Encapsulated Functions: Fortifying Rust's FFI in Embedded Systems

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Abstract

Memory-safe languages like Rust are increasingly popular for systems development. Nonetheless, practical systems must interact with code written in memory-unsafe languages. This is especially true in security and safety-critical embedded systems, where subsystems such as cryptographic implementations are subject to industrial and governmental certification requirements. Direct interactions with such libraries, however, expose memory-safe languages to significant risks: Any single bug in either the foreign code or the cross-language interactions may arbitrarily violate the memory safety of the wrapping language.

We present *Encapsulated Functions*, a framework for safely invoking untrusted code in a memory-safe system with minimal overheads. Encapsulated Functions combines hardware-based memory protection mechanisms with a set of Rust type abstractions to facilitate safe interactions with untrusted and unmodified third-party libraries.

CCS Concepts: • **Computer systems organization** → **Embedded software**; • **Software and its engineering** → **Software safety**; • **Security and privacy** → **Operating systems security**.

Keywords: Rust, memory safety, foreign function interface, memory protection

ACM Reference Format:
Leon Schuermann, Arun Thomas, and Amit Levy. 2023. Encapsulated Functions: Fortifying Rust's FFI in Embedded Systems. In *Kernel Isolation, Safety and Verification (KISV '23), October 23, 2023, Koblenz, Germany*. ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3625275.3625397

1 Introduction

Systems are increasingly built using modern, memory-safe languages such as Rust, Go or Swift. These languages can aid developers in writing correct software and prevent entire classes of bugs due to their design. However, practical systems must often integrate existing libraries, such as cryptographic implementations written in non-memory safe languages or provided in the form of binary blobs. Unfortunately, bugs in those libraries can arbitrarily violate memory safety of the wrapping language. Even internally correct libraries may break safety guarantees in subtle ways due to differing cross-language semantics. We argue that memory-safe languages should be able to invoke unsafe, unmodified third-party libraries safely, and with minimal overhead.

These problems are particularly pronounced in the context of secure and safety-critical embedded systems, where certain subsystems, such as cryptography, timing-critical control loops, and wireless communication, require industrial or governmental certification. Rewriting existing implementations in a memory-safe language is often not feasible: Apart from development and re-certification overheads, software implemented in industry-standard programming languages benefits from a mature ecosystem of toolchains, verification infrastructure, established best practices, and alignment to industrial certification processes. For example, the flight control software of the Airbus A380 is verified to be sufficiently bounded on its worst-case execution time (WCET), an important functional safety property, using analysis techniques currently only available for C [1, 2]. Similarly, industry standards are written for C-based implementations.

Despite these external constraints enforcing the use of non-memory safe languages like C, evidence suggests that memory-safe languages make it easier to write *correct* code. According to Microsoft, around 70% of security vulnerabilities addressed in Microsoft products are caused by memory safety issues [14]. Even within the space of cryptographic libraries, an empirical study attributes 37.2% of vulnerabilities to memory safety issues [5]. A report by Google indicates that with the usage of Rust as a memory-safe language in Android 13 the frequency of these issues has dropped significantly—from 76% to 35% [23]. The absence of memory-safety issues is required to maintain a system's functional safety and security, both especially important properties for many embedded systems.

In fact, Rust is uniquely suited for the requirements of these constrained environments: Its compilation to native

KISV '23, October 23, 2023, Koblenz, Germany

ACM ISBN 979-8-4007-0411-6/23/10.
https://doi.org/10.1145/3625275.3625397

machine code, static memory management, and use of zero-cost abstractions promises to support systems with strict resource and timing constraints. Moreover, its use of a static and strong type system alongside an *ownership*-based memory management model establishes both *spatial* (e.g., preventing out-of-bounds accesses) and *temporal* (e.g., accessing reclaimed memory) memory safety. Projects such as the Tock embedded operating system demonstrate the feasibility of Rust in severely resource-constrained devices [10].

A reasonable step towards memory-safety in these systems may be to take advantage of Rust's safety guarantees wherever possible, and integrate existing legacy or certified implementations of specific subsystems. Unfortunately, it is hard to correctly interact with foreign, unsafe code from a memory-safe language like Rust; any single memory-safety issue in the foreign code can break Rust's memory safety arbitrarily. Moreover, even if foreign code operates correctly, the interactions between such code and Rust can still wreak havoc: Rust has an extensive set of safety requirements that must be maintained, which forbid many otherwise legal behaviors in foreign languages. Notably, these requirements are not just limited to *spatial* and *temporal* safety. Rust further places extensive restrictions on *valid values*. For example, a `bool` type must have a value of either `0` or `1` [21]. Simply having a `bool`-reference to any other value in scope (without dereferencing it) is undefined behavior. Other such violations include a *null*-reference, or an enum-discriminant not included in its type-definition.

To facilitate safe cross-language interactions, this paper presents *Encapsulated Functions*: a framework to execute untrusted foreign code in the context of a memory-safe system. Making Encapsulated Functions special is its ability to work in severely resource-constrained embedded systems, such as microcontrollers, and it being able to safely execute *unmodified* binary code. These properties make it uniquely suited to foster adoption of safe programming languages in safety and security critical embedded devices, while allowing users to reuse existing industrially-certified C libraries.

Throughout this paper we illustrate the two interoperating mechanisms composing Encapsulated Functions: an efficient hardware-based memory isolation mechanism, using hardware features commonly found in modern microcontroller systems, and a set of type-level abstractions to interact with untrusted *foreign* memory. We further demonstrate the applicability of our system by integrating it with the Tock embedded OS and implementing an HMAC-based one-time password generator (HOTP) on the OpenTitan silicon root-of-trust (RoT) platform, using its C-based *CryptoLib* cryptography library.

2 Background

Throughout this section we provide an overview of existing hardware- and software-based isolation mechanisms.

2.1 Hardware-Mediated Process Isolation

Operating system processes are well-suited to isolate untrusted code. As a process operates in its own, isolated address space, memory-safety violations are contained within this process. Furthermore, a process does not have unlimited control over the execution of other processes. Instead, it can signal events and share data with other processes through OS-mediated channels, such as *UNIX domain sockets*.

Unfortunately, such IPC-based isolation mechanisms induce significant overheads when used for individual function calls. As the isolated function executes in a different address space, its parameters must be serialized and transferred into the remote process. Upon return from the function, the remote process must further serialize its result and transfer it back to the original process. Every such transition induces a full context switch which saves the currently executing process' state, performs scheduling decisions in the kernel, and finally restores the to be scheduled process' state. The required extraneous memory allocations and context switch overheads exceed resources available in many constrained embedded systems. Calls into other dynamically-scheduled units of execution also introduce unpredictable delays.

2.2 Software-Based Fault Isolation

In contrast to hardware-based isolation techniques, which execute untrusted code and *fault* upon executing certain dangerous interactions (such as memory writes), Software-Based Fault Isolation (SFI) ensures that such interactions are never issued in the first place [24]. This can be achieved through an ahead-of-execution analysis of the untrusted binary to ensure that all potentially dangerous instructions are limited to a given *protection domain*, modification the untrusted binary to introduce runtime checks ahead of any potentially dangerous instructions, or a combination of both.

While SFI does not require hardware isolation support and avoids significant context-switch overheads to switch between trusted and untrusted code, it is not able to isolate arbitrary untrusted and unmodified binaries. Still, its tightly defined execution model provides inspirations for this work; specifically we mirror Native Client's clear separation of and switches between trusted and untrusted contexts through the *trampoline* and *springboard* mechanisms [25].

3 Design

In this section we present *Encapsulated Functions*, a framework to execute untrusted foreign code in the context of a single-threaded memory-safe system. Encapsulated Functions is composed of two interoperating mechanisms—*lightweight context switches*, an implementation of function calls engaging hardware-based memory protection, and a set of type-level abstractions for safely interacting with untrusted *foreign* memory, which we present separately.

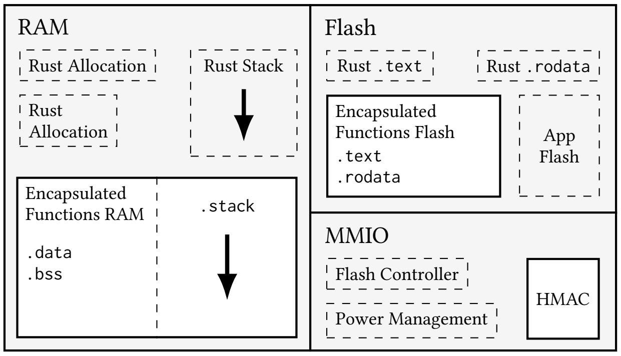


Figure 1. Memory regions accessible to Encapsulated Functions within the larger, unified microcontroller address space (highlighted in white). If required, functions can be granted permissions to access certain MMIO peripherals. Larger regions may be segmented into multiple smaller allocations, provided sufficient memory protection resources.

We design Encapsulated Functions to protect the memory-safe, *wrapping* language against any soundness issues caused by foreign code, or interactions with foreign code or memory. In the variant described in this paper, foreign code is largely trusted for confidentiality and assumed to be *buggy*, but not actively malicious (e.g., address leaks to foreign code are deemed acceptable). We indicate when this design can be adjusted to strengthen its threat model.

3.1 Hardware-based Memory Protection

Untrusted code can arbitrarily break Rust's safety assumptions through simple memory accesses. To prevent this, Encapsulated Functions uses memory protection mechanisms integrated into modern microcontroller systems. Such mechanisms are increasingly common in even the most constrained embedded platforms, like the Memory Protection Unit (MPU) present in ARM Cortex-M0+ cores, or the RISC-V Physical Memory Protection (PMP). Compared to the more complex memory management units (MMUs) present in most modern general-purpose CPUs, these memory protection mechanisms have very limited functionality. They generally do not feature support for virtual address spaces and often support only a very limited set of memory regions with coarse-grained alignment constraints. For instance, the ARM Cortex-M0+ MPU supports defining access-permissions for 8 memory regions, where each region's start address must be aligned to a multiple of the region's size in bytes.

Unfortunately, restrictions on the number of protection regions and their granularity hinder us from defining fine-grained per-allocation protection rules. Instead, Encapsulated Functions provides foreign code with access to a few, sufficiently large memory regions, illustrated in Figure 1. These regions contain at least the foreign code's binary, as well as a given amount of RAM. To maintain memory safety, writeable memory regions do not overlap with any Rust allocations. Separating memory accessible to Rust and foreign code trivially maintains Rust's memory-safety, but is not particularly useful on its own; Section 3.2 presents considerations for interacting with this memory.

To enforce these memory protection rules, Encapsulated Functions must switch to a lower privilege level when executing untrusted functions. For this, we use the same hardware mechanisms as employed for context switches to processes. However, our isolation granularity of function invocations, compared to scheduled and concurrent execution units such as OS processes, allow us to optimize this switching process significantly; we refer to this mechanism as *function calls through lightweight context switches.* Importantly, this mechanism maintains the same synchronous execution model as regular function calls, avoiding overheads of saving state as required when invoking an asynchronous task.

To invoke a function, privileged Rust code (mirroring the SFI *trampoline* mechanism) prepares the function's execution environment by placing function call arguments in their corresponding registers and onto a newly allocated separate stack, located within a foreign-code accessible, writeable memory region. This process implements and follows the untrusted binary's ABI. To strengthen guarantees concerning confidentiality, the priviliged code may wish to further clear other unused registers. To allow foreign code to pass control back to the privileged Rust code, we use an analog to the *springboard* approach from SFI and set the return address register to a well-known inaccessible or privileged and immutable instruction. This ensures that an attempted function return by the untrusted code will trigger a context switch back into the privileged execution context. Finally, the function is executed by switching to a lower privilege mode, enforcing hardware memory protection, and setting the program counter (PC) accordingly. Upon return, the privileged code must assume all registers to be clobbered. Such a function call largely avoids the overhead of a full context switch, which would include scheduling decisions, and saving and restoring a full process execution environment.

The foreign code may choose to never return to the springboard instruction, violating liveness guarantees. The system may optionally use a timer-interrupt to switch back to privileged code in the case that foreign code does not return.

3.2 Unsafe Cross-Language Interactions

The lightweight context switch mechanism of the previous section is sufficient to fully isolate untrusted code in the context of a memory-safe system. However, such an overly constrained system has limited utility; Rust code will need to interact with foreign code by passing data to functions and interpreting returned results. These interactions, however, introduce a yet another way to violate memory safety: While all objects in foreign memory are sufficiently constrained concerning spatial- and temporal-safety (memory accesses by foreign code are limited to the time this function is executing and do not overlap any Rust allocations), they do not necessarily conform to the safety constraints as illustrated in Section 1; specifically they may not be *valid values.*

Furthermore, depending on how memory is divided between Rust and foreign code, this mechanism may also endanger Rust's guarantees around temporal memory safety. For example, if a system were to reuse the Encapsulated Functions' stack memory region while the foreign code is not running, references into this memory may then potentially alias Rust allocations and would thus be able to cause undefined behavior.

One possible approach to overcome this limitation are *pseudo-pointers* (for instance, as used by Galeed [16]). Encapsulated Functions would pass such pointers to foreign code, which can provide them back to trusted Rust accessor functions that provide access to a limited set of Rust allocations. Unfortunately, this model has multiple issues in the context of Encapsulated Functions. For instance, each such memory access would incur a lightweight context switch—a significant overhead compared to other memory protection mechanisms like Intel MPK. Furthermore, usage of accessor methods requires modification of foreign code, which would be in conflict with our requirements. Instead, we develop a set of type-abstractions which allow both Rust and foreign code to directly access shared memory, while maintaining Rust's safety requirements.

3.2.1 Rust Primitives to Access Foreign Memory.

To eliminate the aforementioned safety issues when interacting with foreign code, we propose a set of type-level abstractions for Rust that facilitate safe interactions with foreign memory. Our abstractions place an explicit focus on soundness and runtime-efficiency. In this section we introduce select Rust language constructs useful for designing these abstractions.

Raw Pointers act as the foundation of our type abstractions. Rust's raw pointers (such as `*mut u8`) are not subject to the same constraints that Rust values or references are. Retaining a mis-aligned, dangling or inaccessible pointer to some invalid value is safe, so long as this pointer is never dereferenced or cast into a Rust *reference.* For these reasons, dereferencing Rust's raw pointers is an `unsafe` operation.

Valid Values. To support safely referencing memory which may not contain a valid instance of some type `T`, Rust provides the `MaybeUninit<T>` type [20]. This type can be used to represent a memory allocation that has the same size, alignment and ABI as a type `T`, but does not support safely dereferencing it. Still, as this type is guaranteed to be well-aligned and contained in accessible memory, writing to it is a safe operation. These semantics are suitable to wrap foreign memory, which cannot be guaranteed to always conform to Rust's requirements on *valid values* [21].

Mutable Aliasing. Additionally, Rust's type system distinguishes between shared (*immutable*) references, for which it assumes that referenced memory cannot be mutated, or unique (*mutable*) references, which reference memory that can only be mutated through this reference. These restrictions prevent *mutable aliasing*, where a given memory location is mutated and referenced by at least one other Rust reference simultaneously. However, foreign code does not have to adhere to these constraints: In C, two pointers can generally coexist while referencing (partially) overlapping allocations[1]. Rust provides an escape hatch to circumvent these aliasing restrictions, namely the `UnsafeCell<T>` type. A shared (immutable) reference to this type is allowed to point to data that is being modified [19].

As a consequence, a raw pointer to some type `T` can be converted into a shared reference of some `UnsafeCell<MaybeUninit<T>>`, assuming the pointer is well-aligned, fully contained in mutably accessible memory, and not aliasing other Rust allocations not contained in an `UnsafeCell` or of a different type. A reference to this composite type can be used to safely write to its backing memory, even if it were to alias another `UnsafeCell<MaybeUninit<U>>` reference over a different type `U`. Still, such a reference cannot be safely dereferenced, as it is not guaranteed to contain a valid instance of type `T`.

Finally, for Rust to safely access such references into foreign memory, their memory contents must be validated to conform to Rust's requirements on *valid values.* For instance, a `bool` type is required to have a numeric value in $\{0, 1\}$ [21]. The memory must stay consistent with these requirements for the entire duration that a dereferencable (non-`MaybeUninit`) reference is in scope. This cannot be guaranteed in the case of concurrent execution of Rust and foreign code. Thus, we place a single-threaded restriction on the Encapsulated Functions execution model: A foreign binary is always executed within a single thread, and only a single Rust thread may execute foreign functions or access foreign memory at any given time[2].

Nonetheless, the aforementioned validity of values can be violated from safe Rust even without handing over control to the foreign code. Because C pointers may arbitrarily alias memory allocations, a Rust-issued write through one reference may modify the content of another reference. For instance, a C binary may provide Rust with two byte-sized pointers to the same memory, one represented as a `bool` and another as a `u8`. While the numerical value 2 is a valid member of the `u8` type, it is not valid for the `bool` type. Thus, validated references can only be assumed to remain valid until either control is handed over to the untrusted foreign code, or foreign memory is modified from within Rust.

[1] C does place restrictions around aliasing across *incompatible types.*

[2] In Rust, this can be achieved by marking the Encapsulated Functions runtime type as `Send` (allowed to cross thread-boundaries), but not `Sync` (not safe to share between threads).

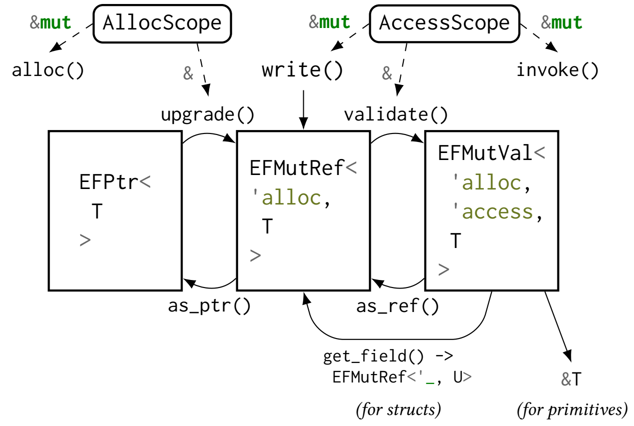


Figure 2. Typestate-transitions between the EFPtr, EFMutRef, and EFMutVal reference types for foreign memory. Pointers can be converted into more capable reference types subject to runtime checks. Reference types are bound to compile-time enforced *allocation*- and *access-scopes*, which expire on changes to the foreign-code accessible memory regions or memory writes and foreign code execution, respectively.

3.2.2 Safe Type-Abstractions for Foreign Memory.

We can use the presented Rust primitives to establish a set of type-level abstractions which safely interact with foreign memory. They integrate with an *allocator* that can allocate objects within foreign memory and track whether a given allocation is contained in said memory. The type-abstractions further interact with the mechanism to hand over control to foreign code, in order to invalidate any validated references across such invocations. Our type-abstractions follow the typestate programming paradigm, which encodes changes in the *validation state* of a foreign memory reference as a transition between types, which in turn expose a set of safe methods applicable in that state [3]. Notably, we further utilize Rust's lifetimes to impose restrictions on the *duration* of validity of certain type representations. Throughout this section we present types applicable to mutably accessible memory (i.e. referencing RAM); our implementation provides an analog set of types for immutable memory (e.g., memory-mapped flash). We illustrate the interactions between our type-abstractions in Figure 2.

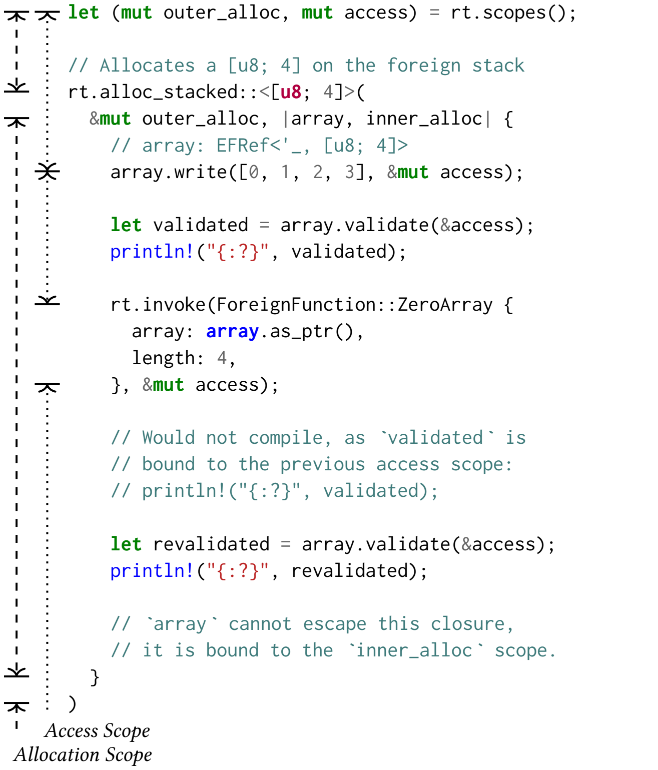
As illustrated in Section 3.2.1, Rust's raw pointers form the foundation of our type abstractions. The EFPtr<T> type wraps a Rust raw pointer and can be passed across FFI boundaries. It exposes convenience methods useful for working with Encapsulated Functions and prevents type confusion, but can be safely constructed from arbitrary raw pointers.

If an EFPtr<T> points to some well-aligned type T wholly contained in mutably accessible foreign memory, it can be converted into an EFMutRef<'alloc, T>. This type allows *writing* through the reference, but does not support dereferencing its memory. It thus represents a useful intermediate type: Even across invocations of untrusted code or modifications of foreign memory, an EFMutRef is still guaranteed to be well-aligned and fully contained in foreign memory, avoiding re-validation of these properties. The EFMutRef<'alloc, T> type internally wraps an &'alloc UnsafeCell<MaybeUninit<T>> shared reference, and is bound to an *allocation scope* 'alloc: To ensure that references into foreign memory never outlive the foreign memory reservation itself, we introduce *allocation scope* marker types. These types serve as a proxy to bind references into foreign memory to Rust's rules around references and lifetimes. For instance, the constructor of an EFMutRef *borrows* a shared reference to an instance of the AllocScope marker type, for the entire lifetime of the resulting EFMutRef<'alloc, T> reference. As constructing such an AllocScope is marked as an unsafe operation, an allocator can ensure that only one such scope is accessible at any given time. By handing out an allocation scope with a limited Rust lifetime, set to expire before releasing the foreign memory reservation, Encapsulated Functions prevents retaining dangling references.

In turn, if an EFMutRef<'alloc, T> contains a valid instance of type T, it can be converted into an EFMutVal<⌟ 'alloc, 'access, T>. To implement this check, we require that types provide an unsafe validate method which, given a well-aligned and accessible raw pointer, must establish whether the referenced value is a valid member of the given type. Notably, for types where every possible memory state represents a valid instance of said type, this method may be implemented as a no-op[3]. The EFMutVal<⌟ 'alloc, 'access, T> type is further bound to an *access scope* 'access, conceptually similar to allocation scopes. An AccessScope is issued by the facility to execute untrusted code, which must ensure that only a single instance of this type can exist at any given time. Instantiating an EFMutVal<'alloc, 'access, T> borrows a *shared* reference to this AccessScope for the entire lifetime of the resulting instance. However, operations which mutate foreign memory or execute untrusted code borrow a *unique* reference to an AccessScope, forcing all shared borrows to be out of scope. In practice, this ensures that access scopes cannot span across writes to foreign memory or invocations of the foreign code; hence no validated references remain in scope across operations that may invalidate them.

Figure 3 illustrates the interactions between the allocation and access scopes, foreign memory allocations (implemented using Rust closures), writes to foreign objects, and invoking foreign functions. It is worth noting that the

[3] MaybeUninit nonetheless requires such allocations to be initialized; the compiler may otherwise determine them to be undefined (undef / poison) [18, 20]. While in practice the compiler is unable to track this taint through invocations of foreign code, to comply with this requirement Encapsulated Functions requires explicit initialization of all foreign memory.



```
let (mut outer_alloc, mut access) = rt.scopes();

// Allocates a [u8; 4] on the foreign stack
rt.alloc_stacked::<[u8; 4]>(
  &mut outer_alloc, |array, inner_alloc| {
    // array: EFRef<'_, [u8; 4]>
    array.write([0, 1, 2, 3], &mut access);

    let validated = array.validate(&access);
    println!("{:?}", validated);

    rt.invoke(ForeignFunction::ZeroArray {
      array: array.as_ptr(),
      length: 4,
    }, &mut access);

    // Would not compile, as `validated` is
    // bound to the previous access scope:
    // println!("{:?}", validated);

    let revalidated = array.validate(&access);
    println!("{:?}", revalidated);

    // `array` cannot escape this closure,
    // it is bound to the `inner_alloc` scope.
  }
)
```

Figure 3. A simplified example outlining the interactions between the Encapsulated Functions runtime, EF* reference types, and the *allocation-* and *access-scope* markers: By binding EFMutRef references to their originating allocation scope scope, we eliminate dangling references. Validated EFMutVal references are further bound to an access scope, which expires upon foreign function execution or when foreign memory is modified.

aforementioned scoping rules are enforced at compile time, through references to scope *marker types*. This ensures that improper use of references causes compile-time errors, and scope-enforcement does not induce runtime overhead. Furthermore, all introduced wrapper types (EFPtr, EFMutRef, EFMutVal) have an identical memory layout, equivalent to that of the underlying pointer type. In many cases, compiler optimizations can thus elide explicit conversions between these types.

4 Case Study

To evaluate the applicability and performance of Encapsulated Functions, we integrate a proof-of-concept implementation into the Tock embedded operating system. The Tock kernel is implemented in Rust and relies on the Rust type system for many of its safety guarantees. It features a stable ABI and uses hardware memory protection mechanisms to isolate preemptively scheduled, unprivileged and language-agnostic processes. While Tock supports both ARM Cortex-M and 32 bit RISC-V platforms, our current implementation targets only RISC-V systems and depends on a Physical Memory Protection (PMP) unit.

For our evaluation, we choose to target the OpenTitan open-source silicon root-of-trust (RoT) system synthesized for the ChipWhisperer CW310 FPGA board. OpenTitan is a mature RISC-V based RoT platform integrating a set of hardened cryptography primitives. It encompasses *CryptoLib*, a C-library to interact with these primitives and provide high-level cryptography interfaces. We demonstrate Encapsulated Functions by integrating the HMAC subsystem of CryptoLib into the Tock kernel. Encapsulated Functions has also been verified to work on other RISC-V targets supported by Tock, without any target-specific modifications.

Our implementation requires a change to Tock’s RISC-V trap handler implementation, in order to remove hard-coded assumptions about interactions with user-mode code. No other modifications to Tock’s core kernel infrastructure or architecture support are required. The Encapsulated Functions runtime and type abstractions are implemented as a Rust crate with 917 lines of code, including a single inline RISC-V assembly block of 93 instructions. Importantly, Encapsulated Functions can co-exist with regular Tock processes despite sharing common resources, such as the PMP.

When switching to a process or invoking a foreign function, the system must configure the PMP to enforce an appropriate set of memory access rules. Once configured, repeated executions of the same process or invocations of the same foreign binary do not require re-configuration of the PMP. The overhead required by PMP configuration is largely independent of the number of memory regions configured and, using an optimized configuration routine, takes approx. 240 instructions in the Tock operating system. Once the PMP is configured, invoking a foreign function through a *lightweight context switch* induces an overhead of approx. 120 instructions. This includes setting of the foreign code’s stack, re-configuring the CPU for user-mode, and switching execution to the function code (64 instructions), as well as 55 instructions to handle a system trap, interpret the context switch reason, extract the function’s return values and restoring other machine-state on the return path. In comparison, an end-to-end context switch to a Tock process requires approx. 530 instructions on a RISC-V RV32IMC system. This includes scheduling the process, restoring the userspace register file, re-configuring the CPU for user-mode, as well as saving the user-space context and machine-state configuration on the return path; it excludes any kernel work, PMP configuration or debug information tracking. Table 1 summarizes these measurements.

To perform an HMAC calculation, both the key and data parameters need to be located in CryptoLib-accessible memory, which we achieve by copying them into appropriately sized allocations on the isolated Encapsulated Functions stack. These operations are conducted through our type abstractions illustrated in Section 3.2. Notably, due to the

PMP Pre-configured	Lightweight Context Switch	Tock Process Context Switch	
✓	120 instr.	530 instr.	23%
✗	360 instr.	770 instr.	47%

Table 1. End-to-end overheads induced by *lightweight context switches* and context switches to Tock processes, measured on a RISC-V `RV32IMC` system. In both cases, PMP reconfiguration constitutes a substantial overhead. If the PMP is already configured for a given process or foreign binary, it does not have to be re-configured.

fine-grained typestate information contained in these reference types, in many cases the compiler is able to optimize these abstractions into direct memory accesses. This holds as long as memory accesses are not made through indirect pointers located in foreign memory, and as long as read operations are limited to types where every memory state constitutes a valid instance of that type.

5 Related Work

There is a significant body of research exploring safety around cross-language interactions and isolation techniques. For instance, [13] establishes *Cross-Language Attacks*, an entirely new set of attack vectors caused by cross-language interactions, such as between Rust and C. The Rust community is addressing these issues by drafting documentation and guidelines around unsafe code and FFI usage [21, 22].

Contributions such as Galeed, XRust, TRust, PKRU-Safe, and SDRaD-FFI utilize heap isolation techniques to protect against a subset of these safety issues [4, 6, 7, 12, 16]. Whereas Galeed, PKRU-Safe, and SDRaD-FFI use a hardware-based memory protection mechanism to isolate Rust from foreign code, TRust additionally employs SFI techniques to confine unsafe Rust code to an untrusted memory domain. By modifying foreign code to use *pseudo pointers*, Galeed supports interactions with Rust objects. Similar to Encapsulated Functions, XRust and TRust and Intra-Unikernel Isolation [17] confine *unsafe* or foreign code to accessing limited memory respectively. Sandcrust uses IPC to automatically isolate unsafe Rust code within a separate process [9]. Both Sandcrust and SDRaD-FFI utilize serialization to convey (updated) variables between Rust and untrusted code.

Works like RLBox and RLBox-Rust combine a set of type-system abstractions with a WebAssembly sandbox to isolate untrusted code from C++ and Rust [15, 26]. Furthermore, progress on static analysis and SFI promises to alleviate overheads associated with hardware-based isolation techniques. For example, [8] uses structural information of code within representations such as WebAssembly to reduce the number of runtime checks required with SFI. `FFIChecker` employs static analysis techniques on the generated LLVM IR to identify potential cross-language memory management issues [11].

Notably, most existing work around cross-language interactions with Rust focuses on maintaining its spatial and temporal memory safety properties; few contributions address more subtle safety issues around valid values.

6 Conclusion

In this paper we present Encapsulated Functions, a framework for integrating untrusted and unmodified code into a memory-safe system. Through our prototype implementation we demonstrate the feasibility of using hardware-based memory protection mechanisms present on modern microcontrollers, along with a set of safe type-abstractions, to facilitate safe interactions with foreign language code while incuring minimal overheads. We further optimize the switch to a hardware-isolated execution environment through our *lightweight context switches* mechanism.

Compared to pior work in this field, Encapsulated Functions is a particularly lightweight cross-language isolation mechanism. It does not require a heap allocator, avoids spurious memory allocations as required for IPC-based approaches, and performs runtime validation of type and memory safety lazily, solely for memory that is accessed by the memory-safe language. Both the memory-safe language and foreign code can access shared memory directly, without any runtime indirection to bypass hardware protection mechanisms.

We implement Encapsulated Functions using the RISC-V Physical Memory Protection (PMP) subsystem. Our type abstractions for maintaining cross-language memory safety, however, are independent of the memory protection mechanism used. We believe that these type abstractions can be equivalently applied to similar mechanisms for other architectures (e.g., the ARM Cortex-M MPU), more complex Memory Mangement Units of general-purpose CPUs, and userspace-configurable hardware memory protection implementations such as Intel MPK. We hope to explore these additional application domains in future work.

This paper validates the design of Encapsulated Functions and performs a limited set of performance evaluations by integrating the *OpenTitan CryptoLib* HMAC subsystem into the Tock embedded OS kernel. By demonstrating support for a wider range of software libraries and porting Encapsulated Functions to other operating systems we hope to further evaluate the expressiveness of our solution. This will also enable an extensive performance evaluation and allow us to revisit certain design restrictions, such as Encapsulated Functions' single-threaded execution model.

Finally, we hope that this work will foster adoption of memory-safe languages even in severely constrained embedded systems, subject to industrial standards and certification processes.

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