CS 5154: Software Testing

Automated Test Generation

Instructor: Owolabi Legunsen

Fall 2021

Review of the six CS5154 themes

1. How to automate the execution of tests? ✓
2. How to design and write high-quality tests? ✓
3. How to measure the quality of tests? ✓
4. How to automate the generation of tests? ←
5. How to reduce the costs of running existing tests?
6. How to deal with bugs that tests reveal? **[??]**

Why care about automated test generation?

- You learned how to design and write high-quality tests
  - **Hypothetical task**: test a project with 80k lines of code in one week
  - Test suites can have more lines than code under test, e.g., hw0, hw1, hw2

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Commons-Math

84,377 lines of **source code**

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

How would you proceed?

On automated test suite generation

- Today: fundamental concepts, alternative approaches

- Next: hands-on demo

Testing: review of basic testing concepts

- **Test case:**
- **Test oracle:**
- **Test suite:**
- **Test adequacy:**

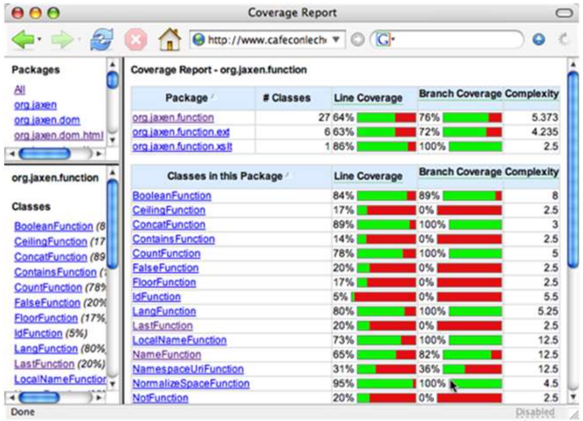
Testing: basic concepts

- **Test case** (or, **test**): executes the code under test and includes
  - Input values
  - execution steps (most times)
  - Expected outputs

- **Test oracle**: compares observed and expected outputs

- **Test suite**: a finite set of tests
  - Usually, can be run together in sequence

- **Test adequacy**: a measurement of test quality
  - e.g., code coverage



Packages

All
org.jaxen
org.jaxen.dom
org.jaxen.dom.html

org.jaxen.function

Classes

BooleanFunction (8
CeilingFunction (17
ConcatFunction (89
ContainsFunction (
CountFunction (78%
FalseFunction (20%
FloorFunction (17%
IdFunction (5%)
LangFunction (80%
LastFunction (20%)
LocalNameFunctior

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
LocalNameFunction	73%	100%	12.5
NameFunction	65%	82%	12.5
NamespaceUriFunction	31%	36%	12.5
NormalizeSpaceFunction	95%	100%	4.5
NotFunction	20%	0%	2.5

automated test generation

Different approaches target these concepts

- Input value generation, e.g., fuzzing, symbolic execution
- Test suite generation, e.g., Randoop, EvoSuite
- Test oracle generation is very hard
- Test Adequacy: used to evaluate automated tests

Who is using automated test generation

- Randoop:

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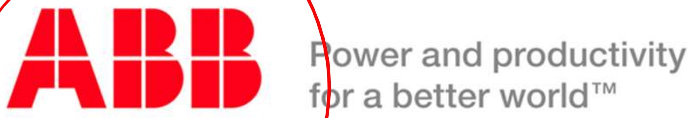
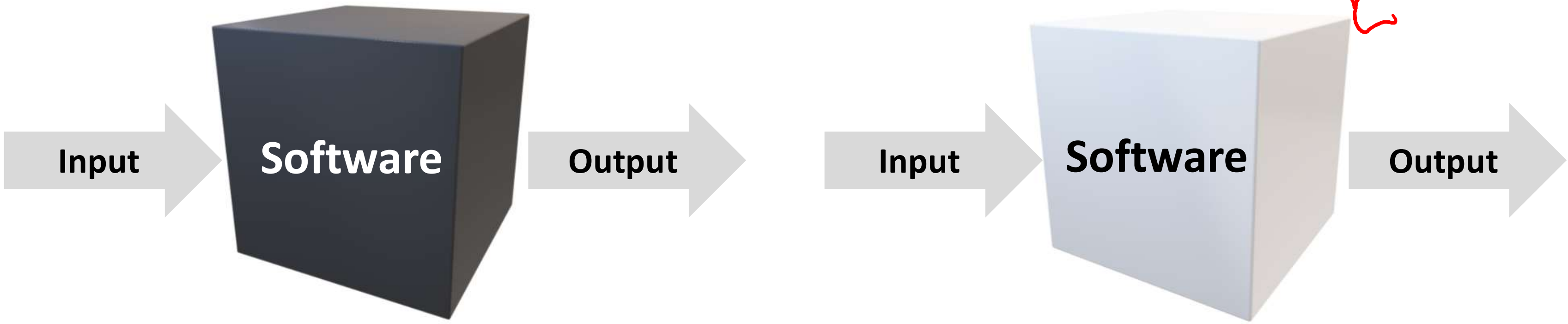


Who is using automated test generation? (2)

- Type in your favorite search engine:
  - “fuzzing at Google”
  - “fuzzing at Microsoft”
  - “fuzzing at Facebook”
  - “fuzzing at X”

Classes of test generation approaches

- Functional vs. structural test generation



- **Functional test generation** is based on the functionality of the code

- **Structural test generation** is based on the structure of the code

Structural generation granularity

- Projects providing public APIs for external use
  - **Method-level test generation**: consider various method invocation sequences to expose possible faults

random

Guided unit test generation (this lecture and the next)

- Projects usually used as a whole
  - **Path-level generation**: consider all the execution paths to cover most code elements

Whole-suite test generation (not covered this semester)

Thought experiment

- How would you go about automatically creating a test suite for class C?

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

- Alternatively, what are the pieces that you need to create a test suite for C?

Your thoughts

Recall: the components of a unit test

Program under test:

```
public class Math{
  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

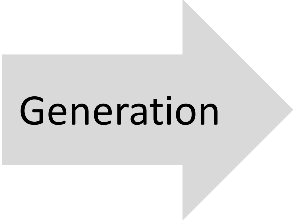
Execution steps

Test oracle

How to do random structural test generation?

Program under test

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



Generated test *t1*

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

Generated test *t2*

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

Generated test *t3*

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

```
…
```

- Needed: generate a random sequence of invocations, each of which has
  - A random method
  - Some random parameters
  - A random receiver object
    - Not required for static methods

Your turn…

- What are some limitations of random method-sequence generation?

Random method-sequence generation: limitations

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

A random test

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

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Random method-sequence generation: redundant and illegal tests

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

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

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

Should not output

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

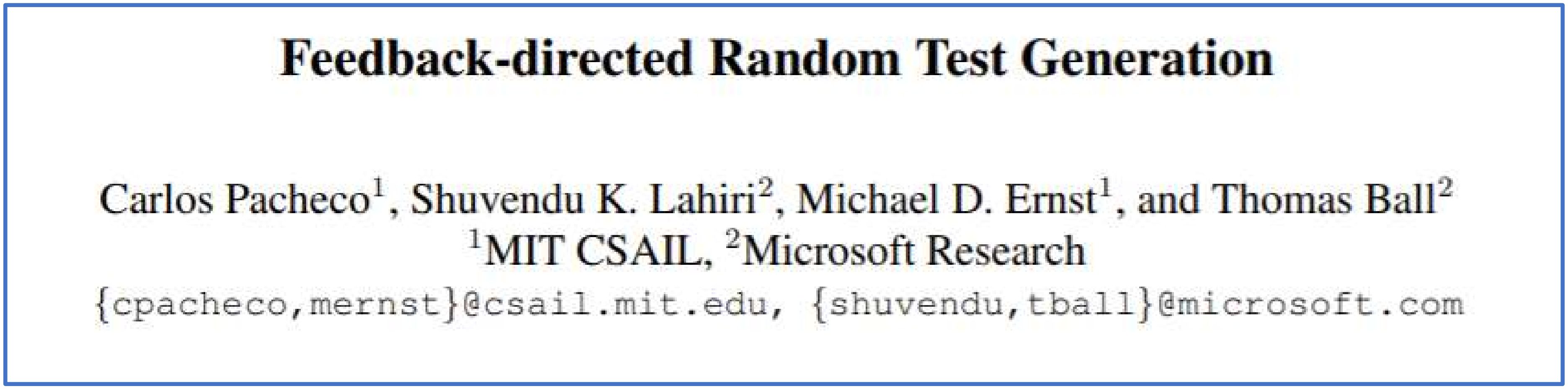
Should not output

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

Should not even generate

We need something more than random

- Randoop: Feedback-directed Random Test Generation (ICSE’07)
  - The intuitions
  - The tool
  - Read the paper for more details!



Feedback-directed Random Test Generation

Carlos Pacheco[1], Shuvendu K. Lahiri[2], Michael D. Ernst[1], and Thomas Ball[2]
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Randoop: feedback-directed random test generation

- Use code contracts as test oracles

- Build tests incrementally
  - new tests extend previous ones
  - in this context, a test 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: inputs and output

- **Input**s: 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”)
  - User-written contracts
- **Output**: contract-violating or contract-preserving unit tests

```
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

Some contracts that Randoop uses

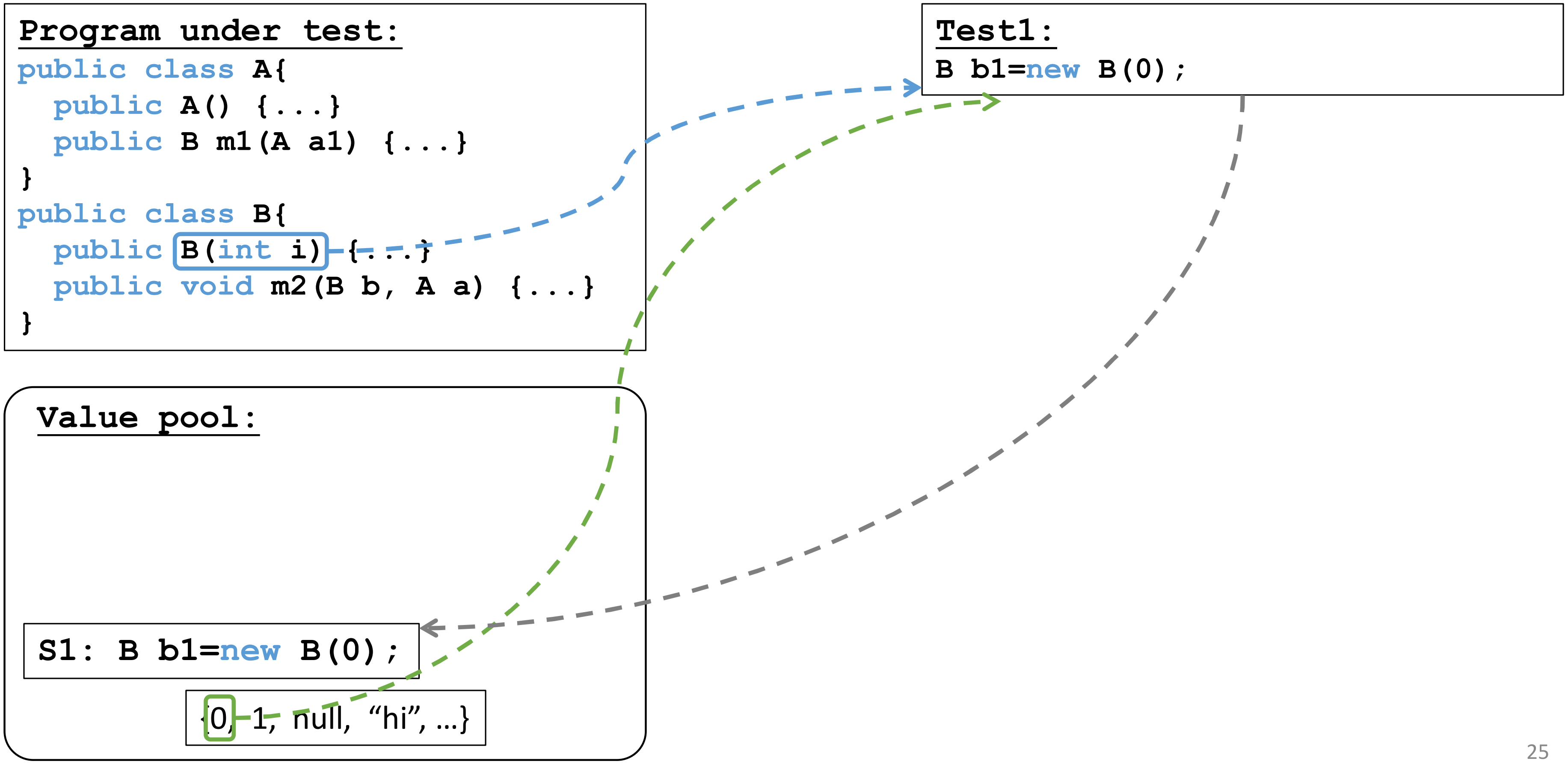
- **o.equals(o)==true**
- **o.equals(o)** throws no exception
- **o.hashCode()** throws no exception
- **o.toString()** throws no exception
- No null inputs and No NPEs

Randoop: algorithm

1. Seed value pool for various types
   - pool = { **0, 1, true, false, “hi”, null** ... }
2. Do until time limit expires:
   1. Create a new sequence
      1. Randomly pick a method call $\mathbf{m}(\mathbf{T_1}...\mathbf{T_k})/\mathbf{T_{ret}}$
      2. 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 $\mathbf{T_i}$
      3. Create new sequence $\mathbf{S_{new}} = \mathbf{S_1}; ... ; \mathbf{S_k} ; \mathbf{T_{ret}}\ \mathbf{v_{new}} = \mathbf{m}(\mathbf{v_1}...\mathbf{v_k});$
      4. If $\mathbf{S_{new}}$ was previously created (lexically), go to step i
   2. Classify new sequence $\mathbf{S_{new}}$ **:** discard, output, 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);
```

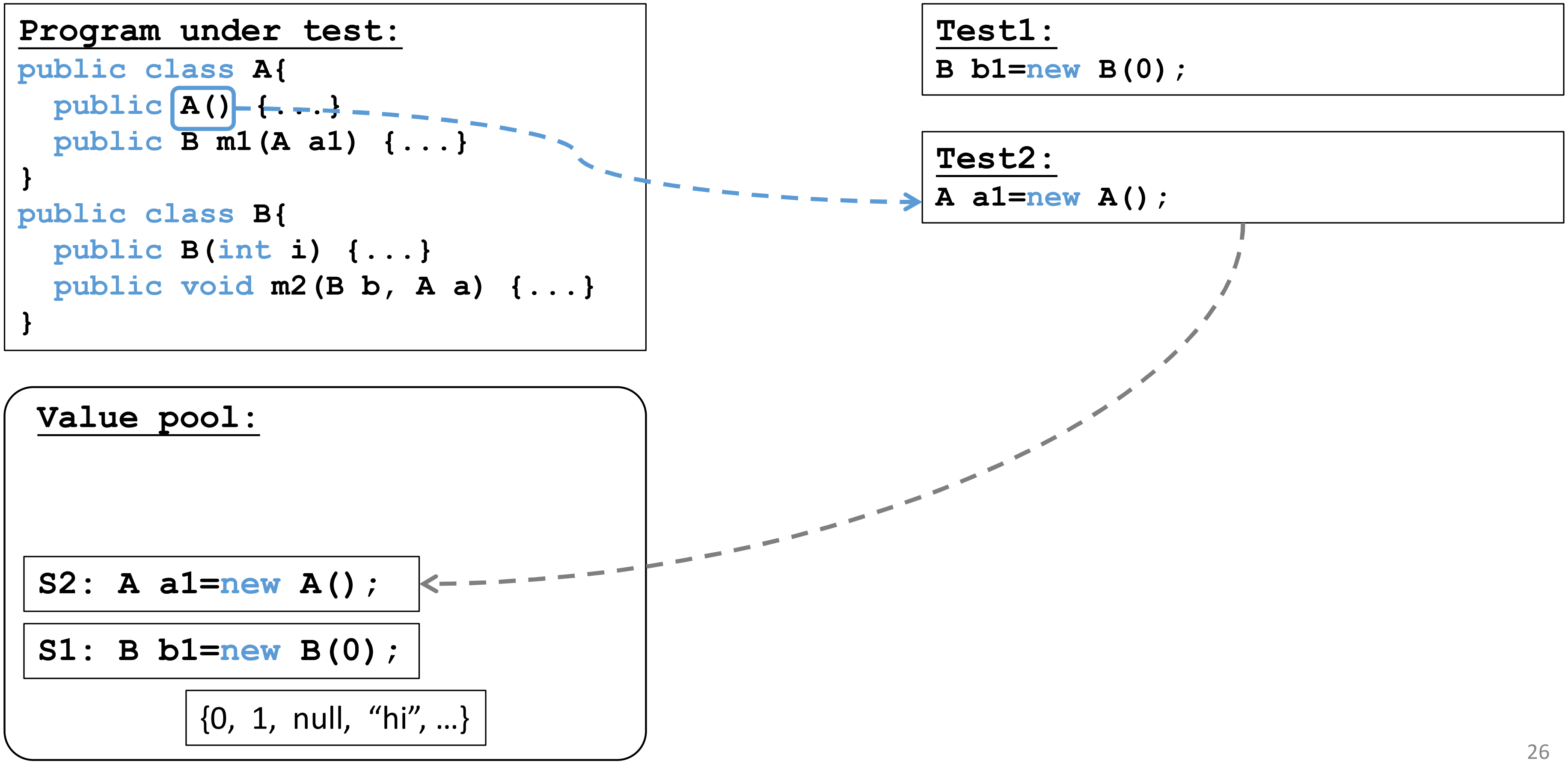
Value pool:

```
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);
```

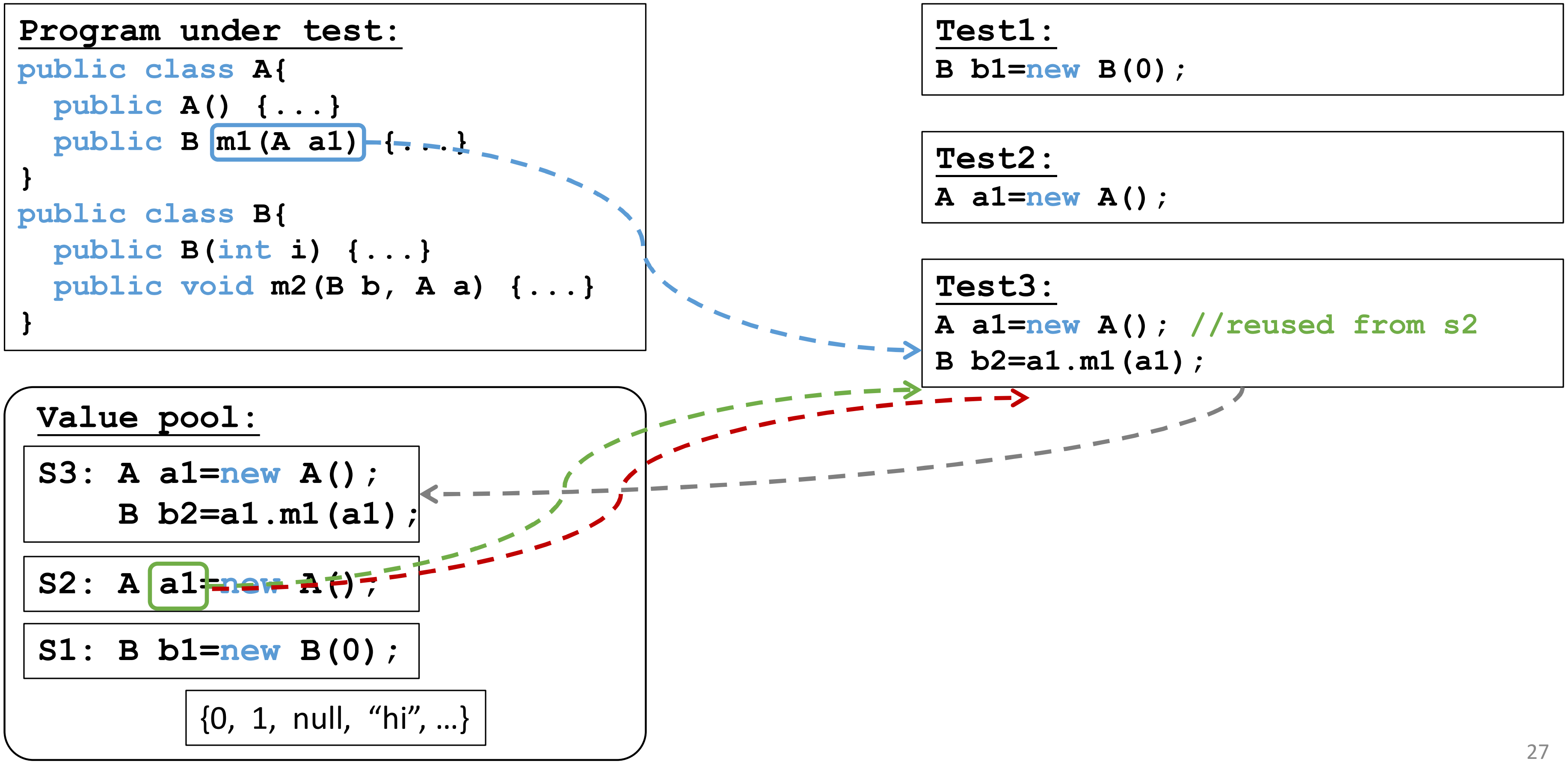
{0, 1, null, “hi”, …}

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) {...}
}
```

Test1:

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

Test2:

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

Test3:

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

Value pool:

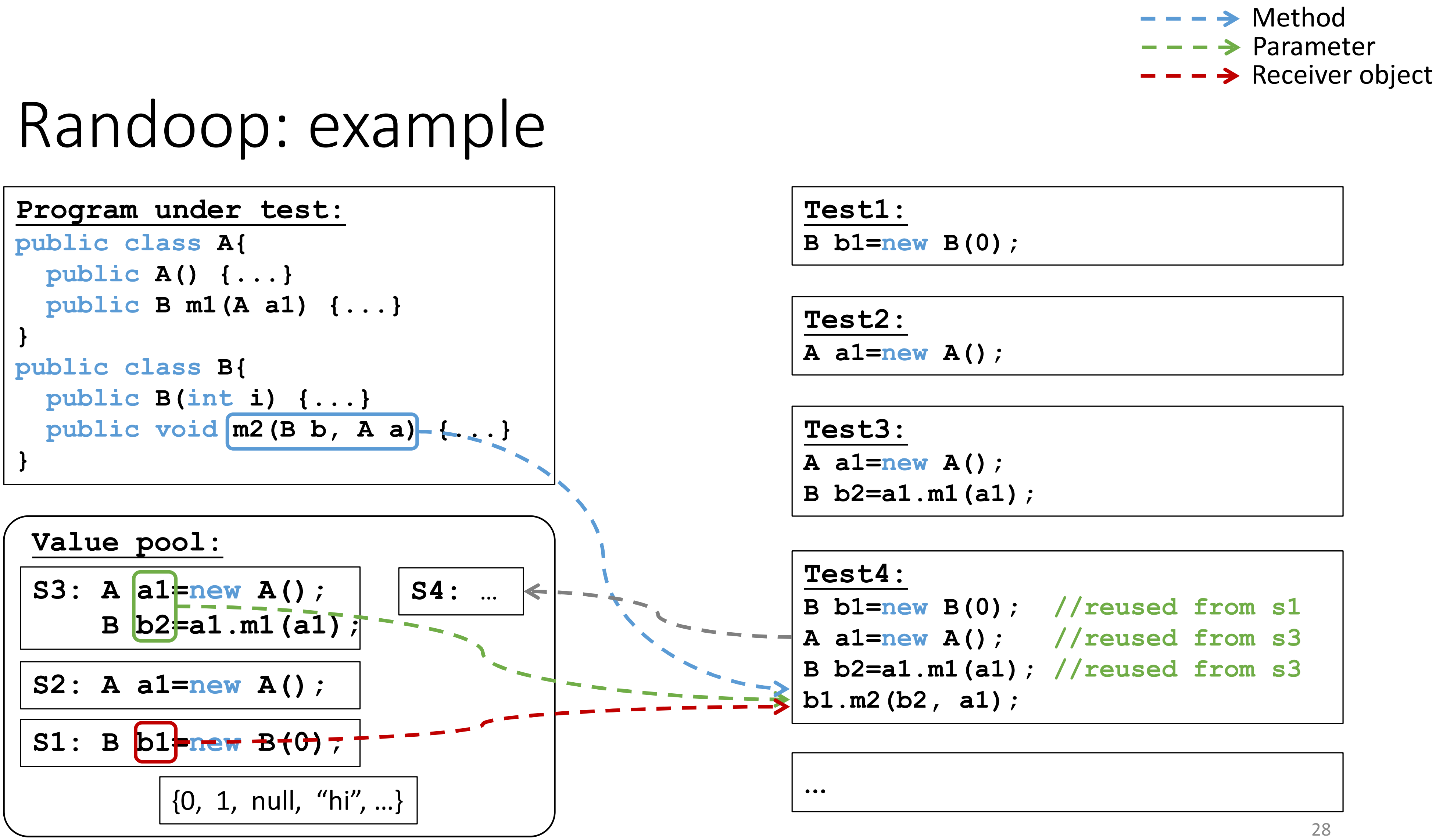
```
S3: A a1=new A();
    B b2=a1.m1(a1);
```

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

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

{0, 1, null, “hi”, …}

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”, …}

```
S4: …
```

Test1:

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

Test2:

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

Test3:

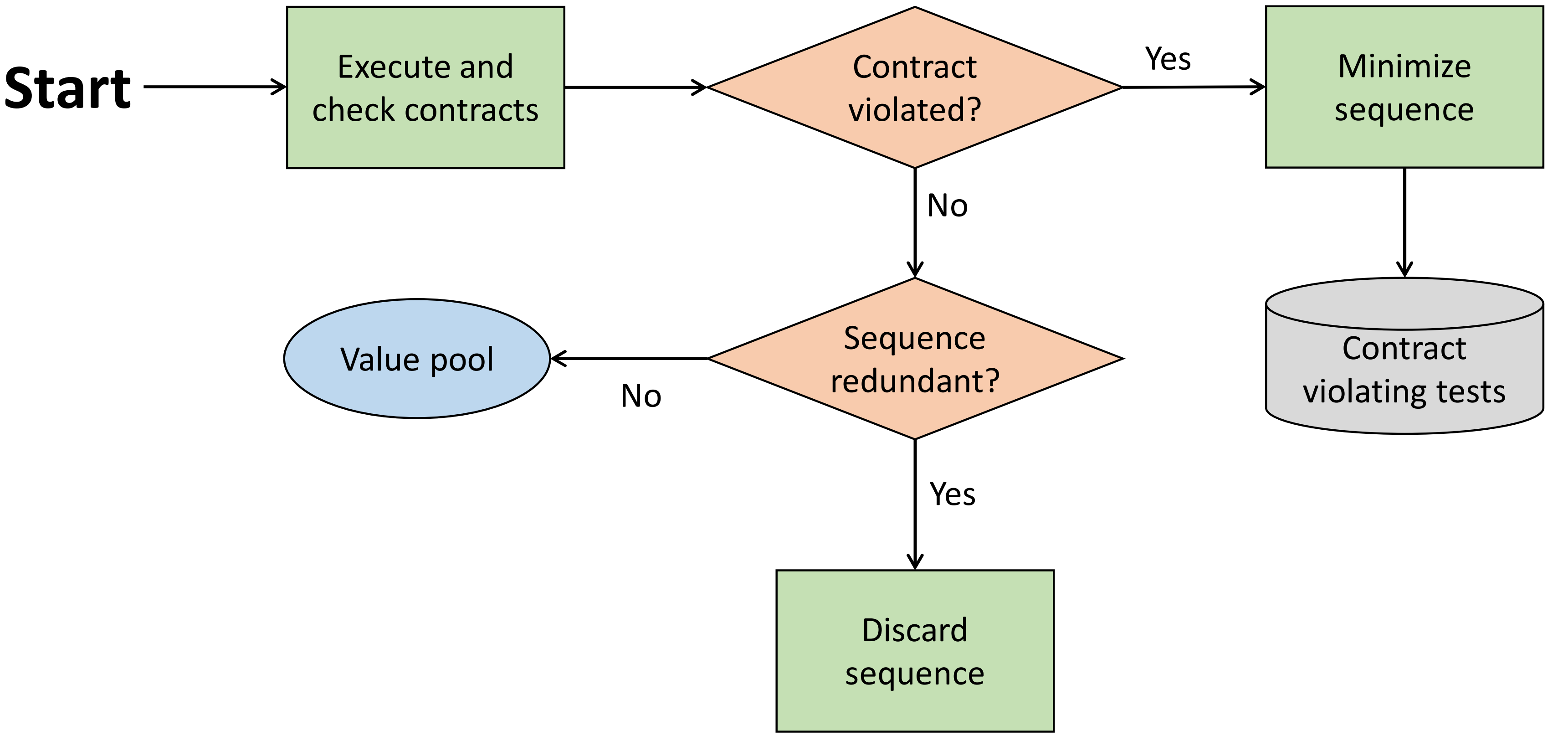
```
A a1=new A();
B b2=a1.m1(a1);
```

Test4:

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

…

Classifying a sequence



Redundant sequences

1. During generation, maintain a set of all objects created

2. A sequence is redundant if all the objects created during its execution are members of the set in 1 (using *equals* to compare)

   - One can also use more sophisticated state equivalence methods to compare, e.g., heap canonicalization

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));// assertion fails
```

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

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

Tool demo