

# “Searching” for the Best Tests

An Introduction to Automated Software Testing  
with Search-Based Techniques

**Gregory M. Kapfhammer**

Department of Computer Science  
Allegheny College

March 31, 2015

# Software is Everywhere

Software is pervasive — and so it must be thoroughly tested!

Program

Computer  
Server

# Software is Everywhere

Software is pervasive — and so it must be thoroughly tested!

Program

Program

Desktop  
Computer

Computer  
Server

# Software is Everywhere

Software is pervasive — and so it must be thoroughly tested!

Program

Program

Program

Desktop  
Computer

Computer  
Server

Mobile  
Computer

# Software is Everywhere

Software is pervasive — and so it must be thoroughly tested!

Program

Desktop  
Computer

Program

Computer  
Server

Program

Mobile  
Computer

Program

Household  
Appliance

# Software is Everywhere

Software is pervasive — and so it must be thoroughly tested!

Program

Desktop  
Computer

Program

Computer  
Server

Program

Mobile  
Computer

Program

Scientific  
Device

Program

Household  
Appliance

# Software is Everywhere

Software is pervasive — and so it must be thoroughly tested!

Program

Program

Program

Desktop  
Computer

Computer  
Server

Mobile  
Computer

Program

Program

Program

Scientific  
Device

Household  
Appliance

Network  
Router

# Software is Complex

Even simple programs are intricate — and difficult to test!

Computer  
Software



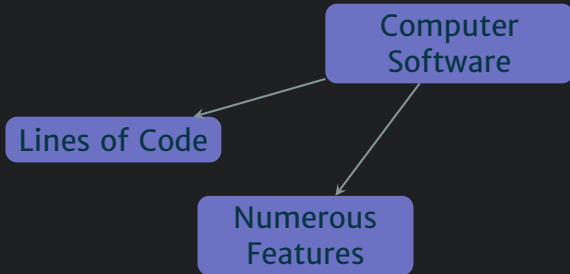
# Software is Complex

Even simple programs are intricate — and difficult to test!



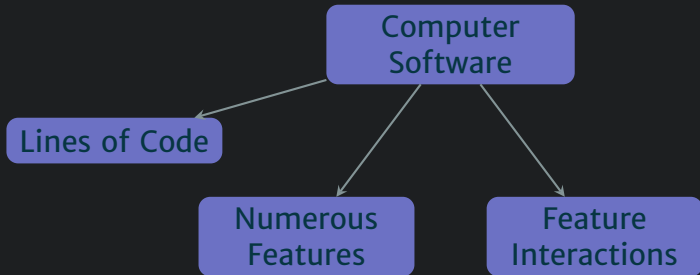
# Software is Complex

Even simple programs are intricate — and difficult to test!



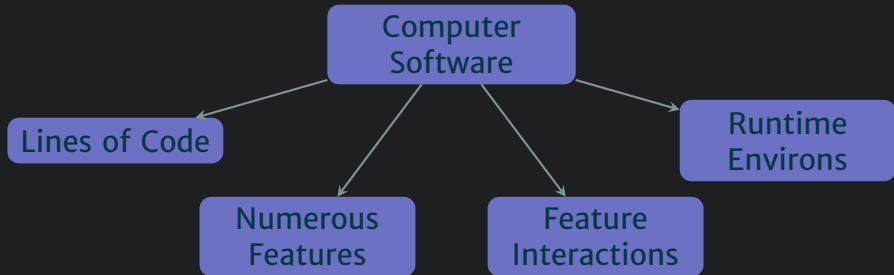
# Software is Complex

Even simple programs are intricate — and difficult to test!



# Software is Complex

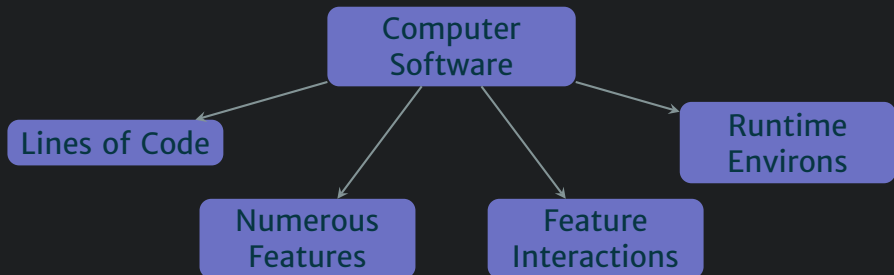
Even simple programs are intricate — and difficult to test!



# Software is Complex

Even simple programs are intricate — and difficult to test!

“Software entities are more complex for their size than perhaps any other human construct” — Frederick P. Brooks, Jr.



# Software is Evolving

Software is continuously updated — making testing critical!

Program

Execution  
Environment

# Software is Evolving

Software is continuously updated — making testing critical!

Program

Program

Execution  
Environment

Execution  
Environment

# Software is Evolving

Software is continuously updated — making testing critical!

Program

Program

Execution  
Environment

Execution  
Environment

**Program Changed** because of the addition  
of a new feature or the correction of a defect



# Software is Evolving

Software is continuously updated — making testing critical!

Program

Execution  
Environment

# Software is Evolving

Software is continuously updated — making testing critical!

Program

Execution  
Environment

Program

Execution  
Environment

# Software is Evolving

Software is continuously updated — making testing critical!

Program

Program

Execution  
Environment

Execution  
Environment

**Execution Environment Changed** due to an upgrade in a kernel, device driver, or virtual machine

# Software is Evolving

Software is continuously updated — making testing critical!

Program

Program

Execution  
Environment

Execution  
Environment

**Execution Environment Changed** due to an upgrade in a kernel, device driver, or virtual machine

**“Release early, release often”** means that programs are regularly updated

# Motivating Example

The computation of an object's velocity presents challenges!

$$K = \frac{1}{2} m \times v^2$$

# Motivating Example

The computation of an object's velocity presents challenges!

$$K = \frac{1}{2} m \times v^2$$

# Motivating Example

The computation of an object's velocity presents challenges!

$$K = \frac{1}{2} m \times v^2$$

# Motivating Example

The computation of an object's velocity presents challenges!

$$K = \frac{1}{2} m \times v^2$$



# Computing Velocity

```
public static String computeVelocity(int kinetic, int mass) {
    int velocitySquared = 0;
    int velocity = 0;
    StringBuffer finalVelocity = new StringBuffer();
    if( mass != 0 ) {
        velocitySquared = 3 * (kinetic / mass);
        velocity = (int)Math.sqrt(velocitySquared);
        finalVelocity.append(velocity);
    }
    else {
        finalVelocity.append("Undefined");
    }
    return finalVelocity.toString();
}
```

# Important Questions

Finding software defects is a challenging and rewarding task

Can you find the  
defect in this  
program?

# Important Questions

Finding software defects is a challenging and rewarding task

Are there general  
purpose strategies  
for defect isolation?



## The Challenges of Software Development

- Pervasiveness of Software

- Complexity of Software

- Evolving Nature of Software

- Motivating Example

- Important Questions

## Benefits of Software Testing

- Test Cases

- Test Suites

- Examples of Tests

- The PIE Model

- Test Case Effectiveness

## Search-Based Software Testing

- Testing Methods

- Random Testing

- Testing with EvoSuite

## Conclusion

## The Challenges of Software Development

- Pervasiveness of Software

- Complexity of Software

- Evolving Nature of Software

- Motivating Example

- Important Questions

## Benefits of Software Testing

- Test Cases

- Test Suites

- Examples of Tests

- The PIE Model

- Test Case Effectiveness

## Search-Based Software Testing

- Testing Methods

- Random Testing

- Testing with EvoSuite

## Conclusion

## The Challenges of Software Development

- Pervasiveness of Software

- Complexity of Software

- Evolving Nature of Software

- Motivating Example

- Important Questions

## Benefits of Software Testing

- Test Cases

- Test Suites

- Examples of Tests

- The PIE Model

- Test Case Effectiveness

## Search-Based Software Testing

- Testing Methods

- Random Testing

- Testing with EvoSuite

## Conclusion

# What is a Test Case?

A test case calls a method and checks its output with an oracle

Method Un-  
der Test



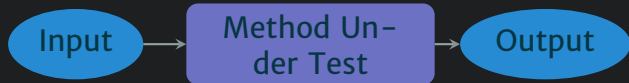
# What is a Test Case?

A test case calls a method and checks its output with an oracle



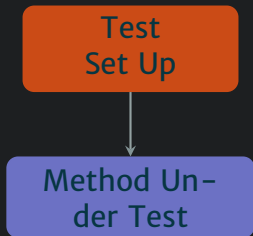
# What is a Test Case?

A test case calls a method and checks its output with an oracle



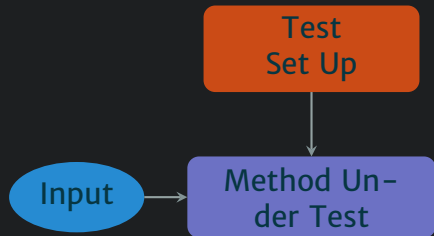
# What is a Test Case?

A test case calls a method and checks its output with an oracle



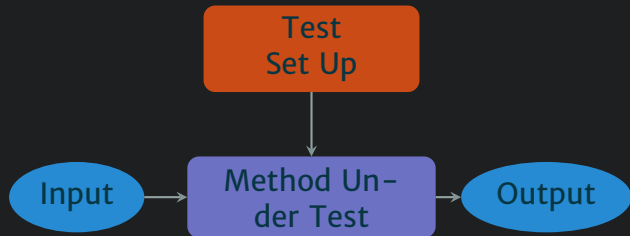
# What is a Test Case?

A test case calls a method and checks its output with an oracle



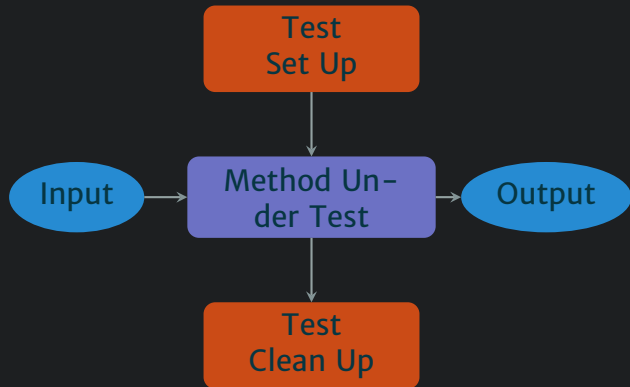
# What is a Test Case?

A test case calls a method and checks its output with an oracle



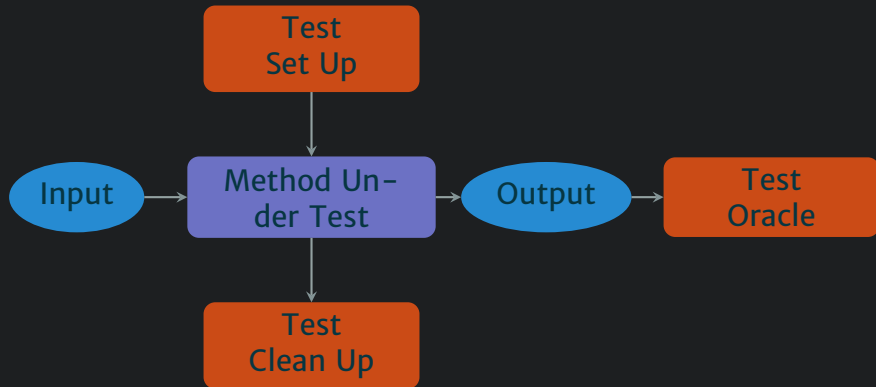
# What is a Test Case?

A test case calls a method and checks its output with an oracle



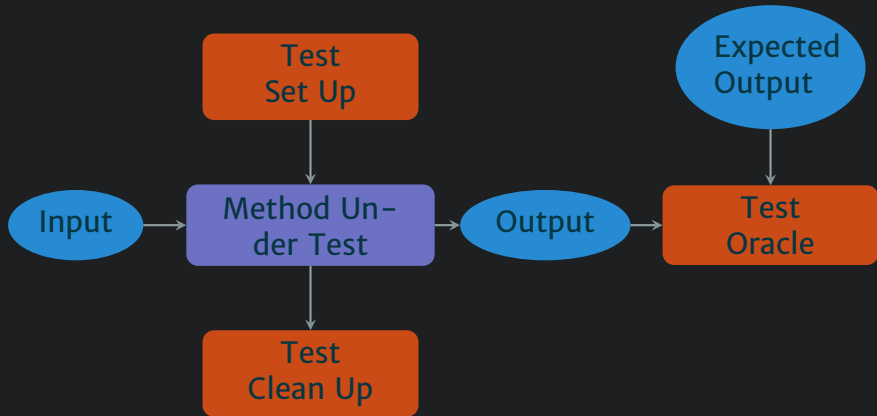
# What is a Test Case?

A test case calls a method and checks its output with an oracle



# What is a Test Case?

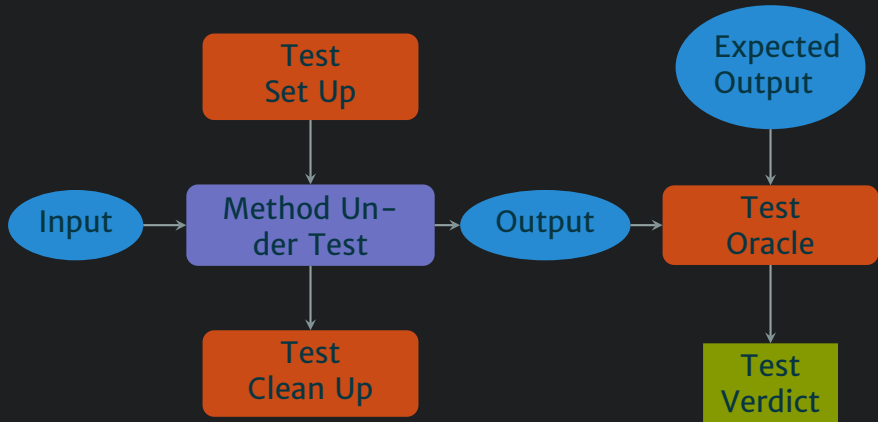
A test case calls a method and checks its output with an oracle





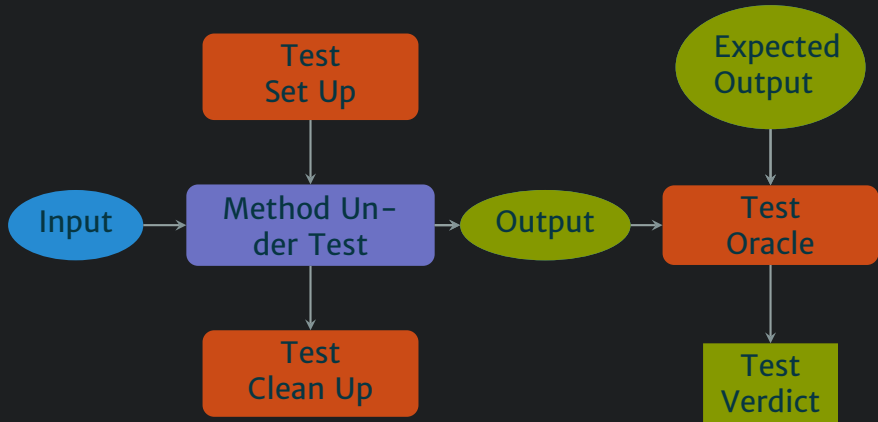
# What is a Test Case?

A test case calls a method and checks its output with an oracle



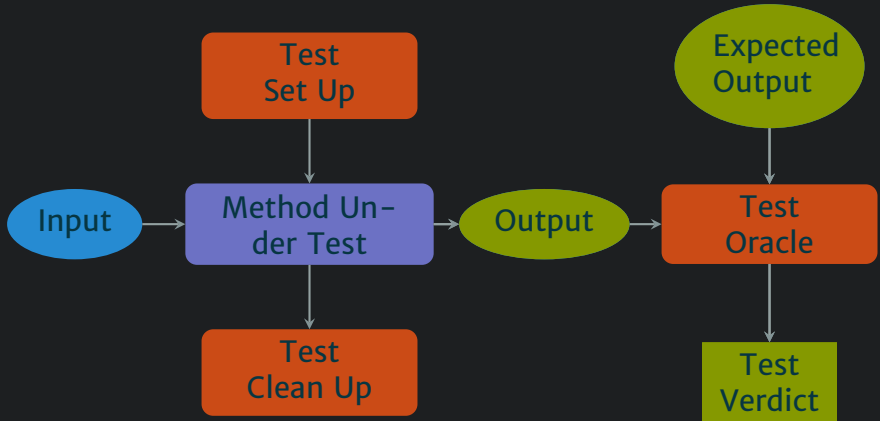
# What is a Test Case?

A test case calls a method and checks its output with an oracle



# What is a Test Case?

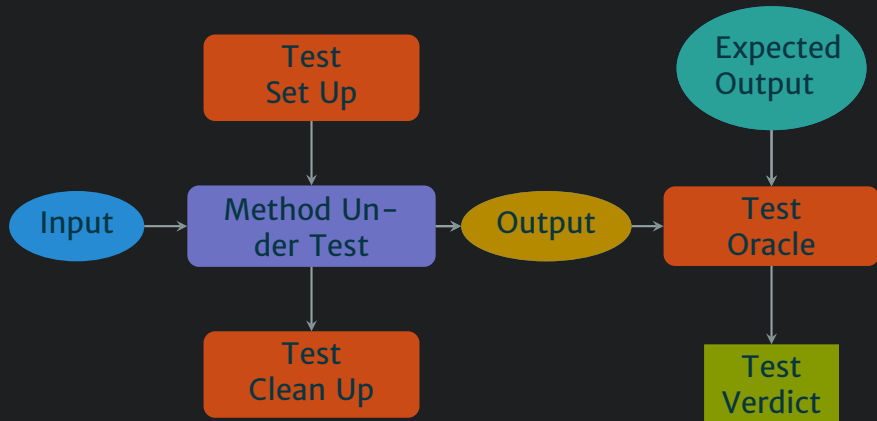
A test case calls a method and checks its output with an oracle



The test case passes and the code is correct!

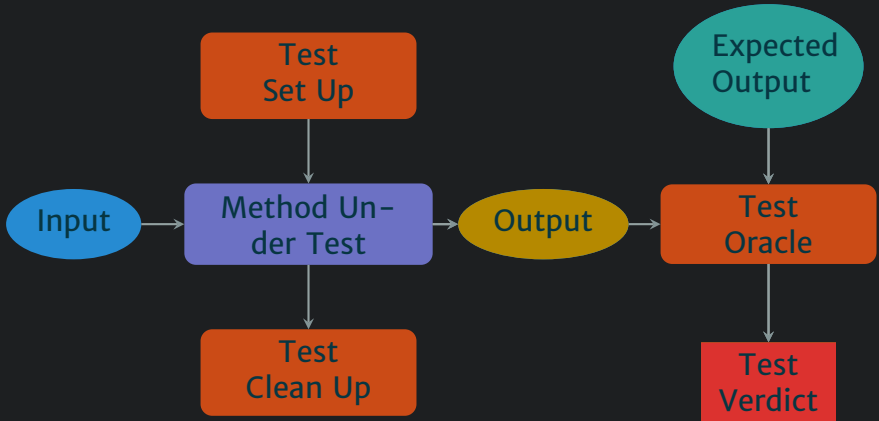
# What is a Test Case?

A test case calls a method and checks its output with an oracle



# What is a Test Case?

A test case calls a method and checks its output with an oracle



The test case fails and a defect is found!

# What is a Test Suite?

A test suite is an organized collection of test cases



$T_1$

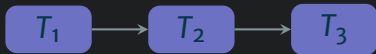
# What is a Test Suite?

A test suite is an organized collection of test cases



# What is a Test Suite?

A test suite is an organized collection of test cases





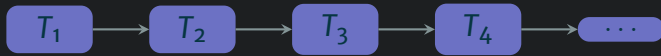
# What is a Test Suite?

A test suite is an organized collection of test cases



# What is a Test Suite?

A test suite is an organized collection of test cases



# What is a Test Suite?

A test suite is an organized collection of test cases



# What is a Test Suite?

A test suite is an organized collection of test cases

Organize the Test Cases into a Test Suite



# What is a Test Suite?

A test suite is an organized collection of test cases

Organize the Test Cases into a Test Suite



Tool Support for Software Testing?

# What is a Test Suite?

A test suite is an organized collection of test cases

Organize the Test Cases into a Test Suite



Tool Support for Software Testing?

JUnit

# What is a Test Suite?

A test suite is an organized collection of test cases

Organize the Test Cases into a Test Suite



Tool Support for Software Testing?

JUnit

Apache Ant

# What is a Test Suite?

A test suite is an organized collection of test cases

Organize the Test Cases into a Test Suite



Tool Support for Software Testing?

JUnit

Apache Ant

Eclipse



# A JUnit Test Case

```
@Test
public void testOne() {
    String expected = new String("Undefined");
    String actual = Kinetic.
        computeVelocity(5,0);
    assertEquals(expected, actual);
}
```

# Another JUnit Test

```
@Test
```

```
public void testTwo() {  
    String expected = new String("0");  
    String actual = Kinetic.  
        computeVelocity(0,5);  
    assertEquals(expected, actual);  
}
```

# Important Questions

Not all tests have the same fault detection effectiveness!

Will these test cases  
find the fault in the  
example program?

# Important Questions

Not all tests have the same fault detection effectiveness!

$T_1$  assigns  
 $K = 5, m = 0$  —  
Pass or fail?

# Important Questions

Not all tests have the same fault detection effectiveness!

$T_2$  assigns

$K = 0, m = 5$  —

Pass or fail?

# Important Questions

Not all tests have the same fault detection effectiveness!

How do we study the effectiveness of different test cases?

# The PIE Model

There are necessary and sufficient conditions for fault detection

- ▶ **Execute the faulty source code**
- ▶ Infect the program's data state
- ▶ Propagate to the program's output

# The PIE Model

There are necessary and sufficient conditions for fault detection

- ▶ Execute the faulty source code
- ▶ Infect the program's data state
- ▶ Propagate to the program's output



# The PIE Model

There are necessary and sufficient conditions for fault detection

- ▶ Execute the faulty source code
- ▶ Infect the program's data state
- ▶ Propagate to the program's output

# The PIE Model

There are necessary and sufficient conditions for fault detection

- ▶ Execute the faulty source code
- ▶ Infect the program's data state
- ▶ Propagate to the program's output

# The PIE Model

There are necessary and sufficient conditions for fault detection

- ▶ Execute the faulty source code
- ▶ Infect the program's data state
- ▶ Propagate to the program's output

*All of these must occur before the fault manifests itself as a failure!*

# The PIE Model

There are necessary and sufficient conditions for fault detection

- ▶ Execute the faulty source code
- ▶ Infect the program's data state
- ▶ Propagate to the program's output

*All of these must occur before the fault manifests itself as a failure!*

Using the PIE model, will the test cases *find* the defect in the program?

# A JUnit Test Case — $T_1$

```
@Test
public void testOne() {
    String expected = new String("Undefined");
    String actual = Kinetic.
        computeVelocity(5,0);
    assertEquals(expected, actual);
}
```

E I P

# A JUnit Test Case — $T_1$

```
@Test
public void testOne() {
    String expected = new String("Undefined");
    String actual = Kinetic.
        computeVelocity(5,0);
    assertEquals(expected, actual);
}
```

E

X

I

X

P

X

# A JUnit Test Case — $T_2$

```
@Test
public void testTwo() {
    String expected = new String("0");
    String actual = Kinetic.
        computeVelocity(0,5);
    assertEquals(expected, actual);
}
```

E I P

# A JUnit Test Case — $T_2$

```
@Test
public void testTwo() {
    String expected = new String("0");
    String actual = Kinetic.
        computeVelocity(0,5);
    assertEquals(expected, actual);
}
```

E



I



P





# A JUnit Test Case — $T_3$

```
@Test
public void testThree() {
    String expected = new String("4");
    String actual = Kinetic.
        computeVelocity(8,1);
    assertEquals(expected, actual);
}
```

E I P

# A JUnit Test Case — $T_3$

```
@Test
```

```
public void testThree() {
```

```
    String expected = new String("4");
```

```
    String actual = Kinetic.
```

```
        computeVelocity(8,1);
```

```
    assertEquals(expected, actual);
```

```
}
```

E



I



P



# A JUnit Test Case — $T_4$

```
@Test
public void testFour() {
    String expected = new String("20");
    String actual = Kinetic.
        computeVelocity(1000,5);
    assertEquals(expected, actual);
}
```

E I P

# A JUnit Test Case — $T_4$

```
@Test
public void testFour() {
    String expected = new String("20");
    String actual = Kinetic.
        computeVelocity(1000,5);
    assertEquals(expected, actual);
}
```

E



I



P



# Test Suite Summary

A test case must create specific inputs in order to cause failure!

Test Case	Status
$T_1$	Pass
$T_2$	Pass
$T_3$	Pass
$T_4$	Fail

# Important Insights

Software testing is fundamentally challenging — is there help?

*I shall not deny that the construction of these testing programs has been a major intellectual effort: to convince oneself that one has not overlooked “a relevant state” and to convince oneself that the testing programs generate them all is no simple matter.*

Edsger W. Dijkstra, *Communications of the ACM*, 1968







## The Challenges of Software Development

- Pervasiveness of Software

- Complexity of Software

- Evolving Nature of Software

- Motivating Example

- Important Questions

## Benefits of Software Testing

- Test Cases

- Test Suites

- Examples of Tests

- The PIE Model

- Test Case Effectiveness

## Search-Based Software Testing

- Testing Methods

- Random Testing

- Testing with EvoSuite

## Conclusion

## The Challenges of Software Development

- Pervasiveness of Software

- Complexity of Software

- Evolving Nature of Software

- Motivating Example

- Important Questions

## Benefits of Software Testing

- Test Cases

- Test Suites

- Examples of Tests

- The PIE Model

- Test Case Effectiveness

## Search-Based Software Testing

- Testing Methods

- Random Testing

- Testing with EvoSuite

## Conclusion

# Manual Testing

While it has benefits, this industry standard may be limited!

Manual Testing

# Manual Testing

While it has benefits, this industry standard may be limited!

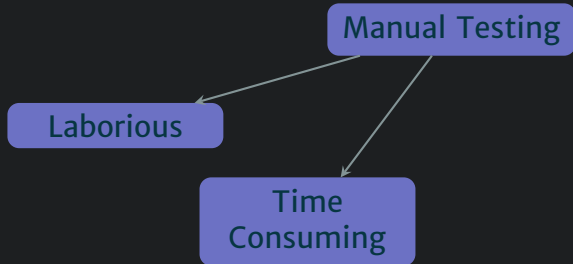
```
graph TD; A[Manual Testing] --> B[Laborious]
```

Manual Testing

Laborious

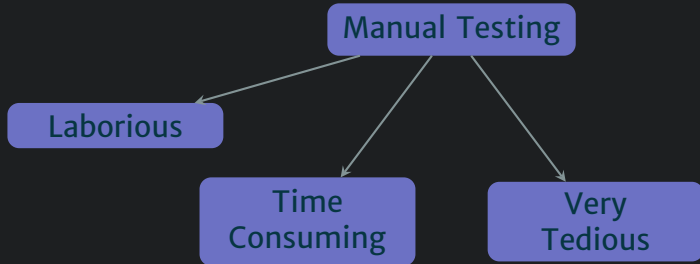
# Manual Testing

While it has benefits, this industry standard may be limited!



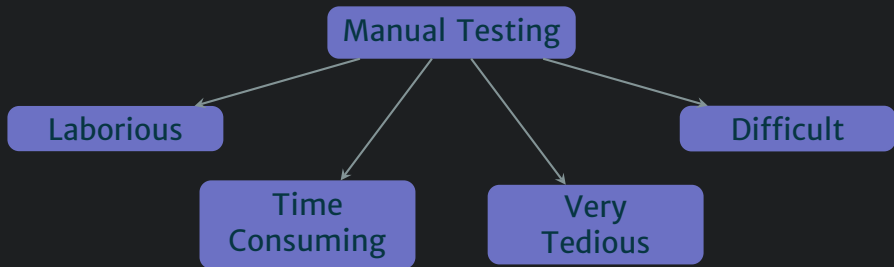
# Manual Testing

While it has benefits, this industry standard may be limited!



# Manual Testing

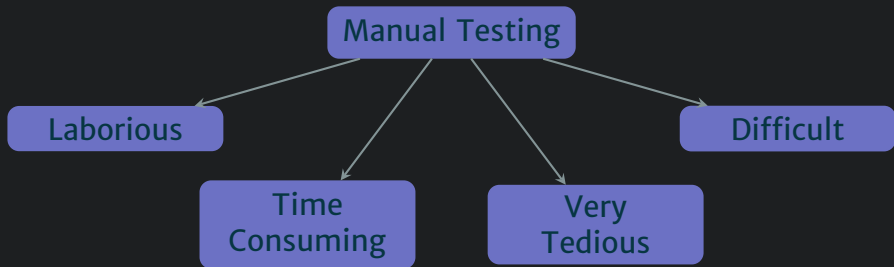
While it has benefits, this industry standard may be limited!



# Manual Testing

While it has benefits, this industry standard may be limited!

Can we develop and employ methods that will automatically generate high-quality test cases for real-world software?





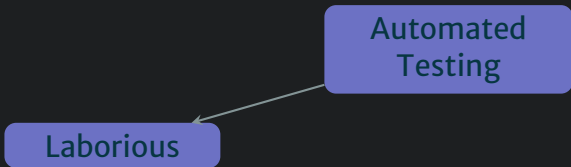
# Automated Testing

Automatically generating tests is amazing — but does it work?

Automated  
Testing

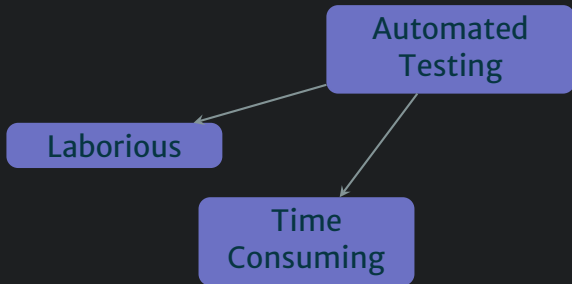
# Automated Testing

Automatically generating tests is amazing — but does it work?



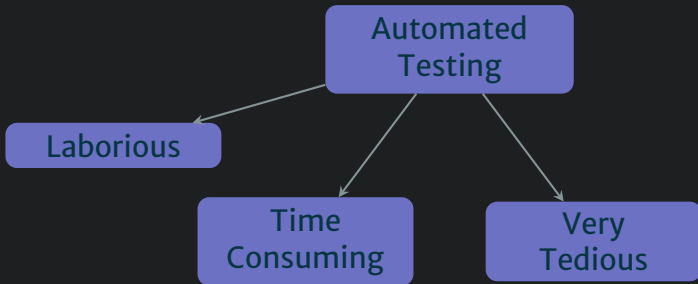
# Automated Testing

Automatically generating tests is amazing — but does it work?



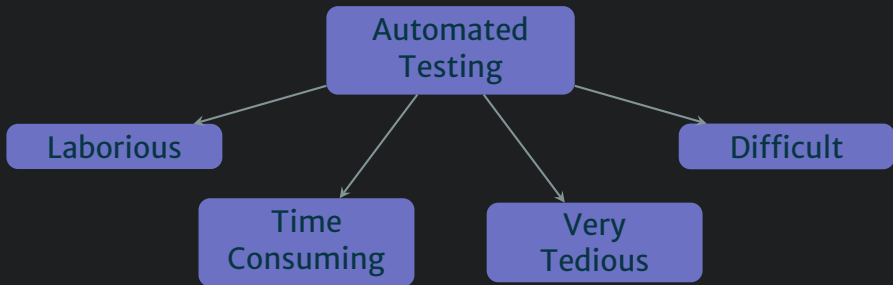
# Automated Testing

Automatically generating tests is amazing — but does it work?



# Automated Testing

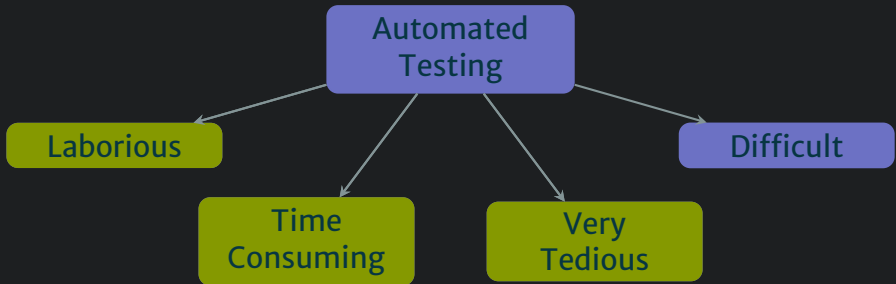
Automatically generating tests is amazing — but does it work?



# Automated Testing

Automatically generating tests is amazing — but does it work?

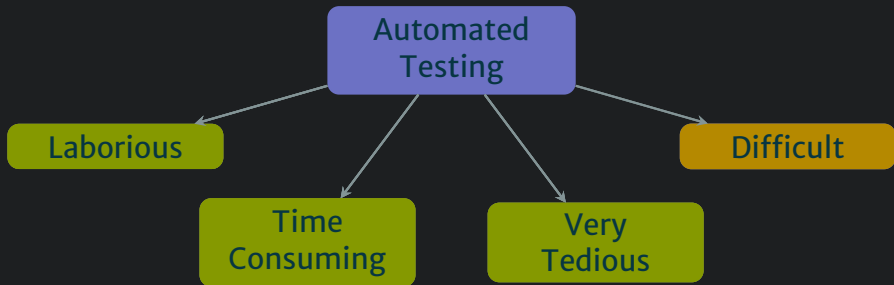
Testing is *less* laborious and tedious because an algorithm generates the tests. While computational time is needed, a human can be *less* involved!



# Automated Testing

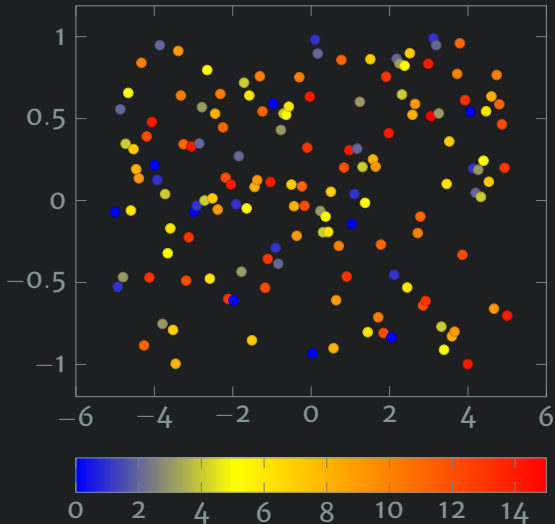
Automatically generating tests is amazing — but does it work?

Automated testing is *less* difficult since a good fitness function can guide the algorithm to inputs that find the faults



# Random Testing

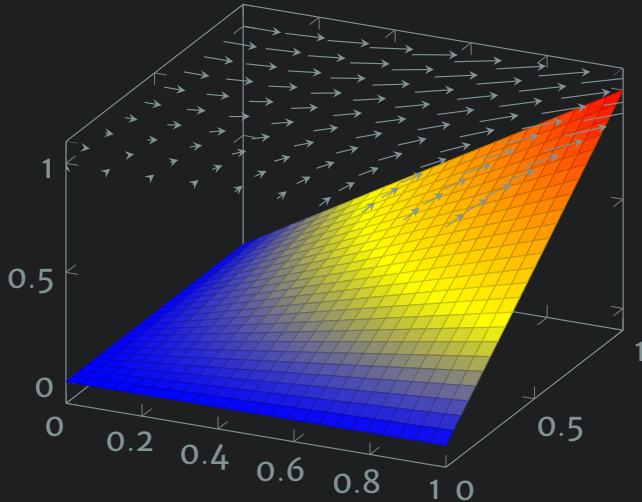
It is easy to randomly generate tests — but how good are they?





# Search-Based Testing

Use a fitness function to guide the search to “good” values



# Mutation Testing

Let's purposefully insert faults into the program under test!

$T_1$

$T_2$

# Mutation Testing

Let's purposefully insert faults into the program under test!

$T_1$

$T_2$

$T_3$

$T_4$

# Mutation Testing

Let's purposefully insert faults into the program under test!

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

# Mutation Testing

Let's purposefully insert faults into the program under test!

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

# Mutation Testing

Let's purposefully insert faults into the program under test!

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

$M_1$

$M_2$



# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

$M_1$

$M_2$

$M_3$

$M_4$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

$M_1$

$M_2$

$M_3$

$M_4$

$M_5$

$M_6$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

$M_1$

$M_2$

$M_3$

$M_4$

$M_5$

$M_6$

$M_7$

$M_8$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

$M_1$

$M_2$

$M_3$

$M_4$

$M_5$

$M_6$

$M_7$

$M_8$

$M_9$

$M_{10}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

$M_1$

$M_2$

$M_3$

$M_4$

$M_5$

$M_6$

$M_7$

$M_8$

$M_9$

$M_{10}$

$M_{11}$

$M_{12}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

$T_1$

$T_2$

$T_3$

$T_4$

$T_5$

$T_6$

$T_7$

$T_8$

$T_9$

$T_{10}$

$M_1$

$M_2$

$M_3$

$M_4$

$M_5$

$M_6$

$M_7$

$M_8$

$M_9$

$M_{10}$

$M_{11}$

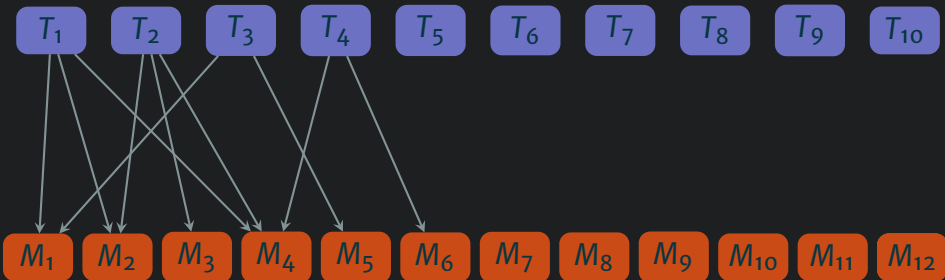
$M_{12}$

Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

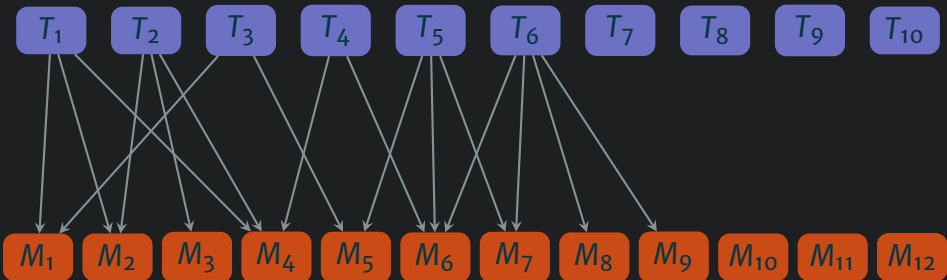


Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$



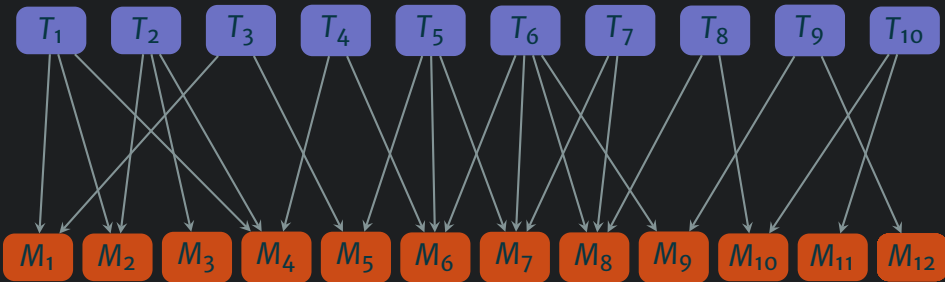
Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$



# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

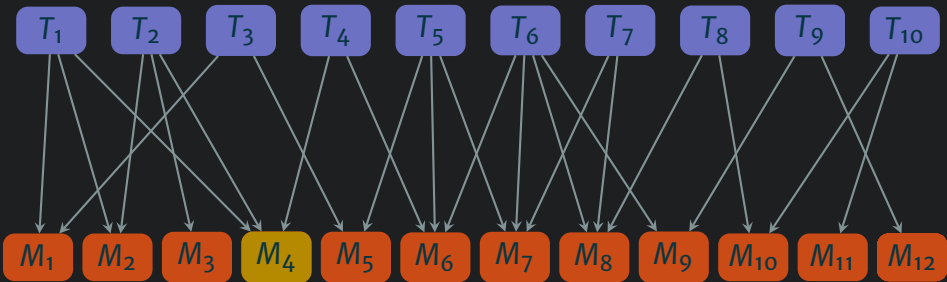


Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

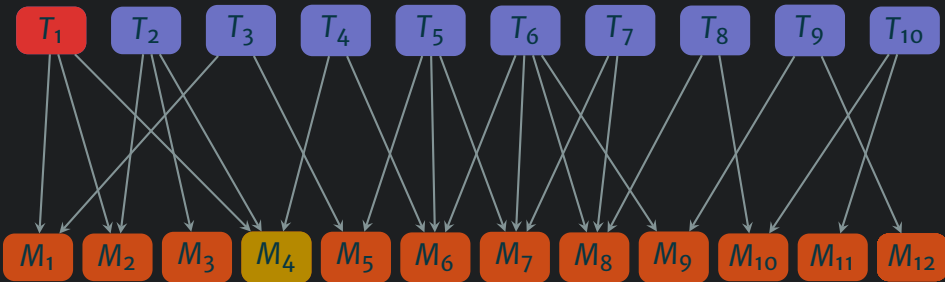


Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

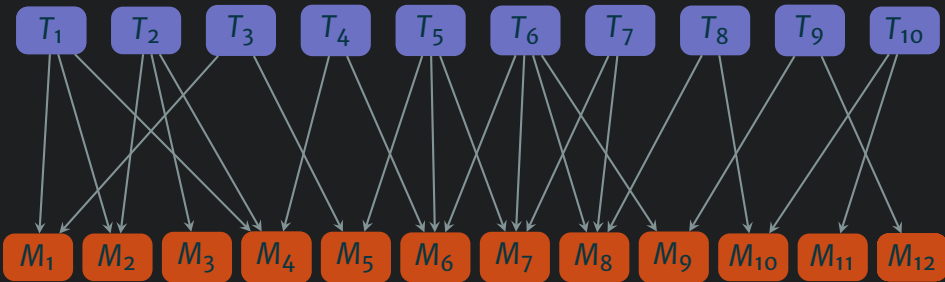


Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$

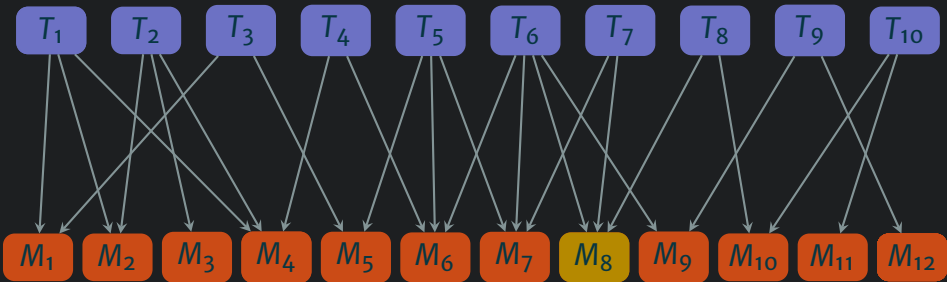


Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$

# Mutation Testing

Let's purposefully insert faults into the program under test!

Test Suite  $T = \langle T_1, T_2, \dots, T_9, T_{10} \rangle$



Set of Program Methods  $M = \{M_1, M_2, \dots, M_{11}, M_{12}\}$

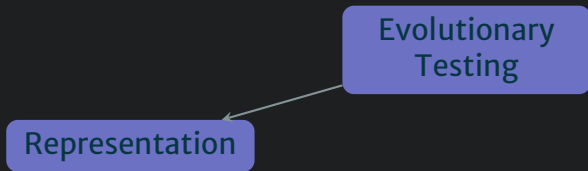
# Testing with EvoSuite

This prototype can automatically generate real JUnit test suites!

Evolutionary  
Testing

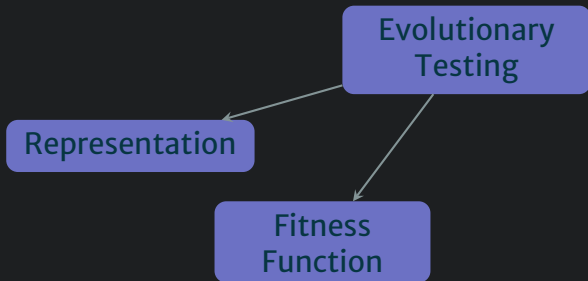
# Testing with EvoSuite

This prototype can automatically generate real JUnit test suites!



# Testing with EvoSuite

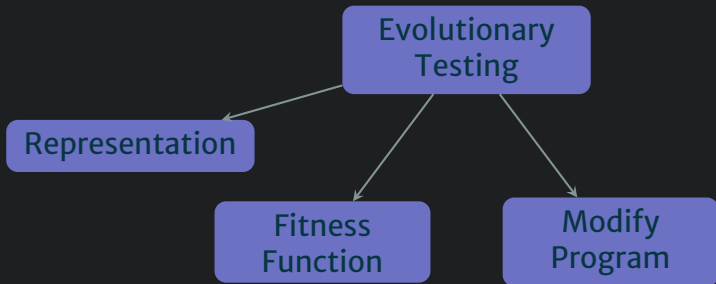
This prototype can automatically generate real JUnit test suites!





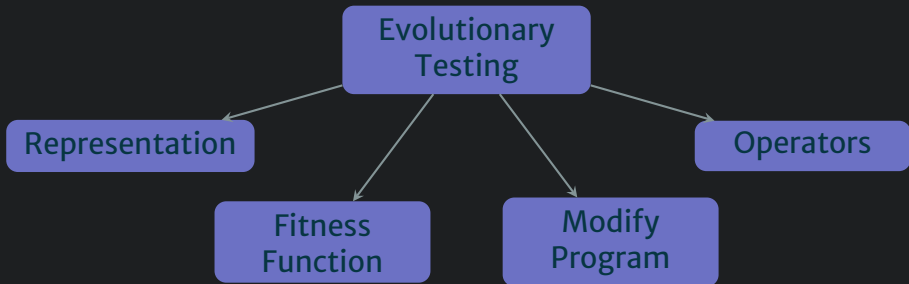
# Testing with EvoSuite

This prototype can automatically generate real JUnit test suites!



# Testing with EvoSuite

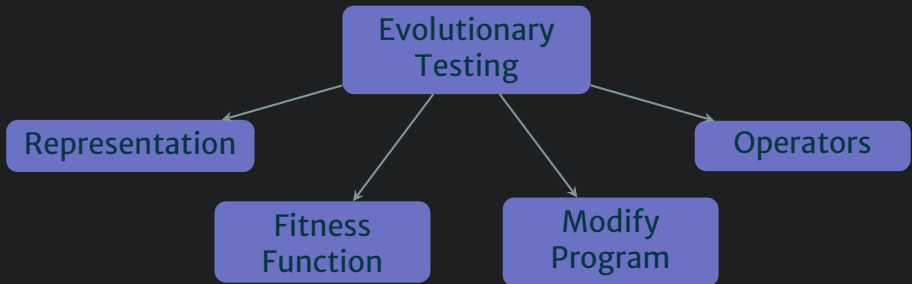
This prototype can automatically generate real JUnit test suites!



# Testing with EvoSuite

This prototype can automatically generate real JUnit test suites!

“1600 Faults in 100 Projects: Automatically Finding Faults While Achieving High Coverage with EvoSuite”, *Empirical Software Engineering*



# Configuring EvoSuite

This tool has many unique configurations — which are best?

EvoSuite's  
Configurations

# Configuring EvoSuite

This tool has many unique configurations — which are best?

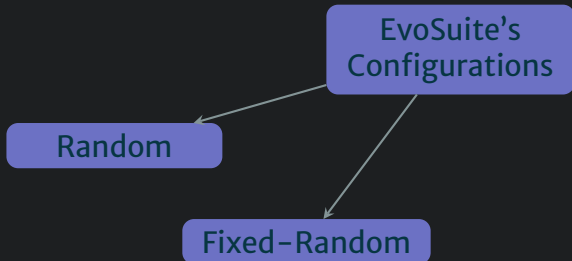
```
graph TD; A[EvoSuite's Configurations] --> B[Random]
```

EvoSuite's  
Configurations

Random

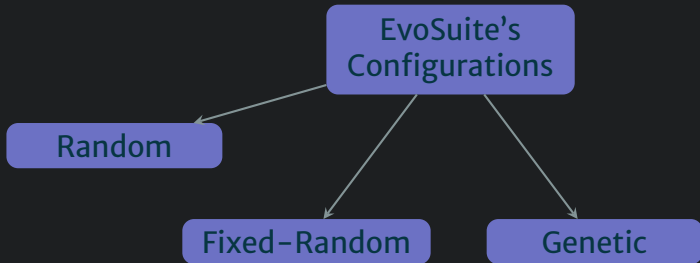
# Configuring EvoSuite

This tool has many unique configurations — which are best?



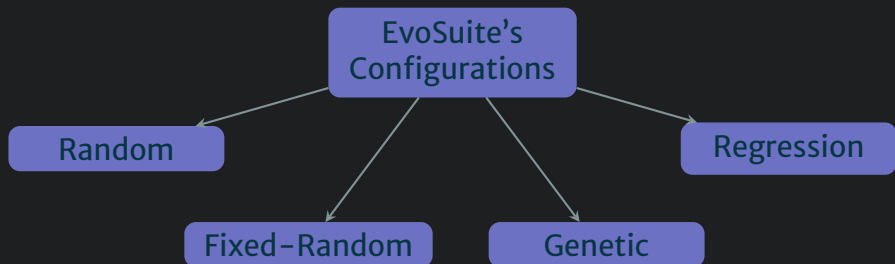
# Configuring EvoSuite

This tool has many unique configurations — which are best?



# Configuring EvoSuite

This tool has many unique configurations — which are best?

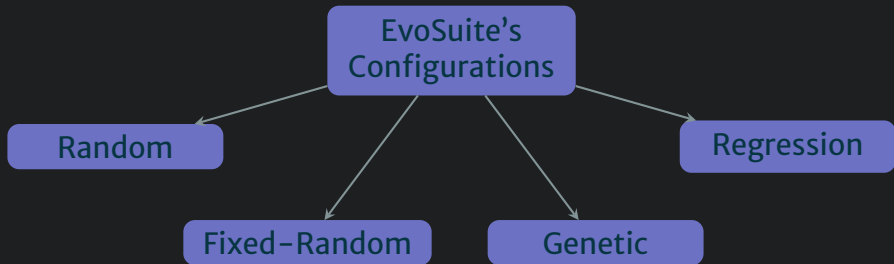




# Configuring EvoSuite

This tool has many unique configurations — which are best?

The fitness function computes *branch coverage*, *weak mutation score*, or *strong mutation score* to guide the search to the “best” test cases



# A Test from EvoSuite

```
@Test
public void test001() throws Throwable {
    int int0 = 0;
    String string0 = Kinetic.computeVelocity(int0, int0);
    assertEquals("Undefined", string0);
    assertNotNull(string0);
    int int1 = 1262;
    String string1 = Kinetic.computeVelocity(int0, int0);
    int int2 = 5349;
    String string2 = Kinetic.computeVelocity(int1, int2);
    int int3 = 0;
    int int4 = 3;
    String string3 = Kinetic.computeVelocity(int3, int4);
    Kinetic kinetic0 = new Kinetic();
}
```

# Important Questions

EvoSuite is an advanced, yet sometimes limited, testing tool

Will EvoSuite's test cases find the fault in the example program?

# Important Questions

EvoSuite is an advanced, yet sometimes limited, testing tool

What is missing from  
the test cases that  
EvoSuite generates?

# Important Questions

EvoSuite is an advanced, yet sometimes limited, testing tool

How does the *oracle problem* influence the effectiveness of EvoSuite?

# Important Questions

EvoSuite is an advanced, yet sometimes limited, testing tool

What are the  
*fundamental*  
limitations of  
automated testing?

# No Silver Bullet

Software tools are fundamentally limited — what is our hope?

*There is no single development, in either technology or management technique, which by itself promises even one order-of-magnitude improvement within a decade in productivity, in reliability, in simplicity.*

Frederick P. Brooks, Jr., *Proceedings of the IFIP Tenth World Computing Conference, 1986*









## The Challenges of Software Development

- Pervasiveness of Software

- Complexity of Software

- Evolving Nature of Software

- Motivating Example

- Important Questions

## Benefits of Software Testing

- Test Cases

- Test Suites

- Examples of Tests

- The PIE Model

- Test Case Effectiveness

## Search-Based Software Testing

- Testing Methods

- Random Testing

- Testing with EvoSuite

## Conclusion

# The Software Crisis

Solutions are available — but not always obvious or popular

What are the  
solutions to the  
software crisis?

# The Software Crisis

Solutions are available — but not always obvious or popular

Great  
Designers

# The Software Crisis

Solutions are available — but not always obvious or popular

Unremitting  
Care

# The Software Crisis

Solutions are available — but not always obvious or popular

**Incremental  
Advances**

# Final Admonishment

An epilogue called “Fifty Years of Wonder, Excitement, and Joy”

*Too many interests, too many exciting opportunities for learning, research, and thought. What a marvelous predicament! Not only is the end not in sight, but the pace is not slackening. We have many future joys.*

Frederick P. Brooks, Jr., *The Mythical Man-Month*, 1995