

Deductive Verification for Rust Programs

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The impact of software bugs

The worst incident I was (partially) responsible for



NEWS SPORTS HIP HOP WATCH PHOTOS TOURS

KYLIE JENNER

Lip Kit Website Glitch
PERSONAL CUSTOMER
INFO EXPOSED

EXCLUSIVE



4/11/2016 2:40 PM PT



Why Verify?

Formal verification is traditionally applied to **critical systems**, where computers make life-or-death decisions

Aeronautics

Rail transport

Automotive

Today, many other candidates for formal verification exist...

Industrial Control

Cloud Platforms

What is **formal verification**?

The application of formal **mathematical** techniques to **reason** about and understand **software**.

We can ask questions like...

“Is my data safe if the program crashes?”

“Is data restricted to authenticated users?”

“Does this program behave correctly?”

What is deductive verification?

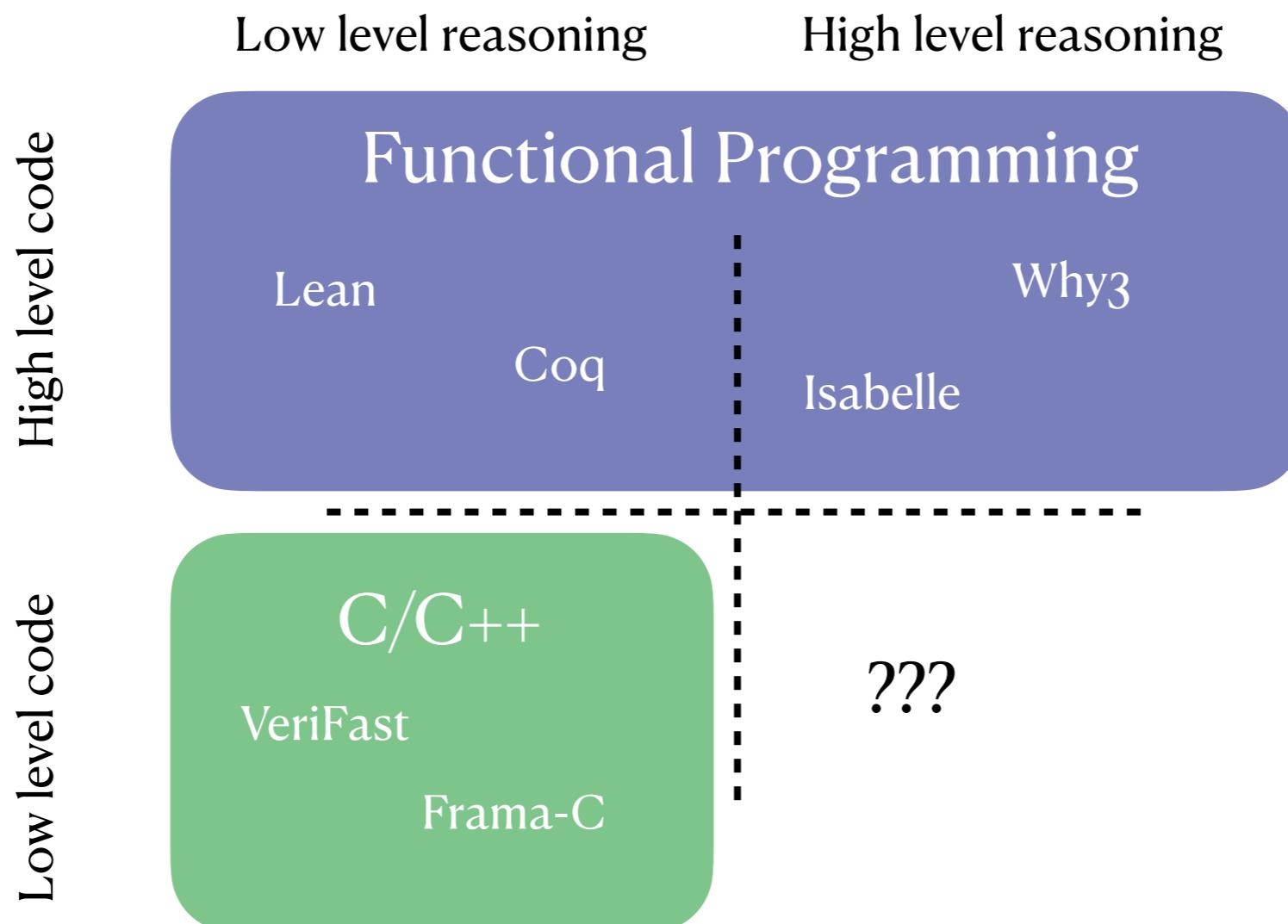
Given the following program, how can we **prove** x becomes positive?

```
if b { x = 20 } else { x = 23 }
```

Informally, we might reason by considering the possible cases.

Deductive verification formalizes this reasoning as a logic

What is the **problem** with verification?



What is the **problem** with verification?

```
void memcpy(char* tgt, char* src, size_t size) {  
    for (int k = 0; k < size; k++) {  
        tgt[k] = src[k];  
    }  
}
```

We want to prove that **size** bytes of **src** are copied to **tgt**

What is the **problem** with verification?

Pointers could **overlap**

```
void memcpy(char* tgt, char* src, size_t size) {  
    for (int k = 0; k < size; k++) {  
        tgt[k] = src[k];  
    }  
}
```

We want to prove that **size** bytes of **src** are copied to **tgt**

What is the **problem** with verification?

Pointers could **overlap**

Pointers could be **uninitialized**

```
void memcpy(char* tgt, char* src, size_t size) {  
    for (int k = 0; k < size; k++) {  
        tgt[k] = src[k];  
    }  
}
```

We want to prove that **size** bytes of **src** are copied to **tgt**

What is the **problem** with verification?

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```
void memcpy(char* tgt, char* src, size_t size) {  
    for (int k = 0; k < size; k++) {  
        tgt[k] = src[k];  
    }  
}
```

Access could be **out-of-bounds**

We want to prove that **size** bytes of **src** are copied to **tgt**

What is the **problem** with verification?

Verified using VeriFast

```
void memcpy(char* src, char* tgt, size_t size)
//@ requires chars(tgt, size, _) && chars(src, size, ?s);
//@ ensures chars(tgt, size, s) && chars(src, size, s);
{
    for(int k= 0; k < size; k)
    /*@
        invariant 0 <= k && k <= size && chars(tgt + k, size - k, _)
            && chars(tgt, k, take(k, s)) && chars(src, k, take(k, s))
            && chars(src + k, size - k, drop(k, s));
    */
    {
        //@ open chars(tgt + k, _, _);
        //@ open chars(src + k, _, _);
        tgt[k] = src[k];
        //@ drop_n_plus_one(k, str);
        //@ assert character(tgt + k, ?c0) && nth(k, s) == c0;
        //@ append_take_take(s, k, 1);
        //@ close chars(tgt + k, 1, _);
        //@ close chars(src + k, 1, _);
    }
}
```

What is the **problem** with verification?

Verified using VeriFast

```
void memcpy(char* src, char* tgt, size_t size)
//@ requires chars(tgt, size, _) && chars(src, size, ?s);
//@ ensures chars(tgt, size, s) && chars(src, size, s);
{
    for(int k= 0; k < size; k++)
    /*@
        invariant 0 <= k && k <= size && chars(tgt + k, size - k, _)
            && chars(tgt, k, take(k, s)) && chars(src, k, take(k, s))
            && chars(src + k, size - k, drop(k, s));
    */
    {
        //@ open chars(tgt + k, _, _);
        //@ open chars(src + k, _, _);
        tgt[k] = src[k];
        //@ drop_n_plus_one(k, str);
        //@ assert character(tgt + k, ?c0) && nth(k, s) == c0;
        //@ append_take_take(s, k, 1);
        //@ close chars(tgt + k, 1, _);
        //@ close chars(src + k, 1, _);
    }
}
```

What is the **problem** with verification?

Formal verification must consider **all** possible behaviors.

In **C-like** languages this means...

- Mutable aliasing, pointer arithmetic

- Pervasive undefined behavior

- Weak abstractions in types

Tools like VeriFast do the best given these constraints, improving requires a **better language**...

What is Rust?

Introduced in 2015, Rust is designed to solve some problems of C

Features a novel ownership type-system

Forbids mutable aliasing, accessing uninitialized memory

Includes useful high-level features: sum types, closures, traits

From C to Rust

Pointers are disjoint

```
fn memcpy(tgt: &mut [u8], src: & [u8]) {  
    let mut i = 0;  
    while i < src.len() {  
        tgt[i] = src[i];  
        i += 1;  
    }  
}
```

Out-of-bounds access is detected at runtime

Verifying Rust programs?

Rust has grown popular among developers of systems software

Interest from automotive, cloud, and other critical systems

The Rust type system eliminates many common bugs, but not all.

Can we leverage it to **simplify** verification?

Contributions of this thesis

This thesis presents the **Creusot** verifier for Rust.

- Design and implementation of the actual tool
- Metatheory for a core model of Creusot

It also considers various applications of Creusot:

- Verified **Iterators** in Rust
- **Sprout**, a formally verified SMT solver

In this presentation

In the rest of this talk I present...

- Creusot's approach to verification
- Its usage for verifying Iterators
- The metatheory and soundness of Creusot
- An overview of software verified using Creusot

Creusot's approach to verification

The Creusot approach to verification

Creusot hails from a lineage of work starting with **RustHorn**

Matsushita, Y., Tsukada, T. and Kobayashi, N. ESOP 2020

Introduces a technique of **prophecies** to reason about pointers

Creusot uses this to translate Rust programs to **functional** ones

Resulting functional programs can be verified with **Why3**

The big secret: Rust is a functional* language

*some squinting required

Encoding Rust in ML

Local variables

```
fn incr(mut x: u64, mut y: u64)  
-> u64 {  
    x += y;  
    x  
}
```

```
let incr x y =  
    let x = x + y in  
    x
```

Locally mut variables can be modeled as shadowing

Encoding Rust in ML

Box

```
fn incr(x: Box<u64>, y: Box<u64>)
-> Box<u64> {
    *x += *y;
    x
}
```



Encoding Rust in ML

Box

```
fn incr(x: Box<u64>, y: Box<u64>)
-> Box<u64> {
    *x += *y;
    x
}
```

```
let incr x y =
    let x = x + y in
    x
```

Boxes are erased!
Consequence of uniqueness

Encoding Rust in ML

Immutable References

```
fn incr_immut(x: &u64, y: &u64)  
-> u64 {  
    *x + *y  
}
```



Encoding Rust in ML

Immutable References

```
fn incr_immut(x: &u64, y: &u64)  
-> u64 {  
    *x + *y  
}
```

```
let incr_immut x y =  
    x + y
```

Also erased!

No mutation = No problems

Encoding Rust in ML

Mutable References

```
fn incr_mut(x: &mut u64, y: u64)
{
    *x += y
}
```

```
fn main() {
    let mut x = 0;
    incr_mut(&mut x, 10);
    assert!(x == 10);
}
```



Encoding Rust in ML

Mutable References

```
fn incr_mut(x: &mut u64, y: u64)      let incr_mut x y = ???  
{  
    *x += y  
}
```

```
fn main() {  
    let mut x = 0;  
    incr_mut(&mut x, 10);  
    assert!(x == 10);  
}  
  
let main () =  
    let x = 0 in  
    incr_mut x 10;  
    assert { x == 10 }
```

Mutable borrows can't be erased.

They require a special encoding

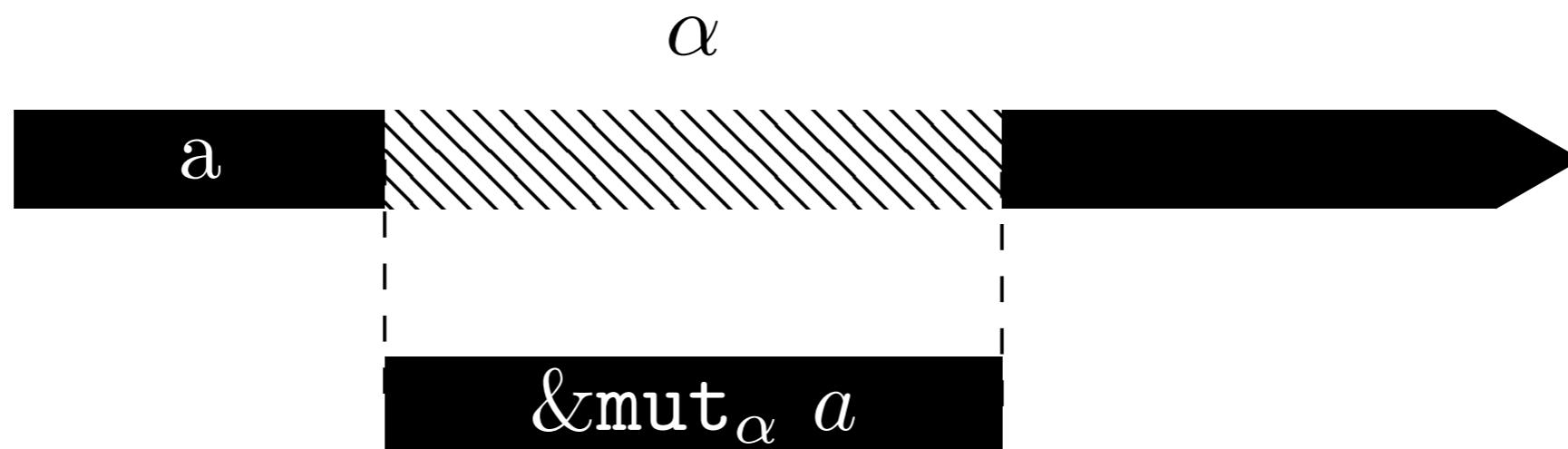
Prophecies

Synchronizing lender and borrower

Models mutable borrows as pair of **current** and **final** values

We prophetize the final value, which the lender recovers.

Depends on **uniqueness** and **lifetimes** of mutable borrows



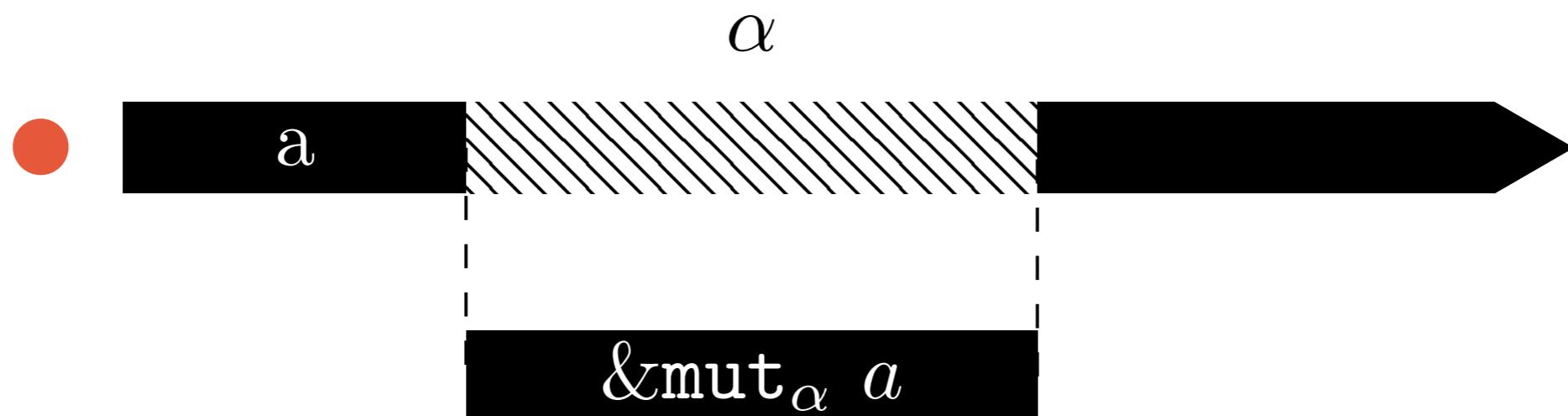
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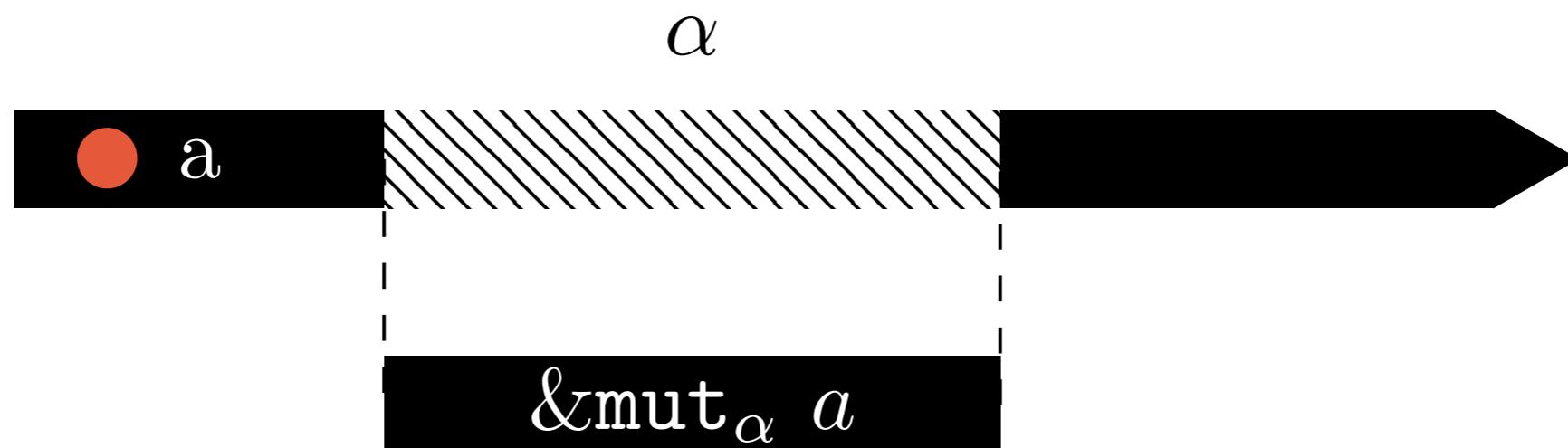
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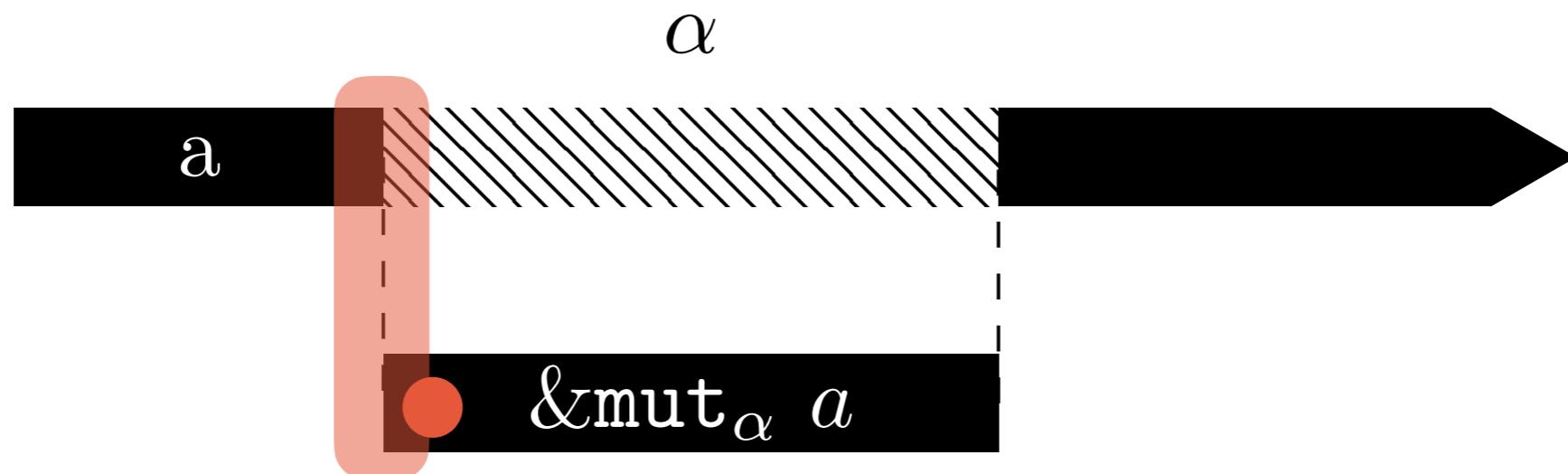
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a is inaccessible for the duration of α

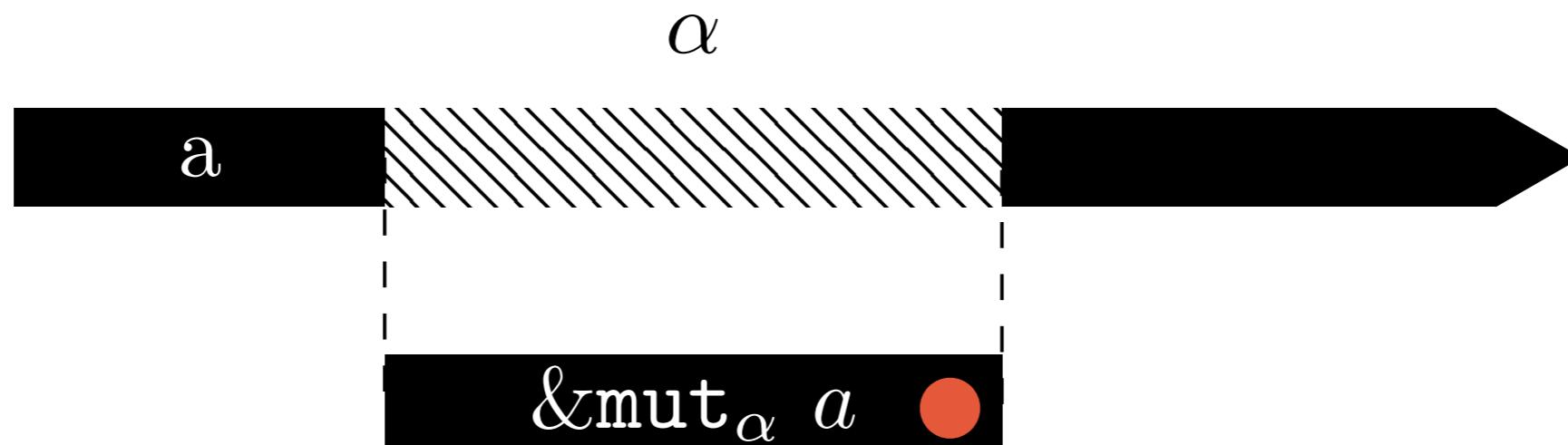
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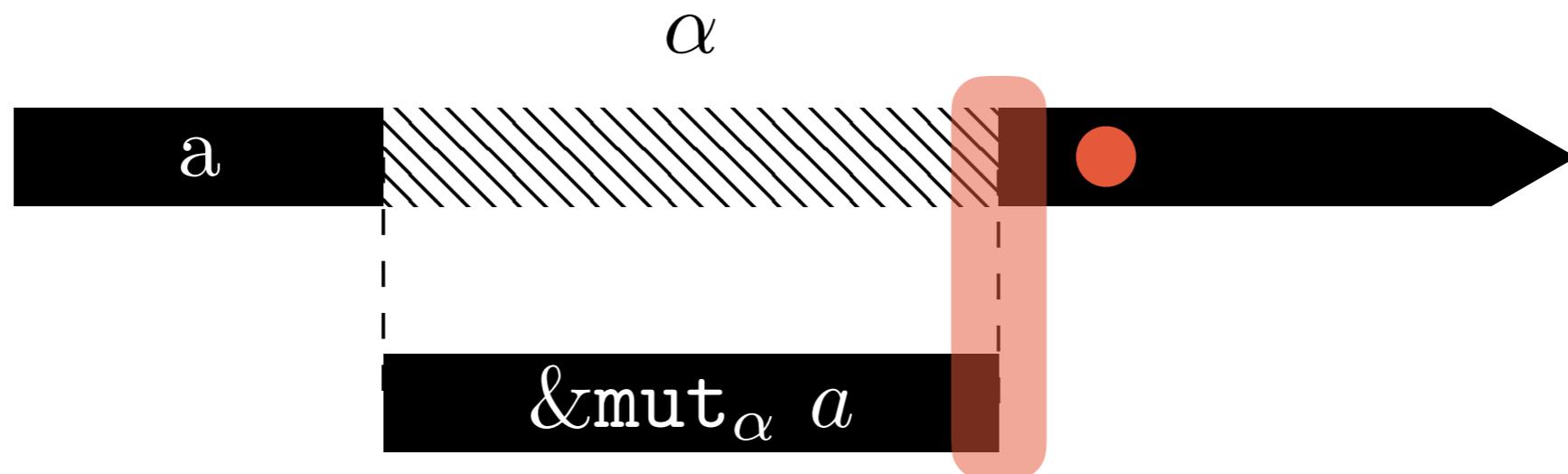
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Can't model the second point; instead *prophetize it*

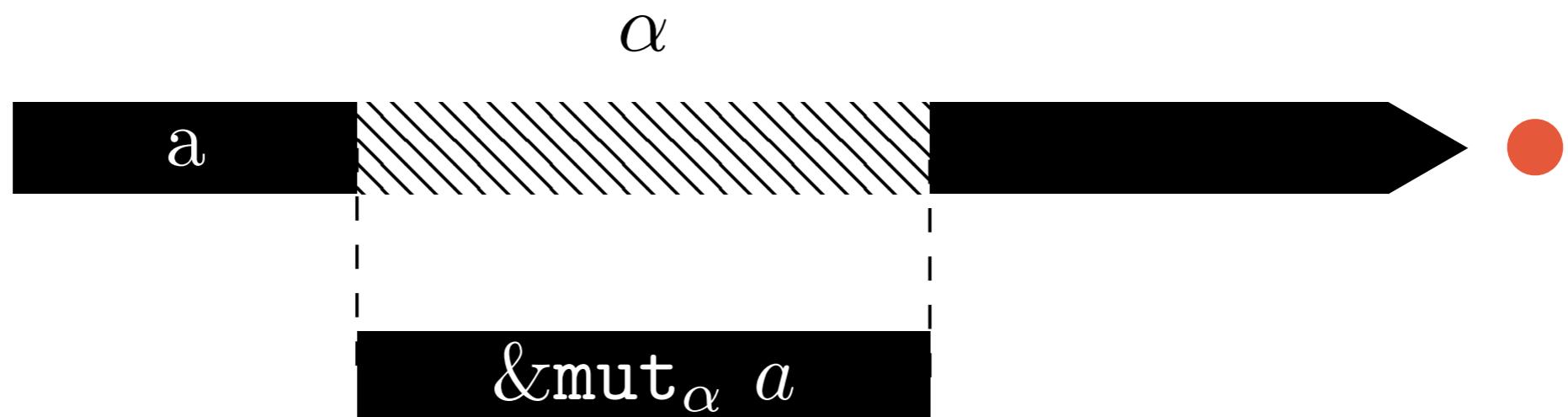
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We prophetize the final value, which the lender recovers.

Depends on **uniqueness** and **lifetimes** of mutable borrows



Can't model the second point; instead *prophetize it*

Prophecies

Synchronizing lender and borrower

We encode this using *any/assume non-determinism*.

any will non-deterministically create a value

assume places constraints on *past* choices

Creation

```
let borwr = { cur = lendr; fin = any } in  
let lendr = borwr.fin in
```

Resolution

```
assume { borwr.cur = borwr.fin }
```

Encoding Rust in ML

Mutable References

```
fn main() {  
    let mut a = 0;  
    let x = &mut a;  
    let y = 10;  
    *x += y;  
    drop(x);  
    assert_eq!(a, 10);  
}
```

```
let main () =  
    let a = 0 in  
    let x = { cur = a ; fin = any } in  
    let a = x.fin in  
    let y = 10 in  
    let x = { x with cur += y } in  
    assume { x.fin = x.cur };  
    assert { a = 10 }
```

Encoding Rust in ML

Mutable References?

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Encoding Rust in ML

Mutable References?

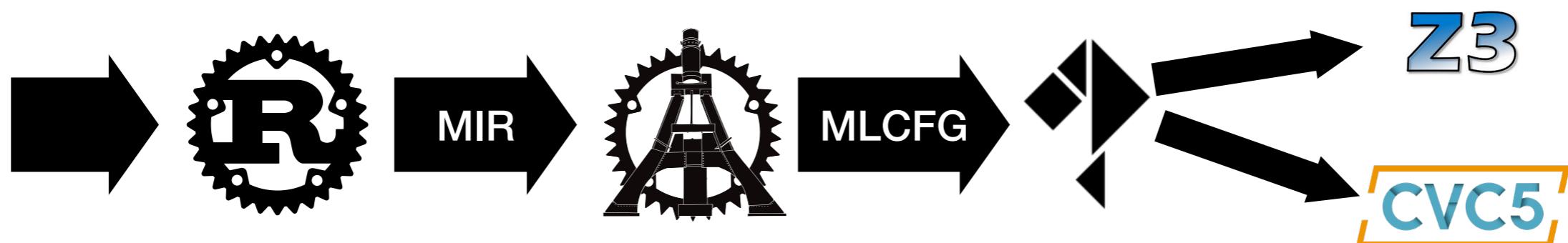
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    let a = x.fin in  
    let y = 10 in  
    let x = { x with cur += y } in  
    assume { x.fin = x.cur };  
    assert { a = 10 }
```

Creusot today

Creusot verifies programs by translation to a functional language

Resulting proof obligations are discharged by Why3



Includes an expressive specification language to write contracts

Also, logical functions, ghost code, and ghost fields

Beyond the status quo

Verifying with Creusot

```
#[requires(tgt.len() == src.len())]
#[ensures(^tgt == *src)]
fn memcpy(tgt: &mut [u8], src: & [u8]) {
    let mut i = 0;
    #[invariant(i <= src.len())]
    #[invariant(forall<j> j < i ==> tgt[j] == src[i])]
    while i < src.len() {
        tgt[i] = src[i];
    }
}
```

Beyond the status quo

Verifying with Creusot

```
#[requires(tgt.len() == src.len())]
#[ensures(^tgt == *src)]
fn memcpy(tgt: &mut [u8], src: & [u8]) {
    let mut i = 0;
    #[invariant(i <= src.len())]
    #[invariant(forall<j> j < i ==> tgt[j] == src[i])]
    while i < src.len() {
        tgt[i] = src[i];
    }
}
```

The `^` operator accesses the
final value of a borrow

Verifying Iterators

An alternative memcpy

```
fn memcpy(tgt: &mut [u8], src: & [u8]) {  
    for (t, s) in tgt.iter_mut().zip(src) {  
        *t = *s;  
    }  
}
```



Uses Iterators

An alternative memcpy

```
fn memcpy(tgt: &mut [u8], src: & [u8]) {  
    for (t, s) in tgt.iter_mut().zip(src) {  
        *t = *s;  
    }  
}
```

Uses Iterators

An alternative memcpy

```
fn memcpy(tgt: &mut [u8], src: & [u8]) {
    let mut it = tgt.iter_mut().zip(src);
    loop {
        match it.next() {
            Some((t,s)) => { *t = *s }
            None => break
        }
    }
}
```

What are Iterators?

```
trait Iterator {  
    type Item;  
  
    fn next(&mut self) -> Option<Self::Item>;  
}
```

Rust uses *external iterators* through the `Iterator` trait.

Iterators can be composed and abstracted over

Need generic reasoning principles

Modeling Iterators

An iterator is a 4-uple $(S, I, \cdot \rightsquigarrow \cdot, C)$:

- A set of states: S
- A set of items: I
- A production relation: $\rightsquigarrow \subseteq S \times I^* \times S$
- Transitive: $a \xrightarrow{s} b \wedge b \xrightarrow{t} c \rightarrow a \xrightarrow{s \cdot t} c$, reflexive: $a \xrightarrow{\epsilon} a$
- A set of accepting states: $C \subseteq S$

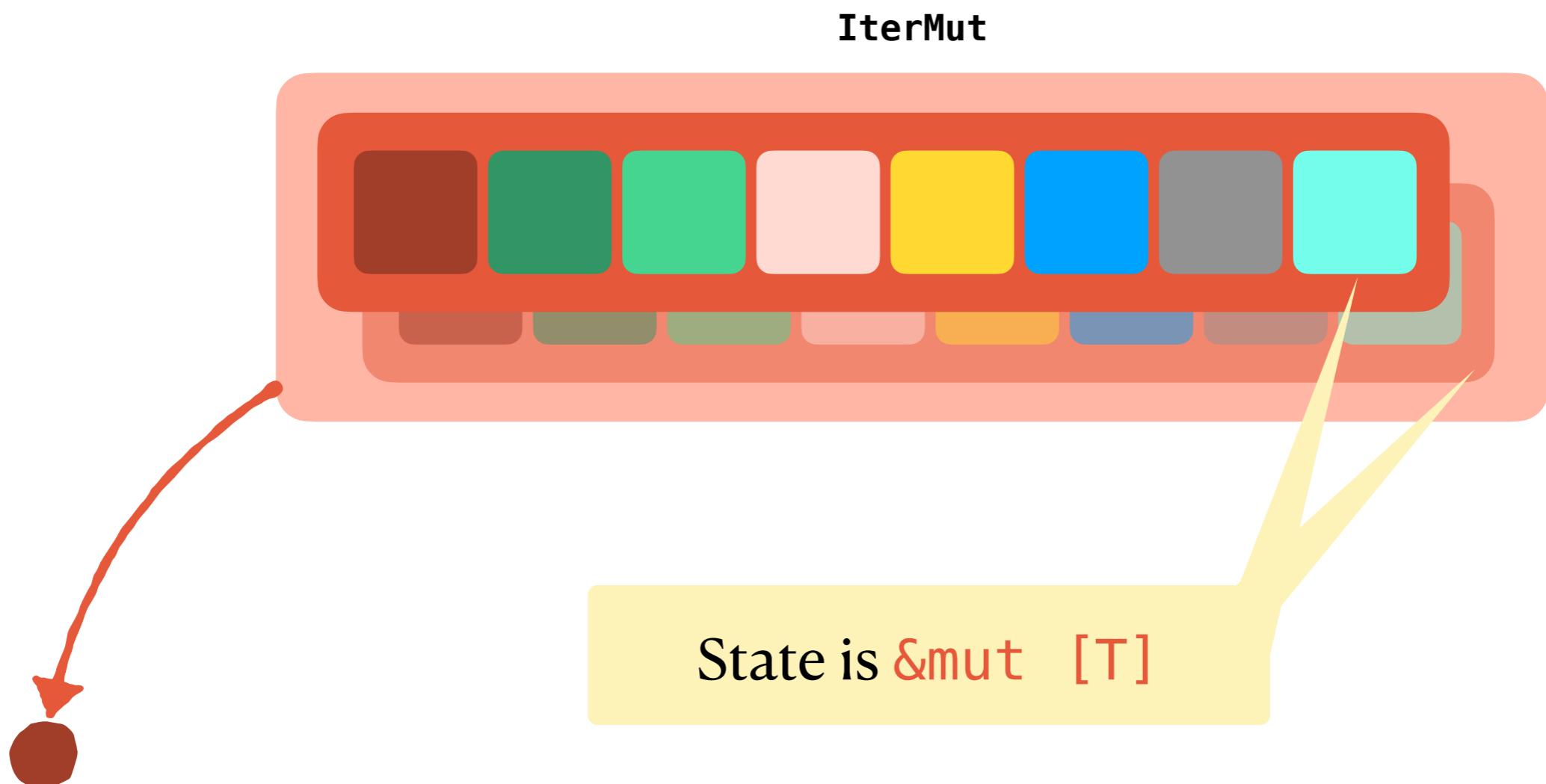
The IterMut Iterator

```
struct IterMut<'a, T> { elems: &'a mut [T] }

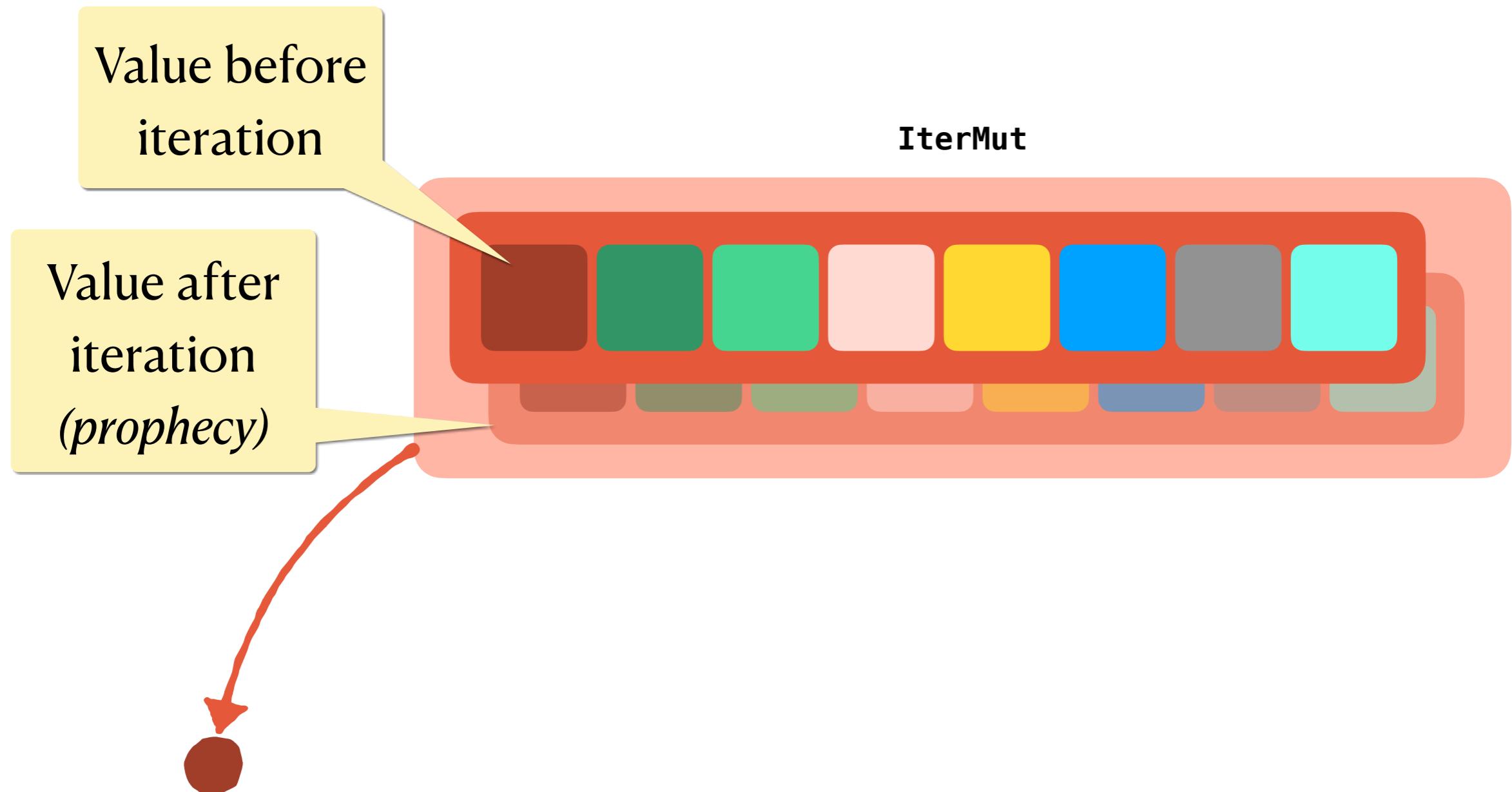
impl<'a, T> Iterator for IterMut<'a, T> {
    type Item = &'a mut T;

    fn next(&mut self) -> Option<Self::Item> { .. }
}
```

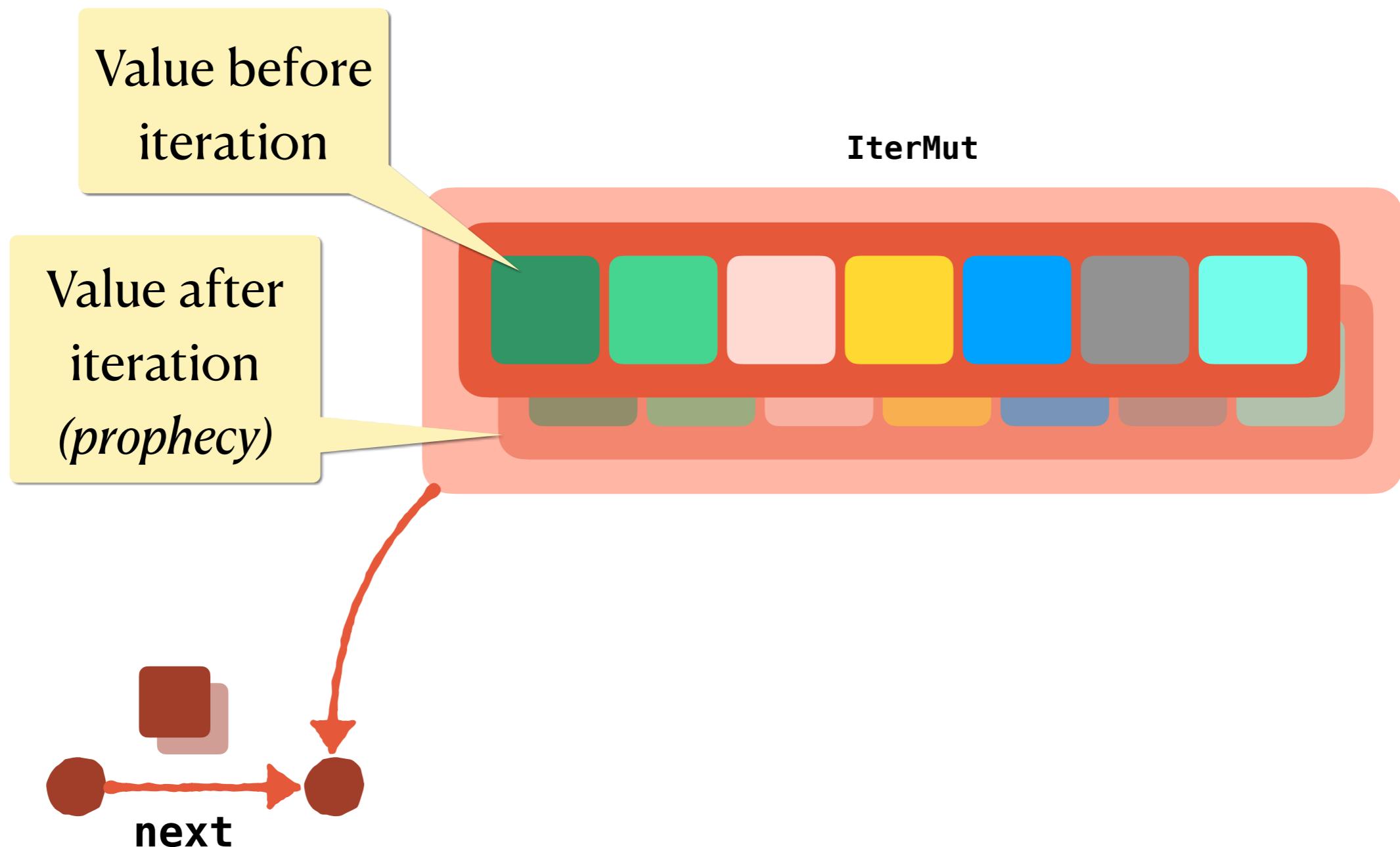
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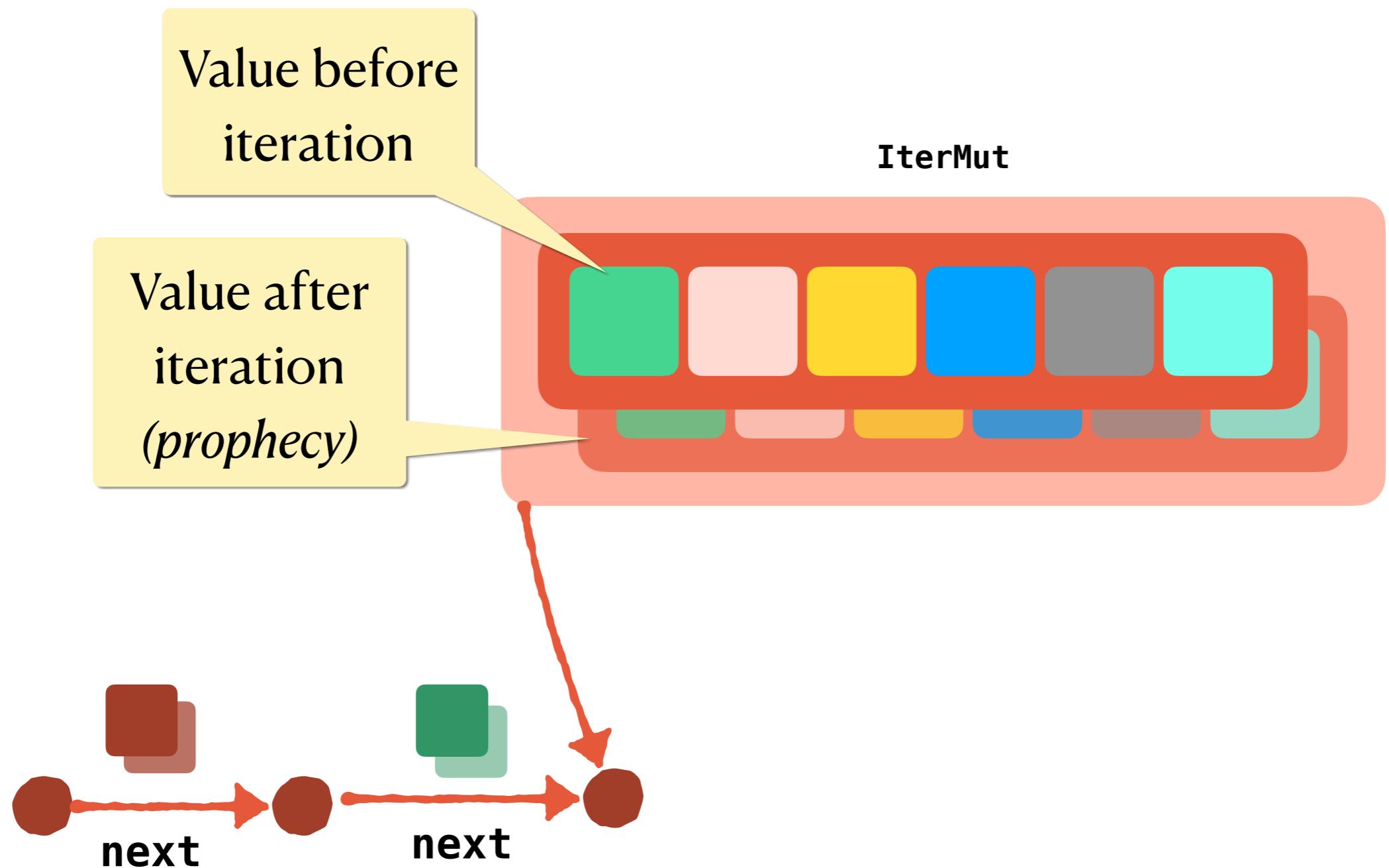
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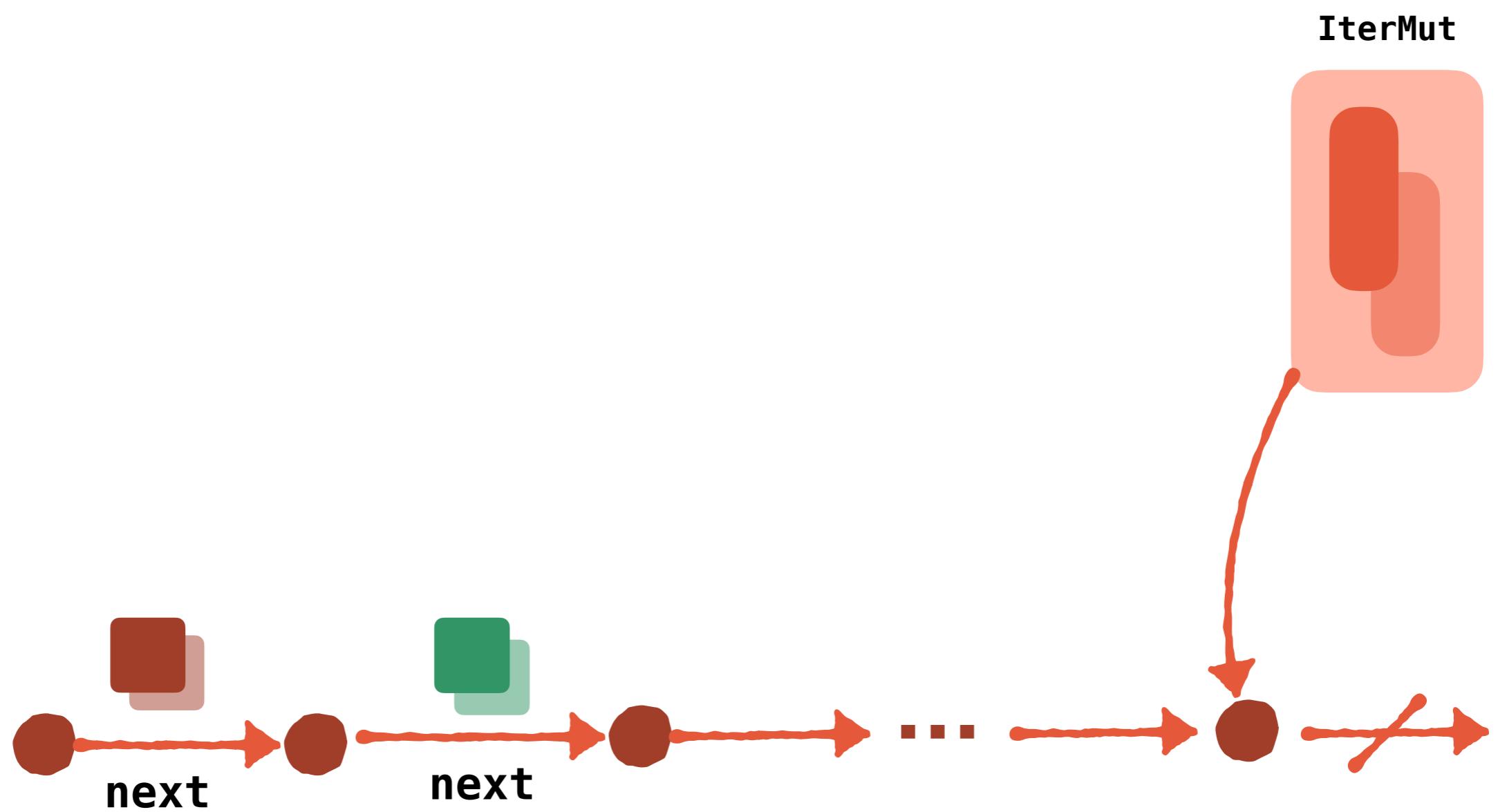
The IterMut Iterator



The IterMut Iterator



The IterMut Iterator



The IterMut Iterator

The transition relation

$$it \xrightarrow{v} it' \triangleq tr(it) = v \cdot tr(it')$$

where

$$tr(s) \triangleq [\&mut s[0], \dots, \&mut s[|s| - 1]]$$

The IterMut Iterator

Accepting States

$$\text{completed}(s) \triangleq |s| = 0$$

An alternative memcpy

With specifications

```
#[requires(tgt.len() == src.len())]
#[ensures(^tgt == *src)]
fn memcpy(tgt: &mut [u8], src: & [u8]) {
    #[invariant(∀ i, 0 ≤ i < produced.len()
        ==> tgt[i] == src[i])]
    for (t, s) in tgt.iter_mut().zip(src) {
        *t = *s;
    }
}
```

produced refers to previous
elements of **for**-loop

Higher-Order Iteration

Motivating Example

```
fn incr_vec() {
    let v = vec![1, 2, 3, 4];
    let mut cnt = 0;
    let w : Vec<u32> = v.iter()
        .map(|x| { cnt += 1; *x })
        .collect();

    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```

Higher-Order Iteration

Motivating Example

```
fn incr_vec() {
    let v = vec![1, 2, 3, 4];
    let mut cnt = 0;
    let w : Vec<u32> = v.iter()
        .map(|x| { cnt += 1; *x })
        .collect();

    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```

We ignore overflow here

The Map Iterator



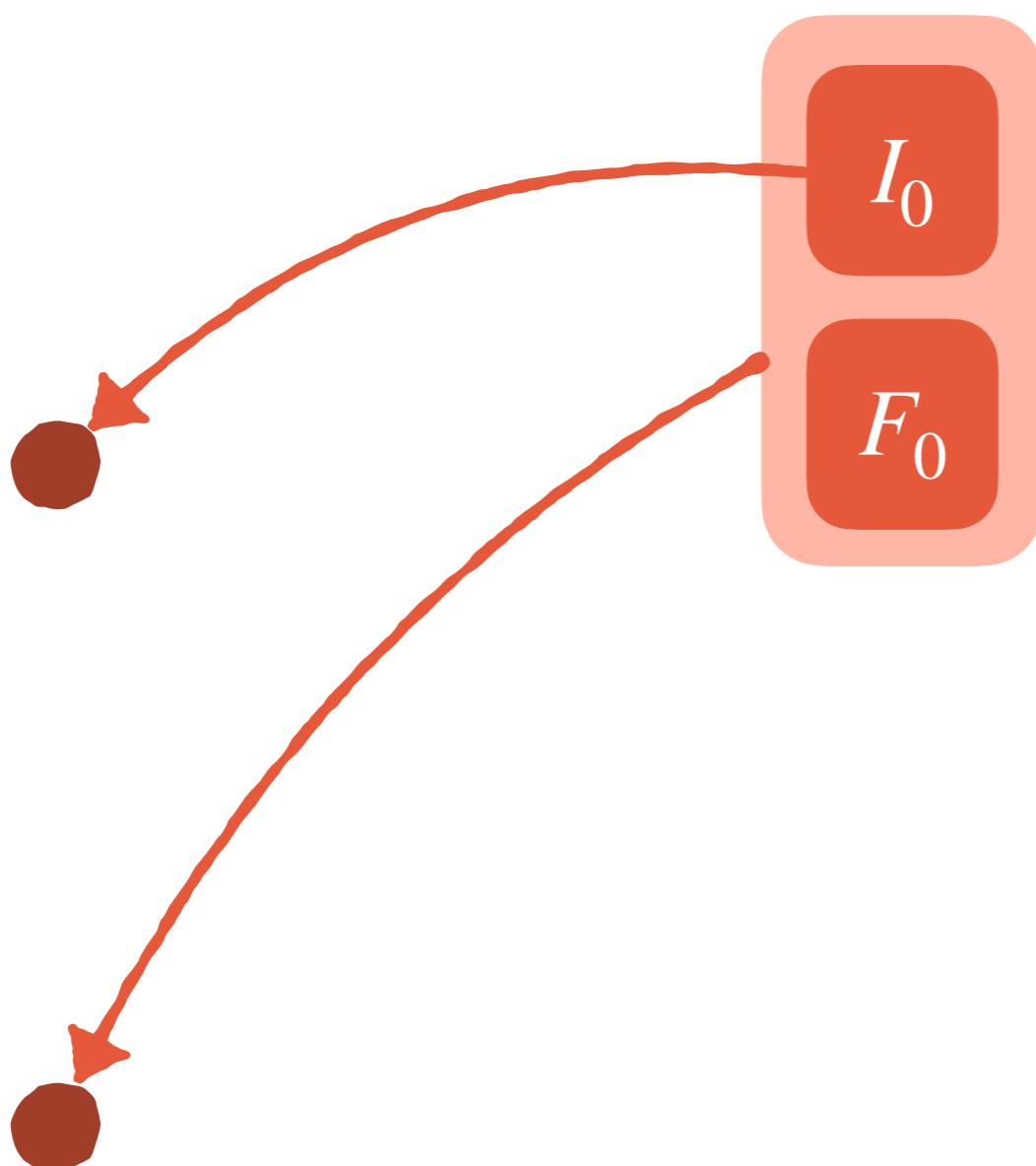
State is a pair of an
iterator and a closure

The Map Iterator

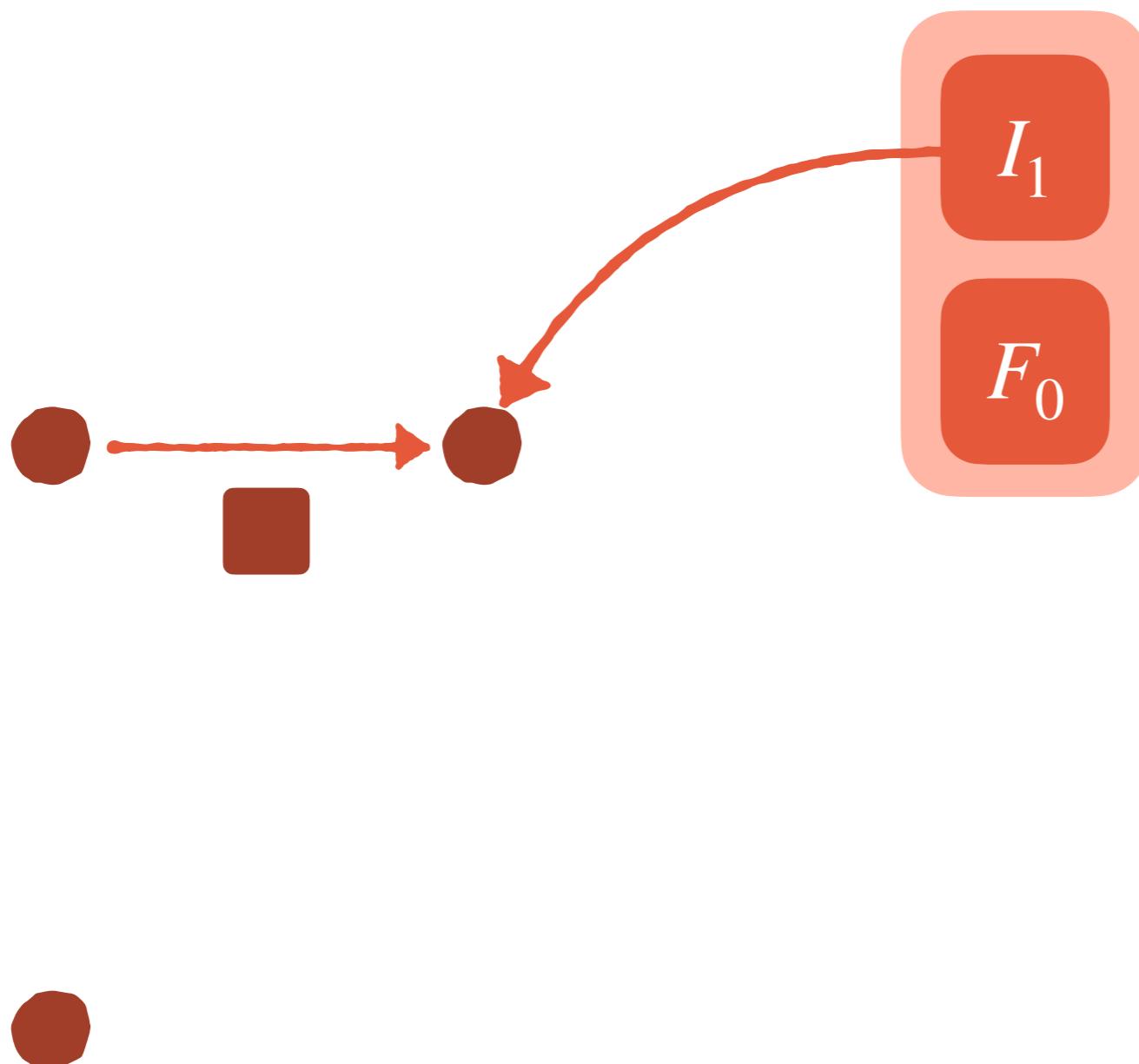


State is a pair of an iterator and a **closure**

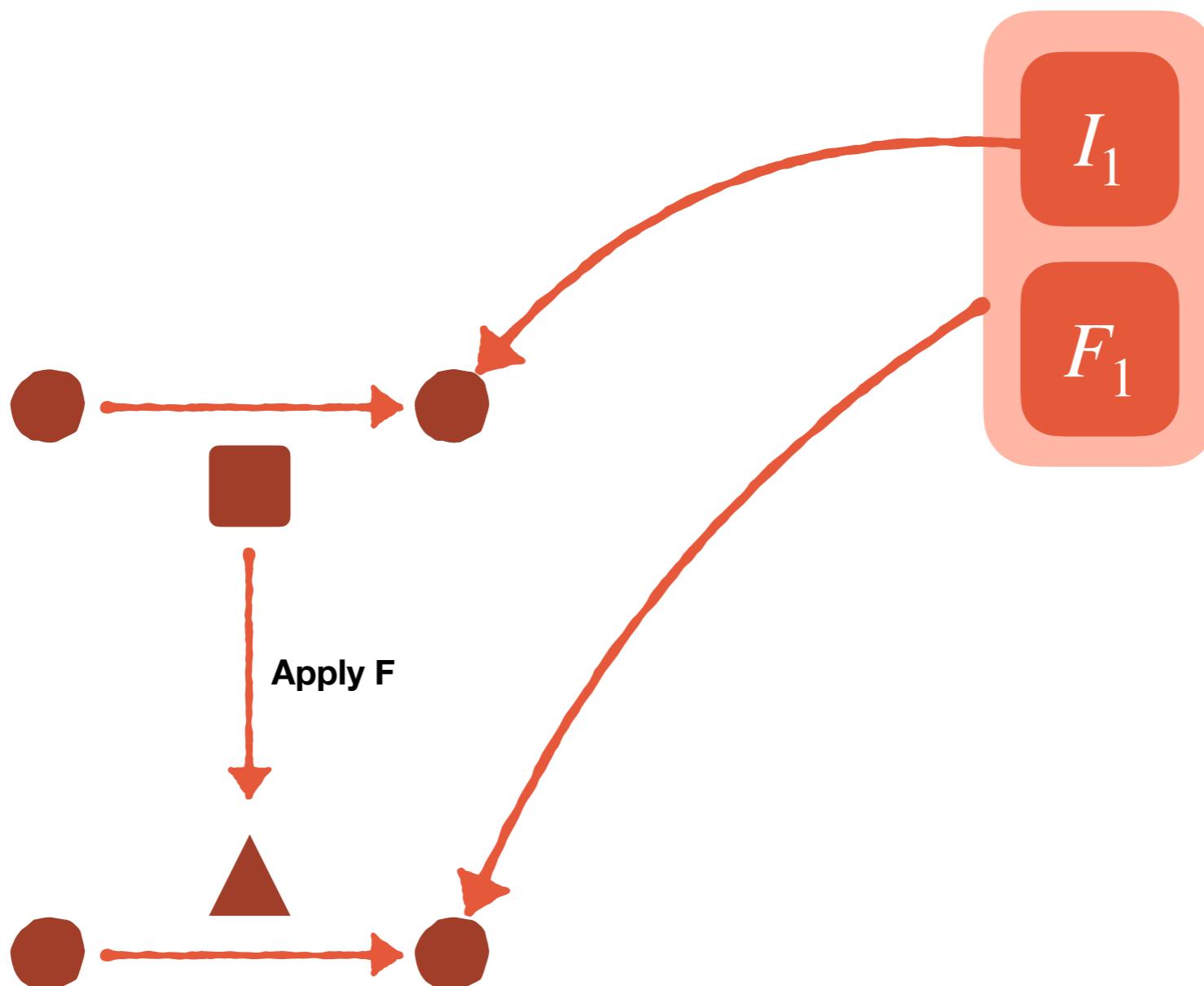
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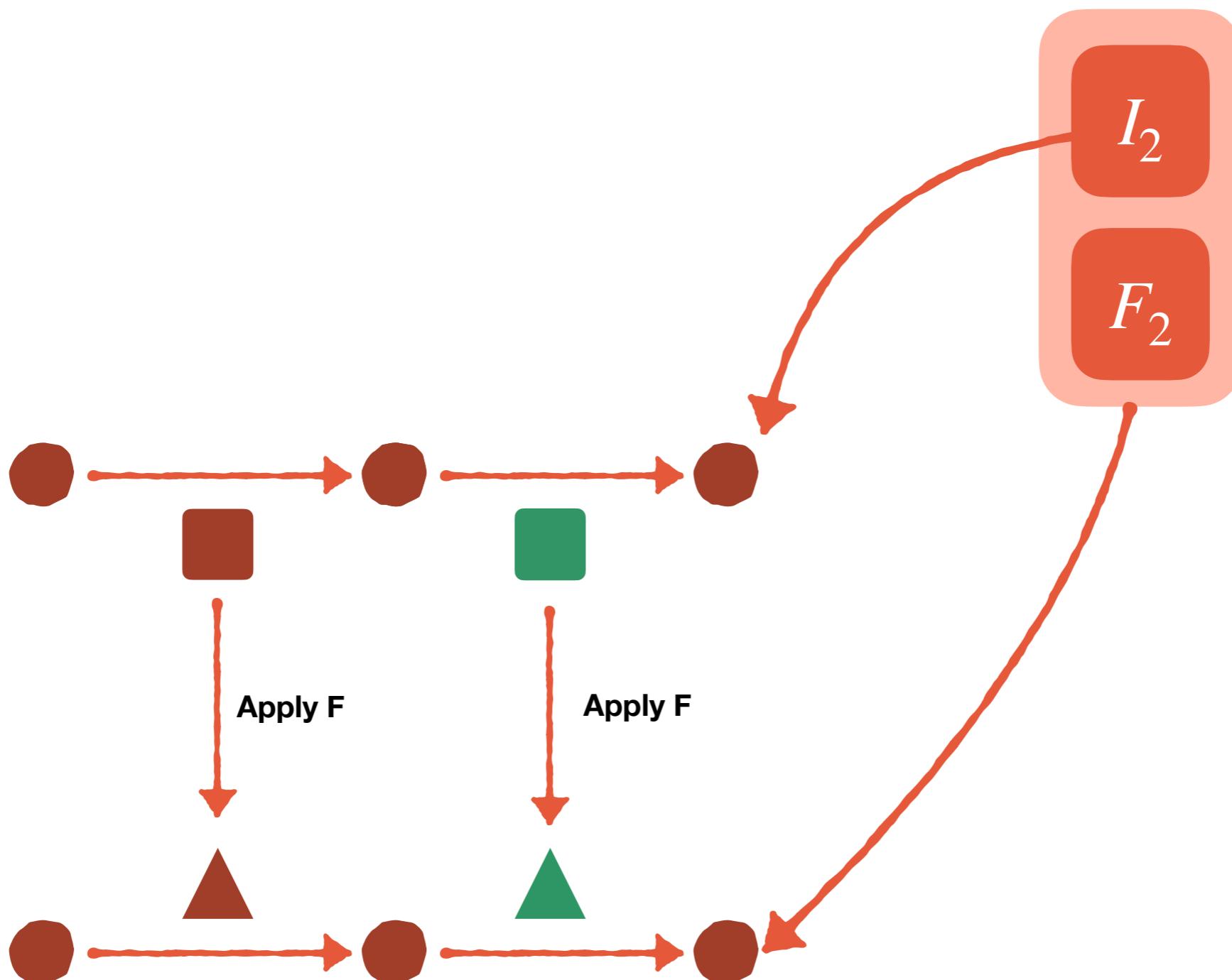
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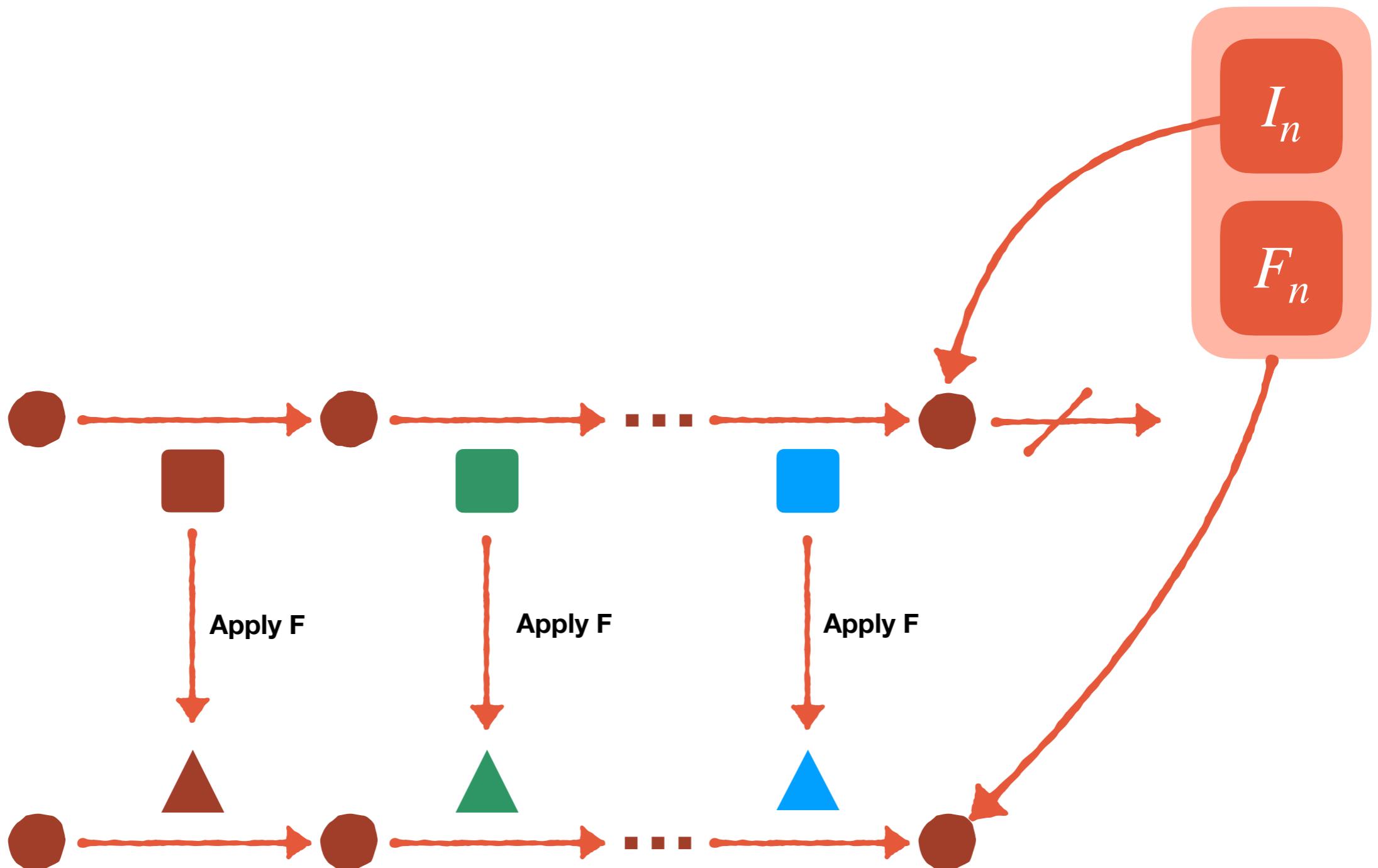
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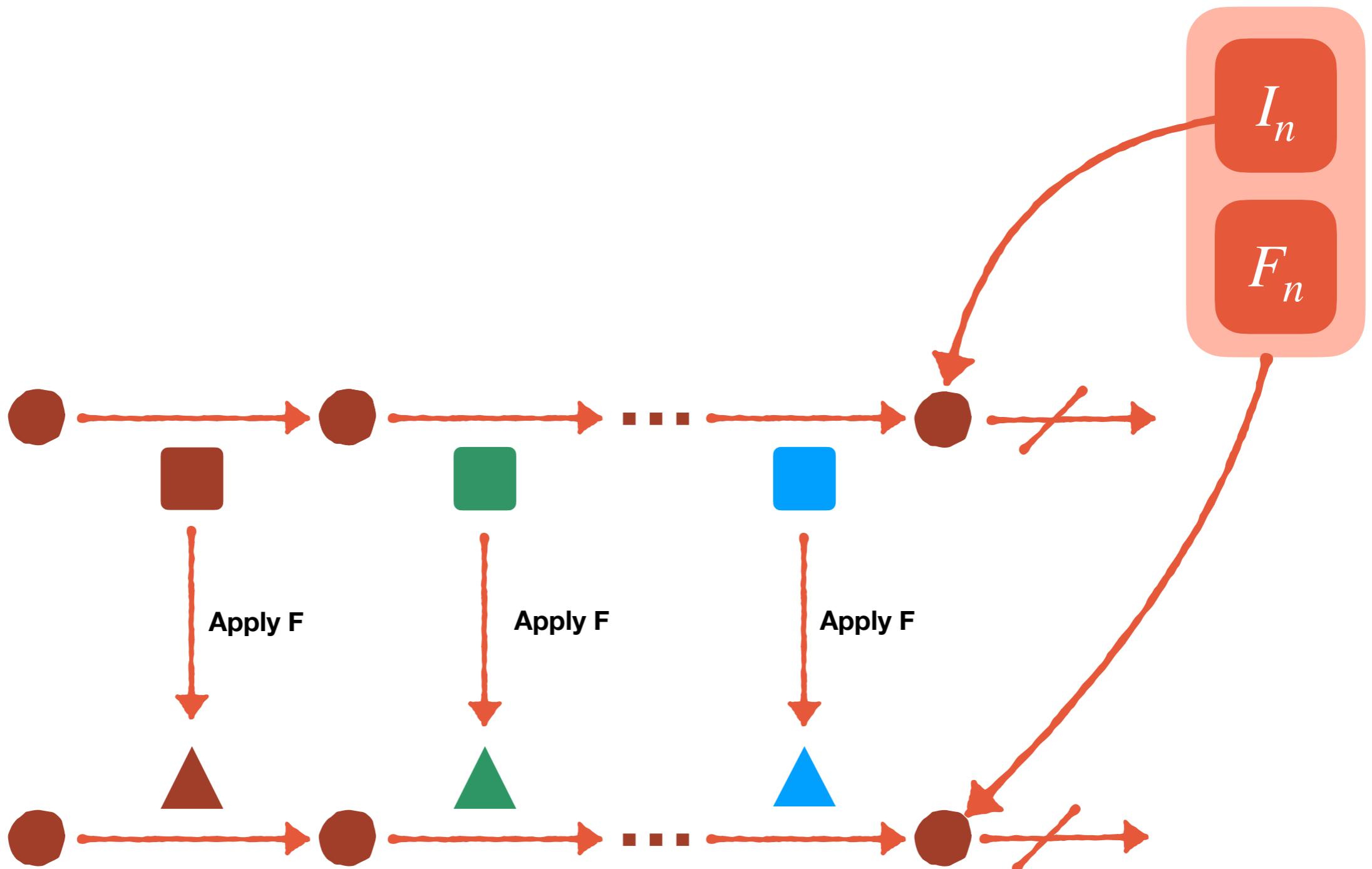
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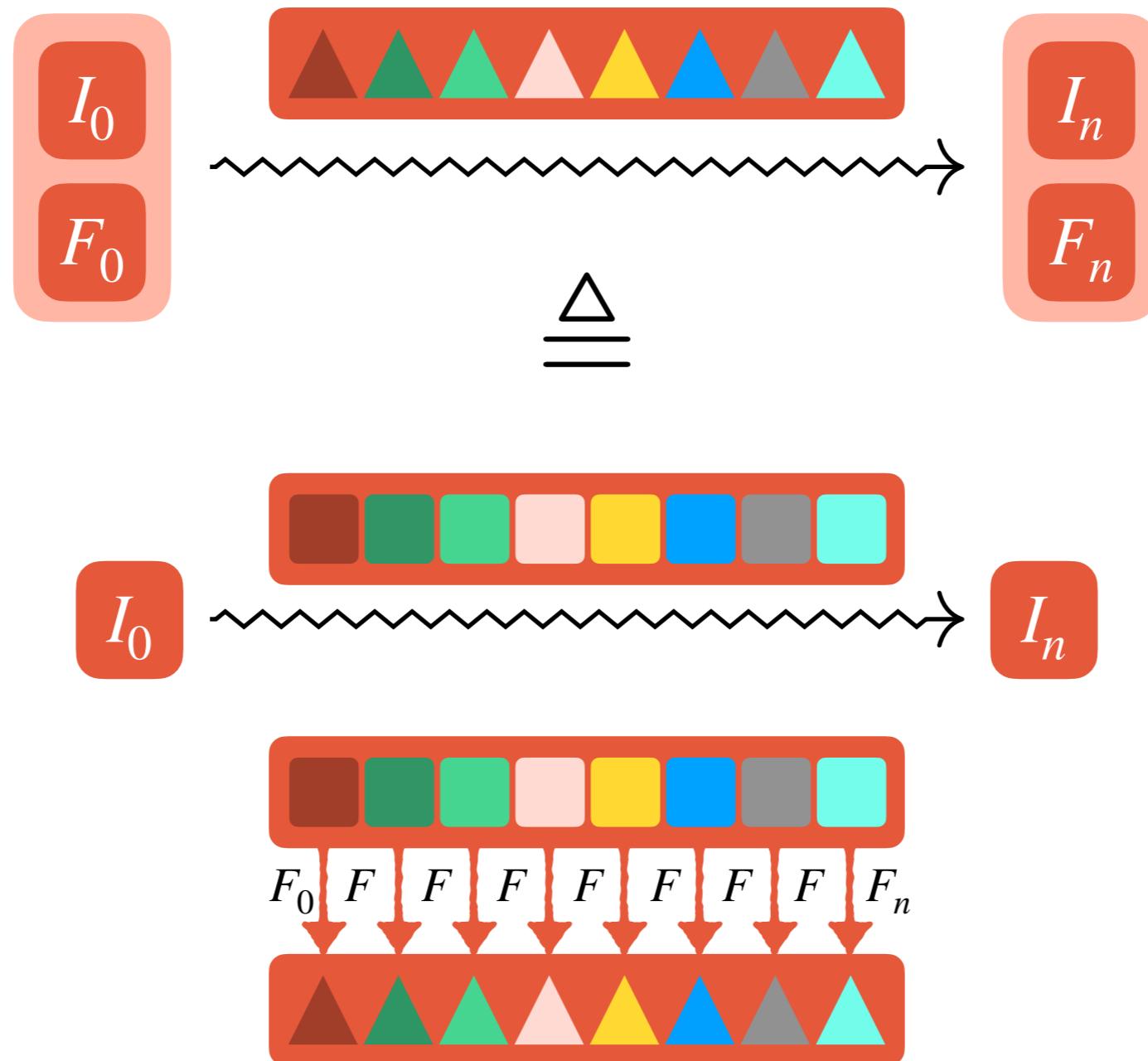


The Map Iterator



The Map Iterator

The produces relation



The Map Iterator

Accepting States

$$\begin{matrix} I \\ F \end{matrix} \in C \Leftrightarrow I \in C$$

The Map Iterator

Side-effects and Preconditions

```
fn incr_vec() {
    let v = vec![1, 2, 3, 4];
    let mut cnt = 0;
    let w : Vec<u32> = v.iter()
        .map(|x| { cnt += 1; *x })
        .collect();

    assert_eq!(w, v);
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```

The Map Iterator

Side-effects and Preconditions

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fn incr_vec() {
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    let mut cnt = 0;
    let w : Vec<u32> = v.iter()
        .map(|x| { cnt += 1; *x })
        .collect();

    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```

How do we prove this assertion?

The Map Iterator

Side-effects and Preconditions

```
fn incr_vec() {
    let v = vec![1, 2, 3, 4];
    let mut cnt = 0;
    let w : Vec<u32> = v.iter()
        .map(
            #[ensures(result == *x)]
            |x| { cnt += 1; *x }
        )
        .collect();

    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```

Map propagates this through collect to w

The Map Iterator

Side-effects and Preconditions

```
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The Map Iterator

Side-effects and Preconditions

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    let w : Vec<u32> = v.iter()
        .map(
            #[ensures(result == *x)]
            |x| { cnt += 1; *x }
        )
        .collect();

    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```



How do we prove *this* assertion?

The Map Iterator

Side-effects and Preconditions

```
fn incr_vec() {
    let v = vec![1, 2, 3, 4];
    let mut cnt = 0;
    let w : Vec<u32> = v.iter()
        .map(
            #[ensures(result == *x)]
            |x| { cnt += 1; *x }
        )
        .collect();

    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```

cnt maintains an *invariant* counting the number of iterated elements.

The Map Iterator

Side-effects and Preconditions

```
fn incr_vec() {
    let v = vec![1, 2, 3, 4];
    let mut cnt = 0;
    let w : Vec<u32> = v.iter()
        .map_hist(
            #[requires(cnt == prod.len())]
            #[ensures(cnt == prod.len() + 1)]
            #[ensures(result == *x)]
            |x, prod| { cnt += 1; *x }
        )
        .collect();
    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```

The Map Iterator

Side-effects and Preconditions

```
fn incr_vec() {
    let v = vec![1, 2, 3, 4];
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            #[ensures(result == *x)]
            |x, prod| { cnt += 1; *x }
        )
        .collect();
    assert_eq!(w, v);
    assert_eq!(cnt, 4);
}
```

Ghost access to past
elements

Recap

We showed a specification for iterators which leverages Rust types

Can handle mutability and side-effects (**IterMut**)

Can handle higher-order with mutable captures in FOL (**Map**)

We have proven **15+ different** iterators and clients

Map, IterMut, Zip, Enumerate, collect, ...

Soundness of Prophecies

Soundness of Prophecies

Prophetic translation is subtle and hard to justify

Does a value always exist for a prophecy?

Syntactic approaches to soundness don't work well for Rust

Unsafe code allows ‘extending’ Rust with new ‘primitive’ types

RustBelt solves this using a semantic model of Rust type system

RustBelt

What is it?

A formal model of the core Rust type system.

Uses a language called λ_{Rust} approximating **MIR**

Typing judgments are *theorems* in Iris, resulting system is *open*

New rules can be proved *post-hoc* without affecting soundness

Theorem. (*Adequacy*). *For any λ_{Rust} function f such that $\emptyset \mid \emptyset \vdash f \dashv x.x : \text{fn}(\emptyset) \rightarrow ()$ holds, no execution of f ends in a stuck state.*

RustHornBelt

Type-Spec Judgements

Extends the type judgements of **RustBelt** with specifications

Specifications are provided as *predicate transformers*

Requires a novel **prophecy resource algebra** for Iris

Uses a ‘many-worlds’ interpretation of prophecies

Reuses much of the proof architecture; a natural extension

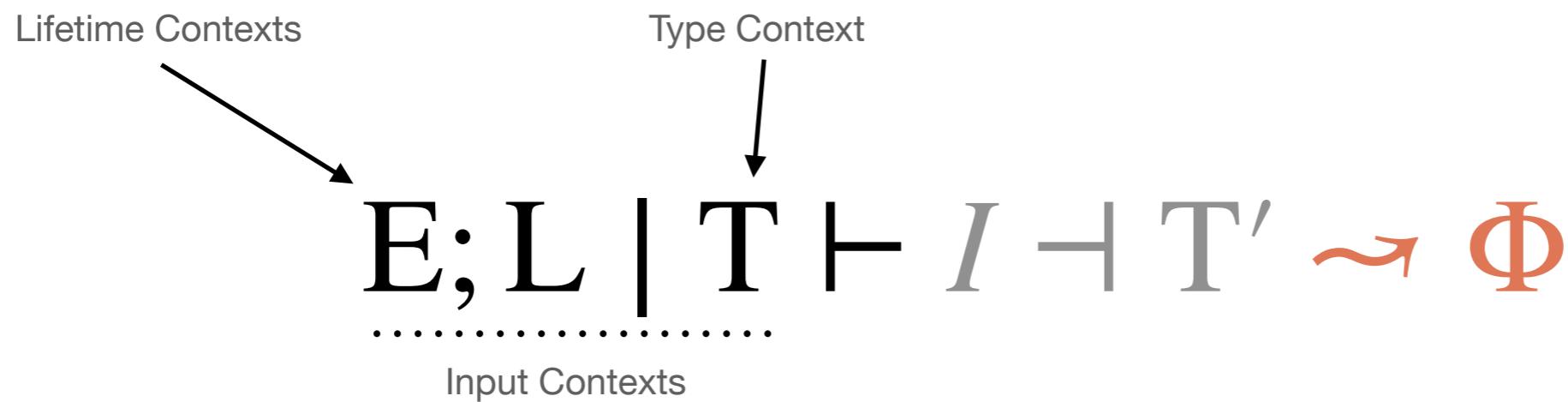
RustHornBelt

Type-Spec Judgements

$$E; L \mid T \vdash I \dashv T' \rightsquigarrow \Phi$$

RustHornBelt

Type-Spec Judgements



RustHornBelt

Type-Spec Judgements

$$E; L \mid T \vdash I \dashv T' \rightsquigarrow \Phi$$

....
Instruction

RustHornBelt

Type-Spec Judgements

$$E; L \mid T \vdash I \dashv T' \rightsquigarrow \Phi$$

.....
Output Contexts

RustHornBelt

Type-Spec Judgements

$$E; L \mid T \vdash I \dashv T' \rightsquigarrow \Phi$$

....
Specification

RustHornBelt

Interpretation of judgments

$$\begin{aligned} \llbracket L \mid T \vdash I \dashv a. T' \rightsquigarrow \Phi \rrbracket &\triangleq \\ \forall \hat{\Psi}. \{ \exists \bar{a}. \llbracket L \rrbracket * \llbracket T \rrbracket(\bar{a}) \\ &* \langle \lambda\pi. \Phi(\hat{\Psi}\pi)(\bar{a}\pi) \rangle \} \\ I \{ r. \exists \bar{b}. \llbracket L \rrbracket * \llbracket T' \rrbracket(\bar{b}) \\ &* \langle \lambda\pi. (\hat{\Psi}\pi)(\bar{b}\pi) \rangle \} \end{aligned}$$

RustHornBelt

Interpretation of judgments

$$\llbracket \mathbf{L} \mid \mathbf{T} \vdash I \dashv a. \mathbf{T}' \rightsquigarrow \Phi \rrbracket \triangleq \begin{array}{l} \text{An instruction is well-typed if:} \\ \forall \hat{\Psi}. \left\{ \exists \bar{a}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T} \rrbracket(\bar{a}) \right. \\ \quad \left. * \langle \lambda \pi. \Phi(\hat{\Psi} \pi)(\bar{a} \pi) \rangle \right\} \\ I \left\{ r. \exists \hat{b}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T}' \rrbracket(\hat{b}) \right. \\ \quad \left. * \langle \lambda \pi. (\hat{\Psi} \pi)(\hat{b} \pi) \rangle \right\} \end{array}$$

RustHornBelt

Interpretation of judgments

$$\llbracket \mathbf{L} \mid \mathbf{T} \vdash I \dashv a. \mathbf{T}' \rightsquigarrow \Phi \rrbracket \triangleq$$

$$\forall \hat{\Psi}. \{ \exists \bar{a}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T} \rrbracket(\bar{a})$$

$$* \langle \lambda\pi. \Phi(\hat{\Psi}\pi)(\bar{a}\pi) \rangle \}$$

$$I \{ r. \exists \hat{b}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T}' \rrbracket(\hat{b})$$

$$* \langle \lambda\pi. (\hat{\Psi}\pi)(\hat{b}\pi) \rangle \}$$

An instruction is well-typed if:

Given resources for \mathbf{L} and \mathbf{T} ...

RustHornBelt

Interpretation of judgments

$$\llbracket \mathbf{L} \mid \mathbf{T} \vdash I \dashv a. \mathbf{T}' \rightsquigarrow \Phi \rrbracket \triangleq$$
$$\forall \hat{\Psi}. \{ \exists \bar{a}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T} \rrbracket(\bar{a})$$
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$$* \langle \lambda \pi. (\hat{\Psi} \pi)(\hat{b} \pi) \rangle \}$$

An instruction is well-typed if:

Given resources for \mathbf{L} and \mathbf{T} ...

...and a precondition from Φ ...

RustHornBelt

Interpretation of judgments

$$\llbracket \mathbf{L} \mid \mathbf{T} \vdash I \dashv a. \mathbf{T}' \rightsquigarrow \Phi \rrbracket \triangleq$$

$$\forall \hat{\Psi}. \{ \exists \bar{a}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T} \rrbracket(\bar{a})$$

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$$I \{ r. \exists \hat{b}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T}' \rrbracket(\hat{b}) \}$$

$$* \langle \lambda\pi. (\hat{\Psi}\pi)(\bar{\hat{b}}\pi) \rangle \}$$

An instruction is well-typed if:

Given resources for \mathbf{L} and \mathbf{T} ...

...and a precondition from Φ ...

...executing I gives back \mathbf{L} and \mathbf{T}' ...

RustHornBelt

Interpretation of judgments

$$\llbracket \mathbf{L} \mid \mathbf{T} \vdash I \dashv a. \mathbf{T}' \rightsquigarrow \Phi \rrbracket \triangleq$$

$$\forall \hat{\Psi}. \{ \exists \bar{a}. \llbracket \mathbf{L} \rrbracket * \llbracket \mathbf{T} \rrbracket(\bar{a})$$

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$$* \langle \lambda\pi. (\hat{\Psi}\pi)(\bar{b}\pi) \rangle \}$$

An instruction is well-typed if:

Given resources for \mathbf{L} and \mathbf{T} ...

...and a precondition from Φ ...

...executing I gives back \mathbf{L} and \mathbf{T}' ...

...and postcondition Ψ

RustHornBelt

Example Judgements

MUTBOR-BOR

$$\alpha \mid a : \mathbf{own} \ T \vdash \&\mathbf{mut} \ * \ a \dashv b. \ a : {}^{\dagger\alpha} \mathbf{own} \ T, b : \&_{\alpha}\mathbf{mut} \ T$$
$$\rightsquigarrow \lambda \Psi, [a]. \forall a'. \Psi[a', (a, a')]$$

MUTBOR-WRITE

$$\alpha \mid b : \&_{\alpha}\mathbf{mut} \ T, c : T \vdash *b = c \dashv b. \ b : \&_{\alpha}\mathbf{mut} \ T$$
$$\rightsquigarrow \lambda \Psi, [b, c]. \Psi[(c, b.2)]$$

MUTBOR-BYE

$$\alpha \mid b : \&_{\alpha}\mathbf{mut} \ T \vdash \dashv$$
$$\rightsquigarrow \lambda \Psi, [b]. \ b.2 = b.1 \rightarrow \Psi []$$

Adequacy Revisited

Theorem. (Adequacy). *For any λ_{Rust} function f such that $\emptyset \mid \emptyset \vdash f \dashv x.x : \text{fn}(\emptyset) \rightarrow () \rightsquigarrow \lambda\Psi, [] . \Psi [\lambda\Psi', [] . \Psi' ()]$ holds, no execution of f (with the trivial continuation) ends in a stuck state.*

Our λ_{Rust} contains assertions, theorem implies their validity

Also implies core safety properties like inbounds array accesses

RustHornBelt

Verifying Unsafe Code

Developed **RustHornBelt** with Y. Matsushita and D. Dreyer

PLDI'22 (Distinguished Paper)

Extends **RustBelt** to reason about *functional correctness*

Final Coq proof totals ~19kloc

Can prove safety of unsafe code including Vec, Mutex, and Cell

Applications

CreuSAT: A *performant* formally verified CDCL Sat solver

Developed and proven by Sarek Skotåm

~3kloc specifications, ~1kloc executable

~3 mins to check proofs

Sprout: A simple SMT solver, but a good benchmark for Creusot

Collaboration with M. Bonacina and S. Graham-Lengrand at SRI

~2kloc specification, ~1.5kloc executable

~1 min to check proofs

Perspectives

Concurrency: Efficiently handling `async/await` is key in Rust

Linear ghost code could open the door, but interaction with prophecies is unclear

Mutable aliasing & raw pointers

Handling *raw pointers* would let Creusot close a gap in verification

User experience & scalability of verification

Verification is limited by how fast *bad proofs* can be solved, how can this be improved?

Conclusion

Creusot is publicly available today

Used in collaboration with laboratories all over the world

Key Publications:

“Creusot: A Foundry for the Deductive Verification of Rust Programs”, ICFEM’22

“RustHornBelt: A Semantic Foundation for Functional Verification of Rust Programs with Unsafe Code”, PLDI’22

Distinguished Paper

“Specifying and Verifying Higher-Order Rust Iterators”, TACAS’23