
CSE 331

Software Design & Implementation

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Testing

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 **opaque**: 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

$(4, 3) \Rightarrow 4$ *(i.e. any input in the subdomain $a > b$)*

$(3, 4) \Rightarrow 3$ *(i.e. any input in the subdomain $a < b$)*

$(3, 3) \Rightarrow 3$ *(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: Transparent testing

Focus on features not described by specification

- control-flow details (e.g., conditions of “if” statements in code)
- performance optimizations
- alternate algorithms for different cases

Combining Transparent and Opaque

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, ...}
```

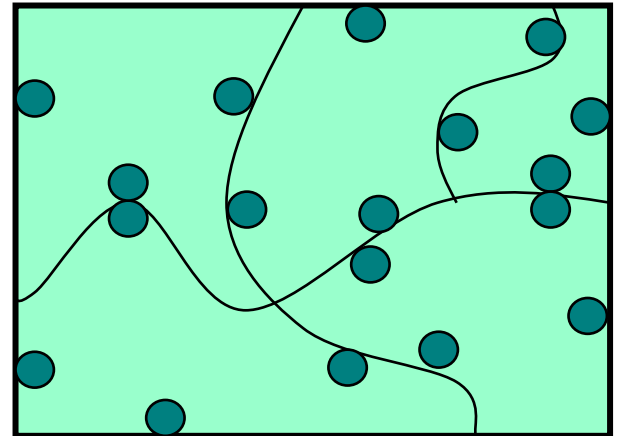
Why *not*: `{..., -6, -5, -4} {-3, -2, -1} {0, 1, 2, ...}`

Heuristic: Boundary & Special Cases

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

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 n and $n+1$

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
- some basic operation cannot be applied to the point

Example: list of integers

- basic operations: *create*, *append*, *set*, *remove*
- adjacent points: $\langle [2,3], [2,4] \rangle$, $\langle [2,3], [2,3,3] \rangle$, $\langle [2,3], [2] \rangle$
- boundary point: $[]$ (can't apply *remove*)

Heuristic: Special Cases

Arithmetic

- smallest/largest values
- zero

Objects

- null
- list containing itself
 - maybe a bit too pathological
- 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 ($\text{sqrt}(x)$ an integer), non-perfect squares

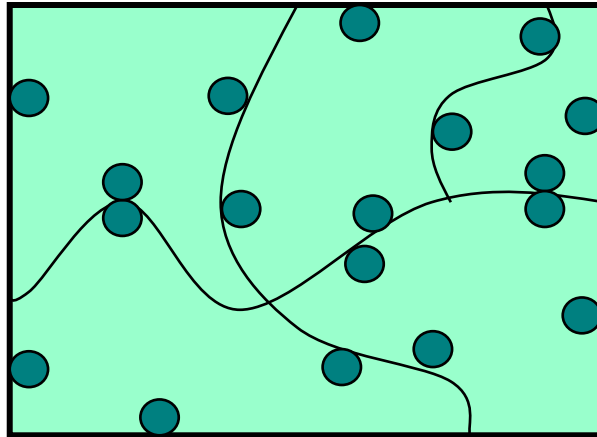
$x < \text{sqrt}(x)$ and $x > \text{sqrt}(x)$ – that's $x < 1$ and $x > 1$ (and $x = 1$)

Specific tests: say $x = -1, 0, 0.5, 1, 4$ (probably want more)

How many tests is enough?

Correct goal should use **revealing subdomains**:

- one from the middle of each subdomain
- examples 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 of 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 definitely bad

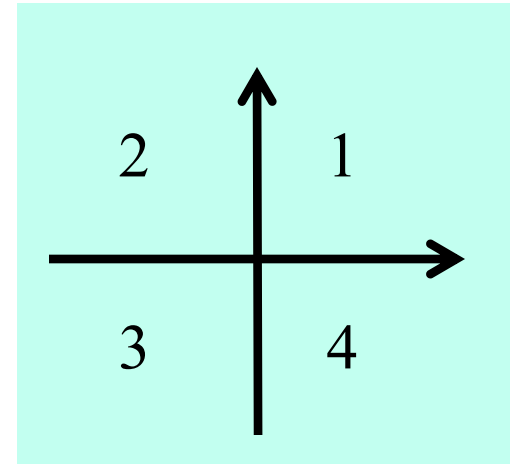
Code coverage: statement coverage

```
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):

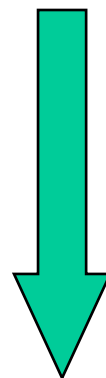
Statement coverage

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 boundaries that commonly lead to errors
- Test special cases like nulls, empty arrays, 0, etc.
- Tests to exercise every branch of the code
 - all paths would be even nicer (but not always possible)
- Test any cases that caused bugs before (to avoid regression)

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

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)
 - ...

Testing Tips

- Write tests both **before** and **after** you write the code
 - (only transparent 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