CS 121
Software Engineering

Testing

(Inspiration from Ben Liblit and Mike Ernst)

Introduction

- Software is hard to write!
  - And like any human activity, we all make mistakes when building software

- Bugs in software can have major, real-world consequences
  - For an ongoing list, see Paul G. Neumann, ACM Risks Forum, http://www.csl.sri.com/users/neumann/#3
  - A few famous examples next…

Therac-25 Radiation Therapy Machine

- Massive radiation overdoses killed or seriously injured patients (1985-1987)
  - New design removed hardware interlocks
    - All safety checks done in software
  - Equipment control task not properly synchronized
- Error missed in testing
  - Bug only triggered if operator changed setup too quickly
  - Didn’t happen during testing because operators didn’t have enough practice yet to do this

Mars Polar Lander

- 290kg robotic spacecraft lander launched in 1999
- Lander failed to reestablish communication after descent phase
- Most likely cause: engine shut down too early
  - Legs deployed led to sensor falsely indicating craft had touched down, yet it was 40m above surface
- Error traced to a single line of code
  - Known that leg deployment could lead to a bad sensor reading, but never addressed

Ariane 5 Failure

- In 1996, Ariane 5 launch vehicle failed 39s after liftoff
  - Caused destruction of over $100 million is satellites!
- Cause of failure
  - To save money, inertial reference system (SRC) from Ariane 4 reused in Ariane 5
  - SRI tried to compute a floating point number out of range to an integer; issued error message (as an int); that int was read by the guidance system, causing nozzle to move accordingly
  - The backup system did the same thing
  - Result was rocket moved toward horizontal
  - Vehicle than had to be destroyed
- Ultimate cause: Ariane 5 has more pronounced angle of attack than Ariane 4
  - The out of range value was actually appropriate

Software Quality Assurance (QA)

- Testing: run software, look for failures
  - Limits: risk of missing behaviors due to inadequate test suite
- Code reviews: manual review of program text
  - Limits: informal, uneven, easy to miss issues
- Software process: development/team methodology
  - Limits: one step removed from the code
- Static analysis: assess source code without running it
  - Limits: hard to scale, typically has many false positives
- Program verification: prove program correct
  - Limits: very difficult, very expensive, not scalable
- …and many more!

No Single QA Approach is Perfect

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

"Program testing can be used to show the presence of bugs, but never to show their absence!" — Edsgar Dijkstra, *Notes on Structured Programming*, 1970

- Most popular QA approach? **Testing** + code review
  - Static analysis has made huge inroads recently, but is a drop in the bucket compared to testing
  - Verification is on the horizon, but is still out of reach for most systems
  - We'll focus on testing in this class

Levels of Testing

- Unit testing: One component at a time
  - A component could be a method, class, or package
  - If test fails, defect localized to small region
  - Done early in software lifecycle, ideally when/before component is developed, and whenever it changes
- Integration/system testing: The whole system together
  - Ensures components work together correctly
  - Possible even if system not complete, as long as there’s some end-to-end slice of its functionality
- Other testing terms
  - “Acceptance test” — test system against user requirements
  - “Regression test” — make sure new version of software behaves identically to old version

Automated Unit Testing with JUnit

- xUnit test frameworks for language x
  - Original was SUnit (Smalltalk), by Kent Beck (1989)
  - JUnit popularized the approach
- Easy to build
  - “Never in the annals of software engineering was so much owed by so many to so few lines of code.” — Martin Fowler
- Key: test cases run and checked automatically
  - This means we can run them early and often
- Testing terminology:
  - System Under Test (SUT) — doesn’t need definition!
  - Test case — code that runs part of SUT and checks result
    - Test cases can *pass* or *fail*, no gray areas
  - Test suite — a set of test cases

Installing JUnit 4

- Download junit
  - https://search.maven.org/artifact/junit/junit/4.13-beta-2/jar
  - Documentation here: https://junit.org/junit4/
- Download hamcrest
  - https://search.maven.org/artifact/org.hamcrest/hamcrest/2.1/jar
- Add them to your `CLASSPATH`

```
# bash, both files in $HOME/java
# add the following as a single line to .bash_profile
export CLASSPATH=$HOME/java/junit-4.13-beta-2.jar:
$HOME/java/hamcrest-2.1.jar:.
```

- Test to see if junit is available

```
$ java org.junit.runner.JUnitCore
JUnit version 4.13-beta-2
…
```

Basic JUnit Example

```
# run with “java org.junit.runner.JUnitCore ListTests”
import static org.junit.Assert.*;
import org.junit.*;
import java.util.*;

public class ListTests {
 @Test public void testAdd() {
  List<Object> l = new LinkedList<>();
  Object o = new Object();
  l.add(o);
  assertTrue(“list should contain o”, l.contains(o));
 }
 @Test public void testIsEmpty() {
  List<Object> l = new LinkedList<>();
  assertTrue(“list should be empty”, l.isEmpty());
}}
```

Things to Notice

- A test case in JUnit is just a class
  - Test methods are *annotated* with `@Test`
    - Java annotations begin with `@`, can be examined via reflection
- Each test method has one or more assertions
  - From `org.junit.Assert`
  - `assertTrue`, `assertFalse`, `assertEquals`, `assertNull`, etc
- Running tests shows passes (`.`) and failures (`E`)
  - Failures come with backtrace
  - Test methods run in deterministic but undefined order
    - Make sure success/failure does not depend on ordering!
  - Why does it report the running time?
    - For large projects, running all tests take significant amount of time
    - Might need to be selective about which tests are run when

Tips for Assertions

- Use `assertEquals` etc rather than `assertTrue`
  - Will get a more useful message if case fails
  - Note: first arg to `assertEquals` is expected value

- Always put messages in assertions

- You can add helper methods for your own kinds of assertions, e.g.,
  - `<E> assertListContains(List<E> expected, E elt)`
  - `assertApproxEqual(double expected, double actual, double delta)`
    - Check `expected-delta ≤ actual ≤ expected+delta`

Tips for Test Cases

- Ideally, each test case should check one thing
  - Makes it easier to understand what went wrong if test fails

```
class ListTests {
  @Test void testAdd() { … }
  @Test void testRemove() { … } …
  /* Rather than one large test */
}
```

- But you can break this rule as needed

```
@Test void testContains {
  List l1 = …, l2 = …;
  assertTrue(l1.contains(1));
  assertFalse(l2.contains(1));
}
```

Tips for Test Cases (cont'd)

- Test cases fail if they throw an (uncaught) exception
  - JUnit will catch the exception and keep running other tests

- If test cases catch exceptions, be specific

```
@Test void testRemoveErr() {
  List l1 = …;
  try {
    l1.remove(-1);
    fail("Removed at position -1?!");
  }
  catch (IndexOutOfBoundsException e) { }
}
```

Test Fixtures

- Creating objects per-test can be painful
  - Sometimes, tests need complex web of objects
    - Expensive to reallocate for every test, leads to duplicate code
- A *test fixture* is an initial set of objects/state of the world for running a set of test cases
  - Test fixtures are "set up" before tests are run
  - They are "torn down" after tests are run
    - E.g., to close files
- JUnit supports four test fixtures annotations
  - `@BeforeClass`, `@AfterClass` — methods to run once per test case class
  - `@Before`, `@After` — methods to run once per test method

Test Fixtures Example

```
class LinkedListTest {
  List<Integer> l; BufferedReader f;

  @BeforeClass void setUp() {
    l = new LinkedList<Integer>();
    l.add(1); l.add(2); l.add(3);
    f = …
  }

  @AfterClass void tearDown() {
    f.close();
} }
```

- Be careful if you mutate fixtures
  - If you do, use `@Before`/`@After` instead of `*Class` varieties
- Make sure `tearDown` releases all resources
  - Even in the presence of exceptions

Test Automation

- JUnit tests are completely automated
  - Run from a single command line invocation
  - Test results checked automatically, without human intervention
  - Critically: tests must be repeatable; avoid non-determinism!
- Drawback: Adds cost
  - Have to write code and tests together
  - Have to ensure tests and code remain in sync over time
- Major benefits
  - Tests can be run often
  - Code maintenance and evolution becomes much safer
    - Rerunning tests after making a change provides a lot of confidence that the change was correct

Regression Testing

- Key idea: When you find a bug
  - Write a test that exhibits the bug
  - Always run the test when code changes
  - ⇒ ensures bug doesn’t reappear
- Helps ensure *forward progress*
  - Ideally, old bugs never reemerge
  - But even if they do, you’ll find them quckly
- Note that automation is key
  - Set of test cases increases over time
  - Without automation, would be too hard to re-execute

Nightly Builds

- Want to run tests as often as possible
  - If bug appears after small code change, easy to attribute bug to that change
  - If bug appears after 1,000 code changes or very big change, tracking down the problem is harder
- But, often too expensive to run all tests on every save
  - Especially as project gets large
- Split tests into two groups
  - *Smoke tests* that make sure nothing is horribly wrong
    - These tests run quickly, not exhaustive
    - Run these all the time
  - Full test suite less often
    - Once per night, once per week, etc

Constructing a Test Suite

- Combine tests from different classes
  - To create set of smoke tests, nightly tests, etc
  - (Example from JUnit documentation)

```
import org.junit.runner.RunWith;
import org.junit.runners.Suite;

@RunWith(Suite.class)
@Suite.SuiteClasses({
  TestFeatureLogin.class,
  TestFeatureLogout.class,
  TestFeatureNavigate.class,
  TestFeatureUpdate.class
})
public class FeatureTestSuite {
  // class is empty, used only for annotations
}
```

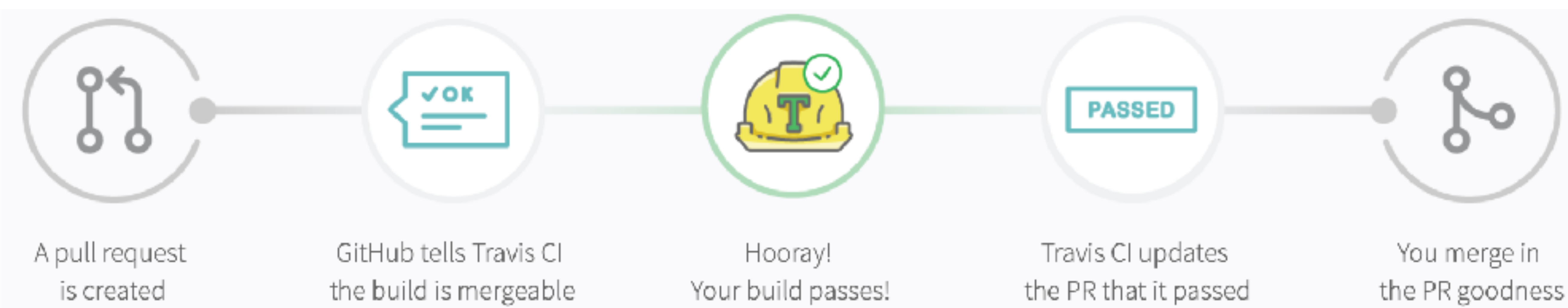
Labeling Tests with Categories

```
public interface TSmoke { /* category marker */ }

public class A {
 @Test public void a() { … }
 @Category(TSmoke.class) @Test public void b() { … }
}

@RunWith(Categories.class)
@IncludeCategory(TSmoke.class)
@SuiteClasses({A.class})
public class SmokeTestSuite {
 // Will run A.b but not A.a
}
```

- Enables flexible groups of tests

Continuous Integration

- *Continuous integration (CI)* = developers merge changes often
  - Typically by pushing to central version control repository
  - Helps ensure different changes do not conflict
- Creates a natural testing workflow: test before push
  - Helps maintain invariant that main branch tests succeed
- Many CI systems support this model
  - Image from Travis CI:



Record-and-Replay Testing

- What about testing GUIs?
  - Can unit test individual methods
  - But how do we test clicking buttons etc?
  - Standard approach: record and replay manual tests
- Key challenges
  - Test recording is fragile
    - Either tightly tied to UI or dependent on OS hooks for keyboard/mouse
  - Test replay is fragile
    - Breaks if UI changes
    - If record *(x,y)* coordinates, breaks with different screen layouts etc
  - Note: manual testers would adapt to these conditions

Developing Test Cases

- Now that we know how to run tests, how do we come up with those test cases?
  - This is a hard problem!
- Two main approaches:
  - Derive tests from specification (*black box testing*)
    - Pros: This is what we actually want the program to do!
    - Cons: Specs are notoriously incomplete; specs don't necessarily tell you every place the code could go wrong
  - Derive tests from implementation (*white/glass box testing*)
    - Pros: This is the code we're actually running!
    - Cons: If our code is completely missing some key property that's in the spec, we might not even know to test it
    - Cons: Tests might be overly specific to this particular implementation
- In practice need to look at both!

Black Box Testing Approaches

- Look only at specification, not at code

Consider Each Path in Spec

- Look at the spec and consider conditional branches

```
// Return true if x in a, else return false
boolean contains(int[] a, int x);
```

  - Two “paths” through spec
    - One test where `x` in `a`, one test case where `x` not in `a`
    - Maybe another one: what if `x` appears twice in `a`?

```
// Return maximum of a and b
int max(int a, int b)
```

  - Three paths through spec
    - if `a<b` returns `b`; if `a>b` — returns `a`; if `a=b` — returns `a`

- In all cases, actual tests will need concrete values
  - E.g., test `max` with `(3, 4)` to cover first case

Consider Edge Cases

- Anticipate common off-by-one errors or forgetting something special that has to happen at the beginning or end of a range

```
// Return true if x in a, else return false
boolean contains(int[] a, int x);
```

  - What if `x` is the first element? What if it's the last element?
  - What if `a` is empty?
- In Java, consider whether `null` should be handled
  - What if `a` is null?

Consider Aliasing

```
// modifies: src, dst
// effects: removes all elts of src and appends
//          them in reverse order to end of dst
<E> void appendList(List<E> src, List<E> dst) {
  while (src.size()>0) {
    E elt = src.remove(src.size()-1);
    dst.add(elt);
}
```

- What happens if `src` and `dst` are same object?
  - This is *aliasing* and it's easy to forget! Watch out for this
- Other useful cases (for other methods)
  - `null`
  - Circular lists

Black Box Testing Advantages

- Process not influenced by tested component
  - Code's assumptions not propagated to test suite
  - Tests are all about using redundancy / redundency to find mistakes
  - To create useful redundancy, avoid strict duplication
- Robust with respect to implementation changes
  - Shouldn't need to change black box tests when code changed
- Allows testers to be independent
  - Testers need not be familiar with code
  - Tests can be developed before writing code

Glass/White Box Testing

- Look at implementation
- Focus on features not described by spec
  - Concrete decisions not made in the abstract spec
    - E.g., data structure implementation decisions, max sizes of arrays, separate handling for cases that are combined in the spec
  - Performance optimizations
    - E.g., “fast path” vs. “slow path” in code, like when a value is in a cache vs. not
  - If you can, details of error handling
- We actually used glass box testing earlier!
  - Even when looking at just the spec, needed to guess where programmer likely make mistakes

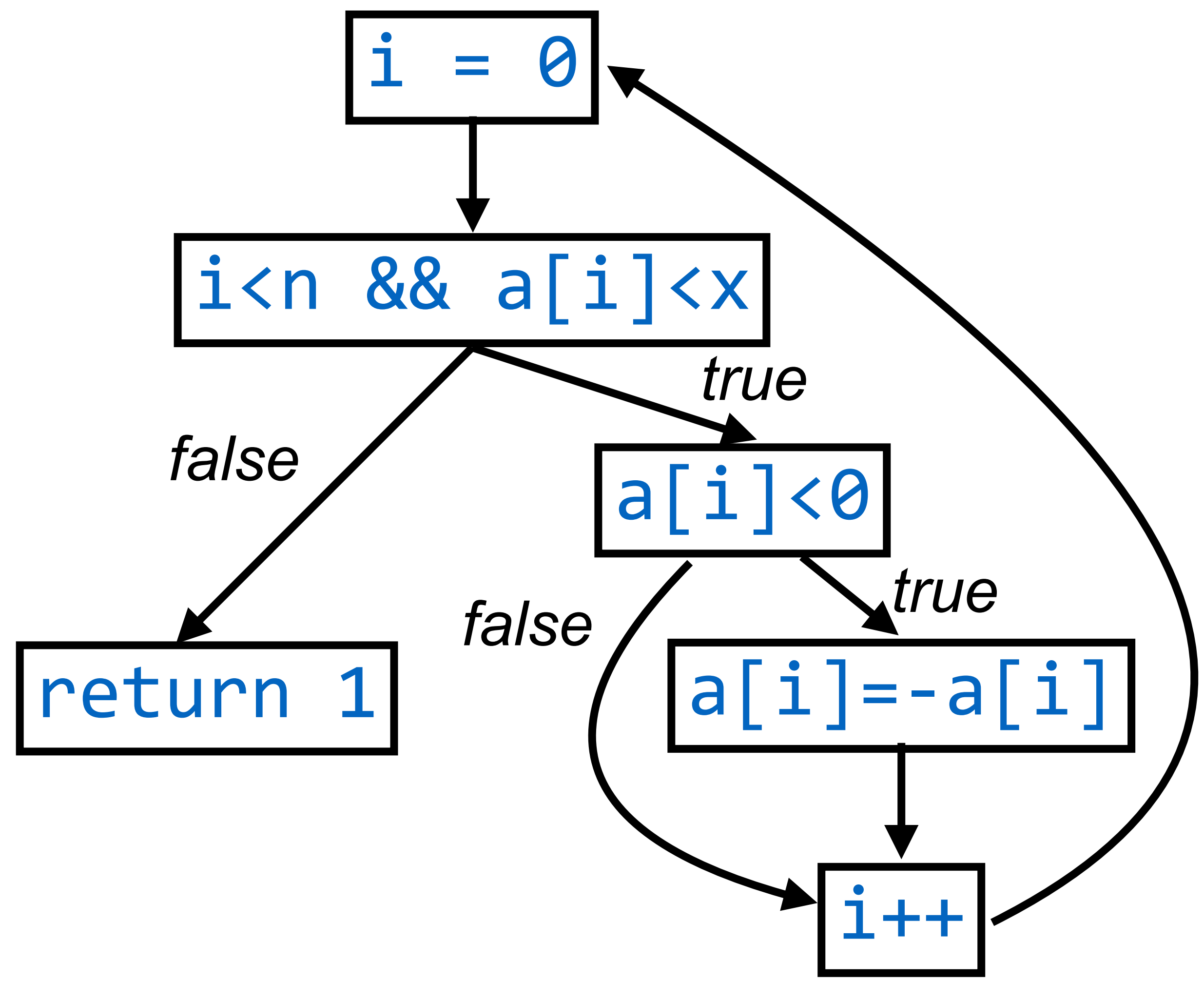
Coverage Criteria

- Common metric for test suite quality: *coverage*
  - Goal: test suite covers all possible program behaviors
    - If test suite doesn't cover some behavior, we aren't testing for bugs in it!
  - Hypothesis: high coverage means few mistakes remain in program
- But what is a *behavior*? Probably not measurable
- Instead: *Structural coverage testing*
  - Divide a program into elements (e.g., methods, statements)
  - Coverage of a test suite is

$$\frac{\text{\# of elements executed by suite}}{\text{\# elements in program}}$$

Statement Coverage

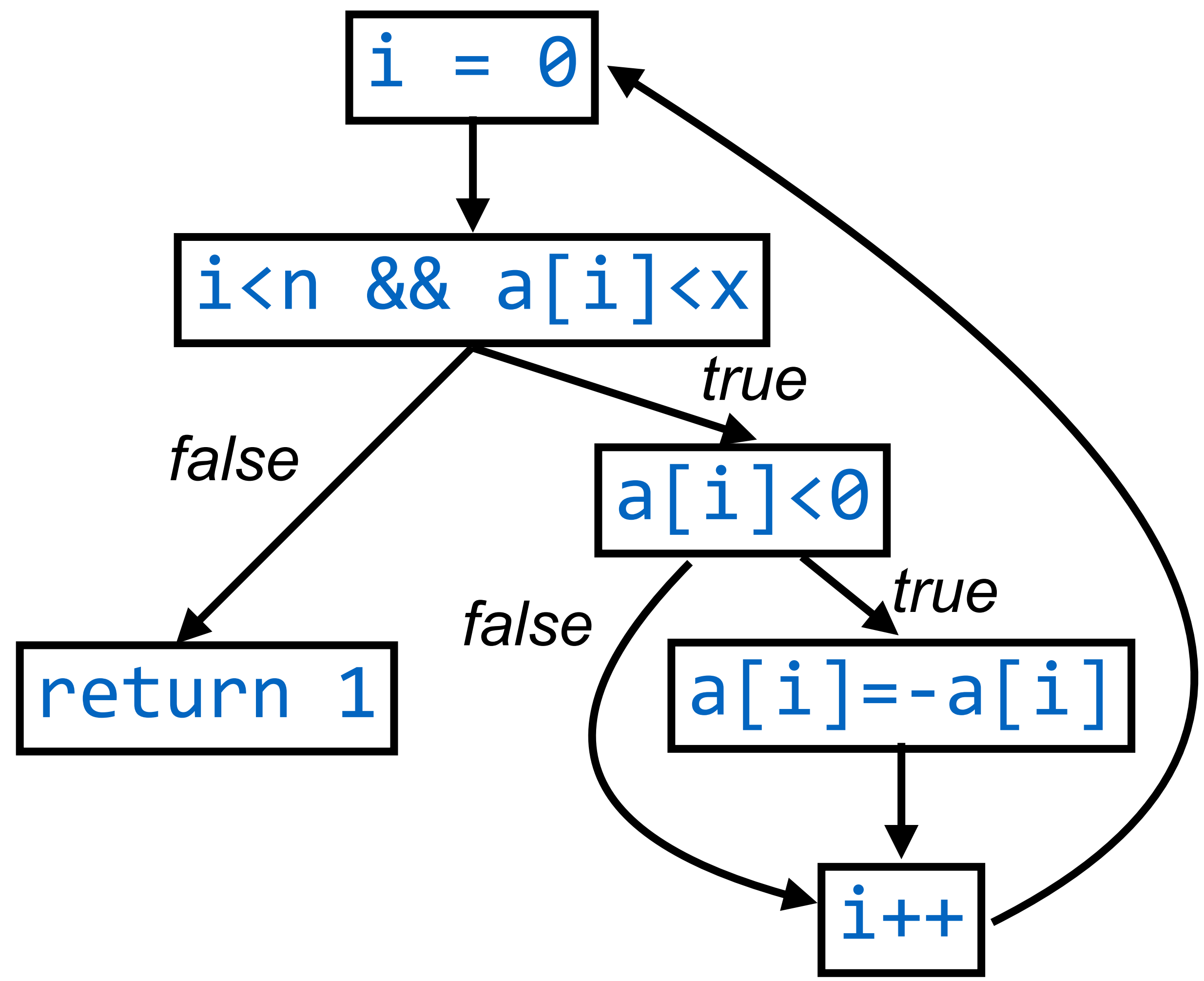
```
int select(int[] a,
           int n, int x) {
 int i=0;
 while (i<n && a[i]<x) {
  if (a[i]<0) {
   a[i]=-a[i];
  }
  i++;
 }
 return 1
}
```



- Consider test `(n=1 a[0]=-7 x=9)`
  - Covers all statements
  - But, doesn't consider case where `a[i]<0`

Condition Coverage

```
int select(int[] a,
           int n, int x) {
 int i=0;
 while (i<n && a[i]<x) {
  if (a[i]<0) {
   a[i]=-a[i];
  }
  i++;
 }
 return 1
}
```



- Add test `(n=1 a[0]=7 x=9)`
  - Covers all branches (all edges in the graph)
  - But, for `i<n&&a[i]<x`, has cases where `i<n`, `i≥n`, `a[i]<x`, but no case where `a[i]≥x` is checked
  - I.e., the branches due to short-circuiting are not covered

Path Coverage

- Execute every path through the program
  - Challenge 1: Which paths are *realizable*, i.e., could occur at runtime
    - Often not obvious from looking at the program text
    - So it's hard to know how many of the possible paths have been covered
  - Challenge 2: Acyclic programs can have exponential number of paths
    - `if(…){…} else {…}; if(…){…} else {…}; if(…){…} else {…};` has eight paths
  - Challenge 3: Programs with loops might have an unbounded number of paths
    - E.g., a program that reads data from the network and processes it in a loop
  - ⇒ Path coverage is not a common metric

Code Coverage Limitations

- Code coverage seems to work well in practice
    - And test suites with low coverage are probably bad in other ways
- But, 100% coverage does not mean no bugs
    - And, 100% coverage not achievable in practice
        - Common to reach 85% coverage
        - Safety-critical software should get 100% statement coverage (feasible)
    - Are remaining statements unreachable (dead code)? Just hard to get to? Hard to know for sure.
- Reality: time and money are limited
    - Should we spend money testing code or adding new features that our customers want?
- Where should we direct testing effort?
    - “High risk” code (= bugs could cause severe damage)

In Practice…

- Statement coverage is most common criterion used
  - Many coverage tools provide *basic block* coverage
    - Basic block = sequence of non-branching statements that can only be entered from the first statement
- *Branch coverage* is another kind of coverage, related to condition coverage
  - Condition = separate `&&` and `||` into their own branches, branch = treat the … in `if (…)` as a block
- *Modified condition/decision coverage* is a more complicated version of condition coverage, sometimes comes up

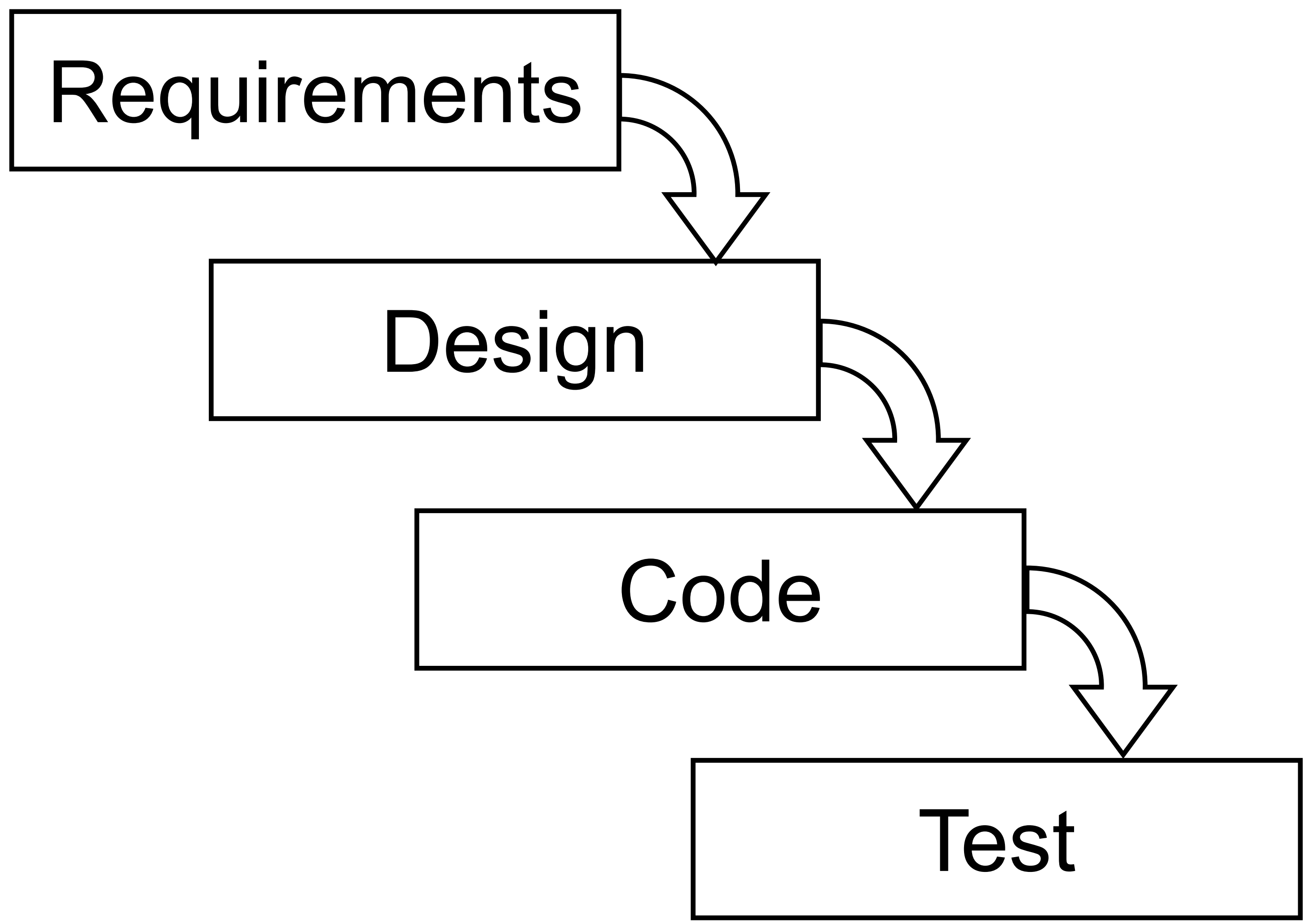
Two Rules of Testing

1. Test early and often
   - Catch bugs as soon as possible after a code change
   - Use automation to make running tests simple
   - Regression testing has a big payoff
     - When you find a bug: (1) write a test for it; (2) show the test fails; (3) fix the bug; (4) show the test passes
2. Be systematic
   - Bugs will hide in whatever you don’t test, so try to test as much as you can
   - Make your tests as small and separate as possible so that when they fail, you can figure out what happened
   - Writing tests helps you think about the programming problem you’re trying to solve

Refactoring

Motivation

- Old-style software design process: “waterfall model”



  - Developed and popularized in 1970’s–1980’s

Pros and Cons of Waterfall Model

- Some good properties
  - Provides structure to the software engineering process
  - Lots of emphasis of careful thought and design early on
- But, critical bad properties
  - Requirements often not known in advance
    - Customers don’t really know what they want
  - Designs often need to be changed
    - Changing requirements
    - Implementation challenges due to unforeseen design issues
- Result: Strict adherence to waterfall leads to inappropriate designs
  - Makes code harder to understand, maintain, and extend

Refactoring

- New approach to software design (*part of extreme programming*)
  - Come up with a reasonable first design
  - But then be willing to change and evolve design over time
- *Refactoring* enables safe design changes
  - Assumption: we have a comprehensive, automatically runnable test suite
  - Then we can divide code changes into two sorts:
    - Bug fixes or feature additions that modify functionality
      - We expect some tests to break; fix them and add new tests
    - Refactoring
      - Change code design, but do not change behavior
        - All refactorings should be *semantics preserving*
      - Implies can rerun all exists tests to ensure change works!

Replace Number with Constant

```
double area(double r) {
  return 3.14 * r * r;
}
```

```
static final double pi = 3.14;
double area(double r) {
  return pi * r * r;
}
```

- New code is more readable
- Can avoid typos if we reuse magic number several times
- Might want to add more digits of pi later

Other Refactorings

- Lots of refactorings out there
  - Some IDEs even have support for automating refactoring
- Examples
  - Move method from one class to another
  - Move method from a subclass to a superclass or the reverse
  - Extract code sequence into its own method
  - Replace conditional branching with dynamic dispatch
  - Group together a long parameter list into an object containing those values

Code Smells

- *Code smells* are coding patterns or idioms that suggest something might be wrong here
  - I.e., might point to code that should be refactored
- Examples
  - Every time I make change X, I have to make lots of little changes to different classes
  - There's a class but it doesn't seem to be useful any more
  - The code has excess generality that's not currently used
  - Classes rely on too many details of each other
  - Subclass doesn't use features of superclass

Practicalities

- Ideal time to refactor: When you want to make a change and the current design impedes the change
  - Much easier to do cost-benefit analysis of refactoring
- Be cautious of refactoring buggy code
  - The refactoring might not go as planned if you don't truly understand the bug
- Be cautious if you keep refactoring the same code over and over
  - Probably need to do more careful thinking of its design
- Refactorings tend to be small changes; so they can't fix every problem
  - If the design is really bad, sometimes you just need to throw it away and start again