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# CSE 331

# Software Design & Implementation

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Subtypes and Subclasses

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

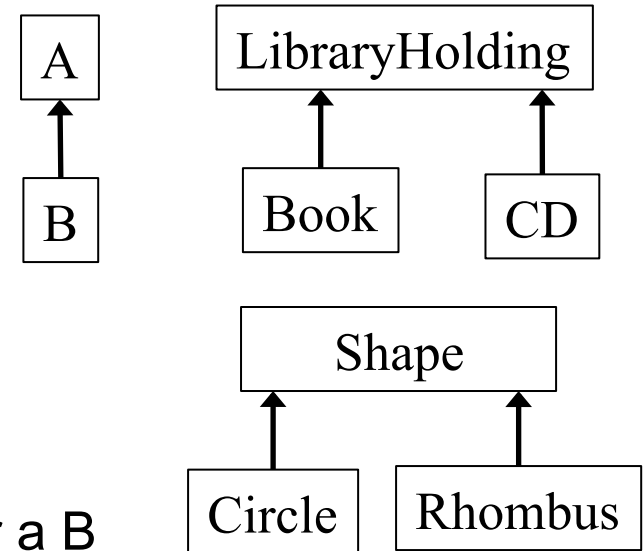
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# What is subtyping?

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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

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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**
  - But unfortunately common poor-design ☹

# Subtyping vs. subclassing

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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
- About 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

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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!

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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;  
    public int getPrice() {  
        return (int) (super.getPrice() * factor);  
    }  
}
```

# Benefits of subclassing & inheritance

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- 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

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- Poor planning can lead to a muddled *class hierarchy*
  - Relationships may not match untutored intuition
- Poor design can produce subclasses that depend on many implementation details of superclasses
- 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
    - *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?

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

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

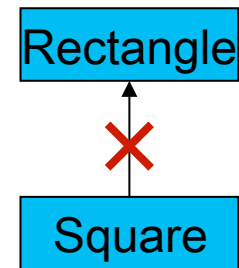
1. // requires: `w = h`  
 // effects: fits shape to given size  
 void `setSize`(int `w`, int `h`);
2. // effects: sets all edges to given size  
 void `setSize`(int `edgeLength`);
3. // effects: sets `this.width` and `this.height` to `w`  
 void `setSize`(int `w`, int `h`);
4. // effects: fits shape to given size  
 // throws `BadSizeException` if `w != h`  
 void `setSize`(int `w`, int `h`) throws `BadSizeException`;

# Square, Rectangle Unrelated (Subtypes)

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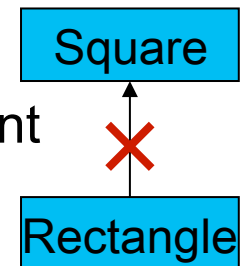
**Square** is not a (true subtype of) **Rectangle**:

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

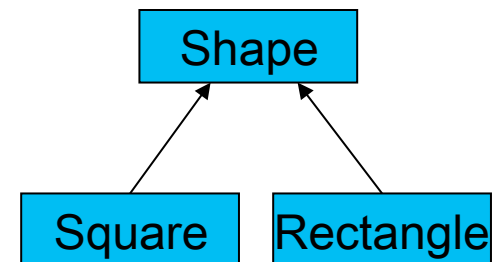


Subtyping is not always intuitive

- 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

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```
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

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**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.***

# Solution 1: Generics

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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

# Solution 2: Composition

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```
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

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If B is a subtype of A, 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

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## 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

# Spec strengthening: argument/result types

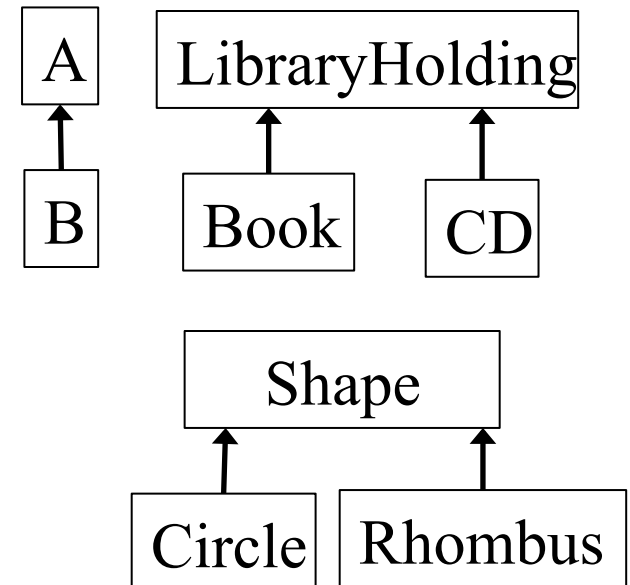
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## Method **inputs**:

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

## Method **results**:

- Result type of A's foo may be replaced by a subtype in B's 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

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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

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- 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

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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

# Inheritance can break encapsulation

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```
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

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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`
- Lesson: Subclassing often requires *designing for extension*

# Solutions

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



# Solution 2b: composition

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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)

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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
  - Tedious to write (your IDE should help you)
  - May be hard to apply to callbacks, equality tests

# Composition does not preserve subtyping

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- **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

Avoid encoding implementation details

# Interfaces reintroduce Java typing

```
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>
}
```

*What's bad about this constructor?*

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

# Interfaces and abstract classes

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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*

- Can minimize number of methods that new implementation must provide
- Makes writing new implementations much easier
- Not necessary to use them to implement an interface, so retain freedom to create radically different implementations that meet an interface

# Java library interface/class example

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```
// 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?

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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

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- 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 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