Principles of Software Construction: Objects, Design, and Concurrency

Part 1: Designing classes

Behavioral subtyping

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Administrivia

- Homework 1 due tonight 11:59 p.m.
  - Everyone must read and sign our collaboration policy
- Reading due Tuesday: Effective Java, Items 17 and 50
- Homework 2 due next Thursday at 11:59 p.m.

Key concepts from Tuesday

Key concepts from Tuesday

- Information hiding: Design for change, design for reuse
  - Encapsulation: Visibility modifiers in Java
  - Interface types vs. class types
- Functional correctness
  - JUnit and friends

Today

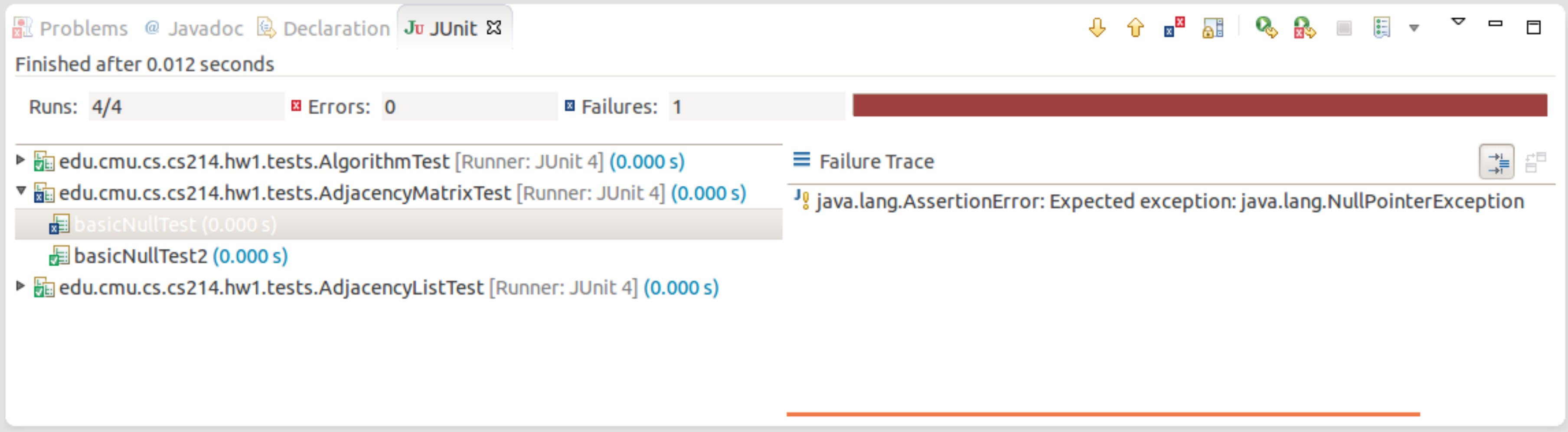
- Functional correctness, continued
- Behavioral subtyping
  - Liskov Substitution Principle
  - The `java.lang.Object` contracts

Unit testing

- Tests for small units: methods, classes, subsystems
  - Smallest testable part of a system
  - Test parts before assembling them
  - Intended to catch local bugs
- Typically written by developers
- Many small, fast-running, independent tests
- Few dependencies on other system parts or environment

JUnit

- A popular, easy-to-use, unit-testing framework for Java



A JUnit example

```
import org.junit.Test;
import static org.junit.Assert.assertEquals;

public class AdjacencyListTest {
       @Test
       public void testSanityTest(){
              Graph g1 = new AdjacencyListGraph(10);
              Vertex s1 = new Vertex("A");
              Vertex s2 = new Vertex("B");
              assertEquals(true, g1.addVertex(s1));
              assertEquals(true, g1.addVertex(s2));
              assertEquals(true, g1.addEdge(s1, s2));
              assertEquals(s2, g1.getNeighbors(s1)[0]);
       }

       @Test
       public void test….

       private int helperMethod…
}
```

Selecting test cases

- Write tests based on the specification, for:
  - Representative cases
  - Invalid cases
  - Boundary conditions
- Write stress tests
  - Automatically generate huge numbers of test cases
- Think like an attacker
- Other tests: performance, security, system interactions, …

A testing example

```
/**
  * computes the sum of the first len values of the array
  *
  * @param array array of integers of at least length len
  * @param len number of elements to sum up
  * @return sum of the first len array values
  * @throws NullPointerException if array is null
  * @throws ArrayIndexOutOfBoundsException if len > array.length
  * @throws IllegalArgumentException if len < 0
  */
int partialSum(int array[], int len);
```

A testing example

```
/**
  * computes the sum of the first len values of the array
  *
  * @param array array of integers of at least length len
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  * @return sum of the first len array values
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  * @throws ArrayIndexOutOfBoundsException if len > array.length
  * @throws IllegalArgumentException if len < 0
  */
int partialSum(int array[], int len);
```

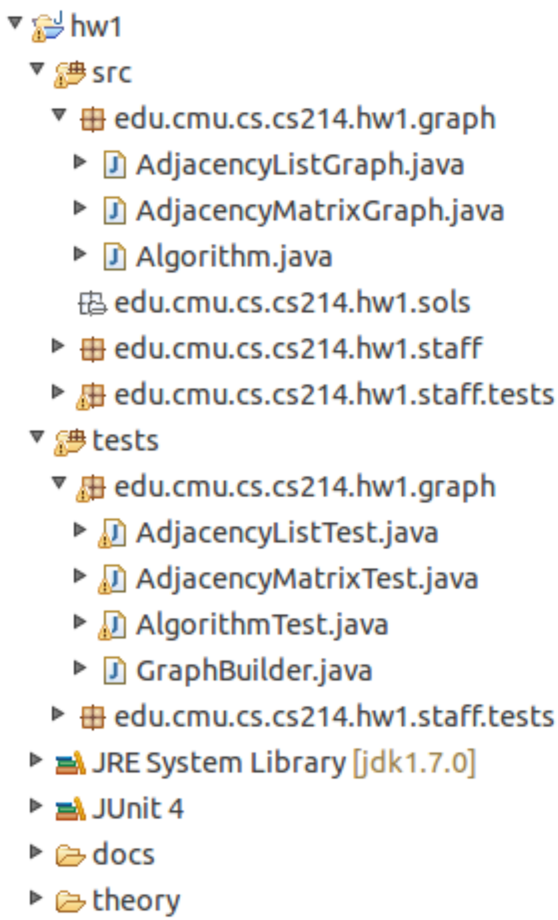
- Test null array
- Test length > array.length
- Test negative length
- Test small arrays of length 0, 1, 2
- Test long array
- Test length == array.length
- Stress test with randomly-generated arrays and lengths

A testing exercise

```java
/**
 * Copies the specified array, truncating or padding with zeros
 * so the copy has the specified length.  For all indices that are
 * valid in both the original array and the copy, the two arrays will
 * contain identical values.  For any indices that are valid in the
 * copy but not the original, the copy will contain 0.
 * Such indices will exist if and only if the specified length
 * is greater than that of the original array.
 *
 * @param original the array to be copied
 * @param newLength the length of the copy to be returned
 * @return a copy of the original array, truncated or padded with
 *     zeros to obtain the specified length
 * @throws NegativeArraySizeException if newLength is negative
 * @throws NullPointerException if original is null
 */
int [] copyOf(int[] original, int newLength);
```

Test organization conventions

- Have a test class `FooTest` for each public class Foo
- Separate source and test directories
  - `FooTest` and Foo in the same package



Testable code

- Think about testing when writing code
  - Modularity and testability go hand in hand
- Same test can be used on all implementations of an interface!
- Test-driven development
  - Writing tests before you write the code
  - Tests can expose API weaknesses

Writing testable code

```
//700LOC
public boolean foo() {
    try {
        synchronized () {
            if () {
            } else {
            }
            for () {
                if () {
                    if () {
                        if () {
                            if ()?
                            {
                                if () {
                                    for () {
                                    }
                                }
                            }
                        } else {
                            if () {
                                for () {
                                    if () {
                                    } else {
                                    }
                                    if () {
                                    } else {
                                        if () {
                                        }
                                    }
                                    if () {
                                        if () {
                                            if () {
                                                for () {
                                                }
                                            }
                                        }
                                    } else {
                                    }
                                }
                            } else {
                            }
                        }
                    }
                }
            }
```

Unit testing as a design mechanism:

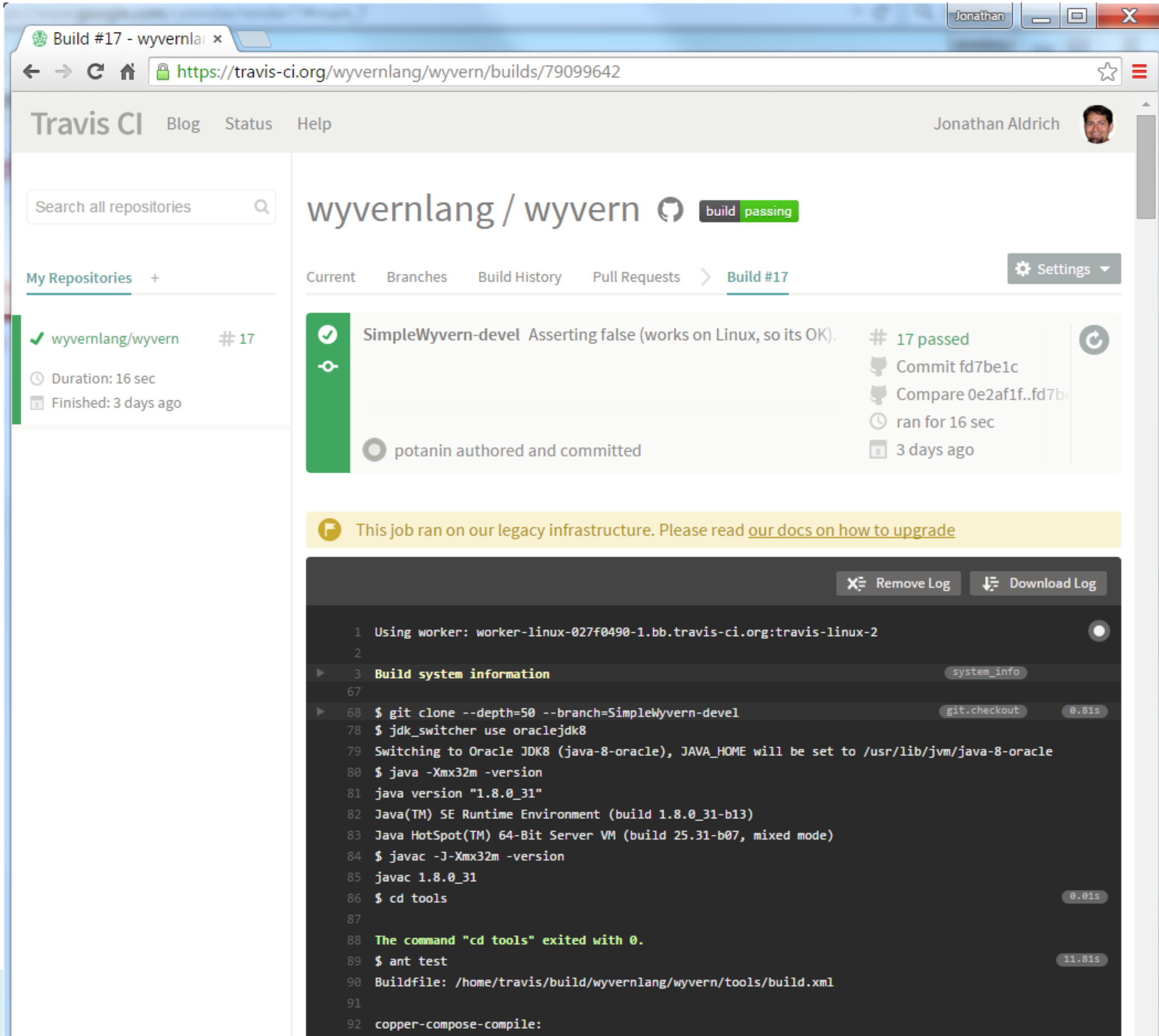
- Code with low complexity
- Clear interfaces and specifications

Source: http://thedailywtf.com/Articles/Coding-Like-the-Tour-de-France.aspx

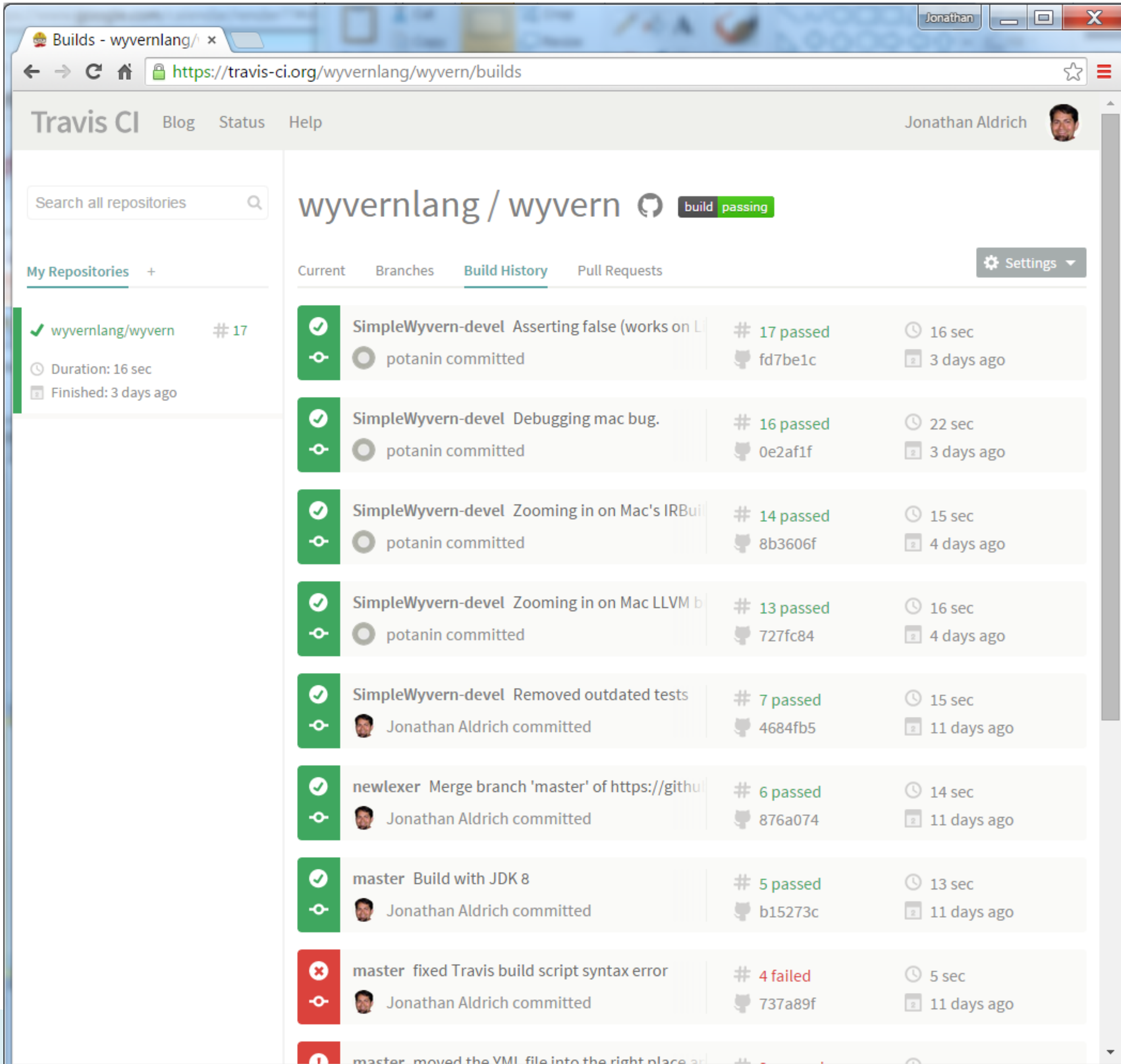
Run tests frequently

- Run tests before every commit
  - Do not commit code that fails a test
- If entire test suite becomes too large and slow:
  - Run local package-level tests ("smoke tests“) frequently
  - Run all tests nightly
  - Medium sized projects easily have 1000s of test cases
- Continuous integration servers scale testing

Continuous integration: Travis CI



Continuous integration: Travis CI build history



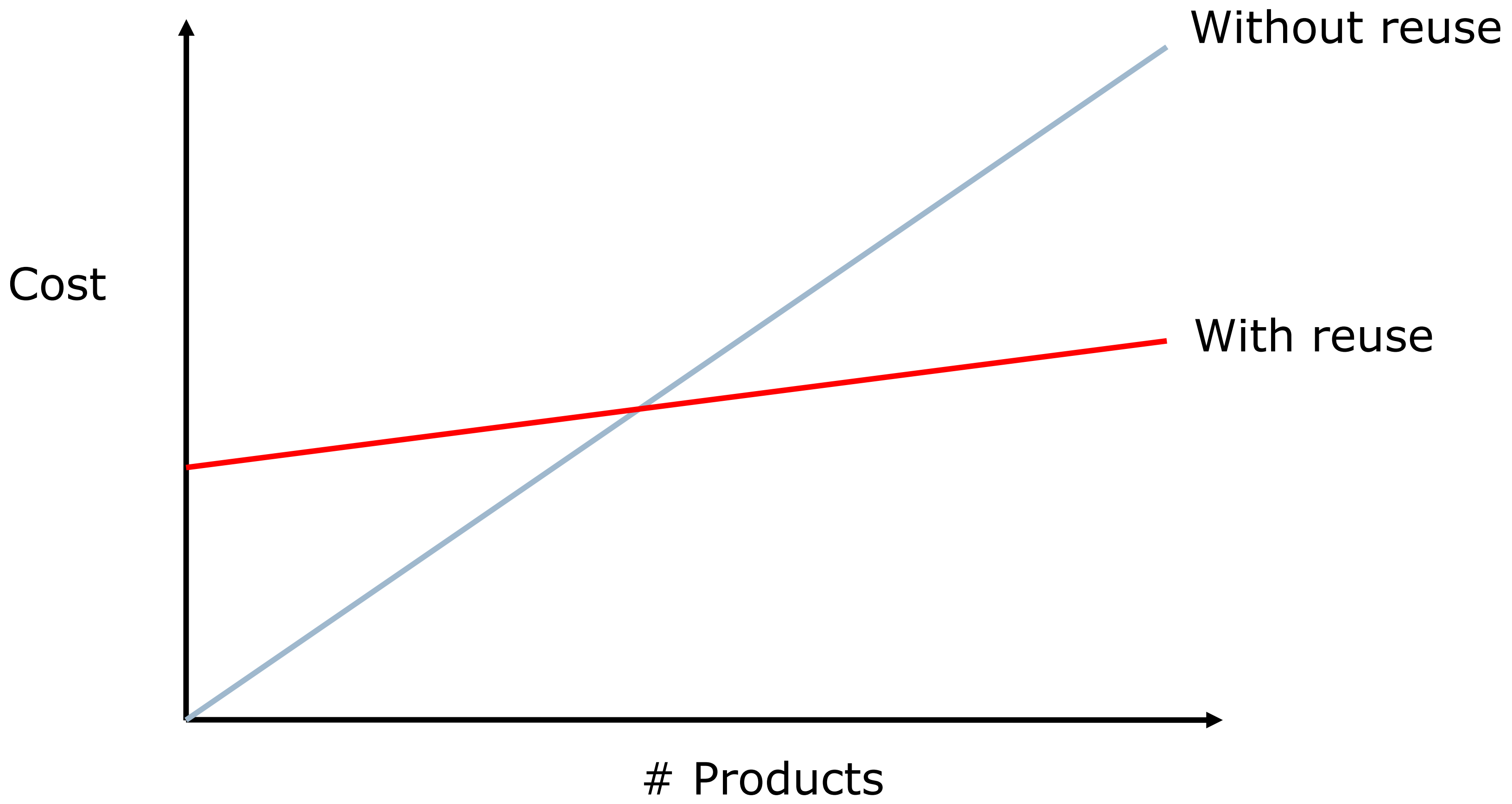
When should you stop writing tests?

When should you stop writing tests?

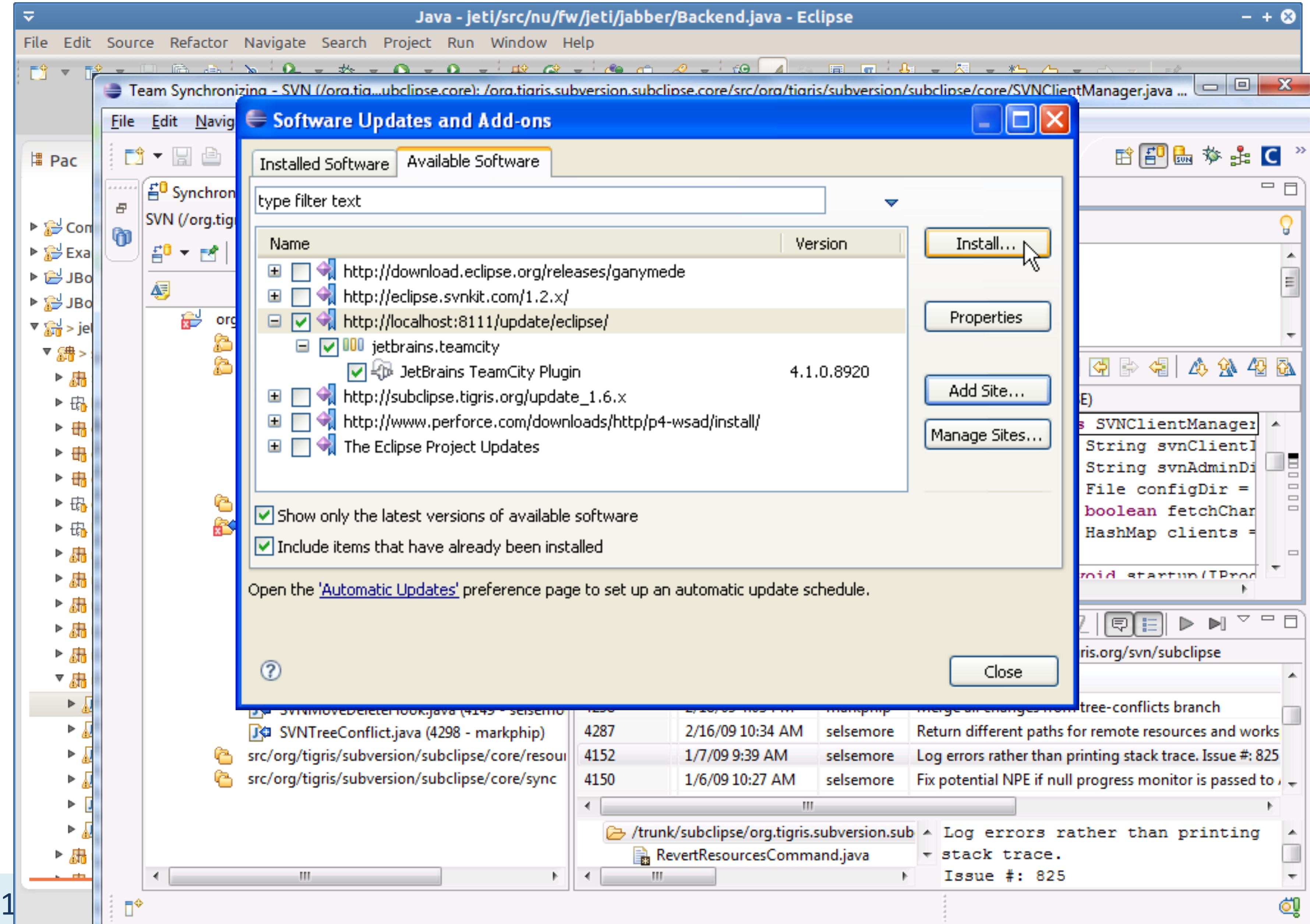
- When you run out of money…
- When your homework is due…
- When you can't think of any new test cases...
- The *coverage* of a test suite
  - Trying to test all parts of the implementation
  - Statement coverage: percentage of program statements executed
    - Compare to: method coverage, branch coverage, path coverage

DESIGN FOR REUSE

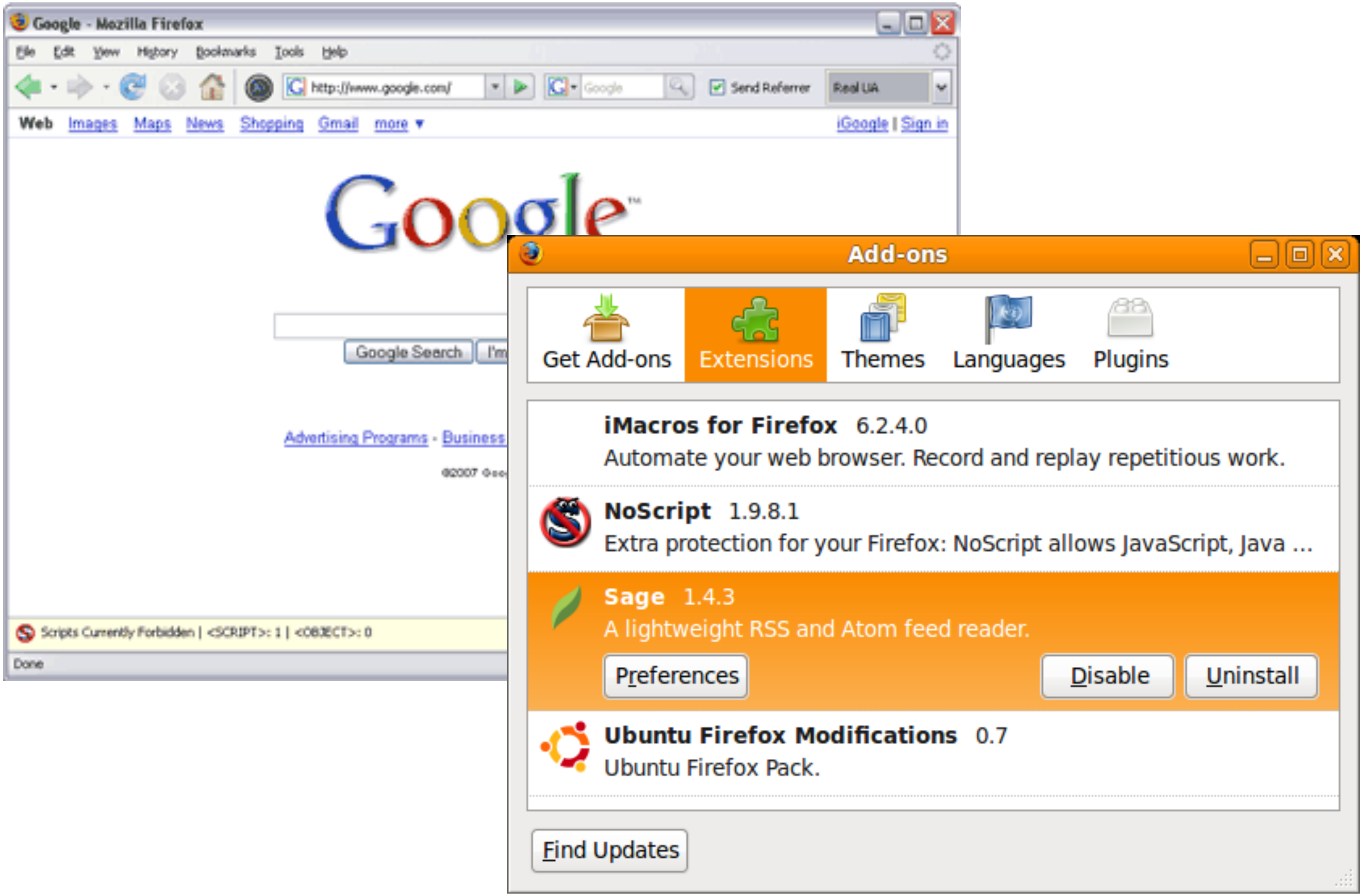
The promise of reuse:



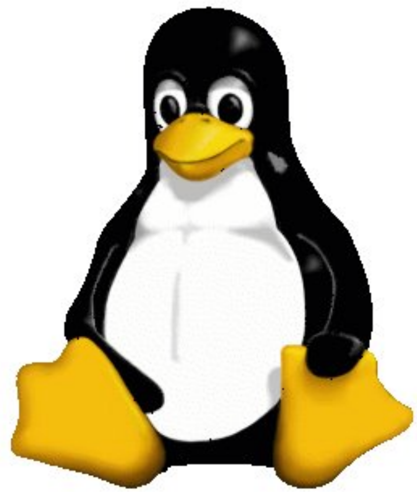
Reuse: Family of development tools



Reuse: Web browser extensions



Reuse and variation: Flavors of Linux



Today: Class-level reuse with inheritance

- Inheritance
  - Java-specific details for inheritance
- Behavioral subtyping: Liskov's Substitution Principle

- Next week:
  - Delegation
  - Design patterns for improved class-level reuse
- Later in the course:
  - System-level reuse with libraries and frameworks

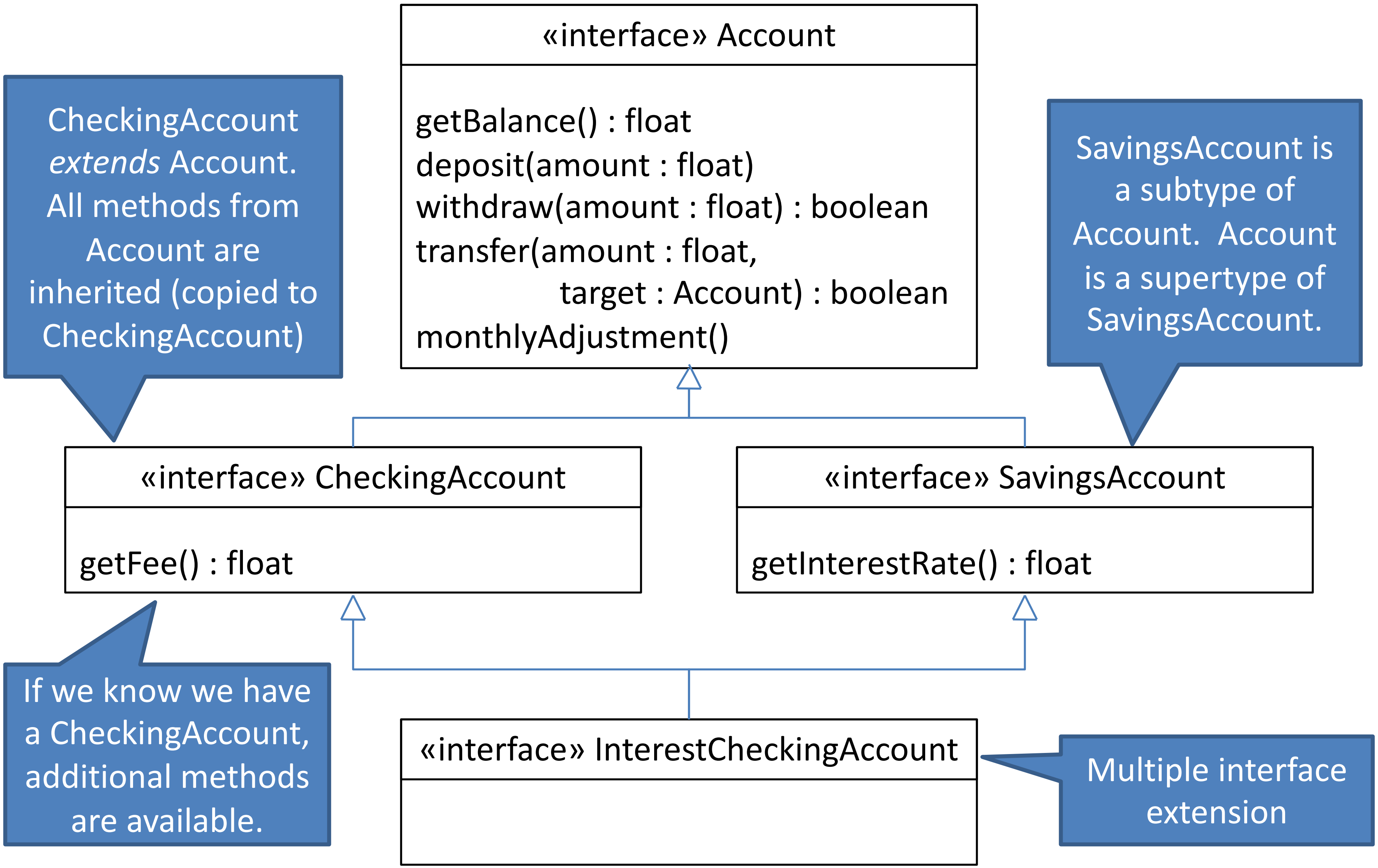
IMPLEMENTATION INHERITANCE AND ABSTRACT CLASSES

Variation in the real world: types of bank accounts

«interface» CheckingAccount
getBalance() : float deposit(amount : float) withdraw(amount : float) : boolean transfer(amount : float, target : Account) : boolean getFee() : float

«interface» SavingsAccount
getBalance() : float deposit(amount : float) withdraw(amount : float) : boolean transfer(amount : float, target : Account) : boolean getInterestRate() : float

Better: Interface inheritance for an account type hierarchy



Interface inheritance for an account type hierarchy

```
public interface Account {
    public long getBalance();
    public void  deposit(long amount);
    public boolean withdraw(long amount);
    public boolean transfer(long amount, Account target);
    public void monthlyAdjustment();
}

public interface CheckingAccount extends Account {
    public long getFee();
}

public interface SavingsAccount extends Account {
    public double getInterestRate();
}

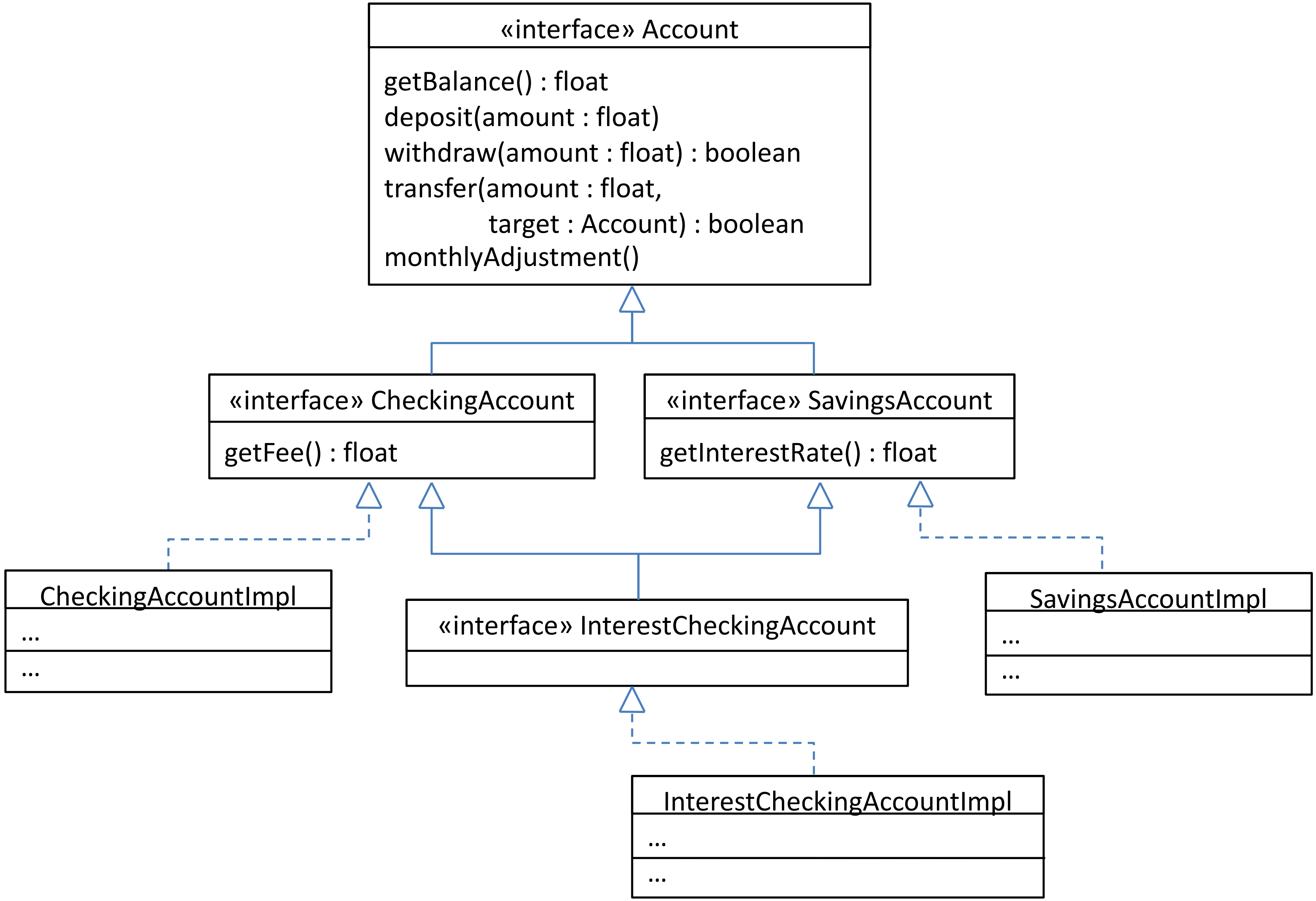
public interface InterestCheckingAccount
                      extends CheckingAccount, SavingsAccount {
}
```

The power of object-oriented interfaces

- Subtype polymorphism
  - Different kinds of objects can be treated uniformly by client code
  - Each object behaves according to its type
    - e.g., if you add new kind of account, client code does not change:

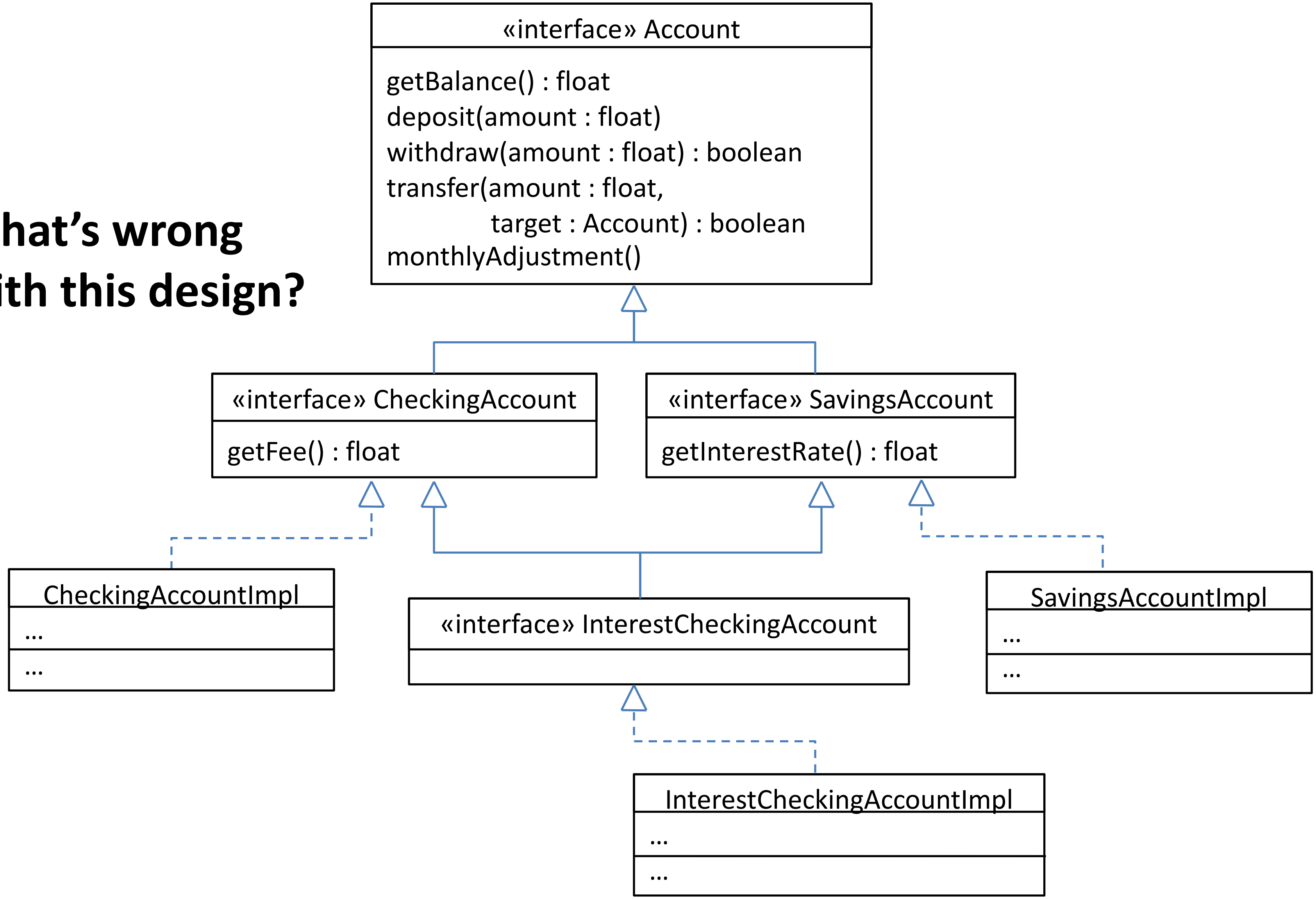
```
If today is the last day of the month:
   For each acct in allAccounts:
      acct.monthlyAdjustment();
```

Implementation inheritance for code reuse



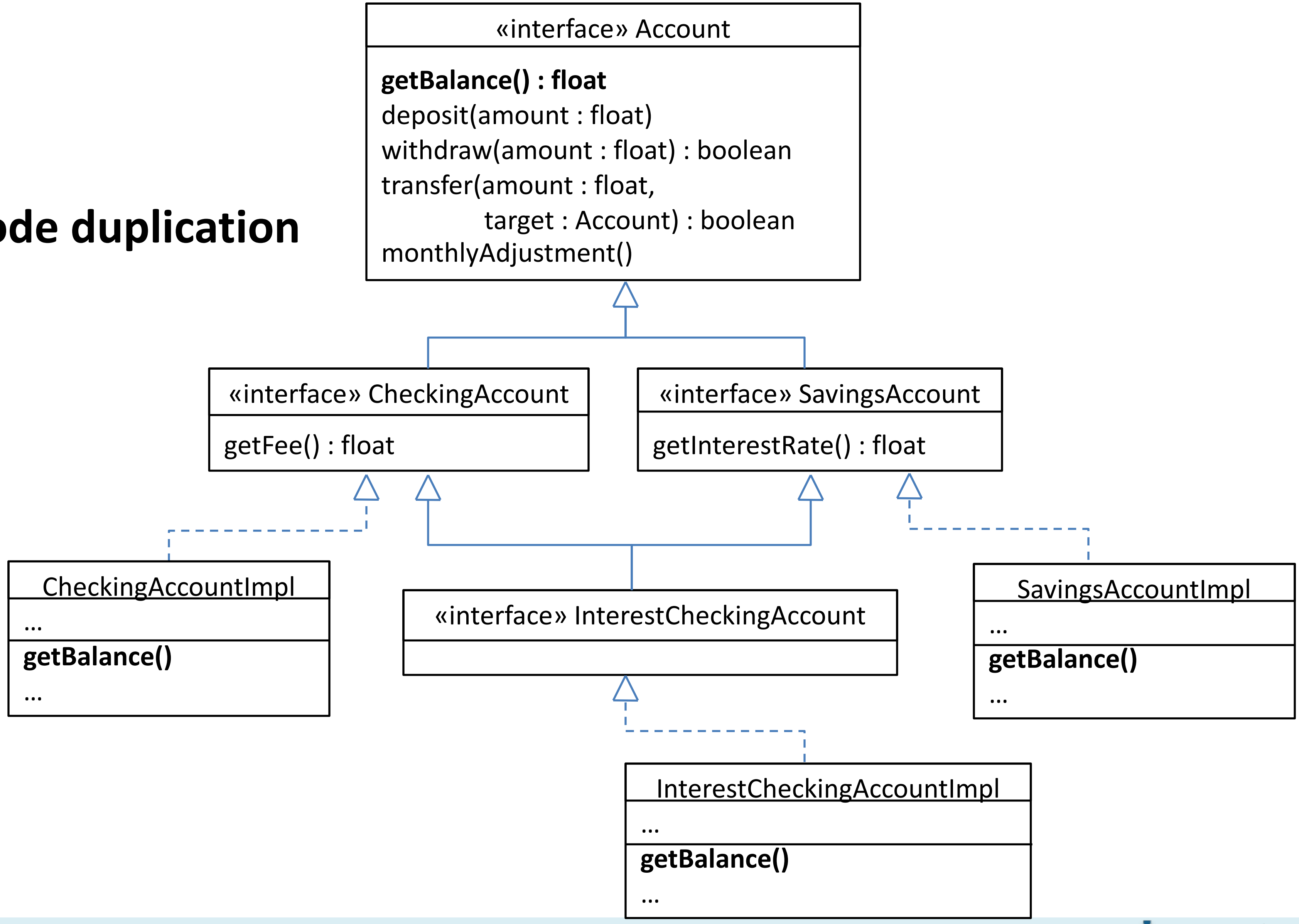
Implementation inheritance for code reuse

What's wrong with this design?



Implementation inheritance for code reuse

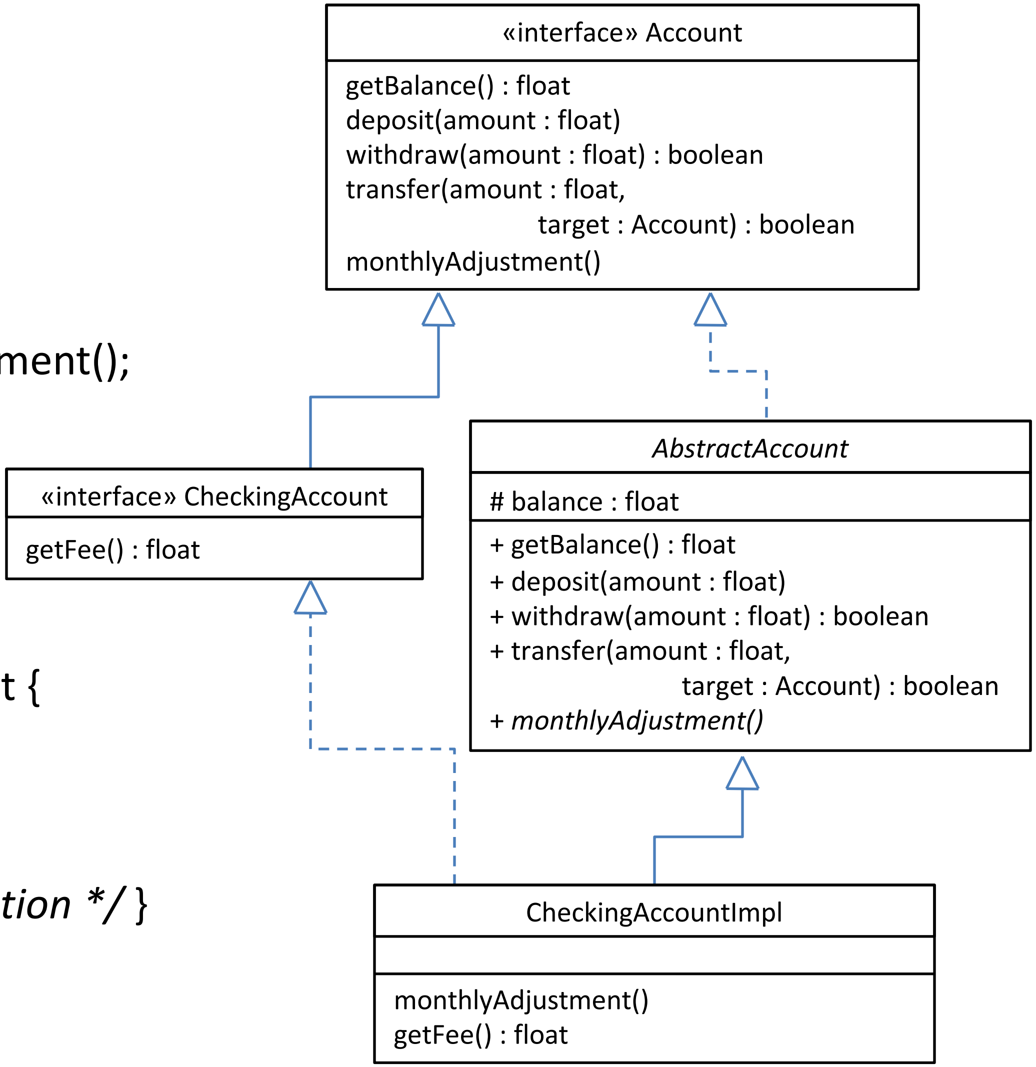
Code duplication



Better: Reuse abstract account code

```
public abstract class AbstractAccount
            implements Account {
    protected float balance = 0.0;
    public float getBalance() {
            return balance;
    }
    abstract public void monthlyAdjustment();
    // other methods…
}

public class CheckingAccountImpl
            extends AbstractAcount
            implements CheckingAccount {
    public void monthlyAdjustment() {
            balance -= getFee();
    }
    public float getFee() { /* fee calculation */ }
}
```



Better: Reuse abstract account code

```
public abstract class AbstractAccount
        implements Account {
    protected float balance = 0.0;
    public float getBalance() {
        return balance;
    }
    abstract public void monthlyAdjustment();
    // other methods…
}

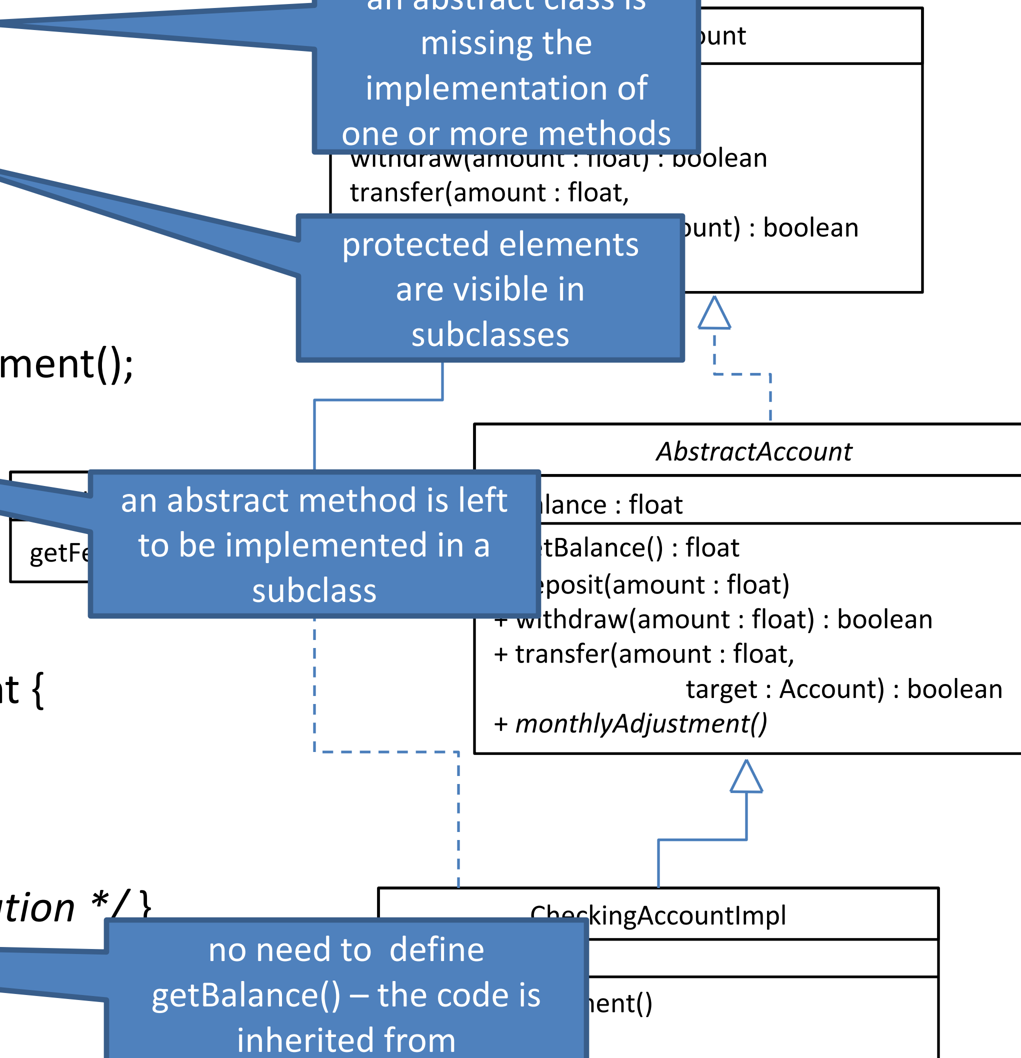
public class CheckingAccountImpl
        extends AbstractAcount
        implements CheckingAccount {
    public void monthlyAdjustment() {
        balance -= getFee();
    }
    public float getFee() { /* fee calculation */ }
}
```

an abstract class is missing the implementation of one or more methods

protected elements are visible in subclasses

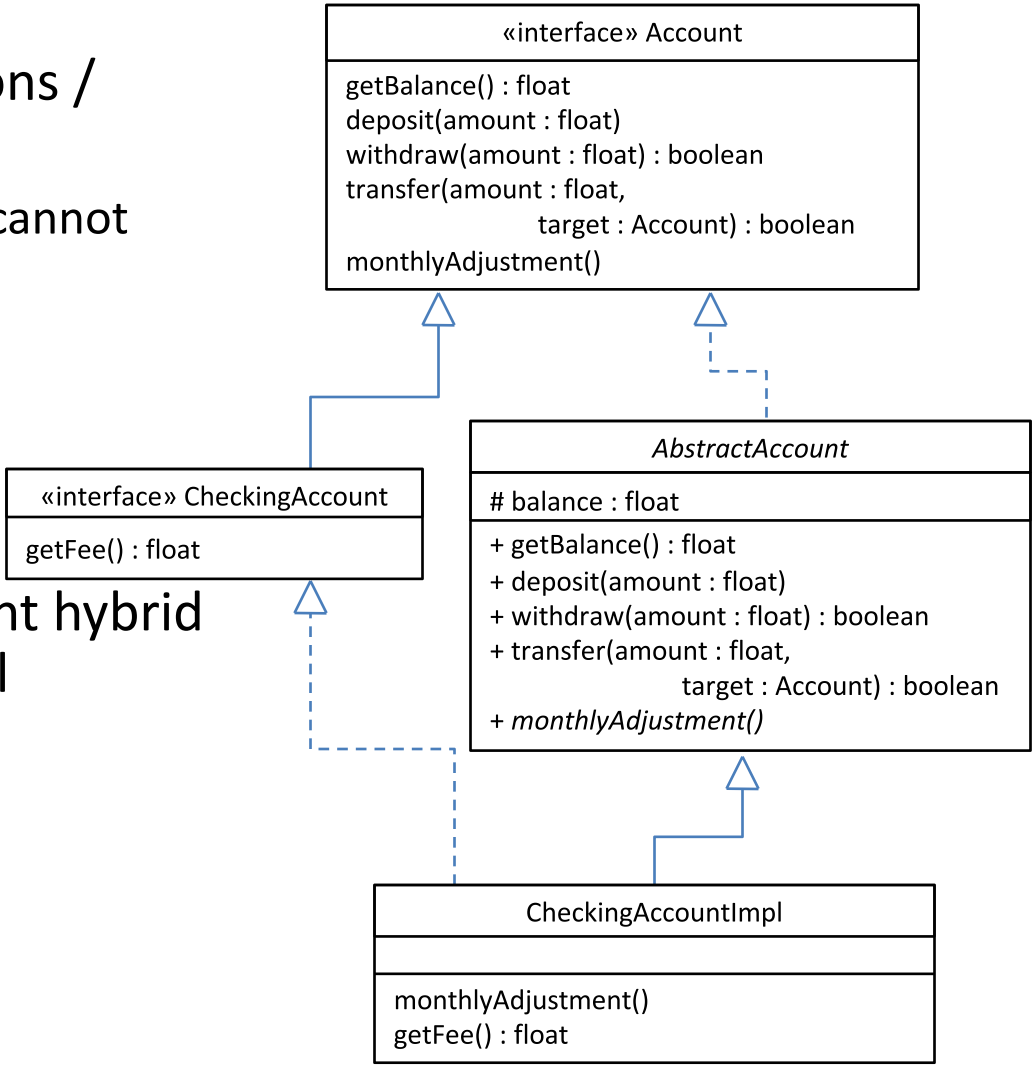
an abstract method is left to be implemented in a subclass

no need to define getBalance() – the code is inherited from AbstractAccount



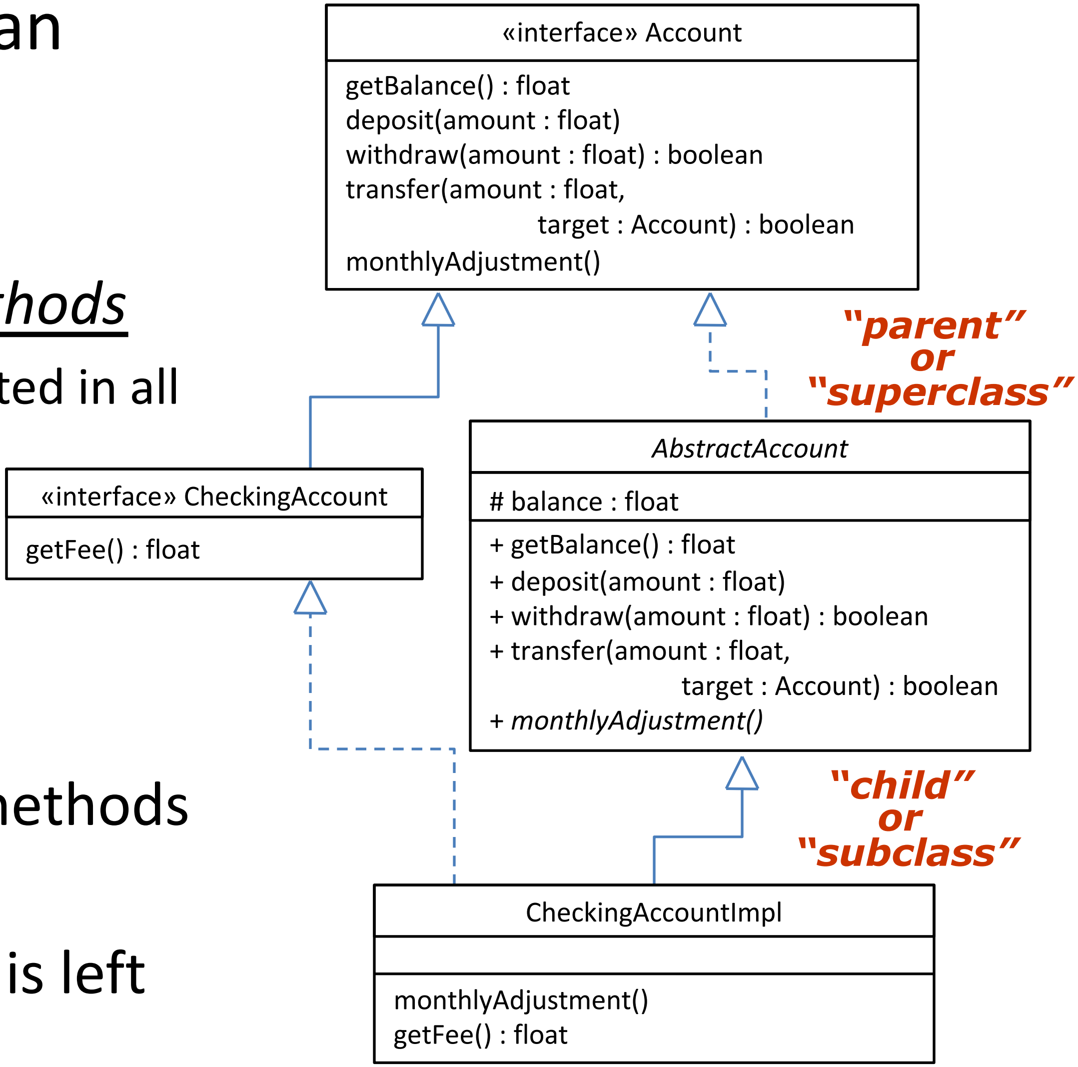
Interfaces vs Abstract Classes vs Concrete Classes

- An *interface* defines expectations / commitment for clients
  - Java: can declare methods but cannot implement them
  - Methods are *abstract methods*
- An ***abstract class*** is a convenient hybrid between an interface and a full implementation. Can have:
  - Abstract methods (no body)
  - Concrete methods (w/ body)
  - Data fields



Interfaces vs Abstract Classes vs Concrete Classes

- Unlike a concrete class, an *abstract class* ...
  - *Cannot be instantiated*
  - *Can declare abstract methods*
    - Which *must* be implemented in all *concrete* subclasses
- An abstract class may *implement* an interface
  - But need not define all methods of the interface
  - Implementation of them is left to subclasses



Aside: Inheritance and subtyping

- Inheritance is for *<u>code reuse</u>*
  - Write code once and only once
  - Superclass features implicitly available in subclass

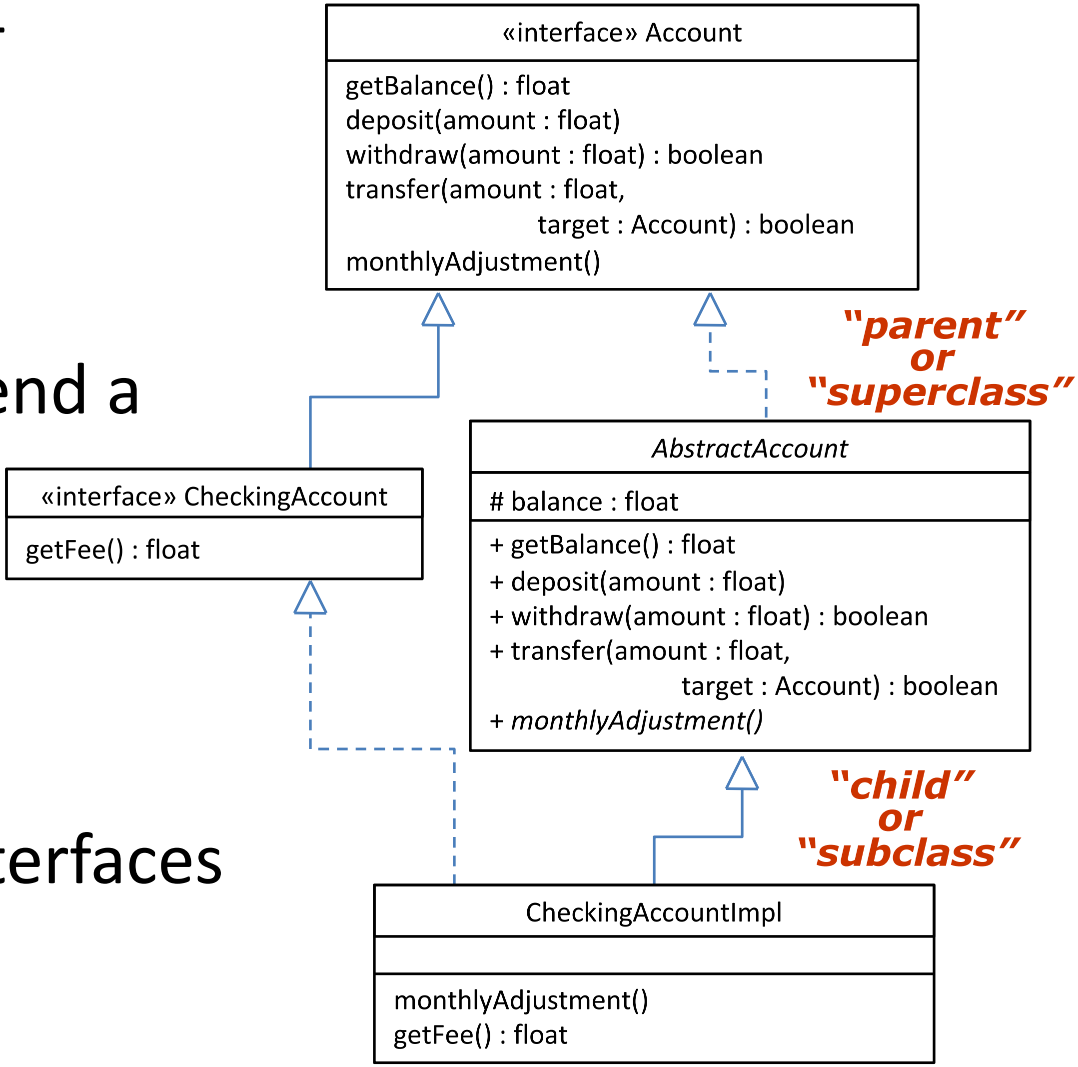
```
class A extends B
```

- Subtyping is for *<u>polymorphism</u>*
  - Accessing objects the same way, but getting different behavior
  - Subtype is substitutable for supertype

```
class A implements I
class A extends B
```

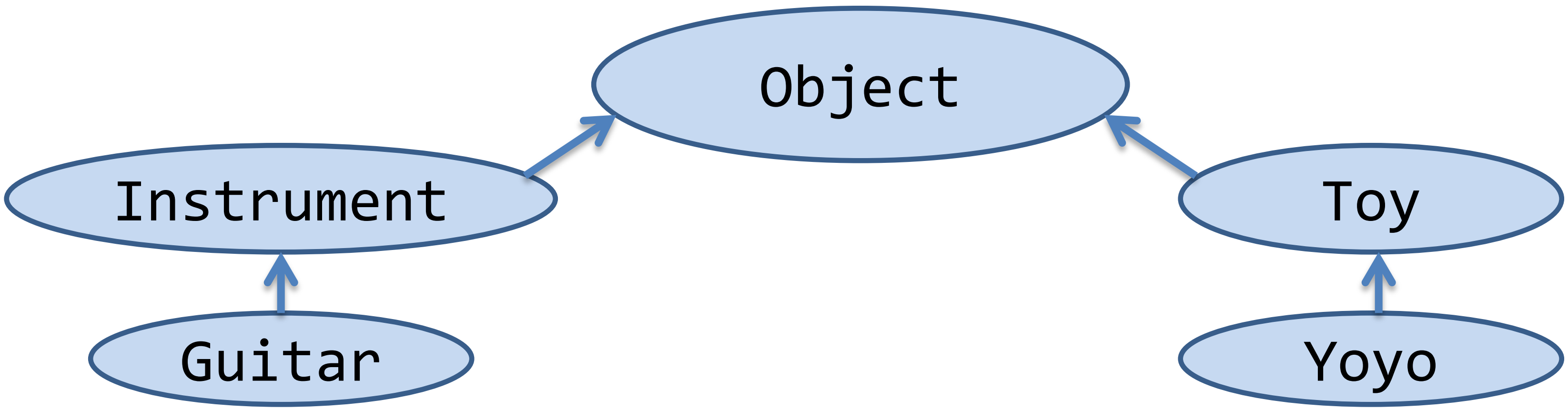
Interfaces vs Abstract Classes vs Concrete Classes

- A class can ***extend*** 0 or 1 superclass
  - Called ***single inheritance***
- An interface cannot extend a class at all
  - (Because it is not a class)
- A class or interface can ***implement*** 0 or more interfaces
  - Closest thing to ***multiple inheritance***



The class hierarchy

- The root is `Object` (all non-primitives are `Objects`)
- All classes except `Object` have one parent class
  - Specified with an `extends` clause:
    `class Guitar extends Instrument { ... }`
  - If `extends` clause is omitted, defaults to `Object`
- A class is an instance of all its superclasses



CLASS INVARIANTS

Recall: Data Structure Invariants (cf. 122)

```
struct list {
   elem data;
   struct list* next;
};
struct queue {
   list front;
   list back;
};

bool is_queue(queue Q) {
   if (Q == NULL) return false;
   if (Q->front == NULL || Q->back == NULL) return false;
   return is_segment(Q->front, Q->back);
}
```

Recall: Data Structure Invariants (cf. 122)

- Properties of the Data Structure
- Should always hold before and after method execution
- May be invalidated temporarily during method execution

```
void enq(queue Q, elem s)
//@requires is_queue(Q);
//@ensures is_queue(Q);
{ … }
```

Class Invariants

- Properties about the fields of an object
- Established by the constructor
- Should always hold before and after execution of public methods
  – May be invalidated temporarily during method execution

Class Invariants

- Properties about the fields of an object
- Established by the constructor
- Should always hold before and after execution of

```
public class SimpleSet {

    int contents[];
    int size;

    //@ ensures sorted(contents);
    SimpleSet(int capacity) { … }

    //@ requires sorted(contents);
    //@ ensures sorted(contents);
    boolean add(int i) { … }

    //@ requires sorted(contents);
    //@ ensures sorted(contents);
    boolean contains(int i) { … }
}
```

```
public class SimpleSet {

    int contents[];
    int size;

    //@invariant sorted(contents);

    SimpleSet(int capacity) { … }

    boolean add(int i) { … }

    boolean contains(int i) { … }
}
```

BEHAVIORAL SUBTYPING

“SHOULD I BE INHERITING FROM THIS TYPE?”

Behavioral subtyping (Liskov Substitution Principle)

> Let q(x) be a property provable about objects x of type T. Then q(y) should be provable for objects y of type S where S is a subtype of T.
>
> Barbara Liskov

- Applies to specified behavior:
  - Same or stronger invariants
  - Same or weaker preconditions for all methods
  - Same or stronger postconditions for all methods
- e.g., Compiler-enforced rules in Java:
  - Subtypes can add, but not remove methods
  - Concrete class must implement all undefined methods
  - Overriding method must return same type or subtype
  - Overriding method must accept the same parameter types
  - Overriding method may not throw additional exceptions

This is called the *Liskov Substitution Principle*.

Barbara Liskov

- First Woman to earn PhD in CS in US
- Turing Award (2008)
- MIT Professor

Car is a behavioral subtype of Vehicle

```
abstract class Vehicle {
    int speed, limit;

    //@ invariant speed < limit;

    //@ requires speed != 0;
    //@ ensures speed < \old(speed)
    void brake();
}
```

```
class Car extends Vehicle {
    int fuel;
    boolean engineOn;
    //@ invariant speed < limit;
    //@ invariant fuel >= 0;

    //@ requires fuel > 0 && !engineOn;
    //@ ensures engineOn;
    void start() { … }

    void accelerate() { … }

    //@ requires speed != 0;
    //@ ensures speed < \old(speed)
    void brake() { … }
}
```

- **Subclass fulfills the same invariants (and additional ones)**
- **Overridden method has the same pre and postconditions**

Hybrid is a behavioral subtype of Car

```
class Car extends Vehicle {
    int fuel;
    boolean engineOn;
    //@ invariant fuel >= 0;

    //@ requires fuel > 0 && !engineOn;
    //@ ensures engineOn;
    void start() { … }

    void accelerate() { … }

    //@ requires speed != 0;
    //@ ensures speed < old(speed)
    void brake() { … }
}
```

```
class Hybrid extends Car {
    int charge;
    //@ invariant charge >= 0;

    //@ requires (charge > 0 || fuel > 0)
                      && !engineOn;
    //@ ensures engineOn;
    void start() { … }

    void accelerate() { … }

    //@ requires speed != 0;
    //@ ensures speed < \old(speed)
    //@ ensures charge > \old(charge)
    void brake() { … }
}
```

- **Subclass fulfills the same invariants (and additional ones)**
- **Overridden method start has weaker precondition**
- **Overridden method brake has stronger postcondition**

Happy and Sad

1) An operation is happy if it can be substituted for its super type's method and sad if it cannot.
2) A smile is wider at the top than at the bottom; a frown is the opposite.
3) Preconditions are at the top of the smile/frown, postconditions are at the bottom of the smile/frown.
4) Ergo: Preconditions can be wider (looser/weaker), postconditions can be narrower (tighter/stronger).

Is this `Square` a behavioral subtype of `Rectangle`?

```
class Rectangle {
int h, w;

Rectangle(int h, int w) {
    this.h=h; this.w=w;
}

//methods
}
```

```
class Square extends Rectangle {
Square(int w) {
    super(w, w);
}
}
```

Is this `Square` a behavioral subtype of `Rectangle`?

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(Yes.)

Is this Square a behavioral subtype of Rectangle?

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class Rectangle {
//@ invariant h>0 && w>0;
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}

//methods
}
```

```
class Square extends Rectangle {
   //@ invariant h>0 && w>0;
   //@ invariant h==w;
Square(int w) {
    super(w, w);
}
}
```

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class Rectangle {
//@ invariant h>0 && w>0;
int h, w;

Rectangle(int h, int w) {
    this.h=h; this.w=w;
}

   //@ requires factor > 0;
void scale(int factor) {
    w=w*factor;
    h=h*factor;
}

}
```

```
class Square extends Rectangle {
   //@ invariant h>0 && w>0;
   //@ invariant h==w;
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   //@ requires factor > 0;
void scale(int factor) {
    w=w*factor;
    h=h*factor;
}
   //@ requires neww > 0;
void setWidth(int neww) {
    w=neww;
}
}
```

```
class Square extends Rectangle {
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   //@ invariant h==w;
Square(int w) {
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```


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void setWidth(int neww) {
    w=neww;
}
}
```

```
class Square extends Rectangle {
   //@ invariant h>0 && w>0;
   //@ invariant h==w;
Square(int w) {
    super(w, w);
}
}
```

```
class GraphicProgram {
    void scaleW(Rectangle r, int f) {
        r.setWidth(r.getWidth() * f);
    }
}
```

← **Invalidates stronger invariant (h==w) in subclass**

(Yes! But the Square is not a square…)

This Square is *not* a behavioral subtype of Rectangle

```
class Rectangle {
//@ invariant h>0 && w>0;
int h, w;

Rectangle(int h, int w) {
    this.h=h; this.w=w;
}

   //@ requires factor > 0;
void scale(int factor) {
    w=w*factor;
    h=h*factor;
}
   //@ requires neww > 0;
   //@ ensures w==neww
             && h==old.h;
void setWidth(int neww) {
    w=neww;
}
}
```

```
class Square extends Rectangle {
   //@ invariant h>0 && w>0;
   //@ invariant h==w;
Square(int w) {
    super(w, w);
}

   //@ requires neww > 0;
   //@ ensures w==neww
             && h==neww;
   @Override
   void setWidth(int neww) {
      w=neww;
      h=neww;
   }
}
```

Today

- Functional correctness, continued
- Behavioral subtyping
  - Liskov Substitution Principle
  - The `java.lang.Object` contracts

Methods common to all `Objects`

- `equals`: returns true if the two objects are "equal"
- `hashCode`: returns an `int` that must be equal for equal objects, and is likely to differ for unequal objects
- `toString`: returns a printable string representation

The built-in `java.lang.Object` implementations

- Provide identity semantics:
  - `equals(Object o)`: returns `true` if o refers to this object
  - `hashCode()`: returns a near-random `int` that never changes
  - `toString()`: returns a string consisting of the type and hash code
    - For example: `java.lang.Object@659e0bfd`

The `toString()` specification

- Returns a concise, but informative textual representation
- Advice: Always override `toString()`, e.g.:

```
final class PhoneNumber {
    private final short areaCode;
    private final short prefix;
    private final short lineNumber;
      ...
    @Override public String toString() {
        return String.format("(%03d) %03d-%04d",
            areaCode, prefix, lineNumber);
    }
}

Number jenny = ...;
System.out.println(jenny);
```

Prints: `(707) 867-5309`

The `equals(Object)` specification

- Must define an equivalence relation:
  - Reflexive: For every object x, `x.equals(x)` is always true
  - Symmetric: If `x.equals(y)`, then `y.equals(x)`
  - Transitive: If `x.equals(y)` and `y.equals(z)`, then `x.equals(z)`
- Consistent: Equal objects stay equal, unless mutated
- "Non-null": `x.equals(null)` is always false

An `equals(Object)` example

```
public final class PhoneNumber {
    private final short areaCode;
    private final short prefix;
    private final short lineNumber;

    @Override
    public boolean equals(Object o) {
        if (!(o instanceof PhoneNumber))  // Does null check
            return false;
        PhoneNumber pn = (PhoneNumber) o;
        return pn.lineNumber == lineNumber
               && pn.prefix == prefix
               && pn.areaCode == areaCode;
    }

    ...
}
```

The `hashCode()` specification

- Equal objects must have equal hash codes
  - If you override `equals` you must override `hashCode`
- Unequal objects should usually have different hash codes
  - Take all value fields into account when constructing it
- Hash code must not change unless object is mutated

A hashCode() example

```
public final class PhoneNumber {
    private final short areaCode;
    private final short prefix;
    private final short lineNumber;

    @Override public int hashCode() {
        int result = 17;  // Nonzero is good
        result = 31 * result + areaCode;   // Constant must be odd
        result = 31 * result + prefix;     //     "      "   "   "
        result = 31 * result + lineNumber; //     "      "   "   "
        return result;
    }

    ...
}
```

An `Object` method exercise

Provide all code needed for a reasonable equals method:

```
public final class Name {
    private final String first, last;
    public Name(String first, String last) {
        if (first == null || last == null)
            throw new NullPointerException();
        this.first = first; this.last = last;
    }
    …
}
```

What does the following code print?

```
public final class Name {
      private final String first, last;
      public Name(String first, String last) {
          if (first == null || last == null)
              throw new NullPointerException();
          this.first = first; this.last = last;
      }
      public boolean equals(Name o) {
          return first.equals(o.first) && last.equals(o.last);
      }
      public int hashCode() {
          return 31 * first.hashCode() + last.hashCode();
      }
      public static void main(String[] args) {
          Set<Name> s = new HashSet<>();
          s.add(new Name("Mickey", "Mouse"));
          System.out.println(
              s.contains(new Name("Mickey", "Mouse")));
      }
}
```

(a) true
(b) false
(c) It varies
(d) None of the above

What does it print?

(a) `true`

(b) `false`

(c) It varies

(d) None of the above

The `Name` class overrides `hashCode` but not `equals`!

The two `Name` instances are thus unequal.

What does the following code print?

```
public final class Name {
      private final String first, last;
      public Name(String first, String last) {
          if (first == null || last == null)
              throw new NullPointerException();
          this.first = first; this.last = last;
      public boolean equals(Name o) {  // Accidental overloading
          return first.equals(o.first) && last.equals(o.last);
      }
      public int hashCode() {
          return 31 * first.hashCode() + last.hashCode();
      }
      public static void main(String[] args) {
          Set<Name> s = new HashSet<>();
          s.add(new Name("Mickey", "Mouse"));
          System.out.println(
              s.contains(new Name("Mickey", "Mouse")));
      }
}
```

A correct `equals` implementation

```
@Override
public boolean equals(Object o) {
    if (!(o instanceof Name))
        return false;
    Name n = (Name) o;
    return n.first.equals(first) && n.last.equals(last);
}
```

Summary

- Please complete the course reading assignments
- Test early, test often!
- Subtypes must fulfill behavioral contracts
- Always override `hashCode` if you override `equals`
- Always use `@Override` if you intend to override a method
  - Or let your IDE generate these methods for you…