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摘要

中文摘要

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Abstract

Hypervisors are extensively utilized in cloud computing settings as they manage hardware resources for virtual machines, making their security a critical concern. An attacker that exploits vulnerabilities in the privileged hypervisor codebase can gain unfettered access to VM data, compromising their safety. Previous attempts to retrofit hypervisors into small trusted cores have limitations, as the security still relies on the implementation of the trusted core. Recently, Rust adoption has been increasing for its strong memory safety guarantees and performance efficiency. Leveraging Rust, our work focuses on rewriting SeKVM, a secure Linux KVM hypervisor, into KrustVM, the first Rust-based secure Linux/KVM hypervisor. KrustVM incorporates Rcore, a small trusted core, to protect VM confidentiality and integrity. We addressed challenges in incorporating Rust TCB into Linux, bringing up KrustVM on real hardware, and rewriting SeKVM's TCB in Rust. Additionally, we minimized unsafe Rust usage, enclosed unsafe code within safe abstractions, and utilized Rust's type system to ensure spatial memory safety. Our

implementation of KrustVM suggests a modest overhead compared to mainline KVM and SeKVM. Our work demonstrates the practicality of securing existing hypervisors through a C-to-Rust rewrite.



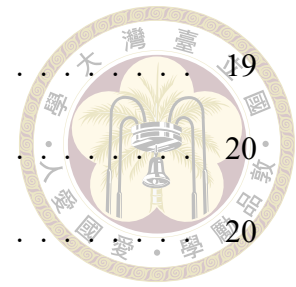
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Chapter 1 Introduction

Hypervisors are essential to cloud computing. They manage the hardware resources to provide the virtual machine (VMs) abstraction and host these VMs in the cloud. The widely used commodity hypervisors, such as KVM [24] or Hyper-V [34], include a large and complex TCB to satisfy users' requirements in performance and functionality. These hypervisors were written in unsafe languages like C, making them vulnerable to safety bugs, such as out-of-bound memory access and use-after-free. For example, KVM integrates an entire Linux OS kernel inside its TCB. Attackers that successfully exploit hypervisor vulnerabilities may gain the ability to steal or modify secret VM data.

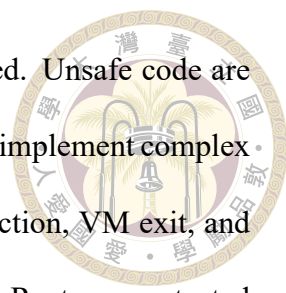
Previous work HypSec [29] has retrofitted commodity hypervisors into a small trusted core that enforces resource access control to ensure the confidentiality and integrity of VM data against hypervisor and host operating system exploits. However, the security of the whole system still depends on the implementation of the small trusted TCB. Any vulnerability in the trusted TCB can void the guarantees of VM data confidentiality and integrity. While SeKVM [30] extended the work of HypSec [29] by formally verifying the smaller TCB, the approach is not scalable since all code modifications including the addition of new features, or code refactoring, requires a new proof.

Rust is an emerging programming language that ensures strong memory safety guar-



antees at compile time while offering performance efficiency. Its distinctive ownership and lifetime system effectively addresses potential safety issues that programmers may encounter. Rust prevents various memory safety bugs, for example, null pointer dereferences are eliminated by distinguishing between nullable and non nullable types, nullable types are not allowed by default, array out-of-bound accesses are prevented by runtime checks that are added by the compiler, and Rust's ownership system prevents dangling pointers. Further, similar to programming languages like C, Rust allows developers to directly manage low-level systems resources such as memory. Due to these attributes, various previous work has adopted Rust to implement systems software with critical security and performance requirements, including operating systems [8, 10, 27, 35], hypervisors [12, 41], web browsers [3], and TEEs [44, 45]. There has been recent adoption of Rust in the mainline Linux kernel. However, instead of replacing the existing Linux kernel code written in C with Rust, the current efforts were limited to developing new Rust-based device drivers.

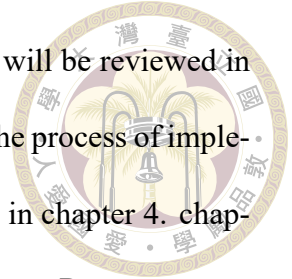
Our work implements a Linux KVM's TCB in Rust, so that the resulting hypervisor benefits from the strong safety guarantees that Rust automatically provides. We build upon the work of SeKVM [30] and forward ported SeKVM from Linux 4.18 to Linux 5.15, to take advantage of new kernel features including Link-Time-Optimization (LTO) and energy-aware scheduling. SeKVM's verified TCB *Kcore* is then rewritten in Rust, which is called *Rcore*. The resulting hypervisor, KrustVM, incorporates the small Rust TCB *Rcore* to protect VM confidentiality and integrity against the large and untrusted hypervisor codebase that encompasses KVM's host Linux kernel. We identified and overcame the challenges that arose when trying to incorporate a Rust TCB inside Linux, rewrite SeKVM's TCB in Rust, and bring up KrustVM on real hardware. *Rcore* is im-



plemented in a way such that the amount of unsafe Rust is minimized. Unsafe code are enclosed within a safe abstraction and a safe API is exposed in order to implement complex functionalities in safe Rust, including CPU, memory, VM boot protection, VM exit, and hypercall handlers. Further, raw pointer accesses, which are unsafe in Rust, are protected using Rust's type system. In Rcore, raw pointers are used for accessing physical memory. Physical memory is divided into multiple disjoint regions, and the Rcore implementation guarantees that all memory accesses done by Rcore are located in the predefined regions, ensuring that bugs caused by pointers pointing to incorrect memory regions are prevented. This is done in two parts, for raw pointer accesses to the region which stores metadata used by Rcore, called the *Rcore metadata region*, these accesses are bound via a set of reference getter functions (RGF). Each RGF wraps a given Rcore's raw pointer usage and returns a mutable reference to the associated shared metadata object after the caller acquires the corresponding lock. Because the raw pointer is turned into a mutable reference, the memory accessed is guaranteed to be bound by the size of the type being referenced, for arrays, the compiler automatically adds runtime checks that checks for out-of-bound array indices. For raw pointer accesses to the other regions, we built customized Rust types for each memory region that enforces bound-checking, and Rcore accesses each memory region via the corresponding type.

By rewriting a C-based hypervisor to a Rust-based implementation, the responsibility of human auditing is shifted to the compiler. This results in safer code and a more straightforward development process. Performance evaluation of KrustVM on real Arm64 hardware shows that KrustVM incurs modest performance overhead to application workloads compared to mainline KVM and SeKVM. We demonstrate the practicality of securing an existing commodity hypervisor by a C-to-Rust rewrite.

The rest of the thesis will be organized as follows. Background will be reviewed in chapter 2. Our threat model and assumptions are listed in chapter 3. The process of implementing a Rust TCB for KVM and the techniques used are described in chapter 4. chapter 5 presents how Rust's safety features are utilized to design and secure Rcore memory accesses. Evaluation of KrustVM and its comparison with mainline KVM and SeKVM is covered in chapter 6. Related work and future work are discussed in chapter 7. At last, we conclude the thesis in chapter 8.





Chapter 2 Background

2.1 Overview of the ARM Architecture

Our work is based on the ARM architecture for its mass adoption in mobile devices, and its rising popularity among major cloud providers [4, 5]. Different from x86, the ARM architecture has a larger general register count, fixed length instructions, and simpler instructions. These properties stem from ARM's original Reduced Instruction Set Computer (RISC) design. CPU privilege levels in ARM are referred as *Exception Levels* (EL), and there are four of them: EL0, EL1, EL2, EL3. The larger the exception level number, the greater the privilege. EL0 is the lowest privilege level designed for userspace software, the `svc` instruction (supervisor call) can be issued in this EL to trap to EL1 for system call service. EL1 is regularly used for running an OS kernel like the Linux kernel. EL1 controls EL0/1 page tables to enable virtual memory for userspace and the kernel space, and sets up the exception vectors to handle EL0 and EL1 exceptions. EL1 can also ask for EL2 service via the `hvc` instruction (hypervisor call). EL2 is designed for running a hypervisor. It is more privileged than EL1, software EL2 is capable of setting various conditions for the hardware to trap to EL2 to intervene the lower EL1 and EL0 execution. For example, it is capable of redirecting all device interrupts to EL2's own exception vector to interpose all interrupts. ARM also provides Nested Page Table (NPT) support in EL2. If EL2 en-



ables NPTs, the physical address that results from an EL0/1 page table walk becomes the *Intermediate Physical Address* (IPA), the IPA must then be translated again by the additional set of page tables set up by the software in EL2 to finally get the physical address used for memory access. The address translation turns into a two stage process, firstly the EL0/1 virtual address is translated into IPA by walking the EL0/1 page table controlled by the kernel in EL1, after that it is translated again by walking the NPT. Thus, when a hypervisor enables NPT, all guest kernels in EL1 only see its own virtual guest physical address space. The hypervisor has full control over the physical memory. Lastly, EL3 is the highest privilege level typically used for running system firmware that initializes the hardware. The *Virtualization Host Extensions* (VHE) is an ARM architecture extension added to support running an unmodified OS kernel designed for an EL1 environment directly in EL2. The extension is needed because originally, EL2 differs from EL1 in a few ways. First, EL1 has two *Translation Table Base Registers* (TTBRs), while EL2 only has one. It was designed like this because OS kernels running in EL1 need the extra base register to separate user process address space and kernel address space, and hypervisors normally do not host applications. Second, there is no *Address Space Identifiers* (ASIDs) support in EL2 for the same reason. Third, the bit layout of some system registers and page table format in EL2 are different from their EL1 counterparts. VHE addresses the problems above by adding another TTBR, ASID support, and synchronized the bit layout of EL2 and EL1 system registers and the page table formats. On hardware that support VHE, the Linux kernel can thus boot in both EL1 and EL2.

2.2 KVM ARM



KVM ARM was merged into the mainline Linux kernel version 3.9 [13]. It was designed to support unmodified guest VMs by utilizing hardware virtualization support introduced in section 2.1. The authors proposed *split-mode virtualization* [14], allowing the KVM ARM hypervisor to split its execution across CPU modes and be integrated into the Linux kernel. Split-mode virtualization installs a small amount of code in EL2 called the *lowvisor* when Linux initializes. The lowvisor is only responsible for hypervisor tasks that can only be done in the more privileged EL2, including running EL2 exception vectors and installing the addresses NPTs in the VTTBR_EL2 register, which holds the NPT root pointer. Split-mode virtualization has various advantages. Kernel features including memory allocation, CPU scheduling can still be done in EL1, thus simplifying the lowvisor, also the small lowvisor makes the addition of KVM ARM a less intrusive change to the Linux codebase, increasing the possibility of it being merged into the mainline kernel for its maintainability and ease of review.

Split-mode virtualization was proposed before the introduction of ARM VHE. With VHE, the entire Linux kernel can be run in EL2, removing the need for KVM to split its execution across CPU privilege levels. Before with split-mode virtualization, the lowvisor must multiplex the EL1 context, or context switch EL1 system registers when entering or exiting VMs, which leads to overhead. By running Linux entirely in EL2, guest EL1 states do not have to be saved or restored each time a VM enter or exit happens, reducing the overhead. KVM ARM was then further developed to support both the new VHE feature (VHE mode), while keeping the option for the original split-mode virtualization, or Non-VHE (NVHE) mode.



2.3 HypSec

HypSec design overview, retrofitted KVM ARM

2.4 SeKVM

extended HypSec, formally verified the trusted TCB KCore

2.5 The Rust Programming Language

Rust is a relatively young programming language compared to C that aims to be safe and fast. It enables programs to be memory-safe without requiring programmers to manually manage memory as in traditional languages (e.g. C/C++). Different from other memory-safe languages such as Python or Go, Rust does not employ garbage collection for managing memory. Instead, the concepts of lifetimes, ownership, and borrowing rules are introduced to mandate the programmer to follow specific rules. This paradigm of statically enforcing programming rules empowers Rust to perform comparably to C since Rust's compiler has complete control over the code that runs during runtime and can optimize it accordingly. Additionally, Rust's safety rules ensure that no memory safety bugs will be present when satisfied, and the compiler automatically checks and prevents any violation of these rules.

Ownership and Lifetimes. In Rust, each piece of data is said to be *owned* by a single variable, and it is automatically *dropped* (freed) when the variable's *lifetime* ends. A variable's lifetime ends as the program control flow exits the block in which the variable

is declared. In Listing 1, *y*'s lifetime starts at line 5 and ends at line 7 as the block closes. Hence, the `println!` macro is unable to find the value *y*, whose lifetime has already ended. Ownership can be transferred or *moved*. For example, assigning the owning variable to a new variable moves the ownership of the data to the new variable. And passing the variable into a function also moves the data ownership into the function. In both situations, the original variable returns to the uninitialized state, and using it would result in a compilation error.

```
1 // this code sample does *not* compile
2 {
3     let x = 1;
4     {                // create new scope
5         let y;
6         y = x;
7     }                // y is dropped
8
9     // compilation error, y's lifetime has ended
10    println!("The value of 'y' is {}", y);
11 }
```

Listing 1: Rust lifetime example

Borrowing. Ownership lacks the flexibility of argument passing. Rust addresses this by *borrowing*, a mechanism that allows accessing data without gaining ownership. A variable can borrow ownership from another variable to acquire a *reference* to the data. References can be divided into two categories, *shared* references and *exclusive* references. The reference can only be read and not modified with a shared reference. Nevertheless, multiple shared references for a specific value can be held simultaneously. On the other hand, exclusive references allow reading from and modifying the value. However, having any other kind of reference active simultaneously for that value is not permitted.

In summary, Rust's borrowing rule enforces *aliasing xor mutability* meaning there can be multiple shared references or a single exclusive reference. In Listing 2, line 6

would not compile because it tries to create a mutable reference (z) to x, while y already borrowed x immutably. y's lifetime ends on line 8 as it gets used for the last time; therefore z can be created on line 10 and used on line 11. However, if line 13 is uncommented, y's lifetime would be extended to line 13, making the creation of z on line 10 break the borrowing rules.

```
1 {
2   let mut x = vec![1, 2, 3];
3   let y = &x; // immutable borrow of x
4
5   // this line would fail to compile because x is already borrowed
   ↪   immutably by y
6   /* let z = &mut x; */
7
8   println!("x = {:?}", x); // This line works
9   println!("y = {:?}", y); // This line works
10
11  let z = &mut x; // mutable borrow of x
12  z.push(4);
13
14  // this line would fail to compile because x is borrowed mutably by z
15  /* println!("y = {:?}", y); */
16 }
```

Listing 2: Rust enforces *aliasing xor mutability*

unsafe Rust. Rust's safety checks are sometimes too restrictive regarding tasks like low-level hardware access or special optimizations. These operations are inherently unsafe and hence impossible to follow the rules mandated by Rust. However, they are still necessary for low-level software such as hypervisors. To provide flexibility for these operations, Rust allows parts of the program to opt out of its safety checks via the *unsafe* keyword. Traits, functions, and code blocks can be marked as unsafe to disable the checks that the compiler would normally enforce. However, using unsafe code also means that the responsibility for ensuring memory safety is shifted from the compiler to the programmer. Therefore, it is crucial to exercise caution when using unsafe code to avoid introducing bugs or security vulnerabilities.

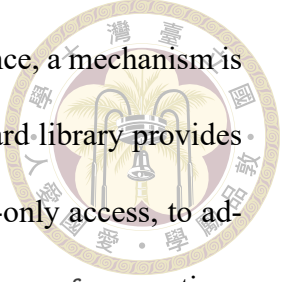
Interior unsafe. While most low-level code is written in unsafe code, Rust introduces the concept of *interior unsafe* [36]. A function is considered interior unsafe if it exposes a safe interface but contains unsafe blocks in implementation. This allows unsafe operations to be encapsulated into safe abstractions. For instance, in Listing 3, Rust’s `replace` function can be called by safe Rust, but it is implemented using unsafe raw pointer operations. At line 6, `ptr::read` is used to copy a bit-wise value from `dest` into `result` without moving it, and at line 7, `ptr::write` overwrites the memory location pointed to by `dest` with the given value `src` without reading or dropping the old value. Lastly, at line 8, `result` is returned to the function’s caller.

```
1 pub const fn replace<T>(dest: &mut T, src: T) -> T {
2   // SAFETY: We read from `dest` but directly write `src` into it
   ↳ afterward,
3   // such that the old value is not duplicated. Nothing is dropped and
4   // nothing here can panic.
5   unsafe {
6     let result = ptr::read(dest);
7     ptr::write(dest, src);
8     result
9   }
10 }
```

Listing 3: interior unsafe in Rust’s `replace` function

This leads to a design practice that interior unsafe functions should provide the necessary checks that prevent the unsafe code from producing any undefined behavior or memory safety bugs. The callee in the safe world hence bears no responsibility to ensure safety.

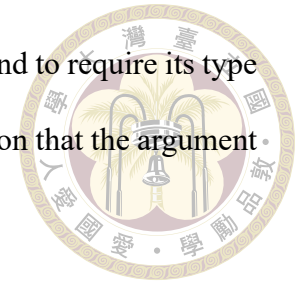
Interior Mutability. Mutating referenced data via an immutable reference is forbidden in Rust. However, this is sometimes too restrictive for implementing efficient algorithms or data structures. For instance, a cache might be desirable for a read-only search data structure to optimize lookup time. Nevertheless, updating the cache state re-



quires mutability for the cache, violating the read-only constraint. Hence, a mechanism is needed for mutating data under a read-only variable. The Rust standard library provides some special types that allow the user to modify data even with read-only access, to address this issue. This design pattern is known as *Interior Mutability*. `unsafe` operations are used to implement these types to bend Rust's usual rules that govern mutation and borrowing. These types ensure the borrowing rules are followed, i.e. one mutable borrower at one time, and no mutable borrowers when read-only borrowers exist, at runtime. A panic occurs whenever the runtime checks fail, stopping the program to avoid safety issues. For example, `Mutex` in Rust provides interior mutability. A lock is used to ensure that only one borrower of the inner data exists at one time. More precisely, when attempting to borrow data that has already been borrowed, the `Mutex` enforces a busy wait until the data is released, thereby allowing only one borrower at a time. However, if a thread borrows the inner data of `Mutex` while it is already borrowing it, `Mutex` will wait forever, i.e., result in a self-deadlock.

Generics and Traits. In addition to the safety mechanisms, Rust also provides features for writing code that operates on values of many different types. `Generic` allows code to work with type parameters, reducing similar code that work with different types. For example, the vector type in Rust's standard library `std::vec::Vec` is capable of holding an array of an arbitrary type. Rust traits are properties or interfaces that can be implemented on types; traits typically require the implementing type to supply function implementations for its trait methods. Additionally, combined with `Generic`, a trait can be treated as a restriction on type specifications such as function arguments or struct fields. The restriction is called a *trait bound*. For example, the `Clone` trait requires the implementing type to provide implementations for its `clone` and `clone_from` functions to make

copies of themselves. A `Generic` function or type can use a trait bound to require its type argument to implement `Clone`, so that it can invoke the `clone` function that the argument implements.



Error Handling. Rust offers enum types `Result<T, E>` and `Option<T>` that have variants to explicitly represent the state of error. A `Result` type can be the enum variant `Ok(T)`, which denotes a proper result with type `T`, or `Err(E)`, which represents an error with reason of type `E`. To simplify error handling, Rust provides a convenient syntactic sugar, the `?` operator. When used on a `Result`, it retrieves the `T` from `Ok(T)`. However, if the `Result` is `Err(E)`, the `Err` variant is immediately returned from the enclosing function, propagating the error to the caller. When handling enum types, the program must handle all variants of the enum, and not doing so results in a compilation error, this enforces the programmer to handle all possible cases, including errors. Similarly, `Option` can have the `Some(T)` variant, or the `None` variant, which represents the state of not having a value. These types prevent unexpected errors when accessing a potentially non-existing value, or a potential error in the program.

Copy and Drop Traits. Some traits in Rust have intrinsic meaning to the compiler. For example, the `Drop` trait tells the compiler that a type has special freeing code, and the `Drop` trait's `drop` function should be invoked when an instance of the type goes out of scope. And the `Copy` trait, when implemented for a type indicates that the type should be byte-by-byte copied when the assignment (`=`) operator is used instead of Rust's typical semantic of moving the ownership to the new variable. Interestingly, Rust forbids a type from being `Drop` and `Copy` simultaneously, the designers of the language observed that if a type requires special deallocating code (the `drop` function), then it should also require a special copying function, rather than just copying it byte-by-byte. For instance, a type

that holds a reference to the heap requires a `drop` function that frees the data pointed to by the reference, copying the object of the type in a byte-by-byte manner introduces risks of double-free, use-after-free, etc.





Chapter 3 Assumptions and Threat Model

We assume a remote attacker or a curious administrator that aims to compromise the integrity and confidentiality of VM data. An attacker can exploit bugs in the host kernel integrated with KVM. A remote attacker cannot access the hardware, so physical attacks such as cold boot attacks [19] attack and memory bus snooping are out of scope. On-site security measure [17] is assumed to be in place to prohibit unauthorized physical access to the hardware. Side-channel attacks [7, 20, 31, 38, 47, 48] are also excluded from our threat model.

We assume a VM does not voluntarily reveal its sensitive data, intentionally or by accident. A VM can be compromised by a remote attacker that exploits vulnerabilities in the VM. We do not provide security features to prevent or detect VM vulnerabilities, so a compromised VM that involuntarily reveals its data is out of scope. However, attackers may try to attack other hosted VMs from a compromised VM for which we provide protection.





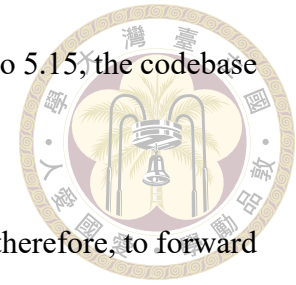
Chapter 4 Implementing a Linux KVM TCB in Rust

The goal of this work is to create a secure hypervisor by leveraging Rust’s safety features in its TCB. Our Rust-based hypervisor, KrustVM, is based upon the SeKVM implementation. We first forward ported SeKVM from its original Linux 4.18 version to the newest long term support version Linux 5.15 at the time of development. Once the forward port of SeKVM to Linux 5.15 is done, we then rewrote the SeKVM TCB Kcore in Rust to create Rcore, KrustVM’s TCB. This chapter describes the challenges that arose when implementing a Rust-based KVM TCB, and the techniques employed to solve them.

4.1 Forward Porting SeKVM from Linux 4.18 to Linux 5.15

The Linux kernel gained many new features between version 4.18 and 5.15, including performance optimizations such as Link-Time-Optimization (LTO) and energy aware scheduling. And new kernel security features including `clang` shadow call stacks, branch target identification, control flow integrity (CFI), ARM Memory Tagging Extension (MTE), ARM pointer authentication, and randomized stack offset per system call. By

forward porting SeKVM from its original Linux kernel version 4.18 to 5.15, the codebase can benefit from these advancements.



SeKVM is based on the mainline KVM ARM in NVHE mode, therefore, to forward port it to a newer kernel version, APIs used by SeKVM must be updated. For example, the data cache flushing function `__flush_dcache_area` is changed to `dcache_clean_inval_poc` in Linux 5.15. All outdated functions and macros in the SeKVM codebase are updated. Moreover, a new KVM mode `pkvm` [21] is added to mainline KVM ARM in Linux 5.11, we made sure the logic of SeKVM and `pkvm` is separated such that the two modes of operation can coexist in the codebase. This is done by checking for the kernel configuration at KVM initialization, if the configuration option for SeKVM is set, `pkvm` will not be initialized. Mainline KVM had also made the code that runs in ARM's hypervisor mode (EL2) more self-contained. A namespace is introduced for symbols belonging to EL2 to isolate kernel mode symbols and hypervisor mode symbols name-wise, a prefix `__kvm_nvhe_` is prepended to all symbols in EL2. Parts of SeKVM that references symbols in the original NVHE KVM EL2 code then must adjust how it references those symbols, the predefined helper macro `CHOOSE_NVHE_SYM()` is used, it prepends the prefix (`__kvm_nvhe_`) for referencing NVHE symbols so that it is not required to write `__kvm_nvhe_` every time the code references a NVHE symbol. This makes our code cleaner and easier to maintain. For SeKVM symbols that need to be referenced by the original NVHE KVM EL2 code, in this case, the helper macro `KVM_NVHE_ALIAS()` is used, which creates an additional symbol referring to the same piece of data as the input symbol whose name is prepended by the NVHE prefix, enabling the NVHE KVM EL2 code to reference it. Furthermore, to resolve the issue that the compiler optimizing struct zeroing operations with `memset` calls, which are not mapped in EL2, the C compiler flag `-ffreestanding` is included during

the compilation of SeKVM.



4.2 Integrating Rust and Linux

In order to write a KVM TCB in Rust, Rust code must be compiled and linked with the rest of the Linux kernel. However, Linux 5.15, which is the latest long term support kernel version at the time of KrustVM development, does not support Rust as a development language. As a result, incorporating our Rust code into the kernel requires manual building and linking, which can be both laborious and susceptible to errors. To overcome this challenge, we integrated the Rust toolchain with the Linux kernel build system. A new subdirectory in Linux's source path `arch/arm64/krustvm` is created. Within it contains the `Rcore` crate and the `Makefile` for this directory. `Rcore` is implemented in a single crate on the `no_std` environment and compiled into a single static library `libkrustvm.a`. To integrate building `libkrustvm.a` and linking it with the rest of the kernel, the following is added to the `Makefile`:

1. append `libkrustvm.a` to Kbuild built-in object goals `obj-y` by adding the line

```
obj-y += libsekvms.a
```

2. define `Makefile` target to instruct make to use `cargo` to generate `libkrustvm.a`.

```
1 $(obj)/libkrustvm.a: $(src)/krustvm/src/*.rs
2     cargo build --release --target=aarch64-unknown-linux-gnu
```

3. link `libkrustvm.a` to generate object file `krustvm.o`

The `Makefile` in `arch/arm64/krustvm` generates `krustvm.o`, and the kernel build system will then link this file with all other object files in the kernel and produce the final kernel image.

4.3 Rewriting C-based Kcore into Rust-based Rcore

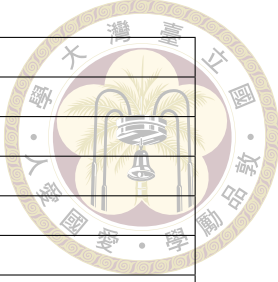


4.3.1 The Rewrite Process

Given the high complexity of the KVM hypervisor and Kcore, it is clear from the beginning that a top-down approach to a Rust rewrite would be error-prone and difficult to test. Therefore, we elected to start the rewriting effort bottom-up, where all previous C functions in the TCB are rewritten in Rust, one by one. This incremental approach allows us to test one rewritten function at a time, reducing the risk of introducing bugs. One major downside of this approach is the difficulty of rewriting individual functions in a manner that adheres to Rust's idiomatic practices. Furthermore, it may result in a lot of `unsafe` blocks. These issues are solved by adding a second phase to the Rust rewrite; after the initial function by function rewrite, we removed unnecessary `unsafe` blocks, refactored the code to be more Rust-idiomatic, and leveraged Rust features to enhance Rcore memory safety.

4.3.2 Rust Code Organization


Rust packages code into *modules*, modules are containers for functions, types, constants, traits, etc. Rust programs or libraries are made up of one or multiple modules. Rcore consists of multiple modules, including the typical utility functions module, and modules that contain functions that implement different hypervisor tasks, for example mapping a page in the host kernel's NPT. Moreover, each of the Rcore metadata types (Table 4.1) used for storing NPT information, physical memory page ownership, VM information, SMMU page table metadata, etc., is implemented as its own module that de-



Name	Decription of Data
vCPU context	The array that stores the state of each vCPU register.
VM info	The per-VM execution state metadata.
NPT info	The NPT pool allocation status.
PMEM info	The physical memory ownership and sharing status.
SMMU info	The SMMU management and page tables metadata.
SMMUPT info	The SMMU page table pool allocation status.

Table 4.1: Rcore metadata

defines the type and its associated type methods. One of the modules is `VMInfo`, it includes the definition of the type `VMInfo`, which stores information of a VM including its VMID, state, and an array of VCPU states. The module also contains methods for reading the VMID, setting the state of the VM, etc. Another module aggregates the Rcore metadata structures into a single big structure `RcoreMetadata` (line 1 in Listing 4) to simplify the memory used by these metadata. All CPU cores share metadata in Rcore; some are per CPU. Fields shared by all CPU cores in `RcoreMetadata` are defined as type `KMutex<T>` (an example is line 3 in Listing 4), where T is the type that actually stores Rcore metadata. Rcore's custom `KMutex` is a generic type which can hold any arbitrary type alongside a lock. The only way to access the data wrapped in `KMutex` is by calling the `lock` method of `KMutex` reference. Different from Rust, C does not support methods for structs, it therefore lacks the ability to present an API that provides type-specific functionalities while abstracting away how the implementation manipulates the structure's data. For instance in Listing 5, users of `VMInfo` is forbidden from accessing the `vmid` field of `VMInfo` directly, but must call the `get_vmid` method. The user thus can not arbitrarily modify data inside the structure. This Rust feature helps eliminate bugs such as writing to read-only fields, and reading internal fields.



```

1 struct RcoreMetadata {
2     [...] // other fields omitted
3     pub pmem_info: KMutex<PMemInfo>,
4     [...] // other fields omitted
5 }
6
7 const RCORE_METADATA_PTR: *mut RcoreMetadata = /* Rcore's memory address
    ↪ */;
8

```

Listing 4: Rcore metadata

```

1 // in the VM module:
2 pub struct VMInfo {
3     vmid: u32,
4     [...] // other fields omitted
5 }
6
7 impl VMInfo {
8     #[inline(always)]
9     pub fn get_vmid(&self) -> u32 {
10         self.vmid
11     }
12 }

```

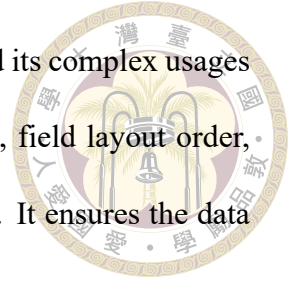
Listing 5: type method example

4.3.3 Rust-Rewrite Challenges

Enforcing Linking Section. KVM separates EL2 code from EL1 by grouping EL2 code in a section `.hyp.text`, then mapping that section in EL2’s address space at initialization. In Rcore, attribute `#[link_section = ".hyp.text"]` is prepended to all code that should be run in EL2, so that they get placed in the `.hyp.text` section as well.

Matching Linux Types and Constants. Our implementation is compatible with the Linux kernel codebase. For example, the page size definition is identical in Rcore and KVM. For types shared between Linux and Rcore like `kvm_vcpu`, the type definitions are generated automatically with the tool `bindgen` [9]. And for constants that are used by both Linux and Rcore, including the page size mentioned above, they are copied from C

to Rust manually. Due to the limited support of macro in `bindgen` and its complex usages by Linux, it is not used to generate constants. Regarding alignment, field layout order, and padding of custom types, the Rust attribute `#[repr(C)]` is used. It ensures the data layout of the marked type has the same layout as in C.



Entry Point Binding. Whenever an exception gets taken to EL2, the CPU switches its exception level to EL2, saves the program status and exception syndrome, and jumps to the preassigned exception vector. We modify the exception vectors, which are written in assembly, to call Rcore's entry point functions instead of the original C handlers to transfer the control flow to our Rust code.

4.3.4 Unsafe Rust Usages

A small part of Rcore's implementation is coded in unsafe Rust. The source of unsafe Rust includes inline assembly, the Foreign Function Interface (FFI), KVM ARM Per-CPU variables, and raw pointer accesses. The first three categories are discussed in this section, and for raw pointer usages, chapter 5 shows how each raw pointer usage scenario is checked to guarantee their memory safety.

Inline Assembly. Inline assembly are used for system instructions and system register accesses. For example, TLB invalidation instructions must run when Rcore updates the NPTs, and the `VTTBR_EL2` register must be switched when preparing to run a guest VM. We make use of Rust's built-in module `core::arch::asm` to insert inline assembly. For system register accesses, the `aarch64-cpu` crate [1] is imported into our Rcore crate, it provides a clean API for reading and writing AArch64 system registers. The inline assembly used for the actual register accesses are abstracted behind safe APIs.

FFI. FFIs are used for calling longer assembly routines, such as the cache invalidation routine, and `__guest_enter` for context switching general purpose registers and entering guest VMs.



KVM ARM Per-CPU Variables in Rust. Using KVM ARM Per-CPU variables is special case for unsafe Rust. Mainline KVM has its EL2 per CPU variable mechanism; it is implemented by first allocating enough space for all cores to have a copy of the per CPU variables, then, for each core, it records the offset from its copy of the variables to the base copy. This per-core offset is then stored in each core's `TPIDR_EL2` system register. When the need to access a per CPU variable arrives, the base address is first acquired by referencing a global variable, then adding `TPIDR_EL2`'s value to the variable's address. KrustVM continues to use this mechanism by declaring the symbol which corresponds to the base address as a Rust extern static variable, take its raw address, then add the value in `TPIDR_EL2` to it. This approach requires three `unsafe` statements, first from reading the address of the extern static variable, then reading `TPIDR_EL2` via inline assembly, and lastly, another `unsafe` to dereference the calculated address. Concurrent accesses will not pose a problem since each core accesses a different address.

4.4 Bringing up KrustVM on Real Hardware

We chose the Raspberry Pi model 4B (Rpi-4B) to verify our implementation on real hardware. SeKVM's trusted core Kcore originally reserved its private memory by defining global symbols whose addresses reside right after the kernel image, in the Linux kernel linker script. Kcore then references those symbols to access and utilize the reserved memory. However, there exists an unusable hole in Rpi-4B's physical memory address space,

and the bootloader of Rpi-4B places the kernel image before the hole, resulting in an overlap of Kcore's private memory and the unusable hole (Figure 4.1). This makes SeKVM unable to initialize on Rpi-4B.

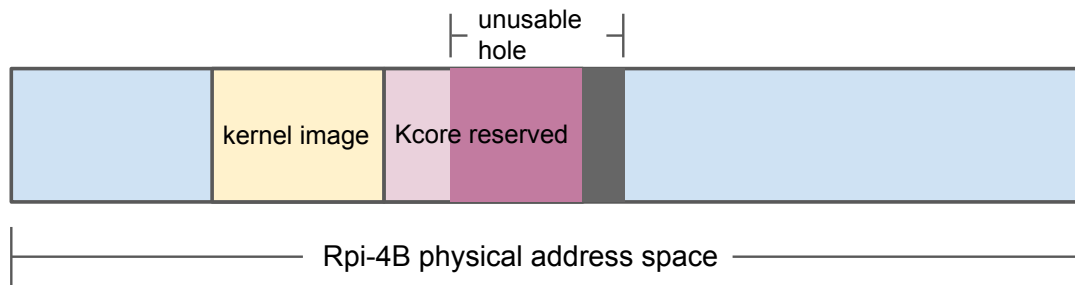
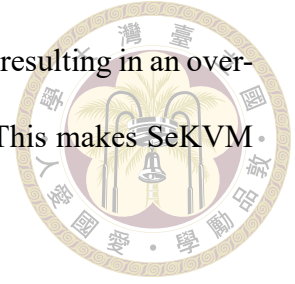


Figure 4.1: Kcore overlaps the unusable hole on Rpi-4B

To solve this issue for KrustVM, instead of allocating memory in the linker script, we first locate a range of memory which does not overlap with the unusable hole of Rpi-4B and the kernel image, then add a new memblock that to correspond to the Rcore's private memory. We mark it as reserved by calling `memblock_reserve`, so that the kernel does not accidentally access this memory range (Figure 4.2). The global symbols previously defined the Linux kernel linker script have also been changed to macros that expand into addresses in the reserved range for KrustVM's Rcore usage.

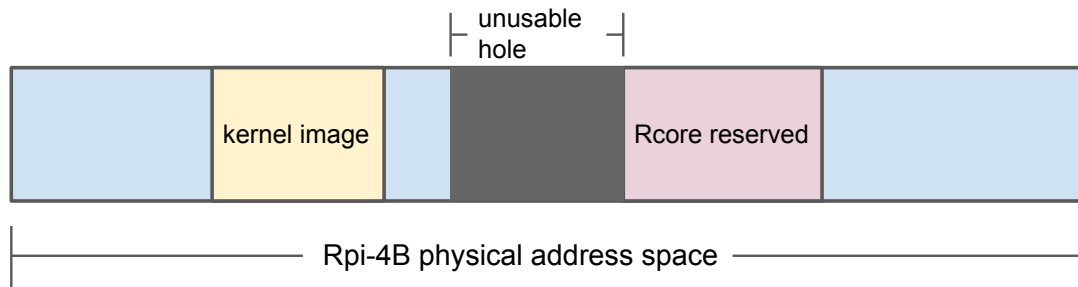


Figure 4.2: Overlap prevention



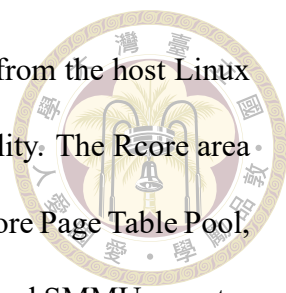
Chapter 5 Securing Rcore Memory

Accesses

Numerous software bugs arise from the disparity between the address to which a pointer is pointing and the intended address it should be pointing to. For example, NPT walking code must calculate addresses of each level's page table entry. If the address calculation is erroneous, the NPT walking code may dereference the pointer which points to an unrelated region of memory, and write to guest memory, or other hypervisor metadata, leading to crashes or vulnerabilities. To tackle these kinds of bugs, Rcore's memory accesses are categorized into disjoint regions, and raw pointer accesses are guaranteed to not cross memory region boundaries. section 5.1 describes each of the memory region defined for Rcore's memory accesses, and section 5.2 presents how raw pointers are guaranteed to access the intended region.

5.1 Rcore Memory Regions

Rcore's memory accesses are categorized into four disjoint regions: *Rcore Metadata*, *Page Table Pool*, *SMMU Area*, and *Generic Area*. Rcore metadata and Rcore Page Table pool combined are referred to as the *Rcore area* in the following.



Rcore Area. Rcore needs a reserved memory region separated from the host Linux kernel and all other VMs, named *Rcore area*, to provide its functionality. The Rcore area comprises the Rcore Metadata and the Rcore Page Table Pool. The Rcore Page Table Pool, as its name suggests, keeps private pools of physical pages for NPTs and SMMU page tables so that Rcore has complete control over the permissions and the virtual-to-physical mappings of the memory accessed by the host Linux kernel, VMs, and I/O devices. The Rcore metadata, on the other hand, is used for storing Rcore metadata described in subsection 4.3.2.

SMMU Area. SMMU is accessed via MMIOs. Rcore unmaps the SMMU from the host NPT to trap-and-emulate its access to the SMMU. This approach assures Rcore has exclusive access to the SMMU.

Generic Area. The *Generic Area* refers to memory outside the Rcore area and the SMMU area. Rcore needs to access this area to modify memory pages belonging to the host or guests for VM services, such as zeroing a page before transferring ownership from a guest back to the host during VM termination.

5.2 Memory Region Isolation

Raw pointers are types in Rust that are not checked by Rust's aliasing xor mutability rule, meaning there can be multiple raw pointers pointing to the same piece of data. Further, raw pointers are also nullable. The relaxation of these safety rules opens up the potential for null pointer dereferences or use-after-free memory bugs when raw pointers are accessed. Hence, raw pointer accesses are prohibited in safe Rust. As detailed in the upcoming paragraphs, we examine the need for raw pointers for accessing the four regions

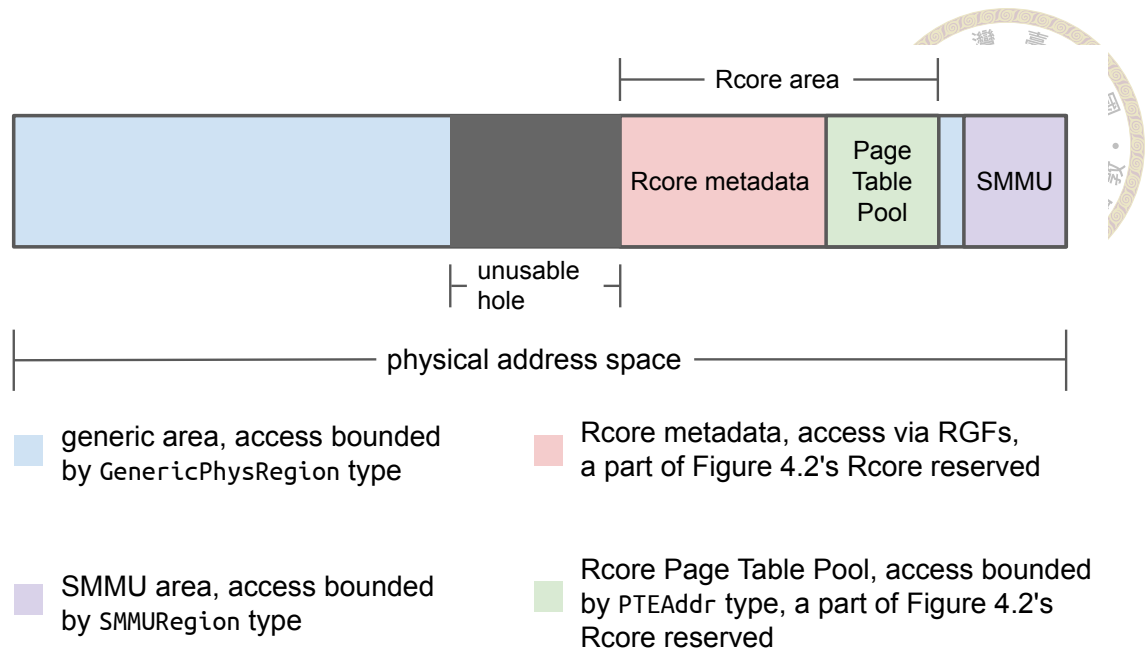


Figure 5.1: Memory Regions

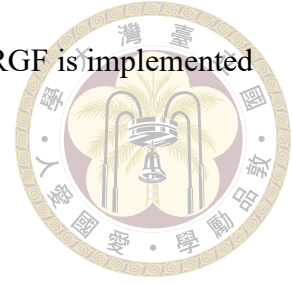
described in section 5.1 and the measures taken to guarantee their isolation, even when employing unsafe Rust in their implementation. The amount of unsafe code that contains raw pointer accesses is also deliberately made small (~ 50 LOC).

5.2.1 Raw Pointer Access: Rcore Metadata

Since there is no existing memory allocator in a hypervisor environment, we directly inform where in the address space Rcore should use. Specifically, the address to the instance of `RcoreMetadata` is pre-defined, and the memory region is manually initialized at boot time, so it can be used safely thereby. Using that raw address, several functions are implemented that transform the raw pointer to `RcoreMetadata` into mutable references to each of its fields and return them to the caller.

A set of reference getter functions (RGFs) is implemented. Rcore can use the RGFs to safely access `RcoreMetadata` with safe Rust. Each RGF returns a mutable reference to one of the fields in `RcoreMetadata`, line 2 of Listing 6 is an example of an RGF, it

returns the mutable reference of the type `KMutex<PMemInfo>`. The RGF is implemented by:



1. dereference the raw pointer using the `*` operator
2. pick the `pmem_info` field of `RcoreMetadata`
3. take the mutable reference of the field by prepending `&mut`
4. return the mutable reference

By defining fields of `RcoreMetadata` as `KMutex<T>`, and with the RGFs, most of `Rcore` is free from directly using raw pointers to access `Rcore` metadata, and proper locks are guaranteed to be held when accessing them.

```
1 // the RGF of pmem_info
2 pub fn get_pmem_info<T: CanGetPMemInfo>(_: &mut T) -> &mut
   ↳ KMutex<PMemInfo> {
3     // SAFETY: The pointer points to an initialized memory.
4     // The data is properly wrapped in a KMutex
5     // and the caller have the permission to get PMemInfo
6     unsafe {
7         &mut (*RCORE_METADATA_PTR).pmem_info
8     }
9 }
```

Listing 6: Rcore Reference Getter Function

The RGFs return mutable references from a raw pointer, thus encapsulating the raw pointer usages when the caller wishes to access `Rcore` metadata (`RcoreMetadata`). All memory accesses done via RGFs are bounded in the range from `RCORE_METADATA_PTR` to `RCORE_METADATA_PTR + sizeof(RcoreMetadata)`, as accesses to non-array fields will not go out of bounds, and Rust automatically adds runtime checks for the indices when array fields are accessed. We manually check this range is only accessible by `Rcore` and disjoint from the page table pool and SMMU area by checking it is within the memory

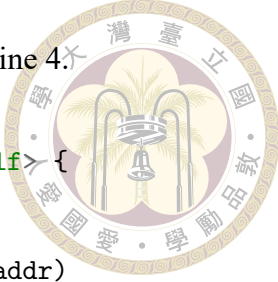
range unmapped from the host Linux kernel for Rcore and comparing the addresses with the page table pool area and SMMU area. Hence, it is impossible for Rcore metadata accesses to access the other three regions accidentally.



5.2.2 Raw Pointer Access: Generic Area

Generic area accesses are done by calculating raw addresses and writing to them via raw pointers. Raw pointers are necessary here because system RAM is just a range of flat address space to Rcore. To ensure that code accessing the generic area does not accidentally access the Rcore area, a new type called `GenericPhysRegion` (Listing 7) has been created, which can only point to a memory range in the generic area. `GenericPhysRegion` only has one constructor, namely the `new` method at line 2 in Listing 7. This method verifies whether the memory range specified by the arguments (start address `start_addr` and access size `size`) is contained within the bounds of the generic area. If the specified range overlaps with the Rcore area or the SMMU area, the constructor returns a `None` variant, indicating that the construction has failed. Listing 8 shows an example usage of `GenericPhysRegion`, which is a function that takes a physical frame number (`pfn`), and clears the contents of the page. The `GenericPhysRegion::new()` function is called at line 2 with the physical address of the page (`pfn << PAGE_SHIFT`) and its size (`PAGE_SIZE`) as arguments and returns a type of `Option<GenericPhysRegion>`. Next, `Option` is transformed to `Result` type through `ok_or.` and use the `?` operator on the `Result` type to return the contained value to `page` if it is an `Ok` variant. Otherwise, `clear_page` immediately returns `Error` without executing anything after line 2, effectively propagating the absence of a value up the call stack. The caller of `GenericPhysRegion::new()` gets a `GenericPhysRegion` if the check passes; otherwise, `clear_page`

returns an Error type. If successful, the page contents are cleared at line 4.



```
1 impl GenericPhysRegion {
2     pub fn new(start_addr: usize, size: usize) -> Option<Self> {
3         let end = start_addr + size;
4         // overlap check
5         if (end > RCORE_AREA_START && RCORE_AREA_END > start_addr)
6             || (end > SMMU_AREA_START && SMMU_AREA_END > start_addr) {
7             return None;
8         }
9         Some(Self {
10             start_addr,
11             size,
12         })
13     }
14
15     // returns a mutable `u8` slice for the caller
16     // to access generic area memory
17     pub fn as_slice(&self) -> &'static mut [u8] {
18         // convert the physical address to the virtual address
19         let va = pa_to_va(self.start_addr);
20         unsafe {
21             core::slice::from_raw_parts_mut(
22                 va as *mut u8, self.size,
23             )
24         }
25     }
26 }
```

Listing 7: GenericPhysRegion guarantees that every instance points to a valid generic area range

5.2.3 Raw Pointer Access: Page Table Pool

Rcore manages the host's and each VM's NPTs to control their access to physical memory. SMMU page tables control I/O devices' memory access. We also leveraged Rust's type system and created the type PTEAddr (Page Table Entry Address). Each instance of type PTEAddr points to an entry in the Rcore Page Table Pool region. Similar to GenericPhysRegion, PTEAddr's constructor verifies whether the physical address provided as an argument for the constructor is within the page table pool region in the Rcore area. If the address falls within the range, it is translated to the corresponding virtual ad-

```

1 fn clear_page(pfn: usize) -> Result<()> {
2   let page = GenericPhysRegion::new(pfn << PAGE_SHIFT,
    ↪   PAGE_SIZE).ok_or(Error::InvalidPfn)?;
3   // the `fill` method for type &[u8] fills the slice with the value
    ↪   passed in
4   page.as_slice().fill(0);
5   Ok(())
6 }

```



Listing 8: Example usage of GenericPhysRegion

dress and stored in a field of the PTEAddr instance. Otherwise, the construction fails, and a None is returned. This type encapsulates the raw pointer address translation and bound checks so for example the NPT walking code, can guarantee it is accessing NPT entries in the Rcore page table pool area by using PTEAddr.

5.2.4 Raw Pointer Access: SMMU

In a manner analogous to the generic area and page table pool, the type SMMURegion for accessing SMMU is created. Rcore uses SMMURegion whenever it reads or writes SMMU registers. SMMURegion's new method takes the MMIO address and verifies its inclusion within the SMMU region. By consistently utilizing this type for SMMU accesses, SMMU accesses are guaranteed to access the correct address region.





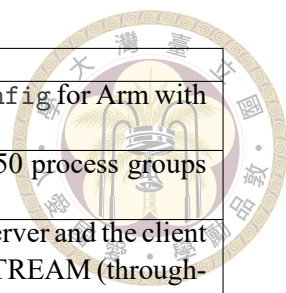
Chapter 6 Evaluation

We evaluated the performance of various application benchmarks on a VM running on KrustVM, SeKVM, and mainline KVM. We also tested the same benchmarks on bare metal environment performances to establish a baseline reference of the benchmark results. The workloads were run on the Raspberry Pi 4 model B development board, with a Broadcom BCM2711, quad-core Cortex-A72 (ARM v8) 64-bit SoC at 1.5GHz, 4GB of RAM, and a 1 GbE NIC device.

KrustVM, SeKVM, and the mainline KVM are all based on Linux 5.15. QEMU v4.0.0 was used to start the virtual machines on Ubuntu 20.04. The guest kernels also used Linux 5.15, and all kernels tested employed the same configuration. We requested the authors of [29] and got a patch for the Linux guest kernel to enable virtio. `rustc` version 1.68.0-nightly was used to compile Rcore, while clang 15.0.0 was used to compile the remaining components of KrustVM, SeKVM, and the mainline KVM.

2 physical CPUs and 1 GB of RAM is configured for the bare metal setup. Each VM that equips with 2 virtual CPUs for the VM setup, and 1 GB of RAM runs on the full hardware available.

We ran the benchmarks listed in Table 6.1 in the VMs on both KrustVM and the mainline KVM. Figure 6.1 shows the normalized results. We normalized the results to



Name	Description
Kernbench	Compilation of the Linux 6.0 kernel using <code>tinyconfig</code> for Arm with GCC 9.4.0.
Hackbench	<code>hackbench</code> [39] using Unix domain sockets and 50 process groups running in 50 loops.
Netperf	<code>netperf</code> [23] v2.6.0 running the netserver on the server and the client with its default parameters in three modes: TCP_STREAM (throughput), TCP_MAERTS (throughput), and TCP_RR (latency).
Apache	Apache v2.4.41 Web server running ApacheBench [43] v2.3 on the remote client, which measures the number of handled requests per second when serving the 41 KB <code>index.html</code> file of the GCC 4.4 manual using 100 concurrent requests.
Memcached	<code>memcached</code> v1.5.22 using the <code>memtier</code> [37] benchmark v1.2.3 with its default parameters.
YCSB-Redis	<code>redis</code> v7.0.11 using the YCSB [11] benchmark v0.17.0 with its default parameters.

Table 6.1: Application Benchmarks

bare-metal performance. 1.00 refers to no virtualization overhead. A higher value means higher overhead. The performance on real application workloads show modest overhead overall for KrustVM compared to SeKVM and mainline KVM. In the TCP_MAERTS benchmark, all four experimental setups saturated the 1GbE NIC on the Raspberry Pi 4 model B. Additionally, system noise had a more noticeable impact during the measurement of the bare-metal setup, making its performance the worst. Benchmarks ran in the three VM setups resulted in at most 20% difference, we believe the differences are caused by various system noise factors e.g. caches, kernel thread wakeups, and dynamic voltage frequency scaling.

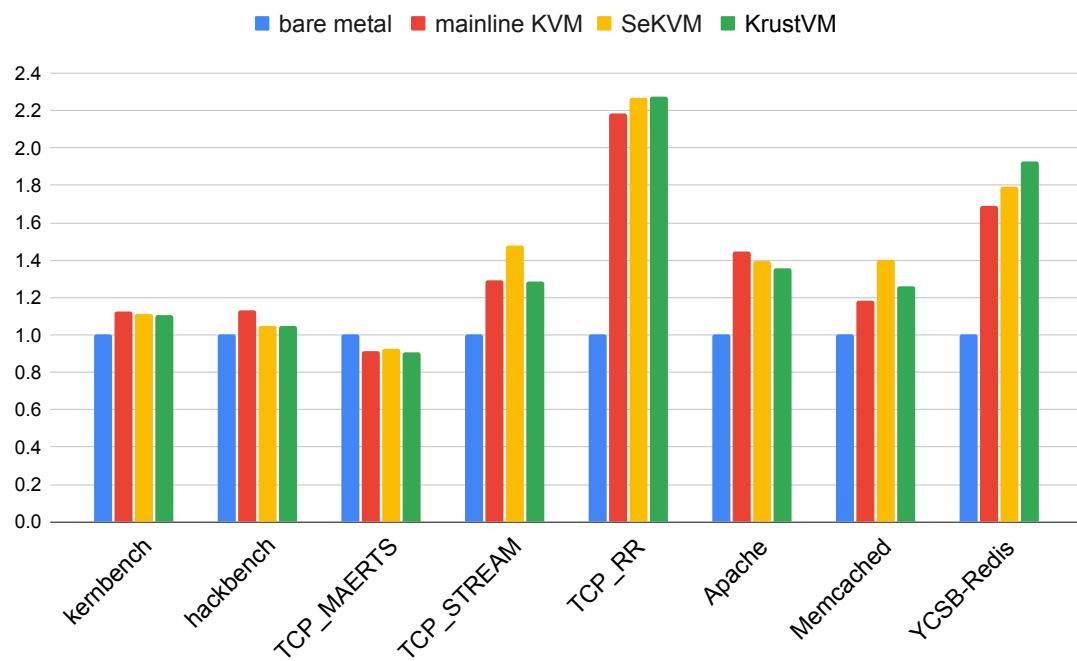


Figure 6.1: Application Benchmark Performance





Chapter 7 Related Work and Future Work

7.1 Related Work

7.1.1 VM Protection

Various previous work redesigned the hypervisor to protect VMs. Cloudvisor [33, 46] introduced a tiny security monitor underneath the commodity hypervisor to protect the hosted VMs. Twinvisor [28] supports regular VMs and confidential VMs by running hypervisors within both of ARM TrustZone’s normal world and secure world. HypSec and pkvm [21, 29] reduced the hypervisor’s resource access control component into to a small core to reduce the attack surface. Unlike our work, none of them used Rust to secure their hypervisor implementation. KrustVM and SeKVM [30] both leveraged HypSec’s design [29] to retrofit and secure KVM, providing the same level of VM protection. SeKVM included a formally verified core to protect VMs against an untrusted host Linux kernel, while KrustVM relies on a Rust-based Rcore to protect VMs. Formal verification of the concurrent C-based SeKVM core requires significant effort. The authors took two person-years to complete the correctness and security proofs. In contrast, our Rust-based imple-

mentation took less than one person-year. Different from formal verification, because the Rust compiler automatically ensures memory safety properties, our hypervisor codebase is flexible to frequent updates.



7.1.2 Rust-based Systems

Recent work extended existing C/C++ systems with a Rust binding to enable a Rust-based programming environment. Rust-SGX [45] and RusTEE [44] wrapped the C/C++ TEE SDK and exposed a safe Rust API to enable Rust programming in TEE environments such as SGX and TrustZone. Similarly, the Rust-for-Linux [16] project added abstraction layers to the Linux kernel to facilitate Rust driver programming with Rust. Besides building a Rust binding, previous work re-implemented C-based components in virtualization systems with Rust. rust-vmm [40] rewrote a subset of QEMU’s functionalities and separated them into libraries in Rust crates. Firecracker [2], crosvm [18], Cloud Hypervisor [32], and VMSH [42] extended the rust-vmm project with extra functionalities. These previous works built on top of existing core systems. In contrast, our work retrofitted Linux/KVM with a Rust-based TCB. HyperEnclave [22] relies on a Rust-based security monitor to enforce isolation between enclave TEEs. Unlike our work, the authors did not discuss the Rust monitor’s implementation and its unsafe Rust usage.

7.2 Future Work

Hardware features such as memory translation done by the Memory Management Unit (MMU), and exception levels, are not modeled by Rust, therefore the compiler is not able to check for misconfiguration or logical errors when building software on top of these

features. In other words, potential logical bugs in Rcore still undermines the security of our hypervisor. As an example, setting the wrong permission bits in the host's NPT makes way for a compromised host kernel to read the memory of a protected VM. We can add one more layer of defense by taking advantage of Rust auto-verification tools [6, 15, 25, 26] which base on Rust's strong type system, to check our code adheres to the specifications.

Rcore demonstrated the ability of Rust to isolate memory regions by leveraging language features like automatic bound checks for array types, and type constructor that checks for their arguments. Furthermore, these features can be used even more extensively to achieve a more fine-grained memory region isolation, such as separating the NPT pools into the first level NPT pool, second level NPT pool, and so on, or splitting the Rcore metadata region into multiple isolated regions, such as VMInfo region, PMemInfo region, etc.





Chapter 8 Conclusions

We have presented KrustVM, the first Rust-based secure KVM hypervisor that is rewritten from the C-based SeKVM. Similar to SeKVM, KrustVM delivers VM confidentiality and integrity protection against an untrusted Linux host kernel integrated with KVM. We overcame challenges that surfaced during the C-to-Rust rewrite. We integrated Rust into the Linux codebase, brought up KrustVM on Rpi-4B by changing the method used for reserving memory, and rewritten the SeKVM's TCB in Rust. Moreover, raw pointer accesses are segregated into a small amount of unsafe code to allow most hypervisor functionalities to be implemented in safe Rust. We also leverage Rust's compile-time checks to eliminate memory safety bugs of the TCB. Rust's type system is used to enforce memory region isolation via custom types. KrustVM preserves the performance efficiency of KVM, demonstrating the practicality for deployments.





References

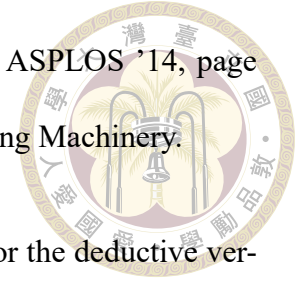
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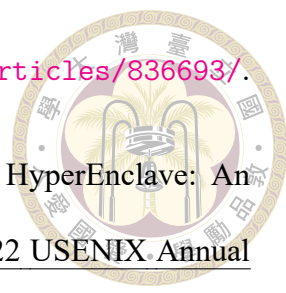


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