

# On the Translation Between C and Rust

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**Abstract**—C and C++ have been dominant languages in the systems programming space since the 1970s. Both of these languages are immensely powerful, but this power comes at the cost of security. Memory security issues have plagued this style of programming since its inception. The tradeoff between speed and security is not necessary, however. Rust is a programming language with the speed of C/C++ and the memory safety guarantees of a garbage collected languages. The tradeoff that Rust makes is for complexity and a slower speed of development. The problem: how can we transfer from a C dominated space to a safer Rust dominated space? This paper will give a background on the security mechanisms of Rust, the current state of automatic translation from C to Rust, and discuss what the future may entail for security minded individuals in the systems programming space.

**Index Terms**—C/C++, Rust, Memory Safety, C2Rust

## I. INTRODUCTION

In the sub-field of systems development, C/C++ are the typical choice when it comes to writing complex yet highly efficient systems. While this offers fast software with relatively expedient speed of development, it comes with one major cost—safety. More specifically, C has had known memory security problems that allow for full take over of a process for more than 40 years [1]. Some of these memory issues include buffer overflow attacks, and use-after-free bugs.

There have been many proposed solutions to these memory safety issues. But the simplest is re-implementing code bases written in C in a memory safe language. While this could be any memory safe language, Rust has recently gained popularity, evident in its appearance in the Linux kernel [2]. Furthermore, in early 2024 the United States Government released a report on the dire nature of software security as it relates to national cyber security goals. The report emphasizes the importance that programming languages play in the development of secure software. They offer the Rust programming language as a potential solution to decades of dubious memory management caused by the C languages [3]. This may signify a push from the government to require that new applications must be written in Rust, or legacy C applications must be rewritten in Rust – a simple solution, but a logistical nightmare.

While Rust offers high performance memory safety, many of the use-cases in which it is needed already have a C implementation. The transition from C to Rust poses a massive logistical problem. This problem is compounded by Rust’s relatively steep learning curve [4], limiting access to talent that

could feasibly implement these C programs in Rust. Attempts to fully automate this process have not yet proven fruitful.

## II. BACKGROUND

The reason that code-bases such as the Linux kernel are written in C is the high level of control these languages offer over the machine, allowing for highly performant code. Two principal aspects of C that aid in performance are the manual memory management and low runtime overhead. The traditional approach to ensure memory safety is to automate away memory management with a garbage collector; Lisp and Java are examples of garbage collected languages. Notwithstanding bugs in the implementation of the garbage collector, this guarantees memory safety, but results in more overhead, as the garbage collector must exist at runtime, causing performance degradation. There are a plethora of algorithms for achieving garbage collection, all of which are outside the scope of this paper. Some of the traditional techniques can cost four times the amount of CPU cycles as opposed to the non-garbage-collected program, while others can have negligible effects on the program performance [5]. More recent techniques have brought this upper bound down to closer to two times the CPU cycles, which is still not ideal [6]. Outside of the performance costs, garbage collectors add a runtime to the execution of a language, which could result in unintended program side effects when developing at the systems-level. This approach to memory management creates a false dichotomy between memory safety and performance.

### A. The Borrow Checker

Rust achieves memory safety without a garbage collector through the enforcement of strict compile time rules: Lifetimes, Ownership, Borrowing, and Exclusive Mutability, all of which are checked at compile time [7]. Lifetimes simply denote how long a variable is valid in a program, which the rust compiler’s borrow checker typically implicitly derives. For more complex lifetimes, the borrow checker will fail to automatically denote the lifetime and thus it must be done manually, which is a point of contention for new Rust programmers [4]. Borrowing Ownership and Borrowing are two related ideas in Rust where each variable owns a value, which changes when another variable takes ownership, or the value is passed to a function. Borrowing is the passing of a reference to a variable or function, without changing ownership. Exclusive mutability is ensured through the compiler through

the following invariant: there is either one mutable reference or an arbitrary amount of immutable references [4], [8].

It is worth noting that there are also checks that are compiled into the machine code for each Rust program, which could be considered overhead. Performance wise, the most impactful of these is the bounds checker, which checks for out-of-bounds accesses [7]. This suite of compile time checks guarantee memory safety so long as they are not deactivated using an unsafe block [8].

### B. Unsafe Rust

The Borrow Checker was designed to be conservative by nature. This assures that any program that passes the Borrow Checking phase of compilation (Borrow Checkable) will be memory safe. It is not the case, however, that every memory safe program will pass by the Borrow Checker's standards; this is intended [9](see Fig. 1). This unsafe feature can be encapsulated in safe functions, which is extensively used in the Rust project itself [10]. This feature makes Rust capable of compiling any program, and can introduce memory bugs. Ideally, however, these unsafe blocks will be small, and will be under high levels of scrutiny.

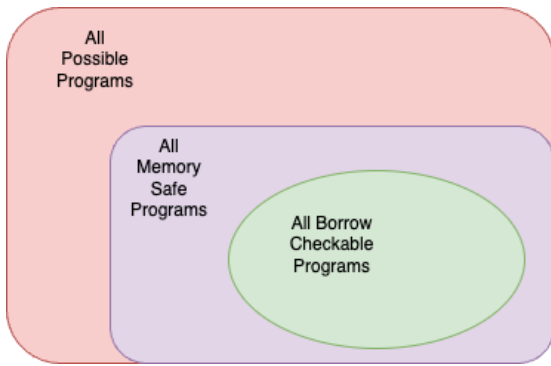


Fig. 1. Conceptual map of the Borrow Checkers conservative nature

## III. EXAMPLE OF VULNERABILITIES

In this section, we will explore examples of some common C vulnerabilities. We will consider two examples: stack buffer overflows, and use-after-free. This section will include code, compilation errors, and explanations. All code for this section is available on GitHub [11].

It is also worth noting the difference between crashing an throwing exceptions, or errors, as this is a crucial difference between Rust and C/C++. Behavior like crashing and throwing exceptions may allow for a programmer to easily find and triage the bug, or allow for the analysis of a crash report. The difference between a crash and an exception is that a crash is completely out of the program's control—it is a system level problem. Exceptions, on the other hand, are still within a program and can often be caught and handled inside the program at runtime. An example of a crash would be a segmentation fault, whereas an exception would be failing a bounds check for an array. Crashes can be used to mount attacks, whereas errors cannot.

### A. Stack Buffer Overflow

A buffer overflow is a vulnerability where the bounds of a buffer are overwritten. This can be used to overwrite the return address of the current stack frame, allowing for arbitrary code execution. Consider the following proof of concept that takes in a user-provided string, and compares it with a hard-coded password. It is certainly feasible that a C programmer may assume that the **const char secret** will remain what they set it to at compilation time.

```
#include <stdio.h>
#include <string.h>

#define MAX_BUF 20

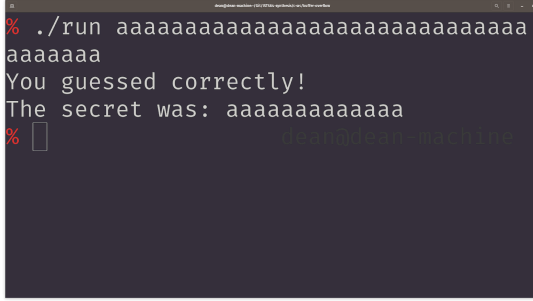
int main(int argc, char **argv) {
    const char secret[] = "letmein";
    char buf[MAX_BUF];
    if (argc < 2){
        printf("Usage: ./run <guess>\n");
        return 1;
    }
    if (argc > 1) {
        strcpy(buf, argv[1]);
    }
    if (0 == strncmp(buf, secret, sizeof(secret))) {
        printf("You guessed correctly!\n");
        printf("The secret was: %s \n", secret);
        return 0;
    }
    printf("' %s' was not the secret.\nTry again later!\n", buf);
    return 0;
}
```

```
use std::env;
fn main() {
    let argv: Vec<String> = env::args().collect();
    if argv.len() < 2 {
        println!("Usage: cargo run <guess>");
        return;
    }
    let secret: String = String::from("letmein");
    let guess: String = argv[1].clone();
    if secret == guess{
        println!("You guessed correctly!");
        println!("The secret was: {} ", secret);
    }else{
        println!("'{}' was not the secret.", guess);
        println!("Try again later!\n");
    }
}
```

Fig. 2. Example C code with a buffer overflow vulnerability and the equivalent Rust code

The program works as expected with sufficiently short input. As stated earlier, this program is vulnerable to a buffer overflow attack. This is due to the lack of bounds checking on the buffer **buf**, which can be overwritten by **strcpy**. By the construction of this program, we are able to overwrite **secret** in such a way that the comparison between the two strings always passes (Fig.3). Importantly in Fig.3, the **secret** variable has been completely overwritten by the user's input—which is

a side effect of the attack, and my have down-stream effects in the program (i.e. if this variable is used multiple times). This type of vulnerability is especially nefarious, as the program doesn't crash or throw an exception.



```

% ./run aaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
aaaaaaa
You guessed correctly!
The secret was: aaaaaaaaaa
% 

```

Fig. 3. A successful overflow attack

### B. use-after-free

A use-after-free vulnerability is when a programmer allows for the use of heap allocated memory after it has already been freed, this may result in a crash, or a malicious corruption of memory [12]. Consider the code block in Fig. 4. This is a simple example that always crashes, but it compiles with no warnings. The reason it crashes is the the function **consume**, consumes the variable **s** in the sense that it frees the allocated variable. It succeeds the first time, but fails the second time, because the memory that the pointer **s** points to is already free (from the first call). We see the code failing in Fig. 5

### C. Rust Implementations

We can rewrite these programs to show how they some of these crashes are solved by re-implementing the code in Rust. In Fig 2, the resulting Rust program does not have a buffer overflow vulnerability. This is because it uses the Rust String type, which is different than the array of characters that C uses. Furthermore, this String type is dynamically allocated on the program's heap [13]. Next, we see in Fig. 6, that the code provided does not compile. The reason for this is that the ownership of **s** is moved into **consume**, and not returned, thus dropped. The purpose of this example is to show that writing the bug the same way as we wrote in C is not possible in safe Rust. This also means that any automatic translation must use unsafe Rust to correctly capture the functionality of the program, or lack thereof.

## IV. LITERATURE REVIEW

### A. C2Rust

C2Rust is a designed with the express purpose of generating a usable Rust implementations from code written in C [14]. To that end, the project is not concerned with implementing the C code in safe Rust, rather it is principally concerned with the initial translation between the languages. It succeeds in this goal. It achieves this through extensive use of unsafe Rust, which allows the automatic translation to mirror exactly what the C code is doing, barring some limitations [15]. The next

```

#include <stdio.h>
#include <stdlib.h>
#include <string.h>

struct String {
    char *s;
    int len;
};

void consume(struct String * s){
    printf("string struct: {'%s',
        len=%d}\n",s->s,s->len);
    free(s);
}

int main(int argc, char **argv) {
    struct String *s = malloc(sizeof(struct String));
    if (argc < 2) {
        printf("Usage: ./run <string>\n");
        return 1;
    }
    s->s = argv[1];
    s->len = strlen(s->s);
    consume(s);
    consume(s);
    return 0;
}

```

```

use std::env;

fn consume(s: String) {
    println!("String: ('{}', {})", s,s.len());
}

fn main() {
    let argv: Vec<String> = env::args().collect();
    if argv.len() < 2 {
        println!("Usage: cargo run <string>");
        return;
    }
    let s: String = argv[1].to_string();
    consume(s);
    consume(s);
}

```

Fig. 4. Example C code with use-after-free bug and the equivalent Rust code

logical step is to transform the unsafe Rust into safe Rust if it is possible. This, however, is not trivial and is the target of ongoing research.

Much of the research on a safer translation has been focused on static analysis, such as the CROWN tool [17], which is able to produce safer code than c2rust. This tool leverages ownership analysis to infer the owners of each variable, allowing for a safer translation, barring some constraints. Another static analysis approach iterates on the C2Rust translation as well. The approach taken by Hong attempted to replace the unsafe Lock APIs output parameters generated by the C2Rust output, and replace them with safe Rust APIs [16]. Lock API is a concurrent programming API that is used to prevent race conditions. Passing output parameters is a technique used in C where a result is written directly to a location pointed to by a parameter of the function. Hong's work is promising, yet preliminary. A slightly different approach is to generate a

```

$ ./run "hello world"
string struct: {'hello world', len=11}
[2] 62229 segmentation fault (core dumped) ./run "hello world"
$

```

Fig. 5. C program from Fig. 4 unconditionally crashing

```

$ cargo run
    Compiling use-after-free v0.1.0 (/home/dean/Git/ISTOS-synthesis/rust-ry/use-after-free)
    Finished dev [unoptimized + debuginfo] target(s) in 0.15s
$ ./target/debug/use-after-free
let s: String = arg(1).to_string();
move occurs because 's' has type 'String', which does not implement the 'Copy' trait
consume(s);
// value moved here
consume(s);
// value used here after move
error: consider changing this parameter type in function 'consume' to borrow instead if using the value isn't necessary
   -> fn consume(s: &String) {
   |
   |     // this parameter takes ownership of the value
   |     // in this function
   |     // consider cloning the value if the performance cost is acceptable
   |     consume(s.clone());
   |
   | }
error: could not compile 'use-after-free' (lib) due to previous error

```

Fig. 6. Rust program from Fig. 4 failing to compile

control-flow graph (CFG) of the C program, then convert that C CFG into a Rust CFG [18]. This offers a distinct approach to that of C2Rust, yet is not able to solve the unsafe problem.

The most effective tool to date is CRustS, which can achieve safe to unsafe ratios ranging from 60% to 99% given the output of C2Rust [19]. This is achieved through the use of a source-to-source translator with hand crafted rules to optimize for safety. Importantly, this tool can be adjusted to adapt to the code base that it is being used on [19].

## B. Use of LLMs

Recently, the programming world has been adopting Large Language Models (LLMs) to aid in programming. This is a very common use of LLMs, however it poses some problems. Chiefly, the current generation of LLMs is extremely sensitive to slight differences in prompting [20] [21]. This is only compounded by the design of LLMs, in which they sample from distribution of responses.

LLMs have also been investigated in work more pertinent to this paper—fixing Rust compilation errors. RustAssistant is a tool that leverages LLMs to solve Rust compilation problems [22]. This paper finds a significant increase in success in solving compilation errors from GPT-3 to GPT-4 [22], implying that this tool will only become more prevalent in the future of software development. This LLM powered translation is not perfect, however. Large real-world projects offer problems for LLMs as the amount of context to consider could be massive, and some is unrepresentable, such as file structure [23]. Overall the main problem with LLMs is their unpredictability and relatively high degree of randomness as

opposed to traditional translation tools. One possible method to remedy this is the use of formal verification tools such as Aeneas [24] to prove correctness at each end of the translation process.

## V. DISCUSSION AND CONCLUSION

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