Detecting Cross-language Memory Management Issues in Rust

Marco Antonio Corallo

University of Pisa

Course of Languages, Compilers and Interpreters

Overview

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- Different assumptions made by different languages make it possible for attackers to maneuver between the FFI boundaries and exploit these vulnerabilities
- Even for Rust packages written in pure safe Rust, they may still be affected because they may depend on other packages that include FFI.

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However, they can only help developers to write correct interfaces with appropriate data types.
Memory corruption caused by heap memory allocation/deallocation across the FFI boundaries remains an open problem.

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Development of a tool called *FFIChecker*, which automatically collects all the generated *LLVM* intermediate representation (*IR*) for both Rust and C/C++ code, then performs static analysis on the LLVM IR and outputs diagnostic reports.

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- *move* the owner variable
- *borrow* the owner variable
    - mutable
    - immutable

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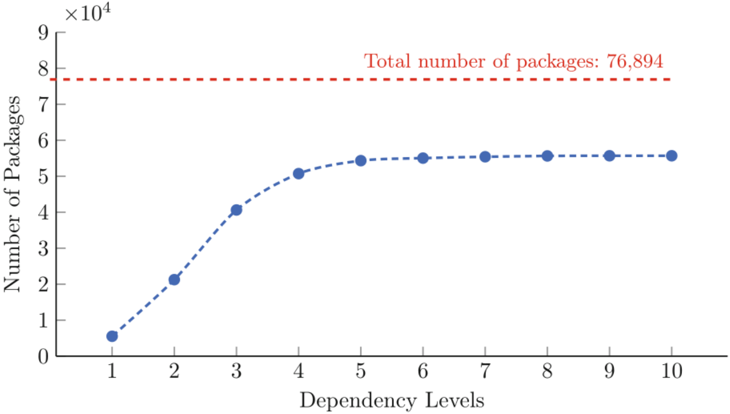
Since the Rust compiler cannot reason about the security of external code, calling FFI is inherently unsafe.
Programmers need to explicitly use the `unsafe` keyword to bypass the security check enforced by the compiler.

FFI

The incorrect use of the FFI has become a severe source of memory safety bugs. Even if programmers restrict themselves in pure safe Rust, their programs may still implicitly rely on FFI through dependencies.
In fact, more than 72% of packages on the official Rust package registry depend on **at least** one unsafe FFI-bindings package.



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- By borrowing the object as a reference
  the ownership remains on the Rust side, so the ownership system is responsible for releasing the memory after it goes out of its scope.
- By moving the ownership to the FFI
  one can first *forget* it from the ownership system, then pass it to the FFI via a raw pointer.
  The responsibility of memory management returns back to the programmers.

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Security and Memory Management Issues via FFI

To explain why the memory management across the FFI boundaries may lead to security vulnerabilities and how the Rust ownership system gets involved, we give several bug examples detected by FFIChecker

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- Common Memory Corruption
- Exception Safety
- Undefined Behaviour caused by Mixing Memory Management Mechanisms

Memory Corruption

When heap memory is passed across the FFI boundaries, the ownership system cannot guarantee its safety. Therefore the responsibility of memory management returns back to the programmers, meaning that all kinds of common memory corruption bugs that happen in C, like *use-after-free*, *double free*, and *memory leak*, still exist.

Memory Corruption

```
let mut cost = Vec::with_capacity(X.rows());
for x in X.outer_iter() {
  let mut cost_i = Vec::with_capacity(Y.rows());  // Allocate a vector
  for y in Y.outer_iter() {
    cost_i.push(distance(&x, &y) as c_double);
  }
  // Forget the memory using `Box::into_raw`
  cost.push(Box::into_raw(cost_i.into_boxed_slice()) as *const c_double);
}

// Call FFI function
let d = unsafe { emd(X.rows(), weight_x.as_ptr(), Y.rows(), weight_y.as_ptr(), cost.as_ptr(), null()) };
```

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- Box is a *smart pointer* used to securely manage heap memory.
- `Box::into_raw` expose the raw pointer of the heap memory managed by the Box in order to pass it to the FFI. The ownership system will *forget* the memory and will not reclaim it.
  The developer is responsible for releasing the memory.
  Otherwise, there will be a memory leak.

Exception Safety

Rust does not support the `try-catch` statement for catching exceptions. Instead, Rust provides a more reliable error handling mechanism: all *recoverable* errors must be handled or propagated back to the caller function, and all *unrecoverable* errors are handled by terminating the execution and unwinding the stack.
All the stack objects' destructors will be called during the stack unwinding to prevent resource leakage.

Exception Safety

When cooperating with external code, developers usually have to transiently create unsound states via unsafe code . Then after the external code finishes, developers manually clean up the states. If some error happens in between, the execution stops and the stack is unwound, so the clean-up procedure will not be executed. The remaining unsound state may cause security issues.

Exception Safety

```
1   pub fn bind(&mut self, params: impl IntoParams) -> Result<(), TaosError> {
2     let params = params.into_params();
3     unsafe {
4       let res = taos_stmt_bind_param(self.stmt, params.as_ptr() as _);
5       self.err_or(res)?;
6       let res = taos_stmt_add_batch(self.stmt);
7       self.err_or(res)?;
8     }
9     for mut param in params {
10      unsafe { param.free() };
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- line 2: variable `params` is initialized by allocating heap memory.

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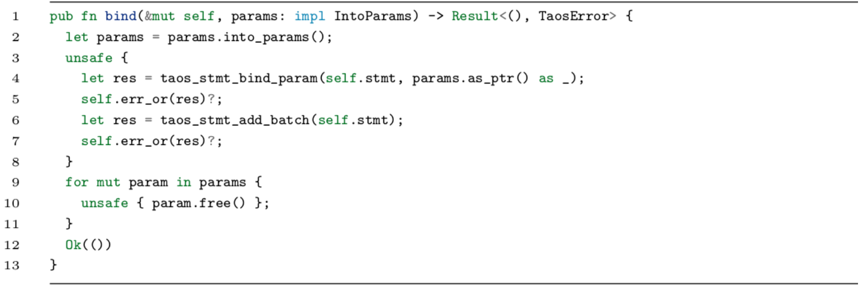

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- line 5 and line 7: the `?` means that if the operation fails, the function returns early and propagates the error to the caller.
- the memory may be leaked if the function returns early and the `free` at line 10 will not be called.

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- Rust and C have totally different memory management mechanisms and they operate on different levels.

Mixing Memory Management Mechanisms

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2   pub unsafe extern "C" fn to_json(from: ext::Ext, text: *const c_char) -> *const c_char {
3     ... ...
4     // CString internally allocates heap memory
5     let output = CString::new(ext::json::serialize(&value.unwrap()).unwrap()).unwrap();
6     let ptr = output.as_ptr();
7     mem::forget(output);  // Memory is "forgotten" by the ownership system
8     ptr  // The raw pointer will be passed across the FFI boundary
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12  int main() {
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- line 7-8: the string is explicitly leaked by `mem::forget` and a raw pointer is returned.
- line 16: the heap memory is freed by C's `free`.

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3. Security and Memory Management Issues via FFI
4. **Abstract Interpretation**
5. Algorithms
6. Evaluation and Conclusion
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Abstract Values

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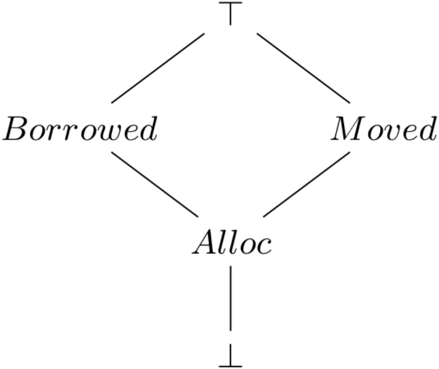
Let **MState** as the lattice



Abstract Domain

To keep track of the abstract values for each basic block, we maintain a lookup table σ_b : **Var** $\rightarrow$ **MState** for each basic block *b*.
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Finally, the *Abstract Domain* is defined as a mapping from **Block** to **AState**.

Transfer Functions

Since the analysis runs on LLVM IR, there is a transfer function for each LLVM instruction according to its semantics.
In particular, we focus on

- `load`

```
fn analyze_load(&mut self, load: &Load) {
    // dest <- address
    let address = &load.address;
    let dest = &load.dest;
    match address {
        Operand::LocalOperand { name, .. } => {
            self.state.propagate_taint(name, dest);
        }
        _ => (),
    }
}
```

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- `load`
- `store`

```
fn analyze_store(&mut self, store: &Store) {
    // address <- value
    let address = &store.address;
    let value = &store.value;
    match (address, value) {
        (
            Operand::LocalOperand {
                name: address_name, ..
            },
            Operand::LocalOperand {
                name: value_name, ..
            },
        ) => {
            self.state.propagate_taint(value_name, address_name);
        }
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- `GetElementPtr`

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fn analyze_getelementptr(&mut self, getelementptr: &GetElementPtr) {
    // dest <- address
    let address = &getelementptr.address;
    let dest = &getelementptr.dest;
    if let Operand::LocalOperand {
        name: value_name, ..
    } = address
    {
        self.state.propagate_taint(value_name, dest);
    }
}
```

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- `store`
- `GetElementPtr`
- `Call`
- `Invoke`

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When analyzing instructions that call other functions, such as `Call` and `Invoke`, the analysis performs *context-sensitive* interprocedural analysis: different functions need different treatments. In particular:

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- Functions that *borrow* a reference or *move* the ownership:

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- Functions that *borrow* a reference or *move* the ownership:
  these functions change the abstract state of heap memory into either *Borrowed* or *Moved*.
- Foreign functions called through FFI:

Function Calls

When analyzing instructions that call other functions, such as `Call` and `Invoke`, the analysis performs *context-sensitive* interprocedural analysis: different functions need different treatments. In particular:

- Functions that allocate heap memory:
  taint source of the algorithm: the resulting variable stores heap memory, so its abstract state will be *Alloc*.
- Functions that *borrow* a reference or *move* the ownership:
  these functions change the abstract state of heap memory into either *Borrowed* or *Moved*.
- Foreign functions called through FFI:
  potentially vulnerable functions, analyze these functions and see whether there are any bugs.

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Fixed-Point Algorithm

FFIChecker traverses a given CFG and iteratively runs transfer functions to update the abstract state until it reaches a fixed point. The fixed-point algorithm chosen is the classical *worklist* algorithm.

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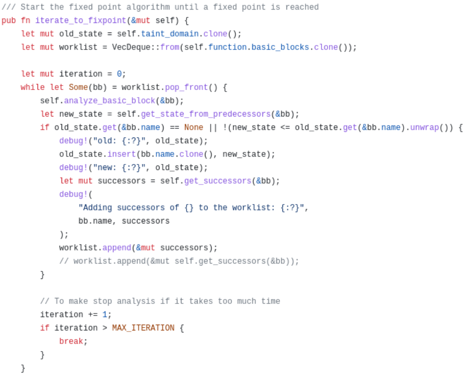
Algorithm 1: Fixed-point algorithm for FFIChecker

```
Input: Control Flow Graph: $CFG$
Output: Abstract State: $State$
Initialization: $State[n] \leftarrow \bot$ for all $n$
Function FixedPoint($CFG$, $State$):
    $W \leftarrow CFG.basicblocks$
    while $W \neq \emptyset$ do
        $b \leftarrow W.$remove()
        foreach $instr \in b.instructions$ do
            Transfer($State[b], instr$)
        Transfer($State[b], b.terminator$)
        $new\_state \leftarrow \bigsqcup_{n \in \texttt{Predecessors}(b)} State[n]$
        if $new\_state \not\sqsubseteq State[b]$ then
            $State[b] \leftarrow new\_state$
            foreach $v \in$ Successors($b$) do
                $W.$insert($v$)
    return $State$
```



```rust
/// Start the fixed point algorithm until a fixed point is reached
pub fn iterate_to_fixpoint(&mut self) {
    let mut old_state = self.taint_domain.clone();
    let mut worklist = VecDeque::from(self.function.basic_blocks.clone());

    let mut iteration = 0;
    while let Some(bb) = worklist.pop_front() {
        self.analyze_basic_block(&bb);
        let new_state = self.get_state_from_predecessors(&bb);
        if old_state.get(&bb.name) == None || !(new_state <= old_state.get(&bb.name).unwrap()) {
            debug!("old: {:?}", old_state);
            old_state.insert(bb.name.clone(), new_state);
            debug!("new: {:?}", old_state);
            let mut successors = self.get_successors(&bb);
            debug!(
                "Adding successors of {} to the worklist: {:?}",
                bb.name, successors
            );
            worklist.append(&mut successors);
            // worklist.append(&mut self.get_successors(&bb));
        }

        // To make stop analysis if it takes too much time
        iteration += 1;
        if iteration > MAX_ITERATION {
            break;
        }
    }
```

Context-Sensitive Interprocedural Analysis

To avoid duplicated analysis for the same function, FFIChecker implements a *summary-based* method: it caches previously computed results (*summaries*) in a lookup table cache : *((f, in_state), out_state)* that maps a calling context *(f, in_state)* to an output *out_state*.

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To avoid duplicated analysis for the same function, FFIChecker implements a *summary-based* method: it caches previously computed results (*summaries*) in a lookup table cache : *((f, in_state), out_state)* that maps a calling context *(f, in_state)* to an output *out_state*.

Before analyzing a function, it first check whether there is an existing summary that has been computed. If it is the case, the fixed-point algorithm is skipped and the result is directly returned. If not, the fixed-point algorithm is performed and the analysis result is cached in the lookup table.

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For example, the LLVM IR of a foreign function is not always available because it may come from a dynamically linked C library. In this case, FFIChecker cannot further analyze the foreign function, so it generates warnings with **lower** confidence.
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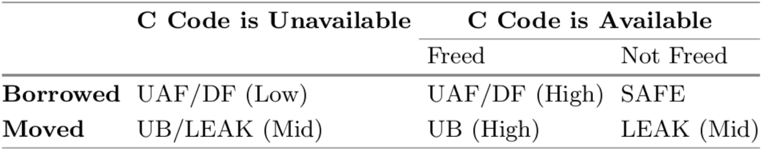

	C Code is Unavailable	**C Code is Available**	
		Freed	Not Freed
Borrowed	UAF/DF (Low)	UAF/DF (High)	SAFE
Moved	UB/LEAK (Mid)	UB (High)	LEAK (Mid)

Evaluation

For testing FFIChecker has been collected 987 packages that are of category *external-ffi-bindings* or depend on other packages that assist the use of FFI, for a total of 3,232,574 lines of Rust and 46,321,573 lines of C/C++.

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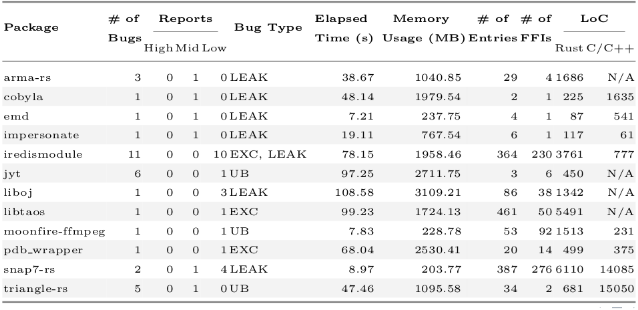
On this dataset, FFIChecker generates 222 warnings. Manually inspect them, 34 bugs (19 memory leaks, 3 exception-related bugs and 12 undefined behaviours) has been confirmed.



Package	# of Bugs	Reports High	Reports Mid	Reports Low	Bug Type	Elapsed Time (s)	Memory Usage (MB)	# of Entries	# of FFIs	LoC Rust	LoC C/C++
arma-rs	3	0	1	0	LEAK	38.67	1040.85	29	4	1686	N/A
cobyla	1	0	1	0	LEAK	48.14	1979.54	2	1	225	1635
emd	1	0	1	0	LEAK	7.21	237.75	4	1	87	541
impersonate	1	0	1	0	LEAK	19.11	767.54	6	1	117	61
iredismodule	11	0	0	10	EXC, LEAK	78.15	1958.46	364	230	3761	777
jyt	6	0	0	1	UB	97.25	2711.75	3	6	450	N/A
liboj	1	0	0	3	LEAK	108.58	3109.21	86	38	1342	N/A
libtaos	1	0	0	1	EXC	99.23	1724.13	461	50	5491	N/A
moonfire-ffmpeg	1	0	0	1	UB	7.83	228.78	53	92	1513	231
pdb_wrapper	1	0	0	1	EXC	68.04	2530.41	20	14	499	375
snap7-rs	2	0	1	4	LEAK	8.97	203.77	387	276	6110	14085
triangle-rs	5	0	1	0	UB	47.46	1095.58	34	2	681	15050

Overview

Conclusion

Most bugs we found are memory leaks. We interpret this as a limitation of Rust's security guarantees: memory leak is considered *safe* in Rust. The reason behind this design choice is that leaking resources is possible in pure safe Rust Therefore, the authors of the Rust standard library decide not to mark functions that leak memory as unsafe.

Conclusion

Most bugs we found are memory leaks. We interpret this as a limitation of Rust's security guarantees: memory leak is considered *safe* in Rust. The reason behind this design choice is that leaking resources is possible in pure safe Rust Therefore, the authors of the Rust standard library decide not to mark functions that leak memory as unsafe.

As a result, the Rust compiler will not give any warnings when inexperienced programmers misuse these functions and cause memory leaks, leading to denial of service attacks or information leakage.

Based on the work of Z. Li, J. Wang, M. Sun and J. C. S. Lui

Thank You.