CSE 331
Software Design & Implementation

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Testing

(Slides by Mike Ernst)

Overview

- Testing principles, strategies, and tactics & why this matters

- You've already seen JUnit basics in section and worked with it on assignments; not covered in detail here, but we can revisit later if there are things we've missed

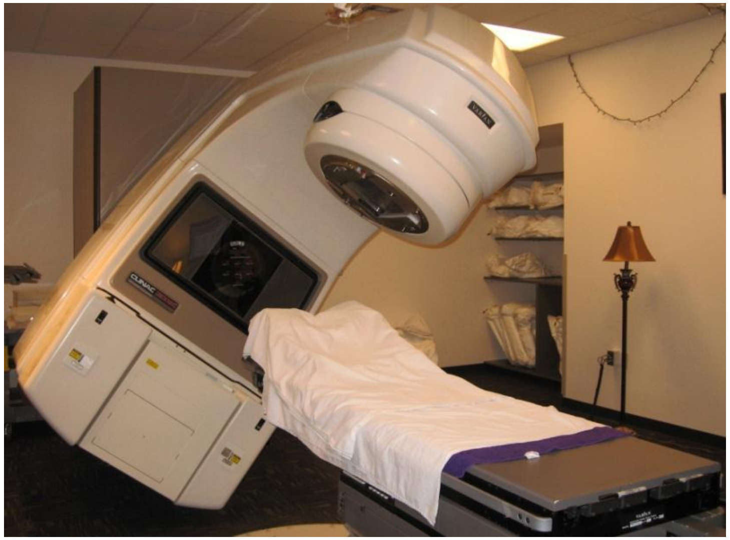
Ariane 5 rocket

- 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

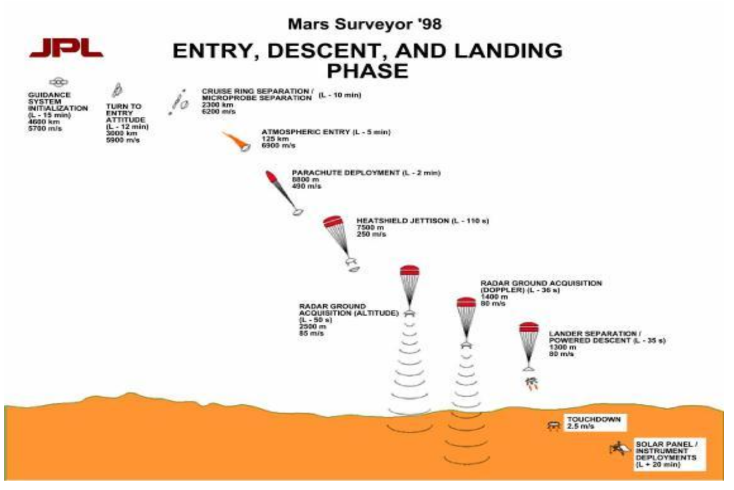
Excessive radiation killed patients (1985-87)

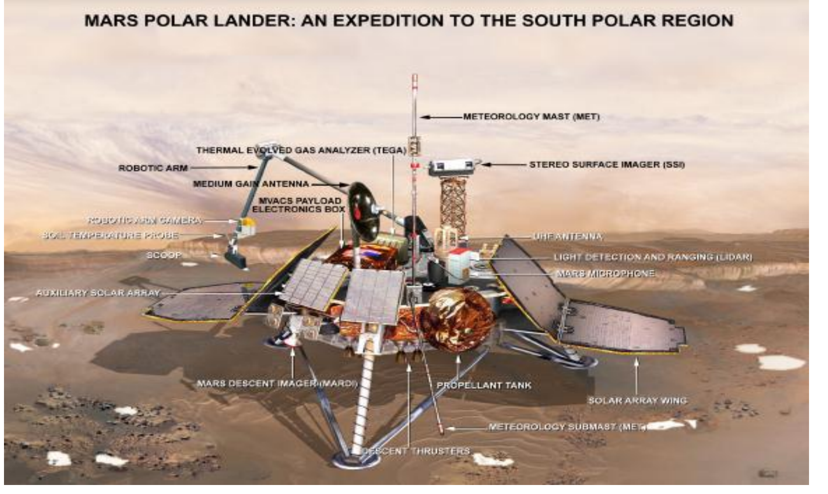
- New design removed hardware interlocks that prevent the electron-beam from operating in its high-energy mode. Now all the safety checks are done in software.
- The equipment control task did not properly synchronize with the operator interface task, so that race conditions occurred if the operator changed the setup too quickly.
- This was missed during testing, since it took practice before operators were able to work quickly enough for the problem to occur.



Panama, 2000: At least 8 dead
Many more! (NYT 12/28/2010)

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

The error was traced to a single bad line of software code.

- Why didn't they blame the sensor?

NASA investigation panel blames for the lander failure, "are well known as difficult parts of the software-engineering process"

More examples

Microsoft Zune's New Year Crash (2008)
iPhone alarm (2011)
Air-Traffic Control System in LA Airport (2004)
Northeast Blackout (2003)
USS Yorktown Incapacitated (1997)
Denver Airport Baggage-handling System (1994)
Mariner I space probe (1962)
AT&T Network Outage (1990)
Intel Pentium floating point divide (1993)
Prius brakes and engine stalling (2005)
Soviet gas pipeline (1982)
Iran centrifuges (2009)

2002 NIST report on costs to society

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 one-third of the cost

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 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.

Software Quality Assurance (QA)

Testing plus other activities including:

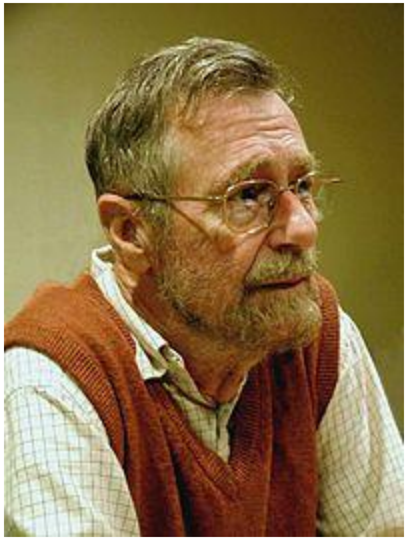
- Static analysis (assessing code without executing it)
- Proofs of correctness (theorems about program properties)
- Code reviews (people reading each others' code)
- Software process (structure on how code is developed and evolved)
- …and many other ways to find problems and increase confidence

No single activity or approach can guarantee software quality

A caution: Dijkstra

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

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 do it often
   - Catch bugs quickly, before they have a chance to hide
   - Automate the process if you can
2. Be systematic
   - If you thrash about randomly, the bugs will hide in the corner until you're gone

Phases of Testing

Unit Testing

Does each module do what it supposed 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 if 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

Testing can't generally prove absence of bugs

But can increase quality and confidence

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*

What's So Hard About Testing?

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

```
// requires: 1 ≤ x,y,z ≤ 10000
// effects:  computes some f(x,y,z)
int proc1(int x, int y, int z)
```

Exhaustive testing would require 1 trillion runs!

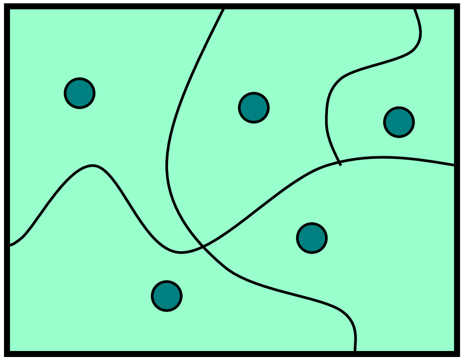
Sounds totally impractical – and this is a trivially small problem

Key problem: choosing test suite (set of partitions of inputs)

Small enough to finish quickly

Large enough to validate the program

Approach: Partition the Input Space



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

```
// 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

Why Execution Equivalence Doesn't Work

Consider the following buggy code:

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

Two executions:

$x < -2$ $x \geq -2$

Three behaviors:

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

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

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, then we are <u>guaranteed</u> to detect the error if it is present

The trick is to guess these revealing subdomains

Example

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

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

Example subdomains:

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

Which is best? $\{-2, -1\}$

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

Different heuristics target different classes of errors

– In practice, combine multiple heuristics

Heuristic: Black Box Testing

Heuristic: Explore alternate paths through specification

Procedure is a black box: interface visible, internals 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 is 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

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 is not in a
```

Two obvious tests:

([4, 5, 6], 5) => 1

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

Have we captured all the paths?

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

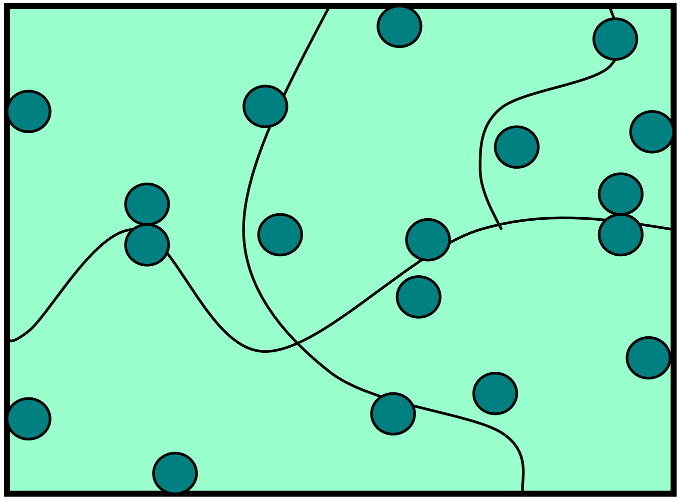
Must hunt for multiple cases in effects or requires

Heuristic: Boundary Testing

Create tests at the edges of subdomains

Why do this?

- off-by-one bugs
- forgot to handle empty container
- overflow errors in arithmetic
- aliasing



Small subdomains at the edges of the "main" subdomains have a high probability of revealing these common errors

Also, you might have misdrawn the boundaries

Boundary Testing

- To define the boundary, need a distance metric
  - Define adjacent points
- 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 integer)

Other Boundary Cases

Arithmetic

- Smallest/largest values
- Zero

Objects

- Null
- Circular list
- 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* ≥ 0 (returns unchanged)
  - around *x* = 0 (boundary condition)
  - *Specific tests: say x = -1, 0, 1*

How about…

```
int x = Integer.MIN_VALUE; // this is -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

```
<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?

- This is *aliasing*
- It's easy to forget!
- Watch out for shared references in inputs

Heuristic: Clear (glass, white)-box testing

Goal:

Ensure test suite covers (executes) all of the program

Measure quality of test suite with % coverage

Assumption:

high coverage → few mistakes in the program

(Assuming no errors in test suite oracle (expected output).)

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* = CACHE_SIZE

Glass Box Testing: Advantages

Finds an important class of boundaries

Yields useful test cases

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

Disadvantages?

Tests may have same bugs as implementation

What is full coverage?

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

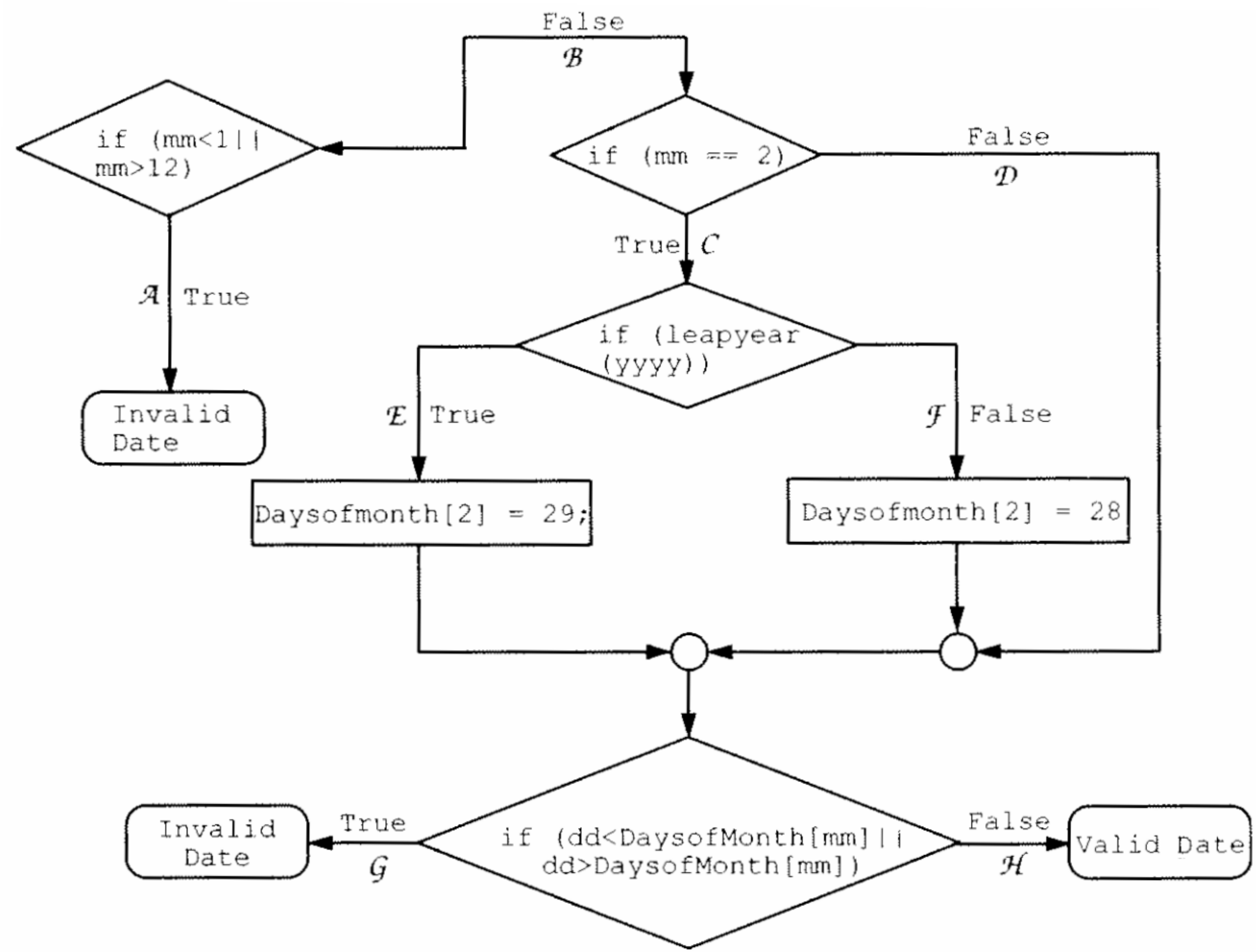
Consider any test with a ≤ b (e.g., **`min(1,2)`**)

It executes every instruction

It misses the bug

Statement coverage is not enough

Path coverage example



Varieties of coverage

Covering all of the program

- Statement coverage
- Branch coverage
- Decision coverage
- Loop coverage
- Condition/Decision coverage
- Path coverage

increasing number of test cases (more or less)

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

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 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 → write a test for it first and then fix it

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

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