Program Testing and Analysis: Manual Testing (Part 2)

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Partly based on slides from Peter Müller, ETH Zurich

Warm-up Quiz

What does the following code print?

```
var a, b;
var x = {};
x[a] = 23;
console.log(x[b]);
```

Nothing 23 undefined false

Warm-up Quiz

What does the following code print?

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console.log(x[b]);
```

Nothing **23** **undefined** **false**

Warm-up Quiz

What does the following code print?

```
var a, b;
var x = {};
x[a] = 23;
console.log(x[b]);
```

Have value `undefined`

Write and then read "undefined" property of `x`

Nothing | **23** | **undefined** | **false**

Outline (Manual Testing)

- **Overview**
- **Control flow testing**
  - Statement coverage
  - Branch coverage
  - Path coverage
  - Loop coverage
- **Data flow testing** 
  - DU-pair coverage
- **Interpretation of coverage**

Data Flow Testing

- **Problem: Testing all paths is not feasible**
  - Number grows exponentially in the number of branches
  - Loops
- **Idea: Test those paths where a computation in one part of the path affects the computation of another part**

Variable Definition and Use

- **A variable definition for a variable v is a basic block that assigns to v**
  - v can be a local or global variable, parameter, or property
- **A variable use for a variable v is a basic block that reads the value of v**
  - In conditions, computations, output, etc.

Definition-Clear Paths

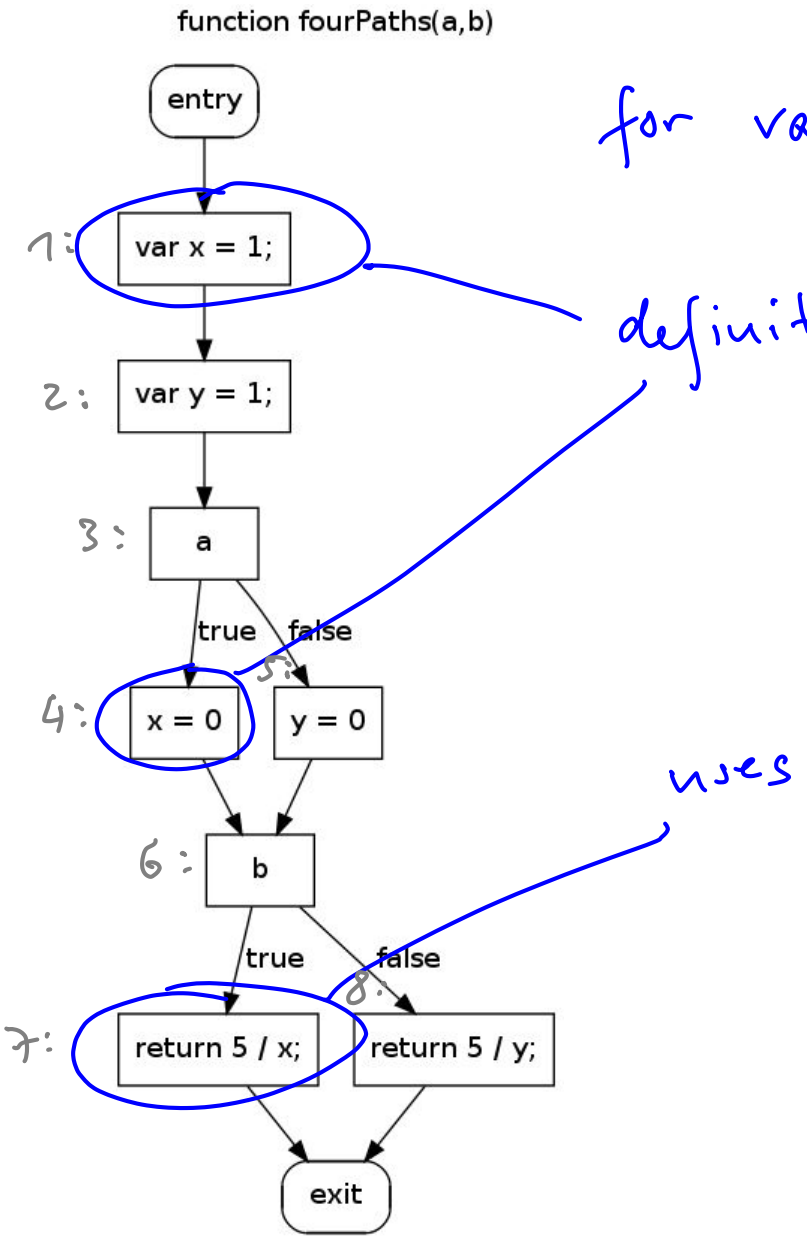
A definition-clear path for a variable v is a path $n_1, .., n_k$ in the CFG such that

- n_1 is a variable definition for v
- n_k is a variable use for v
- No n_i $(1 < i \leq k)$ is a variable definition for v
  - n_k may be a variable definition if each assignment to v occurs after a use

Note: Def-clear paths do not go from entry to exit (in contrast to our earlier definition of paths)

Definition-Use Pair

A definition-use pair (DU-pair) for a variable v is a pair of nodes (d, u) such that there is a definition-clear path $d, .., u$ in the CFG



for variable x:

definition

uses

DU pairs for x?

(1, 7) and

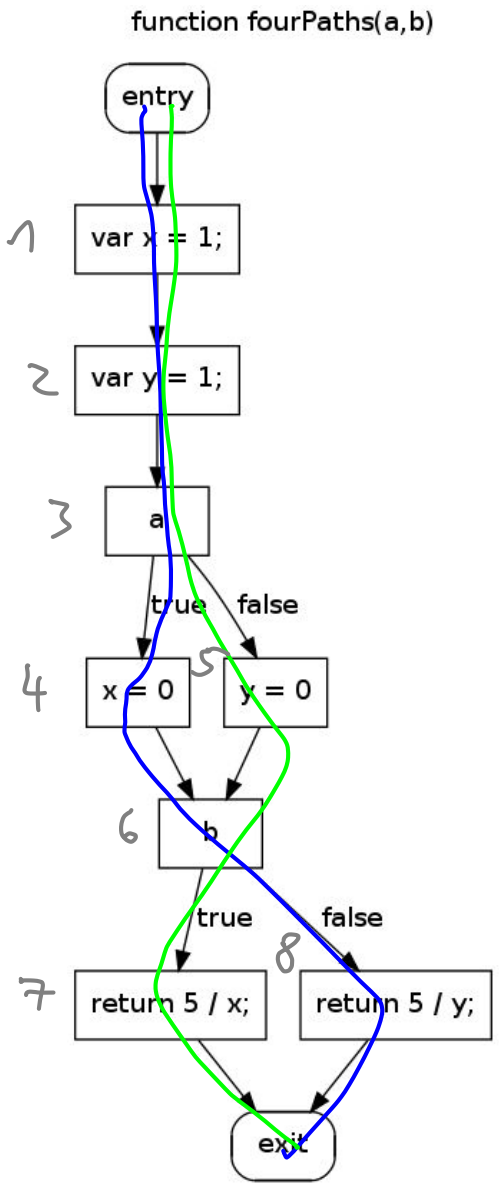
(4, 7)

DU-Pairs Coverage

Idea:

Test all paths that provide a value for a variable use

$$cov_{DU} = \frac{Nb.\ of\ executed\ DU\text{-}pairs}{Total\ nb.\ of\ DU\text{-}pairs}$$



Two tests:

a = true, b = false

a = false, b = true

DU-pairs for x: (1,7), (4,7)

DU-pairs for y: (2,8), (5,8)

→ 50% DU coverage

For full DU coverage: Add tests

a = true, b = true

a = false, b = false

DU-Pair Coverage: Discussion

- **Complements control flow testing**
  - Use both: Choose tests that maximize branch and DU-pair coverage
- **As with path coverage, not all DU-pairs are feasible**
  - Static analysis overapproximates data flow
- **Complete DU-pair coverage does not imply that all bugs are detected**

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Interpreting Coverage

- High coverage does not imply that code is well tested
- But: Low coverage means that code is not well tested
- Do not blindly increase coverage but develop test suites that are effective at detecting bugs

Empirical Evidence

- **Studies on the benefit of coverage metrics**

  E.g., Andrews et al.: ”Using Mutation Analysis for Assessing and Comparing Testing Coverage Criteria”, 2006

- **Approach**
  - Seed bugs into code
  - Develop test suites that satisfy various coverage criteria
  - Measure how many of the seeded bugs are found

Empirical Evidence (2)

- The higher the coverage, the more bugs are detected
- Tests written with coverage criteria in mind are more effective than random tests (for the same test suite size)
- Test suite size grows exponentially in the achieved coverage

Summary: Manual Testing

Black box testing

- Exhaustive testing
- Random testing
- Functional testing

White box testing

- Structural testing
  - Control flow-based coverage criteria:
    Statements, branches, paths, loops
  - Data flow-based coverage criterion: DU-pairs

Program Testing and Analysis: Random and Fuzz Testing

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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

Motivating Examples

Two randomly generated tests:

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

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

Motivating Examples

Two randomly generated tests:

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```

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

Only difference

Motivating Examples

Two randomly generated tests:

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```

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

Redundant test

Motivating Examples (2)

Three randomly generated tests:

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

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

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

Motivating Examples (2)

Three randomly generated tests:

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

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

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

Violates pre-condition

Motivating Examples (2)

Three randomly generated tests:

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

Illegal tests

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

Approach

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

Randoop: Input/Output

Randoop: Implementation of feedback-directed random test generation

- 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: Test cases with assertions

Example

```
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));
```

Example

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Fails when executed

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```

No contracts violated up to last method call

Fails when executed

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

Classifying a Sequence

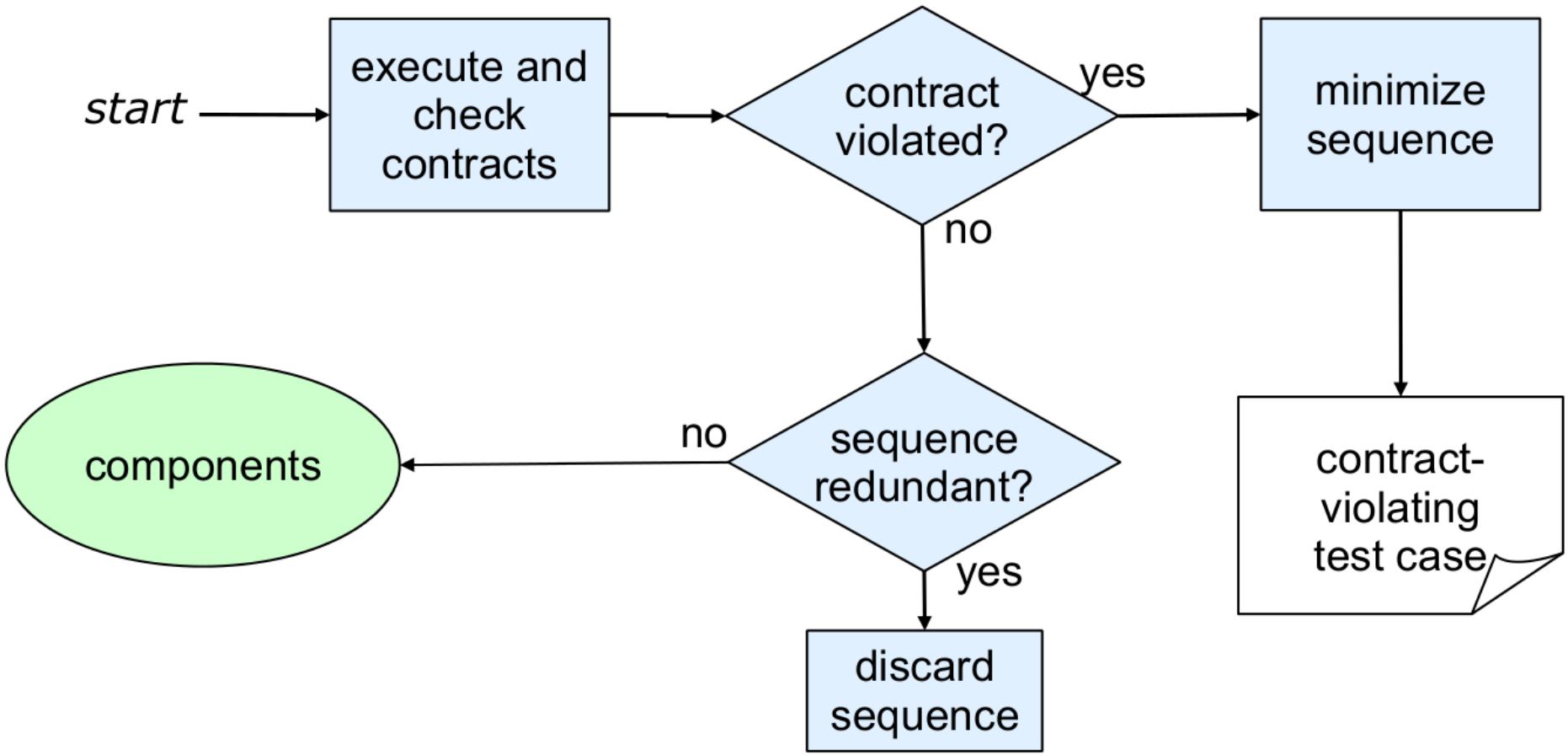

Image source: Slides by Pacheco et al.

Redundant Sequences

- During generation, maintain a set fo all objects created
- Sequence is redundant if all objects created during its execution are in the above set (using `equals()` to compare)
- Could also use more sophisticated state equivalence methods
  - E.g., heap canonicalization

Example of Randoop algorithm

Classes under test: java.util.*

1) Pick a method — new HashMap

→ No values needed

→ New sequence: 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 2)

6) Create sequence: HashMap h = new HashMap()

Collection c = h.values()

→ Clarify: no contract violated
not redundant

→ add to components

etc.

Test Oracles

- **Testing only useful if there is an oracle**
- **Randoop outputs 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

Outline

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- **Fuzz testing**

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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?

- **Initially proposed for numeric values**
  - Distance between two values: Euclidean distance
- **Example: `f(int x)`**
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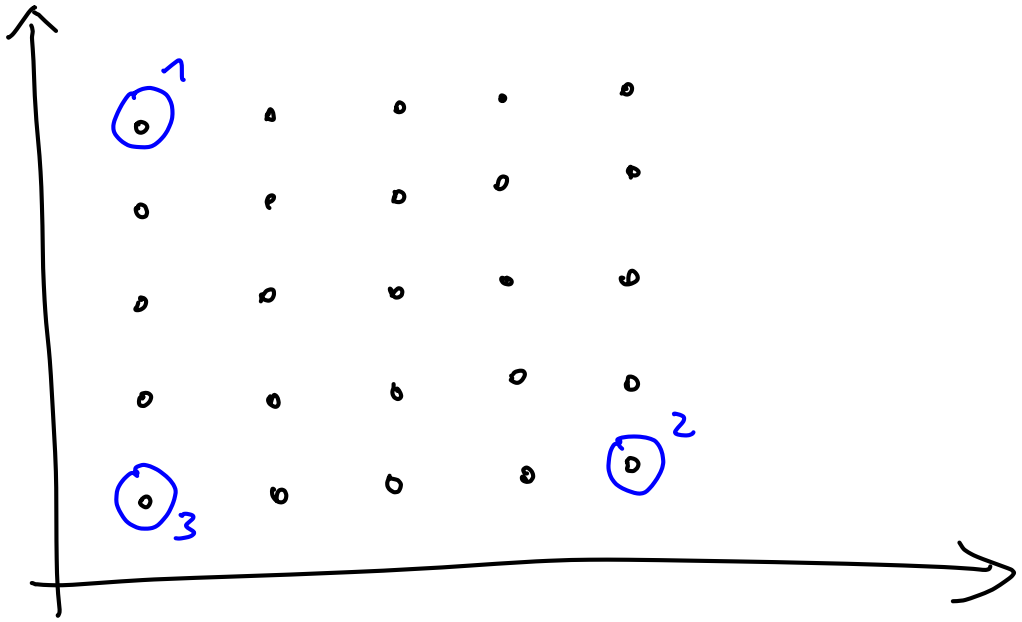
  - Next test: `0`

Challenge:

How to compute distance of objects?

Adaptive random testing



Space of possible inputs

○ .. already tested

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

$$
\begin{aligned}
dist(p,q) = & combination(\\
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Object Distance

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$$typeDistance(type(p), type(q)),$$
$$fieldDistance(\{dist(p.a, q.a) \mid$$
$$a \in fields(type(p) \cap fields(type(q)))\})$$

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) = V

Type Distance

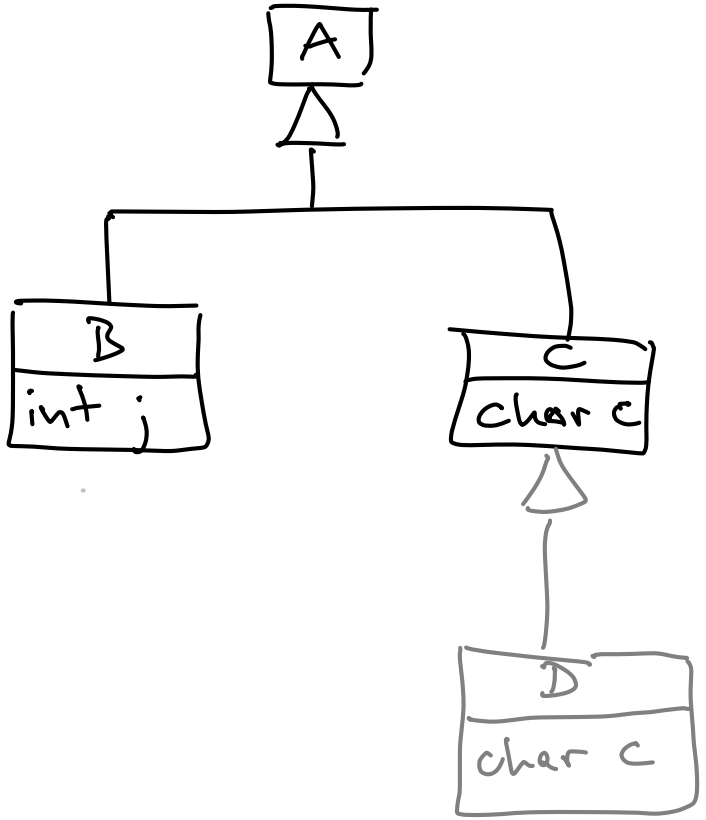
Distance between two types

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

- $pathLength(t,u)$ 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



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

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

$$dist(B, D) = \lambda \cdot 1 + \nu \cdot (1 + 1)$$

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: Adaptive Random Testing

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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