COM3529 Software Testing and Analysis

Mutation Testing

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BE-AB-FH

Roadmap

Beizer's Maturity Model

Test Automation

Unit Testing

Control/Data-Flow Analysis

Code Coverage

Mutation Testing

Regression Testing

Fuzzing

Search-based Test Generation

Model-Based Testing

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Roadmap

Beizer's Maturity Model

Test Automation

Unit Testing

Control/Data-Flow Analysis

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Model-Based Testing

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
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    Double.isNaN(std.getResult());
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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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Key idea: Learning from earlier mistakes to **prevent** them from happening again

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Key technique: **Simulate** earlier mistakes and see whether the resulting defects are found

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

Mutation Coverage

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

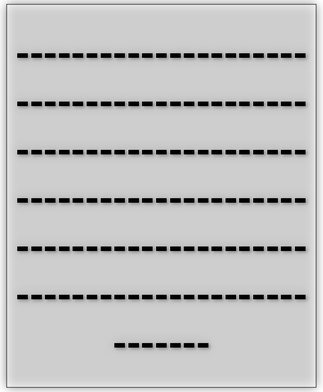
E.g., replacing “**<**” with “**>**”, or “**+**” with “**-**”.

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

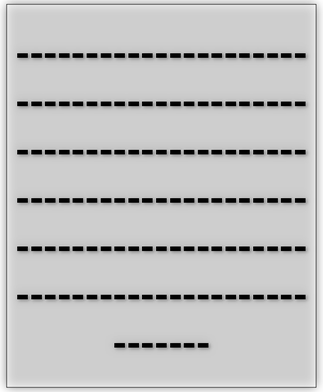
Original Program



Operators

Test 1 Test 2 Test 3

Original Program



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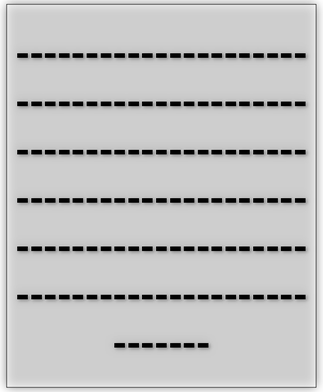
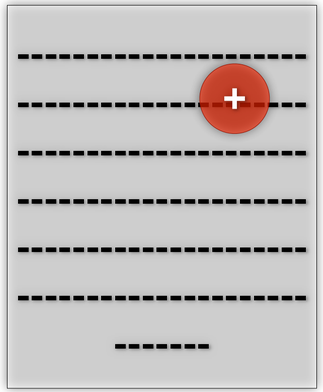
Operators

Test 1 | Test 2 | Test 3

Original Program





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Operators

Test 1 | Test 2 | Test 3

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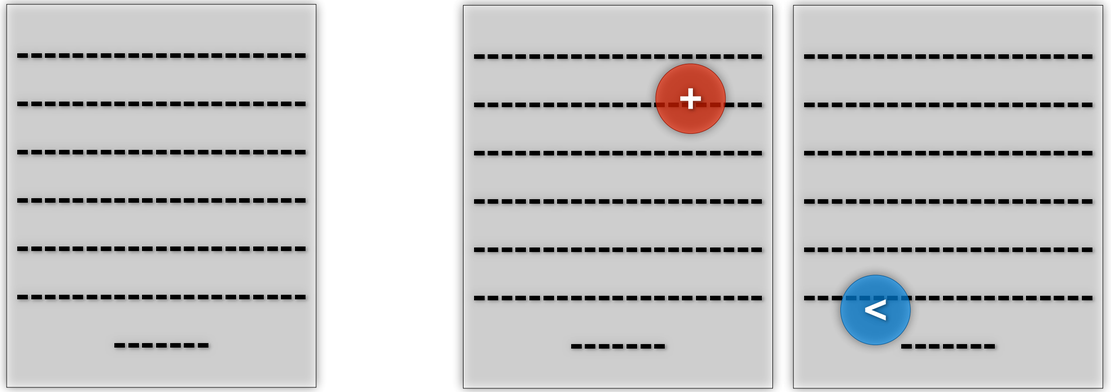

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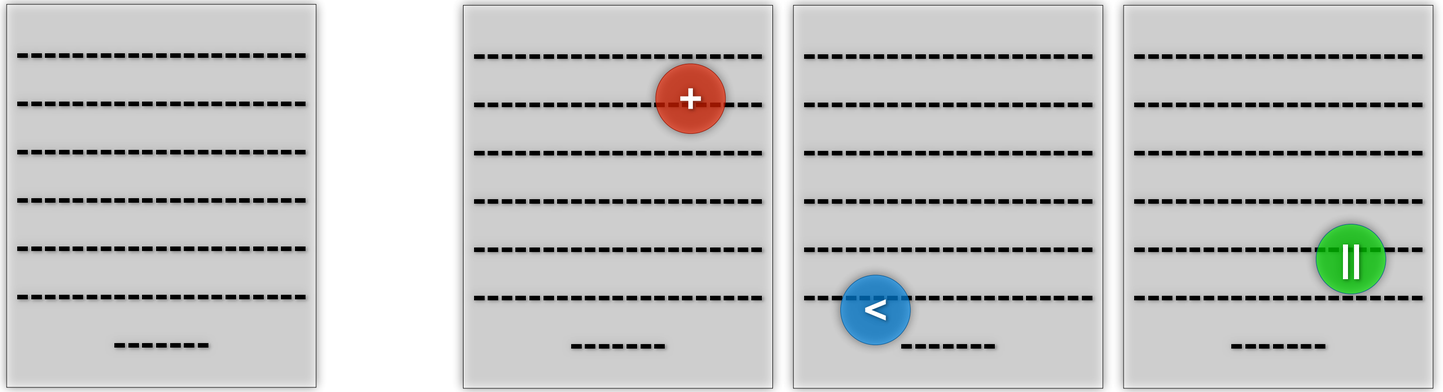
Operators

Test 1 | Test 2 | Test 3

Original Program



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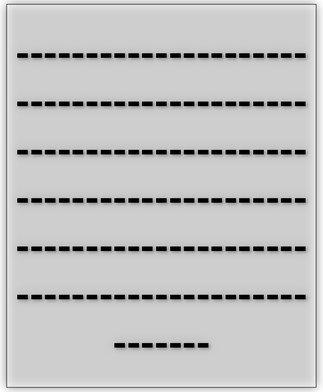
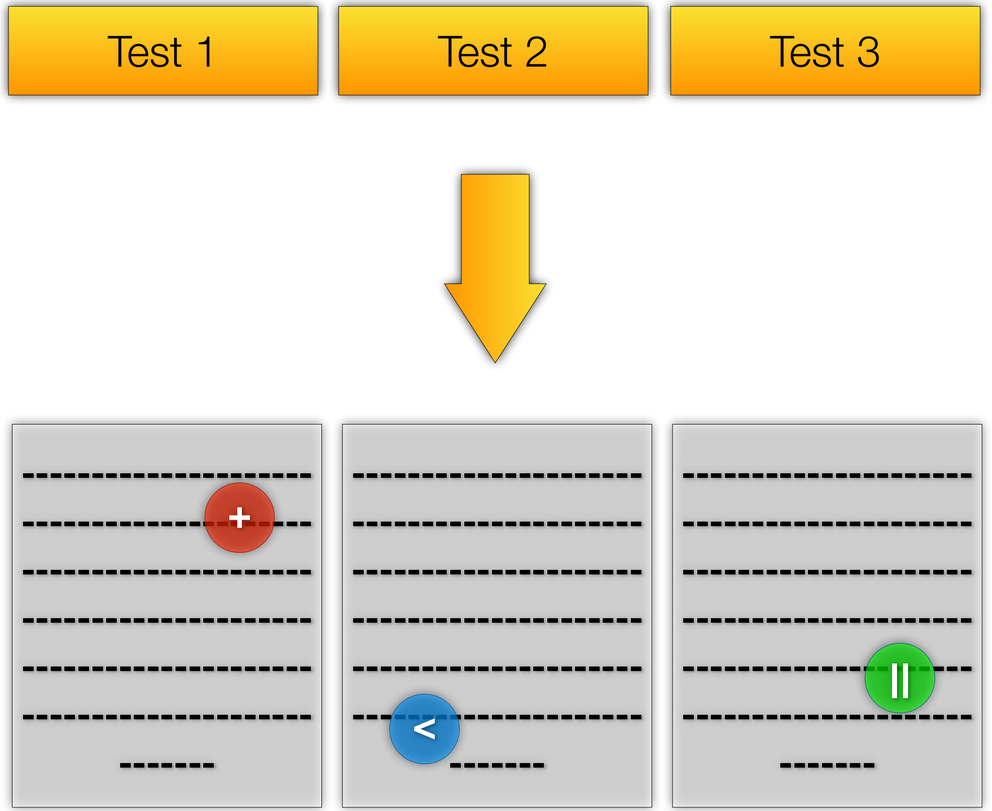
Operators

Original Program





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Operators

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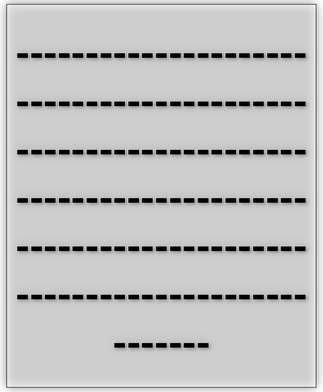
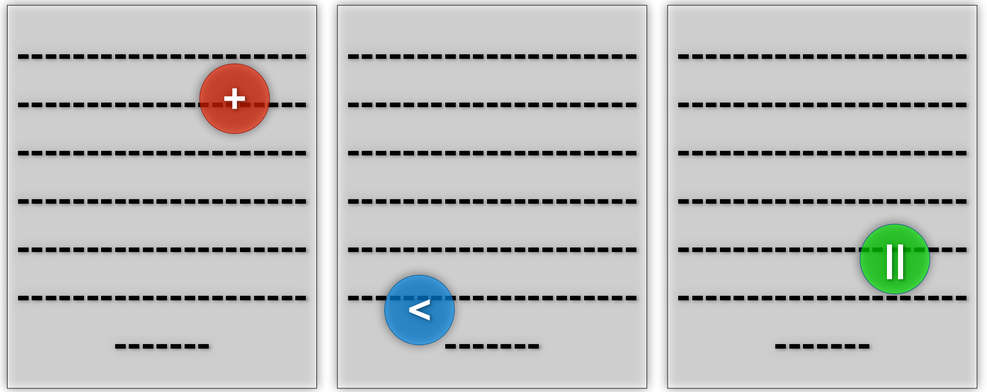
Original Program





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Operators

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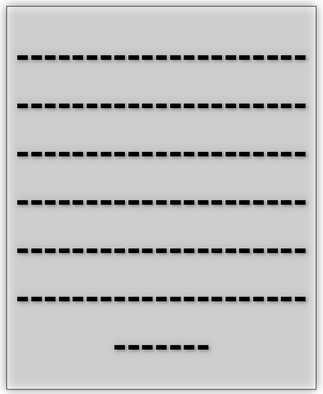

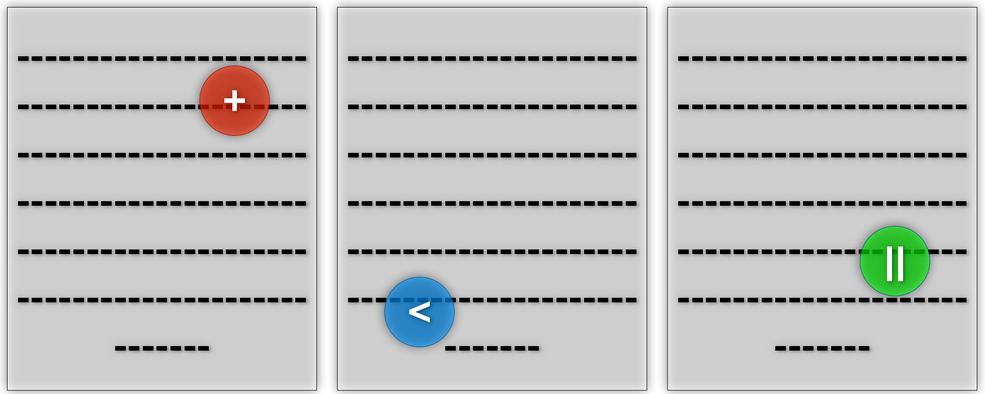

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Operators

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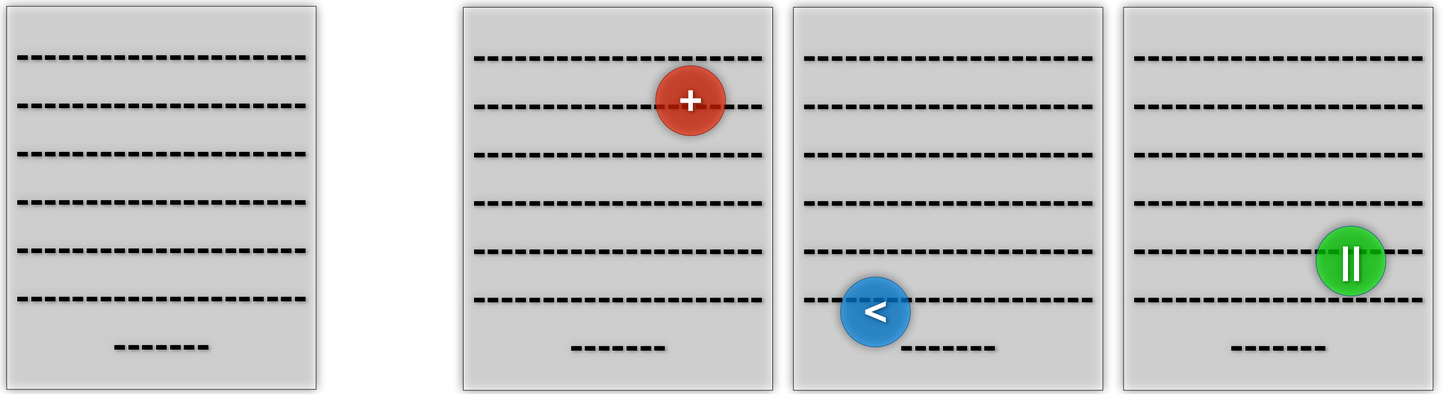

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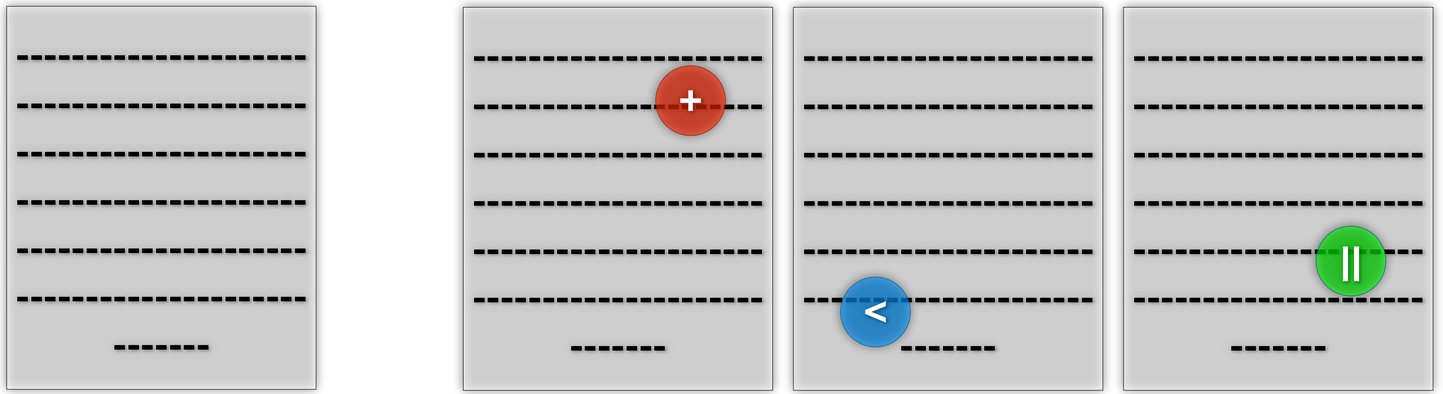
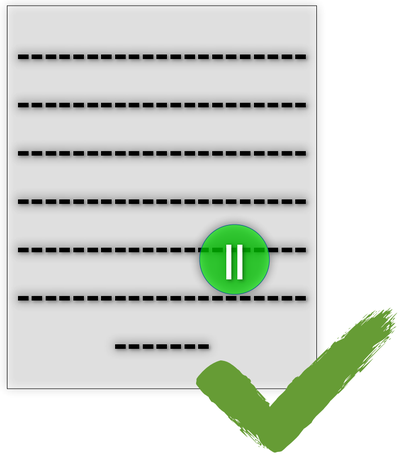
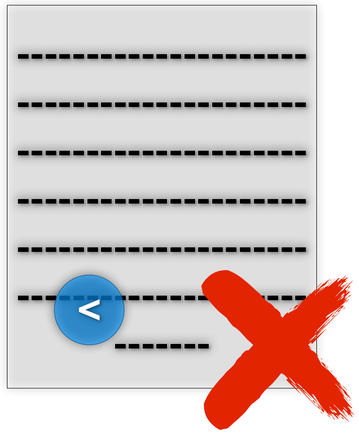
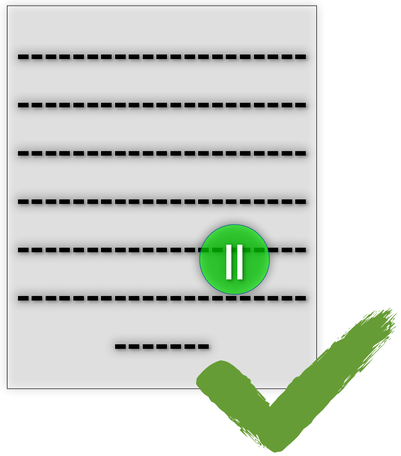


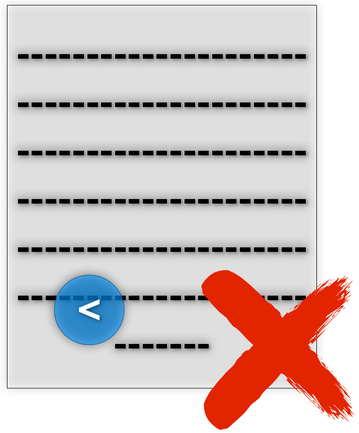


Live mutant - we need more tests



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

```
int do_something(int x, int y)
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  if(x < y)
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Program

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

Test

```
int do_something(int x, int y)
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}
```

Program

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

Test

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

Mutant

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```
int do_something(int x, int y)
{
  if(x < y)
    return x+y;
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Operators

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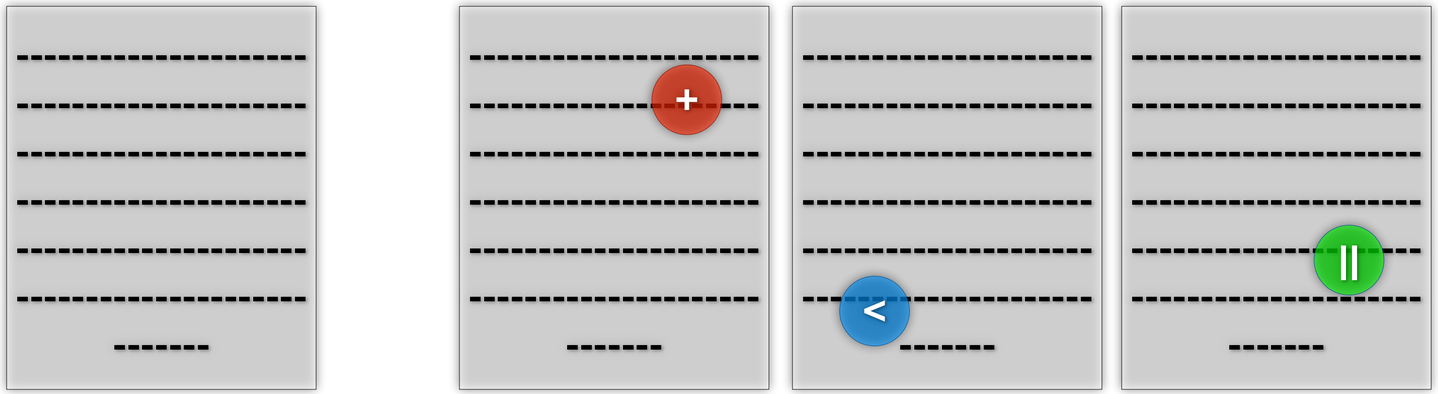
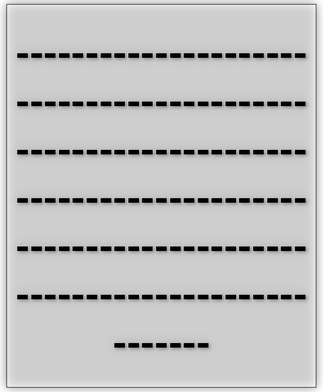
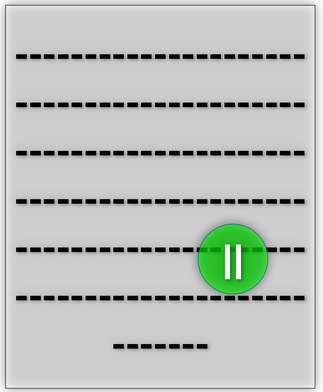
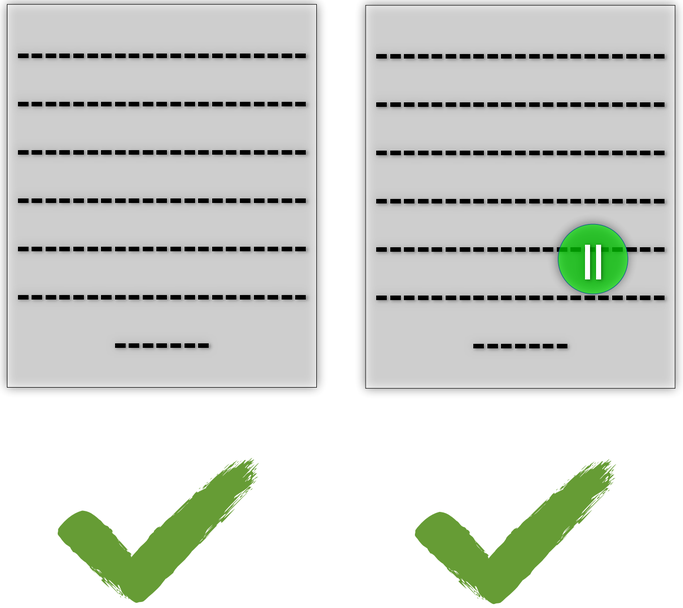
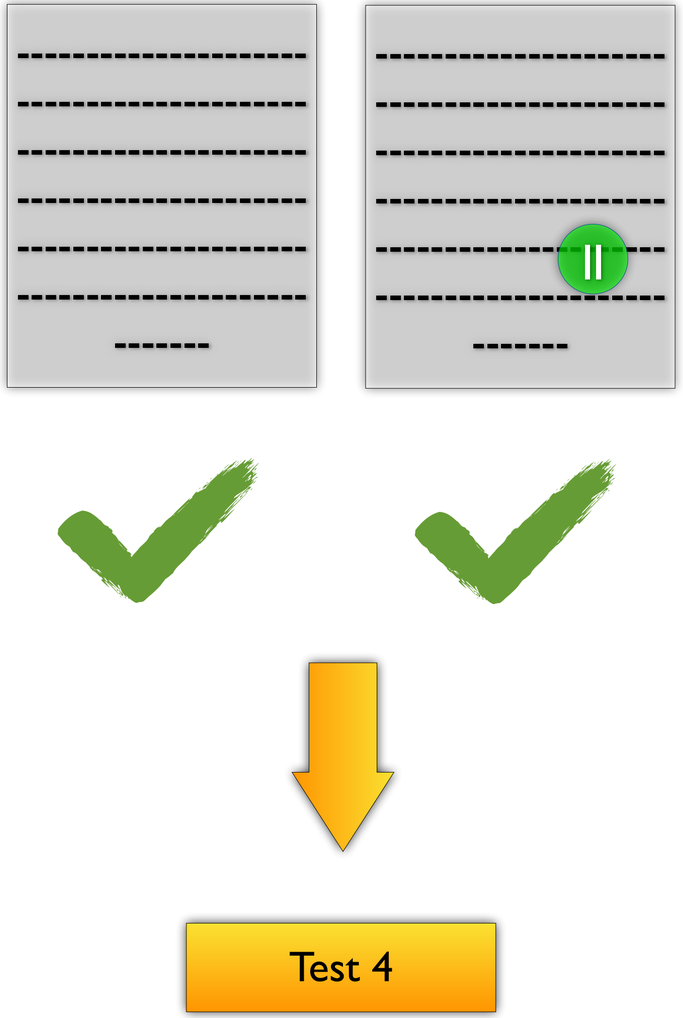
Original Program

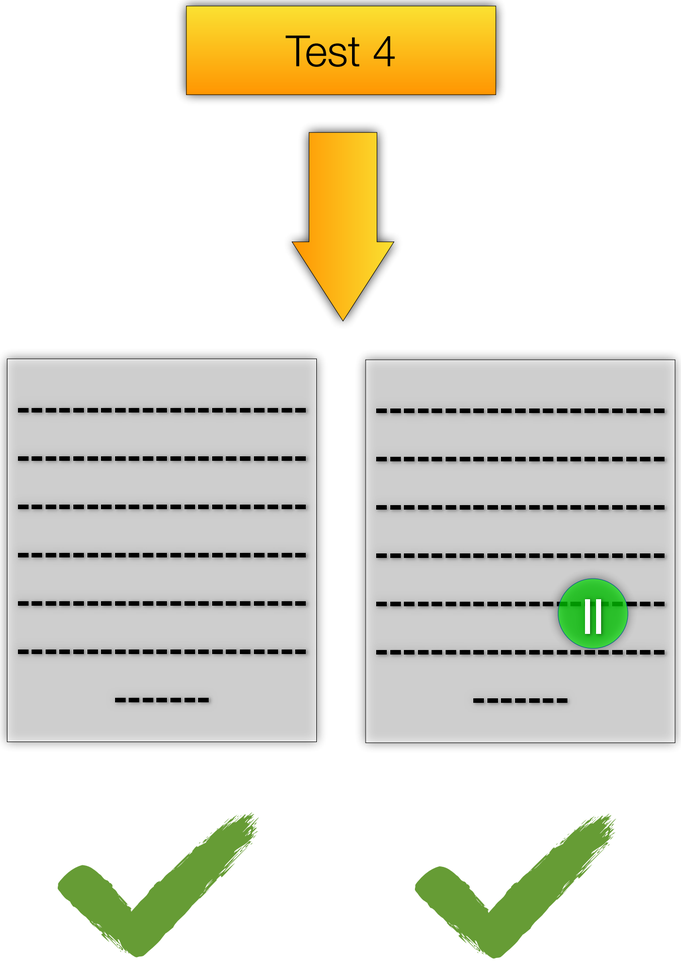


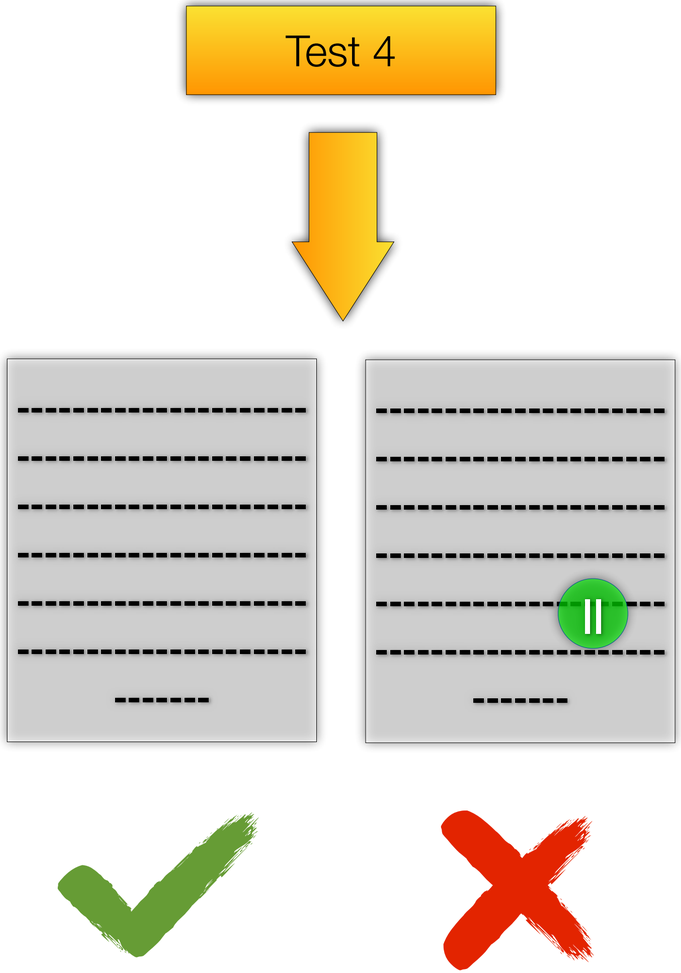






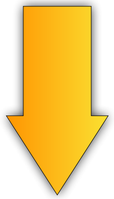

Test 4


Test 4

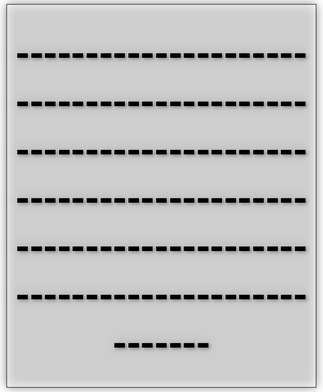

Test 4

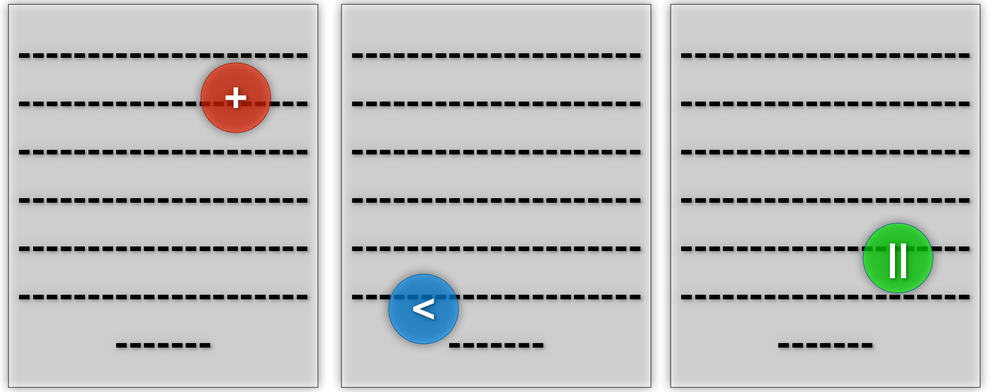
Operators

Test 1 | Test 2 | Test 3 | Test 4



Original Program





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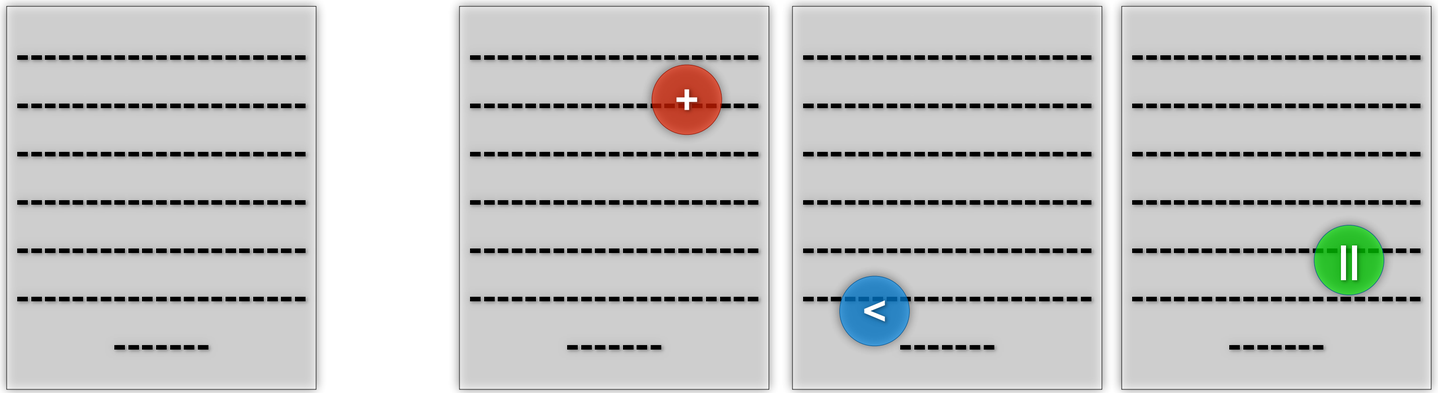
Operators

Test 1 | Test 2 | Test 3 | Test 4

Original Program



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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;
}
```

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ABS - Absolute Value Insertion

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

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

  return x;
}
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ABS - Absolute Value Insertion

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

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

  return -abs(x);
}
```

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ABS - Absolute Value Insertion

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

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AOR - Arithmetic Operator

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

AOR - Arithmetic Operator

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

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

  return x;
}
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AOR - Arithmetic Operator

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AOR - Arithmetic Operator

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

  return x;
}
```

+, -, *, /, %, **, x, y

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) {
  int tmp;

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

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ROR - Relational Operator

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

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

  return x;
}
```

<, >, <=, >=, =,
!=, false, true

COR - Conditional Operator

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

COR - Conditional Operator

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

```
if(a || b)
```

COR - Conditional Operator

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

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

COR - Conditional Operator

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if(a || b)
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if(a | b)
if(a ^ b)
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COR - Conditional Operator

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

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

COR - Conditional Operator

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

```
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)
```

```
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;
}
```

BE-AB-FH

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) {
    tmp = x % +y;
    x = y;
    y = tmp;
  }

  return x;
}
```

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UOI - Unary Operator Insertion

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

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

  return x;
}
```

+, -, !, ~,++,--

SVR - Scalar Variable

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

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

  return x;
}
```

SVR - Scalar Variable

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

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

  return x;
}
```

SVR - Scalar Variable

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

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

  return x;
}
```

SVR - Scalar Variable

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

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

  return x;
}
```

tmp = x % y
tmp = x % x
tmp = y % y
x = x % y
y = y % x
tmp = tmp % y
tmp = x % tmp

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Mutation Operators

id	operator	description	constraint
Operand Modifications			
crp	constant for constant replacement	replace constant $C1$ with constant $C2$	$C1 \neq C2$
scr	scalar for constant replacement	replace constant C with scalar variable X	$C \neq X$
acr	array for constant replacement	replace constant C with array reference $A[I]$	$C \neq A[I]$
scr	struct for constant replacement	replace constant C with struct field S	$C \neq S$
svr	scalar variable replacement	replace scalar variable X with a scalar variable Y	$X \neq Y$
csr	constant for scalar variable replacement	replace scalar variable X with a constant C	$X \neq C$
asr	array for scalar variable replacement	replace scalar variable X with an array reference $A[I]$	$X \neq A[I]$
ssr	struct for scalar replacement	replace scalar variable X with struct field S	$X \neq S$
vie	scalar variable initialization elimination	remove initialization of a scalar variable	
car	constant for array replacement	replace array reference $A[I]$ with constant C	$A[I] \neq C$
sar	scalar for array replacement	replace array reference $A[I]$ with scalar variable X	$A[I] \neq X$
cnr	comparable array replacement	replace array reference with a comparable array reference	
sar	struct for array reference replacement	replace array reference $A[I]$ with a struct field S	$A[I] \neq S$
Expression Modifications			
abs	absolute value insertion	replace e by `abs(`e`)`	$e < 0$
aor	arithmetic operator replacement	replace arithmetic operator ψ with arithmetic operator ϕ	$e_1 \psi e_2 \neq e_1 \phi e_2$
lcr	logical connector replacement	replace logical connector ψ with logical connector ϕ	$e_1 \psi e_2 \neq e_1 \phi e_2$
ror	relational operator replacement	replace relational operator ψ with relational operator ϕ	$e_1 \psi e_2 \neq e_1 \phi e_2$
uoi	unary operator insertion	insert unary operator	
cpr	constant for predicate replacement	replace predicate with a constant value	
Statement Modifications			
sdl	statement deletion	delete a statement	
sca	switch case replacement	replace the label of one case with another	
ses	end block shift	move } one statement earlier and later	

OO Mutations

So far, operators only considered method bodies

Class level elements can be mutated as well:

OO Mutations

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

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Class level elements can be mutated as well:

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

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

OO Mutations

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
```

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$$a + b > c$$

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
```

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Performance Problems

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Performance Problems

Many mutation operators possible

Proteum - 103 Mutation Operators for C

MuJava - Adds 24 Class level Mutation Operators

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

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Each mutant **needs to be compiled**

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Performance Problems

Many mutation operators possible
Proteum - 103 Mutation Operators for C
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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

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

  r = 0;
  for(i = 0; i<values.length; i++) {
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```

Example

```
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  return values[r];
}
```

Example

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

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

  return values[r];
}
```

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

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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];
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Example

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  int r, i;

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

  return values[r];
}
```
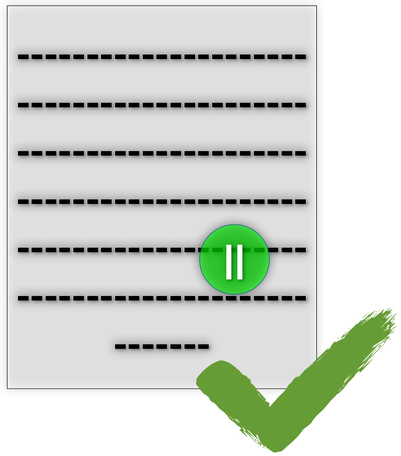
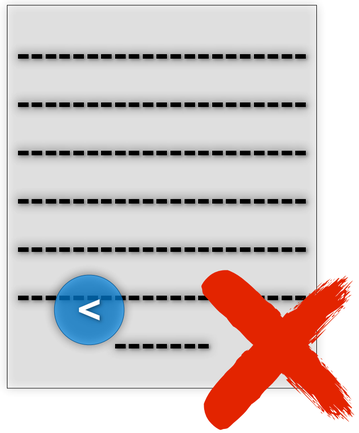
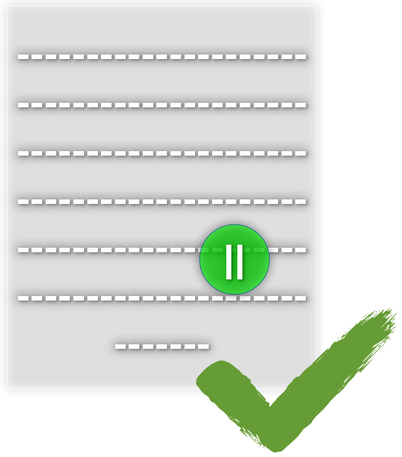
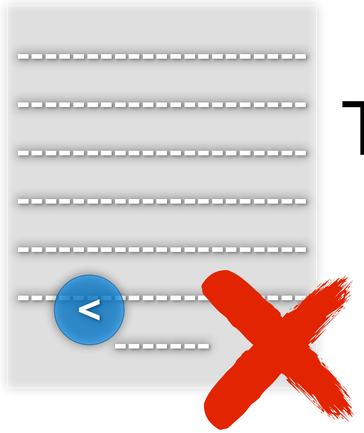





Mutation Score

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





Mutation Score

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

Tools and Resources

PiTest

https://pitest.org/

Major

https://mutation-testing.org/

Universal Mutator

https://github.com/agroce/universalmutator

Mutation Testing @Google

https://testing.googleblog.com/2021/04/mutation-testing.html

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 **tooling available** and **increasingly popular** in industry