CSE 331
Software Design & Implementation

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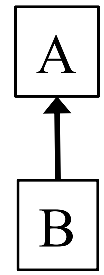
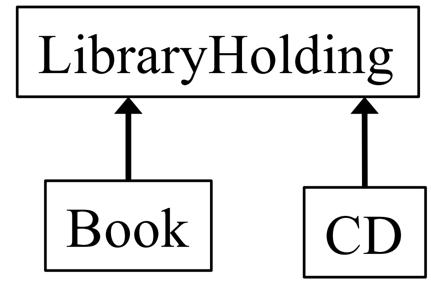
Subtypes and Subclasses

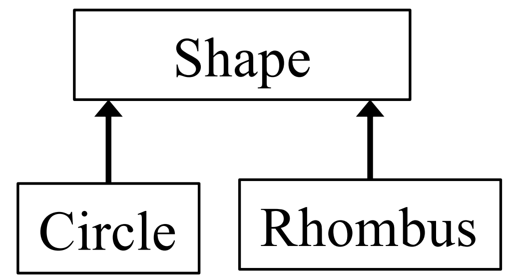
What is subtyping?

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
- i.e., a client that expects a Shape will work fine if given a Circle

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** (**`B extends A`**)
- Java subtypes that are not true subtypes are *confusing* and *dangerous*
  - But unfortunately fairly 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
- Any fact about an A object is true about a B object
- Similar to 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;
    @Override
    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 migth not match untutored intuition
- Poor design can produce subclasses that depend on many implementation details of superclasses
- Changes in superclasses can break subclasses if they are tightly coupled
  - "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 {…}
```

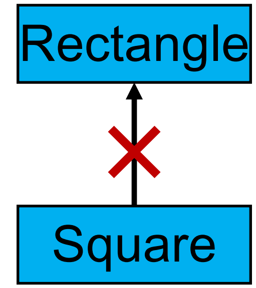
Which is the best option for **Square**'s **setSize** specification?

```
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 (Java)

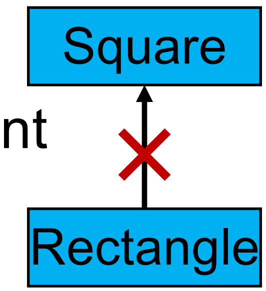
`Square` is not a (true subtype of) **`Rectangle`**:

- **`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

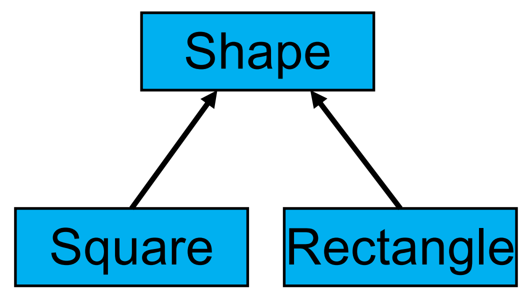


Inheritance is not always intuitive

- 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 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
  - But only **`Hashtable<Object,Object>`** is compatible with all clients that might exist

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 supertype A must be guaranteed by subtype 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

Subtype B is *permitted to strengthen* properties and add properties

- An overriding method must have a stronger (or equal) spec
- Fine to add new methods (that preserve invariants)

Subtype B is *not permitted to weaken* the 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, but nothing new

Spec strengthening: argument/result types

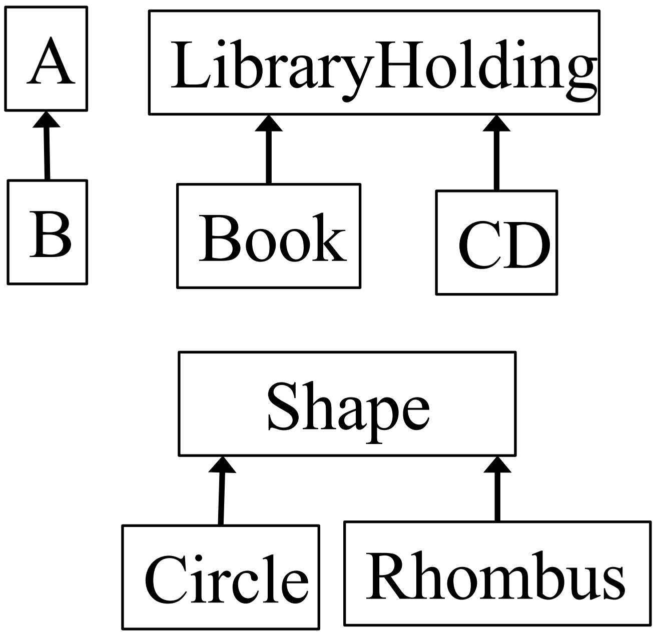
Method inputs:

- Argument types in A.foo may be replaced with supertypes in B.foo (“contravariance”)
- Places no extra demand on the clients
- But Java does not allow such overriding
  - (Why?)

Method results:

- Result type of A.foo may be replaced by a subtype in B.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
    - Added to Java several years after initial release, 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

(A type T is considered to be a subtype of itself to simplify things)

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

Clients can still infer implementation details

- Client use of == can reveal reuse of values
  - Return existing immutable value rather than creating a new copy
- Client use of iterator can reveal whether data is stored in any particular order (sorted or not, …)
- Client use of subclassing can reveal self-calls in implementation (example below)

- Lesson: don't do this!
- Clients should not observe/depend on behavior not promised by the spec

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`**
- Lessons:
  - Subclassing often requires designing for extension
  - Clients should not depend on unspecified implementation behavior

Solutions – how to count inserts

1. Change spec of **`HashSet`** (eliminate ambiguity)
   - Indicate all self-calls
   - Less flexibility for implementers of specification
   - Most clients don't care

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.
      - But avoids dependency on **`HashSet`** spec

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*

- Example of a "wrapper" class
- Easy to reason about; self-calls are irrelevant
- 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

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
      addCount++;
      return s.add(o);
  }
  public boolean addAl
      addCount += c.size();
      return s.addAll(c);
  }
  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

- Clients 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 by providing some implementations in abs. class
- Makes writing new implementations much easier
- Optional – not needed to use interfaces or to create different implementations of 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

Justification for Java decisions:

- 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 wind up depending on unspecified details of the implementation of its superclass
    - example: 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 have clients use composition instead