CSE 331
Software Design & Implementation

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Testing
(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)
How do we ensure correctness?

Best practice: use three techniques

1. **Tools**
   - e.g., type checking, @Override, libraries, etc.

2. **Inspection**
   - think through your code carefully
   - have another person review your code

3. **Testing**
   - usually >50% of the work in building software

Each removes ~2/3 of bugs. Together >97%
What can you learn from testing?

“Program testing can be used to show the presence of bugs, but never to show their absence!”

*Edsger Dijkstra*

*Notes on Structured Programming, 1970*

Testing is essential but it is insufficient by itself
- Need tools **and** inspection **and** testing to ensure correctness
How do we ensure correctness?

No single activity or approach can guarantee correctness

“Beware of bugs in the above code; I have only proved it correct, not tried it.”
-Donald Knuth, 1977

Trying it is a surprisingly useful way to find mistakes!

We need tools and inspection and testing to ensure correctness
Why you will care about testing

- Industry-wide trend toward developers doing more testing
  - 20 years ago we had large test teams
    - developers barely tested their code at all
  - now, test teams are small to nonexistent
    - e.g., Google may not have any

- Reasons for this change:
  1. easy to update products after shipping (users are testers)
  2. often lowered quality expectations (startups, games)
    - some larger companies want to be more like startups

- In all likelihood, you will be expected to test your own code

- This has positive and negative effects…
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
Outline

• Background
• Kinds of testing:
  – black-box testing
  – clear-box testing
  – regression testing
• Basic approach to testing
• Heuristics for good test suites
  – code coverage
• Tools
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 8 varieties total]:
  – *unit* testing versus *system/integration* testing
    • one module’s functionality versus pieces fitting together
  – *black-box* testing versus *clear-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?
Unit Testing

- A unit test focuses on one class / module (or even less)
  - could write a unit test for a single method

- Tests a single unit in isolation from all others

- Integration tests verify that the modules fit together properly
  - usually don’t want these until the units are well tested
    - i.e., unit tests come first
How is testing done?

Write the test

1) Choose input / configuration
2) Define the expected outcome

Run the test

3) Run with input and record the outcome
4) Compare *observed* outcome to *expected* outcome
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)
What’s So Hard About Testing?

“Just try it and see if it works…”

```c
// requires: 1 ≤ x,y,z ≤ 10000
// returns: computes some f(x,y,z)
int proc1(int x, int y, int z){…}
```

Exhaustive testing would require 1 trillion runs!
- impractical even for this trivially small problem

Key problem: choosing test suite
- Large/diverse enough to provide a useful amount of validation
- (Small enough to write/run in reasonable amount of time.)
Approach: Partition the Input Space

Ideal test suite:
Identify sets with “same behavior”
Test at least one input from each set

Two problems:

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

2. Discovering the sets requires perfect knowledge
   • If we had it, we wouldn’t need to test
   • Use heuristics to approximate cheaply
Naive Approach: Execution Equivalence

```c
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

Suggests that {-3, 3}, for example, is a good test suite
Execution Equivalence Can Be Wrong

// returns: x < 0 => returns -x
// otherwise => returns x

int abs(int x) {
    if (x < -2) return -x;
    else return x;
}

{-3, 3} does not reveal the error!

Two possible executions: x < -2 and x >= -2

Three possible behaviors:

- x < -2 OK, x = -2 or x = -1 (BAD)
- x >= 0 OK
Heuristic: Revealing Subdomains

• 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 at least 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
  – even though your reasoning says your code is correct, make educated guesses where the bugs might be
Example

For buggy `abs`, what are revealing subdomains?

- Value tested on is a good (clear-box) hint

```c
// 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?

Why not:

{..., -6, -5, -4} {-3, -2, -1} {0, 1, 2, ...}
A good heuristic gives:
- for all errors in some class of errors E: high probability that some subdomain is revealing for E and triggers 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
Black-Box Testing

Heuristic: Explore alternate cases in the specification

Procedure is a black box: specification visible, internals hidden

Example

```c
// 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 $a = b$)
Black Box Testing: Advantages

Process is not influenced by component being tested
  – avoids psychological biases we discussed earlier
  – can only do this for your own code if you write tests first

Robust with respect to changes in implementation
  – test data need not be changed when code is changed

Allows others to test the code (rare nowadays)
More Complex Example

Write tests based on cases in the specification

```java
// 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: 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

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, set, append, remove
- adjacent points: <[2,3],[2,4]>, <[2,3],[2,3,3]>, <[2,3],[2]>
- boundary point: [ ] (can’t apply remove)
Other Boundary Cases

Arithmetic
- smallest/largest values
- zero

Objects
- null
- list containing itself
- 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
Boundary Cases: 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 ≥ 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 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
Heuristic: Clear (glass, white)-box 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

Common *goal* is 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
Clear-box Motivation

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

```java
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: [Dis]Advantages

• Finds an important class of boundaries
  – 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:
  – buggy code tricks you into thinking it’s right once you look at it
    • (confirmation bias)
  – can end up with tests having same bugs as implementation
  – so also write tests before looking at the code
Code coverage: what is enough?

```c
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., \(\text{min}(1, 2)\))
  – executes every instruction
  – misses the bug

• *Statement coverage* is not enough
Code coverage: what is enough?

```c
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)
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.

• Branch coverage is not enough
  – here, path coverage is enough, but no bound on path-count!
Code coverage: what is enough?

```c
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

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
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)
Summary of Heuristics

- Test boundaries appearing in the specification
- Test boundaries appearing in the implementation
- Test boundaries that commonly lead to errors
- 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 subdomain not 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

• You will see more sophisticated tools in industry
  – systems that ensure tests pass before code is submitted
  – libraries for creating fake 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
  – (clear-box tests 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