A Study of Undefined Behavior Across Foreign Function Boundaries in Rust Libraries

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Abstract-Developers rely on the Rust programming language's static safety guarantees to write secure and performant applications. However, Rust is frequently used to interoperate with other languages which allow design patterns that conflict with Rust's aliasing models. Miri is the only dynamic analysis tool capable of validating applications against these models, but it does not support foreign functions, indicating that there may be a critical correctness gap at the heart of the Rust ecosystem. We conducted a large-scale evaluation of Rust libraries that call foreign functions to determine whether Miri's dynamic analyses remain useful in this context. We used Miri and an LLVM interpreter to jointly execute applications that call foreign functions, where we found 48 instances of undefined or undesired behavior. These include three bugs from libraries that had over 10,000 daily downloads on average during our observation period and one from a library maintained by the Rust Project. Many of the errors we found involved incompatible aliasing patterns, but Rust's latest Tree Borrows aliasing model was significantly more permissive than the earlier Stacked Borrows model. The Rust community must invest in new, production-ready tooling for multi-language applications to ensure that developers can detect these errors.

I. INTRODUCTION

The Rust programming language has been increasingly popular due to its static safety guarantees, which provide security benefits comparable to garbage-collection without additional run-time overhead [1, 2]. However, when Rust's aliasing restrictions become burdensome, developers can bypass them using a subset of **unsafe** features. If these features are used incorrectly, they can break the rules of Rust's aliasing model. The Rust compiler relies on these rules to optimize code. If they are broken, optimizations may be applied incorrectly, which can introduce security vulnerabilities.

Miri [3] is a widely-used Rust interpreter that detects violations of the language's aliasing model via dynamic analysis. A limitation of Miri is that it cannot detect these violations across foreign function boundaries. However, one of the most common reasons for using **unsafe** features is to call foreign functions [4, 5, 6, 7, 8]. We seek to determine whether Miri's dynamic checking would still be useful in this context.

• **RQ1**: Are Miri's methods for dynamically enforcing Rust's aliasing model useful for detecting undefined behavior in programs that call foreign functions?

The Rust community has proposed two aliasing models: Stacked Borrows [9] and Tree Borrows [10]. The goal of these models is to "strike a balance" [9] between performance and usability by providing a set of rules that developers must follow to ensure that compile-time optimizations are applied correctly [11]. Since Stacked Borrows and Tree Borrows both provide rules of this kind, we ask a second research question:

• **RQ2**: Which of Rust's aliasing models permits more realworld programs with foreign function calls?

To answer these questions, we created MIRILLI: a tool which combines Miri with an LLVM interpreter to jointly execute programs and detect undefined behavior across foreign function boundaries. We used MIRILLI to conduct a large-scale study of 9,130 test cases from 957 Rust libraries that call foreign functions. We identified 48 instances of undefined or undesirable behavior from 38 of these libraries. Of the 90 test cases with violations of Stacked Borrows, 66% (59) did not produce an aliasing violation under Tree Borrows.

Our results indicate that Rust's restrictions on aliasing, mutability, and initialization make it easy to inadvertently introduce undefined behavior when calling foreign functions. Developers can take immediate steps to avoid these errors by auditing their use of certain types at foreign callsites. However, the Rust Project must invest in new, production-ready tooling to ensure that these errors can be easily detected.

Overview: In Section II, we compare Rust's semantics with C and C++, and we describe the resources and best-practices that Rust developers can use to ensure correct interoperation. In Section III, we document our methodology for sampling and evaluating test cases from Rust libraries that call foreign functions, and we describe the challenges that we encountered when implementing MIRILLI. In Section IV, we describe each type of bug that we found. We discuss the implications of our findings in Section V. We review prior work on Rust interoperation in Section VI, we discuss threats to validity in Section VII, and we conclude in Section VIII. Our dataset, Appendix, and the source for MIRILLI are available through GitHub¹.

II. BACKGROUND

Rust's safety restrictions begin at the level of a value, which is valid for a particular scope. The type of a value implements "traits" which define its behavior. For example,

¹https://github.com/icmccorm/mirilli

all types have "move semantics" by default, meaning that each value has a unique "owner." However, values with the Copy trait have no owner and can be freely duplicated. Ownership can be transferred through assignment or *borrowed* by creating a reference. References are either mutable, taking the form &mut T, or immutable, with the form &T. Mutable references have move semantics, but immutable references can be copied. Each reference has a "lifetime," which is the portion of the program over which it will be used. Rust's borrow checker statically enforces that the lifetime of a reference must not exceed the scope or lifetime of the value that it refers to. A value can only have a single mutable reference or many immutable references that are active within a given context [12], but not both at the same time.

These restrictions eliminate safety issues, but they can be overly conservative for certain design patterns. When developers need to bypass Rust's restrictions, they can use the **unsafe** keyword to enable a set of additional features that are not restricted by the borrow checker. These features include dereferencing raw pointers, accessing the fields of union types, modifying static mutable state, implementing **unsafe** traits, and calling **unsafe** functions—including those written in other languages [13]. The Rust compiler assumes that programs using **unsafe** code will follow the rules of its aliasing model. Programs that break these rules have *undefined behavior* and may be optimized incorrectly. This can lead to differences in the behavior that have introduced security vulnerabilities [14] in practice.

A. Rust's Aliasing Model

Rust developers can avoid these issues by ensuring that their programs adhere to the rules of Rust's aliasing model. The Tree Borrows [10] model provides the latest definition of these rules. Under this model, a pointer is both an address to a location in memory and a permission to read or write to that location. Each location is associated with a tree that tracks all valid permissions to its contents. When a location is borrowed, a new branch is created in the tree carrying a new permission to access the location. When a pointer is used to access a location, its permission is compared with the current state of the tree to ensure that it is valid and that it permits the kind of access taking place. Each type of access will have a different effect on the tree depending on the position of each permission in the tree relative to the permission used for the access. With respect to a given permission, an access is a considered a child access if requires that permission or any of its descendants; otherwise, it is a foreign access.

It is undefined behavior to access a location using an invalid permission. Figure 1 illustrates the three categories of undefined behavior under Tree Borrows. The first category is an *expired permission* error, which is shown in Figure 1a. When the variable \times is declared on line 1, a new tree is created containing a Active permission, labelled (1). The Active permission allows read and write accesses, and it is the default state for a mutable variable. On line 2, a mutable borrow of \times is assigned to y, which creates an additional,

Fig. 1: Minimal examples of the three categories of Tree Borrows violations.

(a) A code snippet that produces an expired permission error.



(b) A code snippet that produces an *insufficient permission* error.

```
1 unsafe fn mutate(x: &i32) {
2  *(x as *const i32 as *mut _) = 5;
3 }
```

(c) A code snippet that produces a *framing* error.

```
1 unsafe fn free(x: &mut u8, layout: Layout) {
2     dealloc(x as * mut _, layout);
3 }
```

adjacent branch in the tree with the Reserved permission (2). This type of permission behaves like a read-only permission, but it becomes Active when it is used for a write access.

On line 3, the reference assigned to y is cast into a raw pointer, which still carries permission (2). Then, the borrow assigned to z on line 4 creates another Reserved branch in the tree with permission (3). Next, y is mutated line 5, causing permission (2) to transition from Reserved to Active. This is a foreign access relative to permission (3), so its Reserved permission transitions to Disabled. The Disabled permission does not permit any kind of access; this transition enforces the uniqueness of mutable references. Since permission (3) is now Disabled, the write access through z on line 6 is undefined behavior. We refer to this as an *expired permission* error.

The second type of undefined behavior is an *insufficient permission* error, which occurs when a valid permission exists in the tree but does not permit the type of access taking place. This occurs in Figure 1b, where the function mutate writes through a **mut** pointer cast from an immutable reference. Though the cast is valid, the pointer still has the read-only, Frozen permission created by the immutable reference, so writing through it is undefined behavior.

After finding a valid, "granting" permission [9], the tree is modified based on the type of access taking place. A write access may cause permissions to become Disabled, as shown in Figure 1a. However, the permissions associated with reference-type arguments become "protected" upon entering the body of a function. It is undefined behavior for a protected tag to become Disabled before its associated call returns. When a function returns, the permissions of its arguments are no longer protected. We demonstrate this in Figure 1c, where deallocating through \times on line 2 causes its permission to become Disabled. Since \times is a reference-type argument, it is protected, so this is undefined behavior. We refer to an access that disables a protected tag as a *framing* error. Fig. 2: An example of an *invalid range error* under Stacked Borrows that is accepted under Tree Borrows.

```
1 let x: &mut i32 = &mut (0, 0).0;
2 unsafe { *((x as *mut i32).offset(1)) = 1; }
```

1) Differences from Stacked Borrows: Tree Borrows replaces the Stacked Borrows [9] model, which uses a stack to track the active permissions to each location. Under Stacked borrows, a reference cannot be offset and used to access locations outside of the range it originally borrowed from. Figure 2 shows an example of this *invalid range* error; the dereference on line 2 is invalid since x only borrows the first element of the tuple. This pattern is allowed under Tree Borrows; a valid permission can be used to access any location within bounds. Stacked Borrows may also eagerly invalidate permissions when a new reference is created, even if it is never used. Under Tree Borrows, only memory accesses will trigger undefined behavior. However, Tree Borrows' handling of mutable references is more strict than Stacked Borrows in situations involving "two-phase" borrowing, where a unique mutable reference is treated immutable until its first write access. Tree Borrows models this consistently with the Reserved permission, while Stacked Borrows only applies these semantics in certain situations.

B. Rust vs. C and C++

Rust shares several other categories of undefined behavior with current C [15] and C++ [16] standards, such as accessing memory that has been freed, accessing beyond the bounds of an allocation, creating a data race, reading uninitialized memory, and accessing a value at an unaligned address. However, C and C++ have different rules related to initialization, aliasing, and mutability that may conflict with Rust's expectations.

1) Initialization: In both C and C++, accessing an object in memory before it has been initialized produces an "indeterminate value", which is undefined behavior². There are a few exceptions, however; static and thread-local variables are initialized immediately at the beginning of their lifetime, and both unsigned characters and bytes can soundly store indeterminate values. It is also safe to create a reference to a value that is uninitialized. The initialization of a value is not encoded into the type system by default; developers must manually reason about the state of memory or rely on instrumentation to detect uninitialized reads.

Rust's borrow checker prevents variables from being used until they are initialized, and no primitive types tolerate indeterminate values in safe contexts. However, Rust's standard library provides the MaybeUninit<T> struct, which represents an instance of T that may or may not be initialized. It is undefined behavior to produce a safe reference to uninitialized memory, so the macros addr_of! and addr_of_mut! must be used to obtain raw pointers to the interior of MaybeUninit<T> without borrowing it. Once

²C23 §6.2.4.6-7; C++23 §6.7.4.1

an instance has been fully initialized, the **unsafe** function MaybeUninit<T>::assume_init() will unwrap the outer struct to produce the value inside. It is undefined behavior to call assume_init() if T is not fully initialized.

2) Aliasing & Mutability: Neither C nor C++ statically restrict aliasing, but the standards for each language allow implementations to make type-directed assumptions about aliasing. In both languages, it is considered undefined behavior for a pointer to one type to refer to a value of another type if the two types differ³. However, differences do not include qualifiers, so two parameters of types int * and **const** int * may alias. Developers writing C programs can use the restrict type qualifier to hint to the compiler that two pointers with compatible types should never alias⁴, but compilers are not obliged to consider restrict when performing optimizations.

In Rust, both variables and references have distinct, connected capabilities for mutation. Variables are immutable by default, only mutable variables can be mutably borrowed, and only mutable references can be used for mutation. In C and C++, variables are *mutable* by default, and the capability to mutate memory is determined by the mutability of the object being pointed to, regardless of the pointer's type⁵. If a variable was declared as mutable, then a **const** pointer can be cast into a mutable pointer and used to write to it.

3) Provenance: Both C and C++ allow pointers to be converted to and from integers with a size equal to the word size of the current architecture⁶. Implementations may track the "provenance," or origin of pointers to inform compile-time optimizations [17], but neither of the current standards for C or C++ define if or how provenance should be preserved across these conversions. The Rust project has settled on the notion of pointers having provenance [18], but the specifics of Rust's provenance model are still being decided.

MIRI has multiple methods of handling provenance across pointer-to-integer conversion. By default, MIRI uses a "permissive provenance" model, which matches Memarian et al. [19]'s "PVNI-wildcard" model. When a pointer is converted into an integer, its tag is added to a set of tags that have been "exposed" by pointer-to-integer conversion. When integers are converted back into pointers, their allocation identifier is reconstructed from their address, but they receive a "wildcard" provenance value. Under Stacked Borrows, when a memory access occurs using a wildcard tag, MIRI's eagerly interprets it as being equivalent to any tag in the stack that permits the access. Tree Borrows does support this behavior yet; all accesses are allowed through wildcard tags without modifying the tree. Alternatively, developers can enable "strict provenance", which treats integer to pointer conversion as an error.

```
<sup>3</sup>C23 §6.5.7; C++23 §7.2.1.11

<sup>4</sup>C23 §6.7.3.9

<sup>5</sup>C23 §6.7.3.7; C++23 §7.6.1.11.6

<sup>6</sup>C23 §6.3.2.3.5-6; C++23 §6.7.1.10.4-5
```

C. Interoperation

Developers can access foreign functions and static variables using Rust's foreign function interface. Declarations, or "bindings", for each of these objects are written in **extern** blocks, which take an optional qualifier to indicate the Application Binary Interface (ABI) used by the foreign library. Only a subset of Rust's types are guaranteed to be compatible with foreign ABIs, and both structs and enums must be annotated with the #[repr(C)] attribute to ensure that their layout is compatible with C. The Rust compiler enforces the use of ABI-compatible types via lints, but these can be disabled. Bindings are not validated against their definitions, but tools such as BINDGEN [20] and CXX [21] can automatically generate bindings from existing codebases.

Several dynamic analysis tools can find undefined behavior in multi-language Rust applications. VALGRIND [22] is capable of flagging spatial and temporal memory errors, as well as incompatibilities with size and alignment. Many of the LLVM Project's sanitizers are also compatible with Rust [23]. Each of these tools is available as a plugin for CARGO, Rust's build tool. MIRI can call foreign functions from natively compiled shared libraries using libffi [24], but only integer and floating-point arguments are supported. None of these tools can validate foreign libraries against Rust's aliasing model.

III. METHODOLOGY

We seek to determine whether the differences between Rust and other languages lead to undefined behavior in practice. First, we analyzed all libraries published on Rust's central package repository to find the subset with test cases that produce LLVM bitcode for C or C++ libraries during their build process; we describe this stage in Section III-A. Then, we created MIRILLI to analyze runs of these test cases for undefined behavior. MIRILLI extends Miri to interoperate with LLI [25], an LLVM interpreter, so that both interpreters can jointly execute programs defined across LLVM's intermediate representation (LLVM IR) and Rust's Middle Intermediate Representation (MIR). We describe the architecture of our tool in Section III-B, and we account for several changes that were necessary to resolve differences in semantics between each interpreter. In Section III-C, we describe our method for deduplicating test results to identify unique instances of undefined behavior and our approach to reporting bugs.

A. Sampling

We evaluated our design on all compatible Rust libraries with test cases that called foreign functions. Rust libraries are referred to as "crates," and they can be published at crates.io. We used a snapshot of the crates.io database taken on September 20th, 2023. It contained 125,804 unique crates, of which 96% (121,015) had at least one valid, published version. Of all valid crates, 67% (84,106) compiled without intervention. Of the crates that compiled, 36% (44,661) had unit tests and 9% (11,120) produced LLVM bitcode files, leaving 3% (3,785) with both unit tests and LLVM bitcode. We used an unmodified version of Miri to execute all unit tests from this subset of crates to determine which tests called foreign functions. Of the 88,637 test cases we identified, 53% (47,189) passed, 41% (36,766) failed, 4% (3,869) timed out after five minutes, and 1% (1,178) had been manually disabled. Tests can be disabled using the #[ignore] attribute or with conditional compilation directives.

Of the tests that failed in MIRI, 63% (23,116) failed due to foreign function calls. We executed this subset under both Stacked and Tree Borrows using an initial build of our tool to determine which tests called foreign functions that we could execute. Out of all potentially viable test cases, 39% (9,130) called a foreign function we could execute. These tests came from 25% (957) of crates with both test cases and bitcode. Our sample only includes crates that statically link to foreign code in their default configuration; it does not include crates that default to dynamic linking or statically link in non-default configurations. However, the 957 crates we identified were more than enough to find meaningful answers to our research questions. We used this sample to conduct our final evaluation.

B. Implementation

For our tool to function, CLANG [26] must be set as the default C and C++ compiler and configured to emit LLVM bitcode. Otherwise, MIRILLI appears identical to MIRI. Before executing a program, we eagerly link all LLVM bitcode files reachable from the current directory into a single module. When MIRILLI encounters a foreign function call, it looks for a corresponding function definition in the LLVM module. If we find a definition, we pass the function's arguments through a translation layer, which lowers them into the representation used by LLI. After translation, the current Rust thread is set to join on a new LLVM thread that executes the function with the converted arguments. After the LLVM thread terminates, its return value is passed back through the translation layer and given to the Rust thread, which continues to execute. A similar process is used when an LLVM thread calls a Rust function. Though MIRI is single-threaded, it supports concurrency by non-deterministically stepping through multiple simulated "threads" of execution. LLI did not originally support any form of multithreading, but we modified it to be compatible with MIRI's implementation. We support calling foreign functions from parallel Rust threads, but we do not support multithreading within LLVM.

Nearly all of MIRI's mechanisms for detecting undefined behavior are built into the core functions of the interpreter and do not require additional instrumentation of the source program. However, to detect aliasing violations, MIRI inserts **retag** instructions wherever a reference-type value is created, passed to a function, or cast into a raw pointer. A **retag** produces a new permission and adds it to the stack or tree, depending on which aliasing model is in use. We did not need to insert these instructions into the LLVM IR of foreign functions, since we treat LLVM pointers as equivalent to Rust's raw pointers. Stacked Borrows only applies a **retag** to raw pointers at the point where they are cast from referencetype values—which can only ever occur in Rust. Tree Borrows does not **retag** raw pointers at all. This allowed us to extend MIRI's error-detecting capabilities "for free" by replacing every operation that LLI uses to access memory with a foreign function call into Miri's implementation of an equivalent operation. However, to increase test coverage, we had to address two additional difficulties.

a) Translation: Rust's MIR uses different calling conventions and represents values differently than LLVM IR, so we could not rely on a function's definition to have the same signature as its binding. However, foreign function bindings are also allowed to be incorrect, so we could not wholly trust type information to guide our conversion, either. Additionally, neither Rust not LLVM have a formal model of their ABI that we could use as an oracle. When implementing our value translation layer, we settled on a conservative approach that supports the most common ABI differences while still being able to detect certain instances of incorrect bindings. We maintain the invariant that the size of a typed value on one side of the boundary must be equal to the size of the type expected by the other side. We provide a formal model of our value conversion layer in Section 2 of the supplement. It demonstrates that conversion will fail when a difference in size is detected, which is reported as undefined behavior.

Conversion is trivial for primitive types, since they have a canonical representation in Rust and LLVM. We also allow implicit casts between pointers and integers at foreign boundaries, which was necessary for 526 test cases from 70 crates. When aggregate types are passed by value, we require both the size and number of fields to match unless the aggregate is passed as an integer or by reference. However, we also frequently observed functions which expected individual aggregates to be passed through multiple parameters, with one parameter for each field. This only occurred with homogeneous aggregates, where every field is identical and lacks padding. To accommodate this, we treat each field in a homogeneous aggregate as a separate argument if the entire aggregate cannot be passed as a single parameter. We only apply this transformation if the number of fixed parameters is greater than or equal to the number of remaining arguments plus the number of fields in the aggregate. This was necessary for 2% (156) of our test cases from 15% (140) of crates.

Products lack a canonical form in Rust and LLVM, so we do not support passing them as variadic arguments to LLVM or as arguments from LLVM to Miri's shims for system calls, which lack type information to guide our conversion. When an opaque pointer from LLVM is passed to one of Miri's shims, we assign it the type ***mut** u8. However, if it points to stack or static memory with a size equal to that of a primitive type, we assign it to point to that type. This may lead to false positive alignment errors when we cannot resolve an underlying type and Rust expects a type other than u8. We also do not support passing aggregates by value to shims and variadic functions, since we lack a source of type information to determine the underlying layout of the struct.

b) Initialization: MIRI tracks which bits are initialized in each allocation and reports an error when uninitialized

memory is read. However, LLVM will read uninitialized memory for the purpose of propogating undef and poison values, which represent the results of indeterminate or invalid computation. If a single bit needs to be set within an uninitialized byte, instead of writing a zeroed byte with the individual bit set, LLVM will load the uninitialized byte, set only that bit, and then write it back [27, 28]. These accesses are considered undefined behavior by Miri, but we treat them as false positives. We implemented two "memory modes" that allow us to identify true positive uninitialized reads of Rustallocated memory in LLVM. The "Uninit" mode allows load operations to read uninitialized bytes in LLVM, while the "Zeroed" mode treats all uninitialized reads as errors but zeroinitializes LLVM-allocated stack and heap memory. Tests that read uninitialized memory must be run under each mode to ensure a complete evaluation. We cannot detect true positive uninitialized reads that occur outside of interactions with Rust, but these errors can be found with other tools [22, 29] and are out-of-scope for our evaluation.

C. Evaluation

We used MIRILLI to execute each of the 9,130 viable test cases that we identified in Section III-A. We overrode each crate to use version 1.74 (nightly-2023-09-25) of the Rust toolchain with the latest compatible version of Miri (1a82975). We set the global C and C++ compilers to version 16 of CLANG with optimizations disabled. We collected data using Amazon EC2 on-demand instances provisioned through CloudBank [30]. We used c6a.2xlarge instances during the initial stages of data collection, but we switched to c6a.xlarge instances when using MIRILLI. It is singlethreaded, so fewer resources were necessary. All commands were executed in Docker container running Ubuntu 23.04.

a) Executing Tests: We executed each viable test natively and in MIRILLI under both Stacked Borrows and Tree Borrows. We configured Tree Borrows to treated all values of types derived from Unique as having the semantics of a mutable borrow. Without setting this configuration option, only Unique values in the interior of Box<T> are treated this way. We disabled isolation to allow executing non-deterministic operations and enabled symbolic alignment checking. By default, Miri will report an error if the address of a pointer is not a multiple of the requested alignment of the type of value being read or written through it. However, the base address of an allocation is not guaranteed to be a multiple of the requested alignment, so it is possible for a misaligned pointer to be "aligned" by chance. Symbolic checking avoids these false negatives by ensuring that the pointer's offset from the base address is a multiple of the alignment of the value being read, and that the alignment of the allocation is greater than the alignment of the value. We ignored unaligned accesses in LLVM to prioritize detecting Rust-specific errors.

On average across each memory mode, 61% of tests terminated due to an unsupported operation, 19% passed, 10%timed out, 1% failed, and 9% had a potential bug. A "bug" includes both undefined and undesired behaviors, such as memory leaks. Of the 61% of unsupported operations, 56% were dynamically linked functions and inline assembly, which are out-of-scope. An additional 27% were atomic instructions and floating point types that LLI does not implement, 12% were due to types that are not supported by our value conversion layer (discussed in III-B), and 5% were shims that Miri does not fully implement.

b) Deduplicating Errors: We reason about bugs in terms of test outcomes, where an outcome includes the results of a single test under both aliasing models. We deduplicated outcomes based on exit codes, stack traces, and error logs to avoid filing redundant bug reports. Prior to deduplication, we modified error logs to remove unnecessary elements, such as references to specific memory addresses. We also included more or less detail in stack traces depending on the location of an error. For foreign errors, we used the subset of the stack trace up to the Rust boundary to avoid deduplicating errors which appeared to be identical but were caused by mistakes at different callsites. When an error occurred in Rust code, we only used the line where the error occurred, since few of these errors were caused by LLVM.

After deduplication, we had 394 errors to investigate. Multiple factors lead to the number of bugs being significantly smaller than the number of deduplicated test outcomes. Our method of deduplication was conservative, we ignored errors from crates that had been unpublished since the start of our investigation, and we only reported Stacked Borrows violations that were also Tree Borrows violations. We also observed false positives related to alignment and accesses through addresses that we do not emulate (e.g. stdout).

c) Reporting Errors: Not all errors are undefined behavior, and not all instances of undefined behavior are readily exploitable. However, we still attempted to follow ethical vulnerability disclosure practices by reporting bugs privately via email before creating public reports. When we found a bug, we examined its crate's Cargo.toml and the GitHub profile of its repository's owner to find the contact information for its maintainers. If we were unsuccessful, we logged a public issue. We also logged issues if we had not received a response after 1 month or if the type of error did not appear to be exploitable. Our reports included a representative test case, the output from MIRILLI, and a minimal example where applicable. When a fix was trivial, we also filed a pull request. Section 1 of our supplement includes metadata from each library and links to our contributions.

IV. RESULTS

We found 48 new bugs from 38 crates. Currently, 26 of the bugs have been fixed, and none have been identified as security vulnerabilities. Bugs occurred slightly more frequently in LLVM than in Rust; 25 occurred in LLVM, 17 occurred in Rust, and 6 were related to incorrect bindings. The majority (35) were found in crates with less than 100 average daily downloads in the 6 months prior to our snapshot of crates.io. However, we discovered 3 Tree Borrows violations

TABLE I: Counts of each unique error grouped by category, the location of the fix, and the location of the error.

| Fix | Error | Allocation | Ownership | Typing | Total: |
|---------|---------|------------|-----------|--------|--------|
| Binding | Binding | - | - | 6 | 6 |
| Binding | LLVM | - | 3 | - | 3 |
| LLVM | LLVM | 1 | 3 | - | 4 |
| Rust | LLVM | 1 | 16 | 1 | 18 |
| Rust | Rust | 10 | 2 | 5 | 17 |
| | Total: | 12 | 24 | 12 | 48 |

in separate crates which each had more than 10,000 average daily downloads.

We found 18 Tree Borrows violations; they were the most common type of bug. Though they were caused by incorrect encapsulations or arguments in Rust, nearly all occurred in LLVM. Regarding **RQ1**, our results suggest that Miri's methods for dynamically enforcing Rust's aliasing model **are useful** for finding undefined behavior in Rust programs that call foreign functions.

Additionally, we found 90 tests from 37 crates with Stacked Borrows violations that occurred in foreign code. However, 66% (59) of these tests passed or encountered an unsupported operation under Tree Borrows. This is primarily since 50% (45) had invalid range errors similar to the minimal example shown earlier in Figure 2. We found that it was typical for slices of an array to be cast into raw pointers, passed across the FFI, and offset beyond the borrowed range. This is undefined behavior under Stacked Borrows, but it is accepted by Tree Borrows. This provides our answer to **RQ2**; Tree Borrows accepts more real-world programs that call foreign functions than Stacked Borrows due to how it handles pointer arithmetic.

The bugs we discovered fall into three categories. We describe *Ownership* errors in Section IV-A, which include all violations of Tree Borrows and accesses out-of-bounds. *Allocation* errors include both memory leaks and cross-language deallocation, which we describe in Section IV-C. We describe *Typing* errors in Section IV-B, which include incorrect foreign function bindings and values that were invalid due to incorrect alignment or initialization. Table I shows the number of bugs under each category, grouped by the location of the error and the location where a fix would need to be applied. We refer to each bug using a unique numerical ID corresponding to tables in Section 1 of our supplement.

A. Ownership

We found 24 Ownership bugs from 20 crates. These include the 18 Tree Borrows violations and 6 accesses out-of-bounds.

a) Const-Correctness: We found 10 insufficient permission errors caused by incorrect casts from immutable references to mutable raw pointers. In Bug #16, a chain of casts was used to convert &self into *mut T. This pointer had a read-only Frozen permission, so mutating this structure across the FFI triggered an insufficient permission error. There were 6 bugs with equivalent errors. The remaining 4 bugs occurred due to foreign function bindings that incorrectly declared pointers as const instead of mut, leading developers to pass

Fig. 3: A minimal example of Bug #23, an incorrect implementation of a self-referential pattern.

```
struct Alloc {
 1
2
      cache: i32,
    + cache: UnsafeCell<i32>,
      buffer: *mut i32,
 4
5
    fn open(a: &mut Alloc 1 (1)) -> i32 {
    - let cache = &mut a.cache as *mut _; (2)
6
    + let cache = a.cache.get(); 1
 7
      a.buffer = cache;
      let b = &mut *a; 2 3
8
9
      unsafe {
10
        ffi::open(b);
11
        b.cache
      + *b.cache.get()
      }
13
    }
    void open(Alloc *a 2 (3)) { // ffi::open
13
      int *buffer = *((*a).buffer 1(2);
14
      *buffer = 1;
15
    }
```

(a) Tables illustrating the (simplified) subtree of permissions for location of the field "alloc.cache" before (to the left of the arrow) and after (to the right of the arrow) the write access on line 14.



pointers derived from an immutable references instead of a mutable ones.

b) Self-Reference: In Rust, it is not possible to create a struct containing a self-reference using only safe code. Allowing this could lead to use-after-free errors depending on the order in which each field is dropped. It is possible, but non-trivial, to implement self-referential patterns using encapsulated **unsafe** operations [31]. Bug #13 demonstrates how a self-referential pattern can be implemented incorrectly. We found this bug in an encapsulation of a C library implementing a minimal file system for embedded applications. It used separate structs to represent the state of the file system and its configuration. The configuration held a mutable reference to the state, but both objects were contained in a parent struct representing the entire file system. Rust held a single mutable reference to the parent which became invalid when the state was mutated through the configuration by a foreign function.

Figure 3 provides a minimal example of the bug and our fix. Lines that we removed are highlighted in red and marked with a "-", while lines we added are highlighted in green and marked with a "+". Tags within a circle indicate the state of the borrow tree prior to the fix, while tags within a square represent the state of the tree after the fix. When a tag is on a line, it indicates that the pointer or reference on that line has a permission within the subtree corresponding to the tag. The tables at the bottom display the state of the tree before and after the write access on line 14.

The Rust encapsulation for open initializes field buffer of the struct Alloc on line 7 with a mutable raw pointer cast from a mutable reference to the field cache. The struct is mutably Fig. 4: A minimal example of the cyclic aliasing pattern that we observed in Bugs #3 and #13.

```
impl Compression {
 2
       fn new() -> Self {
 3
         let stream = Box::new(Stream::default());
 4
         let mut stream = Box::into_raw(stream);
 5
         unsafe {
 6
          - ffi::init(stream.as_mut()) (1)
         + ffi::init(stream) 1
 7
 8
         Compression { stream }
 9
       }
10
11
       fn compress(&mut self (2) [2]) {
12
         unsafe {
13
           self.stream.data = 0; (2)
           (*self.stream).data = 0; 1
14
            ffi::compress(self.stream.as_mut()) (2)
           ffi::compress(self.stream) 1
15
         }
16
       }
     }
17
     void init(Stream* s 1 1) { // ffi::init
    (*s).state = malloc(sizeof(State));
18
19
20
          (*(*s).state).stream = s;
21
     }
     void compress(Stream* s (2) 1) { // ffi::compress
23
         let data = *((*(*s).state).stream (1) [1).data;
     3
24
```

(a) Tables illustrating the (simplified) subtree of permissions for location of the field stream.data before (to the left of the arrow) and after (to the right of the arrow) the write access on line 13.

| Reserved | \rightarrow | Disabled | -1) | Active | | | -1 |
|----------|---------------|----------|------------|----------|---------------|----------|----|
| Reserved | \rightarrow | Active | L 2 | Reserved | \rightarrow | Disabled | 2 |

borrowed again on line 8, creating a reference that is passed into the foreign function ffi::open. Each of these borrows, indicated by (2) and (3), corresponds to an adjacent Reserved branch in the tree. Across the FFI, a write access occurs on line 14 using (2). This is a child access relative to (1) and (2), so they transition to Active, but it is foreign relative to (3), so it becomes Disabled. This leads to an expired permission error on line 11 when (3) is used for a read access in Rust.

We fixed this bug by wrapping parts of state in an UnsafeCell, which can be mutated through shared references. In Figure 3, we change the first field of Alloc to UnsafeCell<i32> and replace the mutable borrow assigned to a.buffer with a.cache.get(). This expression does not perform a retag, so both a and cache share the permission 1. Since a contains an UnsafeCell, the mutable borrow assigned to b on line 8 associates the tag 2 with a special Reserved* permission that can tolerate foreign writes. Consequentially, this permission is no longer disabled by the write through 1 on line 14, so the read access on line 11 is valid.

c) Multiple Mutable Aliasing: Expired permission errors typically occurred when pointers derived from mutable references were copied into the foreign heap. We observed this type of bug in 5 separate libraries. The most notable examples were Bug #3 from bzip2 and Bug #13 from flate2, which are both popular compression libraries. In particular, flate2 is actively maintained by the Rust project and averaged more than 130,000 downloads per day during our observation period.

Figure 4 shows a minimal example of the cyclic aliasing pattern used by each library. We use the same notation as Figure 3. The structs Stream and State carry pointers to each other. Both are encapsulated in Rust by a Compression object, which carries a heap-allocated instance of Stream. The Rust function new allocates memory for a Stream object and passes a mutable reference carrying the Reserved permission (1) to ffi::init. This foreign function copies the pointer it receives to the Stream object into a newly-allocated State instance on line 20, creating a cyclic structure. Later, when the function compress is called, it creates an adjacent Reserved permission (2). Mutating through this permission on line 13 causes (1) to become Disabled, making it undefined behavior to read using (1) in the body of ffi:compress on line 23.

To fix each error, we unwrapped the Box using into_raw() and stored a raw pointer to the allocation within the Compression struct. We modified the API so that this raw pointer would be used for every access to the allocation, ensuring that the cyclic structure would remain valid. This corresponds to permission 1 in Figure 4, which remains Active through each access. We also had to modify Compression's implementation of Drop to rewrap this pointer using Box::into_raw() to avoid a memory leak.

Bug #23 also involved a mutable reference being copied into the foreign heap, but we needed a different approach to fix it. It occurred in the same file system library as Bug #13, which avoided creating heap allocations in Rust as a constraint of the embedded application context. Instead of using a Box<T>to allocate the equivalent of the Stream object in Figure 4, the Rust encapsulation passed around a mutable reference to a stack allocation. Similar to Bugs #3 and Bug #13, once the reference was created, it was passed to a foreign initialization function that copied the reference into a foreign heap allocation. After the initialization function returned, the mutable reference was moved into a RefCell<&mut T>. This performed a reborrow, creating a new Reserved permission as a child of the Reserved permission held by the foreign heap. Both of these permissions could be used interchangeably for read accesses, but not for write accesses. If the foreign, parent permission was mutated first, it would invalidate the child permission. If the child permission was mutated first, then both permissions would become Active, but the next mutation through the parent permission would cause the child permission to become Frozen, making future write accesses through the child permission undefined behavior.

To fix this error, we stored the mutable borrow as a RefCell<*mut T>, which prevented new child permissions from being created. However, the type T was a struct, and certain foreign functions required pointers to its members. Reborrowing is typically necessary to create a reference to a member of a struct, but this creates a new permission, which we needed to avoid. Instead, we used Rust's addr_of_mut! macro, which creates a pointer to a field without borrowing.

Combined, these two changes ensure that every memory access on each side of the boundary uses the same permission. The authors of Tree Borrows [10] found an equivalent bug in test cases for the Rust toolchain and applied the same fix.

d) Framing: We found one framing violation equivalent to the example in Figure 1c. In Bug #38, a Rust function attempted to use a foreign function to grow a heap-allocated array of values. The function was passed a pointer derived from a reference of type &'static mut [T], which was protected. Similar to Figure 1c, when this pointer was used to reallocate the array, its protected permission became Disabled, which is undefined behavior. We fixed this bug by changing the function to receive *mut [T]. Raw pointers do not receive protectors, so they can be used for deallocation.

e) PhantomData: Rust's PhantomData<T> is a "ghost type;" it behaves like an instance of T, but it can be created without providing a concrete value of that type. However, there is an exception: a value of type PhantomData<UnsafeCell<T>> does not behave like an UnsafeCell<T>; it cannot be mutated through immutable references [32]. In Bug #28, the type Opaque was declared as an alias for PhantomData<UnsafeCell<* mut T>>. It was used to represent a foreign types in Rust without having to declare their layout on both sides of the FFI boundary. Since Opaque did not contain a concrete instance of UnsafeCell, raw pointers derived from &Opague received a read-only permission, leading to an insufficient permission error when they were written through in foreign code. We proposed fixing this error by removing the PhantomData, but other contributors are still discussing the correct fix. The relationship between PhantomData and UnsafeCell is not yet settled, so this pattern may be allowed in the future.

f) Access Out-of-Bounds: We found 6 access out-ofbounds errors in unique crates. Bugs #6 and #7 were found in two encapsulations for libdecnumber, which is part of the GCC toolchain. This library often used the following pattern to iterate over arrays of integers:

for (; *curr==0 && curr+3<end;) curr+=4;</pre>

The first term in the conjunction will execute before the second term, but if the second term is false, then the first term is an access out-of-bounds or an uninitialized read. This was fixed by swapping the order of each term. Bug #1 was found in a disassembler that incorrectly implemented several instructions, leading to an access out-of-bounds into adjacent static arrays. This error was fixed once the correct semantics were implemented.

None of these errors meaningfully involve Rust. However, the remaining errors were caused by Rust encapsulations that did not adequately enforce the preconditions of foreign function calls. Bug #4 involved the following API, which redirected its arguments to foreign functions based on the value of the size parameter:

fn expand(ex_key: &mut [u8], key: &[u8], size: KeySize)

For example, passing KeySize::K128 would call a foreign function which assumed that ex_key and key would each be

128 bytes long. However, this invariant was not enforced by the encapsulation; it was possible to cause an access out-ofbounds error by passing a KeySize larger than the length of either key. We did not propose a fix for this bug, as it could require significant changes to the API.

Bug #30 involved a foreign function that expected to receive a pointer to a string with 6 characters. It was allocated with CString::new(Vec::with_capacity(6)), exposed as a raw pointer using into_raw(), and correctly deallocated after the call using from_raw. However, the implementation of CString::new appends a null-terminator to the vector and then converts it into a value of type Box<[u8]> using into_boxed_slice(), which shortens the capacity of a vector to be equal to its length. The intended capacity was 6, but into_boxed_slice() shortened it to 1, since the string only contained a null-terminator. The encapsulation did not validate that the length of the CString instance was correct, leading to an access out-of-bounds when the C codebase read beyond the first character. We fixed this error by initializing the CString with a constant of the correct length.

B. Typing

We found 12 bugs from 11 crates involving values which were partially initialized or had invalid alignment. Most were caused by incorrect use of MaybeUninit<T>, but several involved incorrect foreign function bindings.

a) Incomplete Initialization: We found 4 bugs involving partial initialization of MaybeUninit<T>. Bugs #7 and #8 were each found in the same library. In each case, an uninitialized instance of a struct T containing an array of values was created using MaybeUninit<T> and passed across the FFI to be initialized. The foreign call only initialized the first element of the array to 0. The remaining uninitialized elements would never be read by C, since every iteration stopped at the null terminator. Miri reported these initialization patterns as an error when MaybeUninit<T>::assume_init() was called. We fixed each bug by zero-initializing the entire array in Rust.

Bug #43 seemed to involve an equivalent pattern; MaybeUninit<T>::assume_init() triggered an error for a struct that was initialized by a foreign function. However, the function properly zero-initialized the struct using memset. After examining the LLVM bytecode of the foreign function, we found that all 88 bytes of the struct were initialized on the LLVM stack, but only the first 80 bytes were copied back into Rust. These missing bytes corresponded to padding fields, which were never directly accessed by the foreign library. Optimizations had been disabled, but LLVM still removed this "unnecessary" write access. We fixed Bug #43 by zeroinitializing the padding fields before calling assume_init().

b) Incorrect FFI Bindings: We found 6 crates with one or more incorrect foreign function bindings. All bindings from each crate had been written manually. Three of these crates had bindings with missing return types. In Bug #37, a binding was declared in a unit test without its 32-bit integer return type. The C implementation used this to return a status code indicating if one of its integer parameters was within bounds. The

remaining two bugs involved bindings with incorrect integer types, which lead to incomplete initialization. In Bug #36, a function was declared to return a 32-bit integer, but its C implementation returned a 1-byte boolean value. In Bug #34, the last parameter of a function was declared as a 32-bit integer, but the C implementation expected a size_t. The width of size_t is architecture dependent, so this binding was only correct for 32-bit architectures. To fix this bug, multiple prior releases needed to be patched to use Rust's usize.

C. Allocation

We found 12 issues related to allocation in 12 distinct crates. These include 10 memory leaks and 1 new cross-language deallocation bug. We also found 1 null-pointer dereference, but it did not have any connection to Rust.

a) Memory Leaks: Rust's Box<U> and CString use similar APIs to encapsulate heap allocations. A new instance is created with T::new and deallocated when it leaves scope. The function T::into_raw consumes an instance of T, producing a pointer to the interior allocation. To avoid a memory leak, this pointer must be reconstituted in its wrapper type using T::from_raw. We found 4 leaks caused by calling into_raw on either Box<T> and CString without later calling from_raw. Each type was used to allocate memory for a foreign function call, and each bug was fixed by adding a call to T::from_raw after the foreign function returned. We also encountered 6 bugs involving leaks of memory allocated by C. Each was caused by neglecting to call the appropriate destructor function exposed by the C API. However, in Bug #20, the C API did not expose a destructor since it had been designed under the assumption that users would be able to call free. We could not use Rust's std::alloc::dealloc to fix this, since that could lead to invalid cross-language deallocation.

b) Cross-Language Deallocation: It is potentially undefined behavior to free a pointer allocated by C in Rust, or vice versa, since each language's binary may use a different allocator. We found one example of invalid cross-language deallocation. In Bug #31, a pointer to a heap-allocated string was returned to Rust by a foreign function call and stored as a Cow<&'static [u8]>, which will lazily clone its data when mutated. This wrapper type is an enumeration with two variants; Cow::Borrowed receives a reference to a value, while Cow::Owned takes ownership of a value, deallocating it when it goes out of scope. When this Cow was dropped, it deallocated the C heap memory using Rust's allocator. There was not an immediate fix for this bug, since the C API did not expose a destructor.

V. DISCUSSION

Our findings indicate that it is easy to inadvertently introduce undefined behavior in Rust libraries that call foreign functions. The errors we found can be prevented with careful auditing, but it is seems likely that many will persist, undetected, until the Rust community develops a productionready method for finding aliasing violations in multi-language applications. We provide the following recommendations:

a) For Rust Developers: Awareness is key to avoiding improper use of unsafe features. Developers who depend on foreign code should validate their tests with language-agnostic bug-finding tools, such as LLVM's sanitizers or Valgrind, which can detect memory leaks (e.g #20) and accesses outof-bounds (e.g. #1). Developers who maintain foreign function bindings should consider that the infrequent cost of generating and committing bindings may be preferable to writing them by hand without assistance, which can lead to errors. When heap objects are accessed on each side of the foreign boundary, it is helpful to be aware of where each object is created, how many references it has, where these references are stored, and what capabilities they require. Each of these attributes can influence the correct design for an encapsulation. For example, Bug #23 was fixable by casting a reference into a pointer, while Bugs #13 and #3 required unwrapping a Box.

b) For The Rust Project: The Rust community is in dire need of a production-ready solution for validating Rust's aliasing model across foreign function boundaries. Though our approach was capable of finding useful results, its scalability is limited due to the requirement of implementing shims for system calls and the lack of a formal specification for the ABIs implemented by Rust, CLANG, and LLVM. Instrumenting a shared, intermediate format is likely to be the most effective approach. The KRABCAKE project [33] is developing an extension to VALGRIND [34] (concurrent to MIRILLI) to provide support for detecting aliasing violations, but it is not yet capable of replicating our results. The Rust community should invest resources into completing a prototype implementation to evaluate on real-world applications. However, since VALGRIND can incur significant runtime overhead, it would also be worthwhile to develop an equivalent approach using LLVM's Sanitizer API [35].

VI. RELATED WORK

Foreign function calls are a common use case for **unsafe** code, but they have been understudied in prior work.

a) Surveys of the Rust Ecosystem: Studies that examined unsafe code in Rust libraries have consistently found that foreign function calls are a significant use-case for unsafe code [4, 5]. In particular, Evans et al. [4] surveyed all published crates in September, 2018 and found that 22.5% of all unsafe function calls were to foreign functions. Rust developers also view foreign function calls as a central use case for unsafe code. Fulton et al [6] interviewed 16 Rust developers and surveyed 178 developers, finding that nearly half of participants interoperated with foreign libraries. Both Höltervennhoff et al. [7] and McCormack et al. [8] focused specifically on Rust developers who use unsafe code, and each found that the majority of participants used Rust's FFI.

b) Types of Bugs & Undefined Behavior: Prior studies have examined open-source contributions to categorize errors caused by **unsafe** code. Most considered foreign function calls to be out-of-scope, and none described aliasing violations in terms of Stacked or Tree Borrows. Both Qin et al. [36] and Xu et al. [37] examined bug and vulnerability reports from open source projects and found examples of allocation and typing errors similar to the ones that we identified. Xu et al. [37] did encounter errors related to FFI use, but they were primarily "straightforward" issues related to applicationspecific invariants, layout, and alignment. Cui et al. [38] evaluated a taxonomy of 19 safety properties required by **unsafe** functions, but they made it an explicit goal to "disregard" foreign functions.

c) Bug-finding Tools & Verifiers: Prior approaches to static analysis [39, 36, 40, 41] have found a wide variety of bugs caused by improper use of unsafe code, but few approaches scale to multi-language applications. Li et al. [42] applied dataflow analysis on LLVM IR and detected several memory leaks and cross-language deallocation errors in Rust libraries. We replicated several of the bugs that they encountered. Hu et al. [43] modified several existing Rust analysis tools, including MIRI, to analyze multi-language programs defined in a custom intermediate representation. However, they did not evaluate their approach on any real Rust libraries and did not consider aliasing violations. Lei et al. [44] took a similar approach using WebAssembly as a target language; their evaluation did not use MIRI or consider aliasing issues. Recent deductive verifiers approaches based on the Rust-Belt [45] model have used compositional verification [46] and automated proof search [47] to verify **unsafe** code, but no static verifiers reason about Stacked or Tree Borrows.

VII. THREATS TO VALIDITY

Construct Validity: We disabled compile-time optimizations in both Rust and LLVM to avoid missing bugs. However, we did not evaluate whether optimization would have had any effect on our results, and we did not determine whether any of the bugs we found had an effect on native execution.

Internal Validity: We did not use the same hardware when investigating the source of each bug as we did for large-scale data collection. Our value translation layer cannot detect when a binding uses an incorrect type that happens to have the correct layout, which may have caused us to miss bugs.

External Validity: Limited support for certain features, such as dynamically linked libraries, prevented us from achieving high test coverage; 61% of tests terminated due to an unsupported operation and 10% timed out. Additionally, the majority of libraries we examined linked against C, and not C++. However, these limitations did not prevent us from answering our research questions. Our goal was not to create a production-ready tool, but to understand the types of errors that can occur in Rust libraries that call foreign functions. The types of errors found in general may differ in unexpected ways from those found with our experimental setup.

VIII. CONCLUSION

We conducted a large-scale evaluation of Rust libraries to determine whether dynamic validation of Rust's aliasing model is useful across foreign function boundaries. We created MIRILLI—a dynamic analysis tool that combines two existing interpreters—and we used it to identify 48 new bugs from 38 libraries. Though many of these bugs were aliasing violations, Rust's Tree Borrows aliasing model was more permissive in this context than the earlier Stacked Borrows model. To ensure that these errors are easy to detect, the Rust project should invest in new dynamic analysis tools that can accommodate multi-language applications.

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