Memory-Safety Challenge Considered Solved? An Empirical Study with All Rust CVEs

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ABSTRACT

Rust is an emerging programming language that aims at preventing memory-safety bugs without sacrificing much efficiency. The property is very attractive to developers, and many projects start using the language. However, can Rust achieve the memory-safety promise? This paper studies the question by surveying the bug reports collected from two public datasets, Advisory-db and Trophy-cases, which contain all existing CVEs (common vulnerability and exposures) of Rust. We manually analyze each bug and extract their memory-safety issues and culprits. Our results show that buffer overflow and dangling pointers are still the major memory-safety issues in Rust, and most culprits are related to unsafe Rust. Such security issues reveal that the security cost of Rust to support unsafe functions is high. To elaborate, the culprits of buffer overflow bugs in Rust are very similar to those in C/C++, which generally involve both logical errors and arbitrary pointer operations that are allowed only by unsafe Rust. However, the culprits of dangling pointers in Rust have unique patterns, especially those related to the vulnerability of Rust’s borrow checker and lifetime checker. Based on these findings, we further suggest two directions to improve the resilience of Rust against dangling pointers, including recommending the best practice of some APIs to program developers, as well as approaches to enhancing the borrow checker and lifetime checker. Our work intends to raise more concerns regarding the memory-safety promise of Rust and facilitates the maturity of the language.

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1 INTRODUCTION

Memory safety is a long-lasting battle between developers and attackers. Typical issues of such bugs include buffer overflow, use-after-free, double free, etc. According to the statistical report of MITRE, memory-safety bugs are enumerated among the most dangerous software vulnerabilities. To combat such issues, classical strategies are two-fold. One is to design memory protection mechanisms, such as stack canary, ASLR, etc. Although such mechanisms are effective, they only increase the difficulty of attacks but cannot prevent them. The other strategy is to prevent introducing memory-safety bugs at the beginning, such as using type-safe languages. However, the enforcement of the memory-safety feature may also pose limitations to the language, making it inefficient for system-level software development with rigorous performance requirements.

Rust is an emerging programming language that aims at preventing memory-safety bugs while not sacrificing much efficiency. It achieves memory-safety via a set of strict semantic rules for writing compilable code and therefore preventing developers from introducing memory-safety bugs. In this way, Rust can be more efficient than other programming languages (e.g., Java and Go) which rely much on runtime memory checking and garbage collection [6]. However, Rust also supports some unsafe features, namely, unsafe Rust. Unsafe Rust allows developers use unsafe APIs (e.g., dereference raw pointers) directly to enrich its features or to promote efficiency. Like C/C++, using unsafe APIs has no memory-safety promise, making Rust programs vulnerable to memory-safety bugs.

Since the release of its stable version in 2015, the community of Rust grows very fast, and many popular projects are developed with Rust, such as the web browser Servo [3], and the operating system TockOS [12]. As Rust surges into popularity, a critical concern to the software community is how Rust performs in combating memory-safety bugs. Although it is well-known that unsafe Rust could undermine the memory-safety of Rust programs, its actual impact on real-world programs remains unclear. Existing work on Rust reliability mainly focus on how to test Rust programs to find bugs [13, 17] or proving the security property of Rust language system via formal verification [4, 5, 9]. Current literature still lacks an understanding of the memory-safety bugs in real-world Rust programs. This paper attempts to address this question via inspecting a set of important, representative real-world programs.

To elaborate, we collect a dataset of memory-safety bugs based on two public datasets, Advisory-db and Trophy-case, which contain all existing CVEs of Rust. We manually remove irrelevant, non-memory-safety bugs, and our final dataset contains 39 memory-safety bugs. For each bug, we manually analyze the culprit and consequence and then cluster them into different subsets. For the consequences of memory-safety bugs, we directly adopt state-of-the-art taxonomy [16] and employ the labels like buffer overflow, use-after-free, double free, and data race. Since we do not know
if the culprits of Rust have unique characteristics in comparison with other languages, we do not assume any labels in advance and cluster them if two culprits are similar.

Our inspection results show that buffer overflow and dangling pointers are the major memory-safety issues in Rust. In particular, there are 18 buffer-overflow bugs, five use-after-free bugs, and nine double-free bugs. Besides, the rest seven bugs are related to data race, leaking uninitialized memory, or other issues. We summarize our detailed findings as follows.

- Most memory-safety bugs are related to unsafe APIs or foreign function interfaces (FFIs). Besides, it is also possible to incur memory-safety issues with safe APIs only, if the API is unsound, such as violating the memory-safety model of Rust. Indeed, many safe APIs also contain unsafe API calls inside. It is the developer’s responsibility to declare whether an API should be safe or unsafe depending on if the function may lead to undefined behaviors, such as dereferencing raw pointers without validity check. Rust has no feature to check the correctness of the declaration. Therefore, some memory-safety bugs may not be related to unsafe APIs directly, but they can be originated from unsafe APIs, e.g., propagation via several function calls (Figure 1). Such issues are very common in third-party Rust libraries.

- The buffer-overflow bugs are very difficult to prevent in unsafe Rust. In particular, a buffer-flow bug generally contains a logical error that makes mistakes and unsafe APIs that propagate the error to buffer overflow. Since Rust has no magic in preventing logical errors, such as boundary checking, using unsafe APIs is as vulnerable as C/C++ in buffer overflow.

- Most issues of dangling pointers are very unique in Rust. Specifically, some use-after-free bugs are related to the lifetime checker, and double-free bugs are related to the borrow checker. To prevent these bugs, one possible direction is to enhance the may-alias analysis feature of Rust compiler. In this way, the compiler could know whether a variable may point to a temporary buffer or whether a buffer has two mutable aliases. Such information is essential to enhance the lifetime checker and borrow checker so that the compiler can detect more memory-safety violations. Besides, we also find the culprits and bug fixes of some dangling pointers have similar patterns. These patterns enable us to recommend the best practice of using some APIs to developers in order to avoid memory-safety bugs.

2 PRELIMINARY

This section reviews the preliminary of memory-safety bugs and discusses the mechanisms of Rust in preventing them.

2.1 Memory-Safety Bugs

Memory-safety bugs are very serious issues for software systems. Most memory-safety bugs exist because of arbitrary pointer operations, such as using dangling pointers or out-of-range access.

2.1.1 Dangling Pointer. When a pointer has been freed, e.g., with `free()` in C, the buffer pointed by the pointer would be recycled by the operating system. However, the old pointer still points to the recycled memory address, known as a dangling pointer. Reading/writing the dangling pointer would cause `use-after-free` bugs. Freeing a dangling pointer would cause `double free` bugs.

2.1.2 Out-of-Range Access. Reading/writing a memory address beyond the allocated buffer range is dangerous. It could happen in two situations: an out-of-range pointer or offset (e.g., due to boundary check faults) or an in-range pointer with an invalid memory size (e.g., due to memory align issue). Reading a buffer that is out of the valid range would result in `buffer over-read`, writing the buffer would result in `buffer overflow`.

2.1.3 Others. Besides, there are other memory-safety issues unbelonging to the previous categories, such as `leaking uninitialized memory`, `memory leakage`, and `data race`. Allocating a memory space without proper initialization might leak the original content saved in the memory, known as leaking uninitialized memory. If a memory is not freed but becomes inaccessible to the program, `memory leakage` happens. `Data race` is another special type of memory-safety issue related to concurrent memory access.

2.2 Memory-Safety Model of Rust

To prevent memory-safety bugs, Rust introduces several specific designs in the compiler level to regulate arbitrary buffer access, and the core is a unique ownership-based memory access model [9]. The model assumes that only one pointer can have mutable alias to a buffer at any program point while other pointers have neither mutable nor immutable access at that point, or only immutable access can be shared among multiple pointers. The ownership can be borrowed among aliases via a `borrow checker`, which checks if borrowing ownership would conflict with the ownership rule. The borrowed ownership expires automatically when the program exits the code block. If no alias owns a buffer anymore, the buffer would be recycled. Associated with the model, Rust introduces a `lifetime checker` which assures that the lifetime of ownership would last long enough for use in other program points. Together, they form a basis for Rust in preventing memory-safety bugs.

However, Rust is in nature a hybrid programming language. As shown in Figure 1, there is a safe Rust and an unsafe Rust. The safe Rust aims to guarantee that all the behaviors of these APIs are under control, and programs using safe APIs should have no memory-safety bugs. However, to meet some specific requirements

![Figure 1: Relationship of safe Rust and unsafe Rust.](image-url)
(e.g., efficient memory access), Rust also provides some unsafe APIs and allows FFIs which may lead to undefined behaviors and incur memory-safety bugs. Any code that may lead to undefined behaviors should be declared as unsafe, such as dereferencing raw pointers and calling FFIs.

Next, we elaborate more on how these mechanisms work in preventing dangling pointer and out-of-range access.

2.2.1 Preventing Dangling Pointer. In safe Rust, pointers should be initiated when defining them. This is a prerequisite for the compiler to check the ownership and lifetime of buffers. Since the ownership and lifetime are properly managed, the compiler can know the validity of pointers during compilation time and prevent dangling pointers. Note that defining raw pointers is valid in safe Rust, but dereferencing them is only allowed in unsafe Rust.

2.2.2 Preventing Out-of-Range Access. Enforcing pointer initialization also benefits in-range buffer access because each pointer points to a memory region of a particular type, such as i32. It guarantees that memory data are properly aligned. For data structures, such as Vec<T>, Rust also maintains a length field (e.g., with smart pointers) of the object so that it can perform boundary checks during runtime. For raw pointers, tracing their data types and buffer sizes can be very hard. Therefore, reading/writing raw pointers is unsafe that may lead to out-of-range access.

2.2.3 Discussion. According to our discussion, the memory-safety of Rust mainly relies on safe Rust. Other APIs that violate the ownership rule or may lead to undefined behaviors should be declared as unsafe. However, there is no explicit rule to check whether a declaration is correct. Actually, many safe APIs employ unsafe APIs internally. As shown in Figure 1, a function calling unsafe APIs can be declared as either safe or unsafe, which mainly depends on the developer’s justification. Therefore, falsely declaring an unsound API as safe is dangerous. Developers should be very careful in declaring a function as safe if it calls unsafe APIs.

Besides, Rust is not interested in memory leakage issues. Any code that may cause memory leakage is safe in Rust. Therefore, our following discussion will not include memory leakage issues.

3 METHODOLOGY

3.1 Objective

Our work aims at evaluating the effectiveness of Rust in preventing memory-safety bugs. Particularly, we are interested in the consequences of memory-safety bugs and the culprits that lead to them. Analyzing these issues has three benefits. Firstly, we can provide objective evaluation results about the memory-safety status of the current Rust language to its potential users. Secondly, we can extract some common patterns of code that are risky to memory-safety issues and warn developers to use them carefully. Moreover, the culprits of some bugs provide essential information for improving the language towards more resilience to memory-safety bugs.

3.2 Challenges and Countermeasures

3.2.1 Data Collection. This first challenge for our study is to collect bugs, especially memory-safety ones. Thanks to GitHub, many influential Rust projects are maintained online, and we can find the issues and bug fixes for particular projects. However, since GitHub is free-organized, the formats and qualities of the bug reports can vary a lot. Such limitations pose difficulties for extracting and analyzing bugs accurately and automatically. As our research does not focus on proposing automatic analysis approaches, we prefer manual inspection which is more accurate. While manual inspection is precise, it sacrifices the scalability. Therefore, we try to find the most representative cases for manual inspection. Luckily, there are two third-party bug repositories that meet our need, Advisory-db and Trophy-cases.

Advisory-db is a repository that collects security vulnerabilities found in Rust software, and it is a superset of existing CVEs related to Rust programs. The dataset contains dozens of entries from 52 contributors. After filtering irrelevant entries, such as denial-of-service bugs and crypto issues (as shown in Figure 2(a)), we find 36 high-quality memory-safety bugs for further study.

Trophy-case collects a list of software bugs found by fuzzing tools. The bug reports originate from the users of fuzzing tools for Rust programs, such as cargo-fuzz2, AFL3, and Honggfuzz4. The repository contains 192 bug entries from 30 contributors. As shown in Figure 2(b), trophy-case categorizes these bugs into several categories, such as panic, arithmetic error, and out-of-range access. Among all these bugs, only five have security issues. Note that most bugs can panic the program, but they may not be dangerous. Next, we discuss two typical cases of non-memory-safety bugs.

Code 1 demonstrates a bug that does not involve invalid buffer operations. The buggy code lies in line 2, which does not handle 0 properly. As a result, the default branch (i.e., unreachable!()) would be taken for 0 and panic the program. Since the issue does not cause other bad consequences but only program panic, it is not a memory-safety bug.

Code 1: Bug in brotli-rs that may falsely trigger unreachable!().

```
match base_word[i] {
    0...96|123...191 => {...}, /*buggy code*/
    0...96|123...191 => {...}, /*bug fix*/
```

1. https://github.com/RustSec/advisory-db/
2. https://github.com/rust-fuzz/trophy-case
3. https://cve.mitre.org/cgi-bin/cvekey.cgi?keyword=rust
4. https://github.com/rust-fuzz/cargo-fuzz
5. https://github.com/rust-fuzz/afl-rs
6. https://github.com/rust-fuzz/honggfuzz-rs

Figure 2: Distribution of bugs in public datasets.
Table 1: Distribution of memory-safety bugs in our dataset.

| Host Program Type | Error Type | Bug # |
|-------------------|------------|-------|
| Executable Program| Error      | 2     |
| Third-Party Library| Error      | 24    |
| Compiler (+standard library) | Undefine Behavior | 10  |
| Total             |            | 39    |

Code 2\(^8\) demonstrates a bug that contains an invalid buffer access. The buggy code falsely employed a static out-of-bound indicator (i.e., MAX_INDEX) for boundary checking. As a result, invalid indexes which are larger than self.buf.len()-1 could be falsely employed as the index for insertion. The code is compilable with Rust compiler, but it panics the program during execution because the trait Vec<T> maintains a length field and checks the index validity during runtime. Therefore, although the bug involves invalid memory access, it is not buffer overflow.

Code 2: Buffer over-read in brotli-rs caused by incorrect boundary checking.

```rust
1 buf: Vec<Option<Symbol>>
2 const MAX_INDEX: usize = 32768 - 2; // buggy code/
3 if insert_at_index > MAX_INDEX { // buggy code/
4   panic!(...) // bug fix/
5 }
6 }
7 self.buf[insert_at_index] = Some(symbol);
```

Because Adversary-db and Trophy-cases have two bugs in common, we finally get 39 (5+36-2) memory-safety bugs for further study. Table 1 overviews the host program types that these bugs lie in and types of errors. Three bugs lie in the standard library of Rust compiler, 34 bugs in third-party libraries, and two bugs in executable programs. It is interesting that some bugs (10+1) of Rust libraries may not be a real bug that has an error inside. They just violate the memory-safety promise of Rust, e.g., violating the rule of no shared mutable aliases. Such bugs may not be treated as bugs in other programming languages.

3.2.2 Bug Analysis. The second challenge is how to analyze memory-safety bugs and extract useful knowledge accordingly. Specifically, we are interested in the consequences and culprits of each memory-safety bug.

For the consequences, we adopt a top-down approach. Because the taxonomy of memory-safety bugs is well studied in the literature (e.g., [16]), we simply adopt existing categorization method, such as buffer overflow, use-after-free, double free, and data race.

For the culprits, we employ a bottom-up approach, i.e., we cluster similar bugs while do not assume prior categorization standards. To elaborate, we manually analyze the commit of each bug fix on Github. By comparing the buggy code and bug fix, we can locate the root cause of each bug. In general, a memory-safety bug can be caused by multiple issues, such as the coexistence of an unsafe pointer dereference and a logical error (e.g., integer overflow, boundary checking). For simplicity, we are not interested in logical errors because Rust is designed to help developers prevent dangerous memory-safety issues even their code contains logical errors. We are interested in how logical errors escalate to memory-safety bugs. Typical culprits should be related to unsafe Rust. We are interested in how they lead to memory-safety issues.

3.3 Compatibility with existing work

Before our work, Yu et al. [18] has studied the concurrency bugs of three real-world Rust projects. They collect 18 concurrency bugs, including 10 deadlock bugs and eight data race bugs. Their analysis results show that 7/10 deadlock bugs are caused by double lock, 3/10 by misusing channels; 5/8 data-race bugs are caused by unsafe APIs, 3/8 do not need unsafe APIs. The work is different from us in two aspects. Firstly, our work studies all memory-safety bugs and does not only focus on concurrency issues. In this way, their work can provide extensions to our work in understanding the concurrency issues of Rust. Secondly, our dataset has no common bugs in comparison with their work. Our dataset is a superset of all CVEs, which should be more representative for studying the memory-safety issues of Rust.

4 PATTERNS OF MEMORY-SAFETY BUGS

This section presents our analysis results of the memory-safety bugs in the collected dataset. We categorize memory-safety bugs based on their consequences and culprits. Table 2 overviews our analysis result. 18 bugs are buffer overflow/over-read issues: four caused by FFI, 11 by unsafe out-of-range access, and three by memory alignment issues. Note that since buffer overflow and buffer over-read often coexist in our dataset, we do not further differentiate them. 14 bugs are related to dangling pointers, including five use-after-free bugs and nine double-free bugs. The culprits of dangling pointers are very unique in Rust, which are mainly related to the objects whose ownership or lifetime cannot be traced by Rust compiler. Besides, there are three data-race bugs, one bug leaking uninitialized memory, and three bugs of other issues.

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\(^8\)https://github.com/ende76/brotli-rs/issues/7
Next, we discuss the details of bugs in each category.

4.1 Buffer Overflow

4.1.1 Foreign Function Interface. FFIs are only allowed in unsafe Rust because they are inconsistent with Rust memory-safety model. In our dataset, we find two types of FFI issues: format string (e.g., CVE-2019-15546, CVE-2019-15547, CVE-2019-15548) and compatibility (e.g., CVE-2018-20998).

Code 3 presents a format string issue in ncurses-rs. The project implements a thin wrapper of the original ncurses library in C. This code sample is a Rust function `printw()` which directly calls the corresponding C function without checking the validity of the arguments. This allows users to pass any format string as the argument, which may incur buffer over-read. It can also incur buffer overflow issues when employing `%n` as the format string and an address `&a` as the arguments, which means over-writing the buffer of `&a` with the number of printed characters before `%n`.

Code 4 presents a compatibility issue between Rust and MSVC (Microsoft Visual C++). The buggy code declares `DType { F32 = 0, C32 = 1, F64 = 2, U64 = 9, }` for the enum `DType`, which tells the compiler to align the memory layout as what C does. However, the declaration is implicit and leads to compatibility issues when collaborating with MSVC. The bug fix replaces the raw arithmetic operators with Rust `+` and `*` plus `checked_add()` and `checked_mul()` function arguments. This allows users to pass any format string as the argument, which may incur buffer over-read. It can also incur buffer overflow issues when employing `%n` as the format string and an address `&a` as the arguments, which means over-writing the buffer of `&a` with the number of printed characters before `%n`.

Code 4: CVE-2018-20998: Buffer overrun in arrayfire caused by FFI compatibility issues.

```rust
1 /*file: lib.rs*/
2 extern pub fn printw(_:char_p) -> c_int;
3 /*file: lib.rs*/
4 pub fn printw(s:&str) -> i32 {
5     unsafe { ll::printw(s.to_c_str().as_ptr()) }
6 }
```

Code 5 presents a buffer overflow bug due to integer overflow. The result could be larger than the max value that an integer type can represent when either of the multiplication

4.1.2 Unsafe Out-Of-Range Access. There are two requirements for accomplishing such bugs: unsafe memory read/write and out-of-range access. Unsafe APIs in Rust, such as `ptr::read()` and `ptr::write()`, enable developers to perform arbitrary buffer read/write without the memory-safety guarantee of Rust. Pure out-of-range access is nothing special but some general logical errors (e.g., boundary checking) that could occur in any language.

Code 5 presents another buffer overflow bug incurred by a boundary-checking error. When checking the boundary in line 8, the code employs a false capacity indicator for comparison. As a result, the allocated memory space could be smaller than the length indicator of a vector. Further using the buffer with unsafe APIs would incur buffer overflow or buffer over-read.

Code 6: CVE-2018-1000657: Buffer overflow bug in standard Rust library VecDeque::reserve().

```rust
1 pub fn reserve(&mut self, additional: usize) {
2     let old_cap = self.cap();
3     let used_cap = self.len() + 1;
4     let new_cap = used_cap.checked_add(additional)
5         .and_then(|needed_cap| needed_cap
6             .checked_next_power_of_two());
7         .expect("capacity_overflow");
8     unsafe { if new_cap > self.capacity() {
9       self.buf.reserve_exact(used_cap, new_cap-used_cap);
10       self.buf.reserve_exact(used_cap, new_cap-used_cap);
11     unsafe { self.handle_cap_increase(old_cap);  }
12   }
```

4.1.3 Buffer Alignment Issue. An alignment issue also triggers out-of-range access, but the size of the overflowed memory is limited to the size of the specified buffer type. We demonstrate a toy example with Code 7. The program allocates a vector with an 8-bit unsigned integer, and then reads/writes the vector as a variable of `u64`.

Code 7: Toy code of alignment issue leading to buffer overflow.

```rust
1 fn main(){
2   let mut x = vec![1u8];
3   let p = x.as_mut_ptr() as *mut u64;
4   unsafe {
5       let u:u64 = p.read(); /*alignment issue: over-read*/
6       p.write(u); /*alignment issue: overflow*/
7   }
```
Code 8 presents a real-world bug very similar to the toy example. The program loads a 256-bit value from the vector of u8. However, it does not check if the vector has been assigned enough memory slots that align the data type (i.e., 32 bytes) properly. If not, buffer over-read would be triggered.

**Code 8: CVE-2019-15550: memory alignment issue in simd-json.**

```
let src: &[u8] = unsafe { &self.input.get_unchecked(idx..) };
let v: __m256i = unsafe { __m256_loadu_si256(src.get_unchecked(..32).as_ptr() as *const __m256i) };
```

Occasionally, such bugs could occur in safe Rust. Code 9 presents an example found in standard Rust library. The function `type_id()` returns the error type of the `Error` trait. This is a safe function and should not incur memory-security bugs. However, developers may falsely downcast the trait and override the default implementation of `type_id()`, e.g., let the function returns a wrong type that requires a larger buffer size. This would lead to memory alignment issues when accessing the buffer. The problem has not been fixed perfectly so far, and developers temporarily marked the function as unstable.

**Code 9: CVE-2019-12083: unsoundness in standard Rust library that may lead to buffer alignment issue.**

```
fn type_id(self: &Self) -> TypeId where Self: 'static {
  TypeId::of::<Self>();
}
```

From these bugs, we can know how Rust fails in preventing buffer overflow. Rust aims at preventing developers from using arbitrary pointers. However, unsafe APIs break the fence and make buffer overflow happen. Since Rust cannot prevent developers from writing logical errors, the risks of writing such buffer overflow bugs is almost the same as other languages when developers using unsafe APIs frequently.

### 4.2 Use-After-Free Bugs

#### 4.2.1 Unsafe Constructor with Temporary Buffer

Rust relies on the lifetime checking mechanism to prevent dangling pointers. However, the mechanism becomes less effective when using unsafe APIs or raw pointers. A typical scenario is using unsafe constructors, such as `from_raw_parts()` for String and Vec<T>. Code 10 demonstrates a toy example. The function composition uses a vector based on a temporary string `s`, which expires when the function returns. In particular, the unsafe function `from_raw_parts()` simply dereferences the pointer and returns a reference, and it leaves the lifetime checking responsibility to developers.

**Code 10: Toy example of use-after-free bugs caused by unsafe constructors.**

```
fn test() -> Vec<u8> {
  let mut s = String::from("lifetime_test");
  let ptr = s.as_mut_ptr();
  unsafe {
    let v = Vec::from_raw_parts(ptr, s.len(), v.len());
  }
}
```

In practice, such bugs may hide deeply in complicated traits. Code 12 presents an example. Apparently, the bug lies in line 8, where the program searches a string from the hash map; if the string is not found, it takes the string (`search_string`) as the key and inserts the pair of (key, value) into the hash map. However, the buffer of the key expires when the function returns. To fix the bug, developers replace HashMap with HashSet. Nevertheless, the root cause is not HashMap. On the other hand, the root cause of the bug lies in the design of the trait `InternedString`, which relates to the raw pointer of its member data in line 17.

**Code 12: Use-after-free bug found in sxd-document.**

```
fn from(buffer: Buffer) -> Vec<u8> {
  let mut slice = Buffer::allocate(buffer.len);
  let len = buffer.copy_to(&mut slice);
  unsafe {
    Vec::from_raw_parts(slice.as_mut_ptr(), len, slice.len());
  }
}
```

[1]https://github.com/shepmaster/sxd-document/issues/47
4.2.2 Unsafe Buffer Deallocation. Rust provides unsafe APIs for fast deallocation. Such operations cannot guarantee whether the released memory will be used later and therefore are vulnerable to use-after-free bugs. Code 13 presents a bug in rust-smallvec. The buggy code misses an else branch. As a result, it falsely calls deallocate() for some cases.

**Code 13: CVE-2019-15551: deallocation error in rust-smallvec.**

```rust
unsafe { 
    if new_cap < self.inline_size() { /*simplified...*/ } 
    else if new_cap != cap { /*simplified...*/ } 
    else { return; } 
    deallocate(ptr, cap); 
}
```

4.3 Double-Free Bugs

4.3.1 Shared Mutable Aliases. If a buffer is owned by multiple objects concurrently, running the destructors of these objects would free the buffer twice. In general, generating multiple mutable aliases is only possible via unsafe Rust. We demonstrate a toy example with Code 14. In this example, the destructor of `src` will run twice: firstly when `func1()`, and secondly when `main()` returns.

**Code 14: Toy example of double free.**

```rust
unsafe { 
    if new_cap <= self.inline_size() { /*simplified...*/ } 
    else if new_cap != cap { /*simplified...*/ } 
    else { return; } 
    deallocate(ptr, cap); 
}
```

To fix such issues, a common practice is to employ either mem::forget() or mem::ManuallyDrop::new() that can prevent executing the destructor of `T` when it expires. Such cases can be found in CVE-2018-20996 (Code 15), CVE-2019-16144.

**Code 15: CVE-2018-20996: double free in crossbeam.**

```rust
enum Payload<T> { 
    Data(T), 
    Data(ManuallyDrop<T>), 
    Blocked(<mut Signal<T>>, 
    )
}
impl<T> Cache<T> { 
    fn into_node(self) -> Owned<Node<T>> { 
        match self { 
            Cache::Data(t) => Owned::new(Node { 

```

4.3.2 Hang Buffer Late. Some double-free bugs have employed mem::forget(), but the program may panic before function context is called. In this way, the shared buffer will still be freed twice during stack unwinding. In our dataset, four bugs are exactly the same pattern, including CVE-2019-16880, CVE-2019-15552, CVE-2019-15553, and CVE-2019-16881. A common fix is to replace mem::forget() with mem::ManuallyDrop<T>. Actually, mem::forget() is a wrapper of ManuallyDrop::new() but does not return a ManuallyDrop object.

**Code 16: CVE-2019-16880: double free in linea.**

```rust
unsafe { 
    let (a, b) = (mem::ManuallyDrop::new(a), 
    mem::ManuallyDrop::new(b)); 
   ...
    
```
Then the program starts to initialize the elements of the vector.

In an extreme case, developers may delay calling set_len() to the destruction state, which is essentially discouraged in Rust. Code 18 presents such an example, the destructor contains an unsafe function call that sets the length of map.entries to 0. Note that the implementation of Iterator for Drain moves (copies) the entries out from the map, which incurs two mutable aliases.

Code 18: Unsafe code that relies on the destructor to be safe leading to double free in http.

```rust
impl<'a, T> Iterator for Drain<'a, T> {
    type Item = (HeaderName, ValueDrain<a, T>);
    fn next(&mut self) -> Option<Self::Item> {
        unsafe {
            let entry = &(*self.map).entries[idx];
            key = ptr::read(entry.key as *const _);
            value = ptr::read(entry.value as *const _);
            next = entry.links.map(|l| l.next);
        }
        let values = ValueDrain {
            map: self.map, first: Some(value),
            next: next, lt: PhantomData,
        }
        Some((key, values))
    }
}
impl<'a, T> Drop for Drain<'a, T> {
    fn drop(&mut self) {
        unsafe {
            let map = &mut self.map;
            debug_assert!(map.extra_values.is_empty());
            map.entries.set_len(0);
            debug_assert!(map.extra_values.is_empty());
        }
        for _ in self {
        }
    }
}

4.3.4 Early Alias Activation. In contrary to late alias invalidation, activating an alias too early may end up dropping invalid pointers if the pointer has not been fully initialized before the program panics. We present one example in Code 19. It applies a vector with entries out from the pool. However, it misuses the atomic read action on the count of a spinlock. However, it misuses the atomic memory ordering Relaxed, which imposes no constraints on other threads regarding the execution order. As a result, the variable may have another mutable reference before the lock is actually released. The correct version should employ Ordering::Relaxed instead.

Code 19: CVE-2019-16138: drop uninitialized memory in image.

4.4 Data Race

4.4.1 Unsynchronized Internal Mutation. A function that takes immutable parameters but mutates internally is likely to be vulnerable to race conditions. Executing the function concurrently in multiple threads would cause data race. Code 20 presents such an example. The function trigger_multi_frame_capture() accepts an immutable argument &self, which however may mutate the object internally when calling TriggerMultiFrameCapture(). Therefore, executing the function concurrently would incur data race. Fixing the bug is simply changing the parameter to mutable. This gives the compiler a hint that the two mutable aliases of self should not exist at the same time.

Code 20: CVE-2019-16142: unsoundness in renderdoc-rs may lead to data race.

4.4.2 Shared Mutable Aliases. Generating multiple mutable aliases is unsafe and is vulnerable to race conditions. We find one such bug in http. As shown in Code 18, the function next returns an item containing a pointer to the self. map. Calling the function multiple times would generate multiple mutable aliases. This is undefined behavior in Rust and may lead to data race.

4.4.3 Memory Ordering Error. Programs errors without unsafe may also incur data-race bugs as well. Memory ordering error is a typical case. Code 21 implements a Drop function for the RwLockWriteGuard of a spinlock. However, it misuses the atomic memory ordering Relaxed, which imposes no constraints on other threads regarding the execution order. As a result, the variable may have another mutable reference before the lock is actually released. The correct version should employ Ordering::Relaxed instead.

Code 21: CVE-2019-16137: memory ordering error in spin-rs.
only, their categories are mainly based on the logical errors in concurrency code, and their analysis does not go into the details of how unsafe APIs lead to memory-safety bugs, which is the focus of this paper.

4.5 Other Issues

There are four other issues related to memory-safety bugs but do not belong to the previous categories.

4.5.1 Leak Uninitialized Buffer. The bug happens when a buffer is not initialized before use and the program has logical errors leaking the historical data stored in the buffer. Rust provides unsafe APIs for fast buffer allocation. Such APIs generally apply a new space without initializating it and therefore are vulnerable to leaking uninitialized memory. Code 22 presents such a bug. The code extends the buffer of Vec<i32> with an unsafe method set_len(), which simply changes the length indicator of the vector and applies new space. There is no problem if the buffer is properly used afterward. However, the code has other logical issues that do not fill the buffer properly.

Code 22: CVE-2018-20992: leak uninitialized buffer in claxon.

```rust
fn ensure_buffer_len(mut buffer: Vec<i32>, new_len: usize) {
    if buffer.len() < new_len {
        if buffer.capacity() < new_len {
            buffer = Vec::with_capacity(new_len);
        }
        unsafe { buffer.set_len(new_len); }
    } else { buffer.truncate(new_len); }
    buffer
}
```

4.5.2 Bad Function Exposure. Some functions should not be exposed to users as safe APIs, and calling these functions directly may lead to segmentation faults. All the three issues we found come from one project generator. As shown in Code 23, one bug (issue 9) exposes the function new taking two raw pointers as a safe function; the second bug (issue 13) exposes a deprecated function to users without declaring the deprecated attribute (the buggy version only comments the function as deprecated); the third bug exposes a function that should not be called by users directly.

Code 23: Unsoundness in generator.

```rust
pub fn new(para:*mut Option<A>, ret:*mut Option<T>) -> Self{
    if buffer.len() < new_len {
        if buffer.capacity() < new_len {
            buffer = Vec::with_capacity(new_len);
        }
        unsafe { buffer.set_len(new_len); }
    } else { buffer.truncate(new_len); }
    buffer
}
```

5 IMPLICATION

In this section, we discuss the implications of our analysis results from three perspectives: the implication to potential users, program developers, and compiler developers.

5.1 Implication to Potential Users

Our analysis result reveals that Rust is very effective in preventing memory-safety bugs if developers use safe Rust only. In most cases of our dataset, unsafe function calls are necessary conditions for triggering memory-safety bugs. However, safe Rust is not powerful and efficient enough in some conditions. That’s why we still have a few memory-safety bugs in Rust programs.

While unsafe functions and FFIs make Rust a powerful language, they also bring memory-safety risks. There is always a tradeoff. Moreover, since Rust has no magics in preventing users from writing buggy code with logical errors, it is mainly the users’ responsibility to check the correctness of their code when using unsafe Rust. The situation is the same as other programming languages.

Besides, considering that three memory-safety bugs in our dataset are compiler bugs and Rust is a young programming language, users might be interested in the stability of the compiler. To address this question, we further investigated the project of Rust compiler on GitHub. There are around two hundred unsoundness issues (labeled as “I-unsound”) raised by Jan, 2020, which could violate the memory-safety promise of safe Rust. Figure 3 presents the numbers of unsoundness issues raised from 2014 to 2019 in a quarterly manner. We can observe that although the trend of new issues does not decline, it is much stable. Why unsoundness issues can hardly be prevented? As the features of Rust keep getting enriched, introducing new unsoundness issues are unavoidable. Besides, some unsoundness issues related to the design of the language are difficult to fix. Taking CVE-2019-12083 (Code 9) as an example, the temporary fix is to destabilize the function which
raises a warning when employing it. However, this fix is not perfect, and the issue still keeps open since raised months ago.

5.2 Implication to Program Developers
Some bugs in our dataset share common patterns. We can extract these patterns and suggest developers that these patterns are likely to incurring memory-safety bugs.

5.2.1 Hang Buffer As Earlier As Possible. Four double-free issues of Section 4.3.2 occur because of calling mem::forget() too late. Using ManualDrop() can prevent such issues, and it should be recommended to developers as a best practice. Developers should pay more attention if they insist on using mem::forget(var). Because the function borrows the ownership of var which can prevent further mutating the buffer, it is often impossible to call the function immediately after allocating the buffer. This gives chances to program panic before the buffer can linger.

5.2.2 Set Length at Appropriate Time. This issue relates to Code 17 and Code 19 which employs set_len(). Code 17 moves the buffer buffer contents and calls set_len() to shrink the buffer. If calling the function too late, there could be duplicated pointers at some program points. Therefore, calling set_len() as earlier as possible can prevent this problem and it should be a recommended practice when shrinking the buffer.

Code 19 relates to creating or expanding a buffer. In this situation, the set_len() function should be called after the new buffer has been fully initialized, or at least as possible. Otherwise, the new buffer may contain pointers that have not been fully initialized, leading to dropping invalid pointers.

5.3 Implication to Compiler Developers
Some culprits of memory-safety bugs in Table 2 may hardly be prevented as long as unsafe functions are allowed, including all the buffer overflow culprits, deallocation error, etc. According to Rice’s theorem [15], it is impossible have a general algorithm that is sound, complete, and can terminate, to analyze these properties by the compiler. However, there are also some interesting culprits worth further investigation, especially those leading to double-free and use-after-free issues. Next, we discuss some directions to enhance the compiler against dangling pointers.

5.3.1 Enforce Alias Checking within Unsafe Constructors. For the use-after-free bugs caused by unsafe constructors and temporary buffer, an intuitive solution is to maintain an alias pool recording the may-alias relationship between the source buffer and the new variable. This could be achieved via e.g., inclusion-based pointer analysis[2]. By knowing that the new variable may align to a temporary buffer, the compiler can detect such bugs automatically.

Another benefit of alias checking is preventing shared mutable aliases, which is essential for avoiding double free. Taking Code 10 as an example, the returned value v contains an alias of s, it is possible to change the buffer via either of these aliases. However, if the compiler knows the two pointers might be aligned via may-alias checking, it can invalidate the ownership of s immediately.

5.3.2 Prevent Shared Mutable Aliases during Copy. Some mutable aliases are generated because of buffer copy, e.g., via ptr::copy() in Code 17. According to the definition, ptr::copy() is semantically equivalent to memcpy in C, which copies the source memory to the destination while keeping the source intact if they are non-overlapping. However, it can lead to multiple mutable aliases if the copied contents contain pointers. Since preserving the source buffer is useless in some scenarios, it might be possible to define another function (e.g., move) that deletes the source buffer after copy.

6 THREATS TO VALIDITY
Our work studies the real-world performance of Rust in combating memory-safety bugs. The study is based on a dataset of 39 bugs. Although the dataset may not be very large, it contains all CVEs, which are the most severe bugs. Therefore, our analysis result should be representative. Moreover, our study approach is qualitative, and the derived results and implications would not be invalidated as the dataset of bugs getting further enriched. If the number of studied bugs grows in the future, there could be new types of culprits found and the classes we employed in Section 4 could be further extended.

7 RELATED WORK
Rust is a newly emerged programming language, and there is not much work studying its security issues. Existing work mainly shares experience in using language, such as [3, 11, 12, 14].

A majority of existing papers on Rust security focuses on formal verification [4, 7, 9] and bug detection [5, 8, 13, 17]. Formal verification aims at proving the correctness of Rust programs mathematically. RustBelt [7, 9] is a representative work in this direction. It defines a set of rules to model Rust programs and employs these rules to prove the security of Rust APIs. It has verified that the basic typing rules of Rust are safe, and any closed programs based on well-typed Rust should not exhibit undefined behaviors. Astrauskas et al. [4] proposed a technique that can assist developers to verify their programs with formal methods. Dewey et al. [8] proposed a fuzzing testing approach to detect the bugs of Rust programs. Lindner et al. [13] proposed to detect panic issues of Rust programs via symbolic execution. Besides, there is also some work focuses on the unsafe part of Rust and studies how to isolate unsafe code blocks(e.g,[1, 10]).

While existing work can tell us some information about Rust security, we still don't know how Rust performs in real-world. Even though there are some positive conclusions derived, e.g., in [9], they generally have strong assumptions and the conclusions may not be consistent with practical experiences. Therefore, our work studies the security issue of Rust by surveying the bugs of real-world projects, and it is different from existing work. One similar paper to ours is [18], which studies 18 concurrency bugs from three Rust projects. Our work is different from them as we do not confine on concurrency bugs but any memory-safety issues.

8 CONCLUSION
This work studies the effectiveness of Rust in fighting against memory-safety bugs. We have manually analyzed the culprits and consequences of 39 memory-safety bugs covering all Rust CVEs. Our study results reveal that buffer-overflow, use-after-free, and double-free bugs are still popular in Rust programs. In particular,
Most of these bugs are related to unsafe APIs or FFIs. It means that Rust is very effective in preventing memory-safety bugs if using safe Rust only. On the other hand, using unsafe Rust is as risky as other programming languages that mainly rely on the developer to prevent memory-safety issues. Our analysis result also reveals some common code patterns that may lead to memory safety bugs, which are useful to make suggestions to developers. Moreover, we find the borrow checker and lifetime checker of Rust might be further enhanced via may-alias analysis to prevent shared mutable aliases and dangling pointers.

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