Principles of Software Construction:
Objects, Design, and Concurrency

Invariants, immutability, and testing

Josh Bloch Charlie Garrod Darya Melicher

Carnegie Mellon University
School of Computer Science

institute for SOFTWARE RESEARCH

Administrivia

- Homework 4a due Thursday at 11:59 p.m.
  – Mandatory design review meeting before the homework deadline
- PA voter registration deadline: Tuesday, October 9^{th}
  – https://www.pavoterservices.pa.gov/pages/VoterRegistrationApplication.aspx

Unfinished business

A simple solution to HW 2 – Main class

How do we turn HW2 into HW3?

Lessons (practical)

- Choose low level abstractions that make higher level tasks easy
- When you want to represent a fixed set of values known at compile time, consider enums
- If users need to extend the set consider emulated extensible enum
- Bit twiddling should be part of every programmers tool kit
  - Don't overuse it…
  - But do consider it, especially when you need high performance

Lessons (philosophical)

- Good habits matter
  - “The way to write a perfect program is to make yourself a perfect programmer and then just program naturally.” – Watts S. Humphrey, 1994
- Don’t just hack it up and say you’ll fix it later
  - You probably won’t
  - but you will get into the habit of just hacking it up
  - Also it’s way more **fun** to work on nice, well-structured code
- Even small design decisions matter
  - If your code is getting ugly, go back to the drawing board
  - “A week of coding can often save a whole hour of thought.”
- Strive for clarity
  - It’s not enough to be merely correct; aim for clearly correct

Outline

- Class invariants and defensive copying
- Immutability
- Testing and coverage
- Testing for complex environments

Class invariants

- Critical properties of the fields of an object
- Established by the constructor
- Maintained by public method invocations
  - May be invalidated temporarily during method execution

Safe languages and robust programs

- Unlike C/C++, Java language *safe*
  - Immune to buffer overruns, wild pointers, etc.
- Makes it possible to write *robust* classes
  - Correctness doesn't depend on other modules
  - Even in safe language, requires programmer effort

Defensive programming

- Assume clients will try to destroy invariants
  - May actually be true (malicious hackers)
  - More likely: honest mistakes
- Ensure class invariants survive any inputs
  - Defensive copying
  - Minimizing mutability

This class is not robust

```
public final class Period {
   private final Date start, end; // Invariant: start <= end

   /**
    * @throws IllegalArgumentException if start > end
    * @throws NullPointerException if start or end is null
    */
   public Period(Date start, Date end) {
      if (start.after(end))
          throw new IllegalArgumentException(start + " > " + end);
      this.start = start;
      this.end   = end;
   }

   public Date start() { return start; }
   public Date end()   { return end; }
   ... // Remainder omitted
}
```

The problem: Date is mutable

Obsolete as of Java 8; sadly not deprecated even in Java 11

```
// Attack the internals of a Period instance
Date start = new Date();  // (The current time)
Date end   = new Date();  //   "     "      "
Period p = new Period(start, end);
end.setYear(78);   // Modifies internals of p!
```

The solution: defensive copying

```
// Repaired constructor - defensively copies parameters
public Period(Date start, Date end) {
    this.start = new Date(start.getTime());
    this.end   = new Date(end.getTime());
    if (this.start.after(this.end))
        throw new IllegalArgumentException(start + " > "+ end);
}
```

A few important details

- Copies made before checking parameters
- Validity check performed on copies
- Eliminates window of vulnerability between validity check & copy
- Thwarts multithreaded TOCTOU attack
  - Time-Of-Check-To-Time-Of-U

```
// BROKEN - Permits multithreaded attack!
public Period(Date start, Date end) {
    if (start.after(end))
          throw new IllegalArgumentException(start + " > " + end);
    // Window of vulnerability
    this.start = new Date(start.getTime());
    this.end   = new Date(end.getTime());
}
```

Another important detail

- Used constructor, not clone, to make copies
  - Necessary because Date class is nonfinal
  - Attacker could implement malicious subclass
    - Records reference to each extant instance
    - Provides attacker with access to instance list
- But who uses clone, anyway? [EJ Item 11]

Unfortunately, constructors are only half the battle

```
// Accessor attack on internals of Period
Period p = new Period(new Date(), new Date());
Date d = p.end();
p.end.setYear(78); // Modifies internals of p!
```

The solution: more defensive copying

```
// Repaired accessors - defensively copy fields
public Date start() {
    return new Date(start.getTime());
}
public Date end() {
    return new Date(end.getTime());
}
```

Now Period class is robust!

Summary

- Don't incorporate mutable parameters into object; make defensive copies
- Return defensive copies of mutable fields…
- Or return unmodifiable view of mutable fields
- **Real lesson – use *immutable* components**
  - Eliminates the need for defensive copying

Outline

- Class invariants and defensive copying
- Immutability
- Testing and coverage
- Testing for complex environments

Immutable classes

- **Class whose instances cannot be modified**
- Examples: `String`, `Integer`, `BigInteger`, `Instant`
- How, why, and when to use them

How to write an immutable class

- Don’t provide any mutators
- Ensure that no methods may be overridden
- Make all fields final
- Make all fields private
- Ensure security of any mutable components

Immutable class example

```java
public final class Complex {
    private final double re, im;

    public Complex(double re, double im) {
        this.re = re;
        this.im = im;
    }

    // Getters without corresponding setters
    public double realPart()      { return re; }
    public double imaginaryPart() { return im; }

    // minus, times, dividedBy similar to add
    public Complex plus(Complex c) {
        return new Complex(re + c.re, im + c.im);
    }
```

Immutable class example (cont.)

Nothing interesting here

```
    @Override public boolean equals(Object o) {
        if (!(o instanceof Complex)) return false;
        Complex c = (Complex) o;
        return Double.compare(re, c.re) == 0 &&
               Double.compare(im, c.im) == 0;
    }

    @Override public int hashCode() {
       return 31 * Double.hashCode(re) + Double.hashCode(im);
    }

    @Override public String toString() {
        return String.format("%d + %di", re, im)";
    }
}
```

Distinguishing characteristic

- Return new instance instead of modifying
- *Functional programming*
- May seem unnatural at first
- Many advantages

Advantages

- Simplicity
- Inherently Thread-Safe
- Can be shared freely
- No need for defensive copies
- Excellent building blocks

Major disadvantage

- Separate instance for each distinct value
- Creating these instances can be costly

```
BigInteger moby = ...;  // A million bits long
moby = moby.flipBit(0); // Ouch!
```

- Problem magnified for multistep operations
  - Well-designed immutable classes provide common multistep operations
    - e.g., `myBigInteger.modPow(exponent, modulus)`
  - Alternative: mutable companion class
    - e.g., `StringBuilder` for `String`

When to make classes immutable

- **Always, unless there's a good reason not to**
- Always make small "value classes" immutable!
  - Examples: `Color`, `PhoneNumber`, `Unit`
  - `Date` and `Point` were mistakes!
  - Experts often use `long` instead of `Date`

When to make classes mutable

- Class represents entity whose state changes
  - Real-world - `BankAccount`, `TrafficLight`
  - Abstract - `Iterator`, `Matcher`, `Collection`
  - Process classes - `Thread`, `Timer`
- If class must be mutable, *minimize mutability*
  - Constructors should fully initialize instance
  - Avoid `reinitialize` methods

Outline

- Class Invariants
- Immutability
- Testing and coverage
- Testing for complex environments

Why do we test?

Testing decisions

- Who tests?
  - Developers who wrote the code
  - Quality Assurance Team and Technical Writers
  - Customers
- When to test?
  - Before and during development
  - After milestones
  - Before shipping
  - After shipping

Test driven development

- **Write tests before code**
- Never write code without a failing test
- Code until the failing test passes

Why use test driven development?

- Forces you to think about interfaces early
- Higher product quality
  - Better code with fewer defects
- Higher test suite quality
- Higher productivity
- It’s fun to watch tests pass

TDD in practice

- Empirical studies on TDD show:
  - May require more effort
  - May improve quality and save time
- Selective use of TDD is best
- Always use TDD for bug reports
  - *Regression tests*

How much testing?

- You generally cannot test all inputs
  - Too many – usually infinite
- But when it works, exhaustive testing is best!

What makes a good test suite?

- Provides high confidence that code is correct
- Short, clear, and non-repetitious
  - More difficult for test suites than regular code
  - Realistically, test suites will look worse
- Can be fun to write if approached in this spirit

Next best thing to exhaustive testing: *random inputs*

- Also know as *fuzz testing*, *torture testing*
- Try "random" inputs, as many as you can
  - **Choose inputs to tickle interesting cases**
  - Knowledge of implementation helps here
- Seed random number generator so tests repeatable

Black-box testing

- **Look at specifications, not code**
- Test representative cases
- Test boundary conditions
- Test invalid (exception) cases
- Don’t test unspecified cases

White-box testing

- Look at specifications **and** code
- Write tests to:
  - Check interesting implementation cases
  - Maximize branch coverage

Code coverage metrics

- Method coverage – coarse
- Branch coverage – fine
- Path coverage – too fine
  - Cost is high, value is low
  - (Related to *cyclomatic complexity*)

Coverage metrics: useful but dangerous

- **Can give false sense of security**
- Examples of what coverage analysis could miss
  - Data values
  - Concurrency issues – race conditions, etc.
  - Usability problems
  - Customer requirements issues
- **High branch coverage is *not* sufficient**

Test suites – ideal and real

- Ideal test suites would
  - Uncover all errors in code
  - Test “non-functional” attributes such as performance and security
  - Minimum size and complexity
- Real test Suites
  - Uncover some portion of errors in code
  - Have errors of their own
  - Are nonetheless priceless

Outline

- Class invariants
- Immutability
- Testing and coverage
- Testing for complex environments

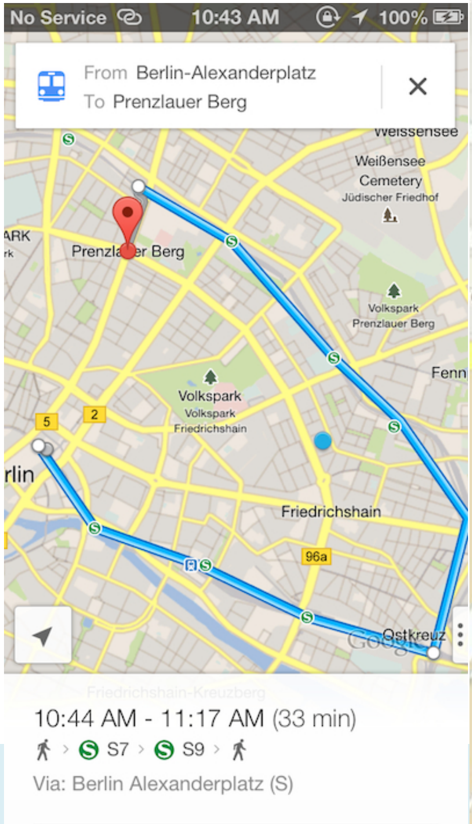
Problems when testing some apps

- User-facing applications
  – Users click, drag, etc., and interpret output
  – Timing issues
- Testing against big infrastructure
  – Databases, web services, etc.
- Real world effects
  – Printing, mailing documents, etc.

- Collectively comprise the *test environment*

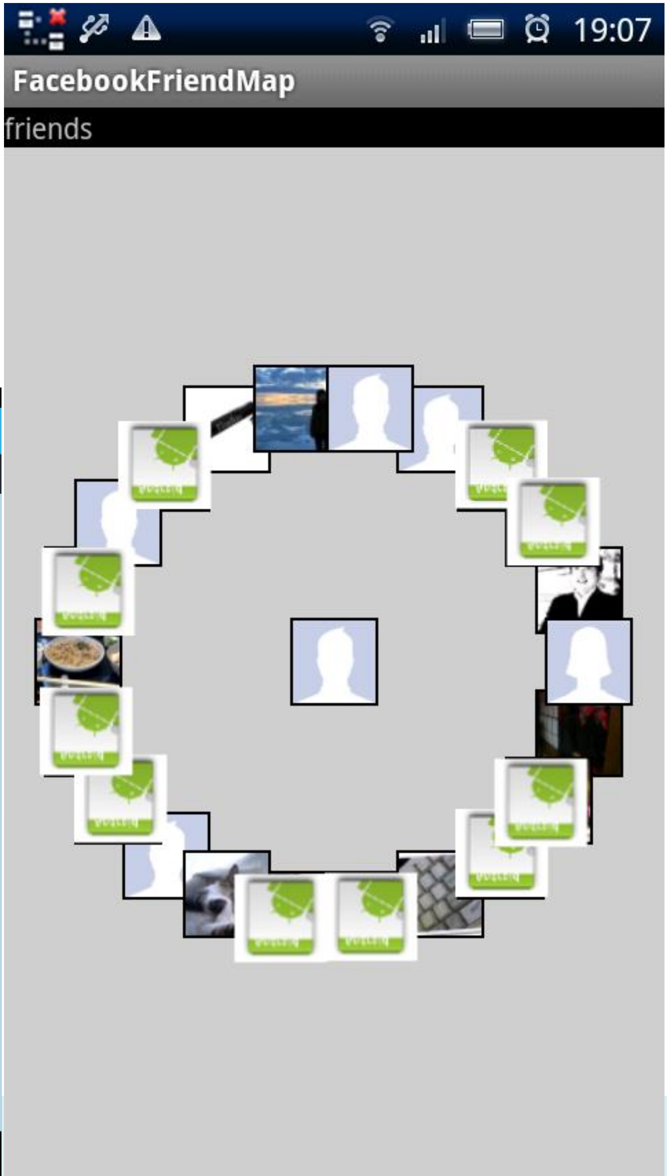
Example – Tiramisu app

- Mobile route planning app
- **Android UI**
- **Back end uses live PAT data**

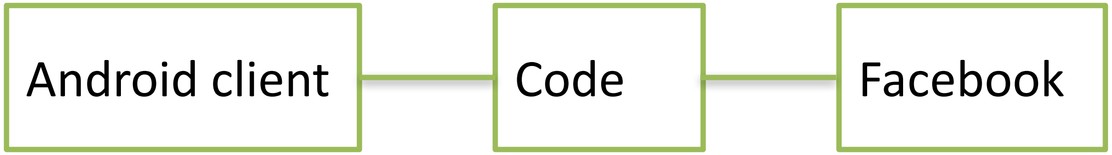


Another example

- 3rd party Facebook apps
- **Android user interface**
- **Backend uses Facebook data**



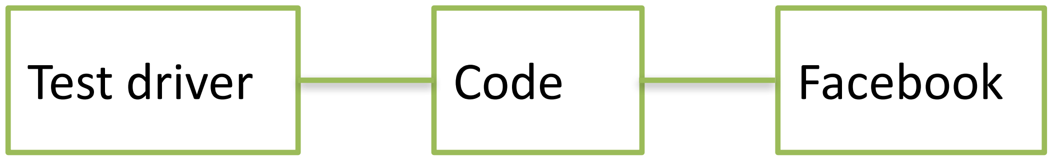
Testing in real environments




```
void buttonClicked() {
   render(getFriends());
}

List<Friend> getFriends() {
   Connection c = http.getConnection();
   FacebookApi api = new FacebookApi(c);
   List<Node> persons = api.getFriends("john");
   for (Node person1 : persons) {
       for (Node person2 : persons) {
      …
       }
   }
   return result;
}
```

Eliminating Android dependency



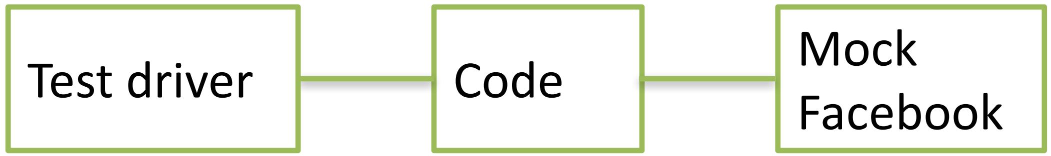

```
@Test void testGetFriends() {
   ... // A Junit test
}

List<Friend> getFriends() {
   Connection c = http.getConnection();
   FacebookApi api = new FacebookApi(c);
   List<Node> persons = api.getFriends("john");
   for (Node person1 : persons) {
       for (Node person2 : persons) {
      …
       }
   }
   return result;
}
```

That won’t quite work

- **GUI applications process *many thousands* of events**
- Solution: automated GUI testing frameworks
  - Allow streams of GUI events to be captured, replayed
- These tools are sometimes called *robots*

Eliminating Facebook dependency



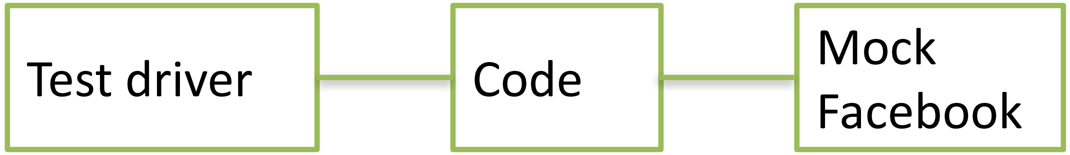

```
@Test void testGetFriends() {
   ... // A Junit test
}

List<Friend> getFriends() {
   FacebookApi api = new MockFacebook(c);
   List<Node> persons = api.getFriends("john");
   for (Node person1 : persons) {
       for (Node person2 : persons) {
      …
       }
   }
   return result;
}
```

That won't quite work!

- **Changing production code for testing unacceptable**
- Problem caused by constructor in code
- Instead of constructor, use special factory that allows alternative implementations
- Use tools to facilitate this sort of testing
  - *Dependency injection* tools, e.g., Dagger, Guice, Spring
  - Mock object frameworks such as Mockito

Fault injection



- Mocks can emulate failures such as timeouts
- Allows you to verify the robustness of system against faults that you can't generate at will

Advantages of using mocks

- Test code locally without large environment
- Enable deterministic tests (in some cases)
- Enable fault injection
- Can speed up test execution
  - e.g., avoid slow database access
- Can simulate functionality not yet implemented
- Enable test automation

Design Implications

- Think about testability when writing code
- When a mock may be appropriate, design for it
- Hide subsystems behind an interfaces
- Use factories, not constructors to instantiate
- Use appropriate tools
  - Dependency injection or mocking frameworks

More Testing in 15-313

Foundations of Software Engineering

- Manual testing
- Security testing, penetration testing
- Fuzz testing for reliability
- Usability testing
- GUI/Web testing
- Regression testing
- Differential testing
- Stress/soak testing

Conclusion

- To maintain class invariants
  - Minimize mutability
  - Make defensive copies where required
- Interface testing is critical
  - Design interfaces to facilitate testing
  - Write creative test suites that maximize power-to-weight ratio
  - Coverage tools can help gauge test suite quality
- Testing apps with complex environments requires added effort