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# HALucinator: Firmware Re-hosting Through Abstraction Layer Emulation

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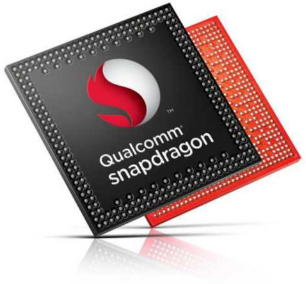
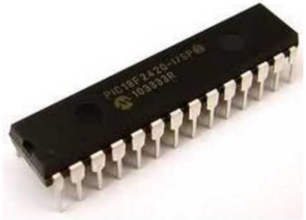
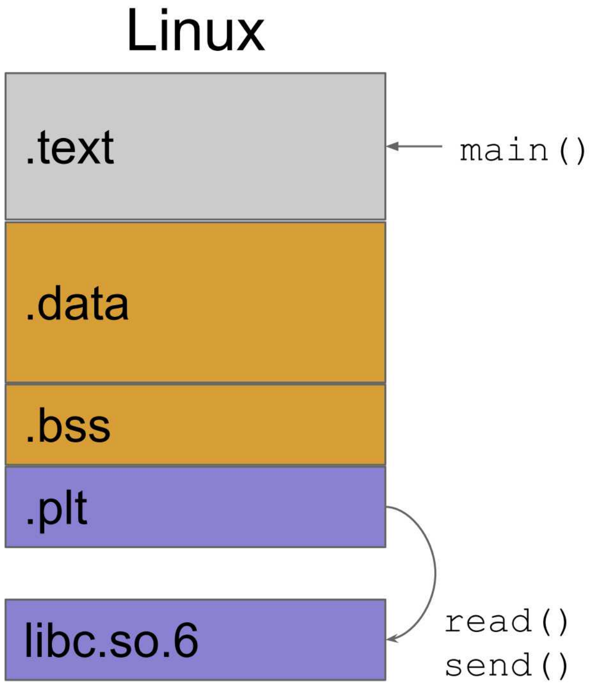
# IoT and Operational Technology

# Device Internals

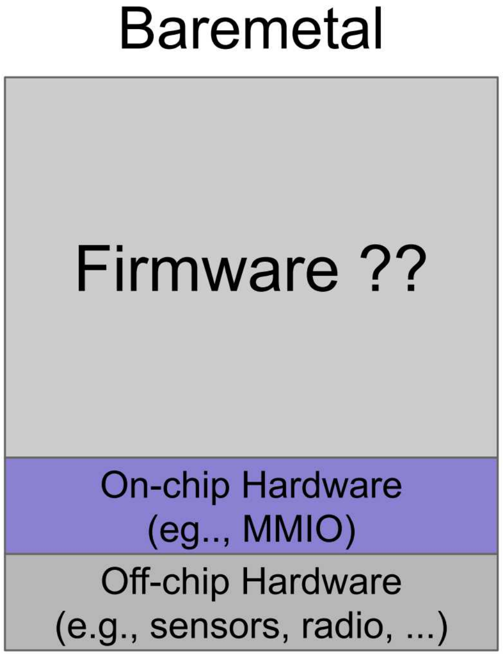




# Many run Baremetal Firmware



Kernel abstractions used for hardware interactions



Raw hardware access

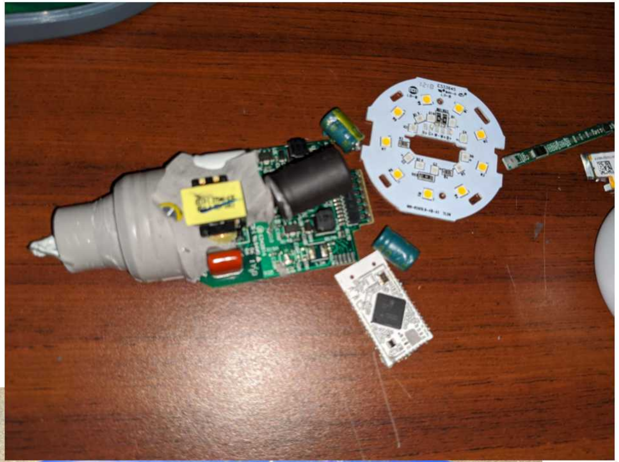
# Dynamic Analysis

## Hardware

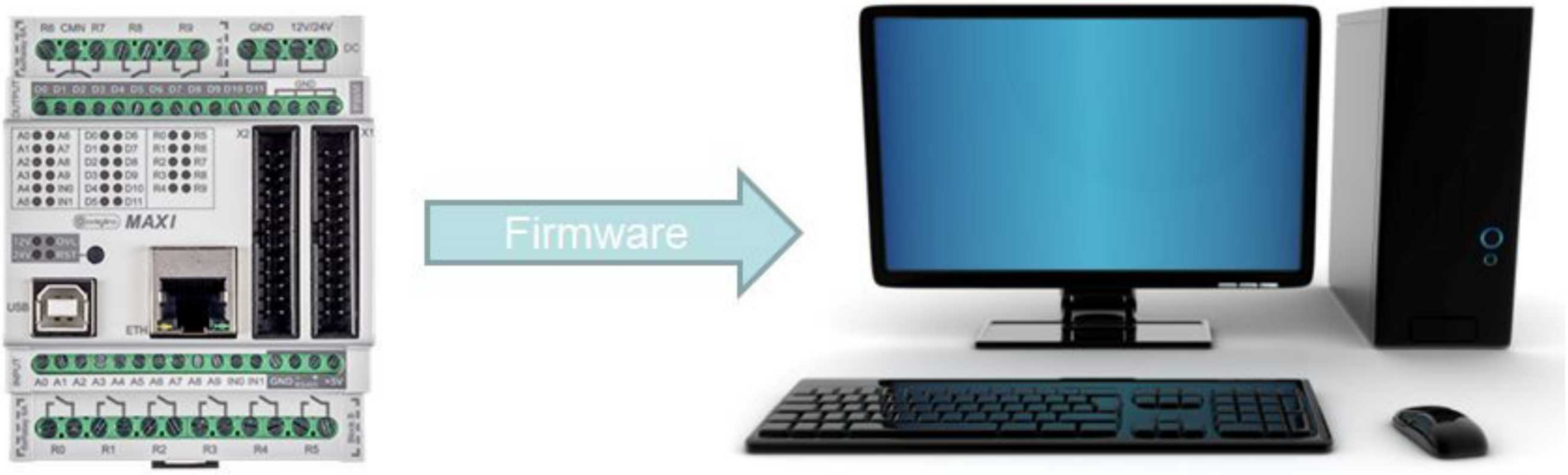
- Expensive ($10,000)
- Brittle, easily bricked
- No parallelism

## Opaque

- Debug ports should be disabled
- If present, very limited

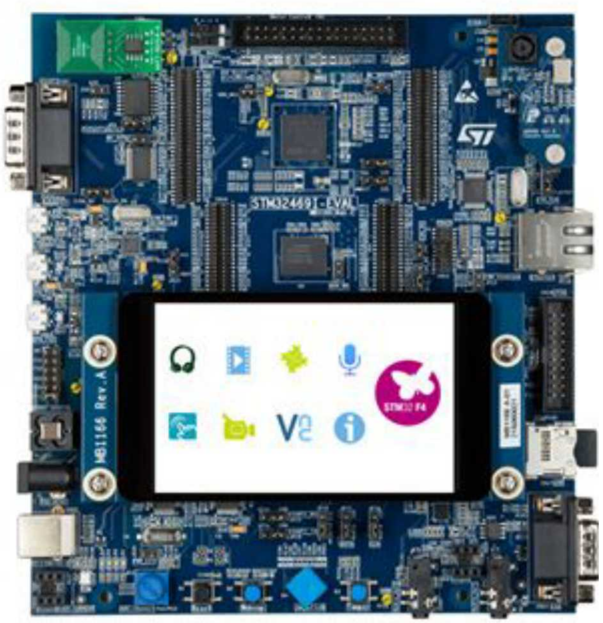


# Re-hosting to the Rescue?



**Goal: Enable firmware testing without requiring its specialized hardware**

# Re-hosting Challenges



**On chip**

**CPU**

AES Accelerator

Hash

Coprocessor

Timers

Counters

Flash Controller

Clock Config

IAP

DMA

**Off chip**

Ethernet

SD-MMC

GPIO

Camera

LCD

Touch Screen

Wireless

EEPROM

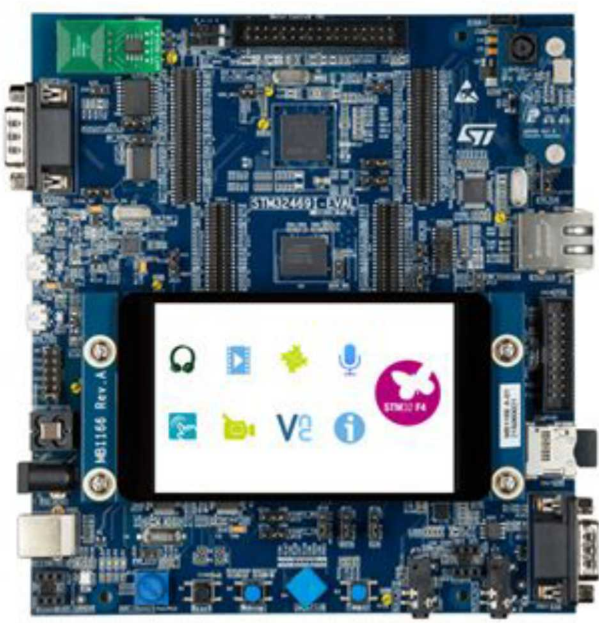
Serial

CAN

Analog IO

USB

# Re-hosting Challenges



| On chip | Off chip |
|---|---|
| **CPU** | Ethernet |
| AES Accelerator | SD-MMC |
| | Analog IO |
| | USB |

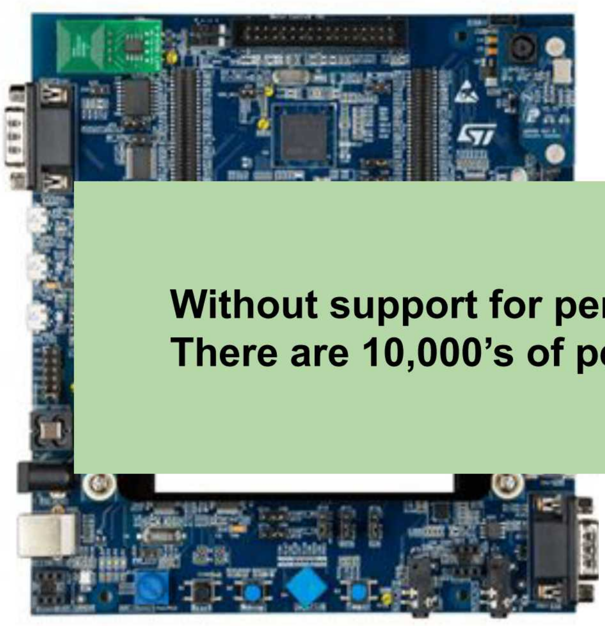
Mouser Lists

44,520 Microcontrollers

3,502 Datasheets

26 Manufactures

# Re-hosting Challenges

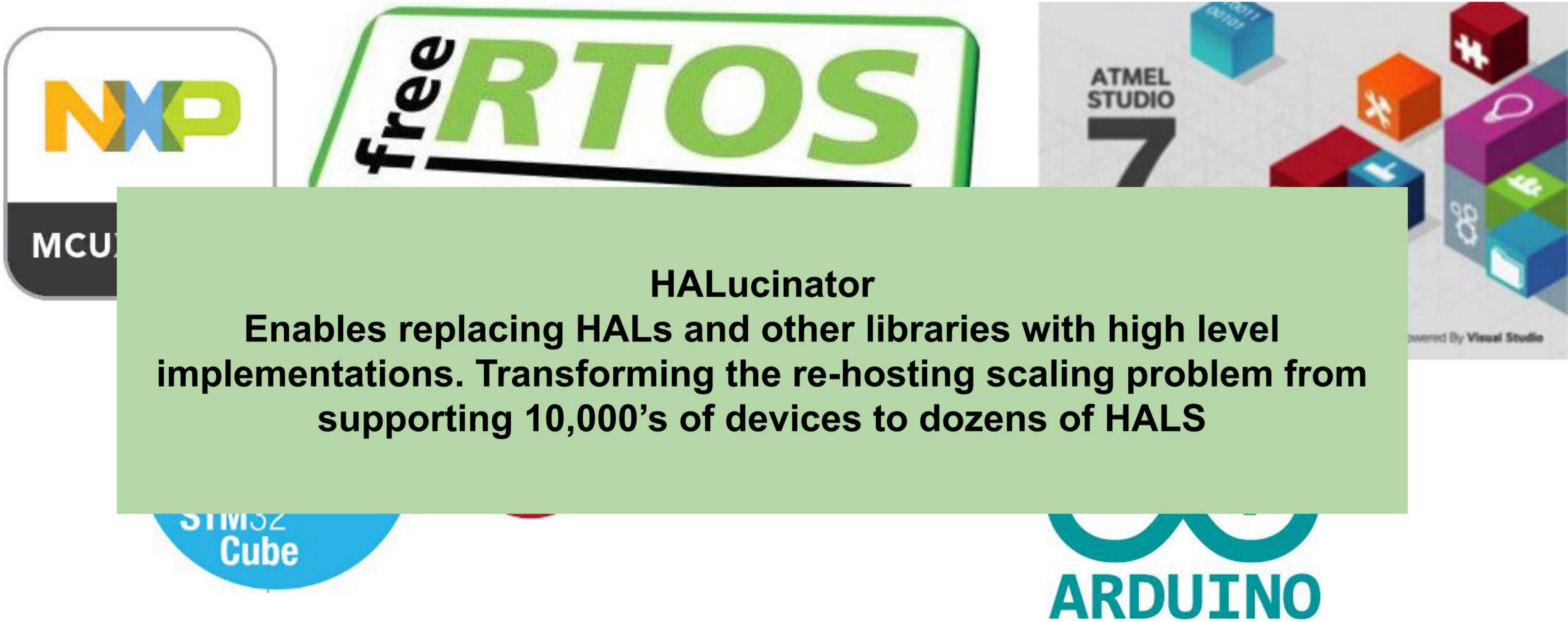


| On chip | Off chip |
|---|---|
| **CPU** | Ethernet |
| AES Accelerator | SD-MMC |
| | Analog IO |
| | USB |

**Without support for peripherals baremetal firmware will not run!**
**There are 10,000’s of peripherals and combinations there of!**

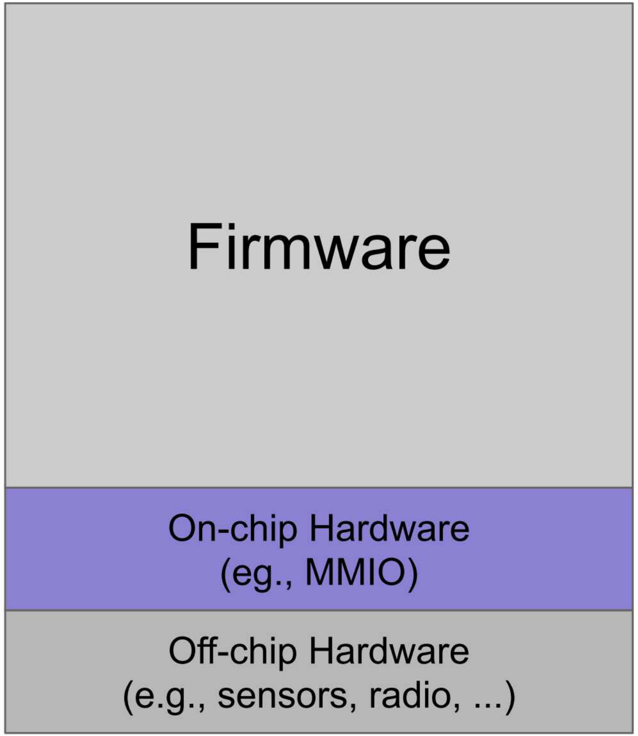
# Hardware Abstraction Libraries

# Hardware Abstraction Libraries



**HALucinator**
**Enables replacing HALs and other libraries with high level implementations. Transforming the re-hosting scaling problem from supporting 10,000’s of devices to dozens of HALS**

# The Modern Firmware Stack

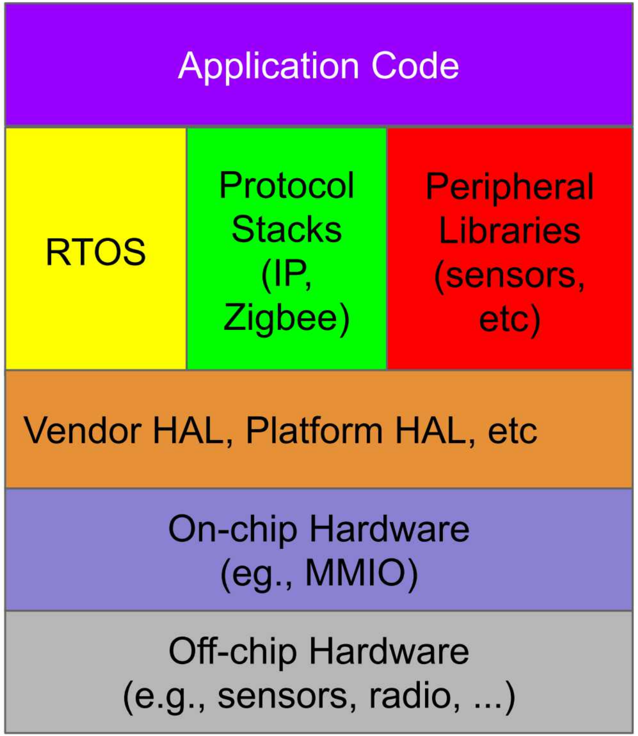


Firmware

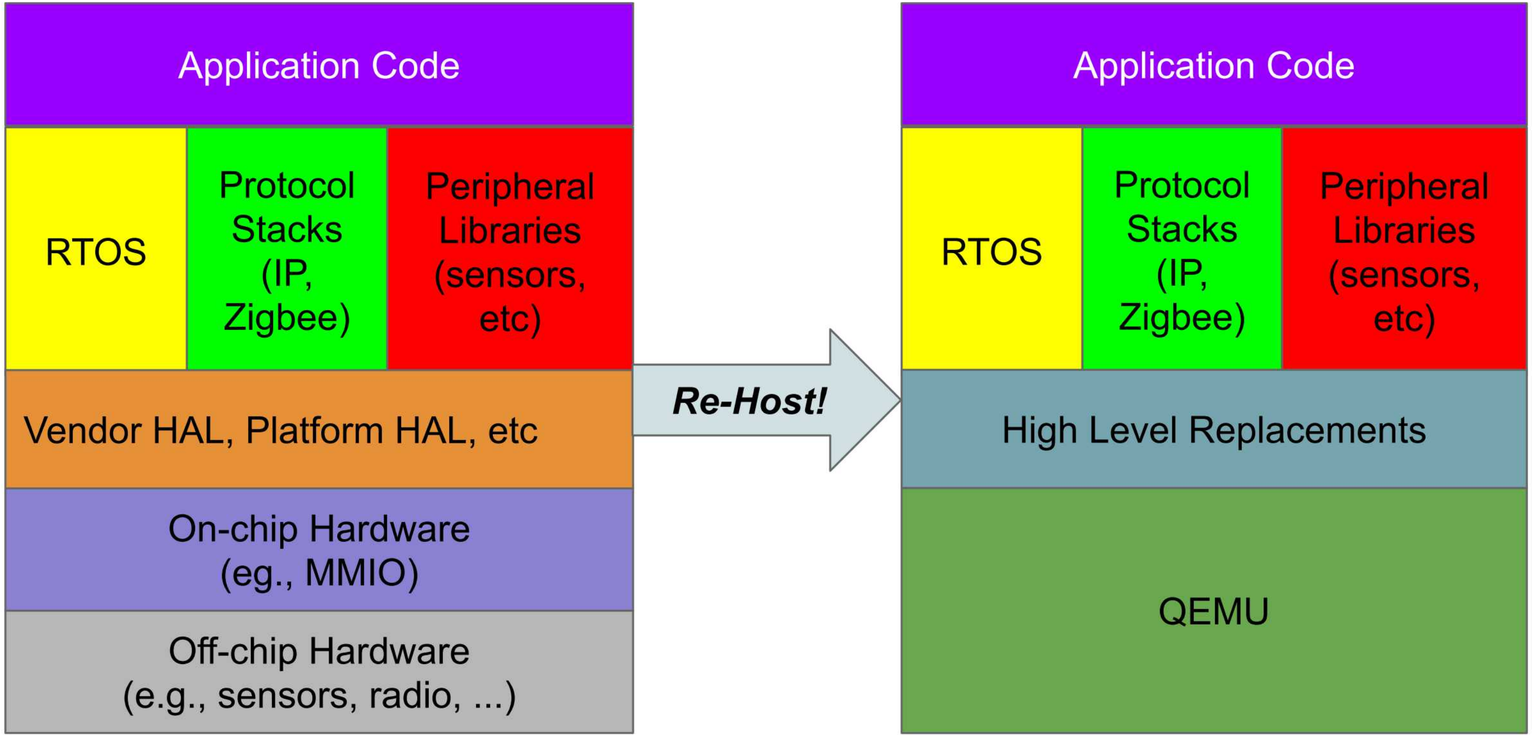
On-chip Hardware
(eg., MMIO)

Off-chip Hardware
(e.g., sensors, radio, ...)

# High Level Emulation


Application Code
RTOS
Protocol Stacks (IP, Zigbee)
Peripheral Libraries (sensors, etc)
Vendor HAL, Platform HAL, etc
On-chip Hardware (eg., MMIO)
Off-chip Hardware (e.g., sensors, radio, ...)

# High Level Emulation


Application Code
RTOS
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Peripheral Libraries (sensors, etc)
Vendor HAL, Platform HAL, etc
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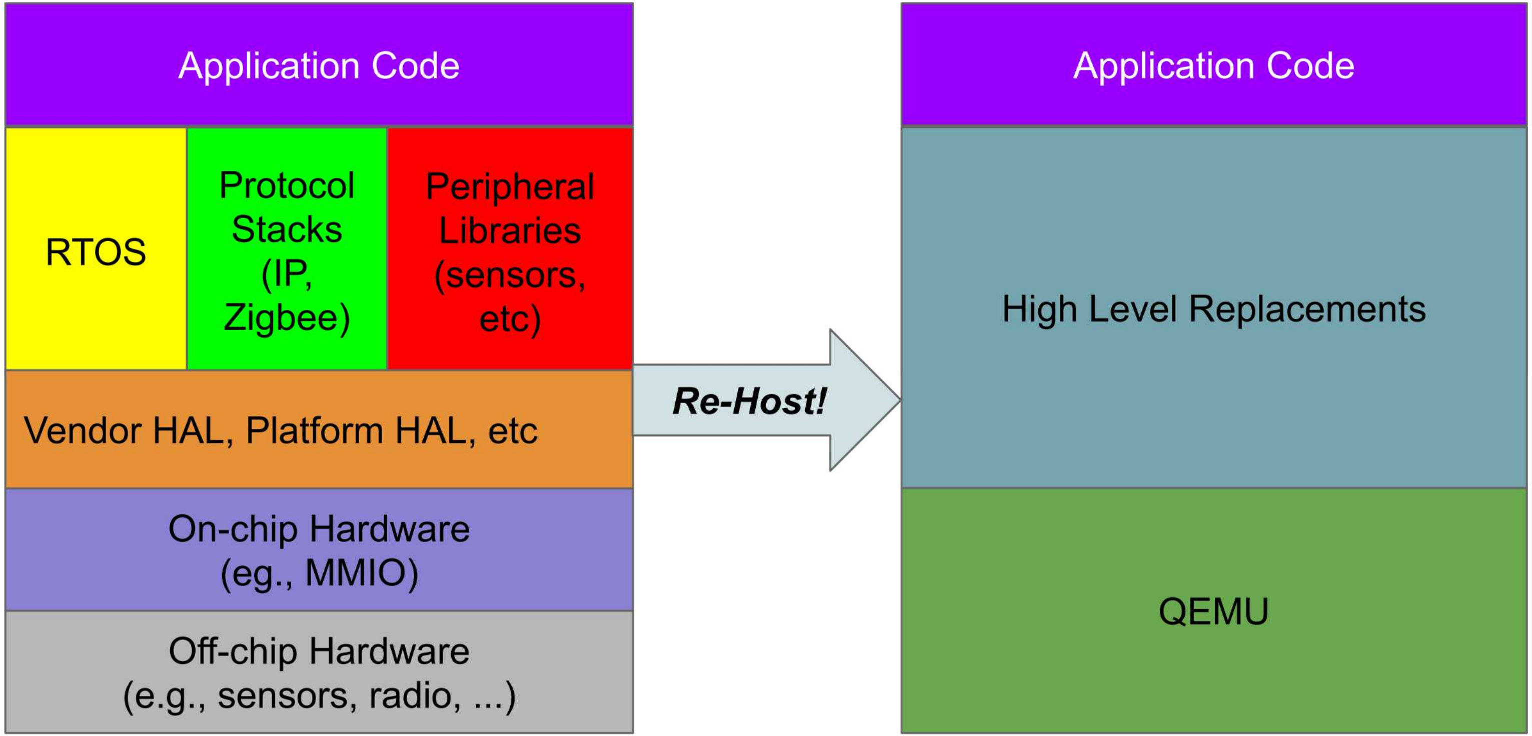
Off-chip Hardware (e.g., sensors, radio, ...)
Re-Host!
Application Code
RTOS
Protocol Stacks (IP, Zigbee)
Peripheral Libraries (sensors, etc)
High Level Replacements
QEMU

# High Level Emulation



Application Code
RTOS
Protocol Stacks (IP, Zigbee)
Peripheral Libraries (sensors, etc)
Vendor HAL, Platform HAL, etc
On-chip Hardware (eg., MMIO)
Off-chip Hardware (e.g., sensors, radio, ...)
Re-Host!
Application Code
High Level Replacements
QEMU

# HALucinator enables

Introspection – What is the firmware doing?

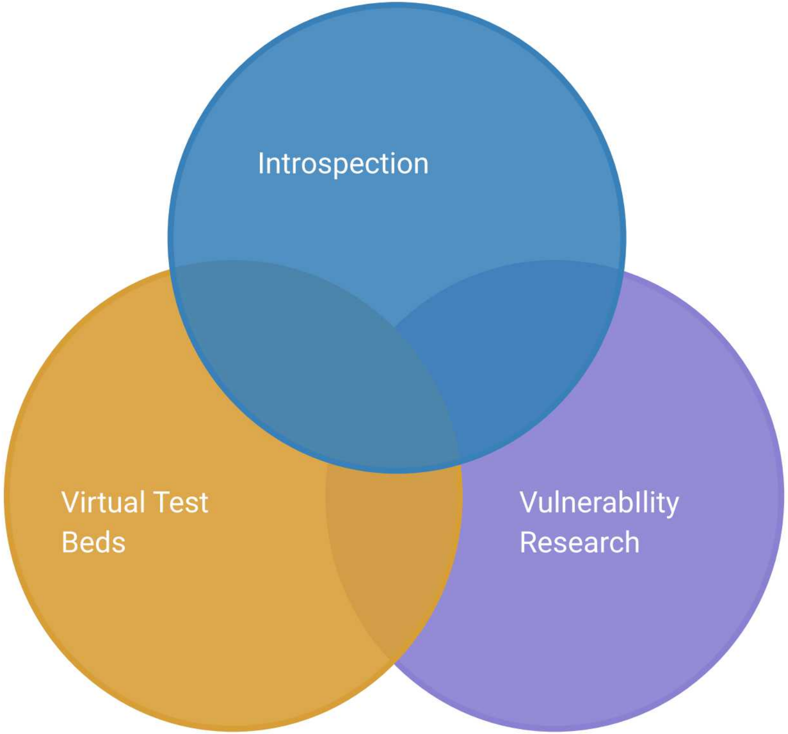
- Debugging/system testing
- Determine effects of malware on firmware
- Experiment with firmware in controlled environment

Vulnerability Research – Is the system vulnerable?

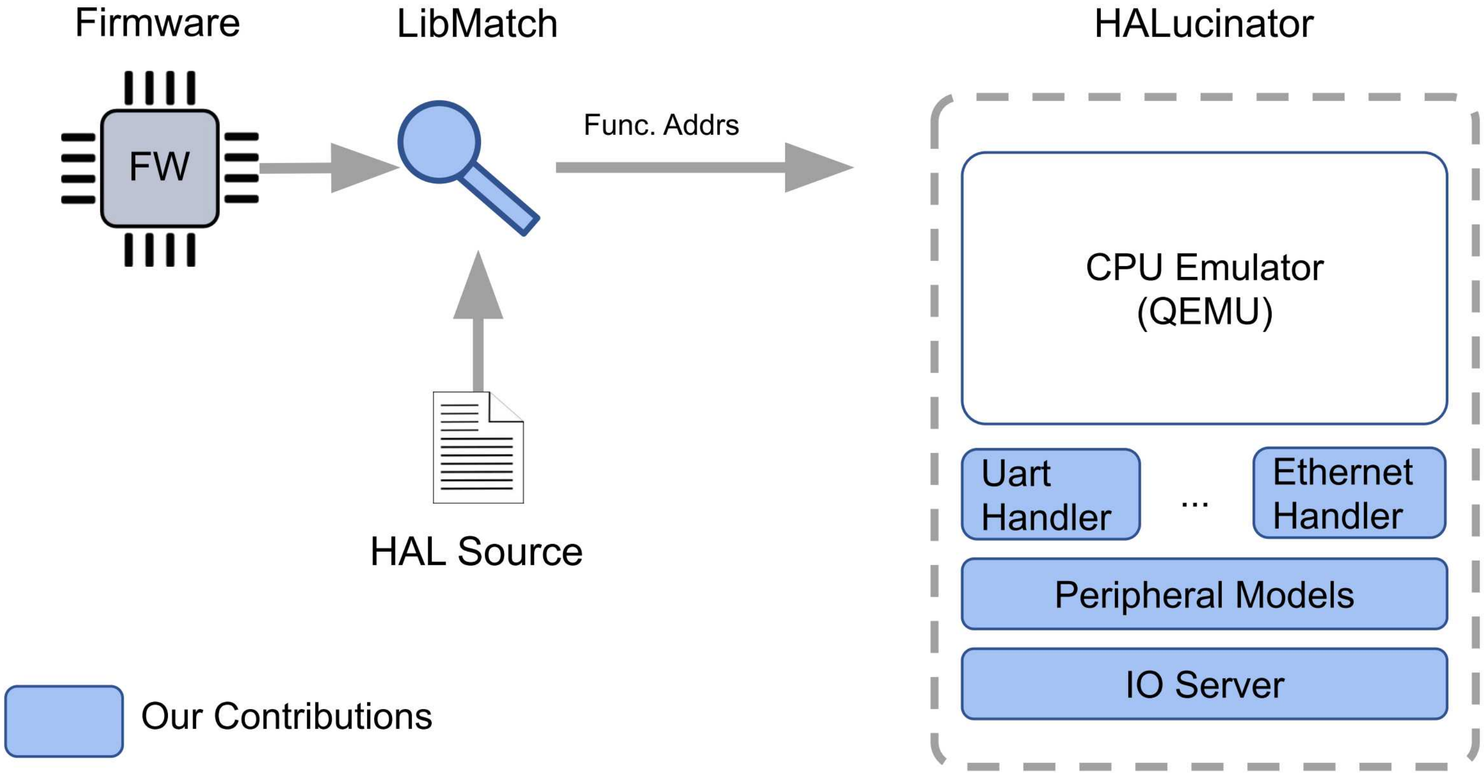
- Identify insecure interfaces
- Find memory corruption errors
- Fuzzing

Virtual Testbeds – How do vulnerabilities impact connected systems?

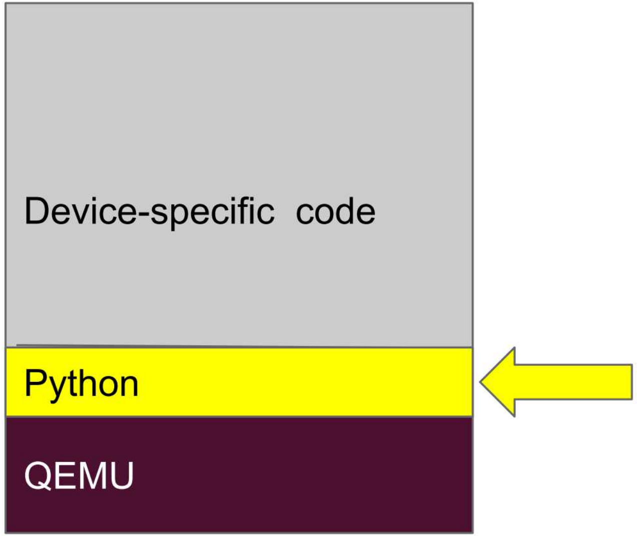
- System of systems modeling
- Firmware in the loop testing
- Software only testbeds of embedded systems



# HALucinator implementation

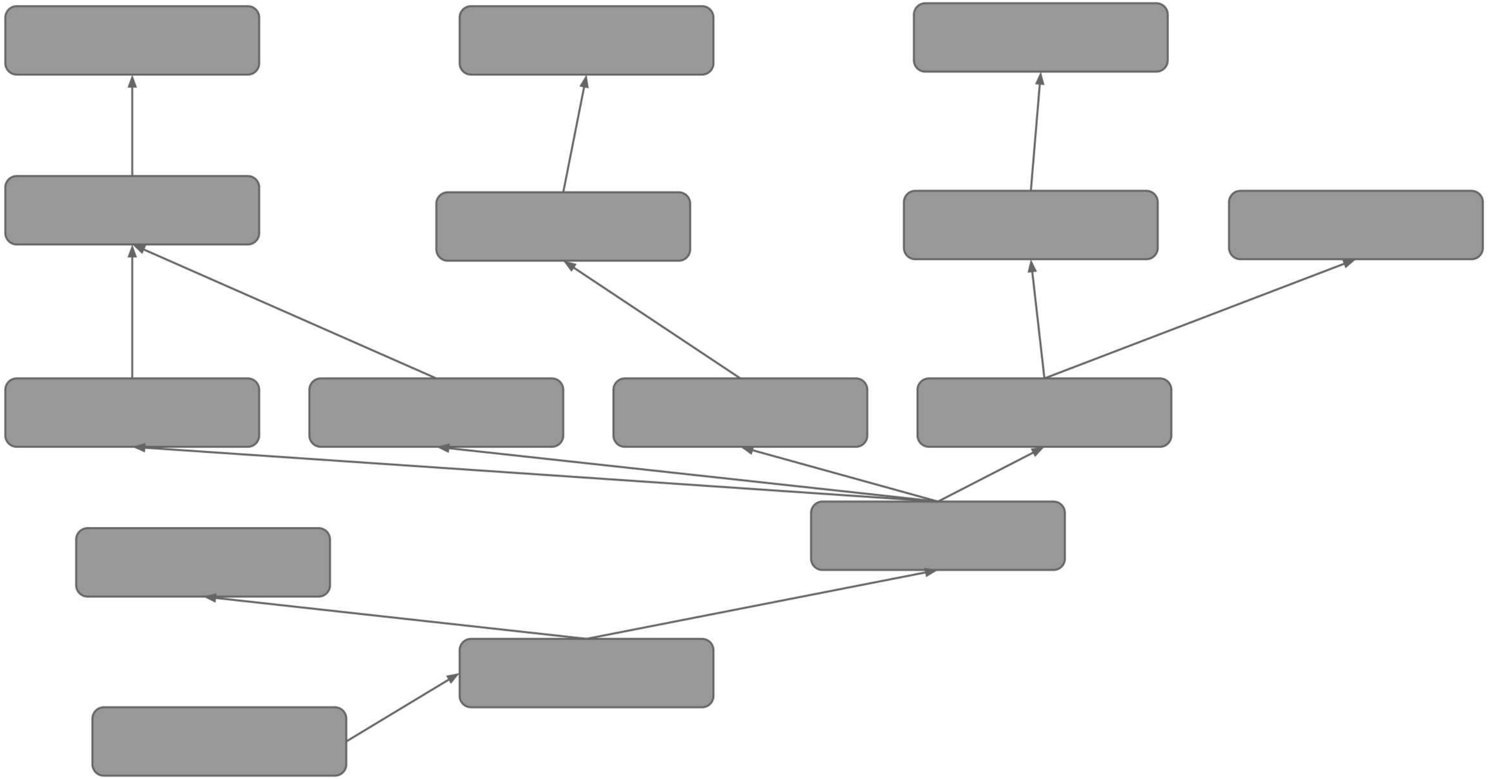


# Handler Example

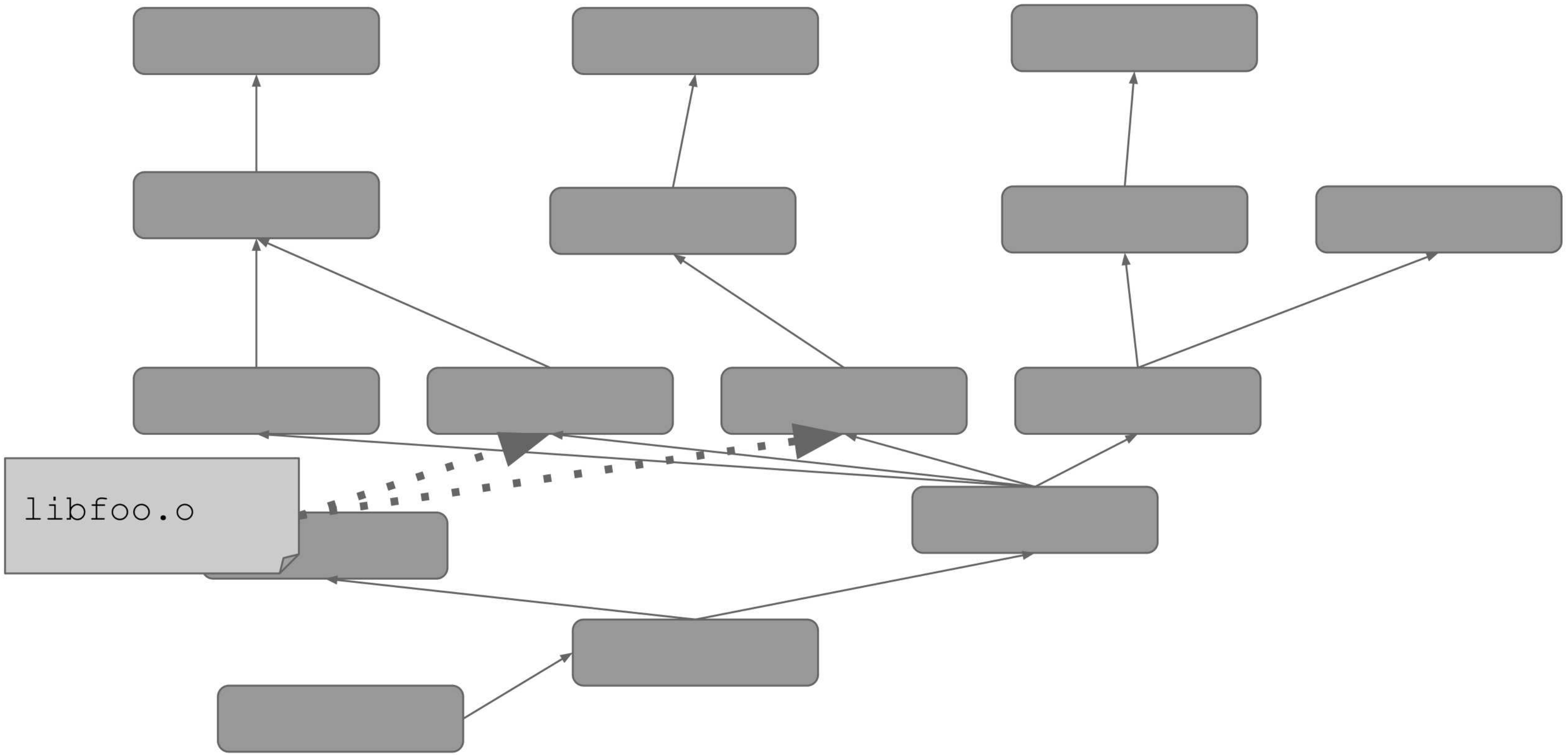


```
def i2c_read_buf(uc):
    # i2c_read_buf(char* buf, int len);
    buf = uc.regs.r1 # arg 0: The buffer
    l = uc.regs.r2   # arg 1: Buffer length
    assert(buf != 0)  # Crash on bad arguments
    assert(len > 0)
    data = I2CModel.rx('i2c', 0, len) # Get the data
                                      # from the virtual bus
    uc.mem[buf] = data                # Store it in the emulator
```

# LibMatch

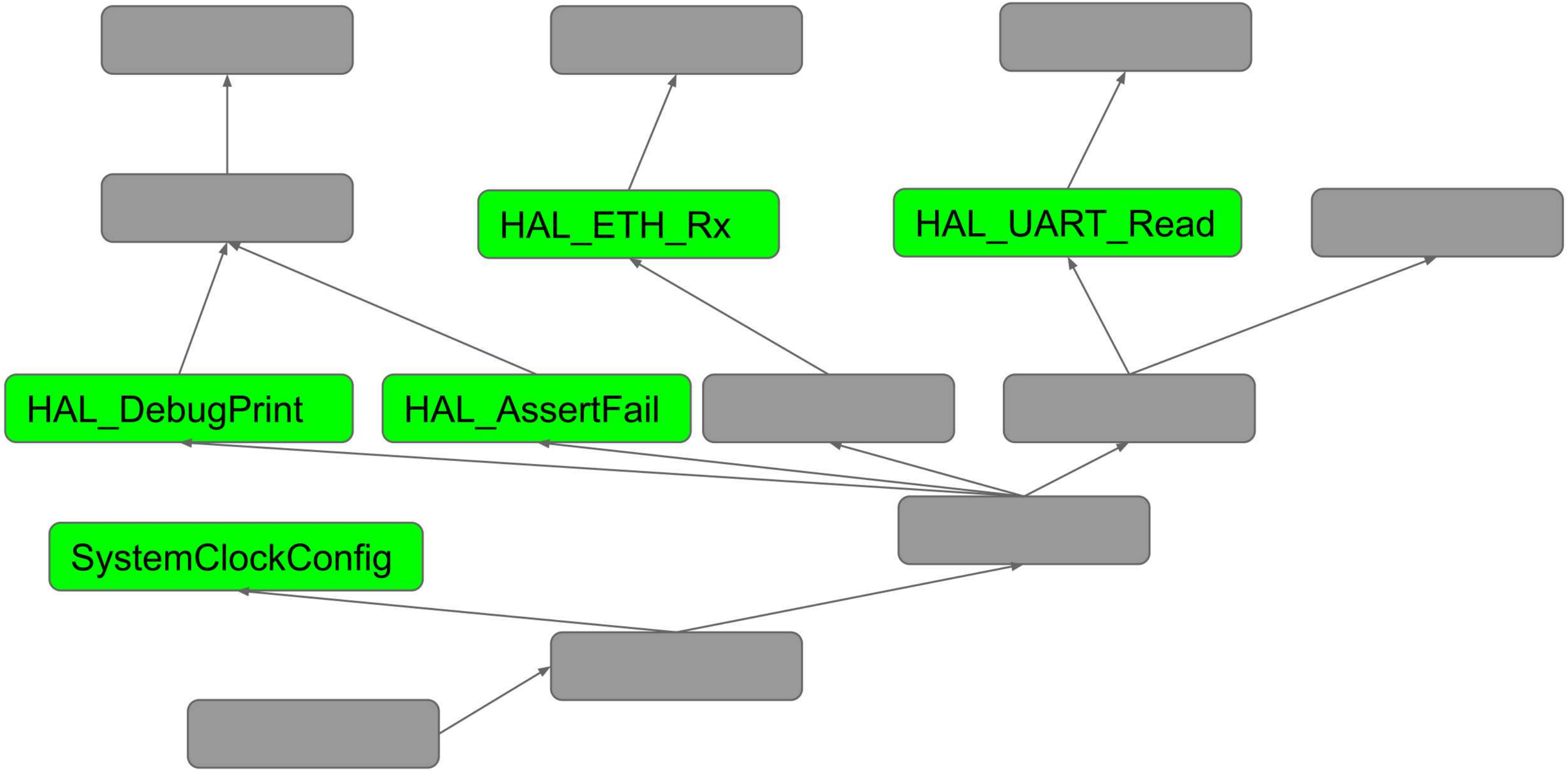


# LibMatch

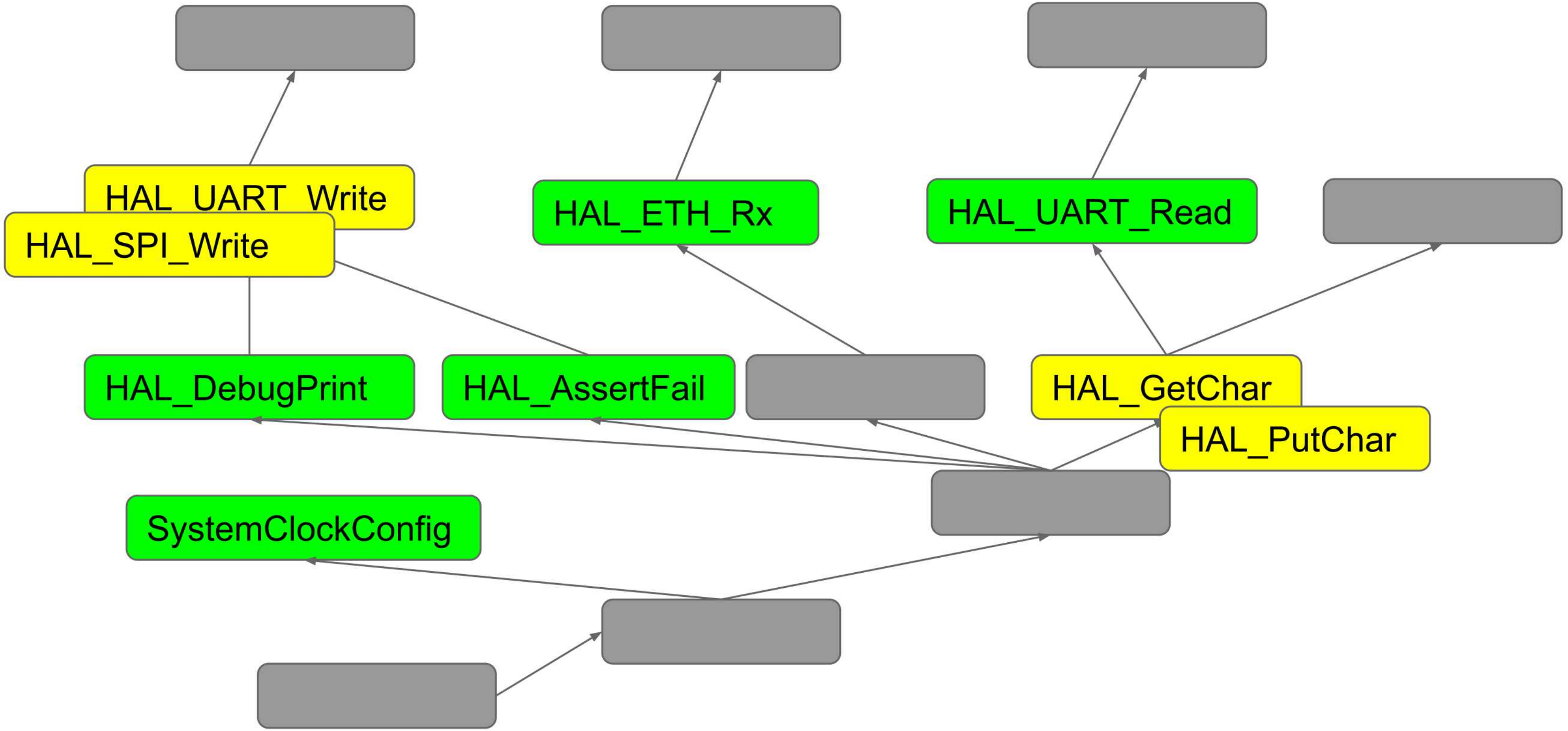


Step 1: Match library content

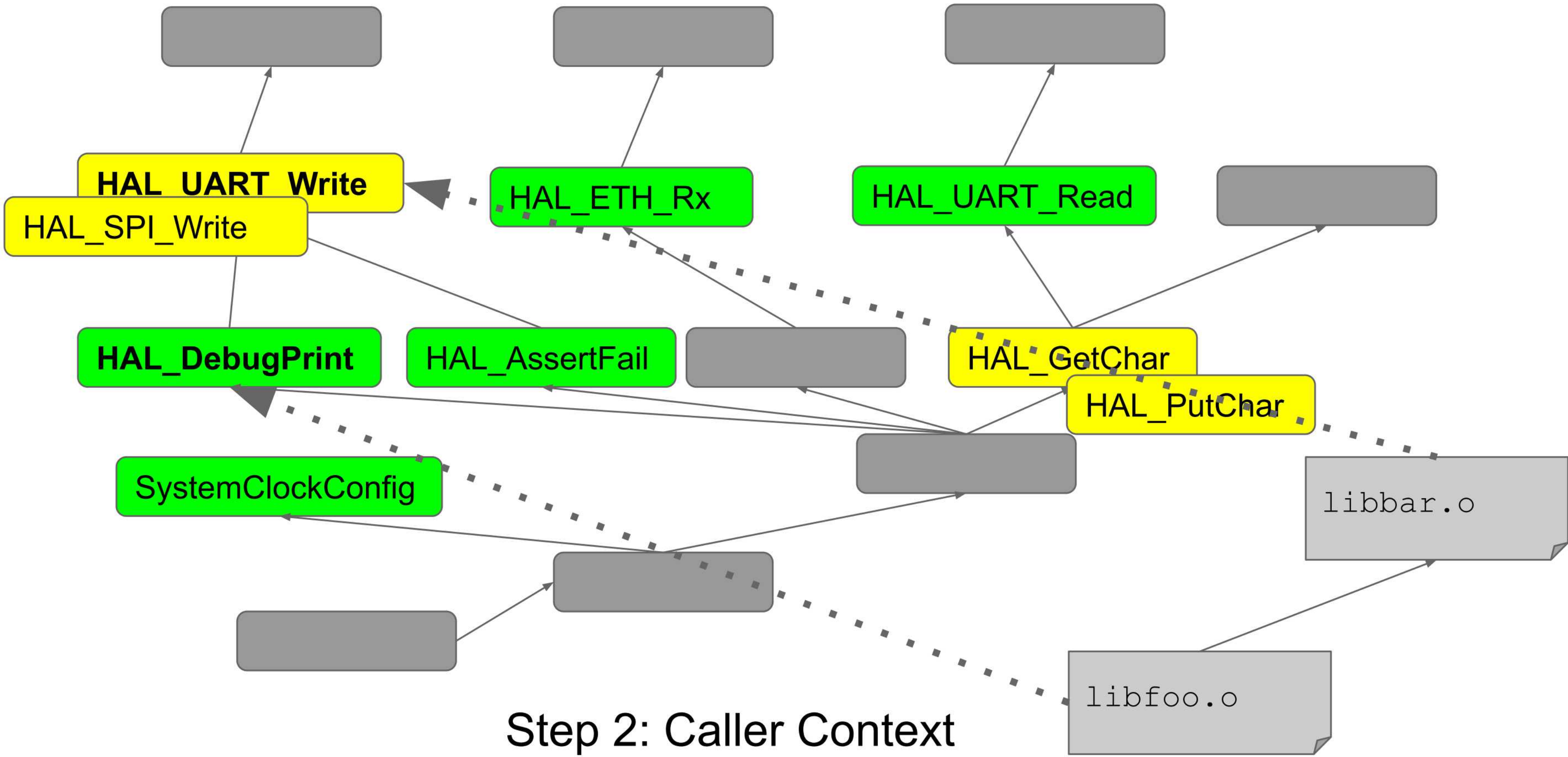
# LibMatch


HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
SystemClockConfig

# LibMatch

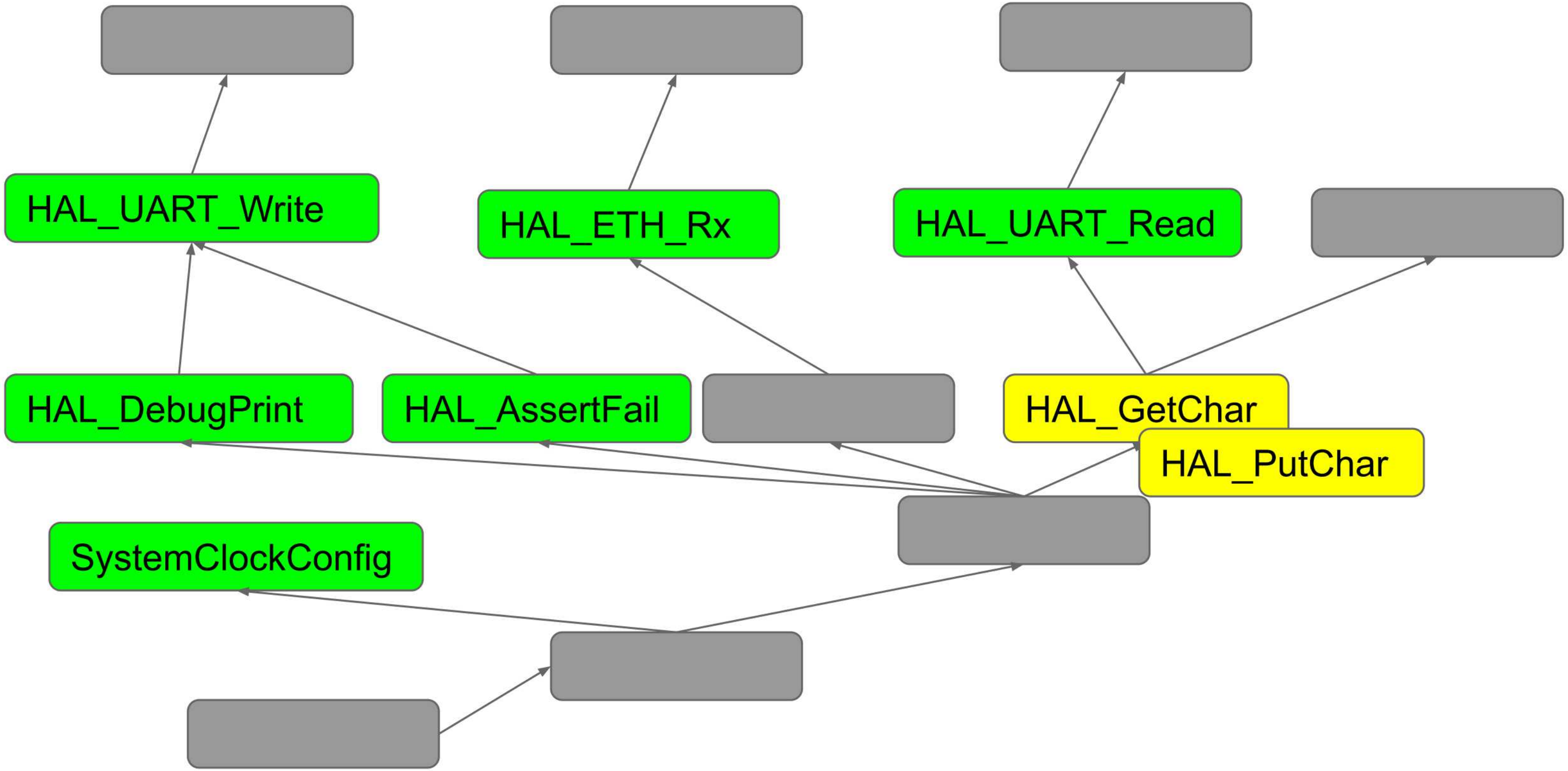

HAL_UART_Write
HAL_SPI_Write
HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
HAL_GetChar
HAL_PutChar
SystemClockConfig

# LibMatch

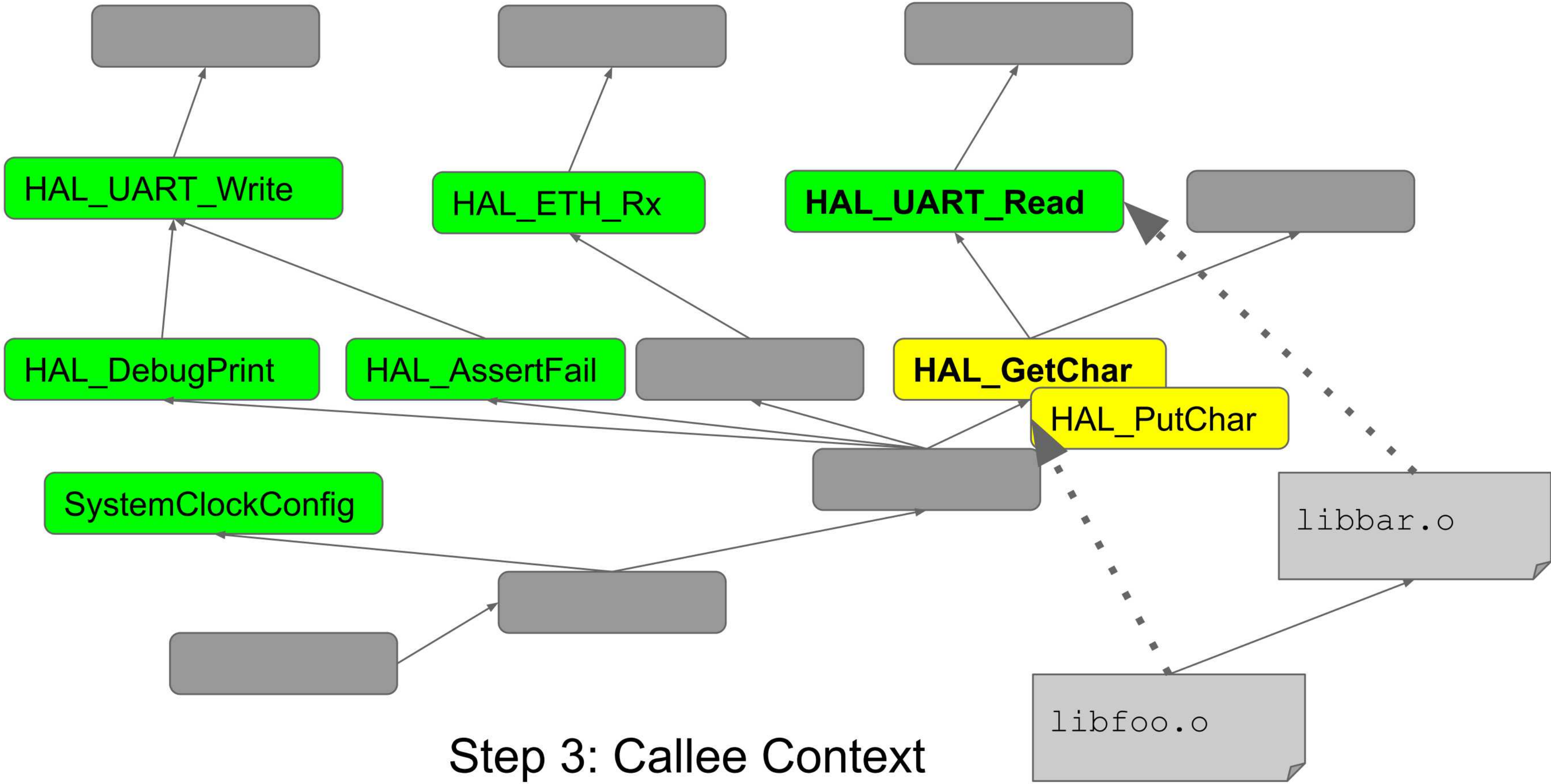


Step 2: Caller Context

# LibMatch

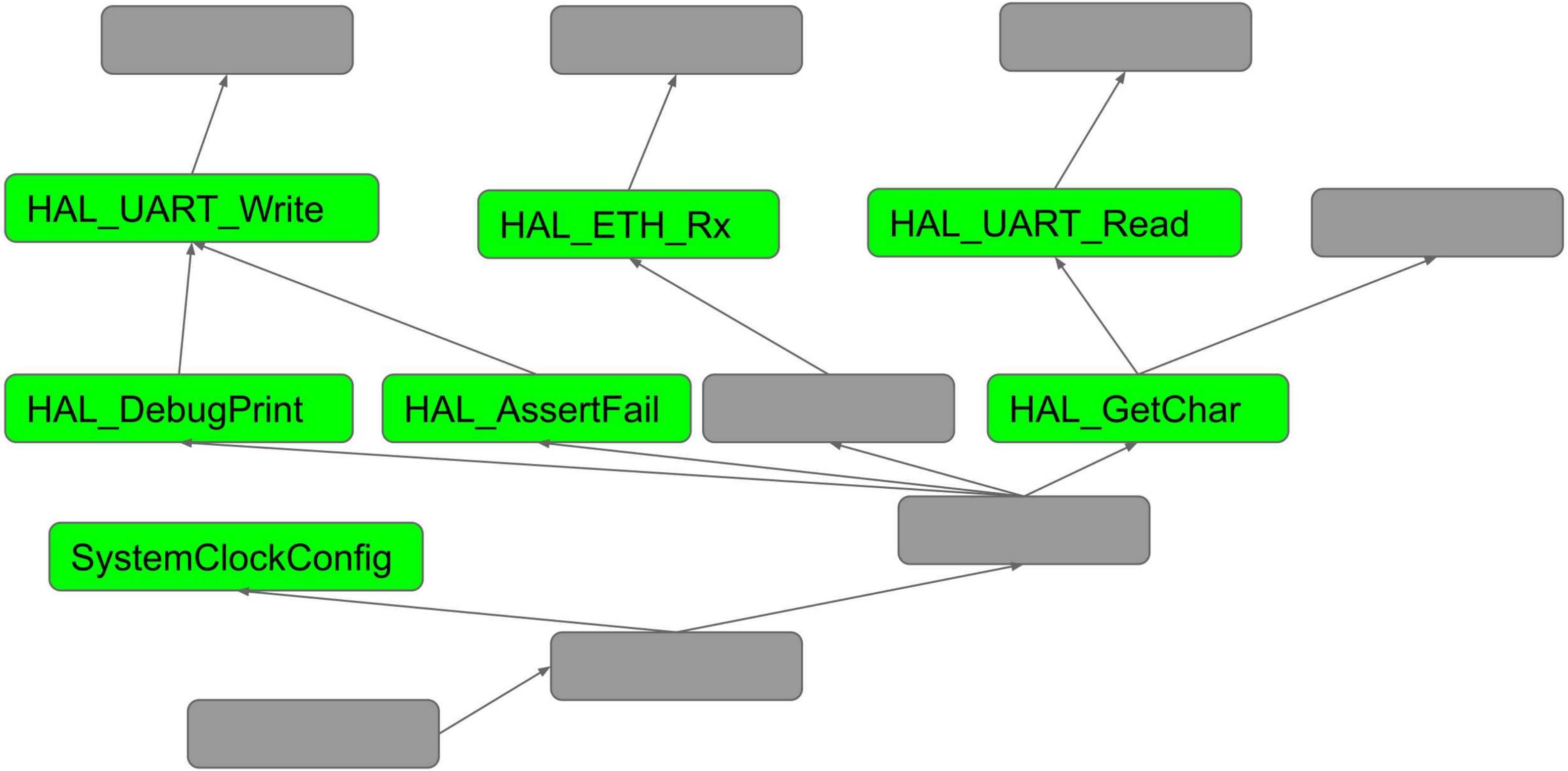

HAL_UART_Write
HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
HAL_GetChar
HAL_PutChar
SystemClockConfig

# LibMatch

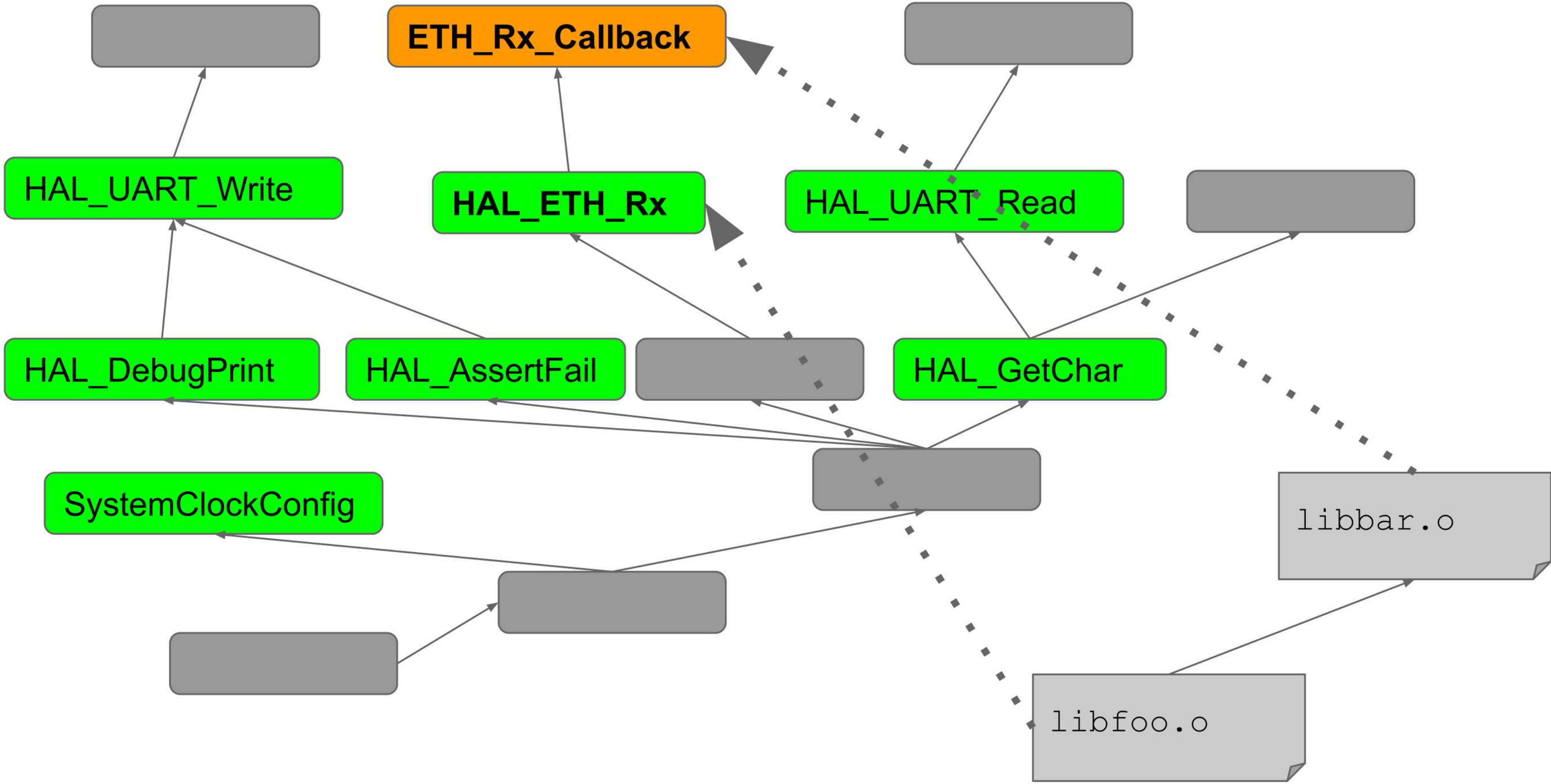


Step 3: Callee Context

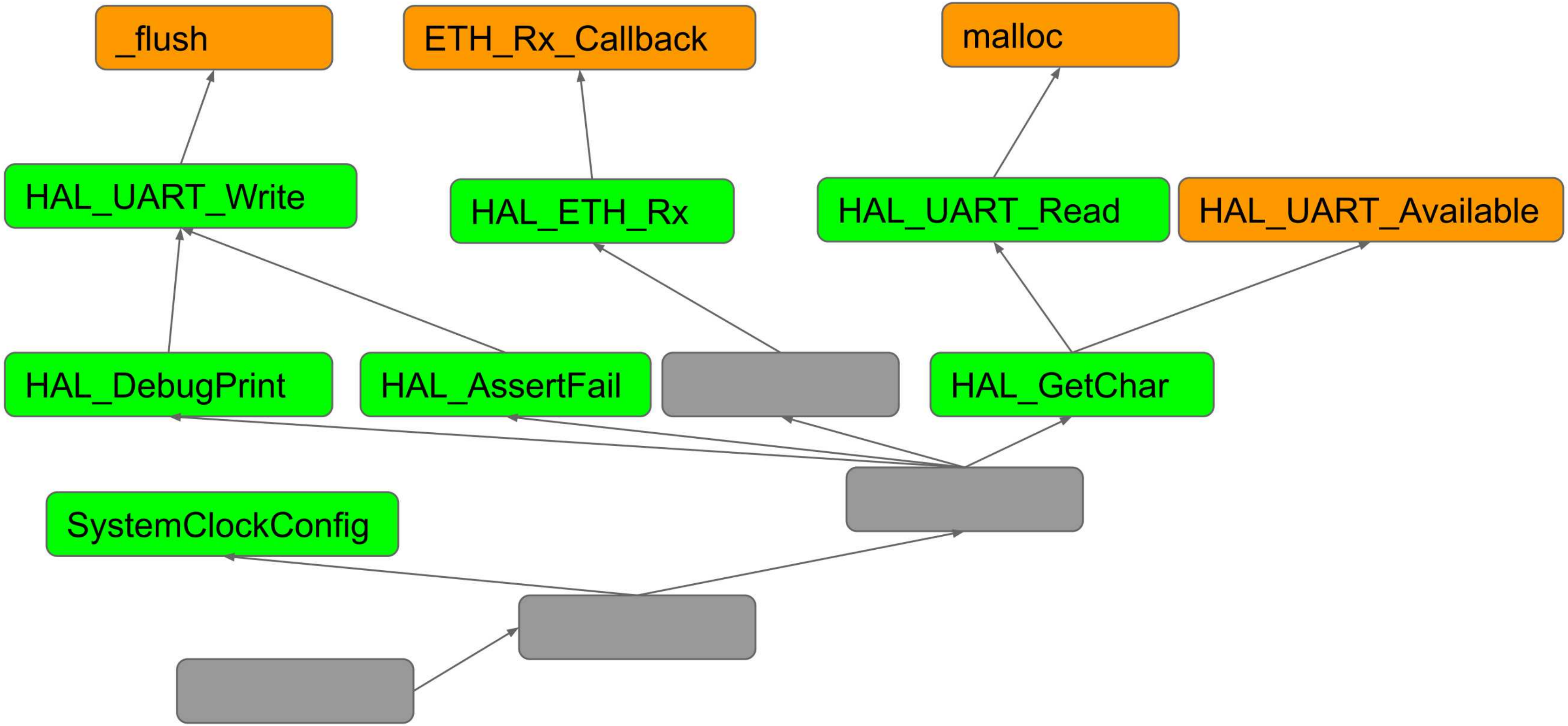
# LibMatch


HAL_UART_Write
HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
HAL_GetChar
SystemClockConfig

# LibMatch


ETH_Rx_Callback
HAL_UART_Write
HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
HAL_GetChar
SystemClockConfig
libbar.o
libfoo.o

# LibMatch


_flush
ETH_Rx_Callback
malloc
HAL_UART_Write
HAL_ETH_Rx
HAL_UART_Read
HAL_UART_Available
HAL_DebugPrint
HAL_AssertFail
HAL_GetChar
SystemClockConfig

# hal-fuzz

- Built on AFL-Unicorn
- Program exits when the input is exhausted
- Deterministic timers based on block counts
- Interrupt events also based on block counts
- Crashes detected via Unicorn’s own error detector as well as handler assertions

# 16 Firmware Samples

- ATMEL ASF
  - USART
  - FAT32 on SD-Card
  - **HTTP Server**
  - **6LoWPAN Sender and Receiver**
- STM32Cube
  - UART
  - FAT32 on SD-Card
  - **UDP-Echo Server and Client**
  - **TCP-Echo Server and Client**
  - **PLC**
- NXP -MCUXpresso
  - UART
  - **UDP Echo Server**
  - **TCP Echo Server**
  - **HTTP Server**

# LibMatch Results

| | “Naive” LibMatch (Bindiff) | LibMatch w/ context |
|---|---:|---:|
| Correct | 74.5% | 87.4% |
| Missing | 5.0% | 3.2% |
| Collisions | 18.8% | 8.5% |
| Incorrect | 2.5% | 0.9% |
| External | -- | 9.96% |

**% avg matches across 16 test binaries**

# Ease of Implementation

Three Handler categories:

- **Trivial**: Does nothing / returns a constant
- **Translating**: Collects arguments, interacts with a Model, returns a result
- **Internal Logic**: Needs to re-implement undocumented internal details

# Ease of Implementation

- Over 85% of handlers require little effort
  - 44.5 are “trivial”
  - 42.2 are “translating”

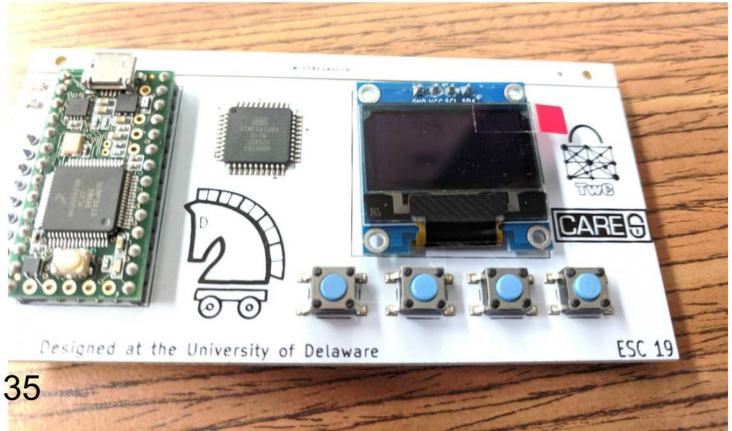
- Remainder: “Internal logic”
  - HAL behavior doesn’t abstract hardware well enough
  - HAL behavior makes assumptions not in the docs (e.g., uses its own heap allocator)

# Fuzzing!

- Hundreds of millions of parallel executions
- Found crashes in ST-PLC, Atmel HTTP server, Atmel 6LowPAN(w/ Contiki)
- Fuzzed HTTP server at two different levels, found crashes in both
- **Discovered CVE-2019-8359 and CVE-2019-9183 in Contiki’s network stack**

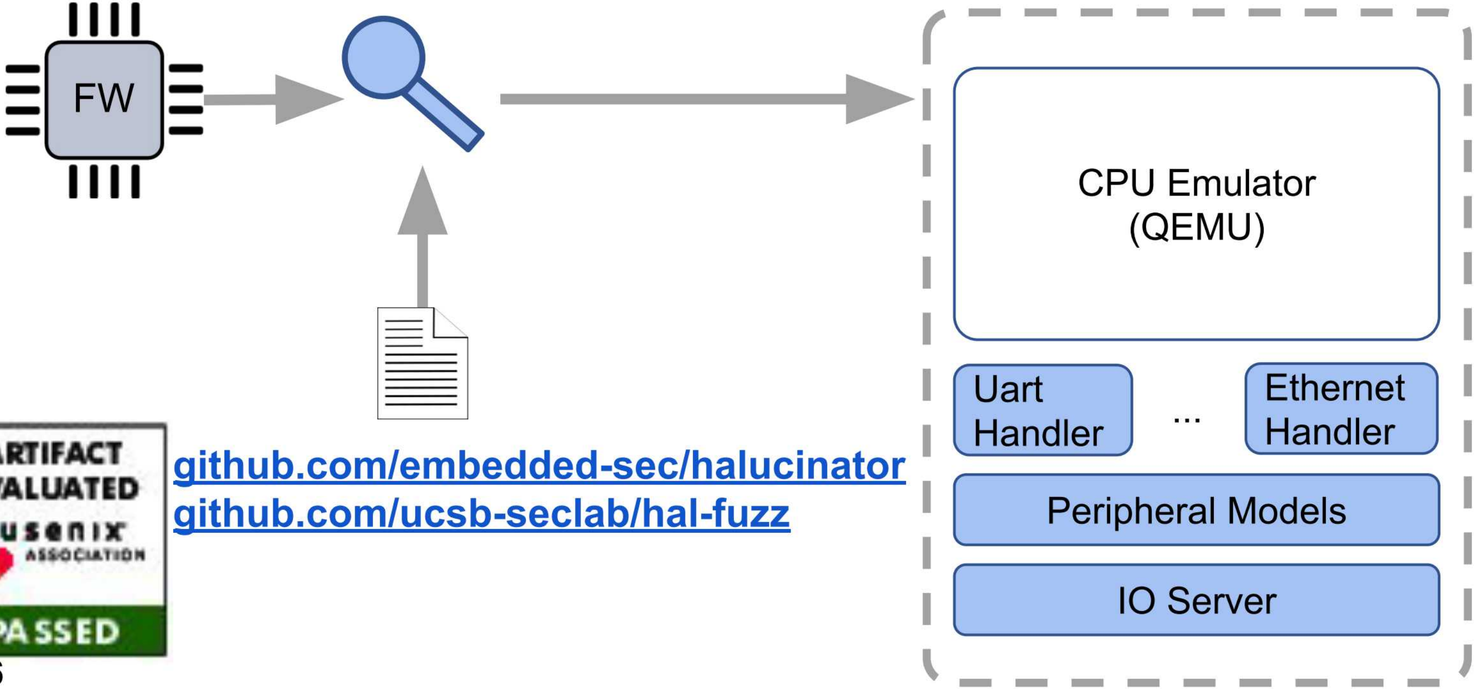
# CSAW ESC 2019 results

- Re-hosted ARM portion of all challenge sets
- Solved 18/19 challenges
- Verified 17/18 solutions w/ just the emulator
- Solved 3 challenges automatically using fuzzing
- Won first place!



# Conclusion

HALucinator eliminates implementing 10,000s of peripherals by using HALs



ARTIFACT EVALUATED usenix ASSOCIATION PASSED

[github.com/embedded-sec/halucinator](https://github.com/embedded-sec/halucinator)
[github.com/ucsb-seclab/hal-fuzz](https://github.com/ucsb-seclab/hal-fuzz)