RefinedRust

A Type System for High-Assurance Verification of Rust Programs

PLDI 2024, Copenhagen

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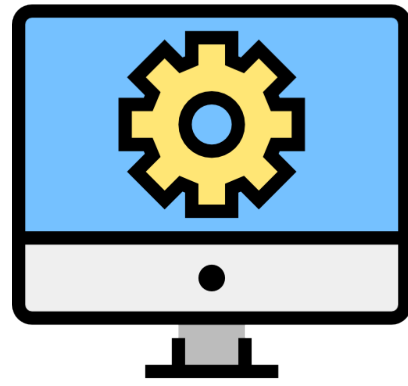
RUST IS AN EXCITING LANGUAGE



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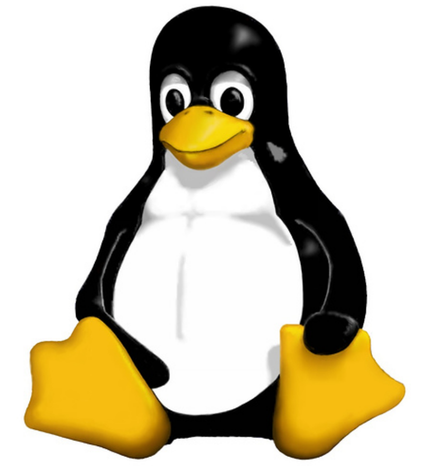
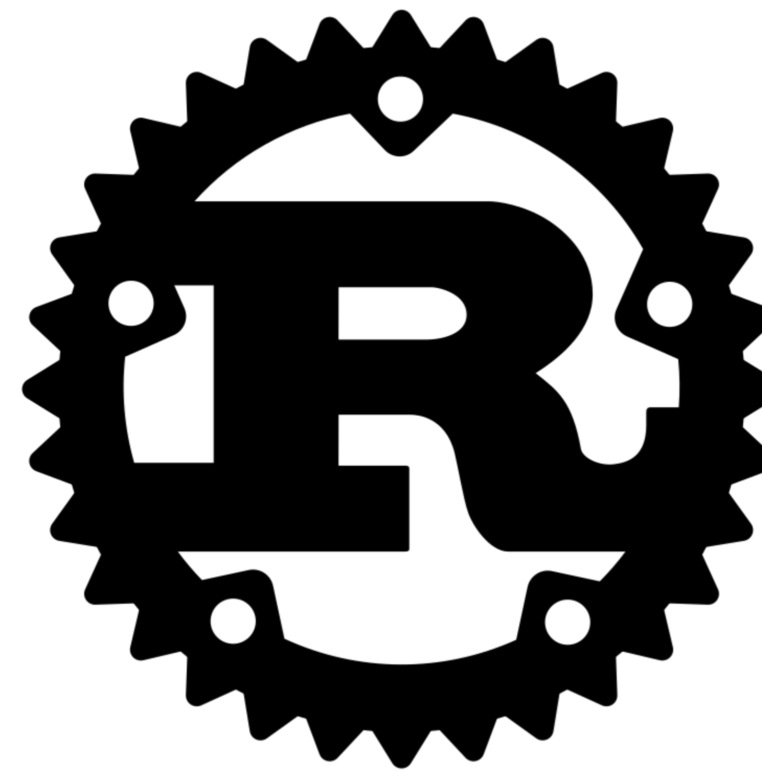
Systems programming
with zero-cost abstractions
for memory management

Growing ecosystem and
increasing popularity





Brings modern programming paradigms
to systems programming

```
x.iter().map(|x| x + 2).collect()
```

Aims to provide **memory safety for free**(*):

- no null-pointer accesses
- no use-after-free
- no data races
- …

(*) not for unsafe code

EXISTING RUST VERIFICATION TOOLS

We want to verify Rust programs!

Creusot [Denis et al. 2022]

Flux [Lehmann et al. 2023]

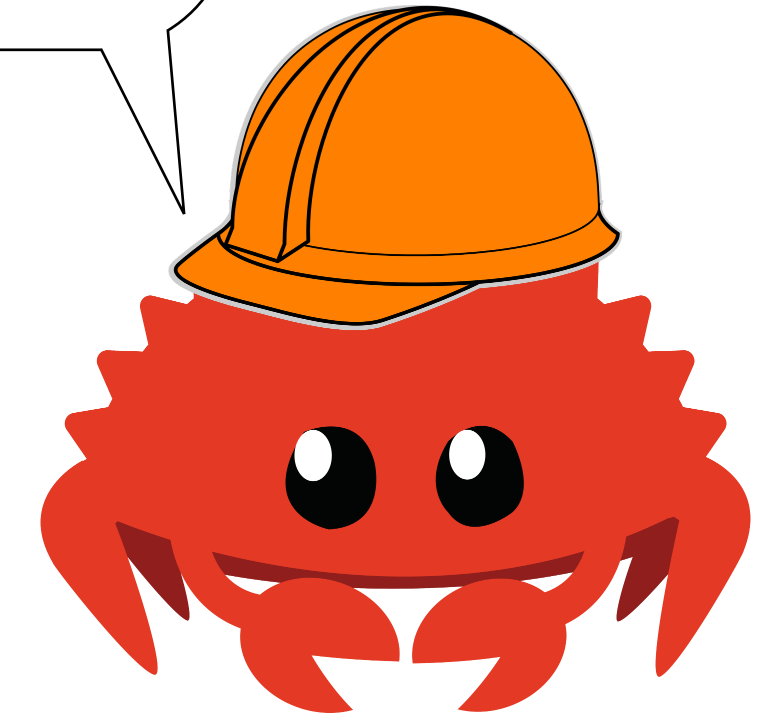
Aeneas [Ho et al. 2022]

RustHorn [Matsushita et al. 2020]

Prusti [Astrauskas et al. 2019]

Verus [Lattuada et al. 2023]

But what about unsafe Rust?



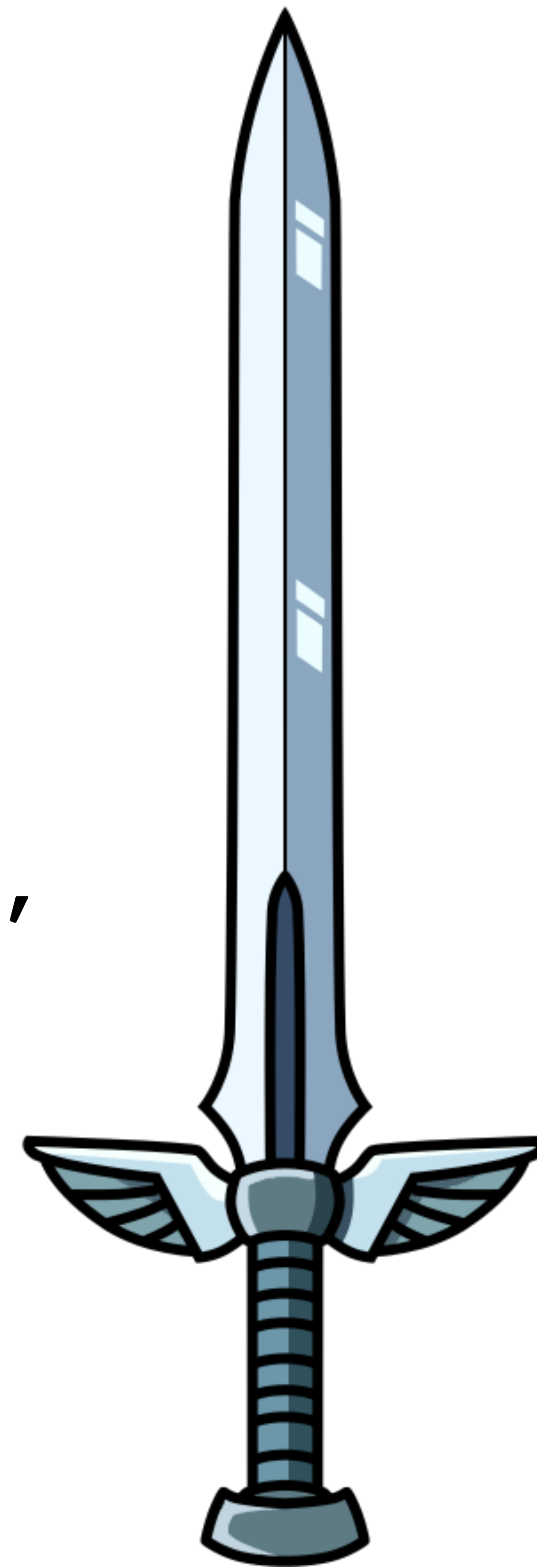
UNSAFE RUST IS A DOUBLE-EDGED SWORD

Unsafe Rust enables C-style raw **pointer manipulation**, but is **not guaranteed to be memory-safe**

Unsafe Rust **is crucial to the success of Rust** as it underlies some of the most **widely-used** Rust code, e.g. in `Vec`

```
unsafe {
    ptr::write(self.ptr().add(self.len),
        elem);
}
```

unchecked pointer arithmetic



Unsafe Rust is inherently **less well-behaved,** making **verification more complicated:**

- custom **ownership reasoning**
- an **accurate memory model**

INTRODUCING REFINEDRUST

RefinedRust is the first system that:

- verifies functional correctness of **both safe and unsafe** Rust code
- and generates **foundational proofs** in the Coq proof assistant

OUR APPROACH: TURNING RUSTBELT INTO A VERIFICATION TOOL

RustBelt [Jung et al., POPL 2018]

a semantic model for Rust

➔ handles Rust's reference types
➔ (manually) reason about safe encapsulation of unsafe code

+

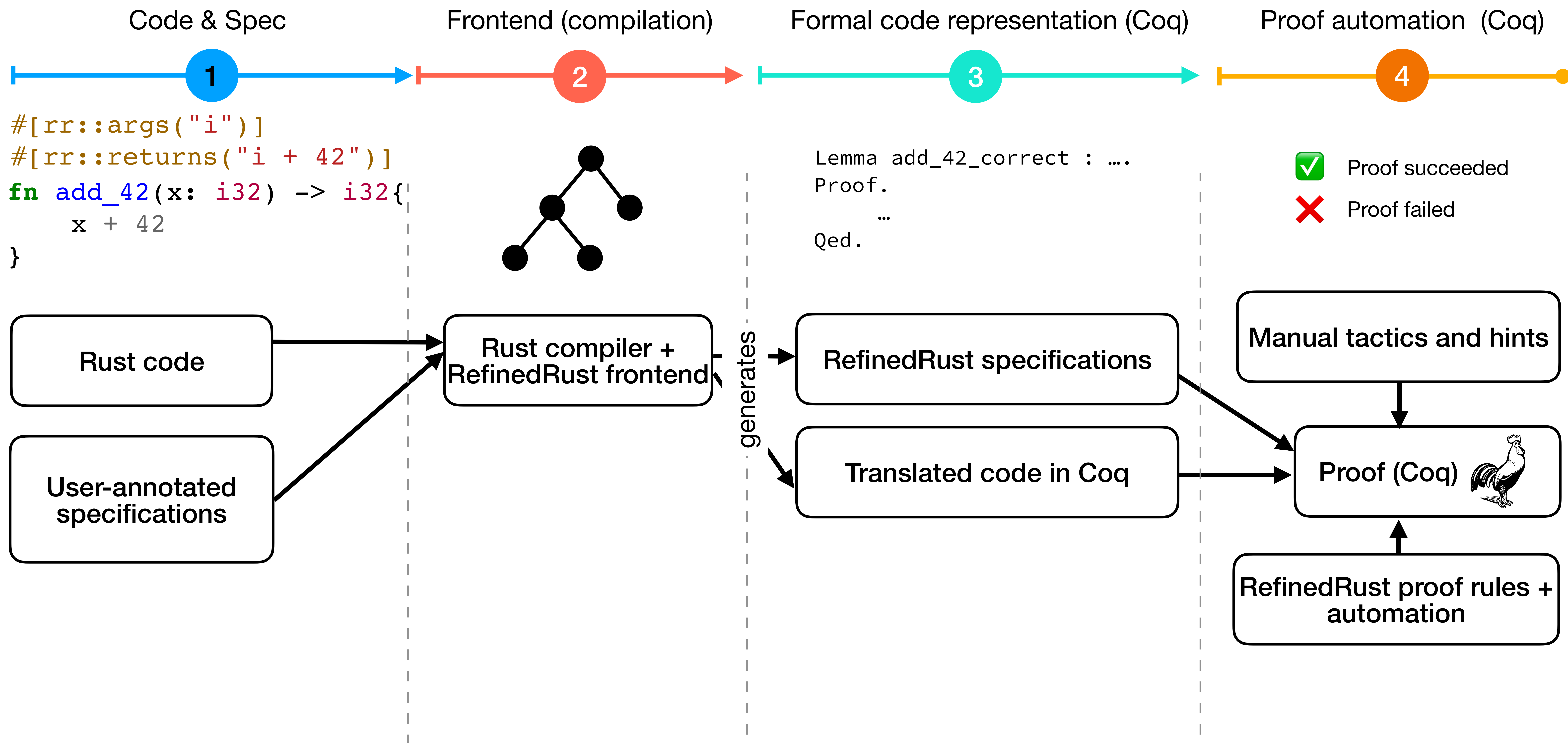
RefinedC [Sammler et al., PLDI 2021]

an ownership-based refinement type system for C

➔ refinement types for functional correctness reasoning
➔ ownership types to handle C code
➔ Lithium: separation logic automation

incompatible ownership systems, RefinedC-style refinements don't work for Rust

THE REFINEDRUST ARCHITECTURE



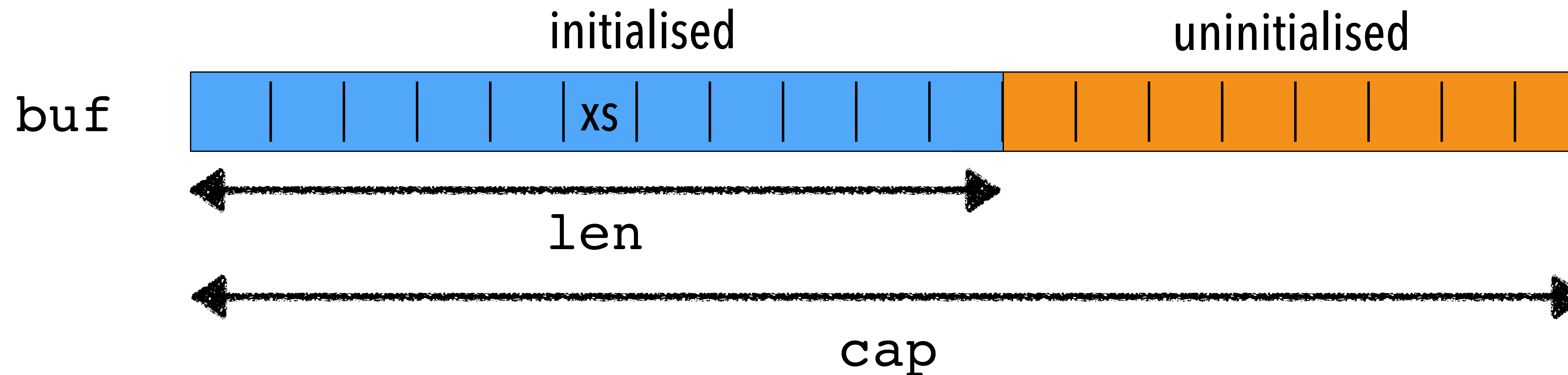
VERIFYING SAFE RUST CODE

```
/// Add 42 to the argument x and return the result.
#[rr::params("i" : "Z")]
#[rr::args("i")]
#[rr::requires("(i + 42) ∈ i32")]
#[rr::returns("i + 42")]
fn add_42(x: i32) -> i32 {
    x + 42
}
```

VERIFYING UNSAFE CODE WITH REFINEDRUST

VERIFYING VEC: MEMORY REPRESENTATION

```rust
pub struct Vec<T> {
    buf: *const T,
    len: usize,
    cap: usize,
}
```



First task: define **representation invariant** of `Vec`

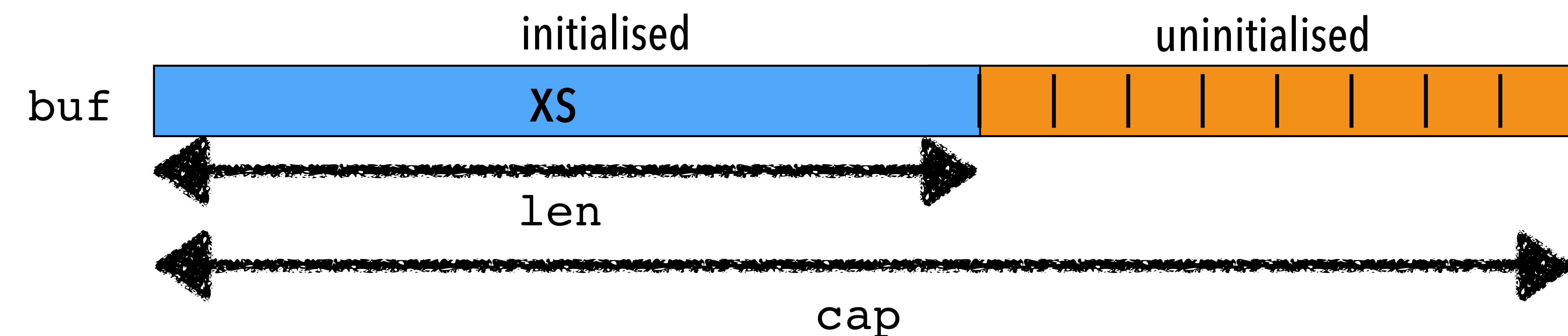
`Vec` just exposes the list `xs` of its initialised elements

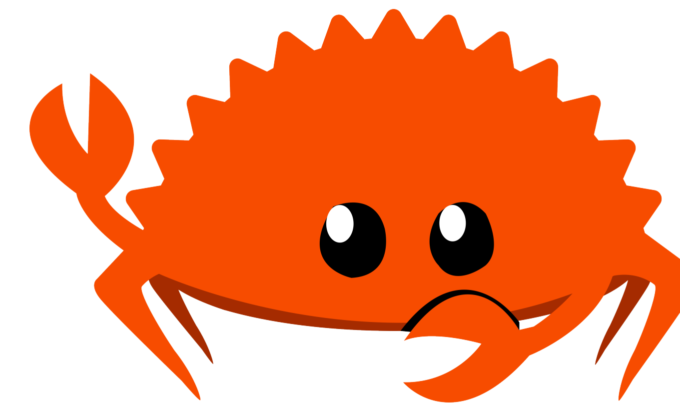
CUSTOM REPRESENTATION INVARIANTS

`Vec` just exposes the list `xs` of its initialised elements

```
#[rr::refined_by("xs" : "list (bor T)")]
#[rr::exists("cap", "len", "l", "els")]
#[rr::invariant(#type "l" : "els" @ "array_t (maybe_init T) cap")]
#[rr::invariant("∀ i, 0 ≤ i < len → els[i] = #(Some (xs[i]))")]
#[rr::invariant("∀ i, len ≤ i < cap → els[i] = #None")]
#[rr::invariant("len = length xs", "len ≤ cap")]
#[rr::invariant("size_of_array_in_bytes {st_of T} cap ≤ max_int isize_t")]
pub struct Vec<T> {
    #[rr::field("l")]
    buf: *const T,
    #[rr::field("len")]
    len: usize,
    #[rr::field("cap")]
    cap: usize,
}
```

Asserts **exclusive ownership**!





VERIFYING GET_MUT

```
#[rr::params("xs", "i"      )]
#[rr::args("(#(<#> xs)     )", "i")]
#[rr::requires("0 ≤ i < length xs")]
#[rr::exists("γi")]
#[rr::returns("(#(xs[i])     )")]
#[rr::resolve("γ": "(<#> xs)[i := *γi]")]
pub unsafe fn get_unchecked_mut(&mut self, index: usize) -> &mut T {
    unsafe {
        let p = self.ptr().add(index);
        let ret = &mut *p;
        ret
    }
}
```

"Return a mutable reference to the element of `self` at the given `index`"

Problem: how does the vector get changed if the i-th element is modified through the reference?

Borrow names **γ** communicate final values of references

How does this uphold the representation invariant of `Vec`? (ownership temporarily moved out)!

PRELIMINARY EVALUATION

We verified most of the Vec Rustonomicon implementation:

	Rust LOC	Translated LOC	Sideconds	Spec + manual proof	Verification time
Vec::new	6	8	23	1 + 0	18s
Vec::push	9	78	215	5 + 38	5min 12s
Vec::pop	8	56	121	4 + 17	2min 30s
Vec::get_unchecked_mut	7	32	69	6 + 11	2min
Vec::get_mut	8	49	108	7 + 29	1min 05s
Vec::get_unchecked	7	28	53	4 + 3	46s
Vec::get	8	49	93	3 + 0	48s
Total (RawVec + Vec)	**120 (14 functions)**	**950**	**>700**	**75 + 105**	**<6min (wall)**

(with ~80 lines of common manually proved Coq theory about lists)

Results:

- We can get a **good degree of automation in most cases**, but pure side conditions sometimes need help
- RefinedRust is **slower than tools for safe Rust code** (due to Coq, complex reasoning about unsafe)

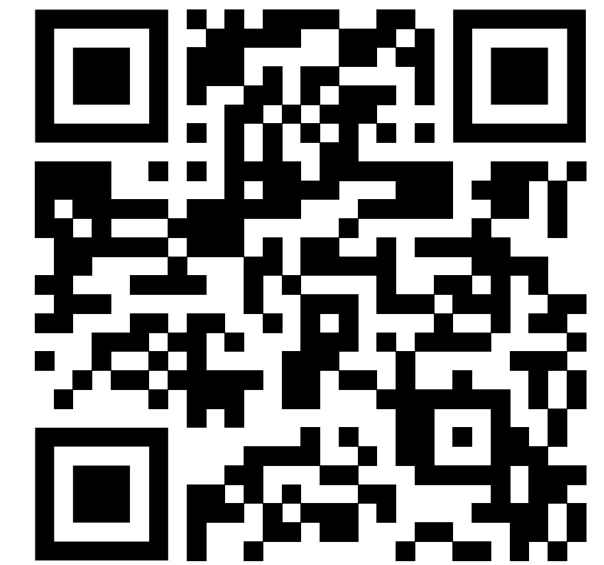
ONGOING WORK: SCALING UP REFINEDRUST

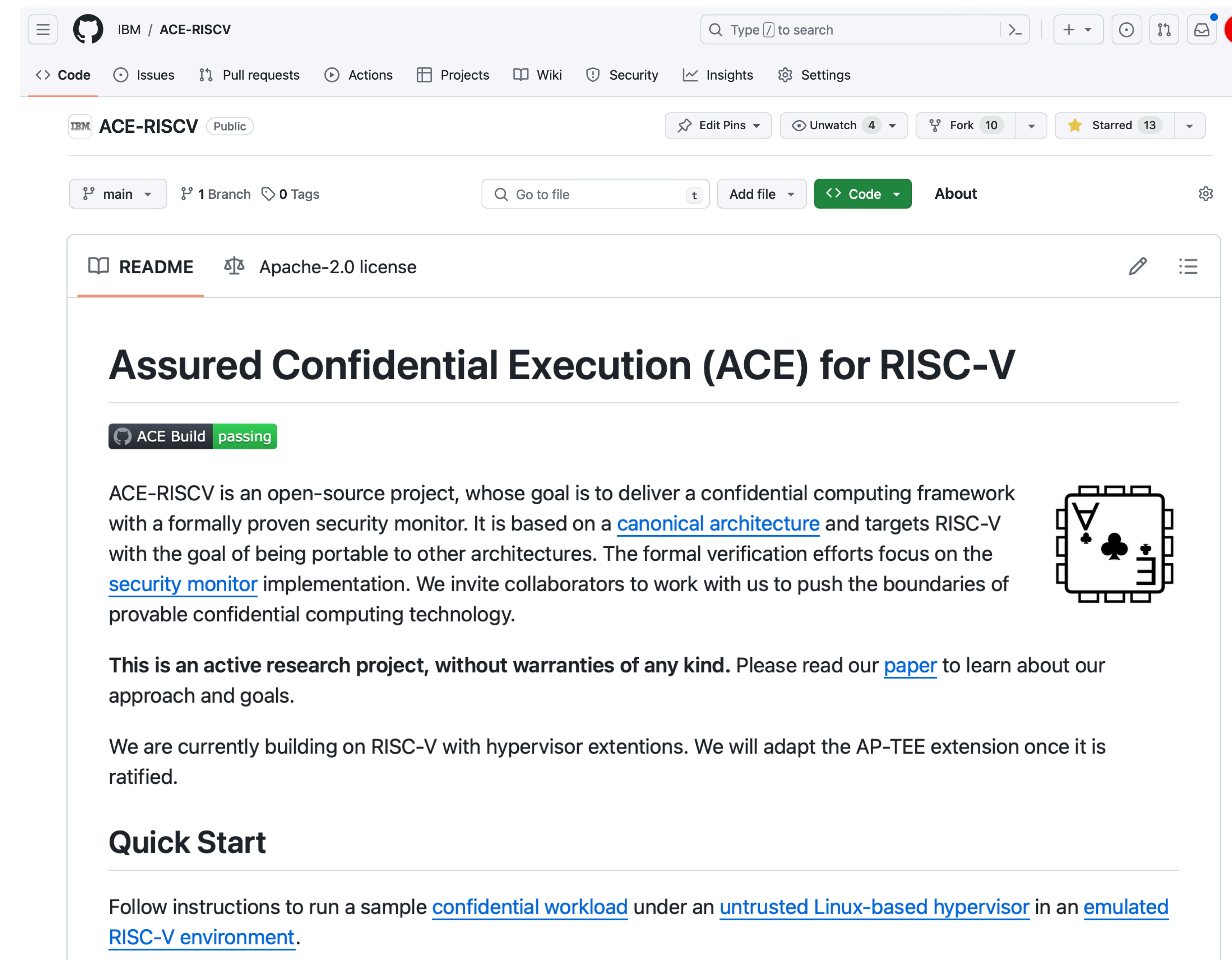
- Adding interior mutability (with Vincent Lafeychine)

- Making RefinedRust more practical & scalable
- Trying to verify memory safety & security of a practical security monitor implementation

(with IBM Research: Wojciech Ozga, Avi Shinnar, Elaine Palmer, Michael Le, Guerney Hunt, Silvio Dragone)

https://github.com/
IBM/ACE-RISCV





Confidential VM Extension (CoVE) for Confidential Computing

Version 0.6, 4/2024: This document is under development. Expect potential changes. Visit http://riscv.org/spec-state for further details.

REFINEDRUST: WHAT ELSE IS IN THE PAPER

Place types to capture intermediate states of the Rust type system
➔ enabled by a novel extension of RustBelt's lifetime logic with "pinned borrows"

Borrow variables to communicate value updates of Rust's mutable references
➔ inspired by RustHornBelt's prophecy variables [Matsushita et al., PLDI 2022]

Syntactic types to enable layout-generic proofs
➔ verification is parameterised by the Rust layout algorithm

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HOW TO CAPTURE INTERMEDIATE STATES OF THE TYPE SYSTEM?

```
let x: (i32, i32) = (1, 2);

let xr: &'a mut i32 = &mut x.0;

*xr = 42;

assert!(x.0 == 42);
```

What is the type assignment of x here?
We need to track that the first component is borrowed…

x.0 is inaccessible, as it is borrowed for lifetime 'a

Key idea: Use **place types** to describe intermediate states of the Rust type system
(e.g. induced by the borrow checker)

PLACE TYPES DESCRIBE INTERMEDIATE STATES OF THE TYPE SYSTEM

type assignment

```
let x: (i32, i32) = (1, 2);
  { x ◁ place (i32, i32) }
let xr: &mut i32 = &mut x.0;
 { xr ◁ place (&mut 'a i32) *
   x ◁ (blocked 'a i32, place i32) }
*xr = 42;
 { xr ◁ place (&mut 'a i32) *
   x ◁ (blocked 'a i32, place i32) }
assert!(x.0 == 42);
 { x ◁ place (i32, i32)}
```

x is a stack variable containing a tuple

The first component of x is inaccessible until the reference's lifetime ‘ a ends

‘ a implicitly ends

Once ‘ a ends, x is fully accessible again

(omitting refinements)

PLACE TYPES

Place types also help us to describe the **intermediate states in unsafe cases** the Rust type system does not support!

```
pub unsafe fn get_unchecked_mut(&mut self, index: usize) -> &mut T {
    unsafe {
        let p = self.ptr().mut_add(index);
        let ret = &mut *p;
        ret
    }
}
```

…and place types are also used to **describe unfolded invariants on datatypes** (see the paper for details)

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