Multiprogramming a 64 kB Computer Safely and Efficiently

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Microcontrollers Becoming Platforms

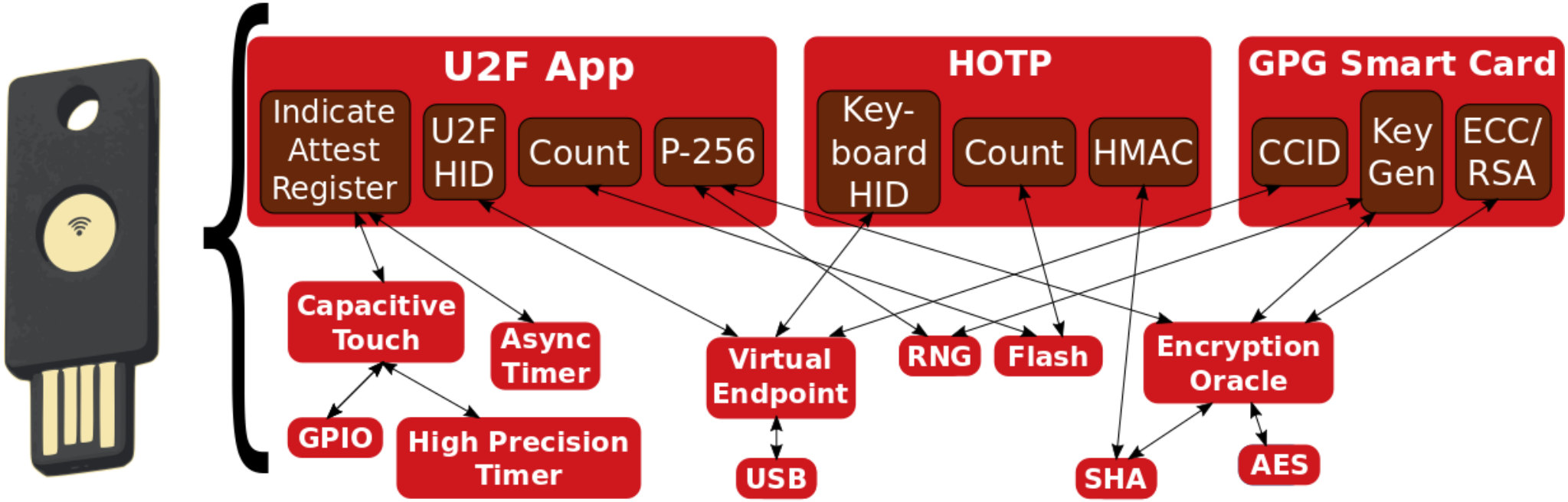
- Low energy: µA sleep current
- Low memory: ~64 kB RAM

- USB authentication keys have multiple functions
  - U2F, SSH, GPG, HOTP
- Sensor networks run several experiments at once
- Fitness watches support different activities
- This should scare you!


Windows
A fatal exception 0E has occurred at 0028:C0031E36 in VXD VMM(01) +
00005E36. The current application will be terminated.
• Press any key to terminate the current application.
• Press CTRL+ALT+DEL again to restart your computer. You will
lose any unsaved information in all applications.
Press any key to continue _

Example: USB Authentication Key

- Multiple independent applications
- No programmability in favor of security



Microcontrollers need fault isolation for applications and OS services.

Fault Isolation on Microcontrollers

But new isolation tools available

- **MPU: Protection bits for 8 memory regions**
- **Rust: a non-GC'd type safe systems language**

What are the operating systems abstractions?

Design Goals

- **Isolate drivers at no resource cost**
  - Rust type-system to prevent safety violations
- **Isolate applications**
  - Process isolation using MPU
  - Must immediately reclaim upon termination
- **Support concurrent applications & I/O**
  - Need memory abstractions in lieu of heap

Tock: A Microcontroller OS

- Kernel components in Rust
- Type-safe API for *safe* drivers development
- Processes abstraction with Memory Protection Unit
- *Grants*: concurrency without a global heap
  - Manages process-specific kernel heap
  - Ensures resources can be freed immediately

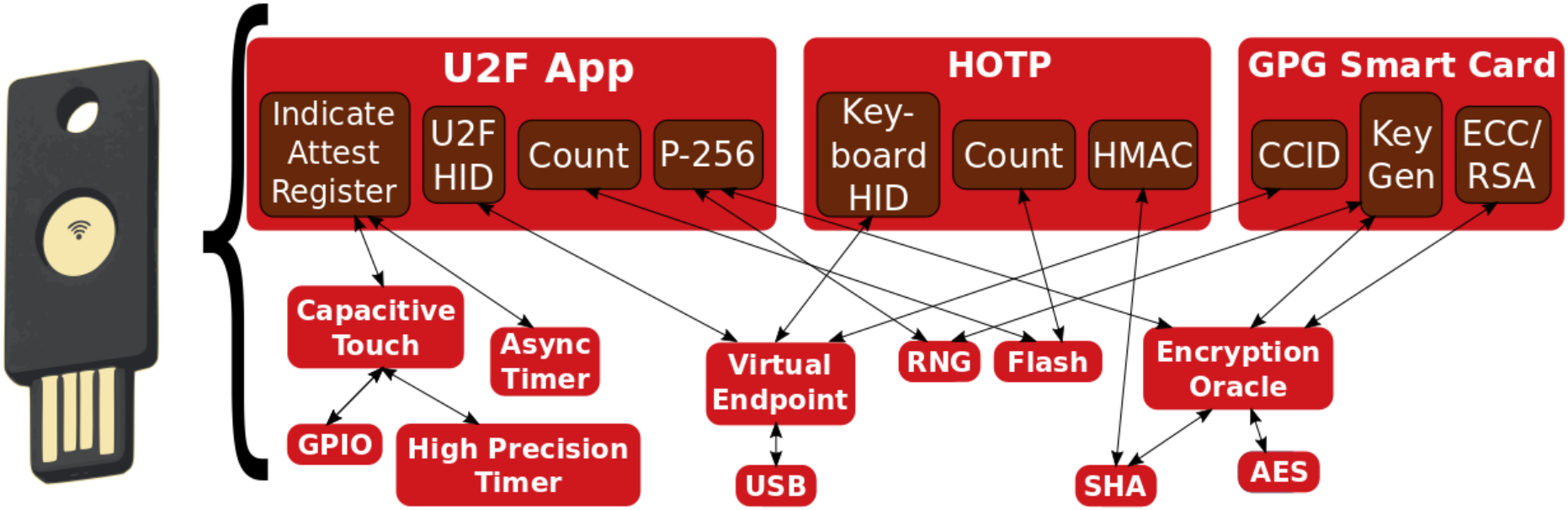
Outline

1. Why Rust?
2. Security Model
3. Two Isolation Mechanisms
4. Grants
5. Case Study: Signpost
6. Limitations & Future Work

Why Rust?

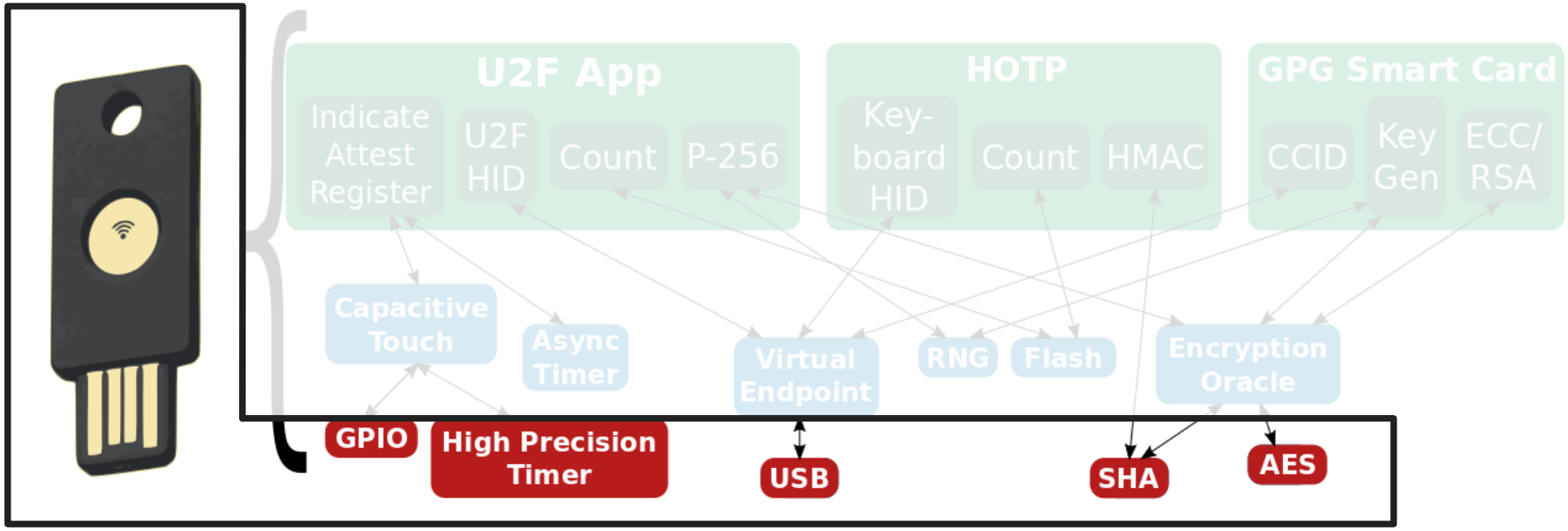
- **Type and memory safe**
  - No buffer overflows, dangling pointers, type confusion…
- **Compile-time enforced type system**
  - No type artifacts at run time
- **No garbage collection**
  - Control over memory layout and execution
- **Runtime behavior similar to C**

Security in a Multiprogrammable MCU



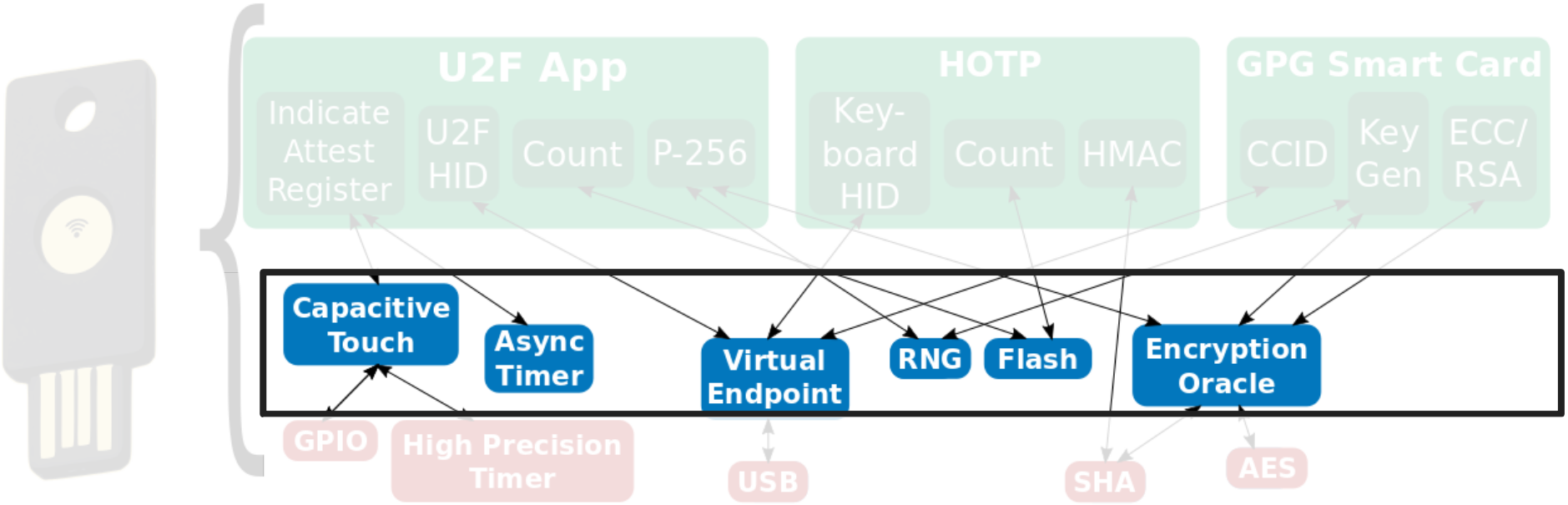
Platform Provider

- Build the hardware
- Responsible for TCB: core kernel, MCU-specific code
- Trusted: complete control over firmware & hardware



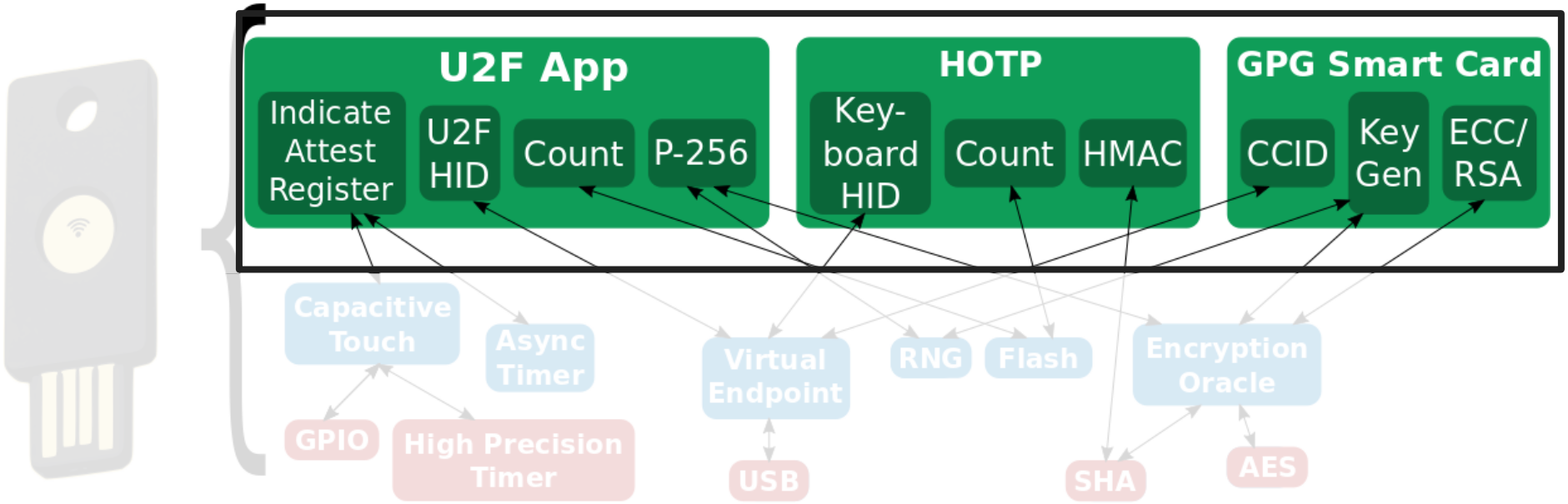
Kernel Component Developers

- Build most kernel functionality
  - Device drivers, networking protocols, timers...
- Platform provider select: audit but won't catch all bugs



Application Developers

- Implement end-user functionality
- “Third-party” developers: unknown to board integrators
- Modeled as *malicious*



Tock's Isolation Mechanisms

Trusted for liveness, not safety

Capsules

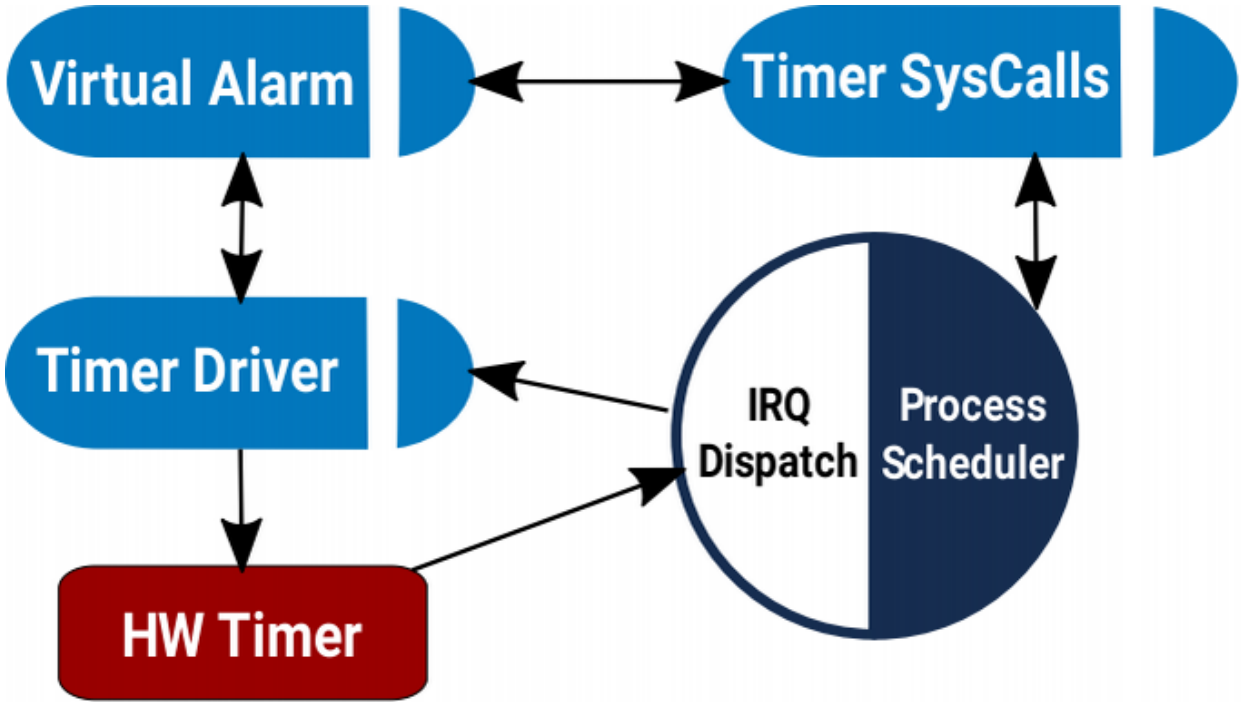
- Rust code linked into kernel
- Isolation enforced at compile-time
- Low overhead
- Used for device drivers, protocols, timers...

Totally untrusted

Processes

- Standalone executable in any language
- Isolation enforced at runtime
- Higher overhead
- Applications

Capsules



- A Rust module and structs
- Event-driven execution with asynchronous I/O
- Shared stack, no heap
- Communicate via references & method calls
  - Often inlined

Kernel Memory Consumption

Example 1: “blink”

	ROM size (B)	RAM size (B)
Tock	3208	916
TinyOS	5296	72
(AWS) FreeRTOS	4848	2984

Example 2: Networked sensor

	ROM size (B)	RAM size (B)
Tock	41744	9704
TinyOS	39604	10460

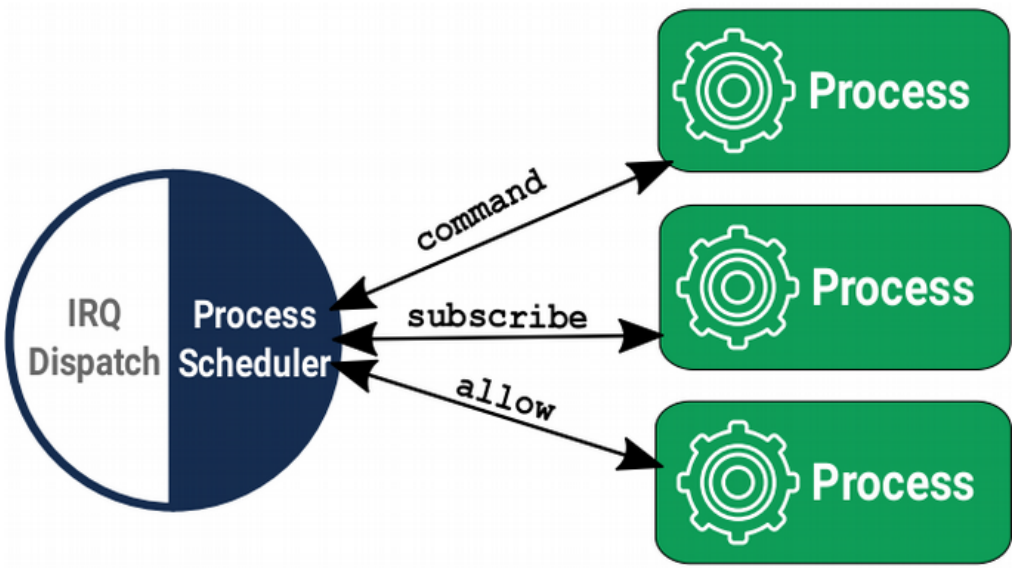
Capsule Isolation

```
struct DMAChannel {
    length: u32,
    base_ptr: *const u8,
}

impl DMAChannel {
  fn set_dma_buffer(&self, buf: &'static [u8]) {
    self.length = buf.len();
    self.base_ptr = buf.as_ref();
  }
}
```

- Exposes the DMA base pointer and length as a Rust *slice*
- Type-safety guarantees user has access to memory

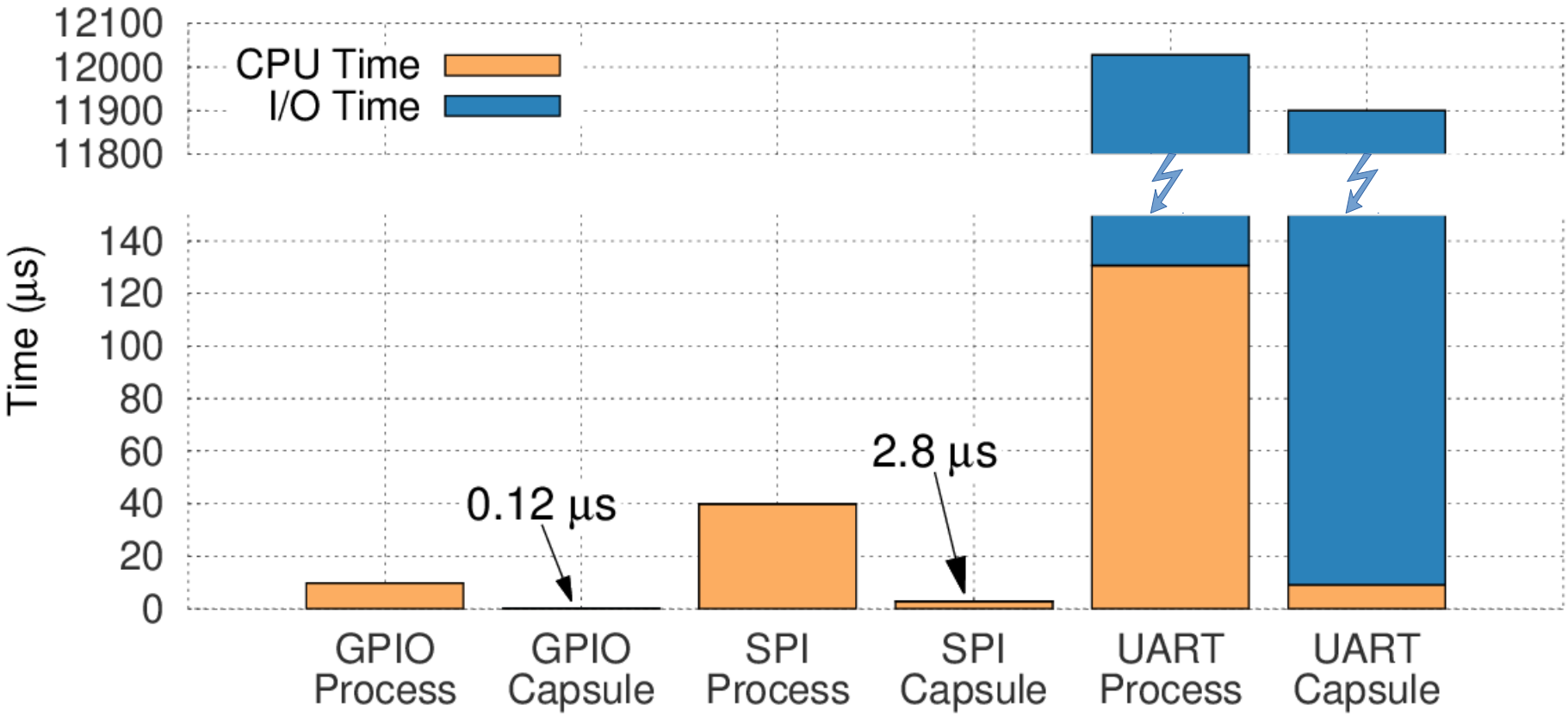
Processes



- Hardware-isolated concurrent executions of programs
  - MPU to protect memory regions without virtualization
  - Independent stack, heap, static variables
- Updated dynamically with position independent code
- Scheduled preemptively
- System calls & IPC for communication

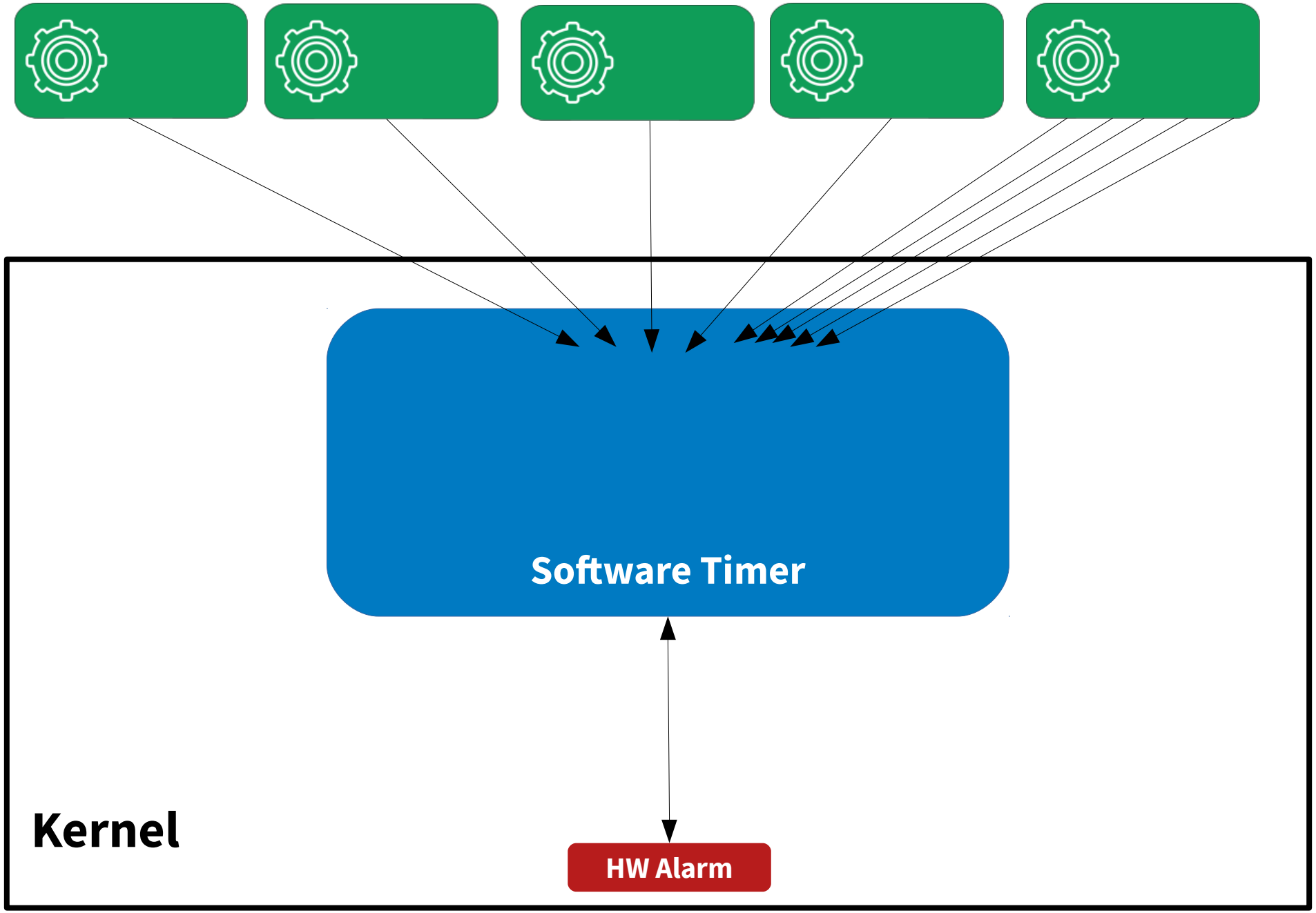
Process Overhead

- Dedicated memory region (at least a stack)
- Context switch for communication (340 cycles)

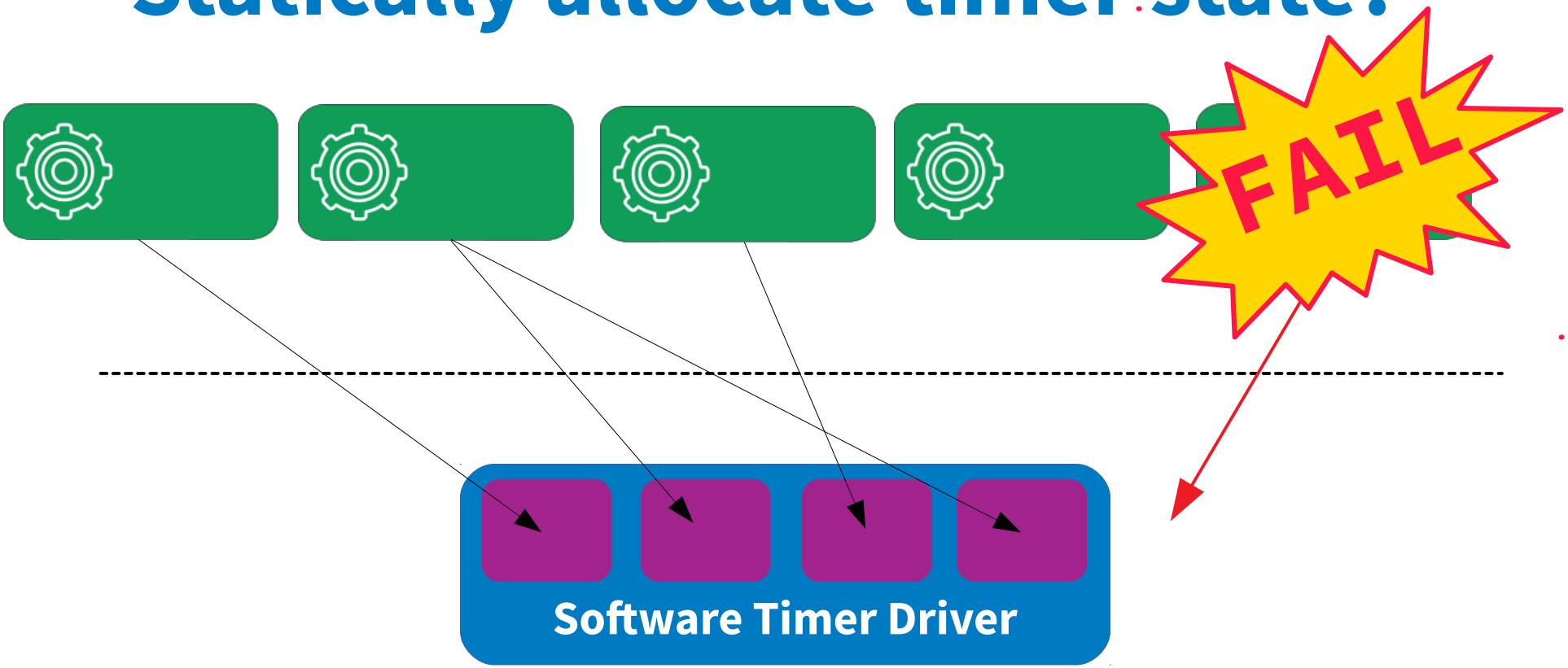


How do capsules and processes interact?

Working Example: Software Timer

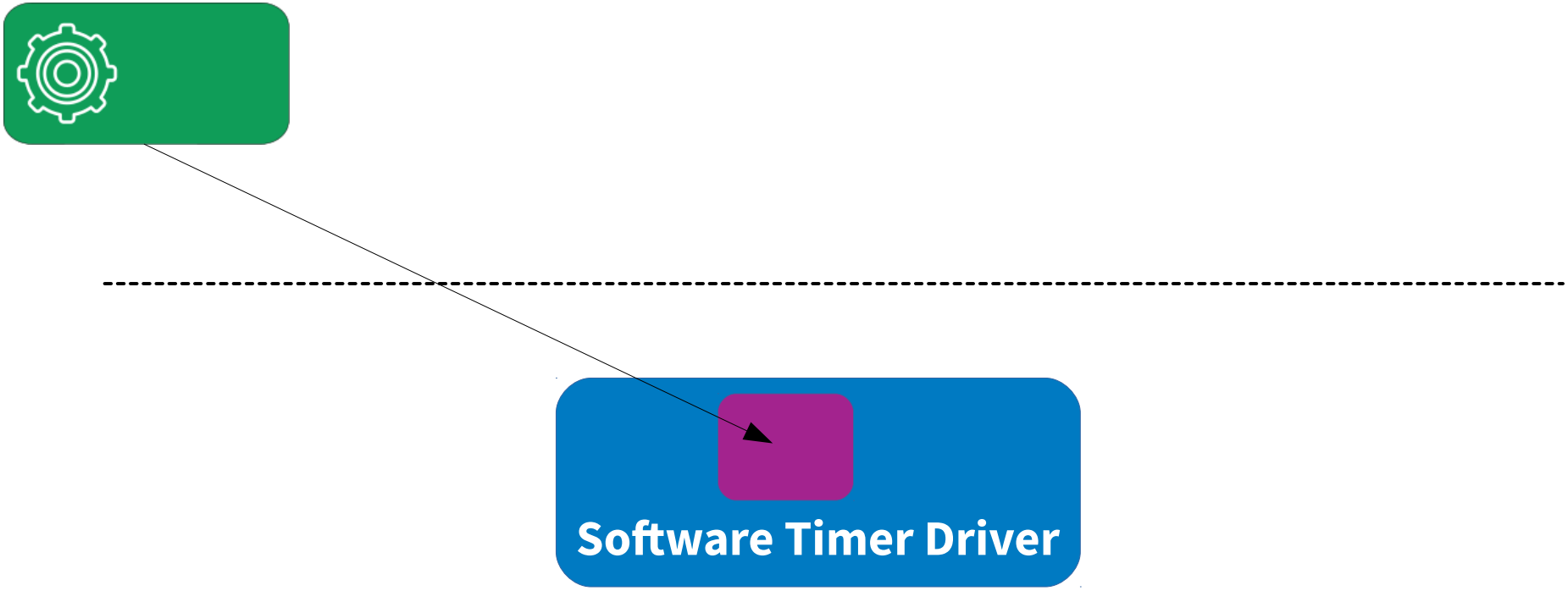


Statically allocate timer state?



Static allocation must trade off memory efficiency and maximum concurrency

What About Dynamic Allocation?



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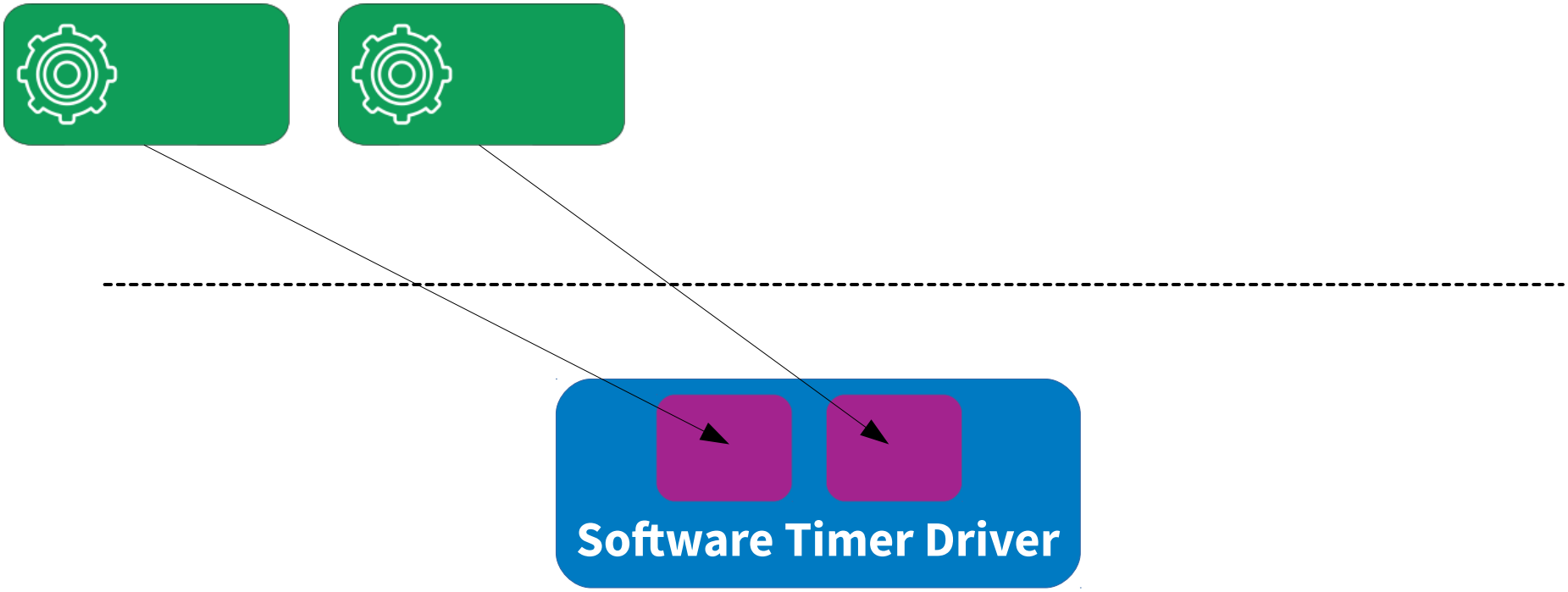

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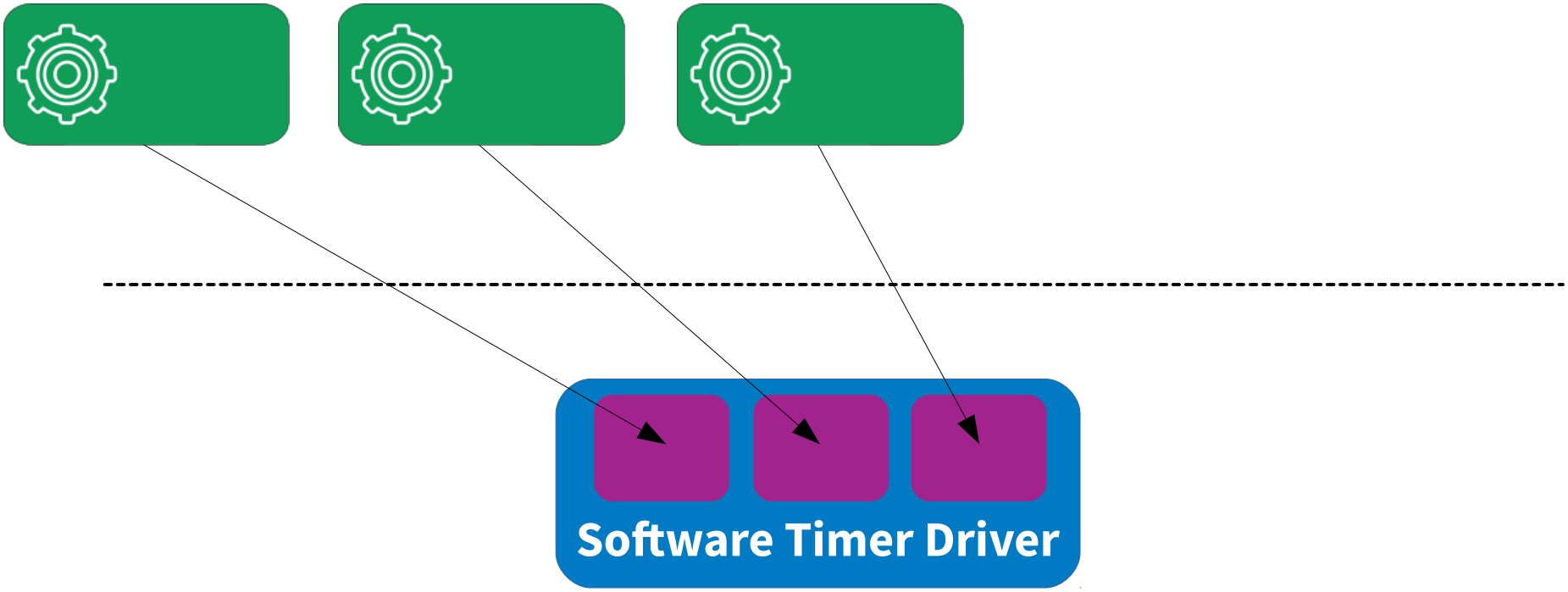

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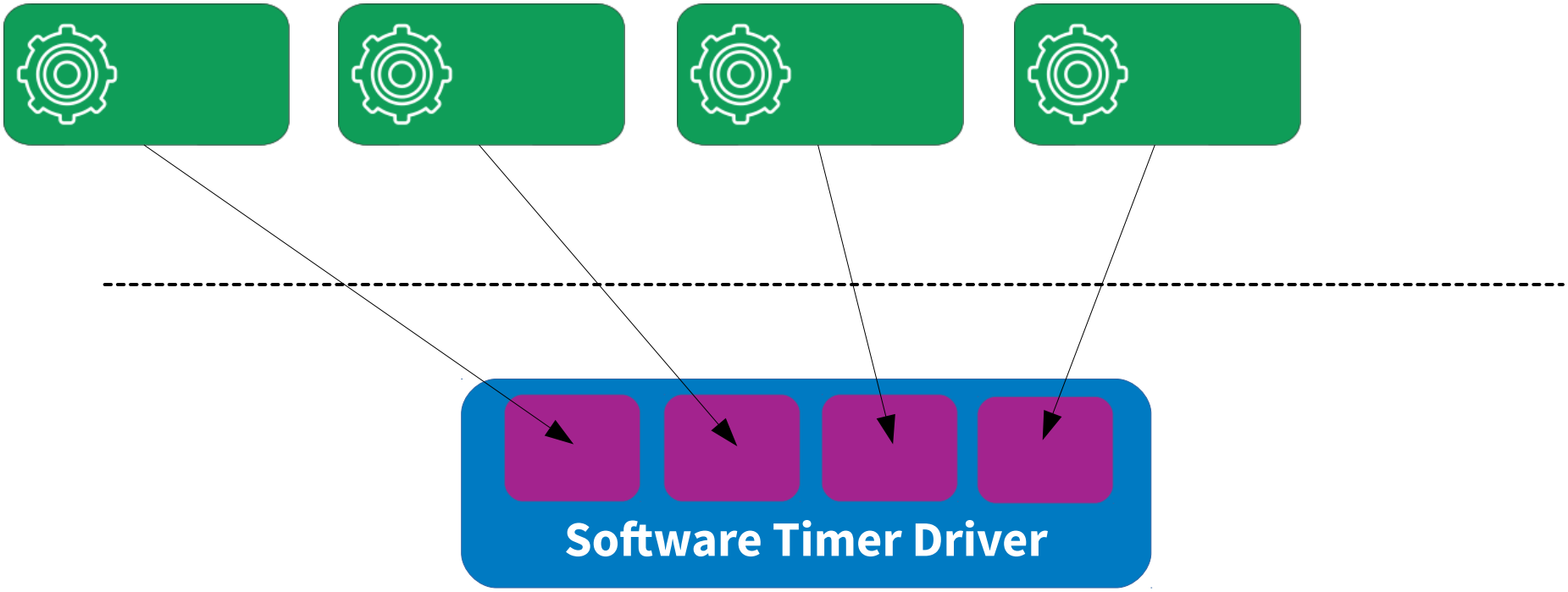

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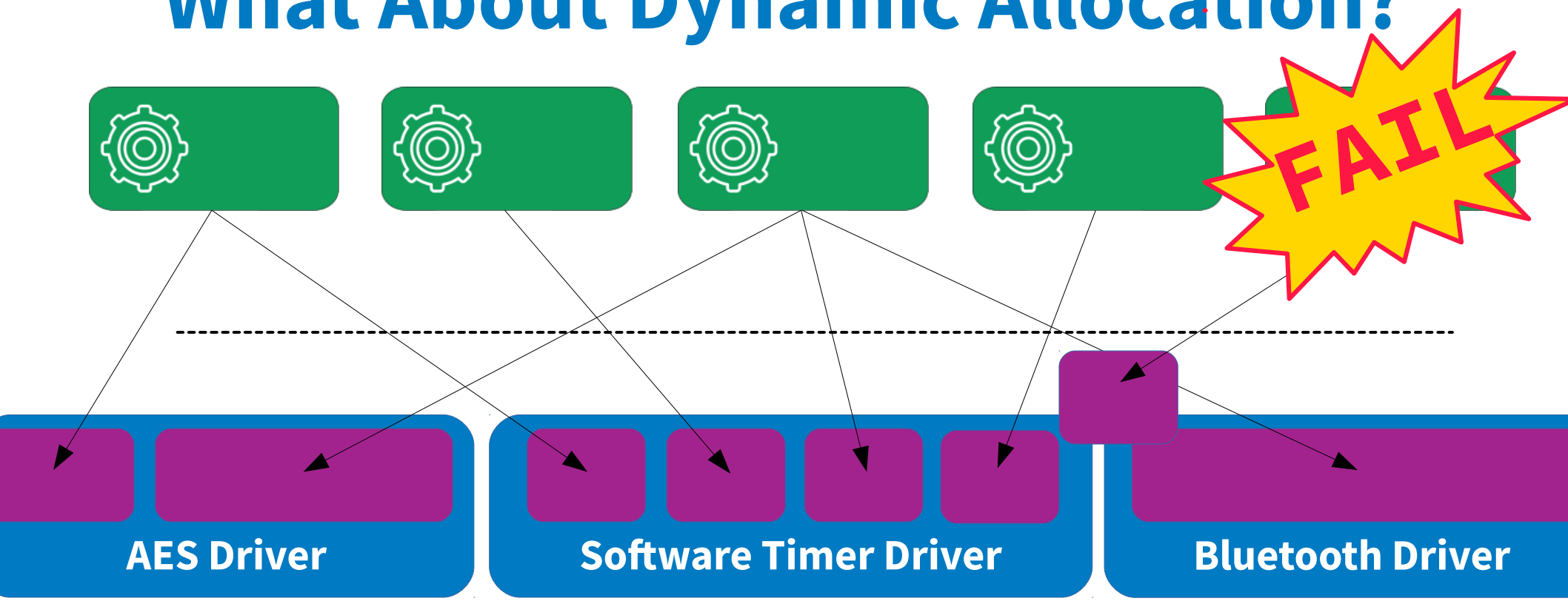
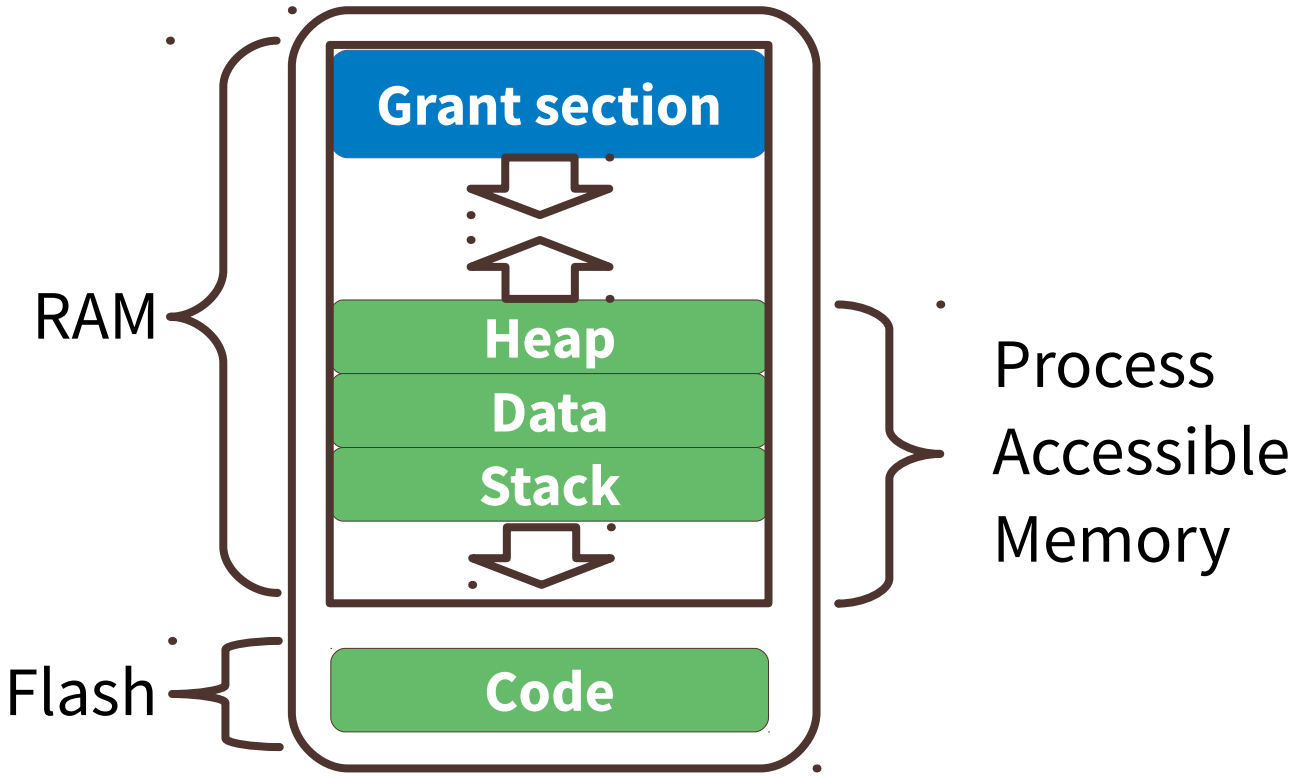


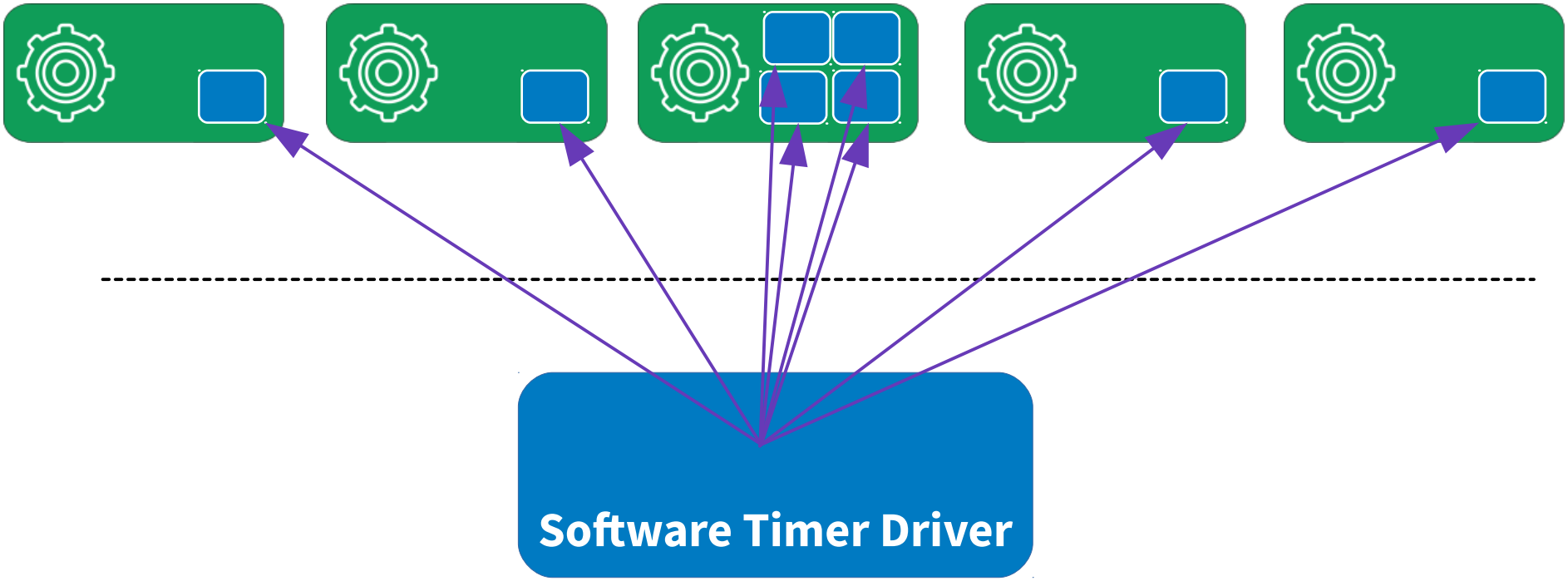
Can lead to unpredictable shortages.
One process's demands impacts capabilities of others.

Grants: Per-Process Kernel Heaps

- Allocations for one process do not affect others
- System proceeds if *one* grant section is exhausted
- All process resources freed on process termination



Grants:
Kernel heap *safely* borrowed from processes



Grants balance safety and reliability of static allocation with flexibility of dynamic allocation

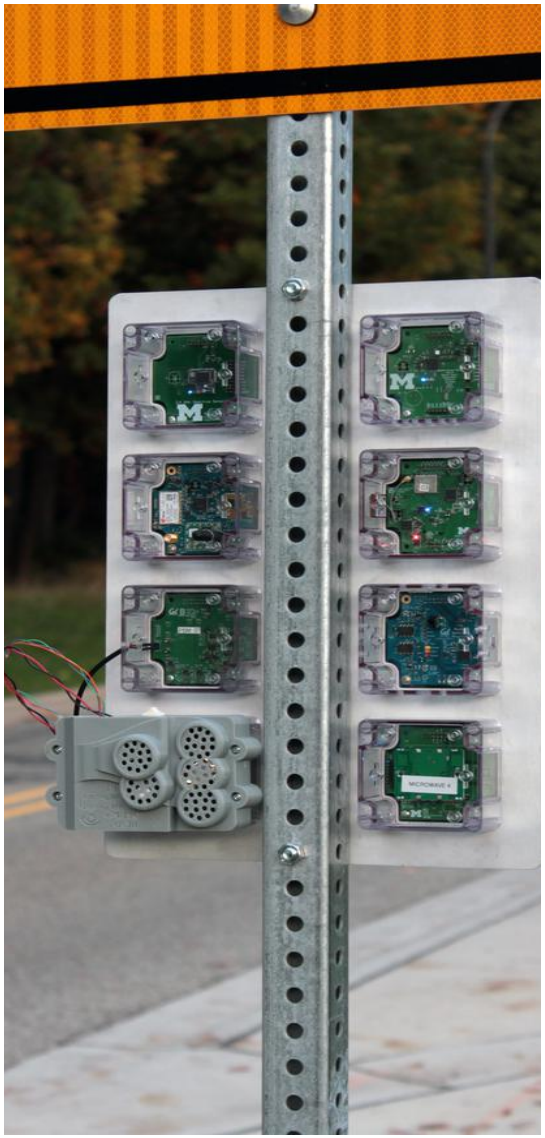
Grants use the type-system to ensure references only accessible when process is live

```
fn enter<'a, F>(&'a self, pid: ProcId, f: F) → where
    F: for<'b> FnOnce(&'b mut T)

    // Can't operate on timer data here

    timer_grant.enter(process_id, |timer| {
        // Can operate on timer data here
        if timer.expiration > cur_time {
            timer.fired = true;
        }
    });

    // timer data can't escape here
```

Case Study: The Signpost Platform

Signpost Overview

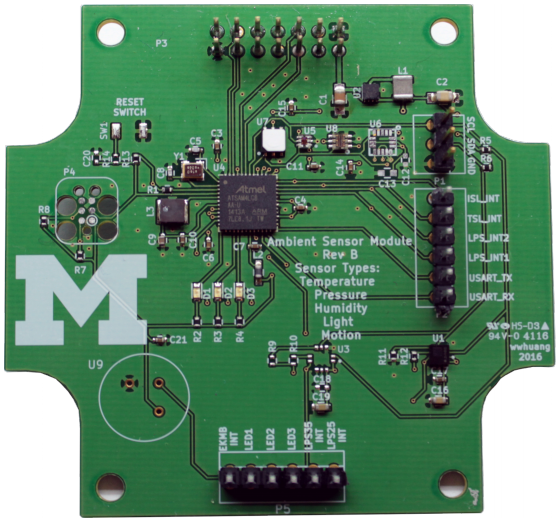
- Modular city-scale sensing platform
  - Ambient conditions tracking
  - Pedestrian density
  - Noise monitoring
- 8 pluggable modules
  - Instead of deploying a new platform
  - 15 mA power budget
  - Microcontroller + Sensors
- Sensing applications
  - Open research platform
  - Mostly run on modules
  - Several apps on the same module

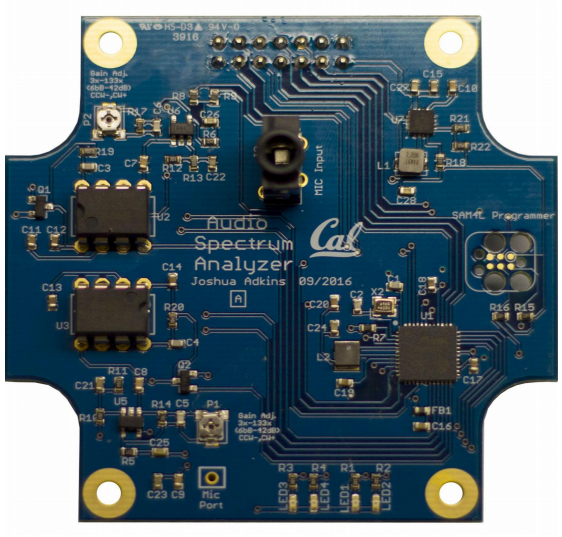


Currently deployed @ U.C. Berkeley

Tock on Signpost

Each Signpost module runs a Tock kernel





	Ambient Module	Audio Module
Process LoC	6990	6688
Capsules LoC	4479	3985
Platform LoC	3252	3244

Limitations & Future Work

- Other kernels in Rust?
- Relationship with verification
- Higher level security abstractions
  - e.g. Permissions? Capabilities? Naming?
- Distributed operating system
- Power management

Conclusion

- Tock: Multiprogramming with 64 kB
- Cheap kernel isolation with type-safe driver API in Rust
- Process abstraction without page virtualization
- Efficient concurrency without a kernel heap

https://tockos.org
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Thanks to the 40 (and growing) Tock contributers!

Grants Cost at Scale