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# CSE 331

# Software Design & Implementation

Hal Perkins  
Winter 2020  
Subtypes and Subclasses

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# Administrivia (Wednesday)

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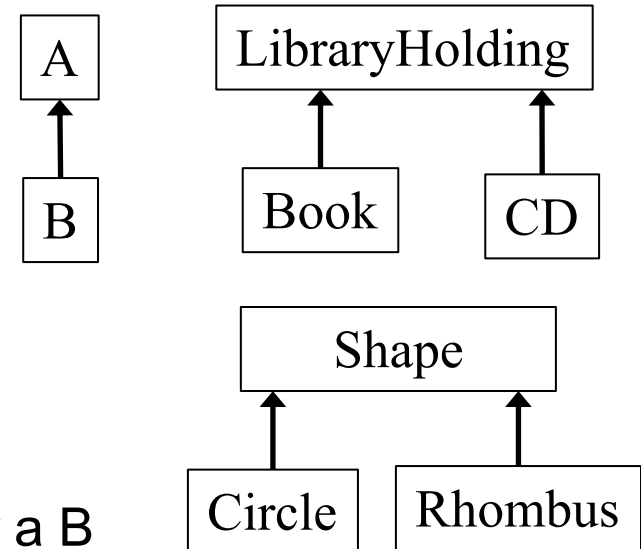
- Midterm done! Congratulations
  - Aiming to get it graded by end of weekend
- HW5 part 2 due tomorrow night (plus late day if you need it and have any remaining)
  - Don't get too ambitious – no generics, for now, for example
  - Remember main graph ADT should not assume that node/edge labels will always be comparable
    - Client code should compare/sort as needed
  - Remember to disable expensive checkRep()s in commit that has the final hw5 part 2 tag on it
  - Don't import libraries that IntelliJ "suggests" – no javafx for example. Stick to standard Java 11 libraries
- Sections tomorrow: hw6 (data files, graph searching, etc.)
  - Starter code will be pushed to repos later tonight

# 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
- 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

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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
- 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

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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

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Much better:

```
class SaleProduct extends Product {  
    private float factor;  
    @Override  
    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 might 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
    - *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:  
    //          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?

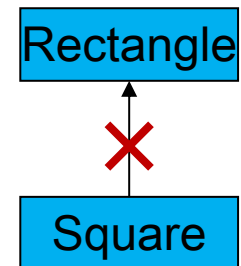
1. `// requires: w = h`  
 `// effects: fits shape to given size`  
 `void setSize(int w, int h);`
2. `// effects: sets all edges to given size`  
 `void setSize(int edgeLength);`
3. `// effects: sets this.width and this.height to w`  
 `void setSize(int w, int h);`
4. `// effects: fits shape to given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

# Square, Rectangle Unrelated (Java)

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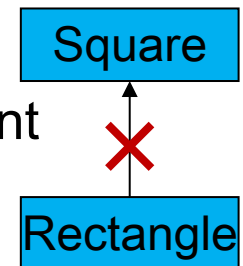
**Square** is not a (true subtype of) **Rectangle**:

- **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

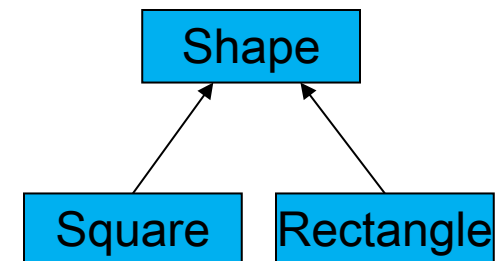


Inheritance is not always intuitive

- 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

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

## 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 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

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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, but nothing new

# Spec strengthening: argument/result types

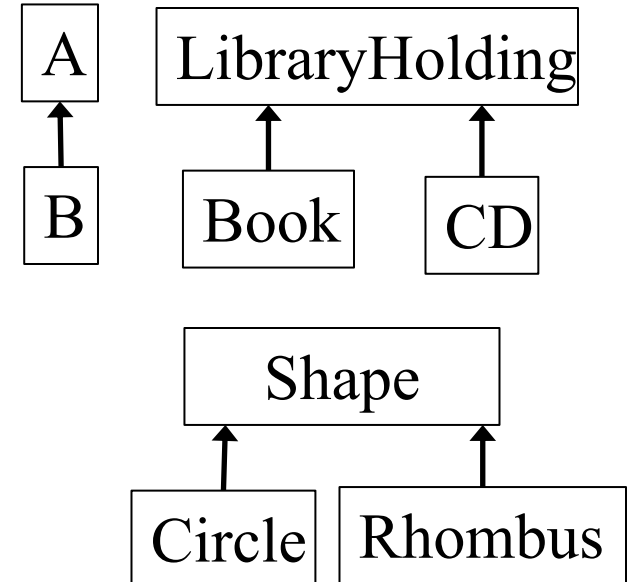
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Method **inputs**:

- 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

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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
    - Added to Java several years after initial release, 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

(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

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- 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

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

# Solutions – how to count inserts

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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

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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*

- 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

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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

# Interfaces reintroduce Java software engineering

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 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

- 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

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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

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

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- 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