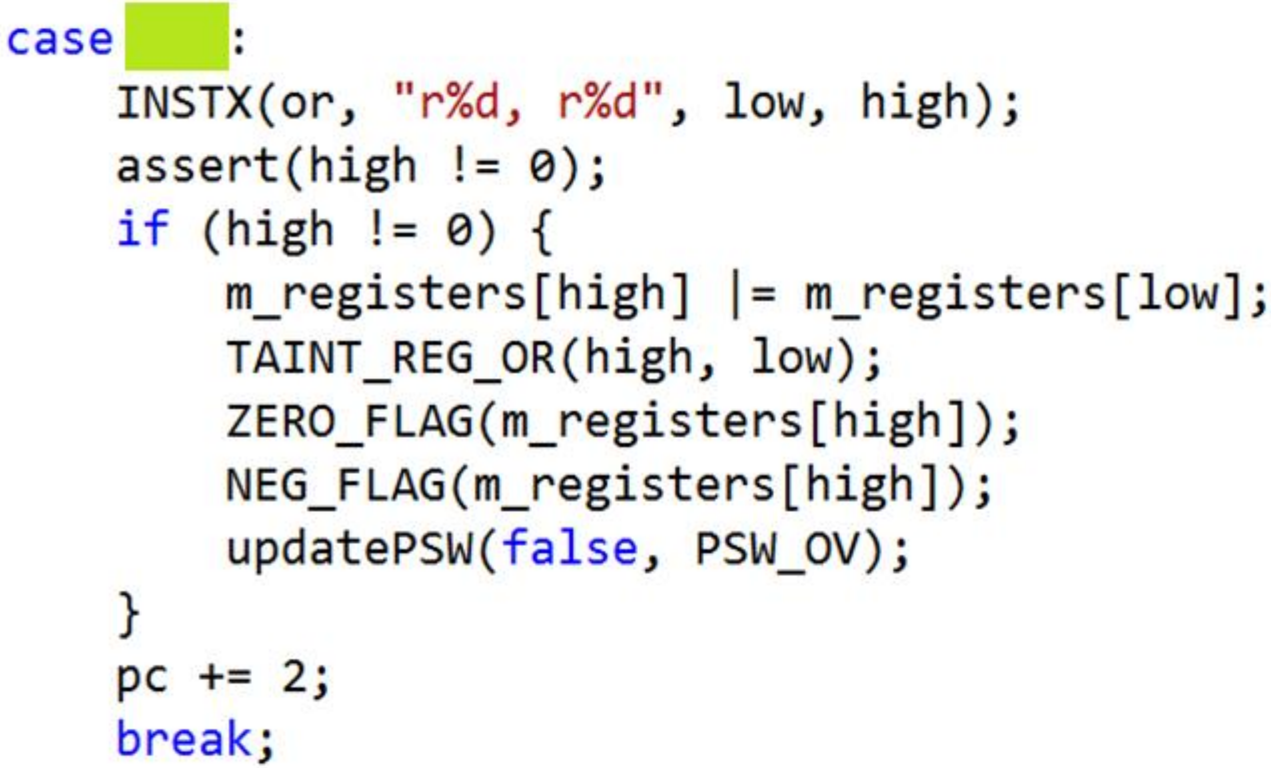
- Instruction set emulator
- Timers, interrupts, …

# What do we need?



- Instruction set emulator
- Timers, interrupts, …

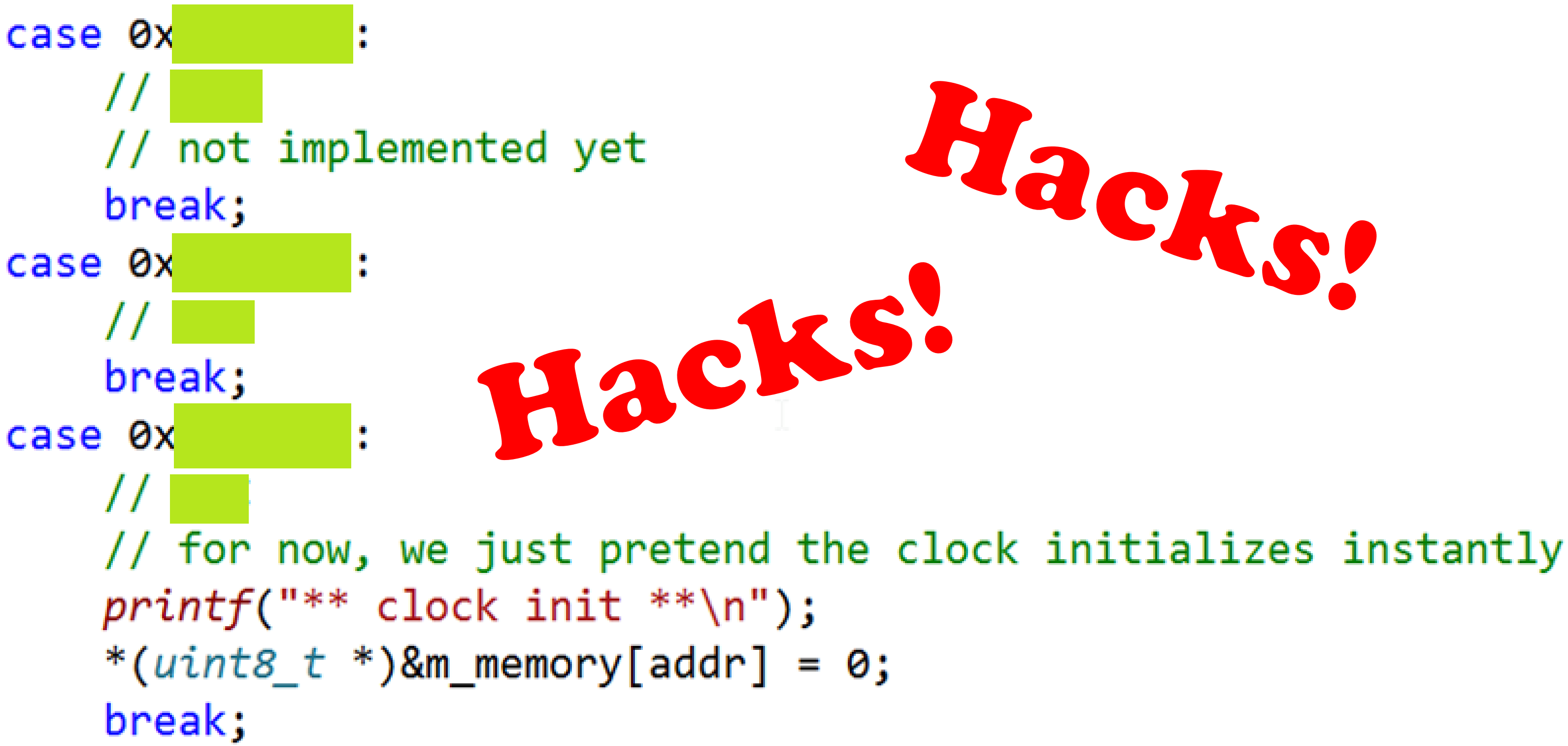
# Emulating the CPU architecture



```
case [redacted]:
    INSTX(or, "r%d, r%d", low, high);
    assert(high != 0);
    if (high != 0) {
        m_registers[high] |= m_registers[low];
        TAINT_REG_OR(high, low);
        ZERO_FLAG(m_registers[high]);
        NEG_FLAG(m_registers[high]);
        updatePSW(false, PSW_OV);
    }
    pc += 2;
    break;
```

# “Implementing” peripherals

# “Implementing” peripherals



```
case 0x[redacted]:
    // [redacted]
    // not implemented yet
    break;
case 0x[redacted]:
    // [redacted]
    break;
case 0x[redacted]:
    // [redacted]
    // for now, we just pretend the clock initializes instantly
    printf("** clock init **\n");
    *(uint8_t *)&m_memory[addr] = 0;
    break;
```

Hacks!

Hacks!

# How difficult was it?

# How difficult was it?

~ **1 (sleepless) week** of work

(for a hacker experienced in writing emulators)

# How difficult was it?

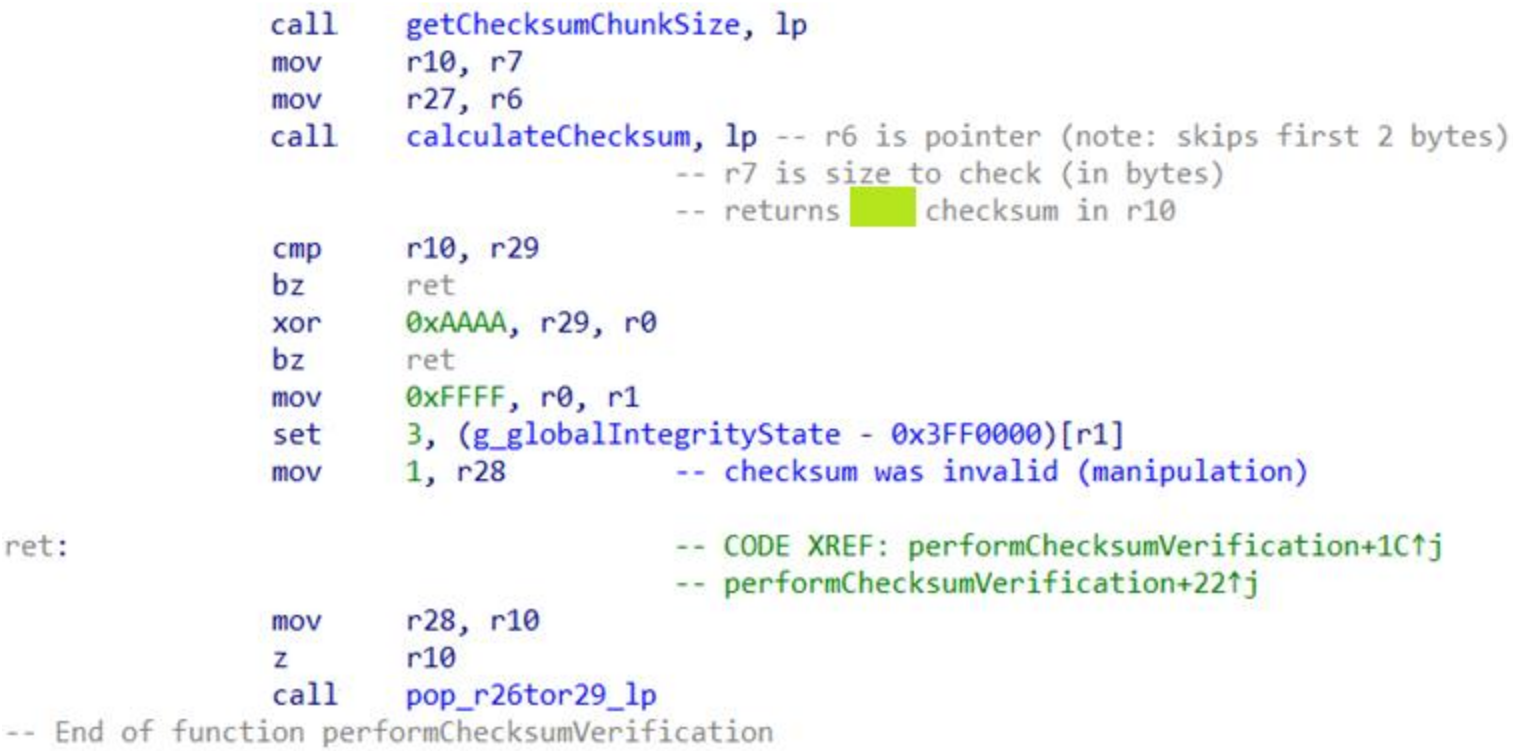
~ **1 (sleepless) week** of work
(for a hacker experienced in writing emulators)

~ **3000 lines** of (terrible) code
(excluding support tooling)

# Why write an emulator?

- Debugging (e.g. GDB stub)
- SocketCAN
- **Execution tracing**
- **Taint tracking**

# Execution tracing



```
                call    getChecksumChunkSize, lp
                mov     r10, r7
                mov     r27, r6
                call    calculateChecksum, lp -- r6 is pointer (note: skips first 2 bytes)
                                          -- r7 is size to check (in bytes)
                                          -- returns [redacted] checksum in r10
                cmp     r10, r29
                bz      ret
                xor     0xAAAA, r29, r0
                bz      ret
                mov     0xFFFF, r0, r1
                set     3, (g_globalIntegrityState - 0x3FF0000)[r1]
                mov     1, r28            -- checksum was invalid (manipulation)

ret:                                      -- CODE XREF: performChecksumVerification+1C↑j
                                          -- performChecksumVerification+22↑j
                mov     r28, r10
                z       r10
                call    pop_r26tor29_lp
-- End of function performChecksumVerification
```

# Execution tracing

```
0x02920
0x02922 (jump)
0x02926
0x02928
0x0292c
0x02930
```

# Execution tracing

**0x02920**

**0x02922 (jump)**

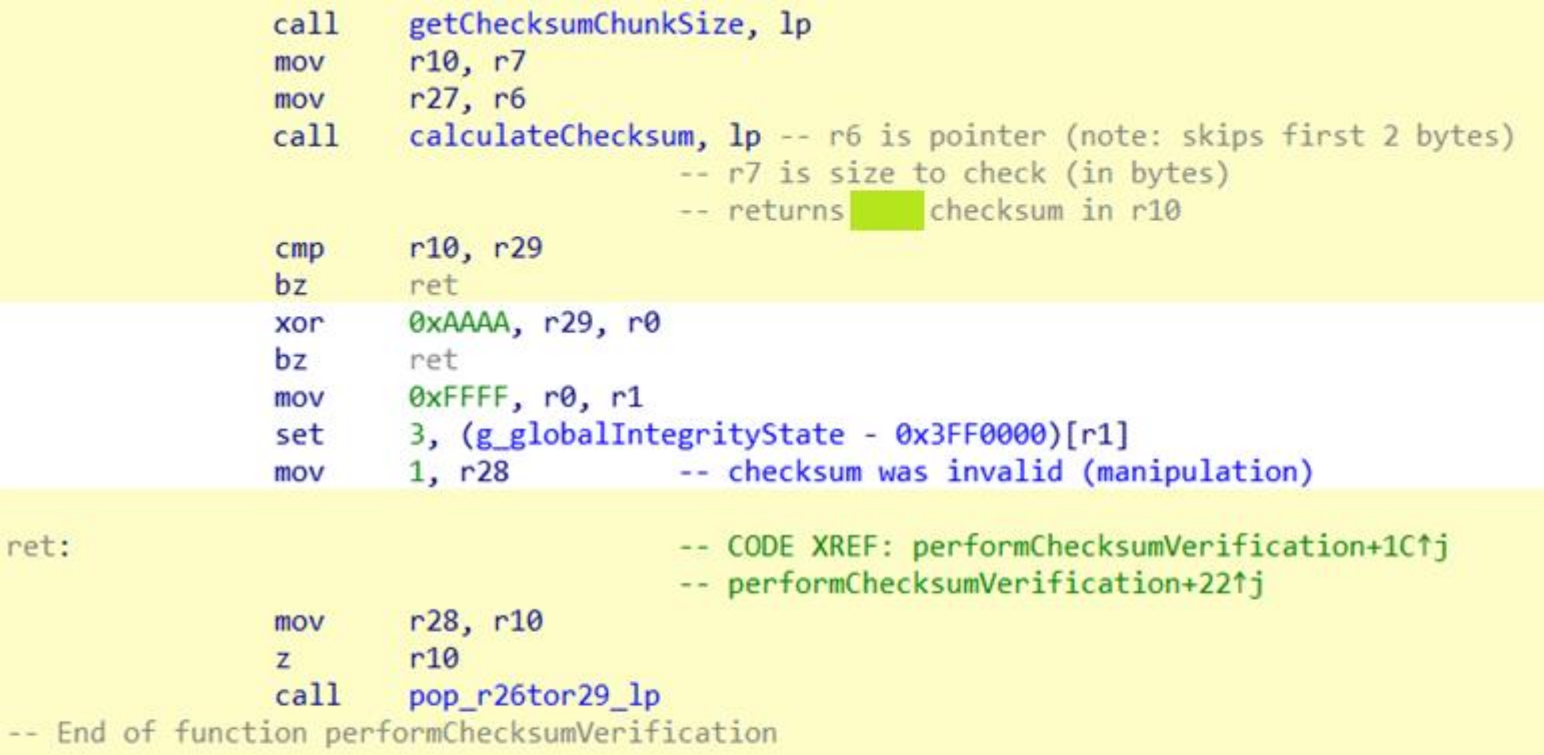
0x02926

0x02928

0x0292c

**0x02930**

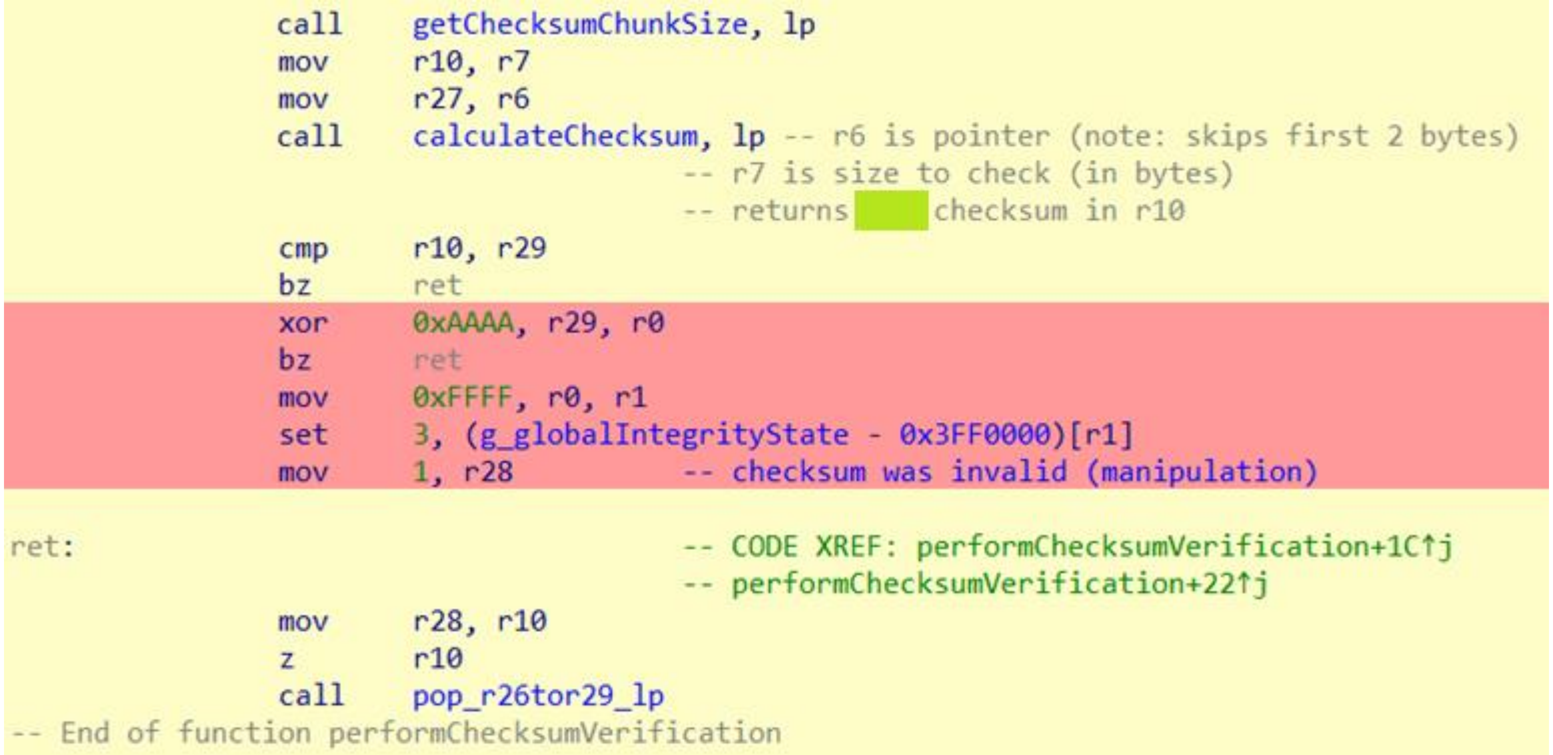
# Execution tracing



```
              call    getChecksumChunkSize, lp
              mov     r10, r7
              mov     r27, r6
              call    calculateChecksum, lp -- r6 is pointer (note: skips first 2 bytes)
                                         -- r7 is size to check (in bytes)
                                         -- returns [redacted] checksum in r10
              cmp     r10, r29
              bz      ret
              xor     0xAAAA, r29, r0
              bz      ret
              mov     0xFFFF, r0, r1
              set     3, (g_globalIntegrityState - 0x3FF0000)[r1]
              mov     1, r28             -- checksum was invalid (manipulation)

ret:                                     -- CODE XREF: performChecksumVerification+1C↑j
                                         -- performChecksumVerification+22↑j
              mov     r28, r10
              z       r10
              call    pop_r26tor29_lp
-- End of function performChecksumVerification
```

# Execution tracing



```
                call     getChecksumChunkSize, lp
                mov      r10, r7
                mov      r27, r6
                call     calculateChecksum, lp -- r6 is pointer (note: skips first 2 bytes)
                                               -- r7 is size to check (in bytes)
                                               -- returns [redacted] checksum in r10
                cmp      r10, r29
                bz       ret
                xor      0xAAAA, r29, r0
                bz       ret
                mov      0xFFFF, r0, r1
                set      3, (g_globalIntegrityState - 0x3FF0000)[r1]
                mov      1, r28                -- checksum was invalid (manipulation)

ret:                                           -- CODE XREF: performChecksumVerification+1C↑j
                                               -- performChecksumVerification+22↑j
                mov      r28, r10
                z        r10
                call     pop_r26tor29_lp
-- End of function performChecksumVerification
```

# Taint tracking

| | |
|---|---|
| **1** | **??** |
| 2 | ?? |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |

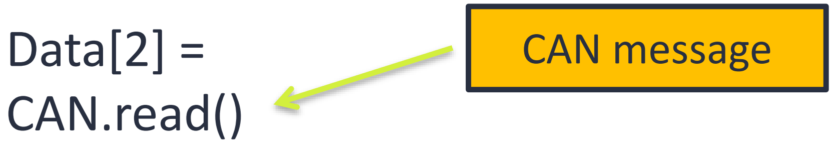
# Taint tracking

| | |
|---|---|
| **1** | **??** |
| 2 | ?? |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |

CAN message

# Taint tracking

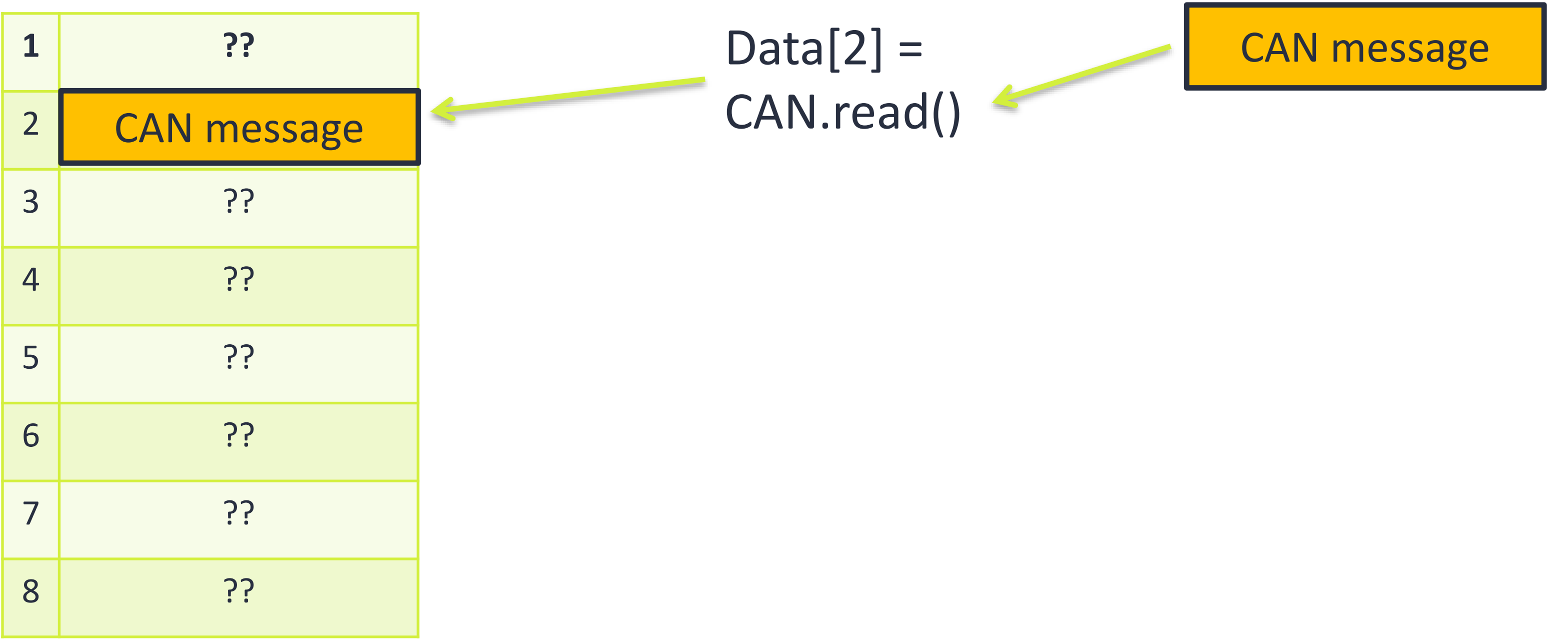
| | |
|---|---|
| **1** | **??** |
| 2 | ?? |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |



Data[2] = CAN.read()

CAN message

# Taint tracking

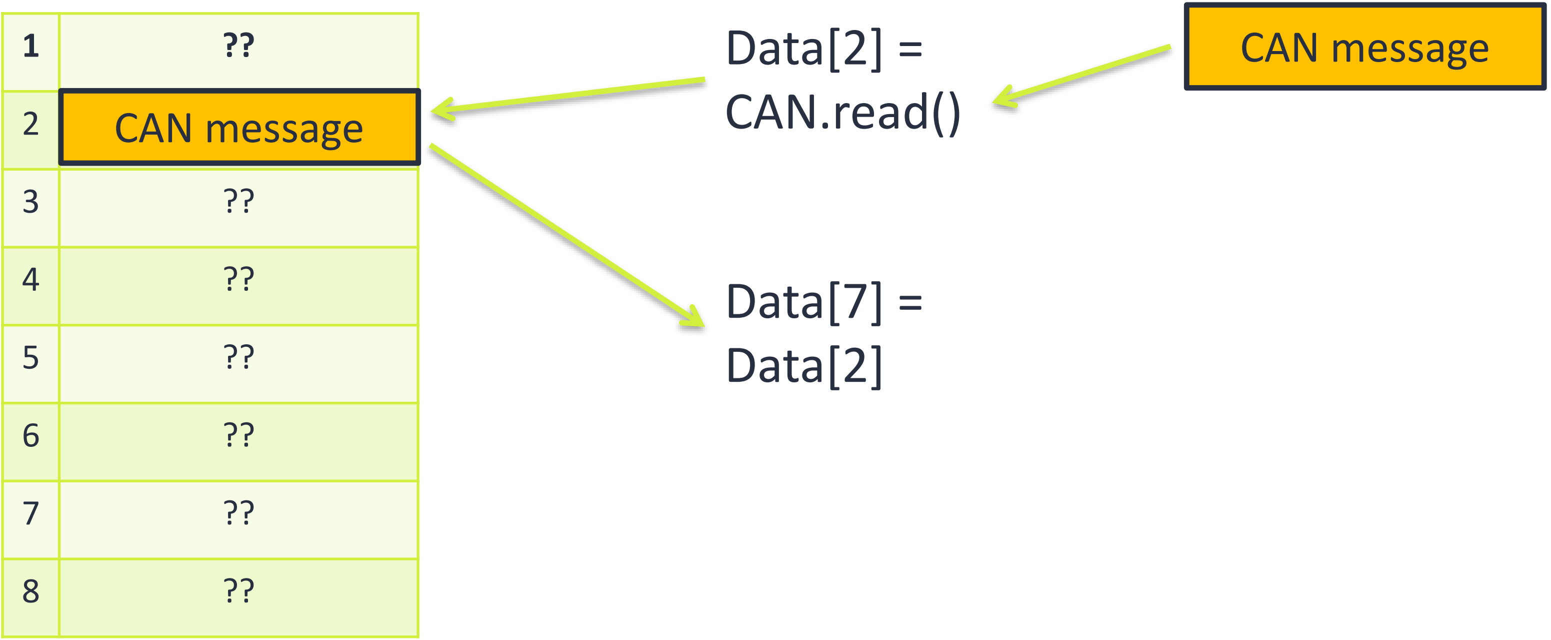


| | |
|---|---|
| 1 | **??** |
| 2 | CAN message |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |

Data[2] =
CAN.read()

CAN message

# Taint tracking



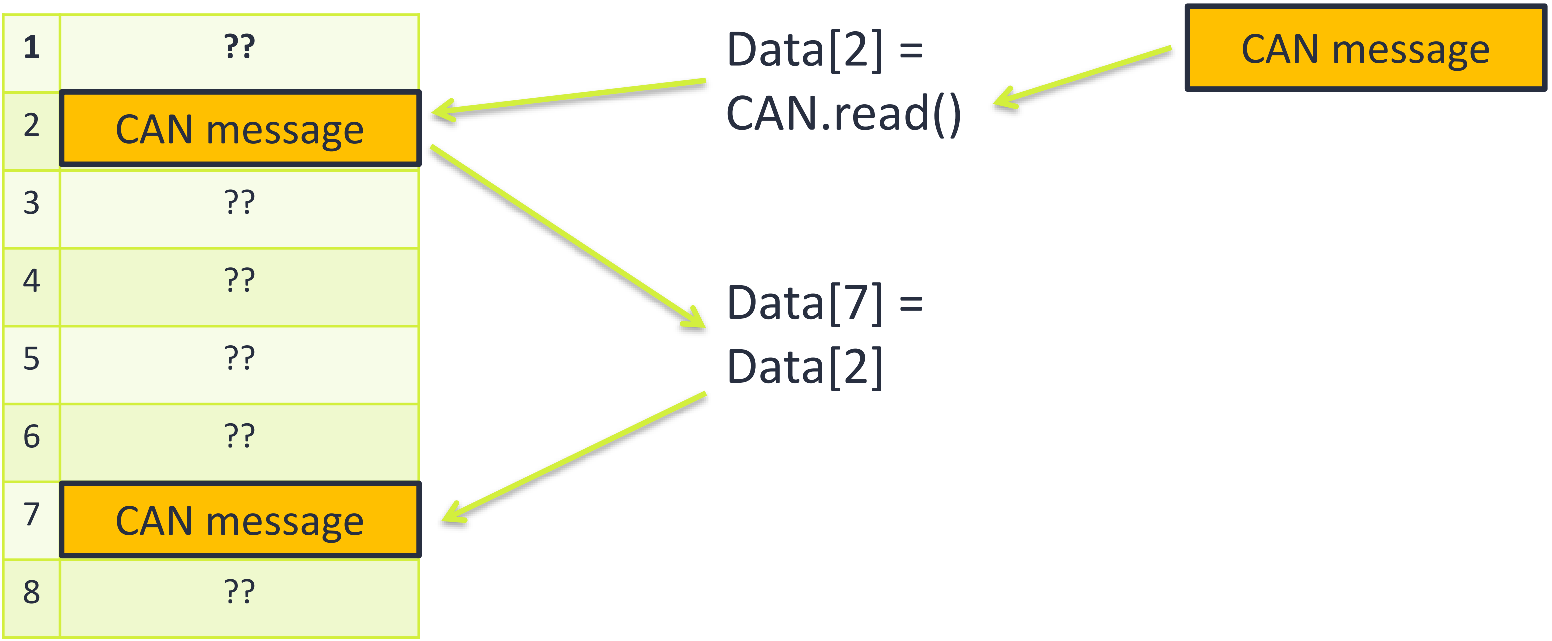
| | |
|---|---|
| 1 | ?? |
| 2 | CAN message |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |

```
Data[2] =
CAN.read()
```

CAN message

```
Data[7] =
Data[2]
```

# Taint tracking



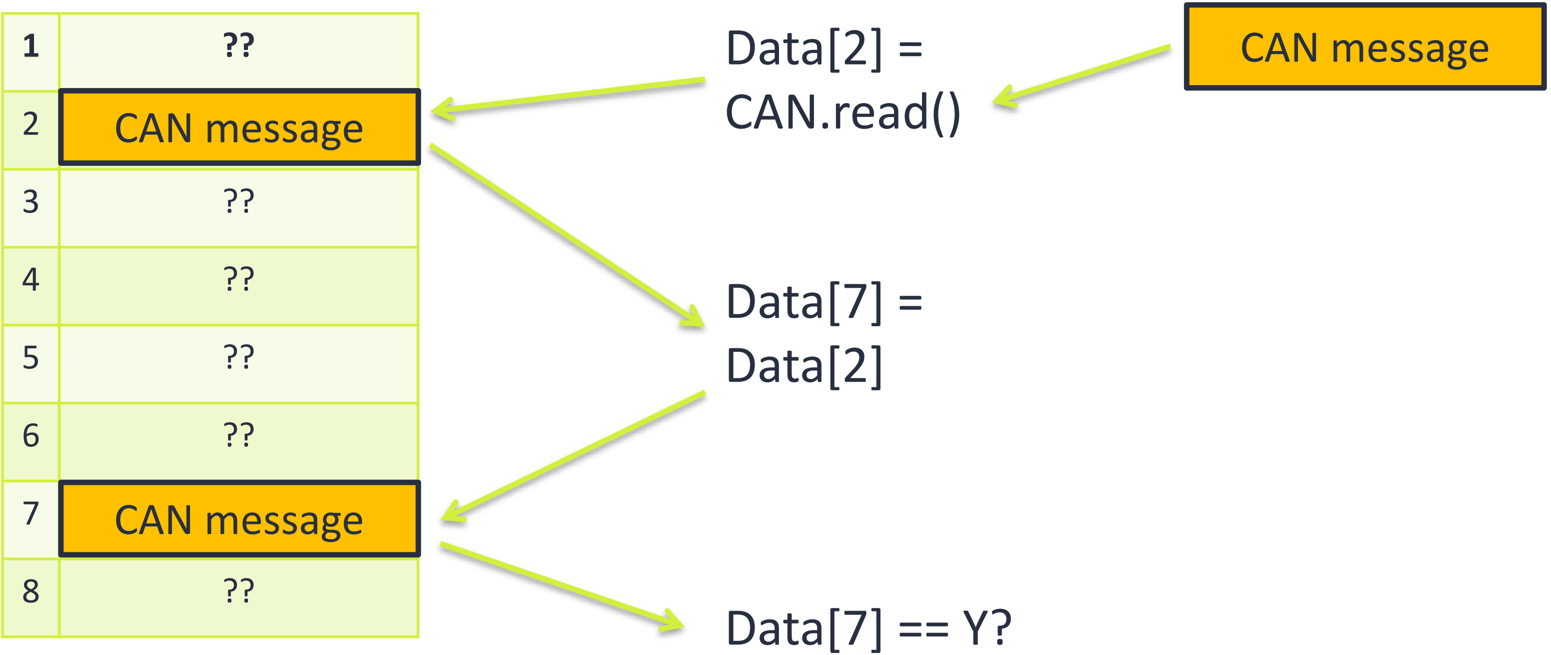
| | |
|---|---|
| 1 | ?? |
| 2 | CAN message |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | CAN message |
| 8 | ?? |

```
Data[2] =
CAN.read()
```

CAN message

```
Data[7] =
Data[2]
```

# Taint tracking



| | |
|---|---|
| 1 | ?? |
| 2 | CAN message |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | CAN message |
| 8 | ?? |

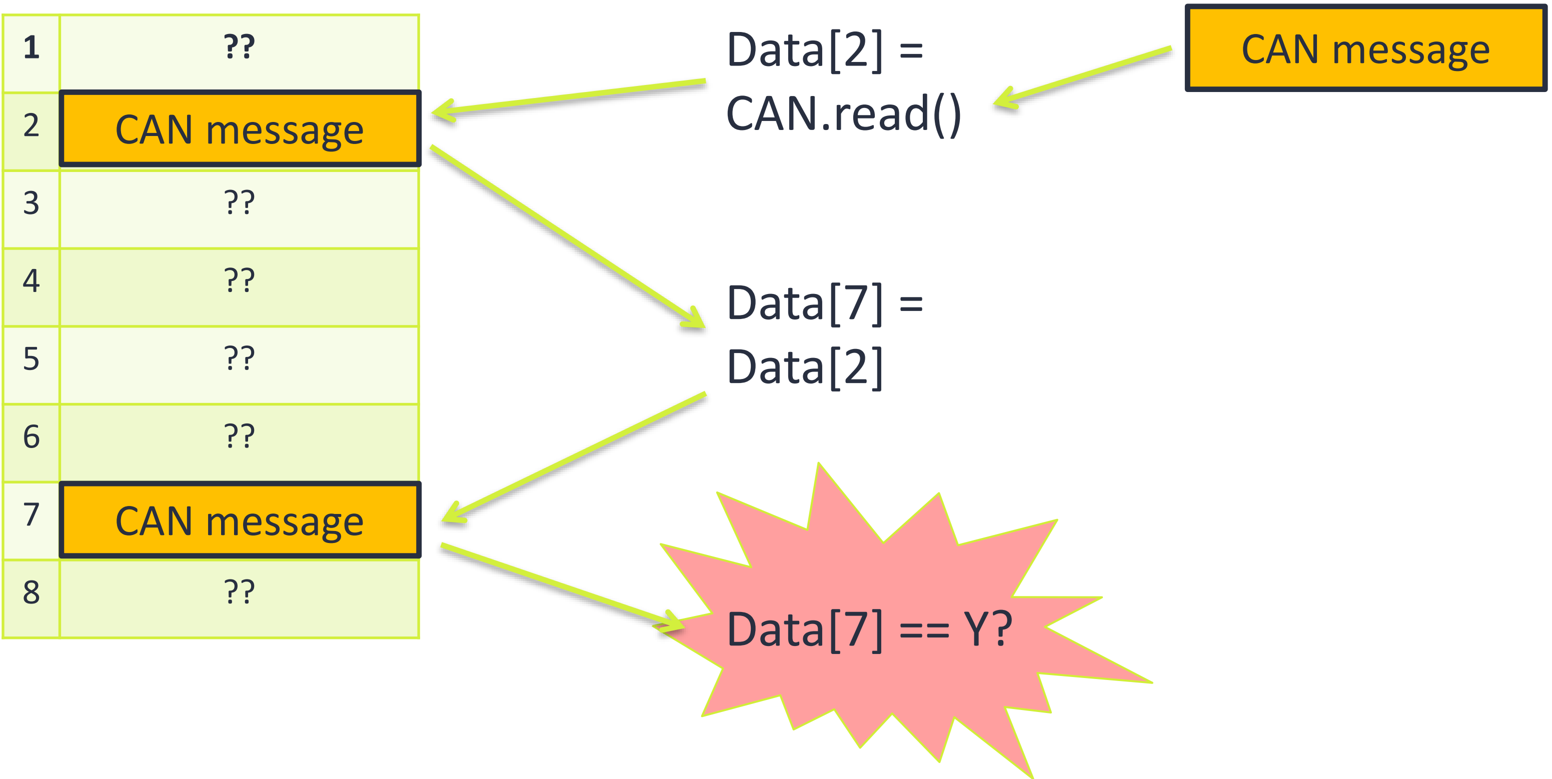
CAN message

Data[2] =
CAN.read()

Data[7] =
Data[2]

Data[7] == Y?

# Taint tracking



| | |
|---|---|
| 1 | ?? |
| 2 | CAN message |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | CAN message |
| 8 | ?? |

Data[2] = CAN.read()

CAN message

Data[7] = Data[2]

Data[7] == Y?

# Taint tracking UDS Security Access

| | |
|---|---|
| **1** | **??** |
| 2 | ?? |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |

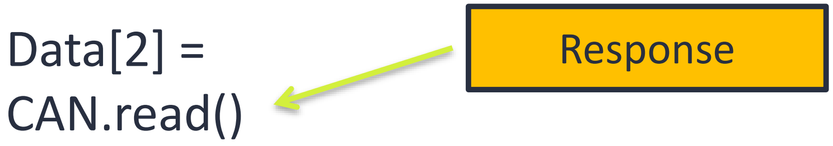
# Taint tracking UDS Security Access

| | |
|---|---|
| **1** | **??** |
| 2 | ?? |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |

Response

# Taint tracking UDS Security Access

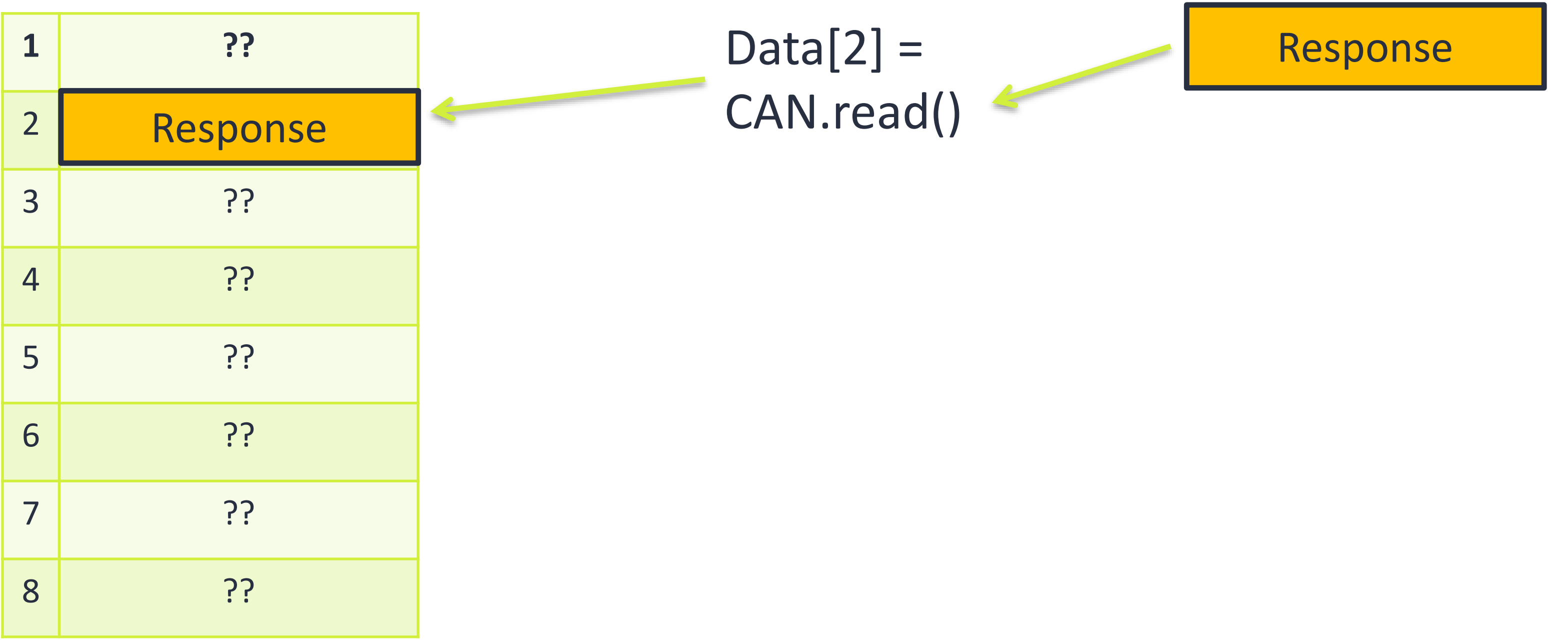
| | |
|---|---|
| 1 | ?? |
| 2 | ?? |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |



Data[2] =
CAN.read()

Response

# Taint tracking UDS Security Access

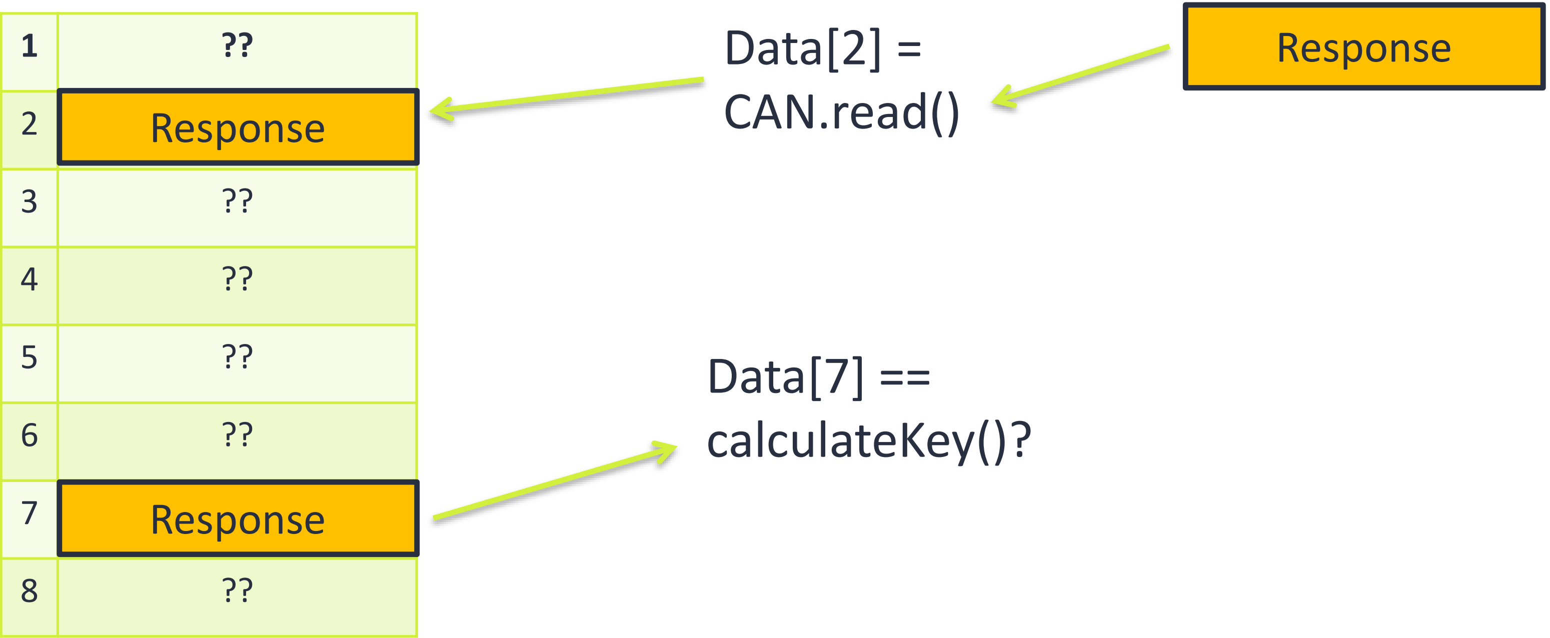


| | |
|---|---|
| 1 | ?? |
| 2 | Response |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | ?? |
| 8 | ?? |

Data[2] =
CAN.read()

Response

# Taint tracking UDS Security Access

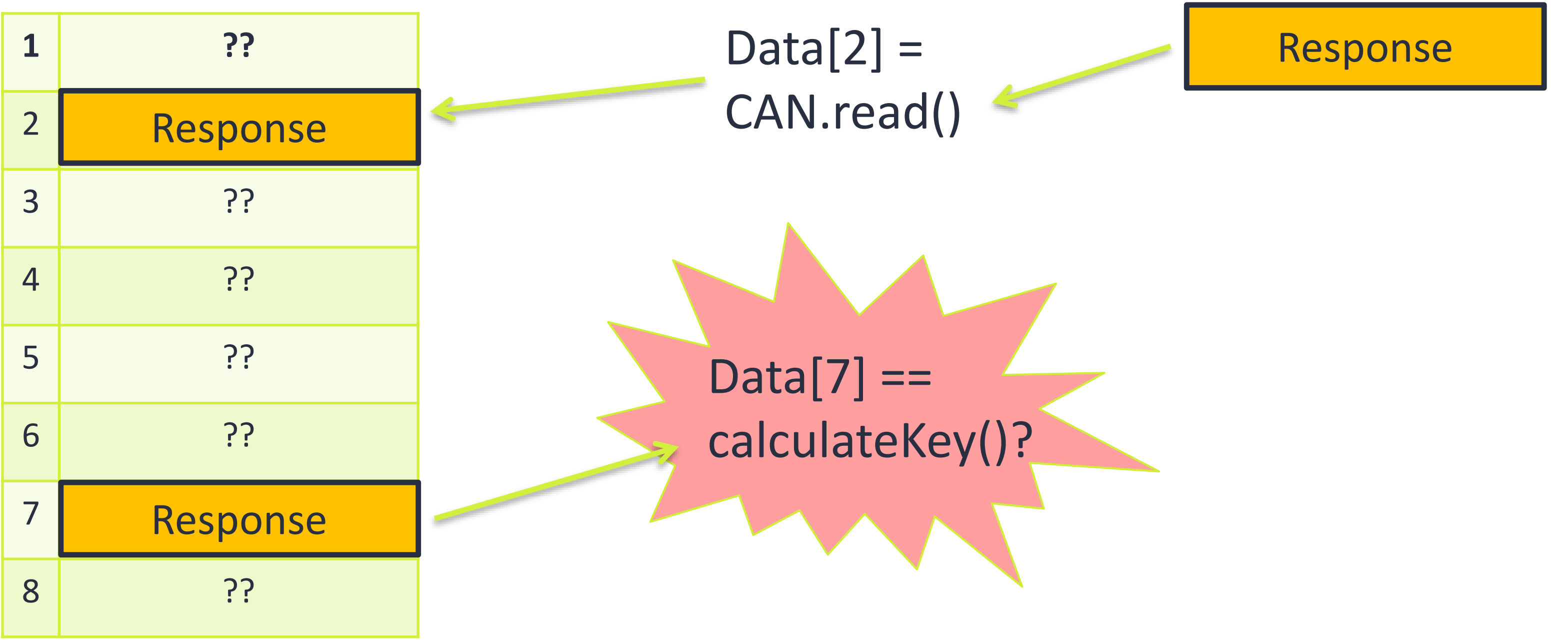


| | |
|---|---|
| 1 | ?? |
| 2 | Response |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | Response |
| 8 | ?? |

Data[2] =
CAN.read()

Data[7] ==
calculateKey()?

# Taint tracking UDS Security Access



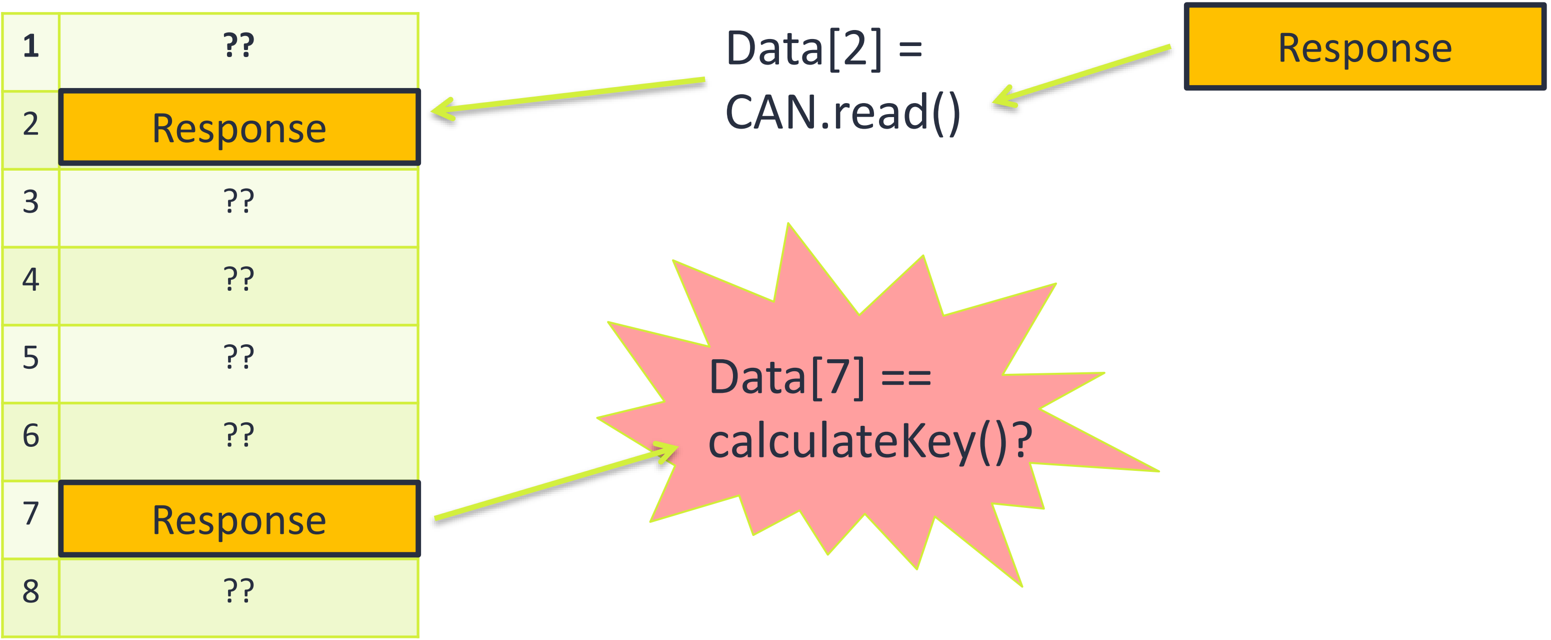
| | |
|---|---|
| 1 | ?? |
| 2 | Response |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | Response |
| 8 | ?? |

Data[2] =
CAN.read()

Response

Data[7] ==
calculateKey()?

# Taint tracking UDS Security Access



|   |   |
|---|---|
| 1 | ?? |
| 2 | Response |
| 3 | ?? |
| 4 | ?? |
| 5 | ?? |
| 6 | ?? |
| 7 | Response |
| 8 | ?? |

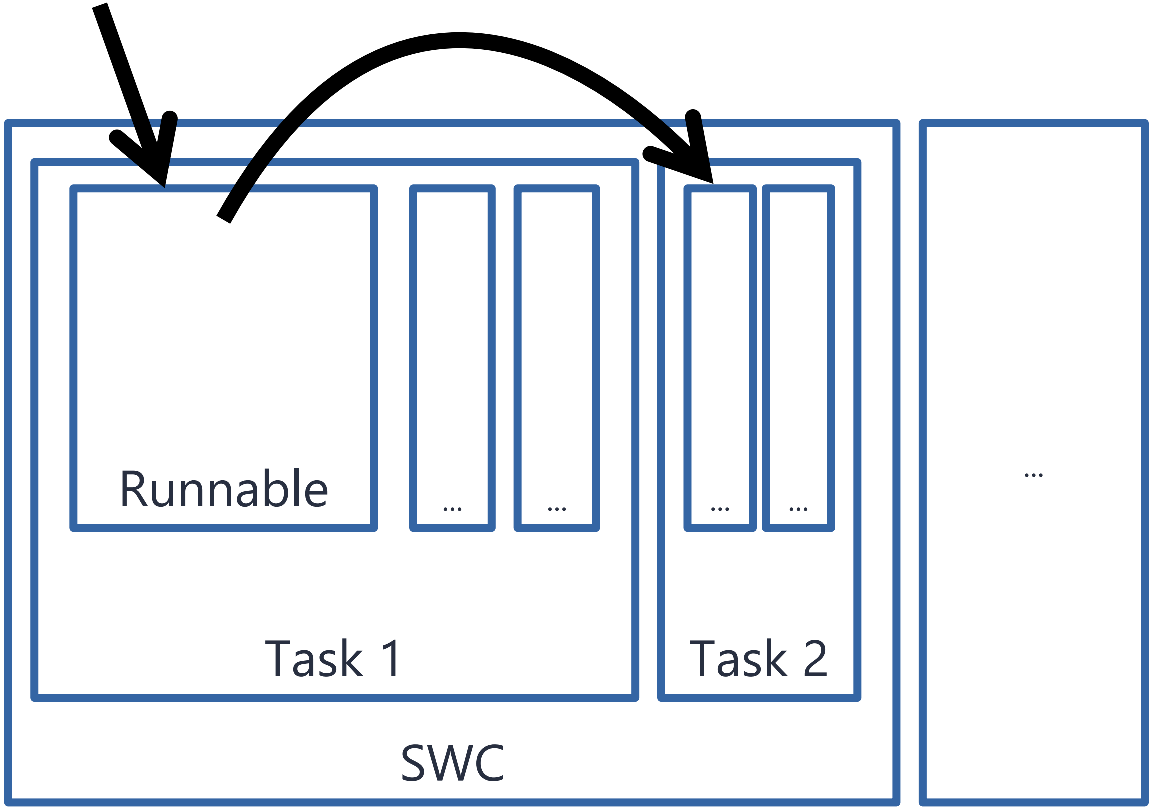
Data[2] =
CAN.read()

Response

Data[7] ==
calculateKey()?

We found the *calculateKey* function!

# Demo Time!!!

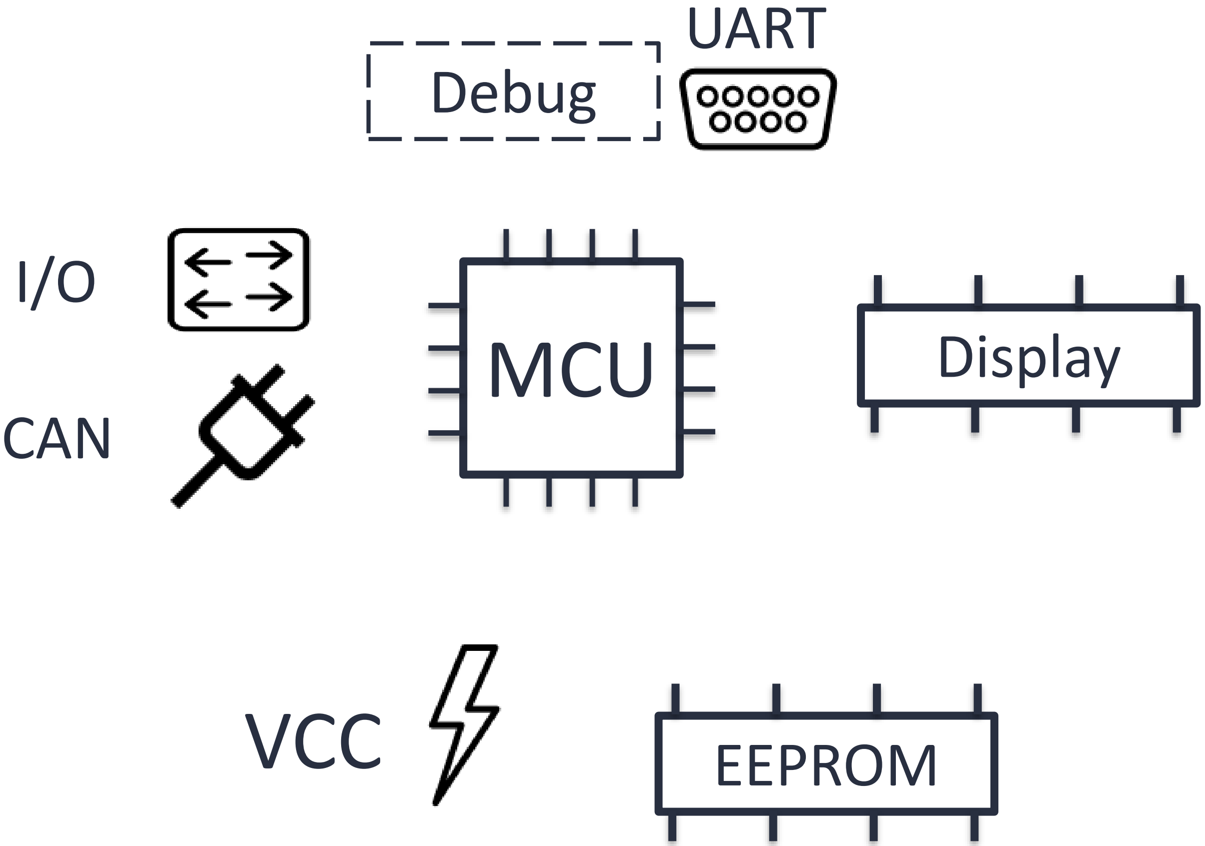


# Wrap up!

- Hardware will betray you!
- Emulating a dashboard is not too tricky?
- Fault injection attacks on UDS are *cool.*

This Fault Injection attack on UDS is **not efficient**!

We can do better...



UART

Debug

I/O

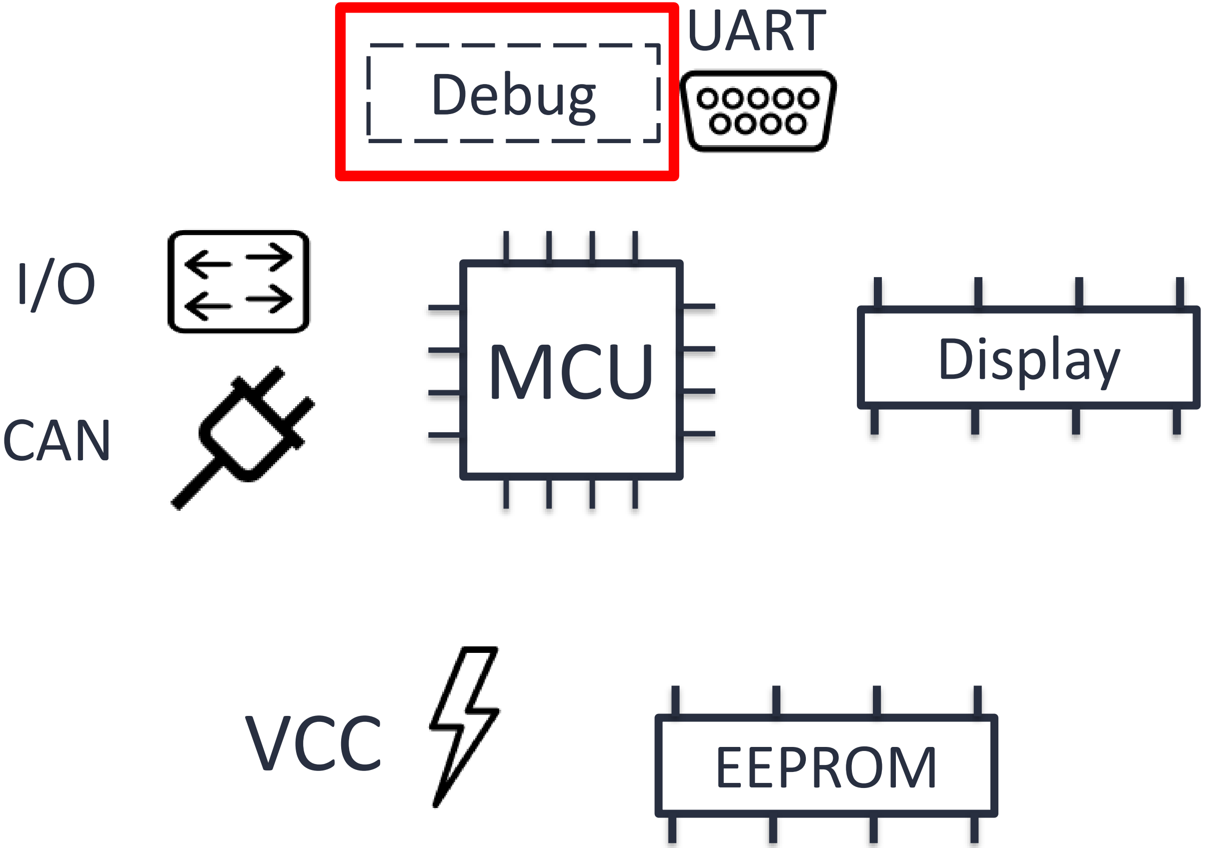
MCU

Display

CAN

VCC

EEPROM


Debug
UART
I/O
CAN
MCU
Display
VCC
EEPROM

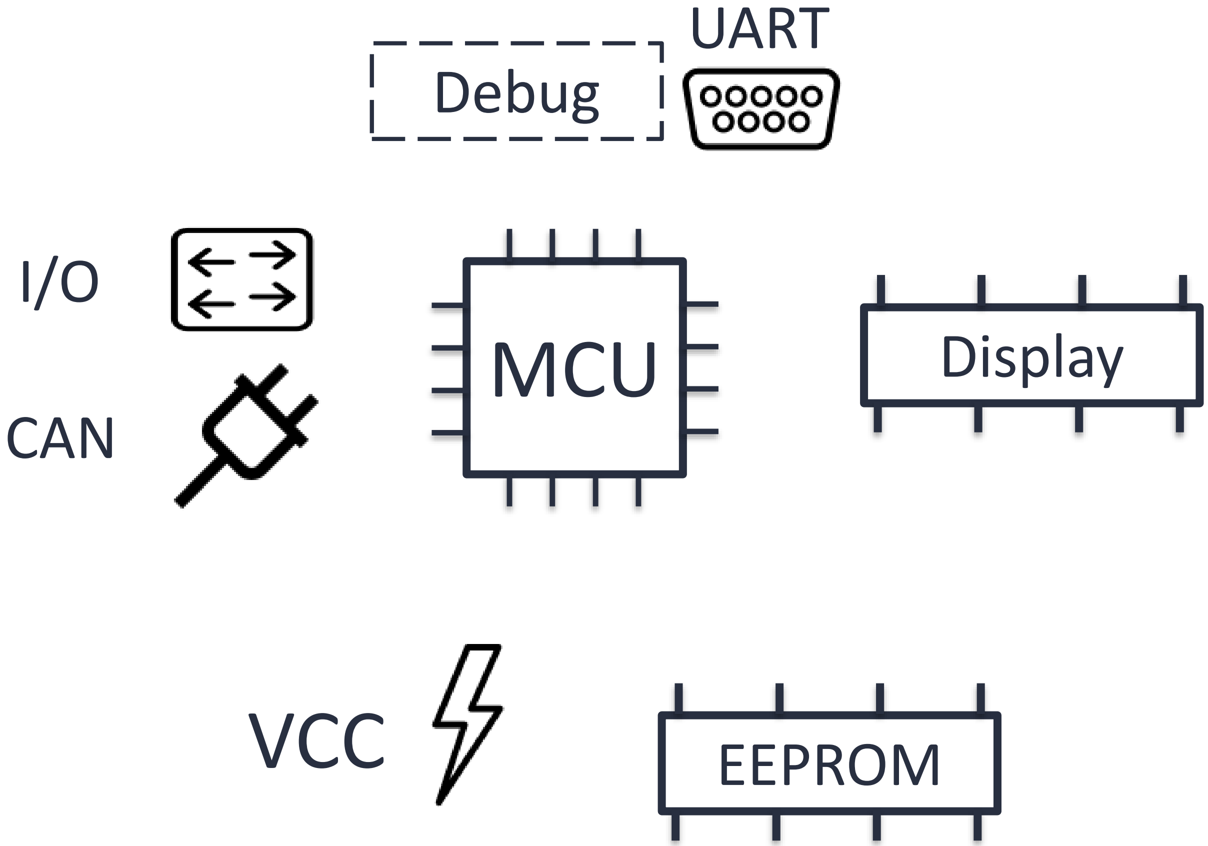
# Debug interfaces

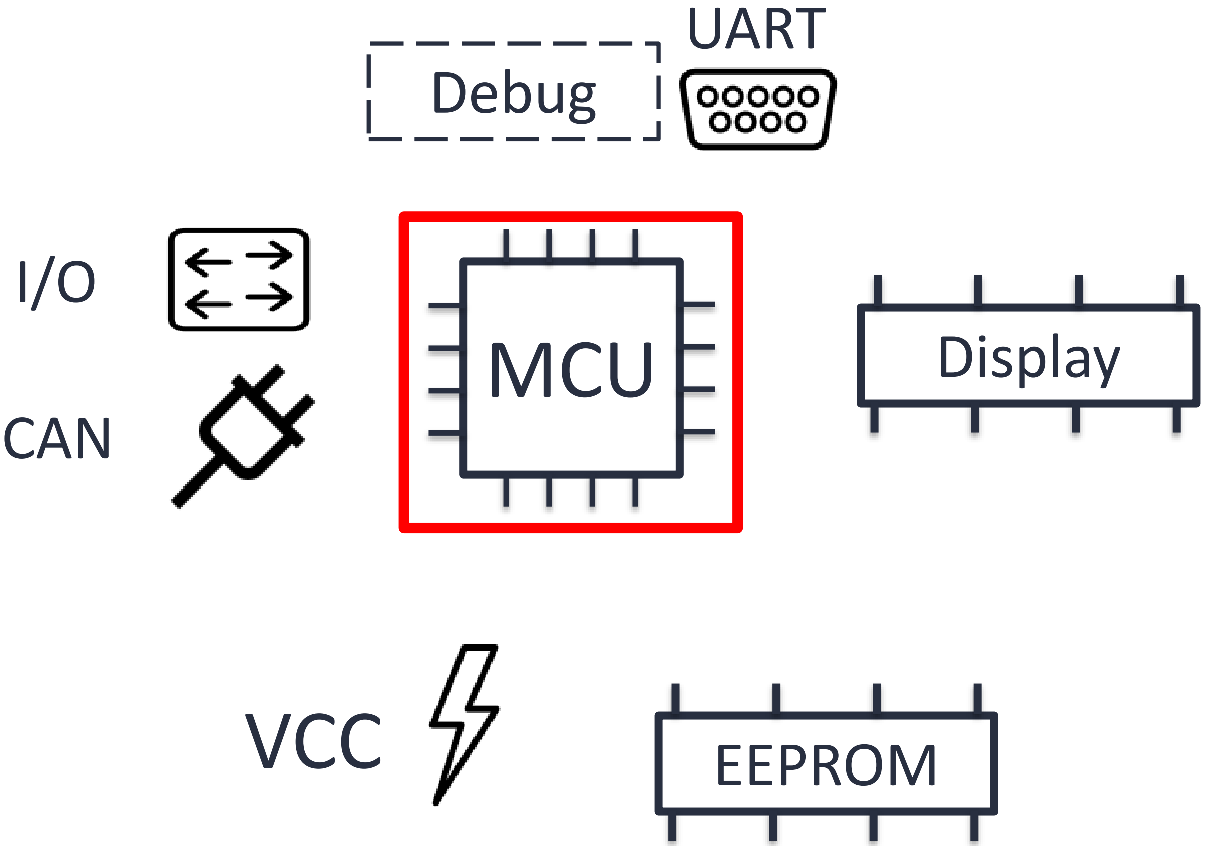
```
if (allow_debug())

{
  open_JTAG();
}
```

# Debug interfaces

```
if (all        bug())
{
  open_JTAG();
}
```


Debug
UART
I/O
CAN
MCU
Display
VCC
EEPROM



UART

Debug

I/O

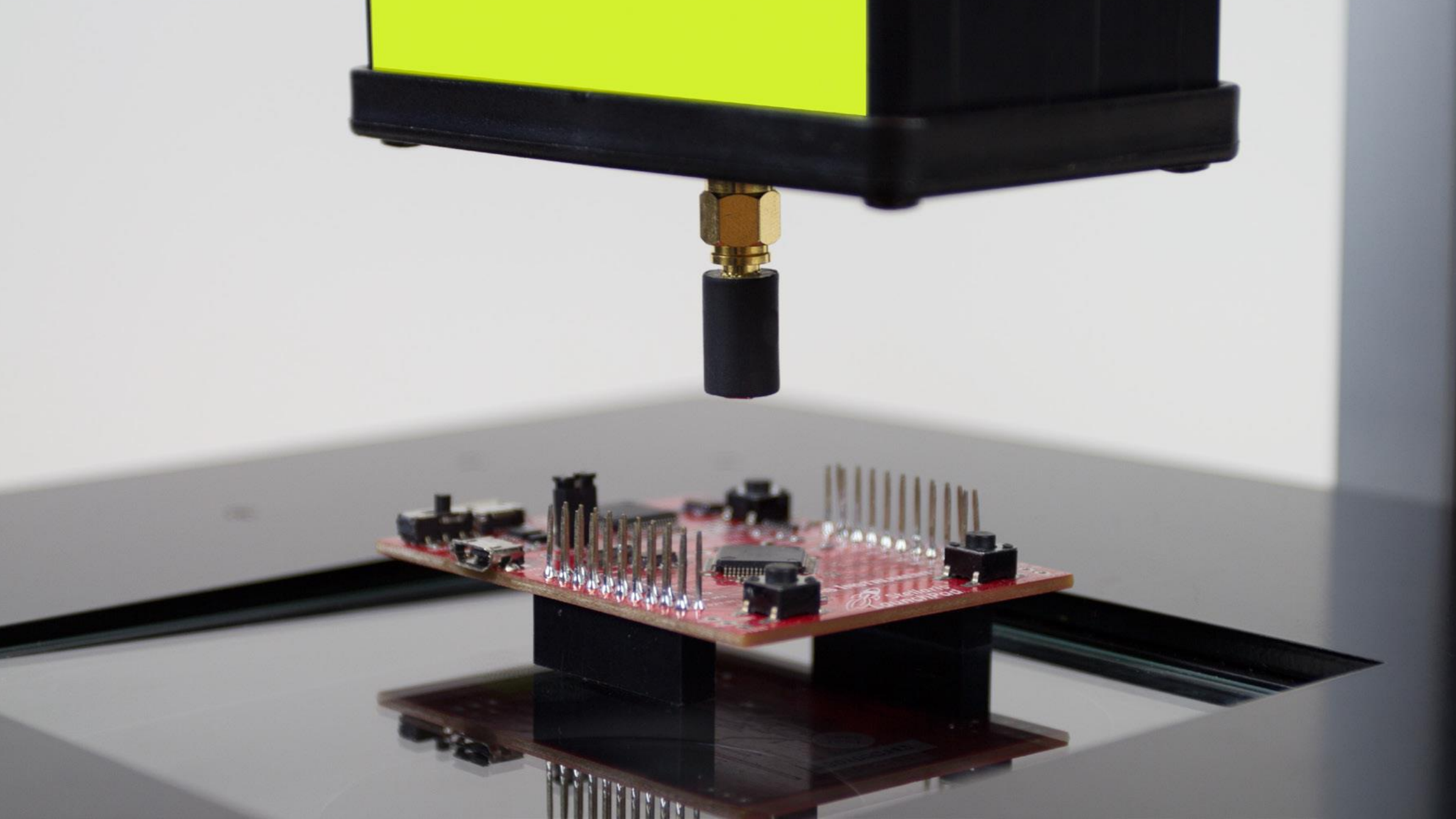
CAN

MCU

Display

VCC

EEPROM


Stellaris
LaunchPad

# Electromagnetic Fault Injection

ARM
FIRE
TO REARM YOU MUST TOGGLE ARM SWITCH ON/OFF CHIPSHOUTER AUTOMATICALLY DISARMS

[**ChipSHOUTER®**]

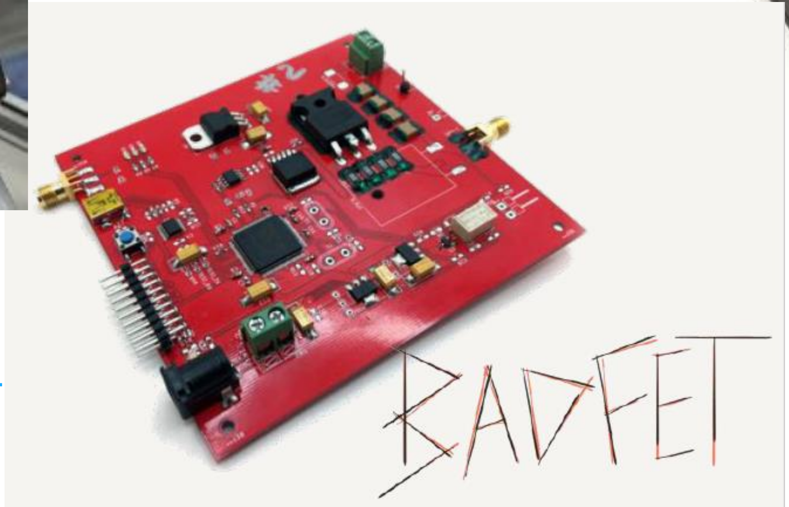
[**Inspector FI**]

# Electromagnetic Fault Injection

Cheap and awesome:

[BADFET](#)

[ChipSHOUTER®](#)



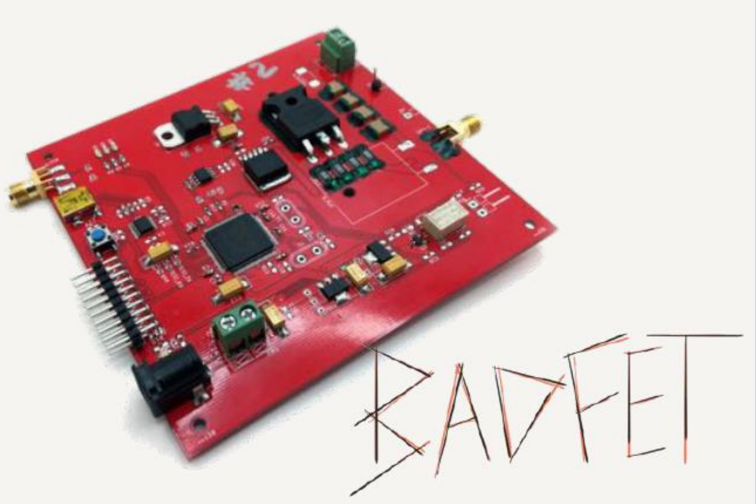
[Inspector FI](#)

# Electromagnetic Fault Injection

ARM
FIRE
TO REARM YOU MUST TOGGLE ARM SWITCH ON/OFF CHIPSHOUTER AUTOMATICALLY DISARMS

Cheap and awesome:

BADFET



ChipSHOUTER®

Inspector FI

***Electromagnetic fault injection available to the masses!***

# Fault Injection is universal

*all devices*

*all CPUs/MCUs*

*all software*

# Can we harden ECUs against fault injection?

# Hardening ECU hardware

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- Processing integrity (e.g. lockstep)
  - However, please: *Safety ≠ Security*
- Don’t forget: **debug interfaces**

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- Add <u>**redundancy**</u>:
  - Duplicate code/checks
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- Add **redundancy**:
  - Duplicate code/checks
  - SW-lockstep
- Be **paranoid**:
  - Control flow integrity
  - Random delays

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- Don’t expose keys to software:
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- Don’t expose keys to software: **use HW crypto engines** (HSMs)

- Avoid having anything to hide: **use asymmetric cryptography**

# As always, defense in depth is key!

# Key takeaways

- No software vulnerabilities ≠ security
- Understanding firmware is easy (with the right tooling)
- Your firmware **will** be extracted

# Thanks to...

Eloi Sanfelix

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Ramiro Pareja

Nils Wiersma

Our papers are available here, here and here!

*There were glitches… hopefully! ;)*

# Thank you! Any questions?

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