Fearless Concurrency? Understanding Concurrent Programming Safety in Real-World Rust Software
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Abstract
Rust is a popular programming language in building various low-level software in recent years. It aims to provide safe concurrency when implementing multithreaded software through a suite of compiler checking rules. Unfortunately, there is limited understanding of how the checking rules influence the safety of concurrent programming in Rust applications.

In this paper, we perform a preliminary study on Rust’s concurrency safety from two aspects: concurrency usage and concurrency bugs. Our study can provide better understanding on Rust’s concurrency and can guide future researchers and practitioners in writing better, more reliable Rust software and in developing debugging and bug detection tools for Rust.

1 Introduction
Rust is a programming language designed to build efficient and safe low-level software [12, 13, 26, 28, 31]. Rust is targeted to achieve performance that is comparable to C, while avoiding many safety issues in C including both concurrency bugs and memory safety bugs. Over the past few years, Rust has gained significant popularity, especially in building low-level software [23–25]. These Rust applications range from simple libraries [2] and utilities [4, 5] to complex browsers [1, 7] and operating systems [6, 8, 10].

A major design goal of Rust is to provide safe concurrency [26, 28]. To achieve the goal, Rust leverages several unique ownership rules, and imposes the rule checking during compilation. It is thus widely believed that Rust is much safer than many other languages. As stated in Rust’s official tutorial, “concurrency is fearlesss” in Rust. Since Rust is widely used to implement low-level systems, it is important to understand whether these compiler rules can really reduce concurrency bugs and provide safer concurrency.

Unfortunately, there is only limited prior work in understanding Rust’s concurrency. Many key questions are left open. For example, how does Rust’s compiler rules influence its programmability? Will developers have to use unsafe code to bypass compiler checkings? What are the common mistakes made by developers when they develop multithreaded Rust programs? Will bypassing Rust’s compiler checkings introduce concurrency bugs?

Will there be no concurrency bugs in safe code? The lack of knowledge in Rust’s concurrency would severely impair Rust software development and make it hard to create Rust development and debugging tools.

In this paper, we conduct the first empirical study on Rust’s concurrency. Our study focuses on two main aspects, concurrency usage (Section 3) and concurrency bugs (Section 4). We conduct our study on three popular open-source Rust applications: Servo [7], a web browser, TiKV [9], a key-value storage system, and Rand [2], a random number generation library.

Although our study is just preliminary, we are already able to identify interesting new findings and insights in Rust concurrent programming. For example, we find that there are still data race bugs in safe Rust code and Rust programmers should not rely solely on Rust’s compiler checkings and be “fearless” in writing concurrent Rust programs. Another interesting finding is Rust’s compiler checkings do restrict its programmability and change developers’ usage habits of concurrency primitives.

Overall, we make four observations in our study of concurrent programming in Rust and infer four implications that can be useful for future Rust programmers and language designers. For example, future research in building Rust bug detectors should focus on unsafe code and atomic operations in safe code. Our findings and implications improve the understanding of Rust’s concurrency and guide future tool design.

2 Background
In this section, we give a brief overview of Rust, its mechanism for concurrency safety, and its thread communication and synchronization mechanisms.

2.1 Rust and Rust-Based Software
Rust is a low-level system programming language, firstly designed by Graydon Hoare in 2006. Rust has been sponsored and maintained by Mozilla since 2009 and was firstly released in 2010 [31]. Providing safe concurrency [26, 28] and safe memory [12] with similar performance to C [13] is the design goal of Rust. In recent years, due to its safety and performance benefits, Rust draws many interests from developers. According to surveys on stack overflow, Rust is the most beloved pro-
gramming language in the last three years\cite{23-25}. Rust has become a popular language in building software systems, such as browsers\cite{11,7} and OSes\cite{6,3,10}.

| Application | Stars | Commits | Contributors | LOC | History |
|-------------|-------|---------|--------------|-----|---------|
| Servo\cite{2} | 13150 | 35876 | 915 | 254K | 5.9 Years |
| TiKV\cite{9} | 4381 | 3345 | 121 | 119K | 2.0 Years |
| Rand\cite{2} | 359 | 1981 | 170 | 11K | 7.5 Years |

Table 1: Information of selected applications. The number of stars, commits, and contributors on GitHub, total source lines of code, and development history on GitHub.

In this paper, we select three popular open-source Rust projects on GitHub to conduct our study (Table 1). According to the number of stars on GitHub, Servo is ranked 4th, TiKV is ranked 19th, and Rand is ranked in the top 3\% among all Rust projects. They cover different types of functionalities, including web browsing (Servo), key-value storage (TiKV), and library utility (Rand). They are of medium to large size and have at least two years’ development history. We believe that these three applications are good representatives of real-world usage of Rust and leave exploring other Rust applications to future work.

2.2 Static Ownership Checking

Rust supports shared variables between threads. By default, one Rust value has exactly one variable as its owner, and a value will be destroyed, if its owner variable leaves its scope. Rust’s compiler conducts static ownership checking on shared variables, with the hope to reduce mistakes during accessing shared variables.

First, the ownership of a value can be moved from one scope to another, through function call or return, message passing, thread creation, and so on. Rust compiler statically guarantees that an owner variable will not be accessed after the ownership is moved to a different scope. Therefore, a shared value can only be owned by one thread at any time.

Second, Rust supports accessing a value using its reference. A reference can be borrowed from one scope to another, without moving ownership. Rust’s compiler does not allow references to be borrowed between threads, since values’ lifetime cannot be statically inferred across threads and Rust’s compiler guarantees a value’s lifetime covers all its reference usage.

Third, to have multiple owner threads, Rust provides a thread-safe reference-counting pointer (Arc). Rust’s compiler guarantees that all owner threads only access an Arc to read a shared variable or update a shared variable through Arc::make_mut(), which will create a per-thread private copy of the shared variable.

Fourth, to allow multiple threads to update the same copy, a shared variable has to be declared with both Arc and Mutex. To access the shared variable, a thread needs to invoke the lock function of the shared variable’s protecting Mutex. A reference of the shared variable is returned after successfully invoking the lock function, so that the thread can read or write the shared variable. Mutual exclusion provided by Mutex guarantees that there is at most one thread accessing a shared value at any time.

2.3 Thread Synchronization in Rust

Thread Model. Rust does not provide any runtime to manage thread scheduling. Rust threads are mapped to OS threads in an 1 to 1 way. To create a thread, thread::spawn() function is invoked with a piece of code (a closure) as parameter. Ownership of shared variables can be moved from a creating thread to a created thread during thread creation.

Thread Synchronization. Similar to C/C++, Rust supports traditional synchronization primitives designed to protect shared memory accesses, such as lock (Mutex), read/write lock (RwLock), conditional variable (Condvar), atomic operations (atomic), and barrier (Barrier). There are three differences between Mutex (or RwLock) in Rust and in C/C++. First, Rust provides a poisoning mechanism\cite{3} for Mutex to propagate panic information among threads. Second, Rust requires a Mutex to be declared together with its protected data. Third, there is no explicit unlock function in Rust, and Rust’s compiler automatically adds unlock at the end of a scope with lock operations. Rust provides Once as a new primitive to guarantee the initializations of a global variable is only conducted once.

Rust provides channel to pass messages between threads. Each channel has a sender and a receiver. Ownership can be moved from sender thread to receiver thread through message passing. When channel buffer is empty, pulling data from the channel will block.

3 Usage Study

In this section, we discuss our study results on concurrency usage in Rust applications, including the usage of unsafe code and the usage of synchronization primitives.

3.1 Unsafe Code

Rust supports unsafe keyword to mark a function or a code scope to bypass some compiler checkings. As discussed in Section 2.2, many static compiler checkings are designed to avoid concurrency bugs. Therefore, the usage of unsafe is highly correlated with whether Rust can really achieve safe concurrency.

We first study the amount of unsafe tags. As shown in Table 2 there are a fair amount of unsafe tags in the
three studied applications, ranging from 47 to 1683. We calculate the average number of unsafe tags over total source lines of code. On average, Servo developers use unsafe most frequently, and there are 6.62 unsafe tags per thousand lines of code. TiKV has the smallest number, and there is less than one unsafe tag per thousand lines of code. unsafe can be used to mark a function or a code scope. For the three studied applications, unsafe is constantly used more often to tag a code scope, ranging from 68.27% to 100.00% over all unsafe usage sites for the three applications. The large number of unsafe tags demonstrates that Rust’s compiler checkings do restrict its programmability, encouraging programmers to bypass them using unsafe. These unsafe sites can potentially contain concurrency bugs, making Rust’s concurrency less safe, as we will discuss in Section 4.3.

We then count the lines of code inside each code scope or function tagged with unsafe. As shown in Table 2, on average, an unsafe is used to tag a very small piece of code. For Servo, each unsafe tags 6.08 lines of code on average, which is the largest number among the three applications. The number drops to 5.62 and 3.63 for TiKV and Rand respectively. These results show that Rust developers are very careful when they use unsafe.

In the end, we count the percentage of unsafe code over all code. As shown in Table 2, the percentage of unsafe code ranges from 0.44% to 4.19% for the three studied applications. For Rust applications, safe code dominates.

**Observation 1:** The majority of code in Rust applications is safe. However, Rust developers often need to carefully use unsafe to bypass compiler checkings.

**Implication 1:** Compiler checkings do restrict Rust’s programmability. Future works on more precise compiler checkings to give developers more flexibility and verifying unsafe code in Rust to provide a certain level of confidence in safety are needed.

### 3.2 Concurrency Usage

Studying the usage of concurrency primitives can help understand how Rust developers implement thread communication and synchronization, and quantitatively get a feeling about which primitives are more likely to be mis-used, leading to concurrency bugs.

**Table 2: unsafe Usage.** In the # of unsafe tags columns, fn and scope: the ratio of unsafe used to tag a function or a code scope, and total: the total number of unsafe. In the LOC columns, average: the average LOC tagged by an unsafe, and percentage: unsafe code over total code.

| Application | # of unsafe tags | LOC |
|-------------|------------------|-----|
|              | fn scope total# per KLOC average percentage| total |
| Servo | 11.72% 68.27% 683 6.62 6.08 4.19% | 154K |
| TiKV | 11.70% 88.29% 94 0.78 5.62 0.44% | 119K |
| Rand | 0 100.00% 47 4.27 3.63 1.55% | 11K |

We also calculate the average number of concurrency operations over lines of code. TiKV developers use concurrency operations most frequently, and there are 8.49 concurrency operations per thousand lines of code. Servo developers use concurrency operations less frequently, and Rand developers use concurrency operations least frequently. The average operations per one thousand lines of code are 5.56 and 2.90 for these two applications respectively.

**Observation 2:** The usage of concurrency primitive in Rust is different from other programming languages, possibly caused by Rust’s compiler checking mechanism.

**Implication 2:** Traditional concurrency bug detection and fixing techniques focus more on Mutex. Future research works should pay more attention to channel and atomic to combat concurrency bugs in Rust.

### 4 Concurrency Bug Study

This section presents a preliminary study of Rust concurrency bugs. Specifically, we will first introduce our methodology of collecting and categorizing bugs and then present our identified deadlock and data-race bugs.

#### 4.1 Methodology

To collect concurrency bugs, we first search for the keywords “deadlock” and “race” in GitHub commit histories of the three applications in Table 1. These two keywords are widely used in previous works to collect concurrency bugs in other programming languages [17, 19, 22, 29]. Many previous works categorize concurrency bugs into...
deadlock bugs and non-deadlock bugs \cite{14, 20, 22}. Data race is one of the common types of non-deadlock bugs.

| Application | Deadlock | Data Race |
|-------------|----------|-----------|
| Servo       | Mutex    | channel   | safe | unsafe |
| TiKV        | 5        | 3         | 1    | 5      |
| Rand        | 2        | 0         | 1    | 0      |
| Total       | 7        | 3         | 3    | 5      |

Table 4: Taxonomy. This table shows how our studied bugs distribute across different categories and applications.

We then manually inspect the resulting commits that contain the two keywords to identify real concurrency bugs. In the last step, we study identified concurrency bugs, by referring their patches and related discussions on GitHub. Right now, we have studied 18 bugs. Their detailed distribution is shown in Table 4.

4.2 Rust Deadlock Bugs

In total, we study 10 deadlock bugs. We categorize them based on which synchronization primitives causing threads not to make future progress. As shown in Table 3, due to implicit unlock in Rust, double locks are the root causes for seven deadlocks. The other three deadlocks are caused by misusing channel.

```rust
1 pub fn insert_rule(...) \{ 2   - let mut rule = stylesheet.shared_lock.write(); 3   - let new_rule = rules.write_with(&mut guard)?; 4   + let new_rule = { 5     - let mut guard = stylesheet.shared_lock.write(); 6     + rules.write_with(&mut guard)?; 7   + } 8   ... 9   let dom_rul = CSSRule::new_specific(...); 10  
11 pub fn new_specific(...) \-> Root\<CSSRule> \{ 12   ... 13   let guard = stylesheet.shared_lock().read(); 14  

Figure 1: A deadlock caused by double RwLock. The code has been simplified to ease our explanation.

Implicit Unlock. Rust does not provide any unlock function. Rust’s compiler automatically adds corresponding unlock functions at the end of a scope with lock functions. Due to this, Rust developers may forget to release acquired lock timely, leading to double-lock deadlocks.

One bug example from Servo is shown in Figure 1 sheet.shared_lock is a RwLock. The write lock is acquired at line 2. The write lock is only needed for the invocation of function write_with(), but it is not released until the end of function insert_rule() at line 10. Unfortunately, insert_rule() invokes new_specific() at line 9. new_specific() acquires the read lock of the RwLock at line 14, leading to a double-lock bug. To fix this bug, Servo developers simply add a pair of {} to create a new scope, so that the write lock can be released after invoking write_with() at line 7.

```rust
1 while !done { 2   match r1.recv() { 3     Some(Exit(...)) \=> { 4       done = true; 5       ... 6     } 7     Some(SetID(s2)) \=> { 8       s2.send(); 9     } 10   } 11   loop { 12     let request = r2.recv(); 13     match request { 14       ExitMsg(s3) \=> { 15         ... 16       s3.send(); 17       break; 18     } 19   } 20   ... 21   let (s2, r2) = channel(); 22   s1.send(SetID(s2)); 23   r2.recv() \blocks 24  

Figure 2: A deadlock caused by circularly waiting for message between two threads. s: sender; r: receiver; numbers after s or r are used to match sender and receiver.

Misusing Channel. As shown in Table 3, channel is widely used in Rust programs. When buffer is empty, pulling data from a channel will block, forming an edge from receiver thread to sender thread in wait-for graph. A circle in wait-for graph means circular wait among threads and deadlock. We have three bugs caused by circular wait involving waiting for channel message.

One example from Servo is shown in Figure 2. There are two threads, master thread and worker thread. Both of them have a message-processing loop to handle messages from r1 and r2 respectively. In Figure 2a, when work thread wants to set its ID, it creates a channel at line 11, send the sender s2 of the created channel in a SetID message to master thread at line 12, and blocks itself to wait for reply from master thread at line 13. In Figure 2b, when master thread receives a SetID message from r1, it replies work thread by sending an empty message () using s2 to unblock worker thread. When master thread receives an Exit message at line 3, it leaves the message-handling loop at line 4. After that, master thread notifies worker thread to exit at line 15, and blocks itself to wait for a reply from worker thread at line 16. Worker thread can unblock master thread by sending out an empty message () at line 6 in Figure 2b.

This bug happens when master thread receives an Exit message just before worker thread sends out a SetID message. Master thread blocks at line 16 in Figure 2b waiting for a message should be sent from work thread at line 6 in Figure 2b. However, worker thread blocks at line 13 in Figure 2b waiting for master thread to unblock it by execution line 8 in Figure 2a. To fix this bug, Servo developers change master thread, and only allow it to leave the message-processing loop after worker thread has exit, so that master thread can always handle messages from worker thread.

Observation 3: Double locks and misusing channels are two common causes of deadlocks in Rust.

Implication 3: To detect deadlocks in Rust, it is useful
to design static analysis which can identify possible lock operations in a function call and can infer thread wait relationship based on inter-thread messaging.

4.3 Rust Data Races

Intuitively, there could be data races inside unsafe code. Our study confirms this intuition. In total, five out of eight races are caused by instructions inside unsafe code. However, what is counter-intuitive is that there are still races inside safe code.

Data Races in Safe Code. Rust supports shared variables in atomic types, such as AtomicBool, AtomicPtr, and AtomicUsize. Read and write conducted on atomic variables are automatically ignored by Rust’s ownership checking. All races in safe code are caused by misusing atomic operations.

An example from Rand is shown in Figure 3. Function is_getrand_available() invokes getrand() at line 7, and checks whether the returned value is -1 at line 8 to decide whether getrand() is available. getrand() is an expensive system call, so that Rand developers decide to cache the previous execution result. Since is_getrand_available() can be executed concurrently, two atomic variables, CHECKED and AVAILABLE, are introduced to achieve the caching functionality. CHECKED represents whether getrand() is called before, and AVAILABLE represents whether getrand() is available. If CHECKED is false at line 5, getrand() will be called at line 7. AVAILABLE will be set to suitable value at line 13, and CHECKED will be set to true at line 14. If CHECKED is true at line 5, the value of AVAILABLE will be returned at line 19.

There is a concurrency bug that can cause is_getrand_available() to return incorrect results. Since either compiler or CPU could reorder the execution of line 13 and line 14, if the reordering happens, the caching mechanism is only correct when line 14 and line 13 are executed atomically. If the execution of line 14 and line 13 of one thread are interleaved by the execution of line 5 and line 19 of another thread, is_getrand_available() will return false, no matter getrand() is available or not. To fix this bug, Rand developers use Once primitive to guarantee the invocation of getrand() and the initialization of AVAILABLE are only conducted once and are conducted atomically.

Observation 4: Unsafe code is indeed one major source of data races in Rust. However, there are also data races from safe code.

Implication 4: Race detection techniques are needed for Rust, and they should focus on unsafe code and atomic operations in safe code.

5 Related Works

Many system reliability researchers conducted empirical studies on real-world bugs before [11, 14–18, 21, 22, 27, 29, 32]. These works have successfully guided techniques to combat bugs from various aspects. To the best of our knowledge, our work is the first empirical study on Rust concurrency usage and concurrency bugs. Although it is still at an initial stage, our current results can inspire and guide future techniques for concurrency bugs in Rust.

6 Conclusion and Future Work

With the increasing usage of Rust to implement various concurrent systems, it is important to understand whether Rust’s static compiler checkings can really bring safe concurrency. We conduct the first study on Rust concurrency from two aspects: concurrency usage and real-world concurrency bugs. We expect our study to deepen the understanding of Rust’s concurrency and motivate more research works on Rust.

This paper is just a starting point to understand Rust. We plan to extend the current work from the following directions.

First, more concurrency bugs should be collected from a wider range of Rust applications. We should build a more comprehensive taxonomy for Rust concurrency bugs from various aspects, such as root causes, fix strategies, how bugs are introduced, and so on.

Second, we plan to systematically evaluate existing concurrency bug detection techniques on Rust. Rust uses
LLVM as its backend and doesn’t have any runtime. It is fairly easy to apply existing techniques designed for C/C++ to Rust applications. Since Rust has message-passing mechanisms, existing techniques are expected to be extended to have more precise detection results.

Third, safe memory usage is another design goal of Rust. We plan to extend our study to memory bugs in Rust and understand whether Rust’s compiler checkings can really reduce memory bugs. Many memory bugs can be exploited by hackers have large security impact. We also plan to evaluate security impact of memory bugs in Rust.

Four, Rust is a very young language, and new language features were added in recent years. We plan to study new language features influence Rust’s programmability and its safety.

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