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

The Liskov Substitution Principle

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 😞

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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

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?

```java
interface Rectangle {
    // effects: fits shape to given size:
    //    thisPost.width = w, thisPost.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 elementary-school 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 value) {
        put(key, value);
    }
    public String getProperty(String key) {
        return (String) get(key);
    }
}

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

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

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 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

```java
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

```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; }
}
```

• 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

Dependence on implementation

```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?!
```

What does this code print?

- 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

```java
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
Interfaces reintroduce Java subtyping

```java
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>
}
```

Avoid encoding implementation details

What's bad about this constructor?

```java
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

```java
// 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