SOFT620020.02
Advanced Software Engineering

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Course Outline

Date	Topic
Sep. 10	Introduction
Sep. 17	Testing Overview
Sep. 24	Holiday
Oct. 01	Holiday
Oct. 08	Guided Random Testing
Oct. 15	Search-Based Testing
Oct. 22	Performance Analysis
Oct. 29	Security Testing

Date	Topic
Nov. 05	**Compiler Testing**
Nov. 12	Mobile Testing
Nov. 19	Delta Debugging
Nov. 26	Presentation 1
Dec. 03	Bug Localization
Dec. 10	Automatic Repair
Dec. 17	Symbolic Execution
Dec. 24	Presentation 2

Discussion – Do You Trust Compilers?

```
int main () {
  // do something
  ...
  return 0;
}
```


```
...
call puts
movl $0, %eax
popq %rbp
ret
```

Developers' **belief**: Compilers are **faithful** translators

Reflect on This Trust – llvm bug 14972

```
struct tiny { char c; char d; char e; };

void foo(struct tiny x) {
    if (x.c != 1) abort();
    if (x.e != 1) abort();
}

int main() {
    struct tiny s;
    s.c = 1; s.d = 1; s.e = 1;
    foo(s);
    return 0;
}
```

removed by optimization

```
$ clang -m32 -O0 test.c ; ./a.out
$ clang -m32 -O1 test.c ; ./a.out
Aborted (core dumped)
```

Reflect on This Trust – gcc bug 58731

```
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        int f = 2147483647 - b;
        for (; c;)
            for (;;) {
                e = a > f;
                if (d) break;
            }
    return 0;
}
```

integer overflow

```
$ gcc -O0 test.c ; ./a.out
$ gcc -O3 test.c ; ./a.out
^C
```

Reflect on This Trust – Debatable Bug 1

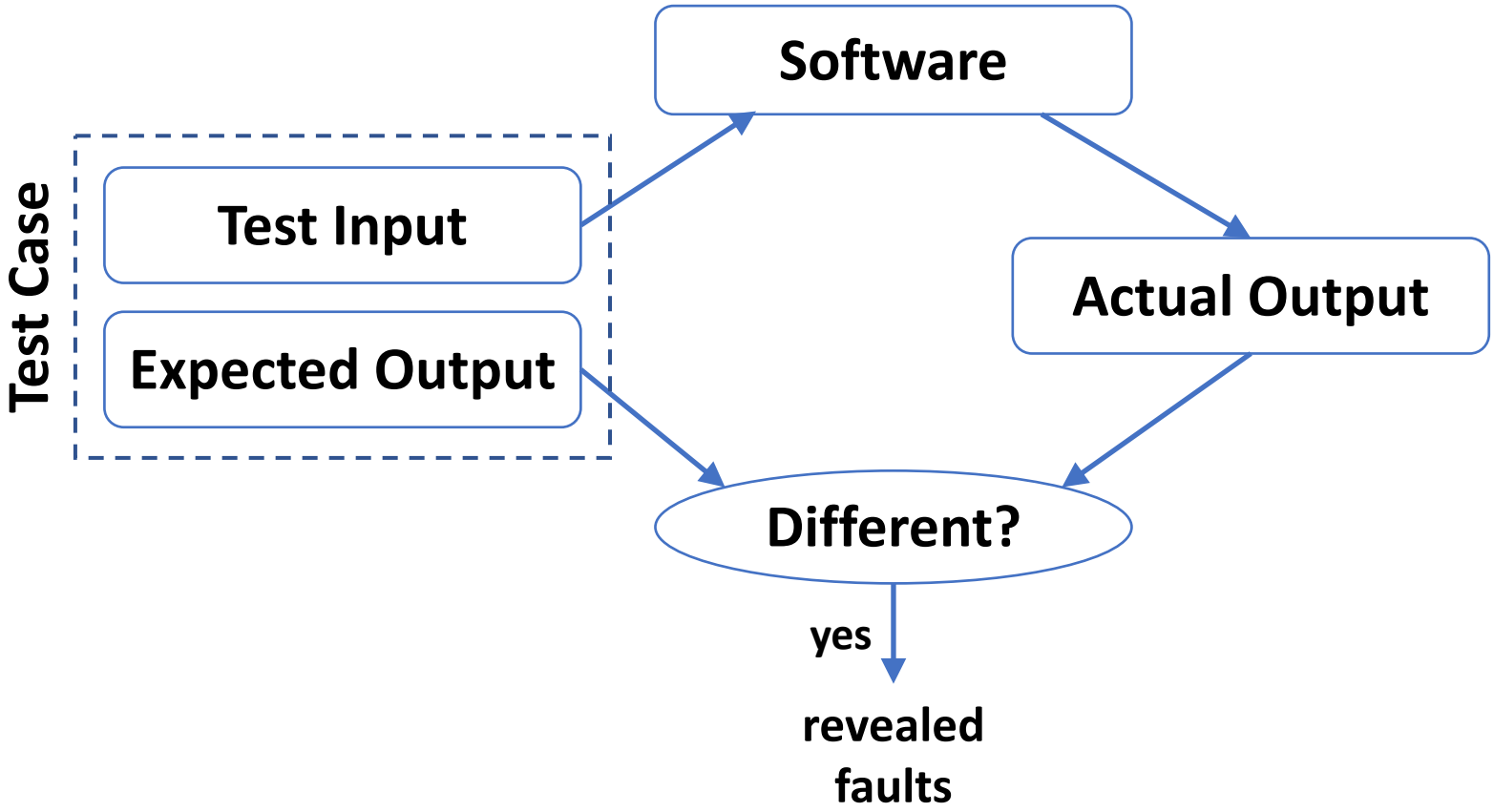
```
char *buf = ...;
char *buf_end = ...;
unsigned int len = ...;

if (buf + len >= buf_end)
  return; // len too large

if (buf + len < buf)
  return; // overflow, buf + len wrapped around

// write to buf[0..len-1]
...
```

But this is a **security threat**, i.e., use a large **len** to trigger **buffer overflow**

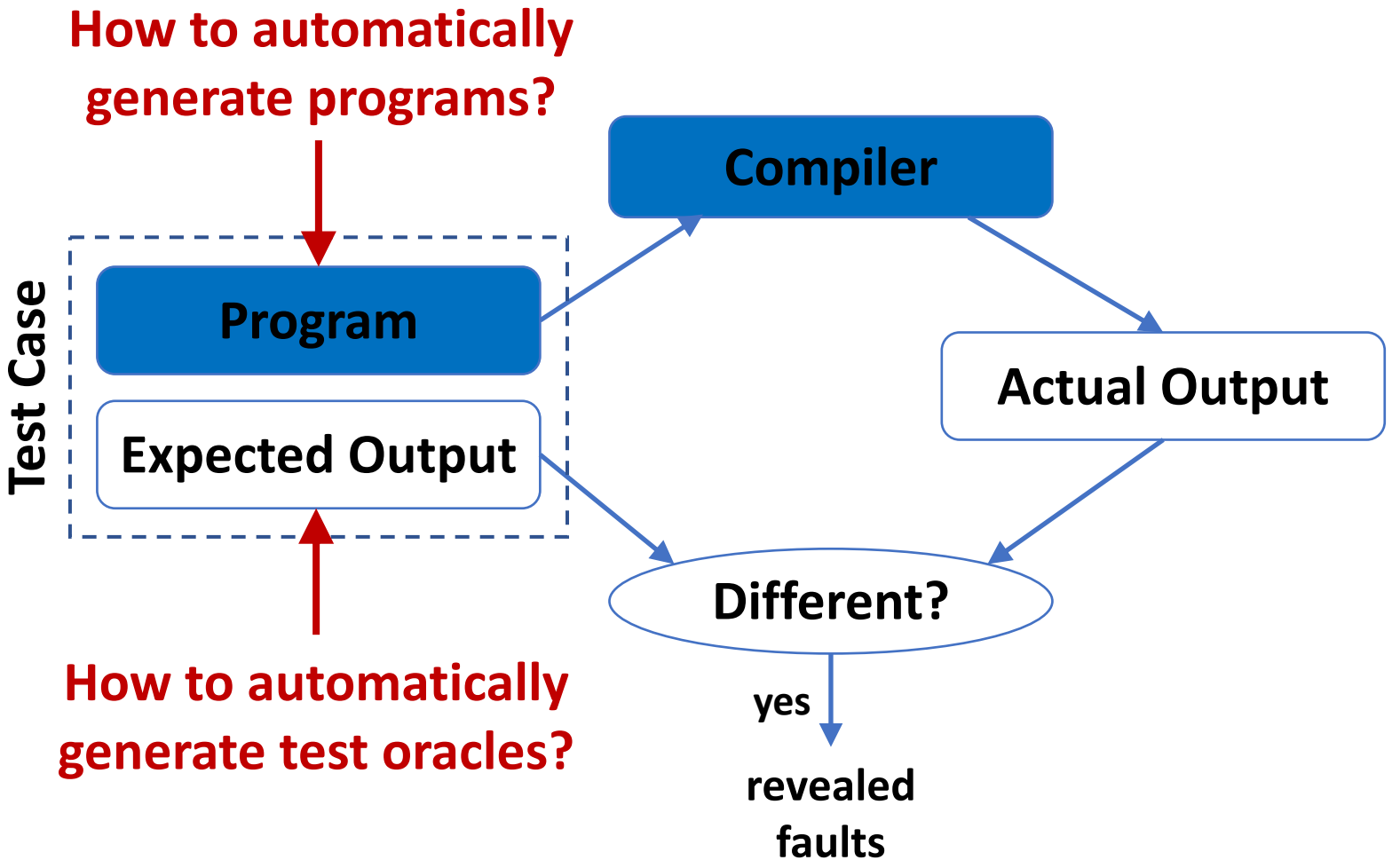
Reflect on This Trust – Debatable Bug 2

```
bool isPasswordCorrect() {
  bool isPasswordCorrect = false;
  string Password("password");

  if(Password == getPasswordFromUser()) {
    isPasswordCorrect = true;
  }
  // removed from the optimized code
  // secure the code by wiping the password from memory
  memset(Password, 0, sizeof(Password));

  return isPasswordCorrect;
}
```

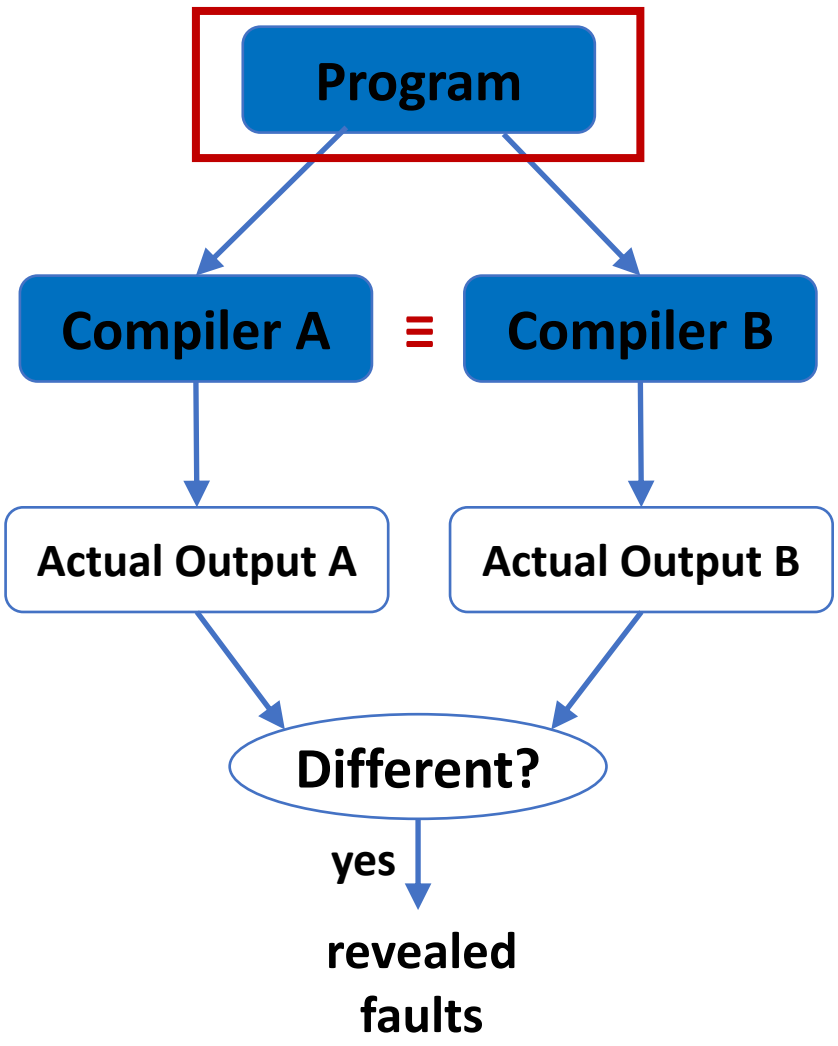
Typical Software Testing

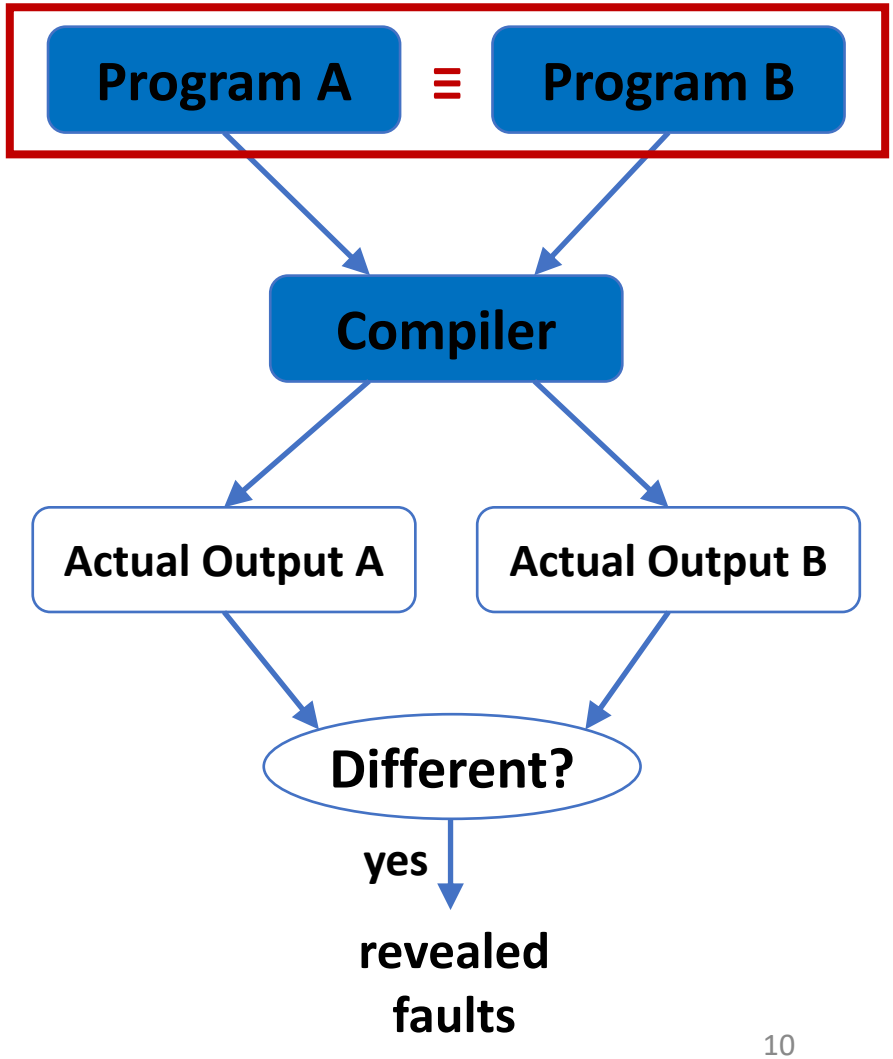


Compiler Testing



Differential Testing (Solving Oracle Problem)



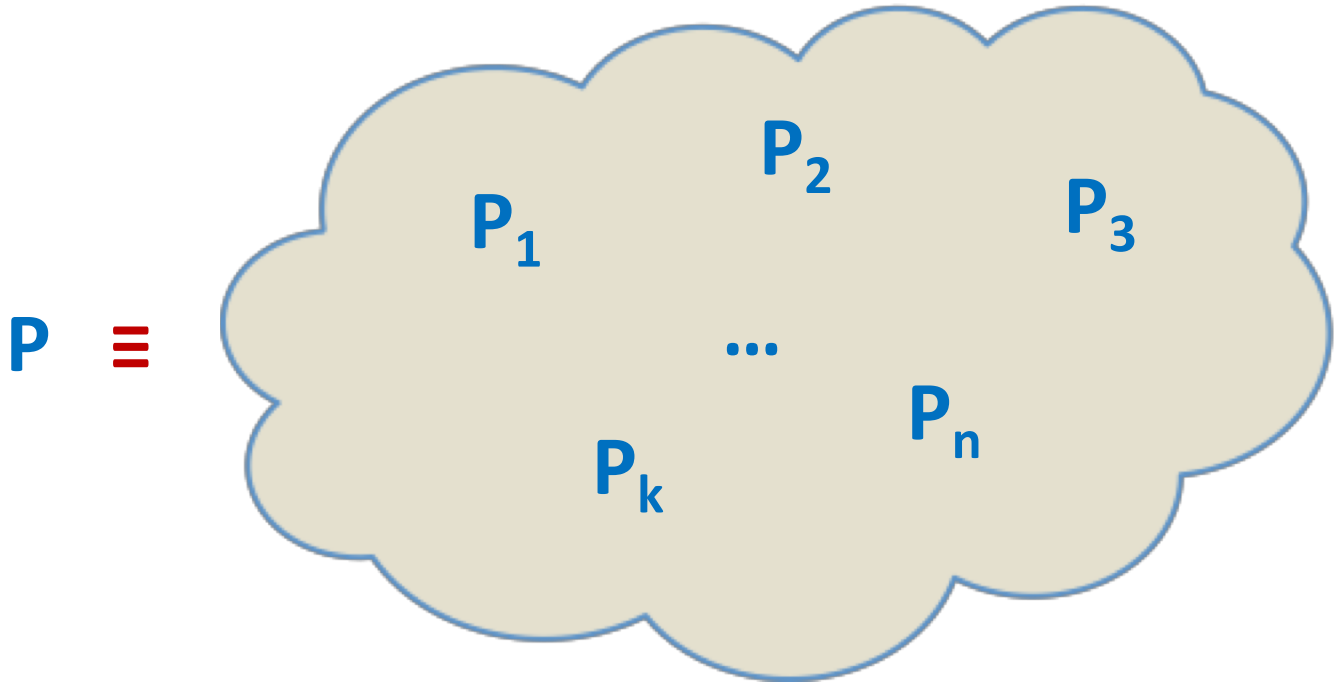


Compiler Validation via Equivalence Modulo Inputs

Vu Le, Mehrdad Afshari, Zhendong Su

PLDI 2014, Distinguished Paper Award

Vision for Equivalent Programs



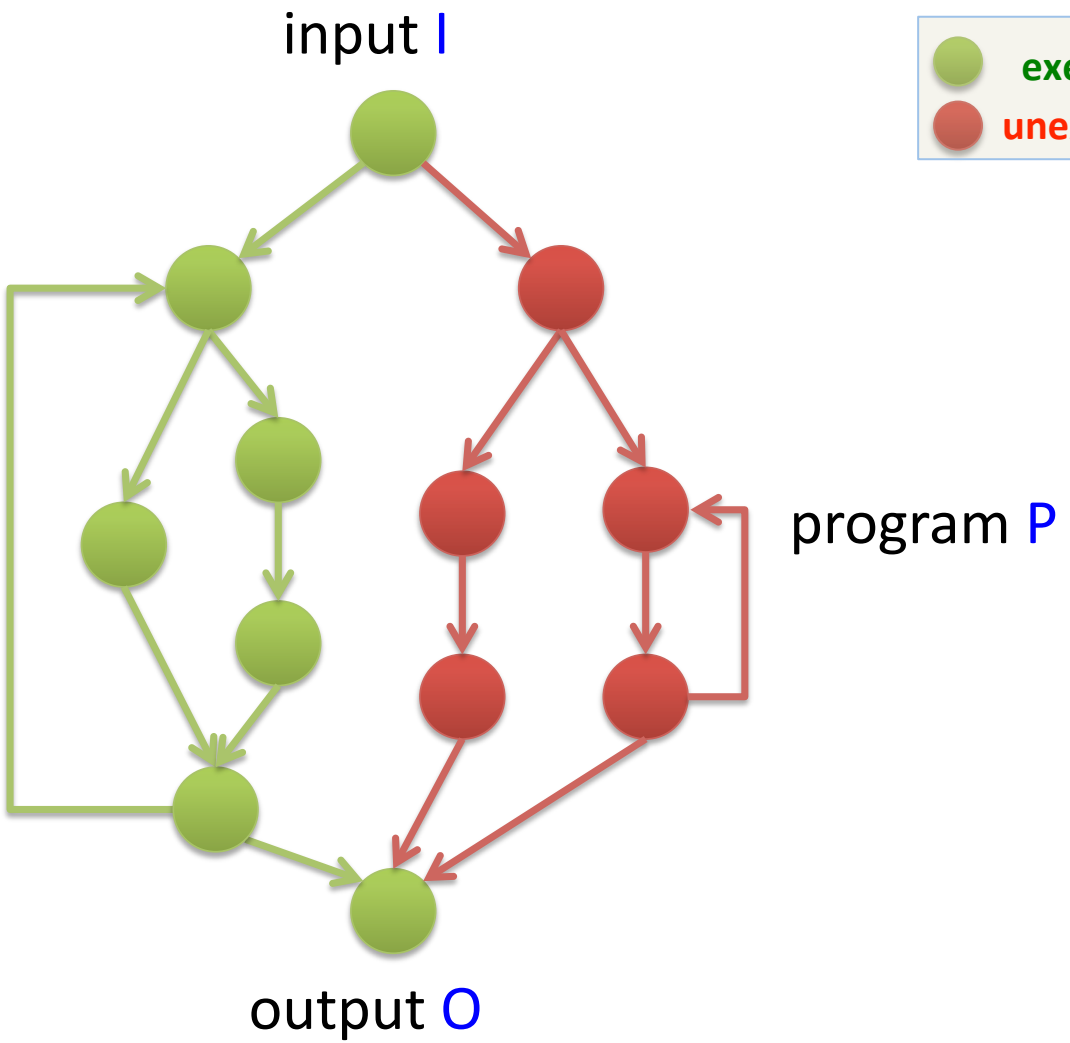
Take existing real-world code and transform it into a different but equivalent variants of the original code

Equivalence Modulo Inputs (EMI)

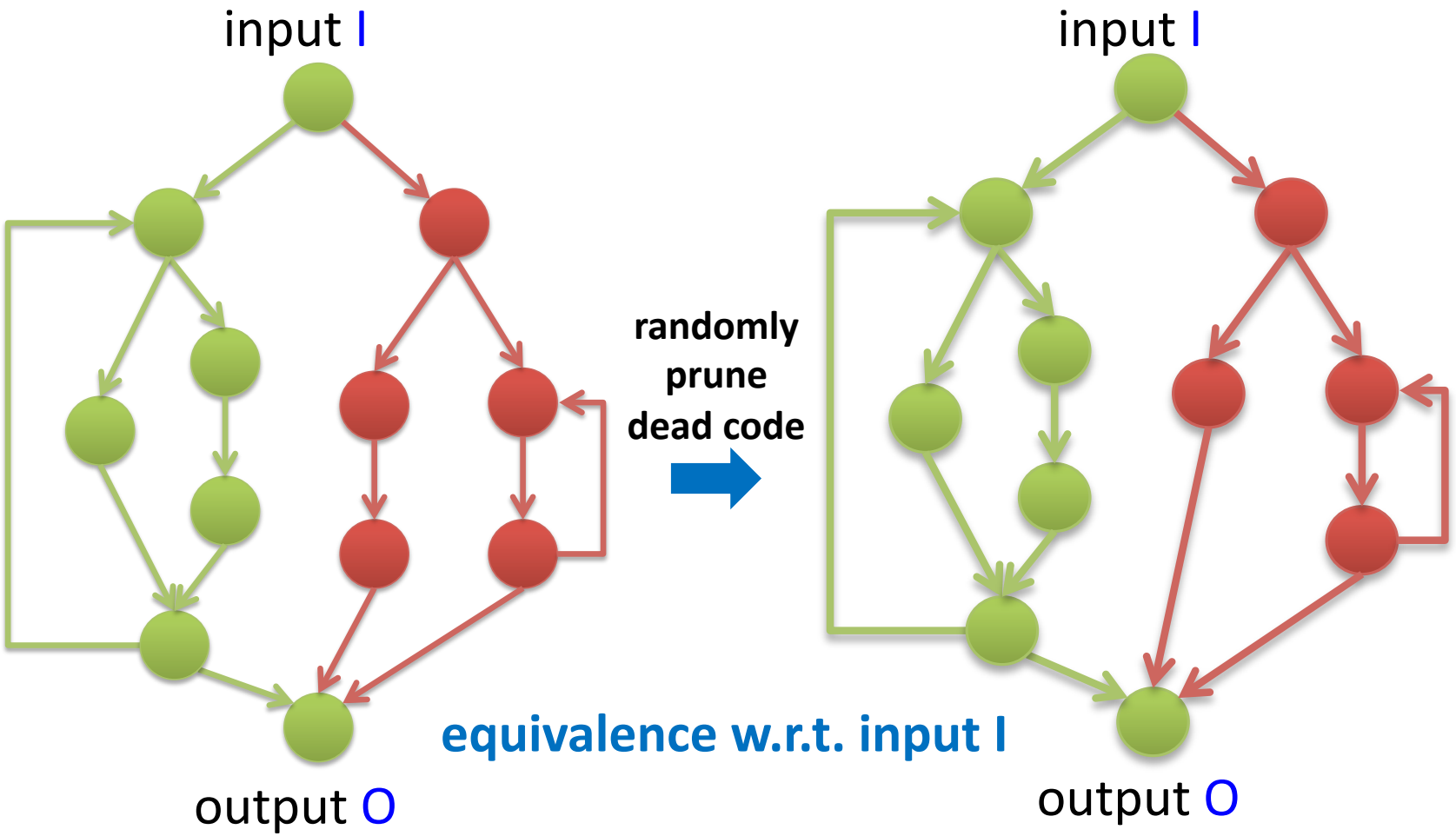
- Relax equivalence w.r.t. a **given input**
  - Variants must satisfy **P(i) = P_k(i)** on input **i**
  - Variants may differ on other input **j**: **P(j) != P_k(j)**

- Exploit the **interplay** between
  - **Dynamic** program execution on **some input**
  - **Static** compilation for **all inputs**

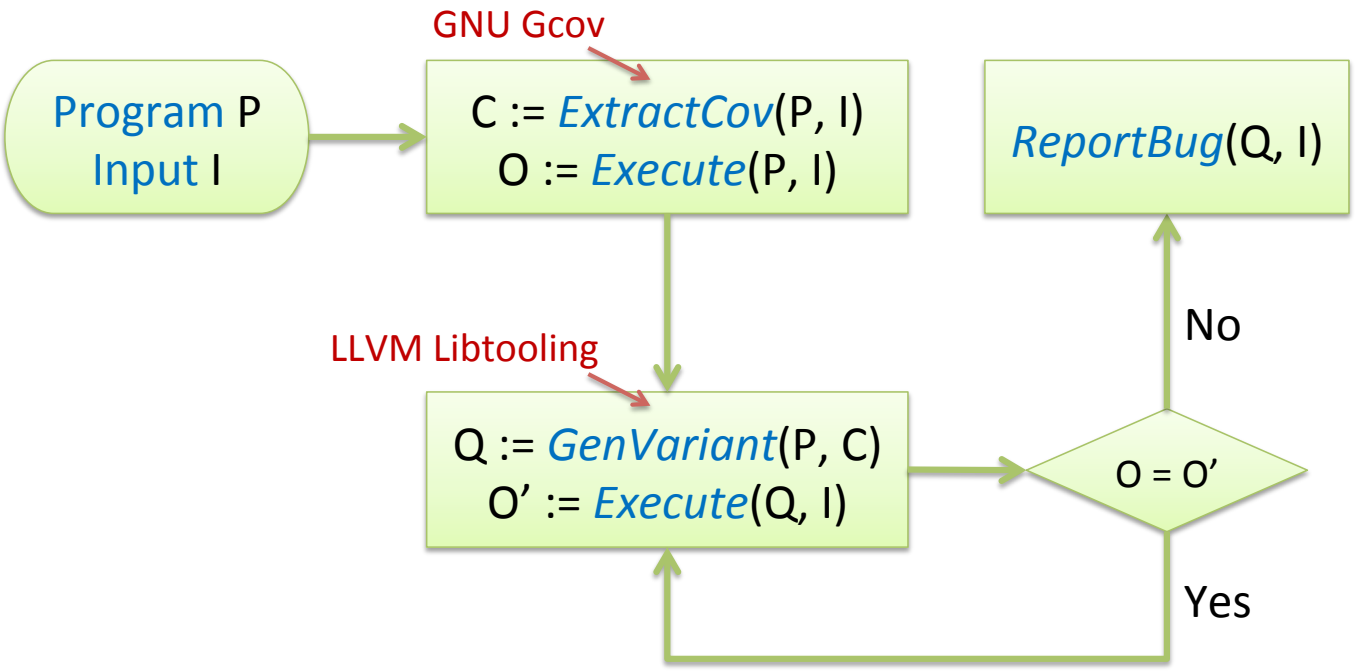
Profile



Mutation


input I
output O
randomly
prune
dead code
input I
output O
equivalence w.r.t. input I

Orion Overview



Examples

```
struct tiny { char c; char d; char e; };
f(int n, struct tiny x, struct tiny y,
  struct tiny z, long l) {
    if (x.c != 10) abort();
    if (x.d != 20) abort();
    if (x.e != 30) abort();
    if (y.c != 11) abort();
    if (y.d != 21) abort();
    if (y.e != 31) abort();
    if (z.c != 12) abort();
    if (z.d != 22) abort();
    if (z.e != 32) abort();
    if (l != 123) abort();
}
main() {
    struct tiny x[3];
    x[0].c = 10;
    x[1].c = 11;
    x[2].c = 12;
    x[0].d = 20;
    x[1].d = 21;
    x[2].d = 22;
    x[0].e = 30;
    x[1].e = 31;
    x[2].e = 32;
    f(3, x[0], x[1], x[2], (long)123);
    exit(0);
}
```

unexecuted

GCC test suite

```
clang -m32 -O0 test.c ; ./a.out
clang -m32 -O1 test.c ; ./a.out
```

```
struct tiny { char c; char d; char e; };
f(int n, struct tiny x, struct tiny y,
  struct tiny z, long l) {
    if (x.c != 10) /* deleted */;
    if (x.d != 20) abort();
    if (x.e != 30) /* deleted */;
    if (y.c != 11) abort();
    if (y.d != 21) abort();
    if (y.e != 31) /* deleted */;
    if (z.c != 12) abort();
    if (z.d != 22) /* deleted */;
    if (z.e != 32) abort();
    if (l != 123) /* deleted */;
}
main() {
    struct tiny x[3];
    x[0].c = 10;
    x[1].c = 11;
    x[2].c = 12;
    x[0].d = 20;
    x[1].d = 21;
    x[2].d = 22;
    x[0].e = 30;
    x[1].e = 31;
    x[2].e = 32;
    f(3, x[0], x[1], x[2], (long)123);
    exit(0);
}
```

```
clang -m32 -O0 test.c ; ./a.out
clang -m32 -O1 test.c ; ./a.out
Aborted (core dumped)
```

Examples (cont.)

```
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        for (; c;)
            for (;;) {
                b++;
                e = a > 2147483647 - b;
                if (d) break;
            }
    return 0;
}
```

unexecuted

Generated by CSmith

```
gcc -O0 test.c ; ./a.out
gcc -O3 test.c ; ./a.out
```

```
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        for (; c;)
            for (;;) {
                e = a > 2147483647 - b;
                if (d) break;
            }
    return 0;
}
```

```
gcc -O0 test.c ; ./a.out
gcc -O3 test.c ; ./a.out
^C
```

Why Effective?

- Compilers produce correct code for **all inputs**
- Variants have different data & control flow
  - Exercise **various** optimization strategies
  - Demand exact **same output** on the given input

Evaluation

- Two multi-core Ubuntu machines
- April 2013 – March 2014
- Seed programs
  - Compiler test suites
  - Open-source projects
  - CSmith-generated programs

Bug Counts and Types

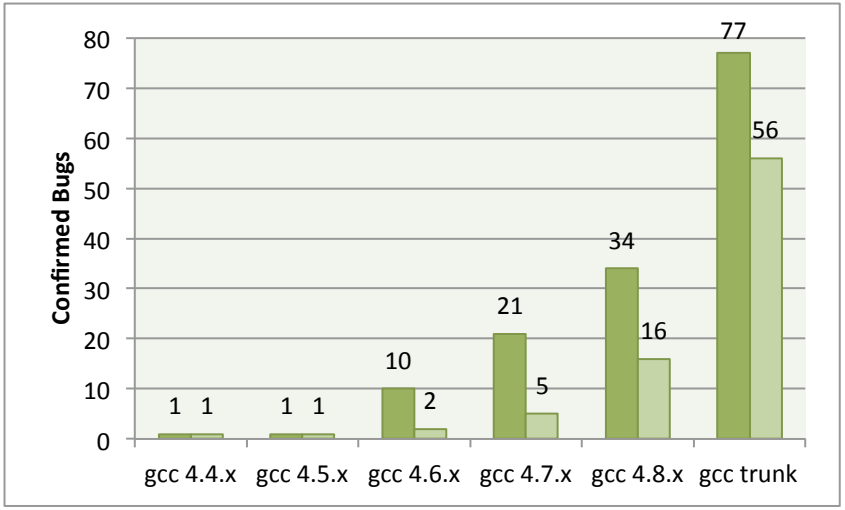
Bug Counts

	GCC	LLVM	TOTAL
Reported	111	84	**195**
Marked Duplicate	28	7	**35**
Confirmed	79	68	**147**
Fixed	56	54	**110**

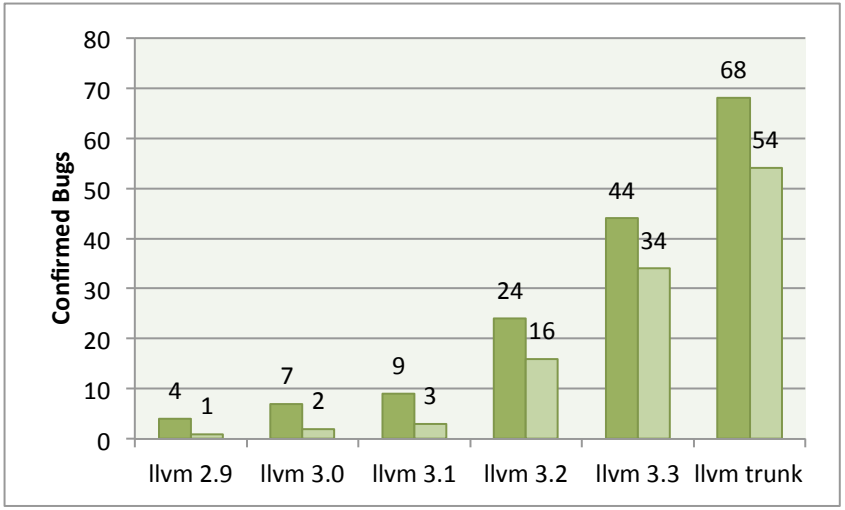
Bug Types

	GCC	LLVM	TOTAL
Wrong code	46	49	**95**
Crash	23	10	**33**
Performance	10	9	**19**

Affected Versions

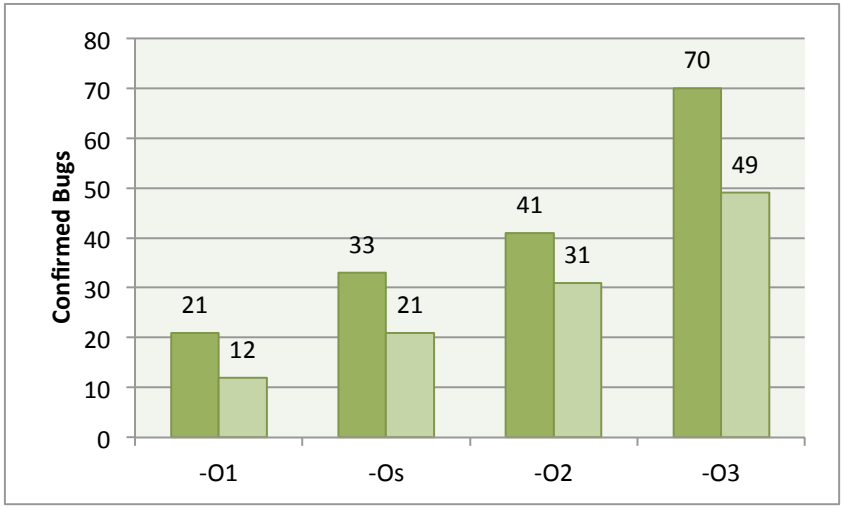


GCC

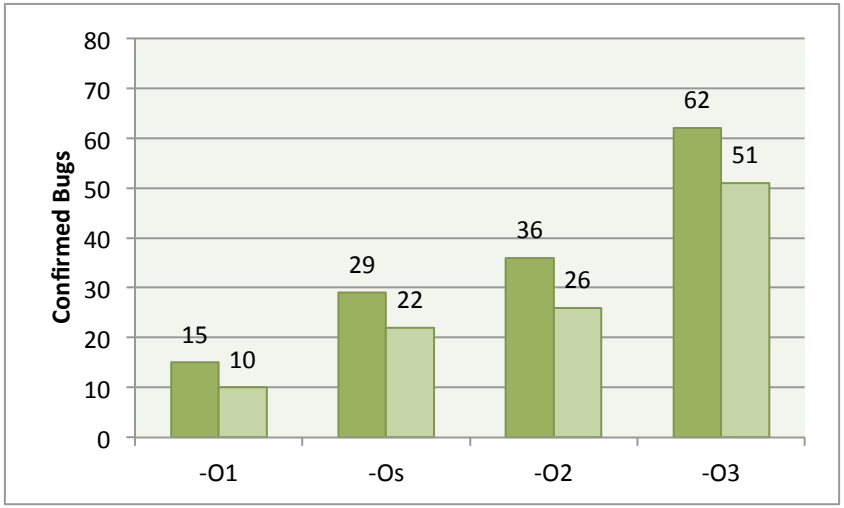


LLVM

Affected Optimization Levels

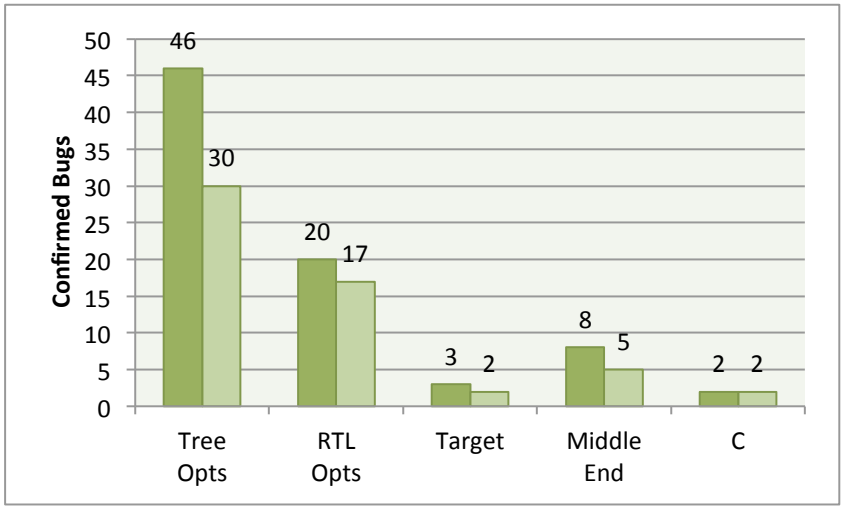


GCC

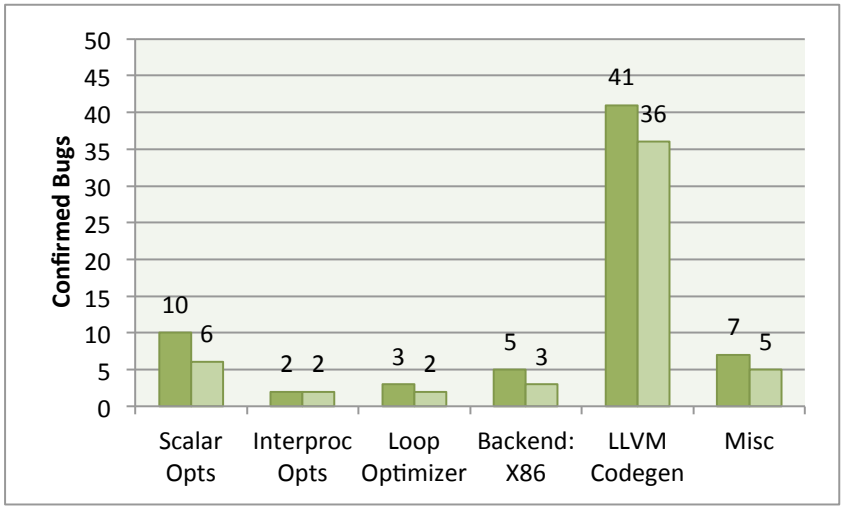


LLVM

Affected Components



GCC

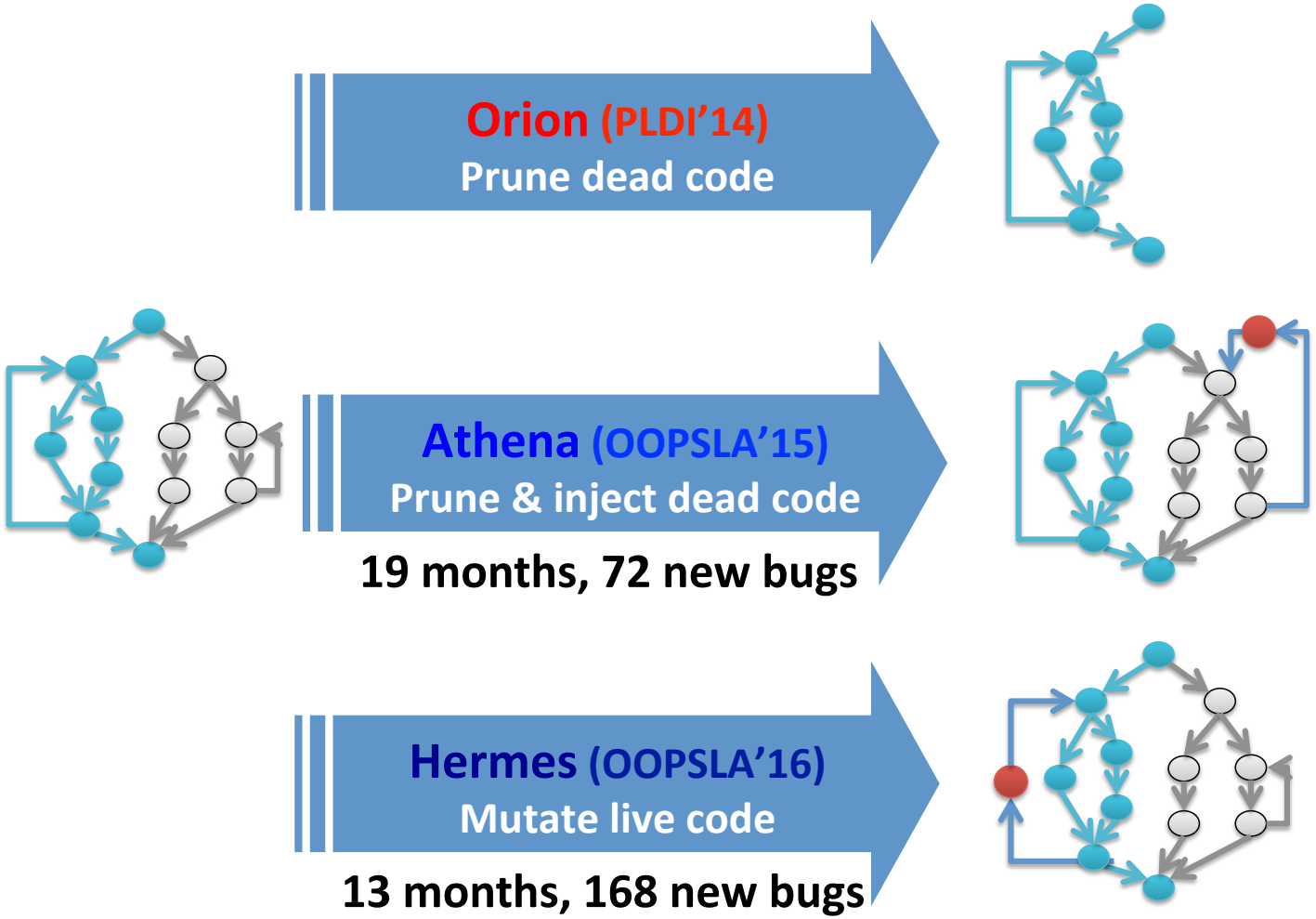


LLVM

Conclusions

- EMI is **general** and **widely applicable**
  - Can test compilers, analysis and transformation tools
  - Generates real-world tests
  - Requires no reference compilers
- Orion is very **effective**
  - Has uncovered **200+ bugs** in GCC and LLVM
  - Majority of the bugs were **miscompilations**
- Plan to investigate other **mutation strategies**

More Mutation Strategies



Bug Counts (till Recently)

	GCC	LLVM	TOTAL
Reported	643	498	**1141**
Fixed	397	239	**636**

Coverage-Directed Differential Testing of JVM Implementations

Yuting Chen, Ting Su, Chengnian Sun, Zhendong Su, Jianjun Zhao

PLDI 2016

Java Virtual Machine (JVM)

Oracle's HotSpot, IBM's J9, Jikes RVM, Azul's Zulu, and GNU's GIJ

*.class
*.jar

Execution Results

Reflect on This Trust – JVM Discrepancy 1

```
1  ...
2   MD5 checksum 8
        fb69050bbcb9a83ddd90ae393368c5e
3  ...
4  class M1436188543
5   minor version: 0
6   major version: 51
7   flags: ACC_SUPER
8  Constant pool:
9   ...
10   #7 = Utf8 <clinit>
11   #8 = Utf8 ()V
12   #9 = Class #19 // java/lang/System
13   #10 = Utf8 Code
14   #11 = Utf8 main
15  ...          clinit method
16 {
17   public abstract {};
18    flags: ACC_PUBLIC, ACC_ABSTRACT
19   public static void main(java.lang.String[]);
20    flags: ACC_PUBLIC, ACC_STATIC
21   Code:
22    stack=2, locals=1, args_size=1
23    0: getstatic #12 // Field java/lang/System.
        out:Ljava/io/PrintStream;
24    3: ldc #4 // String Completed!
25    5: invokevirtual #21 // Method java/io/
        PrintStream.println:(Ljava/lang/String
        ;)V
26    8: return}
```

public abstract {};

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

Cause: the JVM specification says that "other methods named <clinit> in a class file are **of no consequence**"

A class or interface initialization method needs to be strictly defined

Reflect on This Trust – JVM Discrepancy 2

```
1  //The Jimple code of M1433982529
2  public class M1433982529 extends java.lang.
       Object{
3    protected void internalTransform(java.lang.
         String)  {
4      java.util.Map r0;
5      r0 := @parameter0: java.util.Map;
6      staticinvoke <java.lang.Object: boolean
         getBoolean(java.util.Map)>(r0);
7      return;
8  }}
```

GIJ throws a **verification error** because it is unsafe to perform a type casting between java.lang.String and java.util.Map, while **HotSpot** does not report any error

JVMs take their own classfile verification and type checking polices

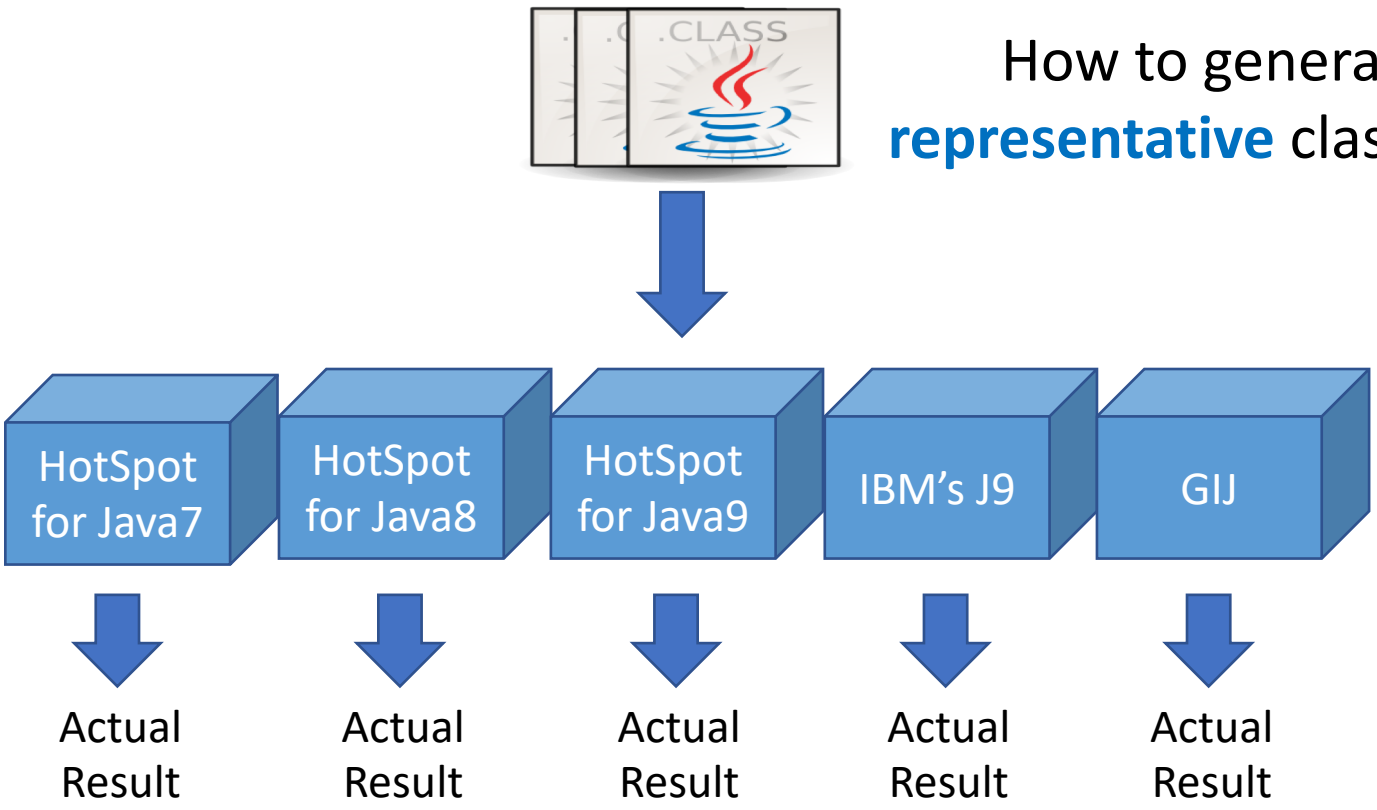
Reflect on This Trust – JVM Discrepancy 3

```
1  //The source code of sun.java2d.pisces.
       PiscesRenderingEngine
2  public class PiscesRenderingEngine extends
       RenderingEngine {
3    ...
4    private static enum NormMode {OFF, ON_NO_AA
         , ON_WITH_AA};
5    ...
6  }
7  //The Jimple code of M1437121261
8  public class M1437121261 {
9    public static void main (String[] r0)
10       throws sun.java2d.pisces.
             PiscesRenderingEngine$2{
11     ...
12 }}
```

HotSpot reports a java.lang.IllegalAccessError, while **J9** and **GIJ** do not

JVMs are not compatible to access some classes

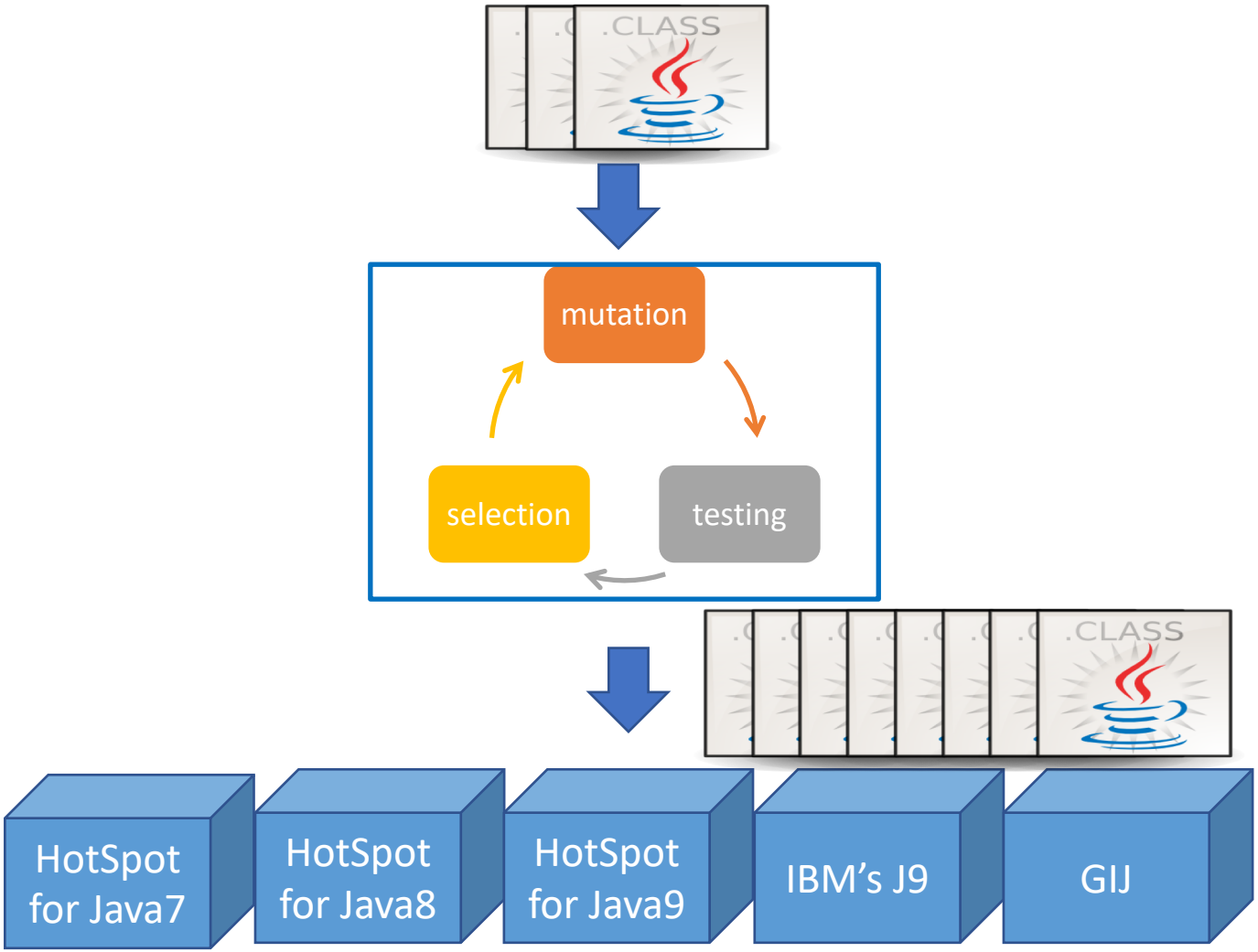
Differential JVM Testing



Two Key Observations

- A classfile can encompass intricate constraints
  - Corner cases can be created through mutating seeds
- Equivalence class partition removes redundancy
  - ECP works only if we can decide whether two tests belong to the same partition

ClassFuzz Overview



Mutating Classfiles

What to mutate	Typical mutators	Example (Jimple code before mutation → Jimple code after mutation)
Class	Reset its attributes (*e.g.*, modifiers, name, package name, superclass), *etc.*	`class M1437185190 extends java.lang.Object` `→ private class M1437185190 extends java.lang.Thread`

Interface	Insert one or more class-implementing interfaces, delete one or more interfaces, *etc.*	`class M1437185190 extends java.lang.Object`
		`→ class M1437185190 extends java.lang.Object`
		`implements java.security.PrivilegedAction`

Field	Insert one or more class fields, delete one or more fields, choose a field and set its attribute(s) (*e.g.*, name, modifiers), *etc.*	`...protected final java.util.Map MAP; ...`
		`→ ...protected final java.util.Map MAP;`
		`public java.lang.Object MAP; ...`

Method	Insert one or more class methods, delete one or more methods, choose a method and set its attribute(s) (*e.g.*, name, modifiers, return type), *etc.*	`public void <init>(){...}` `→ public static void <init>(){...}`

Exception	Select a method and insert one or more exceptions thrown, delete one or more exceptions thrown, *etc.*	`public static void main(java.lang.String[]){`
		`→ public static void main(java.lang.String[])`
		`throws sun.java2d.pisces.PiscesRenderingEngine$2 {`

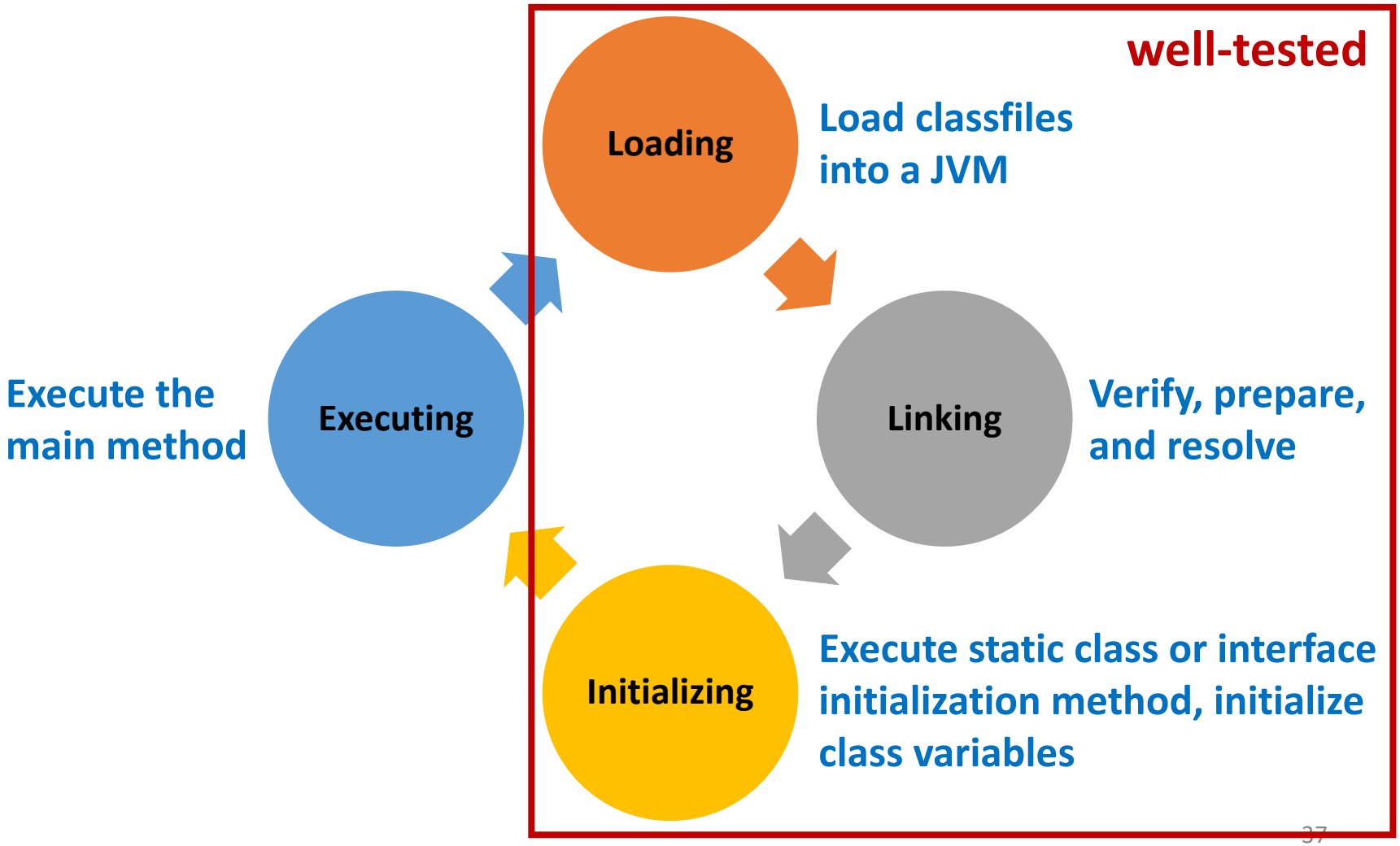
Parameter	Select a method and insert one or more parameters, delete one or more parameters, *etc.*	`public static void main(java.lang.String[])`
		`→ public static void main( java.lang.Object,`
		`java.lang.String[])`

Local variable	Select a method and insert one or more local variables, delete one or more local variables, choose a local variable and set its attribute(s) (*e.g.*, type, name, modifiers), *etc.*	`public static void main(java.lang.String[])`
		`{int $i0; ...}`
		`→ public static void main(java.lang.String[])`
		`{ java.lang.String $i0; ...}`

Jimple file	Insert one or more program statements, delete one or more program statements, *etc.*	`r0:=parameter0: java.lang.String[];`
		`r1:=<java.lang.System: java.io.PrintStream out>;`
		`virtualinvoke $r1.<java.io.PrintStream:void`
		`println(java.lang.String)>("Executed");`
		`→ r0:=parameter0: java.lang.String[];`
		`virtualinvoke $r1.<java.io.PrintStream:void`
		`println(java.lang.String)>("Executed");`
		`r1:=<java.lang.System: java.io.PrintStream out>;`

129 mutators

JVM Startup Process

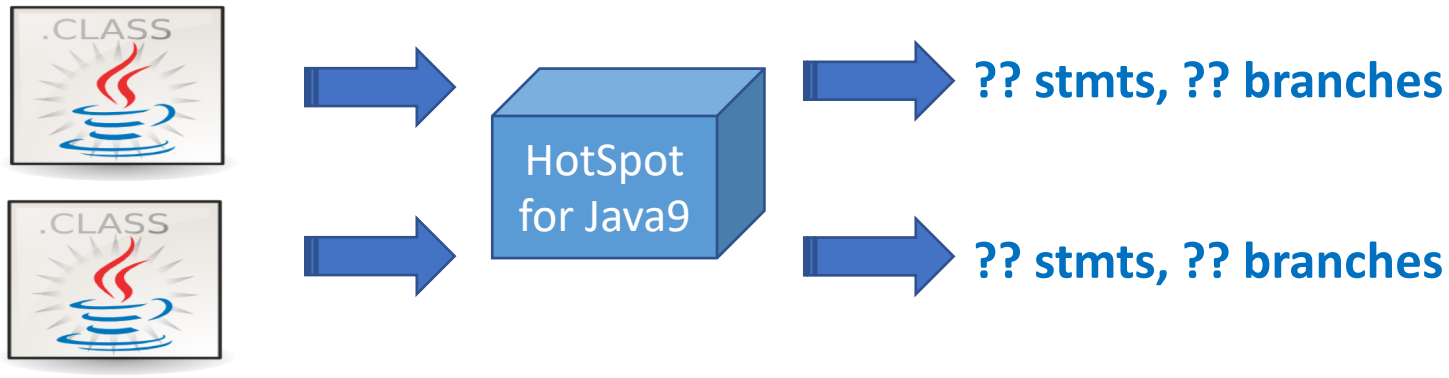


Selecting Mutators

- Fact: mutators are designed arbitrarily; and some are effective, while some others are not effective
- Goal: create representative classfiles as many and fast as possible

- Heuristic: the more number of representative classfiles have been created by a mutator, the more chance should be given for that mutator

Selecting Representative Classfiles



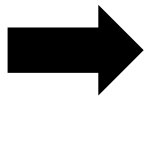
- Several comparison criteria are introduced
  - Statement coverage
  - Branch coverage
  - Trace coverage

Differential Testing of JVMs

- check whether the main method can be normally invoked or during which phase an error/exception is thrown
  - (0) “normally invoked”
  - (1) “rejected during the loading phase”
  - (2) “rejected during the linking phase”
  - (3) “rejected during the initialization phase”
  - (4) “rejected at runtime”

Evaluation 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 Setup (cont.)

- ClassFuzz supplemented with a uniqueness analysis
  - [st], [stbr], [tr]
- Randfuzz, Greedyfuzz, Uniquefuzz

	ClassFuzz	randfuzz	greedyfuzz	uniquefuzz
Mutation-based	✓	✓	✓	✓
Cov. Analysis	✓	×	✓	✓
Uniqueness Analysis	[st] [stbr] [tr]	×	[stbr]	[stbr]
Mutator Selection	✓	×	×	×

How Many Test Classfiles can be Generated?

	Classfuzz [stbr]	Classfuzz [st]	Classfuzz [tr]	Uniquefuzz	Greedyfuzz	Randfuzz
#iterations	2130	2108	1971	1898	1911	46318
$\|GenClasses\|$	1539	1543	1450	1436	1432	29523
$\|TestClasses\|$	898	494	774	628	98	29523
succ	42.2%	23.4%	39.3%	33.1%	5.1%	63.7%
Average time for each generated class (sec.)	168.4	168.0	178.8	180.5	181.0	8.78
Average time for each test class (sec.)	288.6	524.7	334.9	412.7	2644.9	8.78

succ = |testClasses| / #iterations * 100%

How Effective are the Test Classfiles?

	JRE7 classes	seeding classfiles	Classfuzz [stbr]	Classfuzz [st]	Classfuzz [tr]	Uniquefuzz	Greedyfuzz	Randfuzz
$\|GenClasses\|$	21736	1216	1539	1543	1450	1436	1432	
all invoked	77	17	197	199	226	203	195	
all rejected at the same stage	21295	1162	1100	1104	984	1063	980	–
$\|Discrepancies\|$	364	37	242	240	240	170	257	
$\|Distinct\_Discrepancies\|$	16	9	17	14	13	10	15	
$diff$	1.7%	3.0%	15.7%	15.6%	16.5%	11.8%	17.9%	
$\|TestClasses\|$			898	494	774	628	98	29523
all invoked			121	62	122	109	11	3914
all rejected at the same stage			670	374	564	462	72	20072
$\|Discrepancies\|$	–	–	107	58	88	57	15	5537
$\|Distinct\_Discrepancies\|$			17	11	12	9	7	14
$diff$			11.9%	11.7%	11.4%	9.1%	15.3%	18.8%

diff = |Discrepancies| / |Classes| * 100%

Can the Test Classfiles Find JVM Defects?

- 62 new JVM discrepancies

```
...
 MD5 checksum 8
     fb69050bbcb9a83ddd90ae393368c5e
...
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}
```

rename abstract method as <clinit>

set the parameter type from Map to String

```
//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;
}}
```

```
//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{
    ...
}}
```

add a throw exception to the main method

Conclusions

- **Problem**
  - Testing JVMs requires painstaking effort in designing **test classfiles** along with their **test oracles**
- **Proposal: coverage-directed fuzz testing**
  - **Test classfile generation**
    - Mutating classes and selectively applying mutators
    - Deciding the representativeness of a classfile mutant
  - **Differential JVM testing**

Reading Materials

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Q&A?

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