Automatic Testing of Sequential and Concurrent Substitutability

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Motivation

```
void bar(Foo f) {
  f.m();
  ...
}
```

bar() expects functionality from Foo.m()

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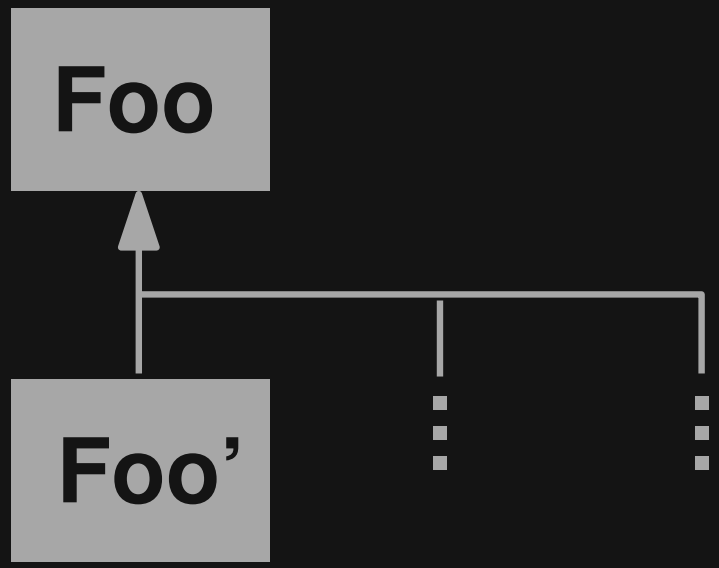


bar() expects functionality from Foo.m()

... even if Foo has subclasses

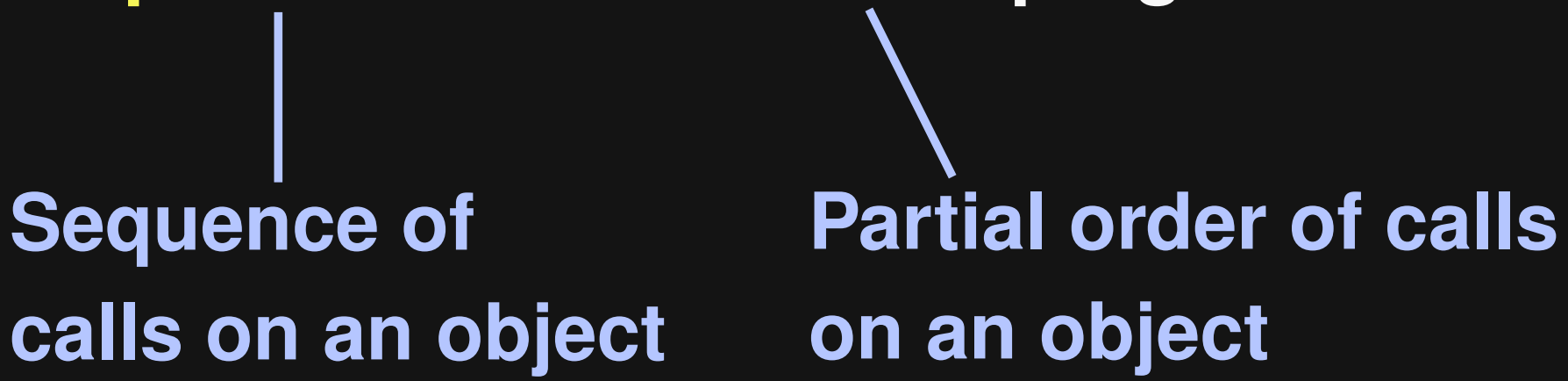
Substitutability

A subclass object should behave like a superclass object when being used through the superclass type.

[Liskov1987]

Sequential + Concurrent

Substitutability: Matters in sequential and concurrent programs



The Problem

How to enforce substitutability?

- **Language restrictions:**
  Not powerful enough
- **Verification:**
  Not practical

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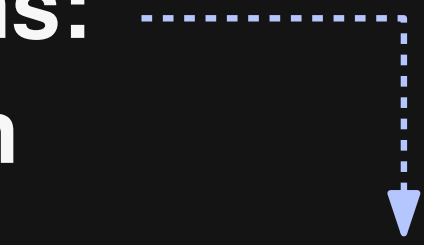

```
class Super {
  m(Object o) {..}
}
class Sub extends Super {
  m(Foo o) {..}
}
```

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In practice: 1/3 of all subclasses broken

(for Java classes from 26 popular libraries)

Real-World Example

```
TreeMap m = ...
m.put(23, m);
m.pollLastEntry();
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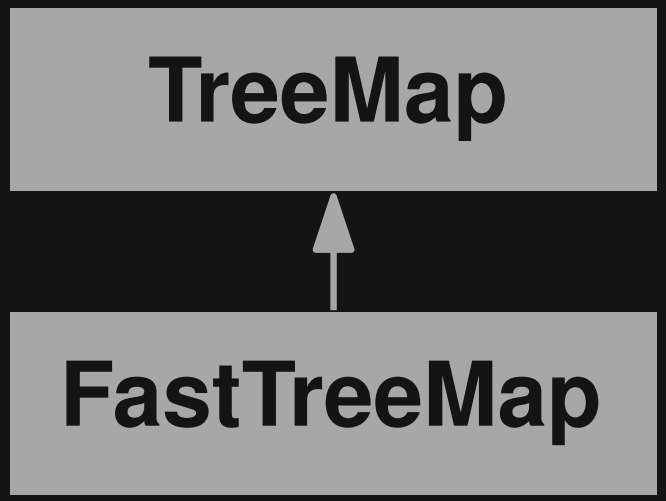


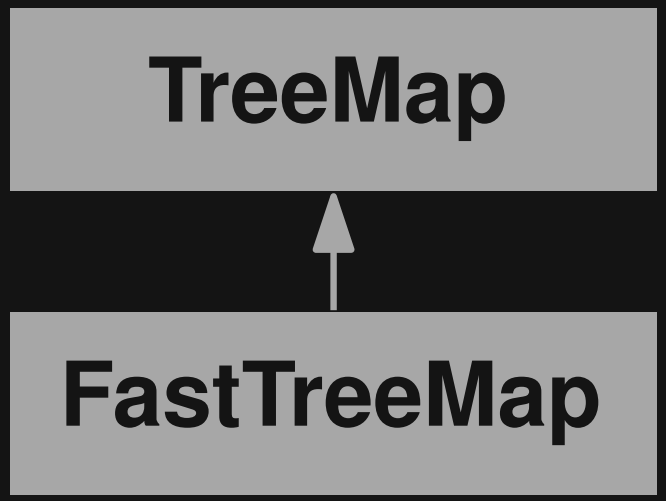
OK

StackOverflow-Error

Real-World Example

```
TreeMap m = ...
m.put(23, m);
m.pollLastEntry();
m.hashCode();
```

Problem:
May surprise clients of `TreeMap`



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This Talk

Automatic and precise

detection of unsafe substitutes

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Subclass that behaves differently from its superclass

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Only input:
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Only input:
Classes to test

Only output:
Unsafe substitutes

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Subclass that behaves
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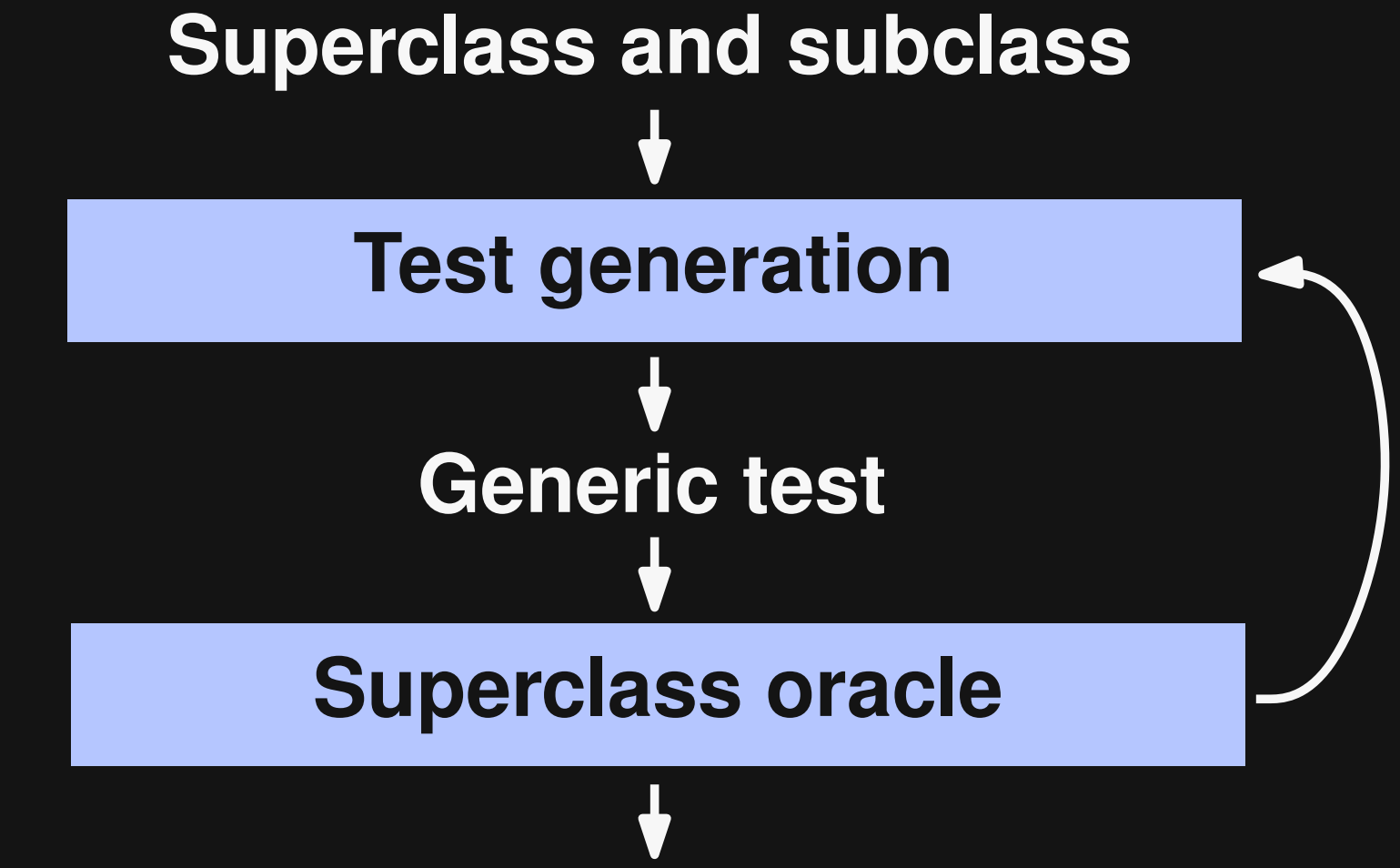
Overview


Superclass and subclass
Test generation
Generic test
Superclass oracle
Warning about unsafe substitute

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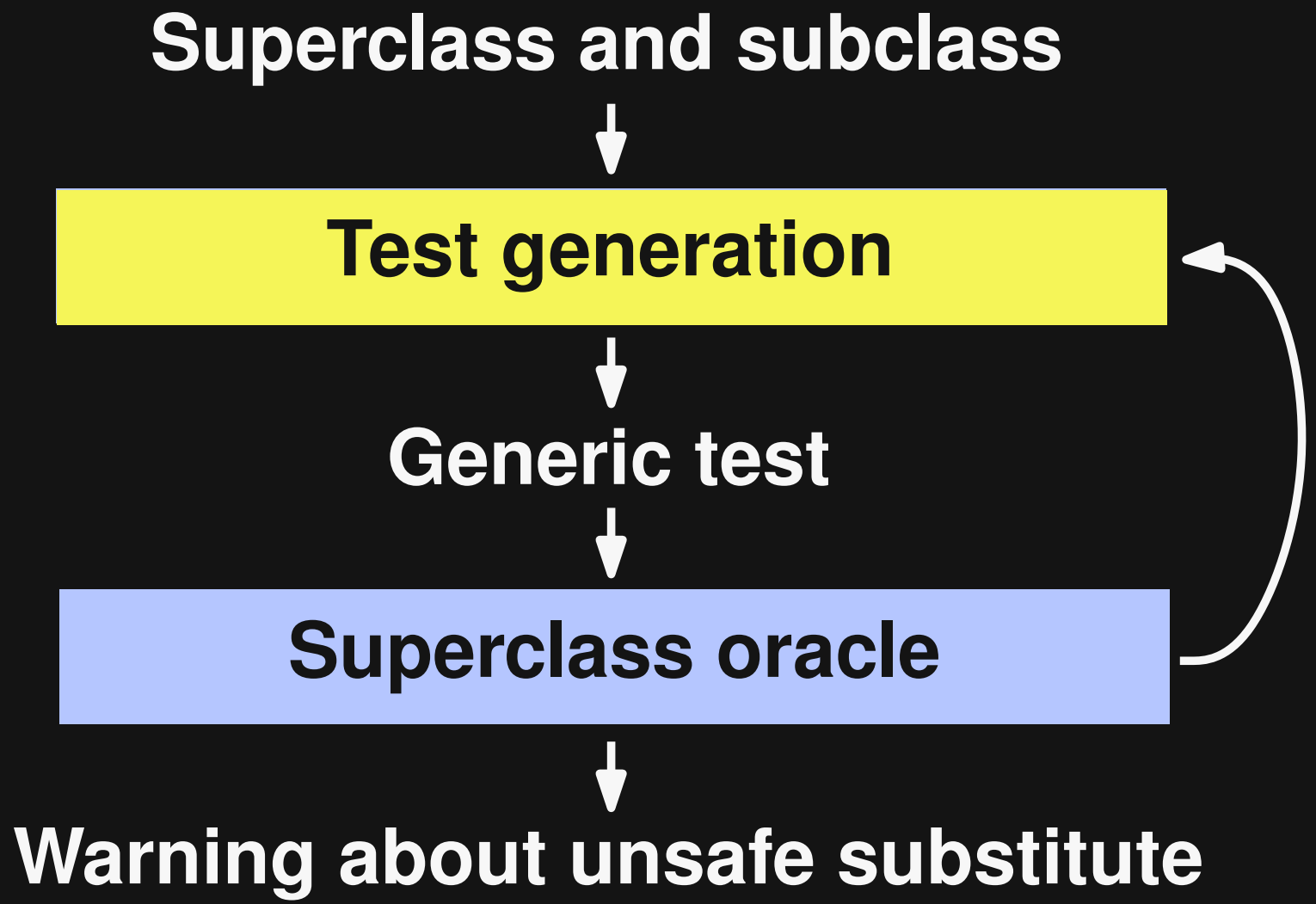
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Generic Tests

⋮ (sequence of calls to prepare arguments)

```
Super s = new Super(..) OR
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```

⋮ (calls to `s` from one or more threads)

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Run the same test with either class

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Test Generation

Feedback-directed, random generation of sequential and concurrent tests [PLDI 2012]

```
TreeMap m = new TreeMap() OR
            new FastTreeMap();
m.put(23, m);
m.pollLastEntry();
m.hashCode();
```

Randomly selected methods with random arguments

Challenge: Constructors

```
TreeMap m = new TreeMap(map1) OR
            new FastTreeMap(map2)
```

Goal: **Semantically equivalent** Super and Sub instances

Problem: **Constructors** are **not inherited** in Java

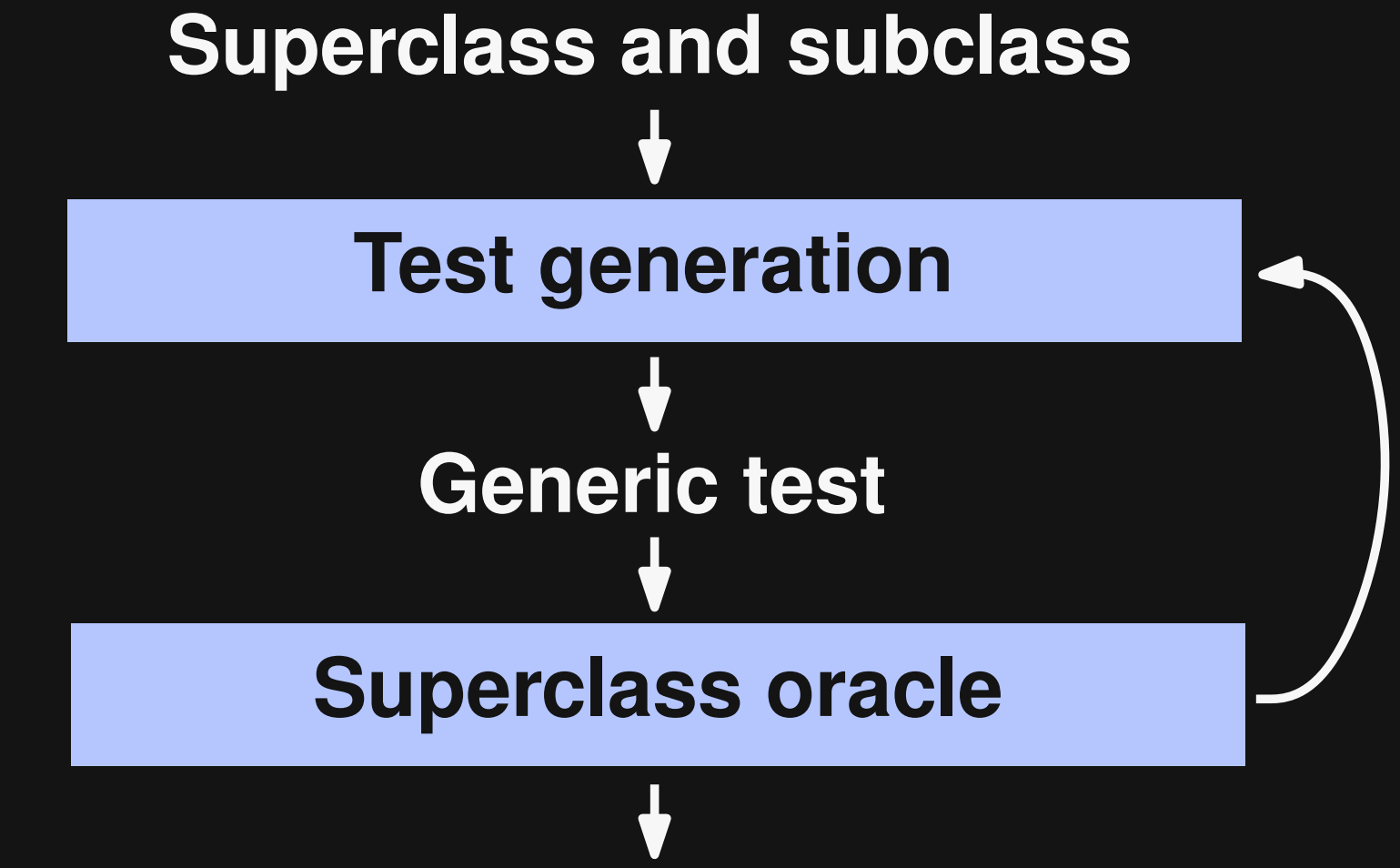
Constructor Mappings

Heuristic:

Map constructors by argument types and pass same arguments

- `Super(int, Foo)` ≡ `Sub(int, Foo)`
- `TreeMap()` ≡ `FastTreeMap()`

Overview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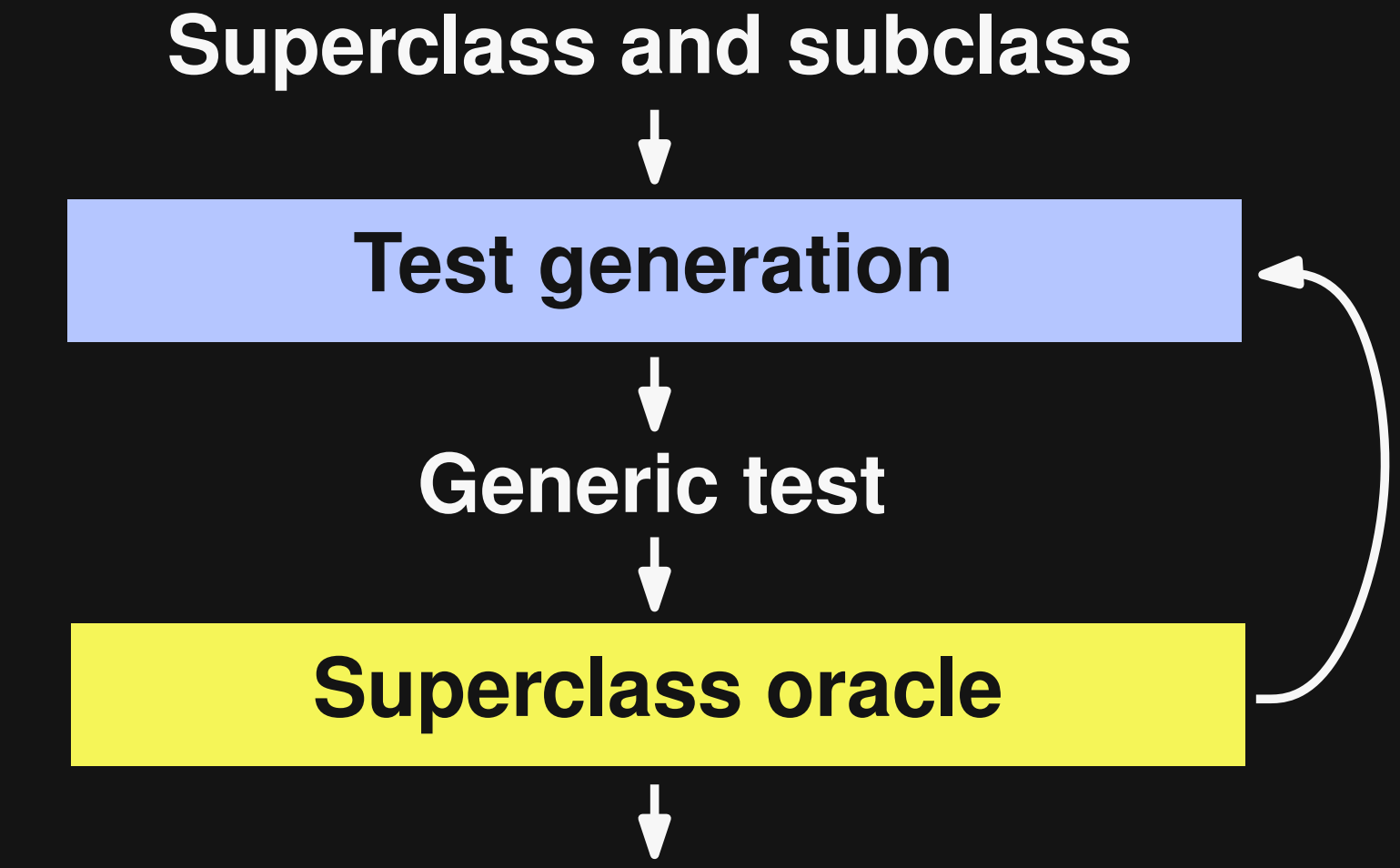
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Superclass Oracle

Idea:

Warn if Sub's behavior diverges from Super's behavior

Sequential tests:
Compare two executions

Concurrent tests:
Compare two sets of executions

Output Oracle

Warn if return values differ

- Primitives & String: Compare values
- Reference values: Compare nullness

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Example:

```
TreeMap m = new TreeMap();
m.put(23, m);       // null
m.pollLastEntry(); // non-null

TreeMap m = new FastTreeMap();
m.put(23, m);       // null
m.pollLastEntry(); // null
```

Output Oracle

Warn if return values differ

- Primitives & String: Compare values
- Reference values: Compare nullness

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Warning

Crash Oracle

Warn if Sub leads to exception or deadlock, but Super doesn’t

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Example:

```
TreeMap m = new TreeMap();
m.put(23, m);       // OK
m.pollLastEntry(); // OK
m.hashCode();       // OK

TreeMap m = new FastTreeMap();
m.put(23, m);       // OK
m.pollLastEntry(); // OK
m.hashCode();       // Exception
```

Crash Oracle

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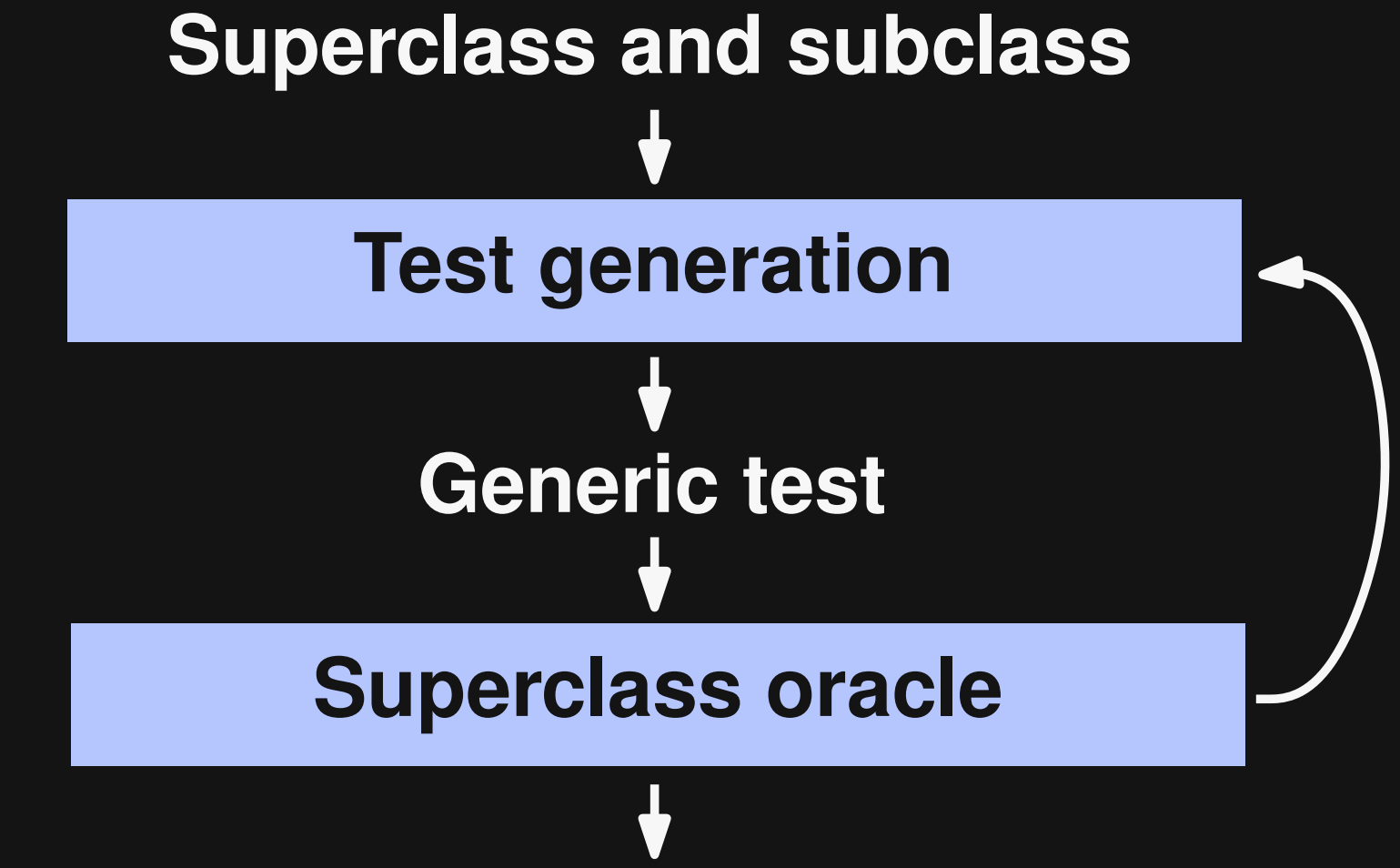
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Evaluation: Setup

145 class pairs from
26 real-world Java libraries

- 116 sequentially used
- 29 concurrently used
- Apache Commons Collections, dom4j, iText, and libraries in Qualitas corpus

Stop testing after a fixed number of tests

Results: Output Oracle

42% of all subclasses are **output-diverging substitutes**

Most of them (93%) are **benign**

Example: Output-divergent

```
Namespace ns = new Namespace("a", "b");
boolean b = ns.supportsParent();  // false
```

```
Namespace ns = new DefaultNamespace("a", "b");
boolean b = ns.supportsParent();  // true
```

Example: Output-divergent

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Different behavior but not a bug

Reasons for False Positives

- **Ad-hoc reflection**
- **String representations differ**
- **Constructor mismatch: Heuristic fails**

Results: Crash Oracle

30% of all subclasses are **crashing substitutes**

All issues are **bugs** that should be fixed

Example: Crashing (1)

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m.hashCode();          // OK

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```
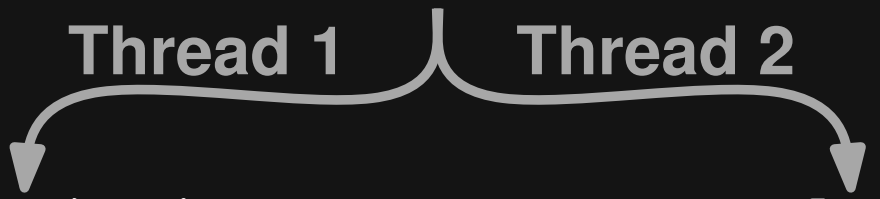

Example: Crashing (2)

```
Properties p = new Properties();
p.setProperty("a", "b");
```

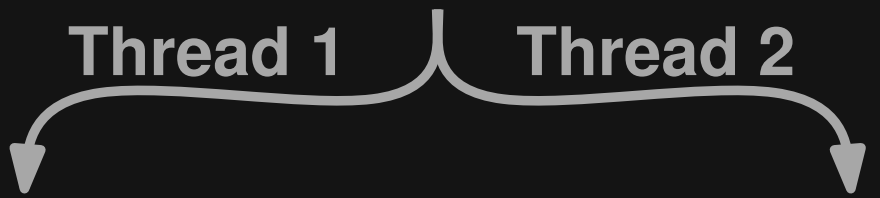



```
p.remove("a");
```

```
p.clear();
```

OK

```
Properties p = new PropertyMap();
p.setProperty("a", "b");
```

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Exception

Root Causes for Bugs

- Sub imposes stronger precondition
- Sub removes methods
  (`UnsupportedOperationException`)
- Sub removes synchronization
- Propagated unsafety

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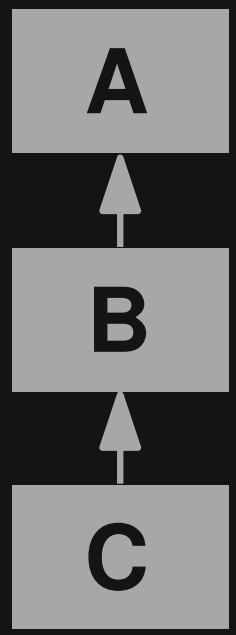

Feedback from Developers

- **Reported 10 bugs**
  (e.g., JBoss, Commons Collections)

  $\rightarrow$ **8 of them fixed by now**

- **3 other bugs found and fixed independently of us**

Conclusion

Substitutability: Broken in practice

Automatic testing approach

- Crash oracle: Only real bugs

Need better language support for avoiding substitutability problems

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Thank you!

Michael Pradel

Artifacts for download:
http://mp.binaervarianz.de/icse2013/