Software QA w/ Generative AI (CS598): Software Testing

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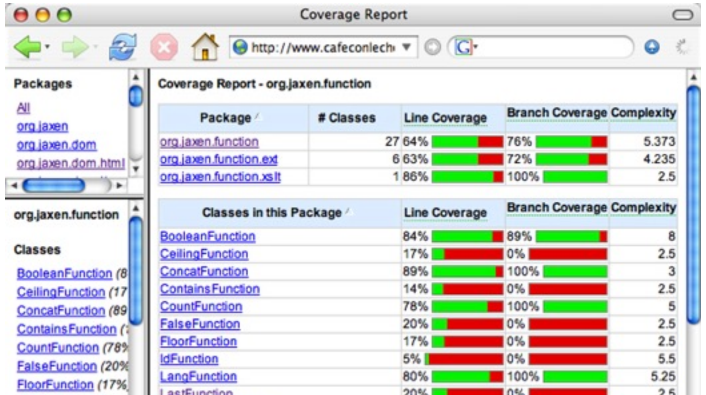
Testing: basic concepts

- **Test case** (or, simply **test**): an execution of the software with a given test input, including:
  - Input values
  - Sometimes include execution steps
  - Expected outputs (**test oracle**)
- **Test suite**: a finite set of tests
  - Usually can be run together in sequence
- **Test adequacy**: a measurement to evaluate the test quality
  - Such as code coverage



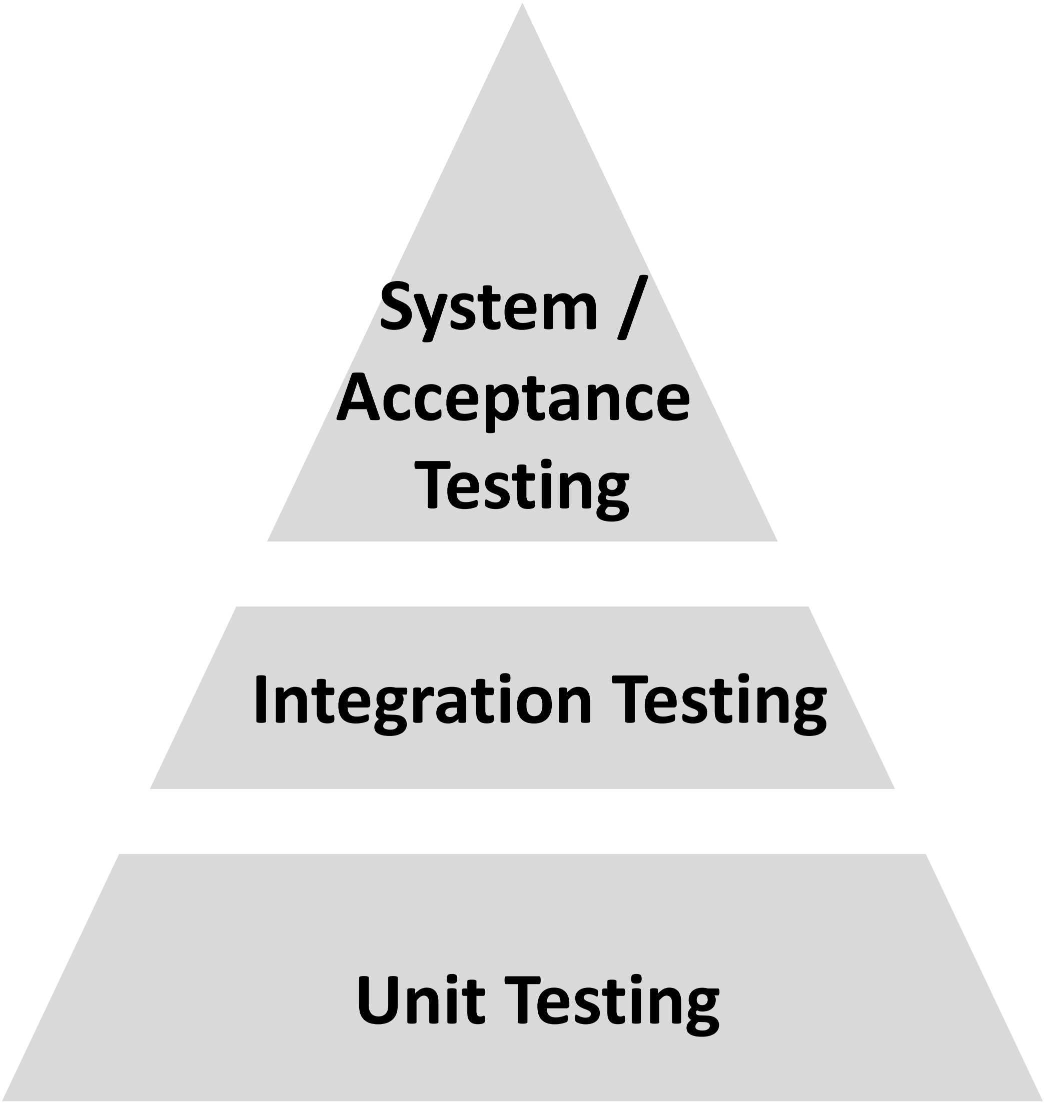
Coverage Report - org.jaxen.function

Package	# Classes	Line Coverage	Branch Coverage	Complexity
org.jaxen.function	27	64%	76%	5.373
org.jaxen.function.ext	6	63%	72%	4.235
org.jaxen.function.xslt	1	86%	100%	2.5

Classes in this Package	Line Coverage	Branch Coverage	Complexity
BooleanFunction	84%	89%	8
CeilingFunction	17%	0%	2.5
ConcatFunction	89%	100%	3
ContainsFunction	14%	0%	2.5
CountFunction	78%	100%	5
FalseFunction	20%	0%	2.5
FloorFunction	17%	0%	2.5
IdFunction	5%	0%	5.5
LangFunction	80%	100%	5.25
LastFunction	20%	0%	2.5

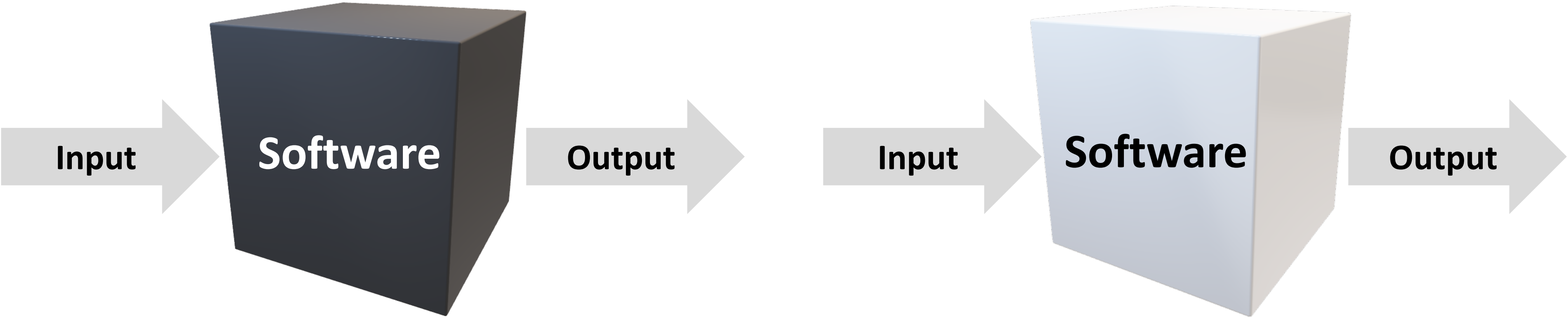
Testing: levels

- Unit Testing
  - Test each single module in isolation
- Integration Testing
  - Test the interaction between modules
- System Testing
  - Test the system as a whole, by developers
- Acceptance Testing
  - Validate the system against user requirements, by customers with no formal test cases



Types of test generation

- Black-box (functional) vs. white-box (structural) testing



- **Black-box test generation**: generates tests based on the functionality of the program
- **White-box test generation**: generates tests based on the source-code structure of the program

Today’s focus

- **Unit testing**: involves testing individual units (e.g., methods or classes) of a software to ensure that each part is correct, typically
  - Unit level
  - White-box
  - Deterministic
  - …

- **Fuzz testing** (fuzzing): involves providing invalid, unexpected, or random data as inputs to a software, typically
  - System level
  - Black-box
  - Non-deterministic
  - …

This class

- Unit Testing
    - Feedback-directed Random Test Generation (ICSE'07)
- Fuzz Testing
    - Finding and Understanding Bugs in C Compilers (PLDI’11)
    - Fuzzing with Code Fragments (SEC'12)
    - Compiler Validation via Equivalence Modulo Inputs (PLDI’14)
    - AFL: American Fuzzy Lop (https://github.com/google/AFL)

Problem: unit test generation

Program under test:

```
public class Math{
  public static int sum(int a, int b){
    return a+b;
  }
  …
}
```

Example JUnit test:

```
public class MathTest{
  @Test
  public void testSum (){
    int a=1;
    int b=1;
    int c=Math.sum(a, b);
    assertEquals(2,c);
  }
  …
}
```

Input values

Execution steps

Test oracle

Is this an important problem?

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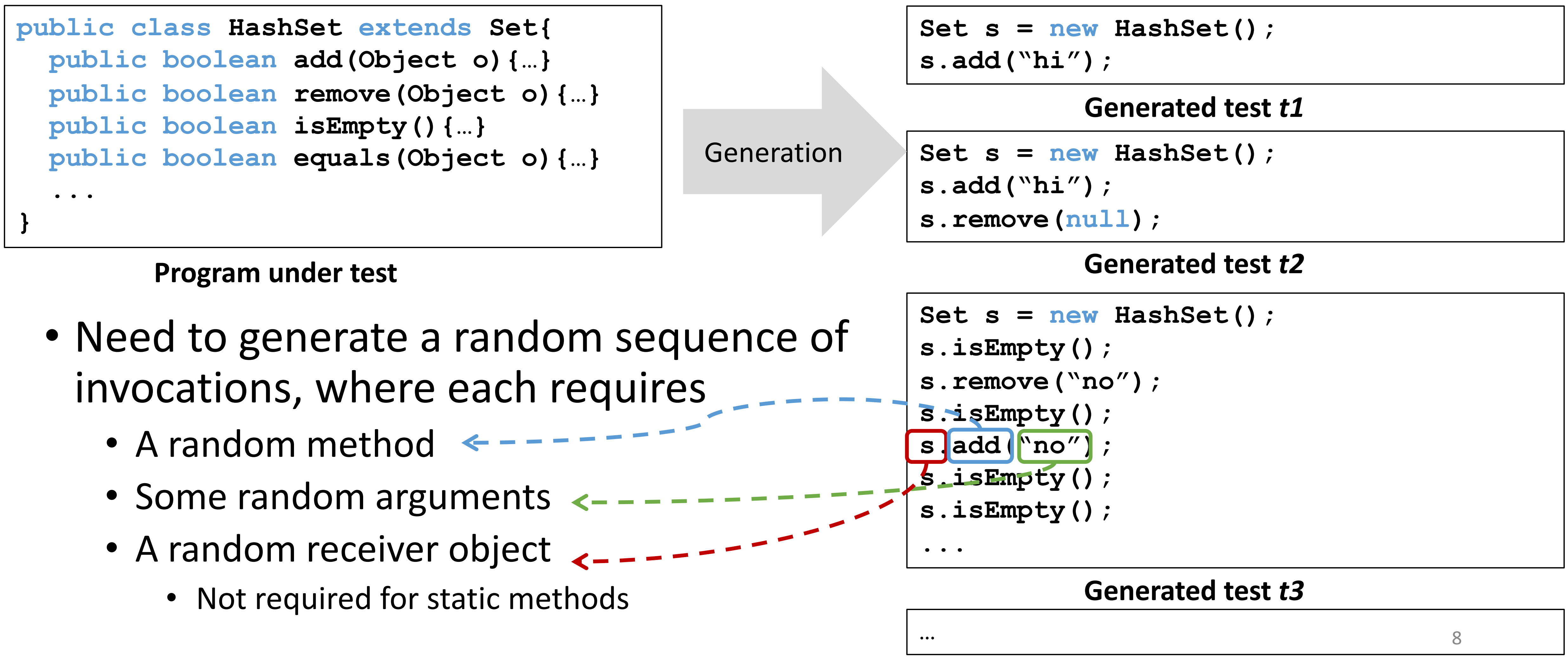
Commons-Math

84,377 lines of **source code**

86,924 lines of **unit-test code**

How to perform random white-box test generation?



```
public class HashSet extends Set{
  public boolean add(Object o){…}
  public boolean remove(Object o){…}
  public boolean isEmpty(){…}
  public boolean equals(Object o){…}
  ...
}
```

Program under test

```
Set s = new HashSet();
s.add("hi");
```

Generated test *t1*

```
Set s = new HashSet();
s.add("hi");
s.remove(null);
```

Generated test *t2*

```
Set s = new HashSet();
s.isEmpty();
s.remove("no");
s.isEmpty();
s.add("no");
s.isEmpty();
s.isEmpty();
...
```

Generated test *t3*

…

- Need to generate a random sequence of invocations, where each requires
  - A random method
  - Some random arguments
  - A random receiver object
    - Not required for static methods

Random method-sequence generation: limitations

- Does not have test oracles
  - E.g., an ideal test oracle for the test below: **assertEquals(1, s.size())**
- Cannot generate complex tests
  - E.g., the arguments of some method invocations can be generated by other method invocations
- Can have many redundant&illegal tests

```
Set s = new HashSet();
s.isEmpty();
s.remove(“no”);
s.isEmpty();
s.add(“no”);
s.isEmpty();
s.isEmpty();
```

A random test

Random method-sequence generation: redundant&illegal tests

```
1. Useful test:
Set s = new HashSet();
s.add(“hi”);
```

```
2. Redundant test:
Set s = new HashSet();
s.add(“hi”);
s.isEmpty();
```

Should not output

```
3. Useful test:
Date d = new Date(2006, 2, 14);
```

```
4. Illegal test:
Date d = new Date(2006, 2, 14);
d.setMonth(-1); // pre: argument >= 0
```

Should not output

```
5. Illegal test:
Date d = new Date(2006, 2, 14);
d.setMonth(-1); // pre: argument >= 0
d.setDay(5);
```

Should not even generate

Randoop: feedback-directed (adaptive) random test generation

- Use code contracts as test oracles
- Build test inputs incrementally
  - New test inputs extend previous ones
  - In this context, a test input is a method sequence
- As soon as a test is created, use its execution results to guide generation
  - away from redundant or illegal method sequences
  - towards sequences that create new object states

Randoop input/output

- **Input**:
  - Classes under test
  - Time limit
  - Set of contracts
    - Method contracts (e.g. “o.hashCode() throws no exception”)
    - Object invariants (e.g. “o.equals(o) == true”)
- **Output**: contract-violating test cases

```
HashMap h = new HashMap();
Collection c = h.values();
Object[] a = c.toArray();
LinkedList l = new LinkedList();
l.addFirst(a);
TreeSet t = new TreeSet(l);
Set u = Collections.unmodifiableSet(t);
assertTrue(u.equals(u));
```

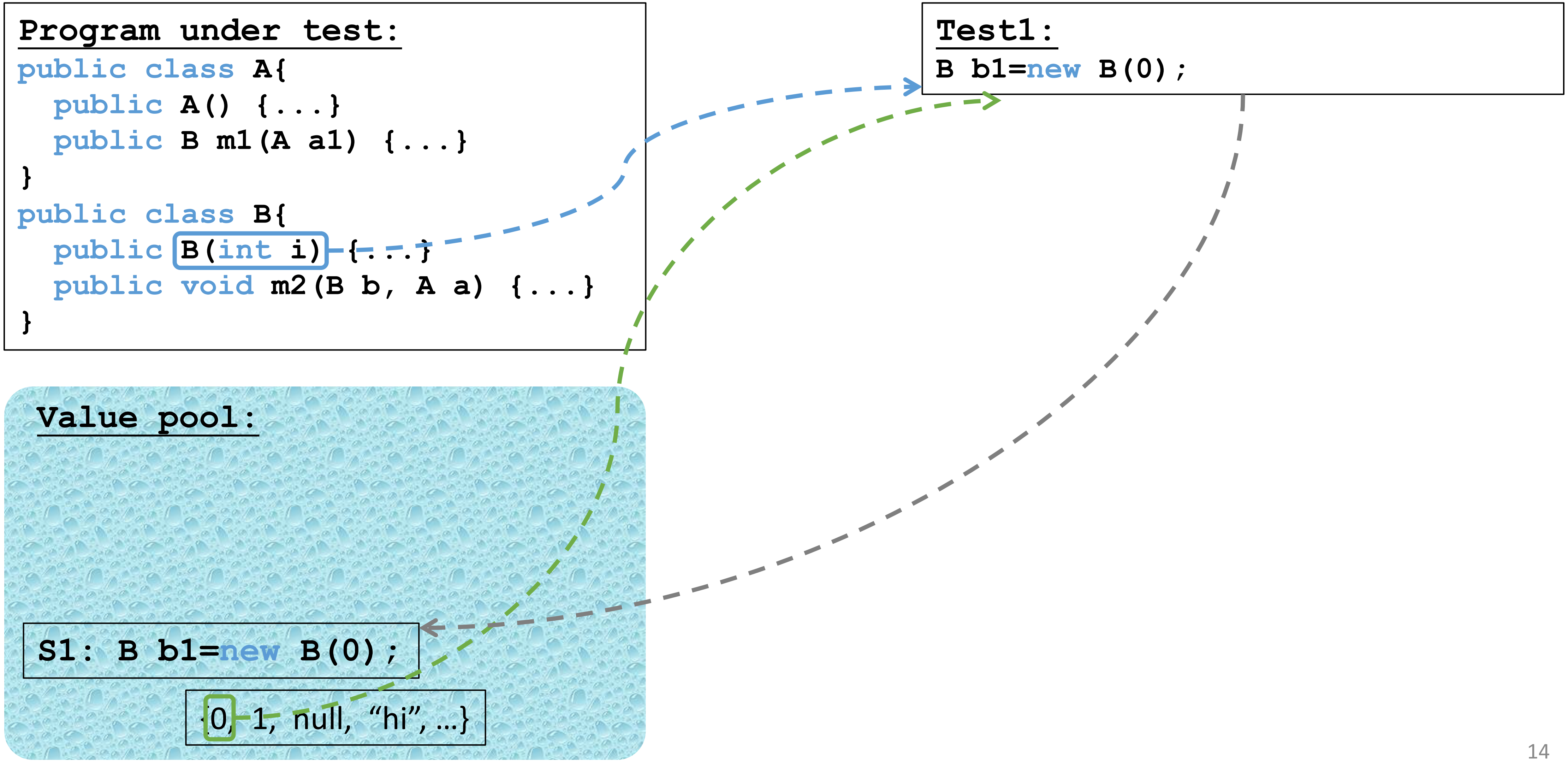
fails on Sun’s JDK 1.5/1.6 when executed

Randoop: algorithm

- Seed value pool for primitive types
    - pool = { **0, 1, true, false, “hi”, null** … }
- Do until time limit expires:
    - Create a new sequence
        - Randomly pick a method call $\mathbf{m}(\mathbf{T_1}\ldots\mathbf{T_k})/\mathbf{T_{ret}}$
        - For each input parameter of type $\mathbf{T_i}$, randomly pick a sequence $\mathbf{S_i}$ from the value pool that constructs an object $\mathbf{v_i}$ of type $\mathbf{T_i}$
        - Create new sequence $\mathbf{S_{new}} = \mathbf{S_1}; \ldots ; \mathbf{S_k} ; \mathbf{T_{ret}}\ \mathbf{v_{new}} = \mathbf{m}(\mathbf{v_1}\ldots\mathbf{v_k});$
        - if $\mathbf{S_{new}}$ was previously created (lexically), go to first step
    - Classify the new sequence $\mathbf{S_{new}}$
        - May discard, output as test case, or add to pool

- - -→ Method
- - -→ Parameter
- - -→ Receiver object

Randoop: example



Program under test:

```
public class A{
  public A() {...}
  public B m1(A a1) {...}
}
public class B{
  public B(int i) {...}
  public void m2(B b, A a) {...}
}
```

Test1:

```
B b1=new B(0);
```

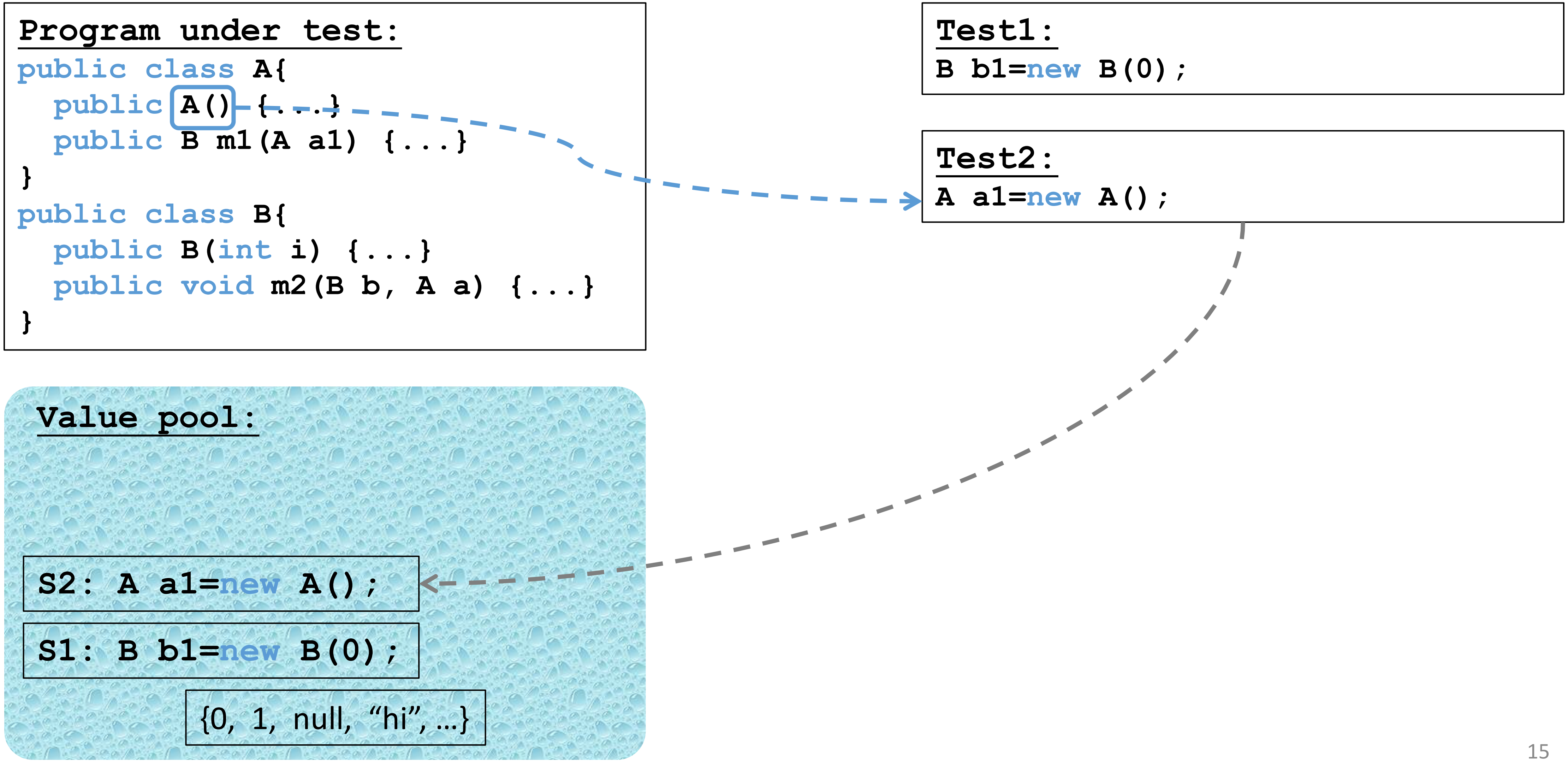
Value pool:

```
S1: B b1=new B(0);
```

{0, 1, null, “hi”, ...}

- - - → Method
- - - → Parameter
- - - → Receiver object

Randoop: example



Program under test:

```
public class A{
  public A() {...}
  public B m1(A a1) {...}
}
public class B{
  public B(int i) {...}
  public void m2(B b, A a) {...}
}
```

Test1:

```
B b1=new B(0);
```

Test2:

```
A a1=new A();
```

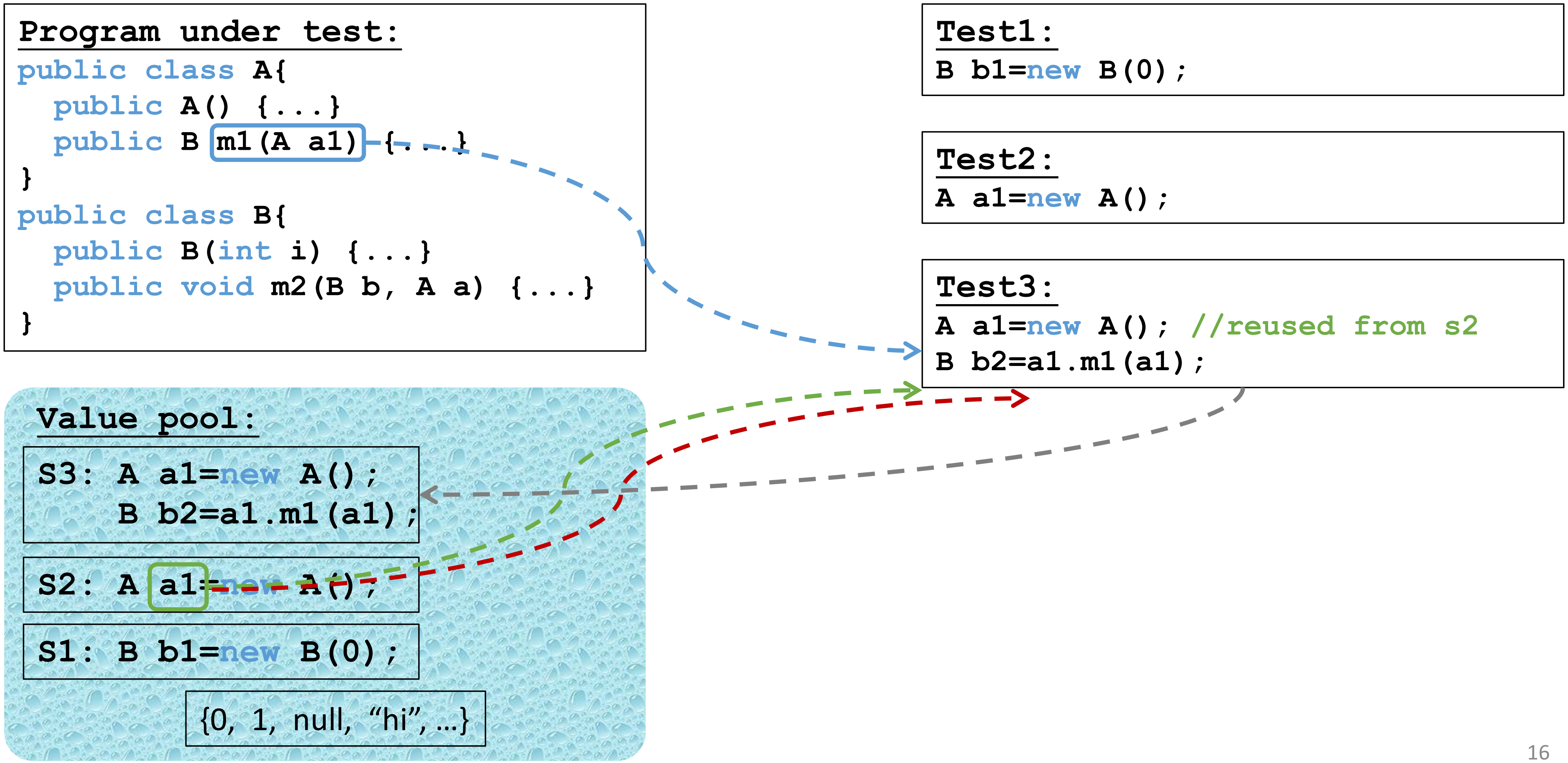
Value pool:

```
S2: A a1=new A();
S1: B b1=new B(0);
```

{0, 1, null, “hi”, ...}

- - - → Method
- - - → Parameter
- - - → Receiver object

Randoop: example



Program under test:

```
public class A{
   public A() {...}
   public B m1(A a1) {...}
}
public class B{
   public B(int i) {...}
   public void m2(B b, A a) {...}
}
```

Value pool:

```
S3: A a1=new A();
    B b2=a1.m1(a1);
```

```
S2: A a1=new A();
```

```
S1: B b1=new B(0);
```

{0, 1, null, “hi”, ...}

Test1:

```
B b1=new B(0);
```

Test2:

```
A a1=new A();
```

Test3:

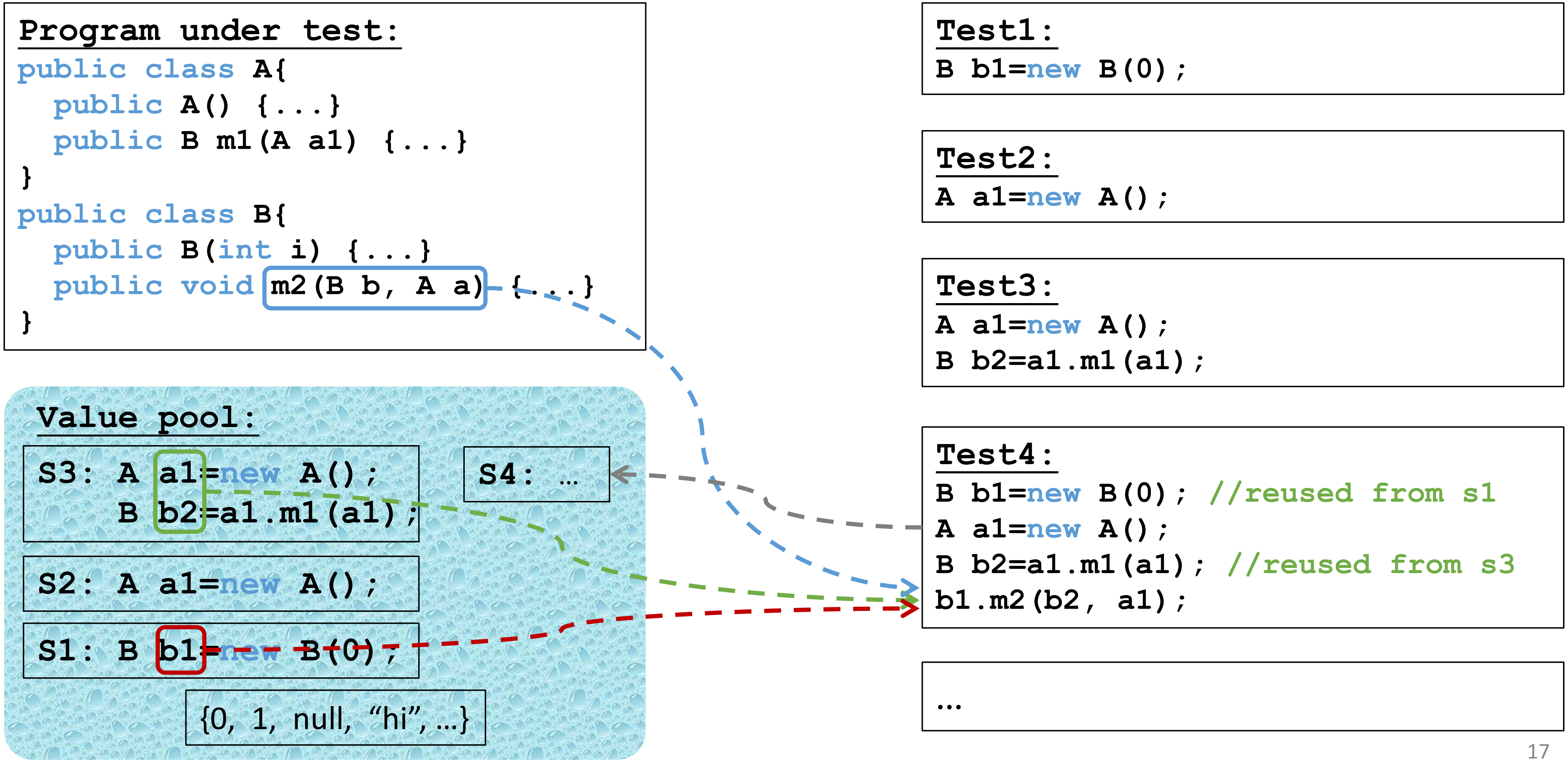
```
A a1=new A(); //reused from s2
B b2=a1.m1(a1);
```

Method

Parameter

Receiver object

Randoop: example



Program under test:

```
public class A{
  public A() {...}
  public B m1(A a1) {...}
}
public class B{
  public B(int i) {...}
  public void m2(B b, A a) {...}
}
```

Value pool:

```
S3: A a1=new A();
    B b2=a1.m1(a1);
```

```
S4: …
```

```
S2: A a1=new A();
```

```
S1: B b1=new B(0);
```

{0, 1, null, "hi", …}

Test1:

```
B b1=new B(0);
```

Test2:

```
A a1=new A();
```

Test3:

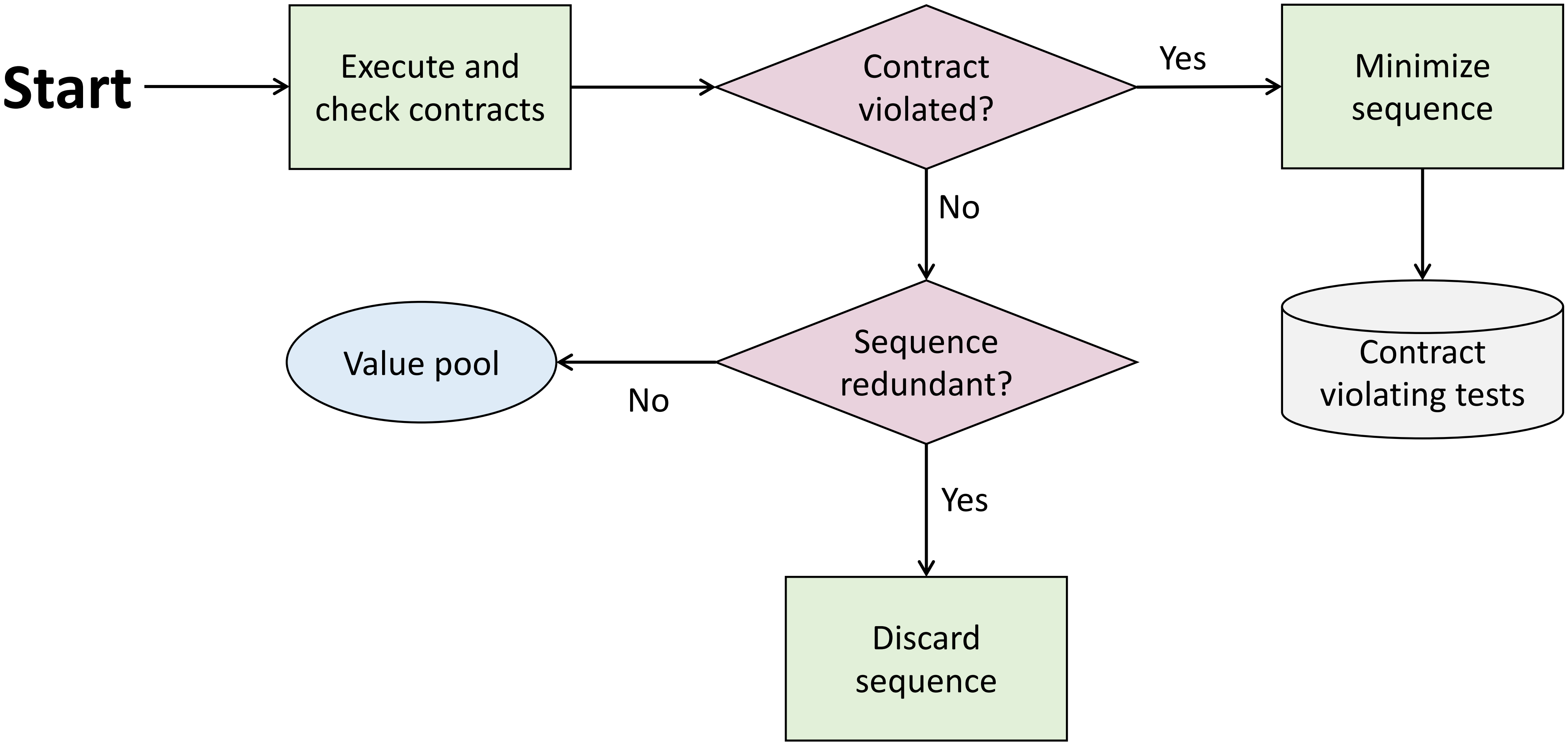
```
A a1=new A();
B b2=a1.m1(a1);
```

Test4:

```
B b1=new B(0); //reused from s1
A a1=new A();
B b2=a1.m1(a1); //reused from s3
b1.m2(b2, a1);
```

…

Classifying a sequence



Redundant sequences

- During generation, maintain a set of all objects created
- A sequence is redundant if all the objects created during its execution are members of the above set (using *equals* to compare)
- Could also use more sophisticated state equivalence methods
  - E.g. heap canonicalization used in model checkers

Tool support

- **Input**:
  - An assembly (for .NET) or a list of classes (for Java)
  - Generation time limit
  - Optional: a set of contracts to augment default contracts
- **Output**: a test suite (JUnit or Nunit) containing
  - Contract-violating test cases
  - Normal-behavior test cases

Randoop

Automatic unit test generation

Randoop outputs oracles

- Oracle for contract-violating tests:

```
Object o = new Object();
LinkedList l = new LinkedList();
l.addFirst(o);
TreeSet t = new TreeSet(l);
Set u = Collections.unmodifiableSet(t);
assertTrue(u.equals(u));//expected to fail
```

Find current bugs

- Oracle for normal-behavior tests (regression tests):

```
Object o = new Object();
LinkedList l = new LinkedList();
l.addFirst(o);
l.add(o);
assertEquals(2, l.size());//expected to pass
assertEquals(false,l.isEmpty());//expected to pass
```

Find future bugs

Some Randoop options

- Avoid use of null

```
Statically:
Object o = new Object();
LinkedList l = new LinkedList();
l.add(null);
```

```
Dynamically:
Object o = returnNull();
LinkedList l = new LinkedList();
l.add(o);
```

- Bias random selection
  - Favor shorter sequences
  - Favor methods that have been less covered
  - Use constants mined from source code
- Source code available:
  - https://randoop.github.io/randoop/

Code coverage by Randoop

Data structure programs	**Time (s)**	**Branch cov.**
Bounded stack (30 LOC)	1	100%
Unbounded stack (59 LOC)	1	100%
BS Tree (91 LOC)	1	96%
Binomial heap (309 LOC)	1	84%
Linked list (253 LOC)	1	100%
Tree map (370 LOC)	1	81%
Heap array (71 LOC)	1	100%

Bug detection by Randoop: subjects

Subjects	LOC	Classes
JDK (2 libraries) (java.util, javax.xml)	53K	272
Apache commons (6 libraries) (logging, primitives, chain, jelly, math, collections)	114K	974
.Net libraries (6 libraries)	615K	3455

Bug detection by Randoop: methodology

- Ran Randoop on each library
  - Used default time limit (2 minutes)
- Contracts:
  - **o.equals(o)==true**
  - **o.equals(o)** throws no exception
  - **o.hashCode()** throws no exception
  - **o.toString()** throw no exception
  - No null inputs and:
    - Java: No NPEs
    - .NET: No NPEs, out-of-bounds, of illegal state exceptions

Bug detection by Randoop: subjects

Subjects	Failed tests	Unique failed tests	Error-revealing tests	Distinct errors
JDK	613	32	29	8
Apache commons	3,044	187	29	6
.Net framework	543	205	196	196
Total	4,200	424	254	210

Errors found: examples

- JDK Collections classes have 4 methods that create objects violating **o.equals(o)** contract
- Javax.xml creates objects that cause **hashCode** and **toString** to crash, even though objects are well-formed XML constructs
- Apache libraries have constructors that leave fields unset, leading to NPE on calls of **equals**, **hashCode** and **toString** (this only counts as one bug)
- .Net framework has at least 175 methods that throw an exception forbidden by the library specification (NPE, out-of-bounds, of illegal state exception)
- .Net framework has 8 methods that violate **o.equals(o)**
- .Net framework loops forever on a legal but unexpected input

Has Randoop been compared to existing solutions?

- Systematic testing:
  - Java PathFinder (JPF)
  - jCUTE
- Undirected Random testing:
  - Randoop-feedback
  - JCrasher

Regression testing scenario

- Randoop can create regression oracles
- Generated test cases using JDK 1.5
  - Randoop generated 41K regression test cases
- Ran resulting test cases on
  - JDK 1.6 Beta
    - 25 test cases failed
  - Sun’s implementation of the JDK
    - 73 test cases failed
  - Failing test cases pointed to 12 distinct errors
  - These errors were not found by the extensive compliance test suite that Sun provides to JDK developers

```
Object o = new Object();
LinkedList l = new LinkedList();
l.addFirst(o);
l.add(o);
assertEquals(2, l.size());//expected to pass
assertEquals(false,l.isEmpty());//expected to pass
```

Randoop: applications

Microsoft

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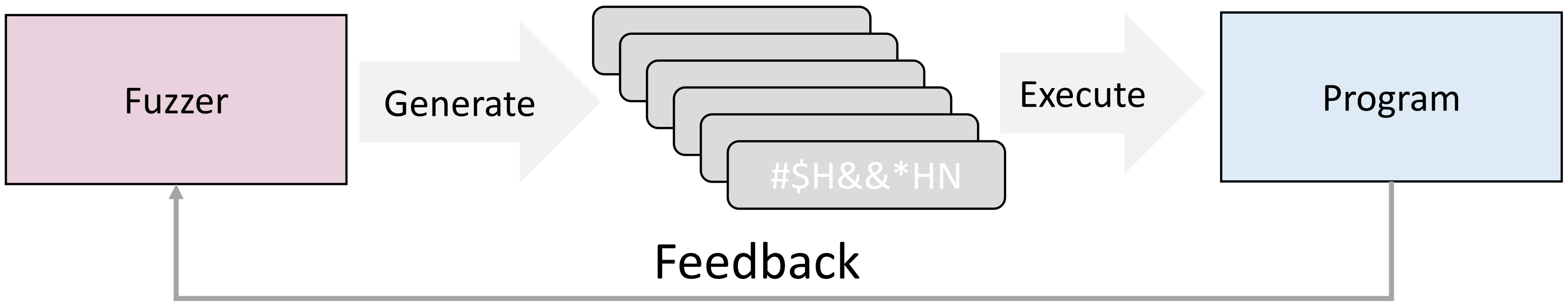
This class

- Unit Testing
  - Feedback-directed Random Test Generation (ICSE'07)
- Fuzz Testing
  - Finding and Understanding Bugs in C Compilers (PLDI’11)
  - Fuzzing with Code Fragments (SEC'12)
  - Compiler Validation via Equivalence Modulo Inputs (PLDI’14)
  - AFL: American Fuzzy Lop (https://github.com/google/AFL)

Fuzz testing

./Program < /dev/random



- Fuzzing strategies
  - Mutation-based
  - Generation-based
  - Learning-based

- Feedback guide
  - New coverage?
  - Shorter execution?
  - Valid input?

- Targeted programs
  - Binaries
  - Compilers
  - Browsers
  - DB systems
  - ML systems
  - …

Generation-based fuzzing

- Create test inputs based on predefined structure/grammar

```
<start> ::= <expr>
<expr> ::= <term> + <expr> | <term> - <expr> | <term>
<term> ::= <term> * <factor> | <term> / <factor> | <factor>
<factor> ::= +<factor> | -<factor> | (<expr>) | <int> | <int>.<int>
<int> ::= <digit><int> | <digit>
<digit> ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
```

Arithmetic expression grammar

Generate

```
(-+++((1 + (+7 - (-1 * (++-+7.7 - -+-4.0))))) * +--4 - -(6) + 64) 8.2 - 27 -
-9 / +((+9 * --2 + --+-+-((-1 * +(8 - 5 - 6)) * (-((-+(((+(4)))))) - ++4) / +(-
+---((5.6 - --(3 * -1.8 * +(6 * +-(((-(-6) * ---+6)) / +--(+-+-7 * (-0 *
(+(((((2)) + 8 - 3 - ++9.0 + ---(--+7 / (1 / +++6.37) + (1) / 482) / +++-
+0)))) * -+5 + 7.513)))) - …
```

Arithmetic expression

C grammar

Csmith

```
void foo (void) {
 int x;
 for (x =0; x < 5; x++){
  if (x) continue;
  if (x) break;
 }
 printf("%d", x);
}
```

C program triggering an LLVM bug

Javascript grammar

LangFuzz

```
var haystack = "foo";
var re_text = "^foo";
haystack += "x";
re_text += "(x)";
var re = new RegExp(re_text);
re.test(haystack);
RegExp.input = Number();
print(RegExp.$1);
```

JS program crashing Mozilla

Generation-based fuzzing: examples

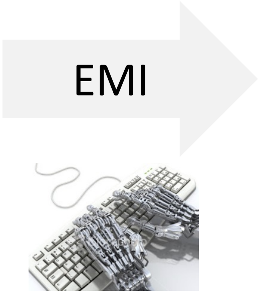
- Finding and Understanding Bugs in C Compilers (PLDI’11)
  - Targeting C compilers
  - Cited for **1,000+** times
  - **400+** GCC/LLVM bugs found

- Fuzzing with Code Fragments (SEC’12)
  - Targeting JS browsers/engines
  - Cited for **400+** times
  - USD **50,000+** bug bounties in the first month
  - **2,000+** bugs found for Mozilla Firefox, Google Chrome, and Microsoft Edge to date

Mutation-based fuzzing

- Apply small mutations on high-quality seed inputs to generate more test inputs

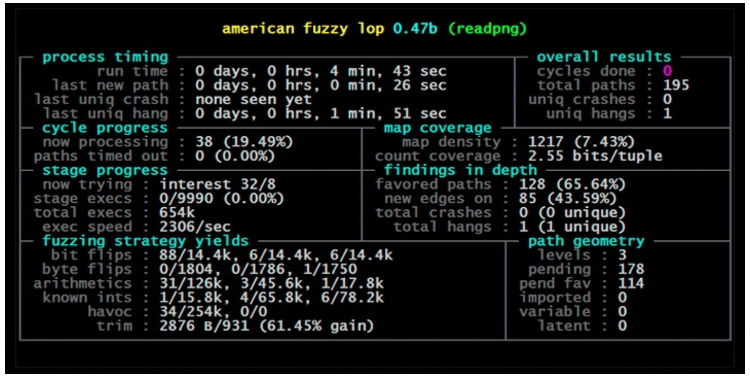
```c
int a, b, c, d, e;
int main() {
  for (b = 4; b > -30; b--)
    for (; c;)
      for (;;) {
        b++;
        e = a > 2147483647 - b;
        if (d) break;
      }
  return 0;
}
```



```c
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;
}
```

▨ : not executed

- Structured mutation not generalizable?
- Mutation at the binary level!



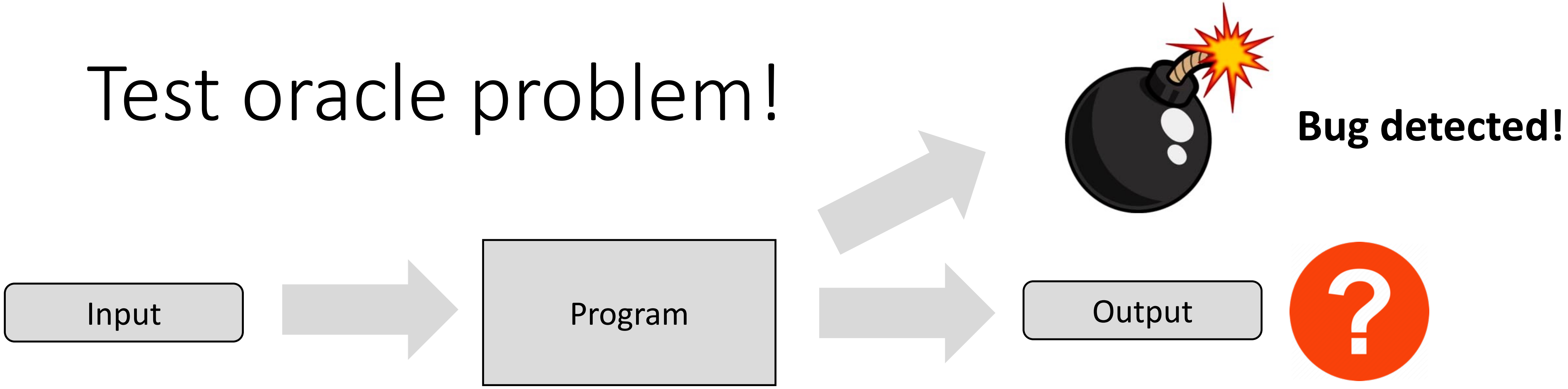
```
                american fuzzy lop 0.47b (readpng)

┌─ process timing ─────────────────────────────────────┬─ overall results ────┐
│        run time : 0 days, 0 hrs, 4 min, 43 sec        │  cycles done : 0     │
│   last new path : 0 days, 0 hrs, 0 min, 26 sec        │  total paths : 195   │
│ last uniq crash : none seen yet                        │ uniq crashes : 0     │
│  last uniq hang : 0 days, 0 hrs, 1 min, 51 sec        │   uniq hangs : 1     │
├─ cycle progress ────────────────────┬─ map coverage ─┴──────────────────────┤
│  now processing : 38 (19.49%)        │    map density : 1217 (7.43%)         │
│ paths timed out : 0 (0.00%)          │ count coverage : 2.55 bits/tuple      │
├─ stage progress ────────────────────┼─ findings in depth ────────────────────┤
│  now trying : interest 32/8          │ favored paths : 128 (65.64%)          │
│ stage execs : 0/9990 (0.00%)         │  new edges on : 85 (43.59%)           │
│ total execs : 654k                   │ total crashes : 0 (0 unique)          │
│  exec speed : 2306/sec               │   total hangs : 1 (1 unique)          │
├─ fuzzing strategy yields ───────────┴───────────────┬─ path geometry ────────┤
│   bit flips : 88/14.4k, 6/14.4k, 6/14.4k             │    levels : 3          │
│  byte flips : 0/1804, 0/1786, 1/1750                 │   pending : 178        │
│ arithmetics : 31/126k, 3/45.6k, 1/17.8k              │  pend fav : 114        │
│  known ints : 1/15.8k, 4/65.8k, 6/78.2k              │  imported : 0          │
│       havoc : 34/254k, 0/0                           │  variable : 0          │
│        trim : 2876 B/931 (61.45% gain)               │    latent : 0          │
└──────────────────────────────────────────────────────┴────────────────────────┘
```

AFL

Mutation-based fuzzing: examples

- Compiler Validation via Equivalence Modulo Inputs (PLDI’14)
  - Insight: EMI takes existing input programs and generates equivalent variants on a particular set of inputs (by removing unexecuted statements) for compiler fuzzing
  - **147** confirmed bugs found in the paper
  - Found **1,000+** LLVM/GCC bugs together with follow-up work
- AFL: American Fuzzy Lop (https://github.com/google/AFL)
  - The pioneer binary fuzzing tool leveraging coverage feedback
  - Highly scalable and generalizable due to the practical design
  - Found numerous bugs in real-world software systems

Test oracle problem!



Input

Program

Output

Bug detected!

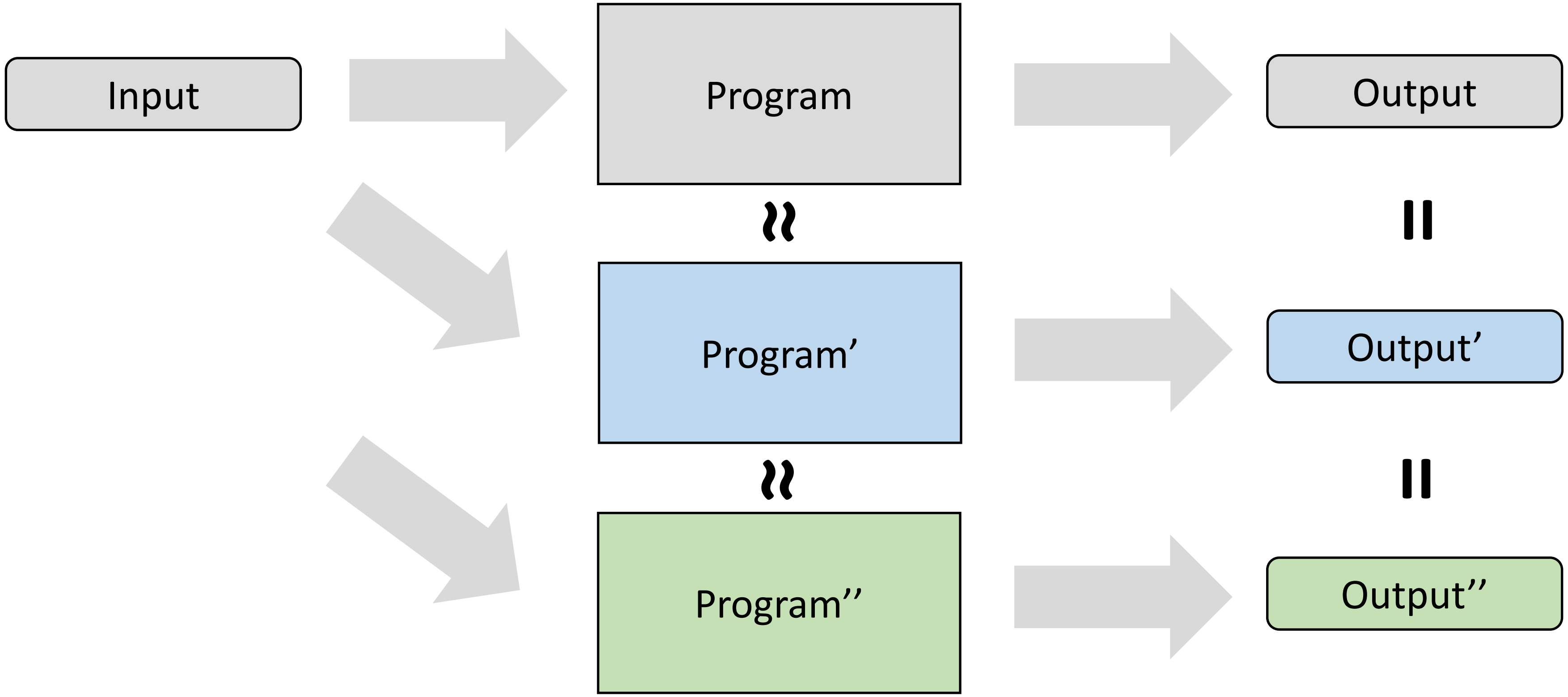
Test oracle: a mechanism for determining whether software executed correctly for a test[1].

One of the hardest problem in Software Engineering!

How to mitigate it?

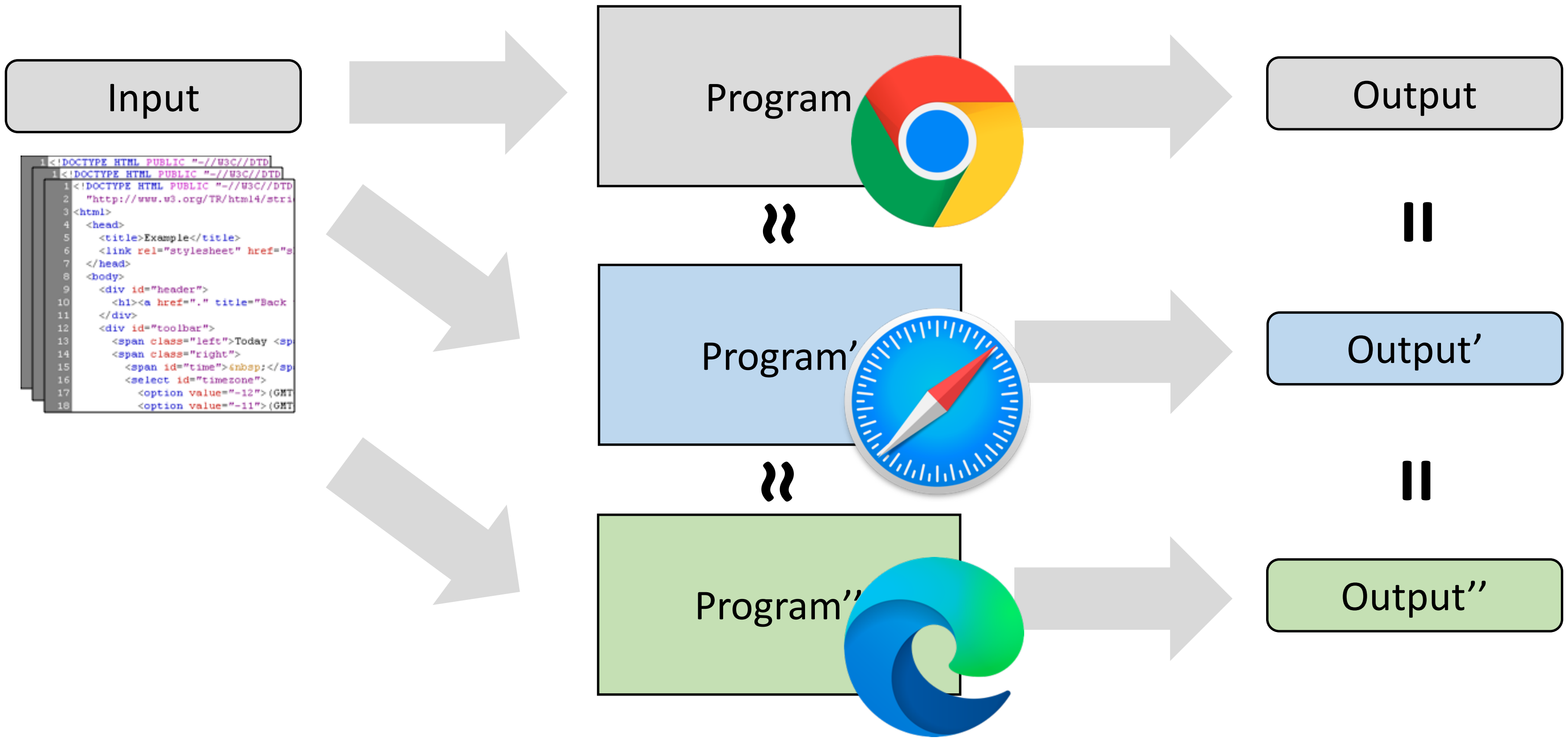
[1] https://en.wikipedia.org/wiki/Test_oracle

Differential testing

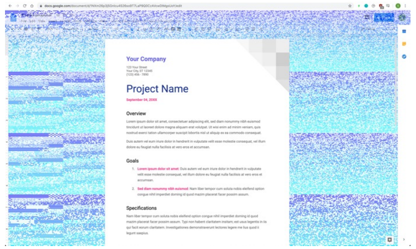


Provide the same input to **similar** applications, and observe output **differences**

Differential testing: browsers



```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD
  "http://www.w3.org/TR/html4/stri
<html>
  <head>
    <title>Example</title>
    <link rel="stylesheet" href="s
  </head>
  <body>
    <div id="header">
      <h1><a href="." title="Back
    </div>
    <div id="toolbar">
      <span class="left">Today <sp
      <span class="right">
        <span id="time">&nbsp;</sp
        <select id="timezone">
          <option value="-12">(GMT
          <option value="-11">(GMT
```


docs.google.com/document/d/1NXm26p3j5Gnlcu4S26so9T7LaP9Q0CzAVcwDiMgsUoY/edit

Your Company

123 Your Street
Your City, ST 12345
(123) 456 - 7890

Project Name

September 04, 20XX

Overview

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Goals

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Specifications

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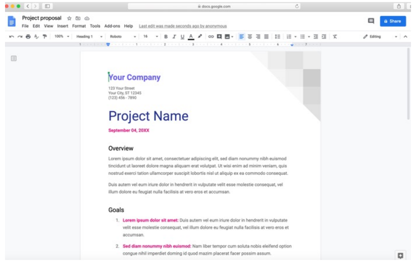

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Goals

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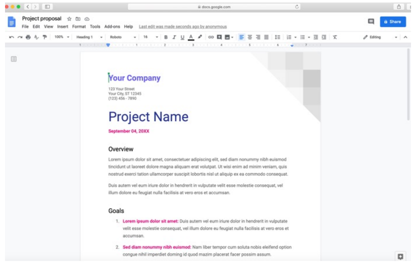

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Project Name

September 04, 20XX

Overview

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Goals

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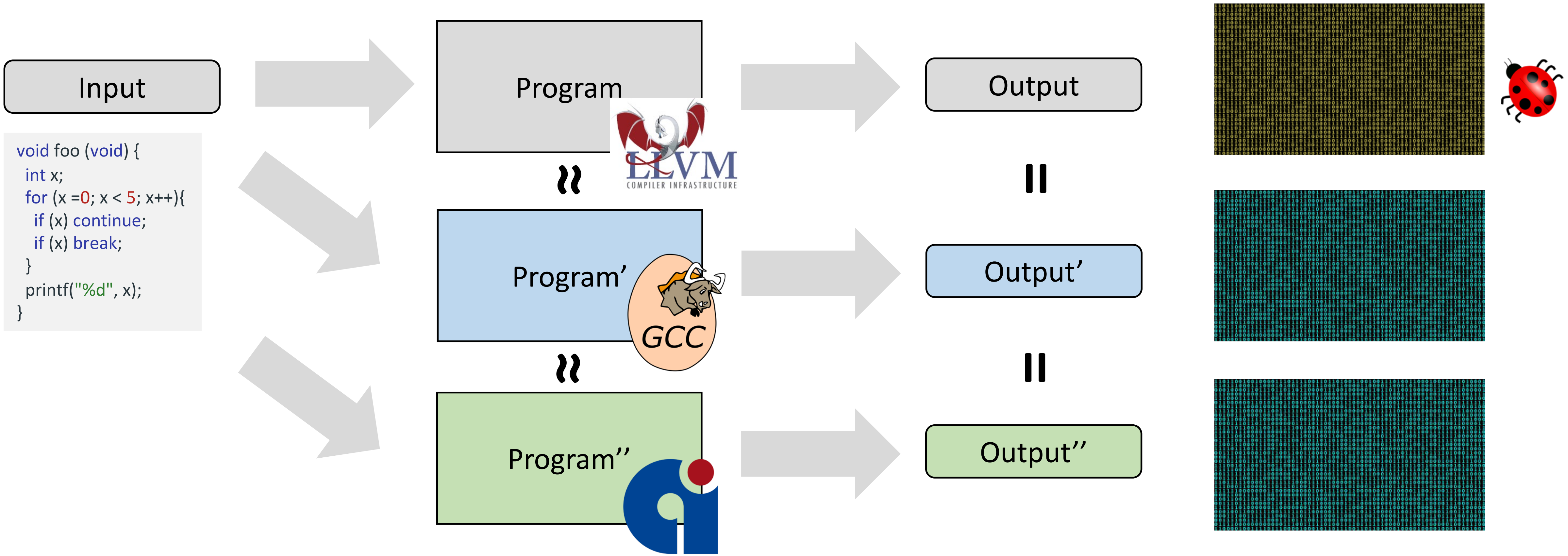
Provide the same input to **similar** applications, and observe output **differences**

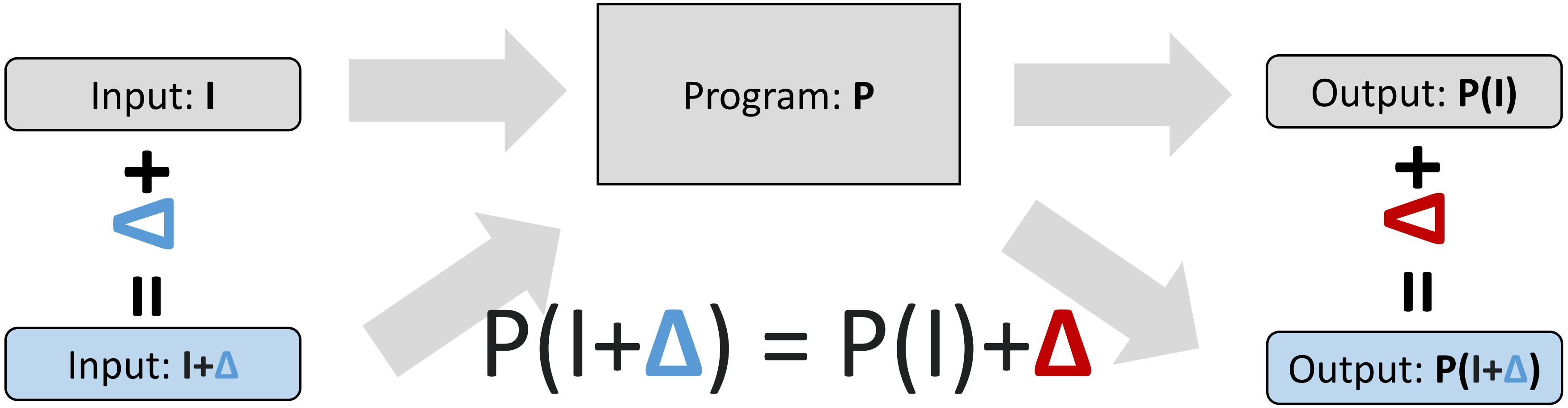
Differential testing: compilers (Csmith)



```
void foo (void) {
  int x;
  for (x =0; x < 5; x++){
    if (x) continue;
    if (x) break;
  }
  printf("%d", x);
}
```

Provide the same input to **similar** applications, and observe output **differences**

Metamorphic testing



Input: **I**

+ Δ =

Input: **I+Δ**

Program: **P**

Output: **P(I)**

+ Δ =

Output: **P(I+Δ)**

$$P(I+\Delta) = P(I)+\Delta$$

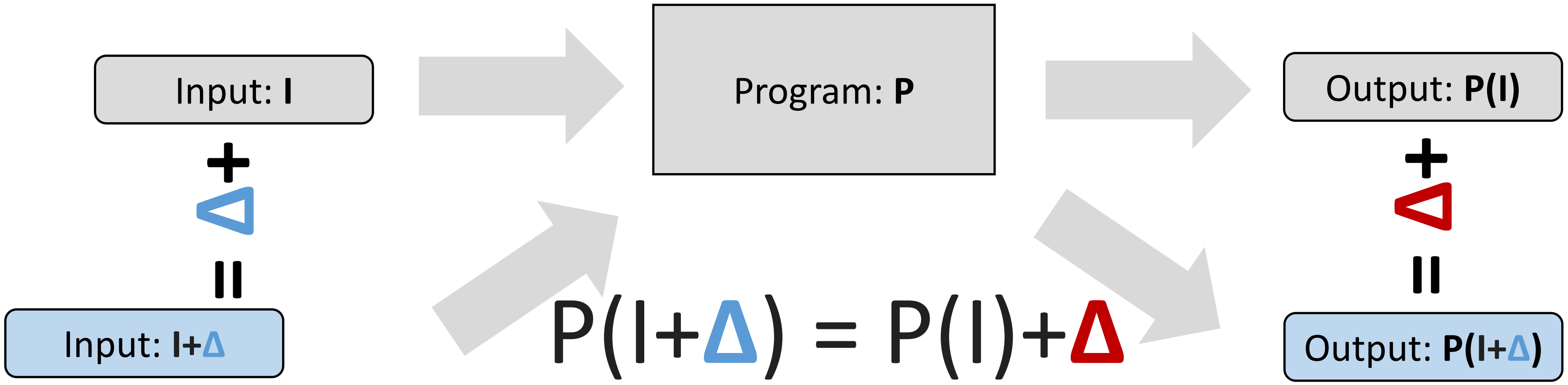
For example:

Sin(x+2π) = Sin(x)

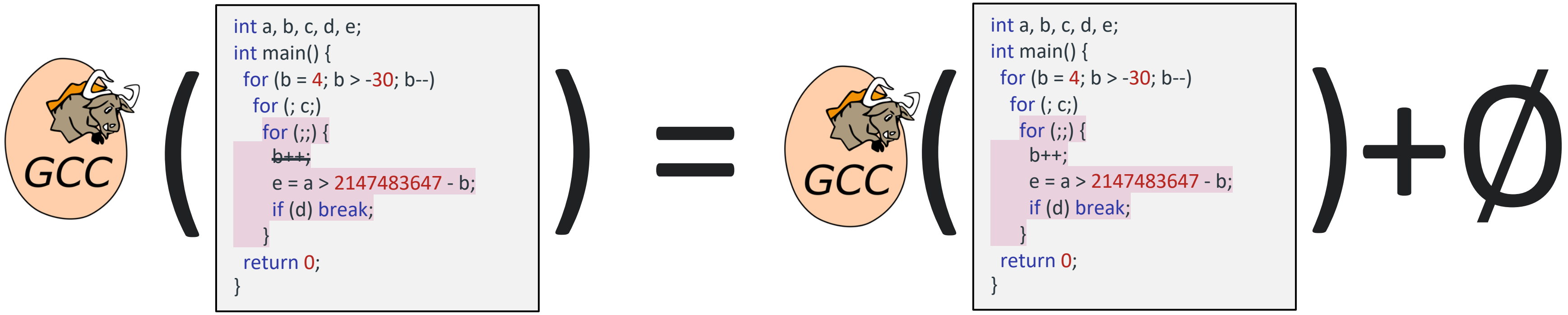
Sin(-x) = -Sin(x)

Provide the manipulated inputs to **same** application, and observe if output **differences** are as expected

Metamorphic testing: compilers (EMI)



$$P(I+\Delta) = P(I)+\Delta$$



```
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;
}
```

```
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;
}
```

Provide the manipulated inputs to **same** application,
and observe if output **differences** are as expected

Thanks and stay safe!