Type-based Object Immutability with Flexible Initialization

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What is this Talk About?

- A pluggable type system ...
- ... for statically checking various immutability properties ...
- ... in Java-like languages.

Kinds of Immutability

Object immutability.

An object is immutable if its state cannot be modified.

Class immutability.

An immutable class is a class whose instances cannot be modified.

- Closed world: assumes that clients of immutable classes follow the rules of the pluggable type system.
- Open world: assumes that clients only follow Java's standard typing rules.

Read-only references.

A reference is read-only if the state of the object it refers to cannot be modified through this reference.

Object Immutability and Object Initialization

Immutable objects mutate during their initialization phase!

- Tying object initialization to object constructors ...
- ... is neither sufficient ...
  - E.g., immutable arrays,
  - immutable collections implemented in terms of mutable collection APIs,
  - immutable cyclic structures.
- ... nor does it simplify the type analysis.
  - Java imposes no restrictions on constructor bodies.

Design Goals

- support the various kinds of immutability
- support object initialization outside constructors
- self-containedness (we do not want to build on top of other more general systems)
- compatibility with JSR 308 annotations
  - a version with explicit ghost commands that indicate the end of object initialization phases
  - an inference algorithm that infers the end of object initialization phases

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`Rd`	read-only access (aka. `@Immutable`)

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If an object has type `Rd` C then its fields may only be read.

```
class C { int f; }

static void m(Rd C x) {
    x.f = 42; // TYPE ERROR
}

static void k(RdWr C x) {
    x.f = 42; // OK
}
```

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Soundness.

Well-typed programs never write to Rd-objects.

Type Qualifiers: Any (aka @Readonly-Reference)

Type Qualifiers.

$q ::= \cdots$

Any "the referred object is either Rd or RdWr"

Subqualifying.

Rd <: Any   RdWr <: Any

Subtyping.

$$\frac{p <: q \qquad C <: D}{p\ C <: q\ D}$$

Writes through Any-references are prohibited.

```
interface Util {
    void foo(int Any [] x);
}
```

```
static void m(Util util) {
    int[] a = new int RdWr [] {42,43,44};
    util.foo(a);
    assert a[0] == 42;
}
```

The Access Right is a Class Parameter

- Classes have a special class parameter `MyAccess`.
- `MyAccess` refers to the access qualifier for `this`.

```
class Point {
    int x;
    int y;
}

class Square {
    MyAccess Point upperleft;
    MyAccess Point lowerright;
}

static void m(Rd Square s) {
    s.upperleft = new Point();      // TYPE ERROR
    s.upperleft.x = 42;             // TYPE ERROR
}
```

The Initialization Discipline

Initialization Token.

$n \in$ Token token for initializing a set of related objects

Ghost command (has no effect at runtime).

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- Typical use: `newtoken n; new Fresh(n)` C`(); new Fresh(n)` D`(); ...`
- `Fresh` objects are writeable (even if they later turn immutable).

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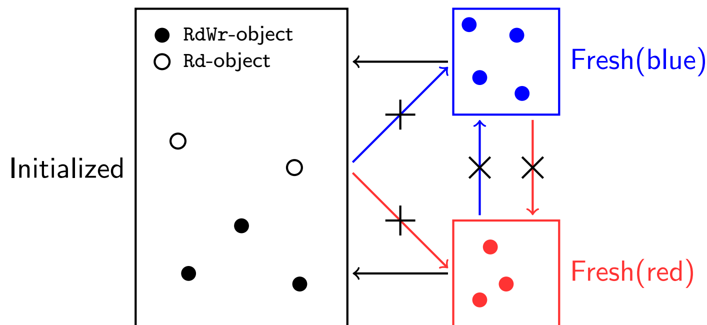
```
static char Rd [] copy (char RdWr [] w) {
    newtoken n;
    char[] r = new char Fresh(n) [w.length];
    for (int i=0; i++; i < w.length) r[i] = w[i];
    commit Fresh(n) as Rd;
    return r;
}
```

Soundness of Commit (Scoping of Init-Tokens)

- Fields cannot have Fresh(n)-qualifiers.

```
class C {
    Fresh(n) D x; // TYPE ERROR: n out of scope
}
```

Soundness of Commit (The Heap Invariant)



Heap Invariant.

There are no ingoing references into `Fresh`-regions.

N.B.: references inside `Fresh` regions are possible, by `MyAccess` qualifier on fields.

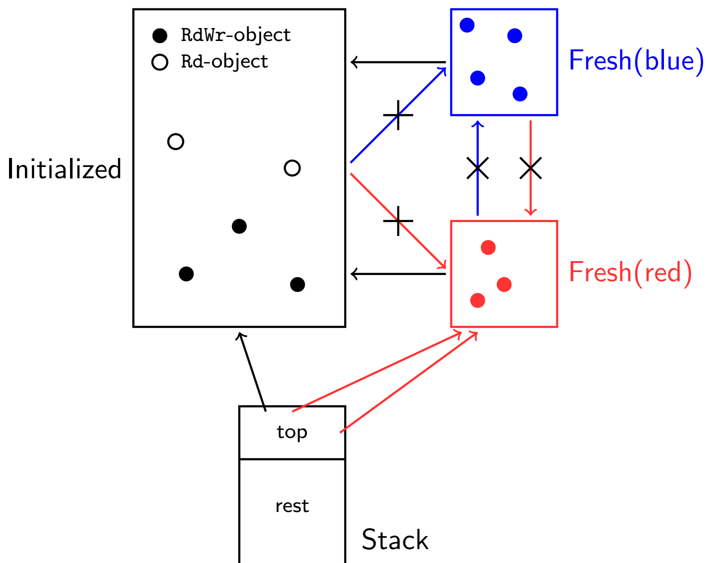
Soundness of Commit (Meth. Confinement of Init-Tokens)

- Each initialization token is to confined to a single method.

```
Rd C commit(Fresh(n) C x) { // TYPE ERROR: n out of scope
    commit Fresh(n) as Rd;
    return x;
}
```

- So, only the method that generates an initialization token has the right to commit the associated fresh region.

Soundness of Commit (The Big Picture)



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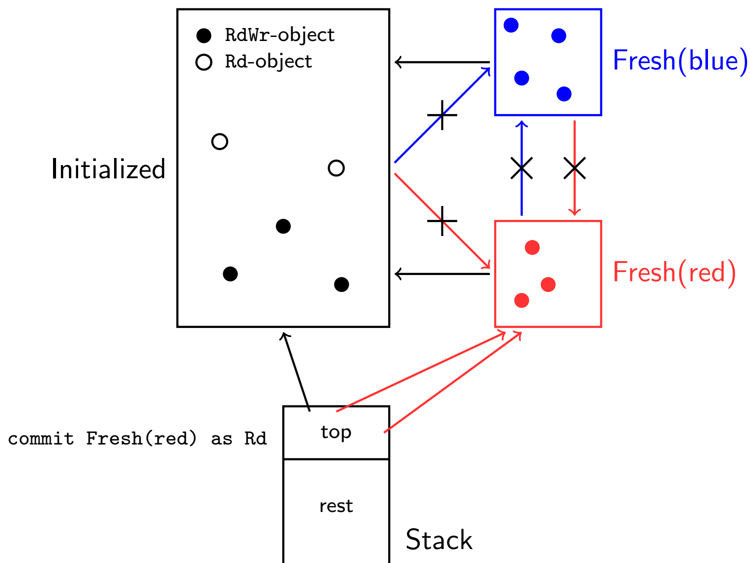

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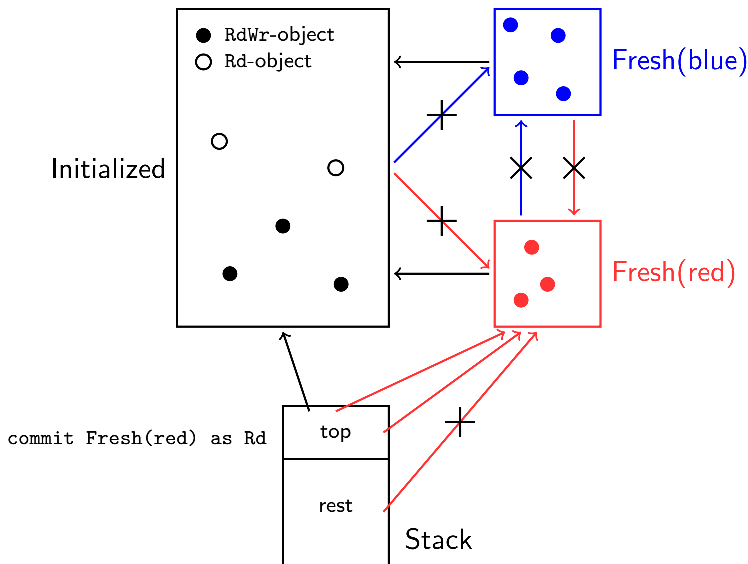

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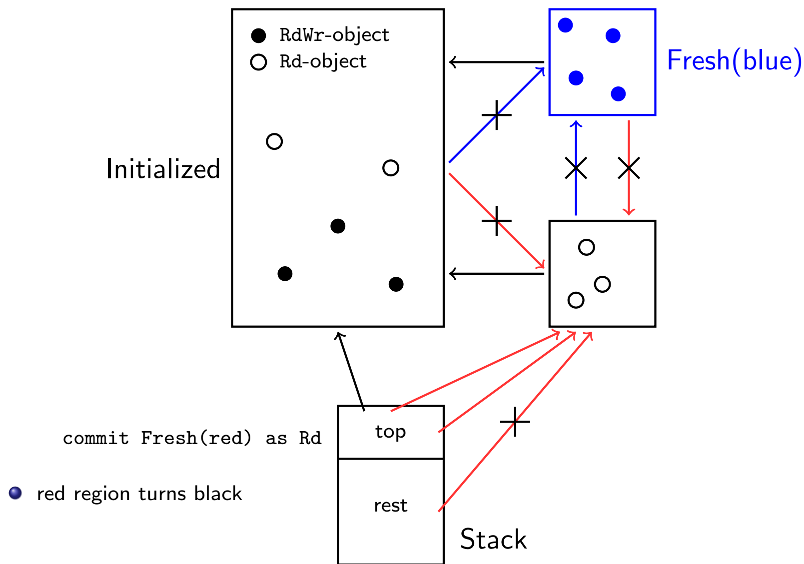

- red region turns black

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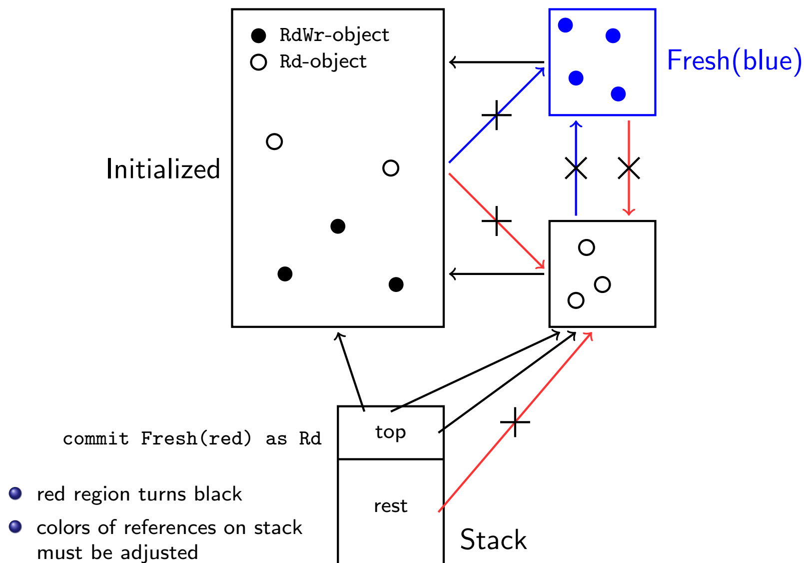

- red region turns black
- colors of references on stack must be adjusted

Qualifier Polymorphism for Methods

```
static void copy(Point src, Point dst) {
    dst.x = src.x;
    dst.y = src.y;
}
```

It should be allowed to pass actual `dst`-parameters of types `RdWr Point` and `Fresh(`n`) Point`.

- This method is similar to `arraycopy()`.
- `arraycopy()` is called in constructors of immutable `String`s.

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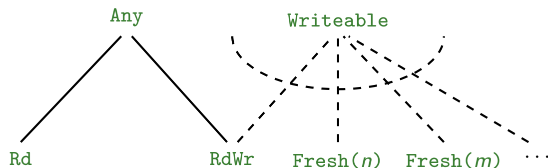

`Writeable` can only be used as a bound, not as a type qualifier.

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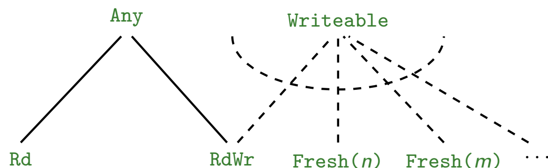

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Typing rule for field sets (incomplete sketch).

$$\frac{x : q\ C \qquad q \text{ extends } \texttt{Writeable}}{x.f = v : \text{ok}}$$

```
static <a, b extends Writeable> void copy(a Point src, b Point dst) {
    dst.x = src.x;
    dst.y = src.y;
}
```

Receiver Qualifiers (supported by JSR 308)

- JSR 308 provides a slot for annotations on the receiver type.
- Inspectors can be called on any receivers.
- Mutators can only be called on `Writeable` receivers.

```
class Hashtable<K,V> {

    <a> V get(K key) a { ... }                                   // INSPECTOR

    <a extends Writeable> V put(K key, V value) a { ... }   // MUTATOR
}
```

```
newtoken n;
Hashtable<String,String> t = new <Fresh(n)> Hashtable<String,String>();
t.put("Alice", "Amsterdam");
t.put("Bob", "Berlin");
commit Fresh(n) as Rd;
t.get("Alice"); // OK
t.put("Charlie", "Chicago"); // TYPE ERROR
```

Constructors

Constructors must have one of the following forms:

1. $<\bar{a}\ \texttt{extends}\ \bar{B}>\ q\ C(\bar{T}\ \bar{x})\ p\ \{\ \mathit{body}\ \}$

   Typically:

   $<a\ \texttt{extends}\ \texttt{Writeable}>\ a\ C(\bar{T}\ \bar{x})\ a\ \{\ \mathit{body}\ \}$

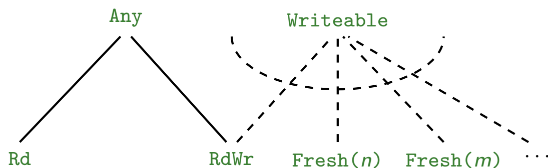
   - Caller commits.
   - Better choice most of the time.

2. $<\bar{a}\ \texttt{extends}\ \bar{B}>\ q\ C(\bar{T}\ \bar{x})\ \{\ \texttt{newtoken n;}\ \mathit{body}\ \}$

   - Constructor commits.
   - Useful for class immutability in an open world.

It is disallowed to call constructors of the second form using `super()`. The second form is therefore most appropriate for `final` classes.

Qualifier-Polymorphic Methods and Confinement



- `static <a> void foo(int a [] x)`
  - does not write to object x through reference x
  - does not create a reference to object x on the heap
- `static void faa(int Any [] x)`
  - does not write to object x through reference x
  - may create a reference to object x on the heap
- `static <a extends Writeable> void fee(int a [] x)`
  - may write to object x through reference x
  - does not create a reference to object x on the heap

Class Immutability (Open World)

```
Immutable final class String {
    private final char MyAccess [] arr;
    ...
}
```

Rules.

- immutable classes must be final and direct subclasses of `Object`
- methods and constructors may only call static or final methods (transitively)
- all fields must be private or final
- types of public methods must have the following form:

  `<a>` U `m(`$\bar{T}\ \bar{x}$`) a { ... }`

  where `MyAccess` and `a` do not occur in U.
- constructors must have the following form

  `Rd C(`$\bar{T}\ \bar{x}$`) { newtoken n; ...; commit Fresh(n) as Rd; }`

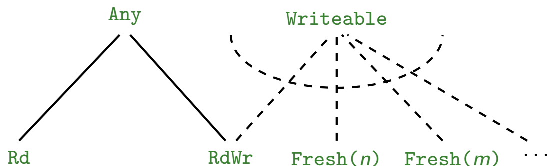
  where `MyAccess` does not occur in $\bar{T}$.

Threads

- We enforce that objects are committed before they get thread-shared.

```
class Thread {

    void run() RdWr { }
    void start(); // Treated specially. The type system uses run()'s type.
}
```



Local Annotation Inference

- An algorithm that infers all annotations inside method and constructor bodies.
- In particular: all ghost statements are inferred.
- The algorithm is syntax-directed.
- Basic idea: insert `commit`-statements lazily whenever this is required to satisfy annotations on fields, methods and constructors.

Contributions

A pluggable type system for immutability:

- Object immutability, class immutability and read-only references.
- Simple and direct.
  - Annotation language is small: only `Rd`, `RdWr`, `Any` and qualifier polymorphism. (`Fresh` can always be inferred.)
  - Only annotations on types are needed. (No effect annotations, constraints, pre/postconditions, loop invariants, or the like.)
- Flexible object initialization (not tied to constructors).
  - Without the need for complex aliasing annotations or destructive reads, as in systems that support typestate changes through unique references.