Verus github.com/verus-lang/verus

Verified Rust for low-level systems code

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Why Verus?

Verification of systems software

to have strong correctness guarantees

- increase software reliability
- avoid data loss, unavailability, bad consequences

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Practical verification for systems software

- use verification in development process
- make the verified artifact maintainable

Tests in Rust

```rust
fn max(a: u64, b: u64) -> u64 {
    if a >= b { a } else { b }
}
```

```rust
fn max_test_1() {
    let x = 4;
    let y = 4;
    let ret = max(x, y);
    assert!(ret == 4);
}

fn max_test_2() {
    let x = 4;
    let y = 3;
    let ret = max(x, y);
    assert_eq!(ret, 4);
}
```

```rust
fn max_test_3() {
    let x = 4;
    let y = 3;
    let ret = max(x, y);
    assert!(ret == x || ret == y);
    assert!(ret >= x && ret >= y);
}

fn main() {
    max_test_1();
    // max_test_2();
    max_test_3();
    println!("success");
}
```

Static check (verification) in Verus

```
use vstd::prelude::*;

verus! {

fn max(a: u64, b: u64) -> (ret: u64)
    ensures
        ret == a || ret == b,
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}
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Languages for systems software verification

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Rust is efficient
and predictable (like C)

imperative, no GC, in-place
mutation, zero-cost abstractions,
low-level operations (unsafe)

Why Verus?

Languages for systems software verification

(Safe) Rust is close to a functional programming language

ADTs, pattern matching, restricted side-effects

Rust is efficient and predictable (like C)

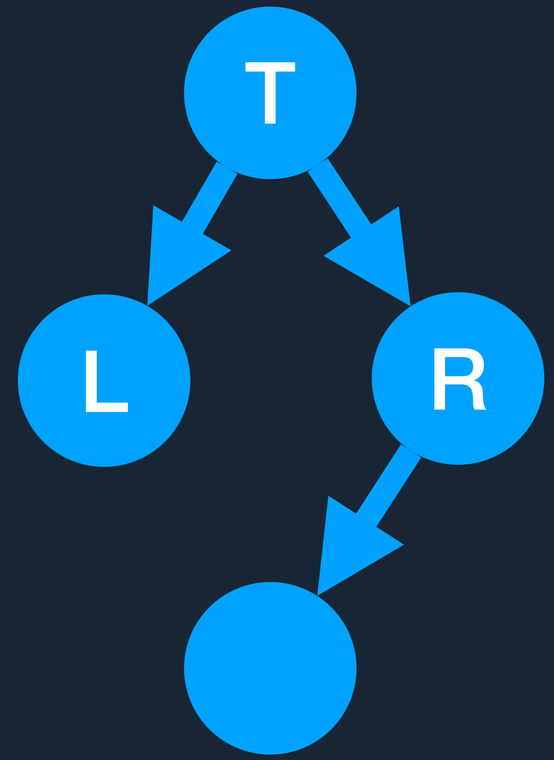
imperative, no GC, in-place mutation, zero-cost abstractions, low-level operations (unsafe)

Why Rust?

Rust enforces single ownership by default

Rust's "linear type system"

```
struct Node {
  left: Option<Box<Node>>,
  right: Option<Box<Node>>,
  value: u64,
}
```



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fn bad(mut tree: Node) -> Option<()> {
    // ...
    tree.left.as_mut()?.right = tree.right.as_mut()?.left;
    // ...
}
```

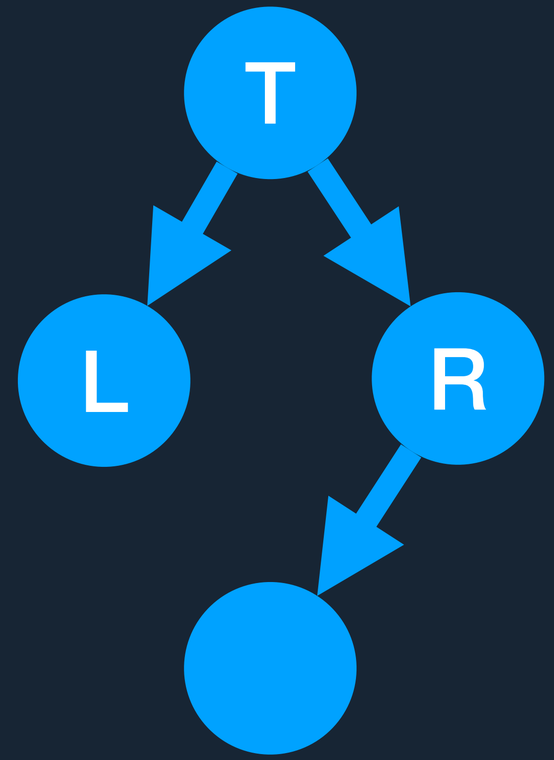

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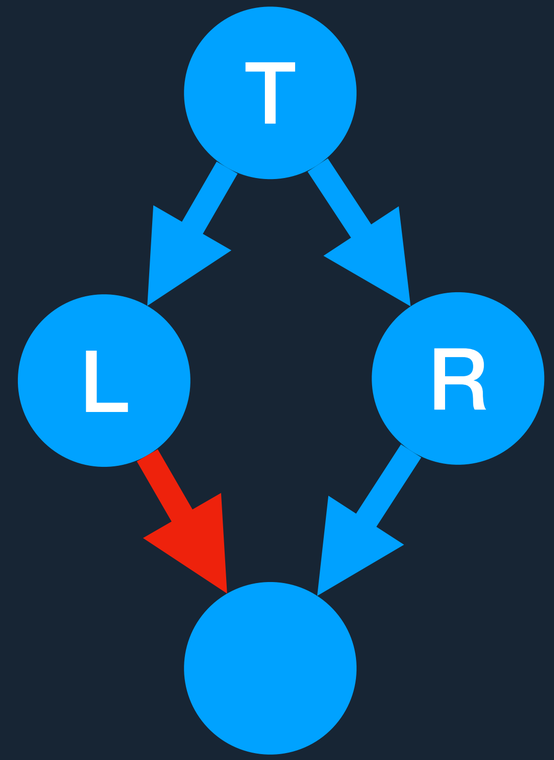

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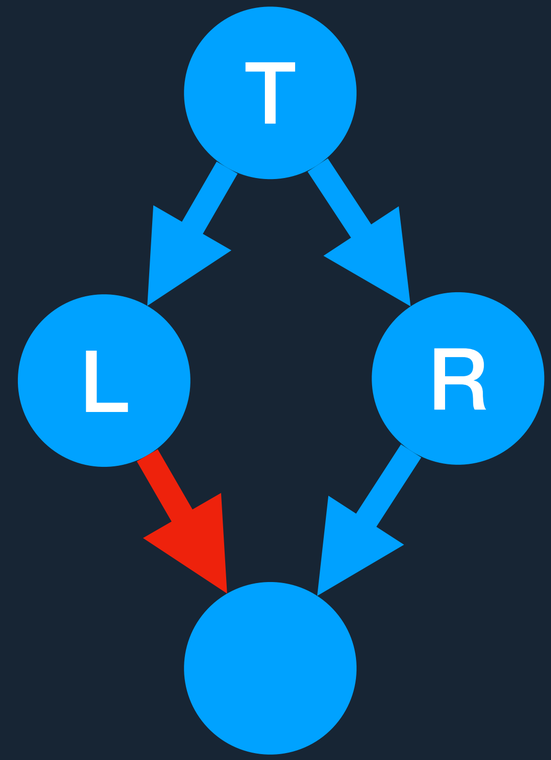


```
error[E0507]: cannot move out of a mutable reference
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Rust's *linear* type system

tracks ownership, prevents aliased mutable references

- no data races
- no use-after-free

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Aliasing is a challenge in functional verification

- requires explicit handling of the heap
- → rely on Rust's linear type system instead

Why Rust?

https://doi.org/10.1145/3360573

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Leveraging Rust Types for Modular Specification and Verification

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FEDERICO POLI, ETH Zurich, Switzerland
ALEXANDER J. SUMMERS, ETH Zurich, Switzerland

Aliasing is a challenge in functional verification
requires explicit handling of the heap
→ rely on Rust's linear type system instead

Rust prevents aliased mutable references

```
pub struct Account { pub balance: u64 }

pub fn transfer(orig: &mut Account, dest: &mut Account, amount: u64)
  // requires
  //   old(orig).balance >= amount, ...
  // ensures
  //   dest.balance == old(dest).balance + amount,
  //   orig.balance == old(orig).balance - amount
{
  orig.balance = orig.balance - amount;
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}
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unique mutable references

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unique mutable references

only true if `orig` and `dest` are not aliases

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  // requires
  //   old(orig).balance >= amount,
  // ensures
  //   dest.balance == old(dest).balance + amount,
  //   orig.balance == old(orig).balance - amount
{
  orig.balance = orig.balance - amount;
  dest.balance = dest.balance + amount;
}

fn main(mut account: Account)
  // requires account.balance >= 100
{
  let mut account = account;
  transfer(&mut account, &mut account, 100);
}
```

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pub struct Account { pub balance: u64 }

pub fn transfer(orig: &mut Account, dest: &mut Account, amount: u64)
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unique mutable references

only true if `orig` and `dest` are not aliases

```
error[E0499]: cannot borrow `account` as mutable more than once at a time
fn main(mut account: Account)
  // requires account.balance >= 100
{
  let mut account = account;
  transfer(&mut account, &mut account, 100);
  --------- ------------  ^^^^^^^^^^^^ second mutable borrow occurs here
  |         |
  |         first mutable borrow occurs here
  first borrow later used by call
```

Rust prevents aliased mutable references

```
pub struct Account { pub balance: u64 }

pub fn transfer(orig: &mut Account, dest: &mut Account, amount: u64)
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Dafny

imperative language, GC, ~C#,
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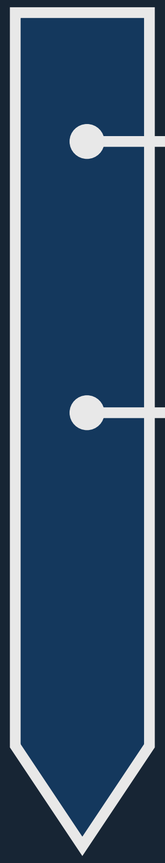

Dafny

imperative language, GC, ~C#,
integrated verification

Linear Dafny

linear type system for Dafny,
(some) deterministic memory management

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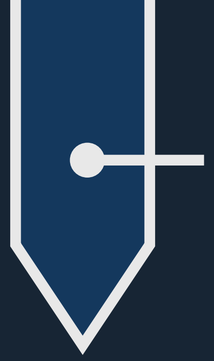
Rust?

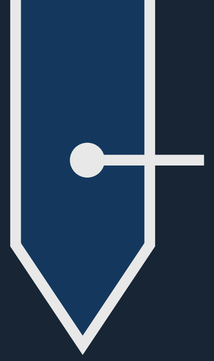


Verus

SMT-based, intrinsic verification of safe[1] Rust[2] code

[1]can do some “unsafe”

[2]a dialect of Rust



Verus

SMT-based, intrinsic verification of safe[1] Rust[2] code

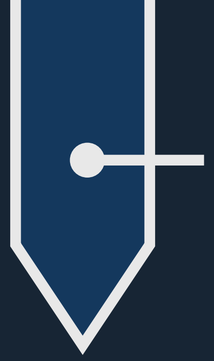
[1]can do some “unsafe”
[2]a dialect of Rust

each function has a Hoare logic specification

Intrinsic verification

```
pub exec fn transfer(orig: &mut Account, dest: &mut Account, amount: u64)
  requires
    old(orig).balance >= amount,
    old(dest).balance + amount < u64::MAX,
  ensures
    dest.balance == old(dest).balance + amount,
    orig.balance == old(orig).balance - amount
{
  orig.balance = orig.balance - amount;
  dest.balance = dest.balance + amount;
}
```

Hoare logic specification



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SAT Boolean satisfiability problem

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```
(x || y) && (!x || y) && (!x)
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∃ x, y :: (x || y) && (!x || y) && (!x)
```

z3

```
x == false
y == true
```

SAT Boolean satisfiability problem

is there an assignment to variables to a boolean formula such that it’s is true

SMT Satisfiability Modulo Theories

generalizes SAT to more complex formulas

real numbers, integers, and/or various data structures,

quantifiers: $\forall, \exists$

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∀a, b :: a * b == b * a

SMT-based verification

```
fn max(a: u64, b: u64) -> (ret: u64)
    ensures
        ret == a || ret == b,
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{
    if a >= b { a } else { b }
}

#[test]
fn max_test() {
    let x = 4;
    let y = 3;
    let ret = max(x, y);
    assert!(ret == x || ret == y);
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}
```

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$!\ \exists$ a,b $!$

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↓ z3

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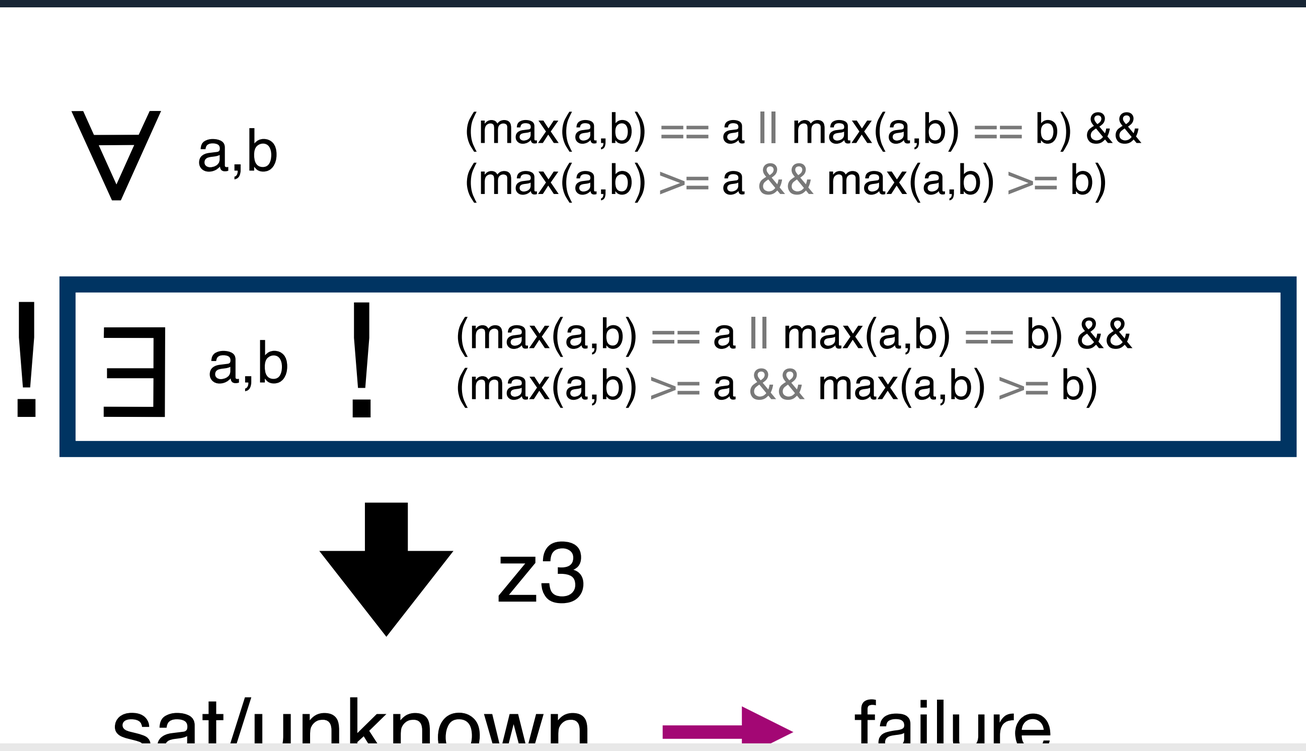
#[test]
fn max_test() {
    let x = 4;
    let y = 3;
    let ret = max(x, y);
    assert(ret == 4 && ret >= y);
}
```

∀ a,b



Verus prioritizes efficient encoding to SMT “queries”

- verification performance

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Verifying code with Verus

```
spec fn fibo(n: nat) -> nat
    decreases n
{
    if n == 0 { 0 } else if n == 1 { 1 }
    else { fibo((n - 2) as nat) + fibo((n - 1) as nat) }
}

spec fn fibo_fits_u64(n: nat) -> bool {
    fibo(n) <= 0xffff_ffff_ffff_ffff
}

proof fn lemma_fibo_is_monotonic(i: nat, j: nat)
    requires i <= j,
    ensures fibo(i) <= fibo(j),
    decreases j - i
{
   if i < 2 && j < 2 {
   } else if i == j {
   } else if i == j - 1 {
       reveal_with_fuel(fibo, 2);
       lemma_fibo_is_monotonic(i, (j - 1) as nat);
   } else {
       lemma_fibo_is_monotonic(i, (j - 1) as nat);
       lemma_fibo_is_monotonic(i, (j - 2) as nat);
   }
}
```

```
exec fn fibo_impl(n: u64) -> (result: u64)
    requires fibo_fits_u64(n as nat),
    ensures result == fibo(n as nat),
{
    if n == 0 {
        return 0;
    }
    let mut prev: u64 = 0;
    let mut cur: u64 = 1;
    let mut i: u64 = 1;
    while i < n
        invariant
            0 < i <= n,
            fibo_fits_u64(n as nat), fibo_fits_u64(i as nat),
            cur == fibo(i as nat),
            prev == fibo((i - 1) as nat),
    {
        i = i + 1;
        proof {
            lemma_fibo_is_monotonic(i as nat, n as nat);
        }
        let new_cur = cur + prev;
        prev = cur;
        cur = new_cur;
    }
    cur
}
```

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spec fn fibo_fits_u64(n: nat) -> bool {
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proof fn lemma_fibo_is_monotonic(i: nat, j: nat)
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   } else {
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```
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    if n == 0 {
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    let mut i: u64 = 1;
    while i < n
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            cur == fibo(i as nat),
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    {
        i = i + 1;
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exec mode

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proof mode exec mode

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spec mode proof mode exec mode

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ghost **spec mode**

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        lemma_fibo_is_monotonic(i, (j - 2) as nat);
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```

exec mode

```
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    requires fibo_fits_u64(n as nat),
    ensures result == fibo(n as nat),
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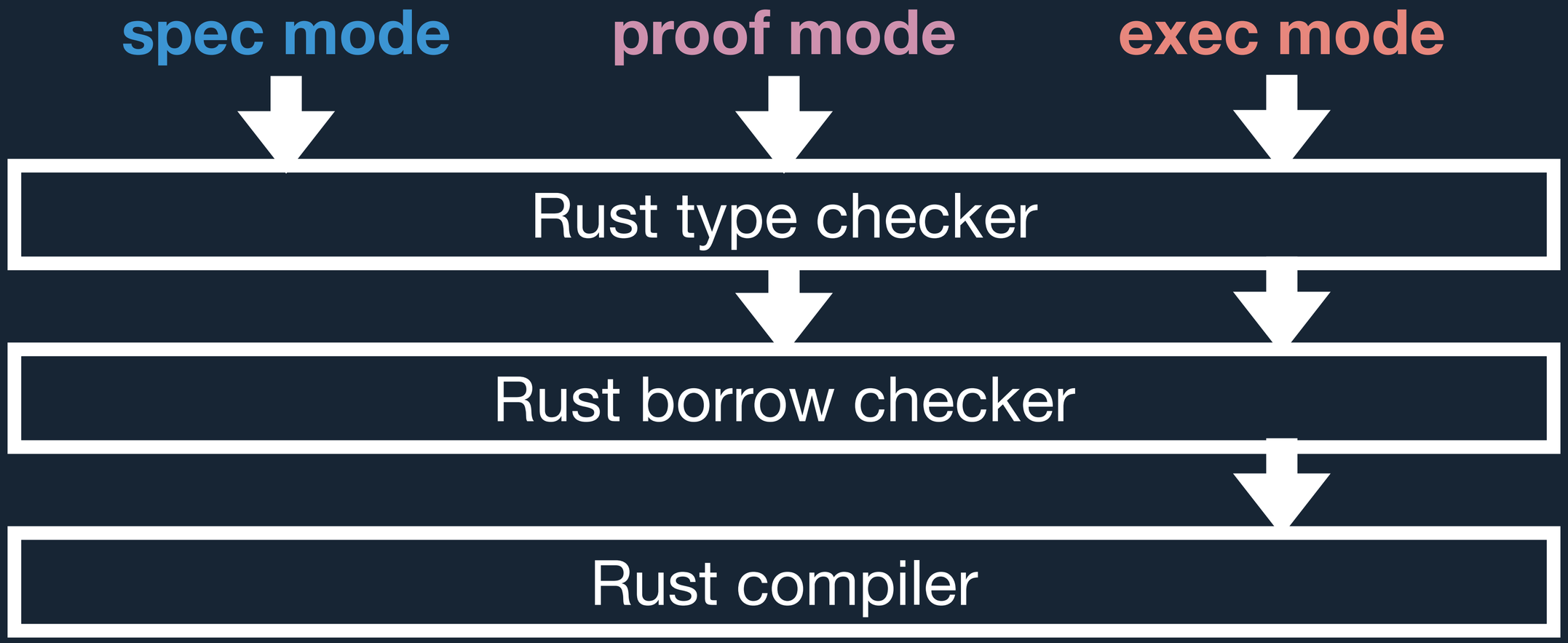
```


spec mode
proof mode
exec mode
Rust type checker
Rust borrow checker
Rust compiler

Verus relies on Rust's type system
but allows going beyond what Rust supports (without UB! 😬)

Rust allows `unsafe` code to break out of linearity

- regular Rust makes assumptions about `unsafe`
- Verus allows access to primitives
  memory- and thread-safe when combined with proof obligations

Verus relies on Rust's type system but allows going beyond what Rust supports (without UB! 😬)

```
#[verifier(external_body)]
proof fn transfer_permission(tracked p: PointsTo<u64>) { /* ... */ }

#[verifier(external_body)]
fn store_copy_of_pointer(p: PPtr<u64>) { /* ... */ }

fn main() {
  let (pptr, Tracked(mut perm)): (PPtr<u64>, Tracked<PointsTo<u64>>) =
    PPtr::<u64>::empty();

  store_copy_of_pointer(pptr.clone());
  assert(perm@.value == Option::None);
  pptr.put(Tracked(&mut perm), 5);
  assert(perm@.value == Option::Some(5));

  proof { transfer_permission(perm); }
  pptr.take(Tracked(&mut perm));
}
```

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like a *mut u64

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like a *mut u64

like *pptr = 5;

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  proof { transfer_permission(perm); }
  pptr.take(Tracked(&mut perm));
}
```

like a *mut u64

like *pptr = 5;

like *pptr = ptr::null();

Verus relies on Rust's type system but allows going beyond what Rust supports (without UB! 😬)

```
#[verifier(external_body)]
proof fn transfer_permission(tracked p: PointsTo<u64>) { /* ... */ }

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  proof { transfer_permission(perm); }
  pptr.take(Tracked(&mut perm));
}
```

like a *mut u64

```
error: borrow of moved value: `perm`
  --> pptr_verus_edit.rs:12:22
   |
12 |   let (pptr, Tracked(mut perm)): (PPtr<u64>, Tracked<PointsT
   |                      ^^^^^^^^
...
21 |   proof { transfer_permission(perm); }
   |                               ^^^^
22 |
23 |   pptr.take(Tracked(&mut perm));
   |                     ^^^^^^^^^
```

Verus relies on Rust's type system but allows going beyond what Rust supports using proof mode

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Verus relies on Rust's type system but allows going beyond what Rust supports using ghost proof mode

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Verus as a pragmatic “toolbox” for verification

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efficient encoding to SMT queries ▶ verification performance

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custom solvers for sytems problems

- non-linear arithmetic
- bit-vector reasoning

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- by encoding many proof obligations in the Rust type system

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```
proof fn div_is_smaller(x: nat, y: nat)
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    requires
        y != 0
    ensures
        divide(x, y) <= x,
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}
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}

fn mod8_bw(x: u32) -> (ret: u32)
    ensures
        ret == x % 8,
{
    assert(x & 7 == x % 8) by (bit_vector);
    x & 7
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```

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scale up verification to real-world systems

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“proving” Verus with systems projects

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- Kubernetes controllers [UIUC, VMware]

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- kernel page-table code / OS verification [ETH, VMware, UBC]
  [Matthias Brun et al.; hotOS’23]
  https://andrea.lattuada.me/assets/hotos23-beyond-isolation.pdf

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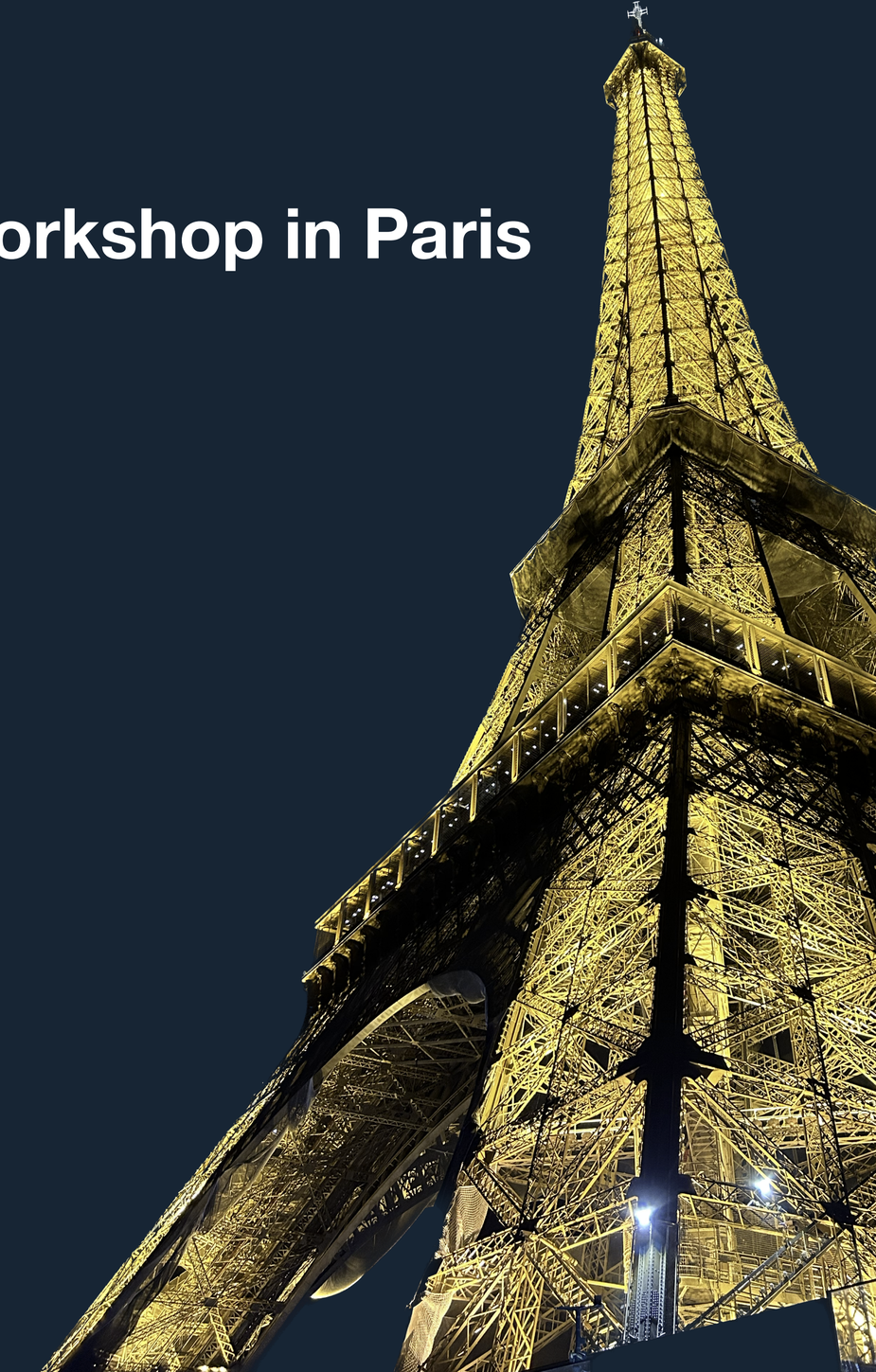
- (more to come) [VMware, MSR, CMU, ETH, …]

Ghost code in rustc

from discussions at the Rust Verification Workshop in Paris

- Verus ported to unmodified rust
- Compiler doesn't understand **ghost code**

▶ Collaborative effort to add ghost code
to the rust compiler
(with Xavier Denis, and many others)



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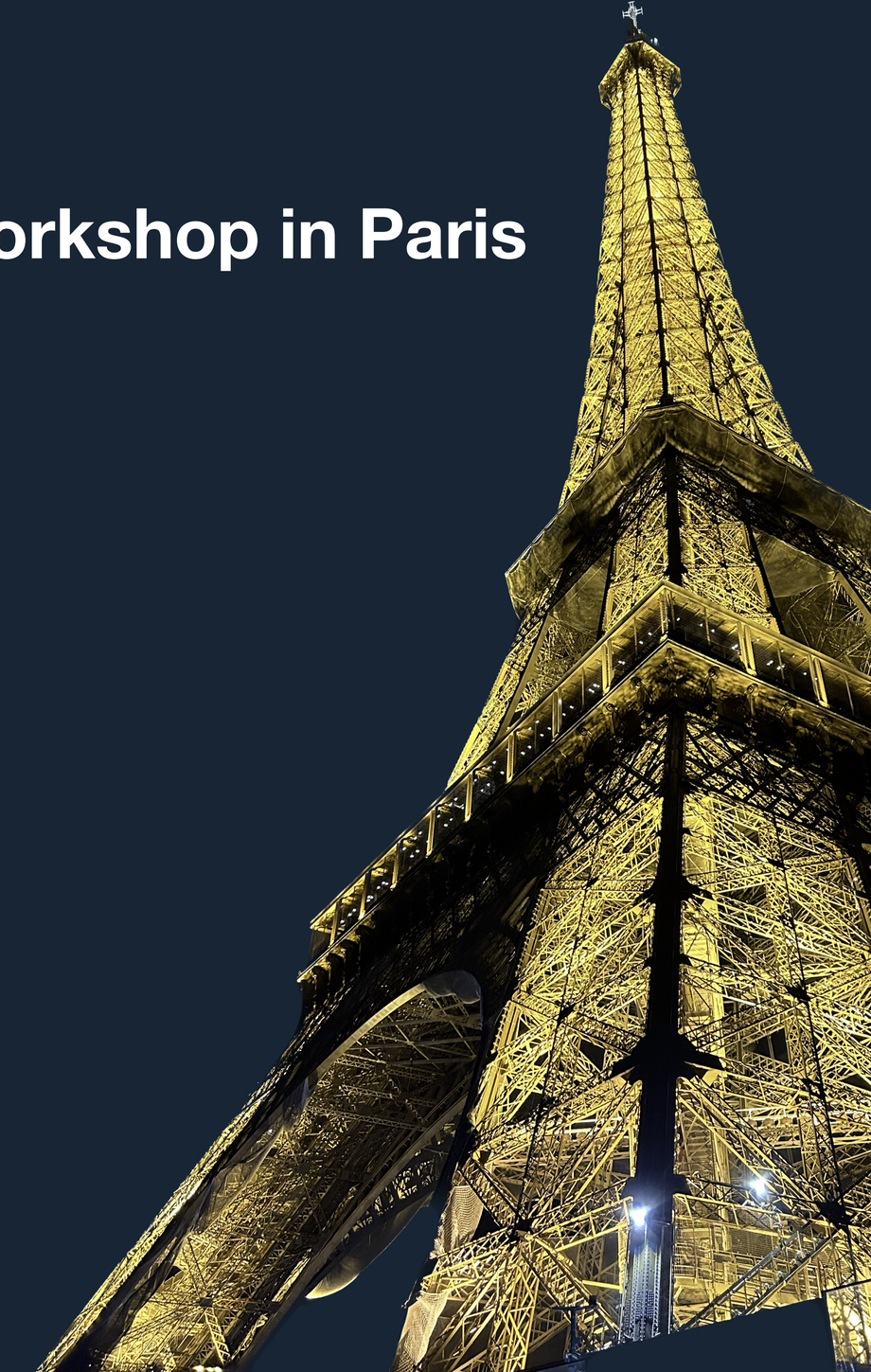

Verus

github.com/verus-lang/verus

a toolbox for systems verification

Andrea Lattuada, Jon Howell (VMware Research), Tej Chajed (VMware/U-Wisconsin)
Chris Hawblitzel, Ziqiao Zhou, Jay Lorch, Weiteng Chen (Microsoft Research)
Travis Hance, Bryan Parno, Chanhee Cho, Jay Bosamiya, Yi Zhou (Carnegie Mellon University)
Reto Achermann (University of British Columbia)
Isitha Subasinghe, Matthias Brun (ETH Zurich)
Tenzin Low (University of Washington), Tony Zhang (U-Michigan), Xudong Sun (UIUC)

Try the guide!

Try Verus at https://play.verus-lang.org/ [experimental]

Read the paper: https://doi.org/10.1145/3586037

Get in touch! lattuada@vmware.com / andrea@lattuada.me

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