Microcontrollers Deserve Protection Too

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Microcontrollers

Microcontrollers

- Tightly integrated hardware
  - A single IC computer (memory, CPU, I/O peripherals)
- Typically:
  - Small amount of code memory (<= 512KB flash)
  - Small amount of RAM (1 – 128KB)
  - Low speed CPU (<<< 80MHz)
  - Low power consumption (μA sleep currents)
  - Little/no hardware support for isolation

Tock*: An Operating System for Microcontrollers

- Designed for multi-programming microcontrollers
- Strict application/kernel boundary
- Written in Rust
  - Safe but low-level programming language
  - Allows compile guarantees on contributed kernel code
- Leverage new hardware features, e.g.
  - Memory Protection Unit (MPU)
  - Faster processor speeds
  - DMA, many more I/O peripherals, etc...

* *Codename*

Today's Microcontroller "Operating Systems"

- "Operating System"
  - Hardware abstraction layer
  - Libraries for complex/common tasks
    - e.g. 6lowpan, Bluetooth, virtual timers etc'
  - No isolation

Outline

- Why?
  - New use cases
  - New developers
  - New hardware
- What?
  - Untrusted application sandboxing
  - Protection from drivers/kernel modules
- How?
  - Hardware sandbox for apps
  - Language-level sandbox for drivers
  - Zero dynamic allocation in the kernel

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New Use Cases

- Ubiquitous computing
  - Fitness bands, medical devices, “smart home”
- Programmable platforms
  - Smart watches
  - Drones
  - Undoubtedly more to come

New Developers

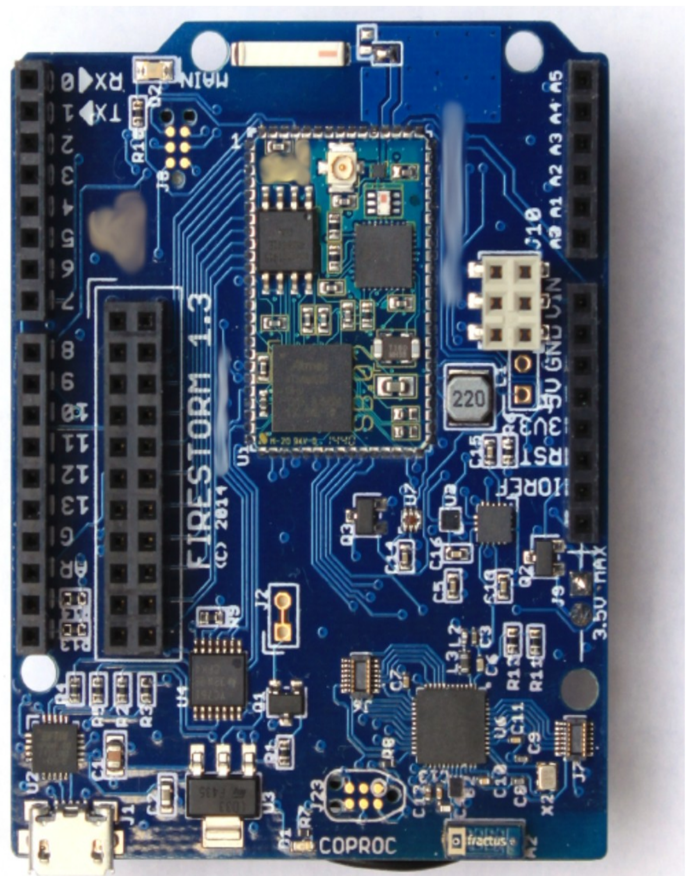
Cost + tools make hardware development more accessible

- Small teams/startups
  - Iterative development process
  - Rapid deployment
- Hobbyists
  - One off applications, modding
- Not necessarily embedded systems experts

Old Hardware - telosb

- Based on MSP430
  - 16-bit
  - 8Mhz, 10Kb RAM, 48Kb code
- 802.15.4 radio
- Power draw
  - 5.1 μA idle
  - 1.8mA idle

New Hardware



- Based on ARM Cortex-M
  - 32-bit
  - 40Mhz, 64Kb RAM, 128Kb code
- 802.15.4 *and* Bluetooth radios
- Power draw
  - 2.3-13.0 μ*A* idle
  - 8 *mA* active
  - < 25% on realistic workloads
- Many more peripherals:
  - USB, several USARTS, SPIs and I2Cs,AES accelerator…
- Memory Protection Unit (MPU)

Why a new Operating System?

- New Use Cases
  - Software updates on my medical device
  - Third-party apps
- New Developers
  - Non expert developers building highly personal/sensitive products
- New Hardware
  - Different power profile → different tradeoffs
  - Some hardware support for multi-programming

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Third-party apps

- Dynamically loadable
- May run concurrently
- Example: Pebble watch
  - 3rd party app ecosystem
    - E.g. pedometer, 2-factor auth, weather info
  - Must protect sensor data as well as other app data
- Potentially malicious threat model
- Need to *sandbox* against arbitrary behavior

Contributed Drivers

- E.g. storage system, network stack, LCD screen, sensors
- Written by the product/platform developer or non-core kernel developers
- Need low-latency access to hardware
  - Bitbanging devices, latency sensitive network stacks etc
- Not modeled as malicious, but potentially buggy
  - Shouldn't bring down the system
- “If I upgrade this flash driver, will my glucose monitor give me bad results?”
- Compiled into the kernel
  - Need compile-time guarantees

What Protections does Tock Provide?

- Applications:
  - Isolated from each other and from the kernel
  - A buggy application cannot bring down the rest of the system
- Drivers:
  - Can reason about behavior at compile time
  - (Relatively) easy to write non-buggy code with help from the compiler
  - Buggy driver cannot interfere with other critical code
  - Model ownership of hardware resources explicitly

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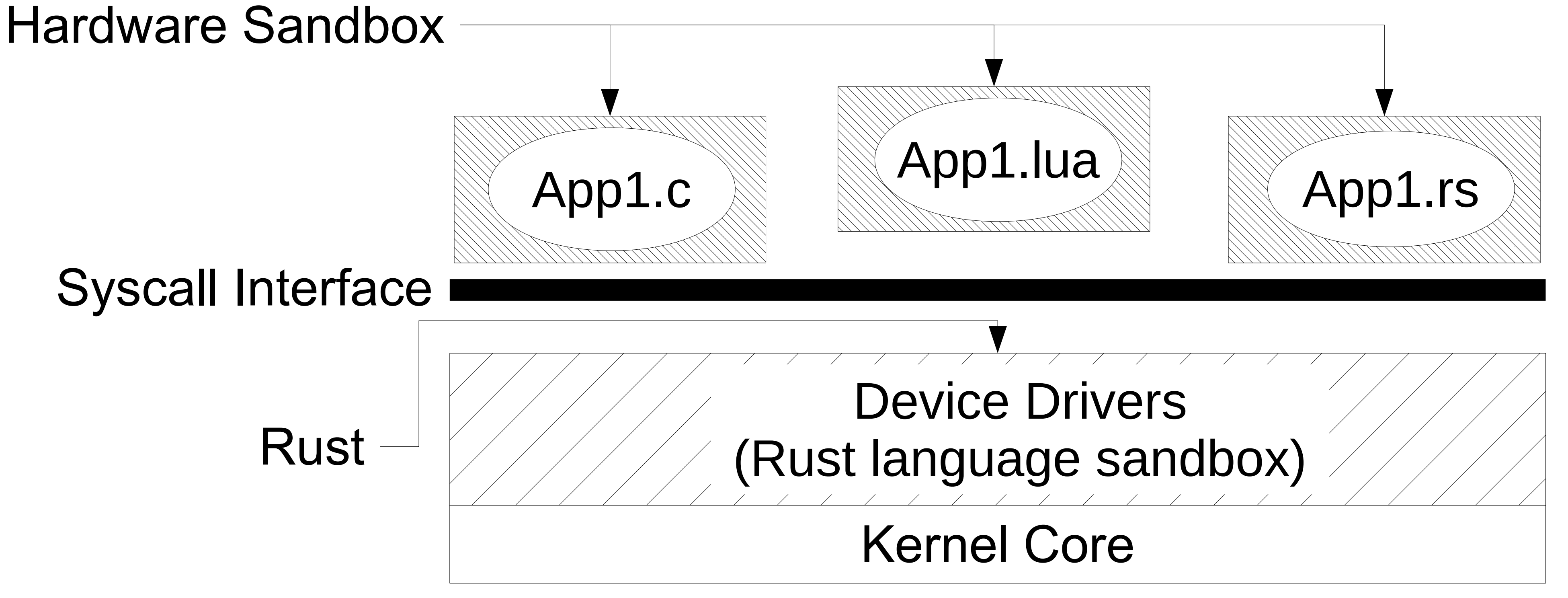
Tock: Overview

- Hardware separation between apps and kernel (MPU)
- Kernel written in safe language (Rust), apps written in any language
  - C, Lua, Rust, etc
  - Helps balance safety with low-level access and ease of use.
- Drivers written in language-level sandbox
  - Unique and exclusive access to underlying hardware

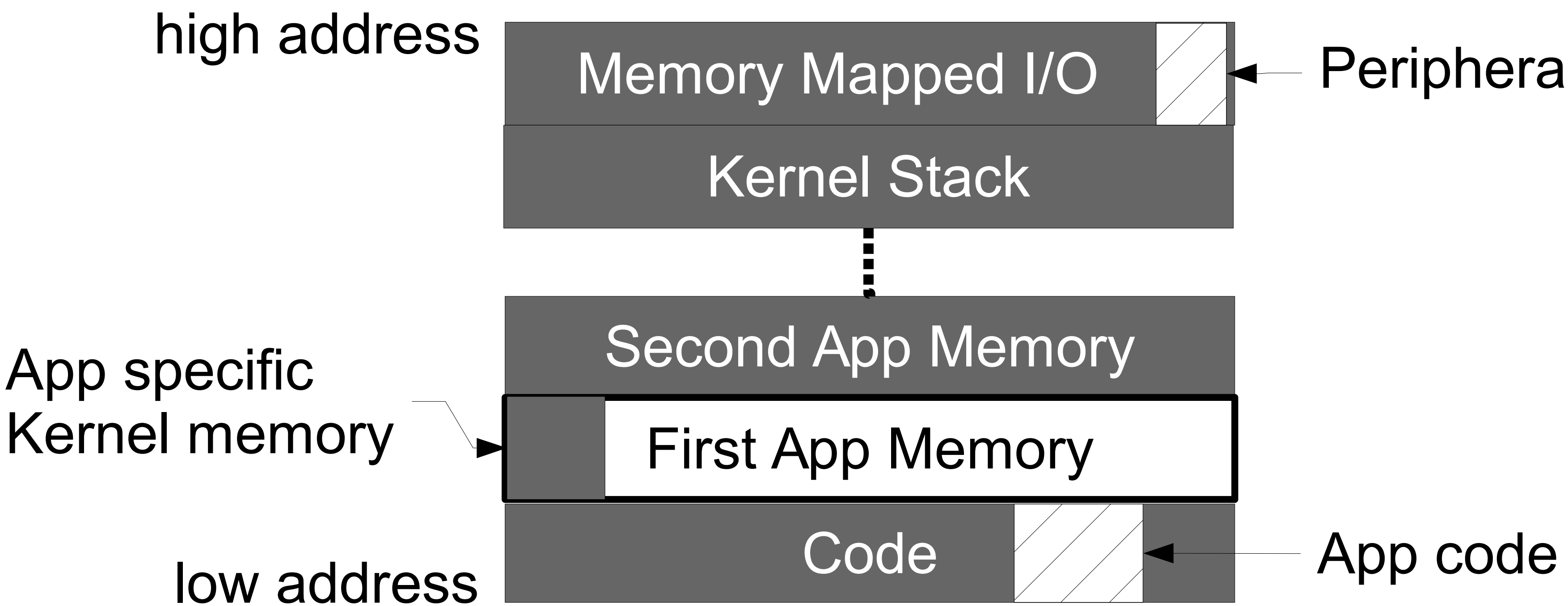
Tock: Architecture



MPU: Hardware App Sandbox

- Enforce read/write/execute on applications for different portions of memory
- No virtual addressing but much finer grained than MMU
- On Cortex-M4:
  - Up to 64 different regions
  - Region size between 32B and 4KB
- Can isolate application memory from each other
- Can allocate sensitive kernel data structures in “application space”
- Can expose specific peripherals directly to applications

MPU: Hardware App Sandbox



Language-level Sanbox: Goals

- Device drivers cannot interfere with each other
  - E.g. a network stack cannot muck with readings from a glucose sensor
- Single threaded execution model
  - Simpler to write correct code
  - Kernel/hardware does not have to worry about concurrent access bugs
  - Much faster processing speeds make this feasible within time contraints

Language-level Sanbox: Why Rust?

- No runtime system
  - Not garbage collected, zero-cost safety abstractions
- Memory Safety
  - Elimates a large class of bugs: dangling pointers, double-frees, pointer arithmetic errors, etc
- Type Safety
  - Can expose low-level hardware interfaces through safe interfaces
- Strict Aliasing
  - Unique references and read/write references obviate many concurrency bugs

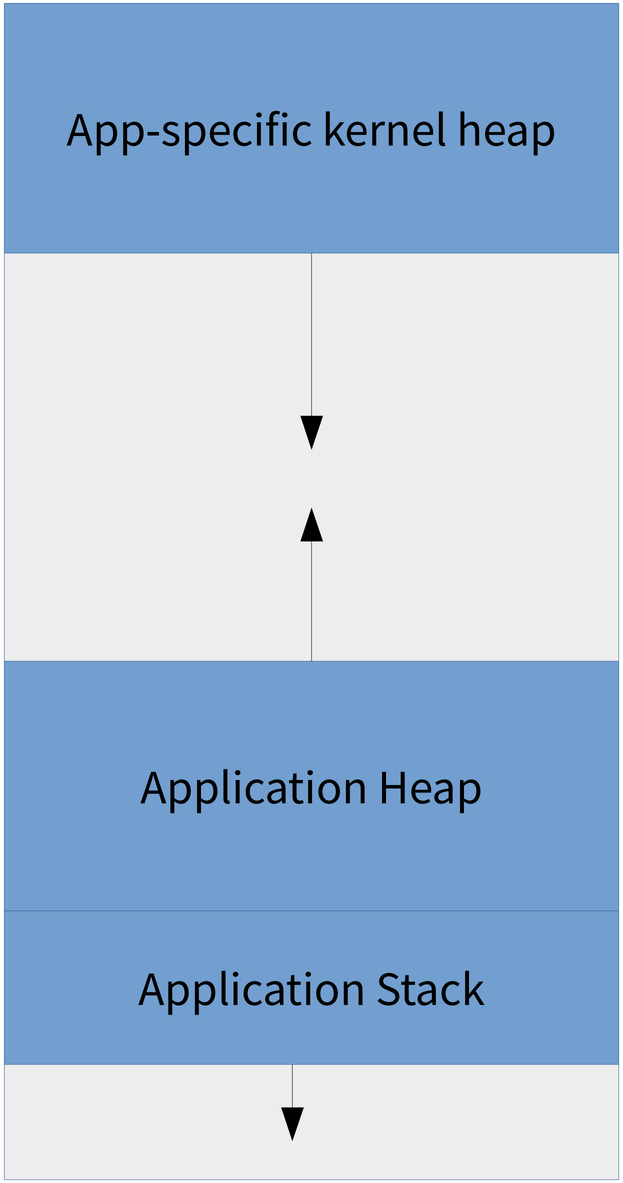
Zero Dynamic Kernel Allocation

- Embedded OSs generally avoid dynamic allocation for good reason
  - Hard to determine in the lab if something will crash in the field
  - No swapping, so no way to deal with memory overflows
- But problematic with dynamically loaded applications
  - A new app may use drivers differently
  - E.g. different number of timers, more buffer, etc

Tock: Dynamic Allocation

Three ways kernel allocates memory:

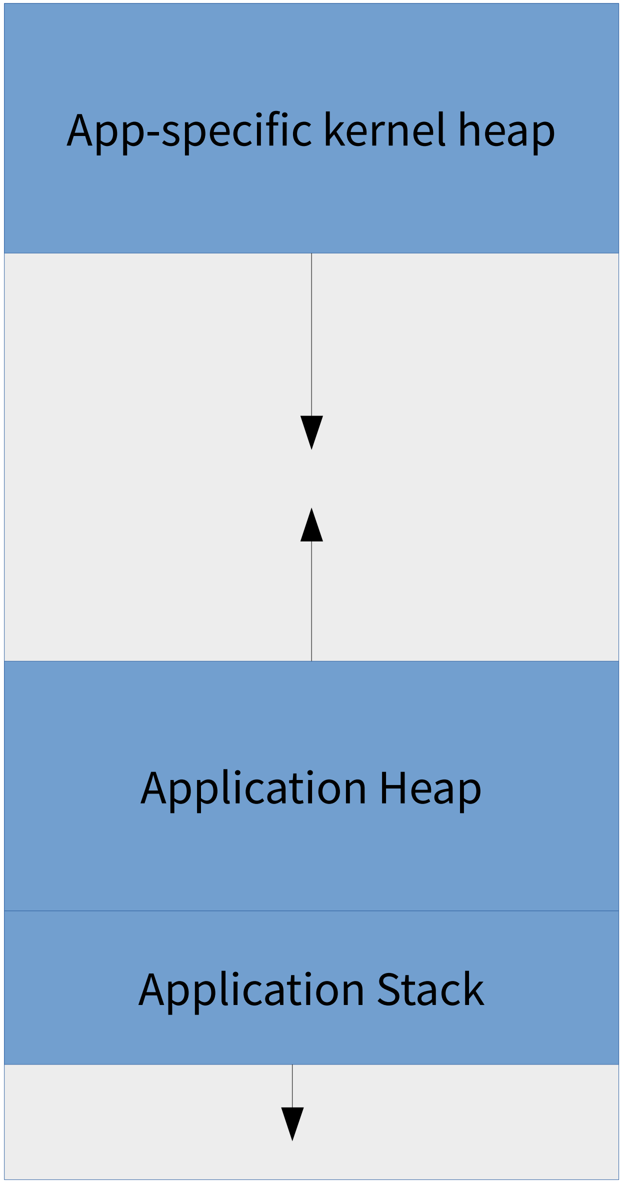
- Statically
  - Size determined at compile-time
- Kernel stack
  - Maximum size *can* be determined at compile-time via anlaysis
- Application memory
  - Fined grained MPU allows dynamic sizing of app-specific kernel-heap.



Tock: Dynamic Allocation

Example kernel allocations in application space:

- Linked list nodes
- Virtual timer structs
- Network stack buffers



Summary

- Traditional embedded systems are outdated:
  - New hardware
  - New use cases
  - New generation of developers
- Security should be a main goal of any new system
- Leverage hardware protection to isolate third-party applications
- Leverage advances in programming languages to make kernel more secure

Challenges & Questions

- Will this work?
  - Maintain reliability and power constraints unique to embedded devices
  - While making security accessible to non-expert developers
- Dynamically updating the kernel/drivers?
- How do we leverage multi-microcontroller platforms?
- MGC security - Applications that span embedded devices, gateways (e.g. smartphones) and the cloud