CSE 331
Software Design & Implementation

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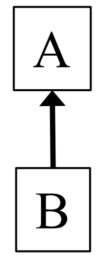
Subtypes and Subclasses

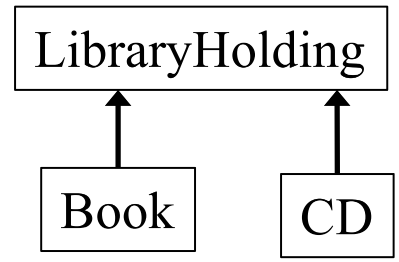
(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)

What is subtyping?

Sometimes "*every B is an A*"

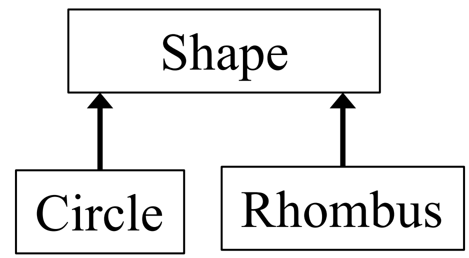
- examples in a library database:
  - every book is a library holding
  - every CD is a library holding





For subtyping, "*B is a subtype of A*" means:

- "every object that satisfies the rules for a B also satisfies the rules for an A"
- (B is a strengthening of A)



Goal: code written using A's **spec** operates correctly if given a B

- plus: clarify design, share tests, (sometimes) share code

Subtypes are substitutable

Subtypes are ***substitutable*** for supertypes

- Liskov substitution principle
- 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 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: *confusing* & *dangerous*
    - but unfortunately common ☹

Subtyping vs. subclassing

Substitution (subtype) is a matter of specifications

- B is a subtype of A iff an object of B can masquerade as an object of A in any context
- B is a subtype if its spec is is a strengthening of A's spec

Inheritance (subclass) is a matter of implementations

- 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() * 0.086);
    }
    …
}
```

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

Copy and Paste

```
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() * 0.086);
    }
    …
}
```

Not a good choice. — Why? (hint: properties of high quality code)

Inheritance makes small extensions small

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 (changeability)
  - in specification:
    - clients who understand the superclass specification need only study novel parts of the subclass (readability)
  - modularity: can ignore private fields and methods of superclass (if properly designed)
  - readability: differences not buried under mass of similarities

- Ability to substitute new implementations (modularity)
  - no client code changes required to use new subclasses

Subclassing can be misused

- Poor design can produce subclasses that depend on many implementation details of superclasses
  - super- and sub-classes are often *highly interdependent*
- 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. instead use:
    - *interfaces*: subtyping without inheritance
    - *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 {…}
```

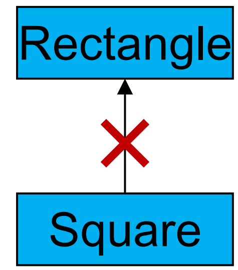
Which is the best option for `Square`'s `setSize` specification?

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 (Subtypes)

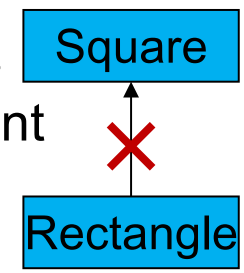
`Square` is not a (true subtype of) **`Rectangle`**:

- **`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

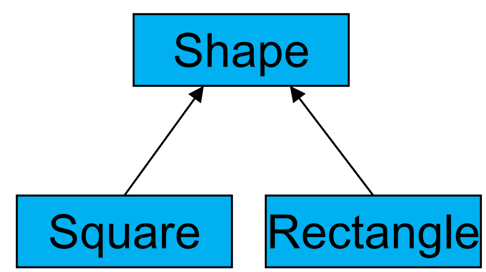


Subtyping is not always intuitive

- but 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)
- (clients can become dependent even on bugs in your code…)

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);
   }

   …
}
```

Now, there are no `get` and `put` methods on `Properties`. (Best choice.)

Substitution principle for classes

If B is a subtype of A, then 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

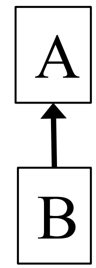
Constraints on methods

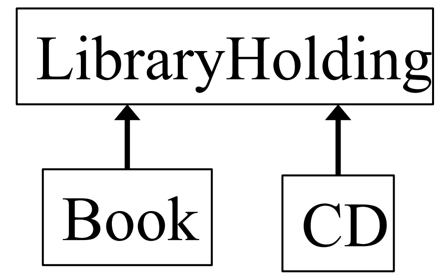
- For each supertype method, subtype must have such a method
  - (could be inherited or overridden)

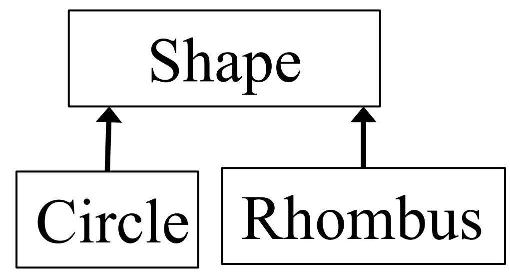
Each overridden method must *strengthen* (or match) the spec:

- 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* & *throws* clauses
    - cannot change return values or switch between return and throws

Spec strengthening: argument/result types







For method inputs:

- argument types in A's foo *could* be replaced with supertypes in B's foo
- places no extra demand on the clients
- but Java does not have such overriding

For method outputs:

- result type of A's foo may be replaced by a subtype in B's foo
- 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, then *overloading* — unrelated methods
  - compatible return types
  - 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

Java subtyping non-guarantees

Java subtyping does **not** guarantee that overridden methods

- have smaller requires
- have smaller modifies
- have stronger postconditions
  - Java only checks the *return type* not the postcondition
  - could compute a completely different function
- have stronger effects
- have stronger throws (& only for the same cases as before)
- have no new unchecked exceptions

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 elements in the specified collection to this collection."
  - does not specify whether it calls **`add`**
- Lesson: subclassing typically requires designing for inheritance
  - self-calls is not the only example… (more in future lectures)

Solutions

1. Change spec of **`HashSet`**
   - indicate all self-calls
   - less flexibility for implementers

2. Avoid spec ambiguity by avoiding self-calls
   a) "re-implement" methods such as **`addAll`**
      - more work

   b) use composition
      - no longer a subtype (unless an interface is handy)
      - bad for equality tests, callbacks, 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
  - sometimes tedious to write
  - may be hard to apply to equality tests, callbacks, etc.
    - (although we already saw equals is hard for subclasses)

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

normal Java style

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
  }
  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*

- makes writing new implementations much easier
- not necessary to use them to implement an interface, so retain 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
    - okay when implementation of both is under control of the same programmer
  - this is tricky to get right and is a source of subtle bugs

- Effective Java:
  - either **design for inheritance** or else **prohibit it**
  - favor composition (and interfaces) to inheritance