CSE 331
Software Design & Implementation

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Subtypes and Subclasses

(Slides by Mike Ernst and David Notkin)

What is subtyping?

Sometimes every B is an A

In a library database:

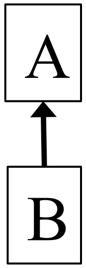
every book is a library holding

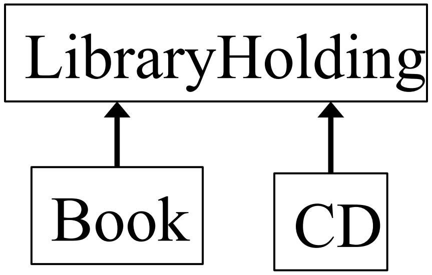
every CD is a library holding

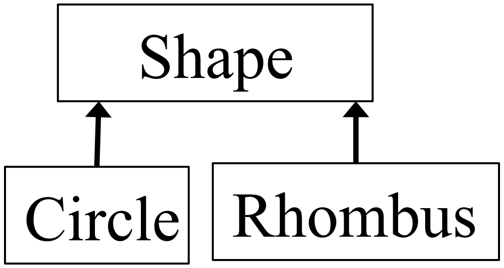
Subtyping expresses this

B is a subtype of A means:

"every object that satisfies interface B also satisfies interface 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

Subtyping and 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
- Similarities to satisfiability (behavior of P is a subset of S)

Inheritance (subclass) — an implementation notion

- Abstract out repeated code
- To create a new class, just write the differences
- Every subclass is a Java subtype
  - But not necessarily a true subtype

Outline of this lecture:

  Specification
  Implementation (& Java details)

Subclasses support inheritance
Inheritance makes it easy to add functionality

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

```
class Product {
    private String title;
    private String description;
    private float price;
    public float getPrice() { return price; }
    public float getTax()
              { return getPrice() * 0.095f; }
    // ...
}
```

... and we need a class for *Products that are on sale*

Code copying is a bad way to add functionality

We would never dream of cutting and pasting like this:

```
class SaleProduct {
  private String title;
  private String description;
  private float price;
  private float factor;
  public float getPrice(){ return price*factor; }
  public float getTax()
                    { return getPrice() * .095; }
  ...
}
```

Inheritance makes small extensions small

It’s much better to do this:

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

Benefits of subclassing & inheritance

- Don’t repeat unchanged fields and methods
  - In implementation
    - Simpler maintenance: just 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 are 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 leads to a muddled inheritance hierarchy
  - Relationships may not match untutored intuition
- If subclass is tightly coupled with superclass
  - Can depend on implementation details of superclass
  - Changes in superclass can break subclass
    - “fragile base class problem”

- Subtyping and implementation inheritance are orthogonal
  - Subclassing gives you both
  - Sometimes you want just one
    - Interfaces: subtyping without inheritance
    - Composition: reuse implementation without subtyping

Every square is a rectangle (elementary school)

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

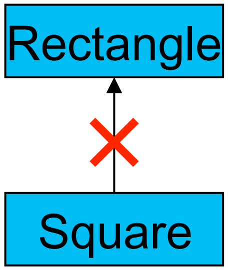
Which is the best option for `Square.setSize()`?

```
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 and rectangle are unrelated (subtypes)

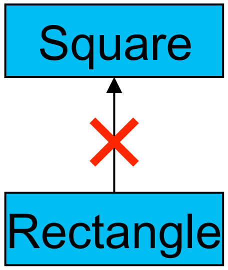
Square is not a (true subtype of) Rectangle:

- Rectangles are expected to have a width and height that can be changed 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

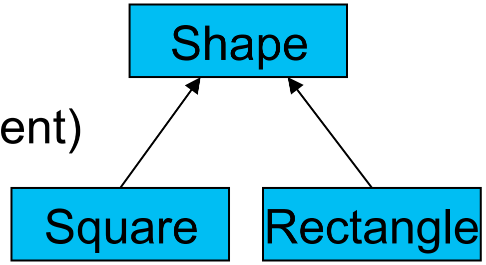


Inheritance isn't always intuitive

- Benefit: it forces clear thinking and prevents errors

Solutions:

- Make them unrelated (or siblings under a common parent)
- Make them immutable



Inappropriate subtyping in the JDK

Properties class stores string key-value pairs.
It extends **Hashtable** functionality.
What's the problem?

```
class Hashtable<K,V> {
    // modifies: this
    // effects: associates the specified value with the specified key
    public void put (K key, V value);

    // returns: value with which the
    // specified key is associated
    public V get (K key);
}
```

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

```
// Keys and values are strings.
class Properties extends Hashtable<Object,Object> {  // simplified
    // modifies: this
    // effects: associates the specified value with the specified key
    public void setProperty(String key, String val) { put(key,val); }

    // returns: the string with which the key is associated
    public String getProperty(String key) { return (String)get(key); }
}
```

Violation of superclass specification

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.

Also, the semantics are more confusing than we've shown

`getProperty("prop")` works differently than **`get("prop")`** !

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?

(postpone for now – we’ll get to generics shortly)

Solution 2: Composition

```
class Properties {  // no “extends” clause!
    private Hashtable<Object, Object> hashtable;   // the “delegate”

    // requires: key and value are not null
    // modifies: this
    // effects: associates specified value with specified key
    public void setProperty (String key, String value) {
        hashtable.put(key,value);
    }

    // effects: returns string with which key is associated
    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 the supertype must be guaranteed by the subtype

- The subtype is permitted to strengthen & add properties
- Anything provable about an A is provable about a B
- If an instance of subtype is treated purely as supertype – only supertype methods and fields queried – the result should be consistent with an object of the supertype being manipulated

No specification weakening

- No method removal
- An overriding method has a stronger (or equal) spec
  - A weaker or equal precondition
  - A stronger or equal postcondition

Substitution principle for methods

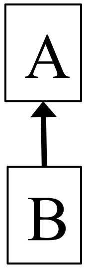
Constraints on methods

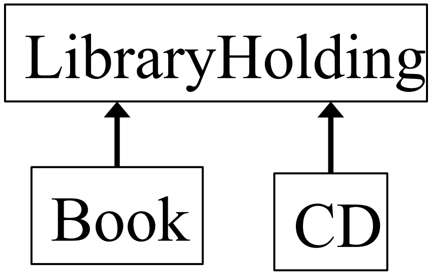
- For each supertype method, subtype must have a corresponding overriding method
    - Can be method implementations inherited from supertype
- Subtype may also introduce new methods

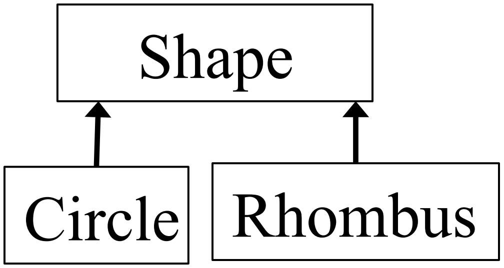
Each overriding method must strengthen (or match) the spec:

- Ask nothing extra of client (“weaker precondition”)
    - *Requires* clause is at most as strict as in the supertype 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

The spec for a substituting (overriding) method must be stronger (or same)







Method inputs:

- Argument types in A.foo() may be replaced with supertypes in B.foo() (“contravariance”)
- This places no extra demand on the client
- But Java forbids any change (Why?)

Method results:

- Result type of A.foo() may be replaced by a subtype in B.foo() (“covariance”)
  - This doesn't violate any expectation of the client
- No new exceptions (for values in the domain)
- Existing exceptions can be replaced with subtypes
  - This doesn't violate any expectation of the client

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) throws NoSaleException; // bad
```

Same kind of reasoning for exception subtyping, and modifies clause

JDK example: not a stronger spec

```
class Hashtable { // class is somewhat simplified (generics omitted)
    //  modifies: this
    // effects: associates the specified value with the specified key
    public void put (Object key, Object value);

    // returns: value with which the
    // specified key is associated
    public Object get (Object key);
}
class Properties extends Hashtable {
    // modifies: this
    // effects: associates the specifi[illegible]e with the specified key
    public void put (String key, Stri[illegible]al) { super.put(key,val); }

    // returns: the string with [illegible]hich the key is associated
    public String get (String key) { return (String)super.get(key); }
}
```

Arguments are subtypes
Stronger requirement =
weaker specification!

Result type is a subtype
Stronger guarantee = OK

Might throw an exception for value in the domain
New exception = weaker spec!

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 (= 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 holds a reference to an object of *actual* (*runtime)* type T', then T' must be a (Java) subtype of T

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

This rules out a huge class of bugs

Inheritance can break encapsulation

```
public class InstrumentedHashSet<E> extends HashSet<E> {
    private int addCount = 0;  // count attempted 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!
  - HashSet.addAll() calls add() ⇒ double-counting
- AbstractCollection.addAll specification states:
  - “Adds all of the elements in the specified collection to this collection.”
  - Does not specify whether it calls add()
- Lesson: designers should plan for their classes to be extended

Solutions

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

Disadvantages (may be a worthwhile price to pay):

- May be hard to apply to callbacks, equality tests
- Tedious to write (your IDE will help you)
- Does not preserve subtyping

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 to just meet specification

Interfaces to the rescue

- Can declare that we implement interface **`Set`**
- If such an interface exists

Interfaces reintroduce Java subtyping

```
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 about this constructor?

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

Interfaces and abstract classes

- Provide interfaces for your functionality
  - The client codes to interfaces rather than concrete classes
  - Allows different implementations later
  - Facilitates composition, wrapper classes
    - Basis of lots of useful, clever tricks
    - We'll see more of these later
- Consider providing helper/template abstract classes
  - Can minimize number of methods that new implementation must provide
  - Makes writing new implementations much easier
  - Using them is entirely optional, so they don't limit freedom to create radically different implementations

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
    - Safe 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