Subtypes

CSE 331
University of Washington

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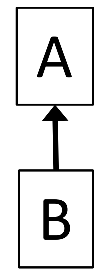
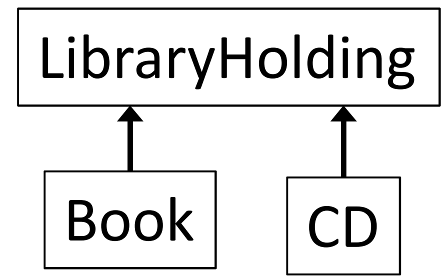
What is subtyping?

- Sometimes every B is an A

  In a library database:
  - every book is a library holding
  - every CD is a library holding

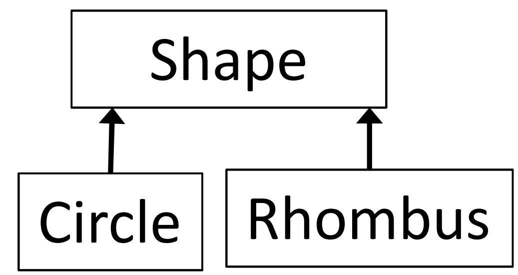




- Subtyping expresses this

  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
  - Clients need not change their code to use new subclasses

Subclassing can be misused

Poor planning leads to 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 the given size
  //     this_post.width = w, this_post.height = h
  void setSize(int w, int h);
}
interface Square implements Rectangle {…}
```

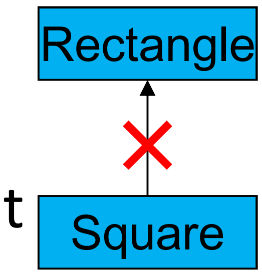
Which is the best option for `Square.setSize()`?

```
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 (Java)

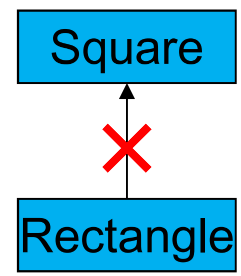
Square is not a (true subtype of) Rectangle:

- Rectangles are expected to have a width and height that can be changed independently
- Squares violate that expectation, could surprise client



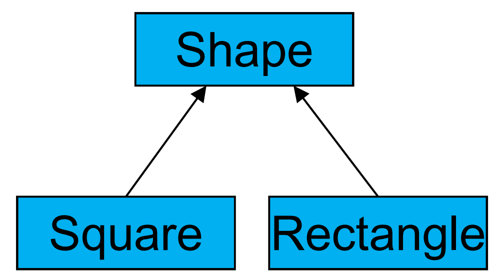
Rectangle is not a (true subtype of) Square:

- Squares are expected to have equal width and height
- Rectangles violate that expectation, could surprise client



Inheritance isn't always intuitive

- Benefit: it forces clear thinking and prevents errors



Solutions:

1. Make them unrelated (or siblings under a common parent)
2. 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 I'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> { ... }
```

Why didn’t the JDK designers make this choice?

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);
    }
    ...
}
```

Aside: Subtyping for generics

Object

List<?>

List

Number

Don't use *raw types* like **`List`**!
(CSE 331 forbids it)

List<Object>

Integer

List<? extends Number>

List<Number>

List<Integer>

List<Double>

ArrayList<Integer>

LinkedList<Integer>

Subtyping requires invariant generic types:
C<X> is unrelated to C<Y> unless X=Y
A later lecture will explain why
Exception: wildcards

Substitution principle for classes

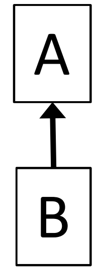
- If B is a subtype of A, a B can always be substituted for an A
- Any property guaranteed by supertype must be guaranteed by subtype
  - The subtype is permitted to strengthen & add properties
  - Anything provable about an A is provable about a B
  - If an instance of subtype is treated purely as supertype – only supertype methods and fields queried – then result should be consistent with an object of the supertype being manipulated
- No specification weakening
  - No method removal
  - An overriding method has a stronger spec
    - a weaker or equal precondition
    - a stronger or equal postcondition

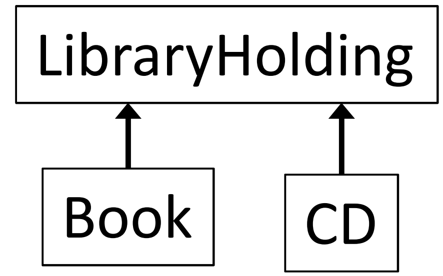
Substitution principle for methods

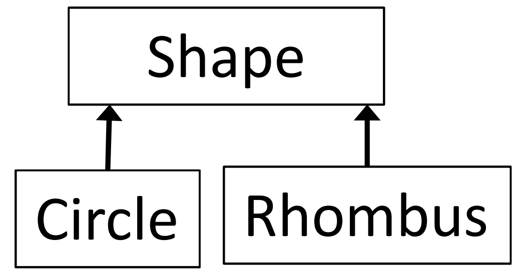
- Constraints on methods
  - For each method in supertype, subtype must have a corresponding overriding method
    - Includes method implementations inherited from supertype
  - May also introduce new methods
- Each overriding method has a stronger (or equal) spec
  - Ask nothing extra of client (“weaker 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 overriding method satisfies the superclass spec

The spec for a substituting (overriding) method is stronger

- Method inputs:
  – Argument types of `A.foo()` may be replaced by supertypes in `B.foo()` in the subclass ("contravariance")
  – This places no extra demand on the client
  – Java forbids any change (Why?)







- Method results:
  – Result type of `A.foo()` may be replaced by a subtype in `B.foo()` in the subclass ("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 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 specified value with the specified key
    public void put (String key, String val) { super.put(key,val); }

    // returns: the string with which the key is associated, OR
    //    throws a ClassCastException
    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 on a value in the doman
New exception = weaker spec!

Is this good inheritance?

Depends on the members, methods and the specifications

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 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() $\Rightarrow$ 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

```
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>
}
```

Delegate

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 (might 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 the class implements interface Set
  - Requires that 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

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

Concrete, abstract, or interface?

Telephone

- $10 landline, Speakerphone, cellphone, Skype, VOIP phone

TV

- CRT, Plasma, DLP, LCD

Table

- Dining table, Desk, Coffee table

Coffee

- Espresso, Frappuccino, Decaf, Iced coffee

Computer

- Laptop, Desktop, Server, Cloud, Phone

CPU

- x86, AMD64, ARM, PowerPC

Professor

- Ernst, Notkin

Type qualifiers

A way of using subtyping when you can't write a new class

- Can express more than Java's built-in type system
- Supported in Java 8

`Date` is a type

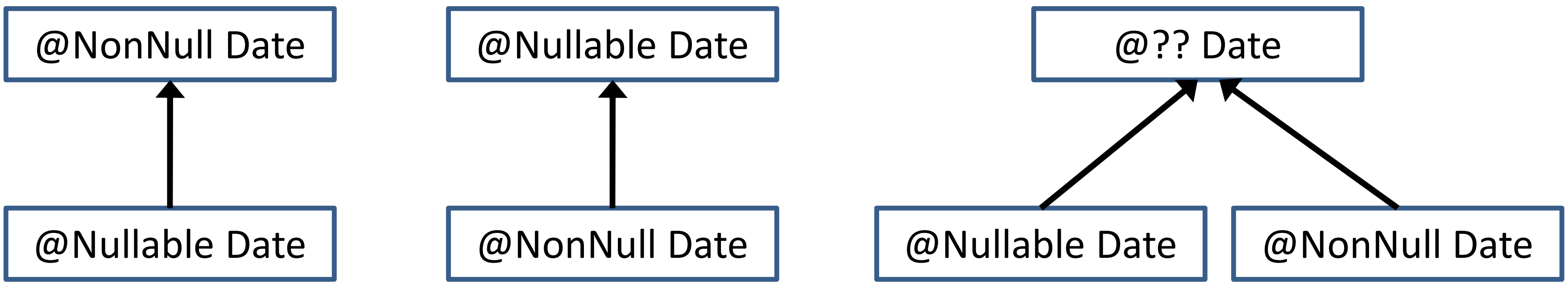
- `@Nullable Date` is a type
- `@NonNull Date` is a type

```
Date d;                    // 7/4/1776, 1/14/2011, null, …
@Nullable Date nbleD;      // same values as Date
@NonNull Date nnD;         // 7/4/1776, 1/14/2011, …

nbleD.getMonth();          // compile-time (not run-time!) error
nnD.getMonth();            // OK
```

Nullness subtyping relationship

- Which type hierarchy is best?



- A subtype has fewer values
- A subtype has more operations
- A subtype is substitutable
- A subtype preserves supertype properties