MATERIALS & SHAPES

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November 25, 2014

OUTLINE

- *Getting F-Bounded Polymorphism Into Shape*
  - with Fabian Muehlboeck and Ross Tate, PLDI 2014
  - and the Ceylon team

- plus some more recent developments

MY GOALS

1. Explain the big discovery of the paper

2. Share the conclusions we drew

3. Convince you that we've acted sensibly

THE PROBLEM

- Type-safe equality in object-oriented languages
  - 42 == 42.00 ✓ Cast to common super
  - 42 == "forty-two" ✗ Type error
  - **λ**x . 42 == **λ**x . 42 ✗ Type error, undecidable*

THE PROBLEM

- Type safe equality
    - **`List<T>`**
    - **`HashMap<T>`**
    - and so on ...

The state of the art? `Object.equals()`

java.lang

Class Object

java.lang.Object

`public class Object`

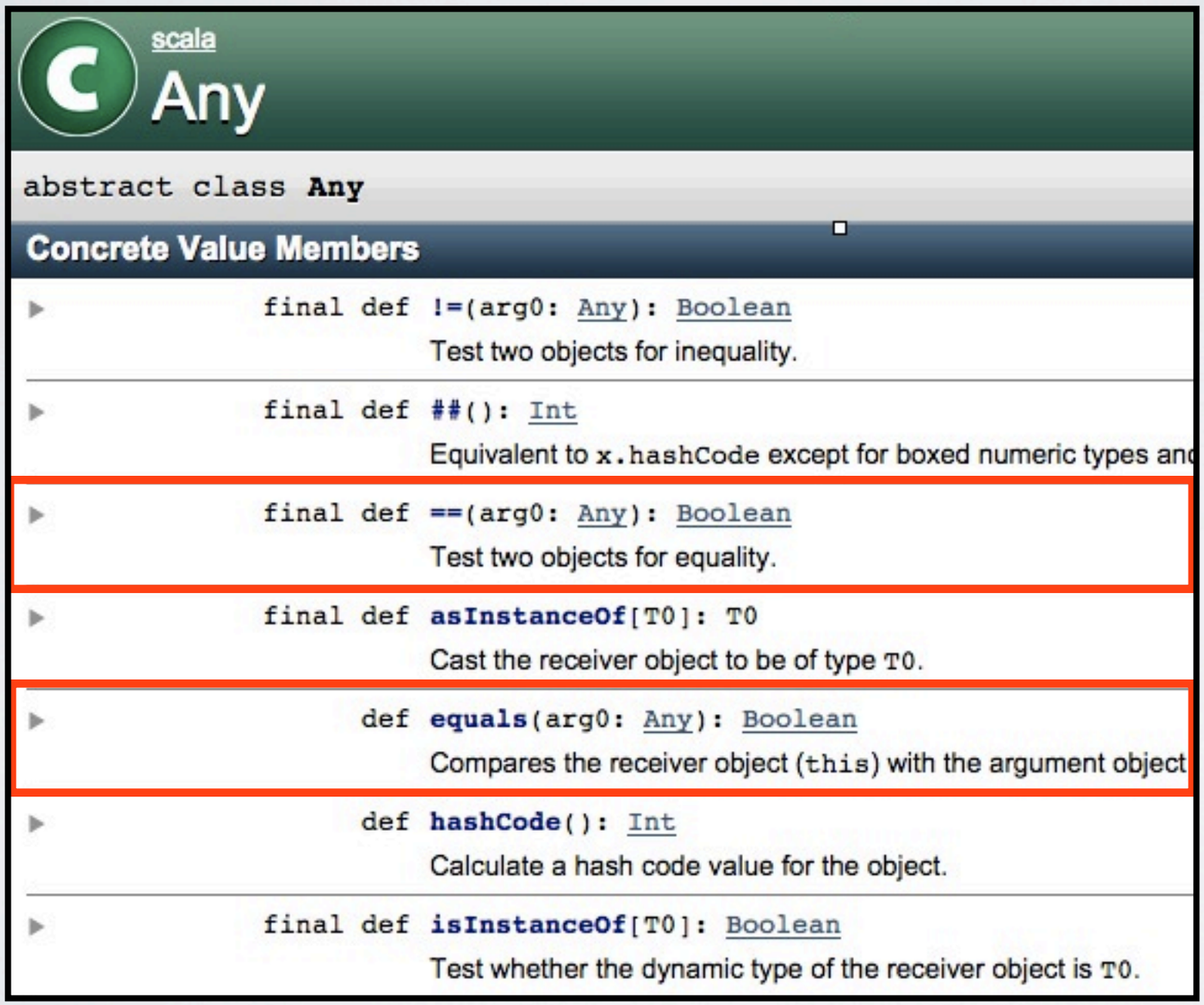
Class `Object` is the root of the class hierarchy. Every class has `Object` as a superclass. All objects, including array

Method Summary

All Methods	Instance Methods	Concrete Methods

Modifier and Type	Method and Description
`protected Object`	`clone()` Creates and returns a copy of this object.
`boolean`	`equals(Object obj)` Indicates whether some other object is "equal to" this one.
`protected void`	`finalize()` Called by the garbage collector on an object when garbage c
`Class<?>`	`getClass()` Returns the runtime class of this `Object`.

The state of the art? `Object.equals()`



WHAT'S WRONG?

- Does not scale.
    - Should there be an **`Object.compareTo()`** ?
- Masks errors that the static type-checker could find.
- The concept of "equality" is not defined for all objects.
- Requires dynamic dispatch

// Typical implementation

```
class Foobar extends Object {
    boolean equals(Object obj) {
        if (obj instanceof Foobar) {
            Foobar that = (Foobar) obj;
            /* Actually compare `this`
             * and `that` */
        }
        return false;
    }
}
```

- ✗ Wrong arg. type
- ✗ Run-time cast
- ✗ Dynamic check
- ✗ Lots of boilerplate

// It just gets worse

- **`instanceof`** checks show up everywhere
    - +300 uses in Java Collections library
- Repetitive, many opportunities for bugs

```
class BinaryTree<T> {

   boolean contains(T elem) {
     if (elem instanceof Comparable) {
         /* Implement me! */
     }
     return false;
   }
```

```
void remove(T elem) {
  if (elem instanceof Comparable) {
      /* Implement me! */
  }
}
```

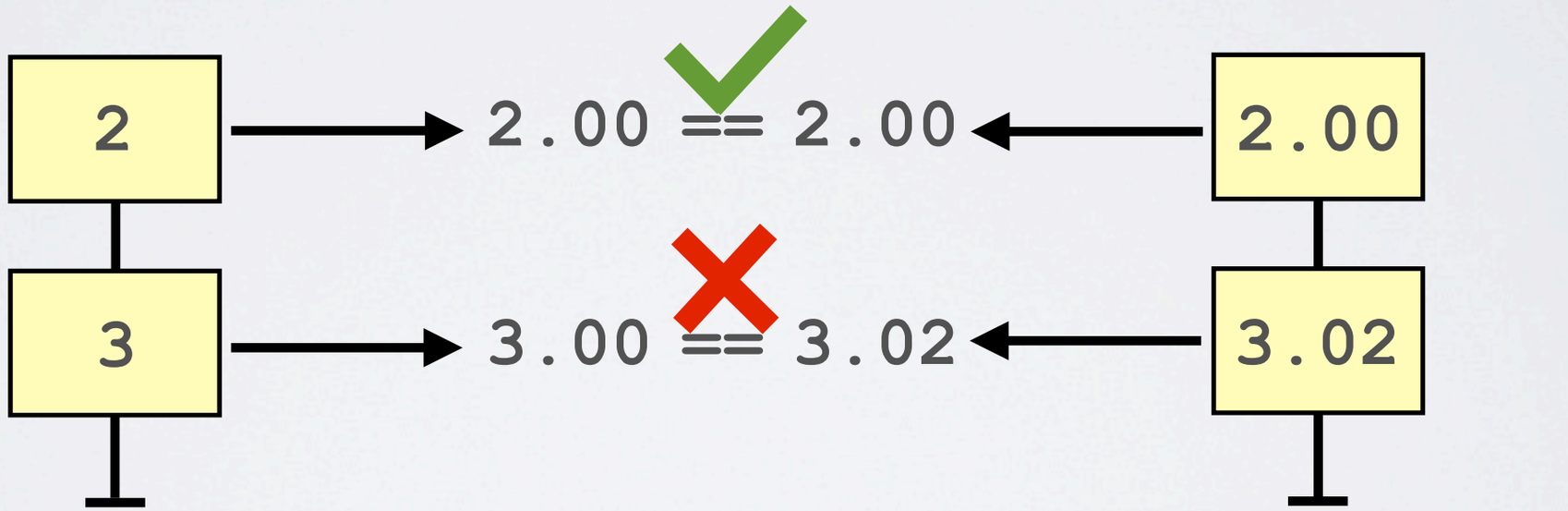
We can do better!

- Ideally, declare an **`interface`**
  - **`Equatable<T> { boolean equalTo(T that); }`**
- Replace **`instanceof`** and casts with F-Bounded polymorphism
  - **`BinaryTree<T extends Equatable<T>> { ... }`**

An example: List

- Two lists are equal if their elements are pointwise equal.

```
List<T> extends Equatable<List<Equatable<T>>>
```

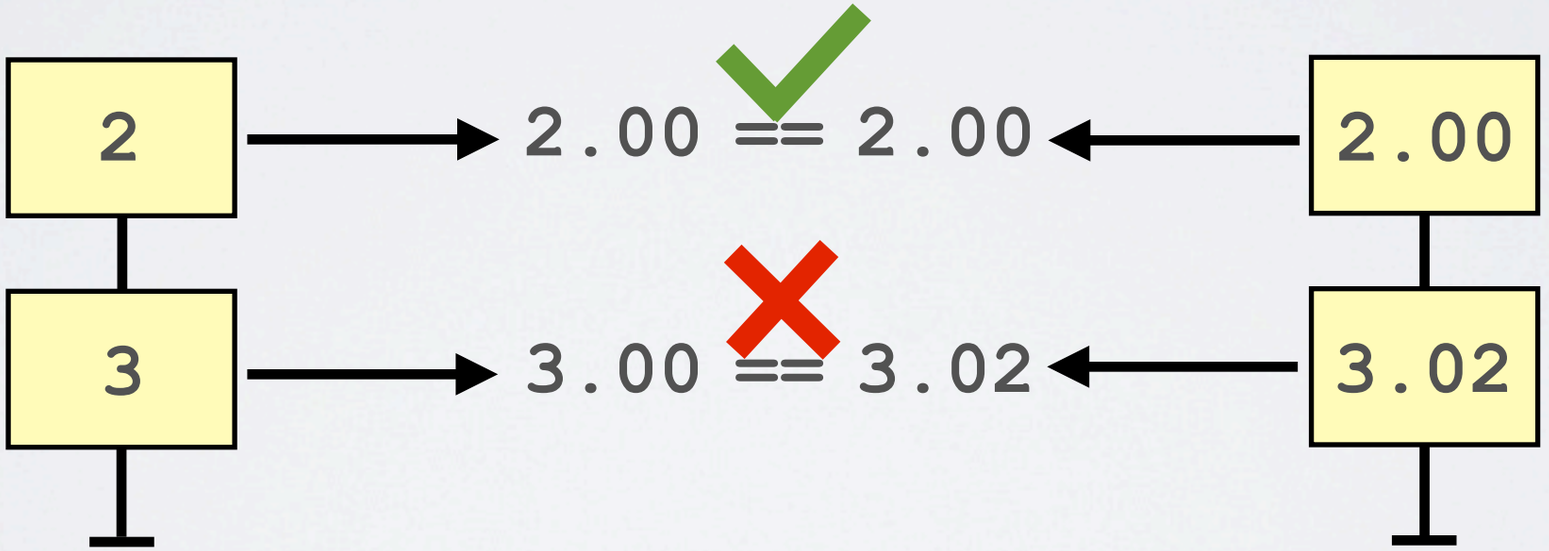


An example: List

Almost!

- Two lists are equal if their elements are pointwise equal.

`List<T> extends Equatable<List<Equatable<T>>>`



`List<Integer>` **`List<Double>`**

VARIANCE

- Read-only types are covariant (**`out`**, **`+`**, **`extends`**, ...)
  - A **`List<Integer>`** can safely be treated as a **`List<Double>`**
- Write-only types are contravariant (**`in`**, **`-`**, **`super`**, ...)
  - A **`Consumer<Animal>`** can be treated as a **`Consumer<Cat>`**
- Read-Write types are invariant
  - An **`Array<String>`** should contain exactly **`Strings`**

VARIANCE

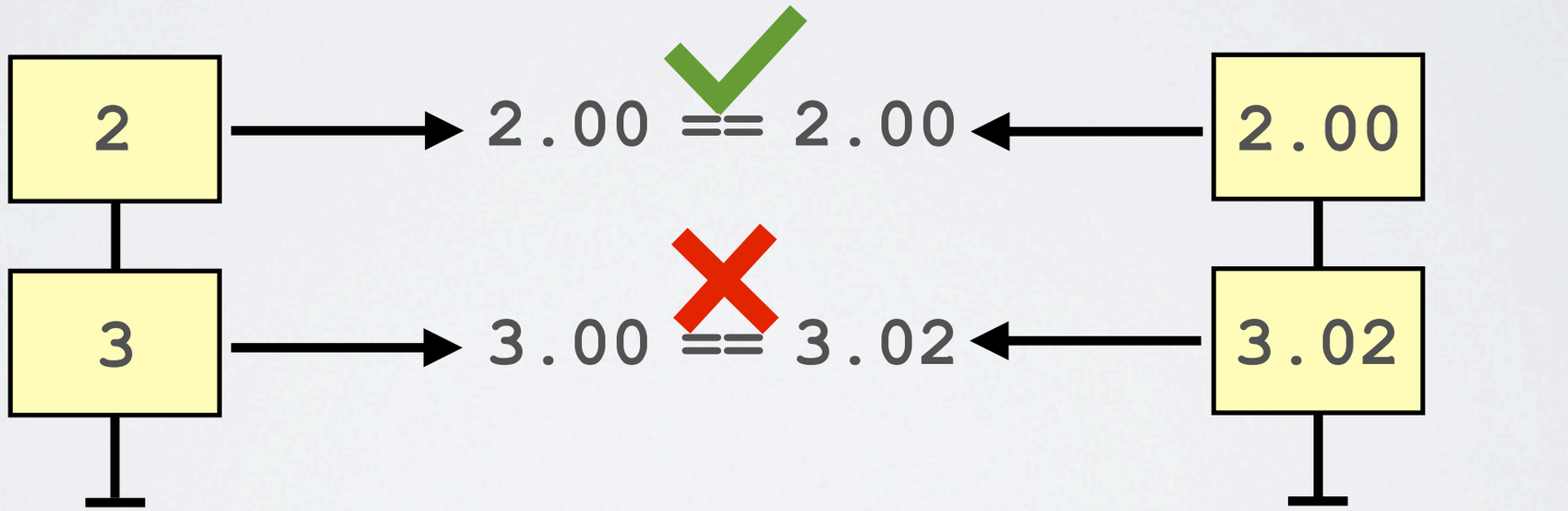
```
class Adult {}
class Baby extends Adult {}

public class ArrayHack {
  public static void main(String[] args) {
    Baby[] crib  = new Baby[1];
    Adult[] house = crib;
    house[0] = new Adult();
    System.out.printf("Success\n");
  }
}
```

```
Exception in thread "main"
   java.lang.ArrayStoreException: Adult
```

An example: List

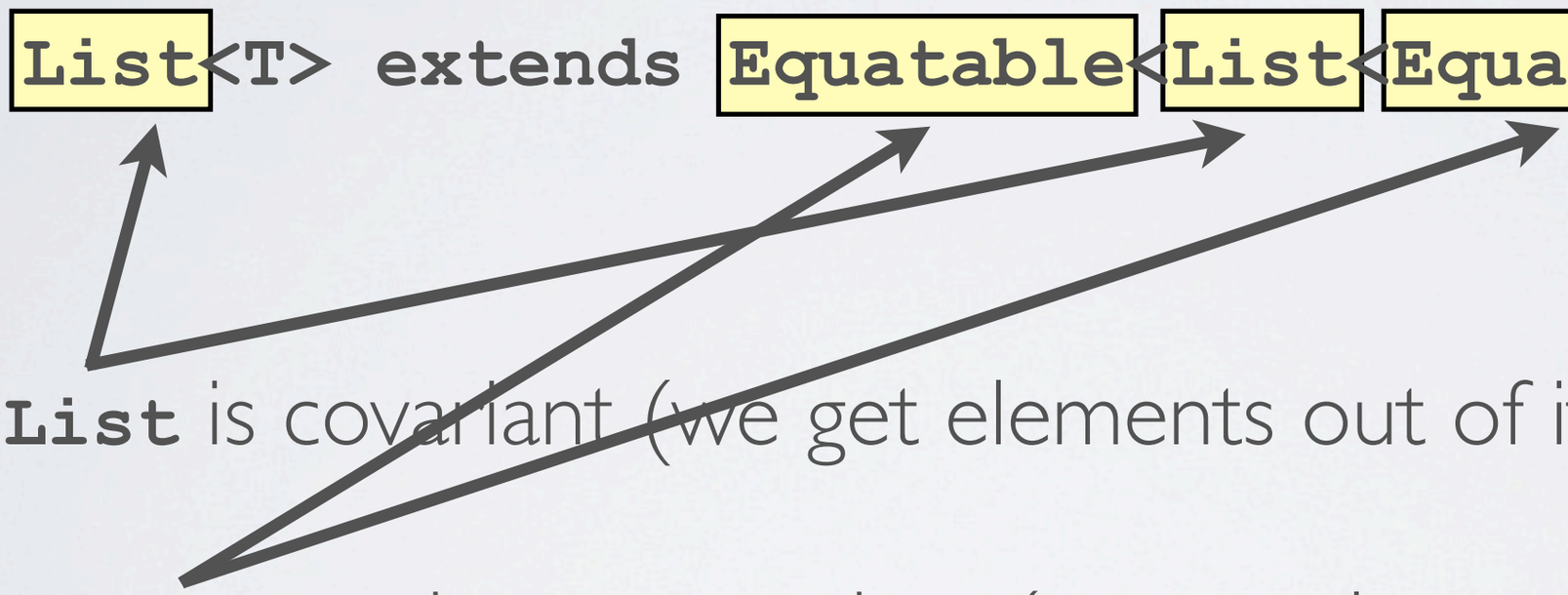
- Two lists are equal if their elements are pointwise equal.

```
List<T> extends Equatable<List<Equatable<T>>>
```



An example: List

- Two lists are equal if their elements are pointwise equal.



- **`List`** is covariant (we get elements out of it)
- **`Equatable`** is contravariant (we supply arguments)

An example: List

- Two lists are equal if their elements are pointwise equal.

```
List<T> extends Equatable<List<Equatable<T>>>
```

This actually works!

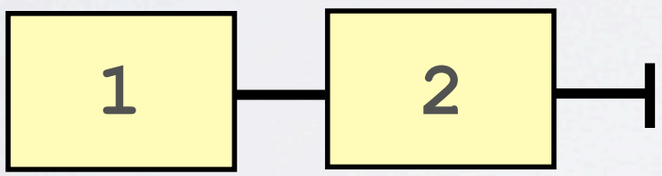
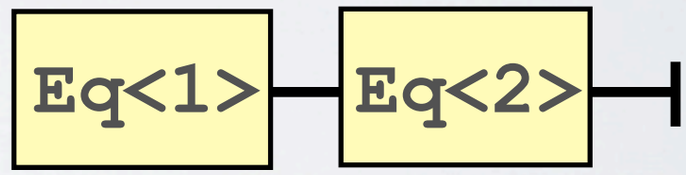
THE BIG DISCOVERY

- The Ceylon team wanted to avoid **`Object.equals()`**
- Ross suggested the above solution
- Ceylon's response:

NO.

THE BIG DISCOVERY

- "A **`List<Equatable<T>>`** is nonsense!"
  - Lists contain data, but **`Equatable`** is an abstract concept.

`List<Integer>>`	`<:`	`List<Equatable<Integer>>>`
		
Ok! ✓		NOT OK ✗

THE BIG DISCOVERY

- "A **`List<Equatable<T>>`** is nonsense!"
  - Lists contain data, but **`Equatable`** is an abstract concept.

`Equatable` is a constraint on **`Integers`**

`Integers` are a valid instantiation for **`List<T>`**

You never want a "list of constraints"

EXPERIMENT

- Ceylon is only one project. We weren't convinced.
- Surveyed 60 Open-Source Java projects
  - ~13.5 million lines of code (avg. 242,113 med. 60,062)
  - ~100,000 classes (avg. 1,962 med. 487)
  - ~10,000 interfaces (avg. 202 med. 41)

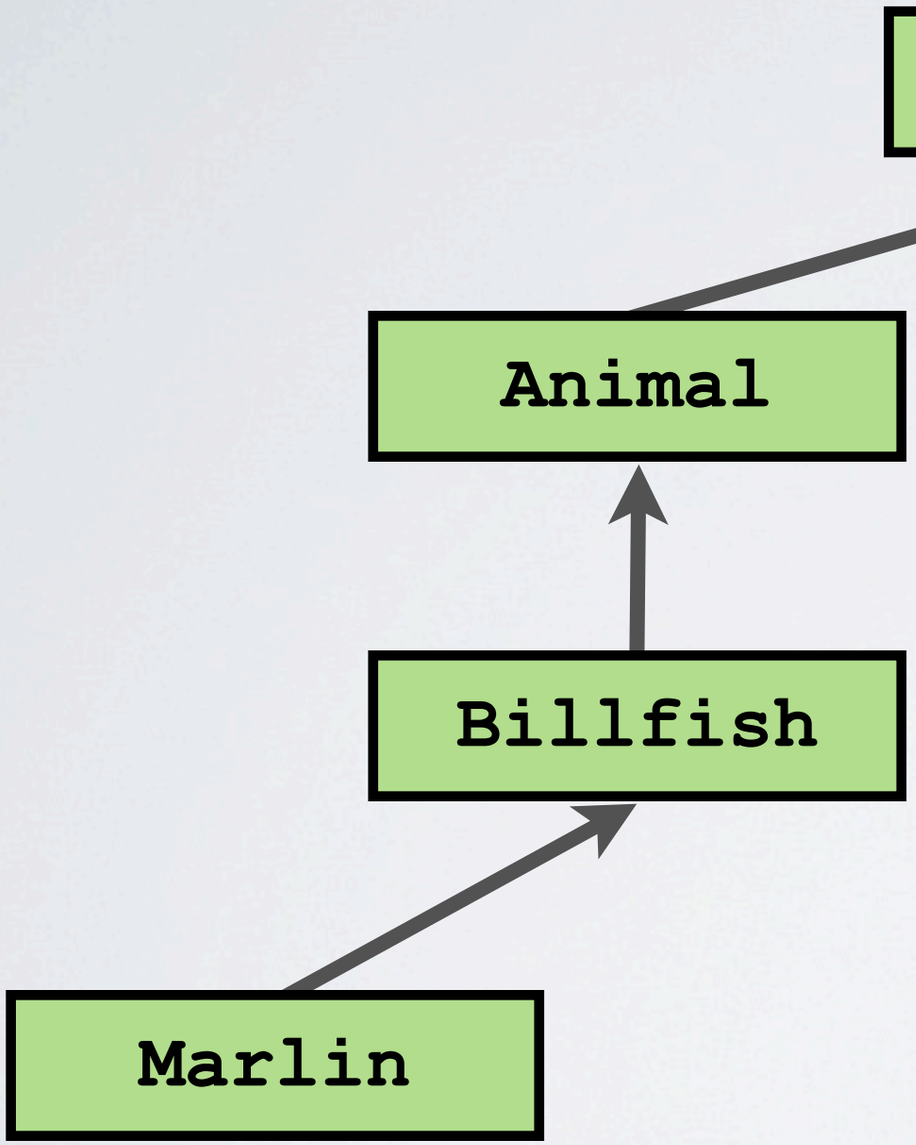



EXPERIMENT

You never want a "list of constraints" 

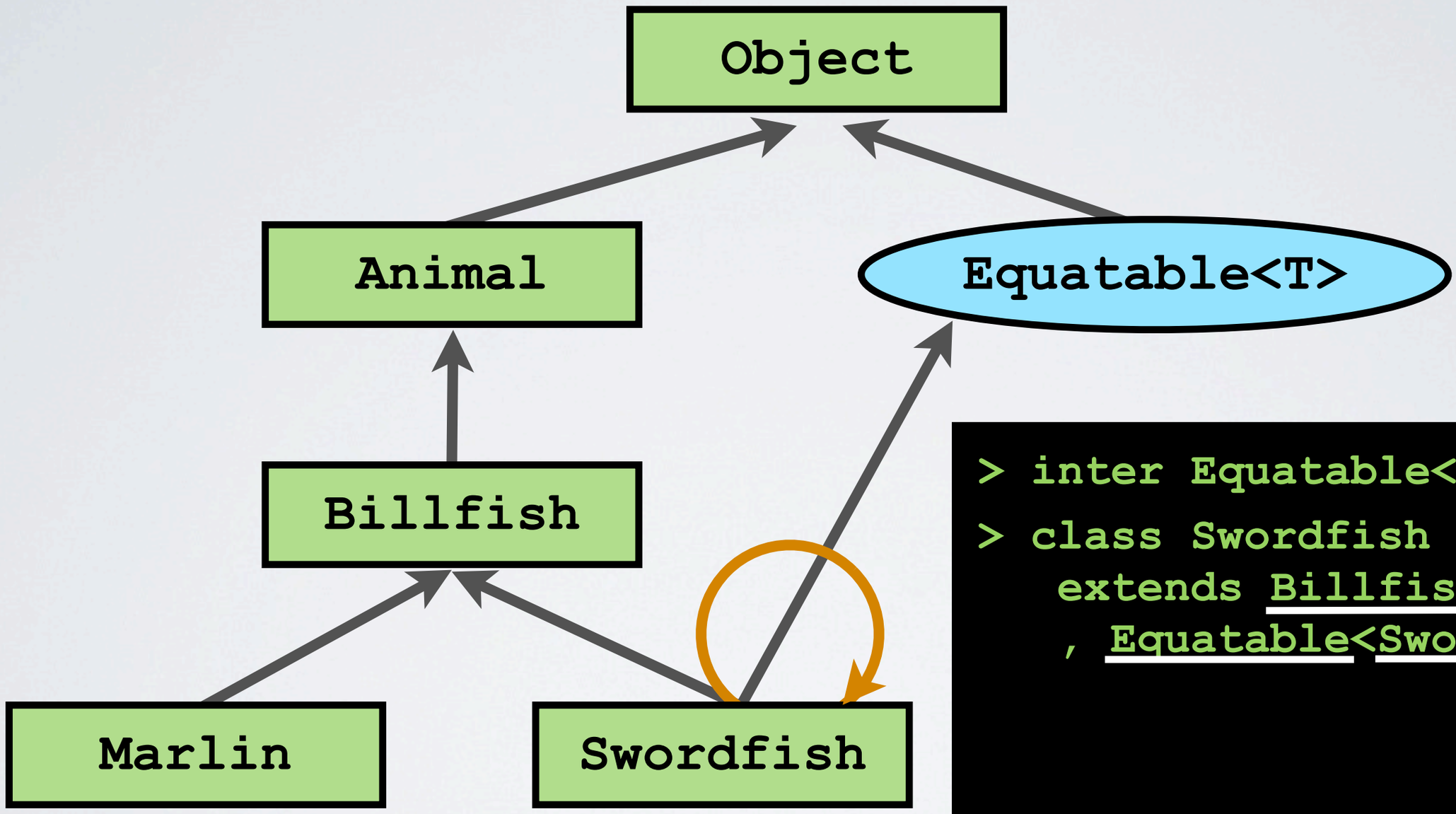
- Types like **`Equatable<Integer>`** were never used as:
- Type Parameters
- Function arguments or return types
- Local variables or fields

What is a "type like" **`Equatable<Integer>`** ?



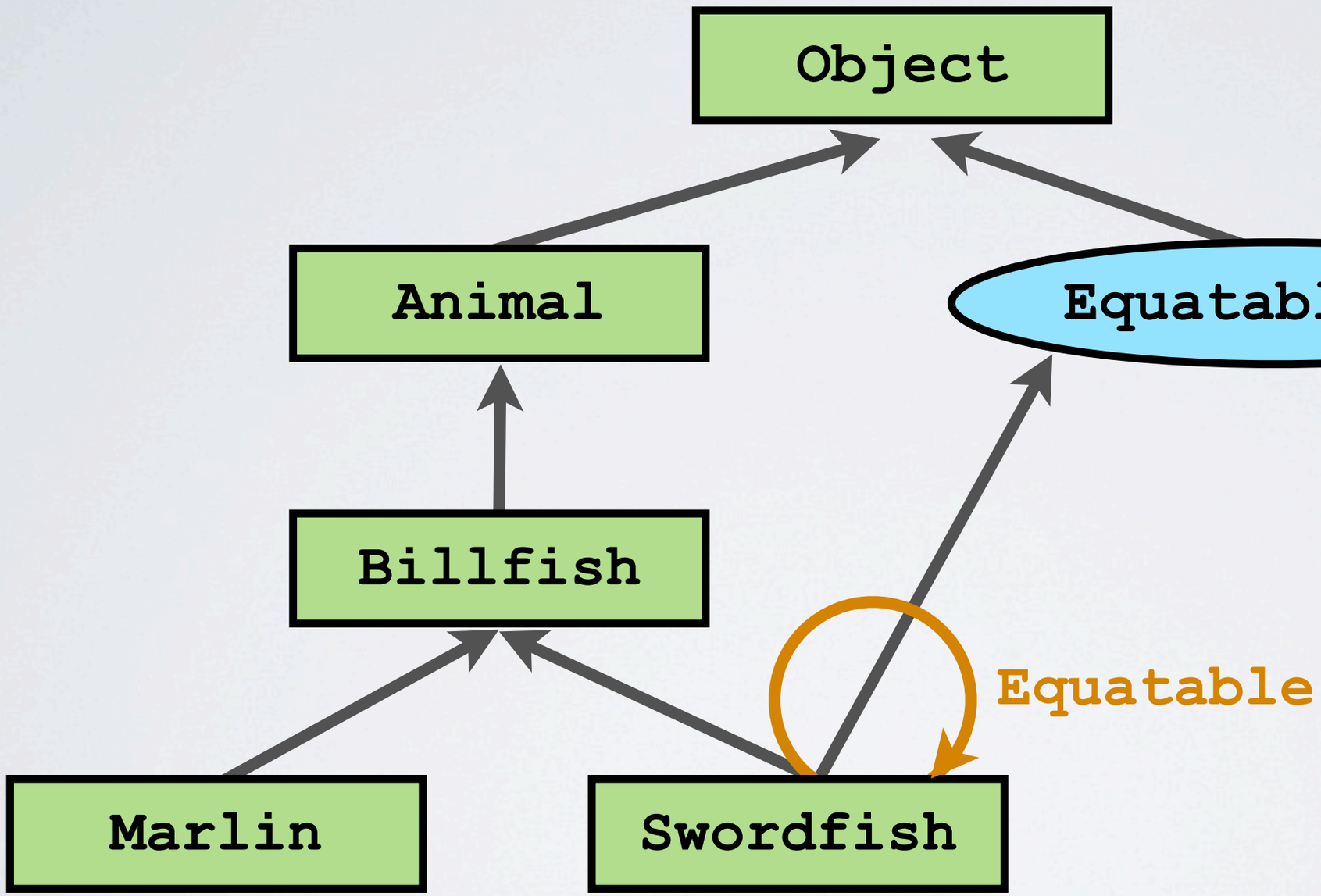

```
> class Object {}
> class Animal {}
> class Billfish
    extends Animal {}
> class Marlin
    extends Billfish {}
```

What is a "type like" **`Equatable<Integer>`** ?




```
> inter Equatable<T> {}
> class Swordfish
    extends Billfish
    , Equatable<Swordfish>
```

What is a "type like" **`Equatable<Integer>`** ?



EXPERIMENT
(more precisely)

- Parameterized types used to complete cycles in the inheritance hierarchy were never used as:
  - Type Parameters
  - Function arguments or return types
  - Local variables or fields

RECAP

1. The problem: type-safe equality

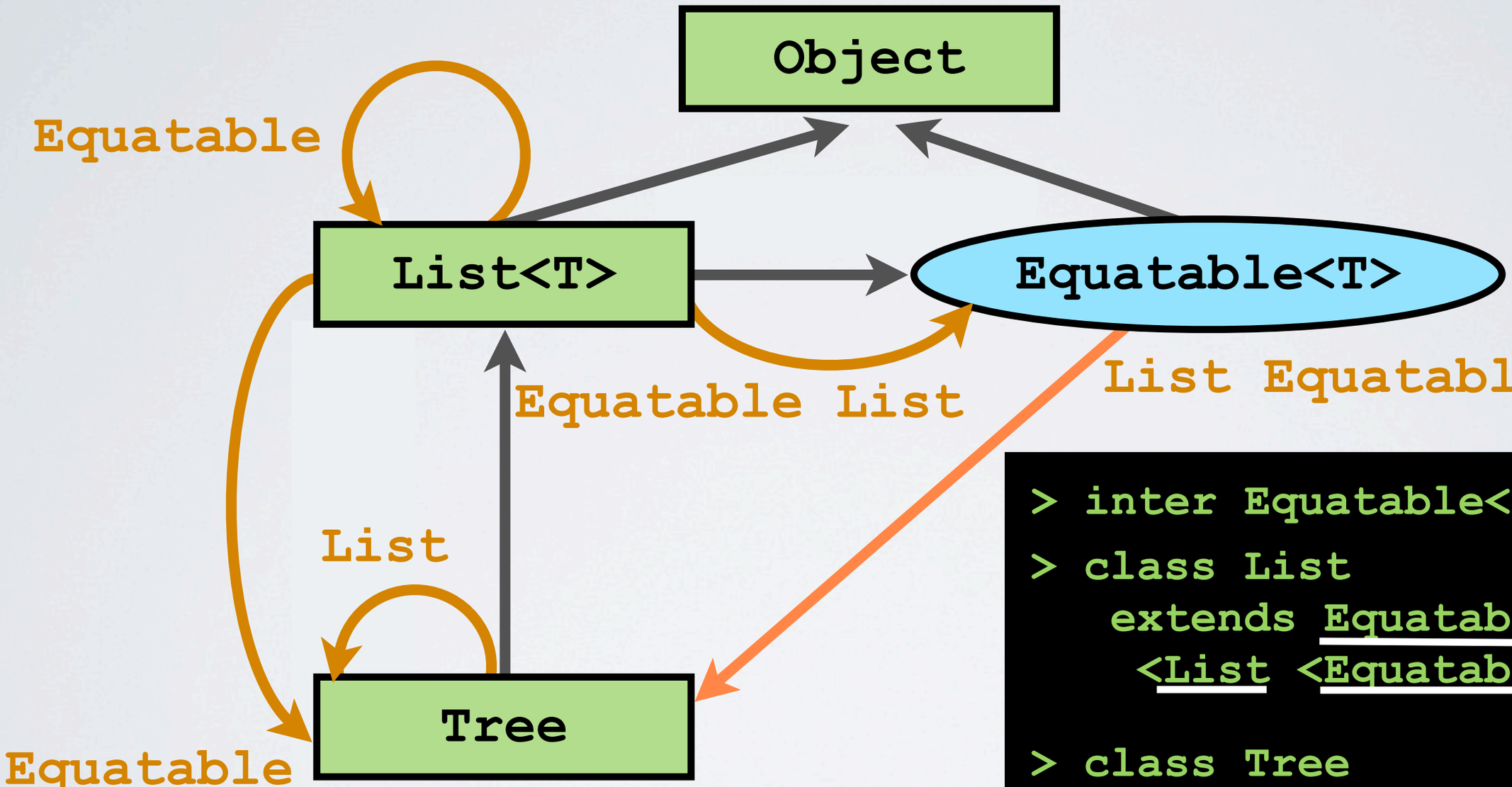
2. Proposed solution: **`Equatable`** and F-Bounded Polymorphism

3. Strong Reject from industry

4. **`Equatable`** is a constraint, and causes cyclic inheritance

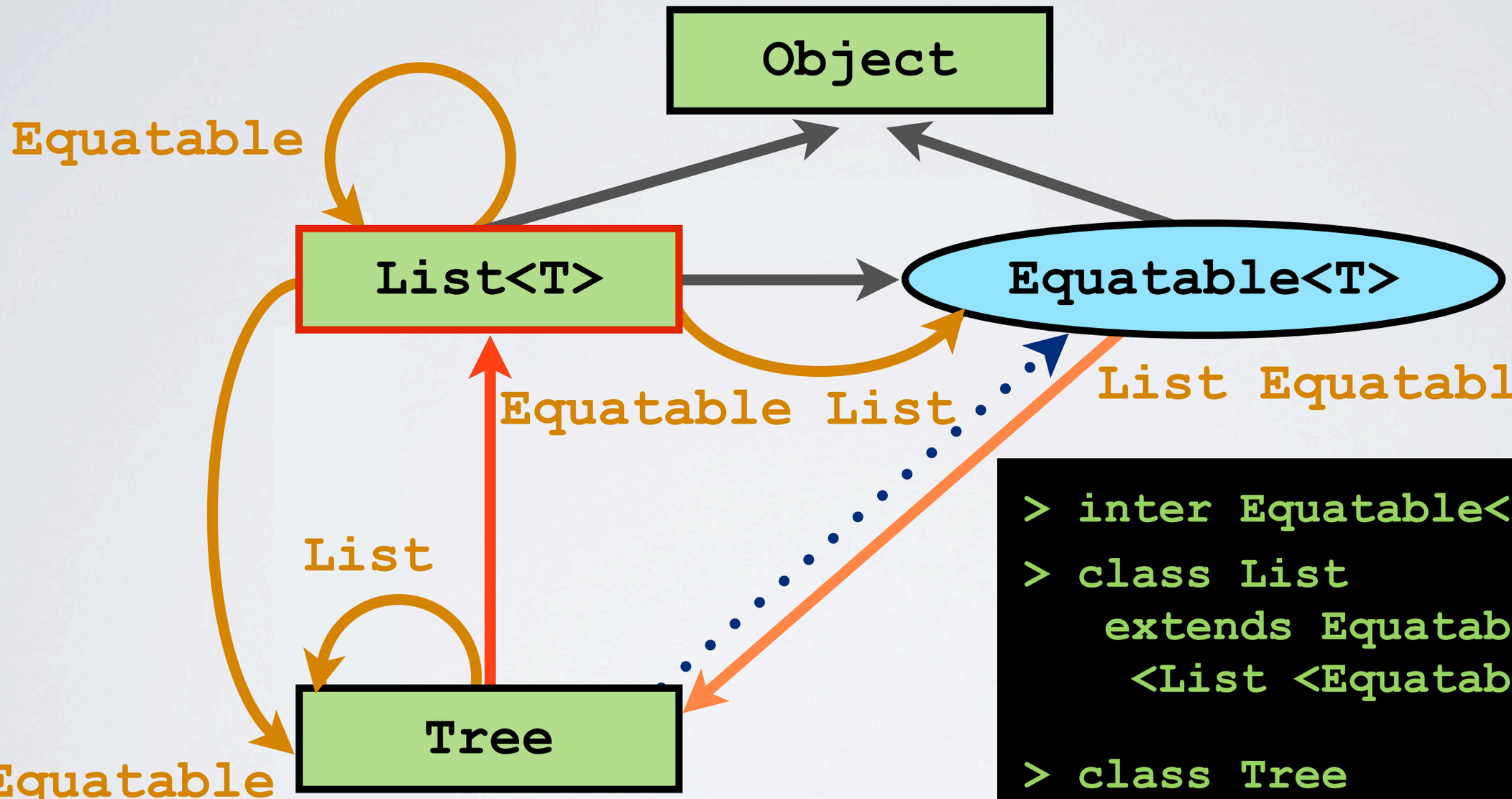
Next Up: the research perspective

The problem with `Equatable<List<...>>`



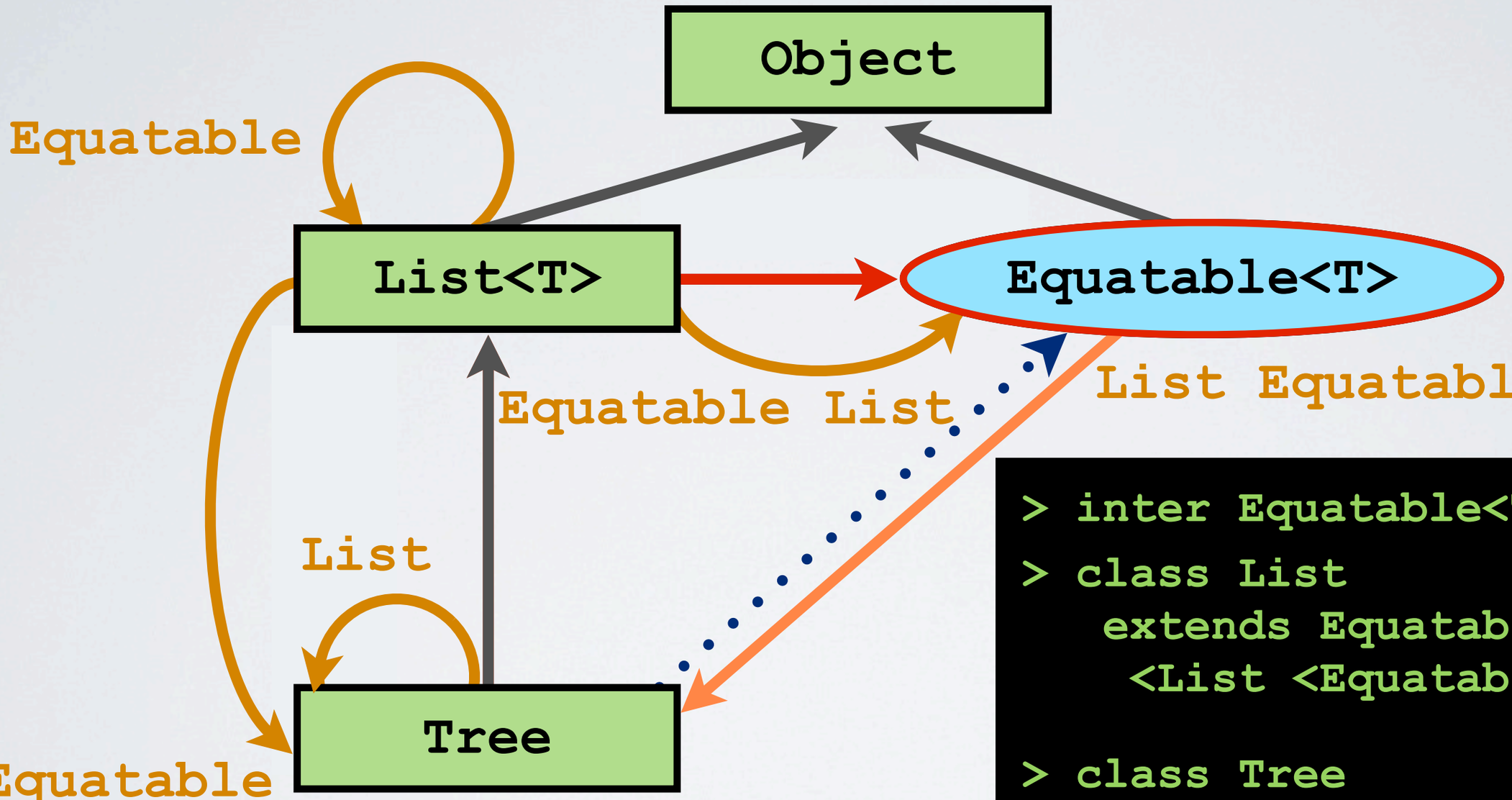

```
> inter Equatable<T> {}
> class List
    extends Equatable
      <List <Equatable <T>>

> class Tree
    extends List<Tree>
```

-? Tree <: Equatable<Tree>



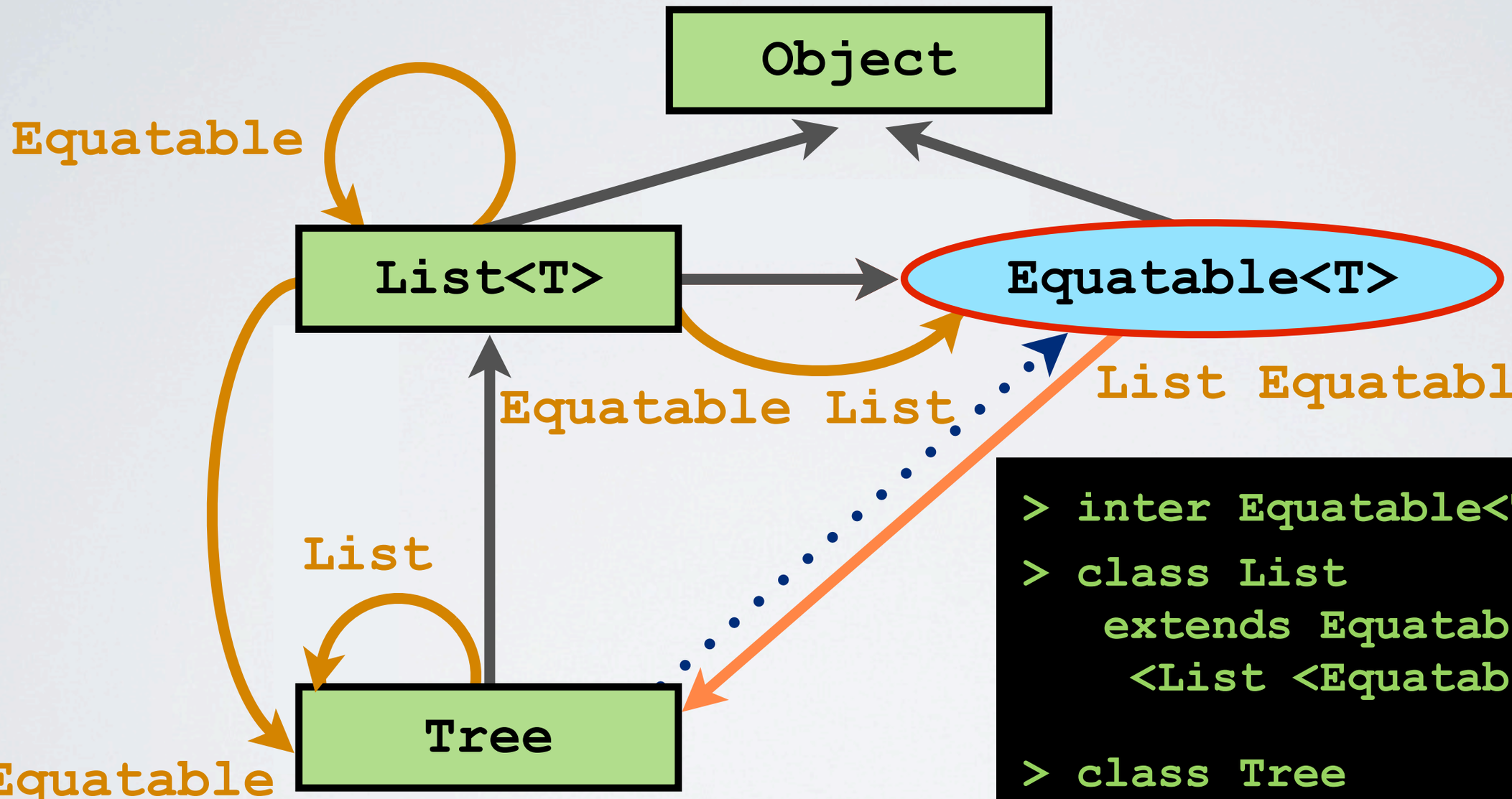

```
> inter Equatable<T> {}
> class List
    extends Equatable
     <List <Equatable <T>>

> class Tree
    extends List<Tree>
```

```
-? List<Tree> <: Equatable<Tree>
```




```
> inter Equatable<T> {}
> class List
    extends Equatable
     <List <Equatable <T>>

> class Tree
    extends List<Tree>
```

-? Eq<List<Eq<Tree>>> <: Equatable<Tree>




```
> inter Equatable<T> {}
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    extends Equatable
     <List <Equatable <T>>

> class Tree
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```

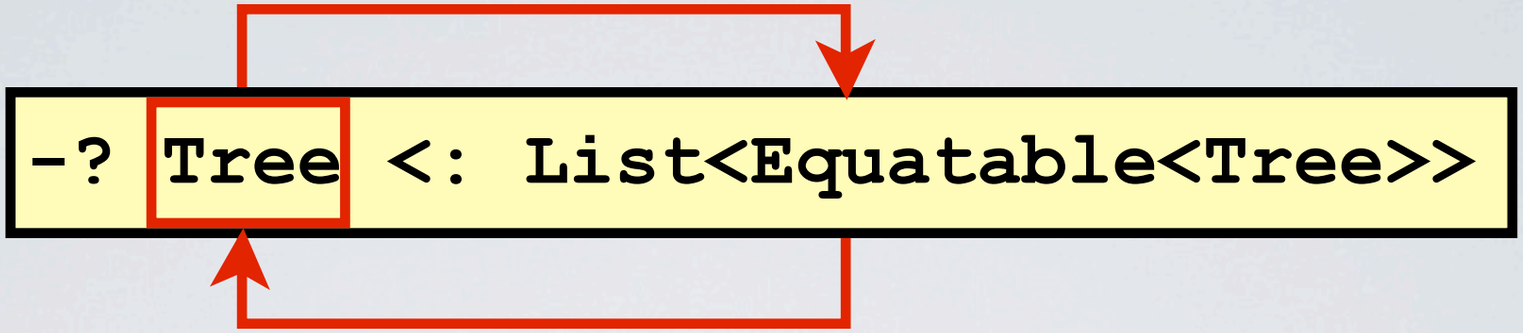

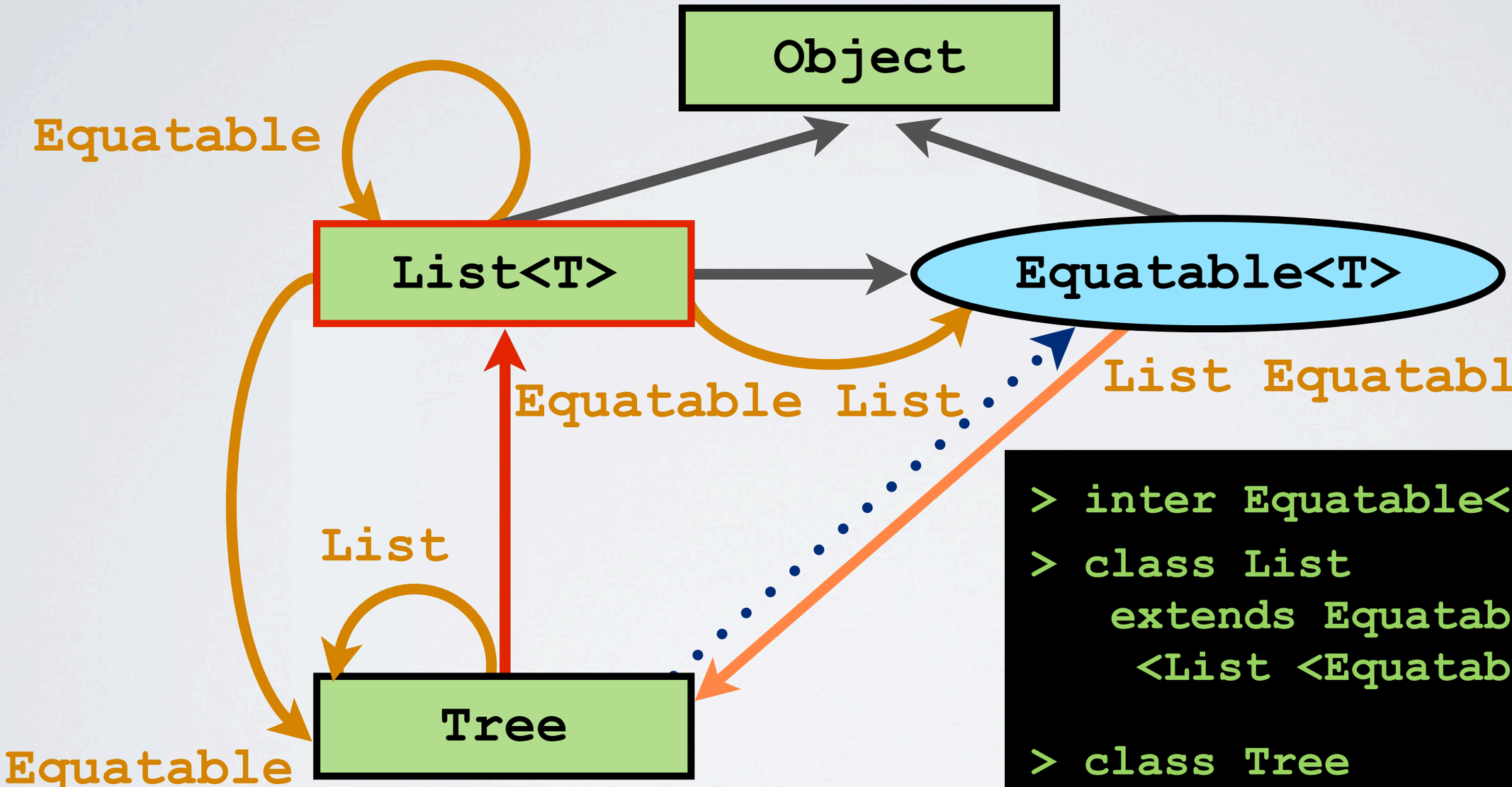


```
> inter Equatable<T> {}
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     <List <Equatable <T>>

> class Tree
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```
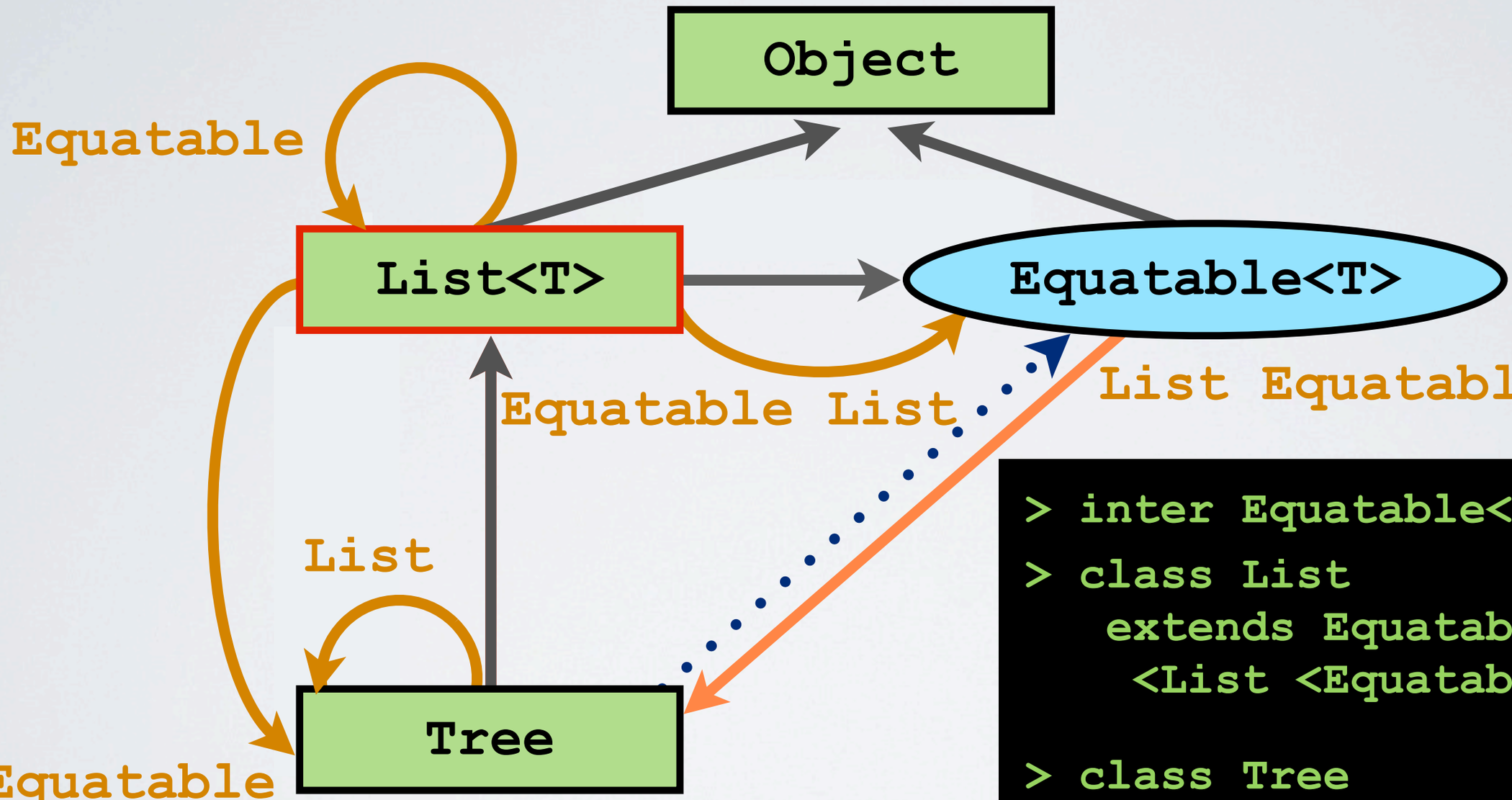
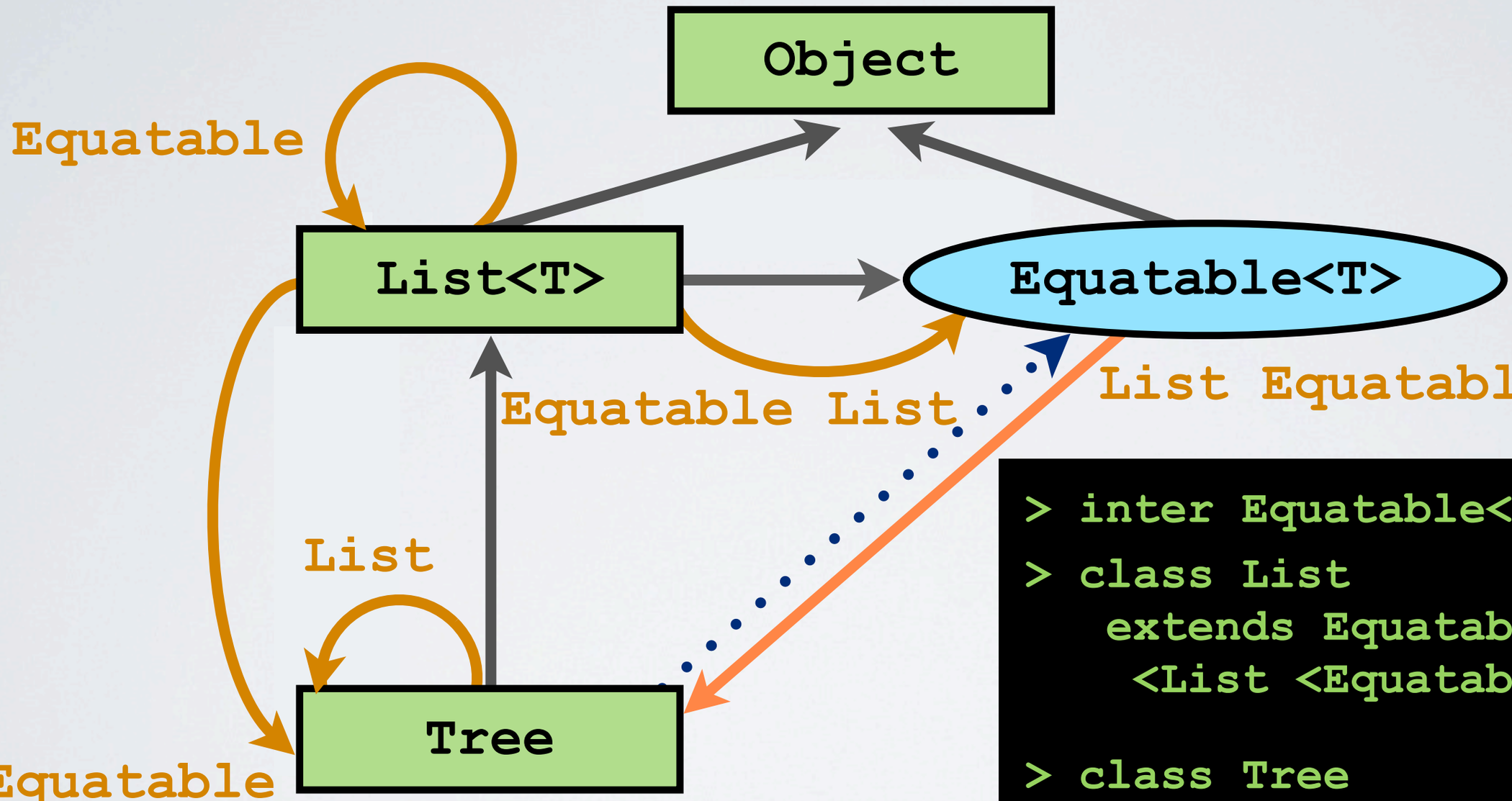

-? ~~List~~<Tree> <: ~~List~~<Equatable<Tree>>




```
> inter Equatable<T> {}
> class List
    extends Equatable
      <List <Equatable <T>>

> class Tree
    extends List<Tree>
```

```
-? Tree <: Equatable<Tree>
```

✗ Cycle!




```
> inter Equatable<T> {}
> class List
    extends Equatable
      <List <Equatable <T>>

> class Tree
    extends List<Tree>
```

PRIOR WORK

- *On the Decidability of Nominal Subtyping with Inheritance*
  - Andrew Kennedy & Benjamin Pierce, FOOL 2007

- The general problem is undecidable

- Can recover decidability by removing either:

1. Contravariance
2. Expansive Inheritance
3. Multiple Instantiation Inheritance*

PRIOR WORK

1. Remove Contravariance

For all types **`C<*>`**, **`D<*>`**, and all values **`X`**, **`Y`**:

`C<X>` is a subtype of **`D<Y>`**

if

`X` is a subtype of **`Y`**

PRIOR WORK

2. Remove Expansive Inheritance

Suppose **`C<X>`** inherits **`D<Y>`**,

Either **`X=Y`**

or

`X` does not appear in **`Y`**

(**`Y`** is no "larger" than **`X`**)

PRIOR WORK

3. Remove Multiple Instantiation Inheritance*

For all types **`C`**, **`D<*>`**, and all values **`X`**, **`Y`**:

`C` cannot inherit

both

`D<X>` and **`D<Y>`**

* All expansive-recursive type parameters must be invariant and linear

PRIOR WORK

- *Taming Wildcards in Java's Type System*
    - Ross Tate, Alan Leung, Sorin Lerner, PLDI 2011

No nested contravariance in:

inheritance clauses

or

type parameters

```
List<T> extends Equatable
        <List <Equatable <T>>
```

❌ Contravariance

❌ Nested Contravariance

❌ Expansive Inheritance

❌ Bad design

```
List<T> extends Equatable
          <List <Equatable <T>>
```

Programmers separate data from "constraints on data".
This separation leads to decidable subtyping.

❌ Nested Contravariance ⊂ ❌ Bad design

Material-Shape Separation

Materials

Shapes

```
T> extends Equatable
  <List <Equatable <T>>
```

Programmers separate data from "constraints on data".
This separation leads to decidable subtyping.

❌ Nested Contravariance ⊂ ❌ Bad design

Programmers separate data from "constraints on data".
This separation leads to decidable subtyping.

Materials

- `Object`
- `List<T>`
- `Swordfish`

Cycle-free inheritance

Shapes

- `Equatable<T>`
- `Cloneable<T>`
- `Addable<T>`

Never used as type parameters

SUMMARY

- While studying type-safe equality, we found a strange *pattern*
  - **`Equatable, Comparable, Hashable`** are different!
- Following this *pattern* intuitively gives decidable subtyping
- These **Shapes** describe the structure and constraints of data
- In contrast, **Materials** are the data used and exchanged

MATERIALS & SHAPES

SUB-GOALS

i.e. "where can we go from here?"

1. Decidable subtyping

2. Type equality, decidable joins

3. Conditional inheritance

4. Shape shifters

WELL-FOUNDED INHERITANCE

- Undecidability results were caused by cyclic inheritance
    - Impossible to predict how type parameters would expand
- Without shapes, inheritance is well-founded
    - No more cycles!
    - An object's inheritance graph is known at compile-time
- Many applications

DECIDABLE SUBTYPING

- Strategy: define a measure on judgments **`X <: Y`**
- Key idea: inheritance never introduces new shapes
- Two components:
  - The number of shapes appearing in each type
  - The maximum number of proof steps until the next shape

TYPE EQUALITY

- Suppose the type system has intersection types, **`X&Y`**
- Is **`List<X&Y>`** equal to **`List<Y&X>`** ? (It should be!)
  - Not true in Java
  - Not true using Kennedy & Pierce's technique
  - Not true using Tate et al.'s technique

TYPE EQUALITY

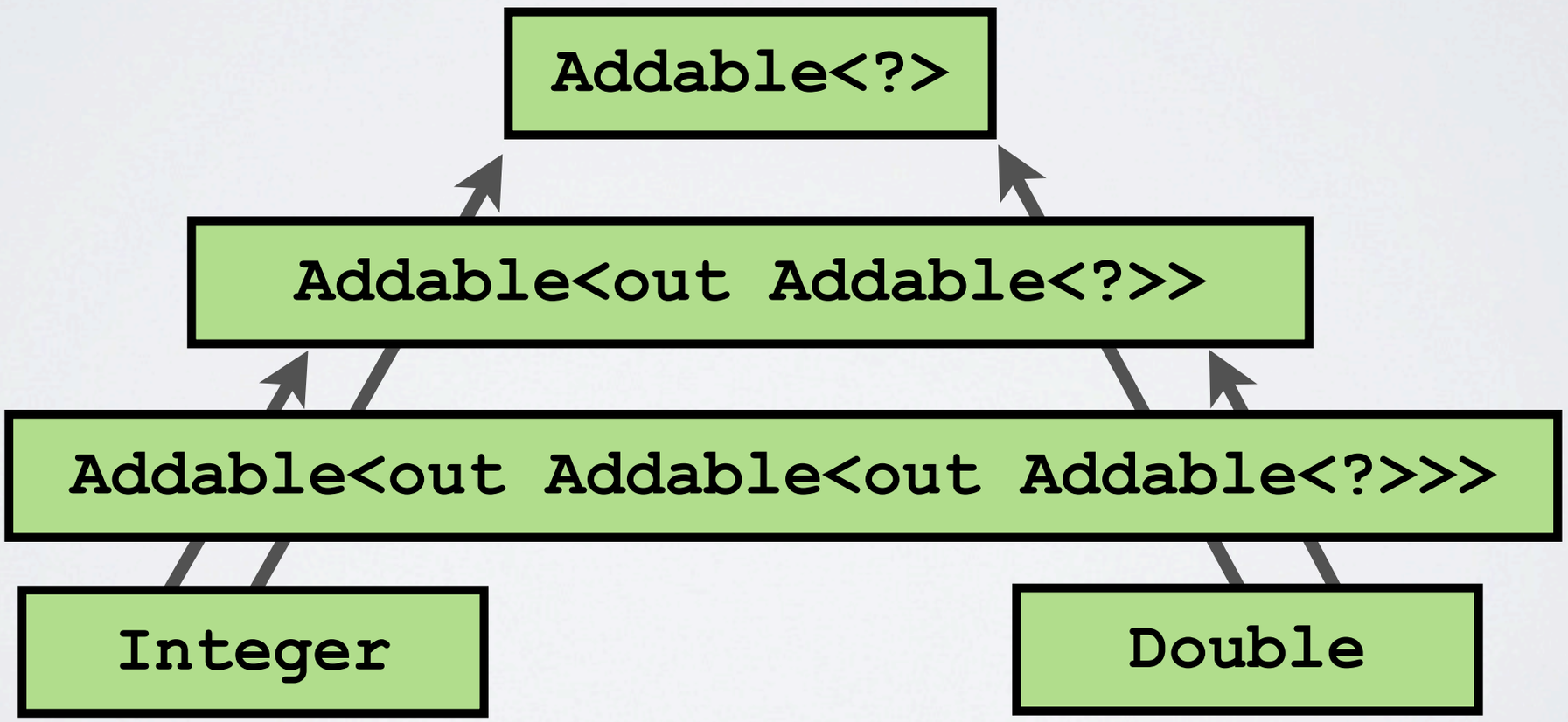
- Our subtyping algorithm only depends on recursion
  - Never uses syntactic equivalences
- We get equality for free: **`(A = B)`** iff **`(A <: B`** and **`B <: A)`**

JOINS

- **`A`** ⊔ **`B`** is the least common supertype of **`A`** and **`B`**
- Useful for type-checking conditional statements.
  - **`if (C) then A else B`** has type **`A`** ⊔ **`B`**
- In many languages, arbitrary joins do not exist

JOINS

```
interface Addable<out T> {}
class Double  implements Addable<Double>  {}
class Integer implements Addable<Integer> {}
```



JOINS

- Our system: the join of two materials always exists
    - Because material inheritance is decidable
- Note: **`Addable<*>`** was never the desired result
    - The result of any computation must be a material

CONDITIONAL INHERITANCE

- Unanswered question: type-safe equality for **`List<T>`**
- First solution, again: **`List<T> extends Eq<List<Eq<T>>>`**
- Bad style
- Nested contravariance & expansive inheritance
- List elements forced to extend **`Eq`** -- cannot make a **`List<Object>`**

CONDITIONAL INHERITANCE

- Ideally, **`List<T>`** is **`Equatable`** if and only if its elements are

```
List<out T> satisfies Equatable
            given T satisfies Equatable
```

- "**`satisfies`**" indicates that shapes are constraints, orthogonal to material classes and interfaces

- "**`given`**" denotes a condition that holds for certain instances

CONDITIONAL INHERITANCE

- Surprisingly challenging! Consider:

```
> interface List<out T> satisfies Cloneable
                  given T satisfies Cloneable

> class Array<inv T> extends List<T>
                      satisfies Cloneable
                given T satisfies Cloneable

> class B satisfies Cloneable

> class A extends B
```

- What is the result of invoking **`Array<A>.clone()`** ?

SHAPE SHIFTERS

- Code reuse is fundamental to object-oriented programming
- Shapes express constraints at the class / interface level
- **Shape Shifters** are a proposal for type variable-level reasoning

```
Set<String with CaseInsensitive>

Set<Function<Int, Int> with RefEqual>
```

The End