Tock Operating System:
Security Model and Implications

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Embedded Software is a Weak Link

- Runs on small, low-power microcontrollers
  - 32-bit ARM CortexM @10-140 MHz
  - 16-256kB RAM, 256kB-1MB code
  - No virtual memory
- Custom, application-specific code written in C
  - Low code-reuse
  - Low testing coverage
- All code must be trusted
  - No isolation: any code can directly all access hardware registers
  - No distinction between “kernel” and “application”

Embedded Software is Security Critical

Tock

- Tock: First secure embedded operating system
  - Key idea: write kernel in Rust, a type-safe systems language
- Platform Lab research project
  - Collaboration between Stanford, UC Berkeley, Michigan
  - Lead: Amit Levy, graduated in 2018 (now Princeton faculty)
- Uses today: Helium, Google (OpenTitan, OpenSK), Oxide (server firmware)

Security Model

- Evolving from research to production requires a much more precise statement of the security model
  - OpenTitan: root of trust on computing devices
  - OpenSK: FIDO two-factor device
  - Oxide: firmware can't be the weak link
- But we need the OS to remain generally and broadly usable in embedded systems
  - Disallowing X because one use case needs it won't scale
  - Allowing Y because one case needs it breaks least privilege
- Basic tension between security and usability

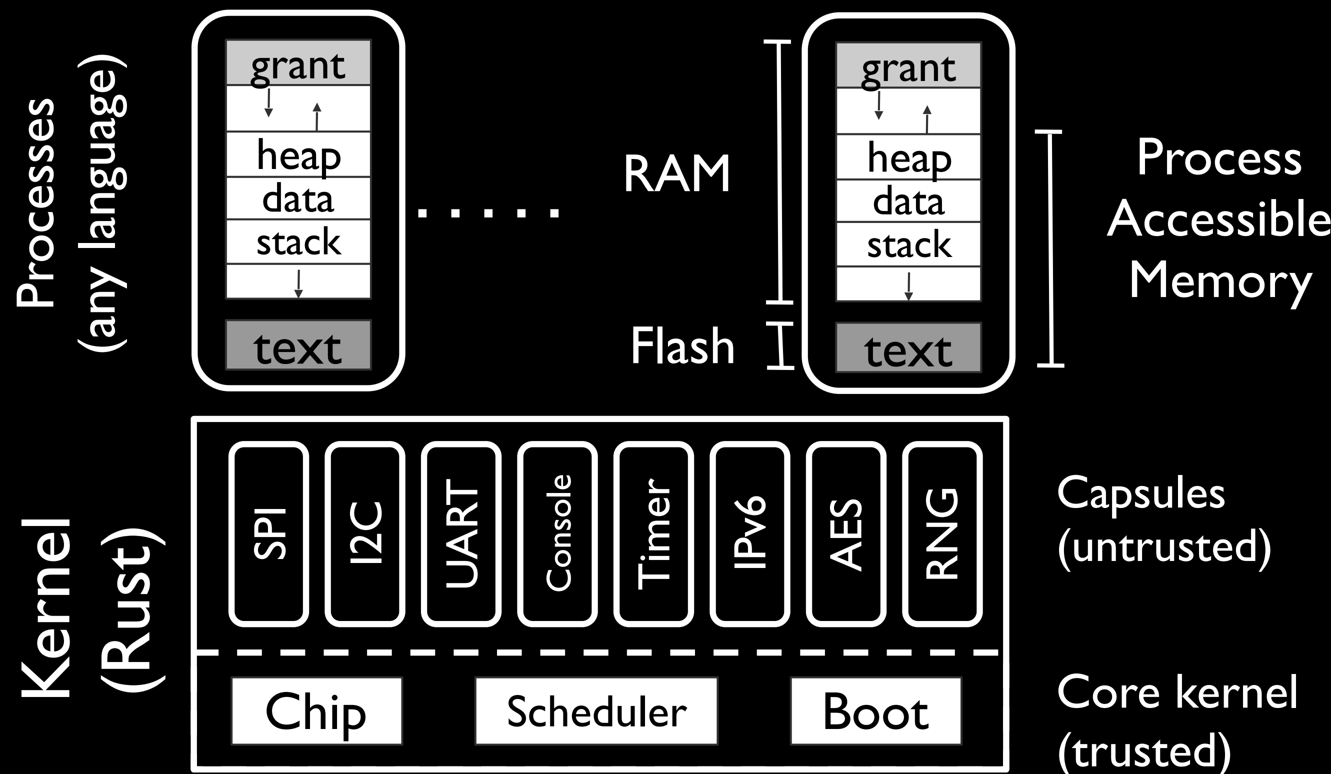
Summary

- Impose a standard security model
  - E.g., no heap allocation, kernel extensions can't control processes
- Some operations violate standard security model
  - E.g., being able to allocate memory, stop a process
- Calling sensitive operations requires having a capability from trusted code, enforced by Rust type system
  - Statically checkable
  - Leverage Tock's model of trusted and untrusted code
  - Two classes of capabilities: functional and global

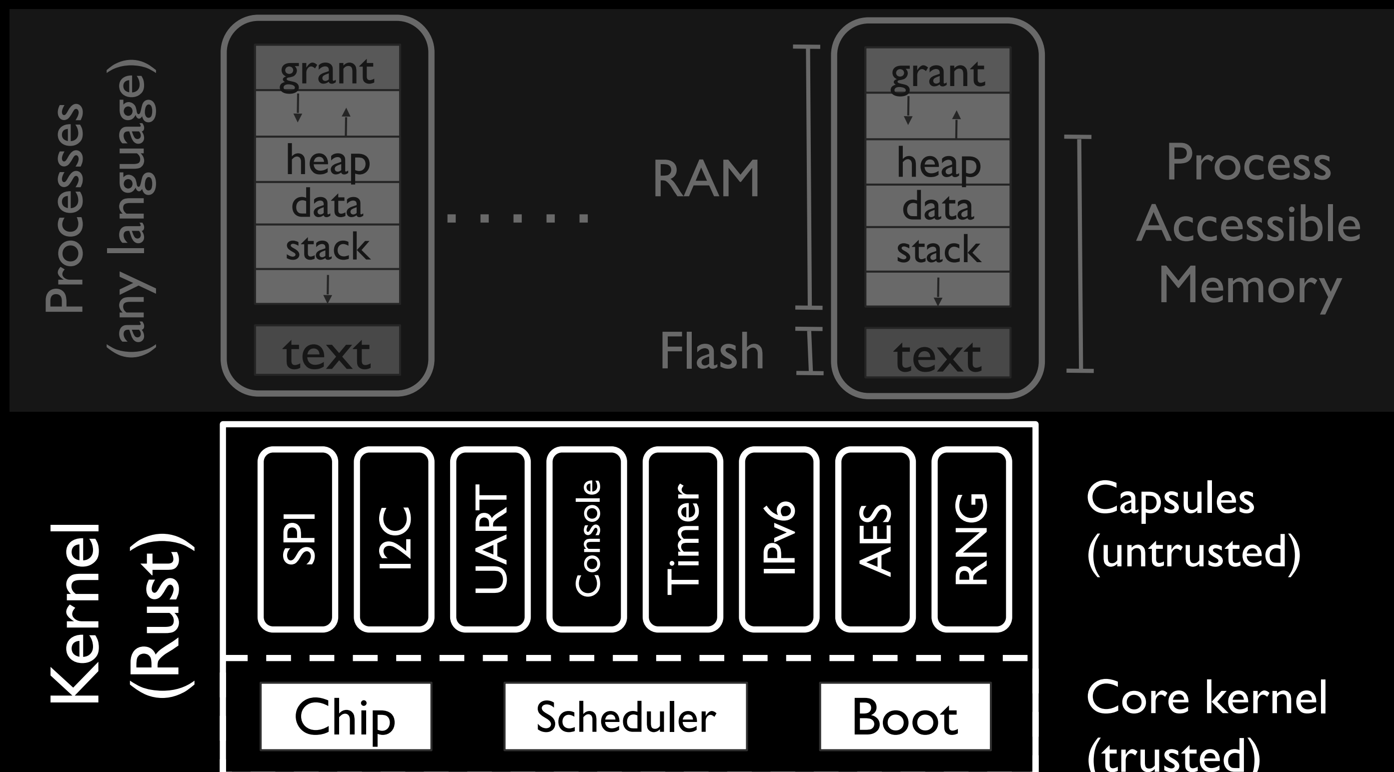
Outline

- Introduction
- Tock overview
- Security model
- Allowing exceptions
- Next steps

Tock Architecture



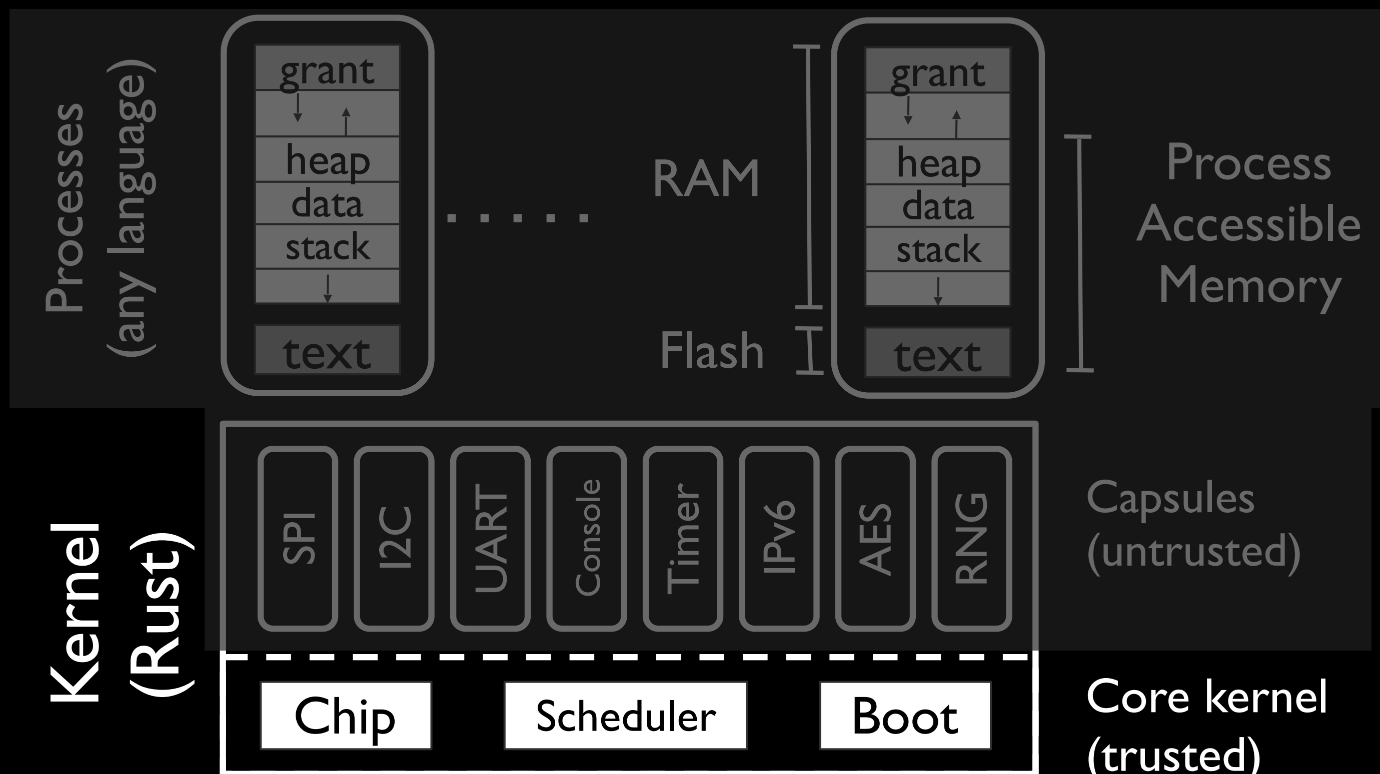
Tock Architecture



Rust Language

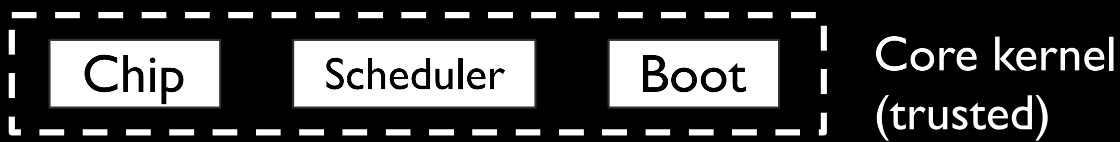
- The Tock kernel is written in Rust, a type-safe systems language
  - Strongly type-safe code: no buffer overflows, access errors, wraparound bugs
  - Fast: within 30% of C in our use cases, overhead due to safety due diligence
  - No garbage collector: uses "lifetimes" and affine type system
- Some kernel code cannot be type safe
  - Address of a memory mapped IO register taken from datasheet
  - Context switches
  - Interrupt handlers
  - System calls and processing userspace pointers
- Use **`unsafe`** keyword to step outside type system
  - Core kernel uses **`unsafe`** 102 times (most uses declare unsafe functions), has 31 unsafe code blocks
  - Chip peripherals use **`unsafe`** to construct a typed structure for register access from an address

Tock Core Kernel

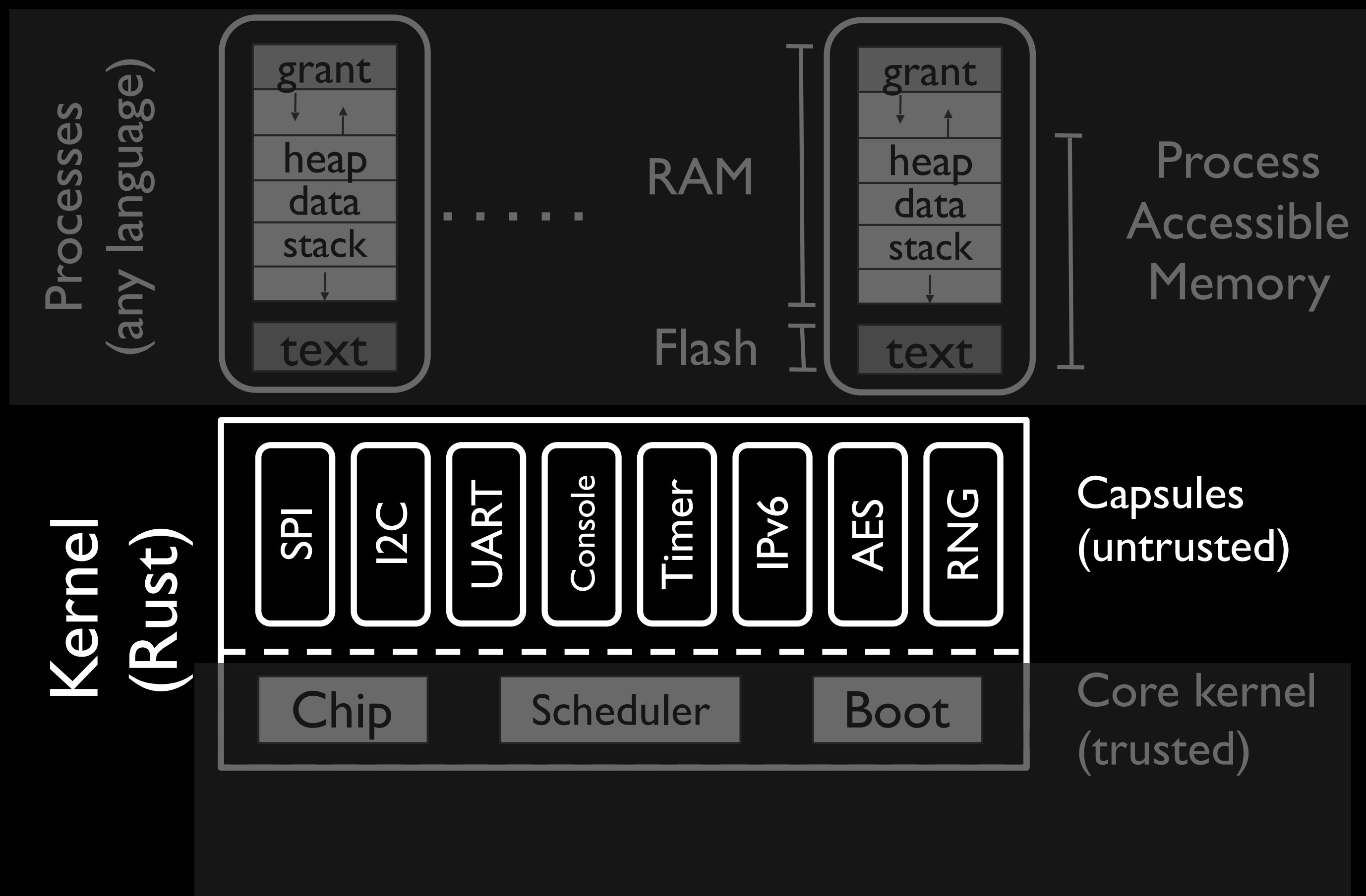


Core Kernel and Peripheral Drivers

- This code may use the unsafe keyword: we trust it
  - kernel/ is the core kernel code, context switches, low-level data types
  - chips/ are chip peripherals (UART, etc.); unsafe is hopefully one line converting a memory address into a type set of register structures
  - boards/ is the board-specific code, including the boot sequence (which is unsafe)

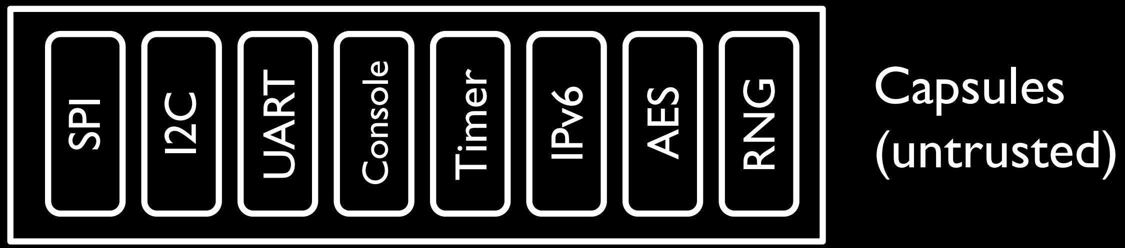


Tock Capsules

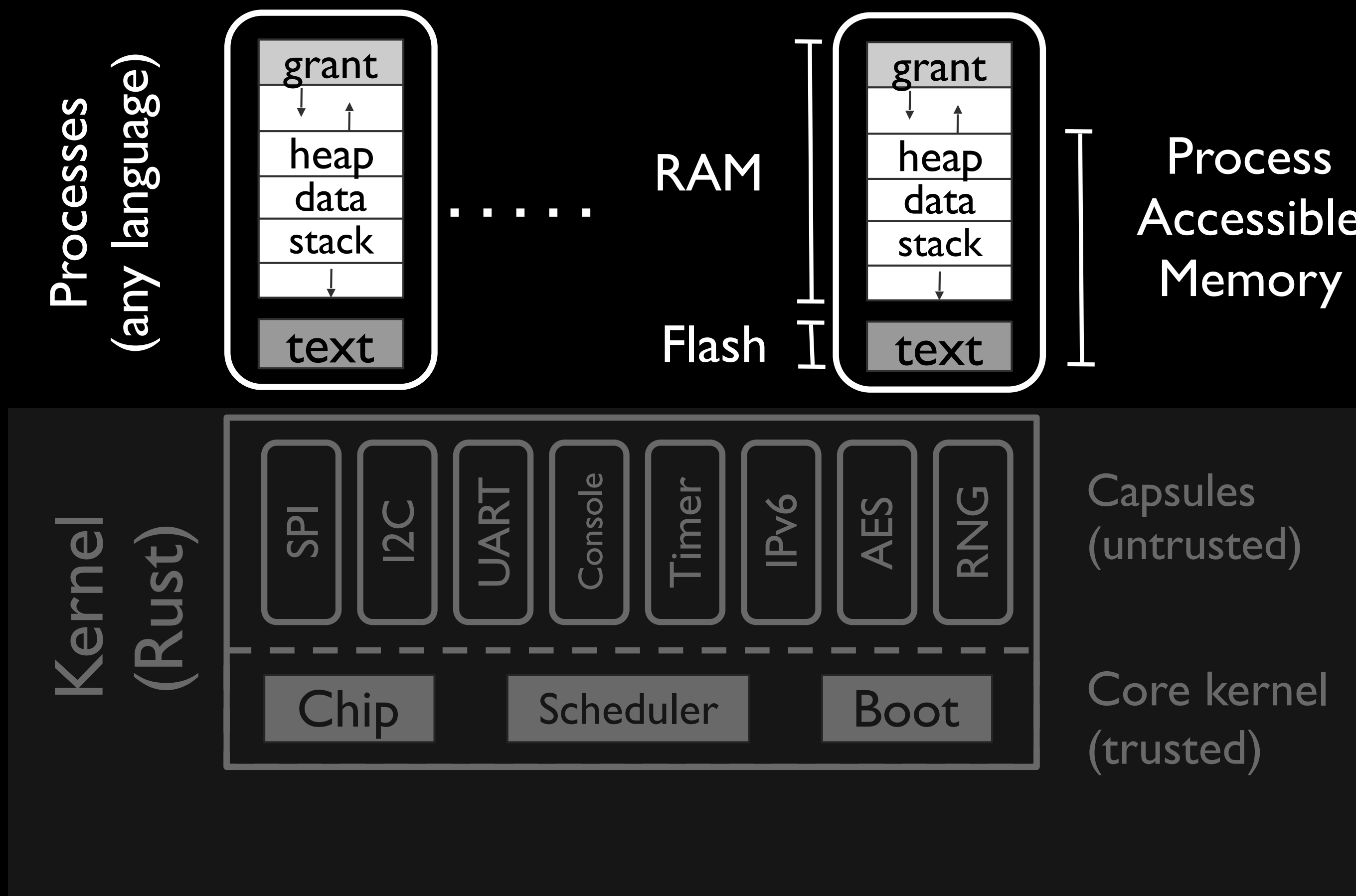


Tock Capsules

- Kernel code (Rust) that *cannot* use the unsafe keyword
- Reusable pieces of kernel code that are chip and board independent
  - Example: virtual_alarm turns one hardware alarm into many software alarms
  - Example: rf233 implements an RF233 radio driver on top of a SPI bus and GPIO pins
  - Example: rng provides system call interface to hardware random number generator



Tock Processes



Tock Processes

- Tock supports processes written in any language (i.e, assembly)
- Kernel isolates processes using memory protection unit (MPU)
- Kernel has no dynamic memory pool/malloc (for dependability)
  - When the kernel needs to dynamically allocate memory for a process, it allocates it from a special region of process RAM, called the *grant* region
  - If a process exits/faults, the grant region is automatically freed
  - References cannot escape grant region
- Some capsules implement system calls to allow processes call into kernel
  - Kernel responsible for multiplexing/virtualizing its operations

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TockWorld 4

- TockWorld: yearly workshop for Tock developers
- Two major work items in November 2019
  - Updating system call API
  - Johnathan van Why (Google) led the effort to clearly define Tock's security model

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Examples: IPC, passing buffer into kernel

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Example: TCP port

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Can only invoke APIs which they have explicitly been given access to through a reference. Type safety and trait-centric API designs mean usually only trusted code passes these references, e.g., at boot.

Example: Writing a Log

```
trait LogWrite {...}
trait LogWriteClient {...}
impl LogWrite for LogStorage {...}
```

- A capsule can only write to the log if it has a reference to an implementer of LogWrite (e.g., LogStorage)
- There are no global variables: a capsule can only have a reference if it was passed one (at boot)

```
let test = LogStorageTest::new(&log_storage,
                               &mut BUFFER,
                               VirtualMuxAlarm::new(mux_alarm),
                               &TEST_OPS);
```

- Strict, narrow APIs mean references don't float around

Kernel Security

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- Availability: Applications cannot starve the kernel of resources or otherwise perform denial-of-service attacks against the kernel. Untrusted capsule code may deny service to trusted kernel code. Virtualized kernel abstractions should be designed to prevent starvation.

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Kernel is single-threaded.

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Starvation is Inevitable

- Most analog-to-digital converters support high-frequency sampling
  - Audio/mic: "Sample pin A7 with a 3.3V reference at 40kHz"
- Samples in some use cases need not only high frequency but also low jitter: driven off a fixed clock
  - Can't stop/change sampling without introducing jitter
  - If a client starts, it might sample forever: this will starve other clients
- Don't want to disallow audio sampling, but also don't want to allow any capsule that performs high frequency sampling to do so forever.

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Allowing Exceptions

- There are a lot of things that most capsules shouldn't be able to do (availability)
  - Sample ADC forever
  - Start/stop processes
  - Allocate memory from processes
  - Invoke kernel main loop
  - Open network connections
- But some capsules need to!

Allowing Exceptions

- There are a lot of things that most capsules shouldn't be able to do (availability)
  - Sample ADC forever: audio sampling
  - Start/stop processes: process management capsule
  - Allocate memory from processes: system call drivers
  - Invoke kernel main loop: scheduler
  - Open network connections: services
- But some capsules need to!

Capabilities

- Some in-kernel operations are especially sensitive and impact dependability
  - Allocating memory from a process
  - Calling main loop
  - Loading/start/stopping process
  - Under development: network communication
- Could control access by requiring a reference to structure that implements feature
  - Requires many references; uglier code and wasted RAM; poor for fine-grained control
- Tock uses *capabilities* to describe and restrict these operations within the kernel
  - A Tock capability is a zero-sized structure that can only be created by trusted code
  - Can be passed but not copied
  - Calling sensitive functions requires a reference to corresponding capability
  - Checked at compile time, requires no RAM and no extra code

Capabilities Example

kernel/src/capabilities.rs:

```
pub unsafe trait ProcessManagementCapability {}
```

kernel/src/sched.rs:

```
/// Run a closure on every valid process. This will iterate the array of
/// processes and call the closure on every process that exists.
crate fn process_each<F>(&self, closure: F) where F: Fn(&process::ProcessType) {...}

/// process_each, when called from outside kernel (by a capsule) requires
/// a ProcessManagementCapability
pub fn process_each_capability<F>(&'static self,
                                  _capability: &capabilities::ProcessManagementCapability,
                                  closure: F) where F: Fn(usize,
                                                          &process::ProcessType) {...}
```

Capabilities Example

```
pub fn process_each_capability<F>(&'static self,
                                 _capability: &ProcessManagementCapability,
                                 closure: F) where F: Fn(usize,&ProcessType) {...}


impl<'a, C: ProcessManagementCapability> ProcessConsole<'a, C> {
    pub fn new(..., capability: C) -> ProcessConsole<'a, C> {
        ProcessConsole {
          ...
          capability: capability,
        }
    }
}


self.kernel.process_each_capability(&self.capability,
                                    |_i, proc| { ... function ... });
```

Allowing Exceptions

- There are a lot of things that most capsules shouldn't be able to do (availability)
  - Sample ADC forever: AdcDurationCapability
  - Start/stop processes: ProcessManagementCapability
  - Allocate memory from processes: MemoryAllocationCapability
  - Invoke kernel main loop: MainLoopCapability
  - Open network connections: NetworkCapability
- Boot sequence (or other trusted code) creates and distributes these capabilities

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Security Through Types

- Rust's type system allows us to statically verify security properties and restrictions
  - Functional: references to objects limit access to APIs
  - Global: capabilities limit access to operations that violate security model
- Current work: network security policies
  - E.g., enforcing that a capsule can only open connections to certain endpoints/ports
  - Parameterized capabilities are not zero-sized and require runtime checks

OpenTitan

- Consortium led by Google to create an open-source hardware root of trust MCU
  - All designs and RTL are public
  - RISC-V (rv32i) design
- Tock is currently OS of record for OpenTitan
  - First port by Alastair Sinclair (Western Digital) from only public information
  - Tock OpenTitan working group has formed (Google, Oxide, Western Digital, a few academics)
- OpenTitan is still in flux: tight collaboration between Tock developers and chip designers

Questions