COM3529 Software Testing and Analysis

Mutation Testing

Dr José Miguel Rojas

Downside of Coverage

```
/**
 * Make sure Double.NaN is returned iff n = 0
 */
@Test
public void testNaN() {
    StandardDeviation std = new StandardDeviation();
    assertTrue(Double.isNaN(std.getResult()));
    std.increment(1d);
    assertEquals(0d, std.getResult(), 0);
}
```

Downside of Coverage

```
/**
 * Make sure Double.NaN is returned iff n = 0
 */
@Test
public void testNaN() {
    StandardDeviation std = new StandardDeviation();
    Double.isNaN(std.getResult());
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Downside of Coverage

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}
```

Coverage does not change!

The Oracle Problem

Executing all the code **is not enough**

We need to **check** the functional behaviour

Does this code **actually do what it is meant to do**?

Automated oracle: specification or model

Else, manual oracles have to be defined

How good are my tests?

Coverage = how much of the code is executed

But how much of it is actually **checked**? 🤔

Unfortunately, we don’t know where the bugs are… 😭

But we know the bugs we have made in the past! 😎

Learning from Mistakes

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Known as **fault-based testing** or **Mutation Testing**

Mutation Coverage

Make many copies of the source code, where **mutations** have been introduced

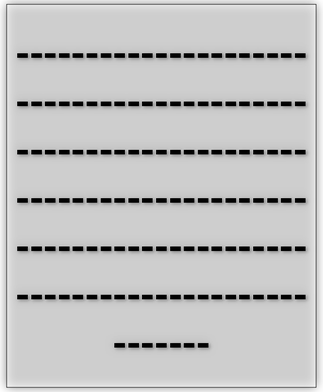
E.g., replacing “**<**” with “**>**”, or “**+**” with “**-**”.

Find the **test (set)** that is able to **kill** the largest number of mutants.

I.e., Executing the test on **both** the original program and the mutated program leads to **different outputs**.

Test 1 Test 2 Test 3

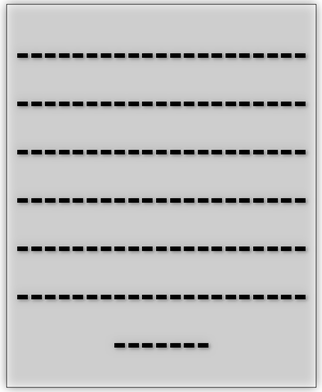
Original Program



Operators

Test 1 | Test 2 | Test 3

Original Program



Operators

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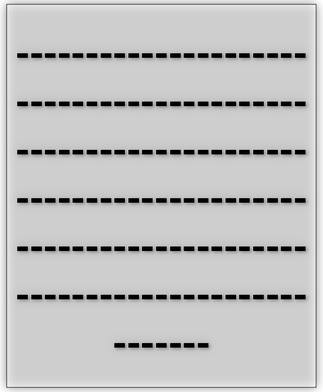

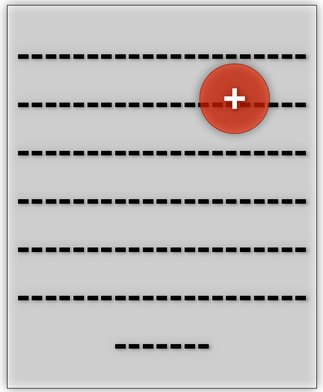

Operators

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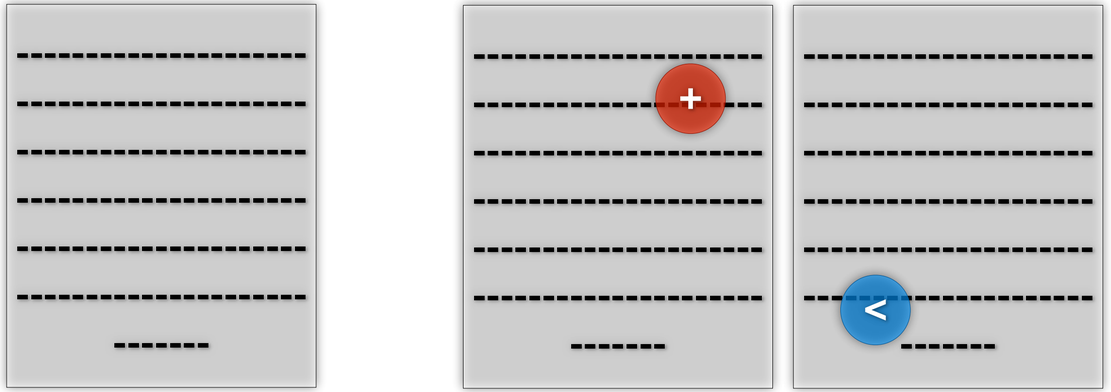

Operators

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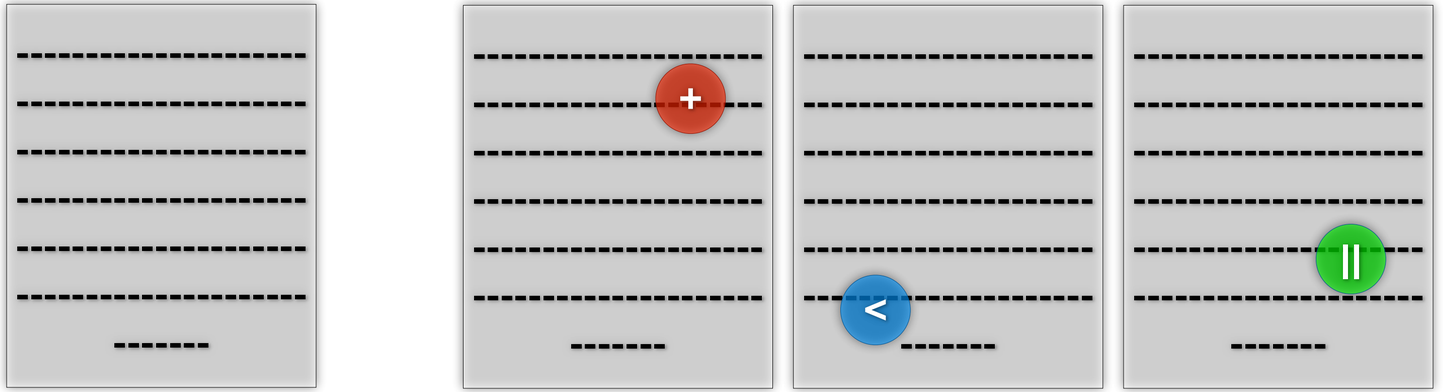

Operators

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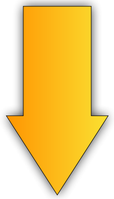

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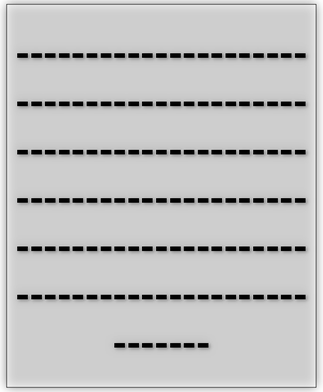

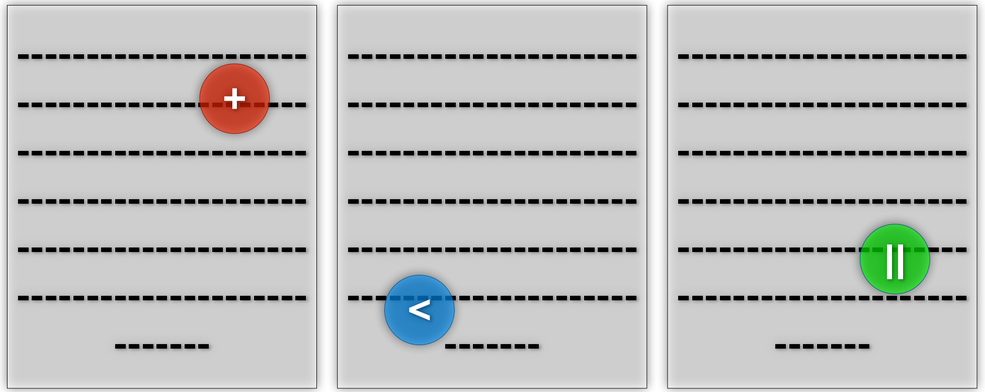

Operators

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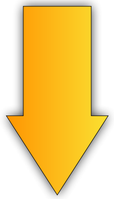

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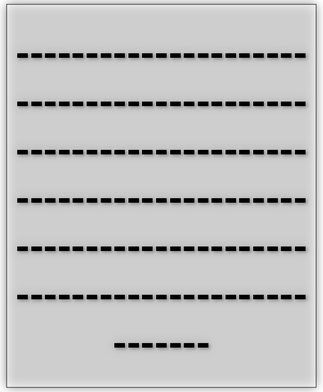

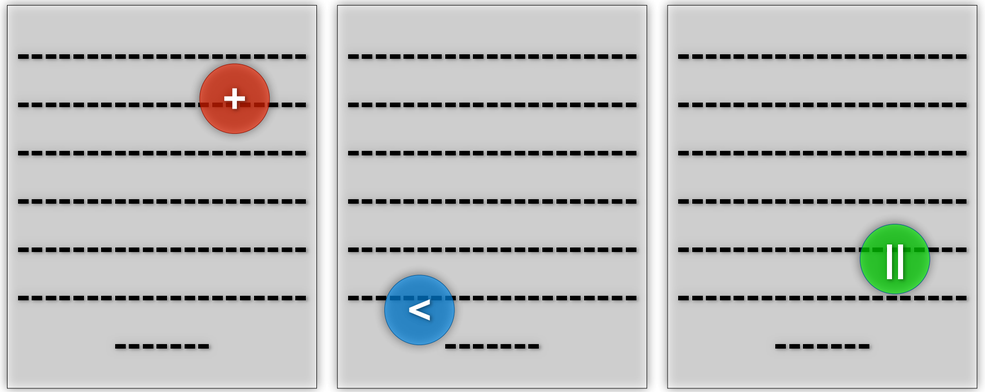

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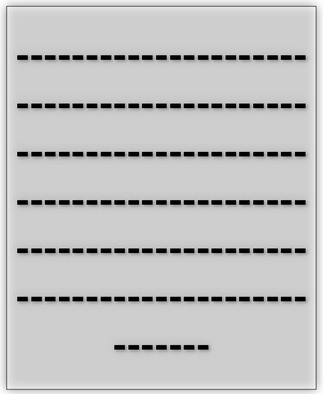

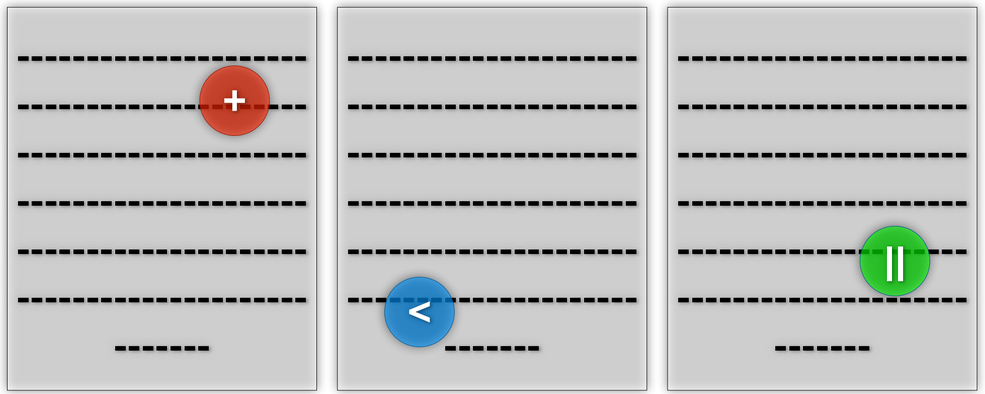

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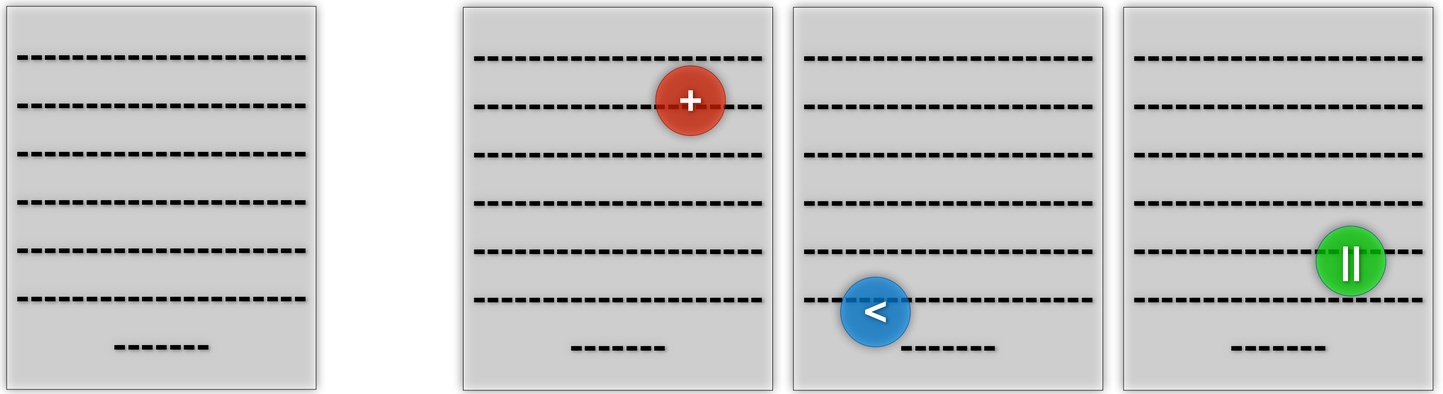

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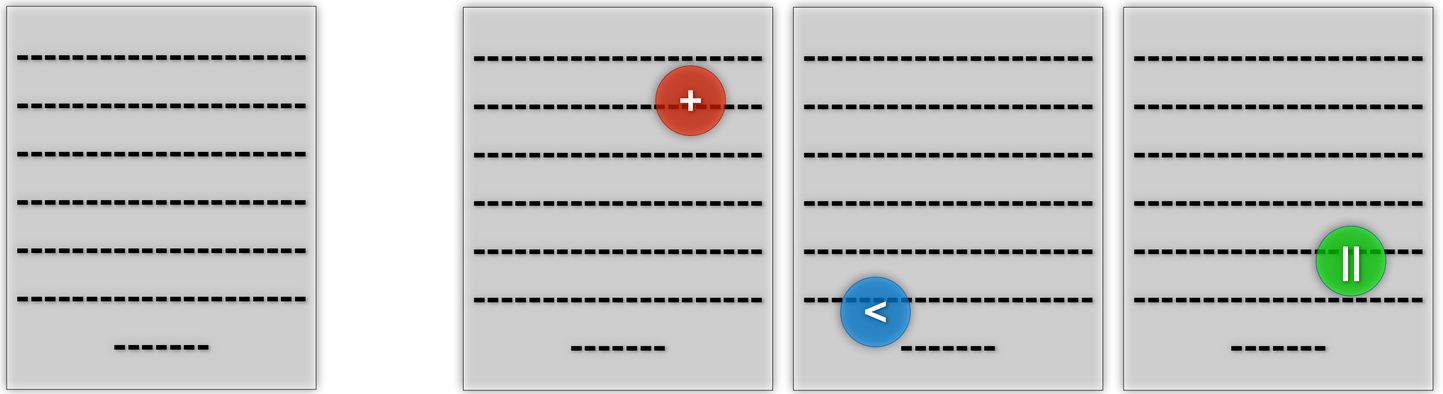
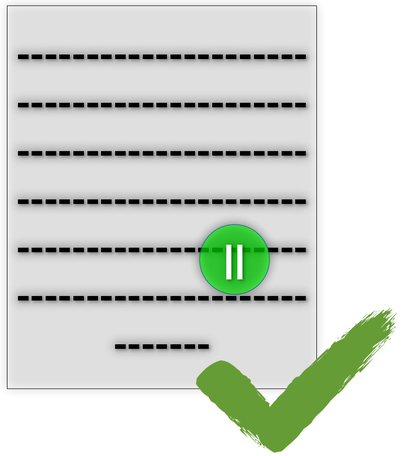
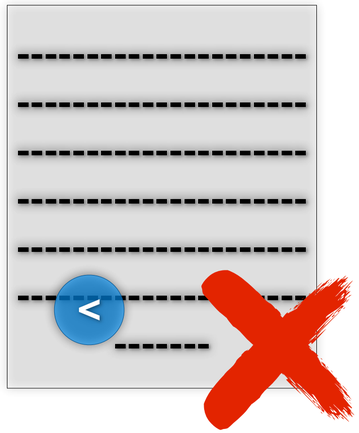
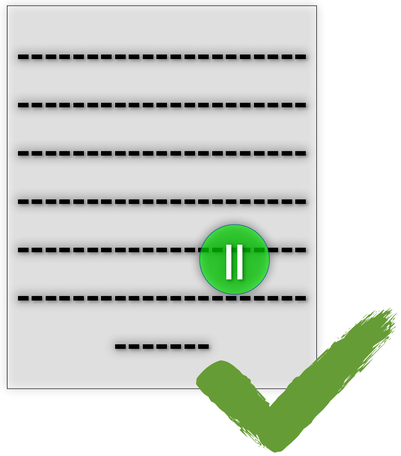


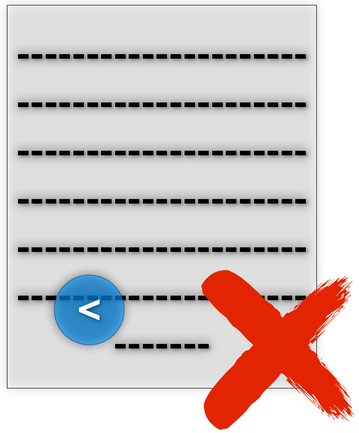


Live mutant - we need more tests



Dead mutant - of no further use





Mutation Score

$$\frac{\text{Killed Mutants}}{\text{Total Mutants}}$$

```
int do_something(int x, int y)
{
  if(x < y)
    return x+y;
  else
    return x*y;
}
```

Program

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int do_something(int x, int y)
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Program

```
int a = do_something(5, 10);
assertEquals(a, 15);
```

Test

```
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Program

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int do_something(int x, int y)
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  if(x < y)
    return x-y;
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Mutant

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Operators

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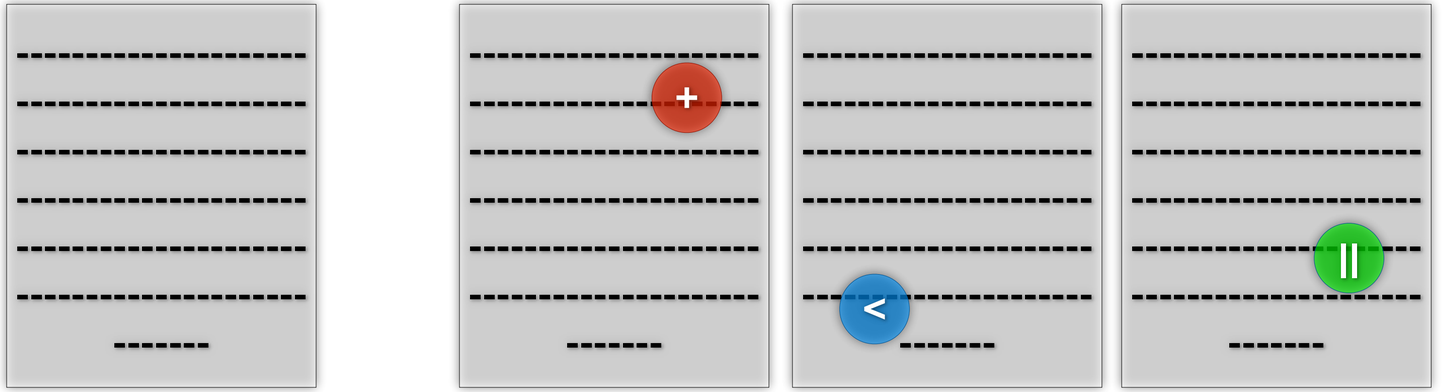
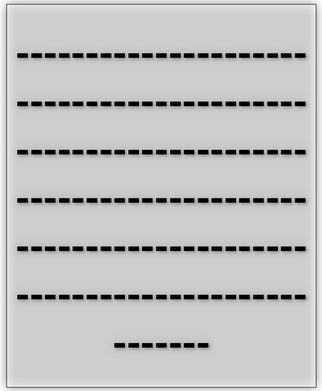
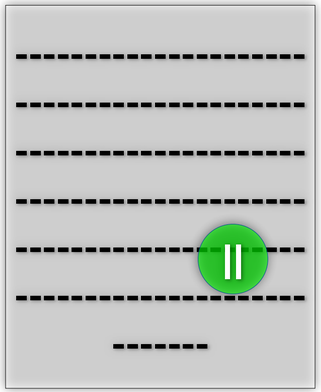
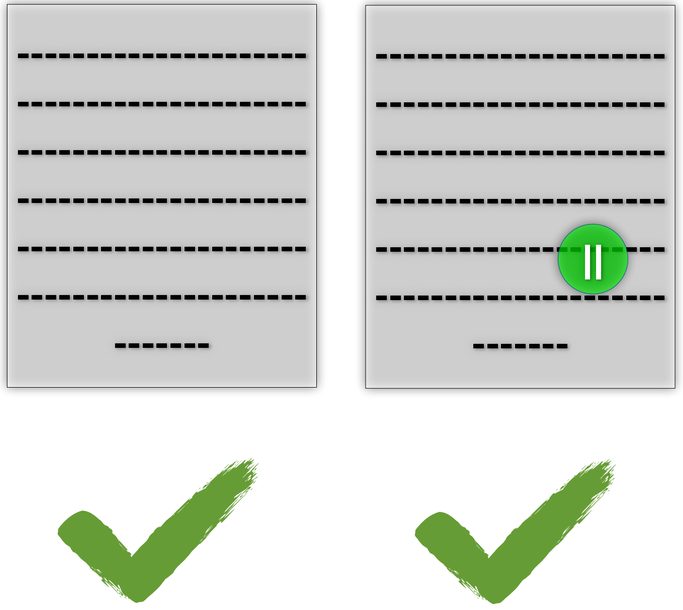
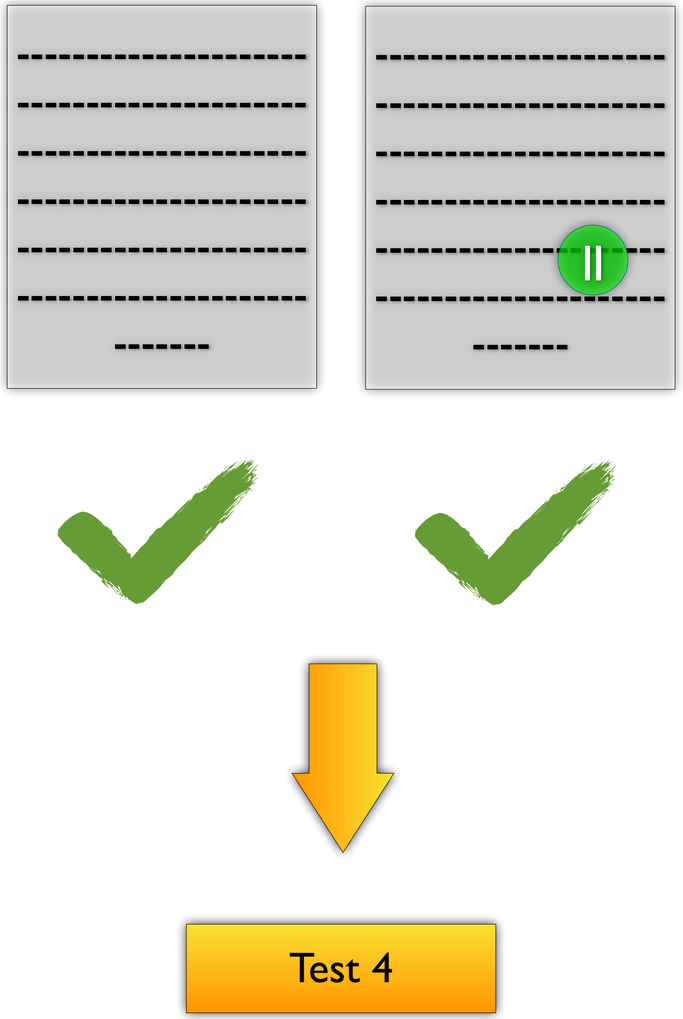
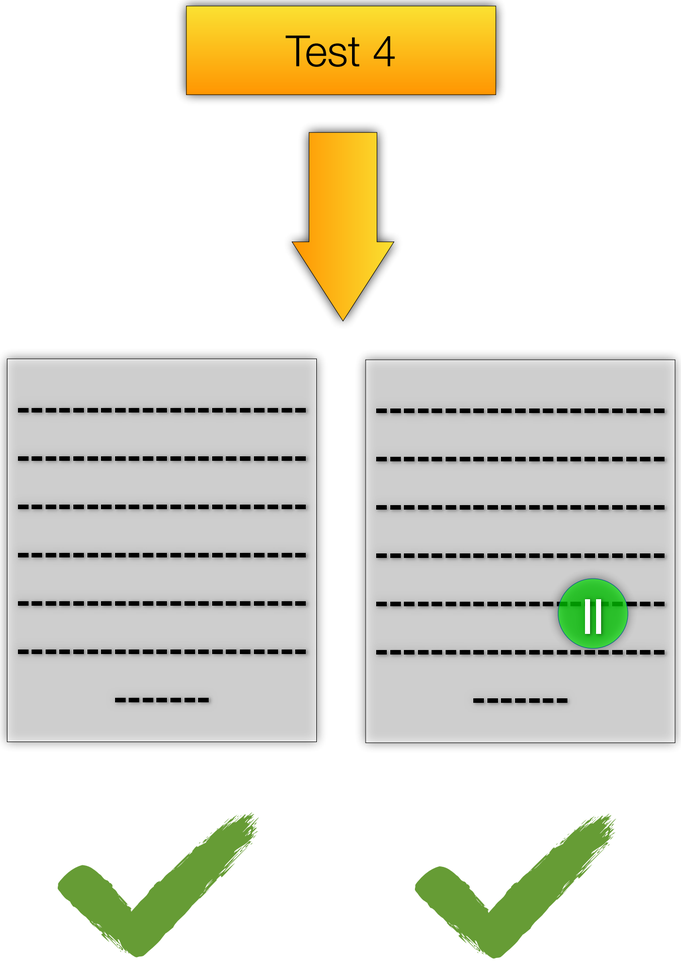









Test 4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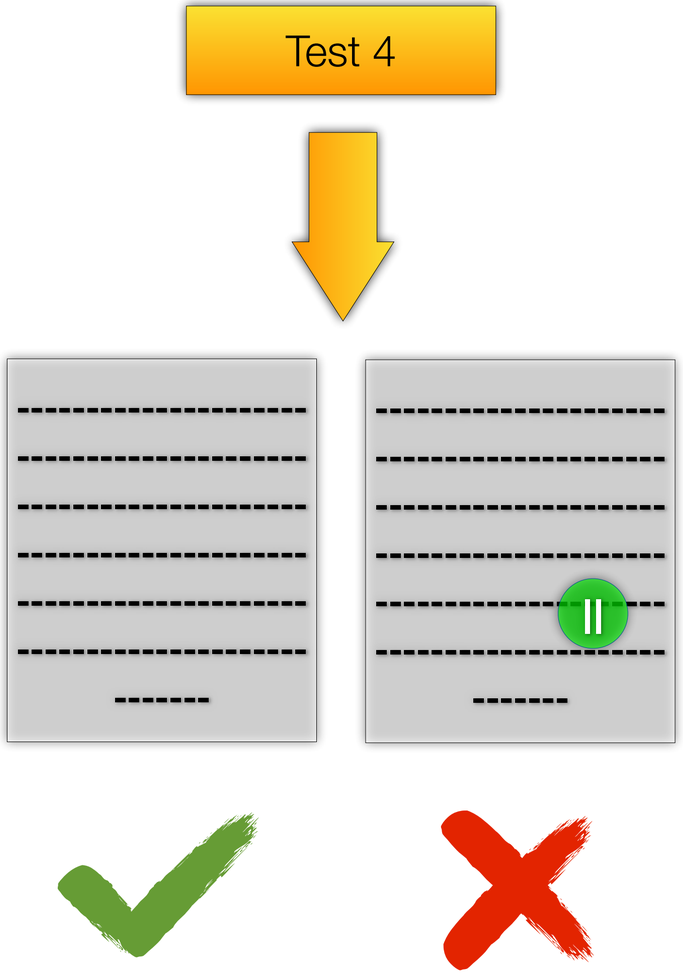
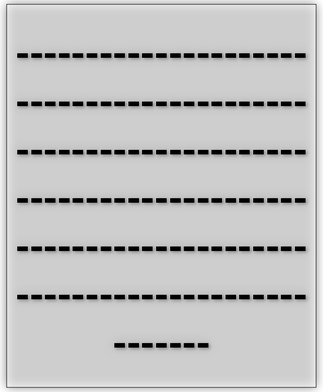
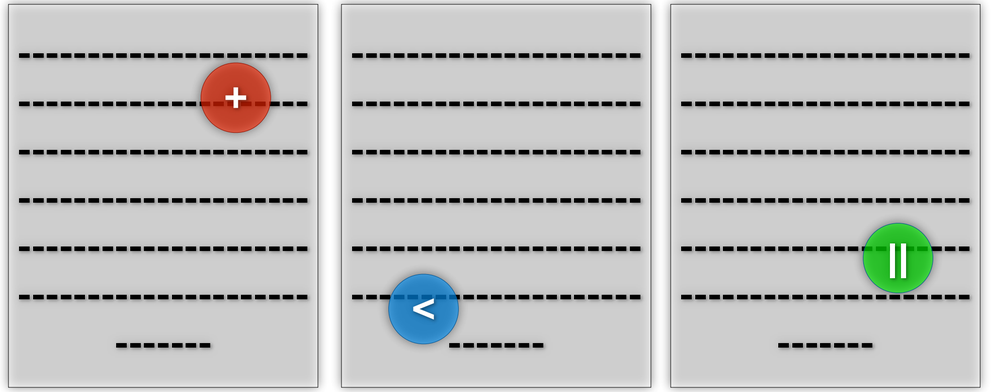

Test 4

Operators

Test 1 | Test 2 | Test 3 | Test 4

Original Program





Operators

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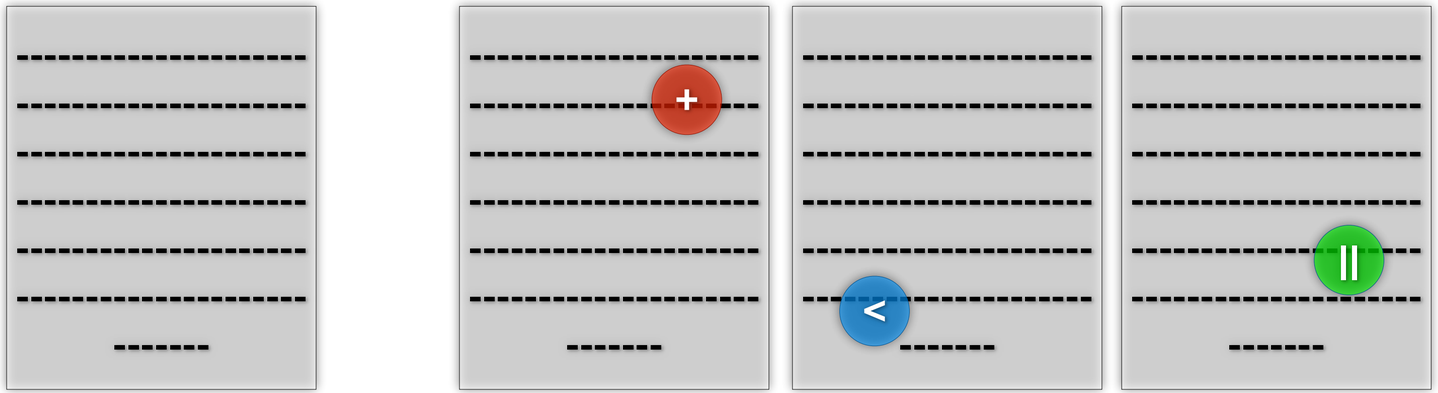

Mutants

Slightly changed version of original program

Syntactic change, i.e., valid, compilable code

Simple, resembling a programming glitch

Based on faults from a fault hierarchy

Generating Mutants

Mutation operators
Rule to derive mutants from a program

Mutations based on real faults
Mutation operators represent typical errors

Dedicated mutation operators have been defined for most languages

For example, 100+ operators for the C programming language

Some example operators…

ABS - Absolute Value Insertion

```
int gcd(int x, int y) {
  int tmp;

  while(y != 0) {
    tmp = x % y;
    x = y;
    y = tmp;
  }

  return x;
}
```

ABS - Absolute Value Insertion

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int gcd(int x, int y) {
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AOR - Arithmetic Operator

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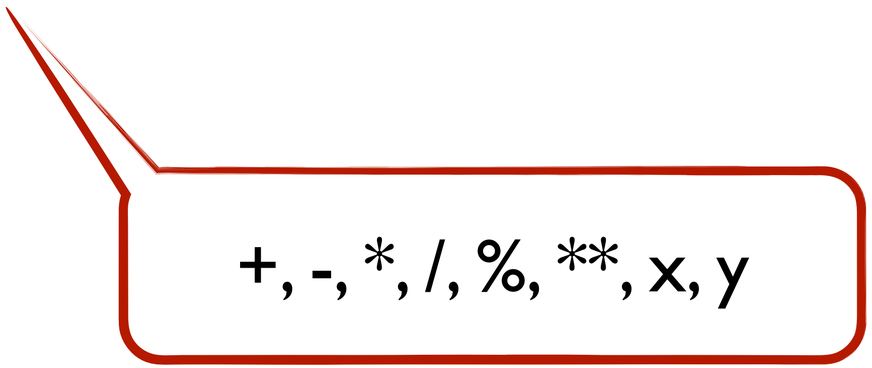

ROR - Relational Operator

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  while(y != 0) {
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    x = y;
    y = tmp;
  }

  return x;
}
```

ROR - Relational Operator

```
int gcd(int x, int y) {
  int tmp;

  while(y > 0) {
    tmp = x % y;
    x = y;
    y = tmp;
  }

  return x;
}
```

ROR - Relational Operator

```
int gcd(int x, int y) {
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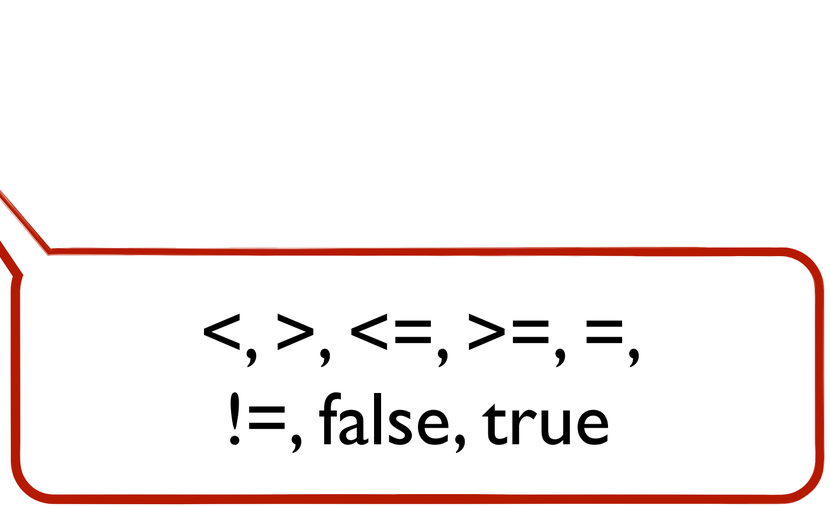

COR - Conditional Operator

```
if(a && b)
```

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```
if(a && b)
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if(a || b)
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COR - Conditional Operator

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if(a && b)
```

```
if(a || b)
if(a & b)
if(a | b)
if(a ^ b)
if(false)
```

COR - Conditional Operator

```
if(a && b)
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if(a || b)
if(a & b)
if(a | b)
if(a ^ b)
if(false)
if(true)
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COR - Conditional Operator

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if(a && b)
```

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if(a || b)
if(a & b)
if(a | b)
if(a ^ b)
if(false)
if(true)
if(a)
```

COR - Conditional Operator

```
if(a && b)
```

```
if(a || b)
if(a & b)
if(a | b)
if(a ^ b)
if(false)
if(true)
if(a)
if(b)
```

UOI - Unary Operator Insertion

```
int gcd(int x, int y) {
  int tmp;

  while(y != 0) {
    tmp = x % y;
    x = y;
    y = tmp;
  }

  return x;
}
```

UOI - Unary Operator Insertion

```
int gcd(int x, int y) {
  int tmp;

  while(y != 0) {
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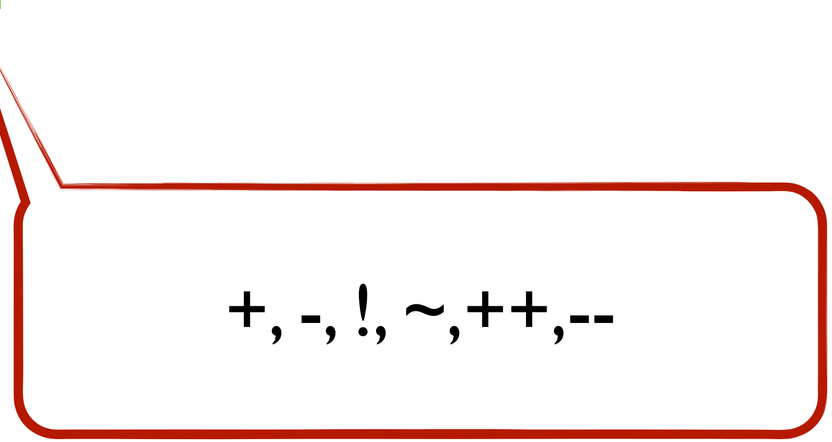

SVR - Scalar Variable

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OO Mutation

So far, operators only considered method bodies

Class level elements can be mutated as well:

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public class test {
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  protected void do() {
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public class test {
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```

```
public class test {
  // ..
  private void do() {
    // ...
  }
}
```

OO Mutation

AMC - Access Modifier Change

HVD - Hiding Variable Deletion

HVI - Hiding Variable Insertion

OMD - Overriding Method Deletion

OMM - Overridden Method Moving

OMR - Overridden Method Rename

SKR - Super Keyword Deletion

PCD - Parent Constructor Deletion

ATC - Actual Type Change

Essential Hypotheses

Competent Programmer Hypothesis

Programmers tend to write programs that are in the general neighbourhood of the set of correct programs, i.e., mostly correct

Coupling Effect

Test data that distinguishes all programs differing from a correct one by only simple errors is so sensitive that it also implicitly distinguishes more complex errors.

Therefore, mutation testing focuses on **first order mutants**

One mutation at a time; as opposed to Higher Order Mutant (HOM), i.e., mutant of mutant.

$$a + b > c$$

a + b > c

```
a - b > c
a * b > c
a / b > c
a % b > c
a > c
b > c
abs(a) - b > c
a - abs(b) > c
a - b > abs(c)
abs(a - b) > c
-abs(a) - b > c
a - -abs(b) > c
a - b > -abs(c)
-abs(a - b) > c
```

```
a - b >= c
a - b < c
a - b <= c
a - b = c
a - b != c
b - b > c
a - a > c
c - b > c
a - c > c
a - b > a
a - b > b
a - b > c
0 - b > c
a - 0 > c
```

```
a - b > 0
++a - b > c
a - ++b > c
a - b > ++c
--a - b > c
a - --b > c
a - b > --c
++(a - b) > c
--(a - b) > c
-a - b > c
a - -b > c
a - b > -c
-(a - b) > c
0 > c
```

$$a + b > c$$

a + b > c

```
a - b > c
a * b > c
a / b > c
a % b > c
a > c
b > c
abs(a) - b > c
a - abs(b) > c
a - b > abs(c)
abs(a - b) > c
-abs(a) - b > c
a - -abs(b) > c
a - b > -abs(c)
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a - 0 > c
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```

Performance Problems

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Many mutation operators possible

Proteum - 103 Mutation Operators for C

MuJava - Adds 24 Class level Mutation Operators

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Each mutant **needs to be compiled**

Performance Problems

Many mutation operators possible
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Each mutation operator results in **many mutants**
Depending on program under test

Each mutant **needs to be compiled**

Each test case needs to be
executed **against every mutant**

Equivalent Mutants

Mutation = **syntactic** change

The change might leave
the **semantics unchanged**

Equivalent mutants are hard
to detect (undecidable problem)

Might be **reached**, but no **infection**

Might **infect**, but without **propagation**

Example

```
int max(int[] values) {
  int r, i;

  r = 0;
  for(i = 1; i<values.length; i++) {
    if (values[i] > values[r])
      r = i;
  }

  return values[r];
}
```

Example

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}
```

This mutant is equivalent because it only introduces an additional comparison of the first element to itself - **this cannot change the functional behaviour**

Example

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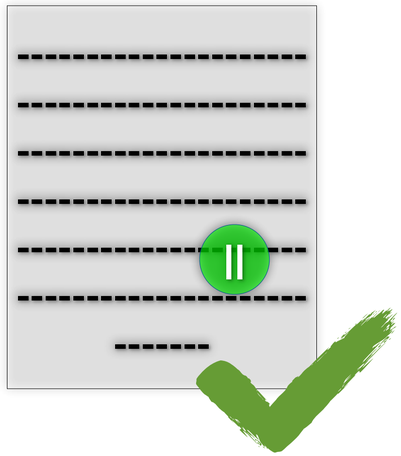
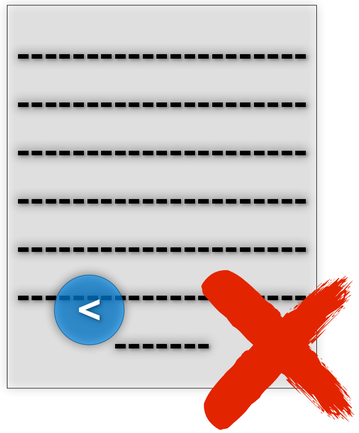
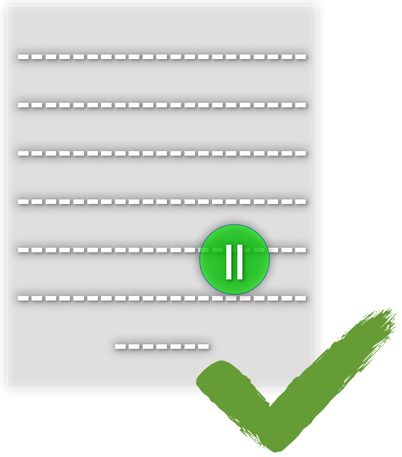
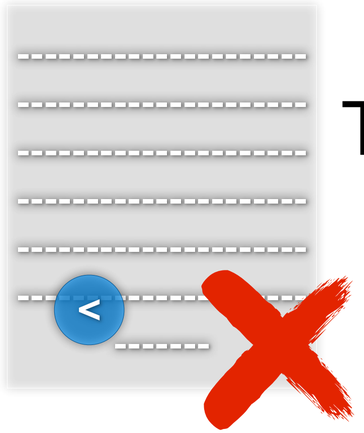




Mutation Score

$$\frac{\text{Killed Mutants}}{\text{Total Mutants}}$$





Mutation Score

$$\frac{\text{Killed Mutants}}{\text{Total Mutants} - \text{Equivalent mutants}}$$

Summary

Mutation Testing uses **mutants** to estimate the **effectiveness** of a test suite

Allows **simulating** other **coverage criteria**

Some **well-known limitations**

- Scalability issues, e.g., high number of mutants
- **Equivalent mutants**

But **increasingly popular** in industry