Joint Degree Program of Fudan University and University College Dublin (UCD)

SOFT620020.01
Advanced Software Engineering

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A Quick Recap

- Software testing
- Unit testing, integration testing, system testing
- Black-box testing
  - Random testing, equivalence partitioning
- White-box testing
  - Coverage testing, mutation testing
- Grey-box testing

Discussion 1 – Testing OO Programs

Write test cases for the following two object-oriented programs.

java.util.HashSet<E>.add(E e)

```
public static void test() {
    Set s = new HashSet();
    s.add("hi");
    assertTrue(s.equals(s));
}
```

java.util.Date.setMonth(int month)

```
public static void test() {
    Date d = new Date(2018, 9, 8);
    d.setMonth(10);
    assertTrue(d.equals(d));
}
```

Course Outline

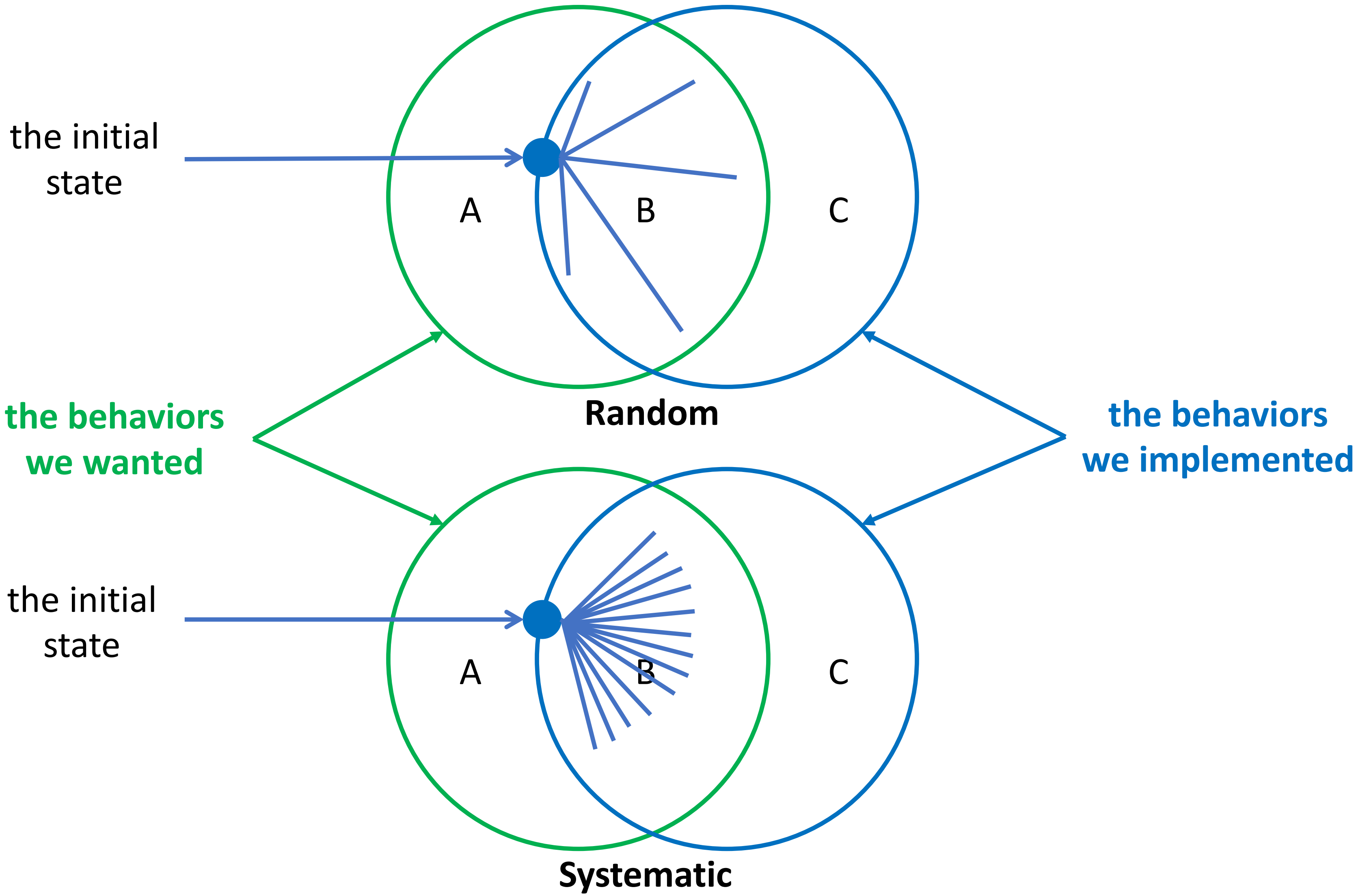
Date	Topic	Date	Topic
Sep. 09	Introduction	Nov. 04	Mobile Testing
Sep. 16	Testing Overview	Nov. 11	Delta Debugging
Sep. 23	**Guided Random Testing**	Nov. 18	Presentation 2
Sep. 30	Search-Based Testing	Nov. 25	Bug Localization
Oct. 12	Performance Analysis	Dec. 02	Automatic Repair
Oct. 14	Presentation 1	Dec. 09	Symbolic Execution
Oct. 21	Security Testing	Dec. 16	Big Code Analysis
Oct. 28	Compiler Testing	Dec. 23	Presentation 3

Feedback-Directed Random Test Generation

Carlos Pacheco, Shuvendu Lahiri, Michael Ernst, Thomas Ball

ICSE 2007, Citation: 668

Random vs. Systematic



Random vs. Systematic (cont.)

- Theoretical work suggests that random testing is as effective as more systematic testing techniques
  - Duran et al. 1984 and Hamlet et al. 1990

- Some empirical studies suggest that systematic testing is more effective than random testing
  - Ferguson et al. 1996: vs. chaining
  - Marinov et al. 2003: vs. bounded exhaustive
  - Visser et al. 2006: vs. model checking and symbolic execution
  - Studies are performed on small benchmarks, and do not measure error revealing effectiveness

RANDOOP (random tester for object-oriented programs)

- Propose feedback-directed random test generation
  - Randomized creation of new test inputs is guided by feedback about the execution of previous test inputs
  - The goal is to generate **new** and **legal** test inputs and avoid **redundant** and **illegal** test inputs

- Conduct intensive empirical evaluations
  - Evaluate coverage **and error-detection capability** on a large number of widely-used and well-tested libraries (780K LOC)
  - Compare against systematic input generation
  - Compare against undirected random input generation

A Test Case Generated by RANDOOP

```
public static void test() {
    LinkedList l1 = new LinkedList();
    Object o1 = new Object();
    l1.addFirst(o1);
    TreeSet t1 = new TreeSet(l1);
    Set s1 = Collections.unmodifiableSet(t1);
    // this assertion fails
    Assert.assertTrue(s1.equals(s1));
}
```

Method Sequence

Testing Oracle

The set s1 returned by unmodifiableSet(Set) returned false for s1.equals(s1). This violates the reflexivity of equals as specified in Sun's API documentation.

The TreeSet(Collection c) constructor failed to throw ClassCastException as required by its specification (i.e., the elements in c must be Comparable)

Input and Output of RANDOOP

- Input
  - A set of classes under test
  - A set of (default or extended) contracts
  - A set of (default or extended) filters
  - Time limit (2 minutes by default)
- Output
  - A set of contract-satisfying test cases
  - A set of contract-violating test cases
- Main idea
  - Generate new test cases by extending previous ones
  - Execute the test case as soon as it is generated
  - Use the execution result to guide test case generation

Algorithm of RANDOOP

GenerateSequences(*classes*, *contracts*, *filters*, *timeLimit*)

errorSeqs ← {} *// Their execution violates a contract.*
nonErrorSeqs ← {} *// Their execution violates no contract.*
while *timeLimit* not reached **do**
    // Create new sequence.
    $m(T_1 \ldots T_k) \leftarrow \mathit{randomPublicMethod}(\mathit{classes})$
    $\langle \mathit{seqs}, \mathit{vals} \rangle \leftarrow \mathit{randomSeqsAndVals}(\mathit{nonErrorSeqs}, T_1 \ldots T_k)$
    $\mathit{newSeq} \leftarrow \mathit{extend}(m, \mathit{seqs}, \mathit{vals})$
    // Discard duplicates.
    if $\mathit{newSeq} \in \mathit{nonErrorSeqs} \cup \mathit{errorSeqs}$ **then**
        continue
    end if
    // Execute new sequence and check contracts.
    $\langle \vec{\mathbf{o}}, \mathit{violated} \rangle \leftarrow \mathit{execute}(\mathit{newSeq}, \mathit{contracts})$
    // Classify new sequence and outputs.
    if $\mathit{violated} = \mathit{true}$ **then**
        $\mathit{errorSeqs} \leftarrow \mathit{errorSeqs} \cup \{\mathit{newSeq}\}$
    else
        $\mathit{nonErrorSeqs} \leftarrow \mathit{nonErrorSeqs} \cup \{\mathit{newSeq}\}$
        $\mathit{setExtensibleFlags}(\mathit{newSeq}, \mathit{filters}, \vec{\mathbf{o}})$ *// Apply filters.*
    end if
end while
return $\langle \mathit{nonErrorSeqs}, \mathit{errorSeqs} \rangle$

Creating Method Sequence

- If Ti is a primitive type
  - Select a value from a fixed pool of values (e.g., -1, 0, 1, ’a’, true)
  - The pool can be augmented by users

- If Ti is a reference type
  - Use a value *v* from a sequence that is already in *seqs*
  - Select a sequence from *nonErrorSeqs*, add it to *seqs*, and use a value *v* from it
  - Use *null*

Example of Creating Method Sequence

```
public class A {
  public A() {...}
  public B m1(A a1) {...}
}
```

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

One receiver object of type B, and two parameters of type B and A

sequence s_1	sequence s_2	sequence s_3
`B b1 = new B(0);`	`B b2 = new B(0);`	`A a1 = new A();` `B b3 = a1.m1(a1);`

seqs	*vals*	*extend*(m2, *seqs*, *vals*)

$\langle s_1, s_3 \rangle$	$\langle\ s_1.1, s_1.1, s_3.1\ \rangle$
	(i.e.: `b1`, `b1`, `a1`)
		`B b1 = new B(0);`
		`A a1 = new A();`
		`B b3 = a1.m1(a1);`
		`b1.m2(b1,a1);`

$\langle s_1, s_2 \rangle$	$\langle\ s_1.1, s_2.1,$ `null` $\rangle$
	(i.e.: `b1`, `b2`, `null`)
		`B b1 = new B(0);`
		`B b2 = new B(0);`
		`b1.m2(b2,null);`

Discussion 2 – Creating Sequences

Create ALL possible sequences for the method m2 in class B.

```
public class A {
  public A() {...}
  public B m1(A a1) {...}
}
```

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

Sequence s1
B b1 = new B(0);

Sequence s2
B b2 = new B(-1);

Sequence s3
A a1 = new A();

Algorithm of RANDOOP

GenerateSequences(*classes*, *contracts*, *filters*, *timeLimit*)

errorSeqs $\leftarrow$ {} *// Their execution violates a contract.*
nonErrorSeqs $\leftarrow$ {} *// Their execution violates no contract.*
while *timeLimit* not reached **do**
    // Create new sequence.
    $m(T_1 \ldots T_k) \leftarrow randomPublicMethod(classes)$
    $\langle seqs, vals \rangle \leftarrow randomSeqsAndVals(nonErrorSeqs, T_1 \ldots T_k)$
    $newSeq \leftarrow extend(m, seqs, vals)$
    // Discard duplicates.
    if $newSeq \in nonErrorSeqs \cup errorSeqs$ **then**
        continue
    end if
    // Execute new sequence and check contracts.
    $\langle \vec{\mathbf{o}}, violated \rangle \leftarrow execute(newSeq, contracts)$
    // Classify new sequence and outputs.
    if $violated = true$ **then**
        $errorSeqs \leftarrow errorSeqs \cup \{newSeq\}$
    else
        $nonErrorSeqs \leftarrow nonErrorSeqs \cup \{newSeq\}$
        $setExtensibleFlags(newSeq, filters, \vec{\mathbf{o}})$ *// Apply filters.*
    end if
end while
return $\langle nonErrorSeqs, errorSeqs \rangle$

Discussion 3 – Redundant Sequence

Which method sequence is redundant?

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

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

```
Set t = new HashSet();
s.add("hi");
s.isEmpty();
assertTrue(s.equals(s));
```

Redundancy Checking

- RANDOOP maintains a set of objects for each type
- A method sequence is redundant if the objects created during its execution are members of the above set
  - Use equals() to compare
  - Or user-defined more sophisticated checking
- RANDOOP uses **observer methods** to capture object state
  - A method is probably an observer method if it has no parameters; it is public and non-static; it returns primitive values; and its name is size, count, length, toString, or begins with get or is

Algorithm of RANDOOP

```
GenerateSequences(classes, contracts, filters, timeLimit)
errorSeqs ← {} // Their execution violates a contract.
nonErrorSeqs ← {} // Their execution violates no contract.
while timeLimit not reached do
    // Create new sequence.
    m(T1 . . . Tk) ← randomPublicMethod(classes)
    ⟨seqs, vals⟩ ← randomSeqsAndVals(nonErrorSeqs, T1 . . . Tk)
    newSeq ← extend(m, seqs, vals)
    // Discard duplicates.
    if newSeq ∈ nonErrorSeqs ∪ errorSeqs then
        continue
    end if
    // Execute new sequence and check contracts.
    ⟨o⃗, violated⟩ ← execute(newSeq, contracts)
    // Classify new sequence and outputs.
    if violated = true then
        errorSeqs ← errorSeqs ∪ {newSeq}
    else
        nonErrorSeqs ← nonErrorSeqs ∪ {newSeq}
        setExtensibleFlags(newSeq, filters, o⃗) // Apply filters.
    end if
end while
return ⟨nonErrorSeqs, errorSeqs⟩
```

Default Contracts in RANDOOP

Method contract	**description**
Exception (Java)	method throws no `NullPointerException` if no input parameter was null
	method throws no `AssertionError`
Exception (.NET)	method throws no `NullReferenceException` if no input parameter was null
	method throws no `IndexOutOfRangeException`
	method throws no `AssertionError`

Object contract	**description**
equals	`o.equals(o)` returns `true`
	`o.equals(o)` throws no exception
hashCode	`o.hashCode()` throws no exception
toString	`o.toString()` throws no exception

Default Filters in RANDOOP

- Filters determine which objects created in a method sequence can be reused as the input to a new method call
  - Equality
  - Null
  - Exception

The Equality Filter

- Use the equals() method to determine whether the resulting object has been created before

- Maintain a set of all reusable objects that have been created across all the sequences

The Null Filter

- Determine whether the resulting object is null
- Null dereference exception occur in the absence of any null value in the inputs indicates some internal problem with the method

The Exception Filter

- Exceptions frequently correspond to pre-condition violations for a method call, and therefore there is little point reusing them

- An extension of the sequence would lead to an exception before the execution completes

Discussion 4 – Filters

Which method sequence or object is filtered?

```
Date d = new Date(2006, 2, 14);
d.setMonth(1);
assertTrue(d.equals(d));
```

```
Date d = new Date(2006, 2, 14);
// pre-condition: argument >= 0
d.setMonth(-1);
assertTrue(d.equals(d));
```

```
Date d = new Date(2006, 2, 14);
d.setMonth(-1);
d.setDay(5);
assertTrue(d.equals(d));
```

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

Repetition

- Repeated calls may be necessary
  - Reach the code that increases the capacity of a container object
  - Create two equivalent objects that can cause a method like equals to go down certain branches

- When generating a new sequence, with probability p, RANDOOP appends m calls of a chosen method
  - p is in the range of 0 and 1, its default value is 0.1
  - m is chosen uniformly at random between 0 and *max*, and the default value of *max* is 100

Discussion 5 – Feedback in RANDOOP

What are the feedbacks used in RANDOOP?

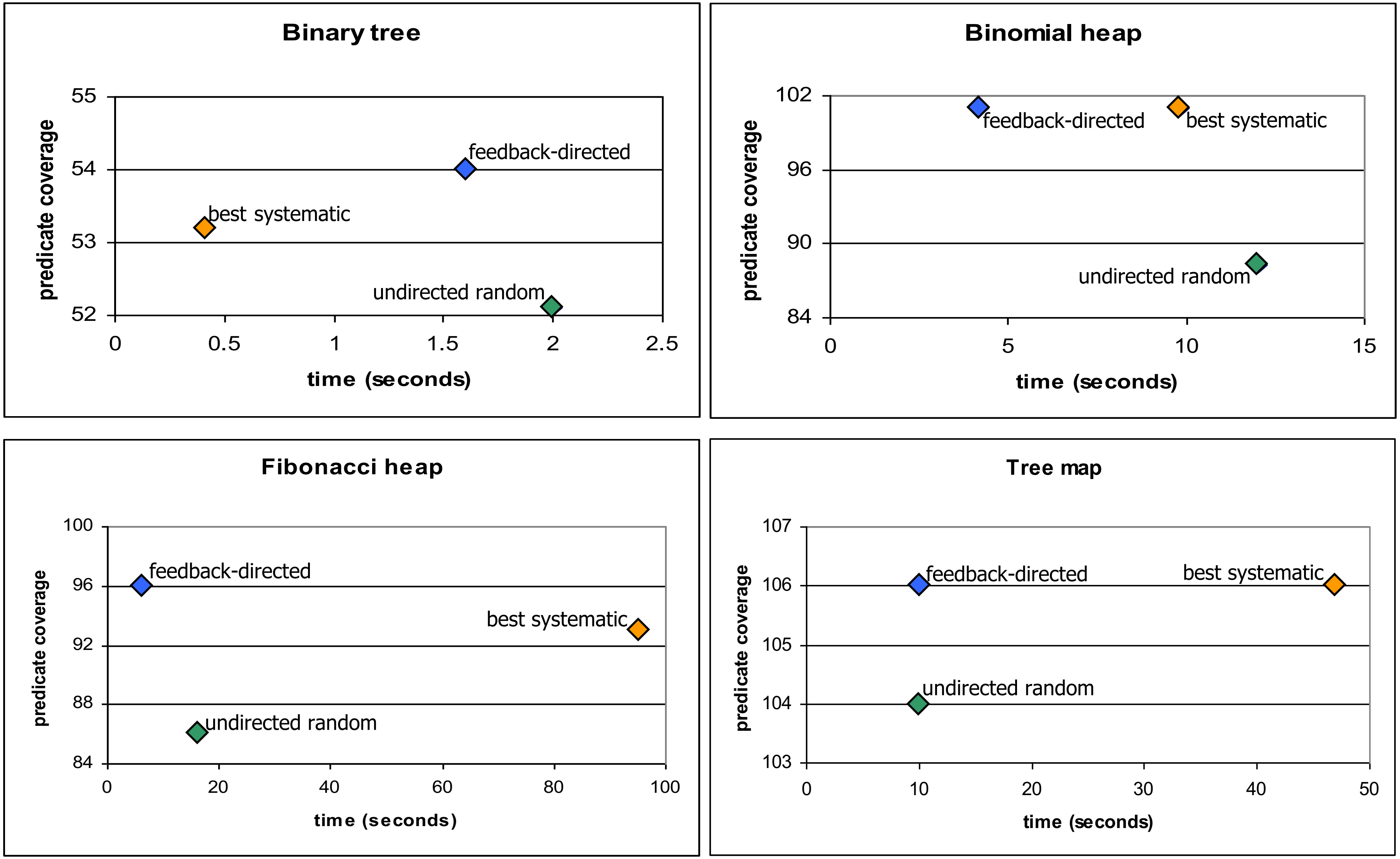
Contracts and Filters

Evaluation – Testing Containers

		coverage				time (seconds)			
		JPF	RP	JPF_U	RP_U	JPF	RP	JPF_U	RP_U
block coverage	BinTree	.78	.78	.78	.78	0.14	0.21	0.14	0.13
	BHeap	.95	.95	.95	.86	4.3	0.59	6.2	6.6
	FibHeap	1	1	1	.98	23	0.63	1.1	27
	TreeMap	.72	.72	.72	.68	0.65	0.84	1.5	1.9
predicate coverage	BinTree	53.2	54	52.1	53.9	0.41	1.6	2.0	4.2
	BHeap	101	101	88.3	58.5	9.8	4.2	12	15
	FibHeap	93	96	86	90.3	95	6.0	16	67
	TreeMap	106	106	104	55	47	10	10	1.9

JPF : Best-performing of 5 systematic techniques in JPF.
RP : RANDOOP: Feedback-directed random testing.
JPF_U : Undirected random testing implemented in JPF.
RP_U : Undirected random testing implemented in RANDOOP.

Evaluation – Testing Containers (cont.)



Evaluation – Checking API Contracts

Java libraries	**LOC**	**public classes**	**public methods**	description
Java JDK 1.5				
java.util	39K	204	1019	Collections, text, formatting, etc.
javax.xml	14K	68	437	XML processing.
Jakarta Commons				
chain	8K	59	226	API for process flows.
collections	61K	402	2412	Extensions to the JDK collections.
jelly	14K	99	724	XML scripting and processing.
logging	4K	9	140	Event-logging facility.
math	21K	111	910	Mathematics and statistics.
primitives	6K	294	1908	Type-safe collections of primitives.
.NET libraries	**LOC**	**public classes**	**public methods**	
ZedGraph	33K	125	3096	Creates plots and charts.
.NET Framework				
Mscorlib	185K	1439	17763	.NET Framework SDK class libraries.
System.Data	196K	648	11529	Provide access to system functionality
System.Security	9K	128	1175	and designed as foundation on which
System.Xml	150K	686	9914	.NET applications, components, and
Web.Services	42K	304	2527	controls are built.

14 widely-used libraries comprising a total of 780K LOC

Evaluation – Checking API Contracts (cont.)

library	test cases generated	violation-inducing test cases	REDUCE reported test cases	error-revealing test cases	errors	errors per KLOC
Java JDK						
java.util	22,474	298	20	19	6	.15
javax.xml	15,311	315	12	10	2	.14
Jakarta Commons						
chain	35,766	1226	20	0	0	0
collections	16,740	188	67	25	4	.07
jelly	18,846	1484	78	0	0	0
logging	764	0	0	0	0	0
math	3,049	27	9	4	2	.09
primitives	49,789	119	13	0	0	0
ZedGraph	8,175	15	13	4	4	.12
.NET Framework						
Mscorlib	5,685	51	19	19	19	.10
System.Data	8,026	177	92	92	92	.47
System.Security	3,793	135	25	25	25	2.7
System.Xml	12,144	19	15	15	15	.10
Web.Services	7,941	146	41	41	41	.98
Total	208,503	4200	424	254	210	

JPF ran out of memory without reporting any errors for all the libraries.
Undirected Random found 60 errors, and did not find errors in java.util or javax.xml

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)
- Many Apache classes require a call of an *init()* method before object is legal—led to many false positives
- .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

Evaluation – Regression testing

- 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

Evaluation Summary

- Feedback-directed random test generation
  - Is effective at finding errors
    - Discovered several errors in real code (e.g. JDK, .NET framework core libraries)
  - Can outperform systematic input generation
    - On previous benchmarks and metrics (coverage)
    - On a new, larger corpus of subjects, measuring error detection
  - Can outperform undirected random test generation

Conclusion

- Feedback-directed random test generation
  - Finds errors in widely-used, well-tested libraries
  - Can outperform systematic test generation
  - Can outperform undirected test generation
- RANDOOP
  - Easy to use — just point at a set of classes
  - Has real clients: used by product groups at Microsoft
- A mid-point in the systematic-random space of input generation techniques

Discussion 6 – Improving RANDOOP

How do we improve RANDOOP?

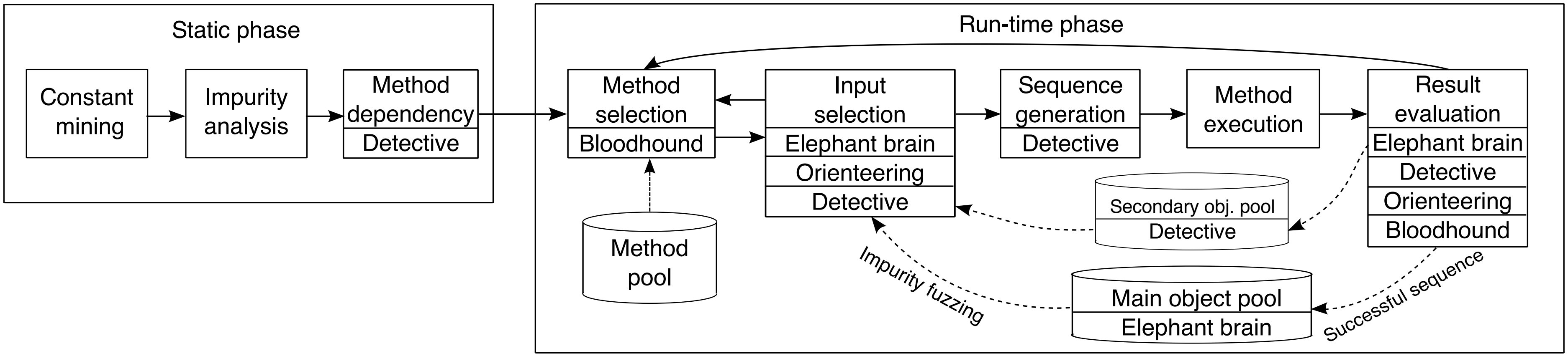
GRT: Program-Analysis-Guided Random Testing

Lei Ma, Cyrille Artho, Cheng Zhang, Hiroyuki Sato, Johannes Gmeiner, Rudolf Ramler

ASE 2015, ACM SIFSOFT Distinguish Paper Award

Overview of GRT

Component	Static / dynamic	Description
Constant mining	static	Extract constants from SUT for both global usage (seed the main object pool) and for local usage as inputs for specific methods.
Impurity	static + dynamic	Perform static purity analysis for all MUTs. At run-time, fuzz selected input from the object pool based on a Gaussian distribution and purity results.
Elephant brain	dynamic	Manage method sequences (to create inputs) in the object pool with the exact types obtained at run-time.
Detective	static + dynamic	Analyze the method input and return type dependency statically, and construct missing input data on demand at run-time.
Orienteering	dynamic	Favor method sequences that require lower cost to execute, which accelerates testing for other components.
Bloodhound	dynamic	Guide method selection and sequence generation by coverage information at run-time.



Constant Mining

```java
package org.apache.commons.cli;
public class PatternOptionBuilder{
  public static final Class STRING_VAL=String.class;
  public static final Class OBJECT_VAL=Object.class;
  public static final Class NUMBER_VALUE = Number.class;
  // 6 more similar fields omitted.
  public static Object getValueClass(char ch) {
    switch (ch) {
     case '@':return PatternOptionBuilder.OBJECT_VAL;
     case ':':return PatternOptionBuilder.STRING_VAL;
     case '%':return PatternOptionBuilder.NUMBER_VALUE;
     // 6 more case branches omitted.
    }
    return null;
} } // 2 more methods omitted.
public class TypeHandler {
  // 1 method omitted.
  public static Object createVal(String s, Class c) {
    if (PatternOptionBuilder.STRING_VAL == c)
      return s;
    else if (PatternOptionBuilder.OBJECT_VAL == c)
      return createObject(s);
    else if (PatternOptionBuilder.NUMBER_VALUE == c)
      return createNumber(s);
    // 6 more else if branches omitted.
    else return null; } } // 7 more methods omitted.
```

Impurity Analysis: Object State Fuzzing

- Primitive value fuzzing
  - When a primitive number *c* is selected as an input, we adopt a Gaussian distribution to probabilistically fuzz its value and use the altered result as the input
- Reference value fuzzing
  - Gather all impure methods that can change the state of a reference object *o*
  - Randomly select an impure method *m*, and invoke *m* on *o*

Demand-Driven Input Construction

```
public class A {
  public A() {...}
  public B m1(A a1) {...}
}
```

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

- Search constructors and methods that return an object of the required type
  - e.g., A(), m1(A), B(int)
- Choose a method *m*, and recursively search for inputs needed to execute *m*
  - e.g., B(int), A()
- Combine *m* with the method under test
  - e.g., B b = new B(0); A = new A(); b.m2(b, a);

Cost-Guided Sequence Selection

- Multiple sequences can return the object of the same type
- Randomly selecting a method sequence as the input makes the generated method sequence grow considerably in length and execution cost
- Select a method sequence based on its execution cost

Coverage-Guided Method Selection

- An equally balanced selection of method under test wastes time on methods that are already well covered
- Too much emphasis on method under test containing uncovered branches may waste time in challenging the difficult branches
- Design a weight function based on both code coverage and the execution history of each method under test

Reading Materials

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Q&A?

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