TickTock: Verified Isolation in a Production Embedded OS

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Abstract

This paper presents TickTock: a case study of formally verifying process isolation in Tock, a production microcontroller OS. Tock combines hardware memory protection units (MPUs) and language-level techniques (by writing the kernel in Rust) to enforce isolation between user and kernel code. Our effort to verify Tock revealed multiple, subtle bugs that broke isolation, many allowing a malicious application to compromise the whole OS. TickTock is a fork of the Tock operating system kernel that eliminates this class of bugs by construction. We use Flux, an SMT-based Rust verifier, to formally specify and verify process isolation across all ARMv7-M architectures Tock supports, along with three RISC-V 32 bit chips. In verifying the original Tock kernel, we unearthed both previously unknown bugs and cleaner design patterns. This led us to the verification-guided design and implementation of a new *granular* process abstraction. The result is a simpler implementation with a clear specification that is provably free of isolation bugs, verifies in half a minute, and outperforms Tock on certain critical code paths.

1 Introduction

Tock [36] is a microcontroller OS that is increasingly being deployed in security-critical systems like the Google Security Chip (GSC) [6], the platform powering Google's Hardware Security Modules, and the Microsoft Pluton 2 security processor [57], the system-on-chip providing functions like the Trusted Platform Module. Like traditional OSes, Tock's strong security guarantees are rooted in isolation: Tock separates user and kernel space and provides a process abstraction that lets users run multiple untrusted applications in isolation. If a malicious or compromised process can access the kernel or another process's memory, all bets are off: the process can potentially steal sensitive data (e.g., cryptographic keys handled by platforms like GSC), brick the embedded system (and the platforms relying on Tock as the root of trust), or even take control of the OS.

Unlike traditional OSes like Linux or even secure microkernels like seL4, Tock is written in Rust. This means kernel-space components are isolated from each other at the language level by Rust's type- and memory-safety. It also means the Tock kernel can use Rust's type system to distinguish kernel and user-space data and prevent confused deputy attacks that exploit the kernel into clobbering (or leaking) arbitrary memory.

Rust's type- and memory-safety only go so far: Tock user applications are written in arbitrary languages (including memory unsafe languages like C and C++). Unlike traditional OSes, Tock cannot rely on virtual memory and memory management units (MMUs) to isolate these applications—the OS was designed to run on resource-constrained devices that lack MMUs. Instead, Tock relies on *memory protection units (MPUs)* to ensure that each user process can only access its own region of memory and is isolated from other processes and the kernel.

In practice, configuring the MPU is hard. First, the configuration itself is a delicate dance that requires balancing the size and alignment constraints of the underlying MPU hardware and the memory requirements of each process (and the kernel). Second, since the MPU can only be configured to enforce access control policies for one process at a time, the Tock kernel must manage MPU configuration, in software, on a per-process basis. Finally, Tock must do this in the presence of interrupts. Consequently, subtle bugs in MPU configuration, interrupt handling and context-switching have broken Tock's isolation [11, 19, 59].

We present TickTock, a fork of the Tock kernel that eliminates isolation bugs by construction. Instead of relying on developers to always get the tricky bits right, TickTock uses an automatic verifier, Flux [34], to *formally verify* that the kernel provides memory isolation. We develop TickTock via three concrete contributions.

1. Design. Our first contribution is a verification guided implementation of a new *granular* abstraction for MPUs that decouples the kernel's requirements from the hardware's constraints (§ 3). In verifying the original kernel, we found that Tock's abstraction of processes and hardware enforcement resulted in complex code–and hence security bugs–as

SOSP '25, Seoul, Republic of Korea

ACM ISBN 979-8-4007-1870-0/2025/10
https://doi.org/10.1145/3731569.3764856

well as a large specification that was slow to check. Fundamentally, this is because the original kernel tries to do too much in a single *monolithic* abstraction, *entangling* the details of process memory layout and hardware constraints. Additionally, we found the *monolithic* design leads to scenarios where the kernel's view of a process's layout *disagrees* with the actual layout enforced by hardware, necessitating various complex and easy-to-miss checks. Instead, our new granular abstraction cleanly separates process memory layout and hardware configuration details and ensures that the kernel and underlying hardware enforcement always agree. The result is a clearer specification, and a simpler kernel that is (more) "obviously free of bugs, rather than just free of obvious bugs" [25].

2. Verification. Our second contribution is a formal verification of isolation using Flux, a refinement type-based verifier for Rust [34] (§ 4). Formally, we analyze the code that configures the ARMv7-M and RISC-V MPU, as well as code that manages the process memory layout to verify that each process can *only* access its code (in flash) and its stack, data, heap (in RAM)—and nothing else. To verify the assembly interrupt handlers and context switching code, we develop explicit operational semantics for ARMv7-M hardware, by lifting ARM's Architecture Specification Language (ASL) [46] to Rust and defining the semantics via Flux specifications.

3. Evaluation. Our third contribution is a discussion of our verification effort and an evaluation of the performance of our new granular abstraction (§ 6). Overall, TickTock has strengthened Tock's safety guarantees. Our verification effort identified five previously unknown bugs in MPU-configuring code and two in interrupt handling code, yielding six bugs that broke isolation. We worked closely with the Tock developers to upstream fixes into Tock itself. Our verification effort was quite modest: about 3.5KLOC of Flux annotations for 22KLOC Rust source. Finally, we find that the verification-guided redesign of Tock's monolithic abstraction is doubly beneficial. First, our granular abstraction greatly simplifies verification: the original code took over five minutes to verify, but the newly designed kernel verifies in under one. Second, the original verification helped uncover simple design patterns that allow us to remove unnecessary checks and recomputations optimizing TickTock's performance on critical code paths.

2 Overview

We start by explaining how Tock uses MPUs to enforce isolation (§ 2.1). Next, we describe how verifying the original Tock kernel unearthed bugs and discuss how these bugs can break isolation guarantees (§ 2.2). Finally, we give an overview of how we formally guarantee isolation by construction (§ 2.3).

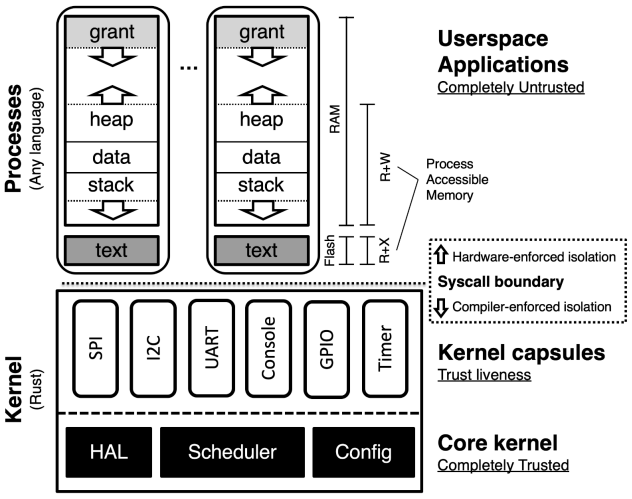

Figure 1. Tock's architecture (from Tock [4], with permission)

2.1 Tock: Isolation via MPUs

Figure 1 gives a high-level overview of the Tock architecture which is fashioned from three kinds of components that use a combination of static (language-based) and dynamic (hardware-based) mechanisms to ensure isolation.

Tock Architecture. First, *Processes* can be written in arbitrary languages and are completely untrusted. These processes are isolated from each other and from the kernel using hardware-based protection mechanisms. Second, *Capsules* (drivers) run at the same level as the kernel and are scheduled cooperatively. Capsule code is untrusted and must be written entirely in *safe* Rust, and hence enjoys the isolation guarantees provided by the language's type system. Finally, we have *Core kernel* components that can use unsafe Rust to (1) provide safe APIs that capsules can use (*e.g.* to access hardware registers), and (2) to configure memory protection. Hence, Tock's safety (isolation) guarantees rest wholly upon the correctness of the *core kernel*: the only layer in Tock trusted to enforce isolation.

Memory Protection Units (MPUs). Modern microcontrollers like the ARMv7-M and RISC-V come equipped with *memory protection units* (MPUs–often referred to as PMP for RISC-V), which are specialized hardware capable of defining and enforcing access controls on *regions* of memory, configured by a start address, a size, and permissions. Specifically, an OS kernel can dynamically configure the MPU to only allow specific combinations of read, write and execute access to specific regions of memory, and to disallow access to all others. Thus, MPUs isolate untrusted processes by ensuring that they only access their own memory, and not the memory of other processes or of the kernel.

Isolation via MPUs. The Tock kernel enforces isolation as follows. First, the kernel tracks the memory regions each

process is allowed to access with a dedicated MPU configuration for that process. The MPU is disabled when control switches into the kernel, and remains disabled during kernel execution. Then, right before it returns to process code, the kernel uses the MPU configuration to configure and enable the MPU to allow read-execute access to the process code, and read-write access to the process stack, data, and heap. Hence, the kernel isolates a process by using the MPU to prevent access of any memory address belonging to the kernel or other processes.

Challenge: MPU Configuration. Like most OSes, Tock's kernel provides several services to user-space applications, and must correctly track the MPU configuration while providing those services, or else risk breaking isolation. For example, the Tock kernel *allocates* the memory that is used by each user-space process for its stack and heap, as well as the kernel-owned *grant* region which is used to save critical information about the process and, thus, must *not* be accessible to user-space. Similarly, Tock provides *syscalls* that allow applications to request certain services of the kernel, *e.g.* the `brk` syscall which lets a process grow or shrink its heap. The implementations of the above must carefully track the accessible regions in the process's MPU configuration: any mistakes in doing so can break isolation.

Challenge: Interrupts and Context Switching. Context switching and interrupts are a critical piece of enforcing isolation. The Tock kernel is a single-threaded, event-driven system, and so interrupts and context switches drive the control flow of the operating system. To this end, Tock manages timers and interrupts to ensure that userspace processes are periodically preempted per a configured scheduling policy. Since an interrupt can preempt any part of kernel (or user process) execution, the (assembly) interrupt handlers that implement the context switching code—from kernel to process and back—must ensure that the MPU is appropriately enabled, and that crucial hardware registers are correctly saved and restored. Failure to do so can crash or corrupt kernel execution, and potentially break isolation.

2.2 Bugs Break Isolation

Tock's language and hardware protections go a long way in ensuring safety, but kernel bugs are not uncommon—and *do* break isolation [11, 19, 59]. Indeed, in verifying the original Tock kernel, we uncovered several new kernel bugs including logic errors, missed checks, and integer overflows, which can break isolation and which cannot be prevented by Rust's type system or run-time checks.[1]

Bug: MPU Configuration Logic. In verifying the ARM Cortex-M memory allocating code, we discovered that the original kernel could inadvertently allow a process to access kernel-owned grant memory [48]. When initially configuring the MPU for a process, Tock uses at most two MPU regions to cover the process stack, data, heap, *and* the kernel-owned grant memory region. This is accomplished using MPU subregions, which can be independently enabled or disabled to provide finer-grained access to memory than a single region (configured by a start address, size, and permissions) can provide. Specifically, the original Tock code enabled a contiguous series subregions to allow the process to access its stack, data, and heap, but *not* the grant region.

Unfortunately, the MPU has non-trivial constraints on the size and alignment of subregions, which affect the overall size of process memory (§ 3). These constraints introduced a possible scenario, where the last configured subregion for a process overlaps the kernel-owned grant region. While the code included a check for such overlaps, the readjustment was insufficient – the last subregion could still overlap the kernel-owned grant region, allowing a process to break out of its sandbox. To verify proper memory allocation, we wrote a postcondition on the memory allocating function specifying that the last enabled subregion should never exceed the start of the grant region. Flux reported that this postcondition could not be proved, revealing the previously unknown bug.

Bug: Interrupt Assembly Missed Mode Switch. The difficulty of MPU configuration is compounded by having to deal with interrupts and context switching. For example, whenever the kernel decides to run a process, or a process is preempted, inline assembly is executed to properly context switch. In addition to yielding execution to either the kernel or process correctly, the inline assembly must be sure to *switch* the CPU's execution mode as defined by the hardware. On ARM devices, this means setting the CPU to *unprivileged* execution mode when branching to a process and *privileged* execution mode when resuming kernel execution. Accidentally leaving the CPU in *privileged* mode when context switching means that a process can bypass the MPU protections the kernel carefully set up, breaking isolation. Unfortunately, we found this critical step was omitted in the inline assembly responsible for context switching, making Tock jump into process code while still in *privileged* execution mode [47].

Bug: Integer Overflow. When we initially ran Flux against the Tock kernel, Flux reported a series of possible integer overflows. However, tugging at these threads revealed serious isolation breaking bugs. When an application uses the `brk` or `sbrk` syscall to grow or shrink its memory, the kernel uses a method `update_app_mem_region` to update the MPU configuration appropriately. When checking this method, Flux flagged an expression `num_enabled_subregions0 - 1` as potentially *underflowing* to `usize::MAX`. To *verify* that this underflow did not occur, we added a *precondition* to the method relating the sizes of certain internal pointers. Upon doing so, Flux reported that the *calling* kernel method failed to

[1] Even if overflow checks were enabled in release builds, the failed check would cause a kernel panic that would crash the OS, and hence could enable denial of service attacks

uphold the precondition, as it did not correctly *validate* the sizes requested by the application's syscall [49]. Indeed, on further investigation we found that a malicious application could pass in parameters that bypassed the kernel's checks, and crash the kernel every time. While arguably a crash is not as bad as an isolation breaking bug, in this particular case, Tock got lucky: a similar underflow could just as easily have configured the MPU in a manner that breaks process isolation. By helping us formally guarantee the absence of overflows, Flux's verification helped us precisely identify the additional validation needed to protect the kernel.

2.3 Formally Verified Isolation

We developed TickTock, a fork of the Tock OS kernel that eliminates isolation bugs by construction. TickTock formally verifies that a process can access its code in flash, and its stack, data, heap and *nothing else* (especially no kernel memory). We assemble TickTock from three key pieces.

1: Decoupling MPU and Kernel Logic. Verification of the Tock kernel made it clear that the complexity and errors in the MPU-configuring code arise in part because the current *monolithic* abstraction used to configure MPUs entangles MPU constraints with the kernel's process logic. Additionally, we found that refactoring the code not only simplified verification, but also removed expensive and easy-to-miss checks critical to enforcing isolation. TickTock's first piece is this verification guided granular MPU abstraction that separates the concerns of the kernel and MPU (§ 3).

2: Verifying Kernel, MPU, and Bridge Logic. Next, we verify that TickTock enforces isolation using Flux: a refinement type checker for Rust [34] that lets programmers specify and verify invariants for types and contracts for Rust functions. Concretely, we use Flux to define key isolation invariants over the kernel's *logical* view of process memory required for isolation, invariants relating this logical layout to that of the *MPU configuration*, and finally that the ARMv7-M and RISC-V hardware enforces the MPU configuration (§ 4).

3: Verifying Interrupts and Context Switching. Finally, for the ARMv7-M architecture, we verify that process isolation holds in the presence of interrupts and context switching which are implemented with inline assembly. To do so we develop FluxArm, a new executable specification of the ARMv7-M assembly by lifting ASL to Rust and formalizing the semantics with Flux contracts. This allows us to verify isolated interrupt handling programs, the ARM hardware's interrupt semantics, and the entire control flow of an interrupt to ensure that the code preserves the machine invariants required for isolation (§ 4.5).

2.4 Flux

Flux is an SMT backed refinement type checker for Rust that enables developers to specify correctness properties and have them verified at compile time [34]. Refinement type systems combine types and predicates to allow programmers to write automatically checked contracts about a program's expected behavior. Flux extends Rust's type system, and thus provides verification capabilities without the complexity typically associated with formal verification approaches.

Built-in Safety Checks. Out of the box, Flux provides automatic verification for several classes of safety properties without any annotation overhead. For example, Flux checks all arithmetic operations for potential overflows, checks all array and vector accesses are within bounds, and checks all arithmetic for division by zero.

Key Specification Features. We use three primary Flux mechanisms to formally specify and prove process isolation in TickTock. *Invariants* allow developers to express properties that must hold through the lifetime of a data structure. For example, the code below uses an invariant on the `NonEmptyRange` data structure to *statically* check that any instance of `NonEmptyRange` has an `end` greater than its' `start`.

```
pub struct NonEmptyRange
    invariant end > start
{
    start: usize,
    end: usize
}
```

Preconditions and *postconditions* are used to specify contracts about legal inputs and outputs of a function. Preconditions specify requirements that must be satisfied when a function is called, and postconditions describe guarantees about a function's behavior upon completion, enabling callers to reason about the function's outputs. For example, the method `update_end` updates the `end` of a `NonEmptyRange`.

```
impl NonEmptyRange {
    pub fn update_end(&mut self, end: usize)
        requires end > self.start
        ensures self.end == end
    {
        self.end = end;
    }
}
```

In order to satisfy the invariant, we use a precondition (specified via the keyword `requires`) that ensures all callers of the method provide a new `end` greater than the current `start`. Additionally, we use a postcondition (specified via the keyword `ensures`) to reason about the precise values of `end` upon function completion. Flux checks that the postcondition and invariant hold against the body of the method.

3 Redesigning the MPU Abstraction

MPU capabilities, and hence, configurations, vary widely across different platforms. Early, single-architecture versions of Tock were tightly coupled to the MPU, and used its constraints to dictate process memory layout. Recent versions support multiple architectures, and hence, decouple the process layout from the MPU. We found that much of the complexity of the MPU configuration, and the attendant bugs,

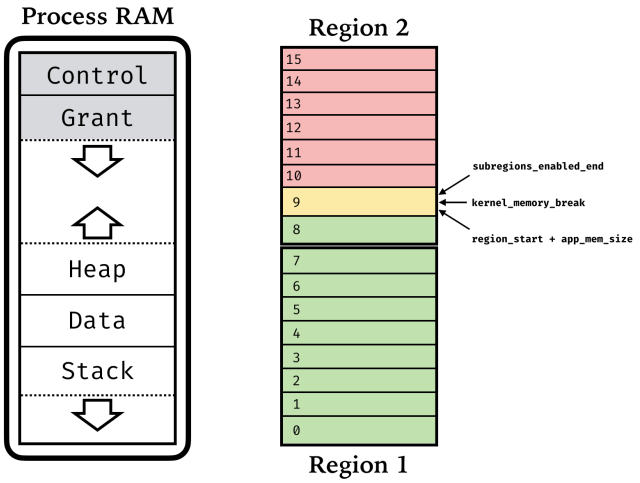

Figure 2. (L) Tock process memory layout (R) MPU Overlap

```rust
trait MPU {
  type MpuConfig;

  fn allocate_app_mem_region(
    &self,
    unalloc_start: *const u8,
    unalloc_size: usize,
    min_size: usize,
    app_size: usize,
    kernel_size: usize,
    permissions: Permissions,
    config: &mut MpuConfig,
  ) -> Option<(PtrU8, usize)>;

  fn update_app_mem_region(
    &self,
    new_app_break: *const u8,
    kernel_break: *const u8,
    permissions: Permissions,
    config: &mut MpuConfig,
  ) -> Result<(), ()>;

  fn configure_mpu(
    &self,
    config: &MpuConfig
  );
}
```

(a) Tock's Original Monolithic MPU Abstraction

```rust
trait MPU {
  type Region: RegionDescriptor;

  fn new_regions(
    max_region_id: usize,
    unalloc_start: PtrU8,
    unalloc_size: usize,
    total_size: usize,
    permissions: Permissions,
  ) -> OptPair<Region, Region>;

  fn update_regions(
    max_region_id: usize,
    region_start: PtrU8,
    available_size: usize,
    total_size: usize,
    permissions: Permissions
  ) -> OptPair<Region, Region>;

  fn configure_mpu(
    &self,
    regions: &[Region]
  );
}
```

(b) TickTock's New Granular MPU Abstraction

Figure 3. Tock and TickTock MPU Abstractions

had to do with the difficulty of designing an abstraction that balances the kernel's requirements with those of the underlying hardware. First, we describe these requirements (§ 3.1), and discuss how Tock's monolithic abstraction makes code complex, leading to security bugs (§ 3.2). Then, we show that the current abstraction leads to scenarios where the kernel's view diverges from the actual hardware-enforced layout, leading to unintuitive checks that *must* be present to enforce isolation. Finally, we present a new granular abstraction that keeps the views aligned. This makes the code simpler, easier to verify, and more efficient to execute (§ 3.5).

3.1 Requirements

Kernel Requirements. Figure 2 shows the layout of application (process) memory in the Tock OS. The stack, data, heap, and grant regions are all allocated in RAM. The stack grows downwards to the start of the process's allocated memory region. The process heap and grant regions grow up and down towards each other. Hence, the kernel's task is to configure the MPU to ensure that it allows access to the (white) stack, data, and heap, but *not* the (grey) grant region.

Hardware Requirements. It is rather tricky to actually enforce the kernel's requirements with MPUs, as MPUs have their own constraints on the structure of enabled or disabled addresses. For example, the ARM Cortex-M MPU has strict region size and alignment constraints: the sizes must be powers of two, starting from a minimum of 32 bytes and start addresses must be aligned to the region size. Further, Cortex-M regions are divided into eight *equal-sized* subregions which can be independently enabled or disabled. This allows finer-grained memory access controls than a single region can provide. As shown on the right in Figure 2, the Tock kernel uses this feature by covering the process stack, data, heap, and kernel-owned grant region with *two* MPU regions. The kernel disables subregions covering the grant region and enables subregions covering the application's stack, data, and heap.

3.2 A Monolithic Design

Figure 3a summarizes Tock's existing monolithic design which abstracts the MPU within a single high-level interface (Rust `trait`) which exposes operations that *allocate* and *update* memory regions for a process. Next, we describe this abstraction and show two problems. First, it *entangles* hardware constraints and process memory allocation, leading to complex code and security bugs. Second, it discards computed values, ultimately causing *disagreement* between what the kernel requires and what the MPU provides, resulting in the kernel performing redundant and easy-to-miss checks which involve re-computations of the MPU configuration in order to ensure isolation.

The method **`allocate_app_mem_region`** is responsible for initially allocating application memory when Tock first loads processes from flash. The method takes as arguments the current available RAM (`unalloc_start` and `unalloc_size`), the memory the application requested (`app_size`), and the memory needed for the kernel's grant region (`kernel_size`). Finally, it takes and updates an MPU Configuration (`config`), which is a representation of the process's MPU regions.

The method **`update_app_mem_region`** changes the MPU configuration when the application requests the kernel grow or

```rust
fn allocate_app_mem_region(
  &self,
  unalloc_start: *const u8,
  unalloc_size: usize,
  min_size: usize,
  app_size: usize,
  kernel_size: usize,
  ...
) -> Option<(*const u8, usize)> {
  ...
  // Make sure there is enough memory for app memory and kernel memory.
  let mem_size = cmp::max(
      min_size,
      app_size + kernel_size,
  );
  let mut mem_size_po2 = math::closest_power_of_two(mem_size as usize);
  ...
  // The region should start as close as possible to start of unallocated memory.
  let mut region_start = unalloc_start as usize;
  let mut region_size = mem_size_po2 / 2;

  // If the start and length don't align, move region up until it does.
  if region_start % region_size != 0 {
      region_start += region_size - (region_start % region_size);
  }
  let mut num_enabled_subregs = app_size * 8 / region_size + 1;
  let subreg_size = region_size / 8;

  // Calculates the end address of enabled subregs and initial kernel memory break
  let subregs_enabled_end = region_start + num_enabled_subregs * subreg_size;
  let kernel_mem_break = region_start + mem_size_po2 - kernel_size;

  if subregs_enabled_end > kernel_mem_break {
    region_size *= 2;
    if region_start % region_size != 0 {
      region_start += region_size - (region_start % region_size);
    }
    num_enabled_subregs = app_size * 8 / region_size + 1;
  }
  ...
  Some((region_start as *const u8, mem_size_po2))
}
```

(a) Tock's Original Memory Allocation Implementation

```rust
fn allocate_app_mem_region(
  unalloc_start: PtrU8,
  unalloc_size: usize,
  min_size: usize,
  app_size: usize,
  kernel_size: usize,
  ...
) -> Result<Self, AllocateAppMemoryError> {
  let mut regions = Self::new_regions();
  ...
  // ask MPU for <= two regions covering process RAM
  let ideal_app_mem_size = cmp::max(min_size, app_size);
  let Pair { fst: ram_region0, snd: ram_region1 } = MPU::new_regions(
    MAX_RAM_REGION_NUMBER,
    unalloc_mem_start,
    unalloc_mem_size,
    ideal_app_mem_size,
    mpu::Permissions::ReadWriteOnly,
  )
  .ok_or(AllocateAppMemoryError::HeapError)?;

  // Compute actual memory start and size using `Region`s above
  let memory_start = ram_region0.start().ok_or(())?;
  let snd_region_size = ram_region1.size().unwrap_or(0);

  let app_mem_size = ram_region0.size().ok_or(())? + snd_region_size;
  // End of process-accessible memory
  let app_break = memory_start.as_usize() + app_mem_size;

  let breaks = AppBreaks::new(
    mem_start,
    app_break,
    kernel_size,
    ...
  );
  // Set the RAM regions
  regions[MAX_RAM_REGION_NUMBER - 1] = ram_region0;
  regions[MAX_RAM_REGION_NUMBER] = ram_region1;

  Ok(Self { breaks, regions })
}
```

(b) TickTock's New Memory Allocation Implementation

Figure 4. Tock and TickTock ARM Cortex-M Memory Allocation Implementations

shrink its memory via the `brk` or `sbrk` syscall. It takes as arguments the desired end of the process heap (`new_app_break`) and the current start (*i.e.* lowest address) of the kernel owned grant region of memory (`kernel_break`). It then updates the MPU configuration for the process (`config`) to give the process access to its new stack, data, and heap but *not* the grant region.

Problem: Entanglement. The monolithic abstraction entangles the details of process memory layout and the hardware constraints, leading to complex code that opens the door to security bugs. Consider the Cortex-M implementation of the `allocate_app_mem_region` trait method shown in Figure 4a. The method starts by trying to compute a total size that the process memory block can fit in on lines 12 and 16. Recall that the ARM Cortex-M MPU requires that the MPU region sizes be powers of two. This detail leaks into the process memory layout, making the total process memory block size a power of two. Additionally, details about start address alignment leak into these computations on lines 23–25. Then, on lines 26–31, the method computes the MPU region configuration required to allow the process to access everything from `region_start` to `region_start + app_size`, *i.e.* the space that will be occupied by the process stack, data, and heap. In particular, the method tries to use two Cortex-M regions, spanning 16 equal-sized subregions, taking care to *only enable* the subregions covering the process' accessible data, stack, and heap. However, due to a subtle error described in detail in section 3.4 the code inadvertently *also* ends up allowing access to the grant region, breaking isolation.

Problem: Disagreement. The monolithic abstraction creates a disagreement between what the kernel *believes* the MPU configuration is, and how the MPU is *actually* configured. The `allocate_app_mem_region` method in Figure 3a computes the end of both the process heap (`subregs_enabled_end`) and the kernel owned grant region of memory (`kernel_mem_break`), but then discards them, returning only the process memory's start `region_start` and size `mem_size_po2`. Clients of this method, like Tock's process loading code, first invoke

the method to (1) allocate memory for the process *and* (2) update the MPU configuration accordingly. However, the process loader only has access to the returned start and size, so it must *redo* the work of carving the remaining pool of RAM into process-accessible memory and kernel grant memory. This recomputation is not just wasteful; crucially, it *always* introduces a *disagreement* between what was actually configured in the hardware (determined inside the call to `allocate_app_mem_region`) and what the kernel believes is the actual memory layout for the process (recomputed inside the process loader).

3.3 Verification Roadmap

Having outlined the key problems with the existing abstraction, we now describe how our verification efforts helped discover these issues and guided our redesign process. We first focused on verifying the existing Tock code. To do so, we had to make small modifications to the monolithic MPU interface shown in Figure 3a. We describe these changes in section 3.4 and explain that once we made these changes, we caught subtle bugs in the existing implementations of this interface. Based on our experience finding and fixing these bugs, we developed a new design of the MPU interface, which we describe in detail in section 3.5.

3.4 Verification-guided Redesign

Our attempt to verify the Tock kernel surfaced the problems of *entanglement* and *disagreement*, and then guided a two-step redesign of the kernel-MPU interface that enabled formally verified isolation.

Step 1: Explication. Recall that the `allocate_app_mem_region` both *allocates* the memory for the process and *updates* the MPU configuration to reflect the allocation. However, the method discards the intermediate results delineating the process- and kernel-accessible memory, returning only the start and size. In particular, the method does not return the exact regions where the process is actually allowed access by the updated MPU configuration. This makes it impossible to even *formally specify* the correctness of the MPU configuration, with respect to the kernel's view of process memory (c.f. Figure 2).

Thus, our first step was to explicitly return these values using a new `struct`, `AllocatedAppBreaksAndSize`, whose fields contain the exact process memory layout the MPU was configured to enforce. This let us formally specify a postcondition contract for `allocate_app_mem_region` that said that the returned struct's fields satisfied the invariants informally shown in Figure 2, in particular, that the process accessible region *did not overlap* the kernel-accessible grant region.

Step 2: Abstraction. When we wrote the contract, Flux complained that method failed its post-condition. Recall that the method attempts to do the allocation using two Cortex-M regions, spanning 16 equal-sized subregions, taking care to *only enable* the subregions covering process-accessible data. The code for doing so was incorrect: `subregs_enabled_end`, computed on line `30`, corresponds to the end of the MPU enforced process-accessible region. Similarly, `kernel_mem_break`, on line `31`, corresponds to the initial end of the kernel owned grant region of memory. Because `region_start` might shift to align with `region_size`, `subregs_enabled_end` may *exceed* the ideal end of the process heap, computed as `region_start + app_size`. The overlap between the end of the MPU enforced memory and the end of the kernel's grant region creates the dangerous scenario illustrated on the right in Figure 2, where the last enabled subregion is 9. Though the `kernel_mem_break` is after the ideal end of the process heap (`region_start + app_size`), it is before `subregs_enabled_end` which means that the end of the grant region and the end of the process heap are in the same *enabled*, and thus accessible, subregion. This means the process can access grant memory, breaking isolation.

Tock's developers added the check on line `33` to defend against such overlaps. Crucially, lines `34 - 38` *should* adjust the memory layout so that the enabled subregions do not overlap kernel memory by doubling the region size and recomputing the start address to be aligned to the new region size. Unfortunately, this fails to mitigate the scenario in Figure 2 as doubling the region size *also* doubles the subregion size. Therefore, in most scenarios, the MPU enforced memory (`subregs_enabled_end`) *still* overlaps the grant region owned by the kernel.

Verification helped pinpoint the bug and validate the fix, which was to *also* double `mem_size_po2`, as suggested in a preceding comment, but absent from the code. Thus, the exercise of verifying the existing code revealed that the low-level details of the region representation and manipulation should be entirely *factored out* of the kernel's allocation code, to entirely eliminate bugs arising due to entanglement and disagreement.

3.5 A Granular Redesign

TickTock solves the entanglement and disagreement problems with a new granular abstraction that focuses solely on the details needed to configure regions on MPU hardware, while ensuring that the process abstraction exposes precisely what the hardware enforces. The key insight is that we can abstract the hardware details under two interfaces: (1) a `RegionDescriptor` interface that abstractly characterizes the properties of a single MPU-enforced hardware region while hiding the hardware details entirely, and (2) an `MPU` interface that has methods to create and modify regions. Next, we describe the above abstraction, and show how it disentangles the kernel's requirements from the low-level hardware constraints, enabling verified and efficient process isolation.

```
trait RegionDescriptor {
  fn start(&self) -> Option<PtrU8>;
  fn size(&self) -> Option<usize>;
  fn overlaps(&self, start: usize, end: usize) -> bool;
  ...
}
```

Figure 5. A subset of the `RegionDescriptor` Abstraction

The* `RegionDescriptor` *Abstraction. summarized in Figure 5 characterizes a single contiguous memory *region*. Intuitively, each region is simply a range, constituting a start address and size, which are respectively returned by the `start` and `size` methods. For ARMv7-M MPU implementation, the `start` and `size` return the accessible start and size as determined by subregions. For the RISC-V PMP implementation, the start and size of the full region are returned, as the RISC-V PMP is far more flexible in terms of region start addresses and sizes. Thus, the `RegionDescriptor` abstracts hardware-specific details about alignment, subregions, *etc.*

The* `MPU` *Abstraction. shown in Figure 3b does the actual work of configuring the MPU. The methods in this abstraction are oblivious to application process layout, and instead deal exclusively with configuring hardware or creating regions with the hardware's restrictions in mind. The interface is parameterized by the *associated* type `Region` which implements the `RegionDescriptor` interface and whose exact representation depends on the hardware implementing the interface. The method `new_regions` takes in the highest region ID reserved for the process RAM, *available* memory start and memory size, a *requested* total size, and the desired access permissions for the new region. The method returns up to two contiguous `Regions` *if* they can be created within the block of available memory, spanning at least the requested total size, while satisfying the underlying hardware constraints. Similarly, the `update_regions` method takes in the highest region ID reserved for the process RAM, the desired start address, available size, and desired new total size and permissions, and again, returns the updated `Regions` if possible. Finally, the `configure_mpu` method configures the MPU hardware to only allow access to the provided list of `Regions`. The new granular abstraction decouples the kernel's requirements from the hardware constraints.

Hardware-agnostic Process Allocation. TickTock refactors the kernel process allocator to be *generic* over the `MPU` and `RegionDescriptor` abstraction, which lets it reuse the same code across all architectures that implement those traits. Figure 4b shows the refactored process allocator. At a high level, the code invokes `new_regions` to obtain—if feasible under the hardware constraints—up to two contiguous `Regions` in the current RAM pool of the given size. If the MPU abstraction succeeds in creating these regions (`ram_region0`, `ram_region1`), the allocator then uses the `RegionDescriptor` interface to compute the *actual* start and size of the process memory block according to hardware, and then creates and stores these in a data structure called `AppBreaks` that saves the pointers describing the actual MPU hardware-enforced layout along the actual MPU configuration.

Solution: Entanglement. TickTock uses the granular abstraction to implement the process allocator independently of the underlying hardware constraints, which are handled within the `new_regions` invocation. That is, the allocation code itself does not have to reason about subregions and power-of-two constraints. Instead, the kernel requests from the `MPU` two contiguous regions spanning at least `app_size`. Then, using these regions, the kernel can simply place the grant region of memory after the end of the process accessible heap.

Solution: Disagreement. Similarly, since the region `start` and `size` can easily be obtained from the `RegionDescriptor` trait, the kernel is no longer required to recompute values related to process memory. The kernel tracked end of process's memory is now computed *exactly* from the hardware-enforced layout. That is, the granular abstraction helps make the code simpler with respect to enforcing process isolation, *and* allows reusing the same allocation code across different architectures.

4 Verification

TickTock's granular redesign of the MPU interface (§ 3.5) simplifies isolation by decoupling the kernel's requirements from the hardware constraints. However, even with this simpler interface, getting process isolation right is still tricky. The high level software description of regions – stored by the kernel – must be correctly translated into individual bits written to hardware registers to configure the MPU. To address this problem, TickTock formally verifies isolation: no userspace process can interfere with the memory of the kernel or other processes.

We structure the proof into four parts. (1) First, we *refine* the methods of the granular interface (Figure 3) with contracts that describe how the MPU drivers create and update regions (§ 4.1); (2) Second, we verify that the kernel's *logical* view of memory matches Tock's memory model specification (§ 4.2); (3) Third, we *use* the refined methods of the granular interface to verify that the kernel's logical view of memory matches the *physical* memory layout actually enforced by the MPU; and (4) Finally, we verify that the each (architecture-specific) MPU driver correctly *implements* the refined contract, *i.e.*that each driver creates and updates regions by configuring the hardware bits in a way that matches the region start, size, and permissions, as required by the kernel to enforce isolation (§ 4.4). Note that the granular redesign ensures that only (4) is architecture-dependent: the rest of the proof generalizes across architectures. We conclude this section by explaining how TickTock handles two

features that complicate this proof: interrupts (§ 4.5) and DMA (§ 4.6).

4.1 A Refined MPU Interface

Recall that Figure 3a summarizes the key methods of our new granular MPU interface which abstracts away details of specific MPU implementations from the kernel code, allowing us to *reuse* the same kernel code across different architectures. However, to *verify* the kernel code in a modular, architecture-agnostic way, we need a way to refine the methods of the MPU interface with contracts that are precise enough to describe how the hardware was configured, but abstract enough to be independent of any particular architecture.

Associated Refinements. In Flux, we can do so by defining *associated refinements* with the `RegionDescriptor` trait (Figure 5), that characterize logical properties of each region, which (1) can be *used* to specify contracts about abstract regions in the kernel, (2) must be *defined* as concrete refinements in each individual MPU driver implementation.

```
trait RegionDescriptor {
  #[assoc] fn start(r: Self) -> int;
  #[assoc] fn size(r: Self) -> int;
  #[assoc] fn is_set(r: Self) -> bool;
  #[assoc] fn matches(r: Self, p: Permissions) -> bool;
  #[assoc] fn overlaps(r1: Self, lo: int, hi: int) -> bool;

  #[assoc] #[final]
  fn can_access(r: Self, start: int, end: int, perms: Permissions) -> bool {
    <Self>::is_set(r) &&
    start == <Self>::start(r) &&
    end == <Self>::start(r) + <Self>::size(r) &&
    <Self>::matches(r, perms)
  }
  ...
}
```

The trait specification says that any `RegionDescriptor` implementation must also furnish Flux with definitions of the refinements `start`, `size`, `is_set`, `perms`, and `overlaps` methods, but the exact implementation details may vary between different MPU architectures. The associated refinement `can_access` is *final*, meaning that it is defined directly using the other associated refinements and not re-defined by individual hardware drivers.

Refined Method Contracts. We use the associated refinements to refine the methods of Figure 3b with pre- and post-conditions that characterize the properties of the created and updated regions. For example, the method `update_regions` is given the following refined contract which says that the regions returned by the method are indeed configured to be accessible with the `permissions` specified by the kernel. Note that the actual implementation of `size` and hence `can_access` will depend on the underlying hardware's architecture.

```
fn update_regions(
  reg_id: usize,
  reg_start: PtrU8,
  available_size: usize,
  total_size: usize,
  permissions: Permissions
) -> OptPair<
  {r1: Region |
     let end = reg_start + Region::size(r1);
     Region::can_access(r1, reg_start, end, permissions)},
  {r2: Region |
     let start = Region::start(r2);
     let end = start + Region::size(r2);
     Region::is_set(r2) => {
        Region::can_access(r2, start, end, permissions) &&
        ...
     }
  }
  >{...}
```

```
pub struct AppBreaks
  invariant
    kernel_break <= memory_start + memory_size &&
    memory_start <= app_break &&
    app_break < kernel_break
{
    pub memory_start: PtrU8,
    pub memory_size: usize,
    pub app_break: PtrU8,
    pub kernel_break: PtrU8,
}
```

Figure 6. The kernel's logical view of process memory.

4.2 Verifying the Kernel's Logical View of Memory

TickTock verifies that the logical process memory layout (as stored in the kernel) matches Tock's application memory layout policy, as shown in Figure 2.

Process Memory Layout Invariants. The process memory layout is stored in a per-process data structure `AppBreaks`, abbreviated in Figure 6, which stores pointers that describe each process's memory layout. To ensure none of the pointers in `AppBreaks` violate the intended process memory layout, TickTock checks a series of invariants which express these pointers' expected relationships in memory (Figure 2).

- `kernel_break <= memory_start + memory_size` checks that the beginning of the grant region of memory (*i.e.* lowest address) is always within the process memory block,
- `memory_start <= app_break` ensures that the end of the process RAM is always greater than or equal to the start of the process memory block, and
- `app_break < kernel_break` ensures that the end of the process RAM and the beginning of grant memory never overlap (*i.e.* the bug described in § 3.4).

Flux statically verifies that these invariants hold anywhere in the code that an `AppBreaks` is *created* or an existing instance is *updated*, *e.g.* through a mutable reference. Crucially, these invariants will catch any buggy code causing the `app_break` to overlap kernel memory in (*e.g.*) the `brk` syscall (responsible for updating the size of the process accessible memory in RAM). The challenge, then, is proving that this logical representation actually holds throughout the kernel, and that this logical representation matches the hardware implementation.

4.3 Verifying Logical-MPU View Correspondance

Next, TickTock uses the (abstract) region's associated refinements to specify and verify that the kernel's logical view of memory (as stored in `AppBreaks`) precisely matches the memory layout that the MPU enforces.

Specifying Logical-MPU View Correspondance. In the kernel, `AppMemoryAllocator` stores both the `AppBreaks` described above, and an array of MPU regions to be written to hardware. Here, we specify that the array of regions – (`RArray<R>`), where `R` implements the `RegionDescriptor` trait – should *allow* access to the application code (in flash), and application stack, data, and heap (in RAM), but should *disallow* access to any other memory. We can specify this property as an invariant of the `AppMemoryAllocator` struct as shown below:

```
struct AppMemoryAllocator<R: RegionDescriptor>
  invariant
    can_access_flash(breaks, regions) &&
    can_access_ram(breaks, regions) &&
    cannot_access_other(breaks, regions)
{
    pub breaks: AppBreaks,
    pub regions: RArray<R>,
}
```

We use the associated refinements of `RegionDescriptor` to define `can_access_flash`, `can_access_ram`, and `cant_access_other`, which respectively specify that the process is allowed read-execute access to the flash region, read-write access to the RAM region, and disallowed access to any other memory, in particular, the kernel-accessible grant region. For example, `can_access_flash` is defined as:

```
fn can_access_flash<R>(breaks: AppBreaks, regions: RArray<R>) -> bool {
  let r = regions[FLASH_REGION_NUMBER];
  let rx_perms = Permissions::ReadExecute;
  let start = breaks.flash_start;
  let end   = breaks.flash_start + breaks.flash_size;
  <R as RegionDescriptor>::can_access(r, start, end, rx_perms) &&
  !<R as RegionDescriptor>::overlaps(r, 0, start - 1) &&
  !<R as RegionDescriptor>::overlaps(r, end + 1, u32::MAX)
}
```

Similarly, `cannot_access_other` specifies that none of the eight regions *except* than the RAM regions (`0` and `1`) should overlap the process-accessible memory block:

```
fn cannot_access_other<R>(breaks: AppBreaks, regions: RArray<R>) -> bool {
  let start = breaks.memory_start;
  let end = breaks.memory_start + breaks.memory_size;
  forall i: int in 2..8 {
    let r = regions[i];
    !<R as RegionDescriptor>::overlaps(r, start, end)
  }
}
```

Verifying Logical-MPU View Correspondence. Flux verifies that the above invariant holds whenever a value of type `AppMemoryAllocator` is created or updated, *e.g.*, in the function `allocate_app_mem_region` from Figure 4b, the invariants are established by calling functions that set up different parts of process memory. For example, `create_regions` creates RAM MPU regions, while `create_exact_region` creates a Flash MPU region. Each function's postconditions establish part of the overall invariant. For instance, when `allocate_app_mem_region` calls `create_exact_region`, the latter's postcondition establishes `flash_can_access`.

4.4 Verifying TickTock's MPU drivers

Finally, we verify that the individual, architecture specific, MPU drivers uphold their part of the bargain by verifying that their `RegionDescriptor`, and hence, `MPU` implementations, satisfy the refined contracts from § 4.1. To do so, we must verify that the code interacts with the MPU hardware correctly to create regions that (1) are well formed according to the logical constraints expressed in the kernel, and (2) satisfy hardware requirements and properly encode logical values as bits used to configure the hardware.

Representing Hardware Regions. The pillar of this part of the proof is a refined representation of the `struct` that represents the configuration of a single hardware MPU region. For example, the following shows (a simplified version of) the implementation of regions in the ARMv7-M Cortex-M MPU driver which comprises a pair of two 32-bit registers: an `rbar`, *base-address* register, and a `rasr`, *region attributes* register, whose values represent the contents of the hardware:

```
struct CortexMRegion {
    rbar: FieldValueU32<RegionBaseAddress::Register>,
    rasr: FieldValueU32<RegionAttributes::Register>,
}
```

Hardware Semantics as Logical Refinements. Next, using the ARMv7-M ISA, we write specifications for the associated refinements needed to implement the `RegionDescriptor` trait.

```
impl RegionDescriptor for CortexMRegion {
  #[assoc] fn start(r: CortexMRegion) -> int {
    r.reg & 0xFFFF_FFE0
  }

  #[assoc] fn size(r: CortexMRegion) -> int {
    let reg = r.rasr;
    let size_base2 = (reg & 0x0000003e) >> 1;
    exp2(size_base2 + 1)
  }

  #[assoc] fn is_set(r: CortexMRegion) -> bool {
    r.rasr & 0x1 != 0
  }

  ...
}
```

Flux uses these specifications to verify that the actual implementations of the MPU methods (*e.g.* `allocate_regions` and `update_regions` from Figure 3b) for the CortexM driver indeed satisfy their refined contracts. In other words, Flux verifies that the bits of the `rbar` (base address) and `rasr` registers are flipped to precisely match the logical values that the kernel tracks, *e.g.*in `AppBreaks` (§ 4.2), and `AppMemoryAllocator` (§ 4.3), thereby formally verifying that the MPU is configured in a way that allows the kernel to enforce isolation.

4.5 Reasoning about interrupts

Like many OSes, Tock pervasively uses interrupts to handle hardware events or context switching between kernel and

```
pub struct Arm7 {
  // General Registers r0-r11
  pub regs: GeneralRegs,
  // Stack Pointer
  pub sp: SP,
  // Control register
  pub control: Control,
  // Program Counter
  pub pc: BV32,
  // Link register
  pub lr: BV32,
  // program status register
  pub psr: BV32,
  // Memory
  pub mem: Memory,
  // current CPU mode
  pub mode: CPUMode,
}
```

```
// `msr` moves the value in general register to
// given special reg. Manual pp A7-301 & B5-677
fn msr(
    self: &strg Arm7[@old],
    reg: SpecialRegister,
    val: GPR
) requires
    !is_ipsr(reg) &&
    (is_sp(reg) || is_psp(reg)) =>
        is_valid_ram_addr(get_gpr(val, old))
  ensures
    self: Arm7[set_spr(reg,old,get_gpr(val,old))]
{
    self.update_special_reg_with_b32(
      register,
      self.get_value_from_general_reg(&val)
    );
}
```

Figure 7. FluxArm: (L) CPU State, (R) `msr` instruction

```
fn sys_tick_isr(
  self: &strg Arm7[@old]
) -> BV32[0xFFFF_FFF9]
  requires
    mode_is_handler(old_cpu.mode)
  ensures
    self: Arm7[cpu_post_sys_tick_isr(old)]
{
  let lr = SpecialRegister::lr();
  self.movw_imm(GPR::R0, 0);
  self.msr(
    SpecialRegister::Control,
    GPR::R0);
  self.isb(Some(IsbOpt::Sys));
  self.pseudo_ldr_special(
    lr,
    0xFFFF_FFF9);
  self.get_value_from_special_reg(lr)
}
```

```
fn control_flow_kernel_to_kernel(
  self: &mut Arm7[@old],
  exception_num: u8
) requires
    15 <= exception_num &&
   mode_is_thread_privileged(
     old.mode,
     old.control)
  ensures self: Arm7[#new],
    cpu_state_correct(new,old)
{
  // context switch asm
  self.switch_to_user_part1();
  // run a process
  self.process();
  // preempt process w/ exception
  self.preempt(exception_num);
  // run rest of the context switch
  self.switch_to_user_part2();
}
```

Figure 8. FluxArm: (L) System Timer Handler, (R) Modeled Context Switch

user processes. Interrupts are handled via a top-bottom half strategy, similar to many other mainstream OSes. All Tock top-half handlers are written in *inline assembly*, and are responsible for properly switching to and from the kernel. While the handlers are short in size, missed details in the low-level assembly can have severe consequences. For example, as shown in § 2.2, failing to appropriately configure the CPU for process or kernel execution can nullify the efforts made to correctly configure the MPU.

TickTock verifies isolation in the presence of interrupts for ARMv7-M architectures using FluxArm—a new Rust-executable formal semantics of the ARMv7-M Instruction Set Architecture (ISA)—to model Tock's interrupt handlers and context switching code. We then use Flux to verify that crucial hardware state is preserved between interrupts firing and subsequent kernel execution, and that upon returning to the kernel, the hardware's configuration matches what the kernel requires for isolation.

Modeling Assembly via FluxArm. We defined FluxArm, an *executable* formal semantics of (the Tock-relevant subset of) the ARMv7-M ISA, by writing an emulator in Rust and writing Flux contracts that specify what each instruction does to the hardware state. The left side in Figure 7 shows the CPU state we model in FluxArm, and the right side shows the semantics of the `msr` instruction that is both executable Rust, and has a formal semantics specified as a Flux contract.

Modeling Handlers. The left in Figure 8 shows the FluxArm model of Tock's timer interrupt handler: a short sequence of assembly instructions represented by the corresponding sequence of FluxArm method calls.

Modeling Switching. The right side shows the FluxArm model of context switching and interrupts from kernel to process, and back to kernel. First, `switch_to_user_part1` models how Tock switches to a process, via code that ensures the hardware is properly configured to run a process (*e.g.* the CPU is in unprivileged mode). Second, `process` models an arbitrary process execution, via a *postcondition* that formalizes the assumptions we can make about the process's effect on memory, *i.e.* that erases all the information currently known about the state of the hardware registers and the process region of memory. Next, we model the triggering of an arbitrary interrupt using the method `preempt` which formalizes how ARMv7-M behaves when exceptions occur by *saving* the caller-saved registers on the stack, using the exception number to decide which `isr` (interrupt handler) to call, and then once the handler finishes, restoring the caller-saved registers off the stack before yielding control back to the specified target (which we verify to be the kernel). We verify that the sequence above doesn't break isolation, with the postcondition `cpu_state_correct` which checks that all the callee-saved registers, kernel's stack pointer, are equivalent upon entry and exit (`old` and `new`) and the CPU is in privileged execution mode.

Note that our verification of the interrupt handlers and hardware semantics only has to reason precisely about the correctness of the *updated* memory. Crucially, we do not need to assert anything about the state of the *kernel's* memory, as (verified) correct configuration of the MPU and CPU execution mode ensures the user process cannot write to any memory other than its own.

4.6 Reasoning about DMA

DMA is used by several chip-specific drivers to efficiently transfer data buffers in Tock. Unfortunately, DMA poses a potential escape hatch to circumvent verification. A driver typically configures the DMA engine by writing to a base pointer-and-length field register. As an MMIO interface, these registers writes occur using just plain `usize` values. This is problematic because just by choosing appropriate `usize` values, the driver can make DMA overwrite memory in a way that violates TickTock's memory invariants or

```rust
pub struct DmaCell<'a, T> { val: OptionalCell<&'a mut T> }
pub struct DmaWrapper { val: usize }

impl<'a, T> DmaCell<'a, T> {
  /// Retrieve buffer when DMA operation finishes; marked `unsafe`
  /// as we must ensure DMA operation is completed before calling.
  pub unsafe fn completed(&self) -> Option<&'a mut T> {
    self.val.take()
  }
  pub fn place(&self, val: &'a mut T) -> Option<DmaWrapper> {
    if self.val.is_some() {
      None // Cannot replace, DMA in progress
    } else {
      let res = Some(val as *const T as usize);
      self.val.set(val);
      DmaWrapper::new(res)
    }
  }
}
```

Figure 9. `DMACell`: A safe DMA interface

Rust's type-soundness! Tock provides a `TakeCell` type *intended* to soundly represent DMA, by obtaining ownership of a given buffer while DMA operations may occur. However, we discovered an instance in which `TakeCell`s can be misused to break Rust's single ownership, by letting the driver read or write the buffer *while* DMA may be writing to it too.

A Safe* `DMACell` *Interface. TickTock introduces a new wrapper and `DMACell` type, summarized in Figure 9, which prevents DMA from writing to arbitrary locations, and hence, violate Rust soundness or isolation. When DMA is configured to write data to a given address, the buffer this address corresponds can be represented as a mutable reference owned by DMA. The `DMACell` type takes ownership of a buffer when placed into the `DMACell` and returns a `DMAWrapper` containing a `usize` that corresponds to the buffer base pointer, which can be subsequently used to initiate the DMA operation. The Rust type system prevents aliasing of buffers passed to the `DMACell`. Further, the `DMAWrapper` ensures the `usize` written to the DMA base pointer register is a valid DMA buffer, and hence, that DMA operations do not violate either Rust's type soundness or TickTock's isolation guarantees.

5 Implementation

The implementation effort required in TickTock is listed in Figure 10. Overall, TickTock's proof consists of `3,603` lines of checked annotation across `2,581` functions.

Trusted Functions. `125` functions are marked `#[trusted]`, meaning that Flux *does not* verify their source against their contract. Of these trusted functions, `14` are facts we prove in Lean due to issues with SMT solvers (as described below), `14` are due to outstanding Flux issues, `17` are for proof specific code (*e.g.* functions used to track certain values in ghost state), and `6` are on functions we consider out of scope (*e.g.* formatting functions called when the kernel hard faults). Additionally, `69` functions in Flux-Std are used to define refined APIs (*e.g.*that wrap Rust pointers `*const u8` into a `PtrU8` that tracks the address of the pointer), and enable verification (*e.g.*non-overflowing) of pointer arithmetic. In FluxArm, `5` functions are marked trusted to define a refined API over hashmaps. Beyond the functions explicitly marked trusted, the actual TCB also includes `67` additional functions from FluxArm that correspond to manual translations of ARM semantics into Rust.

Component	Source	Fns(Trusted)	Specs(Trusted)
Kernel	12,434	1400 (14)	562 (5)
ARM MPU	2,486	777 (19)	506 (38)
Risc-V MPU	2,575	170 (22)	408 (51)
Flux-Std	1,231	116 (65)	227 (47)
FluxArm	3,405	118 (5)	1,900 (45)
Total	**22,131**	**2,581 (125)**	**3,603 (186)**

Figure 10. Proof Effort: **Source** is the Rust LOC; **Fns** is the number of Rust functions in the source code with **Trusted** being the subset of *trusted* functions for which Flux does not verify the source against the contract; **Specs** is the number of LOC of Flux specifications with **Trusted** being the subset LOC that are specifications for trusted functions.

Verifying Trusted Lemmas in Lean. TickTock verification requires reasoning about hardware alignment constraints, which involves facts about bit-operations and modular arithmetic. For example, we determine if an integer is a power-of-two using a classic bithack, shown below.

```rust
fn is_pow2(n: int) -> bool {
  let v = int2bv(n); (v > 0) && (v & v - 1 == 0)
}
```

In the kernel, some specifications require the fact that (sufficiently large) powers of two are aligned to 8 bytes, but modern SMT solvers—both `z3` and `cvc5`—hang when trying to prove this fact about alignment! We circumvent this limitation by encoding these facts as *trusted lemmas*: methods that establish the desired fact as a postcondition

```rust
#[trusted]
fn lemma_pow2_octet(r: u32) requires is_pow2(r) && 8 <= r ensures r % 8 == 0
```

after which we can just "call" `lemma_pow2_octet` in the TickTock code to establish the desired fact. Instead of blindly assuming these as axioms we prove these lemmas interactively in Lean [40]. For example, the theorem below is the encoding of `lemma_pow2_octet` using bounded arithmetic: the proof is done by induction over the binary structure of natural numbers.

```
def is_pow2(n: Fin 2^32) = (n > 0) \wedge (n &&& n - 1 == 0)
theorem lemma_pow2_octet (r : Fin 2^32) : is_pow2 r -> 8 <= r -> r % 8 = 0
```

6 Evaluation

We evaluate TickTock along three dimensions:

1. Does TickTock *run* on real hardware? (§ 6.1)
2. Does TickTock *perform* as well as Tock? (§ 6.2)

3. Does TickTock *verify* efficiently? (§ 6.3)

To answer the first question we perform differential testing on a subset of Tock's test suite. To answer the second question, we add hooks to Tock and TickTock's process abstractions, and measure their performance on a suite of benchmarks. To answer the last question, we measure how long Flux takes to verify the TickTock kernel and interrupt code.

6.1 Running TickTock

As Knuth famously advised, it is not enough to just prove TickTock correct: we need to actually run it! Indeed, as we aim to retrofit verification into an existing production OS, it is especially crucial to demonstrate that TickTock runs properly on real hardware. To this end, we perform differential testing comparing the outputs of TickTock and Tock on the suite of *release tests* from the Tock repository [50]. Due to difficulty obtaining RISC-V hardware supported by the Tock kernel, we ran a subset of Tock's upstream applications on Qemu, to ensure that Tock and TickTock were both able to run each app to completion. For ARM architectures, we run a subset of Tock's upstream tests on a `Nordic NRF52840dk` chip. Overall, we ran 21 test applications on both Tock and TickTock, 5 of which had different outputs. The 5 differing tests were expected as they were either testing memory layout, or reading and printing data from sensors. For example, one test, `Stack Growth`, deliberately crashes the application by overrunning the allocated stack. When the application crashes, the current memory layout is printed. Since we changed the memory allocating code in TickTock, we expect this layout not to match Tock's. However, the application still correctly faulted when it tried to read/write to a location in memory it *should not* be able to access.

Notably, this effort helped us catch (non-isolation breaking) bugs in TickTock's code. For example, when writing to the MPU registers—which is part of TickTock's TCB because this behavior is determined by the MPU hardware—we noticed that the *order* in which regions were written did not match the order of the region ids. Because of this, the MPU faulted on any access to memory by the application that misconfigured hardware. The fix was simple, but we would not have noticed it without testing, since our specifications only ensure that isolation was enforced.

6.2 Benchmarking TickTock

Next, we evaluate the performance impact of TickTock's memory allocation and MPU configuration code changes, relative to Tock. We note that we would have liked to profile RISC-V but since Qemu does not reflect the performance characteristics of the target hardware, we chose not to profile with it. For ARM architectures, we instrumented key methods implemented by the TickTock and Tock process abstractions to count the number of CPU cycles spent in each. Additionally, we instrument the new and old memory allocating code to show the difference in memory usage, waste, and memory updating performance. We then ran the instrumented kernels on the 21 tests from § 6.1, and new benchmarks designed to stress the memory allocating code.

Method	TickTock	Tock	Pct. Diff
`allocate_grant`	641.00	1290.32	-50.32%
`brk`	844.51	1078.66	-21.71%
`build_readonly_buffer`	115.71	144.64	-20.00%
`build_readwrite_buffer`	78.00	118.22	-34.02%
`create`	638,544.67	634,137.40	+0.70%
`setup_mpu`	97.86	90.55	+8.08%

Figure 11. Average CPU cycles for process tasks

CPU Cycles. Figure 11 summarizes the results of our performance benchmarks, taken as the average of three runs of the 21 tests above. In particular, we see that in most cases, TickTock performs as well as or better than Tock. There is one slight performance regression in `setup_mpu`, costing on average 7 extra CPU cycles. We note that although this function is called at every context switch, 7 CPU cycles is a marginal difference that should not affect applications significantly in practice. On other code paths, TickTock performs significantly better. For example, `brk` is significantly more efficient in TickTock, likely because Tock includes an unnecessary call to `setup_mpu` *and* because TickTock uses verified bitwise arithmetic (instead of loops) to set certain fields in the MPU configuration. Similarly, `allocate_grant` in TickTock takes 641 cycles on average and is significantly faster than the Tock implementation because it avoids recomputing MPU regions, as described in § 3.2.

Memory Usage. Evaluating the efficiency of our new memory allocating abstraction is difficult, since it works differently than Tock's in a few nuanced ways. However, based on the design of our abstractions, we expect our allocator to perform similarly to Tock's. Both TickTock and Tock use two RAM regions for Cortex-M and one RAM region for RISC-V. To microbenchmark the memory footprint of both allocators, we wrote an application which incrementally grows its memory by 1 byte until failure. TickTock allocated `7,780` bytes of total memory, with `6,144` bytes of stack, data, and heap memory, `1,200` bytes of kernel grant memory, and `436` bytes of unused memory (`5.60%` of total memory unused). Tock allocated `8,192` bytes of total memory, with `6,656` bytes of stack, data, and heap memory, `1,284` bytes of kernel grant memory, and `252` bytes of unused memory (`3.08%` of total memory unused). This small difference between Tock and TickTock mostly stems from the fact that the grant region in both cases is nearly equal (`1,200` bytes vs `1,284` bytes), but the total size allocated for the process is different. This is because Tock initially sets up more room between the process

Component	Fns.	Total	Max	Mean	StdDev.
TickTock (Monolithic)	660	5m19s	4m57s	0.48s	11.36s
TickTock (Granular)	791	36s	8s	0.05s	0.39s
Interrupts	95	2m34s	2m3s	1.63s	12.82s

Figure 12. Time taken by Flux to verify TickTock. **Fns.** is the number of functions, **Total** is the total time taken to verify the code, **Max** is the maximum time taken to verify a single function, **Mean** is the mean time taken to verify a function, and **StdDev.** is the standard deviation of the verification time across the functions.

and kernel-owned grant regions of memory, and therefore can allocate a few extra bytes when the grant memory is the same between the two. Note that when we configure TickTock to add padding (total process size `8,192` bytes, matching Tock's allocation), the unused memory becomes `336` bytes—within `84` bytes of Tock's `252` bytes, a negligible difference.

6.3 Verifying TickTock

Figure 12 summarizes our measurements of how long it takes Flux to verify TickTock's kernel and interrupt handling code. Flux is a modular verifier that checks each function in isolation, using the specified contracts (refinement types) for the other functions. This allows for incremental and interactive verification during code development. Hence, we report the total time for the kernel and interrupts to verify, as well as the average time to check methods in each case.

Interrupt Verification. The interrupt code takes significantly longer to verify, despite being smaller (both in LoC and functions) than the rest of the kernel. This is because this code is in essence verifying precise functional correctness of assembly instructions, hardware semantics, and interrupt handlers, which requires heavyweight SMT reasoning about specifications over bit-vectors and finite-maps.

Kernel Verification. In the kernel, a function takes, on average, 0.05s to check with a worst case of about 8s, meaning that it is possible to verify with Flux continuously during kernel development. Our granular redesign helps considerably in this regard, as it slashes the total verification time down considerably from over five minutes to about half a minute. Over `90%` of the time verifying the original Tock code was spent checking `allocate_app_mem_region`—a fact that motivated us to redesign the MPU abstraction. Overall, it takes around three minutes to verify the entire project, making verification feasible as part of a CI pipeline.

7 Related Work

To the best of our knowledge, TickTock is the first system to formally specify and verify process isolation in an embedded OS written in Rust. Hence, TickTock is related but complementary to the existing literature on building verified Operating Systems, isolation mechanisms, and Rust-based systems verification.

Interactive OS Verification. Building formally verified operating systems has been a long term goal of the systems community, dating back to the verification of (a model of) PSOS [17] in the late seventies. Operating systems like CertiKOS [20–22], seL4 [29, 52], and μC/OS-II [31, 58], provide formal, end-to-end verification of functional correctness for microkernels using interactive theorem provers like Isabelle [44] and Rocq [8], which imposes a very substantial proof-to-development overhead, where the sizes of the proofs are often $10-100\times$ the size of the kernel itself. In contrast, our work demonstrates that with careful design, the verification of key security properties is feasible with modest effort.

Automated OS Verification. Systems like HyperKernel [41, 42] aim to reduce this overhead by restricting kernel code (*e.g.*to be loop- and recursion- free), and then using SMT solvers to automate proof construction. Closer to our work, ExpressOS [38] develops a new kernel in C# and uses the Dafny verifier [35] to verify key security invariants (like isolation). Recent work has proposed using Rust's (non-)aliasing guarantees to simplify SMT-based verification of newly designed kernels [10, 12] In contrast, TickTock aims to retrofit verification into an existing production kernel.

Verified Isolation Mechanisms. Several groups have formally verified other kinds of isolation mechanisms such as *hypervisors* and *enclaves.* An early example is [1] which uses VCC [15] to verify the functional correctness of an idealized version of the Hyper-V hypervisor. Uberspark[56] abstracts hypervisors in low-level assembly code into higher-level structured objects about which functional correctness and isolation properties are proved using Frama-C [7]. More recently, SeKVM [37, 55] uses layered refinement proofs in Rocq (similar to CertiKOS), to build a formally verified Linux KVM hypervisor that provides memory isolation of userspace VMs using traditional page-table based memory protections. Komodo [18] implements trusted enclaves via a combination of hardware support and a formally verified reference monitor written in assembly using Vale [9], a Dafny based DSL for verifying assembly code, that is similar to how we lift ARM assembly semantics into Flux.

Rust Systems Verification. The VeriSMo system uses Rust to build a security modules for confidential VMs on AMD SEV-SNP [62], and uses Verus a Floyd-Hoare style Rust verifier [32] to verify correctness, and that the module provides confidentiality and integrity. WaVe [26] implements a WebAssembly sandboxing runtime in Rust, and uses Prusti, another Floyd-Hoare style Rust verifier [3], to verify that the runtime is memory safe and correctly mediates access to the host OS' storage and network resources. Finally, SquirrelFS [33] implements a file system in Rust, and uses the

type system's support for the *typestate pattern* [54] to provide crash-safety guarantees by construction. TickTock, like all the above, relies heavily on Rust's non-aliasing guarantees to simplify verification, but unlike the above, retrofits verification into a substantial codebase in production.

Isolation in embedded systems There has been extensive work on isolation in embedded systems using hardware like MMUs [2, 23, 24, 43] and MPUs [16, 30, 61]. Additionally, some work has paired MPUs and verification to provide strong intra-kernel isolation guarantees [27]. Others have explored providing isolation via sandboxing [45, 60], automatically separating system code (e.g. via compilation) and enforcing isolation via hardware [13, 14, 28], or a combination of hardware and software mechanisms [5, 51, 53] including those used by Tock [39]. Unlike the above designs, TickTock aims to provide formal, machine-checked process isolation guarantees.

8 Acknowledgements

We thank the anonymous reviewers and our shepherd Malte Schwarzkopf for valuable feedback on our submission. Additionally, we thank Leon Schuermann, Samir Rashid, and the Tock team for their help throughout the project. This work was supported by grants from the National Science Foundation under Grants Nos. CNS-2327336, CNS-2155235, CNS-2120642, CNS-2120696, CNS-2154964, CNS-2155235, CNS-2048262, CNS-2303639, along with support from the Irwin Mark and Joan Klein Jacobs Chair in Information and Computer Science, and from the UCSD Center for Networked Systems.

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