CSE 331

Software Design & Implementation

Topic: More Testing

Discussion: How would you test a randomized algorithm?

Reminders

- After HW4, things are going to slow down a bit

Upcoming Deadlines

- Prep. Quiz: HW4 due Monday (7/10)
- HW4 due Thursday (7/13)

Last Time…

- Testing
  - unit vs. integration vs. system
  - clear-box vs. opaque-box
  - specification vs. implementation
- Testing Heuristics
  - specification
  - clear-box
  - boundary case

Today's Agenda

- Recap: Testing
- More Testing Heuristics
- Code Coverage
- Discussion: HW4

Extra OH?

- Thinking about hosting Soham OH immediately before lecture
  - Monday/Wednesday/Friday?
  - Start off with 30m on all of the days + Ed Discussion board
- Benefits:
  - Students can work on homework immediately before the lecture
  - Ask questions about course material
  - Students can leave if they have no questions
- Drawbacks:
  - Many people lose focus when they are in the same room for 1.5 hours
  - Technically, I have another commitment at that time...

Kinds of testing

- Testing field has terminology for different kinds of tests
  - we won't discuss all the kinds and terms
- Here are three orthogonal dimensions [so 12 varieties total]:
  - *unit* testing versus *integration* versus *system / end-to-end* testing
    - ???
  - *clear-box* testing versus *opaque-box / black-box* testing
    - ???
  - *specification* testing versus *implementation* testing
    - ???

Kinds of testing

- Testing field has terminology for different kinds of tests
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- Here are three orthogonal dimensions [so 12 varieties total]:
  - *unit* testing versus *integration* versus *system / end-to-end* testing
    - one module's functionality versus pieces fitting together
  - *clear-box* testing versus *opaque-box / black-box* testing
    - did you look at the code before writing the test?
  - *specification* testing versus *implementation* testing
    - test only behavior guaranteed by specification or other behavior expected for the implementation

It's hard to test your own code

Your **psychology** is fighting against you:

- confirmation bias
  - tendency to avoid evidence that you're wrong
- operant conditioning
  - programmers get cookies when the code works
  - testers get cookies when the code breaks

You can avoid some effects of confirmation bias by

writing most of your tests before the code

Not much you can do about operant conditioning

Approach: Partition the Input Space

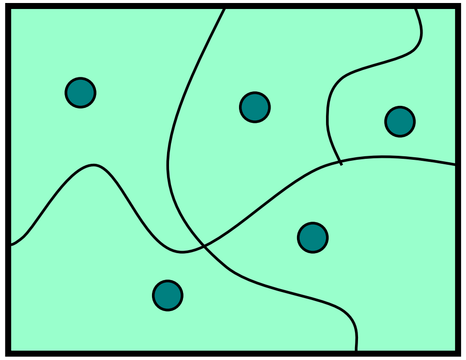
Ideal test suite:

Identify sets with “same behavior”

(actual and expected)

Test **at least** one input from each set

(we call this set a *subdomain*)



Two problems:

1. Notion of same behavior is subtle
   - We want to find revealing subdomains
2. Discovering the sets requires perfect knowledge
   - If we had it, we wouldn’t need to test
   - Use **heuristics** to approximate cheaply

Heuristics for Designing Test Suites

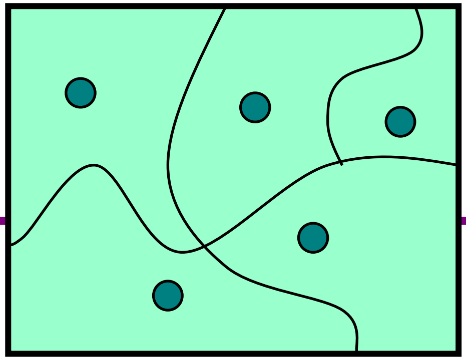
A good heuristic gives:

- for all errors in some class of errors E:
  high probability that some subdomain is revealing for E
- not an *absurdly* large number of subdomains

Different heuristics target different classes of errors

- in practice, combine multiple heuristics
  - (we will see several)
- a way to think about and communicate your test choices

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)*

Practice: Specification Testing

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

What tests might we want to consider for our test suite?

```
find([4, 5, 6], 5)      => 1
find([4, 5, 6], 7)      => throws MissingException
find([4, 5, 5], 5)      => 1
```

In general, we should hunt for multiple cases (look at effects and modifies)

Heuristic: Clear-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

Heuristic: Clear-box testing

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- 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
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```
// returns: an index i such that a[i] == value
// throws:  MissingException if value is not in a
int find(int[] a, int value) throws MissingException
```

Practice: Clear- and Black-Box

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

What **subdomains** might we want to consider for our test suite?

`{…, -4, -3, -2, -1, 0, 1, 2, 3, …}`

is our entire input space.

Practice: Clear- and Black-Box

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

What **subdomains** might we want to consider for our test suite?

`{…, -4, -3, -2, -1} {0, 1, 2, 3, …}`

after applying the specification heuristic.

Practice: Clear- and Black-Box

```
// returns:  x < 0     => returns -x
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int abs(int x) {
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}
```

What **subdomains** might we want to consider for our test suite?

`{…, -4, -3} {-2, -1} {0, 1, 2, 3, …}`

after applying the clear-box heuristic.

Practice: Clear- and Black-Box

Given the following partition

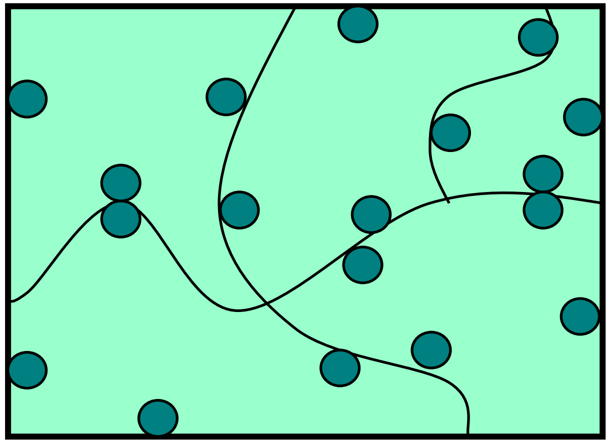
```
{…, -4, -3} {-2, -1} {0, 1, 2, 3, …}
```

what test cases should we consider for `abs`?

```
abs(-4)      => 4
abs(-2)      => 2
abs( 1)      => 1
```

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

Practice: Clear- and Black-Box

```
// returns:  x < 0     => returns -x
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int abs(int x) {
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What **subdomains** might we want to consider for our test suite?

`{…, -4, -3} {-2, -1} {0, 1, 2, 3, …}`

after applying the clear-box heuristic.

Practice: Clear- and Black-Box

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

What **subdomains** might we want to consider for our test suite?

`{…, -4} {-3} {-2} {-1} {0} {1, 2, 3, …}`

after applying the boundary case heuristic.

Practice: Clear- and Black-Box

Given the following partition

```
{…, -4} {-3} {-2} {-1} {0} {1, 2, 3, …}
```

what test cases should we consider for `abs`?

```
abs(-4)    => 4
abs(-3)    => 3   (boundary, clear-box)
abs(-2)    => 2   (boundary, clear-box)
abs(-1)    => 1   (boundary, specification)
abs( 0)    => 0   (boundary, specification)
abs( 1)    => 1
```

Boundary Testing

To define the boundary, need a notion of adjacent inputs

Example approach:

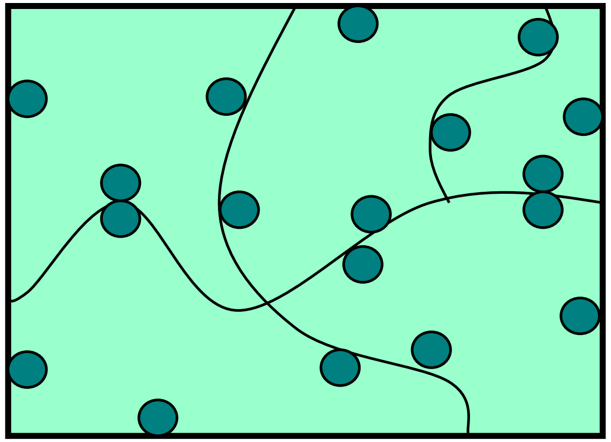
- identify basic operations on input points
- two points are adjacent if one basic operation apart

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

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Example: list of integers

- basic operations: *add*, *remove*, *set*
- adjacent points: <[2,3],[2,3,3]>, <[2,3],[2]>, <[2,3],[4,3]>
- boundary point: [ ] (can't apply *remove*)

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
- $x < \text{sqrt}(x)$ 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)

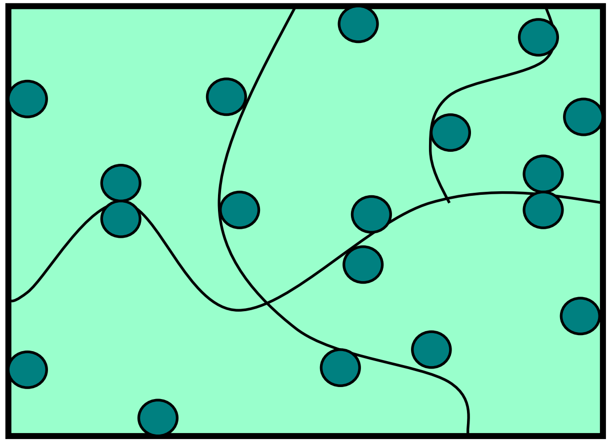
Pragmatics: Regression Testing

- 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
- **very far** from perfect but widely used
- low code coverage is certainly bad

Code coverage: statement coverage

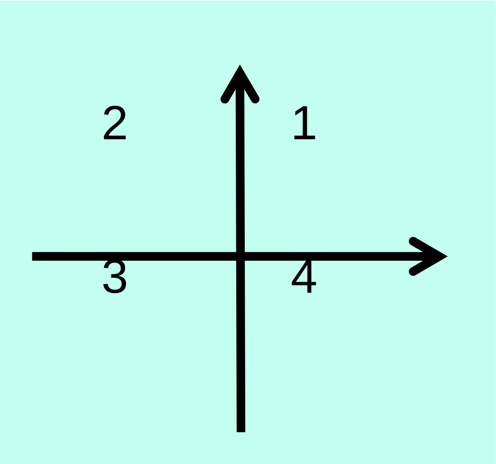
```
int min(int a, int b) {
    int r = a;
    if (a <= b) {
        r = a;
    }
    return r;
}
```

- Consider any test with $a \le b$ (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

HW4 – Background

- FiniteSet represents **`{0, 2, 3, 5}`**
  - has some operations like union, intersection, difference, complement

- SimpleSet represents either **`{0, 2, 3, 5}`** or **`R - {0, 2, 3, 5}`**
  - has the same operations!

HW4 – Part 1

- Reasoning worksheet
- Focuses on the union method in FiniteSet (not SimpleSet)

HW4 – Part 2

- Writing unit tests for FiniteSet
- Testing Heuristics
  - Specification
  - Clear-box
  - Boundary

HW4 – Part 3

- We already chose the representation for SimpleSet for you:
  - A FiniteSet of points
  - A boolean representing whether it is the complement

- Make sure you document the RI and AF
  - Will be *much* simpler than FiniteSet RI and AF

HW4 – Part 4

- If you were comfortable with the earlier parts, this should be straightforward.
- No new advice!

HW4 – Part 5

- Coding methods with many cases
- When union-ing two SimpleSets, how many cases are there?

- Homework Hack: Can you define some operations in terms of others?

HW4 – Part 6

- Start with the toString invariant
- Consider edge cases (e.g. the empty case)

Before next class…

1. Start on Prep. Quiz: HW4 as early as possible!
   - Reminds you about common set operations
     - E.g. union, intersection, complement
   - Think about some non-trivial cases needed for the homework