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Simple Verification of Rust Programs via Functional Purification

Masterarbeit von

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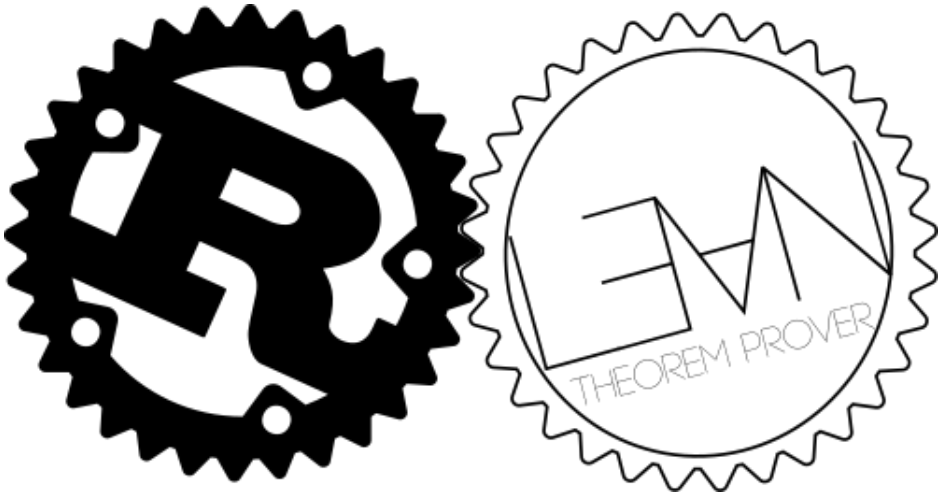

Erstgutachter: Prof. Dr.-Ing. Gregor Snelting

Zweitgutachter: ???

Einfache Verifikation von Rust-Programmen

Imperative Programmiersprachen sind in der modernen Softwareentwicklung allgegenwärtig, stellen aber ein Hindernis für formale Softwareverifikation dar durch ihre Verwendung von veränderbaren Variablen und Objekten. Programme in diesen Sprachen können normalerweise nicht direkt auf die unveränderliche Welt von Logik und Mathematik zurückgeführt werden, sondern müssen in eine explizit modellierte Semantik der jeweiligen Sprache eingebettet werden. Diese Indirektion stellt ein Problem für die Benutzung von interaktiven Theorembeweisern dar, da sie die Entwicklung von neuen Werkzeugen, Taktiken und Logiken für diese "innere" Sprache bedingt.

Die vorliegende Arbeit stellt einen Compiler von der imperativen Programmiersprache Rust in die pur funktionale Sprache des Theorembeweisers Lean vor, der nicht nur generell das erste Werkzeug zur Verifikation von Rust-Programmen darstellt, sondern diese insbesondere auch mithilfe der von Lean bereitgestellten Standardwerkzeugen und -logik ermöglicht. Diese Transformation ist nur möglich durch spezielle Eigenschaften von allen validen Rust-Programmen, die die Veränderbarkeit von Werten auf begrenzte Geltungsbereiche einschränken und statisch durch Rusts Typsystem garantiert werden. Die Arbeit demonstriert den Einsatz des Compilers anhand der Verifikation von Realbeispielen und zeigt die Erweiterbarkeit des Projekts über reine Verifikation hinaus am Beispiel von asymptotischer Laufzeitanalyse auf.

Abstract

Imperative programming, and aliasing in particular, represents a major obstacle in formally reasoning about everyday code. By utilizing restrictions the imperative programming language Rust imposes on mutable aliasing, we present a scheme for transforming a substantial part of the Rust language into the purely functional language of the Lean theorem prover. We use this scheme to verify the correctness of real-world examples of Rust code without the need for special semantics or logics. We furthermore show the extensibility of our transformation by incorporating an analysis of asymptotic runtimes.

Contents

1 Introduction

Imperative programming languages are ubiquitous in today's software development, making them prime targets for formal reasoning. Unfortunately, their semantics differ from those of mathematics and logic – the languages of formal methods – in some significant details, starting with the very concept of "variables". The problem of mutability is only exacerbated for languages that allow references to *alias*, or point to the same memory location, enabling non-local mutation.

The standard way of verifying programs in such languages with the help of an interactive theorem prover is to explicitly model the semantics of the language in the language of the theorem prover, then translate the program to this representation (a "deep" embedding) and finally prove the correctness of its formalized behavior. This general approach is very flexible and allows for the verification of meta programs such as program transformations. The downside of the approach is that the theorem prover's tools and tactics may not be directly applicable to the embedded language, defeating many amenities of modern theorem provers. Alternatively, programs can be "shallowly" embedded by directly translating them into terms in the theorem prover's language without the use of an explicit inner semantics. This simplifies many semantic details such as the identification and substitution of bound variables, but is harder to accomplish the more the semantics of the source language differs from the theorem prover's own semantics.

verification condition generators? Move to Related Work?

Regardless of the type of embedding, an explicit heap that references can point into must generally be modeled and passed around in order to deal with the aliasing problem. References in this model may be as simple as indices into a uniform heap, but various logics such as separation logic [10] have been developed to work on a more abstract representation and to express aliasing-free sets of references.

Languages with more restricted forms of aliasing exist, however. Rust [8], a new, imperative systems programming language, imposes on mutable references the restriction of never being aliased by any other reference, mutable or immutable. This restriction eliminates the possibility of data races and other common bugs created by the presence of mutable sharing such as iterator invalidation. It furthermore enables more aggressive optimizations.

While the full Rust language also provides raw pointers, which are not bound by the aliasing restriction, and other "unsafe" operations, a (informal or formal) memory model for Rust has yet to be proposed. We therefore focus on the "safe" subset of Rust that has no unsolved semantic details.

We utilize safe Rust's aliasing restriction to design a monadic shallow embedding of a substantial subset of Rust into the purely functional language of

the Lean theorem prover without the need for any heap-like indirection. This allows us to reason about unannotated, real-world Rust code in mostly the same manner one would reason about native Lean definitions. The monadic approach gives us further flexibility in modeling additional effects such as function runtime.

We first discuss the simpler cases of the translation, notably excluding mutable references, in Section 4 and show their application by giving a formal verification of Rust's `std::[T]::binary_search` method in Section 5. Section 6 discusses the translation of most usages of mutable references, which is used in Section 7 for a verification of the `fixedbitset` crate.

2 Related Work

While this thesis presents the first verification tool for Rust programs, tools for many other imperative languages have been developed before.

The Why3 project [1] is notable for its generality. It provides an imperative ML-like language *WhyML* together with a verification condition generator that can interface with a multitude of both automatic and interactive theorem provers. While WhyML supports advanced language features such as type polymorphism and exceptions, it does not support higher-order functions, which are ubiquitous in Rust code. WhyML provides a reference type `ref` that can point to a fresh cell on the heap and is statically checked not to alias with other `ref` instances, but cannot point into some existing datum like Rust references can. For example, the first of the following two WhyML functions fails to type check because the array elements are not known to be alias-free, while the second one will return a reference to a *copy* of `a[i]`.

```
let get_mut (a : array (ref int)) (i : int) : ref int = a[i]
let get_mut (a : array int) (i : int) : ref int = ref a[i]
```

WhyML is also being used as an intermediate language for the verification of programs in Ada [6], C [2] and Java [3]. For the latter two languages, aliasing is reintroduced by way of an explicit heap.

The remarkable SeL4 project [7] delivers a full formal verification of an operating system microkernel by way of multiple levels of program verification and refinement steps. The C code that produces the final kernel binary is verified by embedding it into the theorem prover Isabelle/HOL [9], using a deep embedding for statements and a shallow one for expressions. The C memory model used allows type-unsafe operations by use of a byte-size heap, but as with Why3, higher-order functions are not supported. The AutoCorres [4, 5] tool then transforms this representation into a shallow monadic embedding, dealing with the 'uninteresting complexities of C' [5] on the way. The result is an abstracted representation that is quite similar to ours (and in fact inspired it in part, as we shall note below), but doesn't go the last mile of completely eliminating the heap where possible. Without explicit no-alias annotations, the semantics of C would allow that in far fewer places than those of Rust in any case.

It should be noted that our project, like most verification projects based on either embedding or code extraction, relies on both an unverified compiler and an unverified embedding tool, effectively making both part of the trusted computing base. SeL4 is a notable exception in this, providing (at lower optimization levels) a direct equivalence proof [11] between the produced

kernel binary and the verified embedded code, thus completely removing the original C code from the trusted computing base.

3 Background

In this section, we give a basic introduction to our source and target languages. We will discuss finer semantic details where needed in Section 4 and Section 6.

3.1 Rust

3.2 Lean

4 Basic Transformation

5 Case Study: Verification of `std::[T]::binary_search`

6 Transformation of Mutable References

7 Case Study: Verification of `fixedbitset`

8 Conclusion and Future Work

I have no idea where to put the complexity analysis

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Erklärung

Hiermit erkläre ich, Sebastian Andreas Ullrich, dass ich die vorliegende Masterarbeit selbstständig verfasst habe und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe, die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht und die Satzung des KIT zur Sicherung guter wissenschaftlicher Praxis beachtet habe.

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