Coverage-Directed Differential Testing of JVM Implementations

Yuting Chen[1], Ting Su[2], Chengnian Sun[3], Zhendong Su[3], and Jianjun Zhao[1,4]

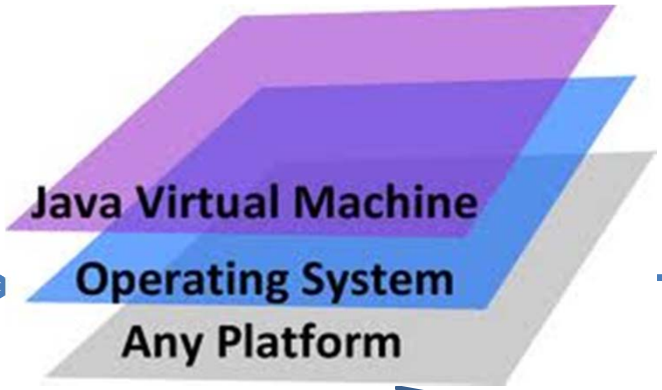
[1]Shanghai Jiao Tong University
[2]East China Normal University
[3]University of California, Davis
[4]Kyushu University

Outline

- Motivation
  - Testing of JVMs
  - Test redundancy
  - Goal + Key Observations
- Design
- Evaluation
- Related Work and Conclusion

Background: JVM

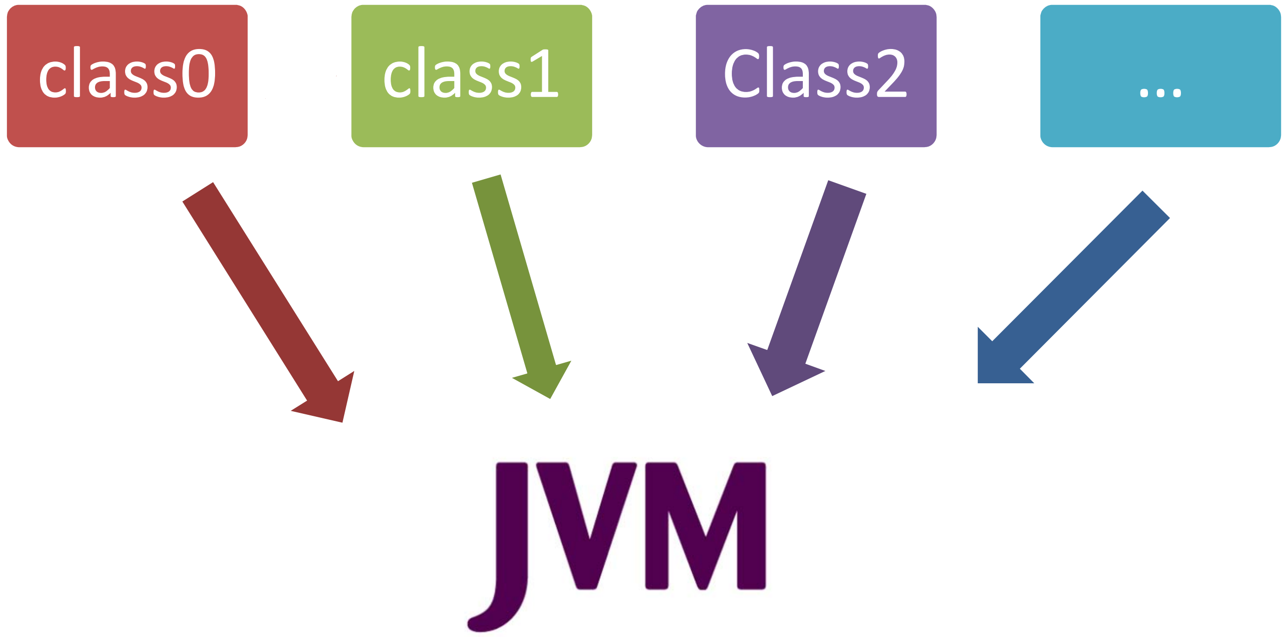
*.class
*.jar



Execution
results

JVM Testing

- Testing a JVM using a number of test classfiles



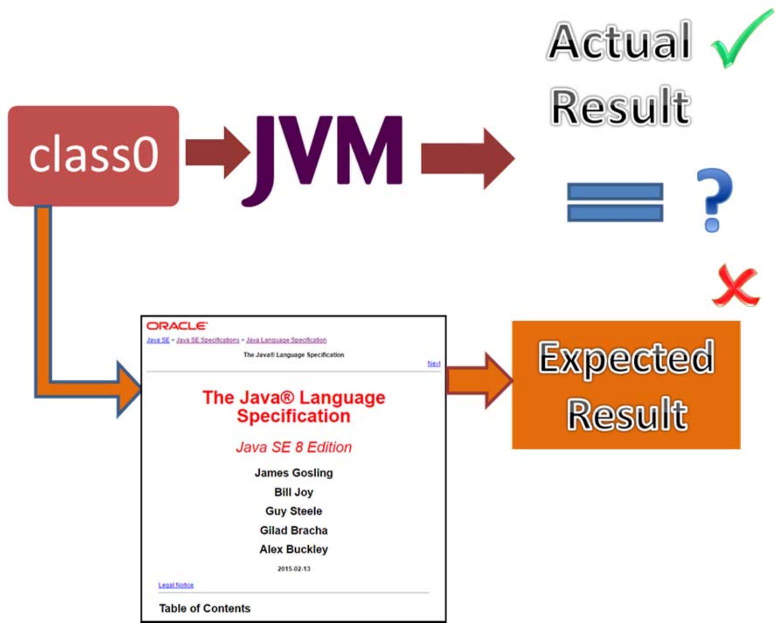
① How is a JVM defect exposed?

② How is a test classfile achieved?

Challenge 1: How to expose a JVM defect?

Challenge:

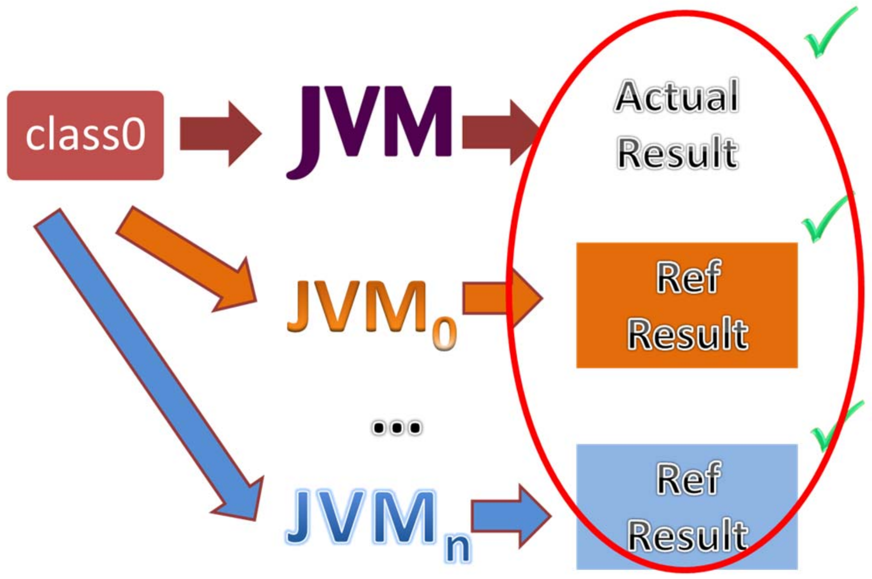
no test oracles



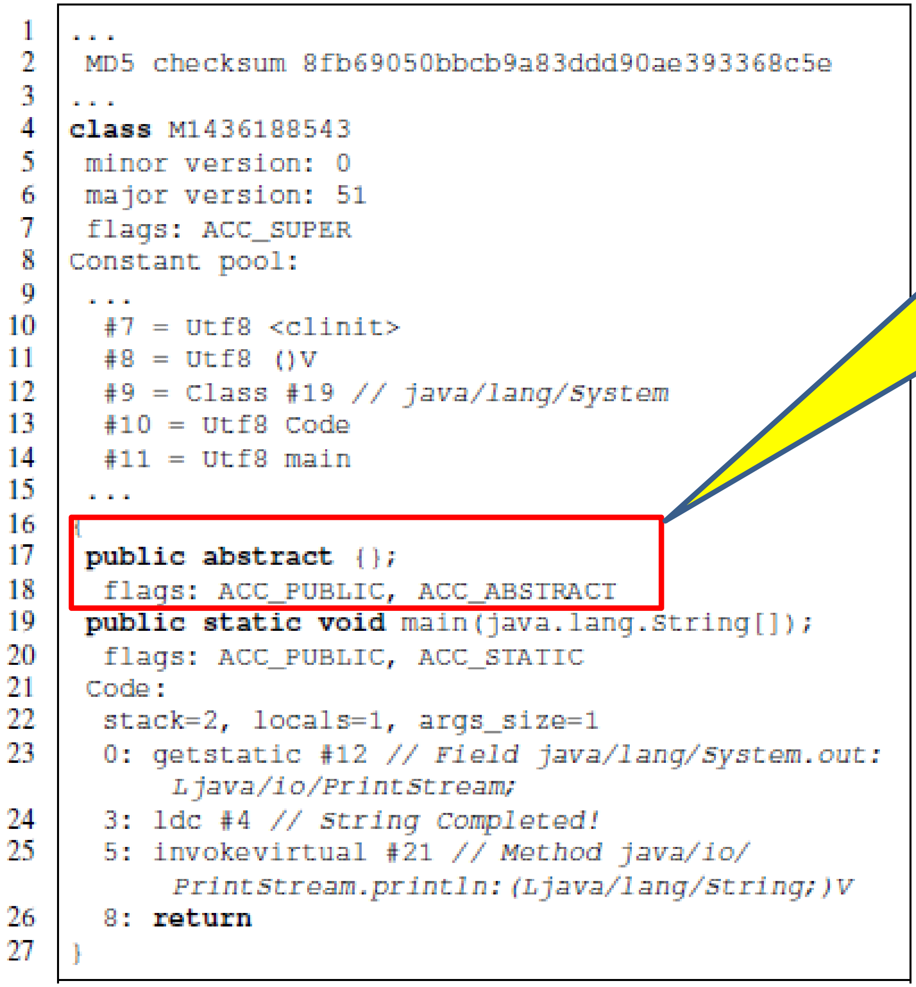
ORACLE
Java SE › Java SE Specifications › Java Language Specification
The Java® Language Specification
Next
The Java® Language Specification
Java SE 8 Edition
James Gosling
Bill Joy
Guy Steele
Gilad Bracha
Alex Buckley
2015-02-13
Legal Notice
Table of Contents

Solution:

differential JVM testing



An Example of JVM Behavior Discrepancy



```
...
 MD5 checksum 8fb69050bbcb9a83ddd90ae393368c5e
...
class M1436188543
 minor version: 0
 major version: 51
 flags: ACC_SUPER
Constant pool:
 ...
  #7 = Utf8 <clinit>
  #8 = Utf8 ()V
  #9 = Class #19 // java/lang/System
  #10 = Utf8 Code
  #11 = Utf8 main
 ...
{
 public abstract {};
  flags: ACC_PUBLIC, ACC_ABSTRACT
 public static void main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
 Code:
  stack=2, locals=1, args_size=1
  0: getstatic #12 // Field java/lang/System.out:
      Ljava/io/PrintStream;
  3: ldc #4 // String Completed!
  5: invokevirtual #21 // Method java/io/
      PrintStream.println:(Ljava/lang/String;)V
  8: return
}
```

public abstract {};

- HotSpot takes it as a ordinary method
- J9 reports a format error

Cause: the JVM specification says that "other methods named <clinit> in a class file are of no consequence. They are not class or interface initialization methods. "

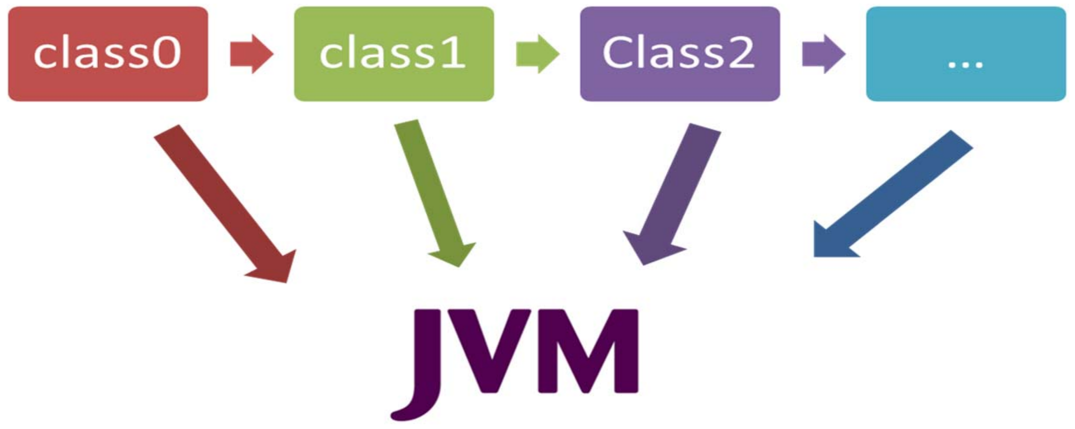
A class method needs to be more strictly defined

Challenge 2: How to obtain test classfiles?

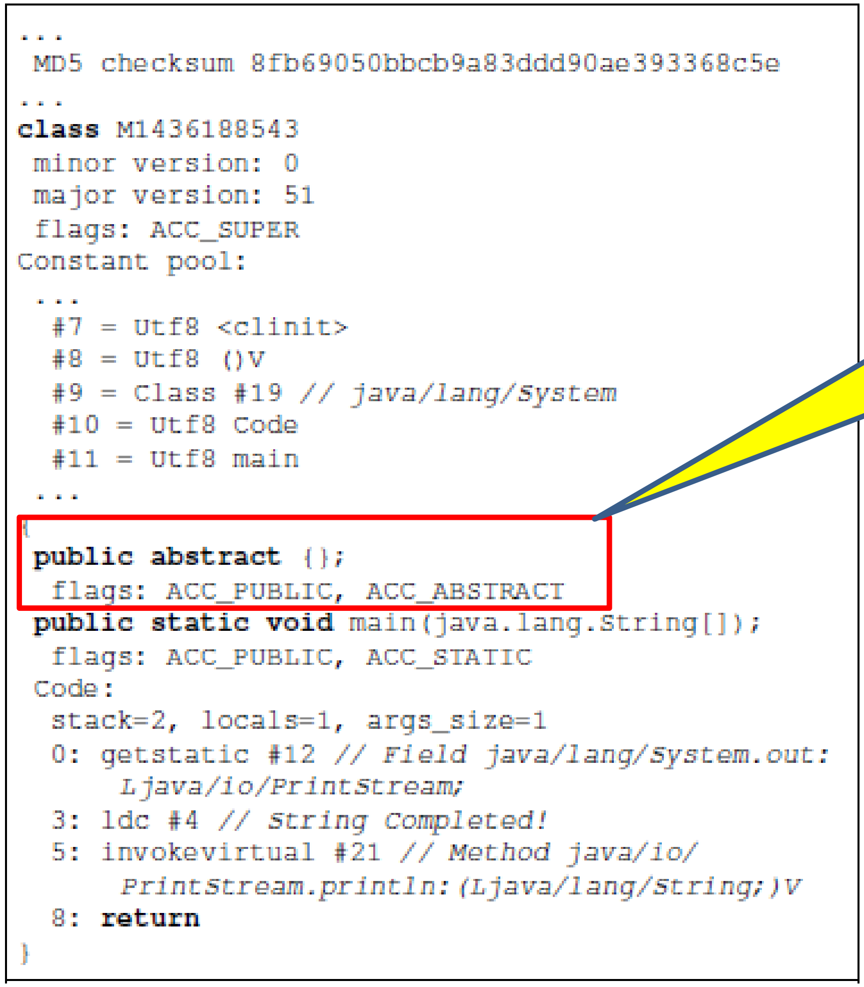
- Option 1: using the real-world classfiles

Some classes can reveal compatibility issues

- Option 2: domain-aware fuzz testing



An Example of JVM Behavior Discrepancy



```
...
 MD5 checksum 8fb69050bbcb9a83ddd90ae393368c5e
...
class M1436188543
 minor version: 0
 major version: 51
 flags: ACC_SUPER
Constant pool:
 ...
  #7 = Utf8 <clinit>
  #8 = Utf8 ()V
  #9 = Class #19 // java/lang/System
  #10 = Utf8 Code
  #11 = Utf8 main
 ...
{
 public abstract {};
  flags: ACC_PUBLIC, ACC_ABSTRACT
 public static void main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
 Code:
  stack=2, locals=1, args_size=1
  0: getstatic #12 // Field java/lang/System.out:
       Ljava/io/PrintStream;
  3: ldc #4 // String Completed!
  5: invokevirtual #21 // Method java/io/
       PrintStream.println:(Ljava/lang/String;)V
  8: return
}
```

public abstract ~~mymethod~~{};

clinit

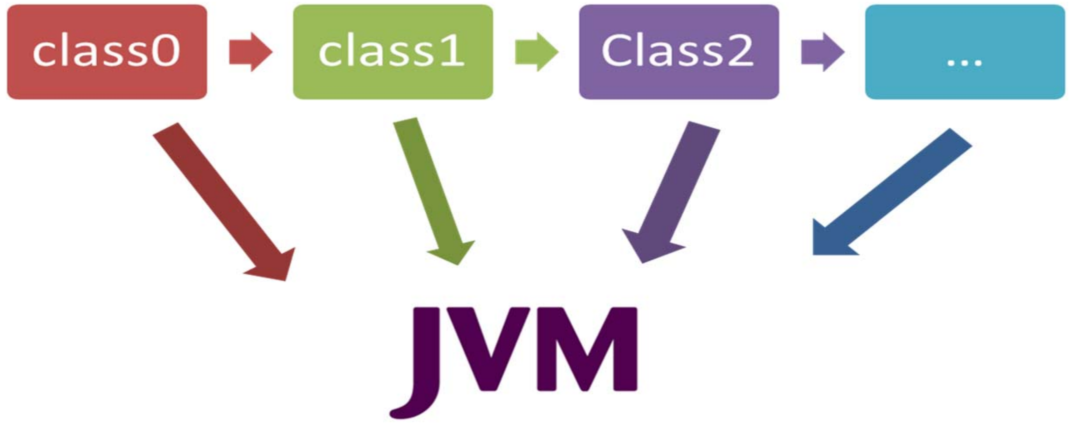
More JVM discrepancies are revealed by domain-aware fuzz testing

Challenge 2: How to obtain test classfiles?

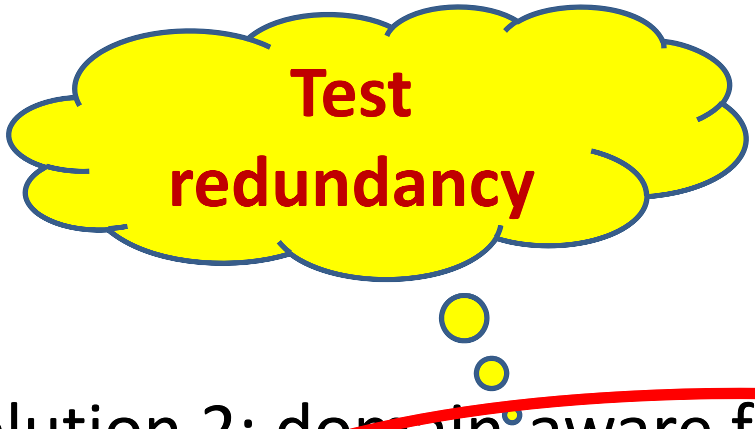
- Option 1: using the real-world classfiles

Some classes can reveal compatibility issues

- Option 2: domain-aware fuzz testing ✓

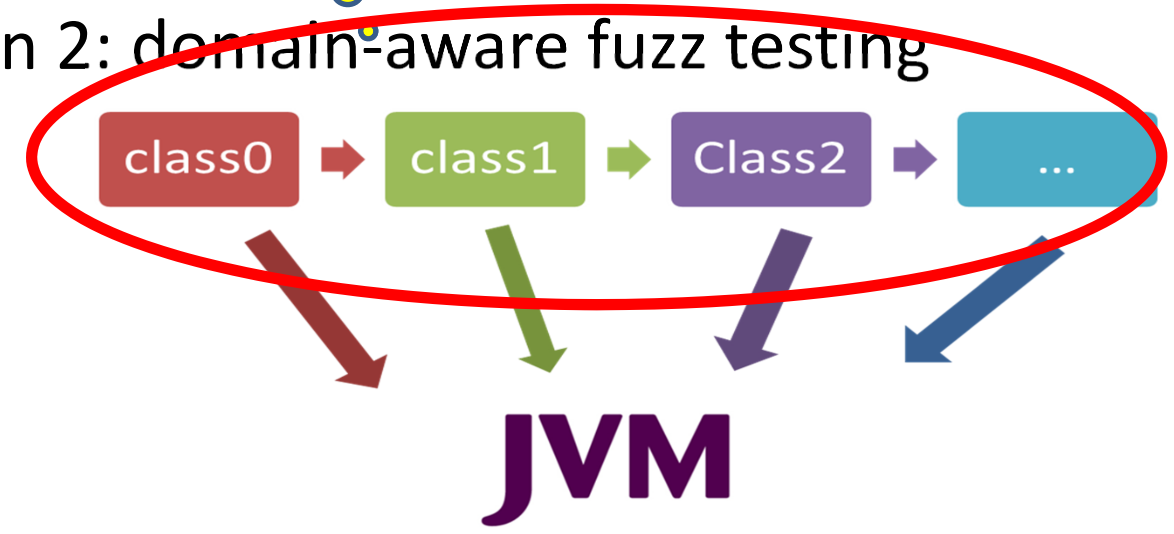


Challenge 2: How to obtain test classfiles?



- **An infinite number of test classfiles can be created**
- **They may reveal a small number of JVM discrepancies**

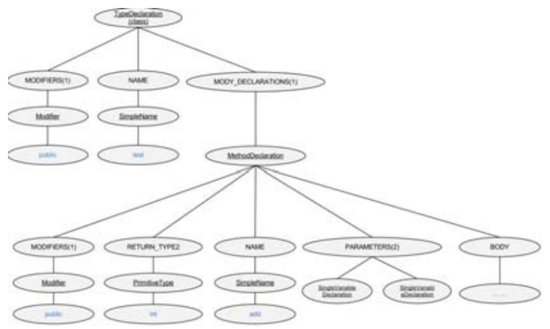
- Solution 2: domain-aware fuzz testing



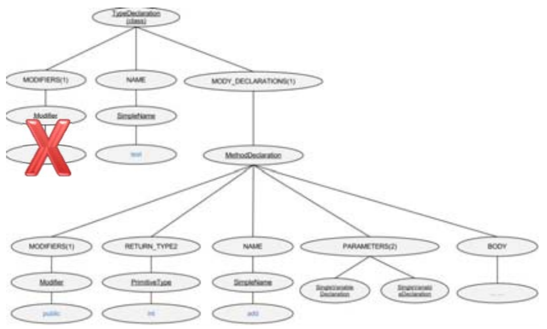
Key Observation (1)

- A classfile can encompass intricate constraints
  - Corner cases can be created through rewriting seeds

legal



Syntax tree

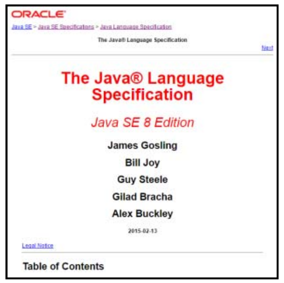


legal

or

illegal

Revised syntax tree



ORACLE

Java SE › Java SE Specifications › Java Language Specification

The Java® Language Specification

Next

The Java® Language Specification

Java SE 8 Edition

James Gosling
Bill Joy
Guy Steele
Gilad Bracha
Alex Buckley

2015-02-13

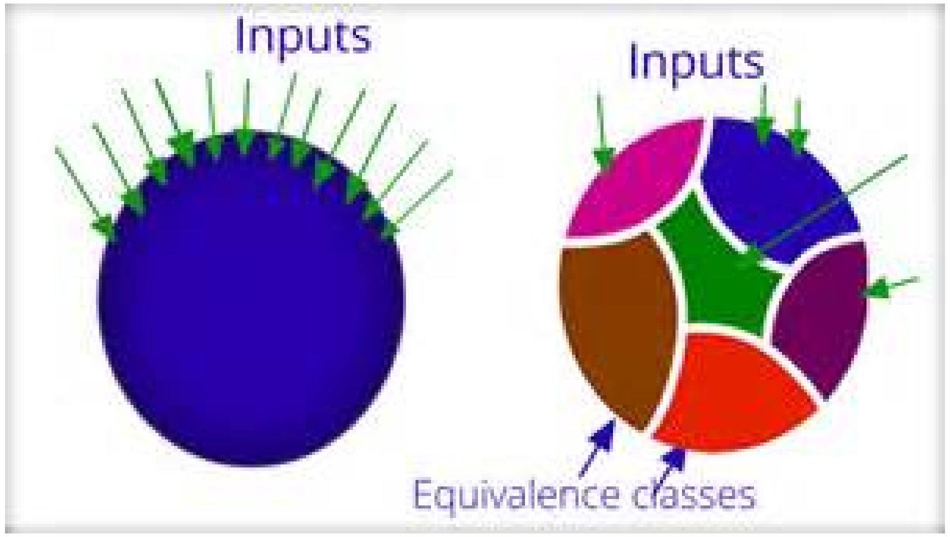
Legal Notice

Table of Contents

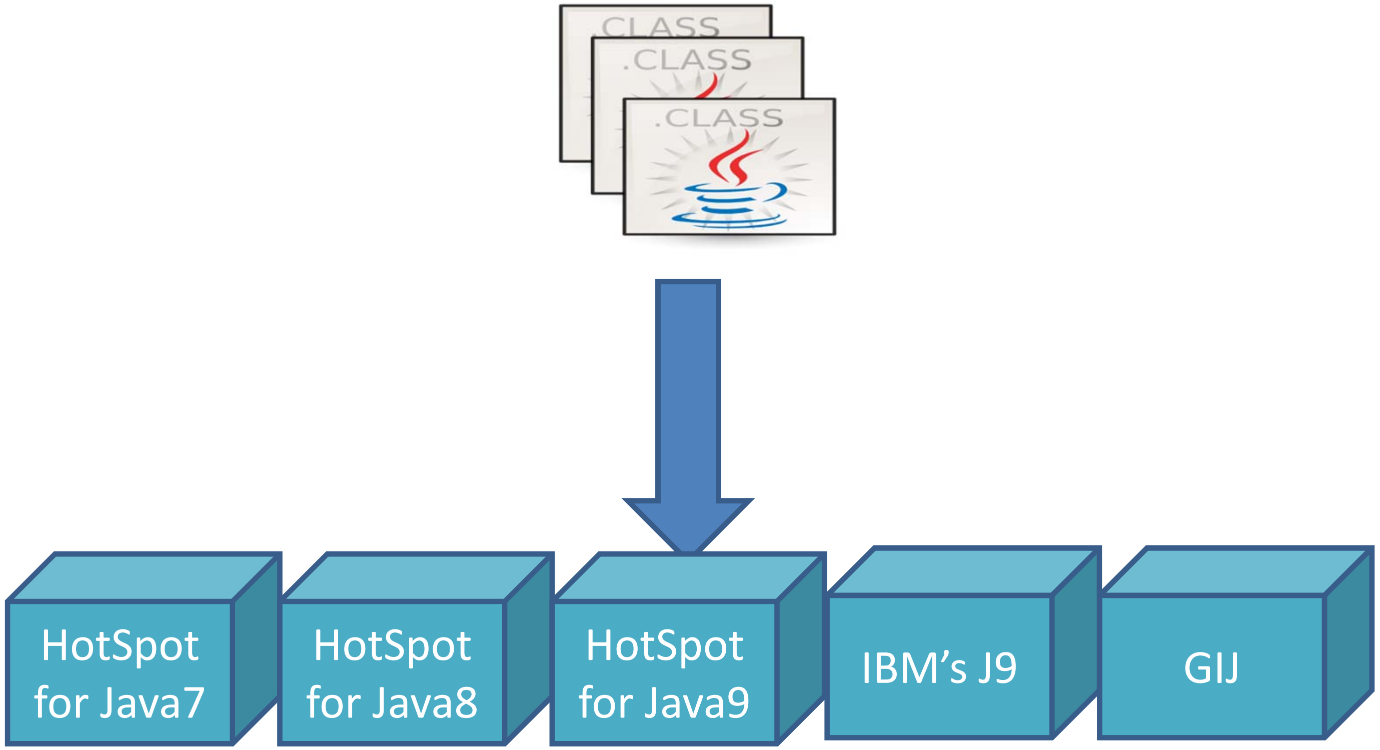
JVM

Key Observation (2)

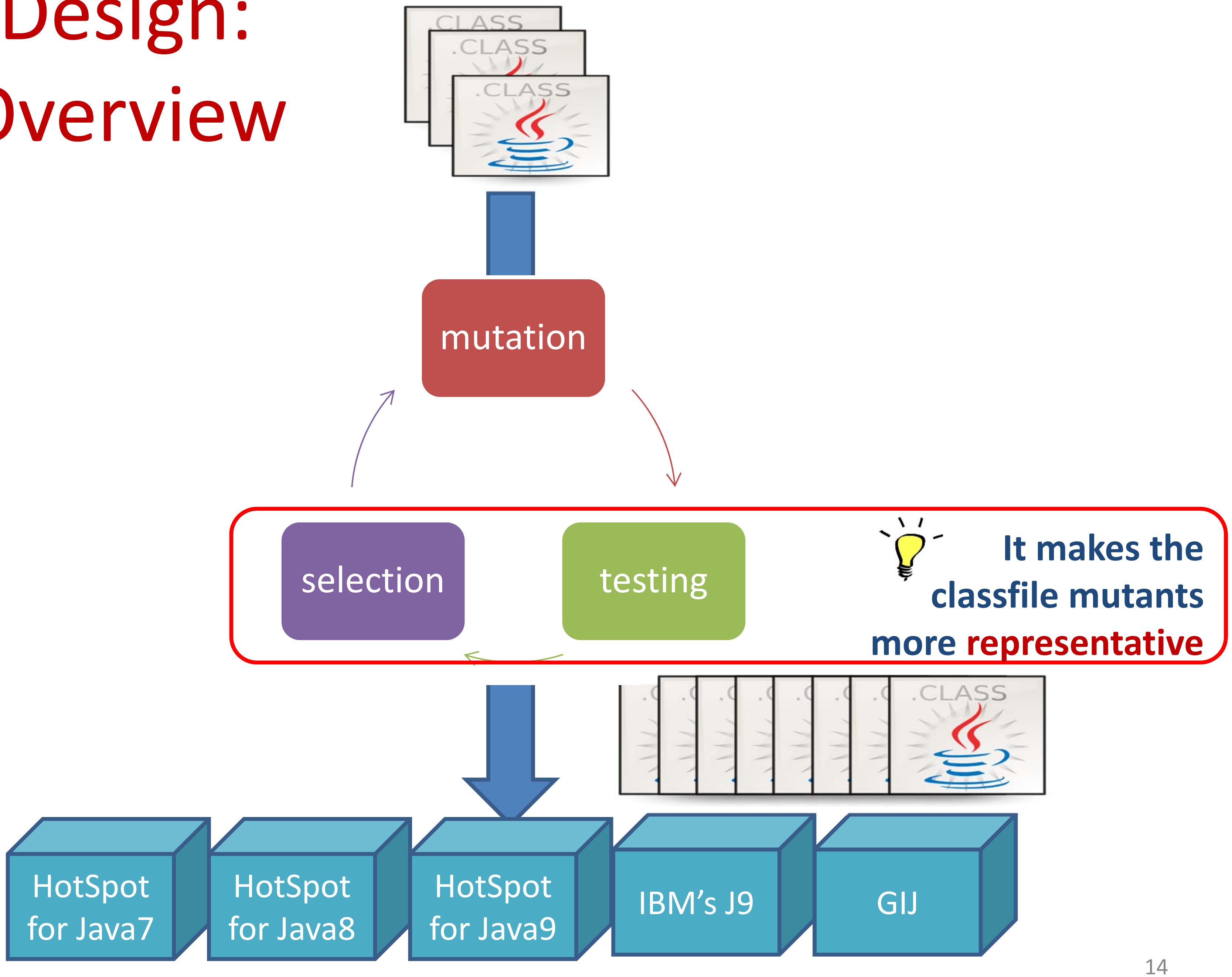
- Equivalence class partition (ECP) saves the testing cost
  - ECP works only if we can decide whether two tests belong to the same partition



Our Design:
An Overview



Our Design: An Overview

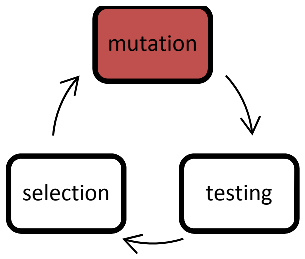


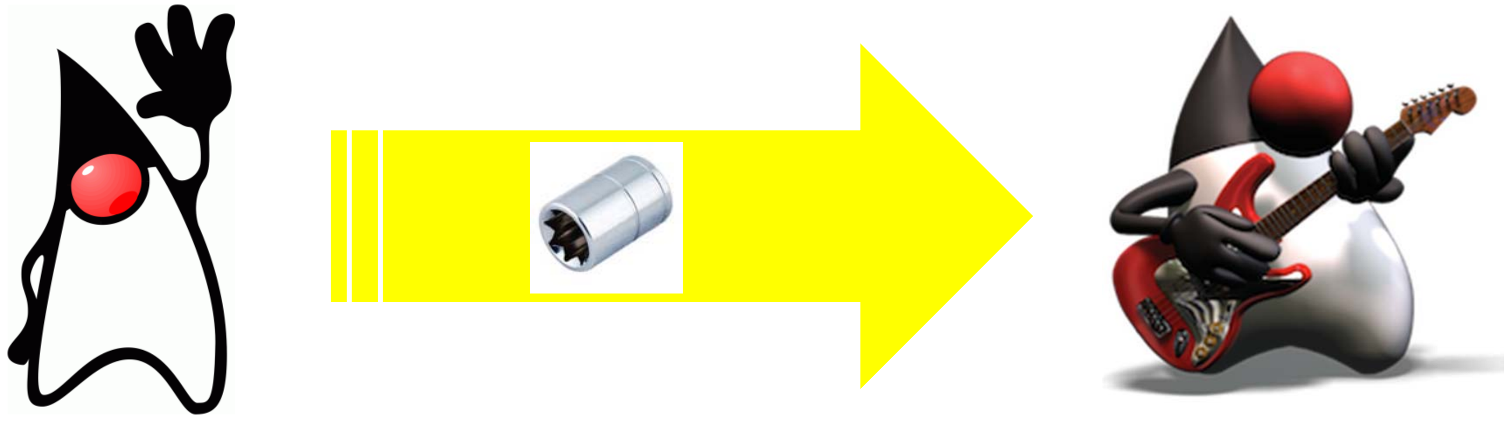
It makes the classfile mutants more **representative**

Outline

- Motivation
- Design
  - Mutating classfiles
  - Selecting representative classfile mutants
  - Selectively applying mutators
  - Differentially testing JVMs
- Evaluation
- Related Work and Conclusion

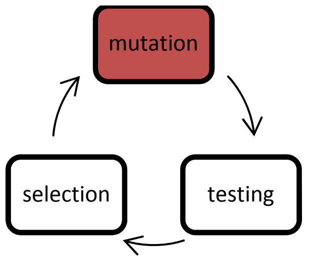
Mutating Classfiles





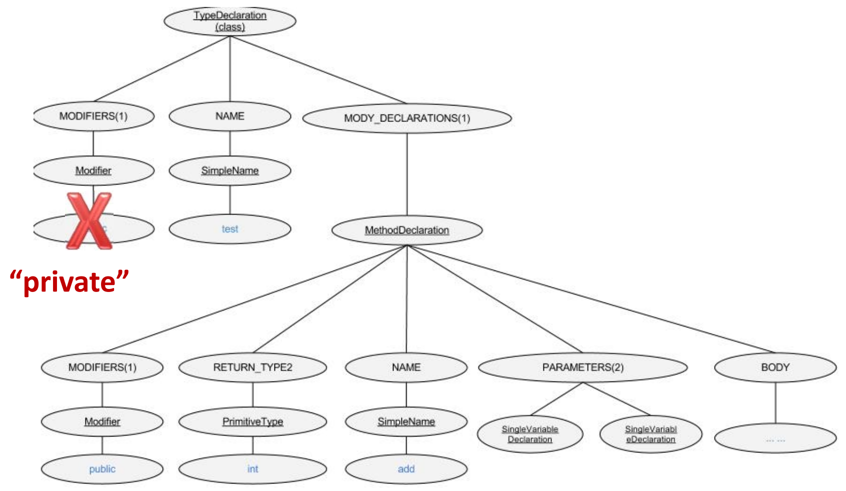
We have designed **129** mutators for mutating classfiles

Mutating Classfiles (2)



123 mutators are designed for rewriting the ASTs of the seeds

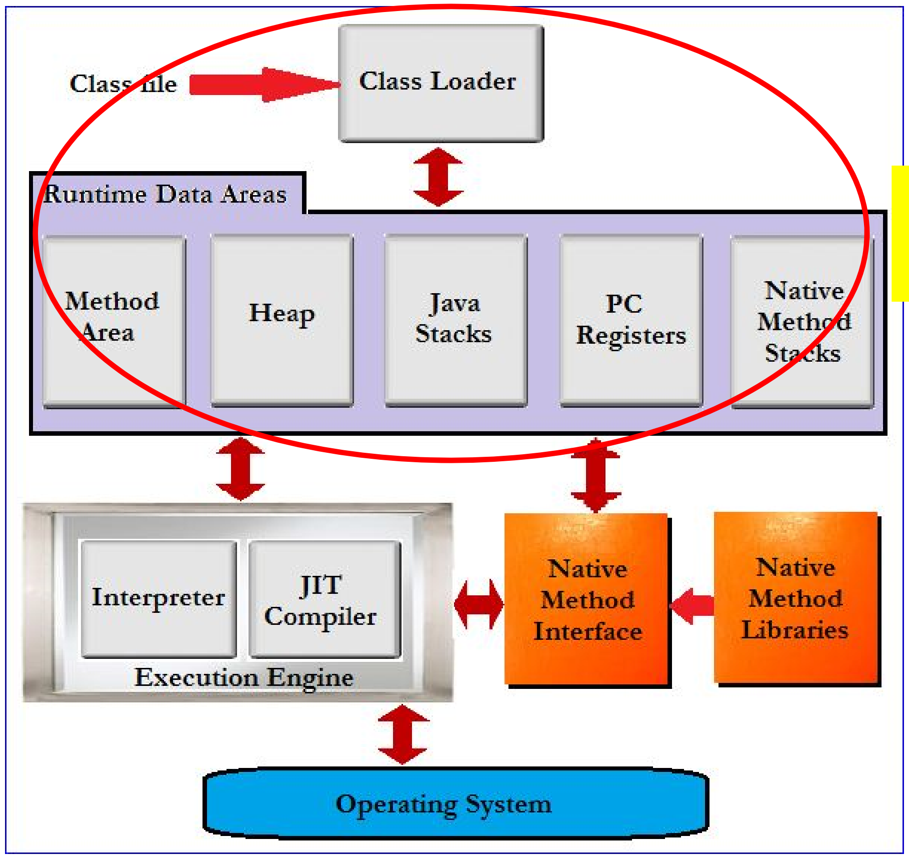
Six mutators are designed for rewriting the Jimple files of the seeds

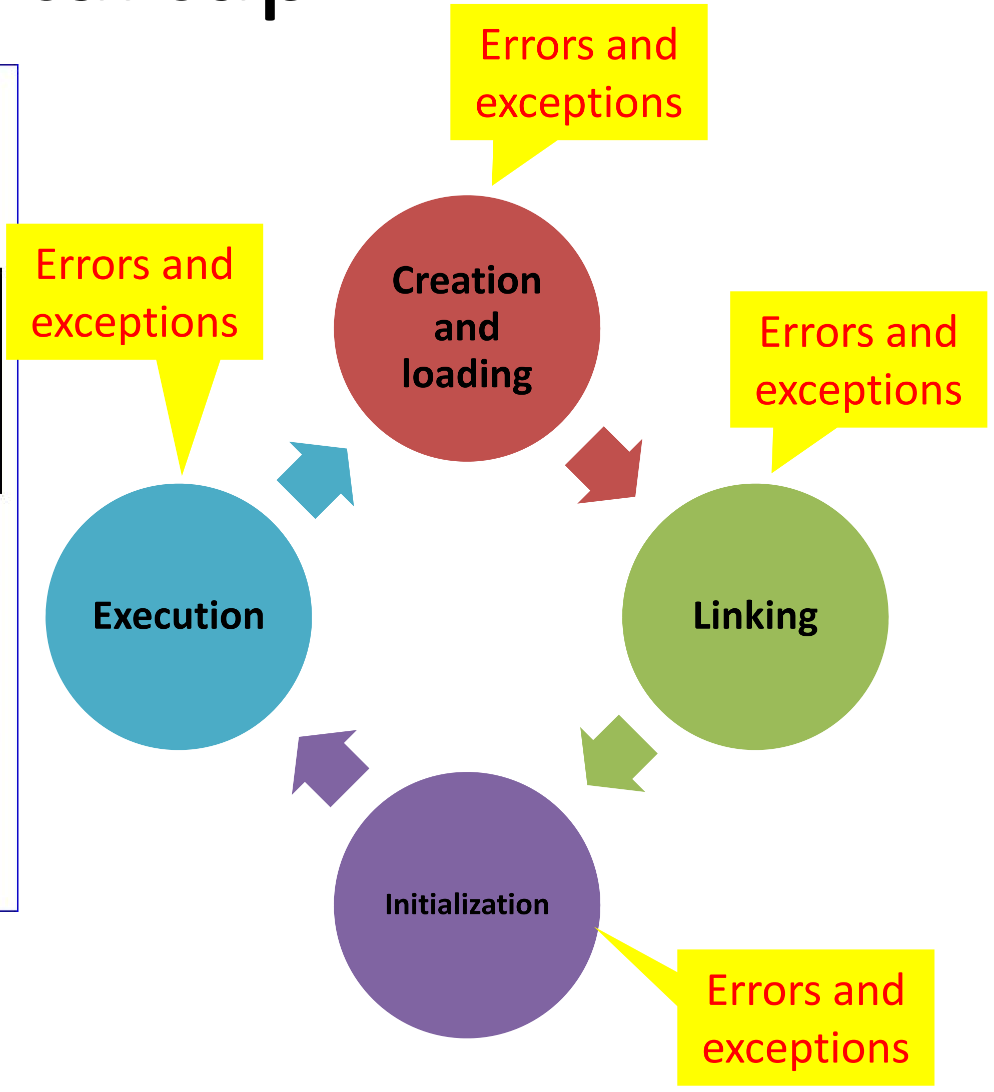


```
r0:=parameter0: java.lang.String[];

r1:=<java.lang.System: java.io.PrintStream out>;

virtualinvoke $r1.<java.io.PrintStream:void
println(java.lang.String)>("Executed");

...
```

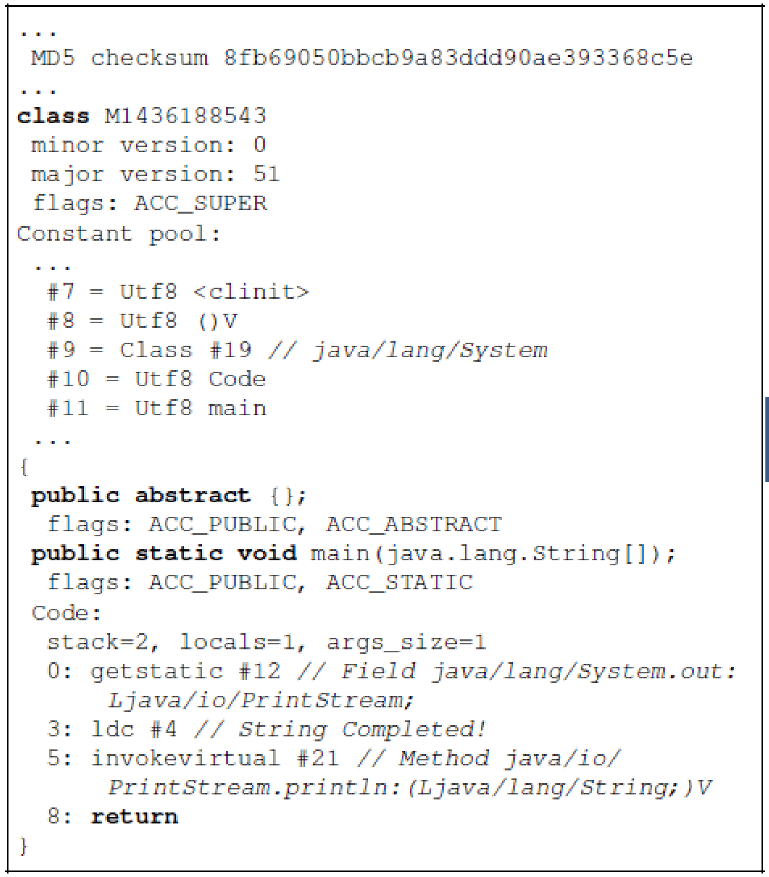
- **Limitation: Only the JVMs' startup processes can be tested**
  - **The mutated program constructs/attributes may be less likely to be activated during execution**

JVM Startup

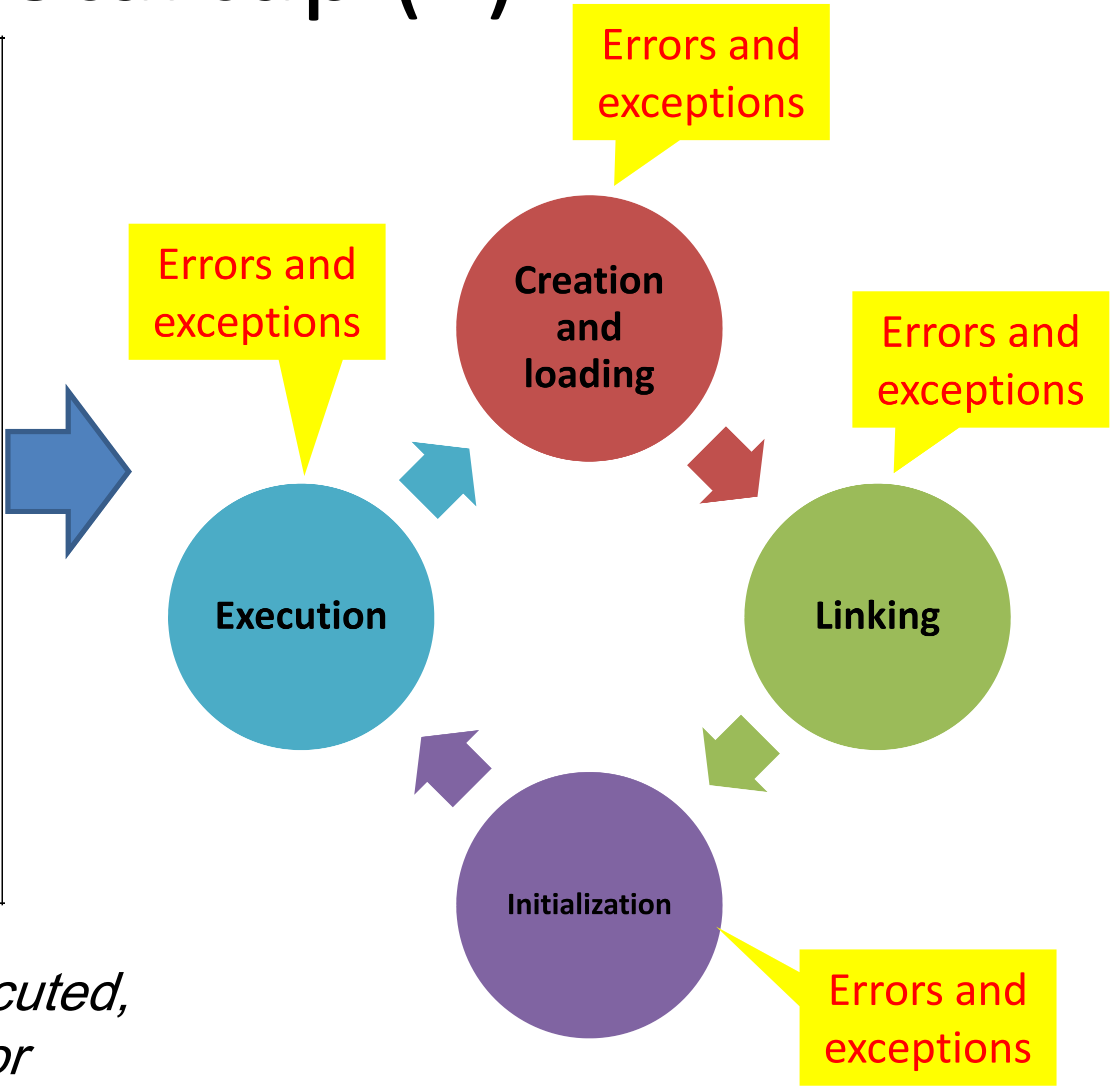

Class file
Class Loader
Runtime Data Areas
Method Area
Heap
Java Stacks
PC Registers
Native Method Stacks
Interpreter
JIT Compiler
Execution Engine
Native Method Interface
Native Method Libraries
Operating System


Errors and exceptions
Creation and loading
Errors and exceptions
Linking
Errors and exceptions
Initialization
Errors and exceptions
Execution

JVM Startup (2)



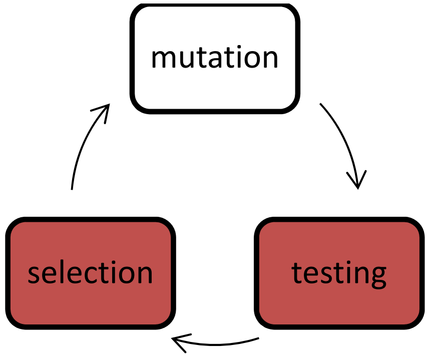
```
...
 MD5 checksum 8fb69050bbcb9a83ddd90ae393368c5e
...
class M1436188543
 minor version: 0
 major version: 51
 flags: ACC_SUPER
Constant pool:
 ...
  #7 = Utf8 <clinit>
  #8 = Utf8 ()V
  #9 = Class #19 // java/lang/System
  #10 = Utf8 Code
  #11 = Utf8 main
 ...
{
 public abstract {};
  flags: ACC_PUBLIC, ACC_ABSTRACT
 public static void main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
 Code:
  stack=2, locals=1, args_size=1
  0: getstatic #12 // Field java/lang/System.out:
      Ljava/io/PrintStream;
  3: ldc #4 // String Completed!
  5: invokevirtual #21 // Method java/io/
      PrintStream.println:(Ljava/lang/String;)V
  8: return
}
```



Can this class be normally executed, or at which stage some errors or exceptions can be thrown out?

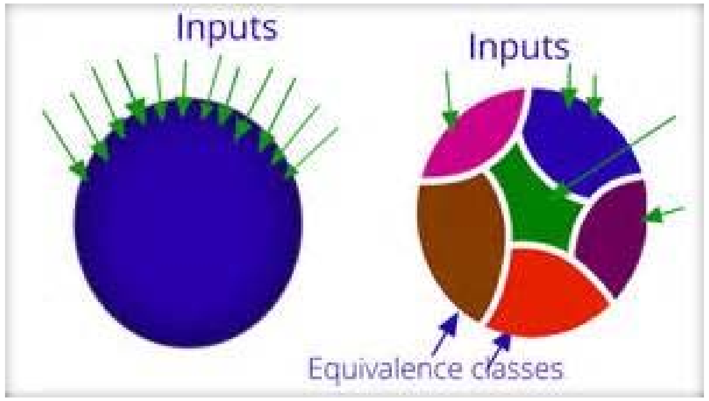
Outline

- Motivation
- Design
  - Mutating classfiles
  - Selecting representative classfile mutants
  - Selectively applying mutators
  - Differentially testing JVMs
- Evaluation
- Related Work and Conclusion

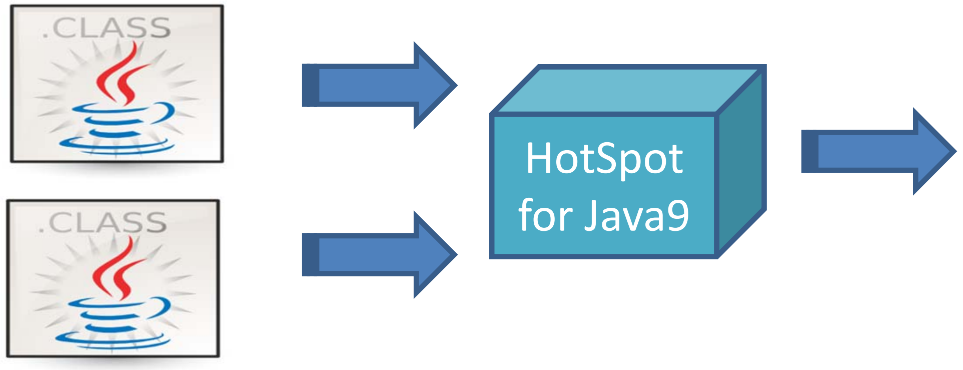


Selecting Representative Classfiles

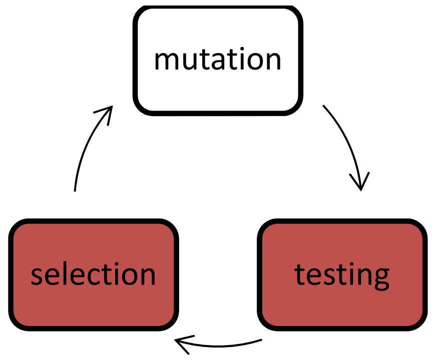
- ECP



- Do two classfiles belong to the same class?

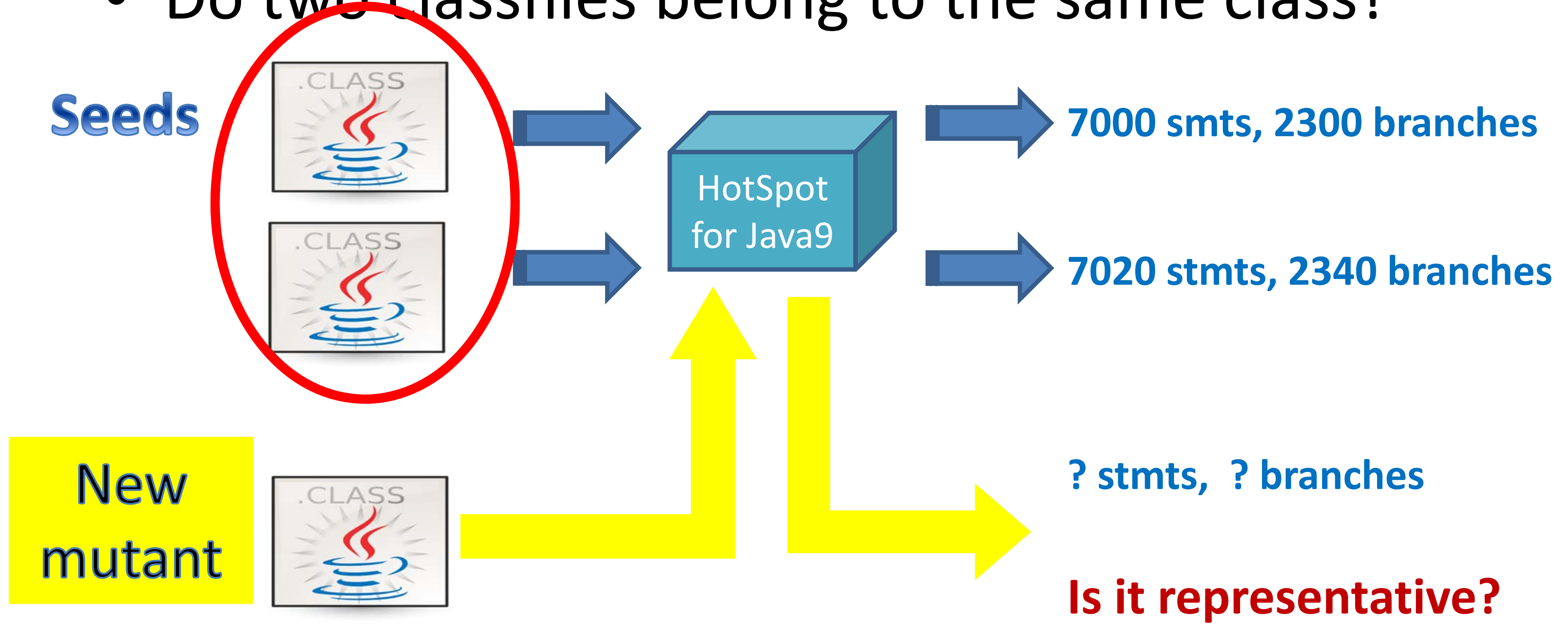


- **Yes, if the reference JVM equally processes them**
- **No, otherwise**



Selecting Representative Classfiles (2)

- Do two classfiles belong to the same class?



Several comparison criteria can be given here

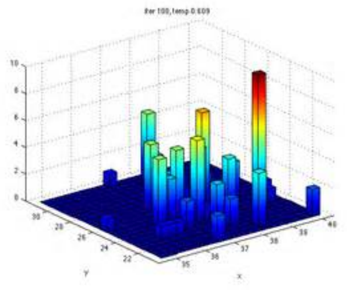
Outline

- Motivation
- Design
  - Mutating classfiles
  - Selecting representative classfile mutants
  - Selectively applying mutators
  - Differentially testing JVMs
- Evaluation
- Related Work and Conclusion

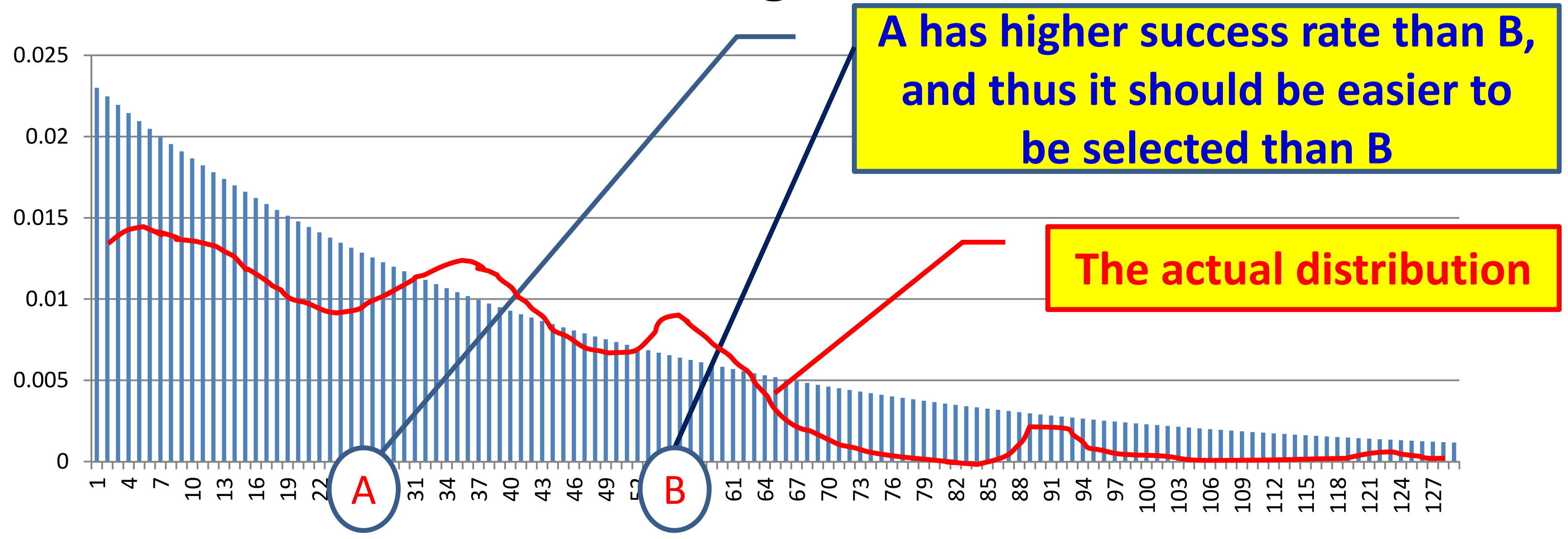
Selecting Mutators

- Goal: to create as many representative classfiles as possible
- Fact: mutators are designed arbitrarily; some are effective, while some others are useless
- A naïve solution: to select mutators by learning from prior knowledge

An MCMC Sampling Method



- Which mutator will be selected at each step?
  – A desired distribution: geometric distribution



Proposition: The more number of representative classfiles have been created by a mutator, the more likely the mutator should be selected for further mutations

More Details

- The desired distribution

$$\Pr(X = k) = (1 - p)^{k-1}\,p$$

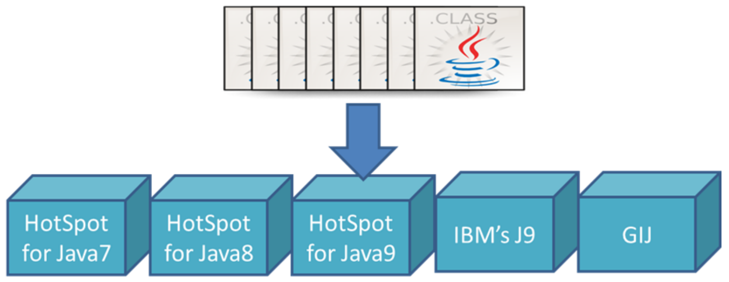
- Classfuzz picks up mutators at random, and then accepts or rejects the mutators by a Metropolis choice

$$\begin{aligned} A(mu_1 \rightarrow mu_2) &= min(1, \frac{\Pr(mu_2)}{\Pr(mu_1)}) \\ &= min(1, (1 - p)^{k_2 - k_1}) \end{aligned}$$

Outline

- Motivation
- Design
  - Mutating classfiles
  - Selecting representative classfile mutants
  - Selectively applying mutators
  - Differentially testing JVMs
- Evaluation
- Related Work and Conclusion

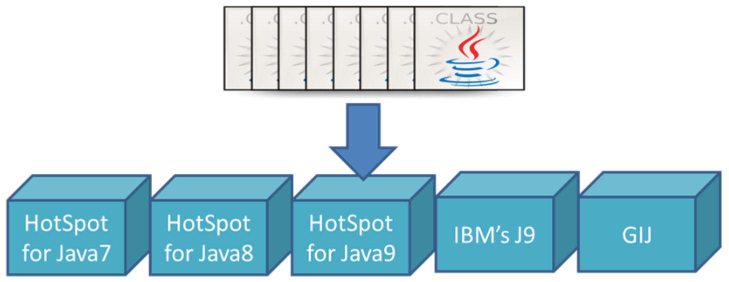
Execution Comparison



$result_0 = jvm_0 (env_0, c, input)$
$result_1 = jvm_1 (env_1, c, input)$
$result_2 = jvm_2 (env_2, c, input)$
$result_3 = jvm_3 (env_3, c, input)$
$result_4 = jvm_4 (env_4, c, input)$

A *JVM discrepancy* appears when $result_i \neq result_j$
It can either be a JVM defect or a compatibility issue

Execution Comparison (2)



$result_0$ = jvm_0 (env_0, c, input)

$result_1$ = jvm_1 (env_0, c, input)

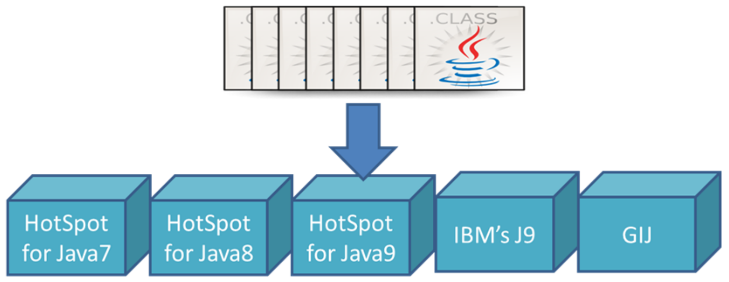
$result_2$ = jvm_2 (env_0, c, input)

$result_3$ = jvm_3 (env_0, c, input)

$result_4$ = jvm_4 (env_0, c, input)

A *JVM defect* appears when $result_i \neq result_j$

Execution Comparison (3)



$result_0 = jvm_0\ (env_0, c, input)$

$result_1 = jvm_1\ (env_0, c, input)$

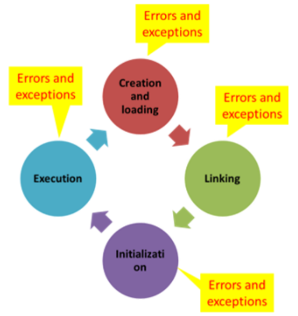
$result_2 = jvm_2\ (env_0, c, input)$

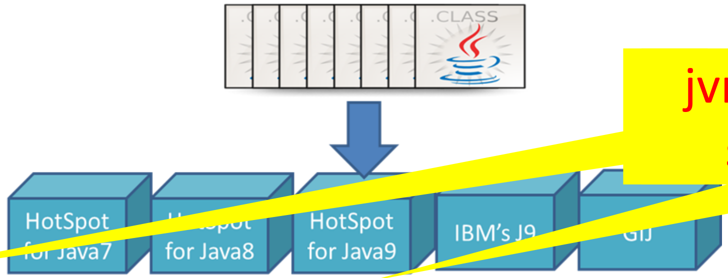
$result_3 = jvm_3\ (env_0, c, input)$

$result_4 = jvm_4\ (env_0, c, input)$

A *JVM defect* appears when $result_i \neq result_j$

Execution Comparison (3)





jvm_0 may miss catching some format errors

0 ⟵ $result_0 = jvm_0\,(env_0, c, input)$

1 ⟵ $result_1 = jvm_1\,(env_0, c, input)$

1 ⟵ $result_2 = jvm_2\,(env_0, c, input)$

1 ⟵ $result_3 = jvm_3\,(env_0, c, input)$

1 ⟵ $result_4 = jvm_4\,(env_0, c, input)$

A *JVM defect* appears when $result_i \neq result_j$

Outline

- Motivation
- Design
- Evaluation
  - Setup
  - Results
- Related Work and Conclusion

Setup

- Coverage collection
  - HotSpot for Java9
  - GCOV + LCOV

At each run the coverage can be conveniently collected

HotSpot (260K LOCs)
Cost for cov. analysis: 30+ mins

share/vm/classfile/ (11977 LOCs) ✓
Cost for cov. analysis: 90 secs

- Seeds
  - 1216 classfiles in JRE 7

Evaluated Methods

- Classfuzz supplemented with a uniqueness criterion
  - [st], [stbr], [tr] – explained in the paper
- Randfuzz, Greedyfuzz, Uniquefuzz

	classfuzz	randfuzz	greedyfuzz	uniquefuzz
Mutation-based	✓	✓	✓	✓
Cov. analysis	✓	✗	✓	✓
Uniqueness criterion	[st] [stbr] [tr]	✗	[stbr]	[stbr]
Mutator selection	✓	✗	✗	✗

Metrics

- **RQ1**: How many test classfiles can be generated?
  - *#Iterations, |GenClasses|, |TestClasses|*

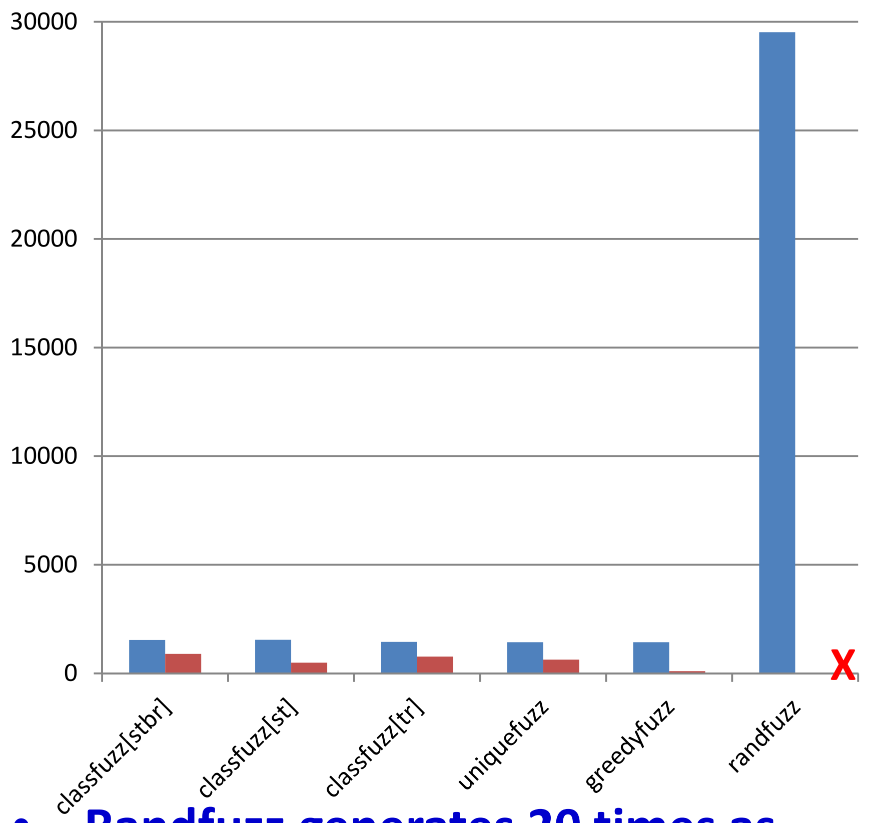
- **RQ2**: How effective are the test classfiles?
  - *|Discrepancies|, |Distinct Discrepancies|, diff rate*

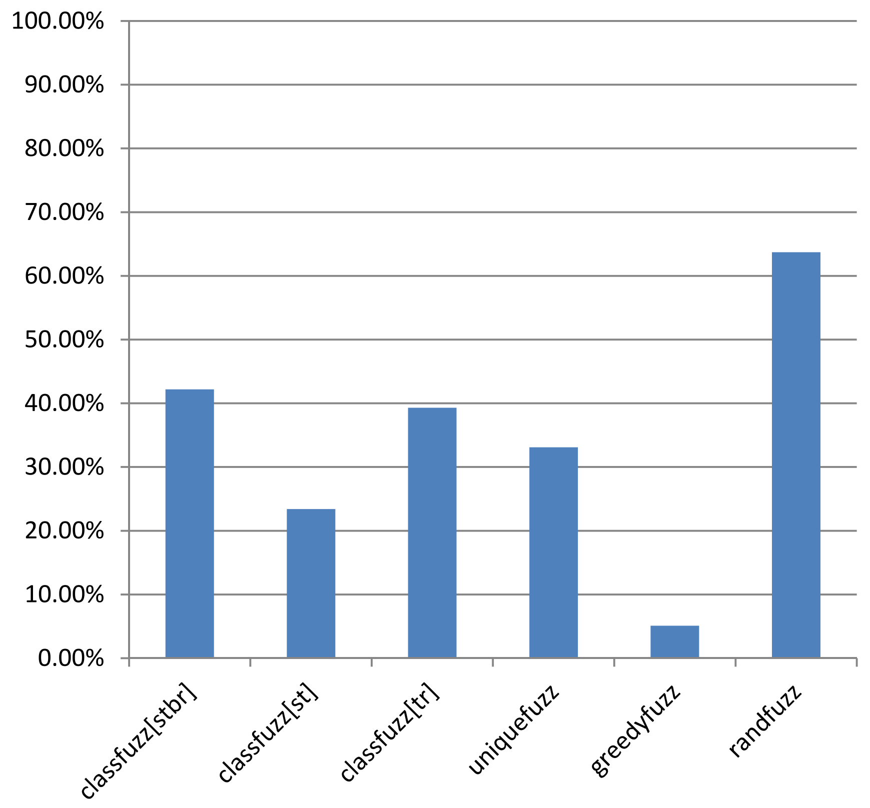
- **RQ3**: Can the test classfiles find any JVM defects?

Outline

- Motivation
- Design
- Evaluation
  - Setup
  - Results
- Related Work and Conclusion

Results on Classfile Generation





- **Randfuzz generates 20 times as many classfiles as those generated by any other algorithm**
- **Classfuzz[stbr] generates the most number of representative classfiles**

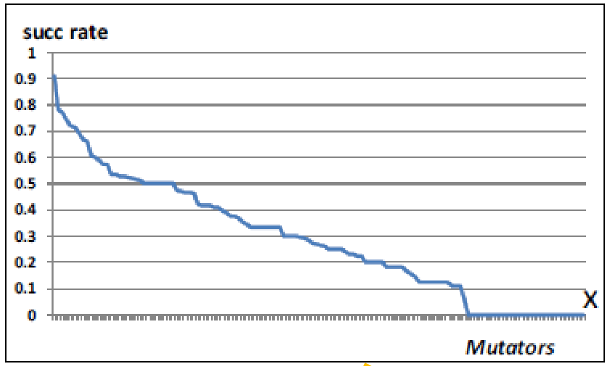
Classfuzz[stbr] achieves the highest success rate among all the coverage-directed algorithms

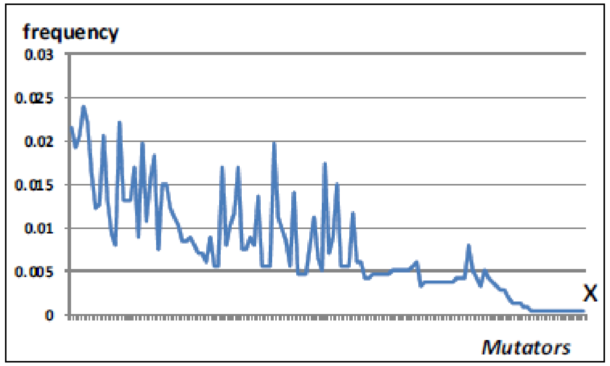
Results on Classfile Generation (2)

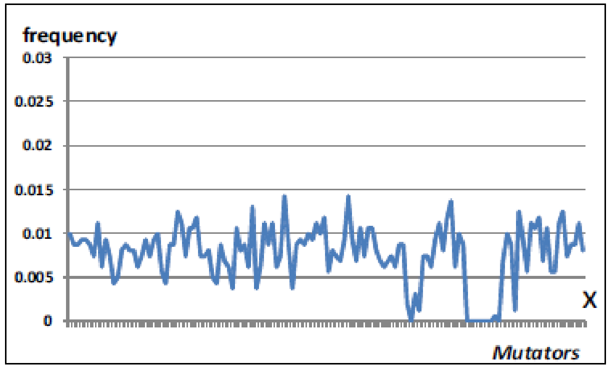
- Classfuzz can utilize the prior knowledge to select mutators

strongly correlated

succ rate **classfuzz** **randfuzz**







(a) Success rates of mutators for generating $TestClasses_{classfuzz[stbr]}$.

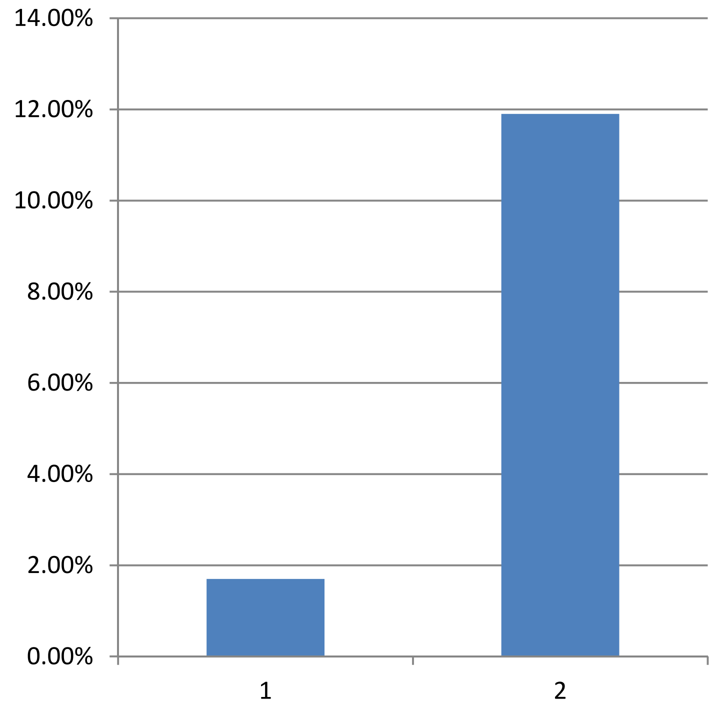
(b) Frequencies of mutators for generating $TestClasses_{classfuzz[stbr]}$.

(c) Frequencies of mutators for generating $TestClasses_{uniquefuzz}$.

weakly correlated

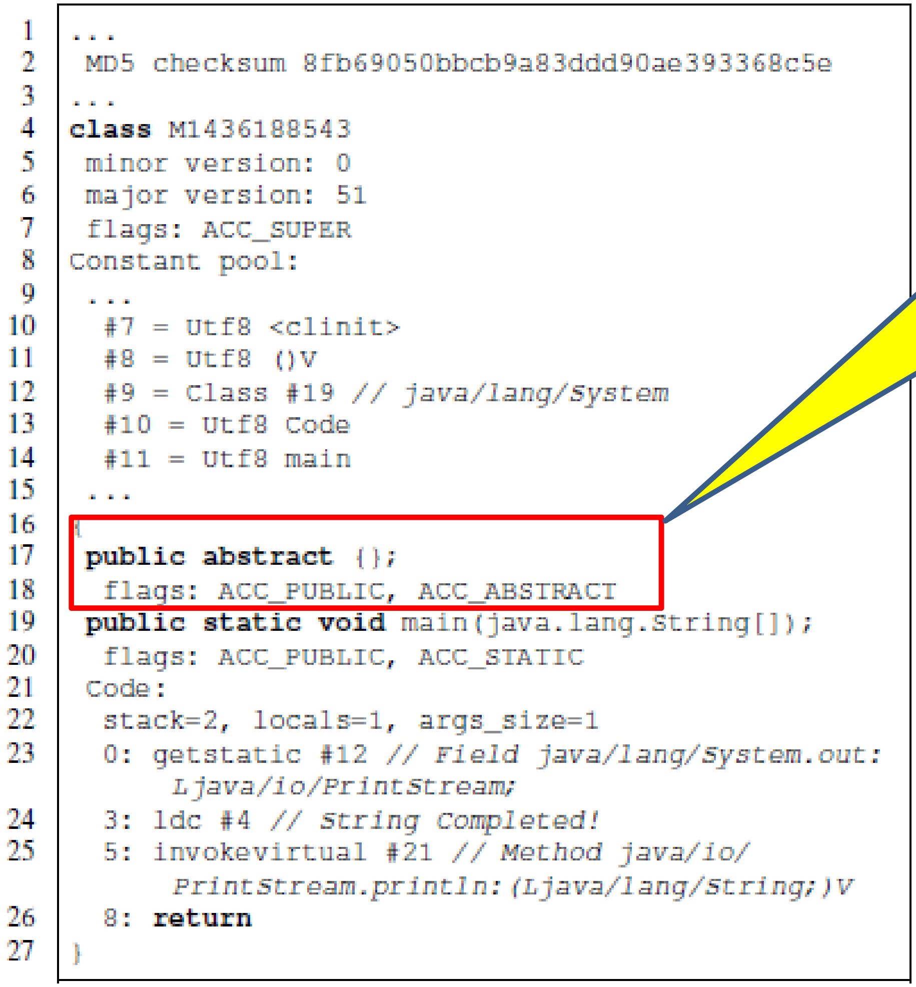
Results on Differential JVM Testing

- Classfuzz can enhance the ratio of discrepancy triggering classfiles from 1.7% to 11.9%



- **JVMs are compatible for most of the classfiles, but differ in processing corner cases**
- **We have experienced 898 different execution paths. 107 paths were related to JVM behavior differences**

Discrepancy Analysis (1)



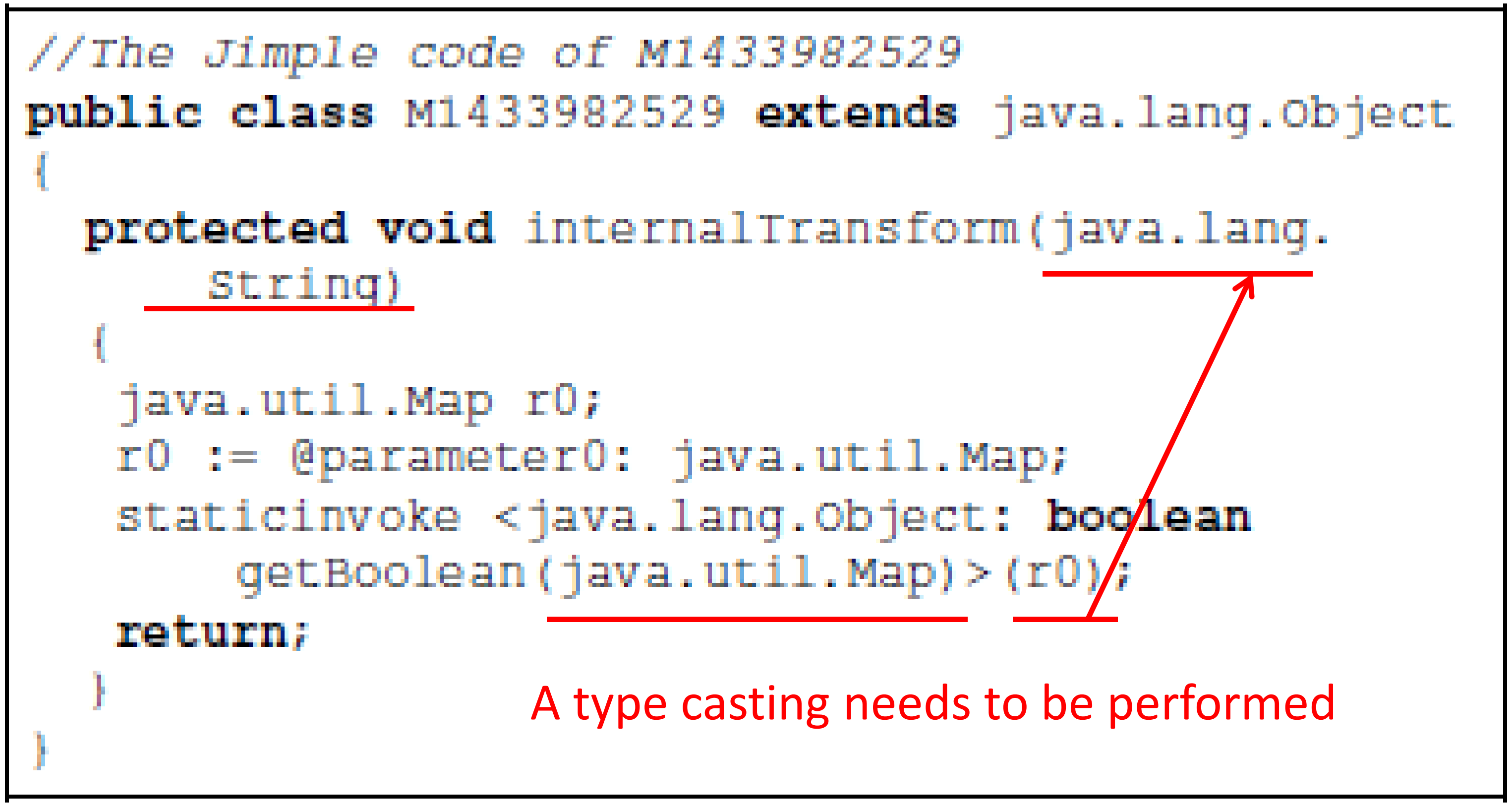
```
...
 MD5 checksum 8fb69050bbcb9a83ddd90ae393368c5e
...
class M1436188543
 minor version: 0
 major version: 51
 flags: ACC_SUPER
Constant pool:
 ...
  #7 = Utf8 <clinit>
  #8 = Utf8 ()V
  #9 = Class #19 // java/lang/System
  #10 = Utf8 Code
  #11 = Utf8 main
 ...
{
 public abstract {};
  flags: ACC_PUBLIC, ACC_ABSTRACT
 public static void main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
 Code:
  stack=2, locals=1, args_size=1
  0: getstatic #12 // Field java/lang/System.out:
       Ljava/io/PrintStream;
  3: ldc #4 // String Completed!
  5: invokevirtual #21 // Method java/io/
       PrintStream.println:(Ljava/lang/String;)V
  8: return
}
```

public abstract {};

- HotSpot takes it as a ordinary method
- J9 reports a format error

The JVM specification needs to be clarified

Discrepancy Analysis (2)

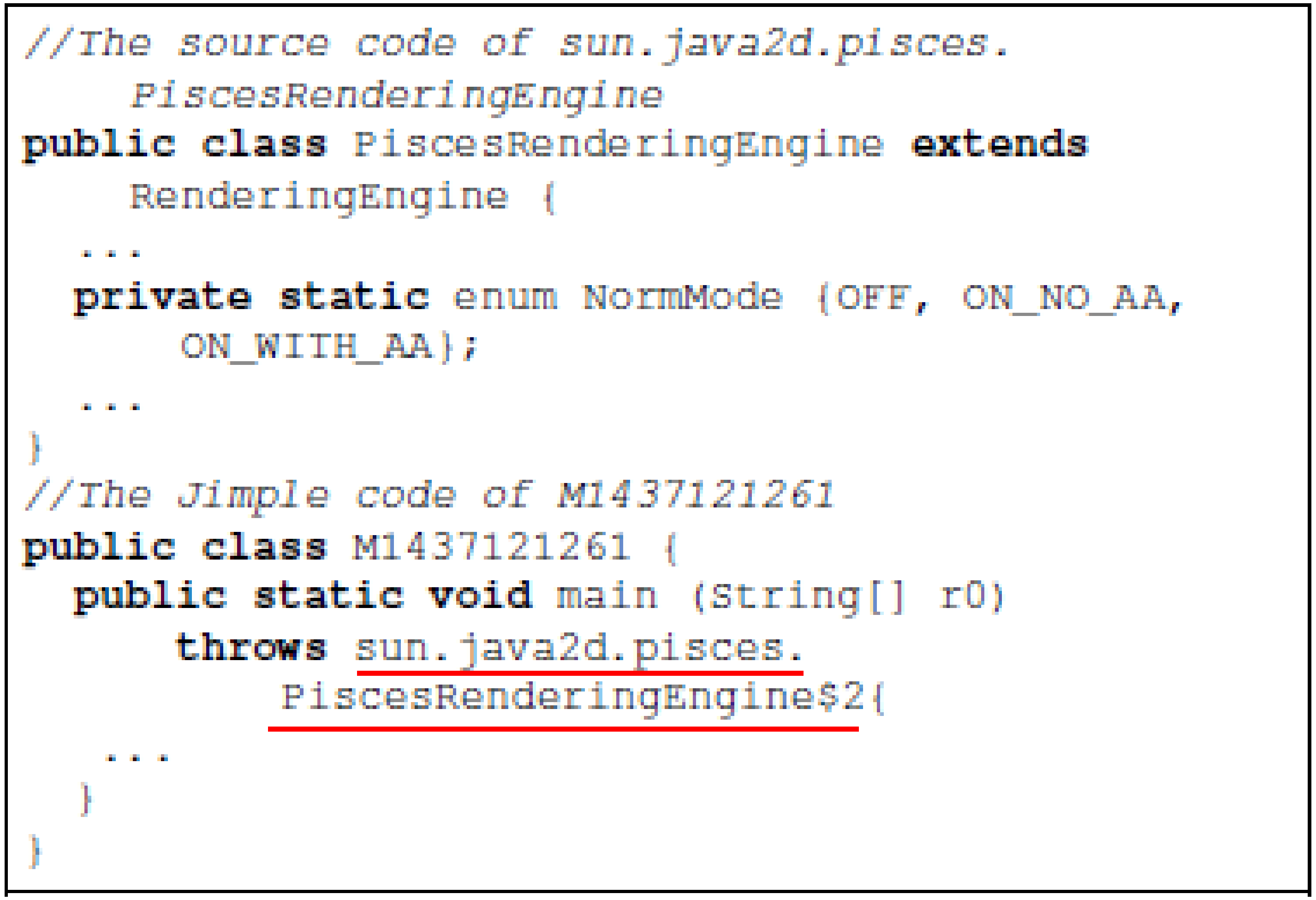


```
//The Jimple code of M1433982529
public class M1433982529 extends java.lang.Object
{
  protected void internalTransform(java.lang.
      String)
  {
   java.util.Map r0;
   r0 := @parameter0: java.util.Map;
   staticinvoke <java.lang.Object: boolean
       getBoolean(java.util.Map)>(r0);
   return;
  }
}
```

A type casting needs to be performed

JVMs take their own classfile verification and type checking polices

Discrepancy Analysis (3)



```
//The source code of sun.java2d.pisces.
    PiscesRenderingEngine
public class PiscesRenderingEngine extends
    RenderingEngine {
  ...
  private static enum NormMode {OFF, ON_NO_AA,
      ON_WITH_AA};
  ...
}
//The Jimple code of M1437121261
public class M1437121261 {
  public static void main (String[] r0)
      throws sun.java2d.pisces.
          PiscesRenderingEngine$2{
    ...
  }
}
```

JVMs are not compatible to access some classes

Discrepancy Analysis (4)

- More findings
  - J9 is less strict than HotSpot because J9 only verifies a method when it is invoked, while HotSpot verifies all methods before execution
  - GIJ can execute an interface having a main method
  - GIJ accepts a class with duplicate fields
  - …
- These discrepancies can be found in a package of 62 discrepancy-triggering classes

Outline

- Motivation
- Design
- Evaluation
- Conclusion

Conclusion

- **Problem**
  - Testing JVMs requires painstaking effort in designing test classfiles along with their test oracles
- **Proposal**: **classfuzz: coverage-directed fuzz testing**
  - **Test classfile generation**
    - Mutating classes and selectively applying mutators
    - Deciding the representativeness of a classfile mutant
  - **Differential JVM testing**
- **Tool is available at** http://stap.sjtu.edu.cn/~chenyt/DTJVM/index.htm