CSE 331
Software Design & Implementation

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Testing

(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins)

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

Non-outline

- 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, …

Ariane 5 rocket (1996)

Rocket self-destructed 37 seconds after launch

- Cost: over $1 billion

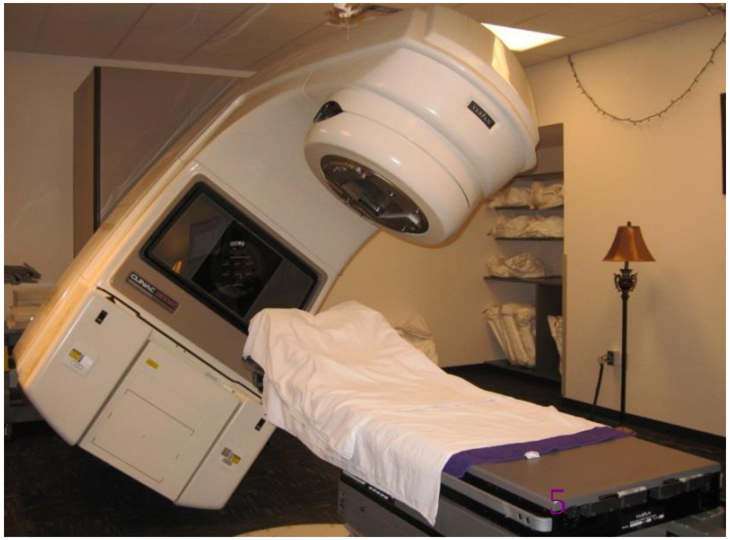
Reason: Undetected bug in control software

- 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

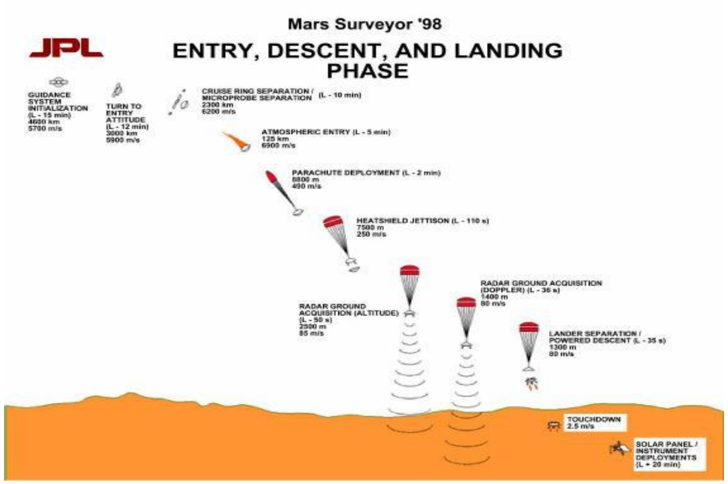
Therac-25 radiation therapy machine

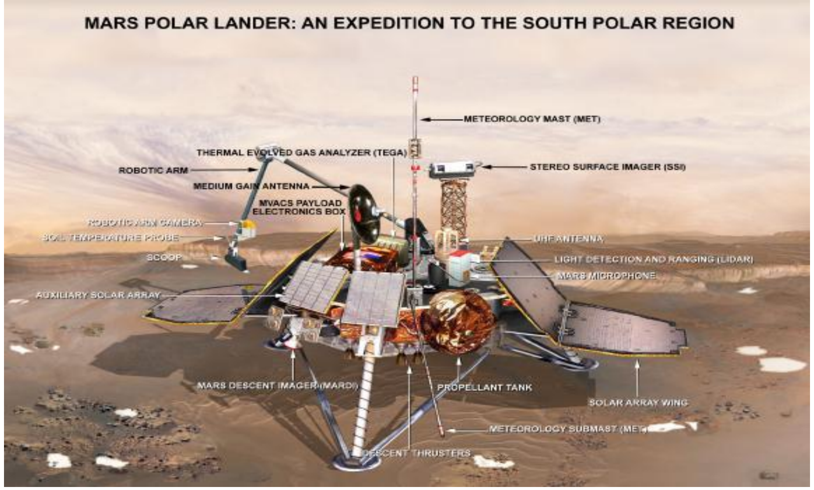
Excessive radiation killed patients (1985-87)

- New design removed hardware prevents the electron-beam from operating in its high-energy mode. Now safety checks done in software.
- Equipment control 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.



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

Error later traced to a single bad line of software code

Why didn't they blame the sensor?

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)
- …

Costs to society as of 2002

- Inadequate infrastructure for software testing costs the U.S. $22-$60 billion per year

- Testing accounts for about half of software development costs
  - Program understanding and debugging account for up to 70% of time to ship a software product

- Improvements in software testing infrastructure might save 1/3 of the cost

(Source: NIST Planning Report 02-3, 2002)

Building Quality Software

What Affects *Software Quality*?

External

Correctness	Does it do what it supposed to do?
Reliability	Does it do it accurately all the time?
Efficiency	Does it do without excessive 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 (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

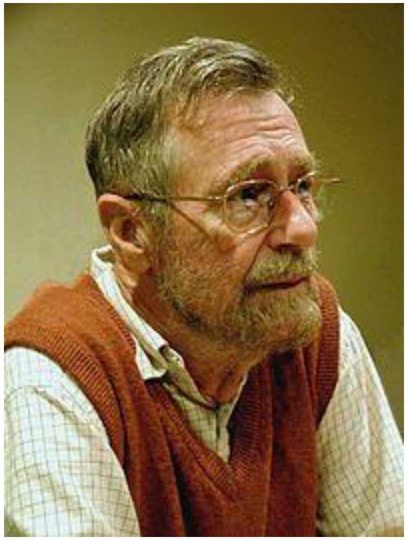
> "Beware of bugs in the above code;
> I have only proved it correct, not tried it."
> -Donald Knuth, 1977

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



Nevertheless testing is essential. Why?

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!

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 [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
    - 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?

Write the test

1) Choose input data/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

```java
// 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* ≥ 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*

What's So Hard About Testing?

"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){…}
```

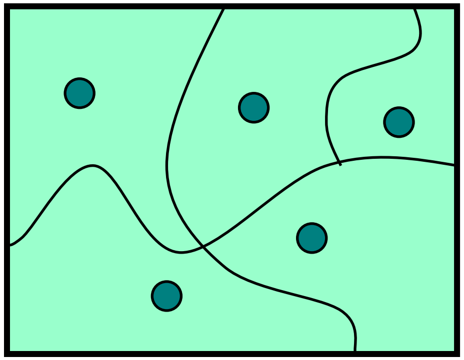
Exhaustive testing would require 1 trillion runs!

- 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:

- Which is best?

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

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

Heuristics for Designing Test Suites

A good heuristic gives:

- Few subdomains
- ∀ 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

Black-Box Testing

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?

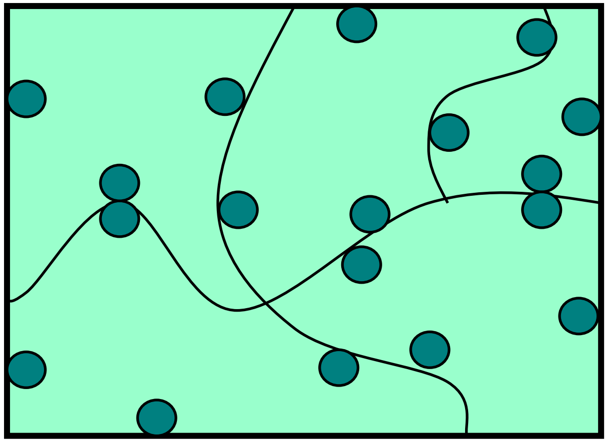
([4, 5, 5], 5) => 1

Must hunt for multiple cases

– 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

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: 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: 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

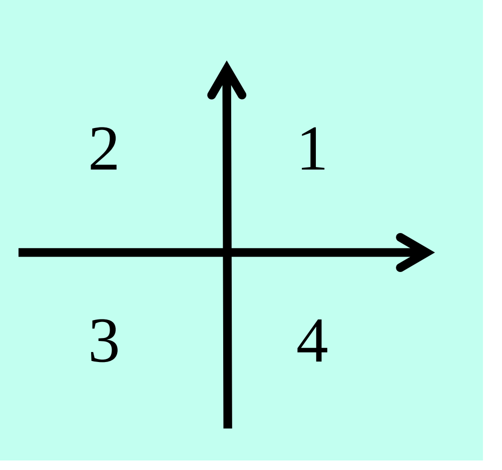
Code coverage: what is enough?

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

- Consider any test with $a \leq b$ (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):

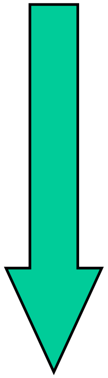
Statement coverage

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

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