Verifying the Rust Standard Library Using Verus

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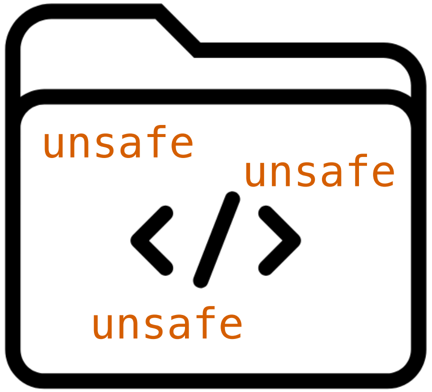
Why Verify the Rust Standard Library?

Memory safety errors

...except in ***unsafe*** code



Rust standard library

20

CVEs

Goal: Provide safety and correctness guarantees

Icon created by SANB from Noun Project

Challenges and Tool Motivation

The Rust standard library is…

Evolving

Large
(500,000 SLOC)

Implemented with **unsafe** code

Verification tools must…

Provide ***“Rust-like”*** proof environment

Provide good ***automation***

Reason about ***raw pointer operations***, among others

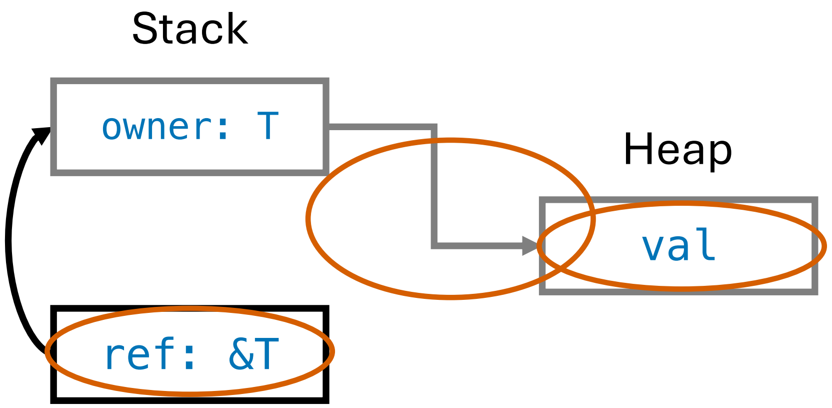
Verus does all of this

Icons created by Larea and Waldis Production from Noun Project

Rust: Ownership, References, and Borrowing

- Each value in Rust has a variable that's its ***owner***.
- Create an alias by making a ***reference***.
  - Called ***borrowing***. Done with **&** operator.
  - Think of a reference ***&T*** as ***(T, ptr)***.

✓ Enforced by the Rust ***borrow-checker***.



Rust shared reference

A reference can be ***shared*** (immutable) or ***mutable***, which determines the read/write access allowed.

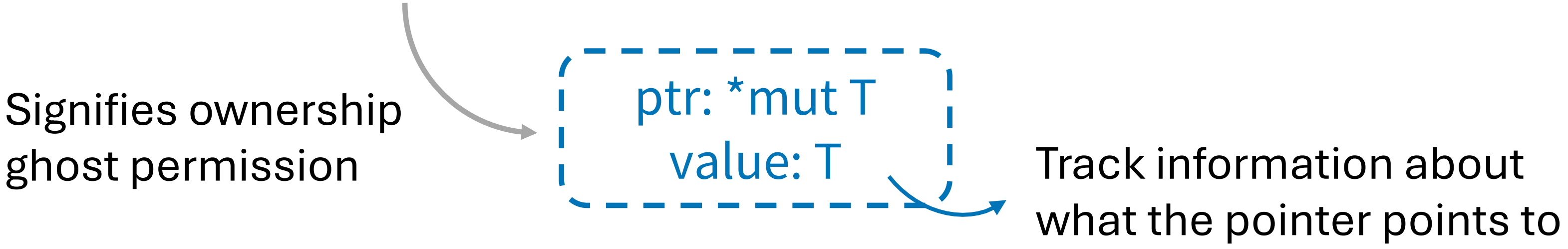
The ***lifetime*** of a reference cannot be longer than the owner's lifetime.

Verus: Ownership Ghost Permissions

- ***Ownership ghost permissions*** track the ***evolving state of a resource*** in unsafe code.
- Type-check permissions with Rust’s ***borrow-checker*** to ensure safety.

```
unsafe {
    let (p, Tracked(mut points_to)) = allocate::<u32>(4);

}
```



Signifies ownership ghost permission

ptr: *mut T
value: T

Track information about what the pointer points to

(example simplified for demonstration purposes)

Ownership Ghost Permissions: Mutability

Mutability of permission reference must ***match*** mutability of the pointer operation.

- Signature of `ptr_mut_write` requires a ***mutable*** reference, to ensure exclusive access to memory.

```
unsafe {
    let (p, Tracked(mut points_to)) = allocate::<u32>(4);
    ptr_mut_write(p, Tracked(&mut points_to), 5);


}
```

(example simplified for demonstration purposes)

Ownership Ghost Permissions: Mutability

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- Signature of `ptr_mut_write` requires a ***mutable*** reference, to ensure exclusive access to memory.
- Enforced by Rust’s ***borrow-checker***.

```
unsafe {
    let (p, Tracked(mut points_to)) = allocate::<u32>(4);
    ptr_mut_write(p, Tracked(&points_to), 5);      // FAILS



}
```

(example simplified for demonstration purposes)

Ownership Ghost Permissions: Lifetime

Permission is valid for ***exactly as long*** as the allocation’s lifetime.

- Signature of `deallocate` requires ***ownership transfer*** of `points_to`.

```
unsafe {
    let (p, Tracked(mut points_to)) = allocate::<u32>(4);
    ptr_mut_write(p, Tracked(&mut points_to), 5);
    deallocate(p, 4, Tracked(points_to));

}
```

(example simplified for demonstration purposes)

Ownership Ghost Permissions: Lifetime

Permission is valid for ***exactly as long*** as the allocation’s lifetime.

- Signature of `deallocate` requires ***ownership transfer*** of `points_to`.
- Rust borrow-checker ***forbids references*** after that: it is no longer in scope.

```
unsafe {
    let (p, Tracked(mut points_to)) = allocate::<u32>(4);
    ptr_mut_write(p, Tracked(&mut points_to), 5);
    deallocate(p, 4, Tracked(points_to));
    ptr_mut_write(p, Tracked(&mut points_to), 5);  // FAILS
}
```

(example simplified for demonstration purposes)

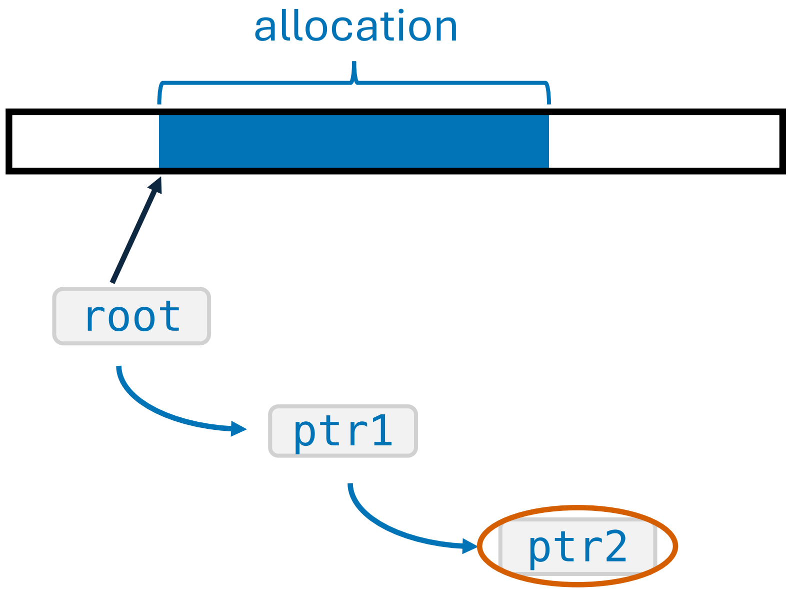
Challenge #1: Handling Pointer Provenance

Provenance captures what you are allowed to *do* with a pointer, based on the *source it was derived from*.

Spatial

Temporal

Mutability



Challenge #1: Handling Pointer Provenance

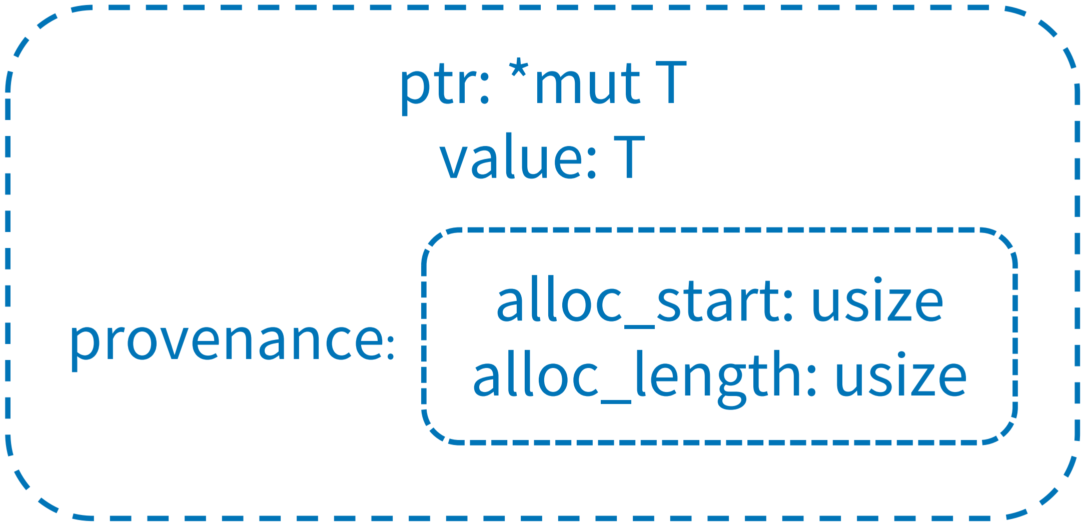
Provenance captures what you are allowed to *do* with a pointer, based on the *source it was derived from*.

✓Spatial → Extend ownership ghost permissions with provenance information

✓Temporal

✓Mutability

Addressed by Rust's borrow-checker on the lifetime and mutability of ghost permisions



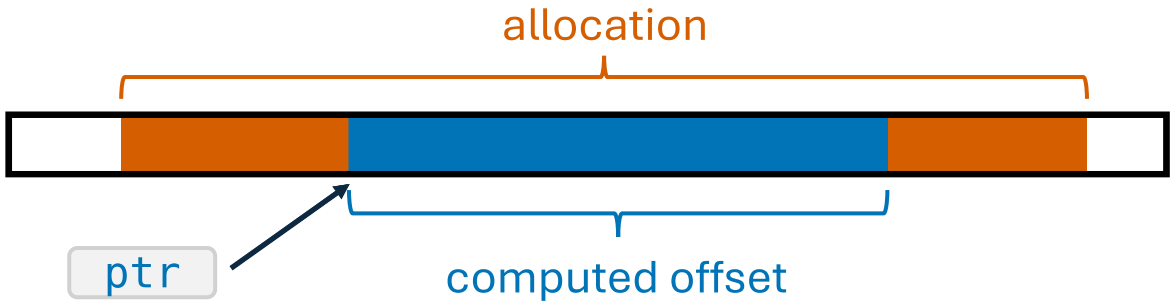
Extended ownership ghost permission

Example: `ptr::add`

```
pub unsafe fn add(ptr: *const T, count: usize) -> *const T
```

Advance `ptr: *const T` by `count` elements of type `T`

Example: `ptr::add`



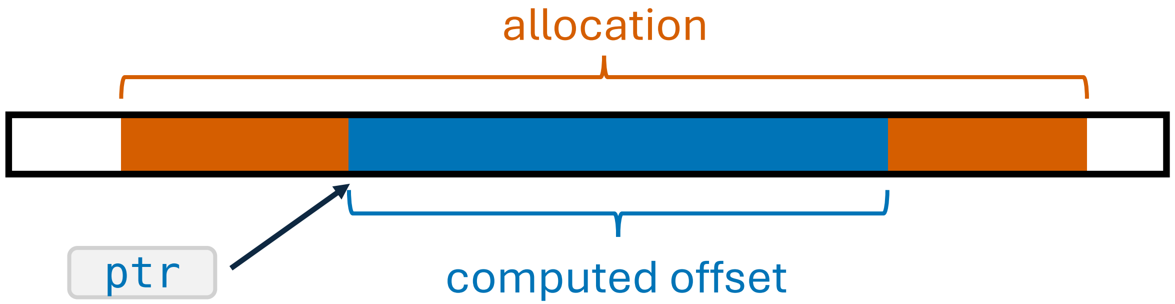
```
pub unsafe fn add(ptr: *const T, count: usize) -> *const T
```

If the computed offset is non-zero, then

1. `ptr` must have a valid allocation (not freed).

2. Memory range between `ptr` and the result must be within bounds.

Example: `ptr::add`



```
pub unsafe fn add_verus<T>(ptr: *const T, count: usize, Tracked(perm): Tracked<&PointsToRaw>) -> *const T
```

If the computed offset is non-zero, then

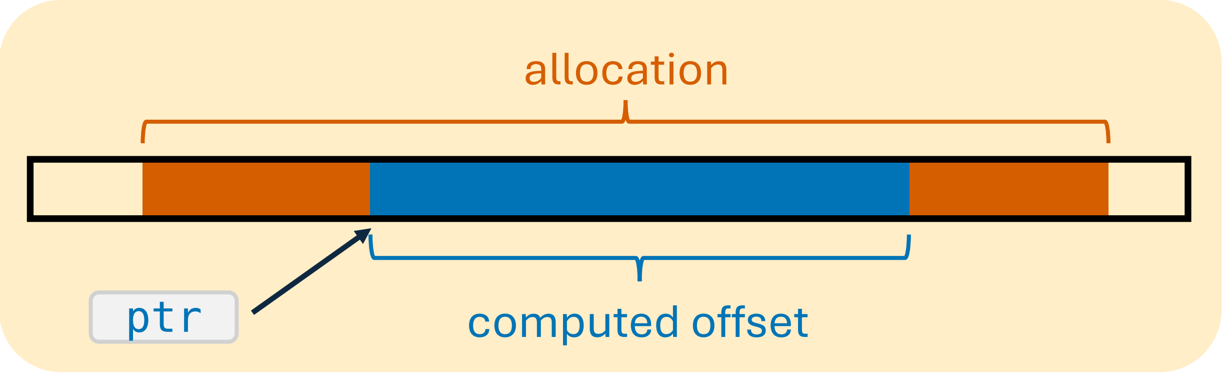
1. `ptr` must have a valid allocation (not freed).

provenance: alloc_start: usize
alloc_length: usize

Tells us that this memory has not been deallocated

2. Memory range between `ptr` and the result must be within bounds.

Example: `ptr::add`



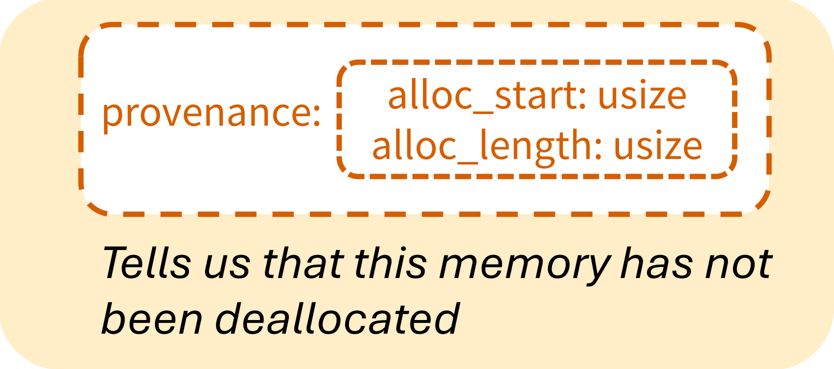
```
pub unsafe fn add_verus<T>(ptr: *const T, count: usize, Tracked(perm): Tracked<&PointsToRaw>) -> *const T
```

If the computed offset is non-zero, then

✓ ❶ `ptr` must have a valid allocation (not freed).

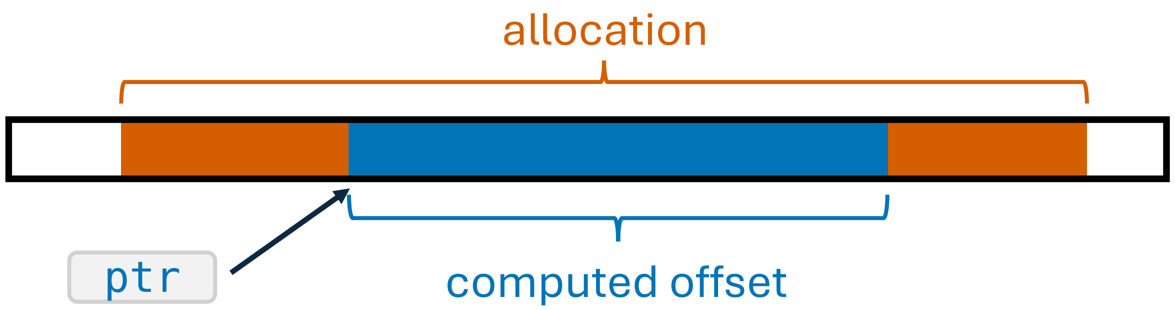
```
perm.provenance() == ptr.provenance
```

❷ Memory range between `ptr` and the result must be within bounds.



Tells us that this memory has not been deallocated

Example: `ptr::add`



```
pub unsafe fn add_verus<T>(ptr: *const T, count: usize, Tracked(perm): Tracked<&PointsToRaw>) -> *const T
```

If the computed offset is non-zero, then

✓ ❶ `ptr` must have a valid allocation (not freed).

```
perm.provenance() == ptr.provenance
```

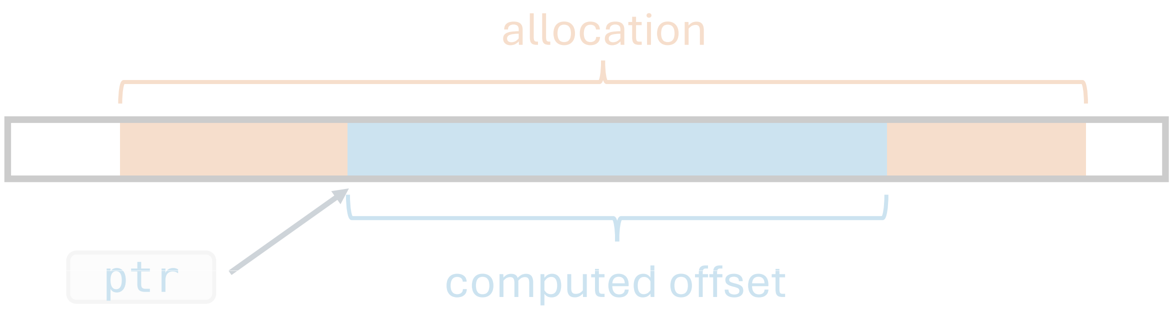
provenance: alloc_start: usize
alloc_length: usize

Tells us that this memory has not been deallocated

✓ ❷ Memory range between `ptr` and the result must be within bounds.

```
ptr.in_bounds(perm.provenance.alloc_start(),
              perm.provenance.alloc_start() + perm.provenance.alloc_length(),
              count)
```

Example: `ptr::add`



```
pub unsafe fn add_verus<T>(ptr: *const T, count: usize, Tracked(perm): Tracked<&PointsToRaw>) -> *const T
```

If the computed offset is non-zero, then

provenance: alloc_start: usize alloc_length: usize

✓ 1 `ptr` must have a valid allocation (not freed)

`perm.pr`

memory has not
d

The only provenance information we needed to add was `alloc_start` and `alloc_length`

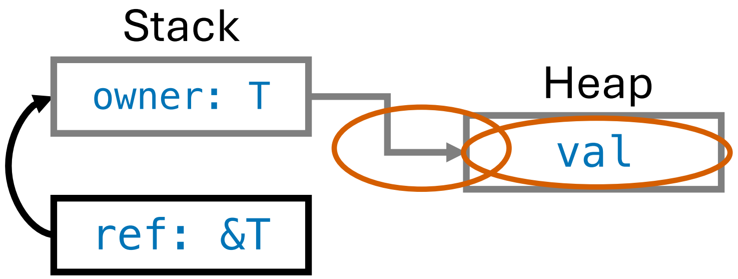
✓ 2 Memory range between `ptr` and the result must be within bounds.

```
ptr.in_bounds(perm.provenance.alloc_start(),
              perm.provenance.alloc_start() + perm.provenance.alloc_length(),
              count)
```

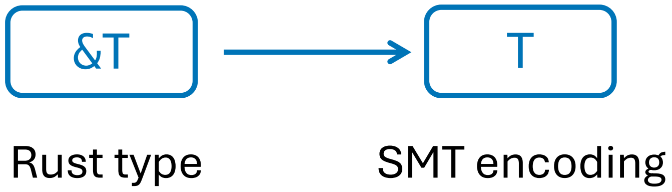
Challenge #2: Shared Reference SMT Encoding

Think of `&T` as `(T, ptr)`

- In most cases, we only care about `T`



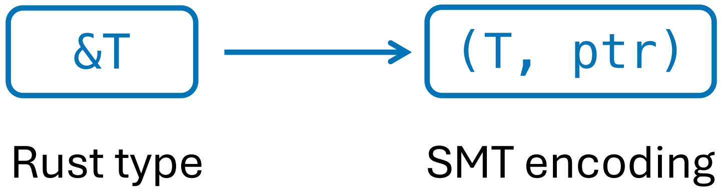
Encoding A



Add `ptr_info(v: &T)` function to get pointer information as needed

- ➢ ***Simpler for users***
- ➢ ***Harder to track and update pointer information internally***

Encoding B

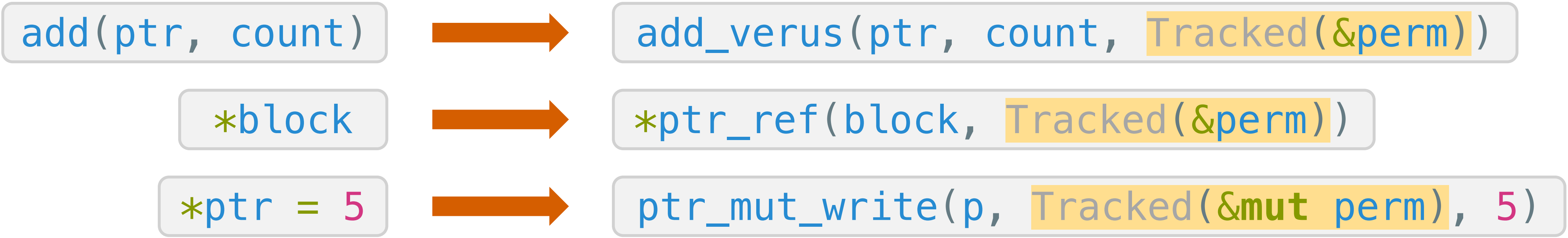


Use `&T` only when you actually need the pointer

- ➢ ***Straightforward to implement***
- ➢ ***Often unavoidable to have &T when we do not need the pointer***

Challenge #3: Ergonomically Incorporating Spec/Proof Code into Existing Rust Code

Need to use Verus versions of functions



```
add(ptr, count)    → add_verus(ptr, count, Tracked(&perm))
*block             → *ptr_ref(block, Tracked(&perm))
*ptr = 5           → ptr_mut_write(p, Tracked(&mut perm), 5)
```

Solution: Support in progress for attribute-based syntax

```
#[with_ghost_arg(Tracked(perm): Tracked<&PointsToRaw>)]
pub unsafe fn add<T>(ptr: *const T, count: usize) -> *const T
```

Challenge #3: Ergonomically Incorporating Spec/Proof Code into Existing Rust Code

Need to use Verus versions of functions

```
add(ptr, count)
```

→

```
add_verus(ptr, count, Tracked(&perm))
```

Need to do this in a way that still enables type-checking, so we can keep borrow-checking our permissions

Solution: Support in progress for attribute-based syntax

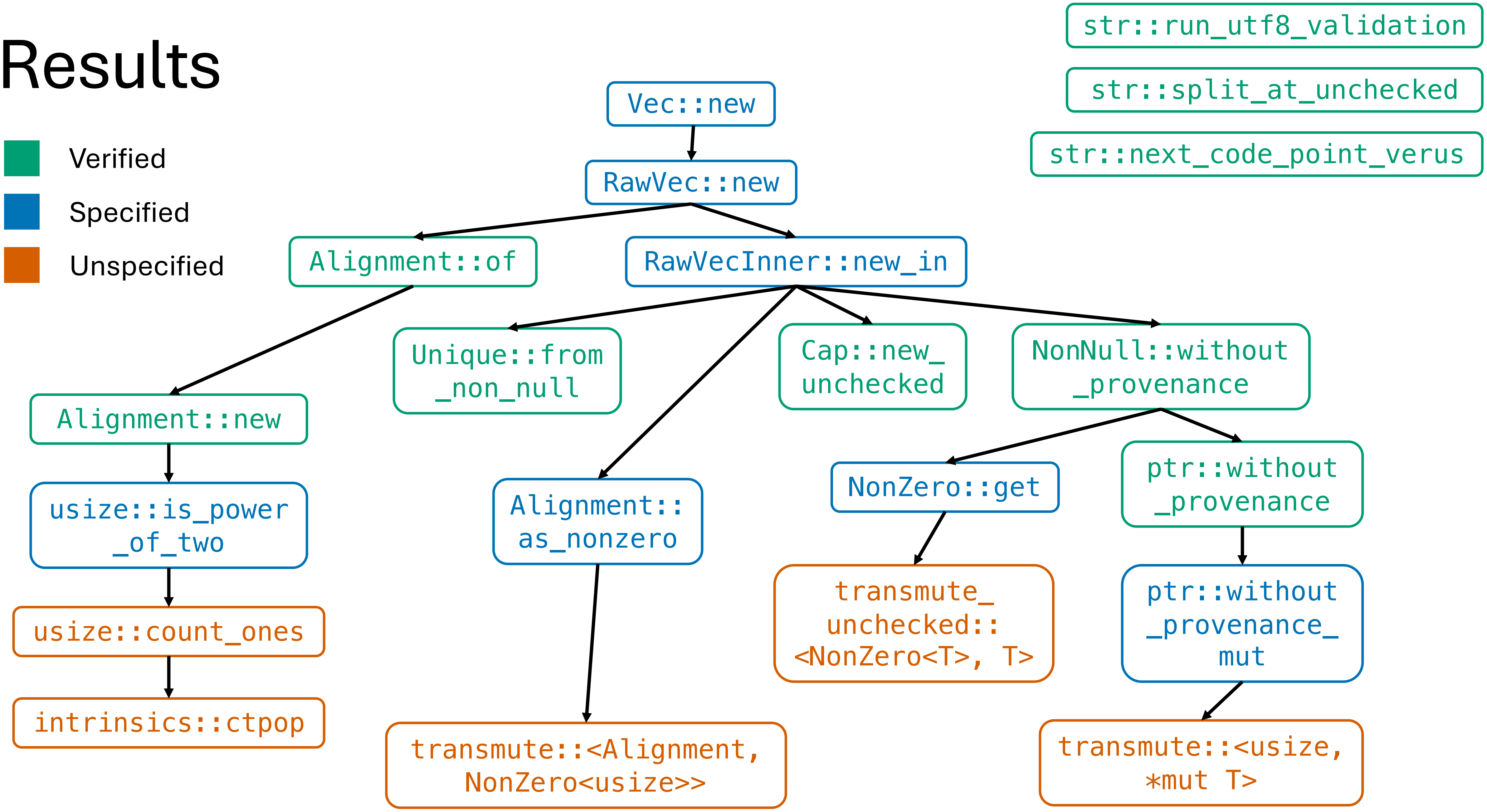
```
#[with_ghost_arg(Tracked(perm): Tracked<&PointsToRaw>)]
pub unsafe fn add<T>(ptr: *const T, count: usize) -> *const T
```

Results

🟩 Verified

🟦 Specified

🟧 Unspecified



str::run_utf8_validation

str::split_at_unchecked

str::next_code_point_verus

Vec::new

RawVec::new

Alignment::of

RawVecInner::new_in

Alignment::new

Unique::from_non_null

Cap::new_unchecked

NonNull::without_provenance

usize::is_power_of_two

Alignment::as_nonzero

NonZero::get

ptr::without_provenance

usize::count_ones

transmute_unchecked::<NonZero<T>, T>

ptr::without_provenance_mut

intrinsics::ctpop

transmute::<Alignment, NonZero<usize>>

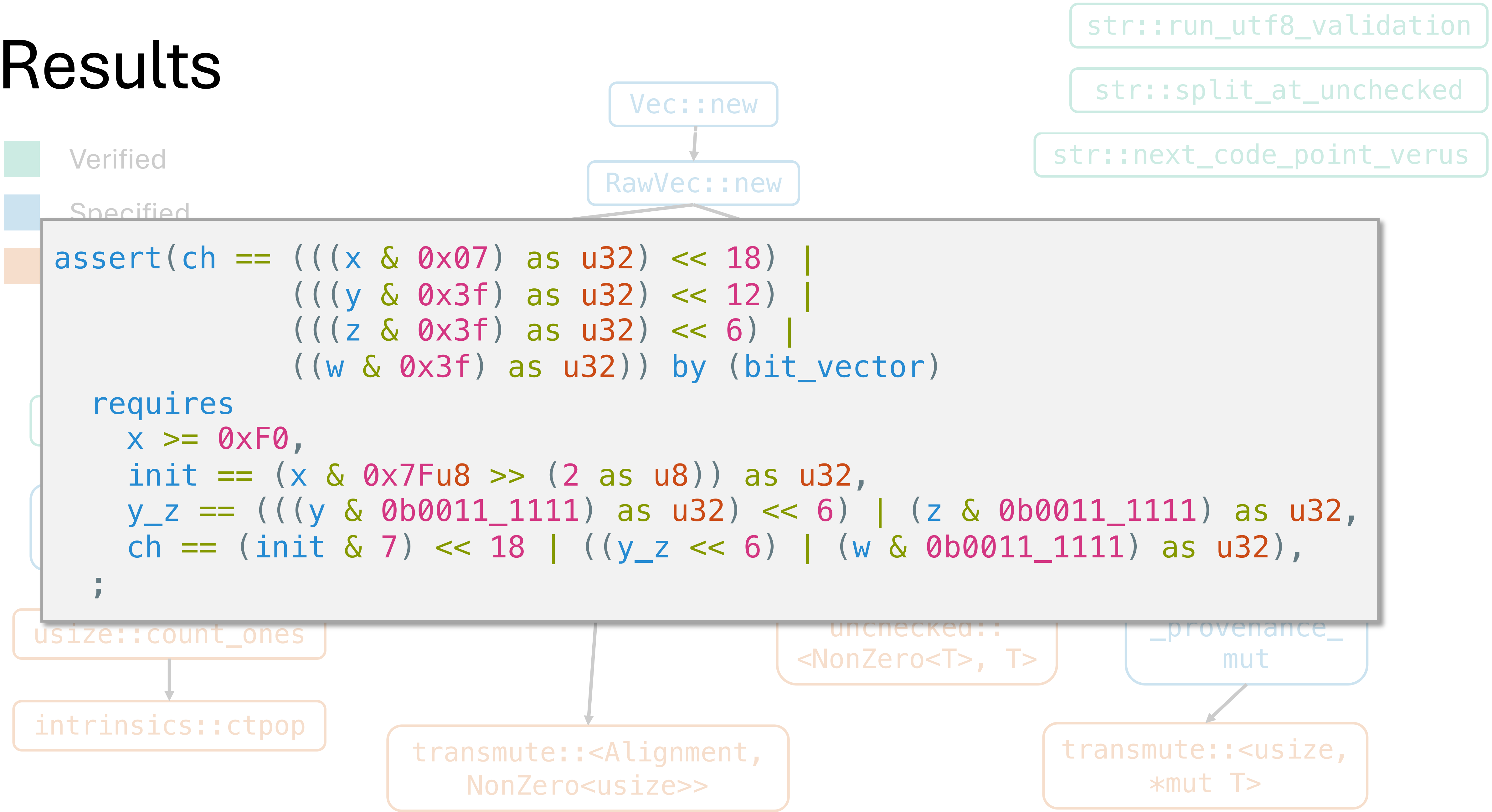
transmute::<usize, *mut T>

Results

🟩 Verified

🟦 Specified

🟧



str::run_utf8_validation
str::split_at_unchecked
str::next_code_point_verus
Vec::new
RawVec::new
usize::count_ones
intrinsics::ctpop
transmute::<Alignment, NonZero<usize>>
unchecked::<NonZero<T>, T>
provenance mut
transmute::<usize, *mut T>

```
assert(ch == (((x & 0x07) as u32) << 18) |
             (((y & 0x3f) as u32) << 12) |
             (((z & 0x3f) as u32) << 6) |
             ((w & 0x3f) as u32)) by (bit_vector)
  requires
    x >= 0xF0,
    init == (x & 0x7Fu8 >> (2 as u8)) as u32,
    y_z == (((y & 0b0011_1111) as u32) << 6) | (z & 0b0011_1111) as u32,
    ch == (init & 7) << 18 | ((y_z << 6) | (w & 0b0011_1111) as u32),
  ;
```

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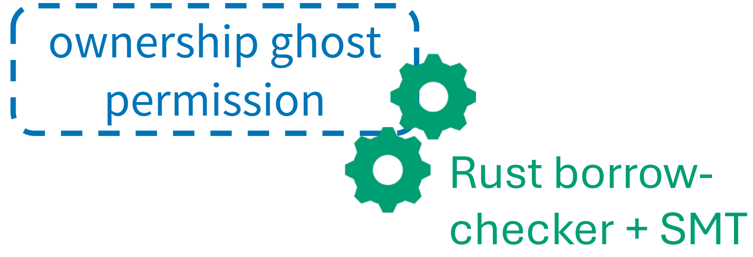
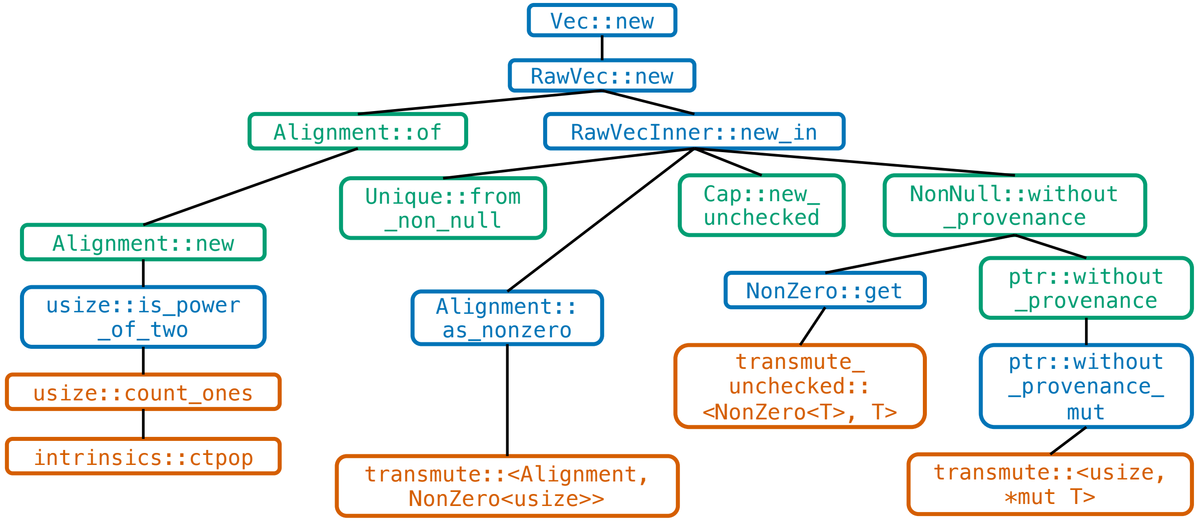
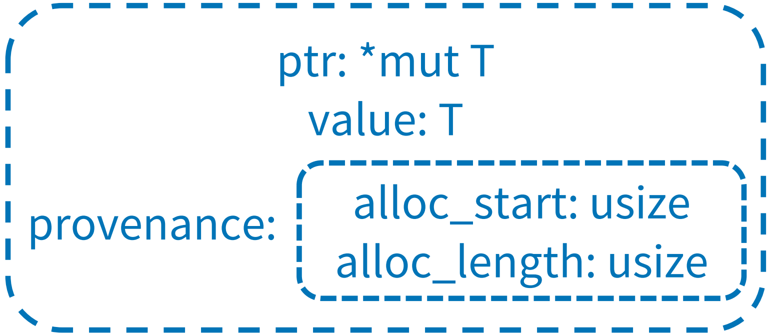
Thank you!

Recap

- Rely on Rust's ***borrow-checker*** and ***ownership ghost types***.
- Straightforward ***pointer provenance*** model.
- Capable of ***verifying complex***, ***real-world code***.







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