CSE 331
Software Design and Implementation

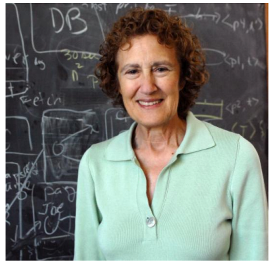
Lecture 11
Subtypes and Subclasses

Zach Tatlock / Spring 2018

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.

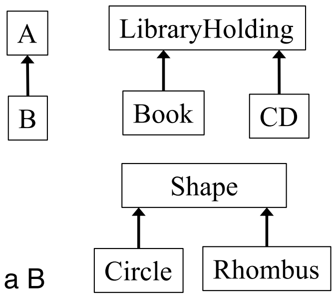


-- Barbara Liskov

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:

```
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?

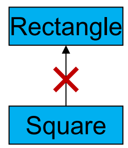
```
interface Rectangle {
  // effects: fits shape to given size:
  //          this_post.width = w, this_post.height = h
  void setSize(int w, int h);
}
interface Square extends Rectangle {…}
```

Are any of these good options for **Square**'s **setSize** specification?

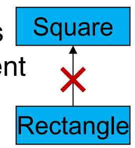
```
1. // requires: w = h
   // effects: fits shape to given size
  void setSize(int w, int h);
2.// effects: sets all edges to given size
  void setSize(int edgeLength);
3.// effects:  sets this.width and this.height to w
  void setSize(int w, int h);
4. // effects: fits shape to given size
   // throws BadSizeException if w != h
  void setSize(int w, int h) throws BadSizeException;
```

Square, Rectangle Unrelated (Subtypes)

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

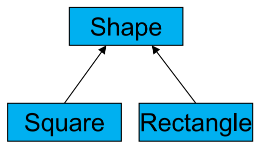


Rectangle is not a (true subtype of) **Square**:
- **Square**s are expected to have equal widths and heights
- **Rectangle**s violate that expectation, could surprise client



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 **`String`**s

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:

```
class Properties extends Hashtable<Object,Object> {
  …
}
```

Better choice:

```
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

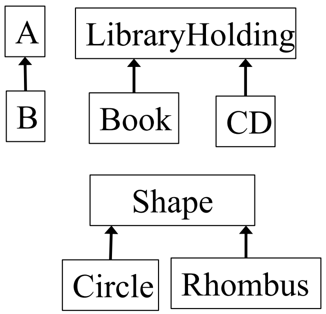
B is *not permitted to weaken* a spec
- No method removal
- No overriding method with a weaker spec

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:

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

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

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

Java subtyping

- Java types:
  - Defined by classes, interfaces, primitives
- Java subtyping stems from **`B extends A`** and **`B implements A`** declarations
- In a Java subtype, each corresponding method has:
  - Same argument types
    - If different, *overloading*: unrelated methods
  - Compatible (covariant) return types
    - A (somewhat) recent language feature, not reflected in (e.g.) **`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 T1 holds a reference to an object of *actual* (*runtime)* type T2, then T2 must be a Java subtype of T1

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

```
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?

```
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.

Solution 2b: composition

Delegate

```
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>
}
```

The implementation no longer matters

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

Interfaces reintroduce Java … typing

Avoid encoding implementation details

```
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 …
  }
  public boole… c) {
      addCount …
      return s…
  }
  public int getAddCount() {  return addCount; }
  // ... and every other method specified by Set<E>
}
```

What's bad about this constructor?

```
InstrumentedHashSet(Set<E> s) {
  this.s = s;
  addCount = s.size();
}
```

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