The Usability of Advanced Type Systems: Rust as a Case Study

Kasra Ferdowsi

04/27/2022

Overview

1. History
2. Rust
3. Usability
4. Future Work

Overview

1. History
    1.1. Linear Types
    1.2. Region-based Memory Management
    1.3. Ownership Types
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1.1 Linear Types

- "Use *Exactly* Once" [25]:

```
copy :: a → (a, a)
copy a = (a, a)
```

```
drop :: a → ()
drop a = ()
```

1.1 Linear Types

- "Use *Exactly* Once" [25]:

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- Memory management:

```
append :: List → List → List
append = λxs → …
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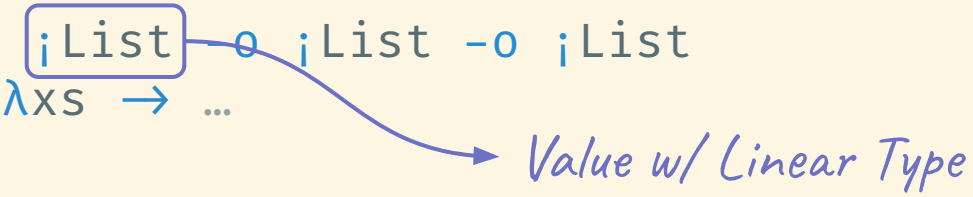

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Function w/ Linear Param

1.2 Region-based Memory Management

- Tofte and Talpin 1997 [24]

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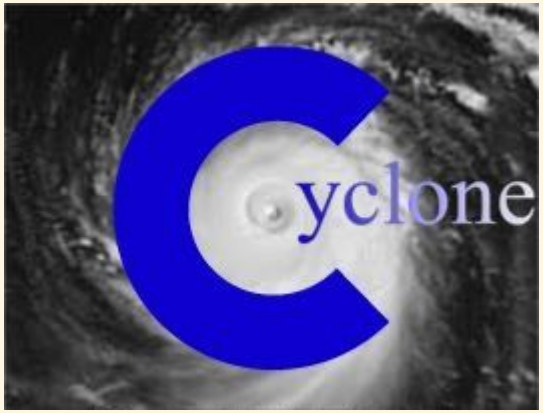
"A Safe Dialect of C"



1.2 Region-based Memory Management

- Region Types [16]

```
region h {
  int* x = rmalloc(h, sizeof(int));
  int? y = rnew(h) { 1, 2, 3 };
  char? z = rprintf(h, "hello");
}
```

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```

maps to a dynamic growable region of memory

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1.3 Ownership Types [6]

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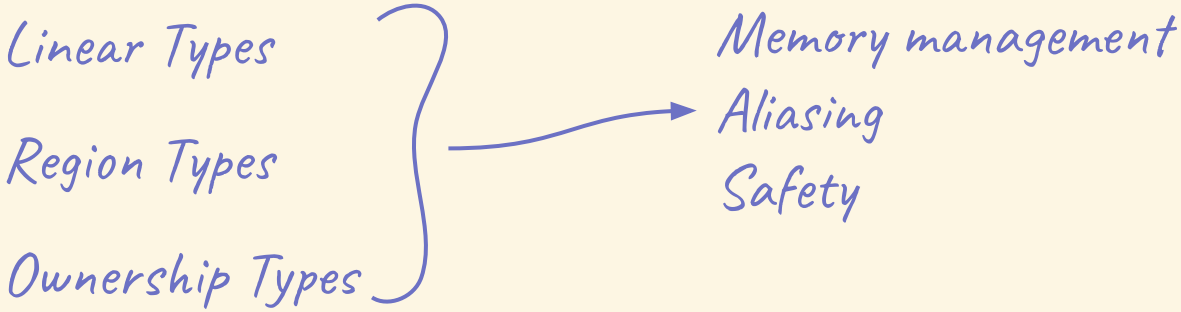
1 History

Linear Types

Region Types

Ownership Types

1 History


Linear Types
Region Types
Ownership Types
Memory management
Aliasing
Safety

Overview

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Overview

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    2.1. Ownership
    2.2. Lifetimes
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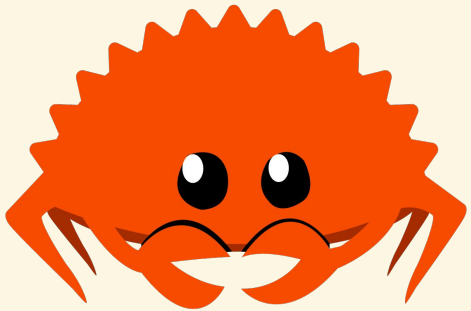
2 Rust

- Started in 2010 @ Mozilla Research
- Mascot is *Ferris*
- Its ~~cultists~~ are know as "Rustaceans"

community



2 Rust

- Ownership & Borrowing

```
fn main() {
  let owner: Vec<i32> = vec![1, 2, 3];
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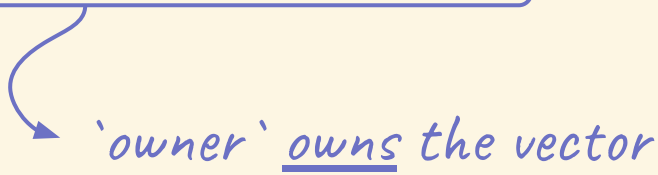

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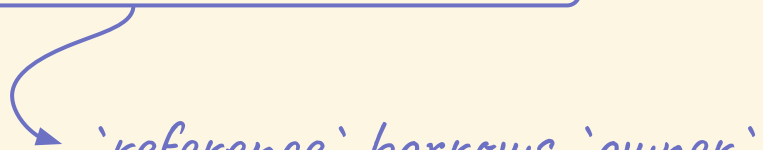

2 Rust

- Mutability

```
fn main() {
  let owner: Vec<i32> = vec![1, 2, 3];
  owner.push(4);

  let reference: &Vec<i32> = &owner;
}
```

2 Rust

- Mutability

```
fn main() {
  let owner: Vec<i32> = vec![1, 2, 3];
  owner.push(4);
  ^^^^^^^^^^^^ cannot borrow as mutable
  let reference: &Vec<i32> = &owner;
}
```

2 Rust

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fn main() {
  let mut owner: Vec<i32> = vec![1, 2, 3];
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fn main() {
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  owner.push(4);

  let reference: &mut Vec<i32> = &mut owner;
  reference.push(5);
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2.1 Ownership

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2.1 Ownership

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```
fn main() {
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  let v2 = v;
  print(v);
}
```

2.1 Ownership

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```
fn main() {
  let v = vec![1, 2, 3];
  let v2 = v;                    value moved here
  print(v);                      value used here after move
}
```

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fn main() {
  let v = vec![1, 2, 3];
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  let y = x + 1;
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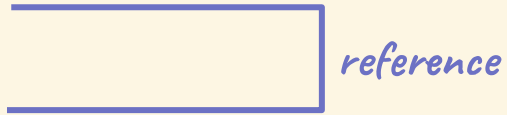

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```
fn main() {
  let v = vec![1, 2, 3];
  let x = &v[0];              borrow out of `v` occurs here
  let v2 = v;                 move out of `v` occurs here
  let y = x + 1;              borrow later used here
}
```

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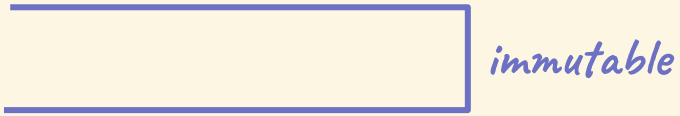


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  v.push(4);                mutable borrow occurs here
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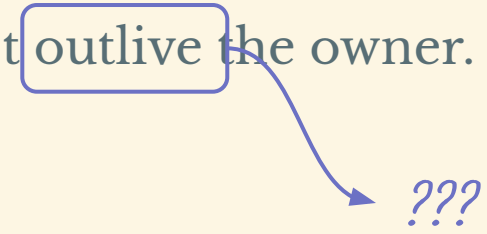

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Lifetimes

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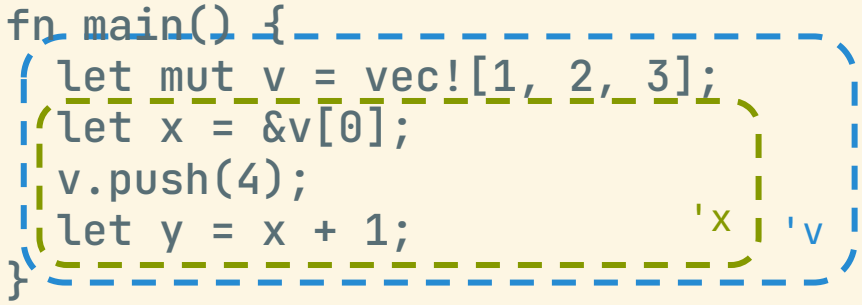

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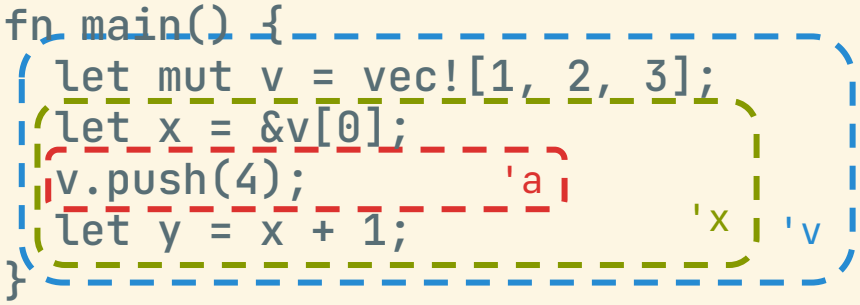

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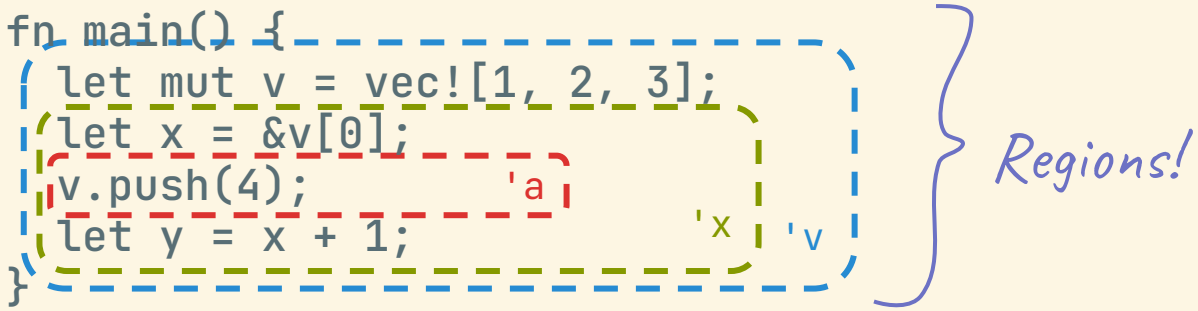

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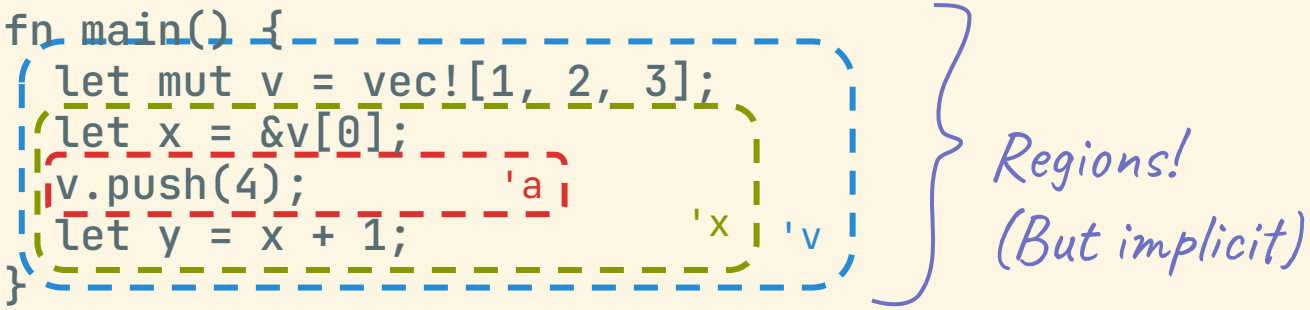

2 Rust

Quick break!

Any questions so far?

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1. History
2. Rust
    a. Ownership
    b. Lifetimes
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Overview

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3.1 Is Rust Difficult?

"Learning Rust Ownership is like navigating a maze where the walls are made of asbestos and frustration, and the maze has no exits, and every time you hit a dead end you get an aneurysm and die." [8]

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    - 3.2. *Why* is Rust's Ownership difficult?
    - 3.3. Why do people use Rust anyway?
4. Future Work

3.1 Is Rust Difficult?

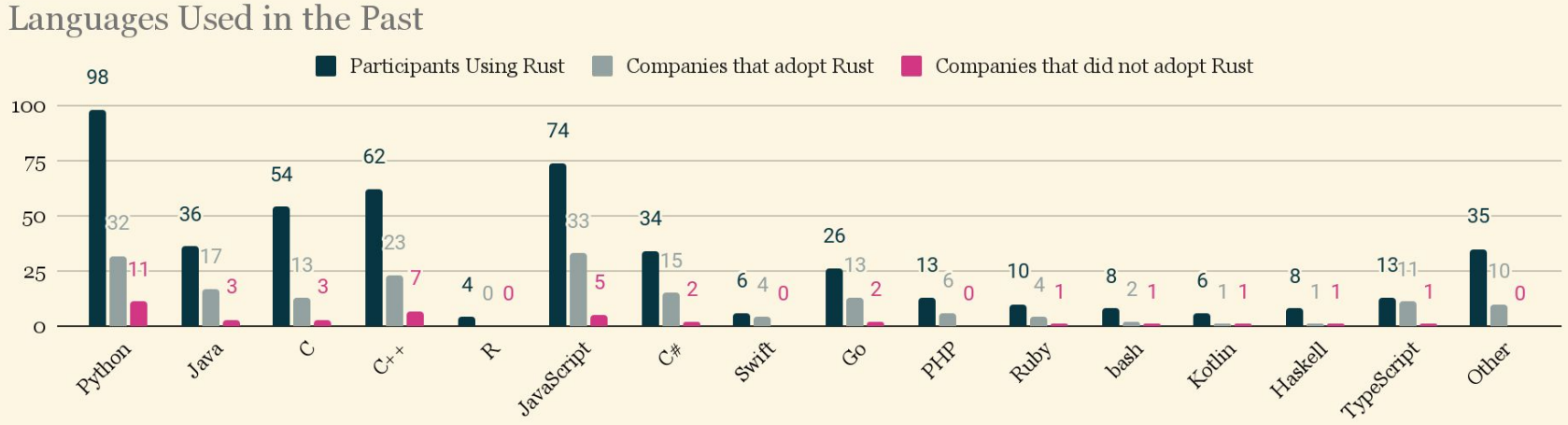
- Zeng and Crichton 2019 [26]

  "The complexity of the borrow checker was the second most frequently mentioned complaint"

3.1 Is Rust Difficult?

- Fulton and friends 2021 [12]

  "A near-vertical learning curve"



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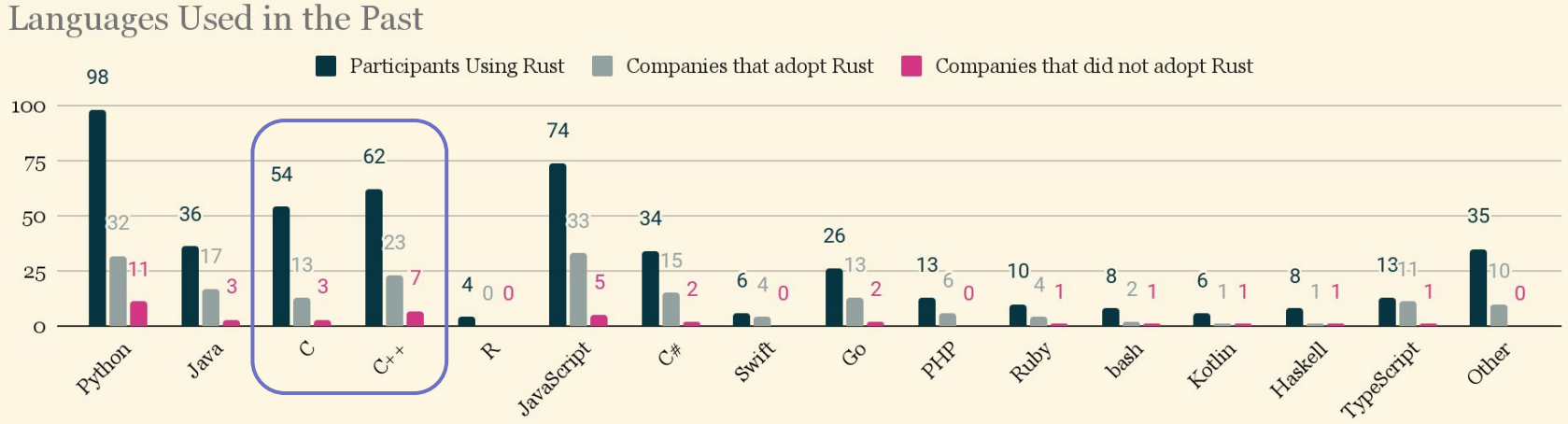

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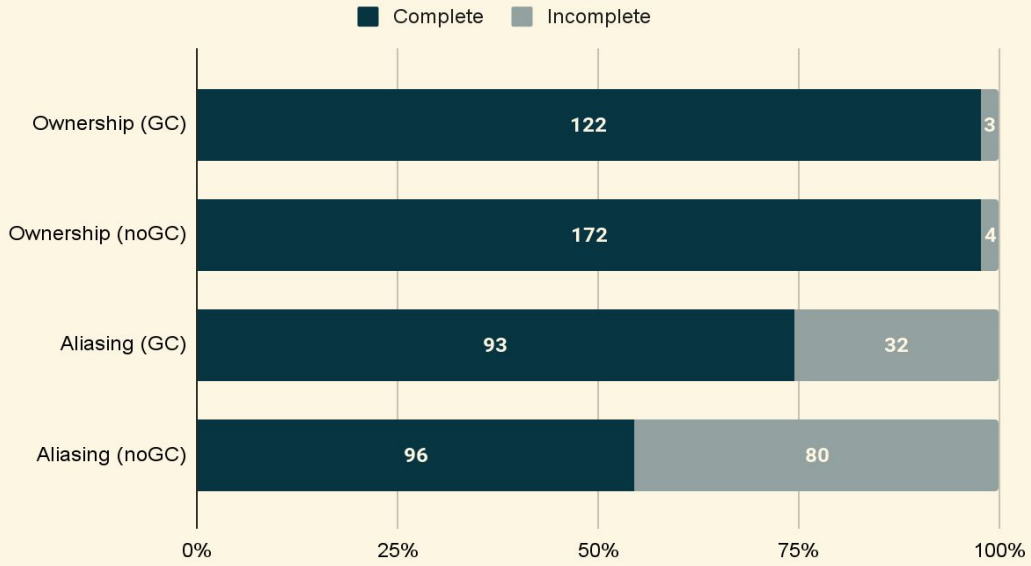

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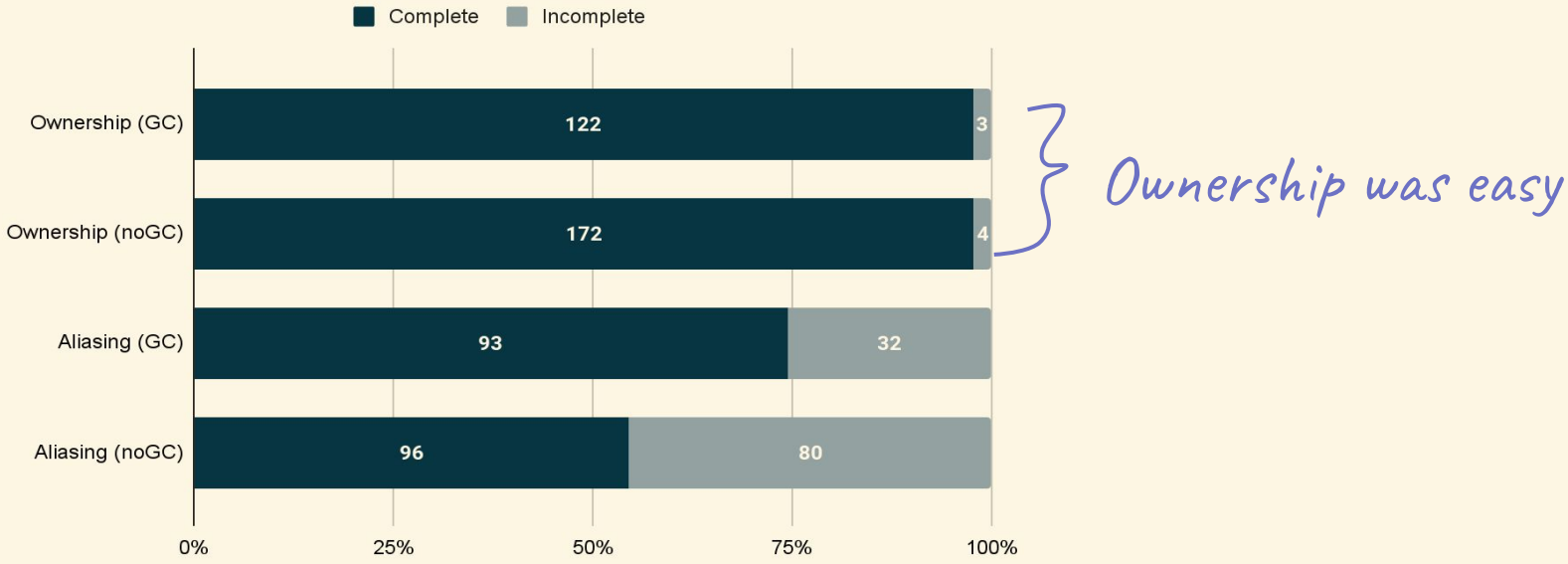

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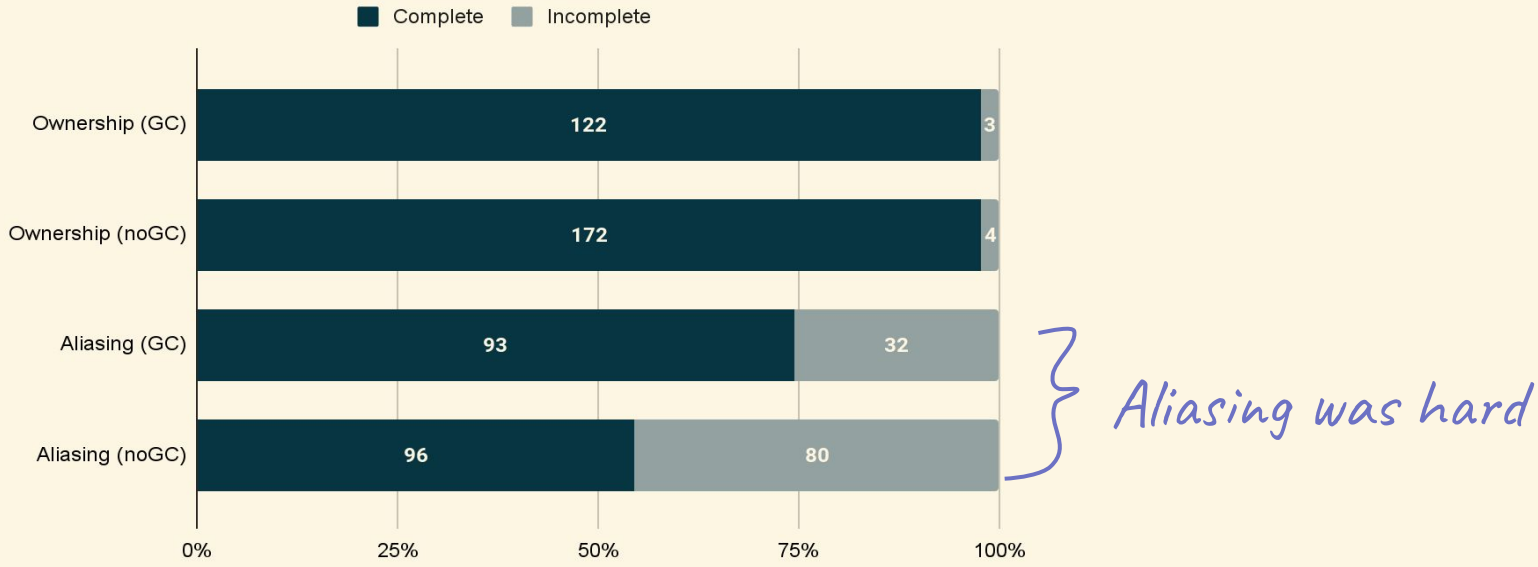

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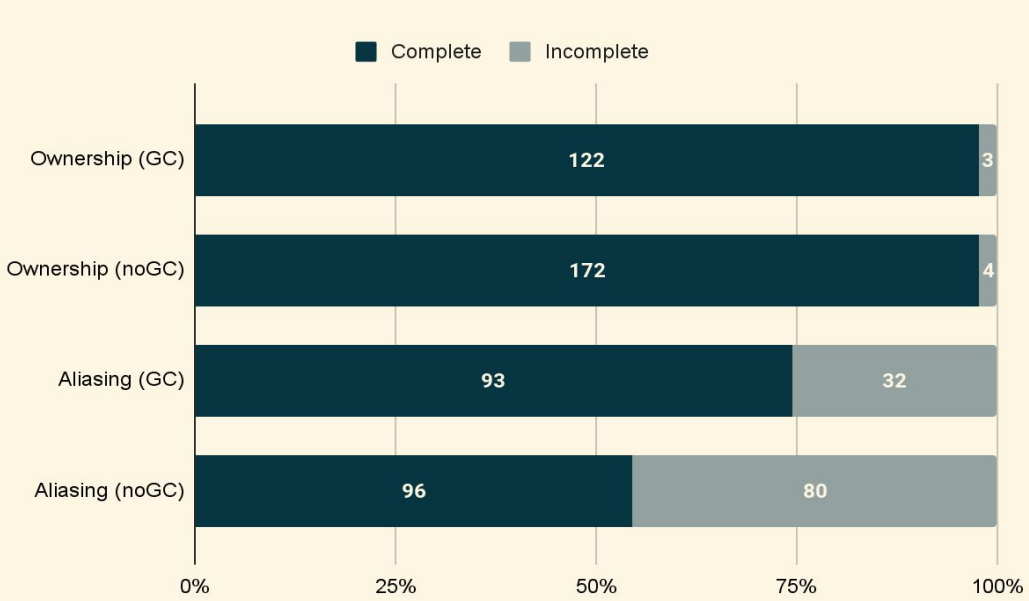

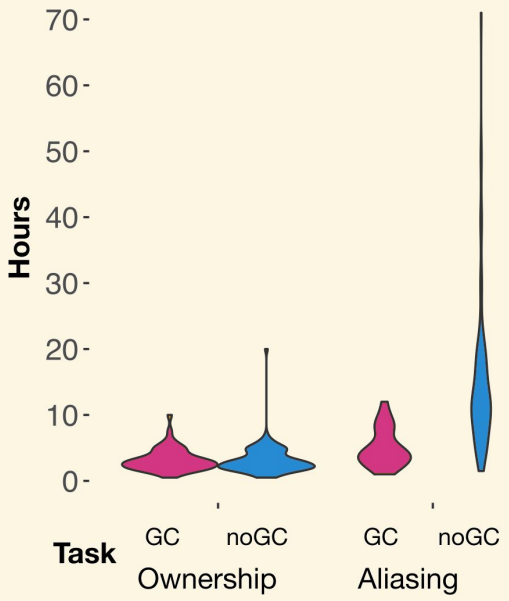

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- What about experienced Rust developers?
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  - The Rust Survey 2020 [20]: "**lifetimes**"
  - Zhu & friends [27]: "complex **lifetime** computations"

3.1 Is Rust Difficult?

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Yes!

Lifetimes are difficult even for experienced Rustaceans.

3.2 Why Is Rust Difficult?

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Walls of text coming...

Sorry!

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  - Rust's borrow-checker "forces a programmer to think differently" [21]
  - *Not just because it's a low-level language!*

3.2 Why Is Rust Difficult?

- Error Messages

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- Error Messages

```
error[E0384]: cannot assign twice to immutable variable `x`
  ⟶ blah.rs:7:5
   |
6  |  let x = 1;
   |      -
   |      |
   |      first assignment to `x`
   |      help: consider making this binding mutable: `mut x`
7  |  x += 1;
   |  ^^^^^^ cannot assign twice to immutable variable

error: aborting due to previous error

For more information about this error, try `rustc --explain E0384`.
```

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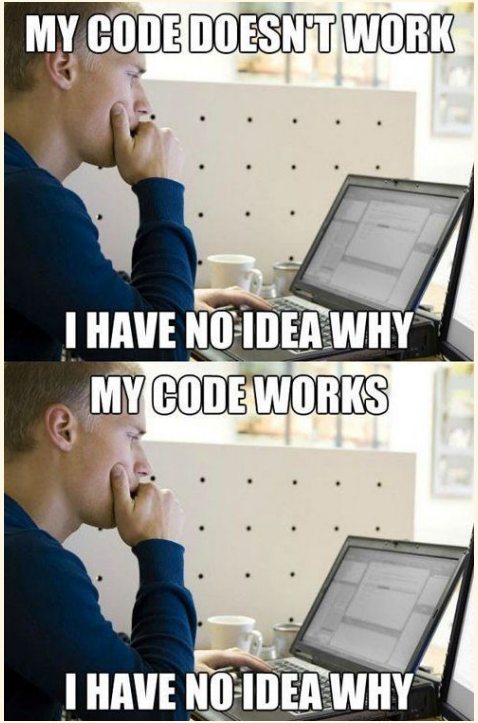
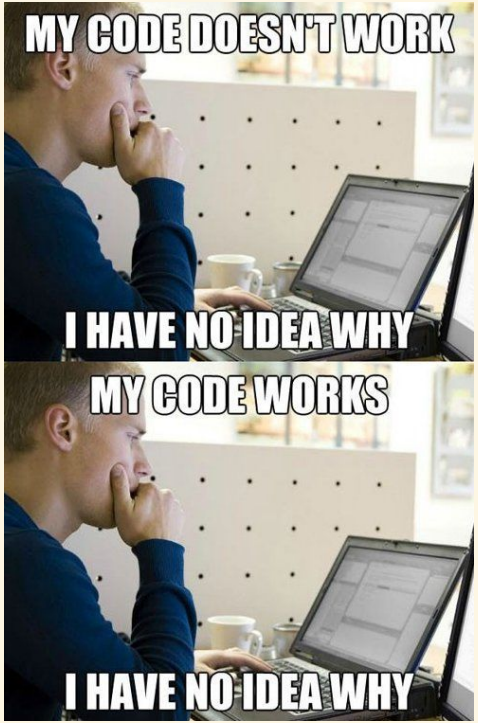


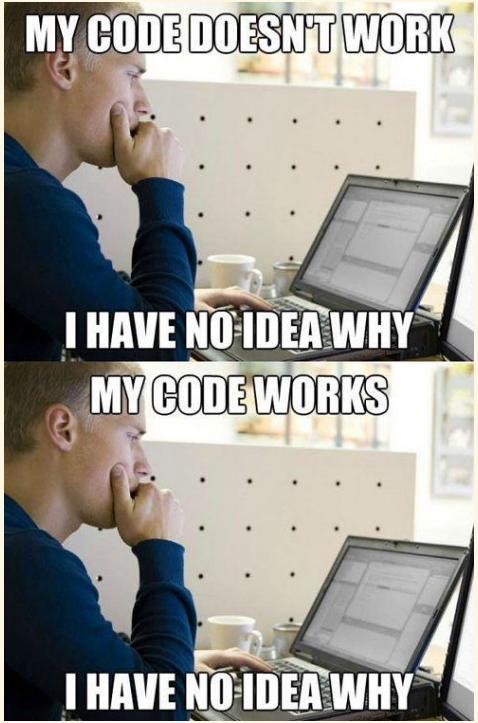
3.2 Why Is Rust Difficult?

- Error Messages & Design Feedback [8]
  - "Getting weird errors I still don't understand but just fixed by listening to the compiler"



3.2 Why Is Rust Difficult?

- Error Messages & Design Feedback [8]
  - "Getting weird errors I still don't understand but just fixed by listening to the compiler"
  - "Error messages were cyclical with things like `remove &` then after removing `try adding &`"



3.2 Why Is Rust Difficult?

- Error Messages & Context [27]

3.2 Why Is Rust Difficult?

- Error Messages & Context [27]
  - Most (59 / 110) contained all necessary information,
  - 9 failed to explain how a safety rule works on a particular code construct,
  - 32 were missing the key steps in computing a lifetime or a borrow relationship,
  - 10 failed to explain the relationship between two lifetime annotations.

3.2 Why Is Rust Difficult?

- The Curse of Incompleteness [9]

3.2 Why Is Rust Difficult?

- The Curse of Incompleteness [9]

> “I can teach the three rules [of Ownership] in a single lecture to a room of undergrads. But the vagaries of the borrow checker still trip me up every time I use Rust!”

3.2 Why Is Rust Difficult?

- The Curse of Incompleteness [9]

```rust
let mut v = vec![1, 2];
let x = &mut v[0];
let y = &mut v[1];
*y += *x;
```

```rust
let mut v = vec![1, 2];
let mut iter = v.iter_mut();
let x = iter.next().unwrap();
let y = iter.next().unwrap();
*y += *x;
```

3.2 Why Is Rust Difficult?

- The Curse of Incompleteness [9]

```
let mut v = vec![1, 2];
let x = &mut v[0];
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```

3.2 Why Is Rust Difficult?

- The Curse of Incompleteness [9]

```
let mut v = vec![1, 2];
v.insert(0, v[0]);
v.get_mut(v[0]);
```

3.2 Why Is Rust Difficult?

- The Curse of Incompleteness [9]

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let mut v = vec![1, 2];
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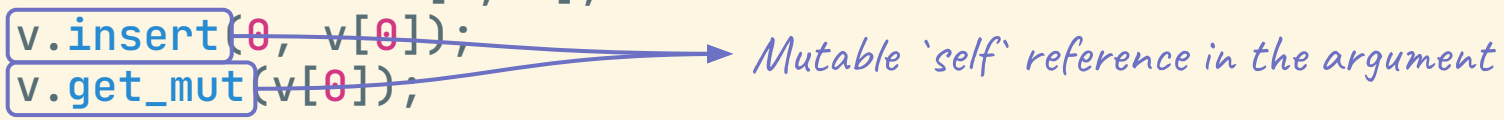

3.2 Why Is Rust Difficult?

- The Curse of Incompleteness [9]

```
let mut v = vec![1, 2];
v.insert(0, v[0]); ✓
v.get_mut(v[0]);   ✗
```

3.2 Why Is Rust Difficult?

3.2 Why Is Rust Difficult?

1. Needs a change of paradigm
2. Error messages are missing design feedback and necessary context
3. Incompleteness makes building an accurate mental model difficult

3.3 Why do people use Rust anyway?

3.3 Why do people use Rust anyway?

Read the report!

(Sorry! ☹ *)*

3.3 Why do people use Rust anyway?

1. They don't
2. Safety is the most important
3. Tooling is great
4. `unsafe` code is used a lot, and for good reason

Overview

1. History
2. Rust
3. Usability
4. Future Work

4 Future Work

Better Error Messages [2]

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- Programmers *do* read error messages

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Provide Context [4,27]

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Provide Context [4,27] → Reduce Cognitive Load

4 Future Work

Better Error Messages [2]

- Programmers *do* read error messages
- Rust follows many of the guidelines, but can do better

Provide Context [4,27]

Reduce Cognitive Load

Allow Dynamic Interaction

4 Future Work

How do Rust programmers write code?

4 Future Work

How do Rust programmers write code?

- Grounded Theory [5]

4 Future Work

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- Used in Software Engineering Research [23]

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Mis Used in Software Engineering Research [23]

4 Future Work

How do Rust programmers write code?

- Grounded Theory [5]

Mis Used in Software Engineering Research [23]

- How Statically-Typed Functional Programmers Write Code [18]

4 Future Work

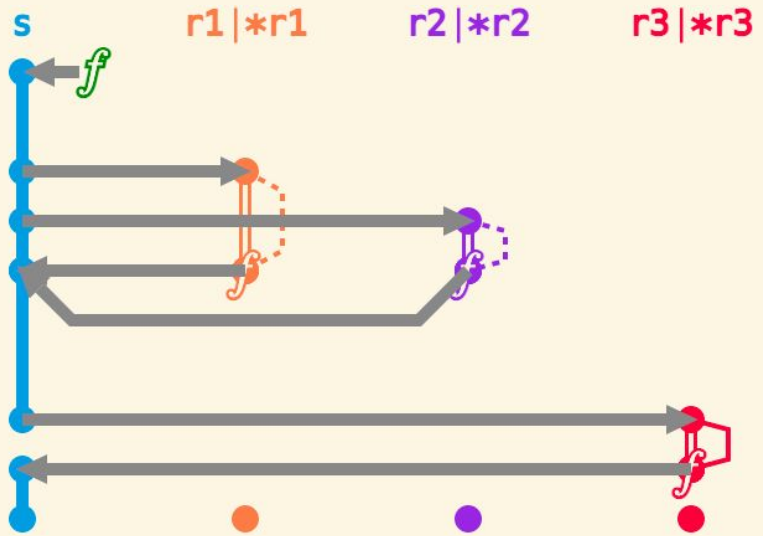
Program Visualization Tools

4 Future Work

Program Visualization Tools

- RustViz [13]

```
1  fn main(){
2      let mut s = String::from("hello");
3
4      let r1 = &s;
5      let r2 = &s;
6      assert!(compare_strings(r1, r2));
7
8      let r3 = &mut s;
9      clear_string(r3);
10 }
```



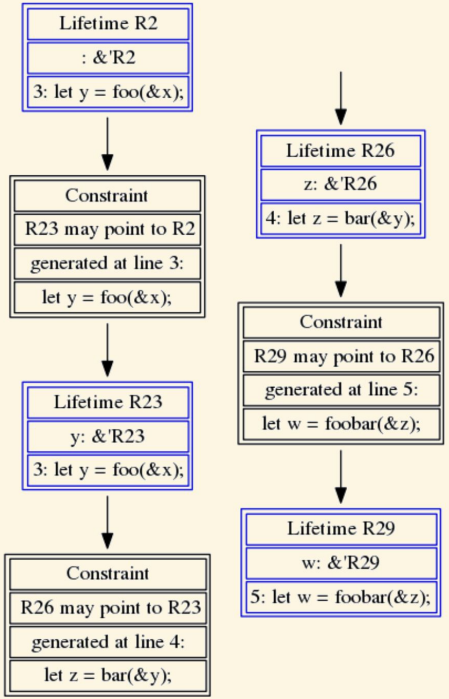
4 Future Work

Program Visualization Tools

- Rust Life Assistant [4]

```
fn main() {
      let mut x = 4;
      let y = foo(&x);
      let z = bar(&y);
      let w = foobar(&z);
      // ...
      x = 5;
      take(w);
}

fn foo<T>(p: T) → T { p }
fn bar<T>(p: T) → T { p }
fn foobar<T>(p: T) → T { p }
fn take<T>(p: T) → T { unimplemented!() }
```



4 Future Work

Program Visualization Tools

- Existing tools focus on *runtime* values [22]
- Rust needs a tool for *static* type constraints

Overview

1. History
    a. Linear Types
    b. Region-based Memory Management
    c. Ownership Types
2. Rust
    a. Ownership
    b. Lifetimes
3. Usability
    a. *Is* Rust's Ownership difficult?
    b. *Why* is Rust's Ownership difficult?
    c. Why do people use Rust anyway?
4. Future Work
    a. Better Error Messages
    b. How Do Rust programmers Write Code?
    c. Program Visualization Tools

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1.1 Linear Types

- Elsewhere in Linear Types:
  a. Vault [11] to Linear Haskell [3]
  b. Region [23] and Ownership types [7]

1.2 Region-based Memory Management

- ~~Tofte and Talpin 1997~~

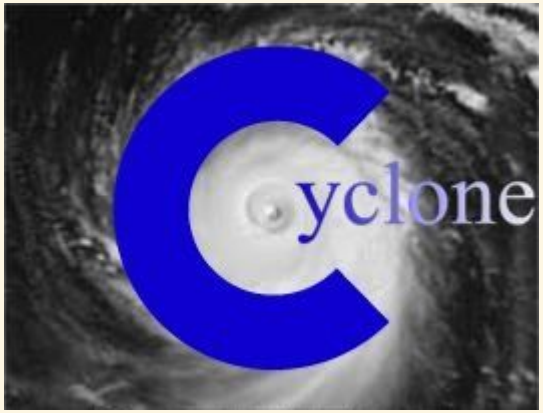
  Cyclone! [15]

Tagged Unions NULL checks

"A Safe Dialect of C"

Existential Types

RBMM

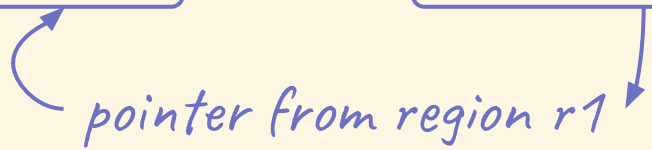


1.2 Region-based Memory Management

- Region Types [15]

```
region h {
  int* x = rmalloc(h, sizeof(int));
  int? y = rnew(h) { 1, 2, 3 };
  char? z = rprintf(h, "hello");
}
```

```
char?`r rprintf(region_t<`r> r1, const char? fmt, /*…*/);
```



1.3 Ownership Types [6]

- Statically enforcing Encapsulation

```
class Rectangle {
  private Point upperLeft;
  private Point lowerRight;

  public Rectangle(Point ul, Point lr) {
    upperLeft = ul;
    lowerRight = lr;
  }

  public Point getUpperLeft() {
    return new Point(upperLeft.x, upperLeft.y);
  }
}
```

1.3 Ownership Types [6]

- AliasJava [1]

```
class Rectangle {
  private owned Point upperLeft;
  private owned Point lowerRight;

  public Rectangle(unique Point ul, unique Point lr) {
    upperLeft = ul;
    lowerRight = lr;
  }

  public unique Point getUpperLeft() {
    return new Point(upperLeft.x, upperLeft.y);
  }
}
```

1.4 Shared Ideas

- Benefits
  a. Memory management
  b. Safety
  c. Comprehension
- Expressiveness
  a. Linear Types: non-linear types + read-only references
  b. RBMM: garbage-collected heap region
  c. Ownership types: external uniqueness

2.3 `unsafe`

- "Escape Hatch", but not really:
    a. Dereference a raw pointer
    b. Call an unsafe function or method
    c. Access or modify a mutable static variable
    d. Implement an unsafe trait
    e. Access fields of unions

2.3 unsafe

```
unsafe fn two_mutable_refs(x: &mut i32) → (&mut i32, &mut i32) {
    (&mut *(x as *mut i32), &mut *(x as *mut i32))
}

fn main() {
    let mut x = 1;
    let (c1, c2) = unsafe { two_mutable_refs(&mut x) };
    *c1 += 1;
    *c2 += 1;
    println!("{}", x);
}
```

2.1 Locking Bugs

```
fn do_request() {
    // client: Arc<RwLock<Inner>>
    match connect(client.read().unwrap().m) {
        Ok(_) ⇒ {
            let mut inner = client.write().unwrap();
            inner.m = mbrs;
        }
        Err(_) ⇒ {}
    }
}
```

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