COMP 587 Lecture 8

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Outline

- Project next steps
- Testability: dependency injection and mocking
  - In-class exercise
- Measuring test quality
  - Coverage
  - Mutation testing / analysis

Project Next Steps

- Join https://github.com/orgs/CSUN-COMP587-F18
- Make new / fork repository in organization
    - Caveat: non-public code
- Start working: submit first pull request by **Tuesday**

Testability, Dependency Injection, and Mocking

```
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  c.charge(100);
}
```

–Code example from here: xywang.100871.net/CS4723_lec3.ppt
–From Prof. Xiaoyin Wang (http://xywang.100871.net/)

```
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  c.charge(100);
}
```

Run with rest of tests: success (and charged $100)

Run alone: fails

-Code example from here: xywang.100871.net/CS4723_lec3.ppt
-From Prof. Xiaoyin Wang (http://xywang.100871.net/)
-Individual tests should operate independently from each other.
-Even if they aren't independent, we should know why

```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  c.charge(100);
}
```

-We dive into the code of CreditCard, and we see that the charge method depends on this CreditCardProcessor class
-We need to initialize that class first

```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  c.charge(100);
}
```

Run with rest of tests: success (and charged $100)

Run alone: fails

–Still missing something

```
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  TaskQueue.init();
  c.charge(100);
}
```

-We dive into the code more, and we see that CreditCardProcessor internally uses a TaskQueue.
-Ok, so we need to initialize TaskQueue

```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  TaskQueue.init();
  c.charge(100);
}
```

Run with rest of tests: success (and charged $100)

Run alone: fails

-We dive into the code more, and we see that CreditCardProcessor internally uses a TaskQueue.
-Ok, so we need to initialize TaskQueue

```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  TaskQueue.init();
  Database.init();
  c.charge(100);
}
```

-Ok, ok, so now we dive into the source code of TaskQueue
-Turns out TaskQueue depends on a Database, so let's initialize that, too

```
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  TaskQueue.init();
  Database.init();
  c.charge(100);
}
```

Run with rest of tests: success (and charged $100)

Run alone: success (and charged $100)

-Ok, ok, so now we dive into the source code of TaskQueue
-Turns out TaskQueue depends on a Database, so let's initialize that, too

```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
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```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  TaskQueue.init();
  Database.init();
  c.charge(100);
}
```

-We started with the code on the top, and ended up with the code on the bottom
-This reveals that the code isn't very testable. Why?

```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  c.charge(100);
}
```

Not very testable. Why?

```java
@Test
public void testCreditCardCharge() {
  CreditCard c = new CreditCard(
    "1234 5678 9012 3456", 5, 2008);
  CreditCardProcessor.init();
  TaskQueue.init();
  Database.init();
  c.charge(100);
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```

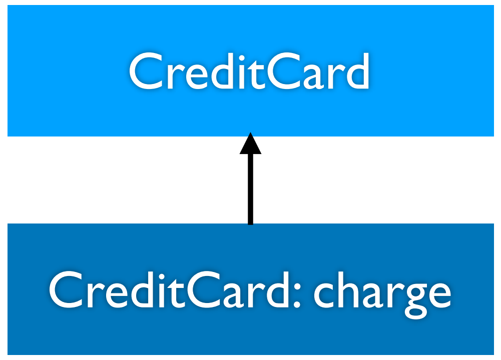
-We started with the code on the top, and ended up with the code on the bottom
-This reveals that the code isn't very testable. Why?

Explicit Dependencies

```
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
CreditCardProcessor.init();
TaskQueue.init();
Database.init();
c.charge(100);
```

Explicit Dependencies

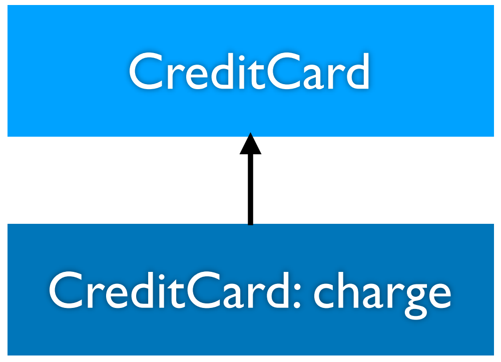
```
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
CreditCardProcessor.init();
TaskQueue.init();
Database.init();
c.charge(100);
```



-This is the only explicit dependency
-Looking at only this code, there is nothing which explicitly requires CreditCardProcessor, TaskQueue, or Database

With Implicit Dependencies

```
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
CreditCardProcessor.init();
TaskQueue.init();
Database.init();
c.charge(100);
```



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With Implicit Dependencies

```
CreditCard c = new CreditCard(
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c.charge(100);
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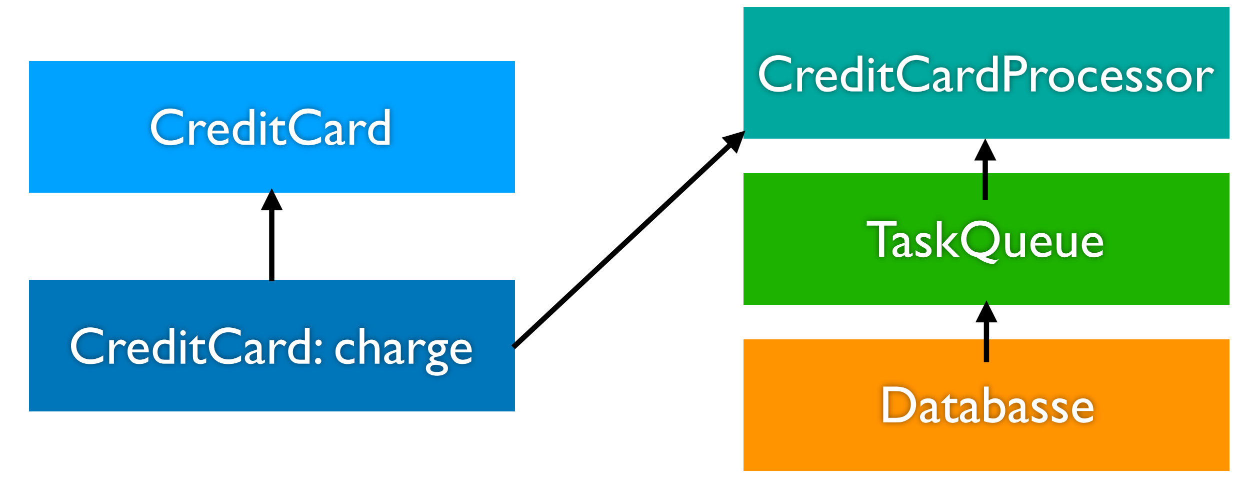

-This is the only explicit dependency
-Looking at only this code, there is nothing which explicitly requires CreditCardProcessor, TaskQueue, or Database

With Implicit Dependencies

```
CreditCard c = new CreditCard(
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Database.init();
c.charge(100);
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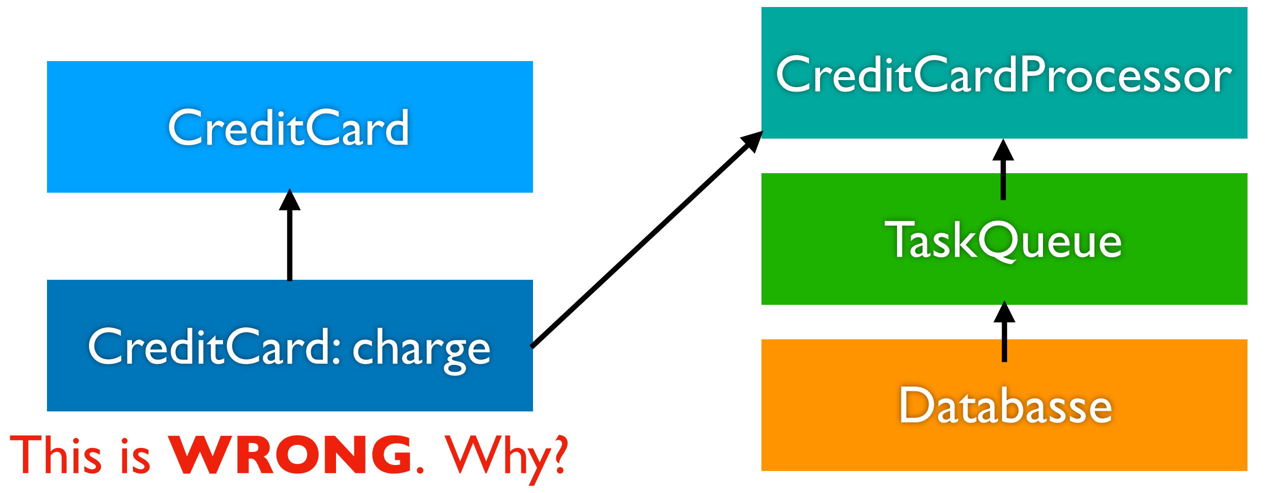

This is **WRONG**. Why?

-This is the only explicit dependency
-Looking at only this code, there is nothing which explicitly requires CreditCardProcessor, TaskQueue, or Database

With Implicit Dependencies

```
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
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Database.init();
c.charge(100);
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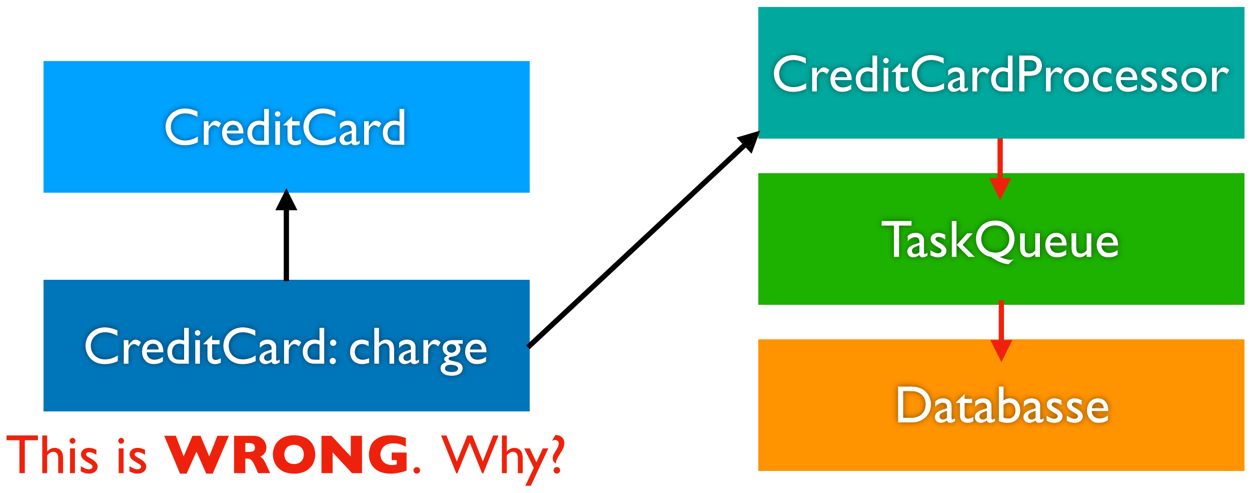
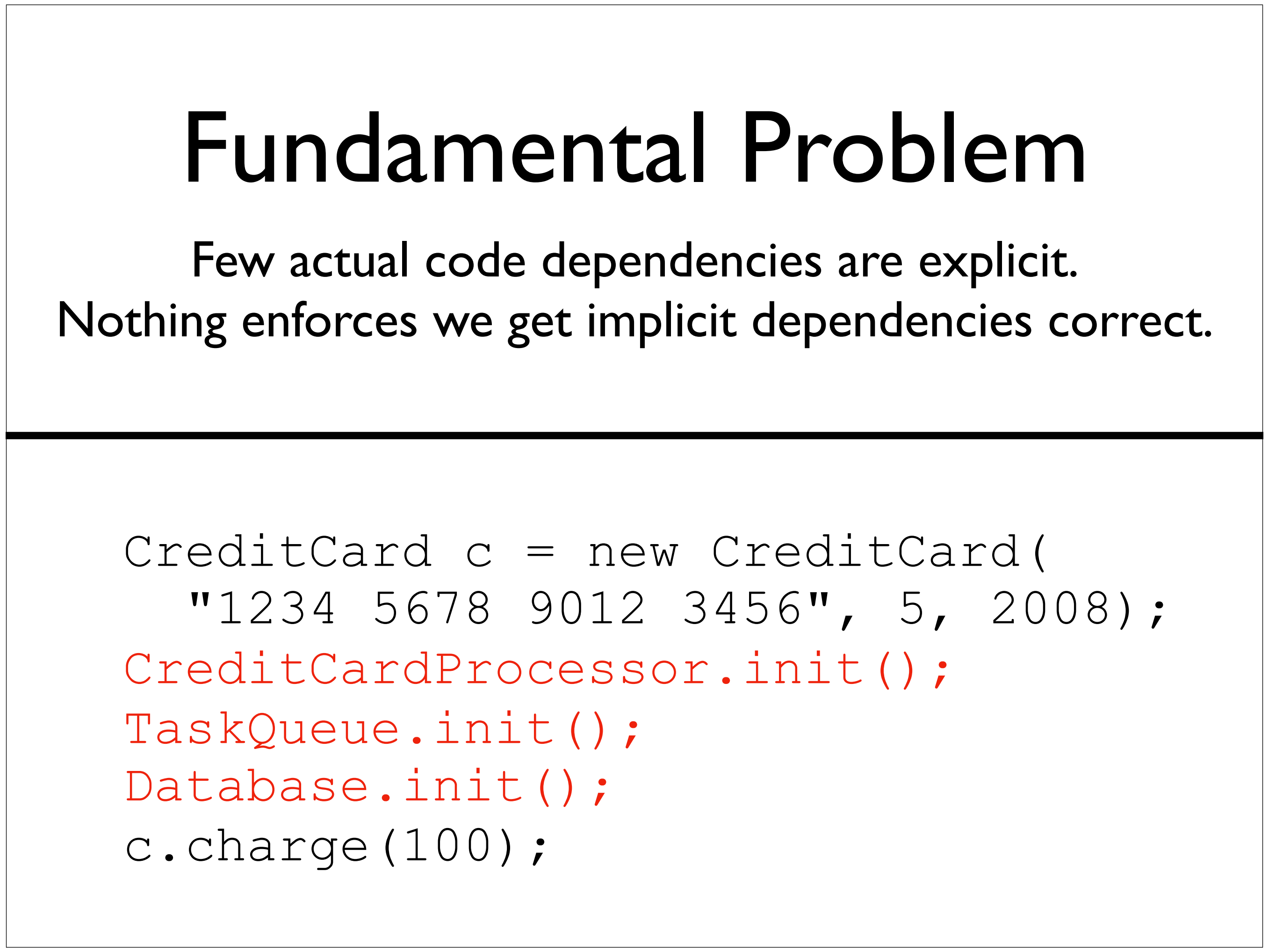


-We said that charge depended on CreditCardProcessor, which in turn depended on TaskQueue, which in turn depended on Database
-We need to flip these arrows to show this.
-Probably should update the code to reverse the initialization order, too



Fundamental Problem

Few actual code dependencies are explicit.
Nothing enforces we get implicit dependencies correct.

```
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
CreditCardProcessor.init();
TaskQueue.init();
Database.init();
c.charge(100);
```

-"Nothing enforces" is another way of saying "nothing stops us from introducing bugs here"
-Implicit dependencies can only be handled with informal documentation and sufficient system knowledge. Generally, we'll never know how much system knowledge is "sufficient".

Dependency Injection

- Fundamentally: make dependencies explicit
- Frequently done by parameter passing

```
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
CreditCardProcessor.init();
TaskQueue.init();
Database.init();
c.charge(100);
```

–This is the code we started with...

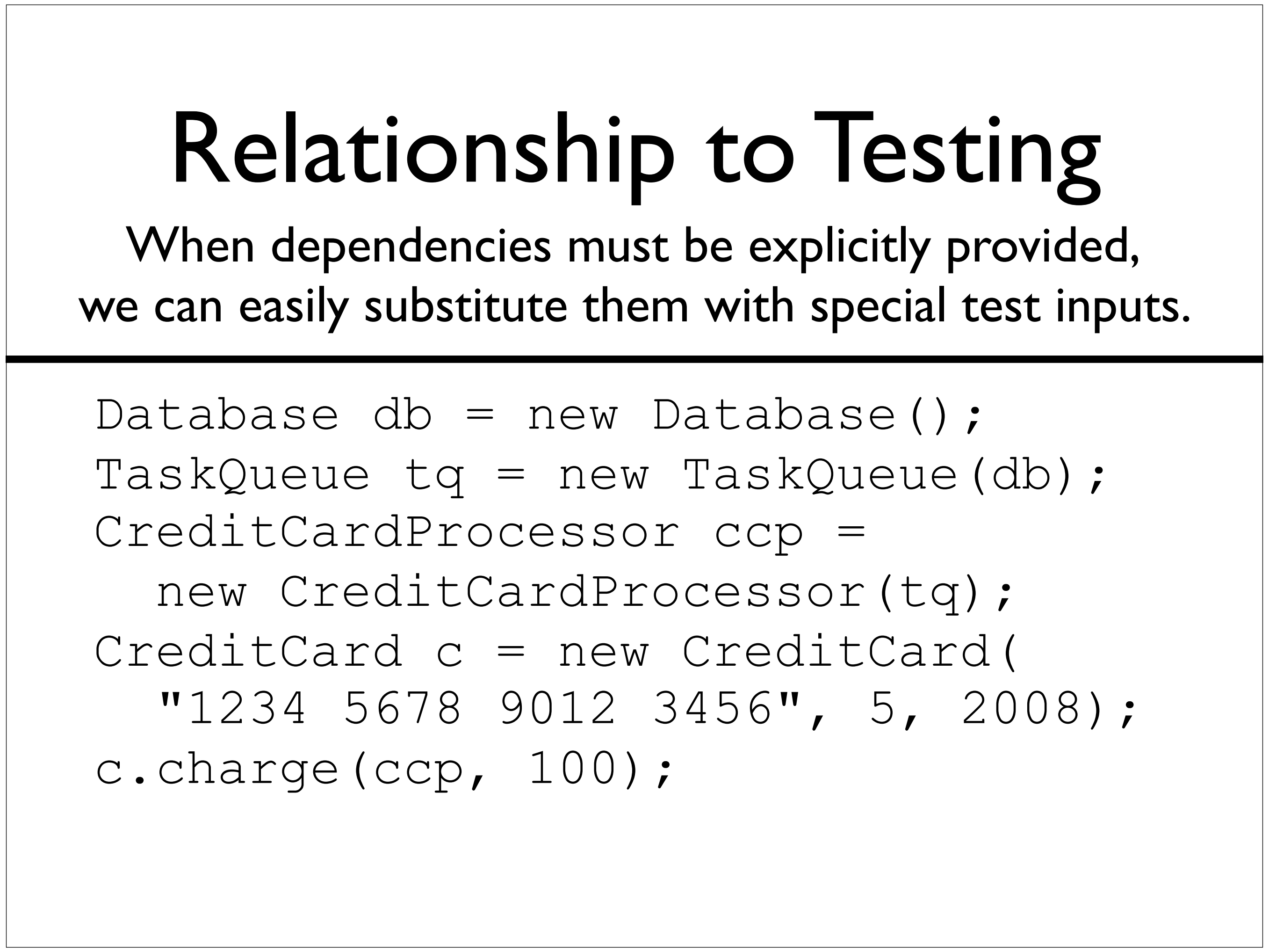
```
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
CreditCardProcessor.init();
TaskQueue.init();
Database.init();
c.charge(100);
```

```
Database db = new Database();
TaskQueue tq = new TaskQueue(db);
CreditCardProcessor ccp =
  new CreditCardProcessor(tq);
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
c.charge(ccp, 100);
```

-...and the code on the bottom is much more explicit
-We cannot make a TaskQueue without a Database. Explicit, enforced dependency.
-We cannot make a CreditCardProcessor without a TaskQueue. Explicit, enforced dependency.
-We cannot call charge without a CreditCardProcessor. Explicit, enforced dependency.

Relationship to Testing

When dependencies must be explicitly provided,
we can easily substitute them with special test inputs.



Relationship to Testing

When dependencies must be explicitly provided,
we can easily substitute them with special test inputs.

```
Database db = new Database();
TaskQueue tq = new TaskQueue(db);
CreditCardProcessor ccp =
  new CreditCardProcessor(tq);
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
c.charge(ccp, 100);
```

-Here we have the code with dependency injection

Relationship to Testing

When dependencies must be explicitly provided,
we can easily substitute them with special test inputs.

```
Database db = new Database();
TaskQueue tq = new TaskQueue(db);
CreditCardProcessor ccp =
  new CreditCardProcessor(tq);
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
c.charge(ccp, 100);
```

-This code still makes a real $100 charge each time we run it

Relationship to Testing

When dependencies must be explicitly provided, we can easily substitute them with special test inputs.

```
CreditCardProcessor ccp =
  new NoSendCreditCardProcessor();
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
c.charge(ccp, 100);
```

-However, we can easily swap out the CreditCardProcessor with a testing variant. CreditCardProcessor is now an interface instead of a concrete class.
-NoSendCreditCardProcessor conforms to the CreditCardProcessor interface, but it won't send the charge.
-Since it doesn't actually do anything, we don't need the Database and the TaskQueue anymore
-We can still have this test, but we won't get charged $100

Mocking

- The name of this substitution for testing is *mocking*
  - As in, a mock-up
- Libraries exist to assist with mocking
  - Easier to define custom test inputs
  - Easy to adapt to different testing scenarios

Example: Mockito (Java)

```
CreditCardProcessor ccp =
  new NoSendCreditCardProcessor();
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
c.charge(ccp, 100);
```

-https://site.mockito.org/
-We had the code on the top originally

Example: Mockito (Java)

```
CreditCardProcessor ccp =
  new NoSendCreditCardProcessor();
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
c.charge(ccp, 100);
```

```
CreditCardProcessor ccp =
  mock(CreditCardProcessor.class);
when(ccp.chargeAccepted(100))
  .thenReturn(true);
CreditCard c = new CreditCard(
  "1234 5678 9012 3456", 5, 2008);
c.charge(ccp, 100);
```

-https://site.mockito.org/
-We can replace this code with the code on the bottom
-Biggest difference: we don't need to define an explicit NoSendCreditCardProcessor anymore
-While it looks like there is more code, and now a chargeAccepted method, this method would have had to have been implemented in NoSendCreditCardProcessor, along with any other functionality needed by the CreditCardProcessor interface. This is a lot less code, and it's more to the point.

In-Class Exercise: Refactoring Code for Testability

Measuring Test Quality: Coverage

Coverage: Basic Idea

Run tests, and see which parts of the code tests touch.

Coverage: Basic Idea

Run tests, and see which parts of the code tests touch.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

-Let's take this code

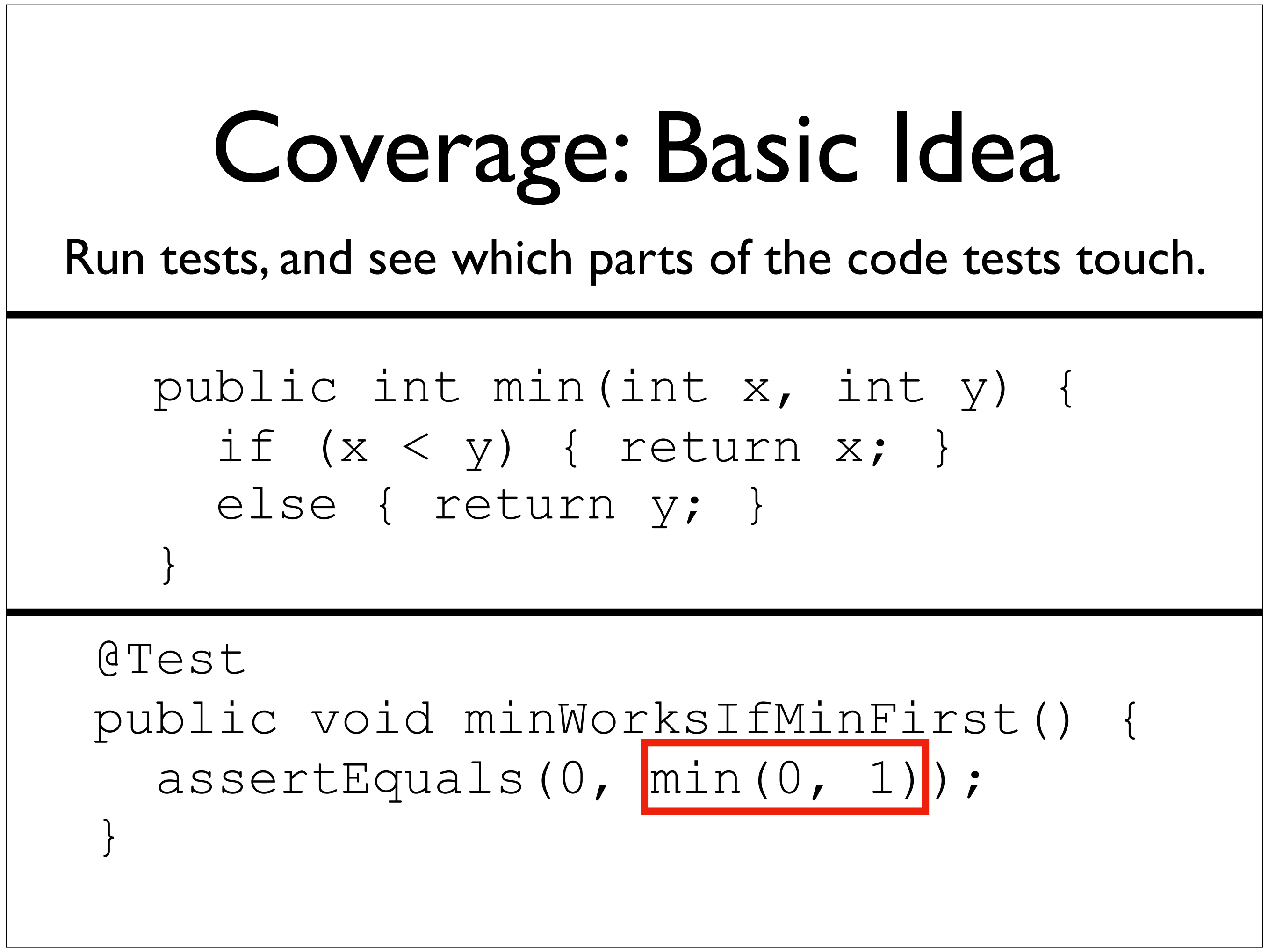
Coverage: Basic Idea

Run tests, and see which parts of the code tests touch.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

–...along with this test



Coverage: Basic Idea

Run tests, and see which parts of the code tests touch.

```
  public int min(int x, int y) {
    if (x < y) { return x; }
    else { return y; }
  }
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-If we run the test, it will touch part of the code

Coverage: Basic Idea

Run tests, and see which parts of the code tests touch.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Hits method entry

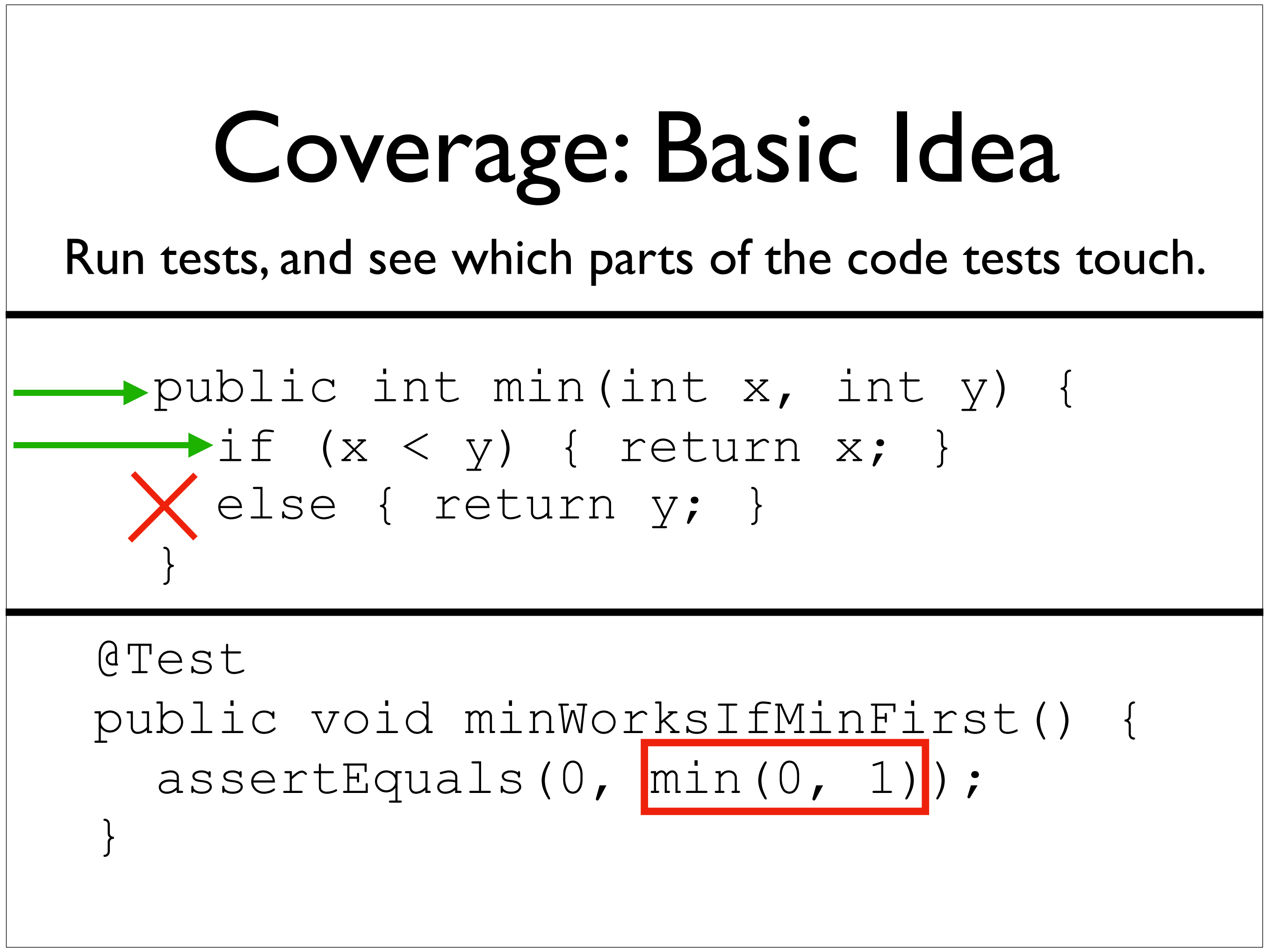
Coverage: Basic Idea

Run tests, and see which parts of the code tests touch.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Hits the if, specifically the true branch



Coverage: Basic Idea

Run tests, and see which parts of the code tests touch.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Does not hit the false branch

Coverage Intuition

Touching more code = better tests.

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Touching more code = better tests.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

-I'll take the same code...

Coverage Intuition

Touching more code = better tests.

```
  public int min(int x, int y) {
    if (x < y) { return x; }
    else { return y; }
  }
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

–...along with the same test

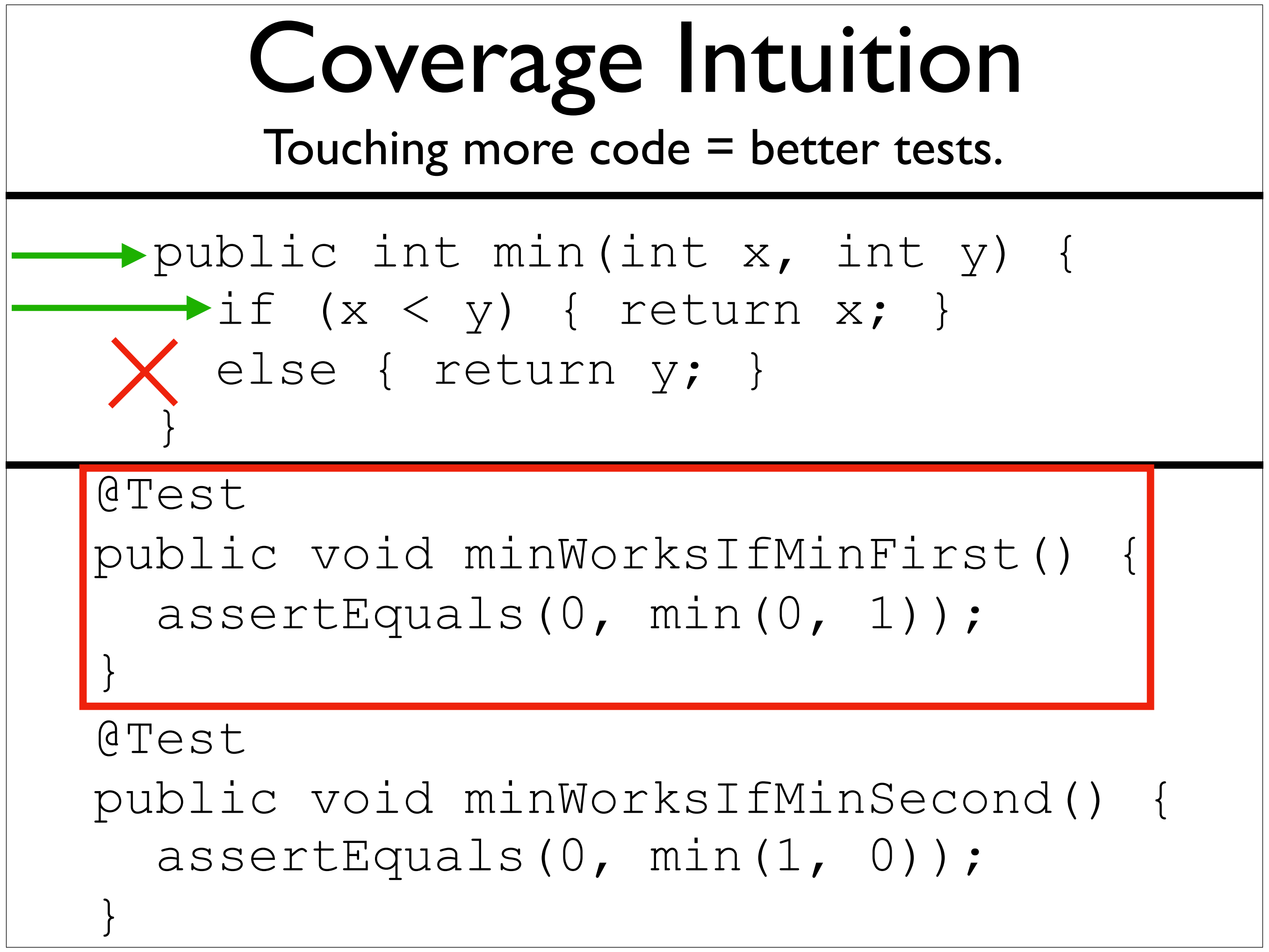
Coverage Intuition

Touching more code = better tests.

```
  public int min(int x, int y) {
    if (x < y) { return x; }
    else { return y; }
  }
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
@Test
public void minWorksIfMinSecond() {
  assertEquals(0, min(1, 0));
}
```

-And add a second test, which tests something different from the first



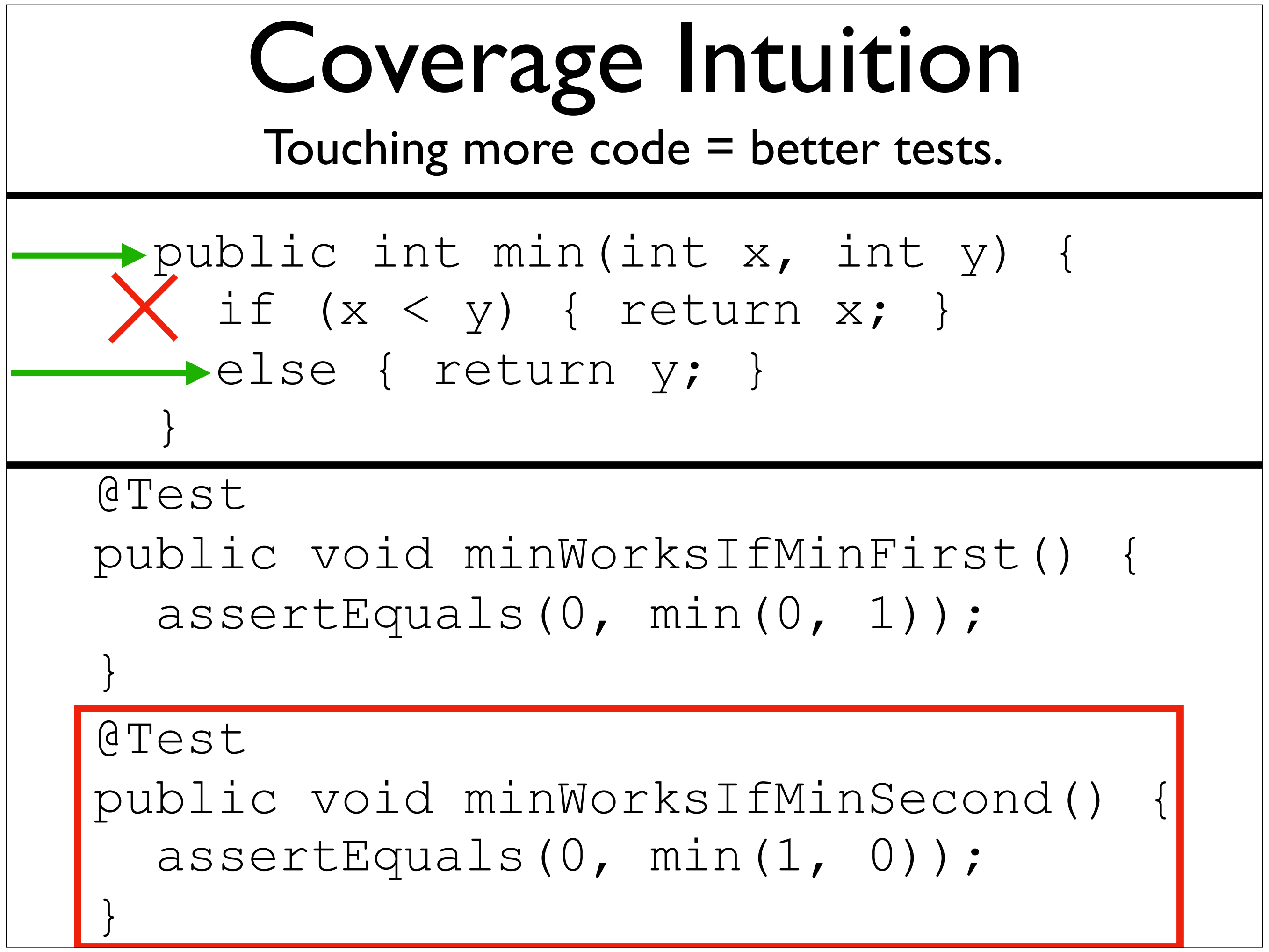
Coverage Intuition

Touching more code = better tests.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
@Test
public void minWorksIfMinSecond() {
  assertEquals(0, min(1, 0));
}
```

-First test hits only the first two lines



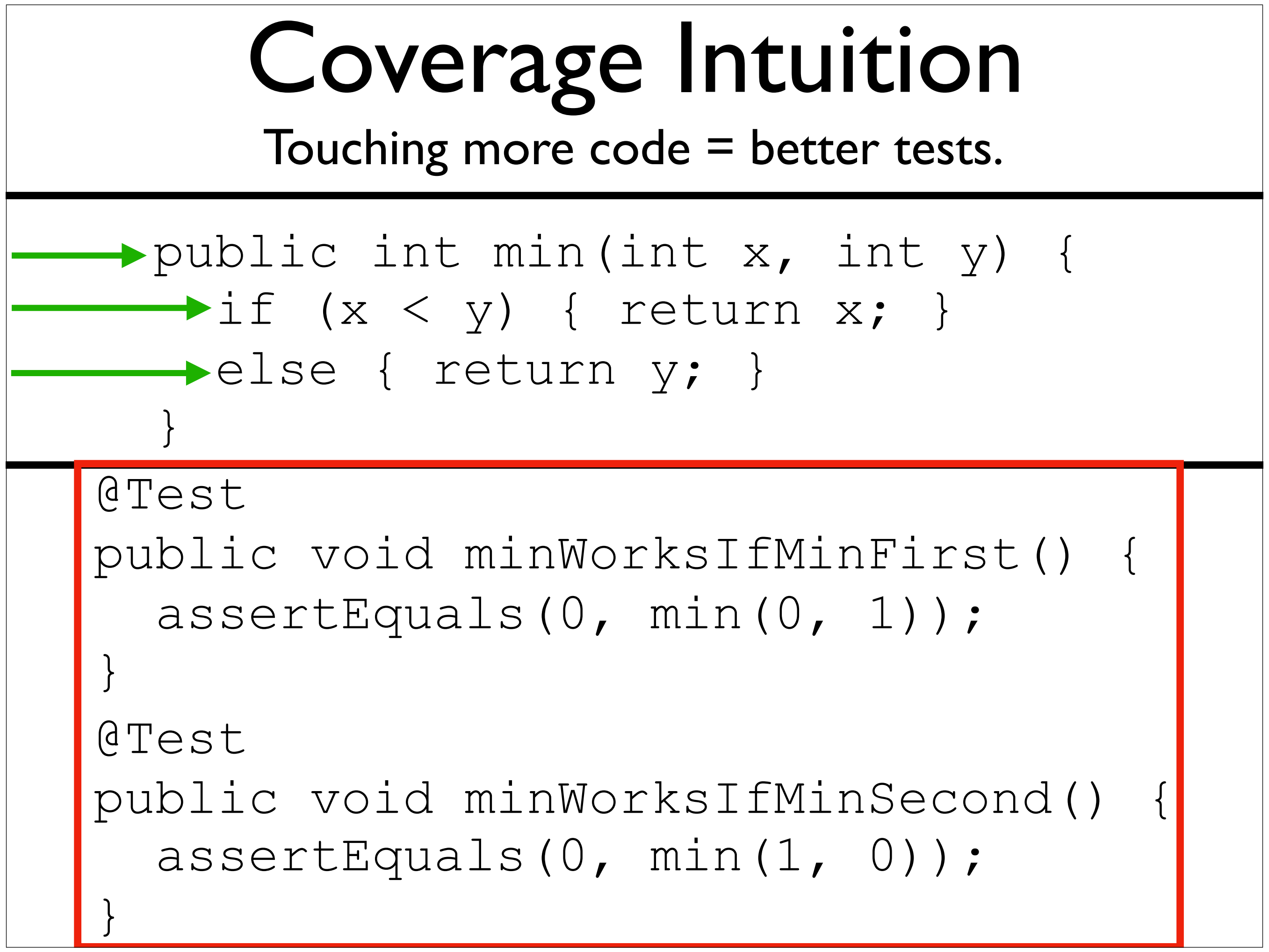
Coverage Intuition

Touching more code = better tests.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
@Test
public void minWorksIfMinSecond() {
  assertEquals(0, min(1, 0));
}
```

-Second test misses the true branch of the if



Coverage Intuition

Touching more code = better tests.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
@Test
public void minWorksIfMinSecond() {
  assertEquals(0, min(1, 0));
}
```

-Together, however, they hit everything

Coverage Reveals Missed Behaviors

More tests != better tests

Coverage Reveals Missed Behaviors

More tests != better tests

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

Coverage Reveals Missed Behaviors

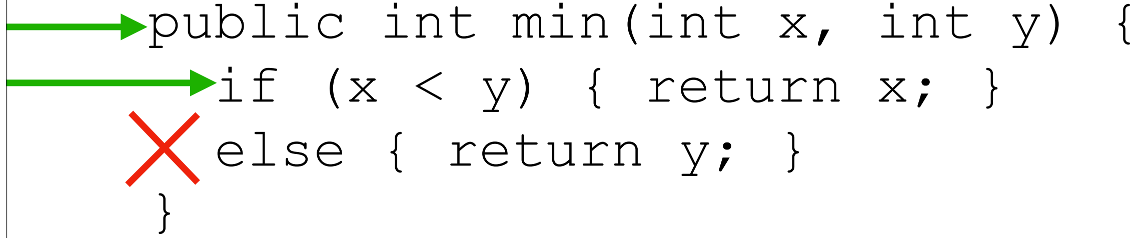
More tests != better tests

```
    public int min(int x, int y) {
      if (x < y) { return x; }
      else { return y; }
    }
```

```
@Test public void minWorksIfMinFirst1(){
  assertEquals(0, min(0, 1));
}
@Test public void minWorksIfMinFirst2(){
  assertEquals(2, min(2, 3));
}
```

Coverage Reveals Missed Behaviors

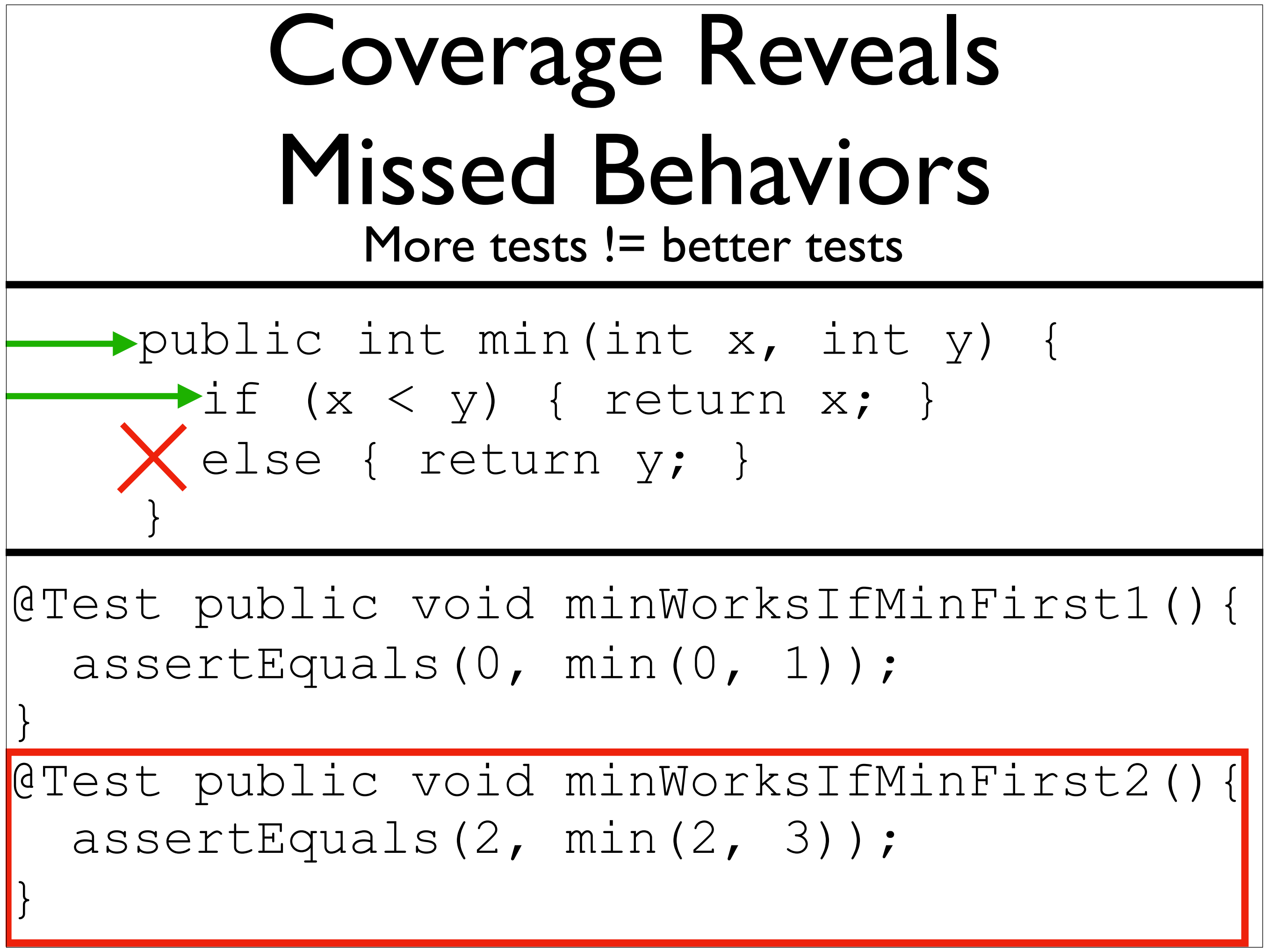
More tests != better tests



```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test public void minWorksIfMinFirst1(){
  assertEquals(0, min(0, 1));
}
@Test public void minWorksIfMinFirst2(){
  assertEquals(2, min(2, 3));
}
```

-Coverage of only the first test



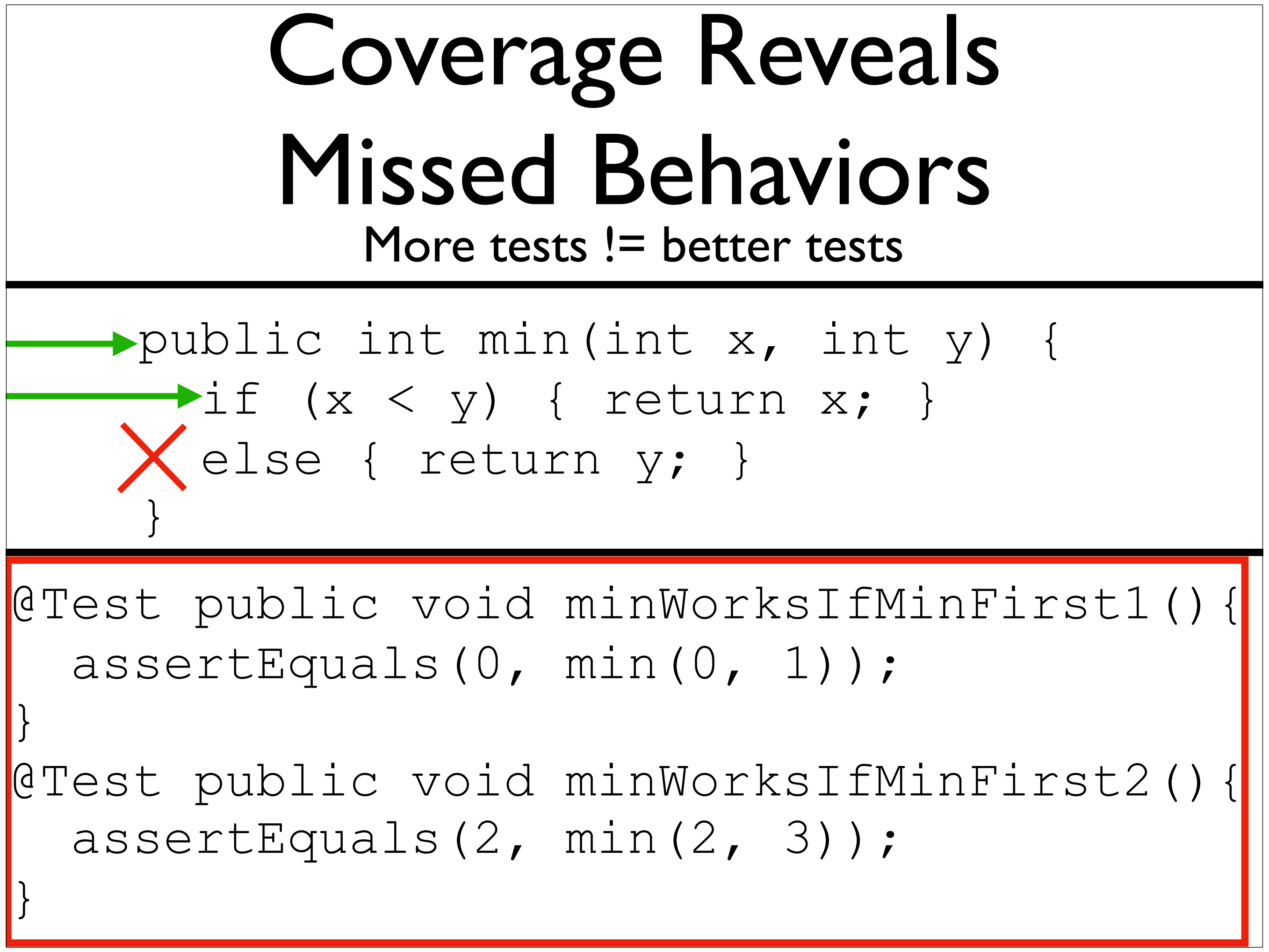
Coverage Reveals Missed Behaviors

More tests != better tests

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test public void minWorksIfMinFirst1(){
  assertEquals(0, min(0, 1));
}
@Test public void minWorksIfMinFirst2(){
  assertEquals(2, min(2, 3));
}
```

-Coverage of only the second test



Coverage Reveals Missed Behaviors

More tests != better tests

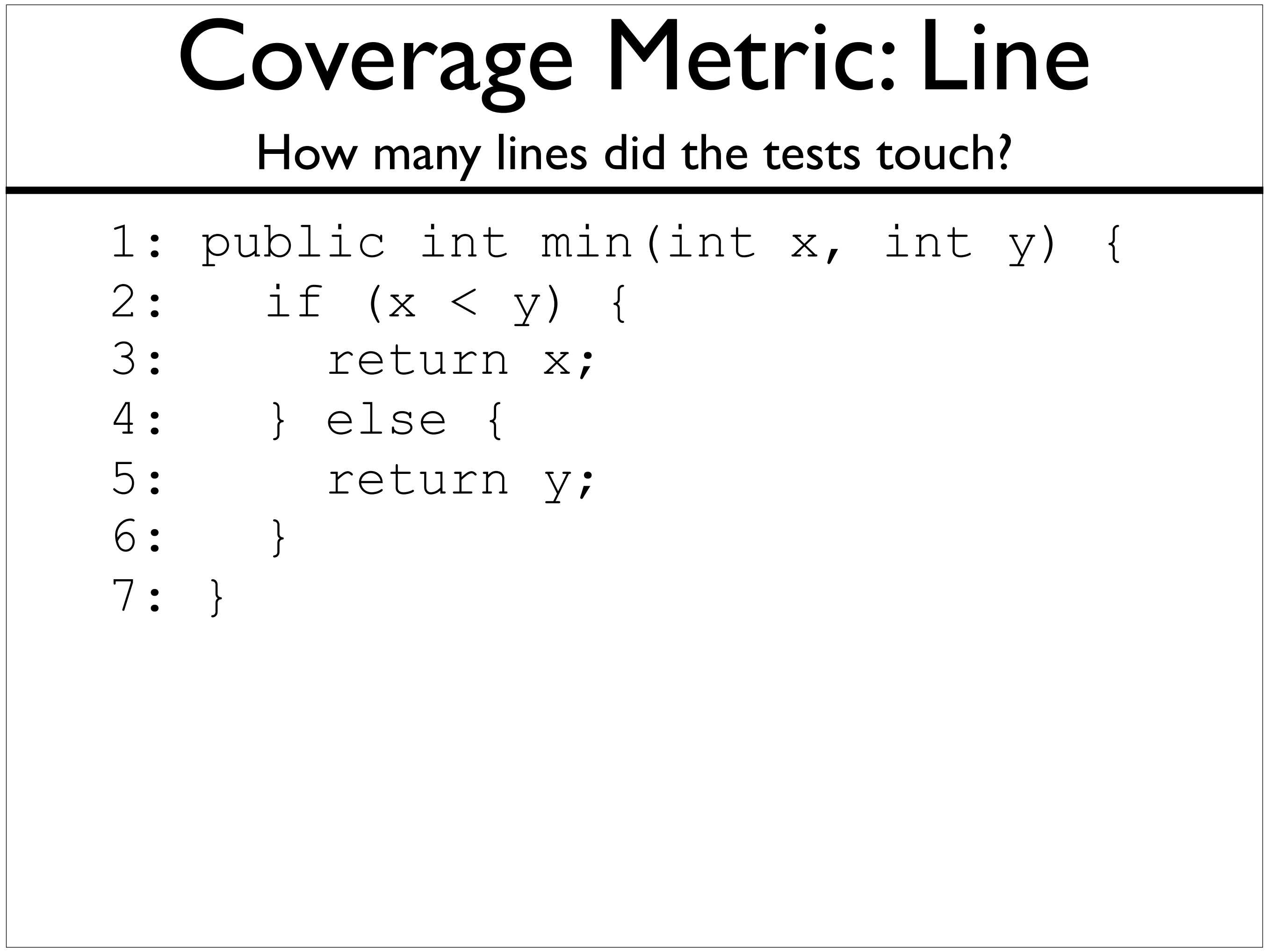
```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
@Test public void minWorksIfMinFirst1(){
  assertEquals(0, min(0, 1));
}
@Test public void minWorksIfMinFirst2(){
  assertEquals(2, min(2, 3));
}
```

-Coverage of both tests combined

Coverage Metric: Line

How many lines did the tests touch?

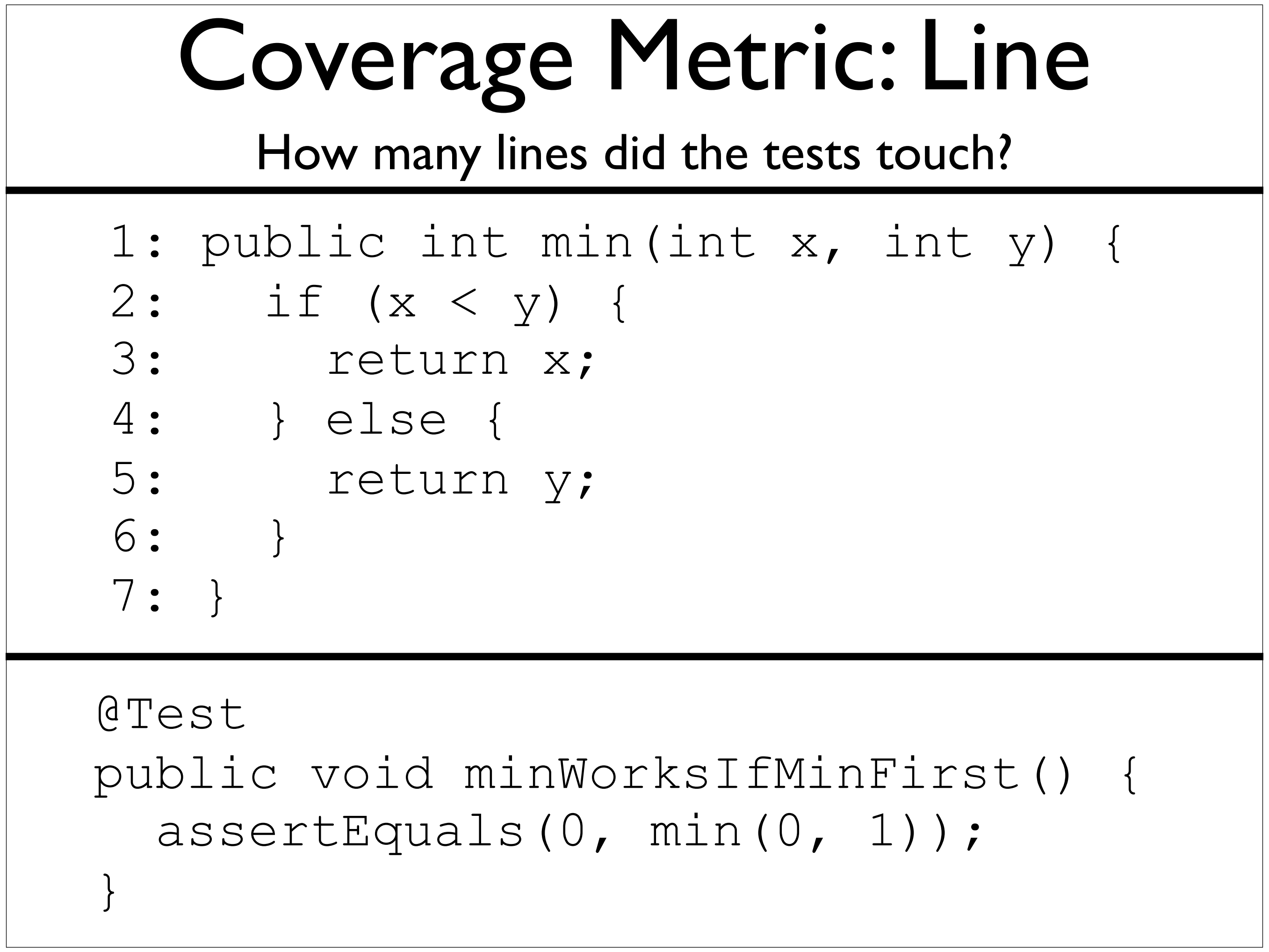


Coverage Metric: Line

How many lines did the tests touch?

```
1: public int min(int x, int y) {
2:   if (x < y) {
3:     return x;
4:   } else {
5:     return y;
6:   }
7: }
```

-Now line numbers have been added
-Explicit moving of code to lines



Coverage Metric: Line

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1: public int min(int x, int y) {
2:   if (x < y) {
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4:   } else {
5:     return y;
6:   }
7: }
```
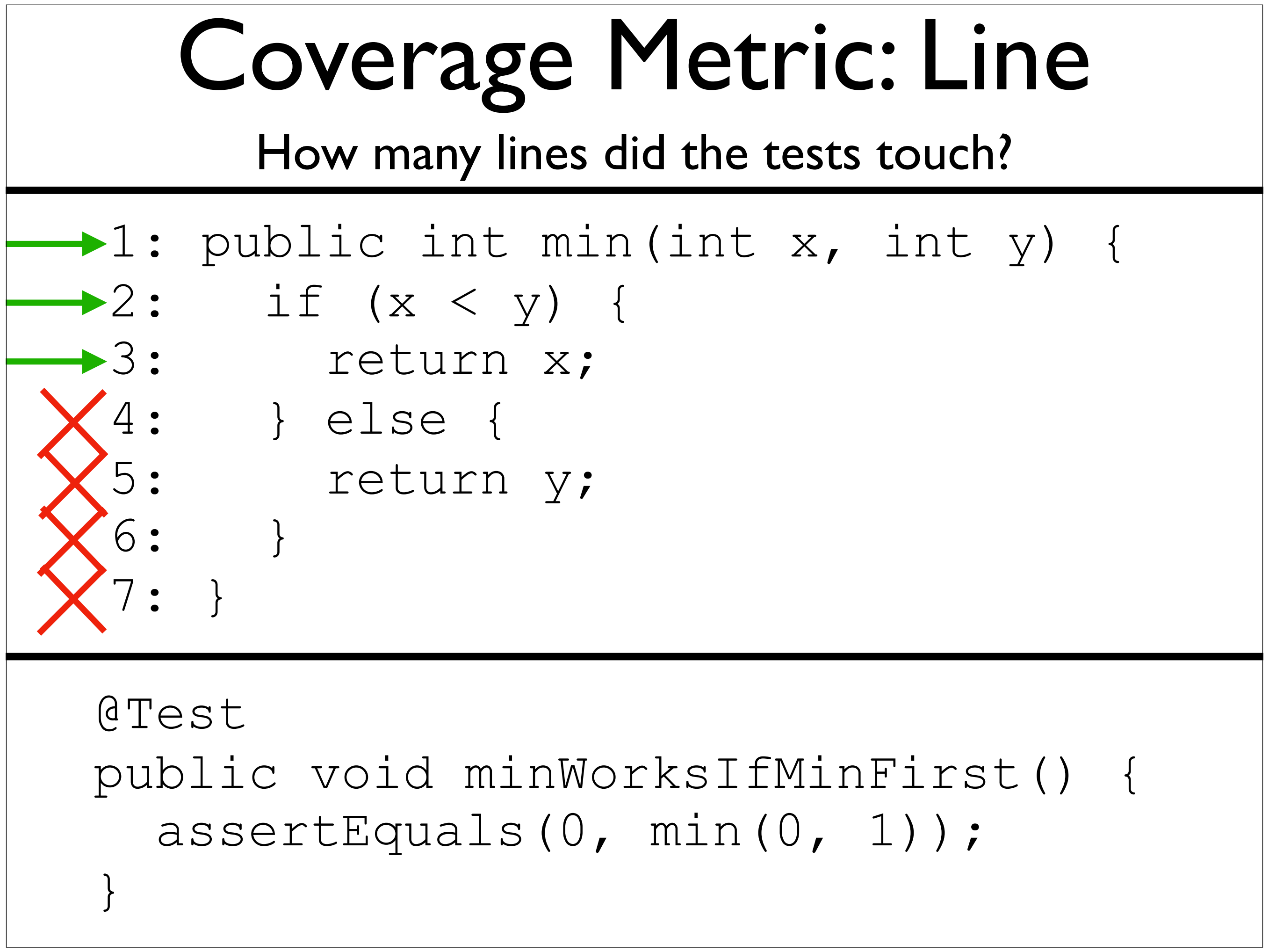

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

–Same test as before



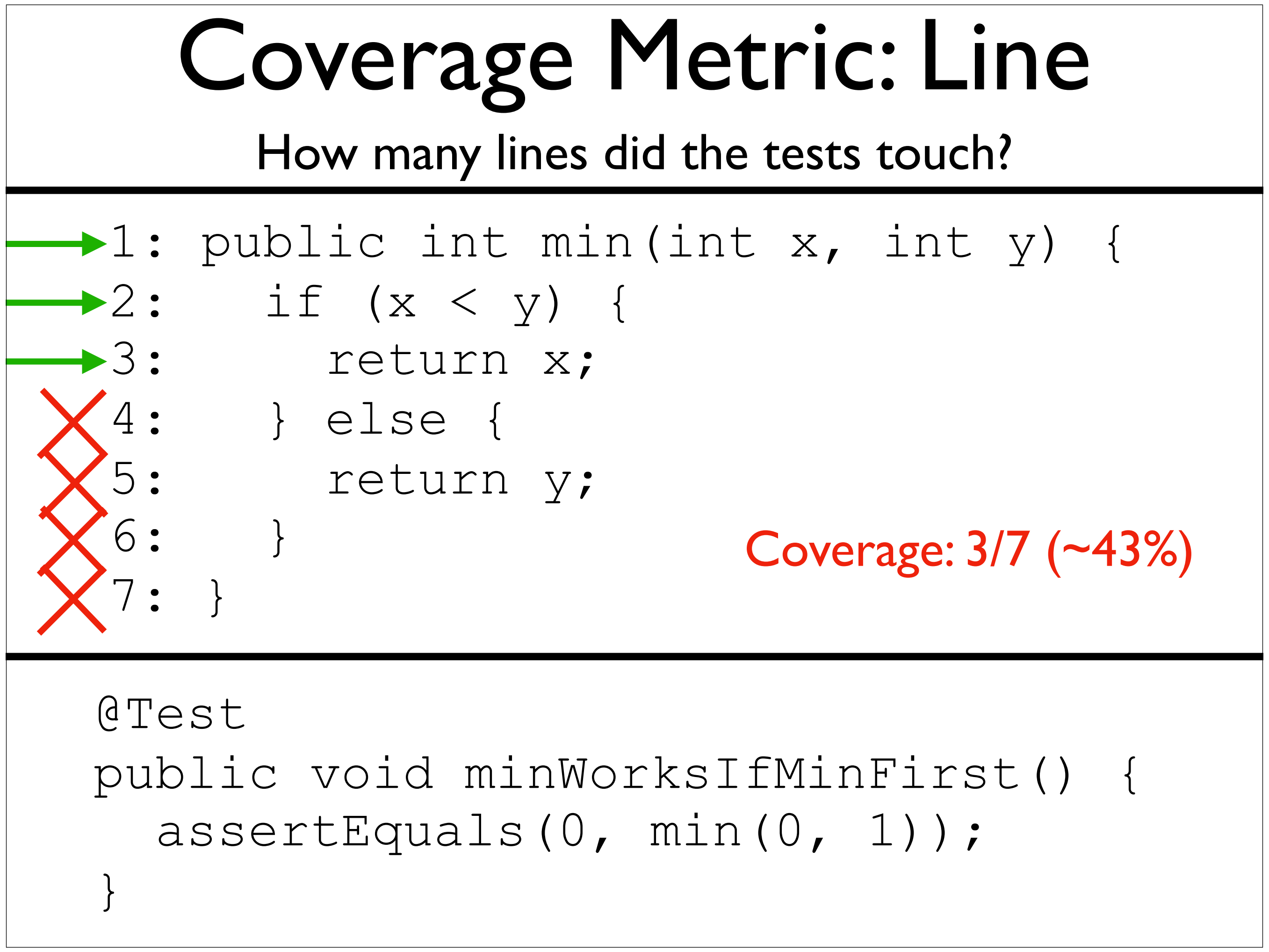
Coverage Metric: Line

How many lines did the tests touch?

```
→1: public int min(int x, int y) {
→2:   if (x < y) {
→3:     return x;
✗4:   } else {
✗5:     return y;
✗6:   }
✗7: }
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Running that test touches these lines



Coverage Metric: Line

How many lines did the tests touch?

```
1: public int min(int x, int y) {
2:   if (x < y) {
3:     return x;
4:   } else {
5:     return y;
6:   }
7: }
```

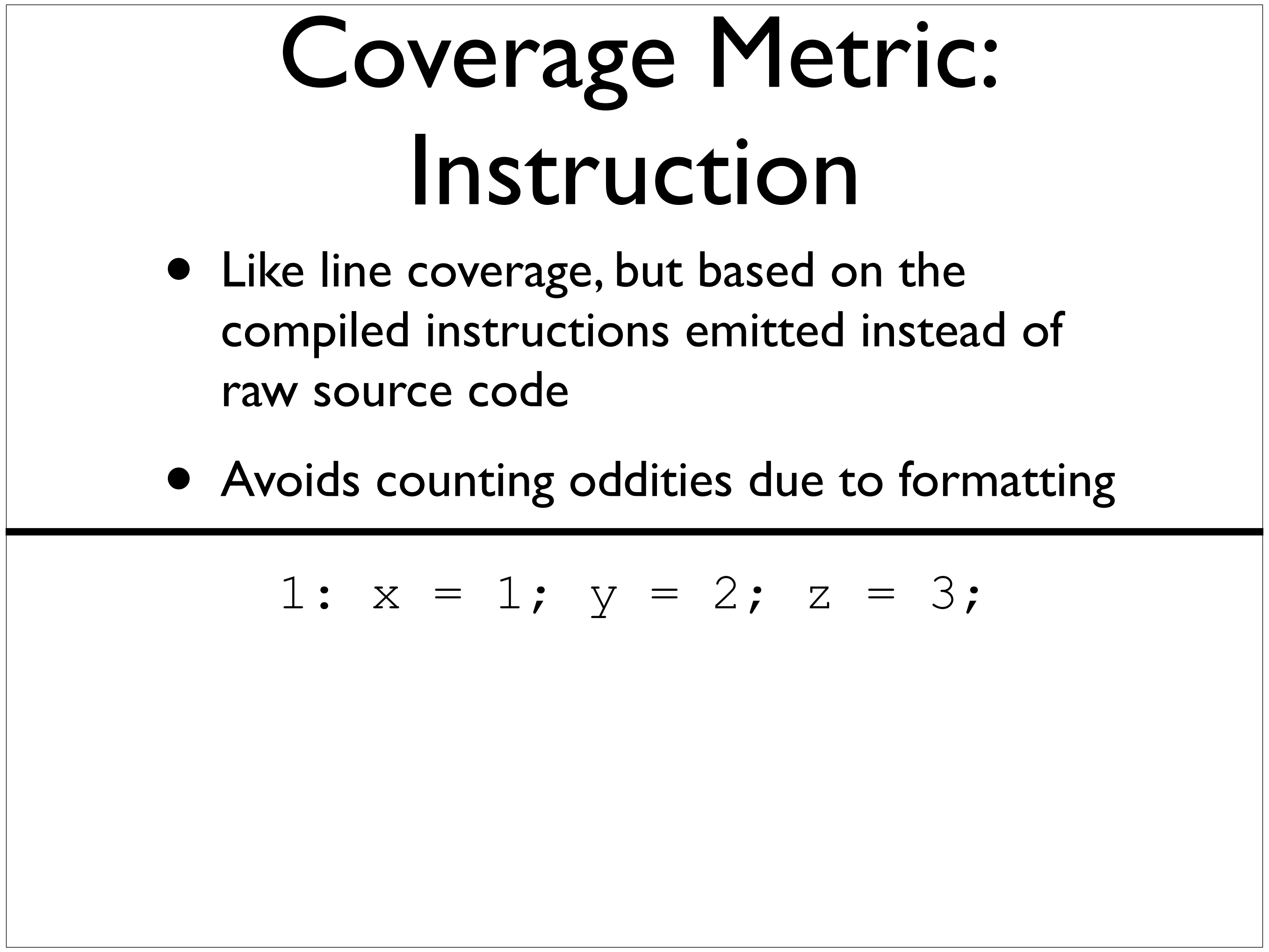
Coverage: 3/7 (~43%)

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Running that test touches these lines

Coverage Metric: Instruction

- Like line coverage, but based on the compiled instructions emitted instead of raw source code
- Avoids counting oddities due to formatting



Coverage Metric: Instruction

- Like line coverage, but based on the compiled instructions emitted instead of raw source code
- Avoids counting oddities due to formatting

```
1: x = 1; y = 2; z = 3;
```

-I might only have one line of code

Coverage Metric: Instruction

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- Avoids counting oddities due to formatting

```
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```

```
1: x = 1;
2: y = 2;
3: z = 3;
```

-I might format the same code differently to get three lines

Coverage Metric: Instruction

- Like line coverage, but based on the compiled instructions emitted instead of raw source code
- Avoids counting oddities due to formatting

```
1: x = 1; y = 2; z = 3;
```

```
1: x = 1;
2: y = 2;
3: z = 3;
```

```
1: li $t0, 1
2: li $t1, 2
3: li $t2, 3
```

-No matter the formatting, I get the same instructions emitted
-As such, measuring coverage over instructions is more robust

Coverage Metric: Branch

How many *branches* did the tests touch?

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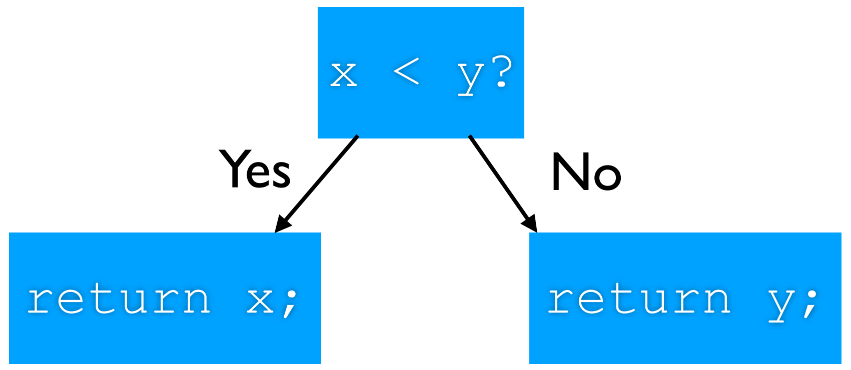
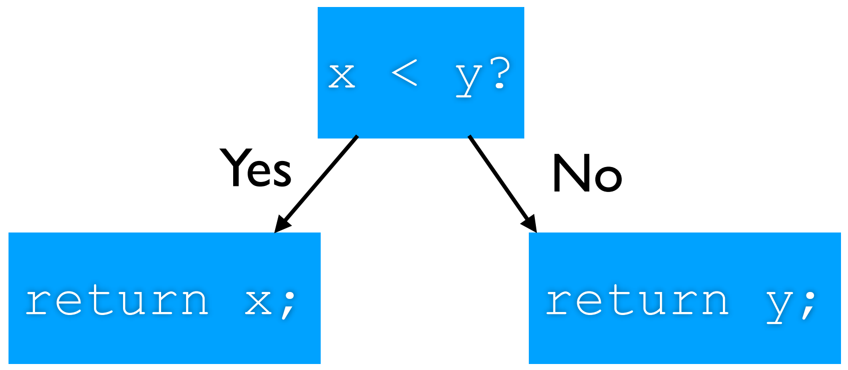
```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

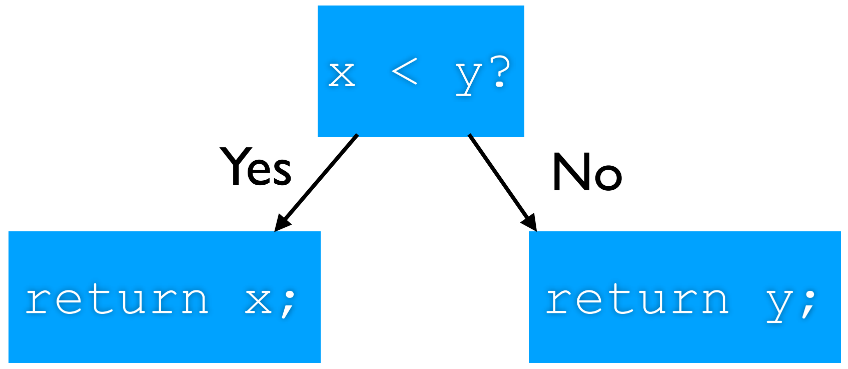
Coverage Metric: Branch

How many *branches* did the tests touch?

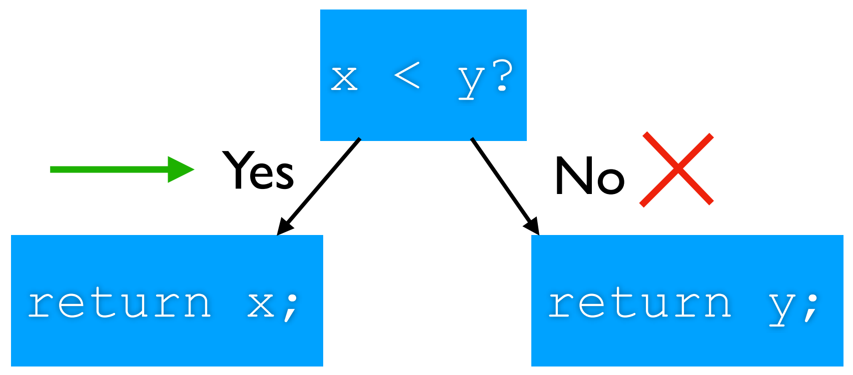
```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```




x < y?
Yes
No
return x;
return y;

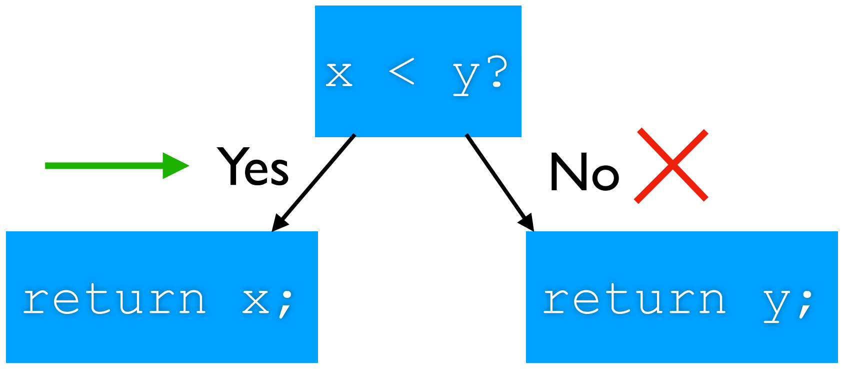


```
@Test public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```



```
@Test public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Running this test hits the yes, but not the no



```
@Test public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

Coverage: 1/2 (50%)

-Running this test hits the yes, but not the no

Coverage Demo: JaCoCo

Coverage Caveat

100% coverage does **not** mean bug-free

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```
public int brokenMin(int x, int y) {
  if (x < y) { return y; }
  else { return x; }
}
```

Coverage Caveat

100% coverage does **not** mean bug-free

```
public int brokenMin(int x, int y) {
  if (x < y) { return y; }
  else { return x; }
}
```

```
@Test public void runMin() {
  min(0, 1);
  min(1, 0);
}
```

Coverage Caveat

100% coverage does **not** mean bug-free

```
public int brokenMin(int x, int y) {
  if (x < y) { return y; }
  else { return x; }
}
```

```
@Test public void runMin() {
  min(0, 1);
  min(1, 0);
}
```

100% coverage, but tests nothing

Coverage Caveat

< 100% coverage does **not** mean buggy

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```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
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```

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< 100% coverage does **not** mean buggy

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
<<no tests written>>
```

Coverage Caveat

< 100% coverage does **not** mean buggy

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
<<no tests written>>
```

0% coverage, but no bugs

Coverage Caveats in Practice

- Automated testing techniques
  - Find tons of bugs
  - Usually don't improve coverage much
- Striving for 100% sees diminishing returns
  - May need extensive code modification
  - Important: what's the repercussions of a bug being in untested code?

Measuring Test Quality: Mutation Testing/Analysis

Intuition

- More bugs found = better tests
- Cannot readily measure this directly
  - We don't want bugs in the codebase!

-Direct measurement requires us to have known bugs in the codebase
-We want bugs fixed - we cannot intentionally bury bugs

Idea

Automatically *inject* bugs in a codebase.
See if tests can find the bugs.

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See if tests can find the bugs.

```
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  else { return y; }
}
```
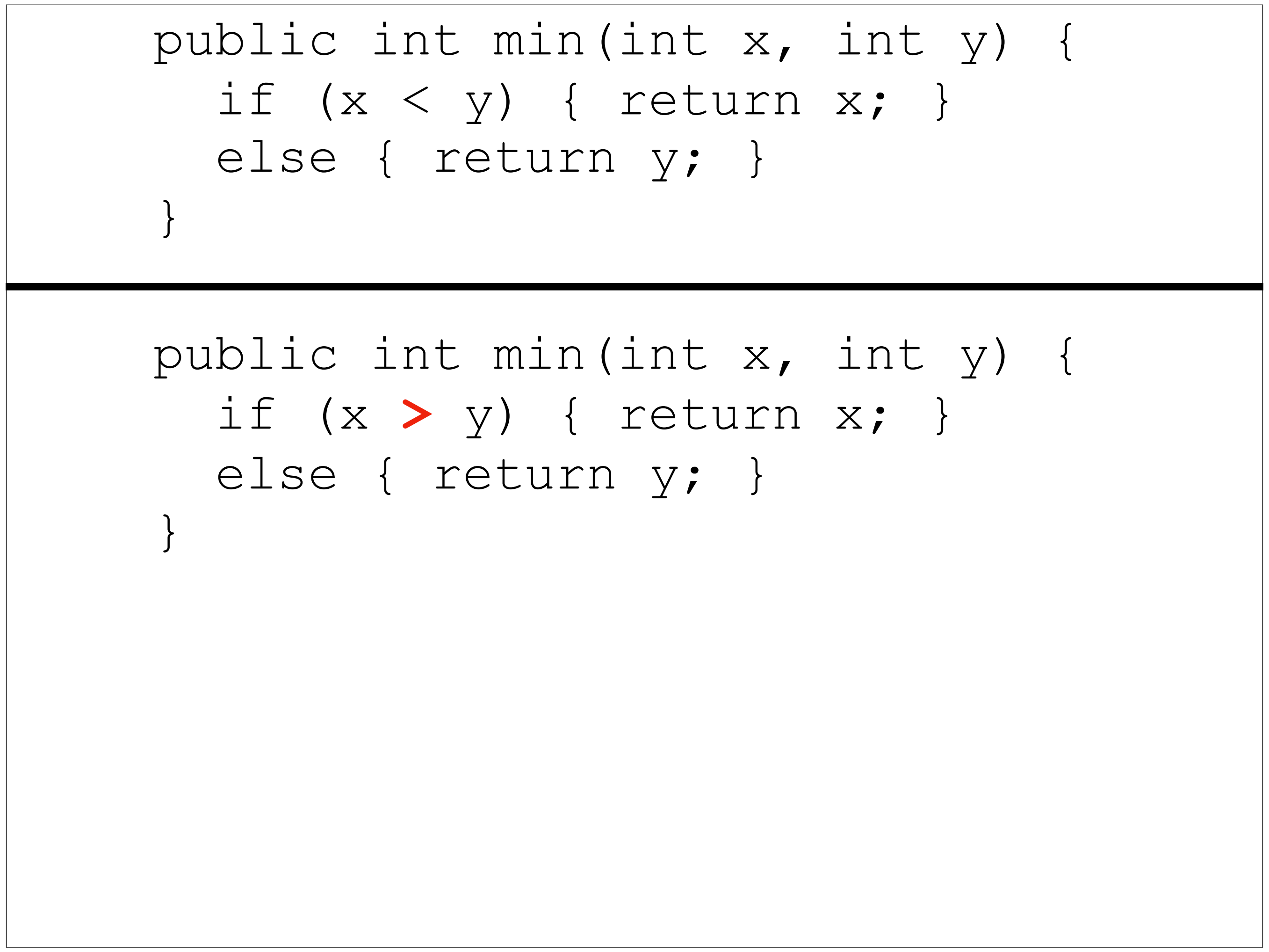

Idea

Automatically *inject* bugs in a codebase.
See if tests can find the bugs.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
public int min(int x, int y) {
  if (x > y) { return x; }
  else { return y; }
}
```



```java
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```java
public int min(int x, int y) {
  if (x > y) { return x; }
  else { return y; }
}
```

-Shift up the code for room...

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
public int min(int x, int y) {
  if (x > y) { return x; }
  else { return y; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-And add in a test

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

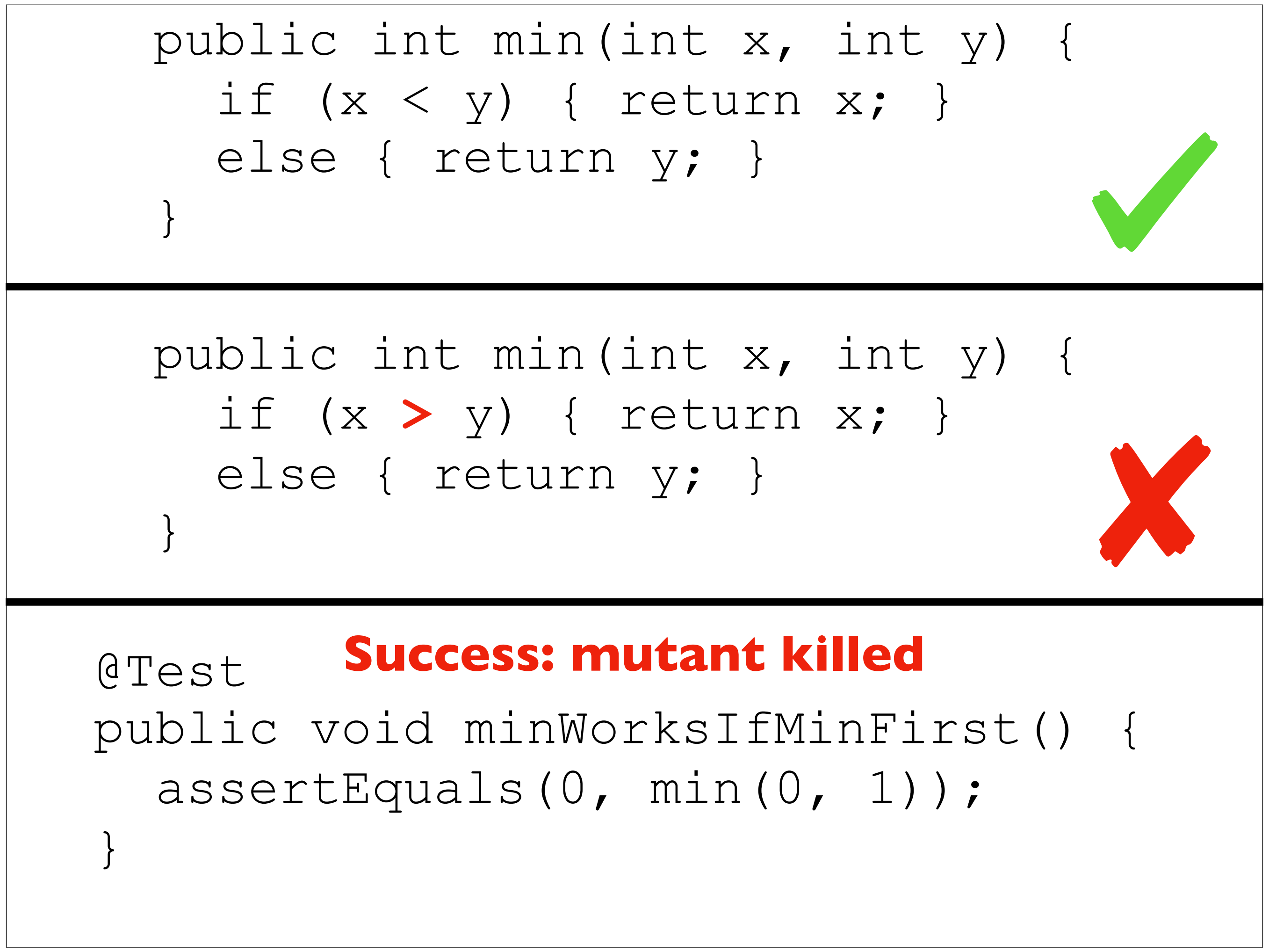
✓

```
public int min(int x, int y) {
  if (x > y) { return x; }
  else { return y; }
}
```

✗

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Test passes on original code
-Test fails on mutant
-This is _good_: it means the test suite was able to detect the injected bug



```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

✓

```
public int min(int x, int y) {
  if (x > y) { return x; }
  else { return y; }
}
```

✗

Success: mutant killed

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-Test passes on original code
-Test fails on mutant
-This is _good_: it means the test suite was able to detect the injected bug

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

–Let's consider this code again

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return 0; }
}
```

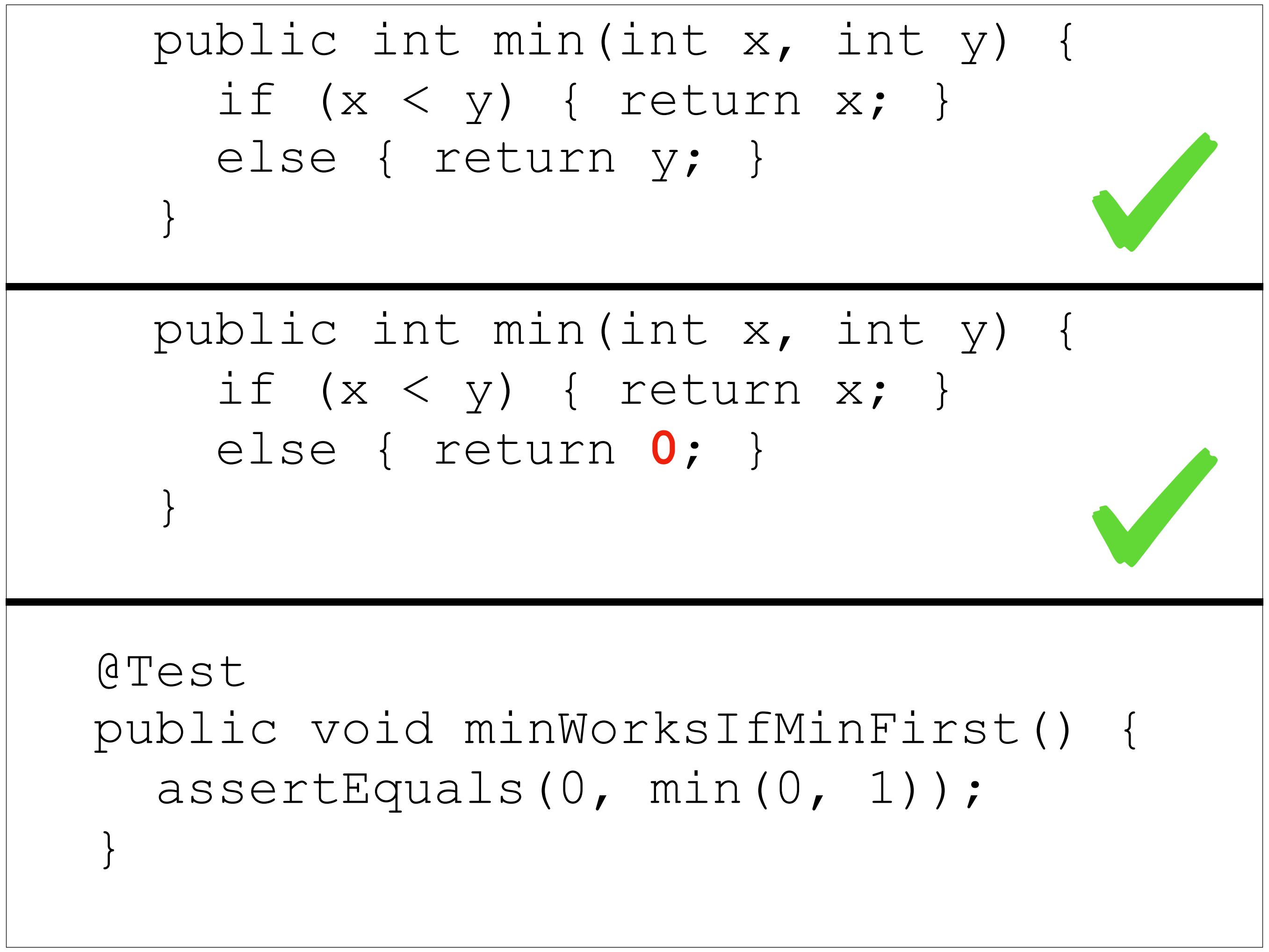
-Let's consider another mutant...

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return 0; }
}
```

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

–...along with the original test



```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

✓

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return 0; }
}
```

✓

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

-In this case, both tests pass
-This is BAD: means our test suite wasn't powerful enough to detect a code change

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

✓

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return 0; }
}
```

✓

```
@Test
public void minWorksIfMinFirst() {
  assertEquals(0, min(0, 1));
}
```

Failure: mutant lives (not detected)

-In this case, both tests pass
-This is BAD: means our test suite wasn't powerful enough to detect a code change

Mutation Analysis Demo: PITest

Caveat

We can't inject bugs, only code changes.

Code changes may be *semantically equivalent*.

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```

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We can't inject bugs, only code changes.
Code changes may be *semantically equivalent*.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
public int min(int x, int y) {
  if (!(x >= y)) { return x; }
  else { return y; }
}
```

Caveat

We can't inject bugs, only code changes.
Code changes may be *semantically equivalent*.

```
public int min(int x, int y) {
  if (x < y) { return x; }
  else { return y; }
}
```

```
public int min(int x, int y) {
  if (!(x >= y)) { return x; }
  else { return y; }
}
```

Semantically-equivalent detection: undecidable in general

-This change is well-localized for simplicity, but in larger codebases this is much harder to determine (e.g., some input has additional invariants on it which are preserved by other parts of the system, and the behavioral change effectively exercises an implicit precondition)

Caveat Implications

- More mutants killed = better tests
- Not all mutants killed != weak tests
- Furthermore:
  - All mutants killed != best tests
- Still useful for comparing testing techniques to each other