Program Testing and Analysis: Random and Fuzz Testing (Part 2)

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Warm-up Quiz

What does the following code print?

```
function f(a,b) {
  var x;
  for (var i = 0; i < arguments.length; i++) {
    x += arguments[i];
  }
  console.log(x);
}
f(1,2,3);
```

3 **6** **NaN** **Nothing**

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```

Array-like object that contains all three arguments

3 **6** **NaN** **Nothing**

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f(1,2,3);
```

Initialized to `undefined`

`undefined` + some number yields `NaN`

3 **6** **NaN** **Nothing**

Outline

- **Feedback-directed random test generation**

  Based on *Feedback-Directed Random Test Generation*, Pacheco et al., ICSE 2007

- **Adaptive random testing**

  Based on *ARTOO: Adaptive Random Testing for Object-oriented Software*, Ciupa et al., ICSE 2008

- **Fuzz testing**

  Based on *Fuzzing with Code Fragments*, Holler et al., USENIX Security 2012

Feedback-directed Test Generation

Idea: Guide randomized creation of new test inputs by feedback about execution of previous inputs

- Avoid redundant inputs
- Avoid illegal inputs

- Test input here means sequence of method calls
- Software under test: Classes in Java-like language

Algorithm

1. Initialize seed components: `i=0; b=false; ...`
2. Do until time limit expires:
   - Create a new sequence
     - Randomly pick a method $T_0.m(T_1, ..., T_k)/T_{ret}$
     - For each T_i, randomly pick a sequence S_i from the components that constructs a value v_i of type T_i
     - Create new sequence $S_{new} = S_1; ...; S_k; T_{ret}\ v_{new} = m(v_1, ..., v_k);$
     - If S_{new} was previously created (lexically), go to
   - Classify the sequence S_{new}
     - May discard, output as test case, or add to components

Classes under test : java.util.*

1) Pick a method

→ No values needed

→ New sequence

new HashMap

HashMap h = new HashMap()

2) Classify sequence

→ no contract violated

→ not redundant

⇒ add to components

3) Pick method new HashMap

→ HashMap h2 = new HashMap()

4) Classify sequence

→ no contract violated

→ redundant

⇒ discard sequence

5) Pick method HashMap.values

→ Need sequence that constructs value of type HashMap

→ use sequence from step 2)

6) Create sequence

```
HashMap h = new HashMap()
Collection c = h.values()
```

→ Classify: no contract violated
not redundant

→ Add to components

Test Oracles

- **Testing only useful if there is an oracle**
- **Randoop outputs tests with two kinds of oracles**
  - Oracle for contract-violating test cases:

```
assertTrue(u.equals(u));
```

  - Oracle for normal-behavior test cases:

```
assertEquals(2, l.size());
assertEquals(false, l.isEmpty());
```

Quiz

Which of these tests may be created by Randoop?

Test 1:

```
LinkedList l = new LinkedList();
l.add(23);
```

Test 2:

```
LinkedList l = new LinkedList();
l.get(-5);
```

Test 3:

```
LinkedList l = new LinkedList();
l.add(7);
assertEquals(l.getFirst(), 7);
```

Quiz

Which of these tests may be created by Randoop?

Test 1:

```
LinkedList l = new LinkedList();
l.add(23);
```

(oracle missing)

Test 2:

```
LinkedList l = new LinkedList();
l.get(-5);
```

(crashes)

Test 3:

```
LinkedList l = new LinkedList();
l.add(7);
assertEquals(l.getFirst(), 7);
```

Results

- Applied to data structure implementations and popular library classes
- Achieves 80-100% basic block coverage
- Finds various bugs in JDK collections, classes from the .NET framework, and Apache libraries

Read Pacheco et al.'s paper for details

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Adaptive Random Testing

Idea: Testing is more effective when inputs are spread evenly over the input domain

- Generate candidate inputs randomly
- At every step, select input that is furthest away from already tested inputs

Spread Out Evenly?

- **Initially proposed for numeric values**
  - Distance between two values: Euclidean distance
- **Example: `f(int x)`**
  - Suppose to have tested with `Integer.MAX_VALUE` and `Integer.MIN_VALUE`
  - Next test: `0`

Spread Out Evenly?

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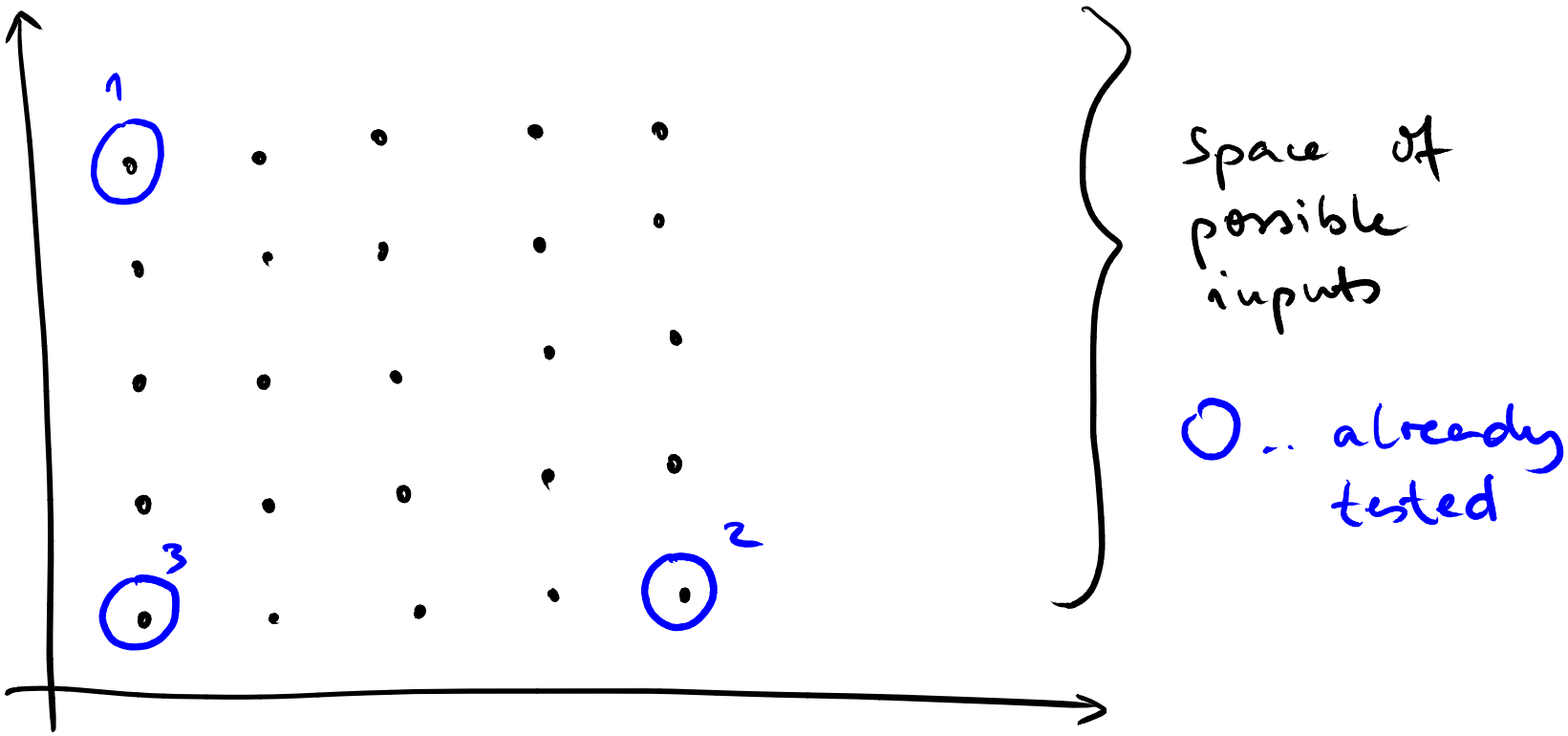
  - Distance between two values: Euclidean distance
- **Example: `f(int x)`**
  - Suppose to have tested with `Integer.MAX_VALUE` and `Integer.MIN_VALUE`
  - Next test: `0`

Challenge:

How to compute distance of objects?

Adaptive random testing



Object Distance

- **Measure how different two objects are**
- **Object: Primitive values, dynamic type, and non-primitive values recursively referred to**

$$
\begin{aligned}
dist(p,q) = & combination(\\
& elementaryDistance(p,q), \\
& typeDistance(type(p), type(q)), \\
& fieldDistance(\{dist(p.a, q.a) \mid \\
& a \in fields(type(p) \cap fields(type(q)))\})
\end{aligned}
$$

Object Distance

- **Measure how different two objects are**
- **Object: Primitive values, dynamic type, and non-primitive values recursively referred to**

Does not require traversing the object

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dist(p,q) = & combination(\\
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Recursively defined

Elementary Distance

Fixed functions for each possible type:

- For numbers: $F(|p - q|)$, where F is a monotonically non-decreasing function with $F(0) = 0$
- For characters: 0 if identical, C otherwise
- For booleans: 0 if identical, B otherwise
- For strings: the Levenshtein distance
- For references: 0 if identical, R if different but none is null, V if only one of them is null

$$C, B, R, V \in \mathbb{N}$$

Examples: Elementary Distance

- int i = 3, j = 9 → dist (|3 − 9|) = 6
- char c = 'a', d = 'a' → dist (c, d) = 0
- String s = "foo", t = "too" → dist(s, t) = 1
- Object o = null, p = new ArrayList() → dist (o, p) = R

Type Distance

Distance between two types

$$typeDistance(t, u) =$$

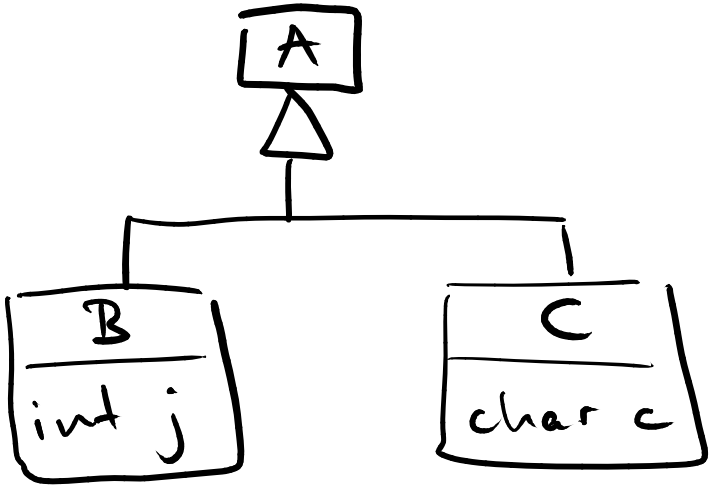
$$\lambda * pathLength(t, u)$$

$$+ \nu * \sum_{a \in nonShared(t,u)} weight_a$$

- $pathLength(t, u)$ is the minimal distance to a common ancestor in class hierarchy
- $nonShared(t, u)$ is the set of non-shared fields
- $weight_a$ is the weight for a specific field

$\lambda, \nu \in \mathbb{N}$

Examples: Type Distance



$$\text{dist}(B, C) = \lambda \cdot 1 + \nu \cdot (1 + 1)$$

$$\text{dist}(A, B) = \lambda \cdot 0 + \nu (1)$$

Field Distance

Recursively compute distance of all shared fields

$$fieldDistance(p, q)$$

$$= \overline{\sum}_a weight_a * (dist(p.a, q.a))$$

Arithmetic mean: Avoid giving too much weight to objects with many fields

Algorithm for Selecting Inputs

- Global sets $usedObjects$ and $candidateObjects$
- Choose object for next test:
  - Initialize $bestDistSum = 0$ and $bestObj = null$
  - for each $c \in candidateObjects$:
    - for each $u \in usedObjects$:
      - $distSum$ += $dist(c, u)$
    - if $distSum > bestDistSum$:
      - $bestDistSum = distSum$; $bestObj = c$
  - Remove $bestObj$ from $candidateObjects$, add to $usedObjects$ instead, and run test with $bestObj$

Example

Method under test:

```
Account.transfer(Account dst, int amount)
```

Pool of candidates:

- Accounts
  - a1: owner=”A” and balance=6782832
  - a2: owner=”B” and balance=10
  - a3: owner=”O” and balance=99
  - a4: null
- Integers:
  - i1: 100, i2: 287391, i3: 0, i4: -50

Example (cont.)

First call:

```
a3.transfer(a1, i2)
```

Example (cont.)

First call:

```
a3.transfer(a1, i2)
```

Second call:

```
a1.transfer(a4, i4)
```

Results

- Implemented for Eiffel
- Use randomly generated objects as candidates
- Use Eiffel's contracts (pre- and post-conditions, class invariants) as test oracle
- Comparison with random testing:
  - Find bugs with 5x fewer tests
  - But: Takes 1.6x the time of random testing

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Fuzz Testing

Generate random inputs

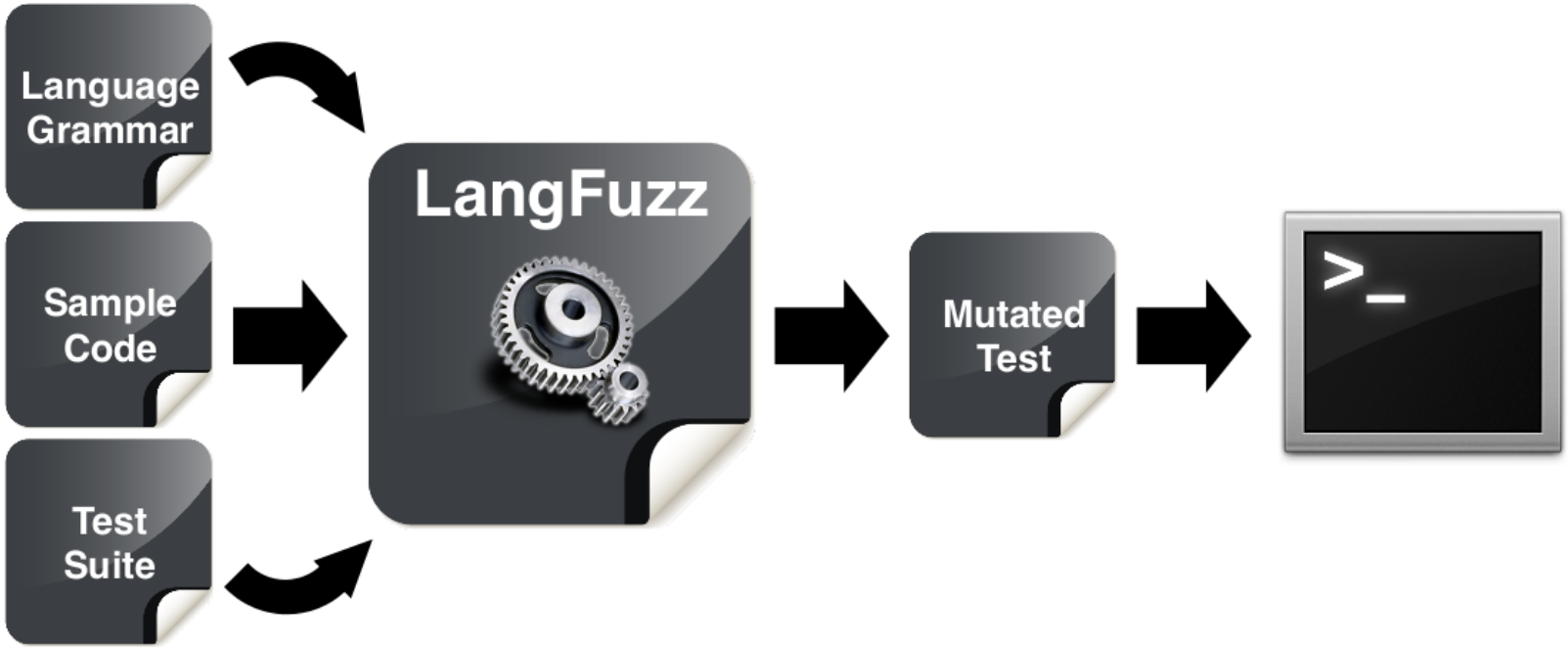
- Generative: Create new random input, possibly based on constraints and rules
- Mutative: Derive new inputs from existing input by randomly modifying it

Grammar-based Language Fuzzing

Idea: Combine generative and mutative approach to test JavaScript interpreter

- Create random JavaScript programs based on language grammar
- Use and re-combine fragments of code from existing corpus of programs
  - Corpus: Programs that have exposed bugs before

Overview of LangFuzz



Phase I

Learning code fragments from sample code and test suite

Phase II

LangFuzz generated (mutated) test cases

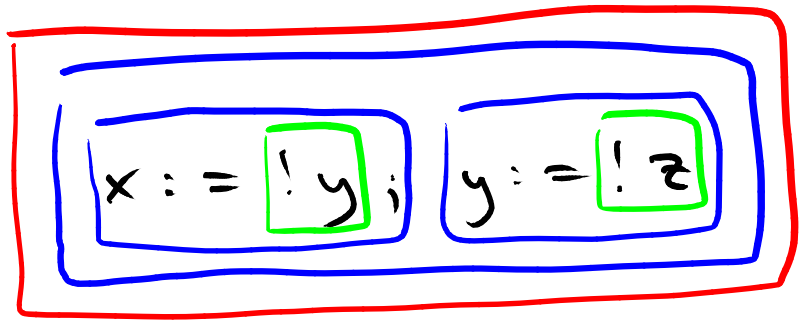
Phase III

Feed test case into interpreter, check for crashes and assertions

Learning Code Fragments

- **Parse existing programs into ASTs**
- **Extract code fragments**
  - Examples for non-terminals of grammar

Corpus:



expressions E

command C

program P

Mutation of Code

- Randomly pick and parse an existing program
- Randomly pick some fragments and replace with fragments from phase 1 of same type

if !x > 4 then y := !z else $\boxed{\text{skip}}$

if !x > 4 then y := !z else $\underbrace{\text{x := !y}}_{\text{command from corpus}}$

Generation of Code

Breadth-first application of grammar rules

- Set current expansion e_{cur} to start symbol P
- Loop k iterations:
  - Choose a random non-terminal n in e_{cur}
  - Pick one of the rules, r, that can be applied to n
  - Replace occurence of n in e_{cur} by $r(n)$

After k iterations: Replace remaining non-terminals with fragments

Code Generation: Example

$k = 3$

$e_{cur} = P$

$\downarrow$

$e_{cur} = C$

$\downarrow$

$e_{cur} = \text{while } B \text{ do } \underline{\underline{C}}$

$\downarrow$

$e_{cur} = \text{while } B \text{ do } C_1 \; C$

$P ::= C \mid \ldots$

$C ::= \ldots \mid \text{while } B \text{ do } C \mid \ldots$

$C ::= \ldots \mid C_1 \; C \mid \ldots$

Replace with fragments learned from corpus

Quiz

Which of the following SIMP programs could have been generated by LangFuzz?

```
if B then C; C
```

```
if !x > 3 then skip; y := 1
```

```
if !x > 3 then while; while
```

Quiz

Which of the following SIMP programs could have been generated by LangFuzz?

```
if B then C; C
```

(has unexpanded non-terminals)

```
if !x > 3 then skip; y := 1
```

```
if !x > 3 then while; while
```

(syntactically incorrect)

Results

- **Used to test Mozilla's and Chrome's JavaScript engines**
- **Found various bugs**

  Mostly crashes of engine due to memory issues
- **Rewarded with $50,000 bug bounties**
- **First author now works at Mozilla**

Summary

Random and fuzz testing

- Fully automated and unbiased
- Non-naive approaches can be very effective
- Trade-off: Cost of generating inputs vs. effectiveness in exposing bugs
  - Quickly generated, less effective tests may be better than slowly generated, more effective tests