Lecture 11
Subtypes and Subclasses
The Liskov Substitution Principle

Let $P(x)$ be a property provable about objects $x$ of type $T$. Then $P(y)$ should be true for objects $y$ of type $S$ where $S$ is a subtype of $T$.

This means $B$ is a subtype of $A$ if anywhere you can use an $A$, you could also use a $B$.

-- Barbara Liskov
What is subtyping?

Sometimes “every B is an A”
- Example: In a library database:
  - Every book is a library holding
  - Every CD is a library holding

Subtyping expresses this
- “B is a subtype of A” means:
  “every object that satisfies the rules for a B also satisfies the rules for an A”

Goal: code written using A's specification operates correctly even if given a B
- Plus: clarify design, share tests, (sometimes) share code
Subtypes are substitutable

Subtypes are *substitutable* for supertypes
- Instances of subtype won't surprise client by failing to satisfy the supertype's specification
- Instances of subtype won't surprise client by having more expectations than the supertype's specification

We say that B is a *true subtype* of A if B has a stronger specification than A
- This is *not* the same as a *Java subtype*
- Java subtypes that are not true subtypes are *confusing* and *dangerous*
  - But unfortunately common poor-design 😞
Subtyping vs. subclassing

Substitution (subtype) — a specification notion
- B is a subtype of A iff an object of B can masquerade as an object of A in any context
- About satisfiability (behavior of a B is a subset of A’s spec)

Inheritance (subclass) — an implementation notion
- Factor out repeated code
- To create a new class, write only the differences

Java purposely merges these notions for classes:
- Every subclass is a Java subtype
  - But not necessarily a true subtype
Inheritance makes adding functionality easy

Suppose we run a web store with a class for products...

class Product {
    private String title;
    private String description;
    private int price; // in cents
    public int getPrice() {
        return price;
    }
    public int getTax() {
        return (int)(getPrice() * 0.096);
    }
    ...
}

... and we need a class for products that are on sale
We know: don’t copy code!

We would never dream of cutting and pasting like this:

```java
class SaleProduct {
    private String title;
    private String description;
    private int price; // in cents
    private float factor;
    public int getPrice() {
        return (int)(price*factor);
    }
    public int getTax() {
        return (int)(getPrice() * 0.096);
    }
    ...
}
```
Inheritance makes small extensions small

Much better:

class SaleProduct extends Product {
    private float factor;
    public int getPrice() {
        return (int)(super.getPrice()*factor);
    }
}

Benefits of subclassing & inheritance

• Don’t repeat unchanged fields and methods
  – In implementation
    • Simpler maintenance: fix bugs once
  – In specification
    • Clients who understand the superclass specification need only study novel parts of the subclass
  – Modularity: can ignore private fields and methods of superclass (if properly defined)
  – Differences not buried under mass of similarities

• Ability to substitute new implementations
  – No client code changes required to use new subclasses
Subclassing can be misused

• Poor planning can lead to a muddled *class hierarchy*
  – Relationships may not match untutored intuition
• Poor design can produce subclasses that depend on many implementation details of superclasses
• Changes in superclasses can break subclasses
  – “fragile base class problem”
• **Subtyping and implementation inheritance are orthogonal!**
  – Subclassing gives you both
  – Sometimes you want just one
    • *Interfaces*: subtyping without inheritance [see also section]
    • *Composition*: use implementation without subtyping
      – Can seem less convenient, but often better long-term
Is every square a rectangle?

interface Rectangle {
    // effects: fits shape to given size:
    //            this.post.width = w, this.post.height = h
    void setSize(int w, int h);
}
interface Square extends Rectangle {...}

Are any of these good options for Square’s setSize specification?
1. // requires: w = h
   // effects: fits shape to given size
   void setSize(int w, int h);
2. // effects: sets all edges to given size
   void setSize(int edgeLength);
3. // effects: sets this.width and this.height to w
   void setSize(int w, int h);
4. // effects: fits shape to given size
   // throws BadSizeException if w != h
   void setSize(int w, int h) throws BadSizeException;
Square, Rectangle Unrelated (Subtypes)

**Square** is not a (true subtype of) **Rectangle**:
- **Rectangles** are expected to have a width and height that can be mutated independently
- **Squares** violate that expectation, could surprise client

**Rectangle** is not a (true subtype of) **Square**:
- **Squares** are expected to have equal widths and heights
- **Rectangles** violate that expectation, could surprise client

Subtyping is not always intuitive
- Benefit: it forces clear thinking and prevents errors

Solutions:
- Make them unrelated (or siblings)
- Make them immutable (!)
  - Recovers mathematical intuition
Inappropriate subtyping in the JDK

class Hashtable<K,V> {
    public void put(K key, V value){...}
    public V get(K key){...}
}

// Keys and values are strings.
class Properties extends Hashtable<Object,Object> {
    public void setProperty(String key, String val) {
        put(key,val);
    }
    public String getProperty(String key) {
        return (String)get(key);
    }
}

Properties p = new Properties();
Hashtable tbl = p;
tbl.put("One", 1);
p.getProperty("One"); // crash!
Violation of rep invariant

Properties class has a simple rep invariant:
- Keys and values are Strings

But client can treat Properties as a Hashtable
- Can put in arbitrary content, break rep invariant

From Javadoc:

Because Properties inherits from Hashtable, the put and putAll methods can be applied to a Properties object. ... If the store or save method is called on a "compromised" Properties object that contains a non-String key or value, the call will fail.
Solution 1: Generics

Bad choice:
```java
class Properties extends Hashtable<Object, Object> {
    ...
}
```
Better choice:
```java
class Properties extends Hashtable<String, String> {
    ...
}
```

JDK designers deliberately didn’t do this. Why?
- Backward-compatibility (Java didn’t used to have generics)
- Postpone talking about generics: upcoming lecture
Solution 2: Composition

class Properties {
    private Hashtable<Object, Object> hashtable;

    public void setProperty(String key, String value) {
        hashtable.put(key, value);
    }

    public String getProperty(String key) {
        return (String) hashtable.get(key);
    }

    ...
}

Substitution principle for classes

If B is a subtype of A, a B can *always be substituted* for an A

Any property guaranteed by A must be guaranteed by B
- Anything provable about an A is provable about a B
- If an instance of subtype is treated purely as supertype (only supertype methods/fields used), then the result should be consistent with an object of the supertype being manipulated

B is *permitted to strengthen* properties and add properties
- Fine to add new methods (that preserve invariants)
- An overriding method must have a stronger (or equal) spec

B is *not permitted to weaken* a spec
- No method removal
- No overriding method with a weaker spec
Substitution principle for methods

Constraints on methods
  – For each supertype method, subtype must have such a method
    • Could be inherited or overridden

Each overriding method must strengthen (or match) the spec:
  – Ask nothing extra of client (“weaker precondition”)
    • Requires clause is at most as strict as in supertype’s method
  – Guarantee at least as much (“stronger postcondition”)
    • Effects clause is at least as strict as in the supertype method
    • No new entries in modifies clause
    • Promise more (or the same) in returns clause
    • Throws clause must indicate fewer (or same) possible exception types
Spec strengthening: argument/result types

Method **inputs**:
- Argument types in A’s foo may be replaced with supertypes in B’s foo (“contravariance”)
- Places no extra demand on the clients
- But Java does not have such overriding
  - (Why?)

Method **results**:
- Result type of A’s foo may be replaced by a subtype in B’s foo (“covariance”)
- No new exceptions (for values in the domain)
- Existing exceptions can be replaced with subtypes
  (None of this violates what client can rely on)
Substitution exercise

Suppose we have a method which, when given one product, recommends another:

```java
class Product {
    Product recommend(Product ref);
}
```

Which of these are possible forms of this method in `SaleProduct` (a true subtype of `Product`)?

```java
Product recommend(SaleProduct ref); // bad
SaleProduct recommend(Product ref); // OK
Product recommend(Object ref); // OK, but is Java overloading
Product recommend(Product ref) throws NoSaleException; // bad
```
Java subtyping

• Java types:
  – Defined by classes, interfaces, primitives

• Java subtyping stems from \texttt{B extends A} and \texttt{B implements A} declarations

• In a Java subtype, each corresponding method has:
  – Same argument types
    • If different, \textit{overloading}: unrelated methods
  – Compatible (covariant) return types
    • A (somewhat) recent language feature, not reflected in (e.g.) \texttt{clone}
  – No additional declared exceptions
Java subtyping guarantees

A variable’s run-time type (i.e., the class of its run-time value) is a Java subtype of its declared type

```
Object o = new Date();  // OK
Date d = new Object();  // compile-time error
```

If a variable of declared (compile-time) type $T_1$ holds a reference to an object of actual (runtime) type $T_2$, then $T_2$ must be a Java subtype of $T_1$

Corollaries:

- Objects always have implementations of the methods specified by their declared type
- *If* all subtypes are true subtypes, then all objects meet the specification of their declared type

Rules out a huge class of bugs
Inheritance can break encapsulation

```java
public class InstrumentedHashSet<E>
    extends HashSet<E> {
    private int addCount = 0; // count # insertions
    public InstrumentedHashSet(Collection<? extends E> c) {
        super(c);
    }
    public boolean add(E o) {
        addCount++;
        return super.add(o);
    }
    public boolean addAll(Collection<? extends E> c) {
        addCount += c.size();
        return super.addAll(c);
    }
    public int getAddCount() { return addCount; }
}
```
Dependence on implementation

What does this code print?

```java
InstrumentedHashSet<String> s =
    new InstrumentedHashSet<String>();
System.out.println(s.getAddCount()); // 0
s.addAll(Arrays.asList("CSE", "331"));
System.out.println(s.getAddCount()); // 4?!
```

• Answer *depends on implementation* of `addAll` in `HashSet`
  – Different implementations may behave differently!
  – If `HashSet`’s `addAll` calls `add`, then double-counting

• `AbstractCollection`’s `addAll` specification:
  – “Adds all of the elements in the specified collection to this collection.”
  – Does not specify whether it calls `add`

• Lesson: Subclassing often requires *designing for extension*
Solutions

1. Change spec of `HashSet`
   - Indicate all self-calls
   - Less flexibility for implementers of specification

2. Avoid spec ambiguity by avoiding self-calls
   a) “Re-implement” methods such as `addAll`
      • Requires re-implementing methods
   b) Use a wrapper
      • No longer a subtype (unless an interface is handy)
      • Bad for callbacks, equality tests, etc.
public class InstrumentedHashSet<E> {
    private final HashSet<E> s = new HashSet<E>();
    private int addCount = 0;
    public InstrumentedHashSet(Collection<? extends E> c) {
        this.addAll(c);
    }
    public boolean add(E o) {
        addCount++;
        return s.add(o);
    }
    public boolean addAll(Collection<? extends E> c) {
        addCount += c.size();
        return s.addAll(c);
    }
    public int getAddCount() { return addCount; }
    // ... and every other method specified by HashSet<E>
}
Composition (wrappers, delegation)

Implementation *reuse without inheritance*

- Easy to reason about; self-calls are irrelevant
- Example of a “wrapper” class
- Works around badly-designed / badly-specified classes
- Disadvantages (may be worthwhile price to pay):
  - Does not preserve subtyping
  - Tedious to write (your IDE should help you)
  - May be hard to apply to callbacks, equality tests
Composition does not preserve subtyping

- **InstrumentedHashSet** is not a **HashSet** anymore
  - So can't easily substitute it

- It may be a true subtype of **HashSet**
  - But Java doesn't know that!
  - Java requires declared relationships
  - Not enough just to meet specification

- Interfaces to the rescue
  - Can declare that we implement interface **Set**
  - If such an interface exists
public class InstrumentedHashSet<E> implements Set<E>{
    private final Set<E> s = new HashSet<E>();
    private int addCount = 0;
    public InstrumentedHashSet(Collection<? extends E> c){
        this.addAll(c);
    }
    public boolean add(E o) {
        addCount++;
        return s.add(o);
    }
    public boolean addAll(Collection<? extends E> c) {
        addCount += c.size();
        return s.addAll(c);
    }
    public int getAddCount() { return addCount; }
    // ... and every other method specified by Set<E>
}
Interfaces and abstract classes

Provide *interfaces* for your functionality

- Client code to interfaces rather than concrete classes
- Allows different implementations later
- Facilitates composition, wrapper classes
  - Basis of lots of useful, clever techniques
  - We'll see more of these later

Consider also providing helper/template *abstract classes*

- Can minimize number of methods that new implementation must provide
- Makes writing new implementations much easier
- Not necessary to use them to implement an interface, so retain freedom to create radically different implementations that meet an interface
Java library interface/class example

// root interface of collection hierarchy
interface Collection<E>

// skeletal implementation of Collection<E>
abstract class AbstractCollection<E>
    implements Collection<E>

// type of all ordered collections
interface List<E> extends Collection<E>
// skeletal implementation of List<E>
abstract class AbstractList<E>
    extends AbstractCollection<E>
    implements List<E>

// an old friend...
class ArrayList<E> extends AbstractList<E>
Why interfaces instead of classes?

Java design decisions:

- A class has exactly one superclass
- A class may implement multiple interfaces
- An interface may extend multiple interfaces

Observation:

- Multiple superclasses are difficult to use and to implement
- Multiple interfaces, single superclass gets most of the benefit
Pluses and minuses of inheritance

- Inheritance is a powerful way to achieve code reuse

- Inheritance can break encapsulation
  - A subclass may need to depend on unspecified details of the implementation of its superclass
    - E.g., pattern of self-calls
  - Subclass may need to evolve in tandem with superclass
    - Okay within a package where implementation of both is under control of same programmer

- Authors of superclass should design and document self-use, to simplify extension
  - Otherwise, avoid implementation inheritance and use composition instead