Dynamic Binary Firmware Analysis With Avatar²

THCon 2023

Paul OLIVIER

2023-04-20

EURECOM Sophia Antipolis

THCON TOULOUSE HACKING CONVENTION

LAAS CNRS

> whoami

Paul OLIVIER

- Recent Ph.D. graduate (EURECOM)
- Just joined as postdoc @ LAAS-CNRS
- Dynamic analysis for embedded system security
- Part of the maintainer team of avatar²

> Content

- Motivation
- Rehosting Firmware
- Avatar^2: A Multi-Target Orchestration Platform
- Framework Overview
- Conclusion

> Introduction

Prevalence of bugs in the Wild

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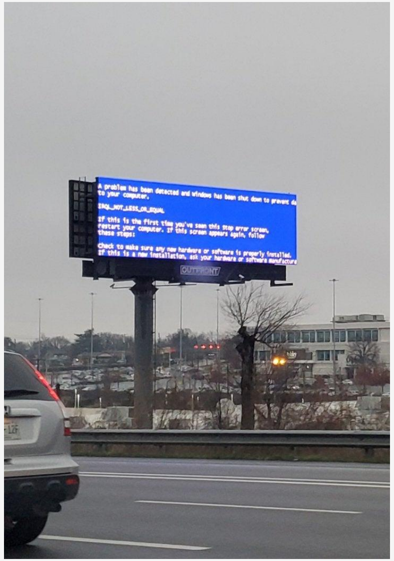

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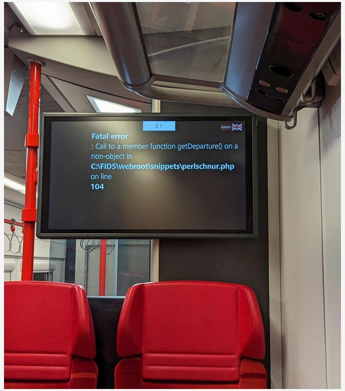

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S1
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C:\FID5\webroot\snippets\perlschnur.php
on line
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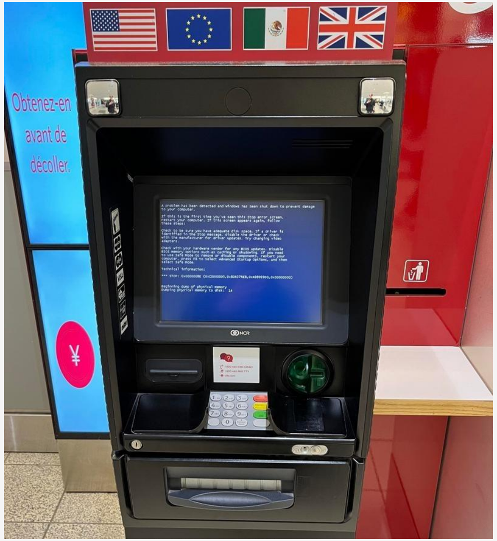

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Check with your hardware vendor for any BIOS updates. Disable
BIOS memory options such as caching or shadowing. If you need
to use Safe Mode to remove or disable components, restart your
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Technical information:

*** STOP: 0x0000008E (0xC0000005,0x806376E8,0xA9893900,0x00000000)


Beginning dump of physical memory
Dumping physical memory to disk:  14
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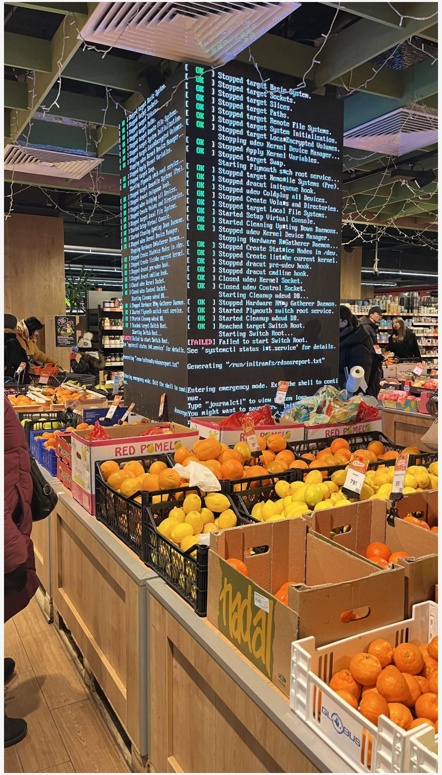

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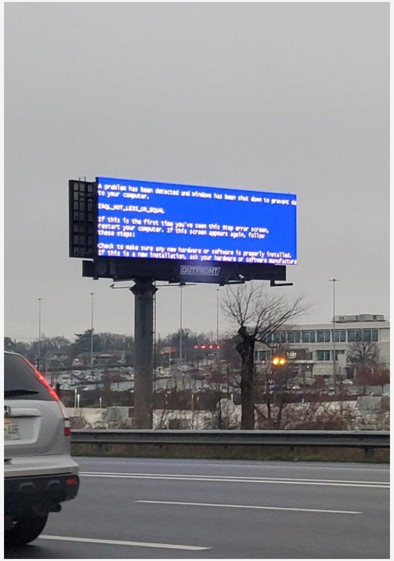

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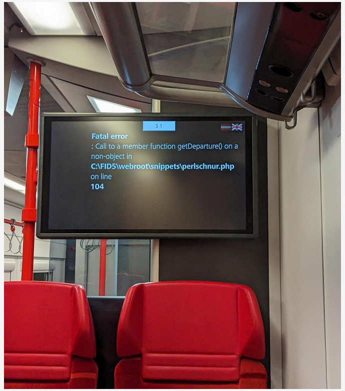

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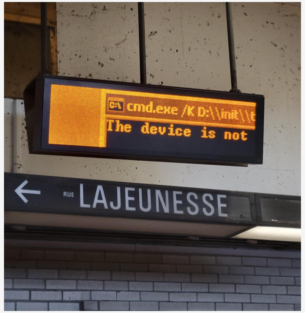

```
cmd.exe /K D:\\init\\
The device is not
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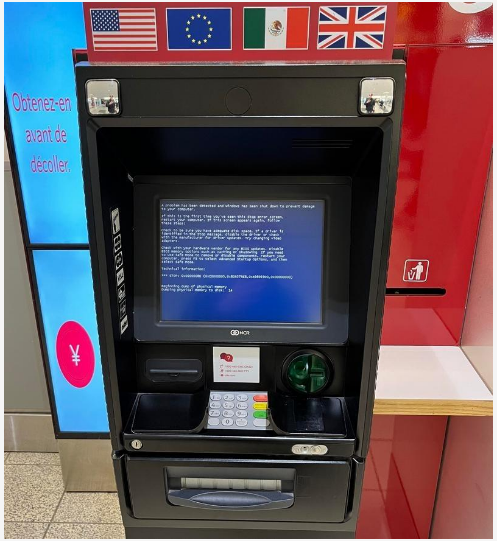

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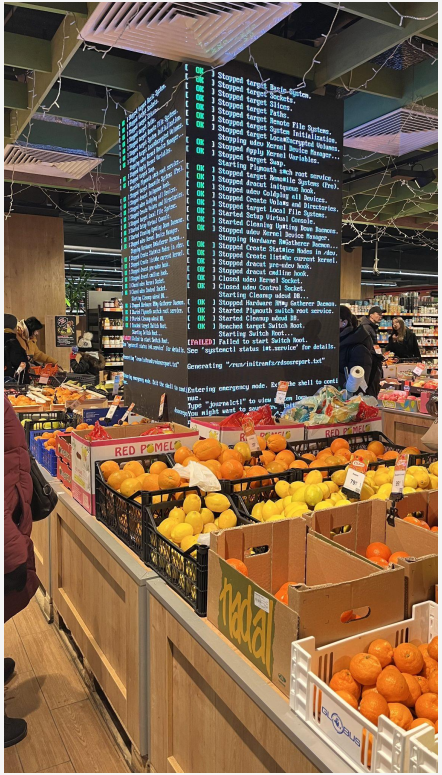

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- **Severity** and **impact** of software bugs
  - Vulnerabilities: *unauthorized access, information leak, denial of service, ransomware*
  - Cost: *finding & fixing, system downtime*
  - Human life: *car driving assistance, Boeing 737 MAX, radiology, etc.*

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- Thorough **testing** of firmware is crucial to guarantee its safety and **security**

- **Static** and **dynamic** analysis are two main approaches.

> Motivation: Firmware Analysis

Static analysis

- Examine without executing code

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Static analysis

- Examine without executing code
- Limitations
    - Achieve **larger coverage**… but **less precise** (no execution context)
    - No need to run code… but does not require external systems

> Motivation: Firmware Analysis

- **Dynamic** analysis techniques are plenty & powerful
  - more precise… but smaller coverage
  - *tracing, profiling, fuzzing, concolic execution, sanitizers, data taint tracking, record-replay, interactive debugging, etc.*

KLEE
PANDA
Manticore
systemtap
FRIDA
DYNAMIC INSTRUMENTATION TOOLKIT
strace
UNICORN
ENGINE
QEMU
NYX
LTTng
avatar2
MULTI TARGET ORCHESTRATION
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Dynamic Binary Analysis

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- Not always feasible to **run** them **on** the physical device:
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- … but require to **setup** the environment
- Not always feasible to **run** them **on** the physical device:
  - **Constrained** environment *(computing power, memory size, network bandwidth)*
  - **Insufficient** ability to **control** & **observe** code execution

> Motivation: Emulation & Rehosting

- Alternative: **emulation**

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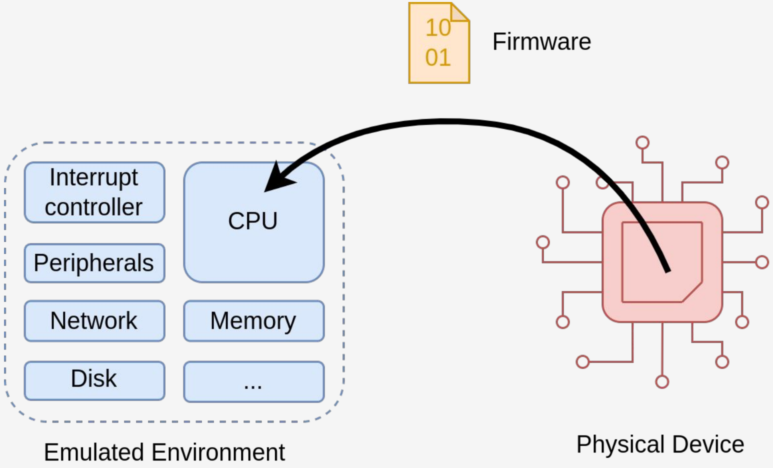
- Alternative: **emulation**
- **Rehosting**:



The process of moving the firmware from its original "host" into a virtualized environment that reproduce the original well enough for its execution and analysis

Fasano, Andrew, et al. *SoK: Enabling security analyses of embedded systems via rehosting*, Asia CCS 2021

> Motivation: Rehosting Challenges

- **Challenges** to run a firmware in an emulator

  1. *Acquisition*:
     - Protected memory, disable debug interface, anti-tampering sensors
     - Encryption, obfuscation, proprietary format

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1. *Acquisition*:
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2. *Execution*:
    - Understand the Instruction Set Architecture (ARM, MIPS, m68k, Blackfin, Xtensa, etc.)
    - Design to run on a specific hardware (peripherals)

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> Problem Statement

- Various techniques
  - *emulation,*
  - *record-replay,*
  - *symbolic execution,*
  - *hardware-in-the-loop,*
  - *hybrid*

QEMU

UNICORN
ENGINE

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QEMU

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ENGINE

- How to **combine tools** to leverage their strengths and tackle complex problems?

> avatar^2

- Facilitate **interoperability** between Dynamic Binary Analysis techniques and tools
- Provide **abstractions** of debuggers, emulators and other frameworks
- Open source https://github.com/avatartwo/avatar2

avatar^2

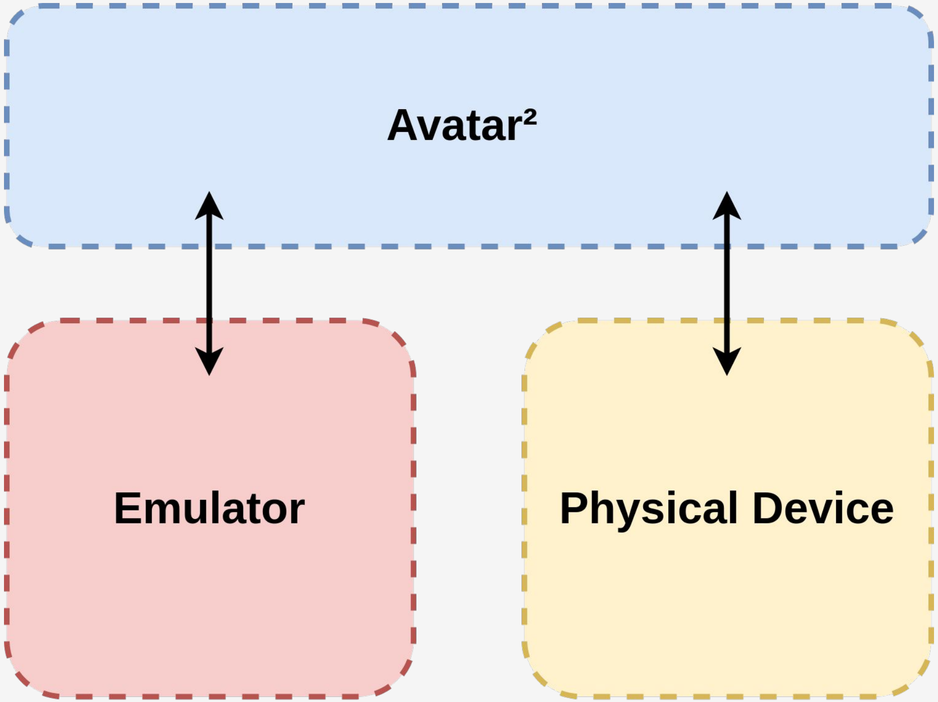
MULTI TARGET ORCHESTRATION

> avatar² Features

- Scriptable (Python based)
- Multiple architecture (ARM, MIPS, x86)
- Target orchestration
    - State transfer & Synchronization
    - Forward memory & I/O accesses
    - Model peripheral

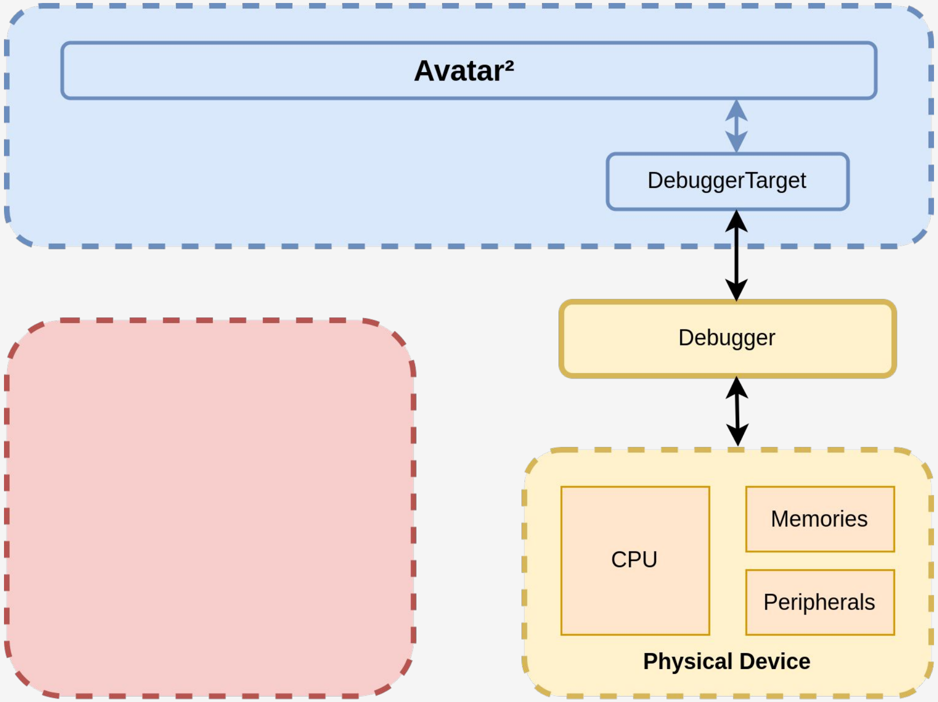
> avatar² Overview

- Orchestration



> avatar² Overview

- Physical device



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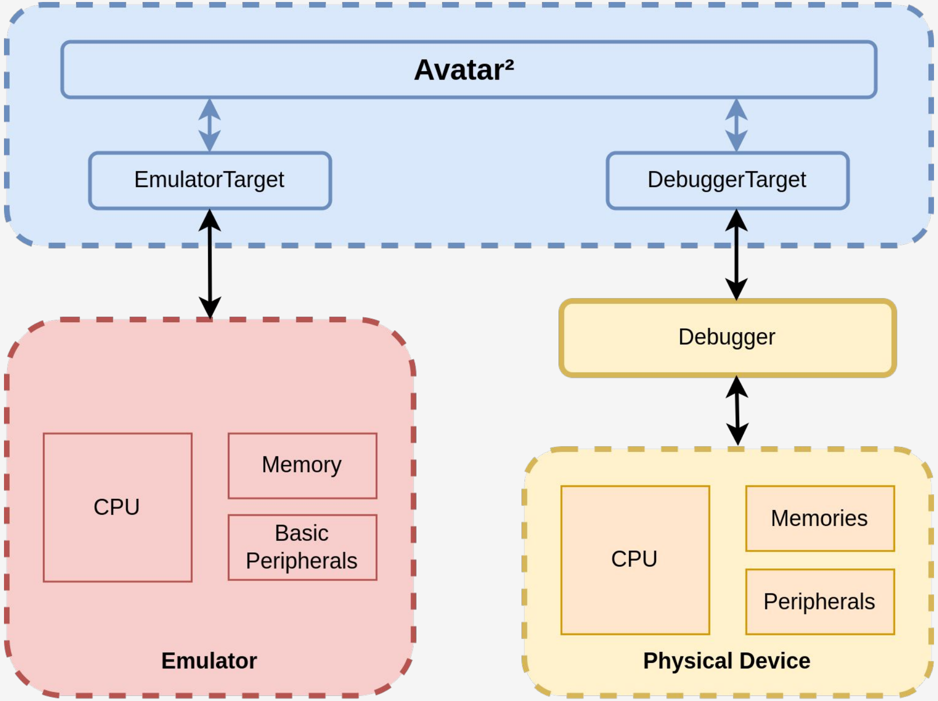
- Emulator



> Initialization

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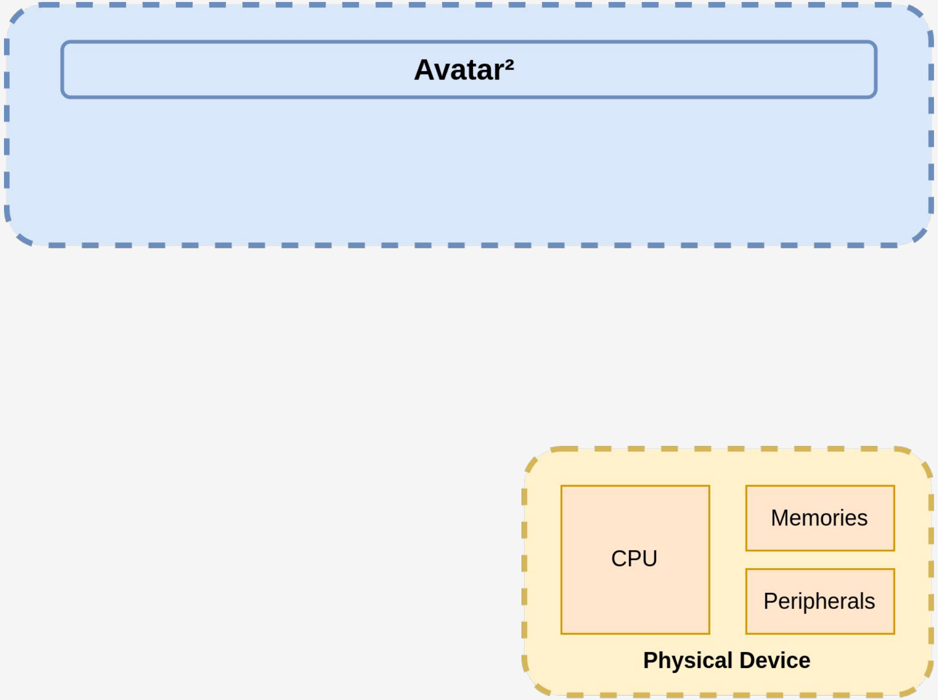

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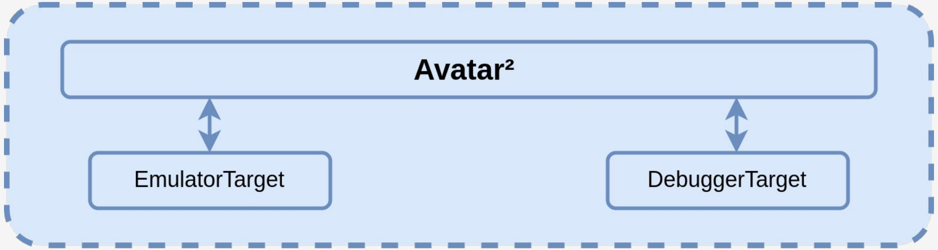

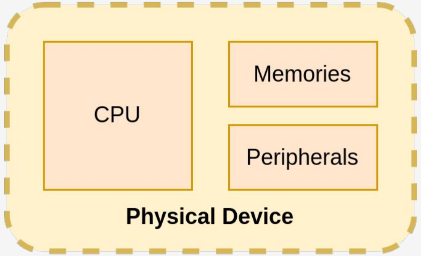

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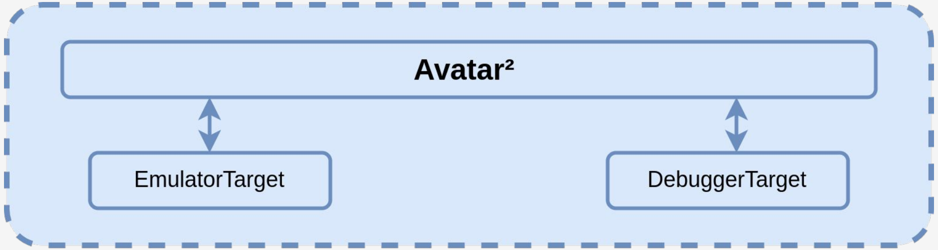

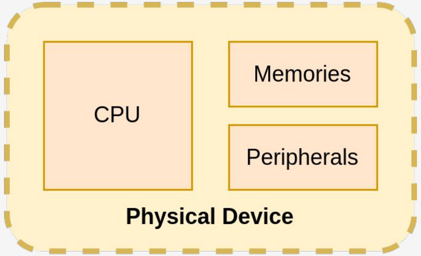

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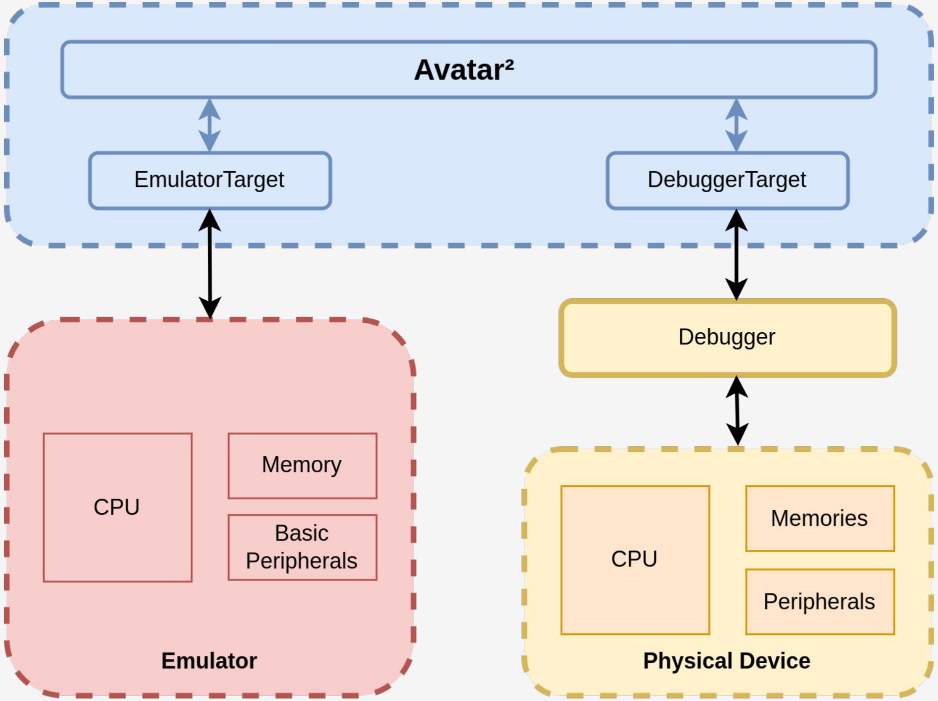
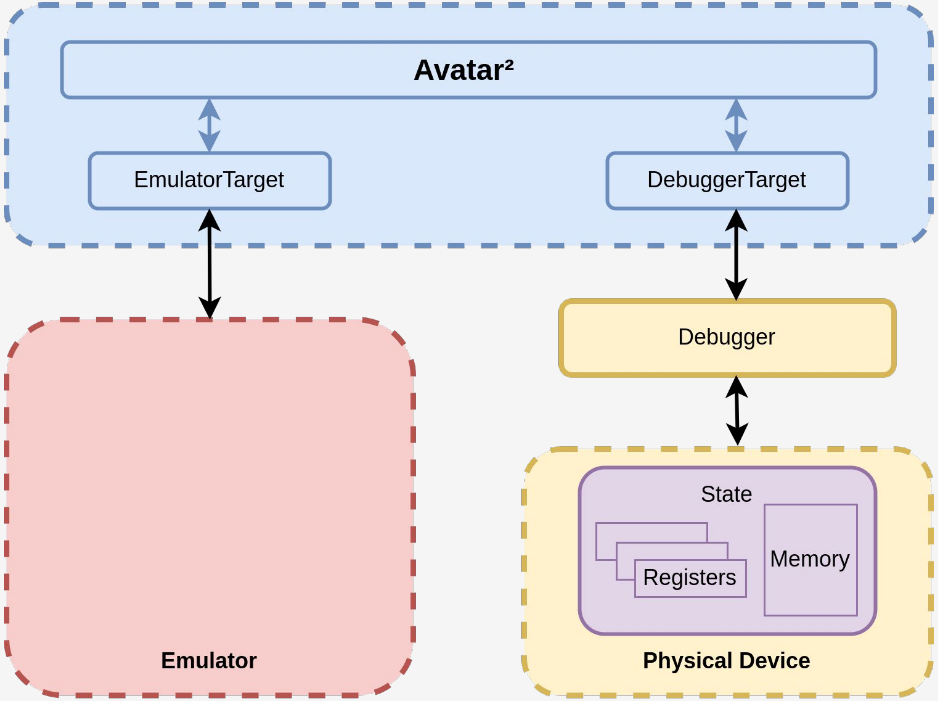


> State Transfer

- **Synchronize** CPU registers and memory content
- **Focus** the analysis (device & firmware initialization)



> State Transfer

```
# 1) Set the breakpoint on the physical device
device.set_breakpoint(0x8005104)
device.cont()
device.wait()
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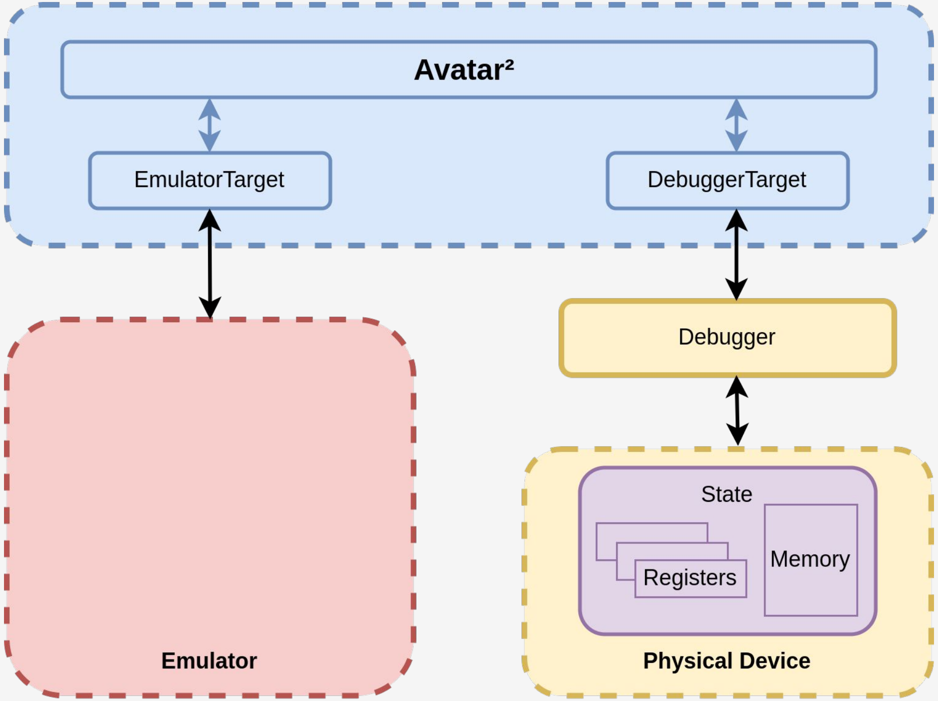

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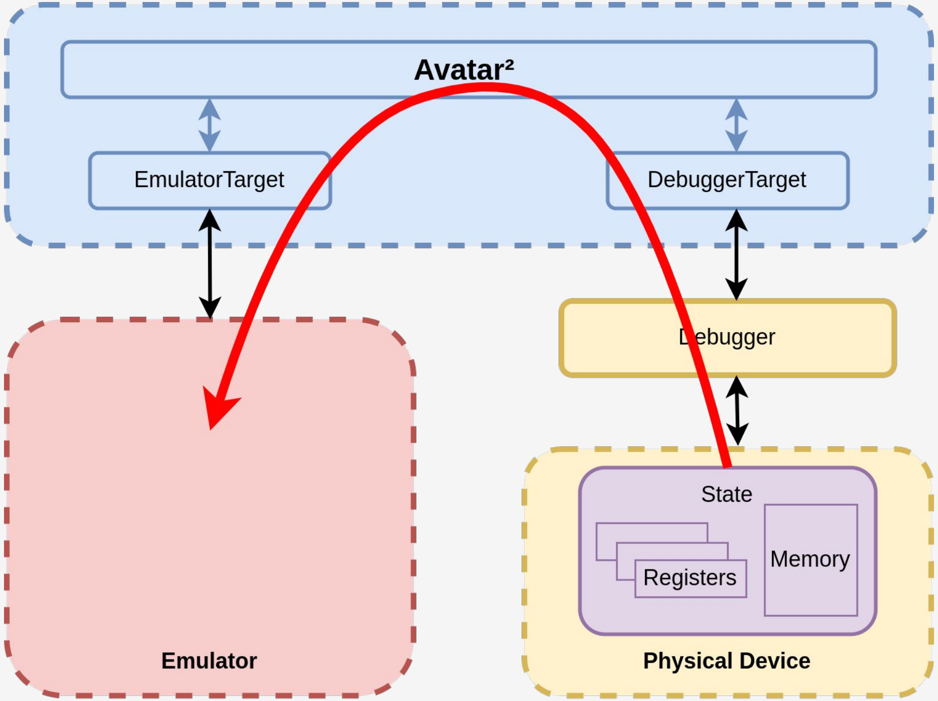

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emulator.cont()
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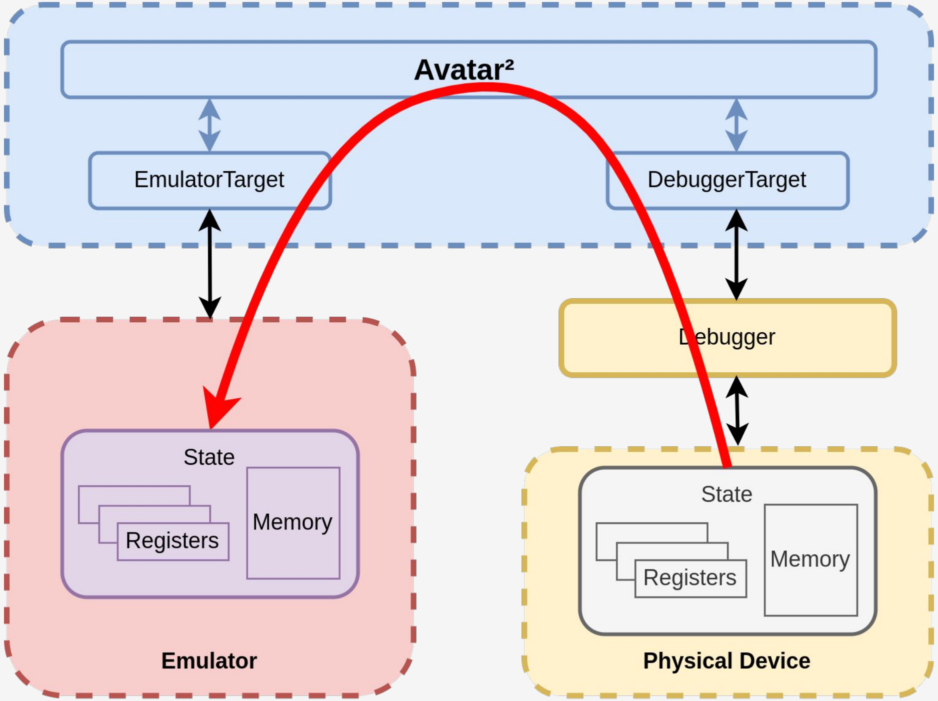
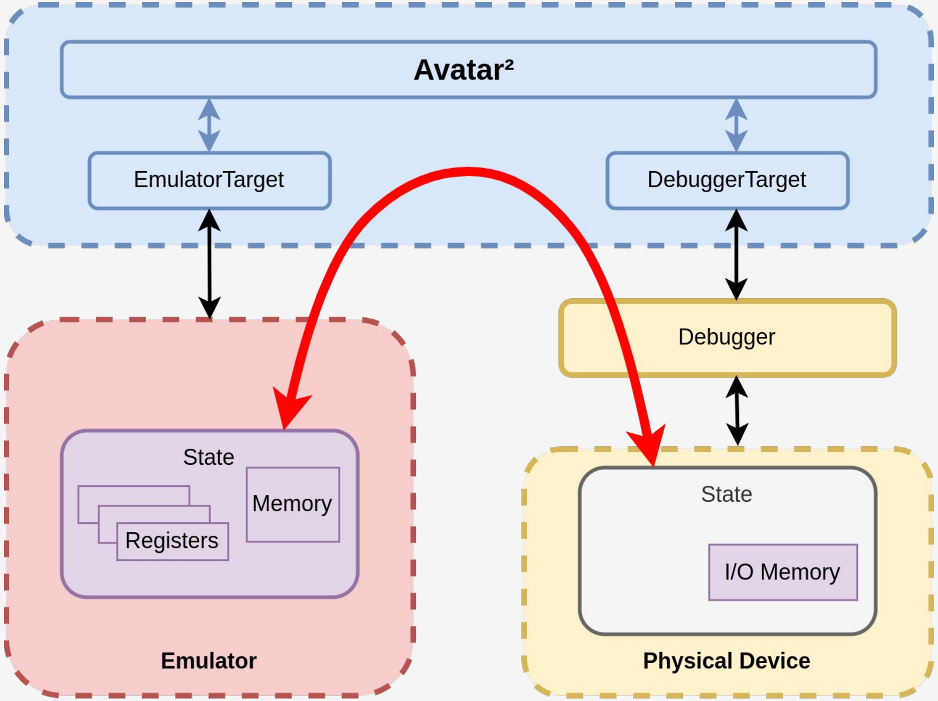


> Peripheral Forwarding

- Forward I/O memory



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ram  = avatar.add_memory_range(0x20000000,
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mmio = avatar.add_memory_range(0x40000000,
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forwarded_to=device)
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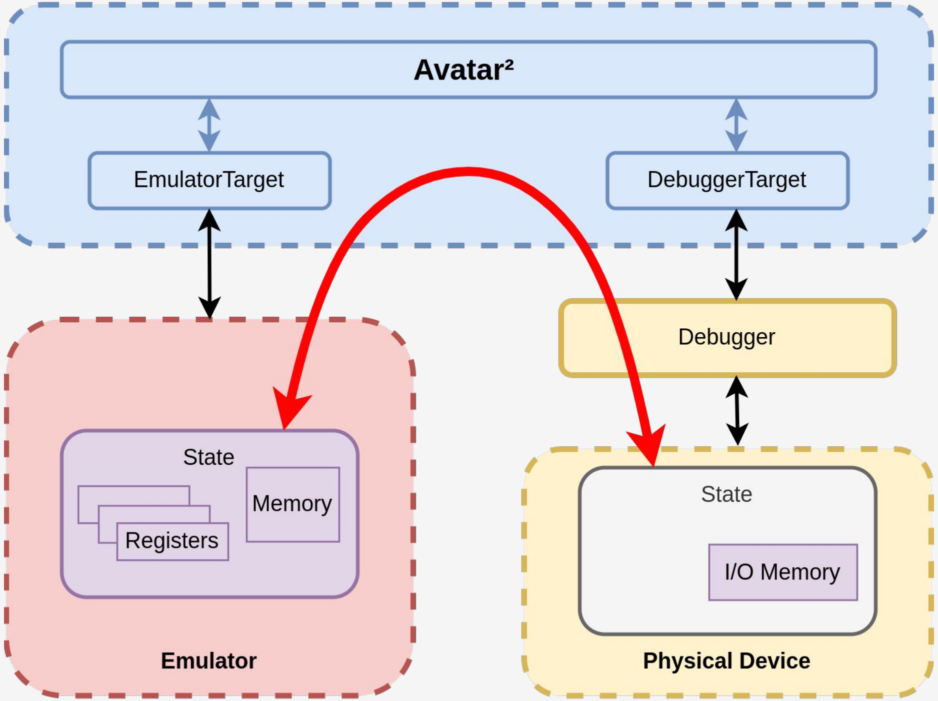
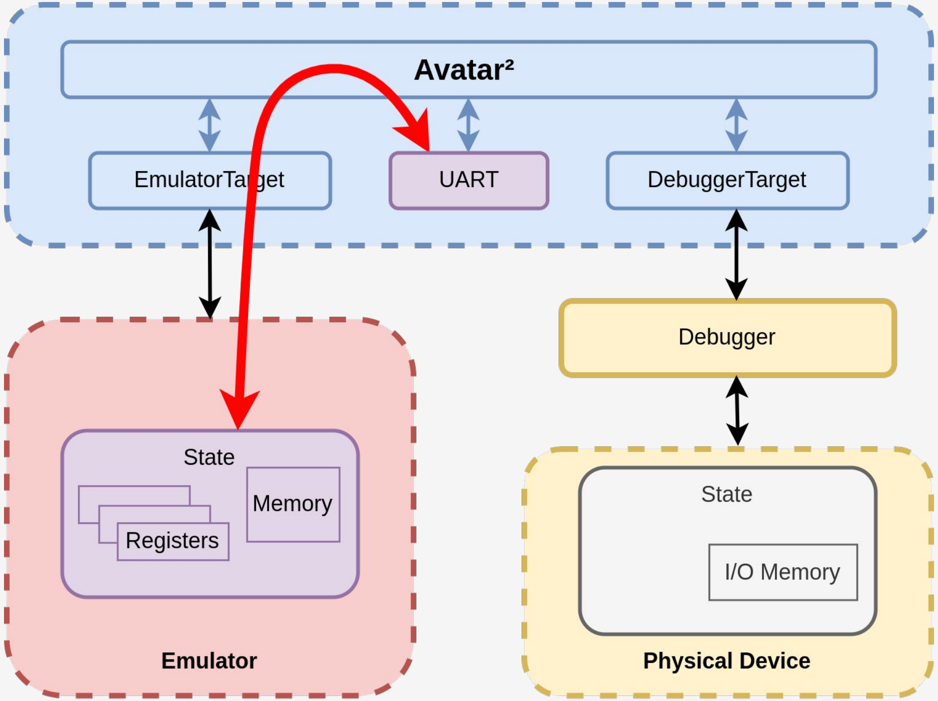


> Peripheral Modeling

- Emulate peripheral in python

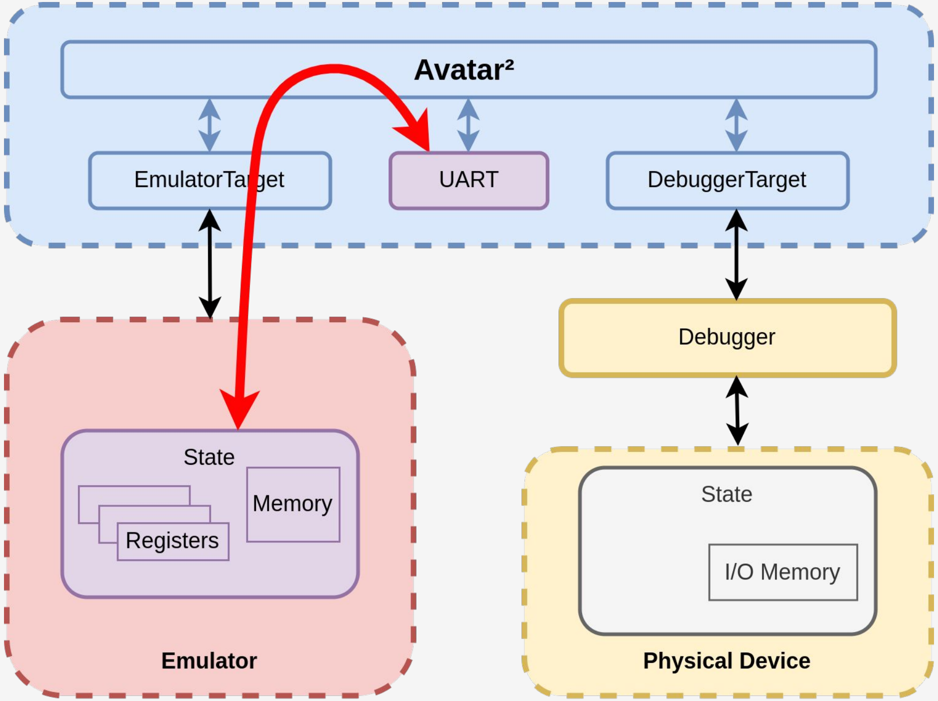


> Peripheral Modeling

```
class UART(AvatarPeripheral):
  # ...

  def dispatch_read(self, offset, size):
    if offset == 0x11c:
      return self.txdone
    return 0x00

  def dispatch_write(self, offset, size, value):
    if offset == 0x11c:
      self.txdone = value
    elif offset == 0x51c:
      print(f">>>> {chr(value)} <<<<")
      self.txdone = 1
    return True
```



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class UART(AvatarPeripheral):
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uart = avatar.add_memory_range(0x40002000,
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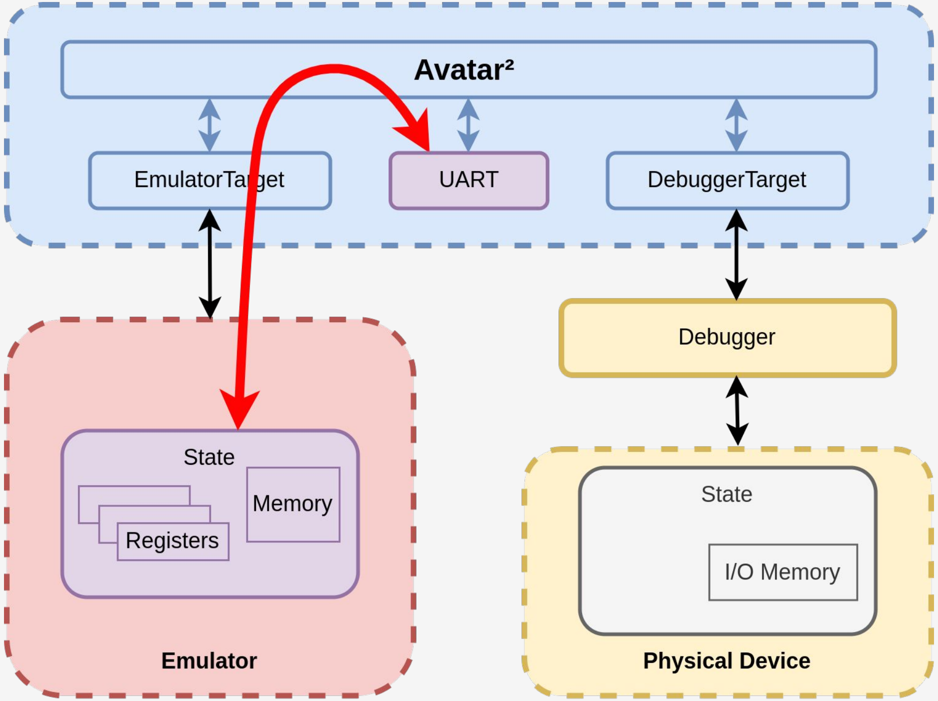

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  - https://github.com/avatartwo/avatar2/tree/main/handbook
- Examples
  - https://github.com/avatartwo/avatar2-examples
  - U-Boot - Example without hardware
  - NUCLEO L152RE - Transfer state
  - NRF51 BLE - WiSec'21 tutorial on avatar2
  - Rehosting the Raspberry Pi Pico blink example

> Going Further

- Rehosting
  - https://github.com/halucinator/halucinator
  - Records peripheral accesses to model them: https://github.com/ucsb-seclab/pretender

- Fuzzing
  - https://github.com/FirmWire/FirmWire
  - https://github.com/fgsect/unicorefuzz

- Symbolic execution
  - https://angr.io/blog/angr_symbion/
  - https://github.com/csvl/SEMA-ToolChain

> Conclusion

- Dynamic firmware binary analysis is still a challenging topic
- Various possible approaches
- Avatar^2 focuses on interoperability of tools

> Links

- Framework
  https://github.com/avatartwo/avatar2
- Examples
  https://github.com/avatartwo/avatar2-examples
- Slack
  https://avatartwo.slack.com/
- Team
  - Paul OLIVIER (paul.olivier@laas.fr)
  - Marius MUENCH
  - Florian ALBRECHT
  - Aurélien FRANCILLON

avatar^2
MULTI TARGET ORCHESTRATION

EURECOM
Sophia Antipolis

Backup slides

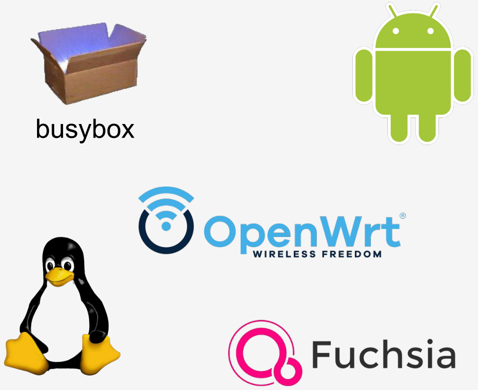
> A wide variety of systems for firmware

OpenWrt
WIRELESS FREEDOM
TinyOS
μClinux
Zephyr™
MicroPython
NUCLEUS
RTOS
STM32
Cube
arm
MBED
uefi
coreboot
THREADX
OP-TEE
.org
freeRTOS
Fuchsia
busybox
U-Boot
VxWorks
ARDUINO™
uClibc-ng
Windows
Embedded CE

> Firmware classification

Type I

- *General purpose* OS-based devices
- minimalist
- lightweight user mode applications



Muench, Marius, et al. *What You Corrupt Is Not What You Crash: Challenges in Fuzzing Embedded Devices*, NDSS 2018

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busybox

OpenWrt
WIRELESS FREEDOM

Fuchsia

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- high performance
- real-time scheduling

freeRTOS

Zephyr™

VxWorks

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- Devices *without an OS-Abstraction*
- monolithic firmware

ARDUINO

MicroPython

U-Boot

arm MBED

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