HALucinator: Firmware Re-hosting Through Abstraction Layer Emulation

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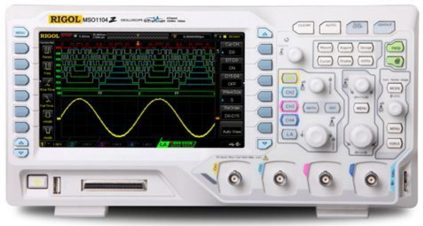
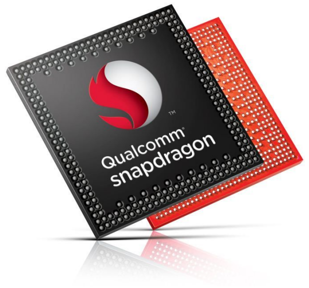
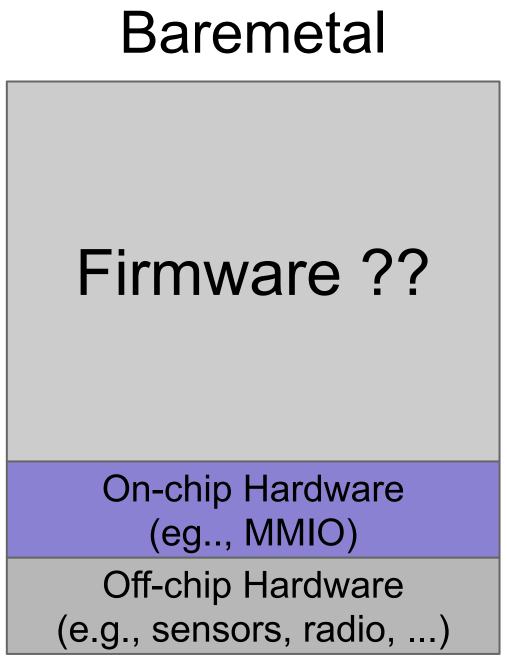
IoT and Operational Technology



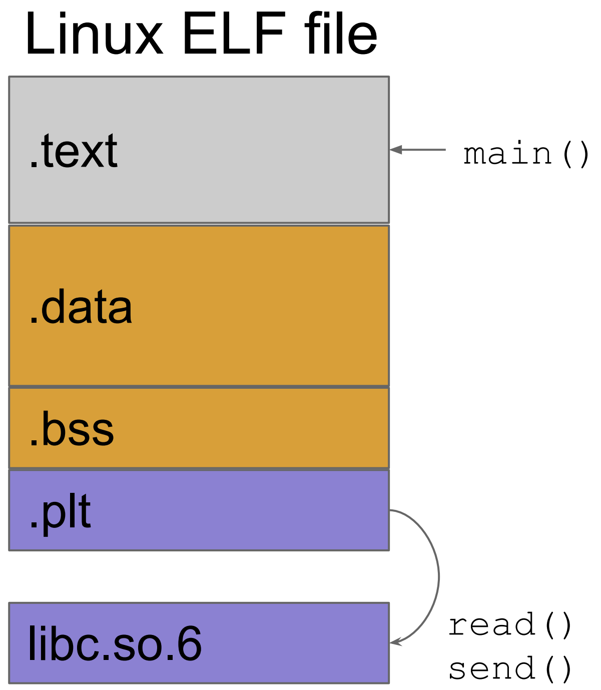
Device Internals



Baremetal Firmware



Raw hardware access



Kernel abstractions used for hardware interactions

Hardware is Hard!

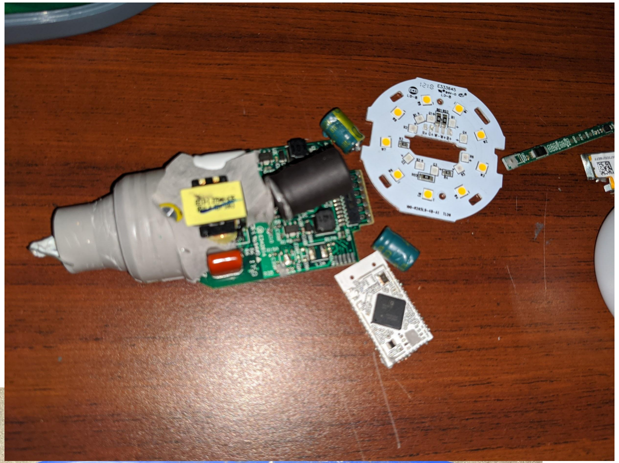
Debug access

- Should be disabled
- If present, very limited

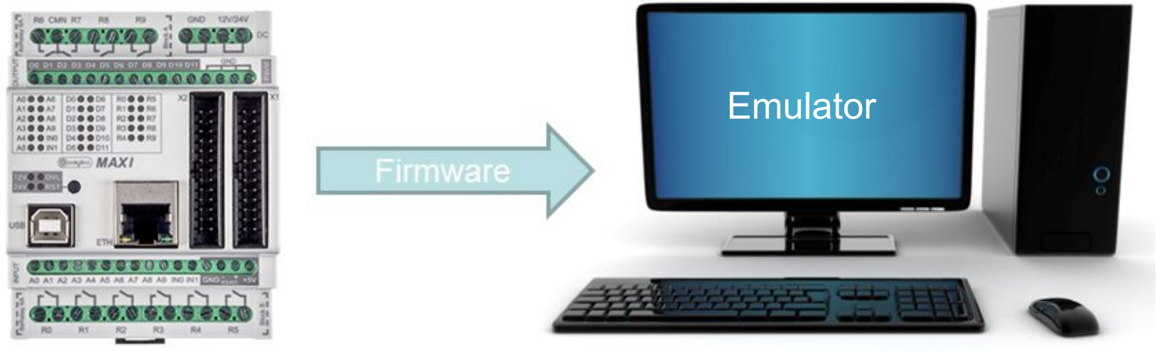
Limits parallelism

Other limitations

- Can be expensive ($100 - $10k)
- Brittle - easily bricked



Re-hosting to the Rescue?



HALucinator's Goal:
Enable scalable firmware testing without requiring specialized hardware

Peripherals Prevent Re-hosting

Peripherals

On chip	**Off chip**
CPU	Ethernet
AES Accelerator	SD-MMC
Hash	GPIO
Coprocessor	Camera
Timers	LCD
Counters	Touch Screen
Flash Controller	Wireless
Clock Config	EEPROM
IAP	Serial
DMA	CAN
	Analog IO
	USB

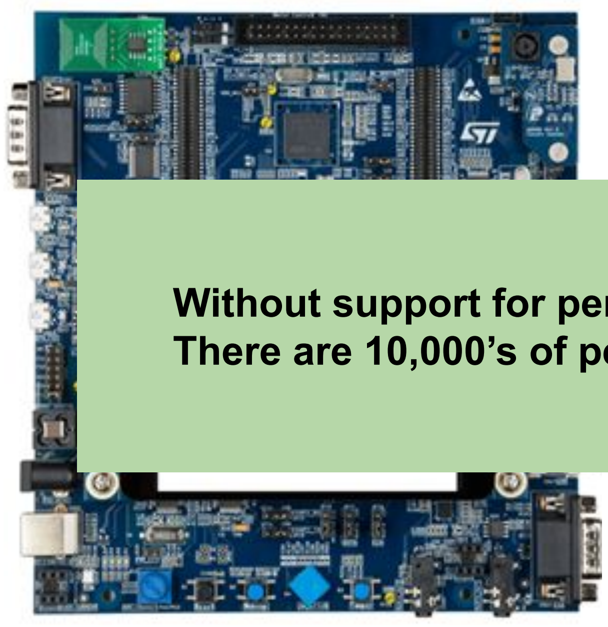
Peripherals Prevent Re-hosting

Peripherals

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

Mouser Lists
44,520 Microcontrollers
3,502 Datasheets
26 Manufacturers

Peripherals Prevent Re-hosting



Peripherals

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

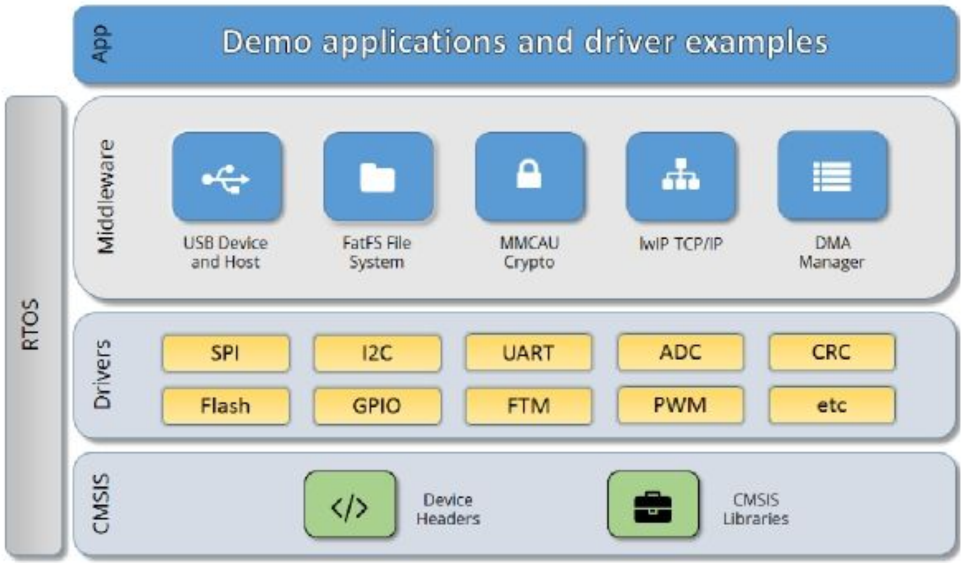


Image credit: NXP

HALs are Everywhere

SECLAB

ATMEL STUDIO 7

Atmel

Powered By Visual Studio

STM32 Cube

freeRTOS

RIOT

ARDUINO™

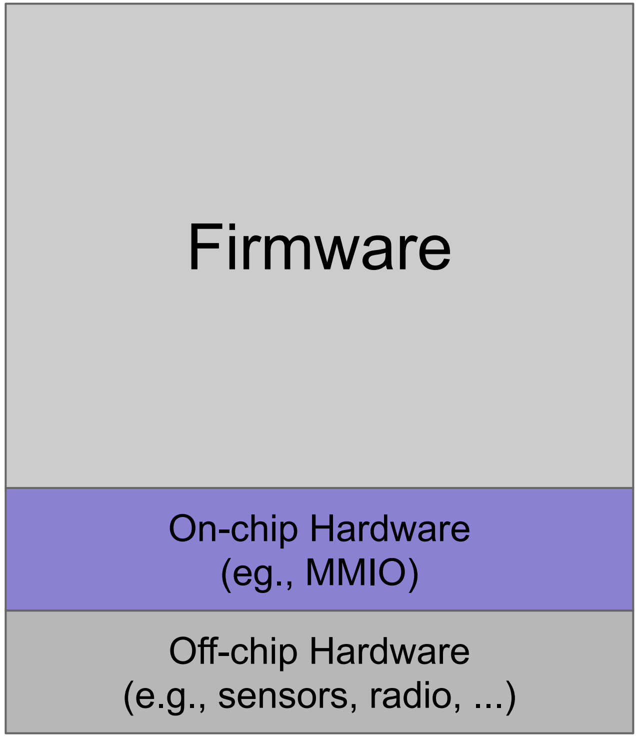
NXP

MCUXpresso

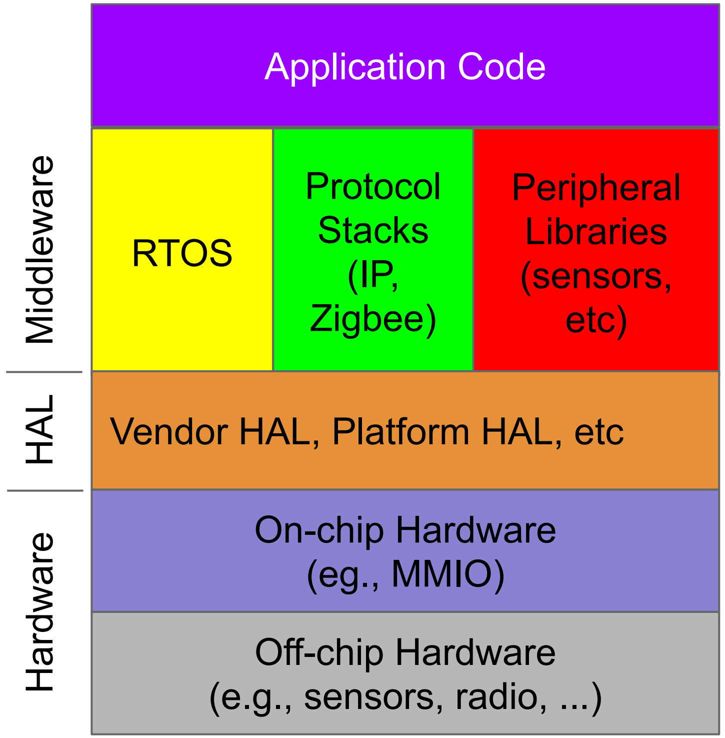
HALs are Everywhere

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

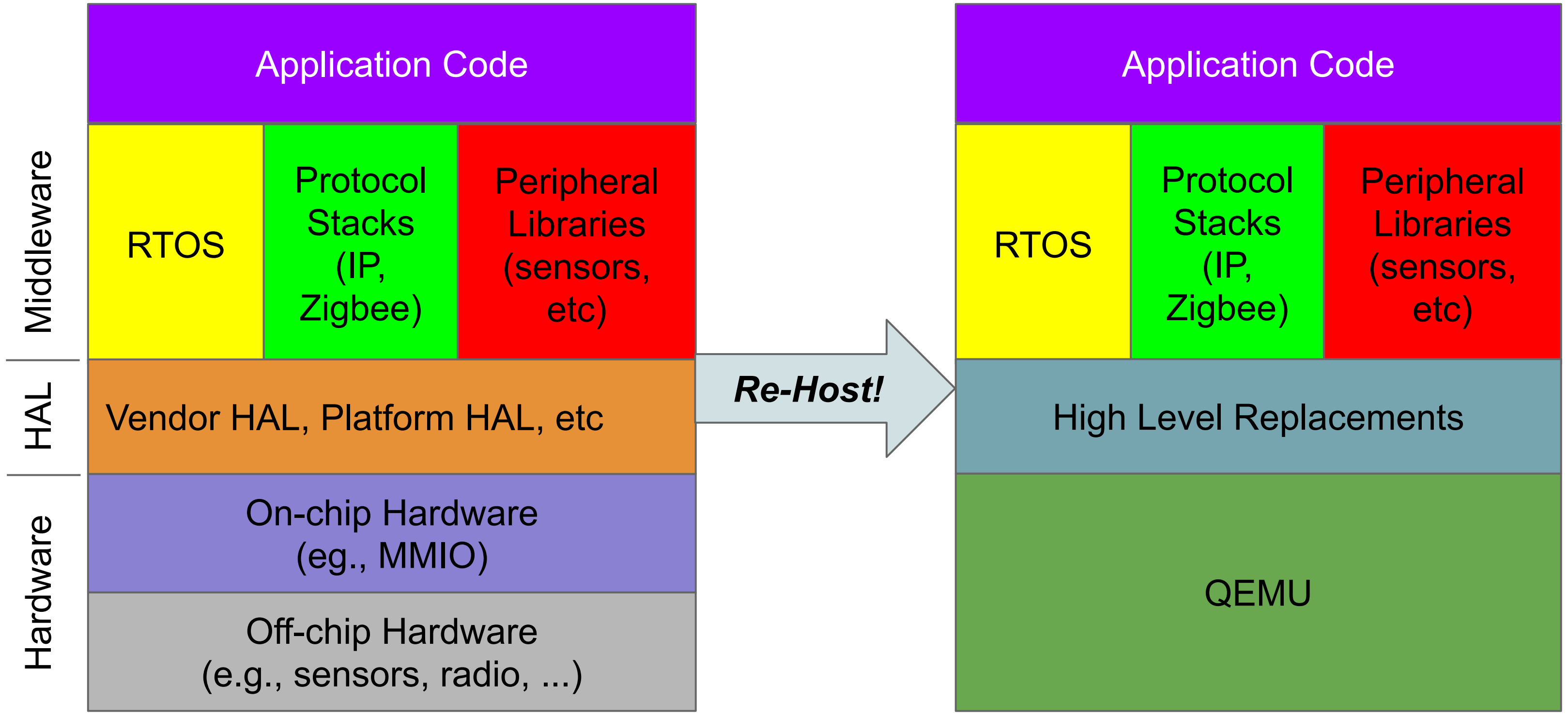
The Modern Firmware Stack


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, ...)
Middleware
HAL
Hardware

High Level Emulation


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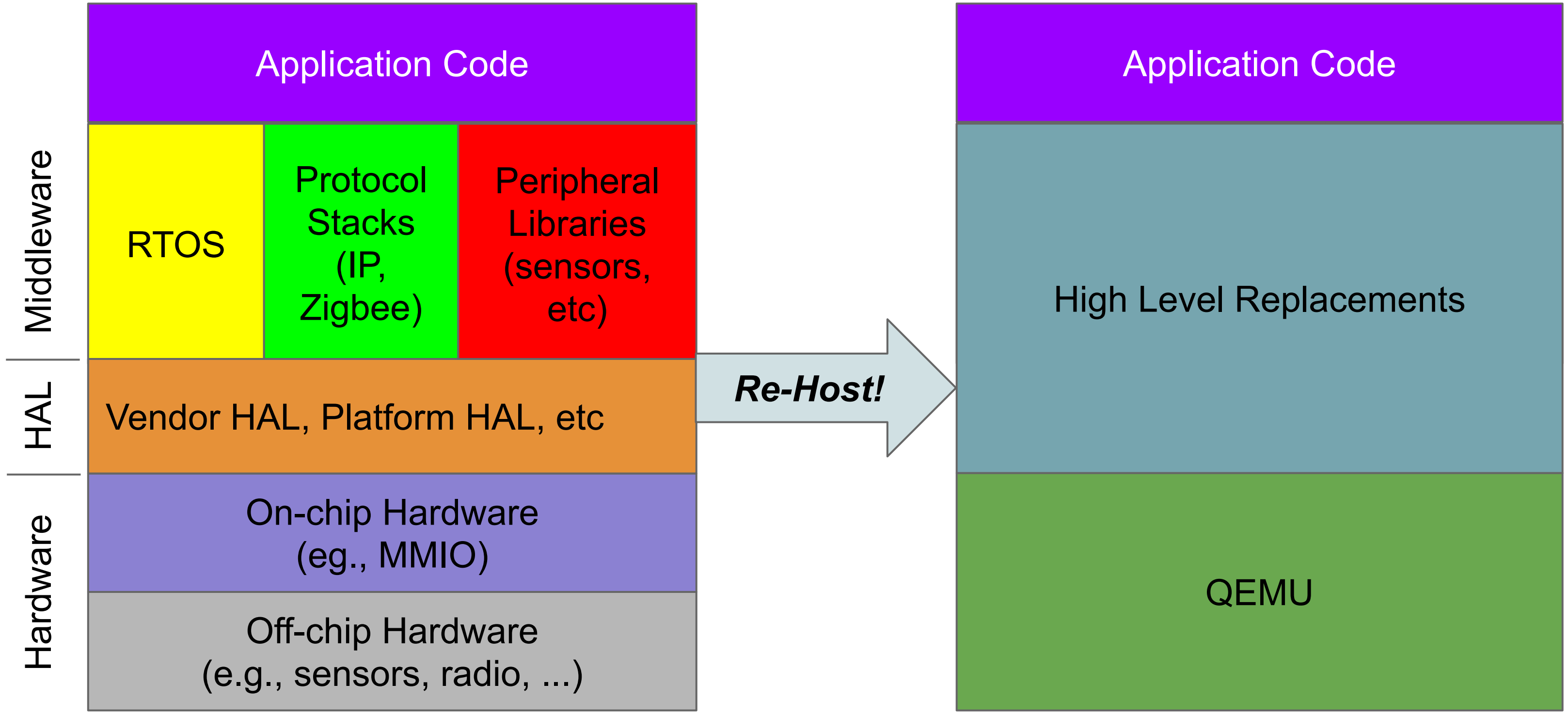
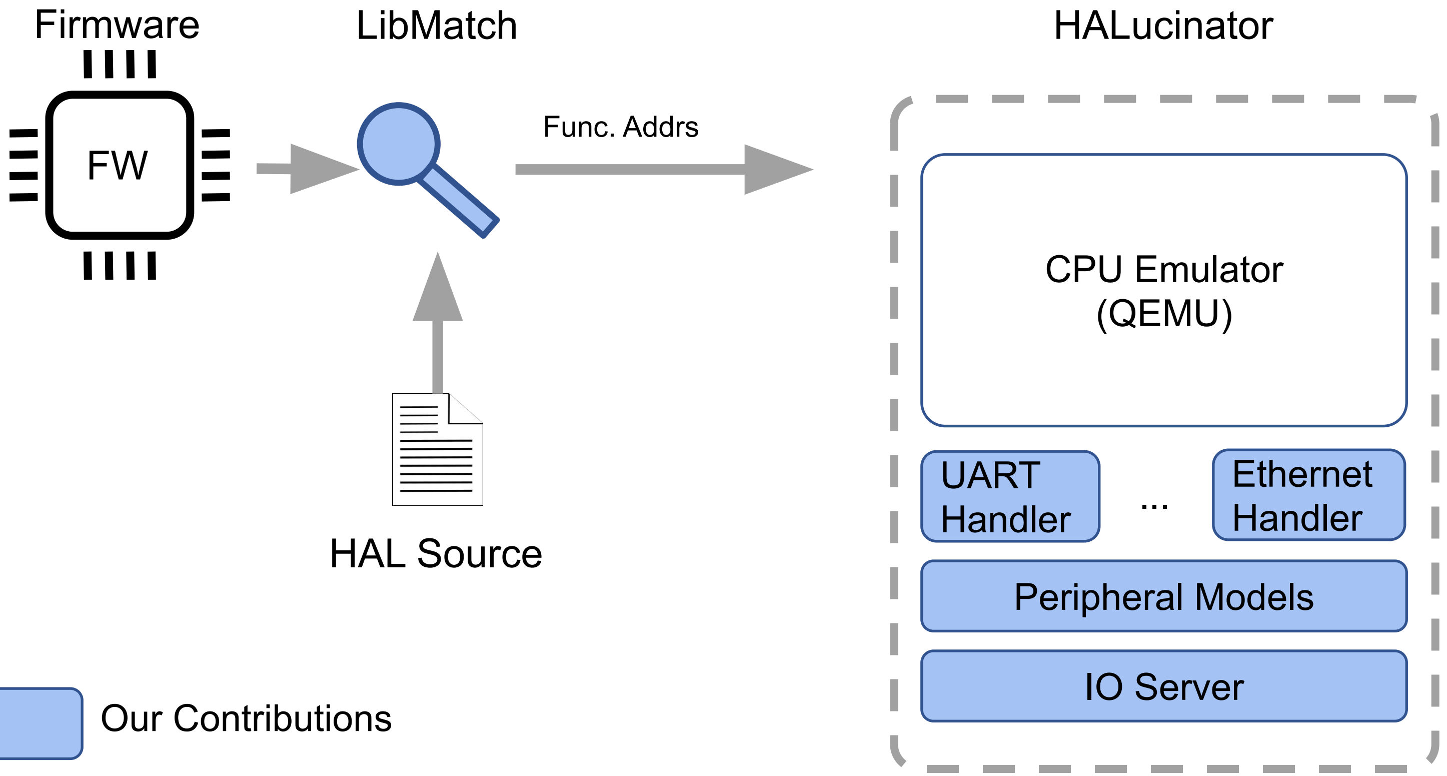
On-chip Hardware (eg., MMIO)
Off-chip Hardware (e.g., sensors, radio, ...)
Re-Host!
Application Code
RTOS
Protocol Stacks (IP, Zigbee)
Peripheral Libraries (sensors, etc)
High Level Replacements
QEMU

High Level Emulation

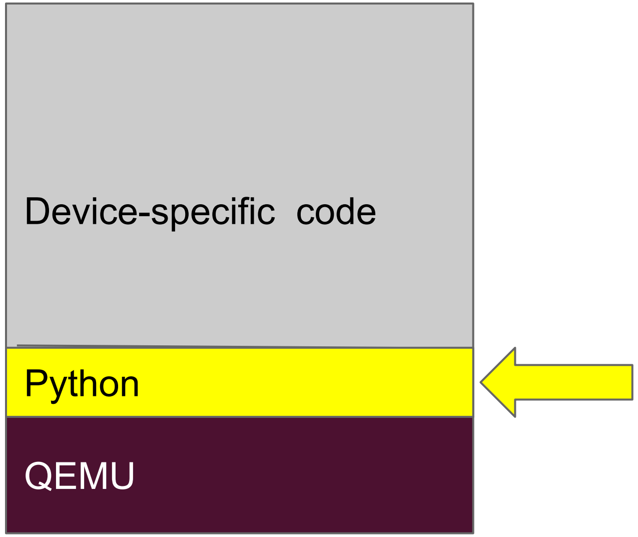

Application Code
Middleware
RTOS
Protocol Stacks (IP, Zigbee)
Peripheral Libraries (sensors, etc)
HAL
Vendor HAL, Platform HAL, etc
Hardware
On-chip Hardware (eg., MMIO)
Off-chip Hardware (e.g., sensors, radio, ...)
Re-Host!
Application Code
High Level Replacements
QEMU

HALucinator implementation



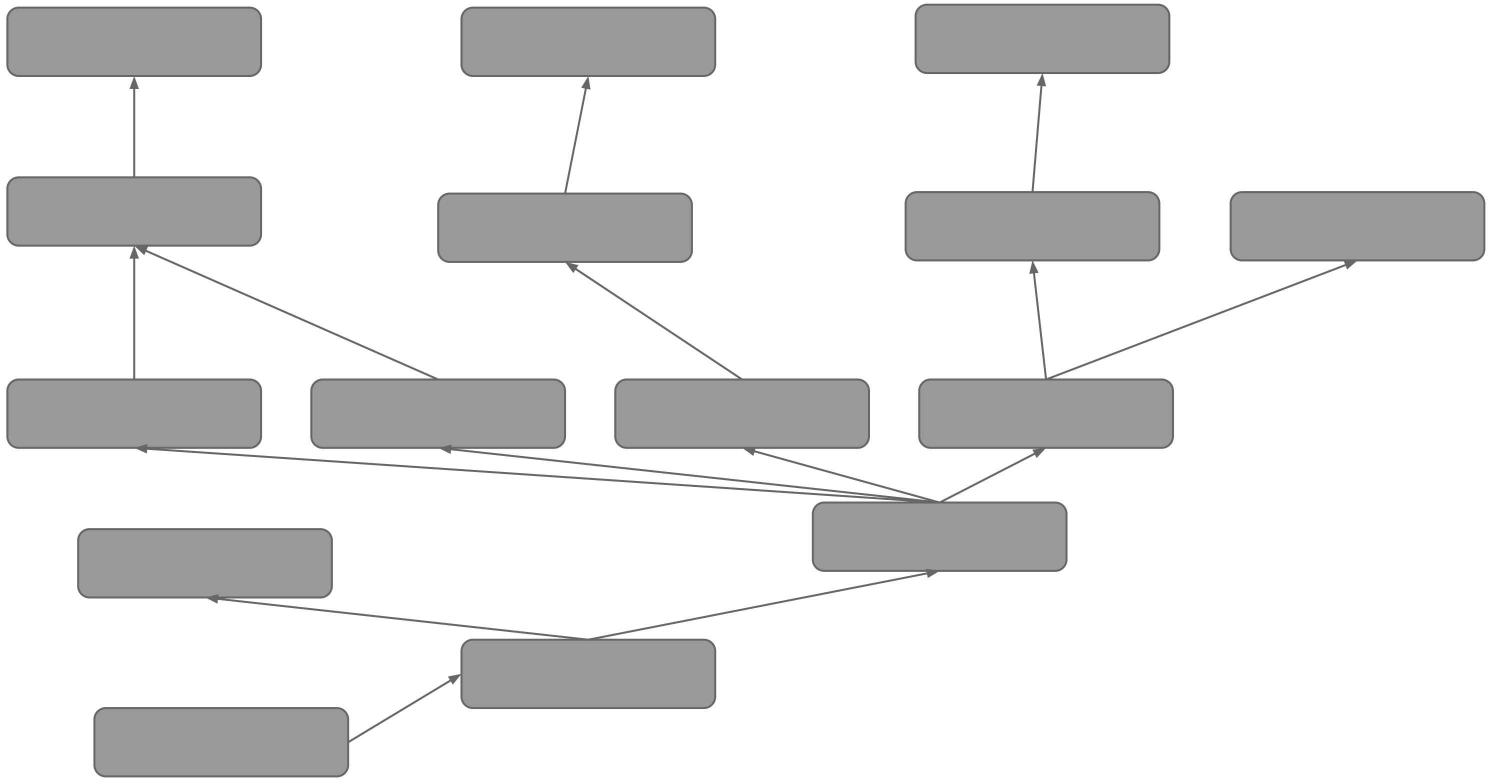
🟦 Our Contributions

Handler Example

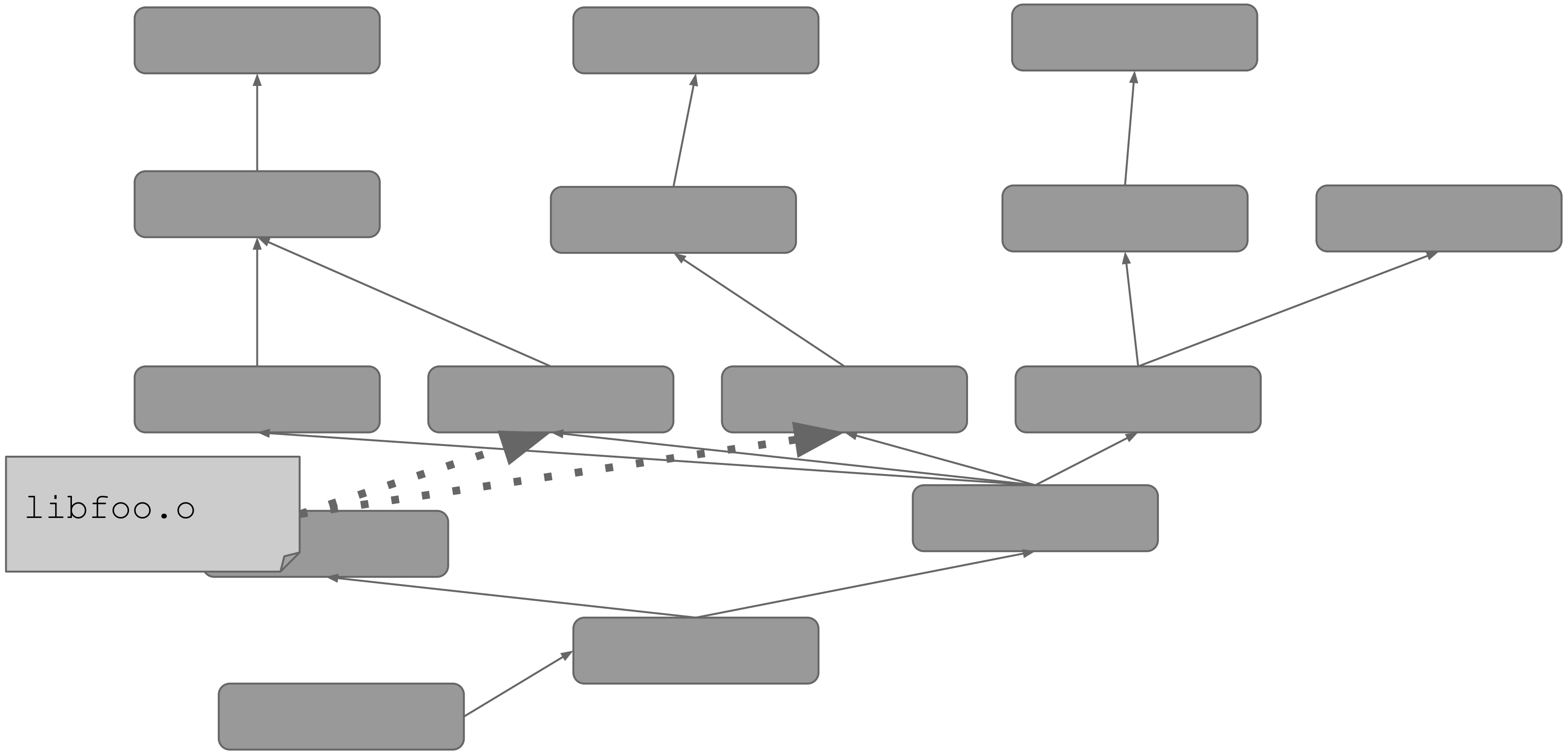


```
def i2c_read_buf(uc):
    # i2c_read_buf(char* buf, int len);
    buf = uc.regs.r1 # arg 0: The buffer
    l = uc.regs.r2   # arg 1: Buffer length
    assert(buf != 0)   # Crash on bad arguments
    assert(len > 0)
    data = I2CModel.rx('i2c', 0, len) # Get the data
                            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

LibMatch

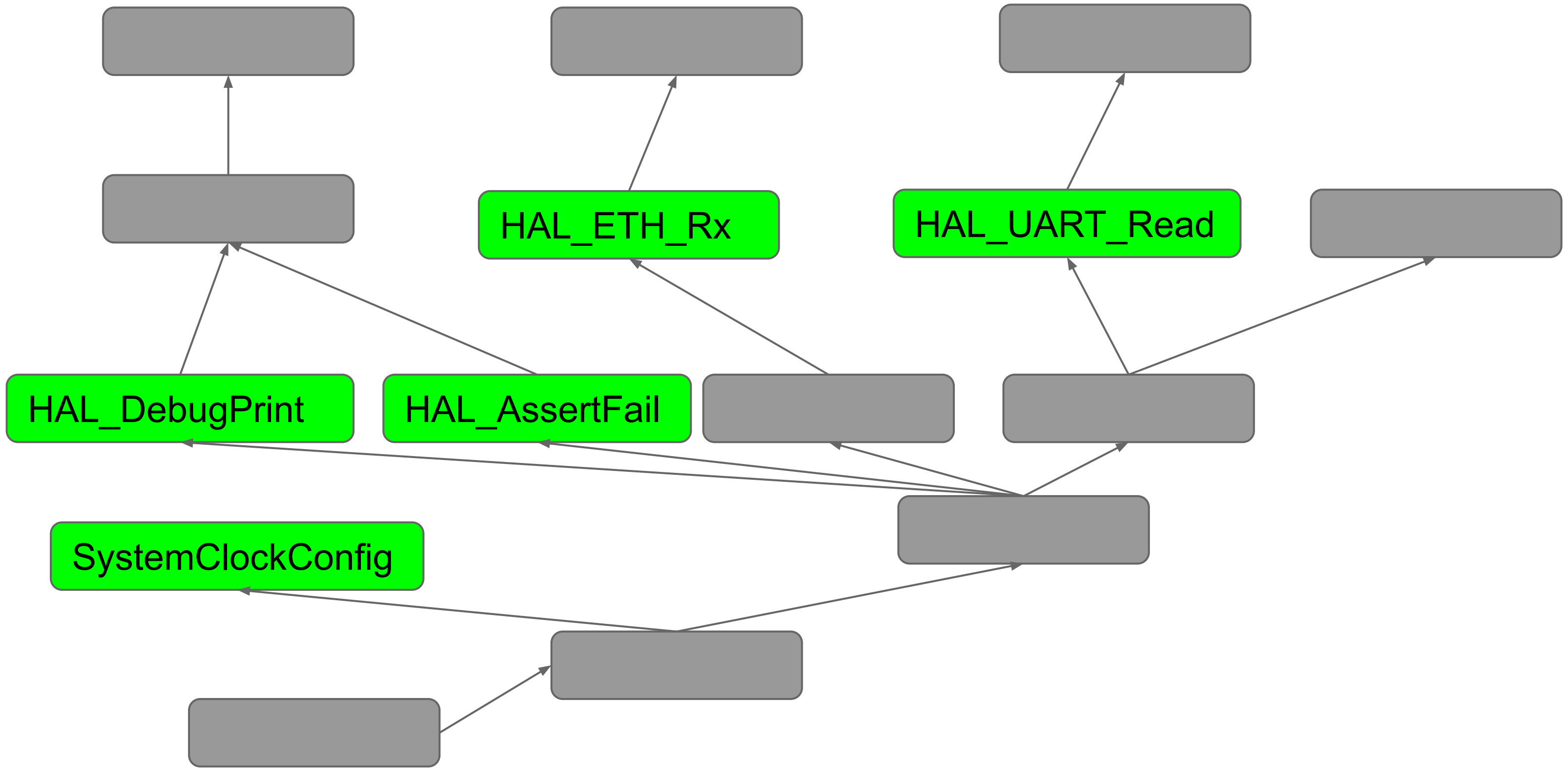


LibMatch

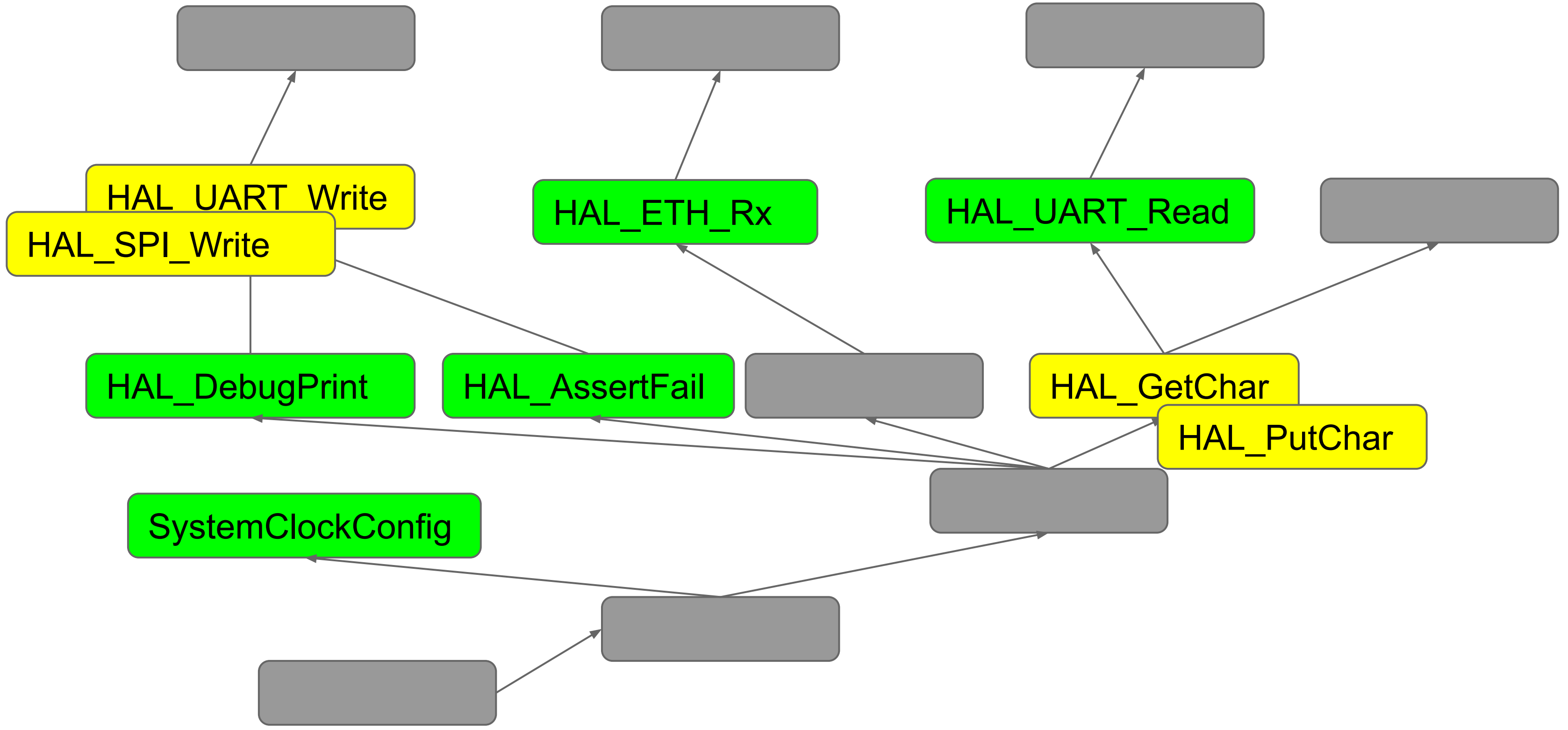


Step 1: Match library content

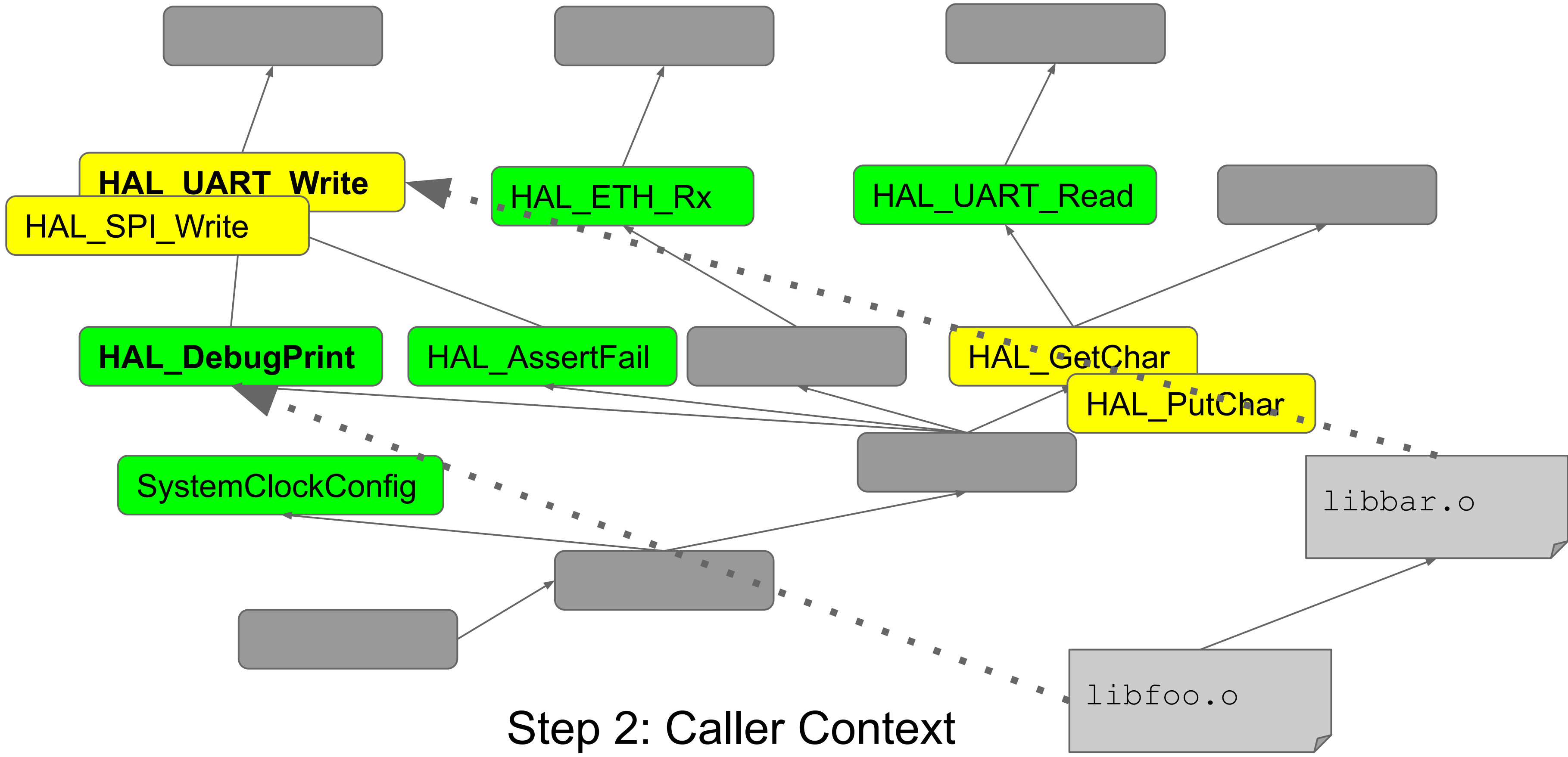
LibMatch


HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
SystemClockConfig

LibMatch

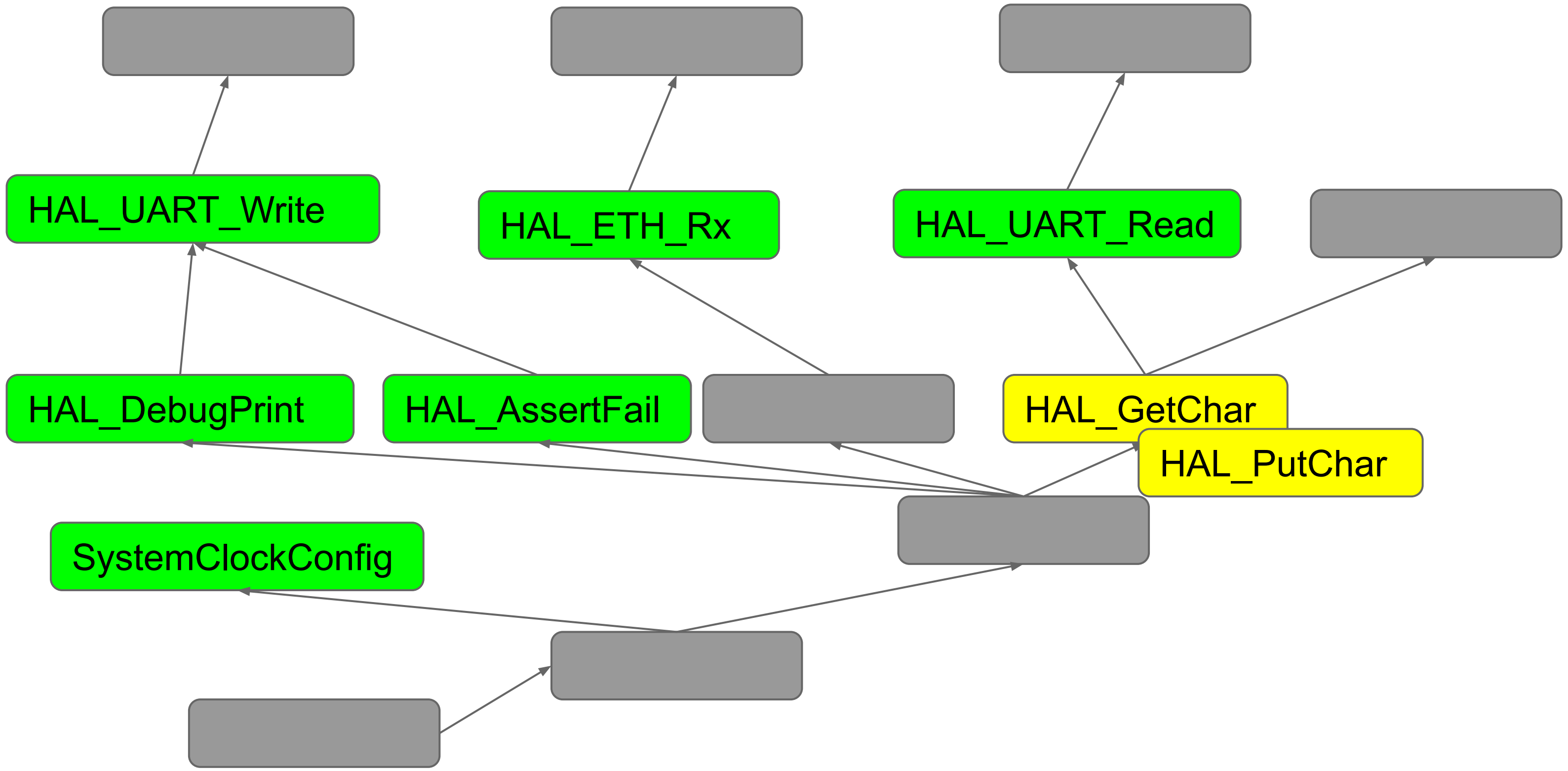

HAL_UART_Write
HAL_SPI_Write
HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
HAL_GetChar
HAL_PutChar
SystemClockConfig

LibMatch

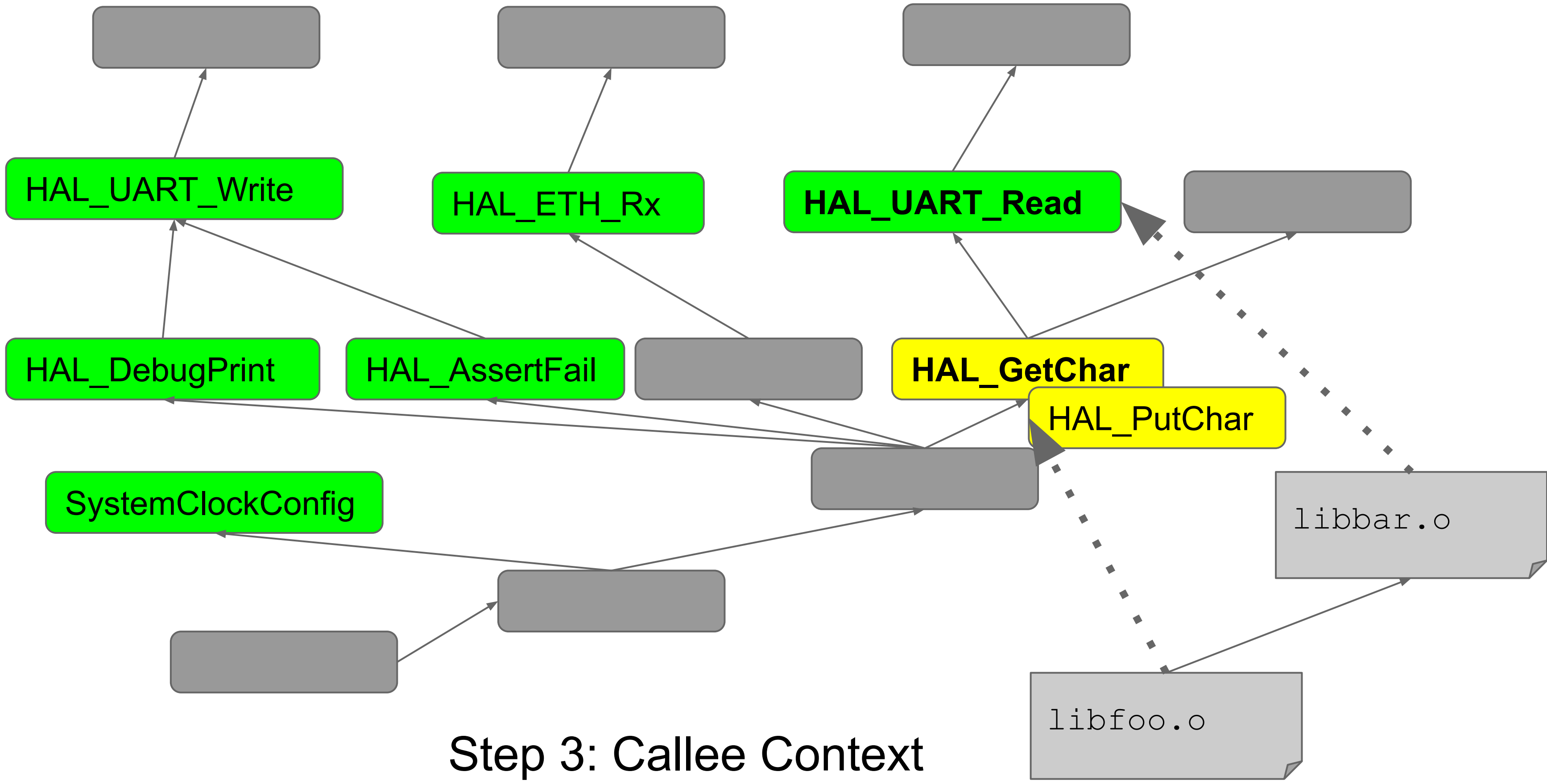


Step 2: Caller Context

LibMatch

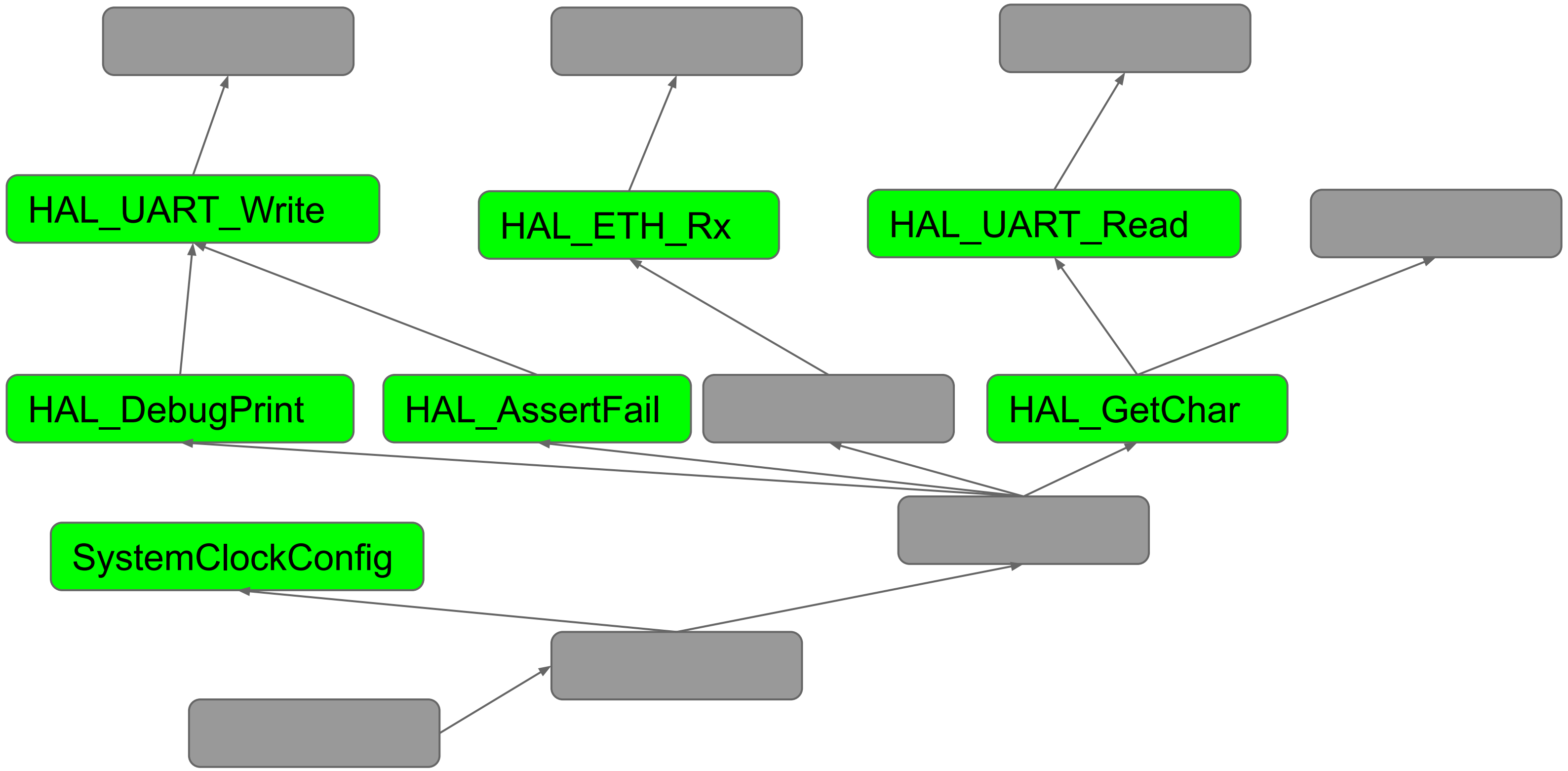

HAL_UART_Write
HAL_ETH_Rx
HAL_UART_Read
HAL_DebugPrint
HAL_AssertFail
HAL_GetChar
HAL_PutChar
SystemClockConfig

LibMatch

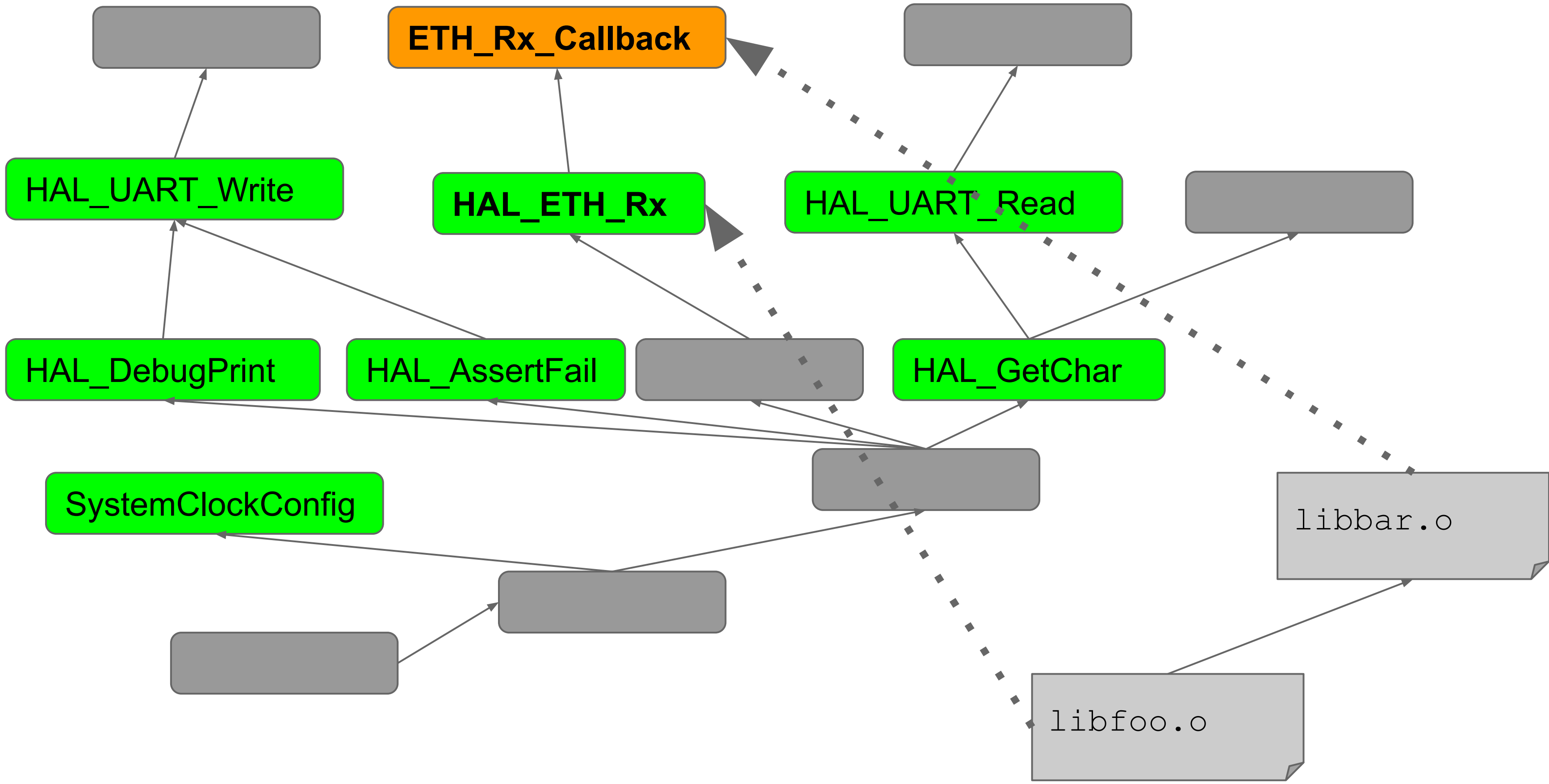


Step 3: Callee Context

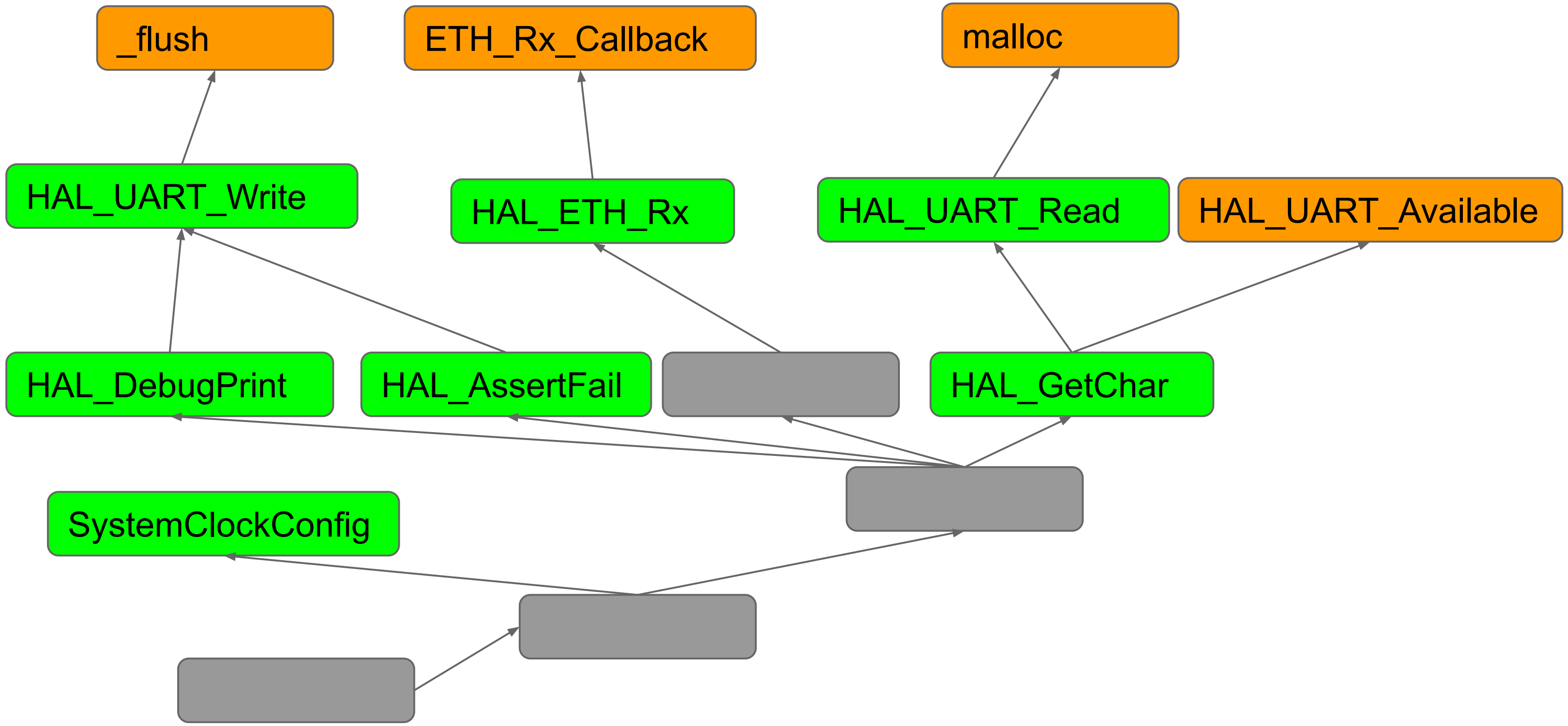
LibMatch


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

	"Naïve" 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%

% matches across 16 test binaries

Ease of Use

Three Handler categories:

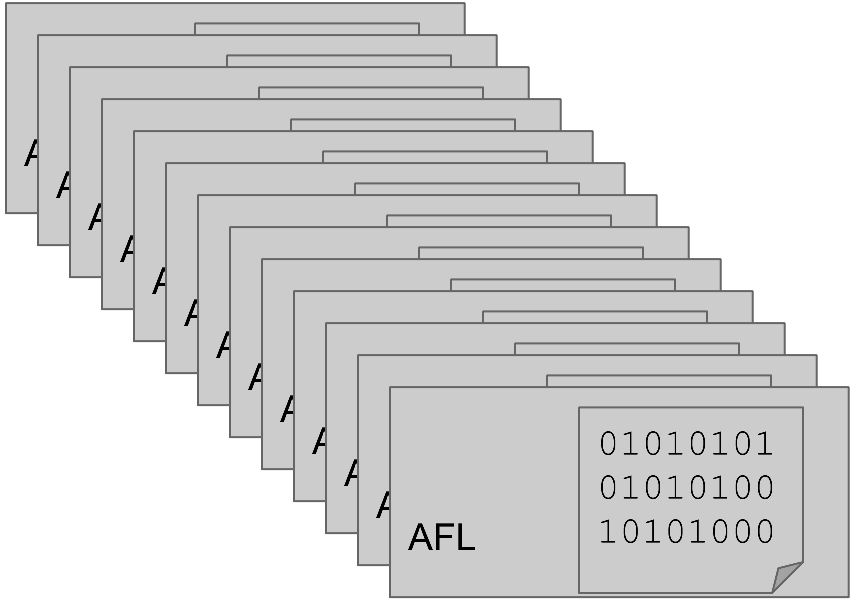
- **Trivial**: Does nothing / returns a constant
- **Translating**: Collects arguments, interacts with a Model, returns a result
- **Internal Logic**: Needs to re-implement undocumented internal details

Ease of Use

- Over 85% of handlers require little effort
  - 44.5% (37) are “trivial”
  - 42.2% (35) are “translating”

- Remainder (11): “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!

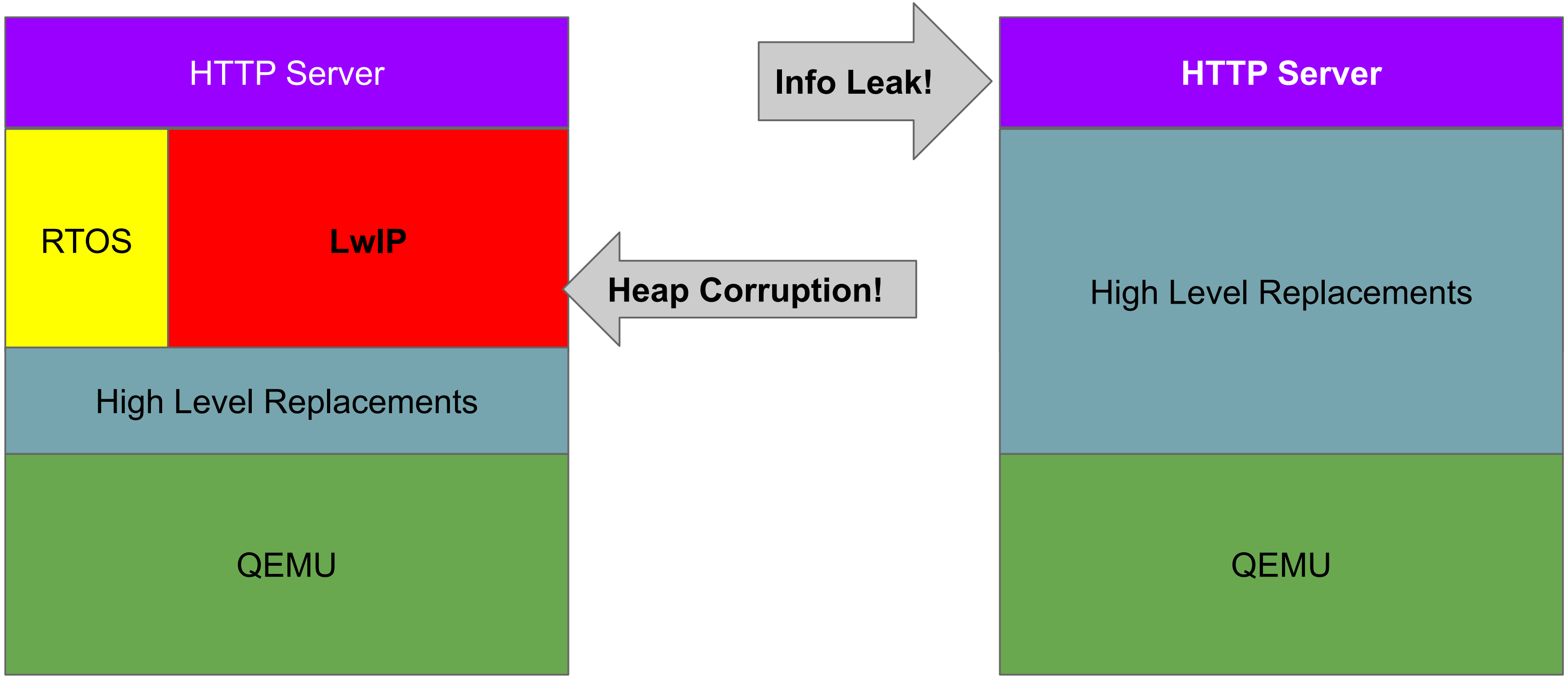


Hundreds of millions of executions with real parallel AFL

New crashes in:

- STM’s ST-PLC Kit
- Atmel’s HTTP Server example
- Atmel’s Contiki 6LowPAN examples

Multi-layer Fuzzing!



Atmel HTTP Server firmware sample

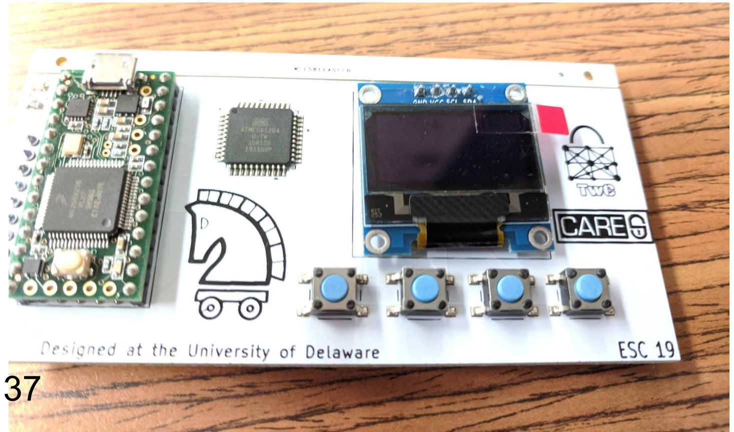
Discovered CVEs

- **CVE-2019-8359**: Remote code execution via buffer overflow in packet reassembly of Contiki OS
- **CVE-2019-9183**: Remote Denial-of-Service via Integer underflow in packet reassembly of Contiki OS

CSAW ESC 2019 results

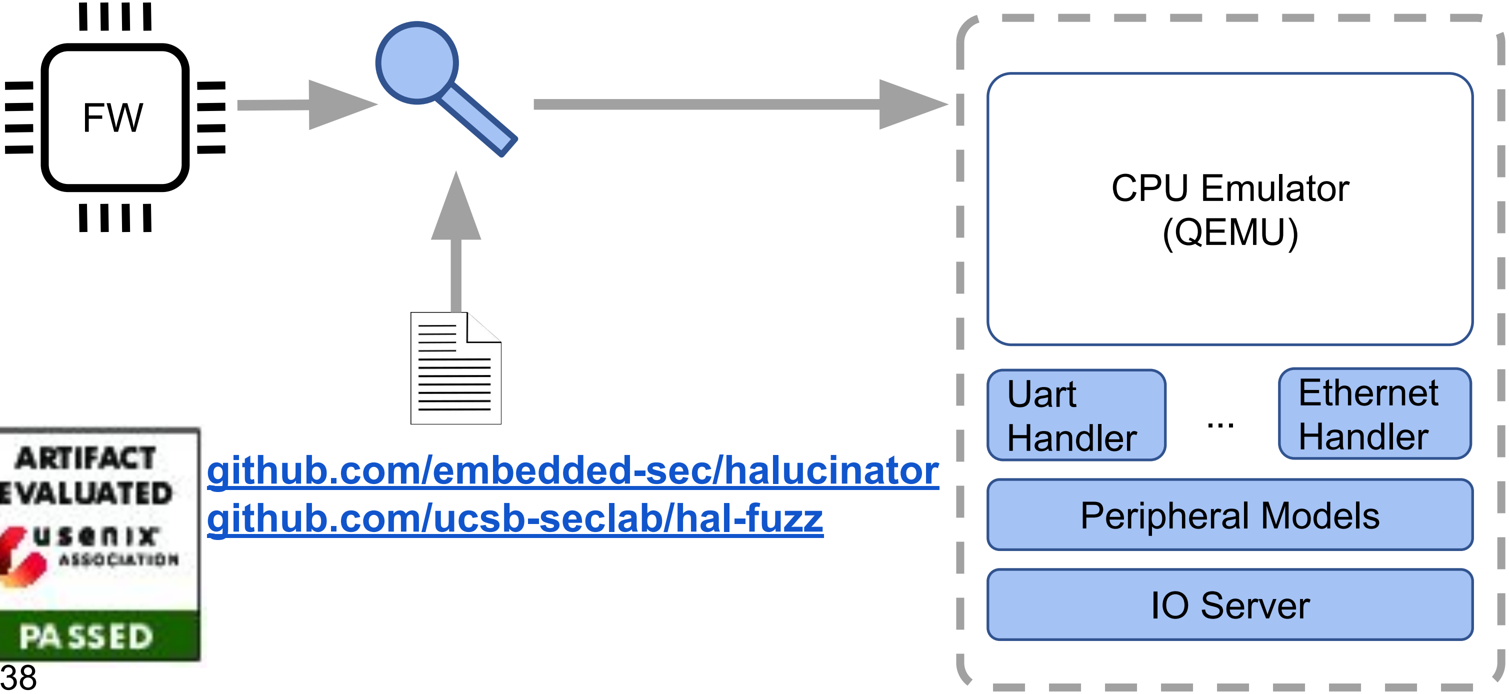
SECLAB

- 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
github.com/ucsb-seclab/hal-fuzz