SEARCH-BASED AUTOMATED TEST GENERATION FOR JAVA PROGRAMS

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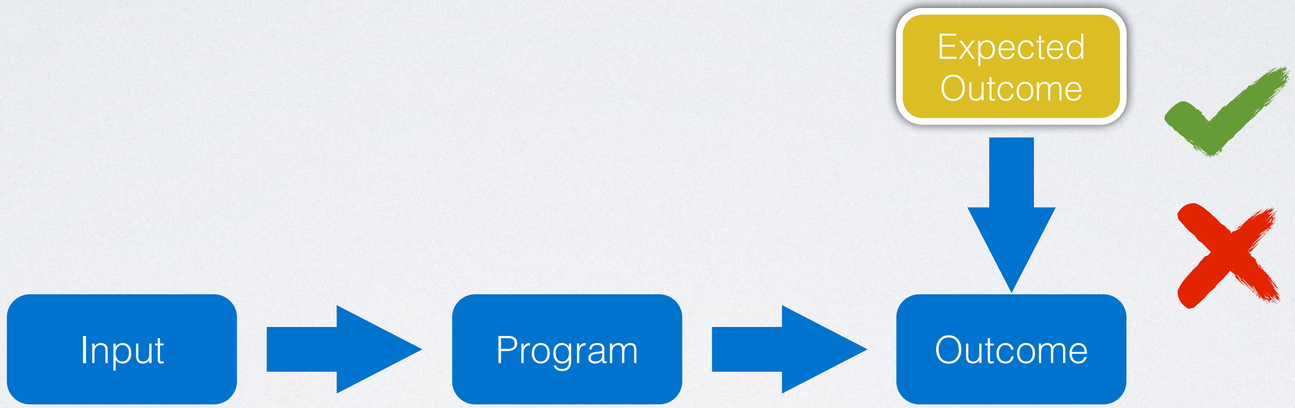
Department of Computer Science
The University of Sheffield

Some slides kindly provided by Prof Gordon Fraser

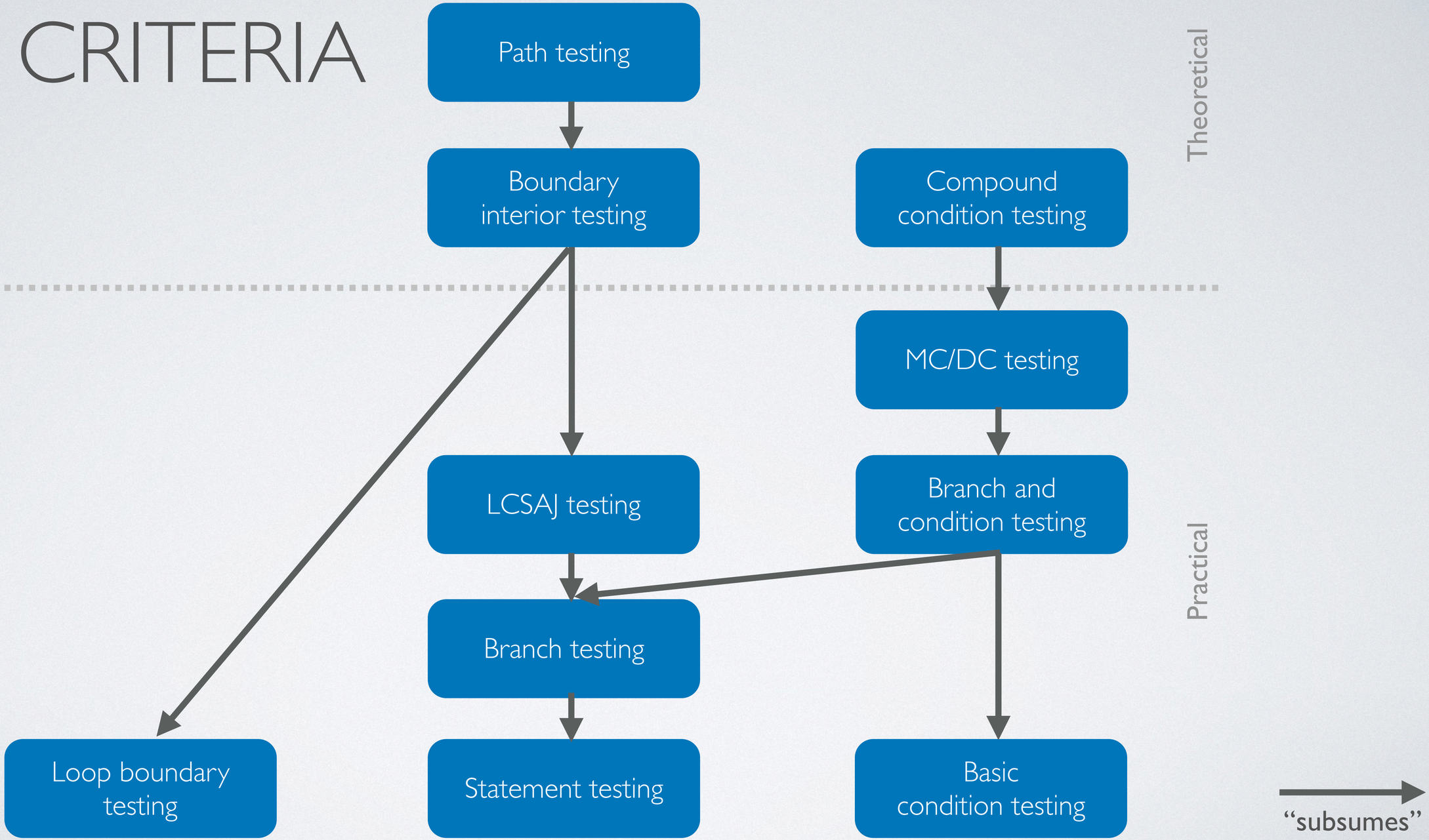
UNIT TESTING



1. Execute program using test data as *input*

2. Verify program *output* using *test oracle*

TEST CRITERIA



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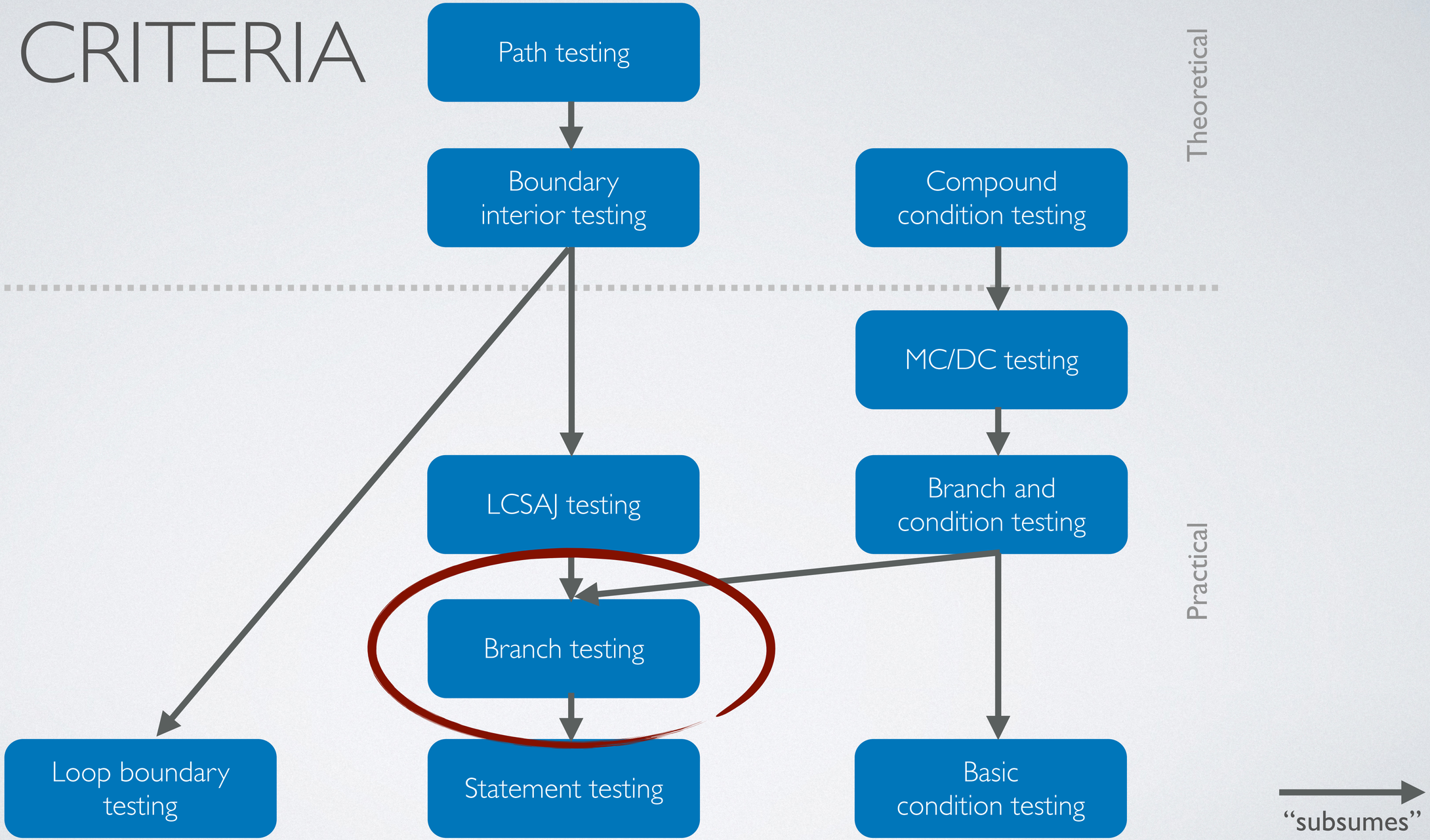

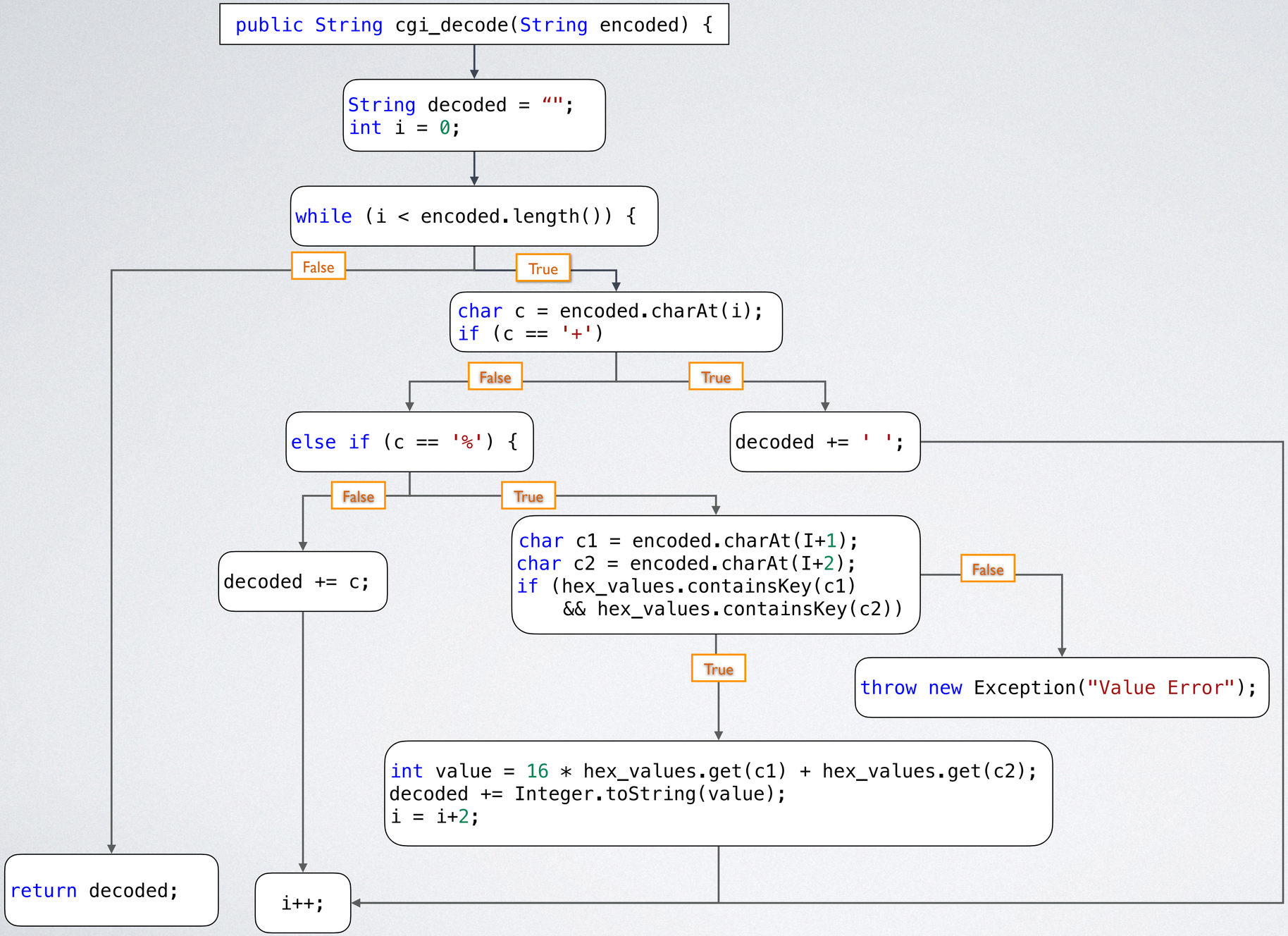
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String decoded = "";
int i = 0;
while (i < encoded.length()) {
False
True
return decoded;
char c = encoded.charAt(i);
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else if (c == '%') {
decoded += ' ';
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decoded += c;
char c1 = encoded.charAt(I+1);
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if (hex_values.containsKey(c1)
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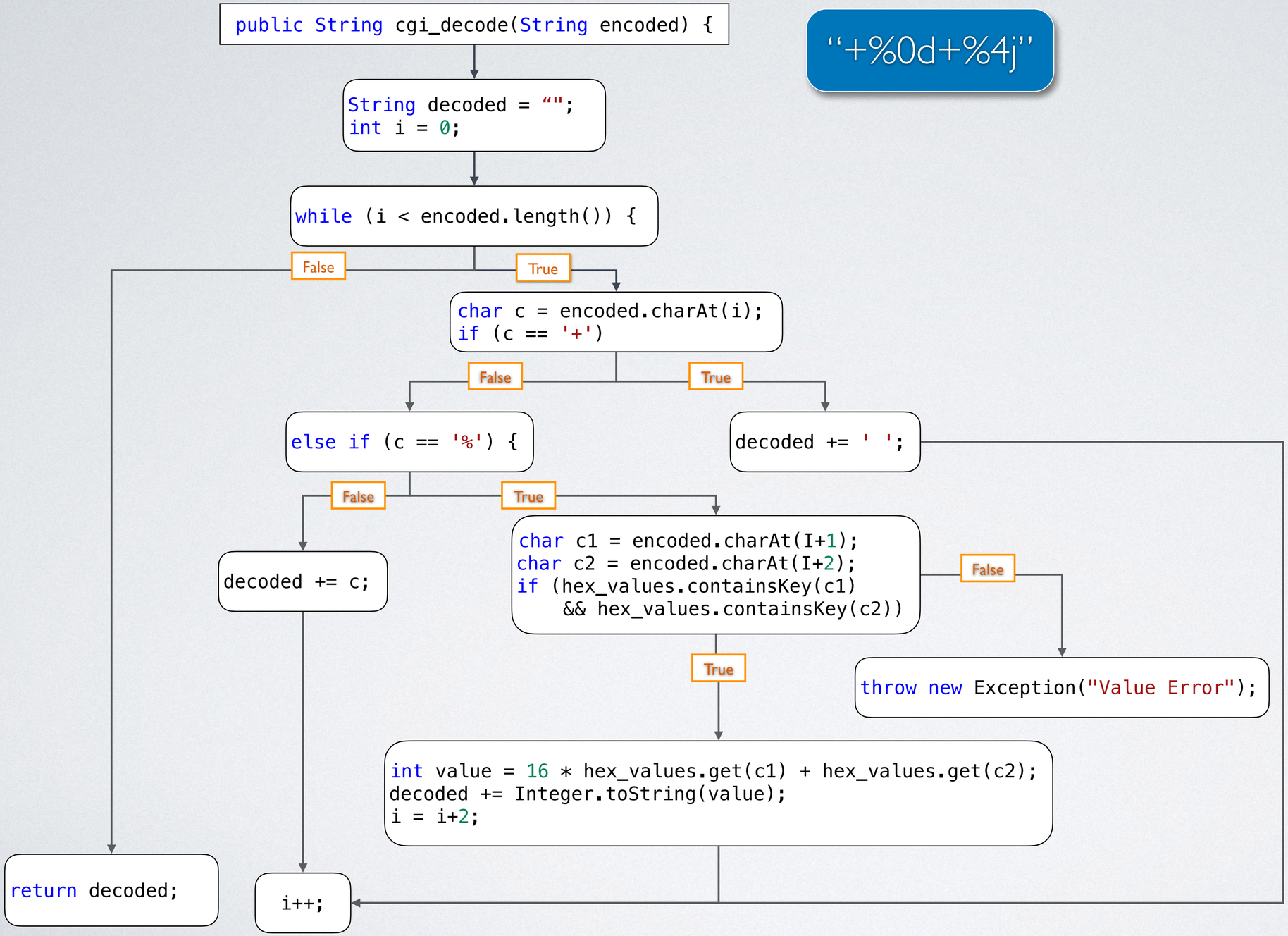
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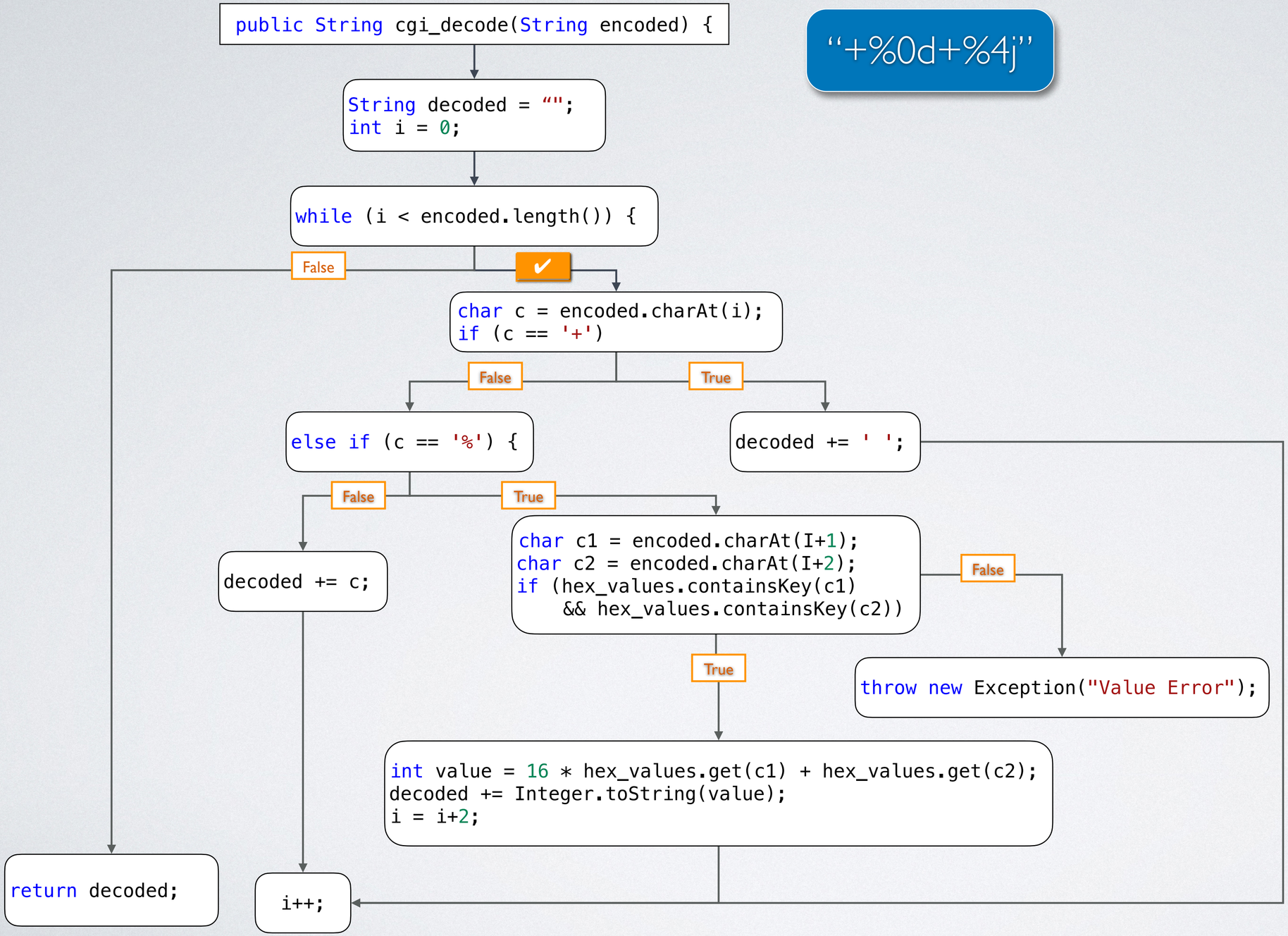
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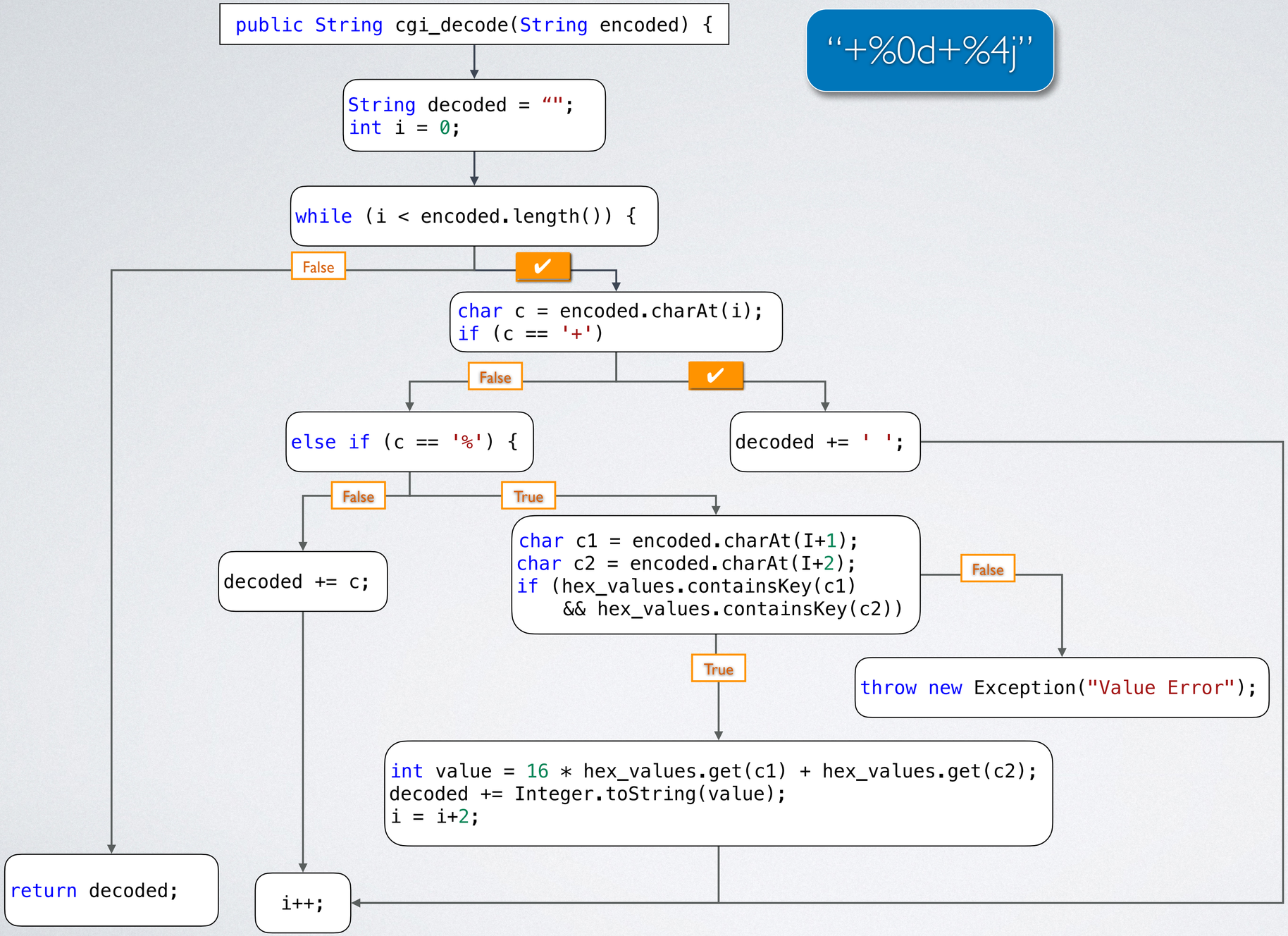
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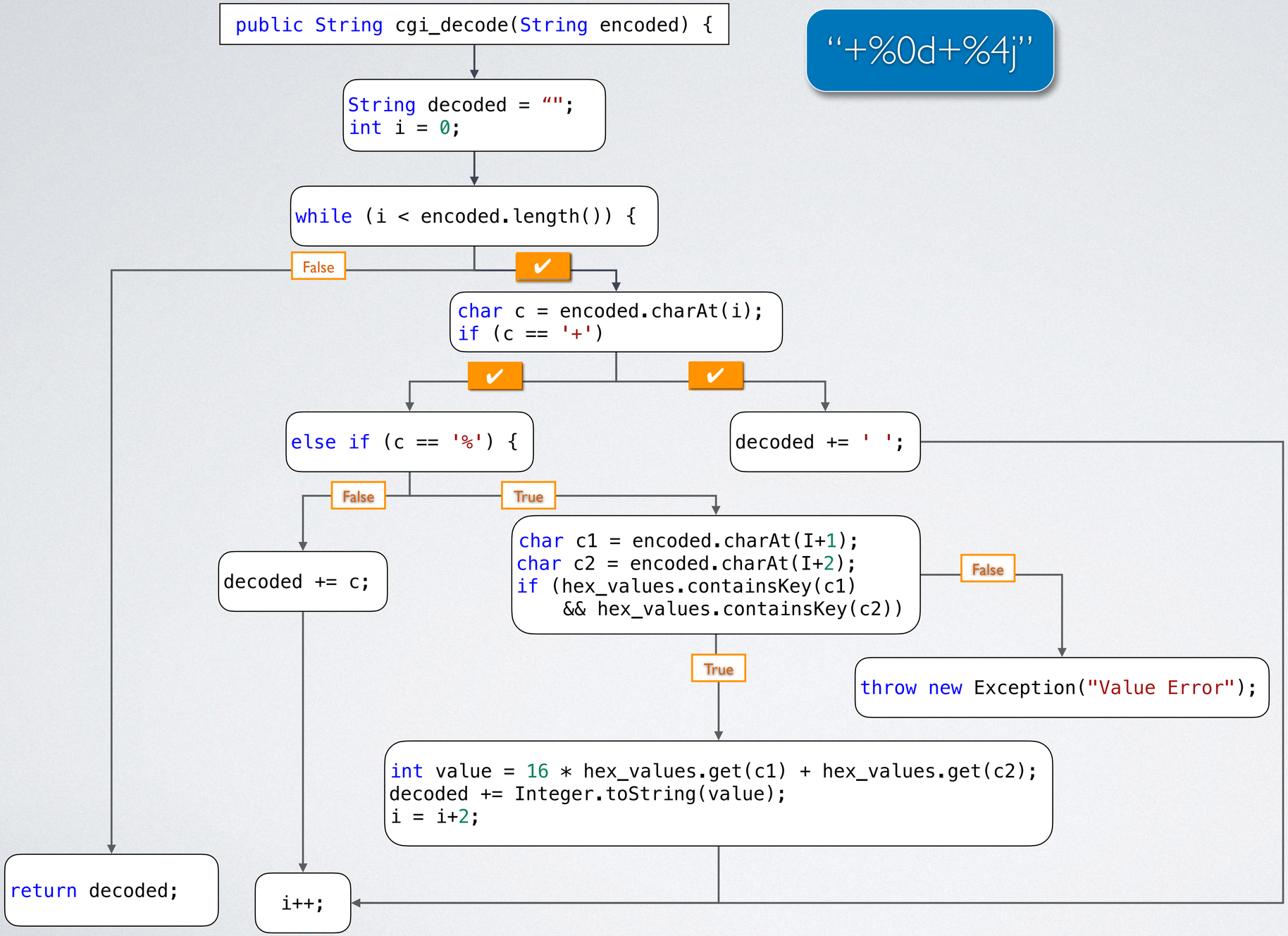
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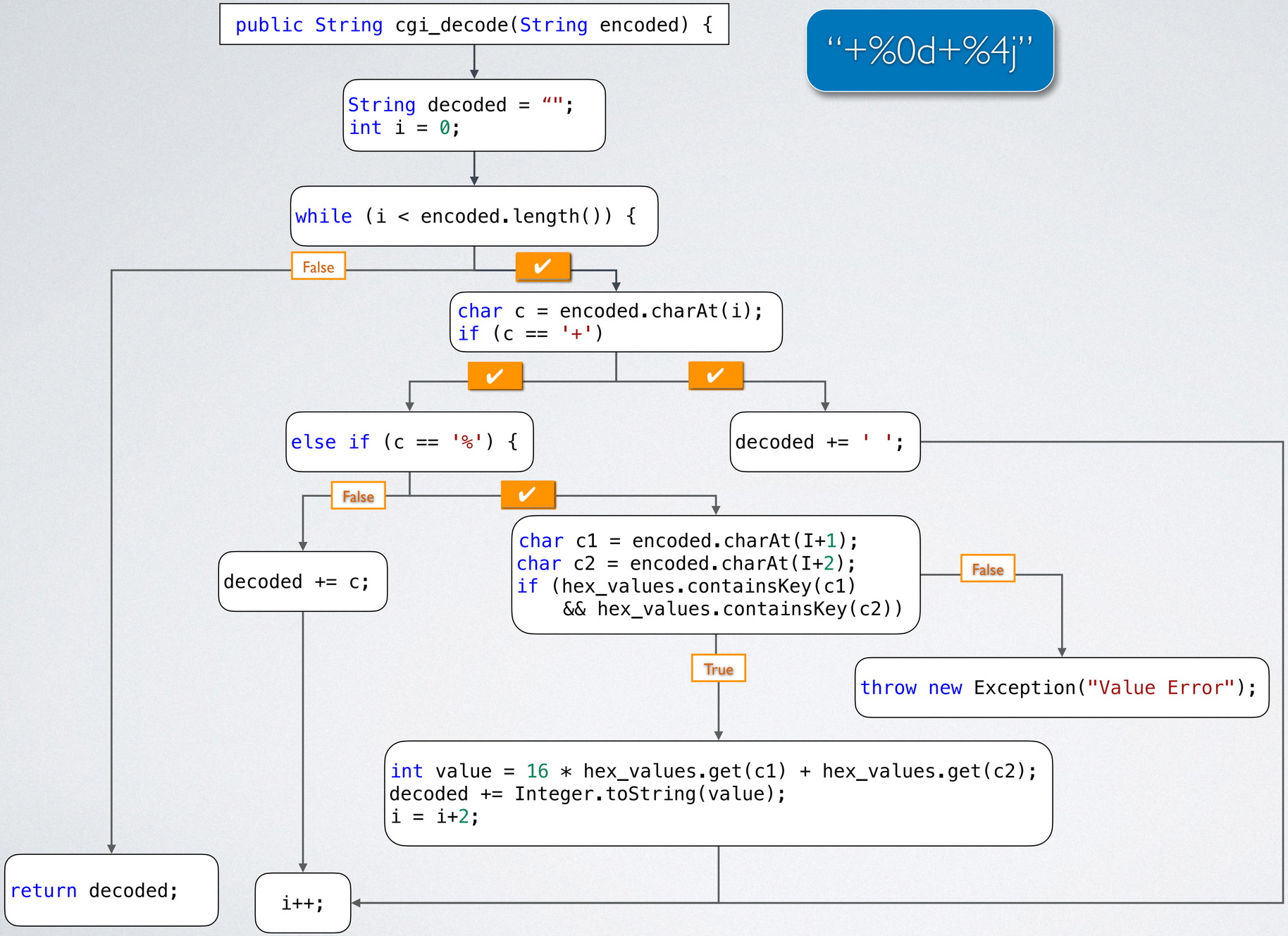
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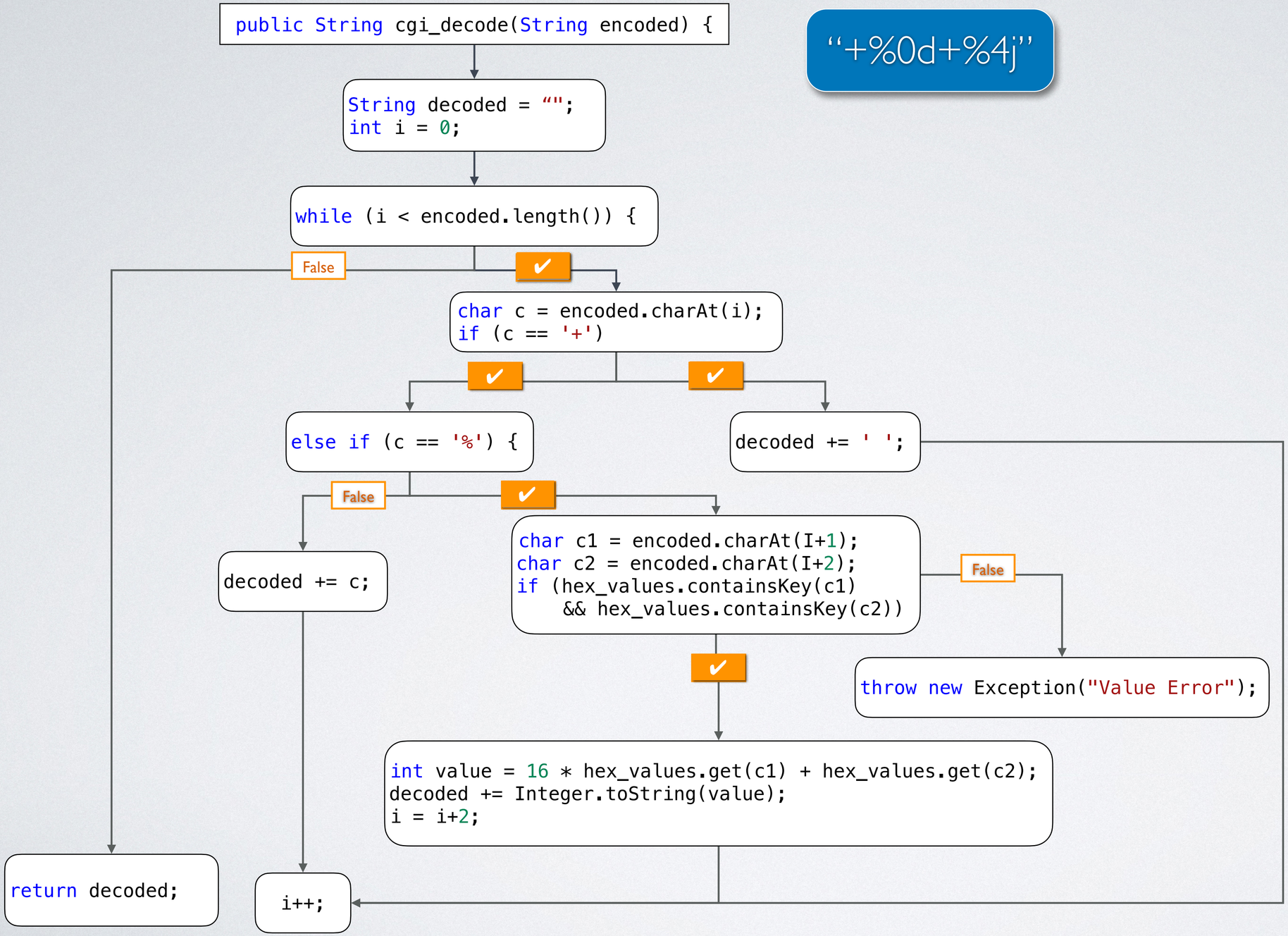
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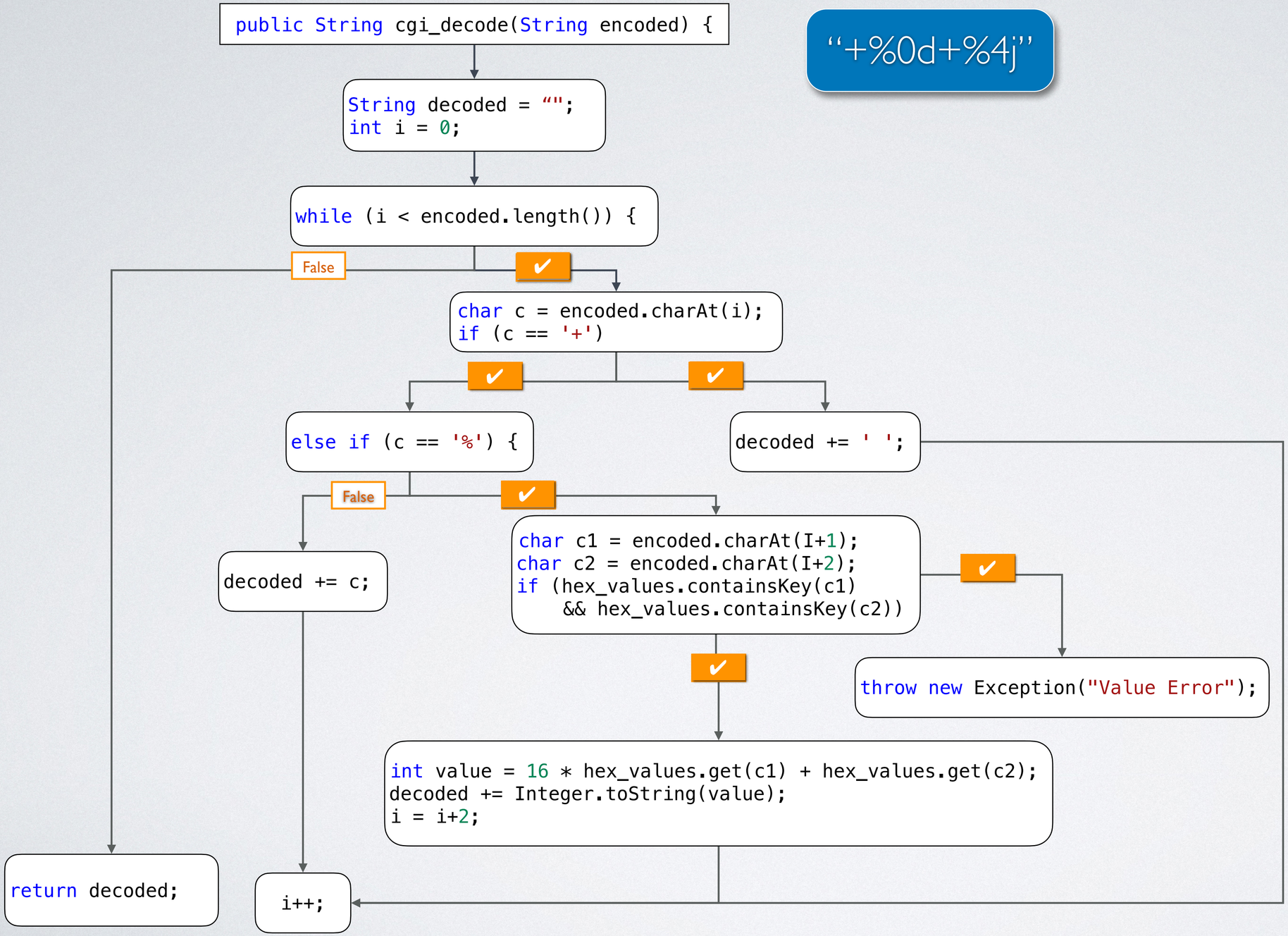
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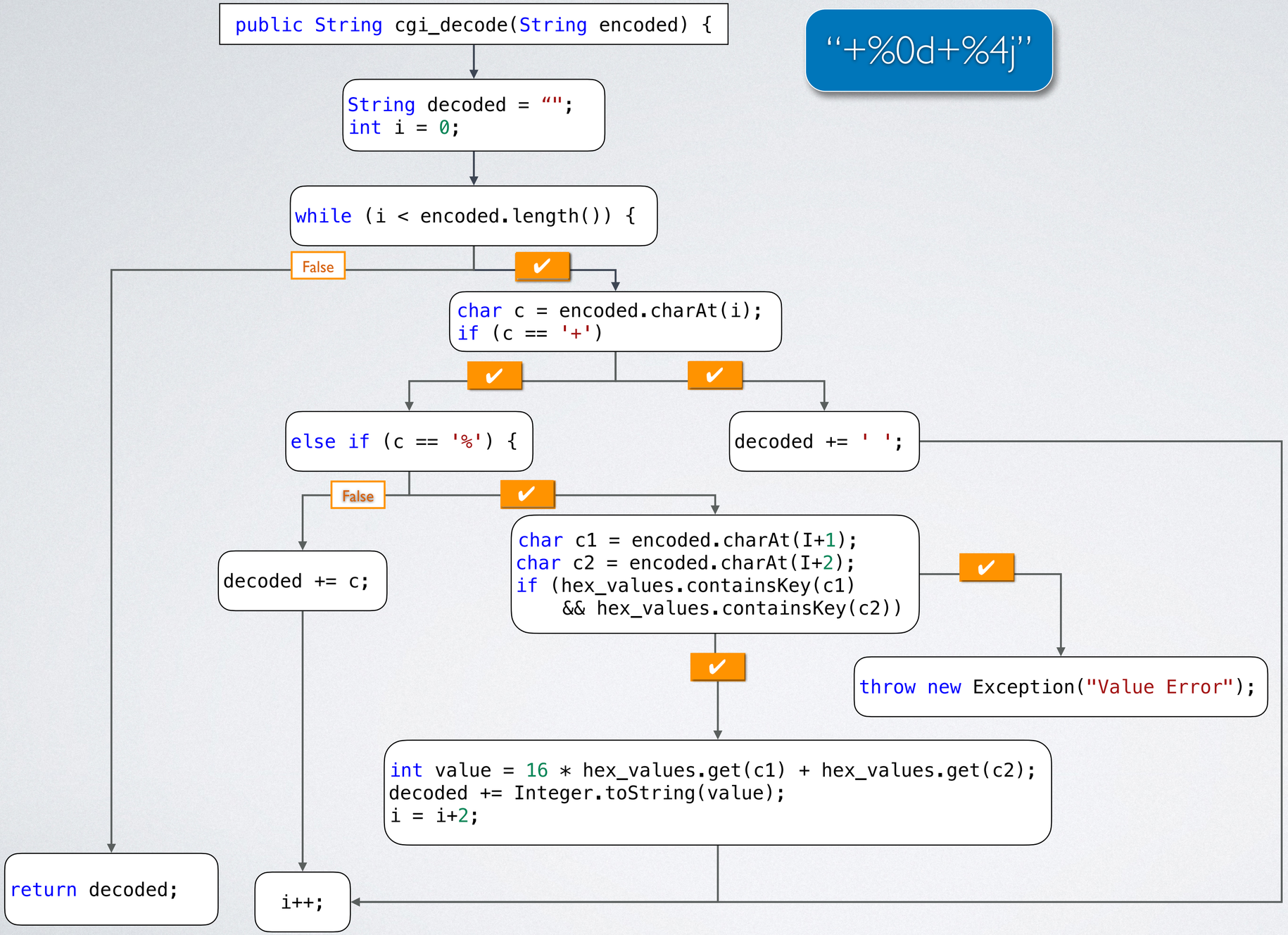
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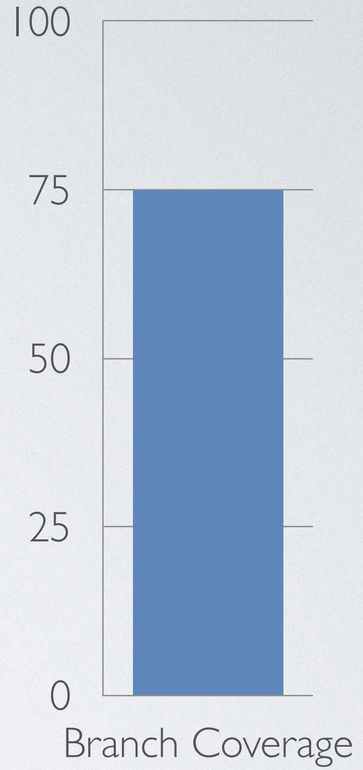
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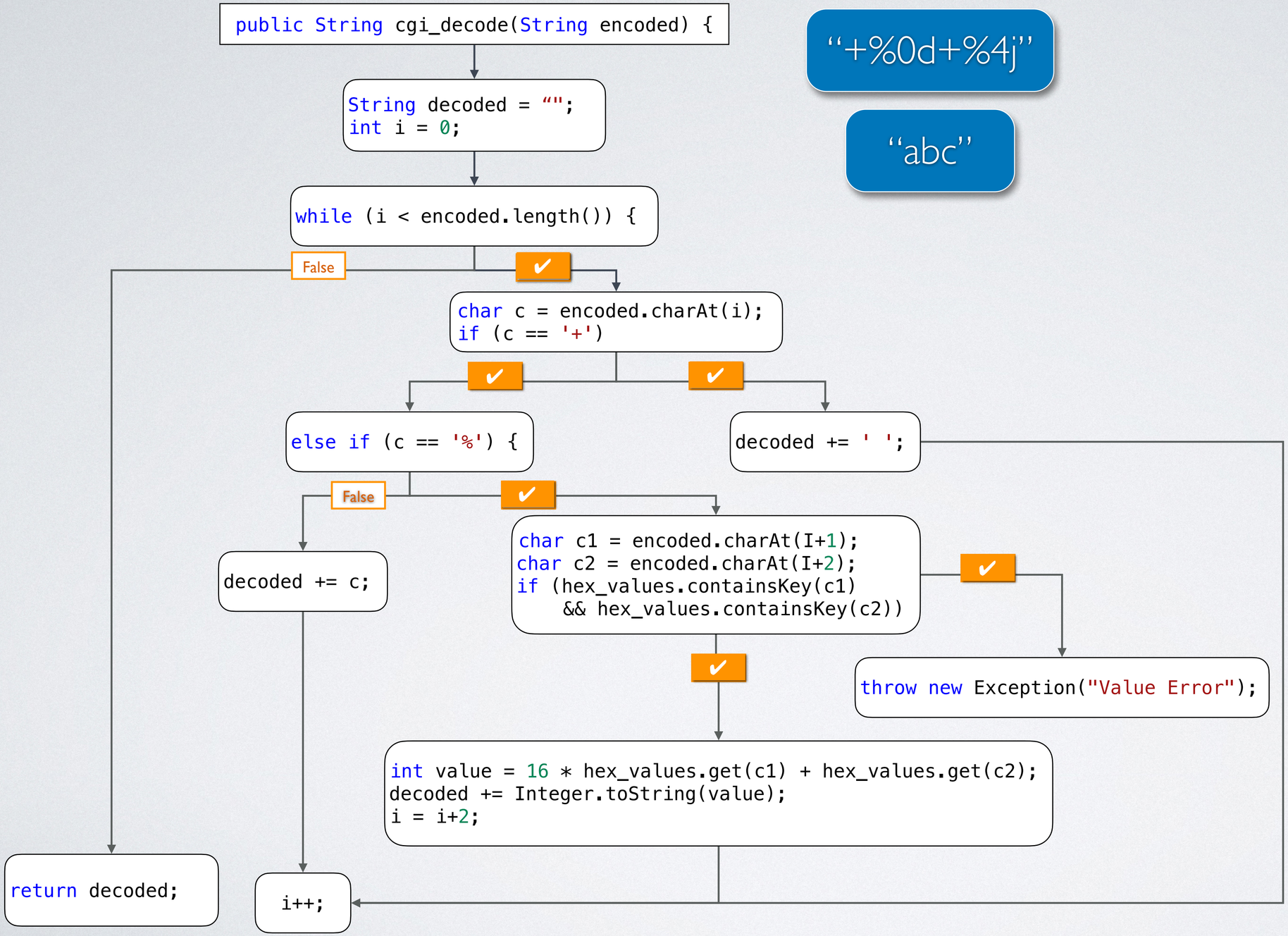
Branch Coverage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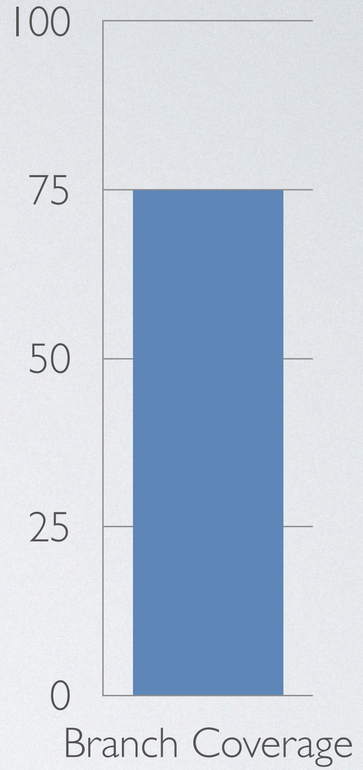
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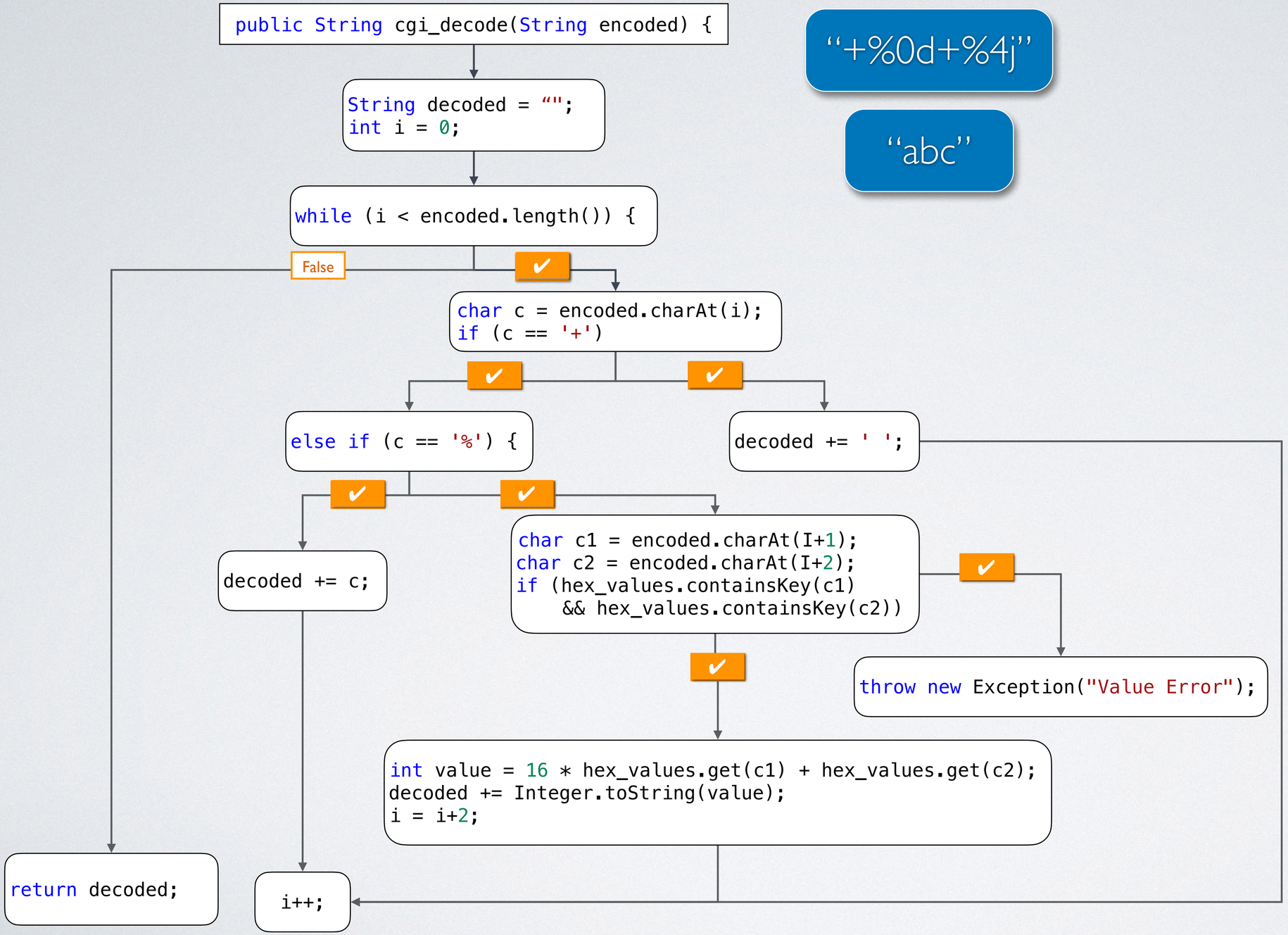
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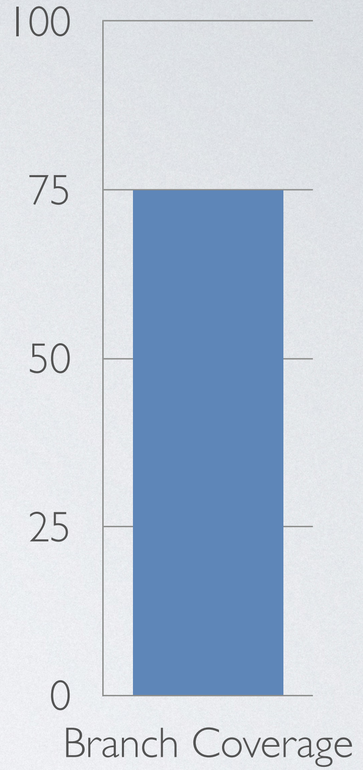
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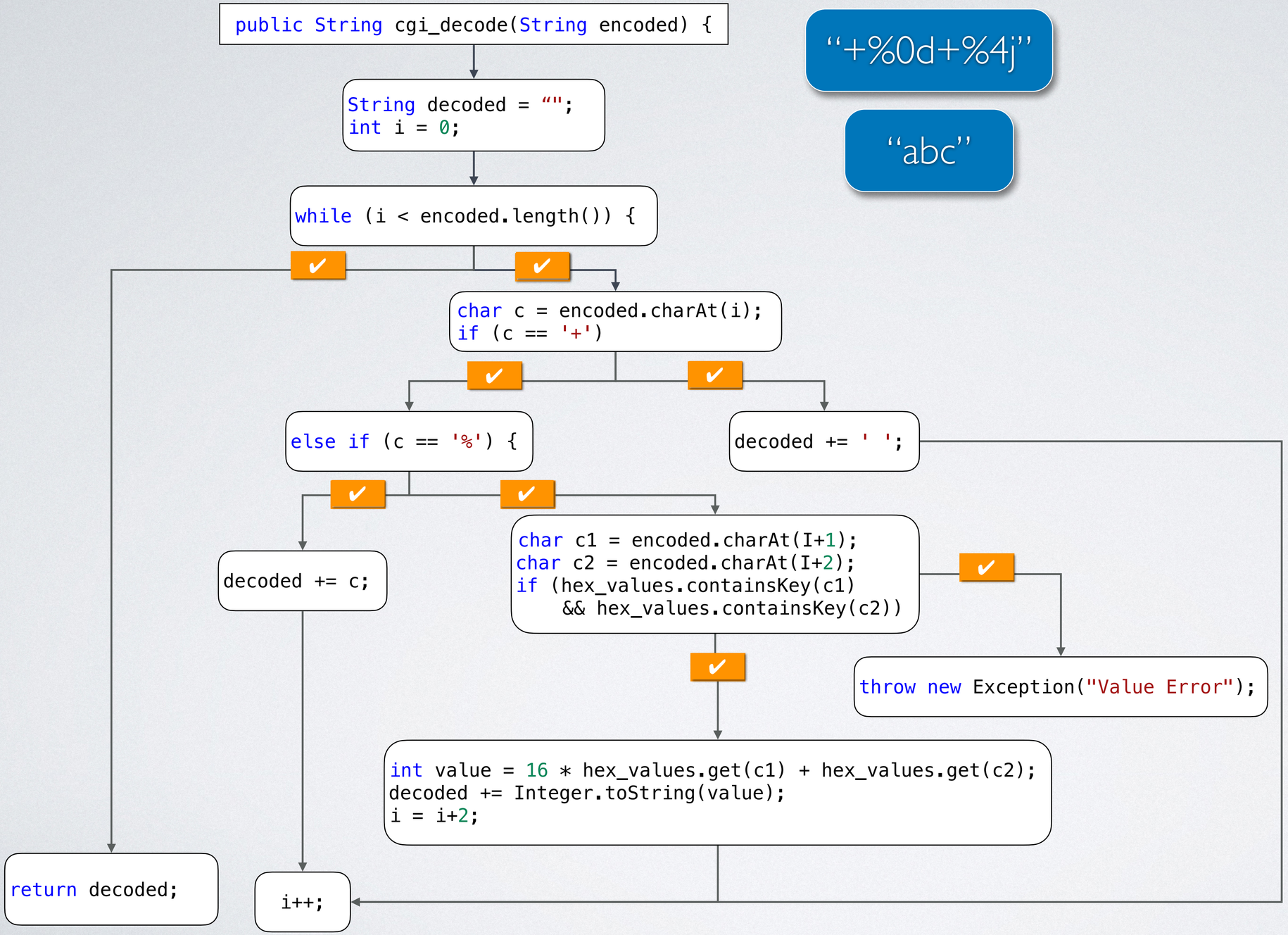
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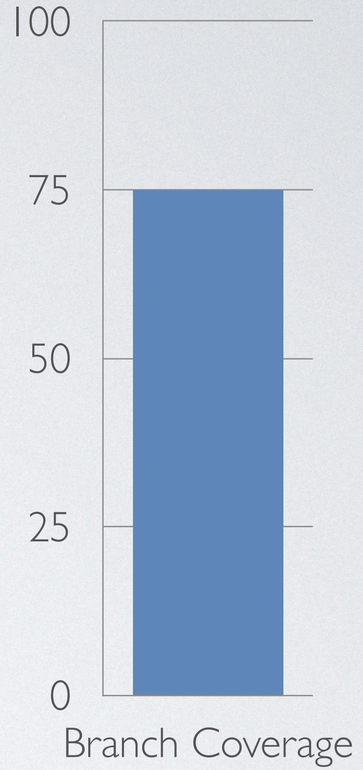
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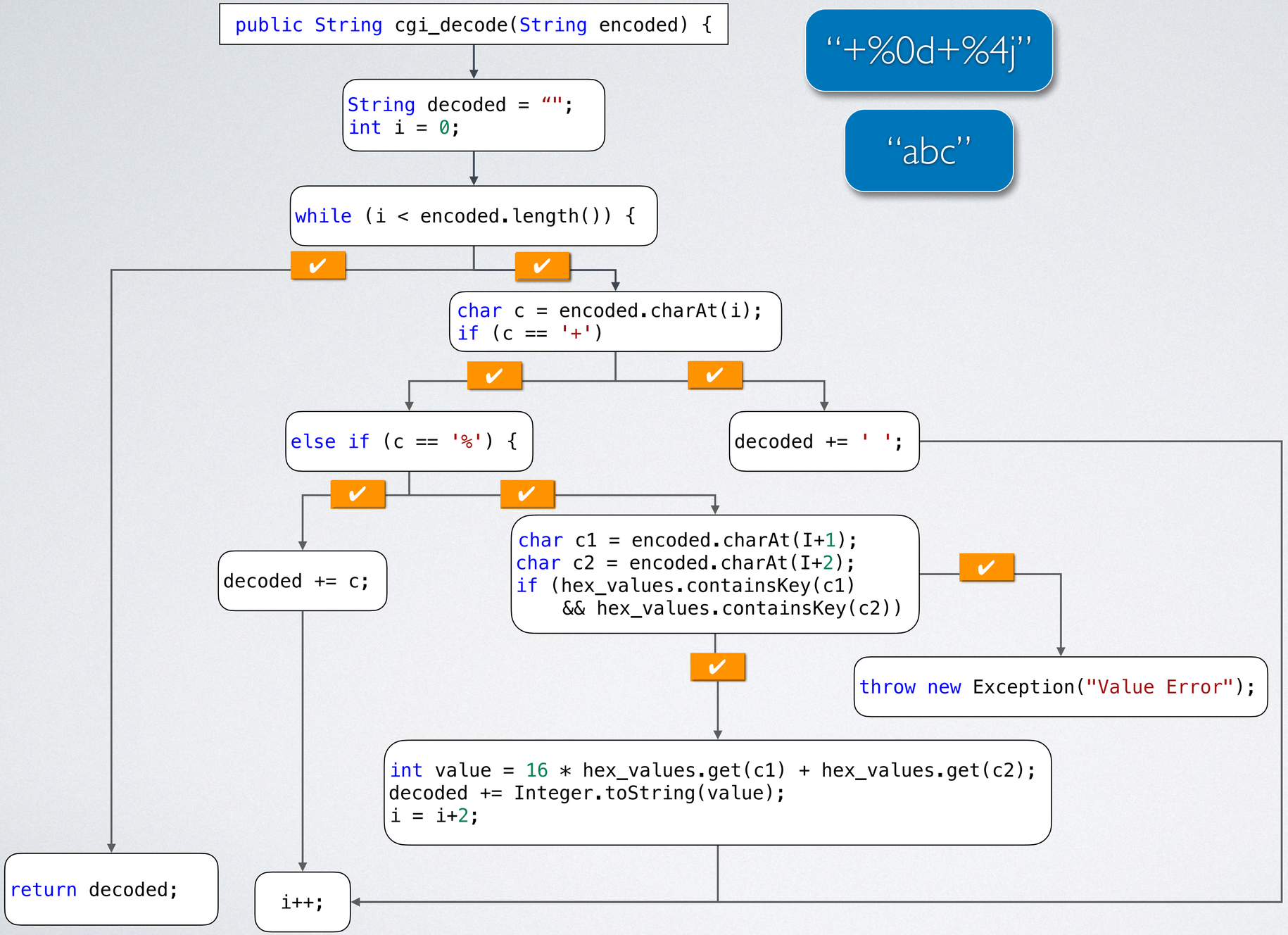
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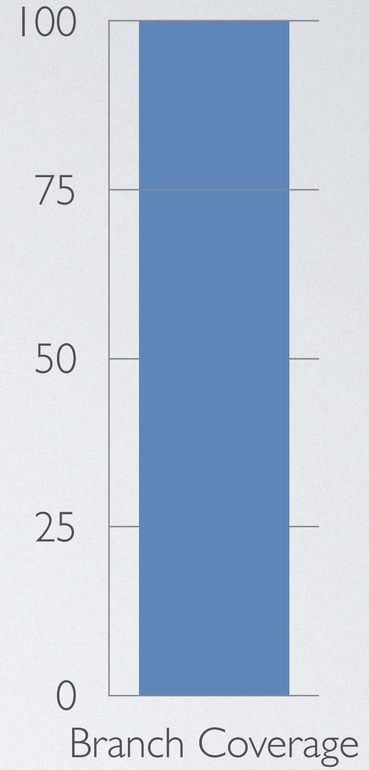
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Branch Coverage

BRANCH COVERAGE

- Each branch in the program must be executed at least once
- Branch Coverage: $\frac{\text{\# Executed Branches}}{\text{\# Branches}}$
- Subsumes statement coverage
- Most used structural criterion in practice
  - Complementary *fault-based* criteria: mutation score

SEARCH-BASED SOFTWARE TESTING

Search-Based Software Testing (SBST) is the application of optimisation search techniques, e.g., Genetic Algorithms, to solve problems in software testing, e.g., test generation.

Stress Testing

L. C. Briand, Y. Labiche, and M. Shousha, "Stress testing real-time systems with genetic algorithms". GECCO 2005.

Combinatorial Interaction Testing

M.B. Cohen, M.B. Dwyer and J. Shi, "Interaction testing of highly-configurable systems in the presence of constraints", ISSTA 2007.

GUI Testing

X. Yuan, M.B. Cohen and A.M. Memon, GUI Interaction Testing: Incorporating Event Context, IEEE Trans on Software Engineering, 2010.

Mobile App Testing

K. Mao, Y. Jia, M. Harman, "Sapienz: Multi-objective Automated Testing for Android Applications". ISSTA 2016.

SBST TECHNIQUES

Local Search

Hill climbing simple programs

Alternating Variable Method

Evolutionary Algorithms

Genetic Algorithms

Multi-Objective Optimisation

Hybrid Approaches

Interactive GA

Memetic Algorithms

Search + DSE

The Test Oracle Problem

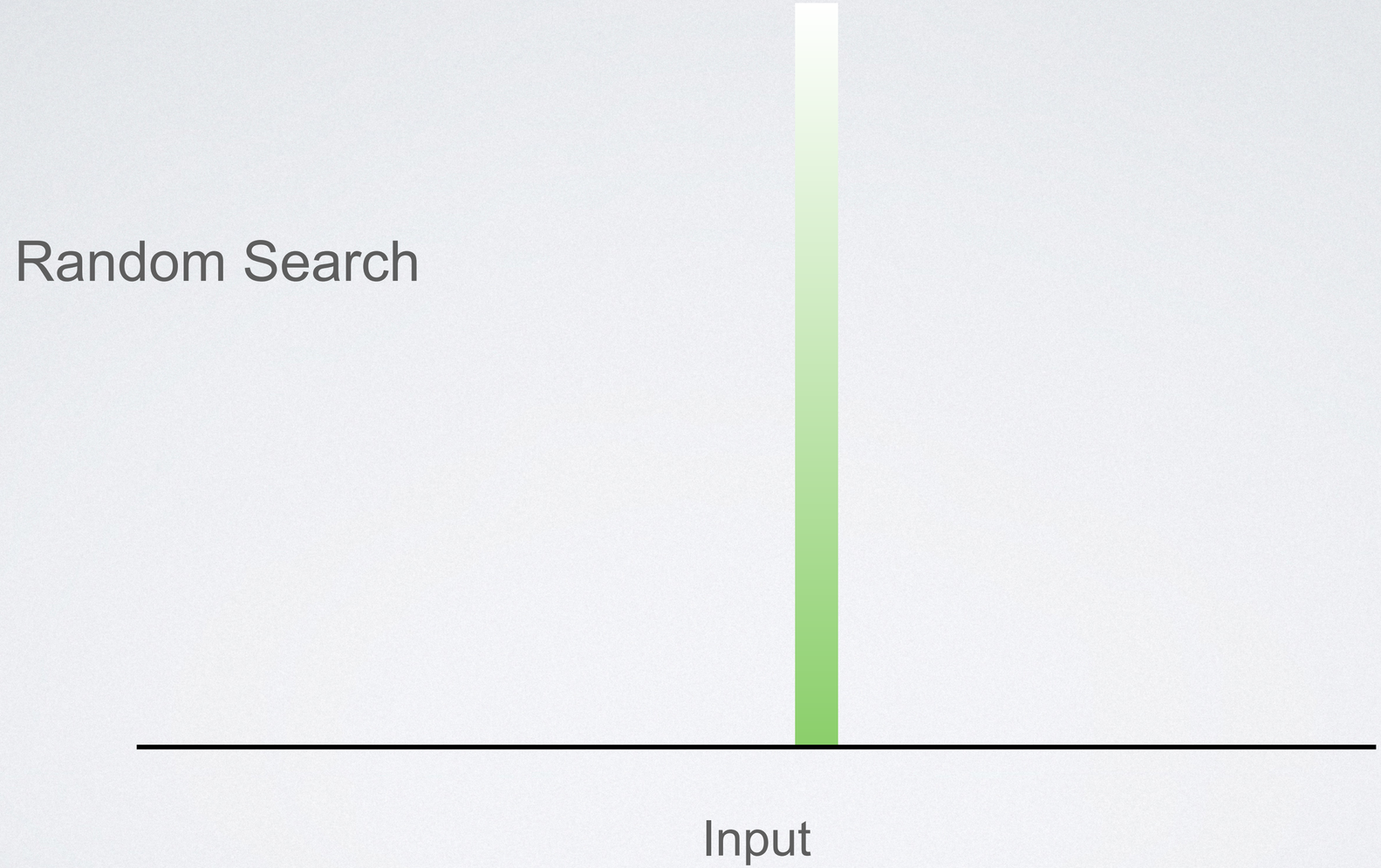
SEARCH-BASED TEST GENERATION

Random Search

Input

C. Pacheco, S. K. Lahiri, M. D. Ernst and T. Ball, "Feedback-Directed Random Test Generation", ICSE 2007.

SEARCH-BASED TEST GENERATION



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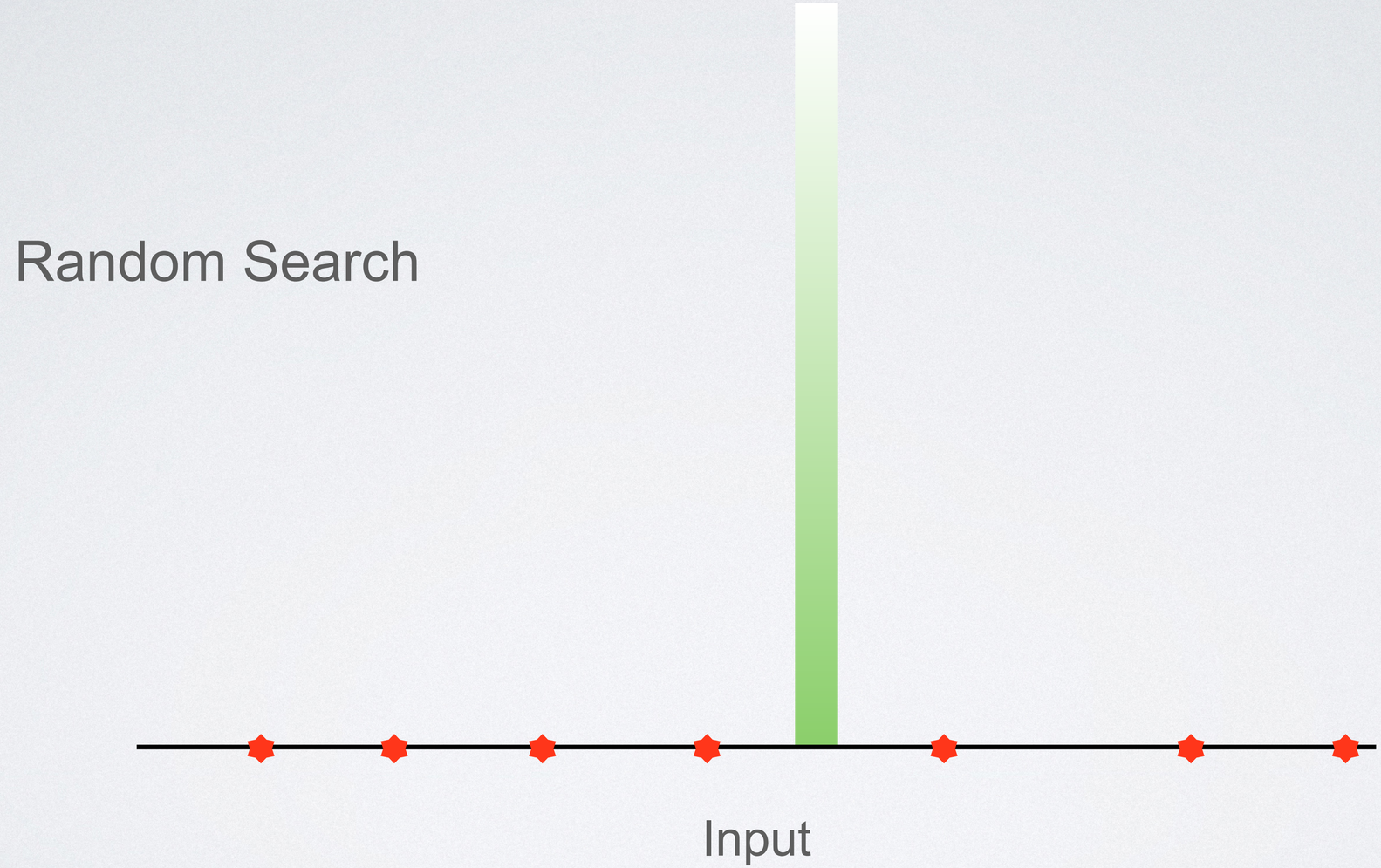

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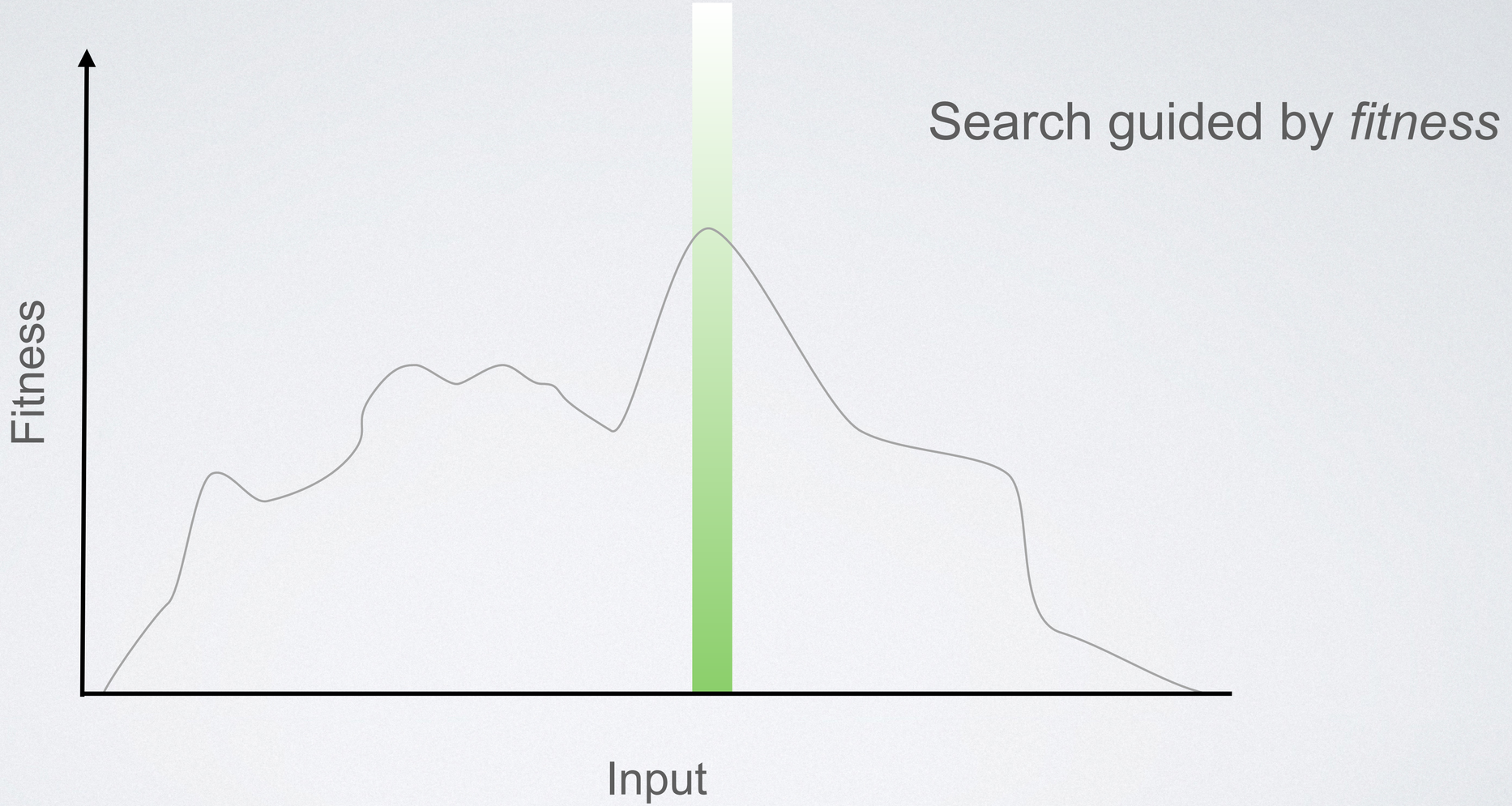
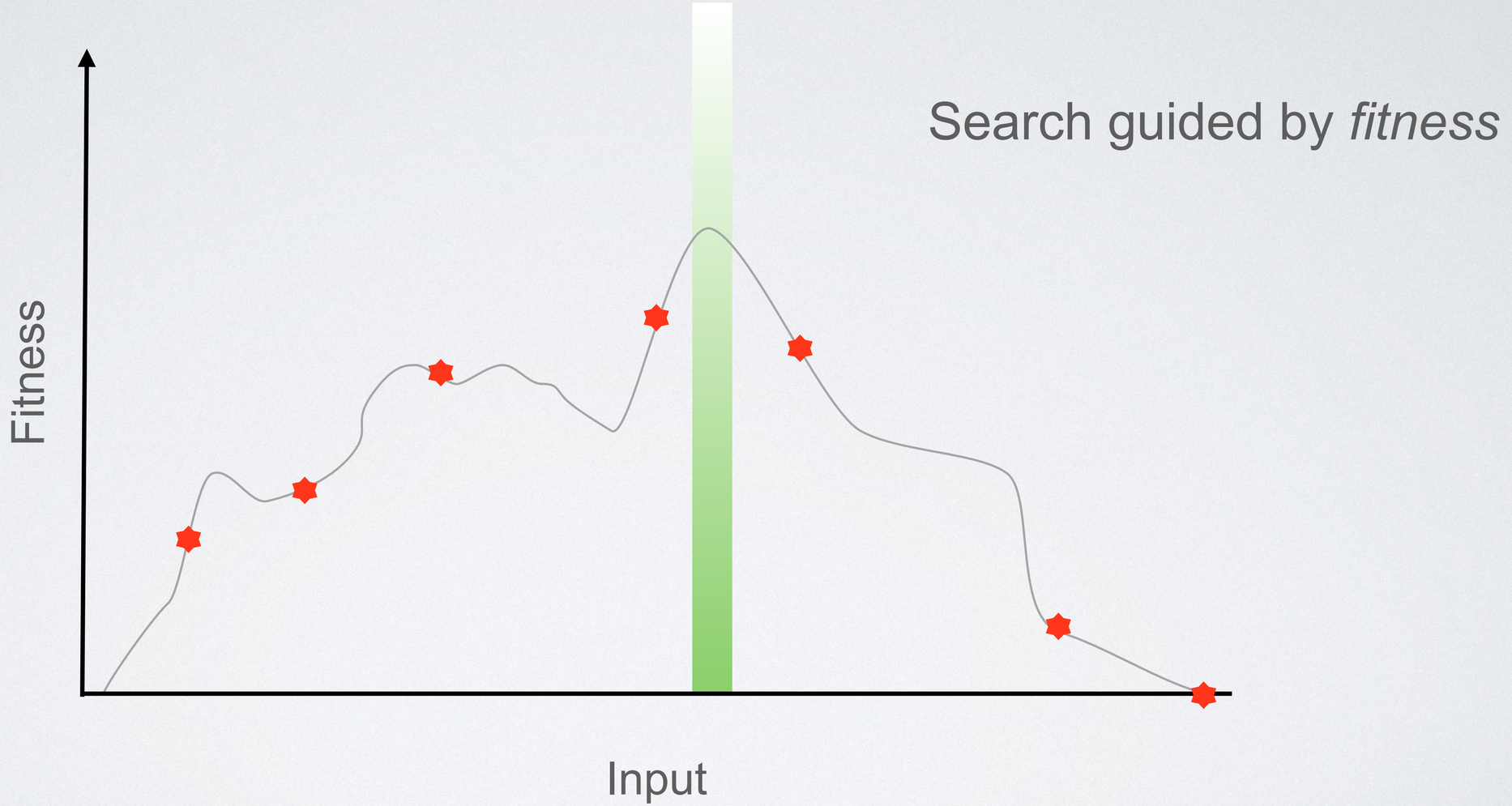


G. Fraser and A. Arcuri, "Whole Test Suite Generation", TSE 2013.

SEARCH-BASED TEST GENERATION



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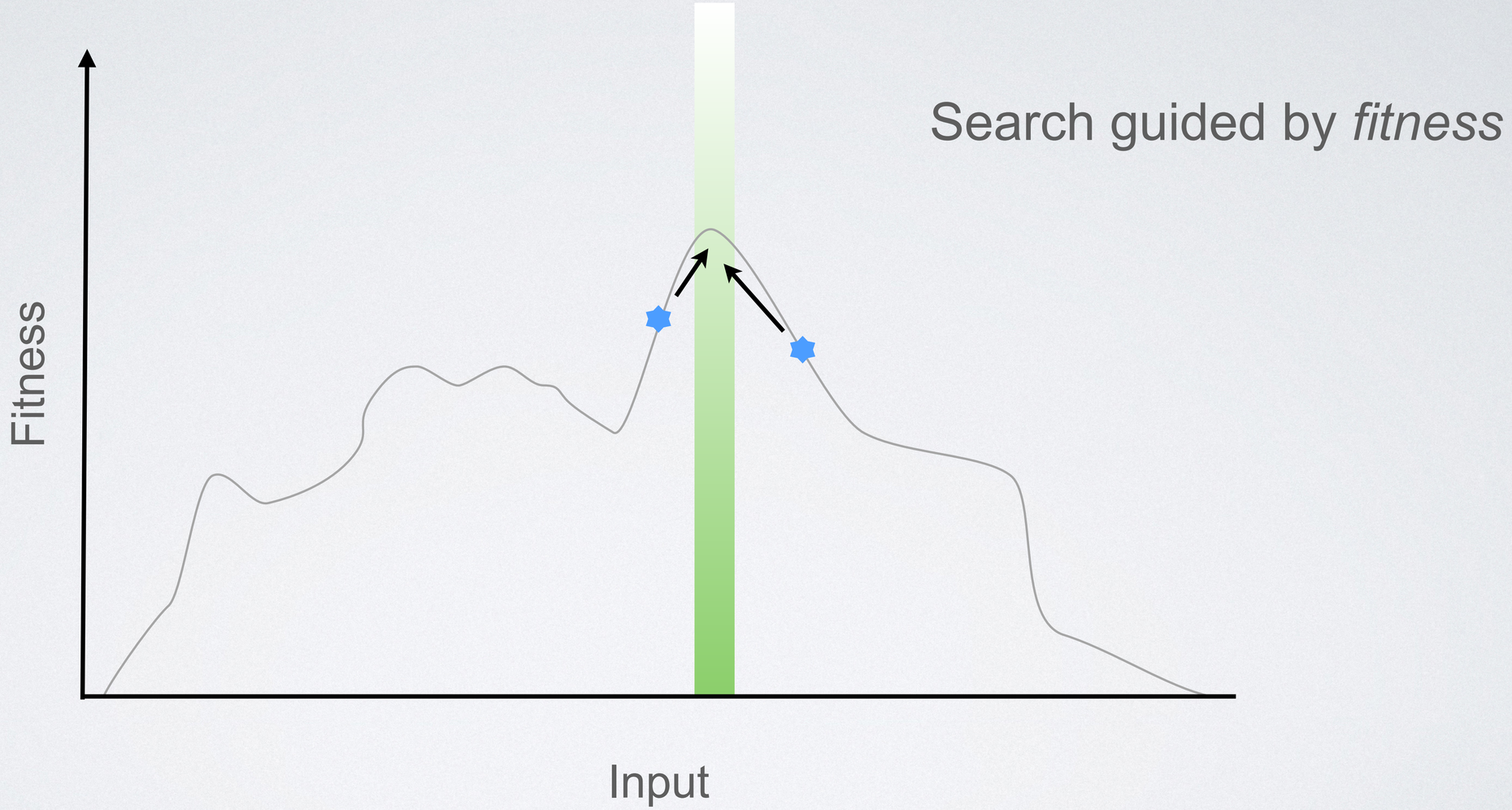

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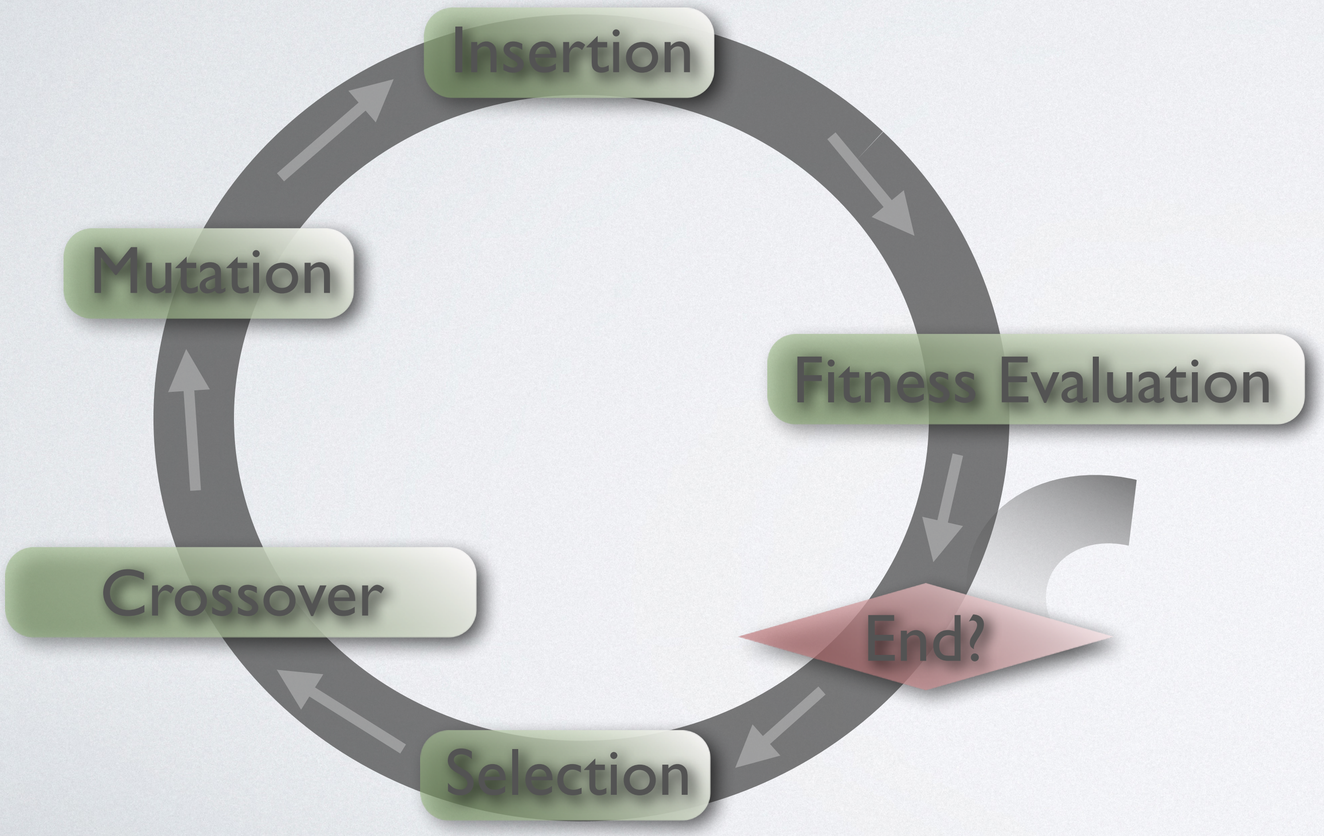
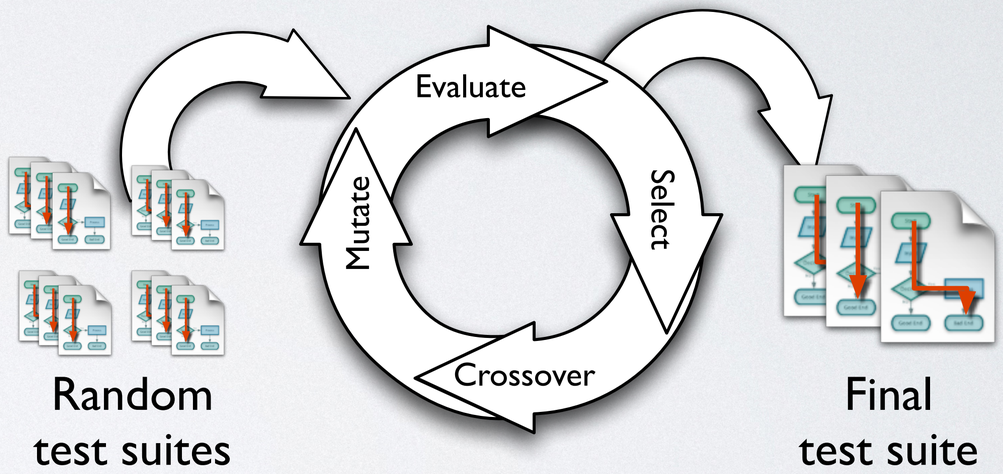
GENETIC ALGORITHM

Search algorithms inspired by the theory of evolution





EvoSuite

TESTS AS INDIVIDUALS

An individual in the search is a test *suite*, i.e., a collection of unit tests:

```
@Test

public void test()
{

   // set up


   // execute code


  // assertions
}
```

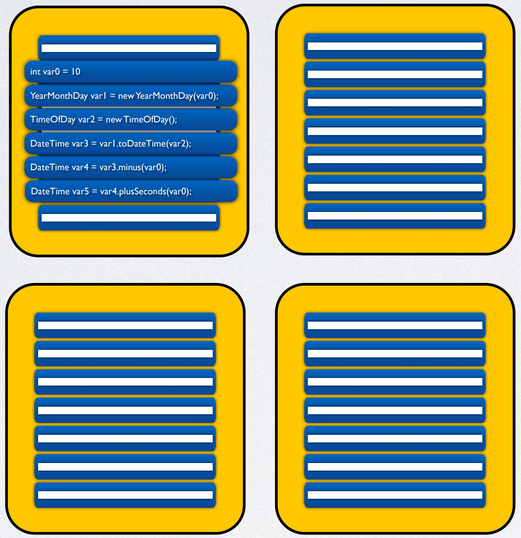
TESTS AS INDIVIDUALS

At first, each test contains a randomly generated sequence of statements

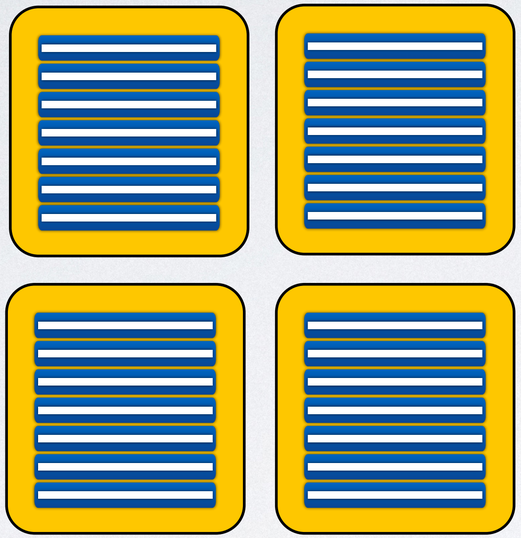
```
@Test

public void test()
{
    int var0 = 10
    YearMonthDay var1 = new YearMonthDay(var0);
    TimeOfDay var2 = new TimeOfDay();
    DateTime var3 = var1.toDateTime(var2);
    DateTime var4 = var3.minus(var0);
    DateTime var5 = var4.plusSeconds(var0);
}
```

Assertions are not generated at this stage, they are added as a post process

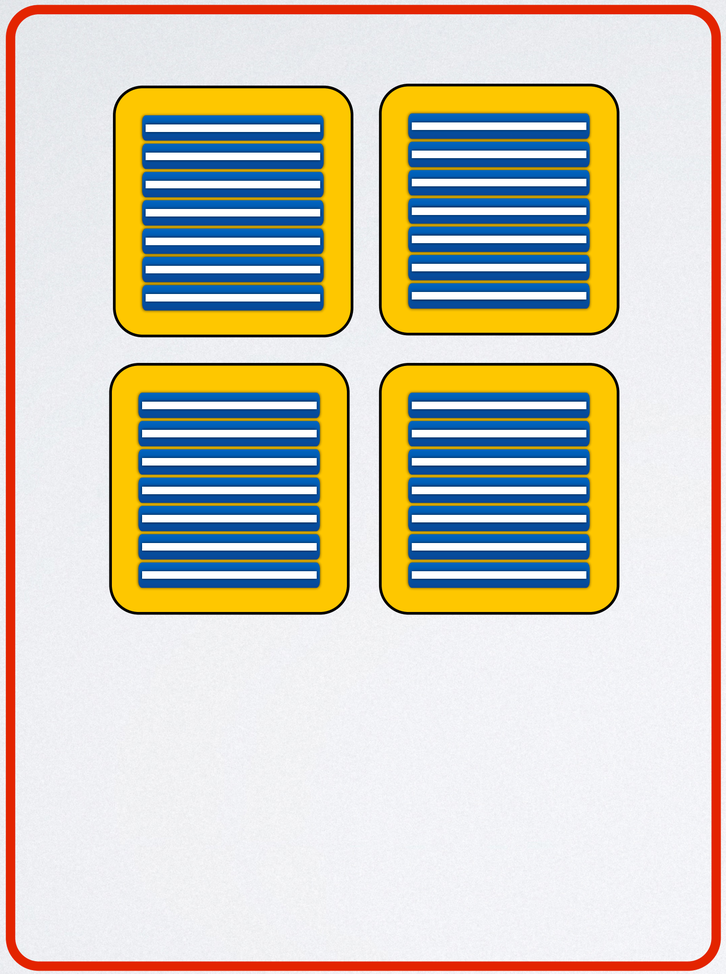
TEST *SUITE* GENERATION



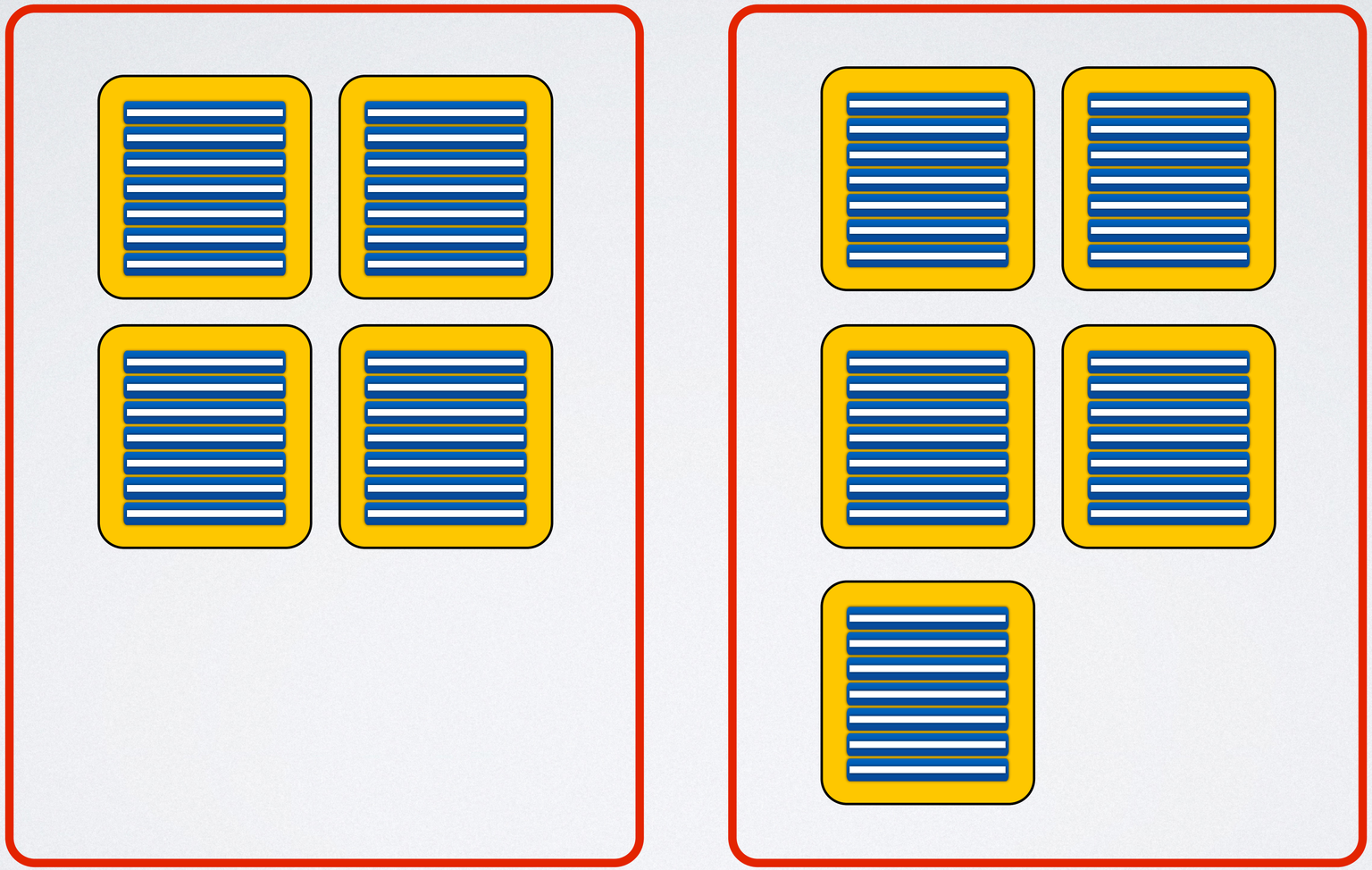
TEST *SUITE* GENERATION



TEST *SUITE* GENERATION

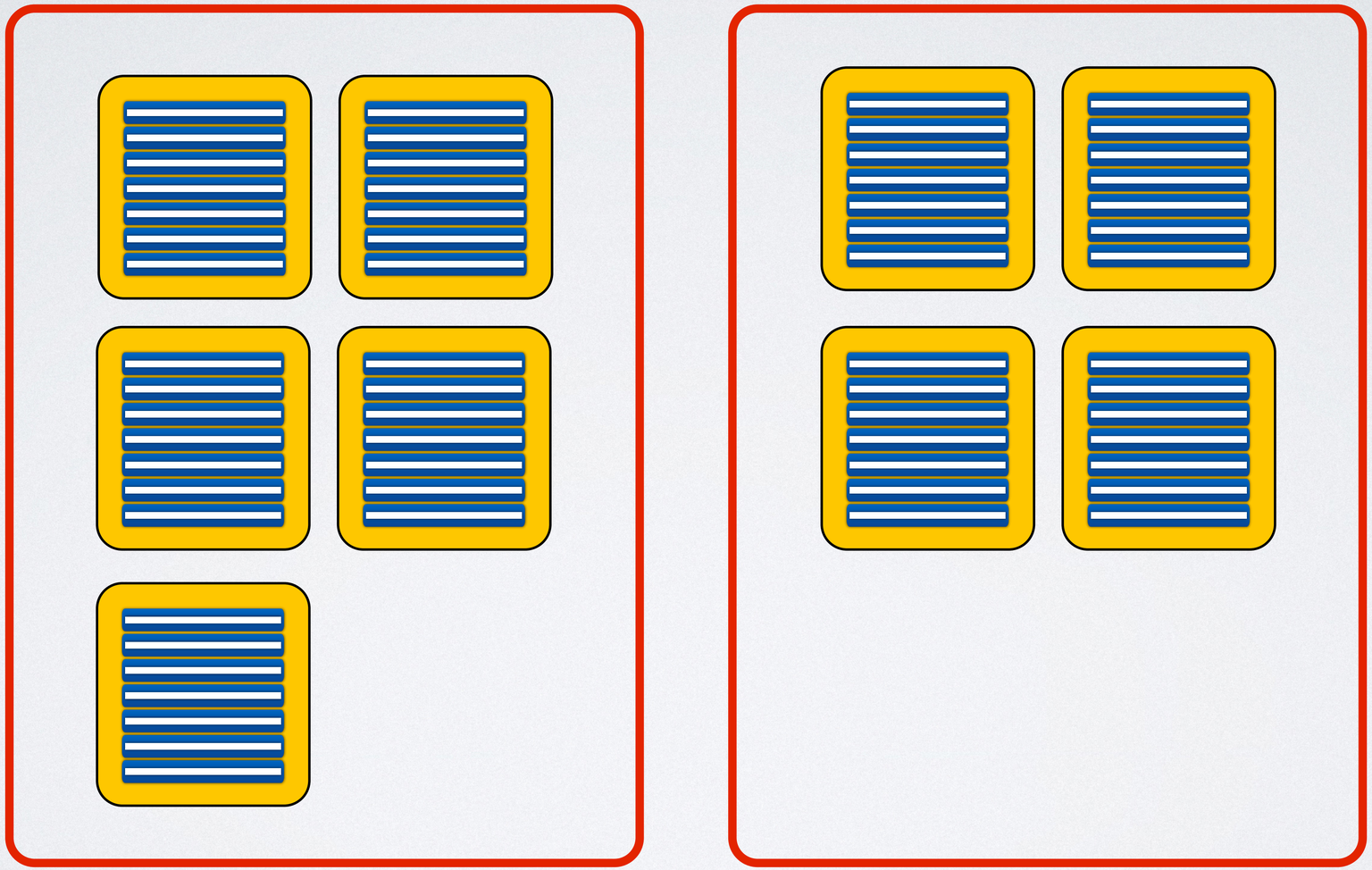


TEST *SUITE* GENERATION



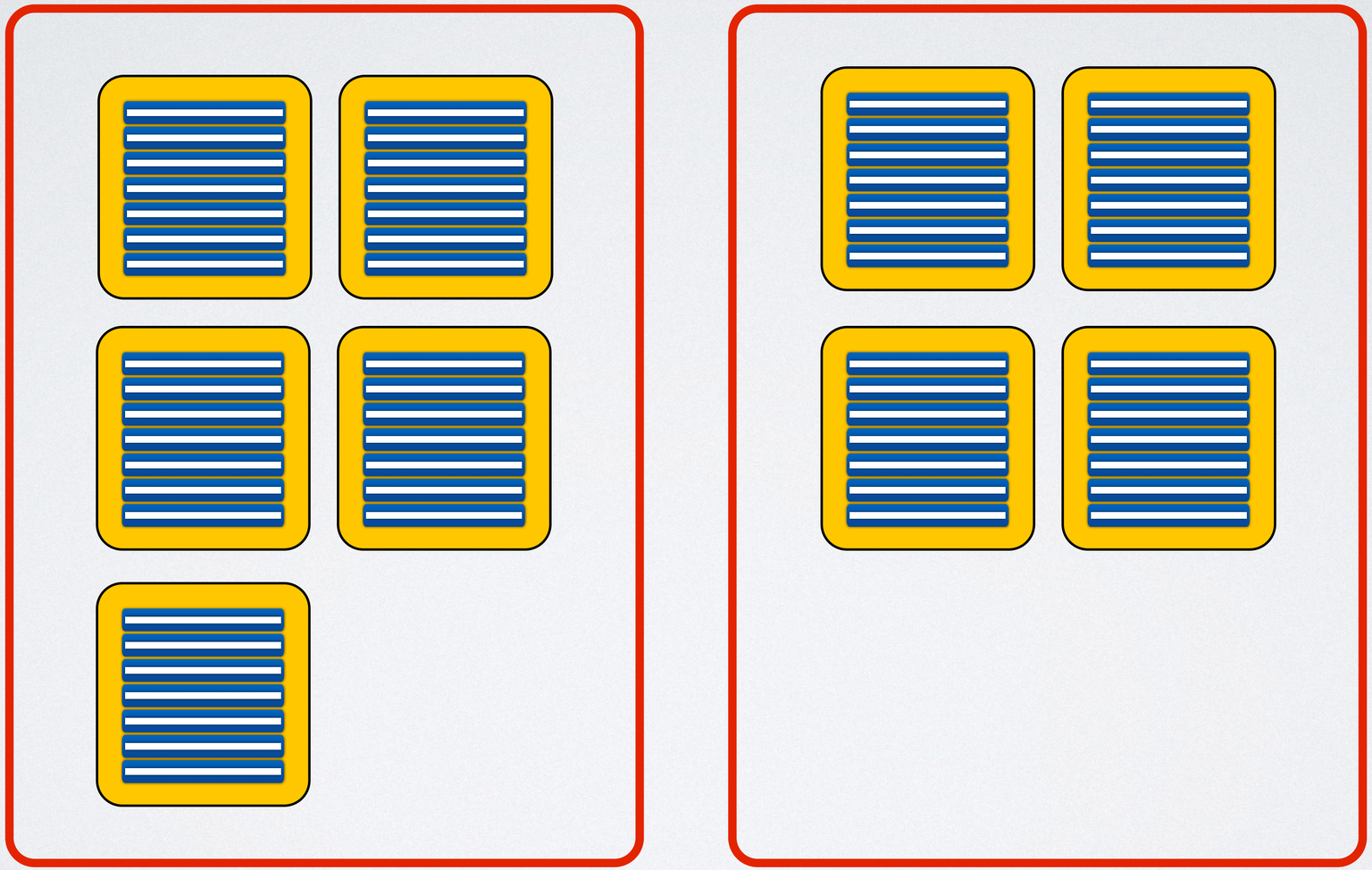
The size of the initial population is configurable

CROSSOVER



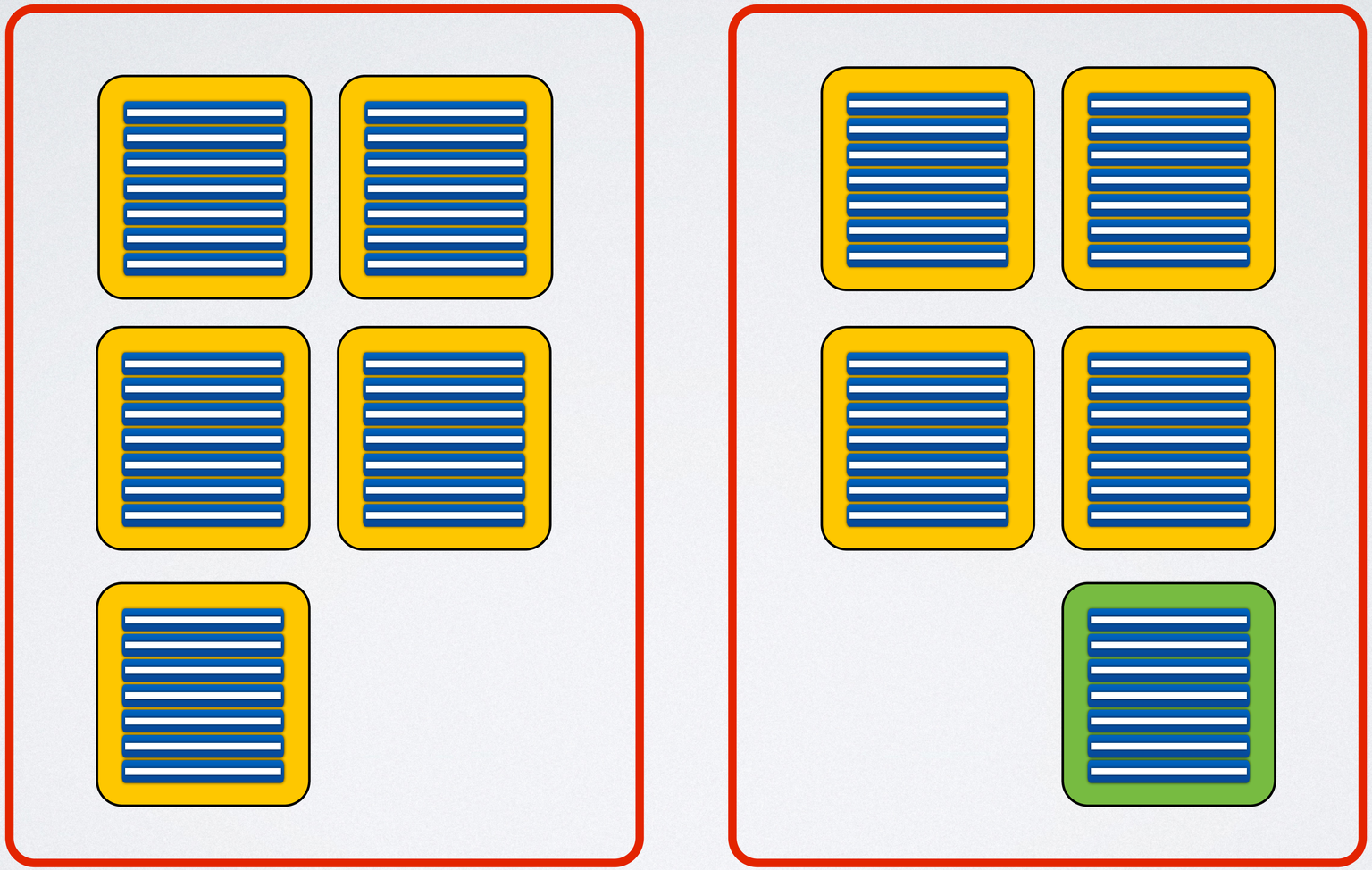
Crossover happens with a certain probability

MUTATION



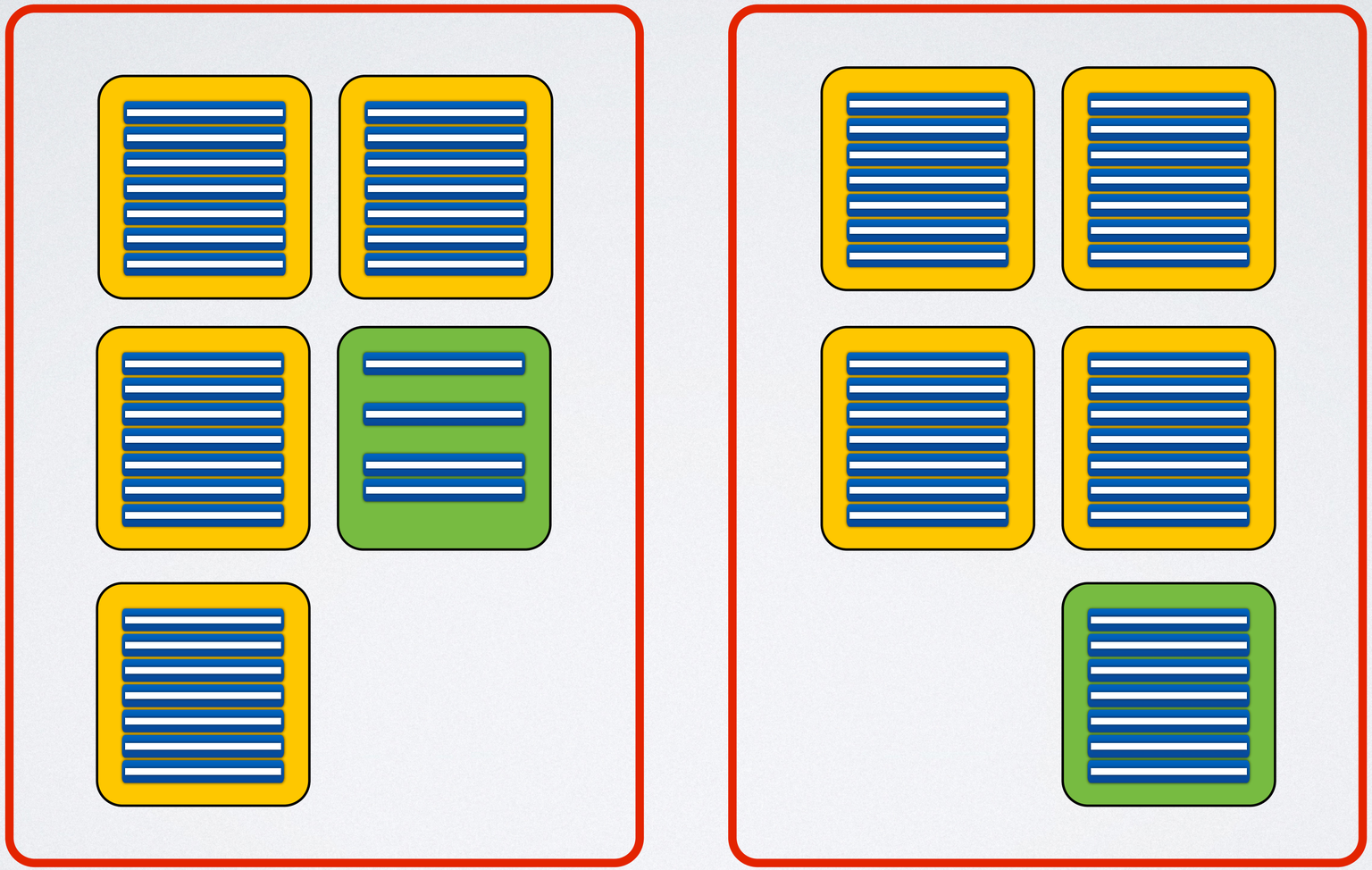
Mutation happens with a certain probability

MUTATION



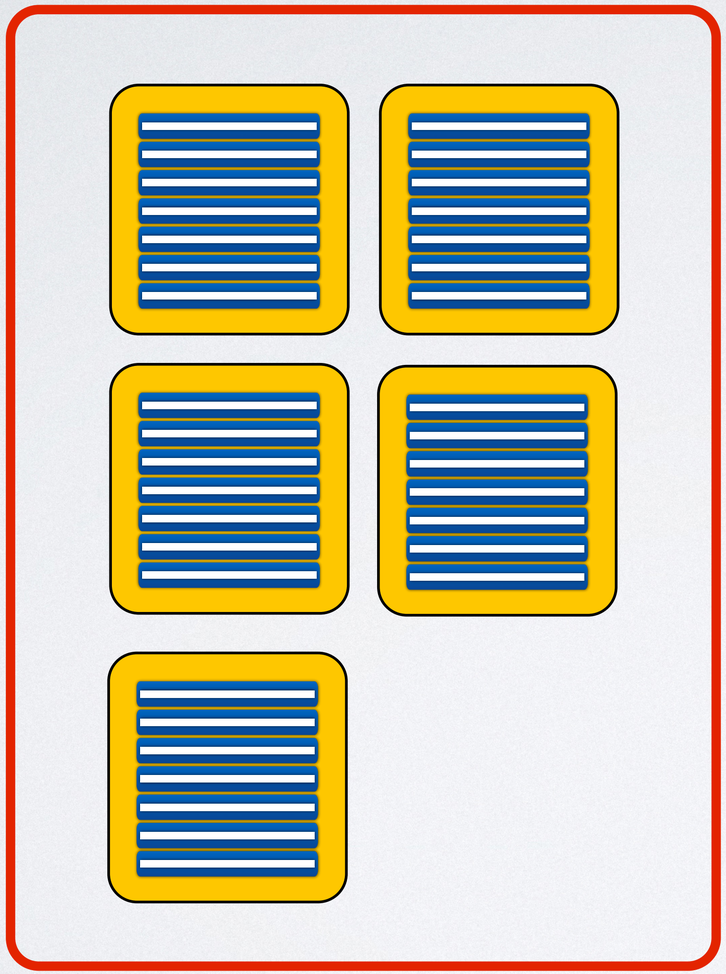
Mutation happens with a certain probability

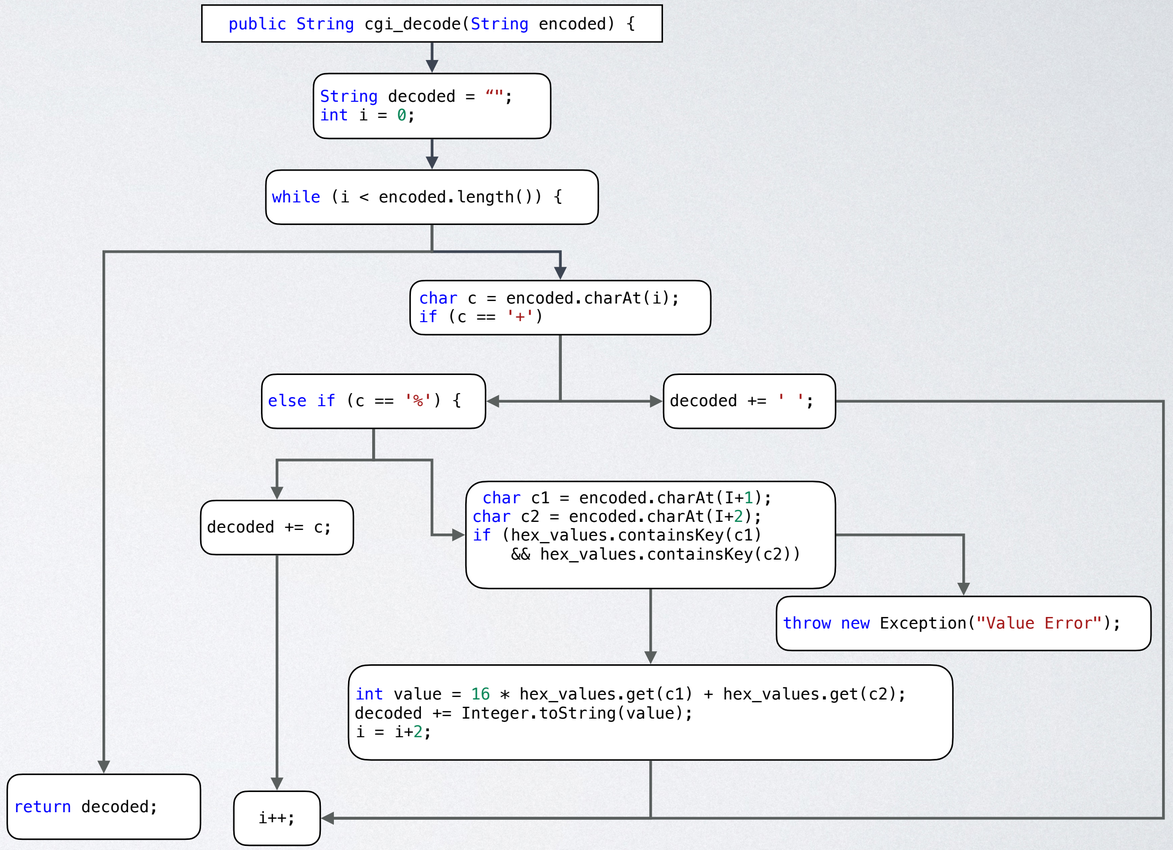
MUTATION



Mutation happens with a certain probability

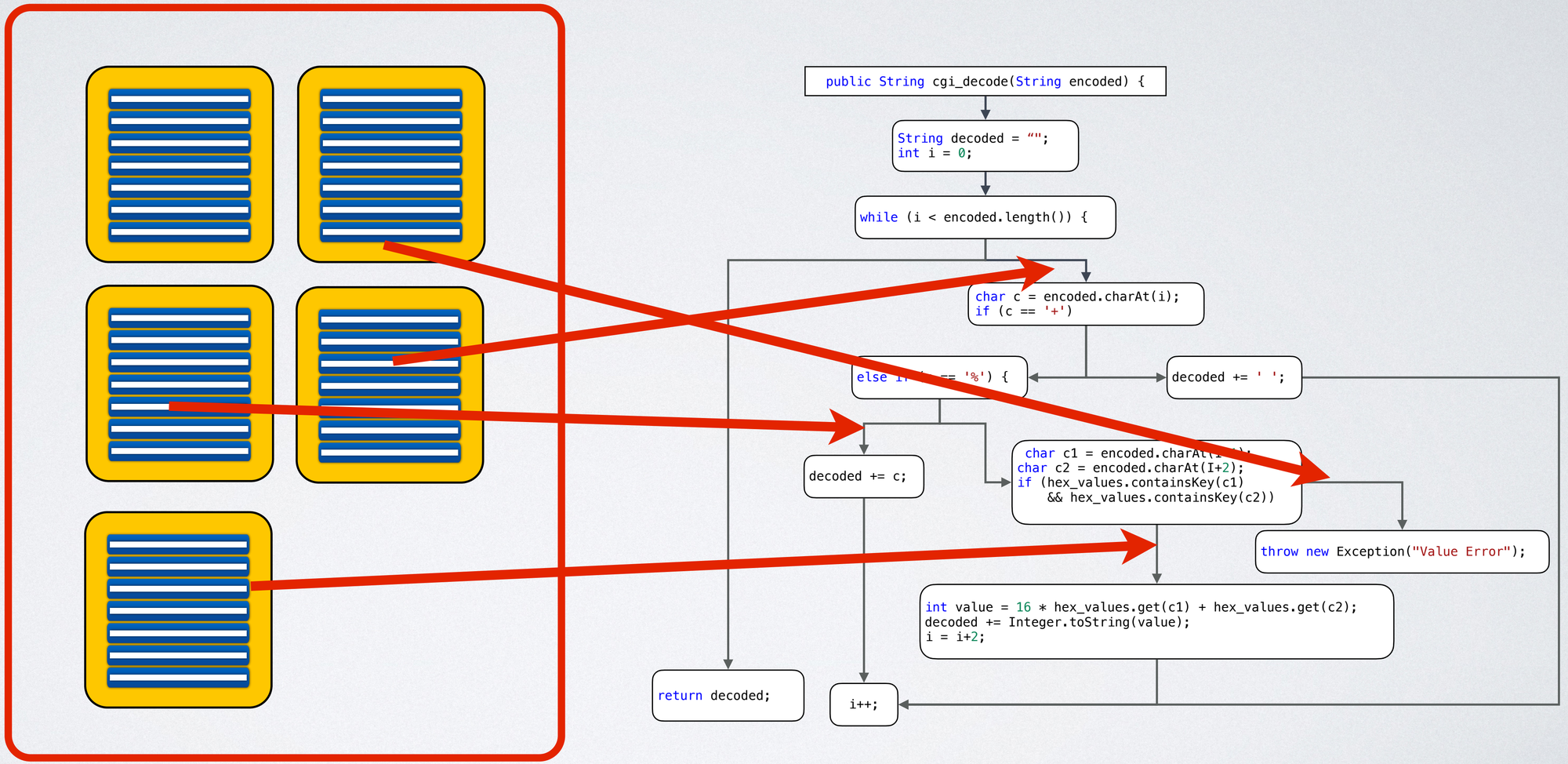
FITNESS EVALUATION





Fitness is computed using *branch distance* and *approach level*

FITNESS EVALUATION

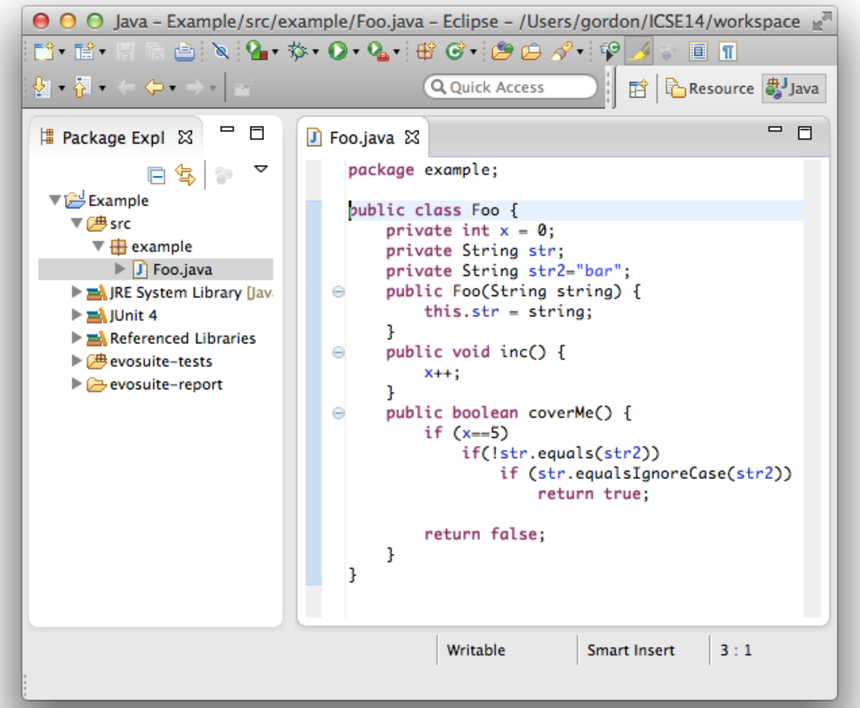


Fitness is computed using *branch distance* and *approach level*

TEST ORACLES

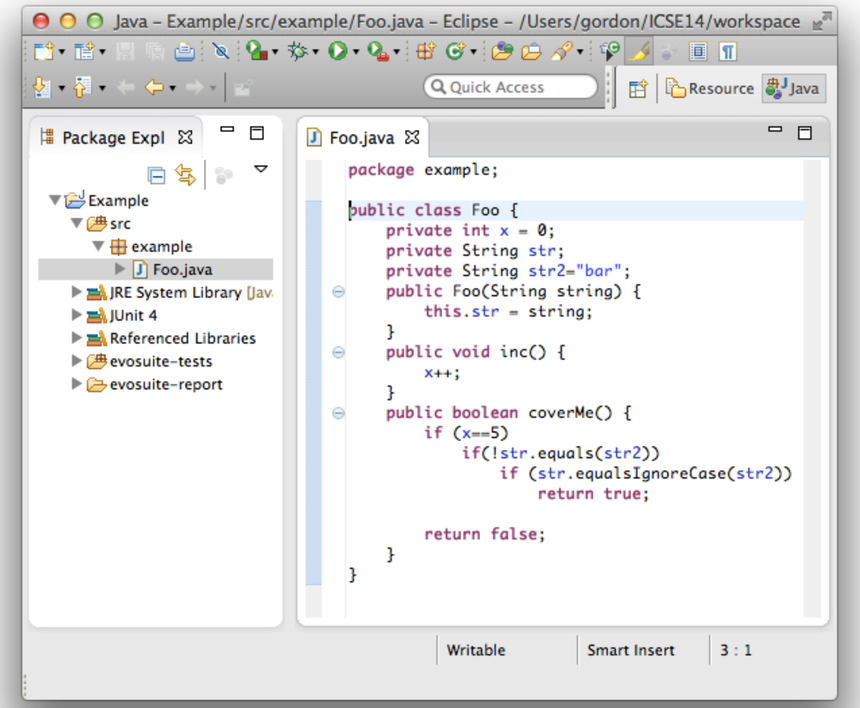
- Assertions are introduced in resulting tests
- These assertions reflect **implemented** behaviour
- The algorithm knows nothing about **intended** behaviour
- **Regression test suite**: All generated tests will pass

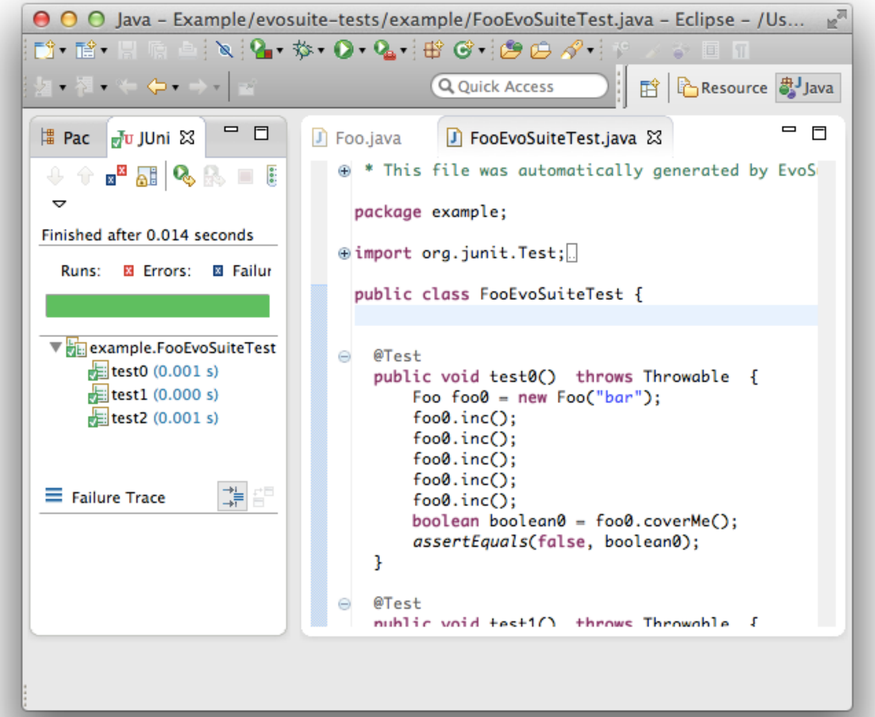
SOFTWARE DEVELOPMENT USE CASE



Source code

SOFTWARE DEVELOPMENT USE CASE



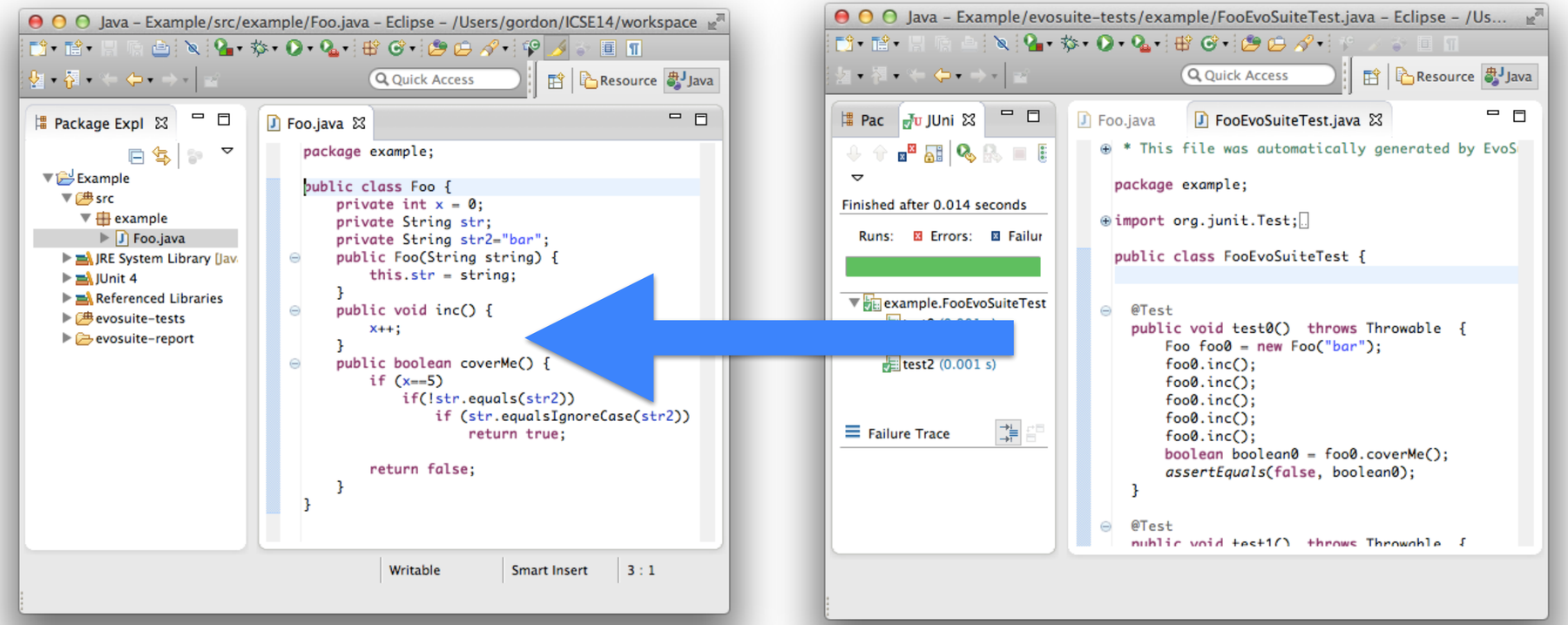


Source code

Test cases optimised for branch coverage

Automated generation

SOFTWARE DEVELOPMENT USE CASE

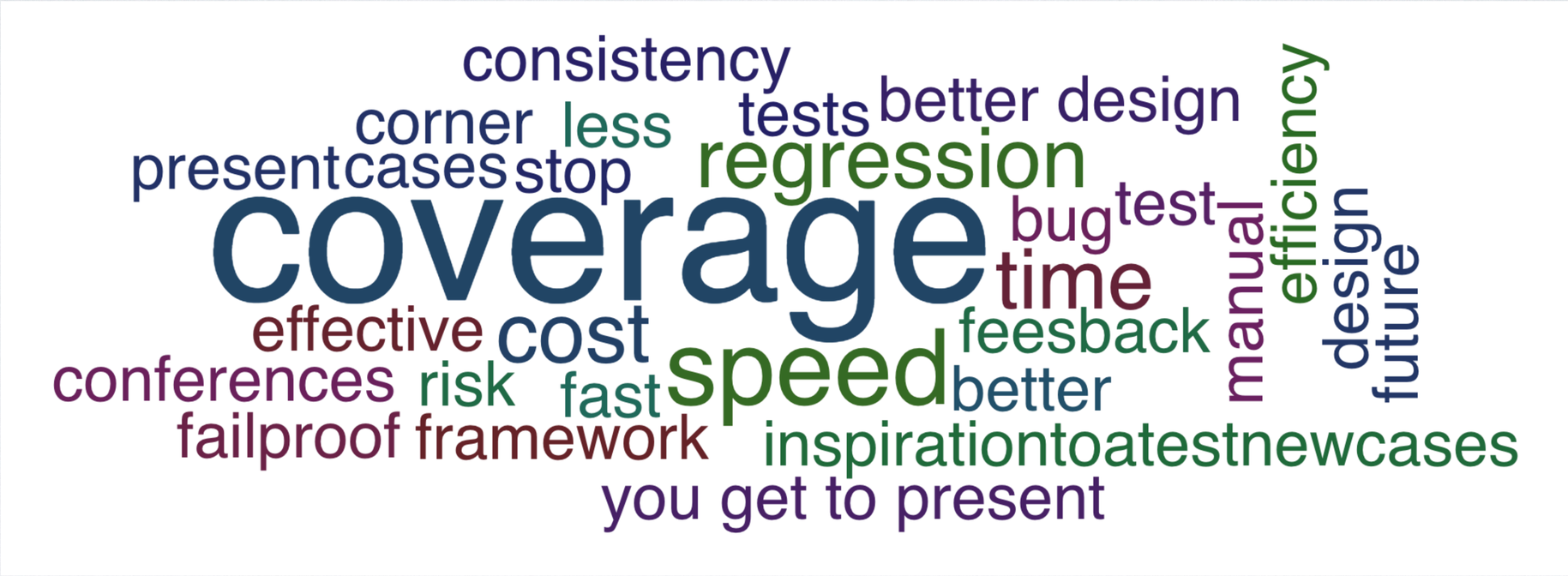


Source code

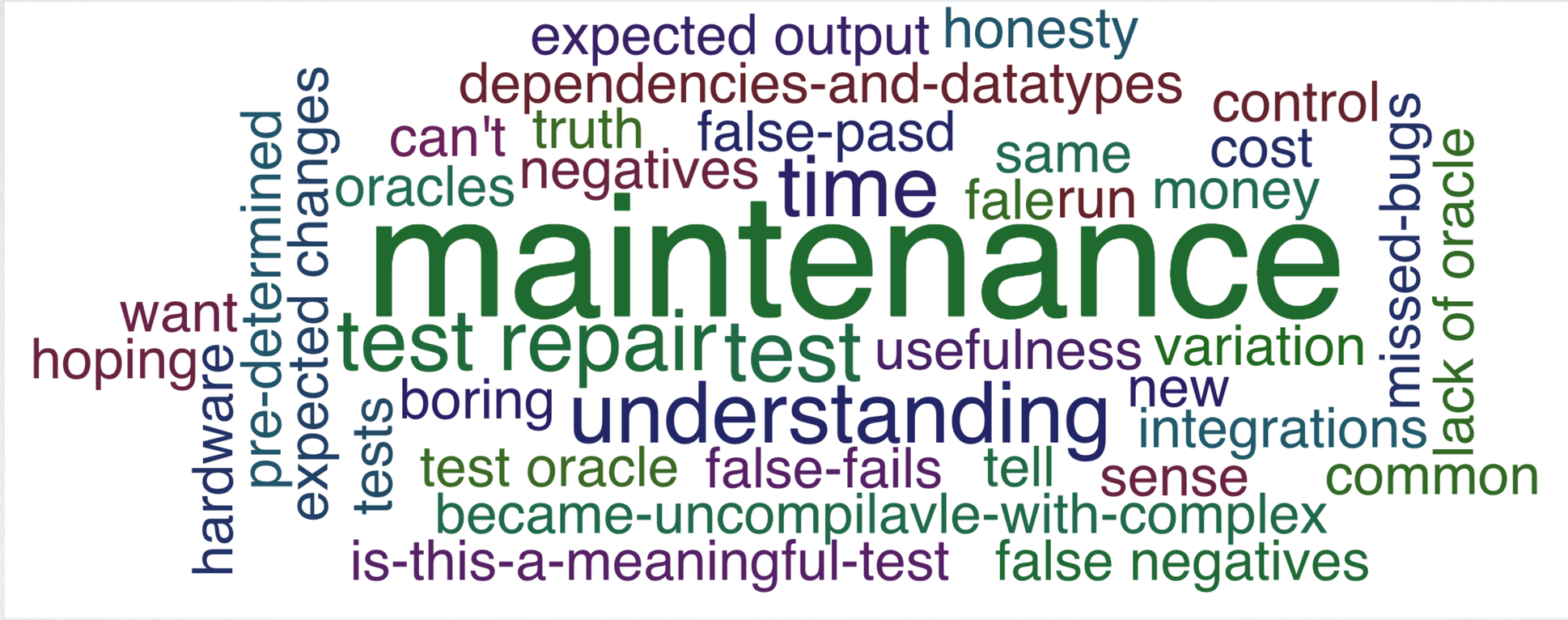
Test cases optimised for branch coverage

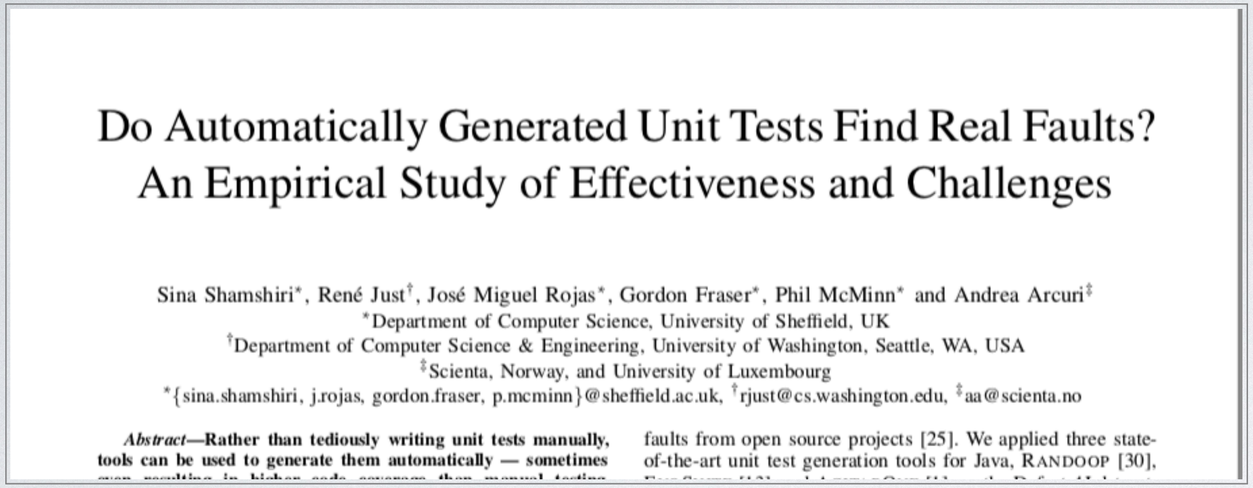
Automated generation

ADVANTAGES


consistency
corner
less
tests
better design
present
cases
stop
regression
coverage
bug
test
time
manual
efficiency
design
future
effective
cost
feesback
conferences
risk
fast
speed
better
failproof
framework
inspiration
to
a
test
new
cases
you get to present

DISADVANTAGES





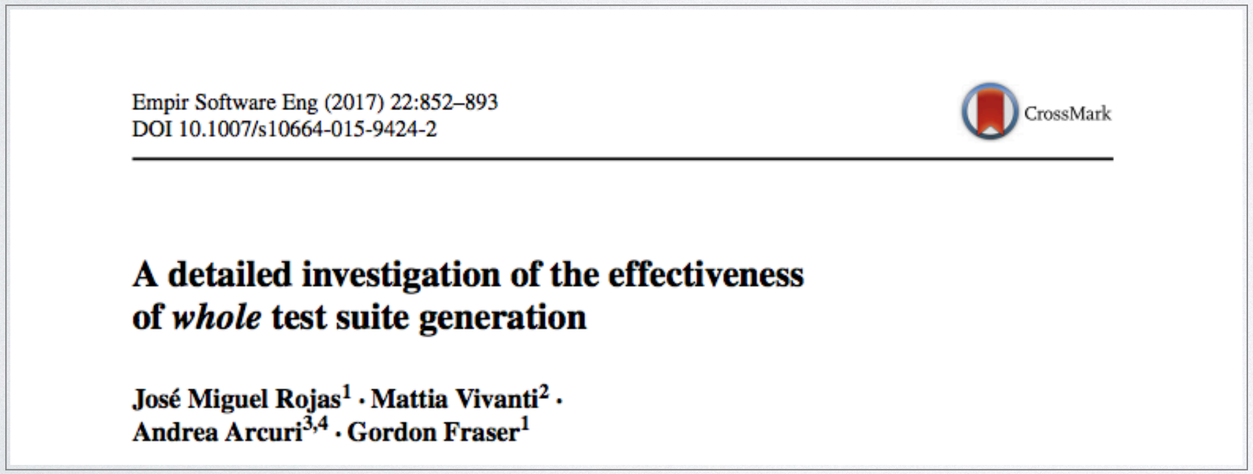
Do Automatically Generated Unit Tests Find Real Faults?
An Empirical Study of Effectiveness and Challenges

Sina Shamshiri*, René Just†, José Miguel Rojas*, Gordon Fraser*, Phil McMinn* and Andrea Arcuri‡
*Department of Computer Science, University of Sheffield, UK
†Department of Computer Science & Engineering, University of Washington, Seattle, WA, USA
‡Scienta, Norway, and University of Luxembourg
*{sina.shamshiri, j.rojas, gordon.fraser, p.mcminn}@sheffield.ac.uk, †rjust@cs.washington.edu, ‡aa@scienta.no

***Abstract*—Rather than tediously writing unit tests manually, tools can be used to generate them automatically — sometimes**

faults from open source projects [25]. We applied three state-of-the-art unit test generation tools for Java, RANDOOP [30],

Fault Detection (ASE 2015)



Empir Software Eng (2017) 22:852–893
DOI 10.1007/s10664-015-9424-2

CrossMark

A detailed investigation of the effectiveness of *whole* test suite generation

José Miguel Rojas[1] · Mattia Vivanti[2] · Andrea Arcuri[3,4] · Gordon Fraser[1]

Code Coverage (EMSE 2017)

OPTIMISATIONS

- Seeding (Rojas et al., STVR 2015)
  - Static values, e.g., constants appearing in code or strings representing email addresses
  - Dynamic values
  - Existing tests

Email addresses, such as `jsmith@example.org`, have two parts. The part before the @ sign is the *local-part* of the address, often the username of the recipient (`jsmith`), and the part after the @ sign is a *domain name* to which the email message will be sent (`example.org`).

P. McMinn, M. Shahbaz and M. Stevenson. "Search-Based Test Input Generation for String Data Types Using the Results of Web Queries". ICST 2012.

- Parameter tuning (Arcuri and Fraser, ESE 2013)
- Multiple coverage criteria at once (Rojas et al., SSBSE 2015)
- Many objectives at once (Panichela et al., TSE 2017)

EVOSUITE

- Search-based Whole Test Suite Generation of JUnit tests for Java programs
- Publicly available at http://www.evosuite.org/
  - Open-source on GitHub: https://github.com/evosuite/evosuite
- Different interfaces
  - Jar file for use from command line
  - Plug-ins for IntelliJ and Eclipse IDEs for use during software development
  - Plug-in for Maven for build integration and Plug-in for Jenkins for continuous integration

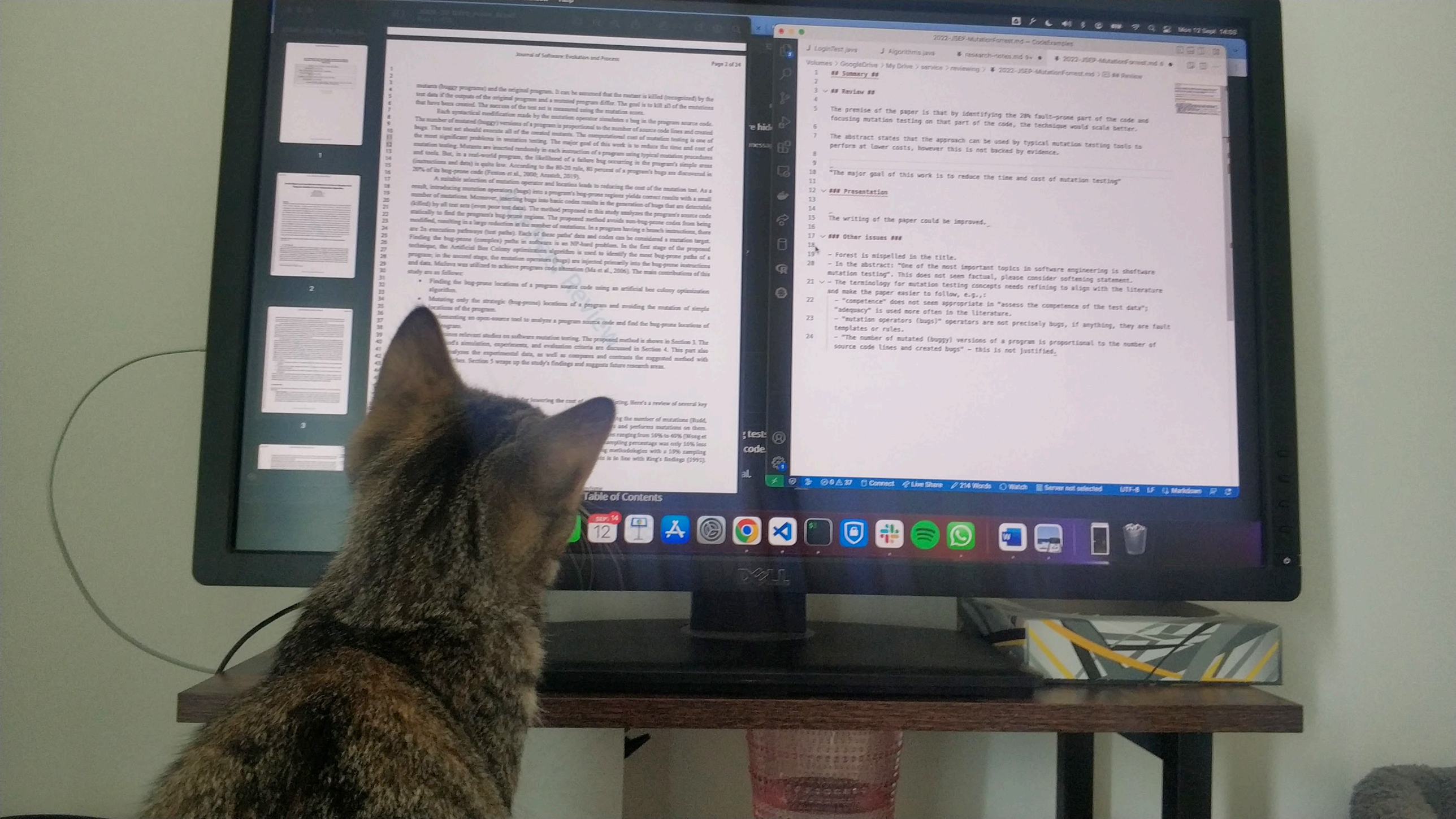
```
@Test(timeout = 4000)
public void test01()  throws Throwable  {
    LinkedList<String> linkedList0 = new LinkedList<String>();
    LinkedList<Object> linkedList1 =
        new LinkedList<Object>((Collection<?>) linkedList0);
    FixedOrderComparator fixedOrderComparator0 =
        new FixedOrderComparator((List) linkedList1);
    linkedList1.add((Object) linkedList1);
    // Undeclared exception!
    try {
      fixedOrderComparator0.compare(linkedList1, linkedList0);
      fail("Expecting exception: StackOverflowError");

    } catch(StackOverflowError e) {
       //
       // no message in exception (getMessage() returned null)
       //
    }
}
```

EVOSUITE

```
@Test
public void test002() throws Throwable {

    if (debug) { System.out.format("%n%s%n","RegressionTest2.test002"); }

    java.lang.Object[] obj_array1 = new java.lang.Object[] { (short)10 };
    collections.comparators.FixedOrderComparator fixedOrderComparator2 =
        new collections.comparators.FixedOrderComparator(obj_array1);
    java.util.Comparator comparator3 = fixedOrderComparator2.reversed();
    java.util.Comparator comparator4 = comparator3.reversed();
    java.lang.Object[] obj_array6 = new java.lang.Object[] { (short)10 };
    collections.comparators.FixedOrderComparator fixedOrderComparator7 =
        new collections.comparators.FixedOrderComparator(obj_array6);
    java.util.Comparator comparator8 =
      comparator4.thenComparing((java.util.Comparator)fixedOrderComparator7);
    boolean b10 = fixedOrderComparator7.add((java.lang.Object)10L);
    int i11 = fixedOrderComparator7.getUnknownObjectBehavior();
    boolean b12 = fixedOrderComparator7.isLocked();
    fixedOrderComparator7.setUnknownObjectBehavior( 0 );
    ...
    ...
}
```

Randoop

```
/**
 * Chromosome :
1)----->org.apache.commons.lang3.math.NumberUtils[]
2)----->min[[30823,57]],
3)----->toString[]
 Covered Branches:[1, 113, 114, 115, 109, 111]
 */
  @Test public void TestCase1() throws Throwable {
    NumberUtils clsUTNumberUtils=null;
      clsUTNumberUtils=new NumberUtils();
    short[] clsUTNumberUtilsP2P1=new short[]{30823,57};
    short clsUTNumberUtilsP2R=0;
      clsUTNumberUtilsP2R=NumberUtils.min(clsUTNumberUtilsP2P1);
    assertTrue(Arrays.equals(new short[]{30823,57},clsUTNumberUtilsP2P1));
    assertEquals(57,clsUTNumberUtilsP2R);
    String clsUTNumberUtilsP3R=null;
      clsUTNumberUtilsP3R=clsUTNumberUtils.toString();
    String clsUTNumberUtilsP3RP0P1=new
String("YfJOufsFnsYRrFHBpCyLgDWEmhiRPOGISMsFFCYjMOSisquxKCuSHIOrrEBbqqwfBtBmhuiUWUSsKUAfloLlYPBYmyihySJwWEVETnqzBRdlRCMk");
    Double clsUTNumberUtilsP3RP0P2P1O0=-11.825526454314883D;
    Object clsUTNumberUtilsP3RP0P2P1=clsUTNumberUtilsP3RP0P2P1O0;
    String clsUTNumberUtilsP3RP0P2P2O0=new String(">?]$#qxd_ (;jiah+un");
    Object clsUTNumberUtilsP3RP0P2P2=clsUTNumberUtilsP3RP0P2P2O0;
    Short clsUTNumberUtilsP3RP0P2P3O0=1689;
    Object clsUTNumberUtilsP3RP0P2P3=clsUTNumberUtilsP3RP0P2P3O0;
    Object[] clsUTNumberUtilsP3RP0P2=new Object[]{clsUTNumberUtilsP3RP0P2P1,clsUTNumberUtilsP3RP0P2P2,clsUTNumberUtilsP3RP0P2P3};
    String clsUTNumberUtilsP3RP0R=null;
      clsUTNumberUtilsP3RP0R=String.format(clsUTNumberUtilsP3RP0P1,(Object[])clsUTNumberUtilsP3RP0P2);

assertEquals("YfJOufsFnsYRrFHBpCyLgDWEmhiRPOGISMsFFCYjMOSisquxKCuSHIOrrEBbqqwfBtBmhuiUWUSsKUAfloLlYPBYmyihySJwWEVETnqzBRdlRCMk",clsUTNumberUtilsP3RP0P1.toStri
ng());
    assertEquals("YfJOufsFnsYRrFHBpCyLgDWEmhiRPOGISMsFFCYjMOSisquxKCuSHIOrrEBbqqwfBtBmhuiUWUSsKUAfloLlYPBYmyihySJwWEVETnqzBRdlRCMk",clsUTNumberUtilsP3RP0R);
  }
```


Journal of Software: Evolution and Process
Page 2 of 24
Table of Contents
Summary
Review
The premise of the paper is that by identifying the 20% fault-prone part of the code and focusing mutation testing on that part of the code, the technique would scale better.
The abstract states that the approach can be used by typical mutation testing tools to perform at lower costs, however this is not backed by evidence.
"The major goal of this work is to reduce the time and cost of mutation testing"
Presentation
The writing of the paper could be improved.
Other issues
- Forest is mispelled in the title.
- In the abstract: "One of the most important topics in software engineering is shoftware mutation testing". This does not seem factual, please consider softening statement.
- The terminology for mutation testing concepts needs refining to align with the literature and make the paper easier to follow, e.g.,:
- "competence" does not seem appropriate in "assess the competence of the test data"; "adequacy" is used more often in the literature.
- "mutation operators (bugs)" operators are not precisely bugs, if anything, they are fault templates or rules.
- "The number of mutated (buggy) versions of a program is proportional to the number of source code lines and created bugs" - this is not justified.

TEST READABILITY

"[Developers] read tests […] 77% of the total time they spend in them"

M. Beller, G. Gousios, A. Panichella, and A. Zaidman, "When, How, and Why Developers (Do Not) Test in Their IDEs". FSE 2015.

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But what does readability mean?

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But what does readability mean?

	Correlation			One feature a time		
Feature name	total	max	avg	total	max	avg
identifier length	**-0.50**	**-0.42**	**-0.46**	0.50	0.41	0.45
commas	-0.15	-0.20	-0.15	0.13	0.14	0.13
line length	**-0.45**	**-0.50**	-0.43	0.4	0.49	0.41
Halstead difficulty	-0.15	-	-	-	-	-
constructor calls	**-0.45**	-	-0.24	0.44	-	0.20
has exceptions	**0.15**	-	-	0.11	-	-
byte entropy	-0.39	-	-	0.31	-	-
identifier ratio	**0.15**	-	-	0.11	-	-
unique identifiers	**-0.37**	-0.25	-0.14	0.36	0.22	0.11
method invocations	-0.14	-0.06	-0.03	0.09	-0.00	-0.07
identifiers	**-0.36**	-0.23	-0.29	0.36	0.20	0.27
string length	-0.14	-0.24	**-0.20**	0.09	0.23	0.19
assignments	-0.33	-	-0.16	0.32	-	0.13
arrays	-0.14	-0.05	-0.06	0.11	-0.05	-0.01
casts	-0.33	-0.33	-0.28	0.32	0.32	0.26
indentation	-0.13	0.08	-0.01	0.10	0.02	-0.25
parentheses	-0.31	-	-0.28	0.30	-	0.26
field accesses	-0.13	-0.14	-0.17	0.11	0.11	0.15
keywords	-0.30	-0.28	-0.17	0.28	0.27	0.14
Halstead effort	-0.13	-	-	0.13	-	-
Halstead volume	-0.27	-	-	0.18		
assertions	**-0.12**	-	-0.04	0.09	-	-0.10
distinct methods	**-0.27**	-0.05	0.00	0.26	-0.02	-0.18
additional assertions	-0.12	-	-	0.09	-	-
single characters	-0.26	-0.32	-0.24	0.17	0.22	0.16
nulls	-0.12	**-0.20**	**-0.15**	0.06	0.19	0.12
periods	-0.25	-0.22	-0.17	0.24	0.20	0.13
class ratio	-0.10	-	-	0.04	-	-
comparison operations	-0.25	-	-0.23	0.24	-	0.23
blank lines	0.08	-	0.21	0.03	-	0.19

E. Daka, J. Campos, G. Fraser, J. Dorn, and W. Weimer. "Modeling readability to improve unit tests". FSE 2015.

```
@Test(timeout = 4000)
public void test1()  throws Throwable  {
    LinkedList<String> linkedList0 = new LinkedList<String>();
    LinkedList<Object> linkedList1 =
        new LinkedList<Object>((Collection<?>) linkedList0);
    FixedOrderComparator fixedOrderComparator0 =
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    linkedList1.add((Object) linkedList1);
    // Undeclared exception!
    try {
      fixedOrderComparator0.compare(linkedList1, linkedList0);
      fail("Expecting exception: StackOverflowError");

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```

COVERAGE-BASED NAMING

COVERAGE-BASED NAMING

```
public class ShoppingCart {
  private int total = 0;
  private final static int MAX = 1000;

  public boolean addPrice(int cost)
        throws IllegalArgumentException {
    if (cost <= 0)
      throw new IllegalArgumentException(“Negative cost");
    if (cost < MAX) {
      total += cost;
      return true;
    } else {
      return false;
    }
  }
  public int getTotal() {
    return total;
  }
}
```

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Method Coverage

COVERAGE-BASED NAMING

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    } else {
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    }
  }
  public int getTotal() {
    return total;
  }
}
```

testCreateShoppingCart
testAddPrice
testGetTotal

Method Coverage

EVOSUITE

COVERAGE-BASED NAMING

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public class ShoppingCart {
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  }
}
```

Exception Coverage

EVOSUITE

COVERAGE-BASED NAMING

```
public class ShoppingCart {
  private int total = 0;
  private final static int MAX = 1000;

  public boolean addPrice(int cost)
      throws IllegalArgumentException {
    if (cost <= 0)
      throw new IllegalArgumentException("Negative cost");
    if (cost < MAX) {
      total += cost;
      return true;
    } else {
      return false;
    }
  }
  public int getTotal() {
    return total;
  }
}
```

Exception Coverage

EVOSUITE

COVERAGE-BASED NAMING

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```

testAddPriceThrowsIllegalArgExc

Exception Coverage

EVOSUITE

COVERAGE-BASED NAMING

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  private final static int MAX = 1000;

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        throws IllegalArgumentException {
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    if (cost < MAX) {
      total += cost;
      return true;
    } else {
      return false;
    }
  }
  public int getTotal() {
    return total;
  }
}
```

Output Coverage

EVOSUITE

COVERAGE-BASED NAMING

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public class ShoppingCart {
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Output Coverage

COVERAGE-BASED NAMING

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    }
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  }
}
```

testGetTotalReturnsZero
testGetTotalReturnsPositive
testGetTotalReturnsNegative

Output Coverage

EVOSUITE

COVERAGE-BASED NAMING

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public class ShoppingCart {
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Input Coverage

EVOSUITE

COVERAGE-BASED NAMING

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public class ShoppingCart {
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Input Coverage

COVERAGE-BASED NAMING

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  public boolean addPrice(int cost)
        throws IllegalArgumentException {
    if (cost <= 0)
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    if (cost < MAX) {
      total += cost;
      return true;
    } else {
      return false;
    }
  }
  public int getTotal() {
    return total;
  }
}
```
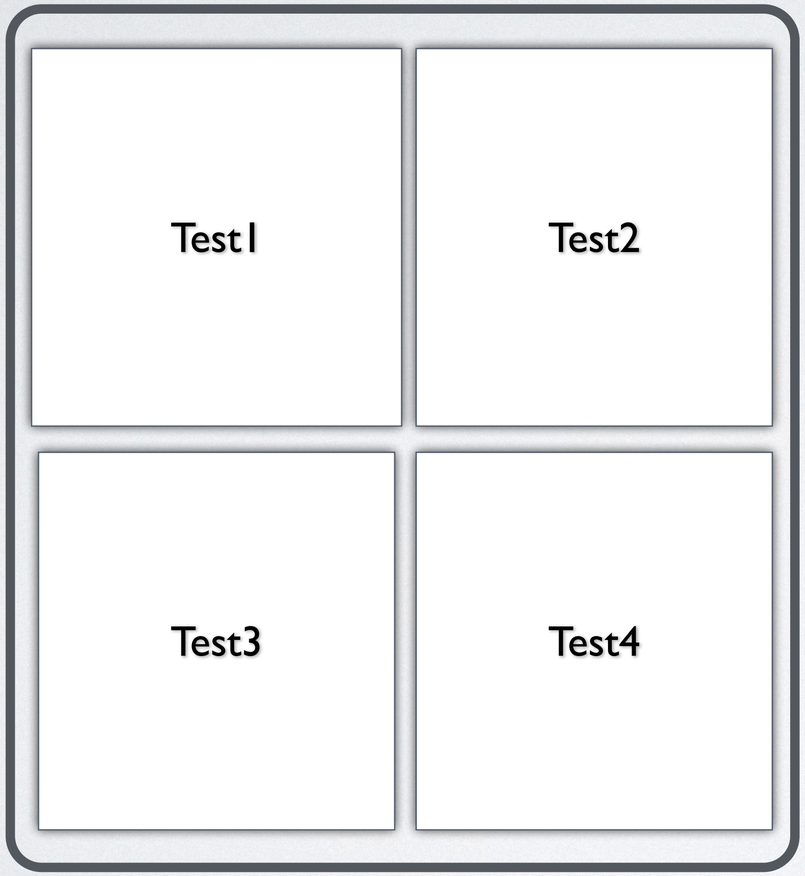

testAddPriceWithZero
testAddPriceWithPositive
testAddPriceWithNegative

Input Coverage

SYNTHESIS OF DESCRIPTIVE TEST NAMES



SYNTHESIS OF DESCRIPTIVE TEST NAMES

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1. Identify goals covered uniquely by each test case

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1. Identify goals covered uniquely by each test case
2. Sort covered goals
   Exception > Method > Output > Input

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SYNTHESIS OF DESCRIPTIVE TEST NAMES

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   Exception > Method > Output > Input
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4. Resolve conflicts when possible based on pairs of goals

SYNTHESIS OF DESCRIPTIVE TEST NAMES

1. Identify goals covered uniquely by each test case
2. Sort covered goals
   Exception > Method > Output > Input
3. Synthesise readable names
4. Resolve conflicts when possible based on pairs of goals
5. Add numerical suffixes

EMPIRICAL EVALUATION

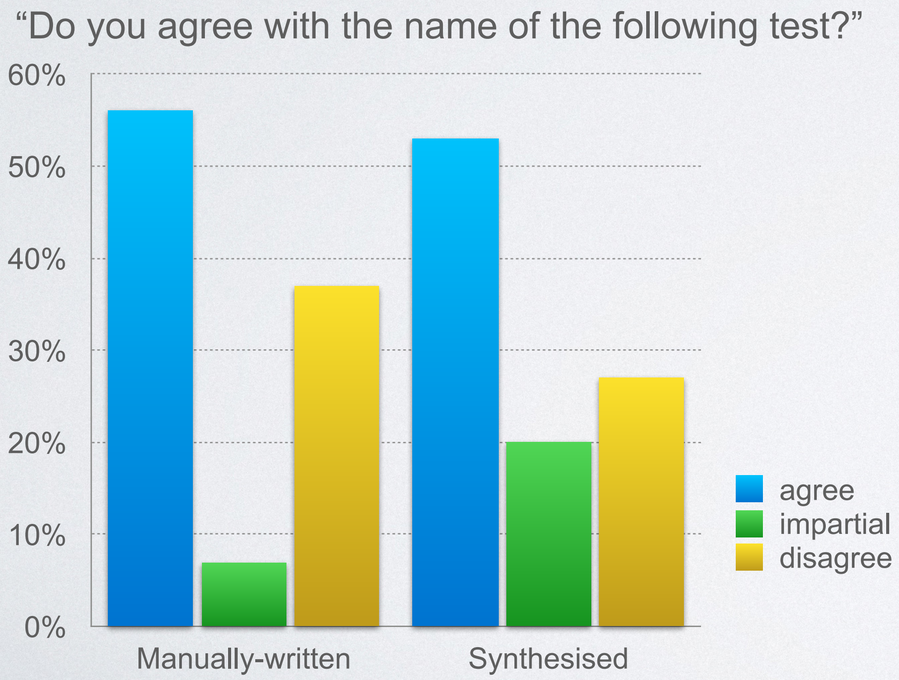
Online study

47 participants

10 Java classes

2 experts as control

No time limit



RQ1: Do developers agree with synthesised test names?

Developers agreed similarly—and disagreed less—with synthesised test names than with manually given names.

RQ2: Can developers match tests with synthesised test names?

Developers were slightly more accurate and faster at matching tests with synthesised names.

RQ3: Can synthesised test names help developers to match tests to code?

Developers were more accurate at identifying relevant tests for given pieces of code using synthesised names.

RELATED WORK

- Natural Language Generation *from test code*
- Test data generation for RESTful APIs – www.evomaster.org
- Unit test generation for Python programs – https://www.pynguin.eu/
- Fuzzing – https://www.fuzzingbook.org/

CAN MODERN AI HELP?

- Software Testing  AI
- Building large datasets of annotated unit tests for training can be very costly
- Inferring test oracles from test code: assertions that capture the developer's *intention*
- GitHub CoPilot
  - Trained on billions of lines of code in a number of programming languages
  - Turns natural language prompts into code snippets
  - Similar work is being done for tests by DiffBlue (https://www.diffblue.com/)

WRAP-UP

- Genetic Algorithms used to generate tests automatically
  - Other optimisation algorithms can also be suitable
- Test readability and understandability remain major challenges
- Opportunities for modern AI approaches