

Formally Specifying the Rust Core

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Outline

1 Introduction

2 A Developer's Tale

3 Our Solution

4 Results

Acknowledgements



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SIMD and Vector Intrinsics

SIMD stands for Single Instruction, Multiple Data. Vector intrinsics are special functions offered by the compiler, that allow the use of SIMD instructions.

SIMD in Rust

The core::arch crate (the Rust equivalent of a C library) is responsible for exposing these vendor-specific intrinsics that typically correspond to a single machine instruction.

```
// Simple program squares elements in 16 bit chunks.
use core::arch::x86_64::*;
fn main() {
    unsafe {
        let a : __m256i = _mm256_set_epi16
            (0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15);
        let b : __m256i = _mm256_mullo_epi16(a, a);
        println!("{}",&_mm256_extract_epi16::<0>(b));
        println!("{}",&_mm256_extract_epi16::<15>(b));
    }
}
```

Importance

Rust has been finding popular use in new security-critical and performance-sensitive projects, and SIMD vector intrinsics are often used for performance/efficiency in such projects.

- Dalek: Elliptic Curve Cryptography
- Hashbrown
- Libcrux

Rust Docs

Let us imagine ourselves as a Rust developer looking through these intrinsics. Let us say we want to understand the intrinsic "vabdq_s8", in core::arch::aarch64, used for performing an absolute difference.

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The screenshot shows a dark-themed Rust documentation page for the function `vabdq_s8`. At the top, it says `core::arch::aarch64`. Below that is the title **Function `vabdq_s8`** with a copy icon. It indicates the function was added in version 1.59.0 and provides a [Source](#) link. The function signature is shown in a code block: `pub fn vabdq_s8(a: int8x16_t, b: int8x16_t) -> int8x16_t`. A note below the signature states: "Available on (AArch64 or target_arch="arm64ec") and target feature neon only." At the bottom, there is a collapsed section titled "Absolute difference between the arguments Arm's documentation". The footer of the slide includes navigation icons for a presentation.

ARM Docs

Not a great start. The Rust documentation barely explains anything, all it does is link to the ARM documentation. But atleast the ARM docs are nice! There is some pseudocode to accompany it too.

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Documentation String

Signed Absolute Difference. This instruction **subtracts** the elements of the vector of **the second source** SIMD&FP register **from the** corresponding elements of the **first source** SIMD&FP register, places the **absolute values of the results** into a vector, and writes the vector to the **destination** SIMD&FP register.

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```
use core::arch::aarch64::*;

fn main() {
    unsafe {
        let a = vld1q_s8(&(127 as i8) as *const i8);
        let b = vld1q_s8(&(-2 as i8) as *const i8);

        let result = vabdq_s8(a, b);
        let result =
            *(&result as *const int8x16_t
               as *const [i8; 16]);
        println!("{}", result[0])
    }
}
```

A Bug in the Rust Source????

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```
pub fn vabdq_s8(a: int8x16_t, b: int8x16_t) -> int8x16_t {  
    unsafe extern "unadjusted" {  
        ...  
        #[cfg_attr(target_arch = "arm",  
               link_name = "llvm.arm.neon.vabds.v16i8")]  
        fn _vabdq_s8(a: int8x16_t, b: int8x16_t)  
            -> int8x16_t;  
    }  
    unsafe { _vabdq_s8(a, b) }  
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The Rust code seems to use FFI to make a call using LLVM IR! So there's no way the Rust Source is wrong. Frustrated with the hours we spent on this, we sit back and sigh, being done for the day.

The Moral of the Story

Essentially, bad documentation means that even the best Rust programmers need to wade through Intel or ARM assembly documentation (and more!) to understand these intrinsics.

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- HACL-STAR (F^*)
- Jasmin (Easy Crypt)
- s2n-bignum (HOL Light)

The Problem

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Challenge 15

Consequently, we believe there is a strong need for a **consistent, formal, testable** specification of the SIMD intrinsics that can aid Rust developers. Furthermore, we believe that **this specification should be written in a way that can be used to aid formal verification of Rust programs using various proof assistants.**

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Model Generation

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- Built-in
- External
- Defined

Built-In Intrinsics

```
/// Adds two SIMD vectors elementwise.  
///  
/// `T` must be a vector of integers or floats.  
#[rustc_intrinsic]  
#[rustc_nounwind]  
pub unsafe fn simd_add<T>(x: T, y: T) -> T;  
  
/// Subtracts `rhs` from `lhs` elementwise.  
///  
/// `T` must be a vector of integers or floats.  
#[rustc_intrinsic]  
#[rustc_nounwind]  
pub unsafe fn simd_sub<T>(lhs: T, rhs: T) -> T;
```

External Intrinsics

```
#[allow(improper_ctypes)]
unsafe extern "C" {
    #[link_name = "llvm.x86.avx2.phadd.sw"]
    fn phaddsw(a: i16x16, b: i16x16) -> i16x16;
    #[link_name = "llvm.x86.avx2.phsub.sw"]
    fn phsubsw(a: i16x16, b: i16x16) -> i16x16;
    #[link_name = "llvm.x86.avx2.pmadd.ub.sw"]
    fn pmaddubsw(a: u8x32, b: i8x32) -> i16x16;
    #[link_name = "llvm.x86.avx2.mpsadbw"]
    fn mpsadbw(a: u8x32, b: u8x32, imm8: i8) -> u16x16;
}
```

Defined Intrinsics

```
pub const fn _mm256_hsub_epi32(a: __m256i, b: __m256i) -> __m256i {
    let a = a.as_i32x8();
    let b = b.as_i32x8();
    unsafe {
        let even: i32x8 = SIMD_shuffle!(a, b, [0, 2, 8, 10, 4, 6, 12, 14]);
        let odd: i32x8 = SIMD_shuffle!(a, b, [1, 3, 9, 11, 5, 7, 13, 15]);
        SIMD_sub(even, odd).as_m256i()
    }
}
```

```
pub fn _mm256_hsubs_epi16(a: __m256i, b: __m256i) -> __m256i {
    unsafe { transmute(phsubsw(a.as_i16x16(), b.as_i16x16())) }
}
```

Hand-Written Models: Built-In

```
pub fn simd_insert<const N: u32, T: Copy>(x: FunArray<N, T>, idx: u32, val: T) -> FunArray<N, T> {
    FunArray::from_fn(|i| if i == idx { val } else { x[i] })
}
```

```
pub fn simd_extract<const N: u32, T: Clone>(x: FunArray<N, T>, idx: u32) -> T {
    x.get(idx).clone()
}
```

```
pub fn simd_add<const N: u32, T: MachineInteger + Copy>(
    x: FunArray<N, T>,
    y: FunArray<N, T>,
) -> FunArray<N, T> {
    FunArray::from_fn(|i| x[i].wrapping_add(y[i])))
}
```

Hand-Written Models: External

```
use crate::abstractions::{bit::MachineInteger, simd::*};

pub fn phaddw(a: i16x16, b: i16x16) -> i16x16 {
    i16x16::from_fn(|i| {
        if i < 4 {
            a[2 * i].wrapping_add(a[2 * i + 1])
        } else if i < 8 {
            b[2 * (i - 4)].wrapping_add(b[2 * (i - 4) + 1])
        } else if i < 12 {
            a[2 * (i - 4)].wrapping_add(a[2 * (i - 4) + 1])
        } else {
            b[2 * (i - 8)].wrapping_add(b[2 * (i - 8) + 1])
        }
    })
}
```

Generated Models: Defined

```
pub fn _mm256_abs_epi32(a: __m256i) -> __m256i {
    {
        let a = a.as_i32x8();
        let r = SIMD_SELECT(SIMD_LT(a, i32x8::ZERO()), SIMD_NEG(a), a);
        transmute(r)
    }
}
```

```
pub fn _mm256_hadd_epi16(a: __m256i, b: __m256i) -> __m256i {
    {
        transmute(phaddw(a.as_i16x16(), b.as_i16x16()))
    }
}
```

Testing!

```
mk!([100]_mm256_srls_epi16{<0>, <1>, <2>, <3>, <4>, <5>, <6>};  
mk!([100]_mm256_srls_epi32{<0>, <1>, <2>, <3>, <4>, <5>, <6>};  
mk!([100]_mm256_srls_epi64{<0>, <1>, <2>, <3>, <4>, <5>, <6>};  
mk!(_mm_srlv_epi32(a: BitVec, count: BitVec));  
mk!(_mm256_srlv_epi32(a: BitVec, count: BitVec));
```

Acceptance of Solution by AWS

Testable Models for SIMD Intrinsics #423

I Merged tautschning merged 8 commits into `model-checking:main` from `cryspen:main` ⏺ on Sep 25

Conversation 19 Commits 8 Checks 27 Files changed 34

 karthikbhargavan commented on Jul 25 • edited

Solution to challenge 15, resolves #173.

This PR provides testable models for `core::arch` intrinsics, including abstractions to streamline the process of implementing these intrinsics and their tests.

Currently there are 384 x86 intrinsics modelled, and 181 aarch64 intrinsics modelled.

Finding a Bug in Rust

A screenshot of a GitHub pull request page. The title of the pull request is "Fix in erroneous implementation of _mm256_bsrl1_epi128 #1823". A purple button indicates it is "Merged". Below the title, it shows "Amanieu merged 9 commits into rust-lang:master from satiscugcat:master" 2 weeks ago. The pull request has 12 conversations, 9 commits, 62 checks, and 2 files changed. A comment from user "satiscugcat" states: "This fixes the error mentioned in issue #1822". On the right side, there are sections for "Reviewers" (bjorn3, sayantn) and "Assignees". The bottom of the page features standard GitHub navigation icons.

Future Work

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- We do not provide models for intrinsics that **mutate** values. This is also a line of further work.

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- Currently, we only have models for intrinsics that operate on integers. We would like to extend our approach to **floating point numbers**.
- We do not provide models for intrinsics that **mutate** values. This is also a line of further work.
- Our methodology efficiently models Rust intrinsics, but **does not discover bugs**.

Concluding

That is all. Thank you for coming to my talk! I hope it was somewhat informative. If you want to get in contact with CRYSPEN, you can do so via the website. You can find the content of this talk at satiscugcat/fsttcs-presentations. Finally, at IIT Gandhinagar, I am organising a student group for PL work called **\AMBDA**. If that sounds interesting to you and you want to be involved/collaborate, please do reach out!