CSE 373: Data Structures & Algorithms
Software Interlude -- Testing and JUnit

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based on work from Michael Ernst, Hal Perkins, Dan Grossman, and Zack Tatlock

Course Logistics

- HW5 out → more graphs!

- Nearing the end! The last main course topic is next week: sorting. HW6 out next Wednesday and due March 10th

Software Quality (QA or QE)

It's a CS research area and can be a full time job! Some activities include:

- Static analysis (assessing code without executing it)
- Correctness proofs (theorems about program properties)
- Code reviews (people reading each others' code)
- Software process (methodology for code development)
- Testing (of course)

Testing is NOT just debugging!

We'll cover lots of testing principles and strategies:

- Heuristics for good test suites
- Black-box testing
- Clear-box testing and coverage metrics
- Regression testing
- Integration/System tests
- Test Driven Development

Kinds of Testing

Testing is so important the field has terminology for different kinds of tests

- Won't discuss all the kinds and terms

Here are three different dimensions:

- ***Unit*** testing versus ***system/integration*** testing
    - One module's functionality versus pieces fitting together
- ***Black-box*** testing versus ***clear-box*** testing
    - Does implementation influence test creation?
    - "Do you look at the code when choosing test data?"
- ***Specification*** testing versus ***implementation*** testing
    - Test only behavior guaranteed by specification or other behavior expected for the implementation?

Unit Testing

- A unit test focuses on one method, class, interface, or module
- Test a single unit in isolation from all others
- Typically done earlier in software life-cycle
  – Integrate (and test the integration) after successful unit testing
- Common Java unit testing framework: JUnit

Square Root Example

```
// throws: IllegalArgumentException if x<0
// returns: approximation to square root of x
public double sqrt(double x){…}
```

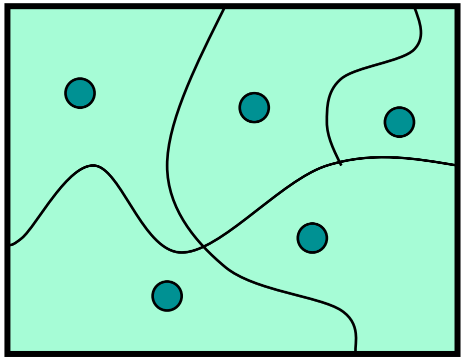
What are some values or ranges of *x* that might be worth probing?

- $x < 0$ (exception thrown)
- $x \geq 0$ (returns normally)
- around $x = 0$ (boundary condition)
- perfect squares (sqrt(*x*) an integer), non-perfect squares
- *x*<sqrt(*x*) and *x*>sqrt(*x*) – that's *x*<1 and *x*>1 (and *x*=1)
- *Specific tests: say x = -1, 0, 0.5, 1, 4*

General Approach: Partition the Input Space

Ideal test suite in theory:

(1) Identify sets of input where all the members have the same behavior.
(2) Try one input from each set.



Two problems with execution:

1. Notion of same behavior is subtle
   - Naive approach: execution equivalence
   - Better approach: revealing subdomains

2. Discovering the sets requires perfect domain knowledge
   - If we had it, we wouldn't need to test
   - Use heuristics to approximate cheaply

Test Suite Example #1

```
// returns:  x < 0       ⇒ returns -x
//           otherwise ⇒ returns x
int abs(int x):
   if (x < 0):
       return -x;
   else:
       return x;
```

All x < 0 are execution equivalent

– Program takes same sequence of steps for any x < 0

All x ≥ 0 are execution equivalent

So {-3, 3} is probably a good test suite (one element from each subset)

Test Suite Example #2

```
// returns:  x < 0      ⇒ returns -x
//           otherwise ⇒ returns x
int abs(int x):
   if (x < -2):
       return -x;
   else:
       return x;
```

For this (buggy) implementation of the method, three possible outcomes:

- $x < -2$ PASS
- $x = -2$ or $x = -1$ FAIL
- $x \geq 0$ PASS

{-3, 3} as a test suite does not reveal the error!

Determining Actual Subsets

- A *subdomain* is a subset of possible inputs

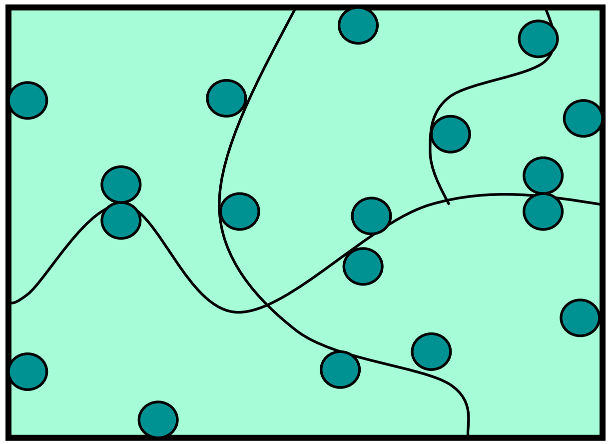
- A subdomain is *revealing* for error *E* if either:
  - *Every* input in that subdomain triggers error E, *or*
  - *No* input in that subdomain triggers error E

- Need test only one input from a given subdomain
  - If subdomains cover the entire input space, we are *guaranteed* to detect the error if it is present

- The trick is to *guess* these revealing subdomains

Heuristic: Boundary Testing

Create tests at the edges of subdomains



Why?

- Off-by-one bugs
- "Empty" cases (0 elements, null, ...)
- Overflow errors in arithmetic
- Object aliasing

Small subdomains at the edges of the "main" subdomains have a high probability of revealing many common errors

- Also, you might have misdrawn the boundaries

Boundary Testing

To define the boundary, need a notion of adjacent inputs

One approach:

- Identify basic operations on input points
- Two points are adjacent if one basic operation apart

Point is on a boundary if either:

- There exists an adjacent point in a different subdomain
- Some basic operation cannot be applied to the point

Example: list of integers

- Basic operations: *create*, *append*, *remove*
- Adjacent points: <[2,3],[2,3,3]>, <[2,3],[2]>
- Boundary point: [ ] (can't apply *remove*)

Some Boundary Cases

Arithmetic

- Smallest/largest values (edge case and overflow)
- Zero

Objects

- null
- Circular list
- Same object passed as multiple arguments (aliasing)

Boundary: Arithmetic Overflow

```
// returns: |x|
public int abs(int x) {…}
```

What are some values or ranges of *x* that might be worth probing?

- $x < 0$ (flips sign) or $x \geq 0$ (returns unchanged)
- Around $x = 0$ (boundary condition)
- *Specific tests: say x = -1, 0, 1*

How about…

```
int x = Integer.MIN_VALUE; // x=-2147483648
System.out.println(x<0);    // true
System.out.println(Math.abs(x)<0); // also true!
```

From Javadoc for **`Math.abs`**:

> Note that if the argument is equal to the value of **`Integer.MIN_VALUE`**, the most negative representable int value, the result is that same value, which is negative

Boundary: Duplicates and Aliases

```
// modifies: src, dest
// effects:  removes all elements of src and
//           appends them in reverse order to
//           the end of dest
<E> void appendList(List<E> src, List<E> dest) {
  while (src.size()>0) {
    E elt = src.remove(src.size()-1);
    dest.add(elt);
  }
}
```

What happens if **`src`** and **`dest`** refer to the same object?

- This is *aliasing*
- It's easy to forget!
- Watch out for shared references in inputs

Black-Box Testing

Heuristic: Explore alternate cases in the specification, plus potentially some boundary conditions around those cases

Procedure is a black box: interface visible, internals hidden

Example

```
// returns:  a > b ⇒ returns a
//           a < b ⇒ returns b
//           a = b ⇒ returns a
int max(int a, int b) {…}
```

3 cases the client knows about leads to 3 tests:

(4, 3) ⇒ 4 *(i.e. any input in the subdomain a > b)*
(3, 4) ⇒ 4 *(i.e. any input in the subdomain a < b)*
(3, 3) ⇒ 3 *(i.e. any input in the subdomain a = b)*

Black-Box Testing: Advantages

Process is not influenced by component being tested

- Assumptions embodied in code not propagated to test data
- (Avoids “group-think” of making the same mistake)

Robust with respect to changes in implementation

- Test data need not be changed when code is changed

Allows for independent testers

- Testers need not be familiar with code
- Tests can be developed before the code

Clear (or white or class) Box Testing

Heuristic: Test the actual implementation (look at the code)

Focus: features not described by specification

- Control-flow details
- Performance optimizations
- Alternate algorithms for different cases

Common *goal*:

- Ensure test suite covers (executes) all of the program
- Measure quality of test suite with % *coverage*

Assumption implicit in goal:

- If high coverage, then most mistakes discovered

Clear-Box Testing: Motivation

What are some subdomains that black-box testing won't catch:

```
boolean[] primeTable = new boolean[CACHE_SIZE];

boolean isPrime(int x) {
    if (x > CACHE_SIZE) {
        for (int i = 2; i < x / 2; i++) {
            if (x % i == 0)
             return false;
        }
        return true;
    } else {
        return primeTable[x];
    }
}
```

Clear-Box Testing

- Finds an important class of boundaries -- ones not necessarily easy to guess given the specification
  - Yields useful test cases

- Consider **CACHE_SIZE** in **isPrime** example
  - Important tests **CACHE_SIZE-1**, **CACHE_SIZE**, **CACHE_SIZE+1**
  - If **CACHE_SIZE** is mutable, may need to test with different **CACHE_SIZE** values

Disadvantage:

- Tests may have same bugs as implementation
- Buggy code tricks you into complacency once you look at it

Code Coverage Example #1

What is enough testing? What cases? Does this code have a bug?

```
int min(int a, int b) {
    int r = a;  // should be r = b
    if (a <= b) {
        r = a;
    }
    return r;
}
```

- Consider any test with $a \leq b$ (e.g., **`min(1,2)`**)
  - Executes every instruction
  - Misses the bug

- *Statement* coverage is not enough

Code Coverage Example #2

What is enough testing? What cases? Does this code have a bug?

```
int num_pos(int[] a) {
    int ans = 0;
    for (int x : a) {
      if (x > 0)
        ans = 1; // should be ans += 1
    }
    return ans;
}
```

- Consider two-test suite: {0,0} and {1}. Misses the bug.
- Or consider one-test suite: {0,1,0}. Misses the bug.

- *Branch coverage* is not enough
  - Here, *path coverage* is enough, but *no bound* on path-count

Varieties of Coverage

Various coverage metrics (there are more):

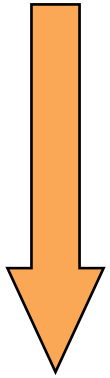
Statement coverage

Branch coverage

Loop coverage

Condition/Decision coverage

Path coverage



increasing number of test cases required (generally)

Limitations of coverage:

1. 100% coverage is not always a reasonable target
   100% may be unattainable (dead code)
   High cost to approach the limit
2. Coverage is *just a heuristic*
   We really want the revealing subdomains

Regression Testing

- Whenever you find a bug
  - Store the input that elicited that bug, plus the correct output
  - **Add these to the test suite**
  - Verify that the test suite fails
  - Fix the bug
  - Verify the fix
- Ensures that your fix solves the problem
  - Don't add a test that succeeded to begin with!
- Helps to populate test suite with good tests
- Protects against reversions that reintroduce bug
  - It happened at least once, and it might happen again

System or Integration Testing

Tests of whether the system as a whole works — whether the (individually correct, unit-tested) modules fit together to achieve correct functionality

- All of the previous topics (black-box, clear-box, regression testing, determining test cases) still apply
- End-to-End tests will test your system from the users (front end) to the persistent data storage (back end)
- Usually involves more complicated operations than unit tests

General Rules of Testing

First rule of testing: ***Do it early and do it often***

- Best to catch bugs soon, before they have a chance to hide
- Automate the process if you can
- Regression testing will save time

Second rule of testing: ***Be systematic***

- If you randomly thrash, bugs will hide in the corner until later
- Writing tests is a good way to understand the spec
- Think about revealing domains and boundary cases
  - If the spec is confusing, write more tests
- Spec can be buggy too
  - Incorrect, incomplete, ambiguous, missing corner cases
- When you find a bug, write a test for it first and then fix it

Hints on Testing

- Write small tests
- Choose good names for your tests:
  - use the proper instance of the assert method
  - write good messages
- Think carefully whether alternative solutions should be correct
  - (e.g., is there more than one shortest path for the given graph?).
- Write targeted tests
  - not an arbitrary number of random examples
- Keep your unit tests de-coupled
  - don't have one test case test multiple things
  - don't rely on certain state in the middle of the test that is not related to the test case

Test Driven Development

Write your tests **before** starting to write any code.

First:

use the specification to identify the abstract-value domain of each non-trivial public method

- what is the set of objects that the method can be called on, and the set of allowed inputs?

Then:

when you actually implement the code, you'll have thought about these cases, cleared up any confusion with the specification, and you are less likely to make mistakes.

JUnit: Testing Framework

- A Java library for unit testing, comes included with Eclipse
  - OR can be downloaded for free from the JUnit web site at http://junit.org
  - JUnit is distributed as a "JAR" which is a compressed archive containing Java .class files

```
import org.junit.Test;
import static org.junit.Assert.*;

public class name {
  ...

  @Test
  public void name() { // a test case method
    ...
  }
}
```

A method with @Test is flagged as a JUnit test case and run

JUnit Asserts and Exceptions

- A test will pass if the assert statements all pass and if no exception thrown. Examples of assert statements:
  - `assertTrue(message, value)`
  - `assertFalse(message, value)`
  - `assertEquals(message, expected, actual)`
  - `assertNull(message, value)`
  - `assertNotNull(message, value)`
  - `fail(message)`

- Tests can expect exceptions or timeouts

```
@Test(expected = ExceptionType.class)
public void name() {
   ...
}
```

Today's Takeaways

- Understand some basic testing principles and strategies
  - Unit testing
  - Heuristics for good test suites
  - Black-box testing
  - Clear-box testing and coverage metrics
  - Regression testing
  - Integration/System tests
  - Test Driven Development

- Understand how to write some basic JUnit