Object and Reference Immutability using Java Generics

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Immutability – What for?

- Program comprehension
- Verification
- Compile- & run-time optimizations
- Invariant detection
- Refactoring
- Test input generation
- Regression oracle creation
- Specification mining
- Modelling

Immutability varieties

- Class immutability
  - No instance of an immutable class can be mutated after creation (e.g., String, Integer)
- Object immutability
  - The same class may have both mutable and immutable instances
- Reference immutability
  - A particular reference cannot be used to mutate its referent (but other aliases might cause mutations)

Previous work

- Access rights
  - Java with Access-Control (JAC)
    - **`readnothing`** < **`readimmutable`** < **`readonly`** < **`writeable`**
  - Capabilities for sharing
    - Lower-level rights that can be enforced at compile- or run- time
- Reference immutability:
  - Universes (ownership + reference immutability)
  - C++'s **`const`**
  - Javari

IGJ - *Immutability Generic Java*

- Class immutability
  - All instances are immutable objects
- Object immutability:
  - An object: mutable or immutable
- Reference immutability:
  - A reference: mutable, immutable, or readonly

IGJ syntax

```
1: // An immutable reference to an immutable date;
   // Mutating the referent is prohibited, via this or any other reference.
   Date<Immutable> immutD = new Date<Immutable>();
2: // A mutable reference to a mutable date;
   // Mutating the referent is permitted, via this or any other reference.
   Date<Mutable> mutD = new Date<Mutable>();
3: // A readonly reference to any date;
   // Mutating the referent is prohibited via this reference.
   Date<ReadOnly> roD = ... ? immutD : mutD;
```

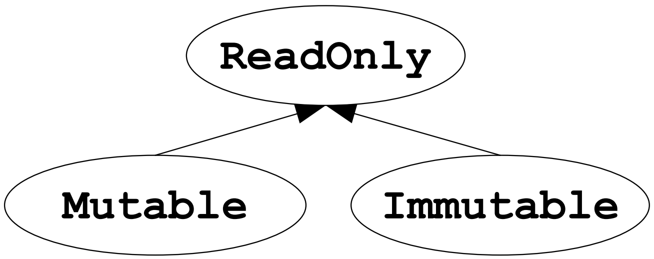
Java syntax is not modified:

- One new generic parameter was added
- Some method annotations were added (shown later)

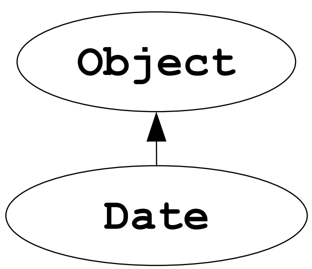
IGJ design principles

- Transitivity
  - Transitive (deep) immutability protects the entire abstract state from mutation
  - Mutable fields are excluded from the abstract state
- Static
  - No runtime representation for immutability
- Polymorphism
  - Abstracting over immutability without code duplication
- Simplicity
  - No change to Java’s syntax; a small set of typing rules

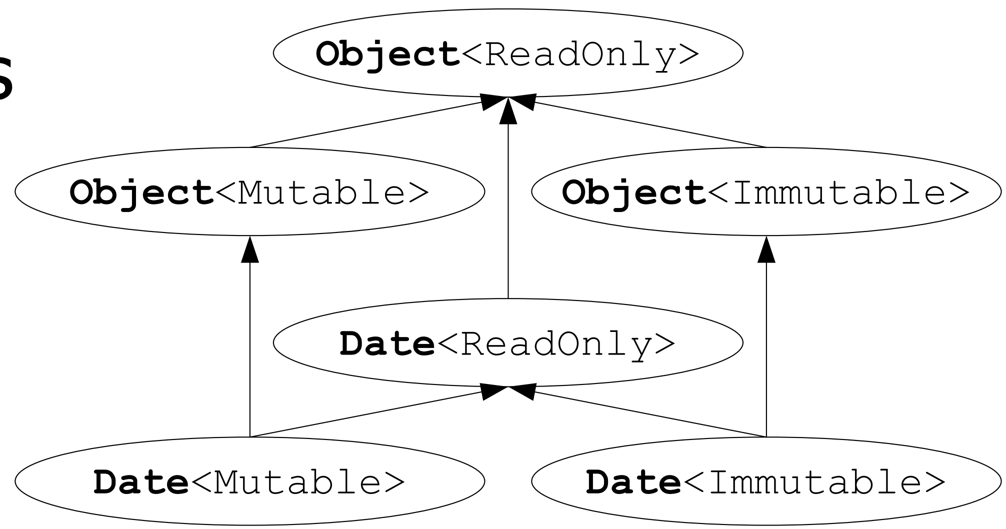
Hierarchies in IGJ



Immutability parameters hierarchy



The **subclass** hierarchy for Object and Date



The **subtype** hierarchy for Object and Date

Covariance problem and immutability

```
void foo(ArrayList<Object> a) { … }
foo(new ArrayList<Object>()); // OK
foo(new ArrayList<String>()); // Compilation error!
```

```
void foo(Object[] a) { a[0] = new Integer(1); }
foo(new Object[42]); // OK, stores an Integer in an Object array
foo(new String[42]); // Causes ArrayStoreException at runtime
```

- IGJ's Solution:
  - **`ReadOnly`, `Immutable`** – allow covariance
  - **`Mutable`** – disallow covariance

`List<ReadOnly,String>` is a subtype of **`List<ReadOnly,Object>`**
`List<Mutable,String>` is NOT a subtype of **`List<Mutable,Object>`**

IGJ typing rules

- There are several typing rules (next slides)
  - Field assignment
  - Immutability of **`this`**
  - Method invocation
- Let **`I(x)`** denote the immutability of **`x`**
  - Example:
    `Date<Mutable> d;`
    `I(d)` is **`Mutable`**

Field assignment rule

`o.someField = …;`
is legal iff `I(o) = Mutable`

Example:

```
Employee<ReadOnly> roE = …;
roE.address = …; // Compilation error!
```

Immutability of `this`

- **`this`** immutability is indicated by a method annotation
  - **`@ReadOnly`, `@Mutable`, `@Immutable`**
- We write **`I(m.this)`** to show the context of **`this`**
- Example:
  - **`@Mutable void m() {... this ...}`**
  - **`I(m.this) = Mutable`**

Method invocation rule

`o.m(...)`

is legal iff **`I(o)`** is a subtype of **`I(m.this)`**

```
1: Employee<Mutable> mutE = ...;
2: mutE.setAddress(...); // OK
3: mutE.getAddress();    // OK
4: Employee<ReadOnly> roE = mutE;
5: roE.setAddress(...);  // Compilation error!
```

Reference immutability (ReadOnly)

```
class Edge<I extends ReadOnly> {
  long id;
  @Mutable Edge(long id) { this.setId(id); }
  @Mutable void setId(long id) { this.id = id; }
  @ReadOnly long getId() { return this.id; }
  @ReadOnly Edge<I> copy() { return new Edge<I>(this.id); }
  static void print(Edge<ReadOnly> e) {... }
}

class Graph<I extends ReadOnly> {
  List<I,Edge<I>> edges;
  @Mutable Graph(List<I,Edge<I>> edges) { this.edges = edges; }
  @Mutable void addEdge(Edge<Mutable> e) { this.edges.add(e);}
  static <X extends ReadOnly>
           Edge<X> findEdge(Graph<X> g, long id) { ... }
}
```

Object immutability: Motivation

- Compile- & run-time optimizations
- Program comprehension
- Verification
- Invariant detection
- Test input generation
- ...
- Example: Immutable objects need no synchronization

```
@ReadOnly  synchronized long getId()          { return id; }
@Immutable              long getIdImmutable() { return id; }
```

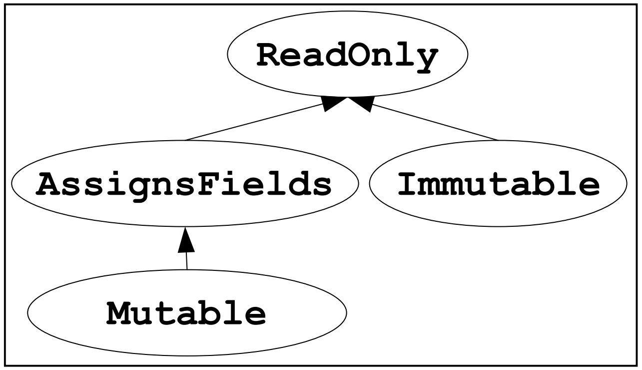
Object immutability: Challenge

```
class Edge<I extends ReadOnly> {
  private long id;
  @????????????? Edge(long id) { this.setId(id); }
  @Mutable       void setId(long id) { this.id = id; }
```

- Challenge: How should the constructor be annotated?
  - **`@Mutable`** ?
    - A mutable alias for **`this`** might escape
  - **`@Immutable`** or **`@ReadOnly`** ?
    - Cannot assign to any field, nor call **`this.setId`**

Object immutability: Solution

```java
class Edge<I extends ReadOnly> {
  private long id;
  @AssignsFields Edge(long id) { this.setId(id); }
  @AssignsFields void setId(long id) { this.id = id; }
  Edge<I> e;
  @Mutable void foo(long id) { this.e.id = id; }
```



- `@AssignsFields`
  - Can only assign to the fields of this, i.e., it is not transitive
  - Private: **cannot** write `Date<AssignsFields>`
  - Conclusion: `this` can only escape as `ReadOnly`

Case studies

- IGJ compiler
  - Small and simple extension of javac
  - Using the visitor pattern for the AST
  - Modified **`isSubType`** according to IGJ’s covariant subtyping
- Case studies:
  - Jolden benchmark, htmlparser, svn client
  - 328 classes (106 KLOC)
  - 113 JDK classes and interfaces

Case studies conclusions

- Representation exposure errors
  - In **`htmlparser`**: constructor takes an array and assigns it to a field, without copying; an accessor method also returns that array
- Conceptual problems
  - In Jolden: an immutable object is mutated only once immediately after it creation.
    We refactored the code, inserting the mutation to the constructor
- Found both immutable classes and objects
  - **`Date`**, **`SVNURL`**, lists

See the paper for …

- CoVariant and NoVariant type parameters
- Method overriding
- Mutable and assignable fields
- Inner classes
- **Circular immutable data-structures**
- Formal proof (Featherweight IGJ)

Conclusions

- Immutability Generic Java (IGJ)
  - Both reference, object, and class immutability
  - Simple, intuitive, small, no syntax changes
  - Static – no runtime penalties (like generics)
  - Backward compatible, no JVM changes
  - High degree of polymorphism using generics and safe covariant subtyping
- Case study proving usefulness
- Formal proof of soundness

Future work

- Add default immutability

```
class Graph<I extends ReadOnly default Mutable>
```

- An alternative syntax
  (in JSR 308 for Java 7)

```
new @mutable ArrayList<@immutable Edge>(...)
```

- Runtime support (e.g. down-cast)