Note Card Survey (Anonymous)

1. Keep: What have I been doing well that I should continue doing?

2. Change: What is something I already do, but should change so I do it better?

3. Stop: What is one bad thing I should stop doing?

4. Start: What is one good thing I haven't done that I should start doing?

5. Any other feedback you wish to give!

Topic Suggestions:

- Lecture: Clarity, Speed/Pacing, Active Learning, Interaction with Students
- Office Hours
- Homework

CSE 331
Software Design and Implementation

Lecture 8
Testing

Leah Perlmutter / Summer 2018

Announcements

Announcements

- Homework
  - Congrats on making it past the HW3 due date!
    - technical issues persisting?
  - HW4 is out! Due Thursday, July 12, 10 pm
- Midterm: Monday, July 16
  - in our normal lecture time and location
- Midterm Review: Friday, July 13, 3:30 - 5 pm
  - Location TBD

Testing

Outline

- Why correct software matters
  - Motivates testing *and* more than testing, but now seems like a fine time for the discussion
- Testing principles and strategies
  - Purpose of testing
  - Kinds of testing
  - Heuristics for good test suites
  - Black-box testing
  - Clear-box testing and coverage metrics
  - Regression testing

There is no one right answer

The way you test depends on many things

- Who your customers are
- How safety-critical your code is
- The conventions at your company

Testing is as much an art as a science

- Need to be systematic
- Also need to be creative

I will tell you some things I know about testing!

Note about tools

- Modern development ecosystems have much built-in support for testing
  - Unit-testing frameworks like JUnit
  - Regression-testing frameworks connected to builds and version control
  - Continuous testing
  - …
- No tool details covered here
  - See homework, section, internships, …

Motivation

Building Quality Software

What Affects *Software Quality*?

External

Correctness	Does it match what the customer wanted?
Reliability	Does it do it accurately all the time?
Efficiency	Does it do without excessive resources?
Integrity	Is it secure?

Internal

Correctness	Does the software match the spec?
Portability	Can I use it under different conditions?
Maintainability	Can I fix it?
Flexibility	Can I change it or extend it or reuse it?

Quality Assurance (QA)

- Process of uncovering problems and improving software quality
- Testing is a major part of QA

Software Quality Assurance (QA)

Testing plus other activities including:

- 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)
- …and many other ways to find problems and increase confidence

No single activity or approach can guarantee software quality

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

Kinds of Software Customers

How much assure software quality before we "ship it" ?

- Depends on the cost of mistakes
  - Depends on the customer!

Some potential customers

- The person at the next desk
- Business contract customers
- Web or app customers
- Airplane passengers
- Medical patients
- The Space Program

Clinical Neutron Therapy System


Therac-25 radiation therapy machine

Excessive radiation killed patients (1985-87)

- New design removed hardware that prevents the electron-beam from operating in its high-energy mode. Now safety checks done in software.
- Equipment control software task did not properly synchronize with the operator interface task, so race conditions occurred if the operator changed the setup too quickly.
- Missed during testing because it took practice before operators worked quickly enough for the problem to occur.

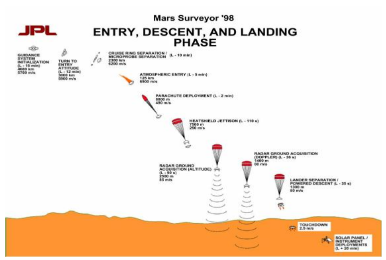
Ariane 5 rocket (1996)

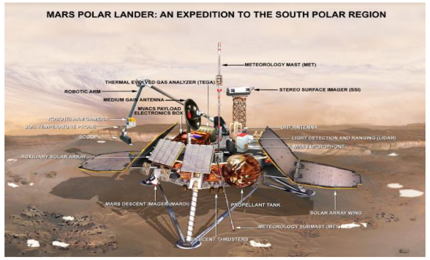


Rocket self-destructed 37 seconds after launch
- Cost: over $1 billion

Reason: Undetected bug in control software
- Conversion from 64-bit floating point to 16-bit signed integer caused an exception
- The floating point number was larger than 32767
- Efficiency considerations led to the disabling of the exception handler, so program crashed, so rocket crashed

Mars Polar Lander





Legs deployed → Sensor signal falsely indicated that the craft had touched down (130 feet above the surface)
Then the descent engines shut down prematurely

More examples

- Mariner I space probe (1962)
- Microsoft Zune New Year's Eve crash (2008)
- iPhone alarm (2011)
- Denver Airport baggage-handling system (1994)
- Air-Traffic Control System in LA Airport (2004)
- AT&T network outage (1990)
- Northeast blackout (2003)
- USS Yorktown Incapacitated (1997)
- Intel Pentium floating point divide (1993)
- Excel: 65,535 displays as 100,000 (2007)
- Prius brakes and engine stalling (2005)
- Soviet gas pipeline (1982)
- Study linking national debt to slow growth (2010)
- …

Software bugs cost money

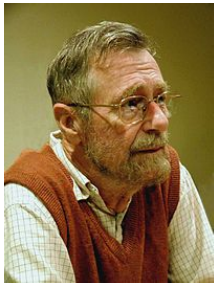
- 2013 Cambridge University study: Software bugs cost global economy $312 Billion per year
  - http://www.prweb.com/releases/2013/1/prweb10298185.htm
- $440 million loss by Knight Capital Group in 30 minutes
  - August 2012 high-frequency trading error
- $6 billion loss from 2003 blackout in NE USA & Canada
  - Software bug in alarm system in Ohio power control room

What can you learn from testing?

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

Edsgar Dijkstra

Notes on Structured Programming, 1970



What Is Testing For?

Validation = reasoning + testing

- Make sure module does what it is specified to do
- Uncover problems, increase confidence

Two rules:

1. Do it early and often
   - Catch bugs quickly, before they have a chance to hide
   - Automate the process wherever feasible
2. Be systematic
   - If you thrash about randomly, the bugs will hide in the corner until you're gone
   - Understand what has been tested for and what has not
   - Have a strategy!

Summary: Why test?

- Low quality can have great costs
  - human lives
  - billions of dollars
  - ruined business relationships
  - your company's reputation
  - making your life harder as a programmer

- Software quality is important
  - Testing is one way to improve quality

331 homeworks will give you the opportunity to practice testing!

How to Test

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 orthogonal 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

How is testing done?

1) Choose a part to test
2) Choose input data/configuration
3) Define the expected outcome
4) Run with input and record the outcome
5) Compare *observed* outcome to *expected* outcome

Lots of these!

Input selection is hard!

sqrt example: Input Selection

```
// 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*

Why is Input Selection Hard?

"Just try it and see if it works..."

```
// 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!

- Sounds totally impractical – and this is a trivially small problem

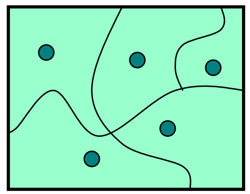
Key problem: choosing test suite

- **Small enough** to finish in a useful amount of time
- **Large enough** to provide a useful amount of validation

Approach: Partition the Input Space

Ideal test suite:

- Identify sets with same behavior
- Try 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

```
// 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

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 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

Example

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

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

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

Example sets of subdomains:

… {-2} {-1} {0} {1} … too many!

{…,-6, -5, -4} {-3, -2, -1} {0, 1, 2, …} not revealing!

{…, -4, -3} {-2, -1} {0, 1, …} just right!

Heuristics for Designing Test Suites

A good heuristic gives:

- Few subdomains
- for all errors in some class of errors E,

  High probability that some subdomain is revealing for E and triggers E

Different heuristics target different classes of errors

- In practice, combine multiple heuristics
- Really a way to think about and communicate your test choices

Heuristic: Cases in Specification

Heuristic: Explore alternate cases in the specification

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 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

- 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

More Complex 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?

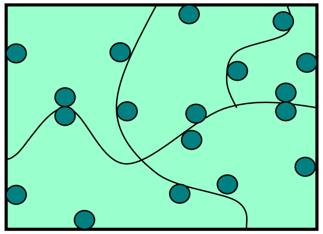
([4, 5, 5], 5) ⇒ 1

Must hunt for multiple cases

- explicit cases in the spec are not enouch

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*)

Other Boundary Cases

Arithmetic

- Smallest/largest values
- Zero

Objects

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

Boundary cases are also called "edge cases" and "corner cases"

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 $x \geq 0$ (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 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

Buggy abs Revisited

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

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

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

Subdomains based on spec (black box)	{… -2, -1, 0} {1, 2, …}
Boundary cases	0 1

Heuristic: Clear (glass, white)-box testing

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

Glass-box Motivation

There 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];
    }
}
```

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

Buggy abs Revisited

For buggy **abs**, what are revealing subdomains?
- Value tested on is a good (clear-box) hint

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

Subdomains based on spec (black box) **{… -2, -1, 0} {1, 2, …}**

Boundary cases **0 1**

Subdomains based on internals (glass box) **{… -3, -2} {-1, 0 , …}**

Boundary cases **-2 -1**

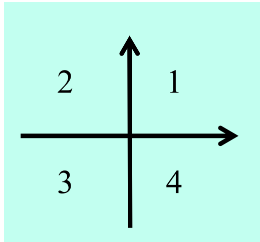
Code coverage: what is enough?

```
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: what is enough?

```
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: what is enough?

```
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

Code coverage: what is enough?

```
int sum_three(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
   100% may be unattainable (dead code)
   High cost to approach the limit
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!
- Helps to populate test suite with good tests
- Protects against reversions that reintroduce bug
  - It happened at least once, and it might happen again

Concepts so far

Input Selection
- Challenging to find the right set of inputs to reveal bugs

Revealing Subdomains
- The “true” subdomains that will reveal your bugs

Black box
- Choose inputs by looking at cases in spec
- Misses subdomains based on implementation

Clear box
- Choose inputs by looking at cases in code

Code Coverage
- A measure of how much of the code is executed by a test
- Can measure by lines, branches, paths
- Misses bugs of omission

Closing Thoughts

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

Closing thoughts on testing

Testing matters
- You need to convince others that the module works

Catch problems earlier
- Bugs become obscure beyond the unit they occur in

Don't confuse *volume* with *quality* of test data
- Can lose relevant cases in mass of irrelevant ones
- Look for revealing subdomains

Choose test data to cover:
- Specification (black box testing)
- Code (glass box testing)

Testing can't generally prove absence of bugs
- But it can increase quality and confidence

Announcements

Announcements

- HW4 is dueThursday, July 12, 10 pm
- Midterm: Monday, July 16
  - in our normal lecture time and location
- Midterm Review: Friday, July 13, 3:30 - 5 pm
  - Location TBD