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A Dataflow Approach to Reference Ownership Analysis for the Rust Programming Language

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Title page logo

Abstract

This thesis is about something.

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1. Introduction

Rust is a young systems language originally developed at Mozilla Research [1]. Its stated intention is to combine high-level programming language features like automatic memory management and strong safety guarantees, in particular in the presence of concurrency or parallelism, with predictable performance and pay-as-you-go abstractions in the style of C++ and similar systems languages.

One of its core features is the memory ownership model, which enables compile-time safety guarantees against data races, unsafe pointer dereferencing, and runtime-free automatic memory management, including for dynamic memory allocated on the heap.

This report describes the implementation of Rust's memory safety checker, called the borrow checker, in an embedded Datalog engine, as well as its optimisation.

2. Background

Whenever a reference to a resource is created in Rust, its borrowing rules described in Section 2.1 must be respected for as long as the reference is alive, including across function calls [2]. In order to enforce these rules, the Rust language treats the scope of a reference, called its lifetime, as part of its type, and also provides facilities for the programmer to name and reason about them as they would any other type.

Since its release, the Rust compiler has been extended through proposal RFC 2094 to add support for so-called non-lexical lifetimes (NLLs), allowing the compiler to calculate lifetimes of references based on the control-flow graph rather than the lexical scopes of variables [3]. During the spring of 2018, Nicholas Matsakis began experimenting with a new formulation of the borrow checker, called Polonius, using rules written in Datalog [4]. The intention was to use Datalog to allow for a more advanced analysis while also allowing for better compile-time performance through the advances done centrally to the fixpoint solving provided by the Datalog engine used for the computations [5].

Datalog has been previously employed for program analysis, including in the Soufflé system, which is used to synthesise performant C++ from Datalog specifications, showing promising performance for analysis of large programs [6].

Formally, the semantics of Rust’s lifetime rules has been captured in the language Oxide, described by Weiss, Patterson, Matsakis, *et al.* [7].

2.1 The Borrowing Rules

Most of these examples are borrowed from Weiss, Patterson, Matsakis, *et al.* [7].

Variables must be provably initialised before use Whenever a variable is used, the compiler must be able to tell that it is guaranteed to be initialised:

```
let x: u32;  
let y = x + 1; // ERROR: x is not initialised
```

A move deinitialises a variable Whenever ownership of a variable is passed on (*moved* in Rust parlance), e.g. by a method call or reassignment, the variable becomes deinitialised:

```
struct Point(u32, u32);  
  
let mut pt = Point(6, 9);  
let x = pt;  
let y = pt; // ERROR: pt was already moved to x
```

There can be any number of shared references A reference, also called a *borrow* of a variable, is created with the `&` operator, and there can be any number of references to a variable:

```
struct Point(u32, u32);

let mut pt = Point(6, 9);
let x = &pt;
let y = &pt; // This is fine
```

There can only be one simultaneous live unique reference Whenever a unique reference is created, with `& mut`, it must be unique:

```
struct Point(u32, u32);

let mut pt = Point(6, 9);
let x = &mut pt;
let y = &mut pt; // ERROR: pt is already borrowed

// code that uses x and y
```

This error happens even if the first borrow is shared, but not if either `x` or `y` are dead (not used).

A reference must not outlive its referent A reference must go out of scope at the very latest at the same time as its referent, which protects against use-after-frees:

```
struct Point(u32, u32);

let x = {
    let mut pt = Point(6, 9);
    &pt
};

let z = x.0; // ERROR: pt does not live long enough
```

In this example, we try to set `x` to point to the variable `pt` inside of a block that has gone out of scope before `x` does.

2.2 The Borrow Check in the Rust Compiler

The logic of the borrow check as described in Section 2.3 is calculated at the level of an intermediate representation of Rust called the Mid-Level Intermediate Representation (MIR), corresponding to the basic blocks of program control flow. Describe what this means in terms of desugaring etc?

Describe Prefix Rules

2.3 From Lifetimes to Reference Provenance

As lifetimes are a part of a variable's types, they can be referred to by name like any other type using the syntax `&'lifetime`. In the literature, the terms “region” [4], “(named) lifetime” , and “reference provenance” [7] are all employed. As the section heading suggests, I will use the last one of them, as I believe it best captures the concept.

From a type system perspective, the reference provenance is part of the type of any reference and corresponds to the borrow expressions that might have generated it. For example, if a reference `r` has the type `&'a Point`, `r` is only valid as long as the terms of the loans in `'a` are upheld. Take for example the code of Listing 2.1, where `p` would have the type `&'a i32` where `a` is the set $\{L_0, L_1\}$.

Listing 2.1. An example of a multi-path borrow.

```
let x = vec![1, 2];

let p: &'a i32 = if random() {
    &x[0] // Loan L0
} else {
    &x[1] // Loan L1
};
```

If a reference is used in an assignment like `let p: &'b i32 = &'a x`, the reference, `p`, cannot outlive the assigned value, `x`. More formally the type of the right-hand side, `&'a i32`, must be a subtype of the left-hand side's type; `&'a i32 <: &'b i32`. In practice, this establishes that `'b` lives at most as long as `'a`, which means that the subtyping rules for regions establishes a set membership constraint, as seen in Formula 2.1.

$$\frac{a \subseteq b}{\&'a\ u32 <: \&'b\ u32} \quad (2.1)$$

How to incorporate the fact that this is with respect to the current point?

Finally, when talking about the *liveness* of a reference provenance `r`, we will mean that `r` occurs (what does occurs mean? Does it encompass exploded subset-types etc?) in the type of a variable that is live at some point in the control-flow graph `p`, with the meaning that any of the loans in `r` might be dereferenced at control-flow points reachable from `p`, and thus that the terms of the loans in `r` must be respected.

2.4 Deallocation As a Special Case of Variable Use

describe the difference between drop-uses and normal uses and what is even a drop.

2.5 Datalog

Describe datalog's syntax and execution model.

3. A Borrow Checker in Datalog

3.1 The Borrow Checker in Datalog

3.1.1 Starting Facts

Verify the terminology for this in Datalog parlance!

```
/// `borrow_region(R, B, P)` -- the region R may refer to data
/// from borrow B starting at the point P (this is usually the
/// point *after* a borrow rvalue)
pub borrow_region: Vec<(R, L, P)>,

/// `universal_region(R)` -- this is a "free region" within fn body
pub universal_region: Vec<R>,

/// `cfg_edge(P,Q)` for each edge P -> Q in the control flow
pub cfg_edge: Vec<(P, P)>,

/// `killed(B,P)` when some prefix of the path borrowed at B is assigned
pub killed: Vec<(L, P)>,

/// `outlives(R1, R2, P)` when we require `R1@P: R2@P`
pub outlives: Vec<(R, R, P)>,

/// `invalidates(P, L)` when the loan L is invalidated at point P
pub invalidates: Vec<(P, L)>,

/// `var_used(V, P)` when the variable V is used for anything but a drop
pub var_used: Vec<(V, P)>,

/// `var_defined(V, P)` when the variable V is overwritten by the point
pub var_defined: Vec<(V, P)>,

/// `var_used(V, P)` when the variable V is used in a drop at point P`
pub var_drop_used: Vec<(V, P)>,

/// `var_uses_region(V, R)` when the type of V includes the region R`
pub var_uses_region: Vec<(V, R)>,

/// `var_drops_region(V, R)` when the type of V includes the region R and
/// it when dropping`
pub var_drops_region: Vec<(V, R)>,
```

3.1.2 Reference Liveness

```
var_live(V, P) :-
    var_live(V, Q),
```

```
cfg_edge(P, Q),  
!var_defined(V, P).
```

3.1.3 Loan Constraint Propagation

3.1.4 Loan Violations

3.1.5 Illegal Subset Relations

3.2 A Field Study of Borrow Patterns

3.3 Optimising the Borrow Checker

4. Conclusions and Future Work

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