

Beta

- Beta is due April 2, at noon
That's 1 week from today!
- Beta includes presentations
 - 15 minutes per group
 - at least 2 students per group
 - practice practice practice

Exam

- What did you guys think of the exam?
- Too easy?
- Too hard?

Exam stats

Grades are on Moodle

- Mean: 72
- Median: 72
- Mode: 65
- Standard deviation: 8.5

Rough grade breakdown

A or A-	75 or above
B+ or B or B-	67-74
C+ or C or C-	66 or below

Things to remember

- The project is worth 50% of your overall grade!
- Each exam is only 20%
- There is one more exam
 - May 6, 10:30 AM

Testing

Real programmers need no testing!

- 5) I want to get this done fast, testing is going to slow me down.
- 4) I started programming when I was 2. Don't insult me by testing my perfect code!
- 3) Testing is for incompetent programmers who cannot hack.
- 2) We are not Notre Dame students, our code actually works!
- 1) "Most of the functions in Graph.java, as implemented, are one or two line functions that rely solely upon functions in HashMap or HashSet. I am assuming that these functions work perfectly, and thus there is really no need to test them."
– an excerpt from a student's e-mail

Ariane 5 rocket

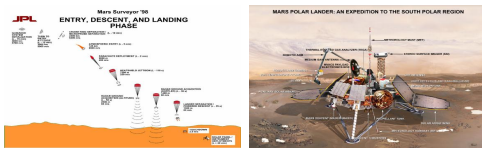


- The rocket self-destructed 37 seconds after launch
- Reason: A control software bug that went undetected
 - Conversion from 64-bit floating point to 16-bit signed integer value had caused an exception
 - The floating point number was larger than 32767 (max 16-bit signed integer)
 - Efficiency considerations had led to the disabling of the exception handler.
 - Program crashed → rocket crashed
- Total Cost: over \$1 billion

Therac-25 radiation therapy machine

- Caused excessive radiation, **killing patients** from radiation poisoning
- What happened?
 - Updated design had removed hardware interlocks that prevent the electron-beam from operating in its high-energy mode. Now all the safety checks are done in the software.
 - The software set a flag variable by incrementing it. Occasionally an arithmetic overflow occurred, causing the software to bypass safety checks.
 - The equipment control task did not properly synchronize with the operator interface task, so that race conditions occurred if the operator changed the setup too quickly.
 - This was evidently missed during testing, since it took some practice before operators were able to work quickly enough for the problem to occur.

Mars Polar Lander



- Sensor signal falsely indicated that the craft had touched down when it was 130-feet above the surface.
 - the descent engines to shut down prematurely
- The error was traced to a single bad line of software code.
- NASA investigation panels blame for the lander's failure, "are well known as difficult parts of the software-engineering process,"

Testing is for *every* system

- Examples showed particularly costly errors
- But every little error adds up
- Insufficient software testing costs **\$22-60 billion** per year in the U.S. [NIST Planning Report 02-3, 2002]
- If your software is worth writing, it's worth writing right

Building quality software

- What Impacts the Software Quality?
- External
 - Correctness *Does it do what it suppose to do?*
 - Reliability *Does it do it accurately all the time?*
 - Efficiency *Does it do with minimum use of resources?*
 - Integrity *Is it secure?*
- Internal
 - 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
 - The process of uncovering problems and improving the quality of software.
 - Testing is a major part of QA.

The phases of testing

- Unit Testing
 - Is each module does what it suppose to do?
- Integration Testing
 - Do you get the expected results when the parts are put together?
- Validation Testing
 - Does the program satisfy the requirements
- System Testing
 - Does it work within the overall system

Unit Testing

- A test is at the level of a method/class/interface
Check that the implementation matches the specification.

Black box testing

- Choose test data *without* looking at implementation

- Glass box (white box) testing

- Choose test data *with* knowledge of implementation

How is testing done?

Basic steps of a test

- 1) Choose input data / configuration
- 2) Define the expected outcome
- 3) Run program / method against the input and record the results
- 4) Examine results against the expected outcome

What's so hard about testing ?

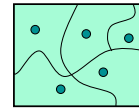
- "just try it and see if it works..."
- ```
int procl(int x, int y, int z)
// requires: 1 <= x,y,z <= 1000
// effects: computes some f(x,y,z)
```
- Exhaustive testing would require 1 billion runs!
  - Sounds totally impractical
- Could see how input set size would get MUCH bigger
- Key problem: **choosing test suite (set of partitions of inputs)**
  - Small enough to finish quickly
  - Large enough to validate the program

## Approach: partition the input space

- Input space very large, program small  
→ behavior is the "same" for sets of inputs

- Ideal test suite:

- Identify sets with same behavior
- Try one input from each set



- Two problems

- 1. Notion of **the same behavior** is subtle
  - Naive approach: **execution equivalence**
  - Better approach: **revealing subdomains**
- 2. Discovering the sets requires perfect knowledge
  - Use heuristics to approximate cheaply

## Naive approach: execution equivalence

```
int abs(int x) {
// returns: x < 0 => returns -x
// otherwise => returns 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  $x \geq 0$  are execution equivalent

Suggests that  $\{-3, 3\}$ , for example, is a good test suite

## Why execution equivalence doesn't work

Consider the following buggy code:

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

if (x < -2) return -x;
else return x;
}
```

**$\{-3, 3\}$  does not reveal the error!**

Two executions:

$x < -2$        $x \geq -2$

Three behaviors:

$x < -2$  (OK)     $x = -2$  or  $-1$  (bad)     $x \geq 0$  (OK)

### Revealing subdomain approach

- “Same” behavior depends on specification
- Say that program has “same behavior” on two inputs if
  - 1) gives correct result on both, or
  - 2) gives incorrect result on both
- Subdomain is a subset of possible inputs
- Subdomain is **revealing** for an error, E, if
  - 1) Each element has **same behavior**
  - 2) If program has error E, it is revealed by test
- Trick is to divide possible inputs into sets of revealing subdomains for various errors

### Example

- For buggy abs, what are revealing subdomains?

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

~~{-1} {-2} {-2, -1} {-3, -2, -1}~~

{-2, -1}

- Which is best?

### Heuristics for designing test suites

- A good heuristic gives:
  - few subdomains
  - $\forall$  errors **e** in some class of errors **E**, high probability that some subdomain is revealing for **e**
- Different heuristics target different classes of errors
  - In practice, combine multiple heuristics

### Black-box testing

- Heuristic: explore alternate paths through specification the interface is a **black box**; internals are hidden

- Example

```
- int max(int a, int b)
 // effects: a > b => returns a
 // a < b => returns b
 // a = b => returns a
```

- 3 paths, so 3 test cases:

(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 not influenced by component being tested
  - Assumptions embodied in code not propagated to test data.
- 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

### A more complex example

- Write test cases based on paths through the specification

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

- Two obvious tests:

( [4, 5, 6], 5 ) => 1  
 ( [4, 5, 6], 7 ) => throw Missing

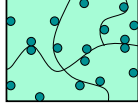
- Have I captured all the paths?

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

- Must hunt for multiple cases in effects or requires

## Heuristic: boundary testing

- Create tests at the edges of subdomains
- Why do this?
  - off-by-one bugs
  - forget to handle empty container
  - overflow errors in arithmetic
  - program does not handle aliasing of objects
- Small subdomains at the edges of the “main” subdomains have a high probability of revealing these common errors



## Boundary testing

- To define boundary, must define adjacent points
- One approach:
  - Identify basic operations on input points
  - Two points are adjacent if one basic operation away
  - A point is isolated if can't apply a basic operation
- Example: list of integers
  - Basic operations: create, append, remove
  - Adjacent points: <[2,3],[2,3,3]>, <[2,3],[2]>
  - Isolated point: [] (can't apply remove integer)
- Point is on a boundary if either
  - There exists an adjacent point in different subdomain
  - Point is isolated

## Common boundary cases

- Arithmetic
  - Smallest/largest values
  - Zero
- Objects
  - Null
  - Circular
  - Same object passed to multiple arguments (aliasing)

## Boundary cases: arithmetic overflow

- ```
public int abs(int x)
// returns: |x|
```
- Tests for abs
 - 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 = -2147483648; // this is Integer.MIN_VALUE
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 and aliases

```
<E> void appendList(List<E> src, List<E> dest) {
// modifies: src, dest
// effects: removes all elements of src and
// appends them in reverse order to
// the end of 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 thing?  
 – **Aliasing** (shared references) is often forgotten

## Clear (glass, white)-box testing

- Goals:
  - Ensure test suite covers (executes) all of the program
  - Measure quality of test suite with % coverage
- Assumption:
  - High coverage →
  - (no errors in test output → few mistakes in program)
- Focus: features not described by specification
  - Control-flow details
  - Performance optimizations
  - Alternate algorithms for different cases

## 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];
 }
}
```

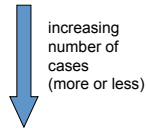
Important transition around  $x = \text{CACHE\_SIZE}$

## Glass-box testing: advantages

- Insight into test cases
  - Which are likely to yield new information
- Finds an important class of boundaries
  - Consider `CACHE_SIZE` in `isPrime` example
- Need to check numbers on each side of `CACHE_SIZE`
  - `CACHE_SIZE-1`, `CACHE_SIZE`, `CACHE_SIZE+1`
- If `CACHE_SIZE` is mutable, we may need to test with different `CACHE_SIZE`'s

## Glass-box challenges

- Definition of **all of the program**
  - What needs to be covered?
  - Options:
    - Statement coverage
    - Decision coverage
    - Loop coverage
    - Condition/Decision coverage
    - Path-complete coverage
- 100% coverage not always reasonable target



100% may be unattainable (dead code)  
High cost to approach the limit

## Regression testing

- Whenever you find a bug
  - Reproduce it (before you fix it!)
  - Store input that elicited that bug
  - Store correct output
  - Put into test suite
  - Then, fix it and verify the fix
- Why is this a good idea?
  - Helps to populate test suite with good tests
  - Protects against regressions that reintroduce bug
    - It happened once, so it might again

## 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 you're gone
  - 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, and missing corner cases
  - When you find a bug → fix it first and then write a test for it

## Testing summary

- Testing matters
  - You need to convince others that 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 ("characteristic tests")
- 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