Feedback-directed Random Test Generation

(ICSE '07 with minor edits)

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Random testing

- Select inputs at random from a program's input space
- Check that program behaves correctly on each input
- An attractive error-detection technique
  - Easy to implement and use
  - Yields lots of test inputs
  - Finds errors
    - Miller et al. 1990: Unix utilities
    - Kropp et al.1998: OS services
    - Forrester et al. 2000: GUI applications
    - Claessen et al. 2000: functional programs
    - Csallner et al. 2005,
      Pacheco et al. 2005: object-oriented programs
    - Groce et al. 2007: flash memory, file systems

Evaluations of random testing

- Theoretical work suggests that random testing is as effective as more systematic input generation techniques (Duran 1984, Hamlet 1990)
- Some empirical studies suggest systematic is more effective than random
  - Ferguson et al. 1996: compare with chaining
  - Marinov et al. 2003: compare with bounded exhaustive
  - Visser et al. 2006: compare with model checking and symbolic execution

Studies are performed on small benchmarks,
they do not measure error revealing effectiveness,
and they use completely undirected random test generation.

Contributions

- We propose feedback-directed random test generation
  - Randomized creation of new test inputs is guided by feedback about the execution of previous inputs
  - Goal is to avoid *redundant* and *illegal* inputs
- Empirical evaluation
  - Evaluate coverage *and* error-detection ability on a large number of widely-used, well-tested libraries (780KLOC)
  - Compare against systematic input generation
  - Compare against undirected random input generation

Outline

- Feedback-directed random test generation
- Evaluation:
  - Randoop: a tool for Java and .NET
  - Coverage
  - Error detection
- Current and future directions for Randoop

Random testing: pitfalls

1. Useful test

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

2. Redundant test

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

3. Useful test

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

4. Illegal test

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

5. Illegal test

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

do not output

do not even create

Feedback-directed random test generation

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

Technique 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. Example:

no contracts violated up to last method call

```
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 when executed

Technique

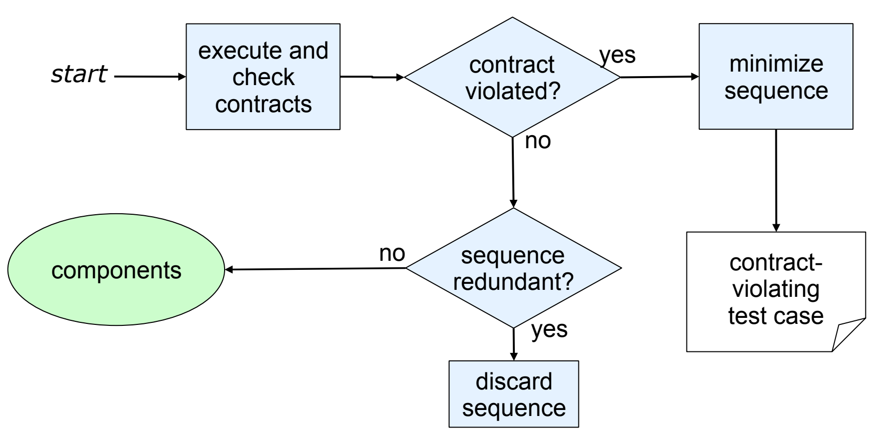
1. Seed components

   components = { `int i = 0;` `boolean b = false;` ... }

2. Do until time limit expires:
   a. Create a new sequence
      i. Randomly pick a method call $m(T_1 \ldots T_k)/T_{ret}$
      ii. For each input parameter of type T_i, randomly pick a sequence S_i from the components that constructs an object v_i of type Ti
      iii. Create new sequence S_{new} = S_1; ... ; S_k ; T_{ret} v_{new} = m(v1...vk);
      iv. if S_{new} was previously created (lexically), go to i

   b. Classify the new sequence S_{new}
      a. May discard, output as test case, or add to components

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

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Randoop

- **Implements feedback-directed random test generation**
- **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 outputs oracles

- Oracle for contract-violating test case:

```
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
```

- Oracle for normal-behavior test case:

```
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 uses **observer methods** to capture object state*

Some Randoop options

- Avoid use of null

statically…

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

…and dynamically

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

- Bias random selection
  - Favor smaller sequences
  - Favor methods that have been less covered
  - Use constants mined from source code

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Coverage

- Seven data structures (stack, bounded stack, list, bst, heap, rbt, binomial heap)
- Used in previous research
  - Bounded exhaustive testing [Marinov 2003]
  - Symbolic execution [Xie 2005]
  - Exhaustive method sequence generation [Xie 2004]
- All above techniques achieve high coverage in seconds
- Tools not publicly available

Coverage achieved by Randoop

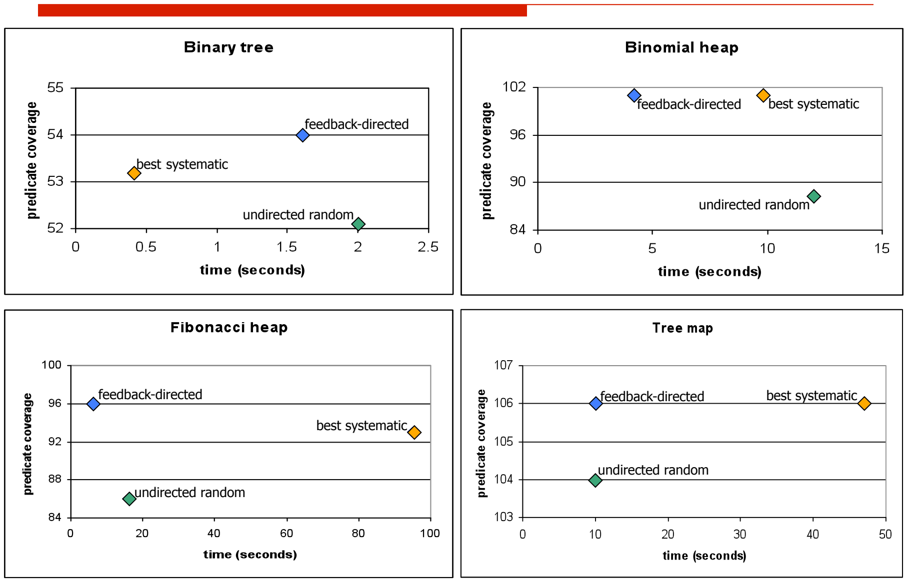
- Comparable with exhaustive/symbolic techniques

data structure	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%

Visser containers

- Visser et al. (2006) compares several input generation techniques
  - Model checking with state matching
  - Model checking with abstract state matching
  - Symbolic execution
  - Symbolic execution with abstract state matching
  - Undirected random testing
- Comparison in terms of branch and predicate coverage
- Four nontrivial container data structures
- Experimental framework and tool available

Predicate coverage



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Subjects

	LOC	Classes
JDK (2 libraries) (java.util, javax.xml)	53K	272
Apache commons (5 libraries) (logging, primitives, chain jelly, math, collections)	114K	974
.Net framework (5 libraries)	582K	3330

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

Results

	test cases output	error-revealing tests cases	distinct errors
JDK	32	29	8
Apache commons	187	29	6
.Net framework	192	192	192
Total	***411***	***250***	***206***

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, or illegal state exception)
- .Net framework has 8 methods that violate o.equals(o)
- .Net framework loops forever on a legal but unexpected input

JPF

- Used JPF to generate test inputs for the Java libraries (JDK and Apache)
  - Breadth-first search (suggested strategy)
  - max sequence length of 10
- JPF ran out of memory without finding any errors
  - Out of memory after 32 seconds on average
  - Spent most of its time systematically exploring a very *localized* portion of the space
- For large libraries, random, sparse sampling seems to be more effective

Undirected random testing

- JCrasher implements undirected random test generation
- Creates random method call sequences
  - Does not use feedback from execution
- Reports sequences that throw exceptions
- Found 1 error on Java libraries
  - Reported 595 false positives

Regression testing

```
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 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

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), and
    - On a new, larger corpus of subjects, measuring error detection
  - Can outperform undirected random test generation

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Tech transfer

- Randoop is currently being maintained by a product group at Microsoft
  - Spent an internship doing the tech transfer
    - How would a test team actually use the tool?
      - Push-button at first, desire more control later
    - Would the tool be cost-effective?
      - Yes
      - Immediately found a few errors
      - With more control, found more errors
      - Pointed to blind spots in
        - existing test suites
        - Existing automated testing tools
    - Which heuristics would be most useful?
      - The simplest ones (e.g. uniform selection)
      - More sophisticated guidance was best left to the users of the tool

Future directions

- Combining random and systematic generation
  - DART (Godefroid 2005) combines random and systematic generation of *test data*
  - How to combine random and systematic generation of *sequences*?
- Using Randoop for reliability estimation
  - Random sampling amenable to statistical analysis
  - Are programs that Randoop finds more problems with more error-prone?
- Better oracles
  - To date, we have used a very basic set of contracts
  - Will better contracts lead to more errors?
  - Incorporate techniques that create oracles automatically

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