Subtypes

CSE 331
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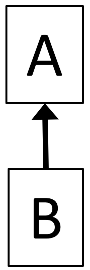
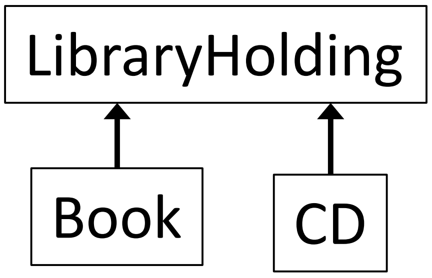
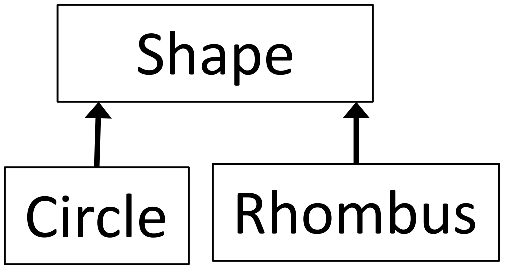
What is subtyping?

- 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 specification B also satisfies specification 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 (preconditions *and* postconditions)
  - If code is written to handle a Shape, it works if supplied 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**
  - 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
  - Any fact about A objects is true about B objects
  - Similarities to satisfiability (behavior of P is a subset of S)
- Inheritance (subclass) — an implementation notion
  - Factor 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() * 0.101; }
  ...
}
```

... 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() * 0.101; }
  ...
}
```

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 a mass of similarities
- Ability to substitute new implementations
  - Clients can use new subclasses without changing their code

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 {…}
```

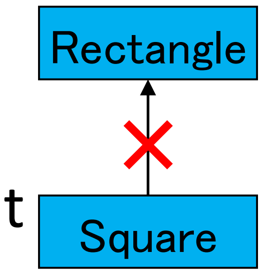
Which of these options are permissible for `Square.setSize()`?

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)

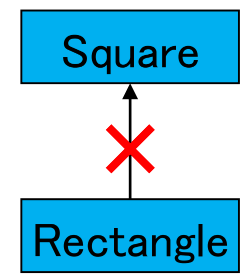
Square is not a (true subtype of) Rectangle:

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



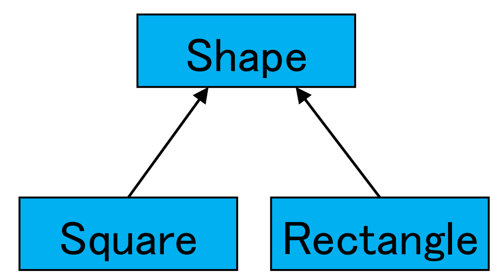
Rectangle is not a (true subtype of) Square:

- 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);
}
```

```
Properties p = new Properties();
Hashtable tbl = p;
tbl.put("One", new Integer(1));
p.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 `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.*

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?

Backward compatibility

- Properties was defined before Java had generics
- Only `Hashtable<Object,Object>` is compatible with all clients that might exist

Solution 2: Composition

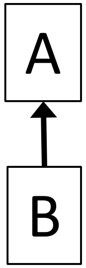
```
class Properties {  // no "extends" clause!
    private Hashtable<Object, Object> hashtable;   // the "delegate"

    // 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);
    }
    ...
}
```

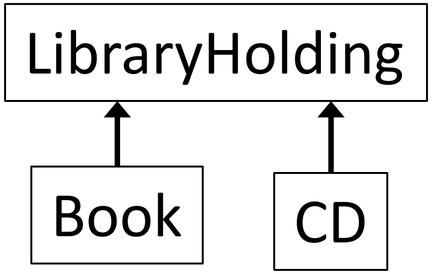
Substitution principle for classes

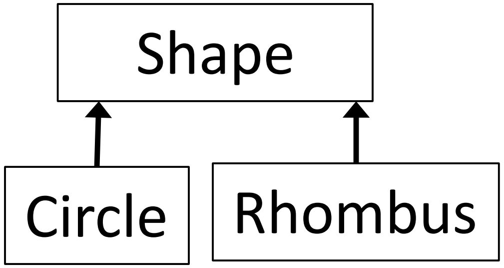
- If B is a subtype of A, a B can always be substituted for an A
- Any property guaranteed by the supertype must be guaranteed by the subtype
  - Anything provable about an A is provable about a B
  - If an instance of a subtype is treated purely as supertype (only supertype methods and fields queried) then result should be consistent with an object of the supertype being manipulated
- Subtype may strengthen the spec
  - May add new methods
  - An overriding method must have a stronger or equal spec
- Subtype may not weaken the spec
  - No method removal
  - No overriding method with a weaker spec

A stronger spec's Java signature

- Method inputs: weaker precondition
  - Parameter 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: stronger postcondition
  - 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

Simplified example (generics omitted)

```
class Hashtable {
    // 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!

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
    - not reflected in (e.g.) `clone` which predates this Java capability
  - 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_c holds a reference to an object of *actual* (*runtime)* type T_r, then T_r is a (Java) subtype of T_c
- 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 infer implementation details

- Client use of == can reveal library caching
  - Return existing immutable value, rather than creating a new value
- Client use of iterator can reveal whether library stores data in sorted order
- Client use of subclassing can reveal self-calls in implementation

- Lesson: Don't do that!
- Clients should not observe behavior not promised by the spec

Inheritance can reveal implementation details

```
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!
  - If **`HashSet.addAll()`** calls **`add()`**, then 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()`**
- Specification made no promises about implementation details
- *Clients shouldn't assume unspecified implementation behavior*

How to get a count of insertions

1. Change spec of **`HashSet`** (eliminate ambiguity)
   - Strengthen the spec
     - Indicate all self-calls (maybe indicate none are made)
   - Less flexibility for implementers of specification
     - May require re-implementing methods
   - Most clients don't care

2. Use a wrapper
   - No dependence on **`HashSet`** spec
   - No longer a subtype (might be able to use an interface)
     - Bad for callbacks, equality tests, etc.

Solution 2: Composition (wrapper)

```
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 of **HashSet** no longer matters

Composition (wrappers, delegation)

Implementation *reuse* without *inheritance*

- Easy to reason about; self-calls are irrelevant
- Enables control of implementation details
  - Can also work around badly-designed classes
- Disadvantages (might be a worthwhile price to pay):
  - Does not preserve subtyping
  - May be hard to apply to callbacks, equality tests
  - Tedious to write (your IDE will help you)

Composition does not preserve subtyping

- `InstrumentedHashSet` is not a `HashSet` anymore
  - So can't 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's bad 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, etc.
- Consider providing helper/template abstract classes
  - Abstract class:
    - Declared with **`abstract class`**
    - Does not implement all methods
    - Cannot be instantiated
  - Concrete subclass only implements missing methods
  - Using an abstract class optional; doesn't limit freedom 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>

class ArrayList<E> extends AbstractList<E>
```

Interfaces add flexibility to Java

- Java design decisions:
  - A class has exactly one superclass
  - A class may implement multiple interfaces
  - An interface may extend multiple interfaces
- Justification for Java design 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
- A subclass can observe unspecified implementation details
  - Example: pattern of self-calls
- If a class needs to control implementation details:
  - Author of superclass may design and document self-use, to simplify this type of extension
  - Client can avoid inheritance and use composition instead

Concrete, abstract, or interface?

Telephone
- $10 corded, 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

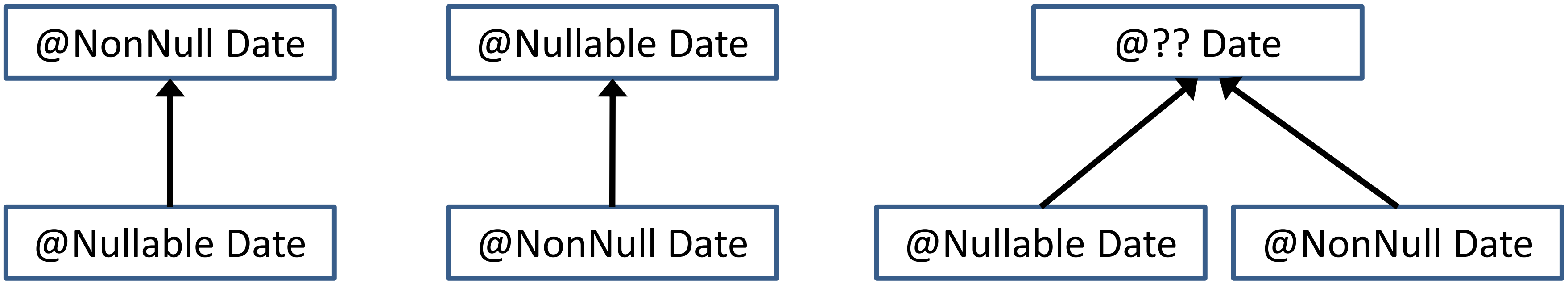
`Date` is a type

- **`@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