Testing

CSE 331
University of Washington

Michael Ernst

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

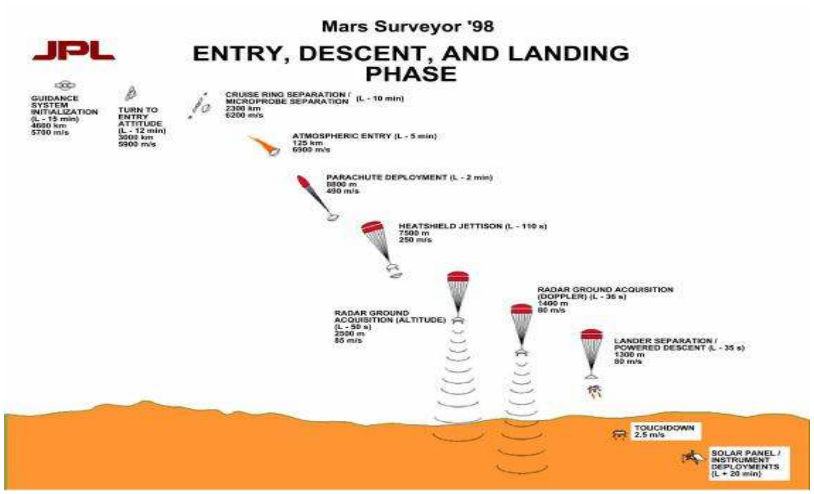
Excessive radiation killed patients (1985-87)

- 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 "difficult parts of the software-engineering process"

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)
  - Iran centrifuges (2009)

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 ⅓ 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 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.

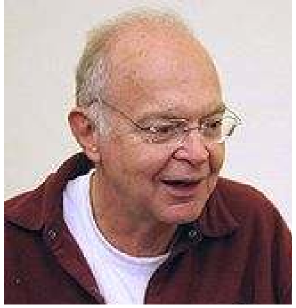
Software Quality Assurance (QA)

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 (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



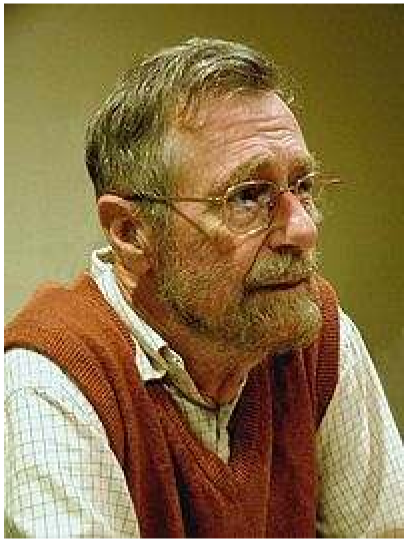
What can you learn from testing?

"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 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 unit test focuses on one method, class, interface, or module

Test a single unit in isolation from all others

Do you look at the code?

Black box testing

Choose test data *without* looking at implementation

Clear box (white box, glass 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) Compare results to 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)
```

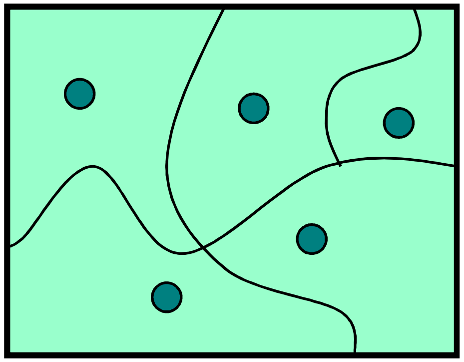
Exhaustive testing would require 1 trillion runs!

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

Key problem: choosing test suite (partitioning 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:  if 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 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 execution behaviors:

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

Three behaviors:

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

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

Example subdomains:

... {-2} {-1} {0} {1} ...

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

Which is best? ~~... {-6, -5, -4} {-3, -2, -1} {0, 1, 2} ...~~

Heuristics for Designing Test Suites

A good heuristic gives:

- few subdomains
- $\forall$ errors E in some class of errors,
  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 each path through specification

Procedure is a black box: interface visible, internals hidden

Example

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

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
  - Tests can be developed before the code

More Complex Example

Write test cases based on paths through 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 I captured all the paths? **([4, 5, 5], 5) => 1**

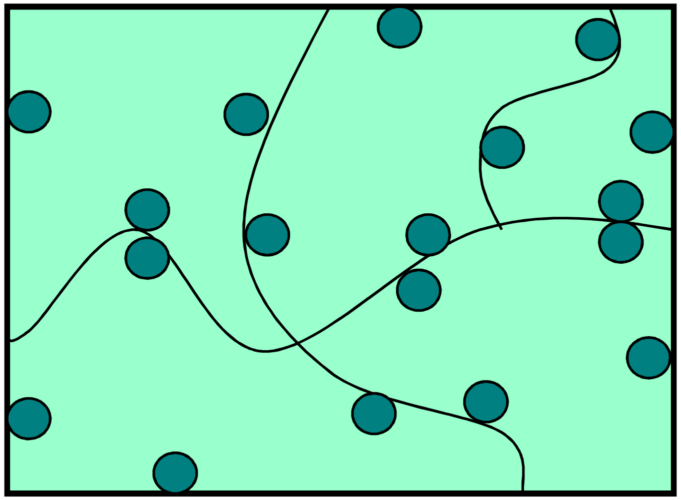
Must hunt for multiple cases in effects or requires

Heuristic: Boundary Testing

Create tests at the edges of subdomains

Why do this?

- off-by-one bugs
- 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

```
// returns: |x|
public int abs(int 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 = 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:

- If the argument is 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 thing?

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

Heuristic: 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 → 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 give:

```
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];
    }
}
```

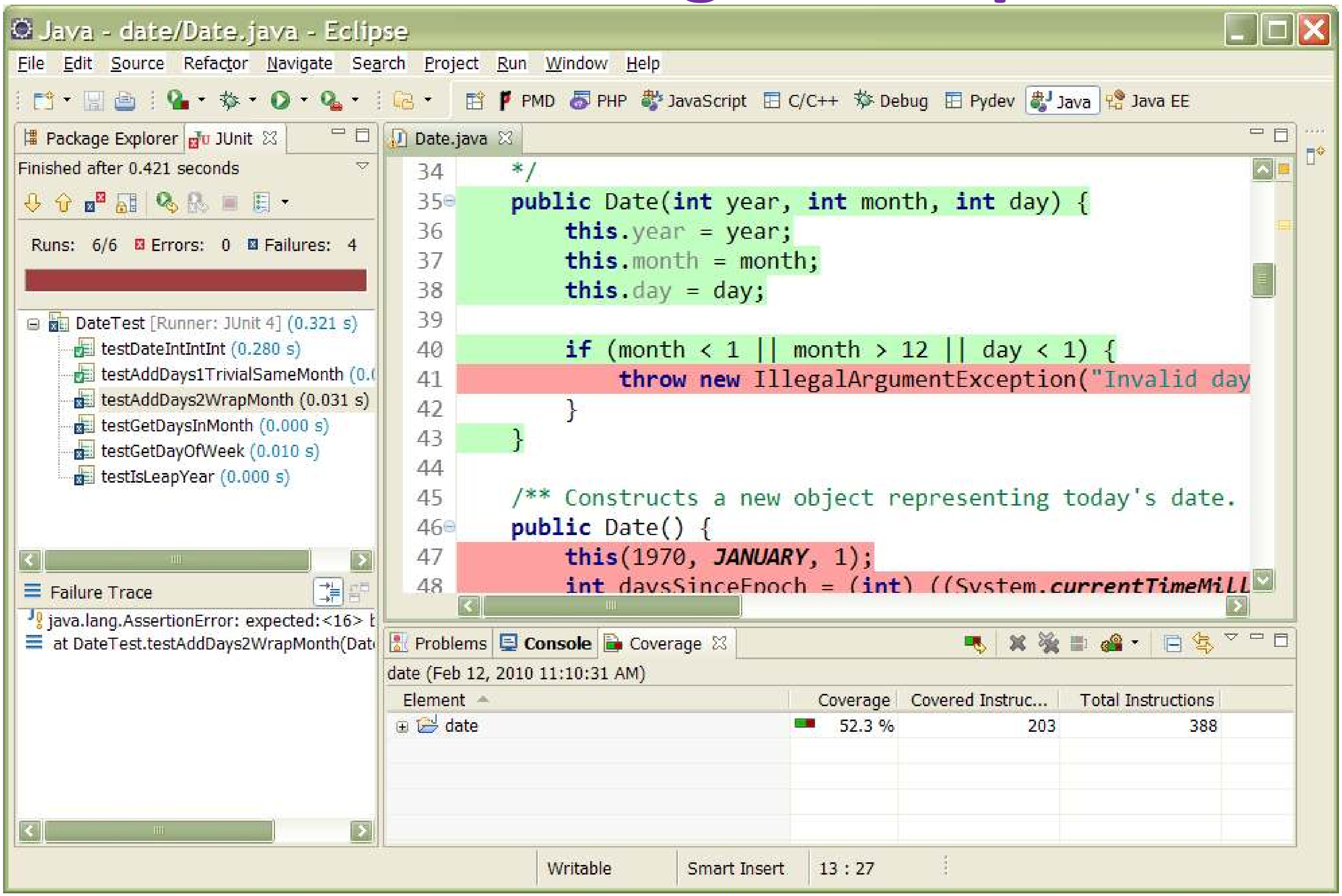
Important transition around *x* = CACHE_SIZE

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_SIZES`**

- **Disadvantages?**
  - **Tests may have same bugs as implementation**

Code coverage example



What is full coverage?

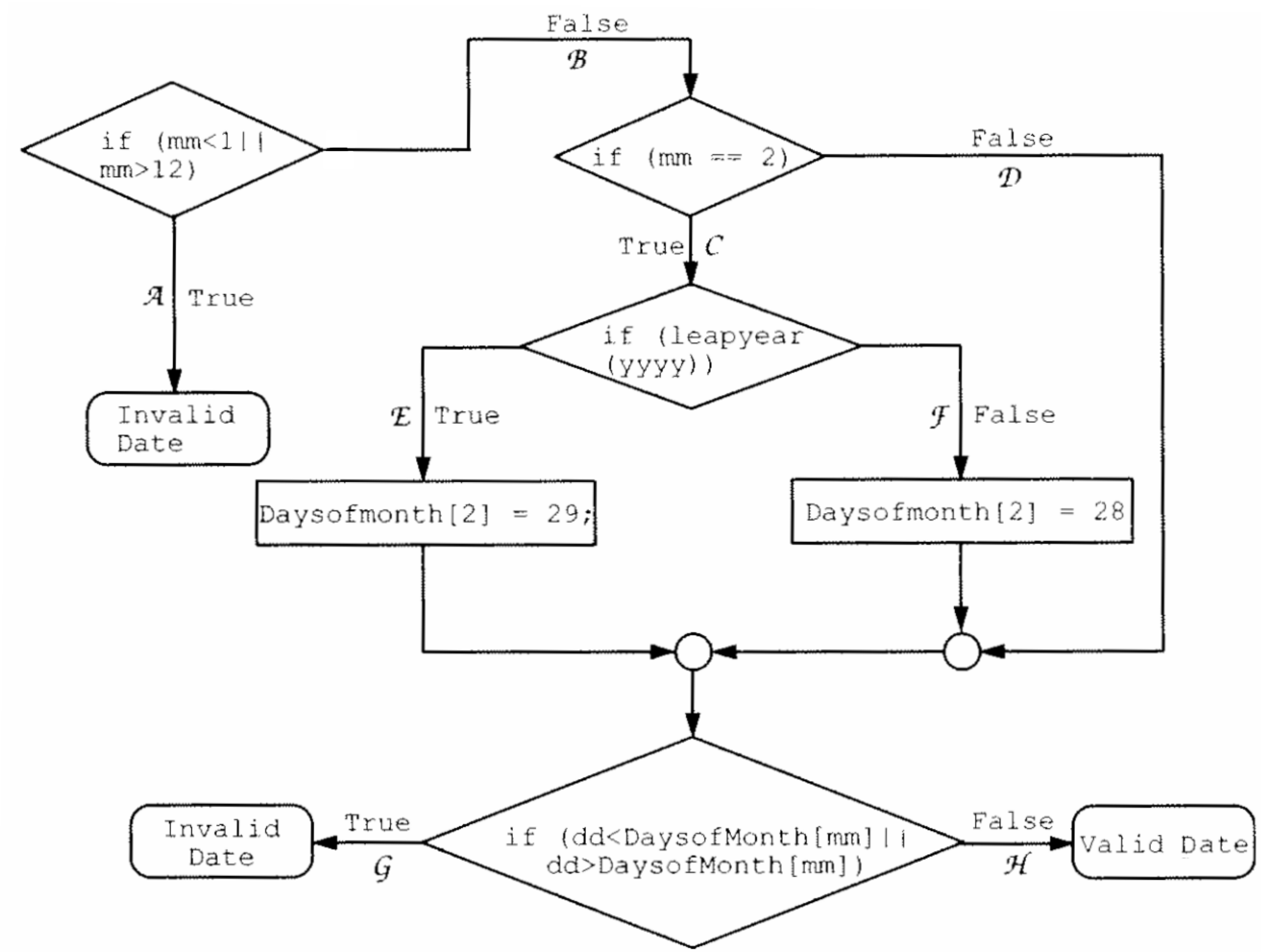
```
static int min (int a, int b) {
    int r = a;
    if (a <= b) {
       r = a;
    }
    return r;
}
```

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 required

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
- Why is this a good idea?
- 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

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
- Choose test data to cover
  - Specification (black box testing)
  - Code (glass box testing)
- Testing can't generally prove absence of bugs
  - But can increase quality and confidence