CSE 331
Software Design & Implementation

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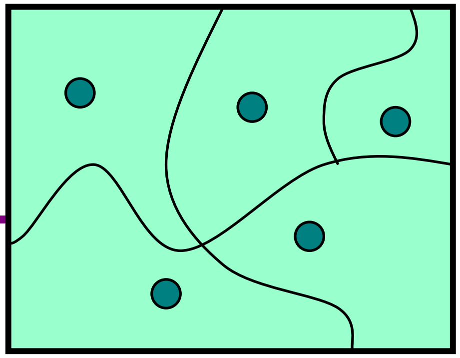
Testing

Administrivia

- HW3 due this evening

- HW4 out tonight
  - write tests for *some* of the parts
  - write tests for all the parts in HW5

Testing Heuristics



- Testing is *essential* but difficult
  - want set of tests likely to reveal the bugs present
  - but we don't know where the bugs are
- Our approach:
  - split the input space into enough subsets (subdomains) such that inputs in each one are likely all correct or incorrect
  - think carefully through the subdomains you are using
  - can then take just one example from each subdomain
- Some heuristics are useful for choosing subdomains...

Specification Testing

Heuristic: Explore alternate cases in the specification

Procedure is a black box: specification 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 lead 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)*

Specification Testing Example

Write tests based on cases in the specification

```
// returns: the smallest i such
//          that a[i] == value
// throws:  Missing if value is not in a
int find(int[] a, int value) throws Missing
```

Two obvious tests:

([4, 5, 6], 5) => 1

([4, 5, 6], 7) => throw Missing

Have we captured all the cases?

([4, 5, 5], 5) => 1

Must hunt for multiple cases

– Including scrutiny of effects and modifies

Heuristic: Clear (glass, white)-box testing

Focus on features not described by specification

- control-flow details (e.g., conditions of “if” statements in code)
- alternate algorithms for different cases
- behavior of the implementation not promised in the spec
  - e.g., spec doesn’t promise smallest index,
    but implementation does produce that

Combining Clear- and Black-Box

For buggy **`abs`**, what are revealing subdomains?

```
// returns:  x < 0     => returns -x
//           otherwise => returns x
int abs(int x) {
   if (x < -2) return -x;
   else        return x;
}
```

Example sets of subdomains:

– Which is best?

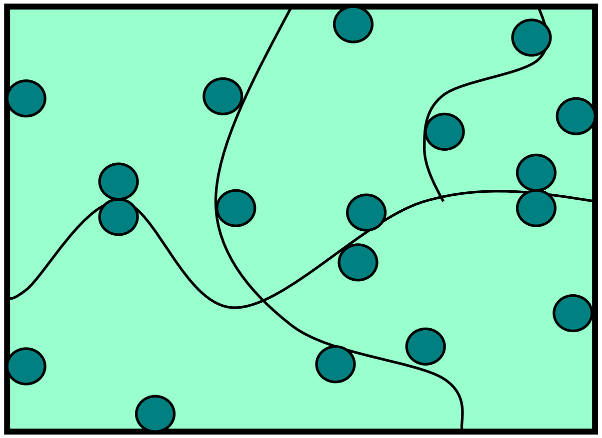
… {-2} {-1} {0} {1} …

{…, -4, -3} {-2, -1} {0, 1, …}

Why *not*: **{…,-6, -5, -4} {-3, -2, -1} {0, 1, 2, …}**

Heuristic: Boundary Cases

Create tests at the edges of subdomains



Why?

- off-by-one bugs
- smallest & largest numbers
- empty collection

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

Point is on a boundary if either:

- there exists an adjacent point in a different subdomain
- there is no point to one side

Example: function has different behavior on 1, …, n versus n+1…

Example: f(x) which requires x >= 0

- x = 0 is a boundary because x < 0 is not allowed

Boundary Cases: Integers

```
// 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*

Boundary Testing

To define the boundary, need a notion of adjacent inputs

Example 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
- *no* adjacent point in some direction

Example: f(x) which requires x >= 0

- x = 0 is a boundary because x < 0 is not allowed

Boundary Testing

To define the boundary, need a notion of adjacent inputs

Example 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
- *no* adjacent point in some direction

Example: list of integers

- basic operations: *push*, *pop*, *replace*
- adjacent points: <[2,3],[2,3,3]>, <[2,3],[2]>, <[2,3],[4,3]>
- boundary point: [ ] (can’t apply *pop*)

Heuristic: Special Cases

Arithmetic

- zero
- overflow errors in arithmetic

Objects

- null
- same object passed as multiple arguments (aliasing)

All of these are common cases where bugs lurk

- you'll find more as you encounter more bugs

Special Cases: Arithmetic Overflow

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

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

Special Cases: Duplicates & 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

sqrt 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* (probably want more)

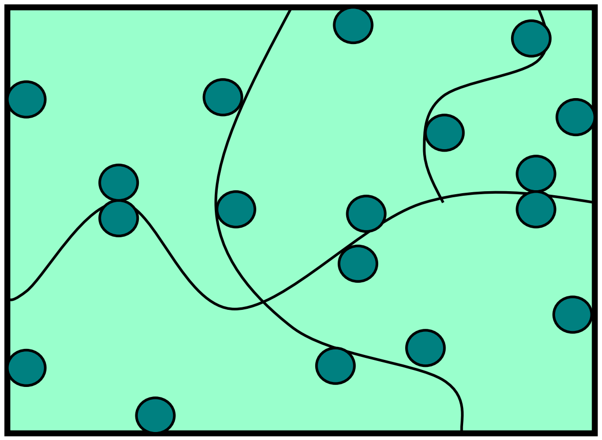
Pragmatics: Regression Testing

- 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!
    - another reason to try to write tests before coding
- Protects against reversions that reintroduce bug
  - it happened at least once, and it might happen again (especially when trying to change the code in the future)

How many tests is enough?

Correct goal should use **revealing subdomains**:

- one from each subdomain
- along the boundaries of each subdomain



How many tests is enough?

Common goal is to achieve high **code coverage**:

- ensure test suite covers (executes) all the program
- assess quality of test suite with % *coverage*
  - tools to measure this for you

Assumption implicit in goal:

- if high coverage, then most mistakes discovered
- **far** from perfect but widely used
- low code coverage is certainly bad

Code coverage: statement coverage

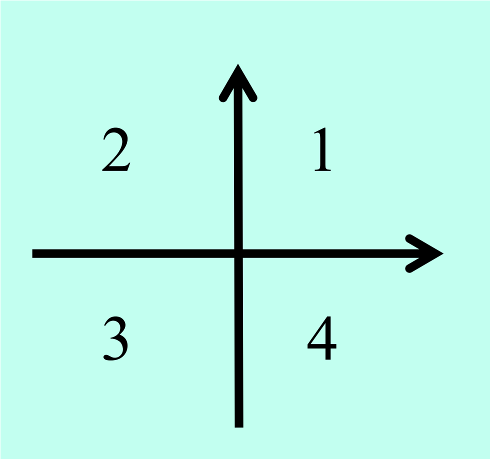
```
int min(int a, int b) {
    int r = a;
    if (a <= b) {
       r = a;
    }
    return r;
}
```

- 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: branch coverage

```
int quadrant(int x, int y) {
  int ans;
  if (x >= 0)
    ans=1;
  else
    ans=2;
  if (y < 0)
    ans=4;
  return ans;
}
```



- Consider two-test suite: (2,-2) and (-2,2). Misses the bug.
- *Branch coverage* (all tests "go both ways") is not enough
  - here, *path coverage* is enough (there are 4 paths)

Code coverage: path coverage

```
int countPositive(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.

- *Path coverage* is enough, but *no bound* on path-count!

Code coverage: what is enough?

```
int sumOfThree(int a, int b, int c) {
  return a+b;
}
```

- *Path coverage* is not enough
  - consider test suites where `c` is always 0

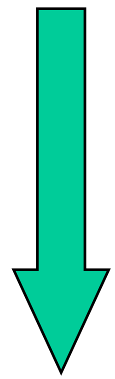
- Typically a “moot point” since path coverage is unattainable for realistic programs
  - but do not assume a tested path is correct
  - even though it is more likely correct than an untested path

- Another example: buggy `abs` method from earlier in lecture

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
   – may be *high cost* to approach 100%
2. Coverage is *just a heuristic*
   – we really want the revealing subdomains for the errors present

Summary of Heuristics

- Split subdomains on boundaries appearing in the specification
- Split subdomains on boundaries appearing in the implementation
- Test examples on the boundaries
- Test special cases like nulls, 0, etc.
- Test any cases that caused bugs before (to avoid regression)
- Make sure tests exercise *at least* every branch & statement

On the other hand, don't confuse *volume* with *quality* of tests

- look for revealing subdomains
- want tests in every revealing subdomain not **just** lots of tests

More Testing Tips

- Write tests both **before** and **after** you write the code
  – (only clear-box tests need to come afterward)

- Be systematic: think through revealing subdomains & test **each one**

- Test your tests
  – try putting a bug in to make sure the test catches it

- Test code is different from regular code
  – changeability is less important; **correctness** is more important
  – do not write **any test code** that is not obviously correct
    - otherwise, you need to test that code too!
    - unlike in regular code, it's *okay* to repeat yourself in tests

Testing Tools

- Modern development ecosystems have built-in support for testing
- Your homework introduces you to Junit
  – standard framework for testing in Java
- Continuous integration
  – ensure tests pass **before** code is submitted
- You will see more sophisticated tools in industry
  – libraries for creating mock implementations of other modules
  – automated tools to test on every platform
  – automated tools to find severe bugs (using AI)
  – …