Principles of Software Construction:
Class invariants, immutability, and testing

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Administrivia

- Homework 4a due **today**, 11:59 p.m.
- Design review meeting is **mandatory**
  - But we expect it to be really helpful
  - Feedback is a wonderful thing
- PSA – You have less than one week left to register to vote! Dealine is October 11!

Key concepts from Tuesday…

- Internal representations matter
  - The wrong representation can be toxic
- Code must be clean and concise
  - Repetition is toxic
- Good coding habits matter

Outline

- Class invariants and defensive copying
- Immutability
- Testing and coverage
- Testing for complex environments
- Implementation testing with assertions

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

```
// 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 parameter check and 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

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Immutable classes

- **Class whose instances cannot be modified**
- Examples: `String`, `Integer`, `BigInteger`
- 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

```
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; }

    // subtract, multiply, divide similar to add
    public Complex add(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 as primitives
  - 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

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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
  - 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

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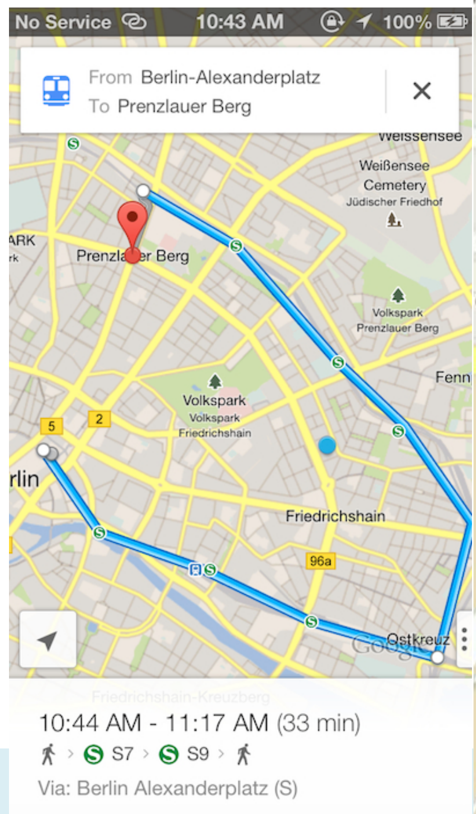
Problems when testing some apps

- 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*

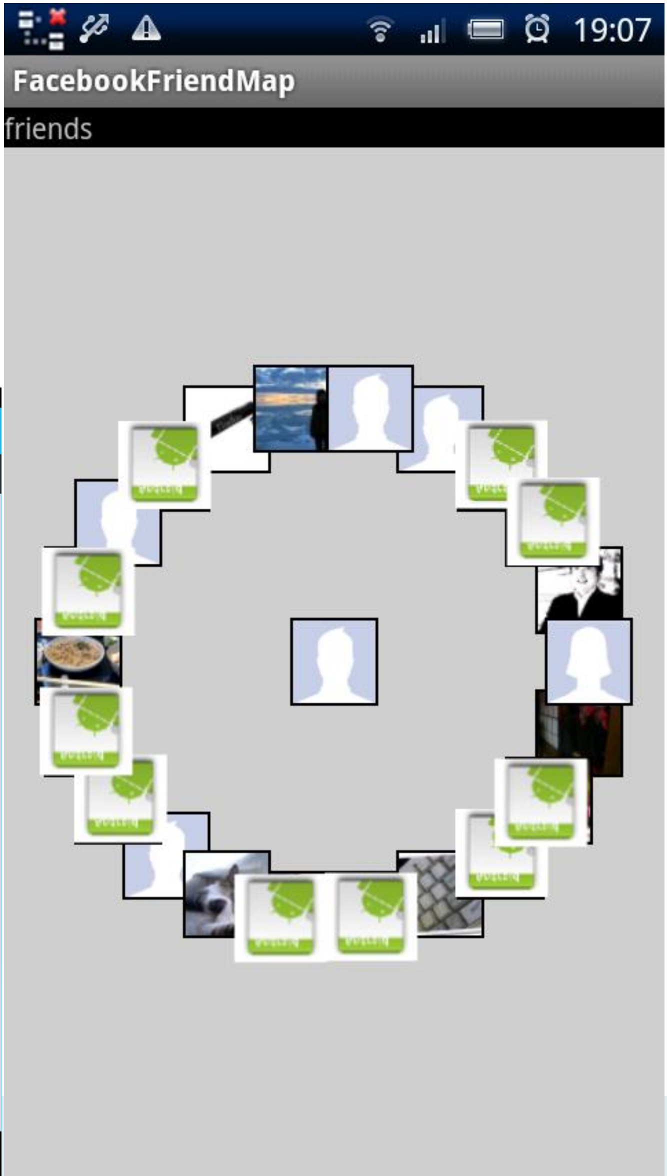
Example – Tiramisu app

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

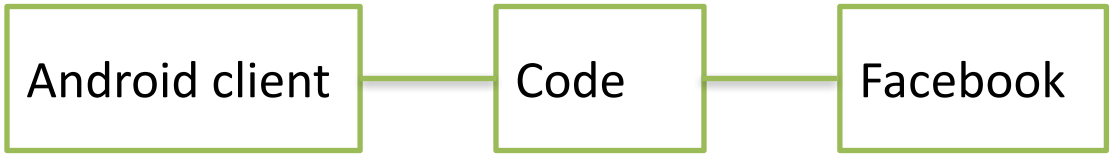


Another example

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

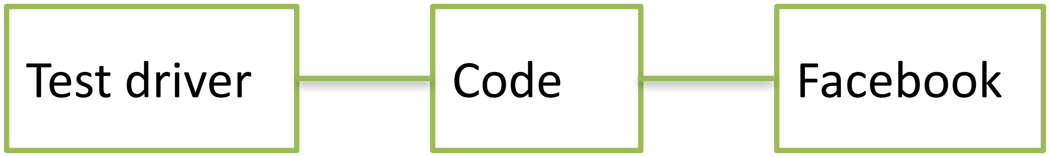


Testing in real environments




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

Eliminating Android dependency

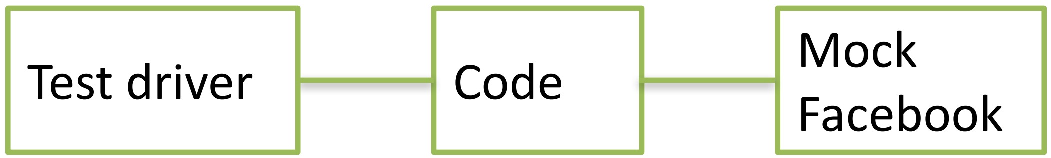



```
@Test void testGetFriends() {
   assert getFriends() == ...;
}
List<Friend> getFriends() {
   Connection c = http.getConnection();
   FacebookAPI api = new FacebookAPI(c);
   List<Node> persons = api.getFriends("john");
   for (Node person1 : persons) {
       for (Node person2 : persons) {
    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

That won’t quite work

- **GUI applications process *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



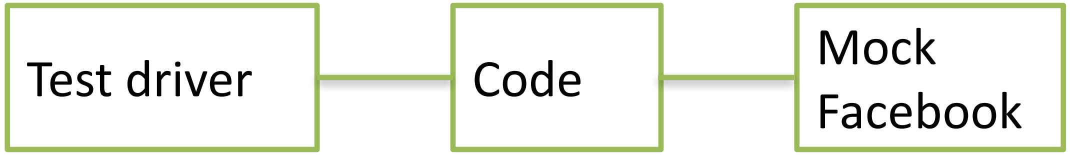

```
@Test void testGetFriends() {
   assert getFriends() == …;
}
List<Friend> getFriends() {

   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
- Use factory instead of constructor
- Use tools to facilitate this sort of testing
  - *Dependency injection* tools, e.g., Dagger, Guice
  - Mock object frameworks such as Mockito

Fault injection



- Mocks can emulate failures such as timeouts
- Allows you to verify the robustness of system

Advantages of using mocks

- Test code locally without large environment
- Enable deterministic tests
- 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

Outline

- Class Invariants
- Immutability
- Test suites and coverage
- Testing for complex environments
- Implementation-testing with assertions

What is an assertion?

- Statement containing boolean expression that programmer believes to be true:

```
assert speed <= SPEED_OF_LIGHT;
```

- Evaluated at run time – throws `Error` if `false`
- Disabled by default - no performance effect
- Typically enabled during development
- Can enable in the field when problems occur!

Syntax

```
AssertStatement:
    assert Expression1 ;
    assert(Expression1, Expression2) ;
```

- *Expression*$_1$ - asserted condition (boolean)
- *Expression*$_2$ - detail message of `AssertionError`

Why use assertions?

- Document & test programmer's assumptions
  - e.g., class invariants
- Verify programmer's understanding
- Quickly uncover bugs
- Increase confidence that program is bug-free
- Asserts turn black box tests into white box tests

Look for "assertive comments"

```
int remainder = i % 3;
if (remainder == 0) {
    ...
} else if (remainder == 1) {
    ...
} else { // (remainder == 2)
    ...
}
```

Replace with real assertions!

```
int remainder = i % 3;
if (remainder == 0) {
    ...
} else if (remainder == 1) {
    ...
} else {
    assert remainder == 2;
    ...
}
```

Use second argument for *failure capture*

```
if (i % 3 == 0) {
    ...
} else if (i % 3 == 1) {
    ...
} else {
    assert (i % 3 == 2, i);
    ...
}
```

Look for switch with no default

```
switch(flavor) {
  case VANILLA:
    ...
    break;
  case CHOCOLATE:
    ...
    break;
  case STRAWBERRY:
    ...
}
```

Add an "assertive default"

```
switch(flavor) {
  case VANILLA:
    ...
    break;
  case CHOCOLATE:
    ...
    break;
  case STRAWBERRY:
    ...
    break;
  default:
    assert (false, flavor);
}
```

Do not use assertions for *public* preconditions

```
/**
 * Sets the refresh rate.
 *
 * @param  rate refresh rate, in frames per second.
 * @throws IllegalArgumentException if rate <= 0
 *         or rate > MAX_REFRESH_RATE.
 */
public void setRefreshRate(int rate) {
    if (rate <= 0 || rate > MAX_REFRESH_RATE)
        throw new IllegalArgumentException(...);
    setRefreshInterval(1000 / rate);
}
```

Do use assertions for *non-public* preconditions

```java
/**
 * Sets the refresh interval (which must correspond
 * to a legal frame rate).
 *
 * @param  interval refresh interval in ms
 */
private void setRefreshInterval(int interval) {
    assert interval > 0 && interval <= 1000, interval;
    ... // Set the refresh interval
}
```

Do use assertions for postconditions

```
/**
 * Returns BigInteger whose value is (this-1 mod m).
 * @throws ArithmeticException  if m <= 0, or this
 *         BigInteger is not relatively prime to m.
 */
public BigInteger modInverse(BigInteger m) {
    if (m.signum() <= 0)
        throw new ArithmeticException(m + "<= 0");
    ... // Do the computation
    assert this.multiply(result).mod(m).equals(ONE);
    return result;
}
```

Complex postconditions

```
void foo(int[] a) {
    // Manipulate contents of array
    ...

    // Array will appear unchanged
}
```

Assertions for complex postconditions

```
void foo(final int[] a) {
    class DataCopy {
        private int[] aCopy;
        DataCopy() { aCopy = (int[]) a.clone(); }
        boolean isConsistent() {
            return Arrays.equals(a, aCopy);
        }
    }
    DataCopy copy = null;
    assert (copy = new DataCopy()) != null;
    ... // Manipulate contents of array
    assert copy.isConsistent();
}
```

Caveat – asserts must not have *side effects* visible outside other asserts

Do this:

```
boolean modified = set.remove(elt);
assert modified;
```

Not this:

```
assert set.remove(elt);  //Bug!
```

Sermon: accept assertions into your life

- Programmer's interior monologue:
  - "Now at this point, we know..."
- During, not after, development
- Quickly becomes second nature
- Pays big code-quality dividends

Conclusion

- To maintain class invariants
  - Minimize mutability
  - Make defensive copies where required
- Interface testing is critical
  - Design interfaces to facilitate testing
  - Coverage tools can help gauge test suite quality
- Use assertions to test implementation details
  - Asserts amplify the value of your interface tests