Allocating Dynamic Kernel Memory in Low-Memory Microcontrollers

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Microcontrollers Becoming Platforms

• Fitness watches support different activities
• USB security keys perform multiple functions
  – U2F, SSH, GPG, HOTP
• Sensor networks run several experiments at once
Embedded Software Isn’t Ready

- Run all code in a single address space
- Trust all code
- Can’t update components
- Can’t recover components
Safe Multiprogramming by Isolating Applications and OS Services
Can’t Use Normal Isolation Techniques

- Limited memory: **64 kB** of RAM
  - Memory isolation techniques limit granularity
  - `malloc` can fail!

- No page virtualization
  - Instead protection bits for 8 memory regions

- Moore’s Law doesn’t fix the problem
  - Sleep current is limiting factor
  - Memory capacity < 10x in 15 years
Microcontrollers demand new multiprogramming abstractions.
How to Multiprogram a Microcontroller

- Use *type safety* to isolate most of the system
- Use memory isolation sparingly
  - Preemptive scheduling
  - Recover or update components at runtime
- Support dynamic workloads without `malloc`

**Tock**

- Kernel written in Rust
- Processes abstraction using Memory Protect Unit (MPU)
- *Grants*: mechanism to account for dynamic workloads
Outline

1. Security Model & Design Principles

2. Two Isolation Mechanisms

3. Grants
Let’s consider a programmable USB security key
Board Integrators

- Build the hardware
- Combine core kernel, MCU-specific glue code & drivers
- Complete control over firmware
Kernel Component Developers

- Build most kernel functionality
- Source code available to board integrators
- But auditing won’t catch all bugs
Application Developers

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

• Isolation guarantees should be clear
  – What exactly can a component do?

• System should be dependable
  – Unanticipated runtime behavior shouldn’t cause crashes

• Maximize concurrency
  – I/O operations can overlap

• Minimize resource consumption
  – Resources don’t dictate isolation granularity

• Maximize programmability
  – Applications will have unknown behavior
Tock’s Two Isolation Models

**Capsules**
- Compile-time
- Kernel
- Limited trust
- Fine grained

**Processes**
- Runtime
- Applications
- Potentially malicious
- Coarse grained
Capsules

- A Rust module and structs
- Event-driven execution
- Communicate via references & method calls
Capsule Isolation

```rust
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
  - Logical memory region: stack, heap, static variables
  - Uses the ARM Memory Protection Unit (MPU) to protect memory regions without virtualization
- Scheduled preemptively
- System calls & IPC for communication
- Updated dynamically
# Processes vs. Capsules

<table>
<thead>
<tr>
<th>Capsules</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Isolated by compiler</td>
<td>• Isolated at run-time</td>
</tr>
<tr>
<td>• Shared stack, no heap</td>
<td>• Dedicated stack &amp; heap</td>
</tr>
<tr>
<td>• Cooperative</td>
<td>• Preemptive</td>
</tr>
<tr>
<td>• Rust only</td>
<td>• Any language</td>
</tr>
<tr>
<td>• Method calls</td>
<td>• Context switch</td>
</tr>
<tr>
<td>• Replaceable at compile-time</td>
<td>• Replaceable at runtime</td>
</tr>
</tbody>
</table>

_Different isolation mechanisms for different use cases_
Process

Application Developers

Kernel

Kernel component developers

Microcontroller

Peripherals

Board Integrators

Timer SysCalls

Virtual Alarm

RF233 Driver

I2C Driver

Temp Sensor

802.15.4 Net.

Timer Driver

SPI Driver

Microcontroller

Timer

SPI

I2C
A static kernel needs resources to respond to unpredictable process requests.
Working Example: Timer Driver

Kernel

Software Timer Driver

HW Alarm
Statically allocating timer state?

Static allocation must trade off memory efficiency and maximum concurrency
What About Dynamic Allocation?
What About Dynamic Allocation?

Software Timer Driver
What About Dynamic Allocation?
What About Dynamic Allocation?
What About Dynamic Allocation?

Can lead to unpredictable shortages.
One process’s demands impacts capabilities of others.
Separate kernel heap for each process
Grants

- Safely account for process-specific 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 uses the type-system to ensure references only accessible when process is live

```rust
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
```
Resource Management in Tock

- Extremely limited memory limits isolation with traditional mechanisms
- Capsules decouple isolation from concurrency
- Still need dynamic allocations in static components
- Grants “borrow” memory from processes to service process requests
- Need to ensure grants for different processes can’t reference each other