Principles of Software Construction: Objects, Design, and Concurrency
(Part 1: Designing Classes)

Design for Reuse (class level)

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Administrivia

- Homework 2 due today
- Homework 3:
  - Out tonight / tomorrow
  - Due Thursday, February 9

Delegation

- *Delegation* is simply when one object relies on another object for some subset of its functionality
  - e.g. here, the `Sorter` is delegating functionality to some `Comparator`
- Judicious delegation enables code reuse

  - `Sorter` can be reused with arbitrary sort orders
  - `Comparators` can be reused with arbitrary client code that needs to compare integers

```
public class Sorter {
  void sort(int[] list, Comparator cmp) {
    …
    boolean mustswap;
    mustswap = cmp.compare(list[i], list[j]);
    …
  }}

interface Comparator {
  boolean compare(int i, int j);
}

class UpComparator implements Comparator {
  boolean compare(int i, int j) { return i<j; }}

class DownComparator implements Comparator {
  boolean compare(int i, int j) { return i>j; }}
```

Review

Using delegation to extend functionality

- One solution:

The `LoggingList` *is composed of* a `List`, and delegates (the non-logging) functionality to that `List`

```
public class LoggingList<E> implements List<E> {
  private final List<E> list;

  public LoggingList<E>(List<E> list) { this.list = list; }

  public boolean add(E e) {
      System.out.println("Adding " + e);
      return list.add(e);
  }

  public E remove(int index) {
      System.out.println("Removing at " + index);
      return list.remove(index);
  }
  …
```

Review

Review

Interface inheritance for an account type hierarchy

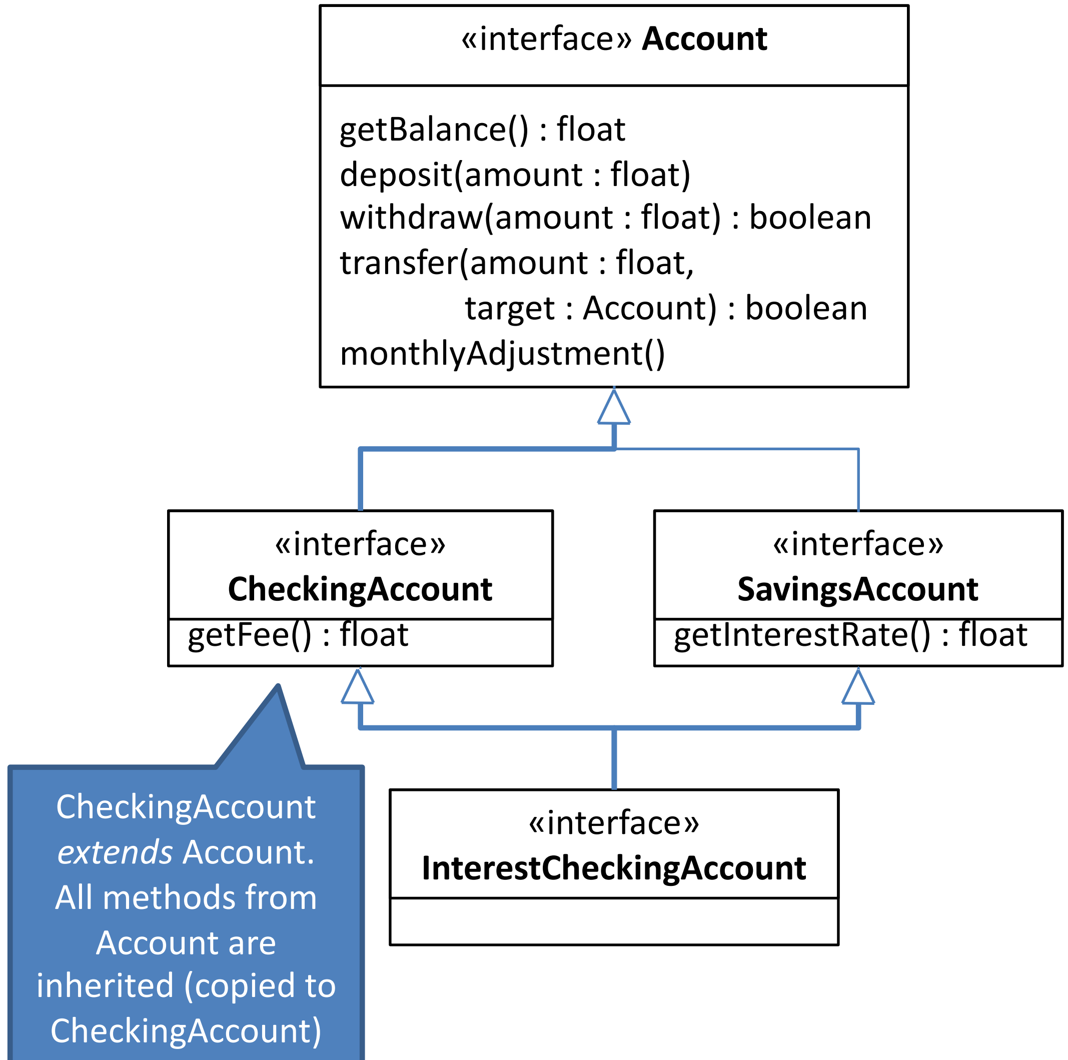
«interface» **CheckingAccount**

getBalance() : float
deposit(amount : float)
withdraw(amount : float) : boolean
transfer(amount : float,
  target : Account) : boolean
getFee() : float

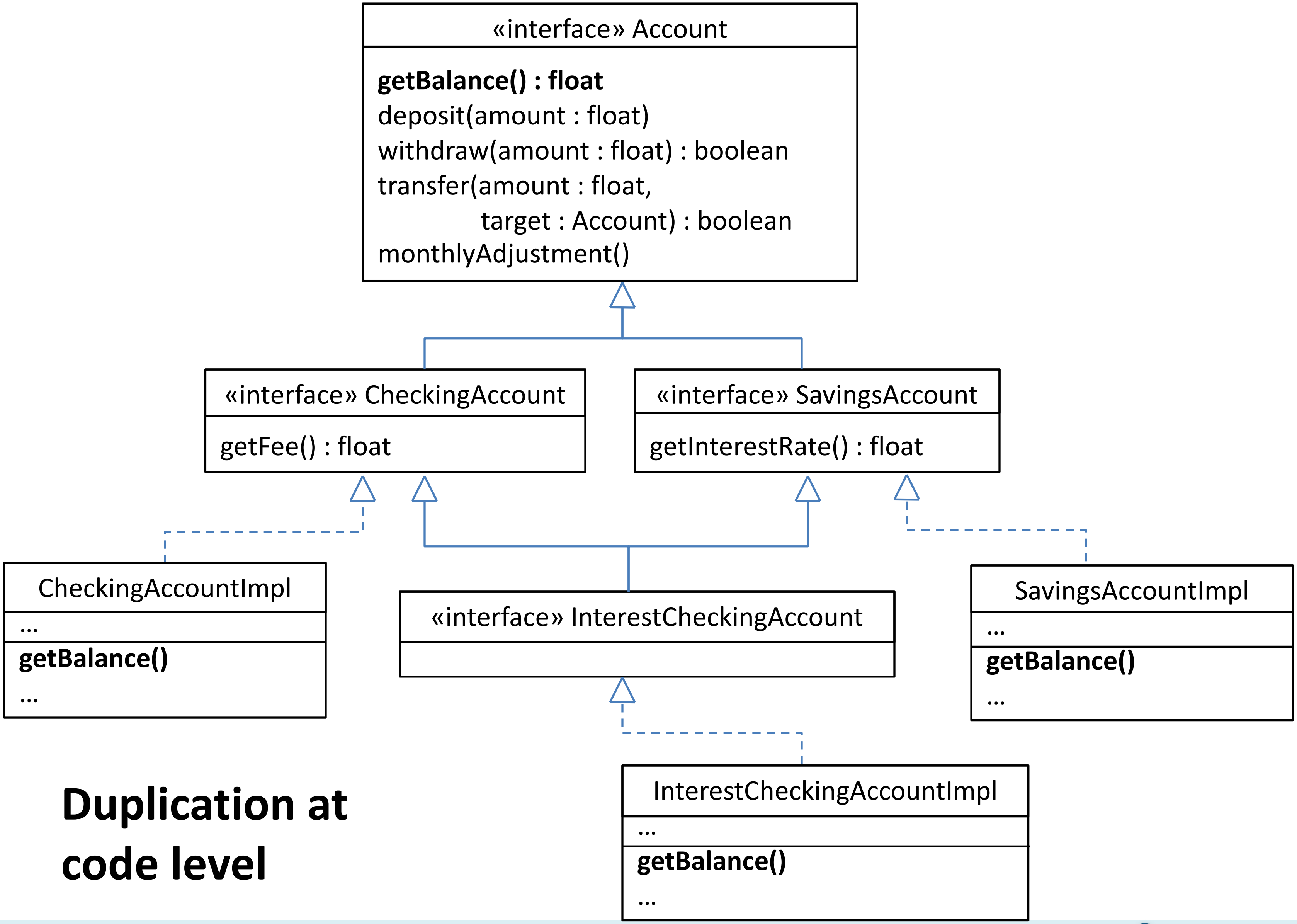
«interface» **SavingsAccount**

getBalance() : float
deposit(amount : float)
withdraw(amount : float) : boolean
transfer(amount : float,
  target : Account) : boolean
getInterestRate() : float

Duplication at design level



Implementation inheritance for code reuse



Duplication at code level

Review

Better: Reuse abstract account code

Review

an abstract class is missing the implementation of one or more methods

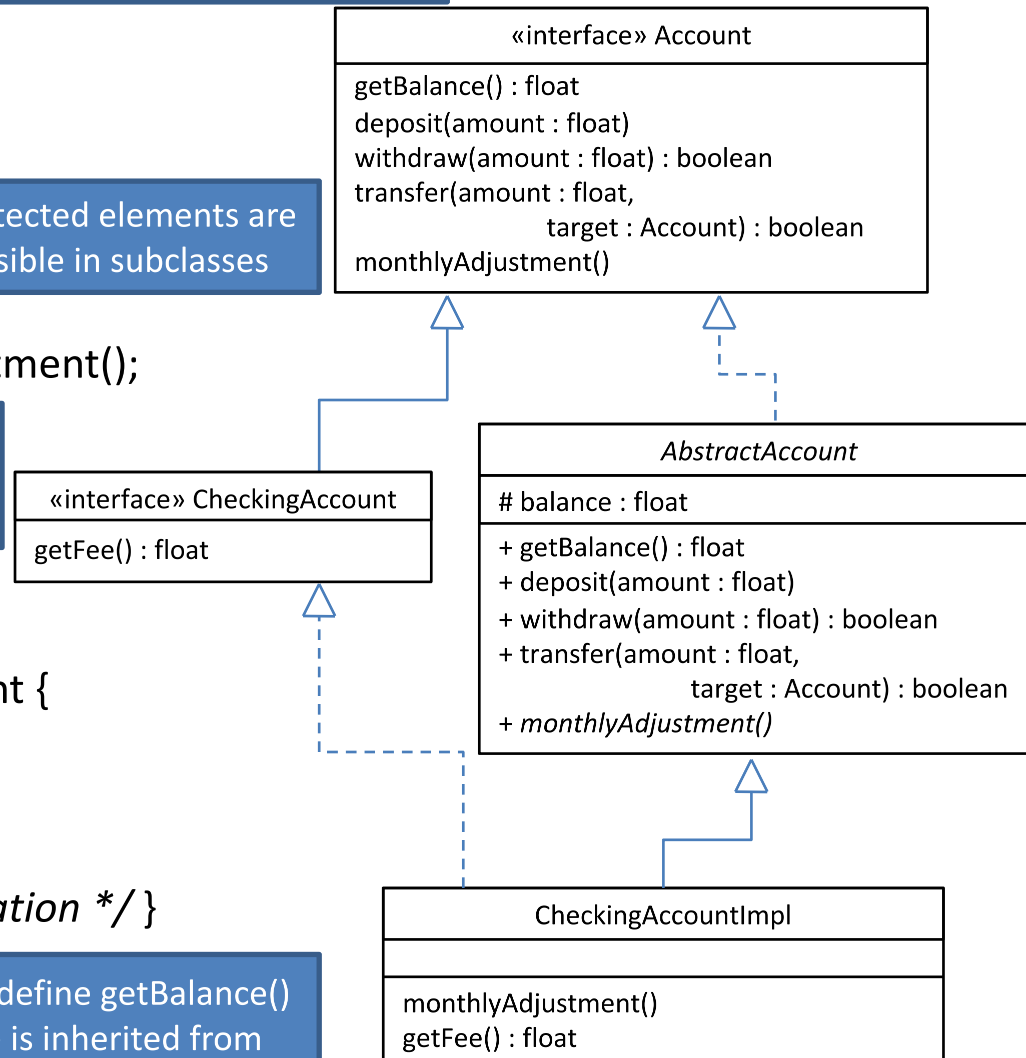
```
public abstract class AbstractAccount
            implements Account {
    protected float balance = 0.0;
    public float getBalance() {
            return balance;
    }
    abstract public void monthlyAdjustment();
    // other me
}
```

protected elements are visible in subclasses

an abstract method is left to be implemented in a subclass

```
public class CheckingAccountImpl
            extends AbstractAcount
            implements CheckingAccount {
    public void monthlyAdjustment() {
            balance -= getFee();
    }
    public float getFee() { /* fee calculation */ }
}
```

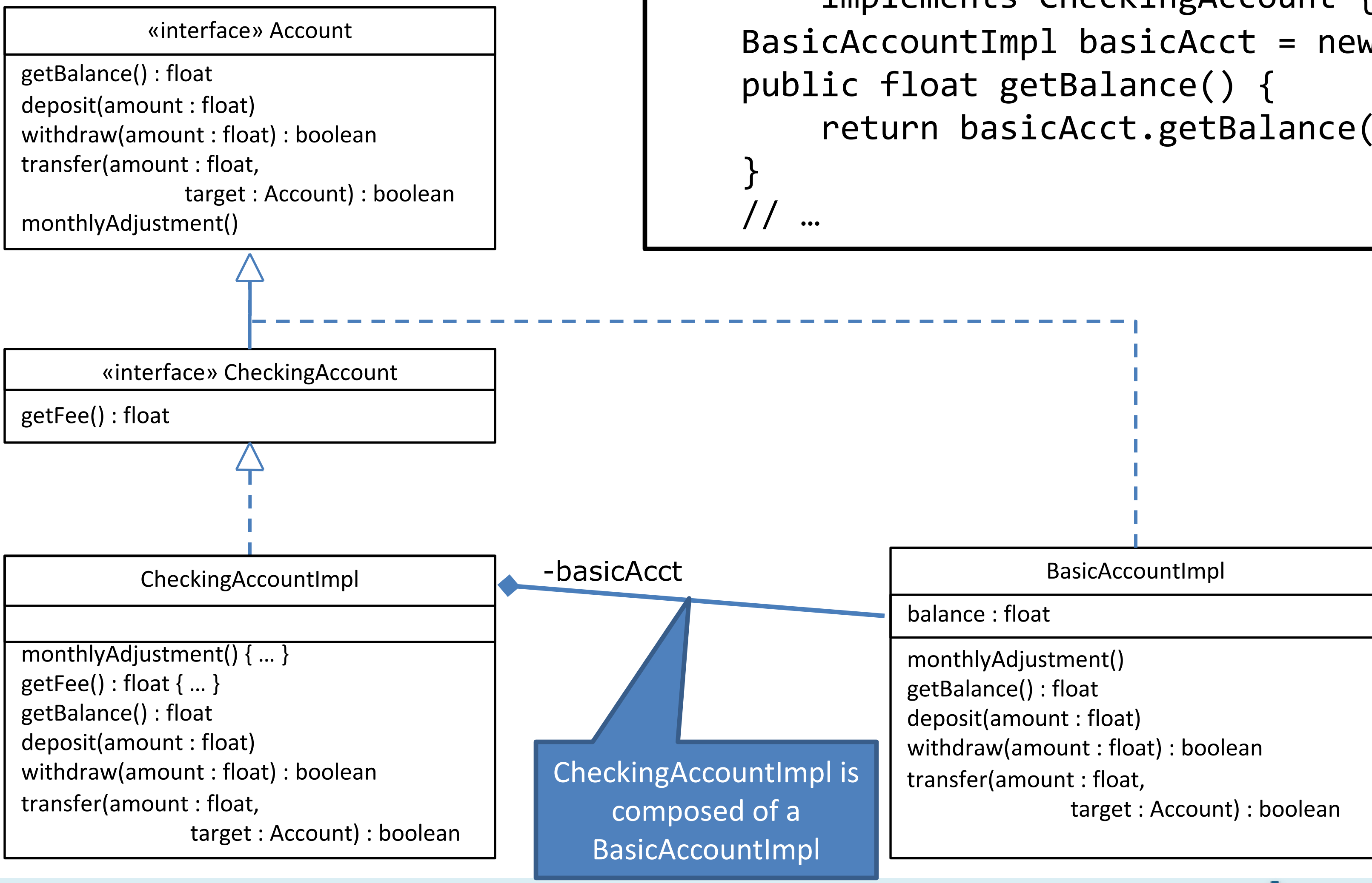
no need to define getBalance() – the code is inherited from AbstractAccount



Alternatively: Reuse via composition and delegation

Review

```
public class CheckingAccountImpl
        implements CheckingAccount {
    BasicAccountImpl basicAcct = new(…);
    public float getBalance() {
        return basicAcct.getBalance();
    }
    // …
```



(Almost always) Prefer composition over inheritance

- Tight coupling:
  - Changes to superclass → changes to subclass implementation
- Base class breaks encapsulation:
  - Exposes implementation details to subclasses (protected members)
- Inherited implementation can't change at runtime
- Inheritance stack may get very deep and confusing

- Inheritance: IS-A
  - Can use subclass where superclass is expected
  - E.g., Cessna biplane “is a” Airplane
- Composition: HAS-A
  - Only want some of the behavior of the superclass
  - E.g., Bird could (but shouldn’t) inherit from Airplane, they both fly()

THE DECORATOR DESIGN PATTERN

Limitations of inheritance

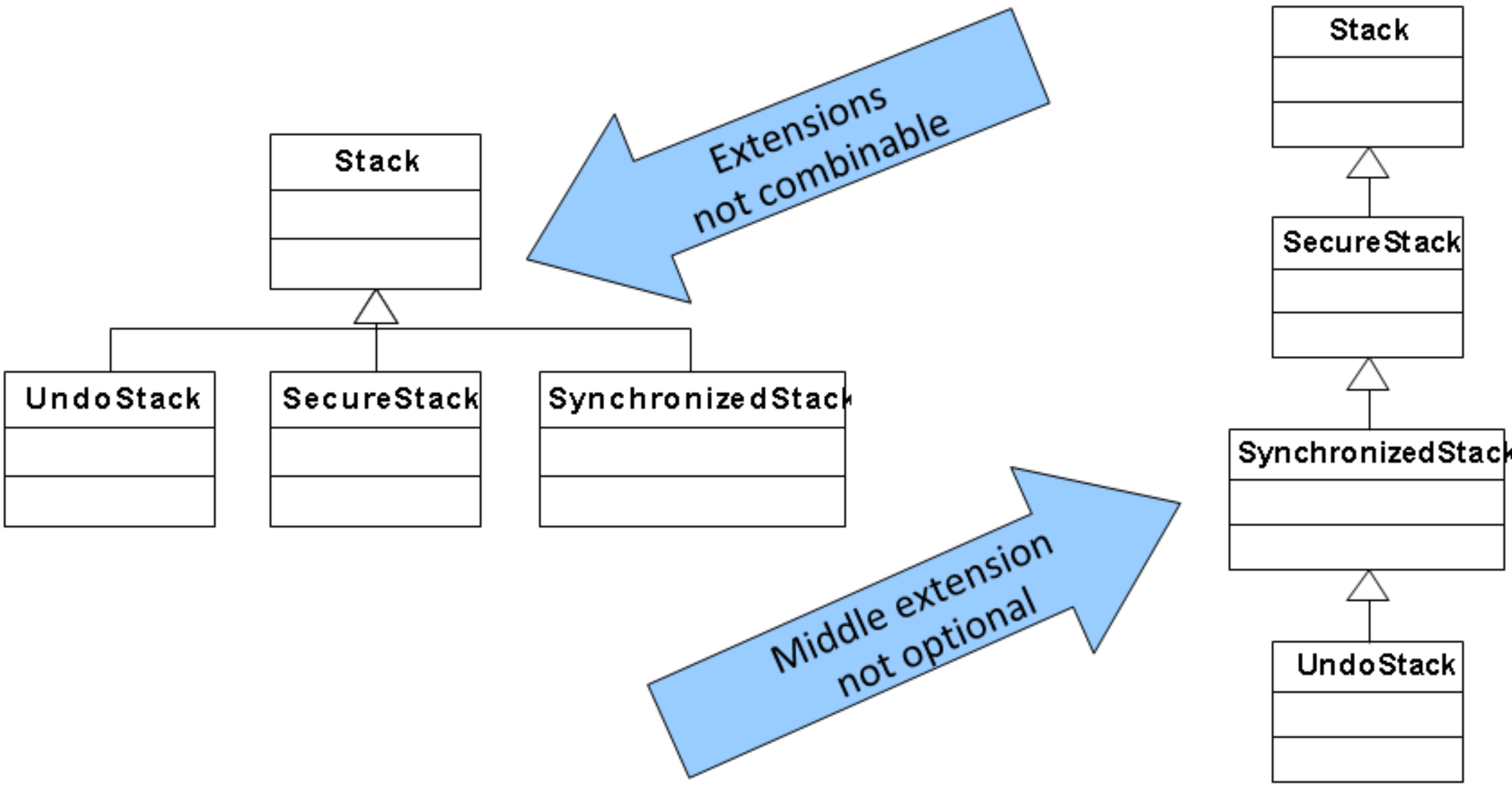
- Suppose you want various extensions of a `Stack` data structure…
  - `UndoStack`: A stack that lets you undo previous push or pop operations
  - `SecureStack`: A stack that requires a password
  - `SynchronizedStack`: A stack that serializes concurrent accesses

Limitations of inheritance

- Suppose you want various extensions of a `Stack` data structure…
  - `UndoStack`: A stack that lets you undo previous push or pop operations
  - `SecureStack`: A stack that requires a password
  - `SynchronizedStack`: A stack that serializes concurrent accesses
  - `SecureUndoStack`: A stack that requires a password, and also lets you undo previous operations
  - `SynchronizedUndoStack`: A stack that serializes concurrent accesses, and also lets you undo previous operations
  - `SecureSynchronizedStack`: …
  - `SecureSynchronizedUndoStack`: …

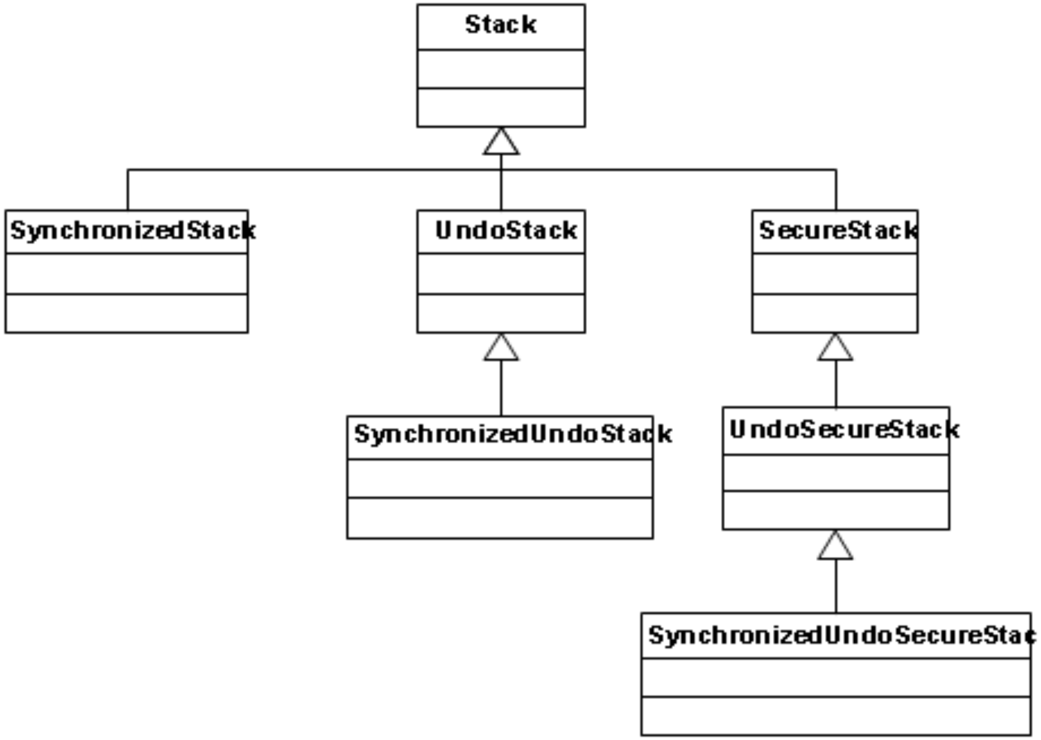
Goal: arbitrarily composable extensions

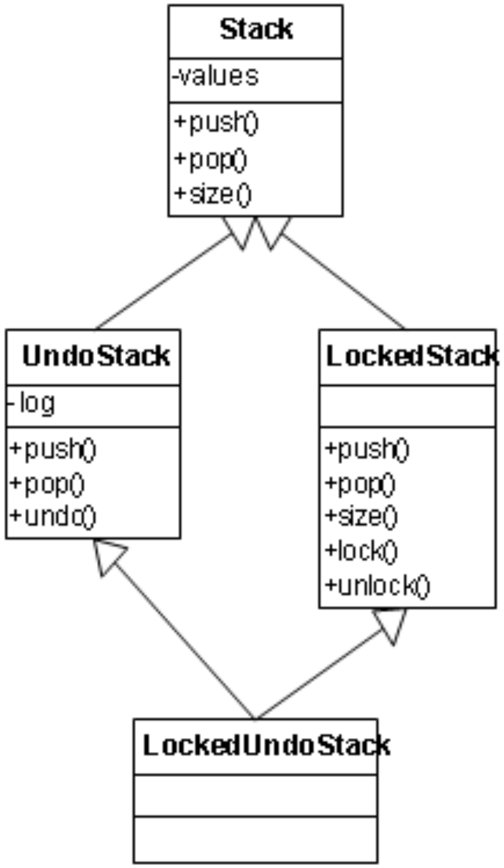
Limitations of inheritance



Workarounds?

- Combining inheritance hierarchies
  - Combinatorical explosion
  - Massive code replication

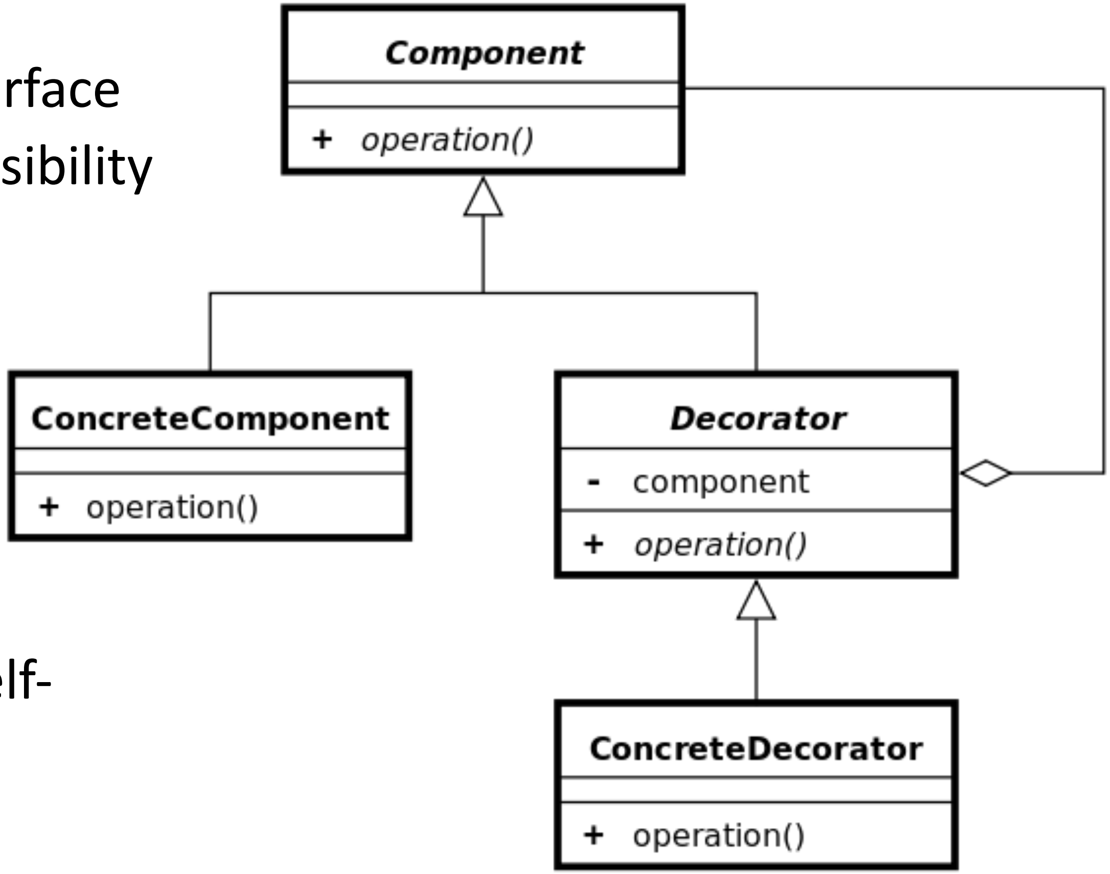




Multiple inheritance
- Diamond problem

The *Decorator* design pattern

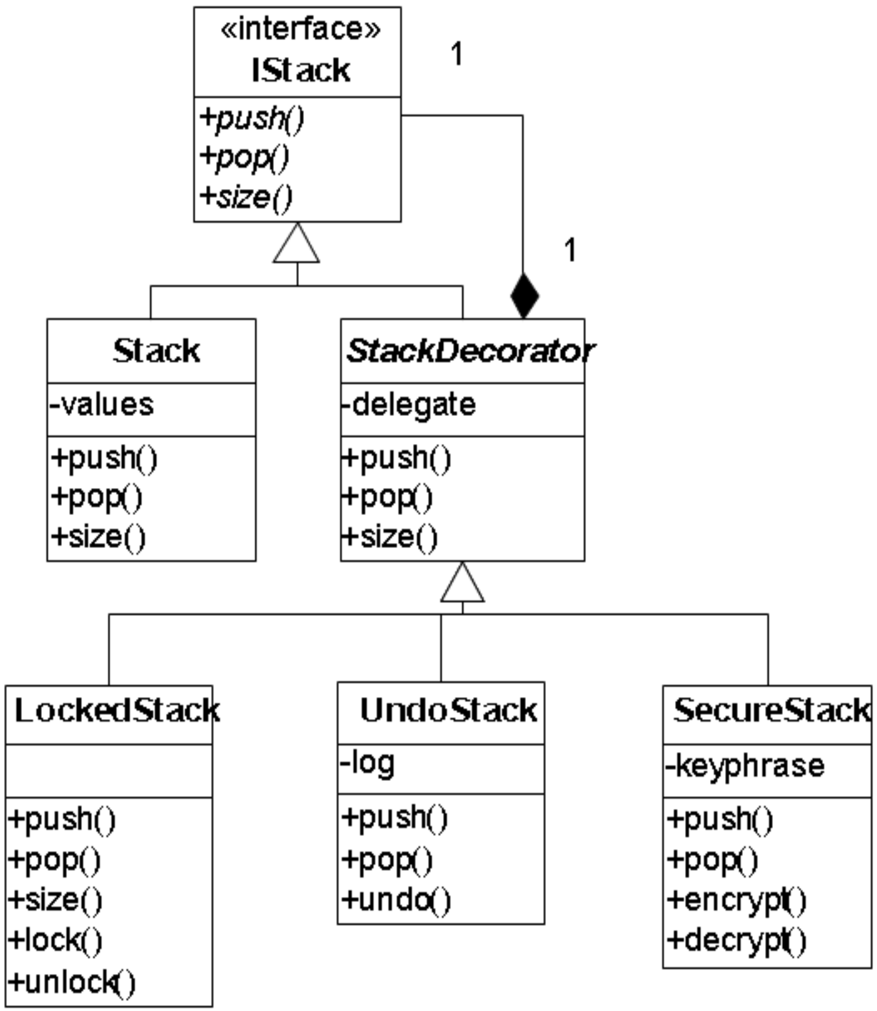
- *Problem*: Need arbitrary / dynamically composable extensions to individual objects.
- *Solution*:
  - Implement common interface
  - Delegate primary responsibility to an underlying object.
- *Consequences*:
  - More flexible than static inheritance
  - Customizable, cohesive extensions
  - Breaks object identity, self-references



Decorators use both subtyping and delegation

```
public class LoggingList<E> implements List<E> {
  private final List<E> list;
  public LoggingList<E>(List<E> list) { this.list = list; }
  public boolean add(E e) {
      System.out.println("Adding " + e);
      return list.add(e);
  }
  public E remove(int index) {
      System.out.println("Removing at " + index);
      return list.remove(index);
  }
  …
```

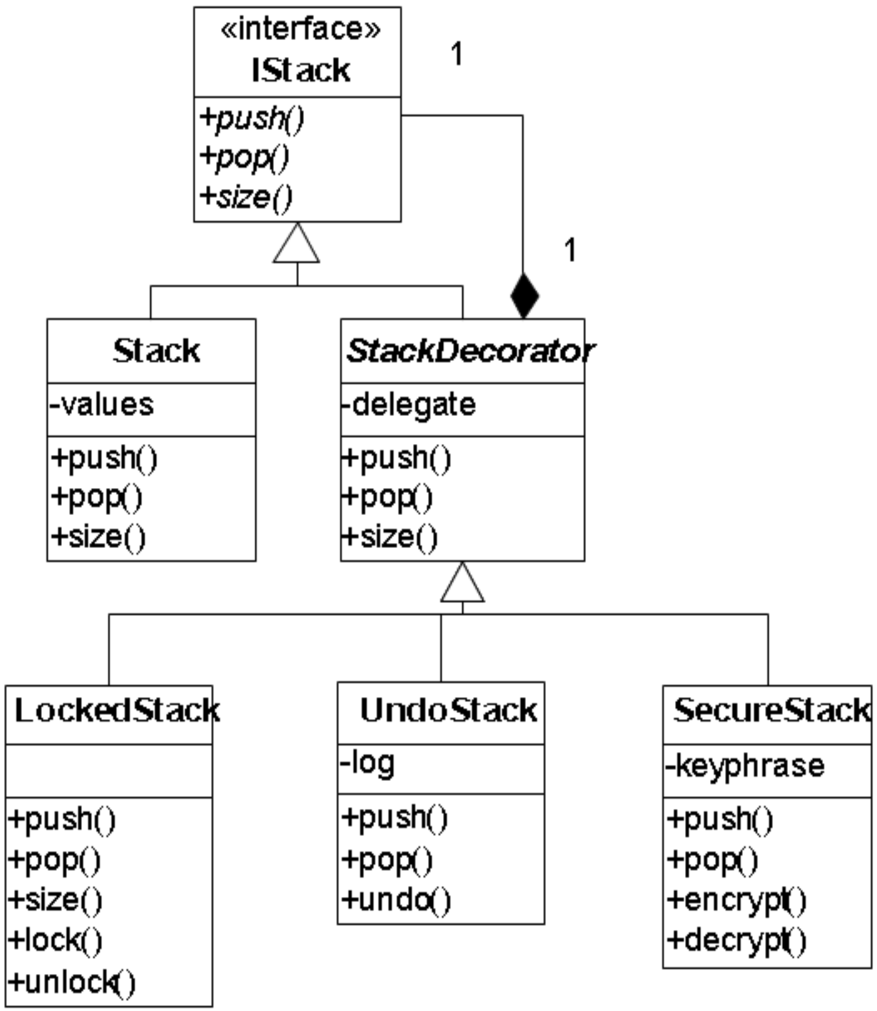
Using the Decorator for our Stack example



The abstract forwarding class

```
public abstract class StackDecorator
           implements IStack {
  private final IStack stack;
  public StackDecorator(IStack stack) {
      this.stack = stack;
  }
  public void push(Item e) {
        stack.push(e);
  }
  public Item pop() {
        return stack.pop();
  }
  …
}
```

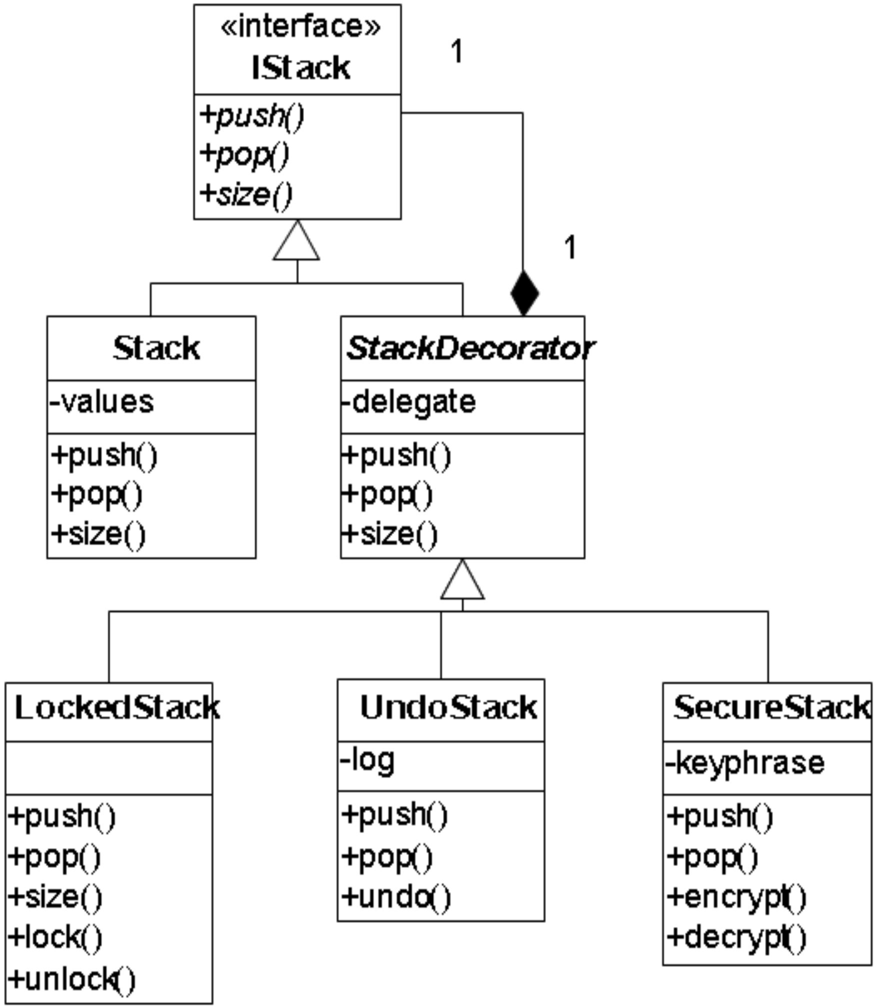
Using the Decorator for our Stack example



A concrete decorator class

```
public class UndoStack
        extends StackDecorator
        implements IStack {
  private final UndoLog log = new UndoLog();
  public UndoStack(IStack stack) {
        super(stack);
  }
  public void push(Item e) {
        log.append(UndoLog.PUSH, e);
        super.push(e);
  }
  …
}
```

Using the Decorator for our Stack example



Using the decorator classes

- To construct a plain stack:

```
Stack s = new Stack();
```

- To construct an plain undo stack:

```
UndoStack s = new
    UndoStack(new Stack());
```

- To construct a secure synchronized undo stack:

```
SecureStack s = new
    SecureStack(new
    SynchronizedStack(new
    UndoStack(new Stack())));
```

Decorators from `java.util.Collections`

- Turn a mutable list into an immutable list:

```
static List<T>  unmodifiableList(List<T>  lst);
static Set<T>   unmodifiableSet( Set<T>   set);
static Map<K,V> unmodifiableMap( Map<K,V> map);
```

- Similar for synchronization:

```
static List<T>  synchronizedList(List<T>  lst);
static Set<T>   synchronizedSet( Set<T>   set);
static Map<K,V> synchronizedMap( Map<K,V> map);
```

The UnmodifiableCollection (simplified excerpt)

```
public static <T> Collection<T> unmodifiableCollection(Collection<T> c)
        return new UnmodifiableCollection<>(c);
}
class UnmodifiableCollection<E> implements Collection<E>, Serializable
        final Collection<E> c;
        UnmodifiableCollection(Collection<> c) {this.c = c; }
        public int size() {return c.size();}
        public boolean isEmpty() {return c.isEmpty();}
        public boolean contains(Object o) {return c.contains(o);}
        public Object[] toArray() {return c.toArray();}
        public <T> T[] toArray(T[] a) {return c.toArray(a);}
        public String toString() {return c.toString();}
        public boolean add(E e) {throw new UnsupportedOperationExceptio
        public boolean remove(Object o) { throw new UnsupportedOperatio
                public boolean containsAll(Collection<?> coll) {  return
        public boolean addAll(Collection<? extends E> coll) { throw new
        public boolean removeAll(Collection<?> coll) { throw new Unsuppo
        public boolean retainAll(Collection<?> coll) { throw new Unsuppo
        public void clear() {  throw new UnsupportedOperationException()
    }
```

The decorator pattern vs. inheritance

- Decorator composes features at run time
  - Inheritance composes features at compile time
- Decorator consists of multiple collaborating objects
  - Inheritance produces a single, clearly-typed object
- Can mix and match multiple decorations
  - Multiple inheritance has conceptual problems
- Risk when multiple clients: Danger of inconsistent references, possibility of different perspectives

CLASS INVARIANTS

Recall: Data Structure Invariants (cf. 122)

```
struct list {
   elem data;
   struct list* next;
};
struct queue {
   list front;
   list back;
};

bool is_queue(queue Q) {
   if (Q == NULL) return false;
   if (Q->front == NULL || Q->back == NULL) return false;
   return is_segment(Q->front, Q->back);
}
```

Recall: Data Structure Invariants (cf. 122)

- Properties of the Data Structure
- Should always hold before and after method execution
- May be invalidated temporarily during method execution

```
void enq(queue Q, elem s)
//@requires is_queue(Q);
//@ensures is_queue(Q);
{ … }
```

Class Invariants

- Properties about the fields of an object
- Established by the constructor
- Should always hold before and after execution of public methods
  - May be invalidated temporarily during method execution

Class Invariants

- Properties about the fields of an object
- Established by the constructor
- Should always hold before and after execution of

```
public class SimpleSet {

    int contents[];
    int size;

    //@ ensures sorted(contents);
    SimpleSet(int capacity) { … }

    //@ requires sorted(contents);
    //@ ensures sorted(contents);
    boolean add(int i) { … }

    //@ requires sorted(contents);
    //@ ensures sorted(contents);
    boolean contains(int i) { … }
}
```

```
public class SimpleSet {

    int contents[];
    int size;

    //@invariant sorted(contents);

    SimpleSet(int capacity) { … }

    boolean add(int i) { … }

    boolean contains(int i) { … }
}
```

BEHAVIORAL SUBTYPING

"SHOULD I BE INHERITING FROM THIS TYPE?"

(Almost always) Prefer composition over inheritance

Review

- Tight coupling:
  - Changes to superclass → changes to subclass implementation
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Behavioral subtyping (Liskov Substitution Principle)

> Let q(x) be a property provable about objects x of type T. Then q(y) should be provable for objects y of type S where S is a subtype of T.
>
> Barbara Liskov

- Applies to specified behavior:
  - Same or stronger invariants
  - Same or stronger postconditions for all methods
  - Same or weaker preconditions for all methods

- e.g., Compiler-enforced rules in Java:
  - Subtypes can add, but not remove methods
  - Concrete class must implement all undefined methods
  - Overriding method must return same type or subtype
  - Overriding method must accept the same parameter types
  - Overriding method may not throw additional exceptions

This is called the *Liskov Substitution Principle*.

Behavioral subtyping in a nutshell

- If `Cowboy.draw()` overrides `Circle.draw()` somebody gets hurt!

Car is a behavioral subtype of Vehicle

```
abstract class Vehicle {
    int speed, limit;

    //@ invariant speed < limit;

    //@ requires speed != 0;
    //@ ensures speed < \old(speed)
    void brake();
}
```

```
class Car extends Vehicle {
    int fuel;
    boolean engineOn;
    //@ invariant speed < limit;
    //@ invariant fuel >= 0;

    //@ requires fuel > 0 && !engineOn;
    //@ ensures engineOn;
    void start() { … }

    void accelerate() { … }

    //@ requires speed != 0;
    //@ ensures speed < \old(speed)
    void brake() { … }
}
```

- **Subclass fulfills the same invariants (and additional ones)**
- **Overridden method has the same pre and postconditions**

Hybrid is a behavioral subtype of Car

```
class Car extends Vehicle {
     int fuel;
     boolean engineOn;
     //@ invariant fuel >= 0;

     //@ requires fuel > 0 && !engineOn;
     //@ ensures engineOn;
     void start() { … }

     void accelerate() { … }

     //@ requires speed != 0;
     //@ ensures speed < old(speed)
     void brake() { … }
}
```

```
class Hybrid extends Car {
     int charge;
     //@ invariant charge >= 0;

     //@ requires (charge > 0 || fuel > 0)
                       && !engineOn;
     //@ ensures engineOn;
     void start() { … }

     void accelerate() { … }

     //@ requires speed != 0;
     //@ ensures speed < \old(speed)
     //@ ensures charge > \old(charge)
     void brake() { … }
}
```

- **Subclass fulfills the same invariants (and additional ones)**
- **Overridden method start has weaker precondition**
- **Overridden method brake has stronger postcondition**

Is this Square a behavioral subtype of Rectangle?

```
class Rectangle {
    //@ invariant h>0 && w>0;
    int h, w;

    Rectangle(int h, int w) {
        this.h=h; this.w=w;
    }

    //methods
}
```

```
class Square extends Rectangle {
    //@ invariant h>0 && w>0;
    //@ invariant h==w;
    Square(int w) {
        super(w, w);
    }
}
```

Yes!

- **Subclass fulfills the same invariants (and additional ones)**
- **Overridden methods: NA**

Is this Square a behavioral subtype of Rectangle?

```
class Rectangle {
    //@ invariant h>0 && w>0;
    int h, w;

    Rectangle(int h, int w) {
        this.h=h; this.w=w;
    }
    //@ requires factor > 0;
    void scale(int factor) {
        w=w*factor;
        h=h*factor;
    }
}
```

```
class Square extends Rectangle {
    //@ invariant h>0 && w>0;
    //@ invariant h==w;
    Square(int w) {
        super(w, w);
    }
}
```

Yes!

- **Subclass fulfills the same invariants (and additional ones)**
- **Overridden methods: NA**

Is this Square a behavioral subtype of Rectangle?

```
class Rectangle {
    //@ invariant h>0 && w>0;
    int h, w;

    Rectangle(int h, int w) {
        this.h=h; this.w=w;
    }
    //@ requires factor > 0;
    void scale(int factor) {
        w=w*factor;
        h=h*factor;
    }
    //@ requires neww > 0;
    void setWidth(int neww) {
        w=neww;
    }
}
```

```
class Square extends Rectangle {
    //@ invariant h>0 && w>0;
    //@ invariant h==w;
    Square(int w) {
        super(w, w);
    }
}
```

```
class GraphicProgram {
    void scale(Rectangle r, int factor) {
        r.setWidth(r.getWidth() * factor);
    }
}
```

No!

- **Invalidates stronger invariant (w==h) in subclass**

Is this Square a behavioral subtype of Rectangle?

```
class Rectangle {
    //@ invariant h>0 && w>0;
    int h, w;

    Rectangle(int h, int w) {
        this.h=h; this.w=w;
    }

    //@ ensures getArea = h*w
    float getArea()
        return(this.h * this.w);

    //@ requires factor > 0;
    //@ ensures w == \old(w)*factor
    //      && h == \old(h)
    void scaleW(int factor) {
        w=w*factor;
    }
}
```

```
class Square extends Rectangle {
    //@ invariant h>0 && w>0;
    //@ invariant h==w;
    Square(int w) {
        super(w, w);
    }

    //@ ensures getArea = h*w
    float getArea()
        return(this.h * this.w);

    //@ requires factor > 0;
    //@ ensures w == \old(w)*factor
    //      && h == \old(h)*factor
    void scaleW(int factor) {
        w=w*factor;
        h=h*factor;
    }
```

```
Rectangle alwaysTrue(Rectangle r) {
   double intialArea = r.getArea();
   double finalArea = r.scaleW(2).getArea();
   return(finalArea == 2*initialArea);
}
```

No!

- **Invariants OK**
- **Preconditions OK**
- **Overridden method scaleW has incompatible postcondition**

Is this Rectangle a behavioral subtype of Square?

```
class Rectangle extends Square {
    //@ invariant h>0 && w>0;
    int h, w;

    Rectangle(int h, int w) {
        this.h=h; this.w=w;
    }

    //@ ensures getArea = h*w
    float getArea()
        return(this.h * this.w);

    //@ requires factor > 0;
    //@ ensures w == \old(w)*factor
    //        && h == \old(h)
    void scaleW(int factor) {
        w=w*factor;
    }
}
```

```
class Square {
    //@ invariant h>0 && w>0;
    //@ invariant h==w;
    Square(int w) {
        super(w, w);
    }

    //@ ensures getArea = h*w
    float getArea()
        return(this.h * this.w);

    //@ requires factor > 0;
    //@ ensures w == \old(w)*factor
    //        && h == \old(h)*factor
    void scaleW(int factor) {
        w=w*factor;
        h=h*factor;
    }
```

```
Square alwaysTrue(Square s) {
  double intialArea = s.getArea();
  double finalArea = s.scaleW(2).getArea();
  return(finalArea == 4*initialArea);
}
```

No!

- **Rectangle doesn't fulfil Square invariant h==w**
- **Preconditions OK**
- **Overridden method scaleW has incompatible postcondition**

Summary: Designing reusable classes

- Favor composition over inheritance
  - Inheritance violates information hiding
- Design and document for inheritance, or prohibit it
  - Document requirements for overriding any method

- Reusable implementations with simple, clear contracts
- Inheritance for reuse, its pitfalls, and its alternatives
- Liskov's Substitution Principle for behavioral subtyping

CLASS INVARIANTS AND DEFENSIVE COPYING

Defensive programming

- Assume clients will try to destroy invariants
  - May actually be true (malicious hackers)
  - More likely: honest mistakes
- Ensure class invariants survive any inputs
  - Defensive copying
  - Minimizing mutability

This class is not robust

```
public final class Period {
   private final Date start, end; // Invariant: start <= end

   /**
    * @throws IllegalArgumentException if start > end
    * @throws NullPointerException if start or end is null
    */
   public Period(Date start, Date end) {
      if (start.after(end))
          throw new IllegalArgumentException(start + " > " + end);
      this.start = start;
      this.end   = end;
   }

   public Date start() { return start; }
   public Date end()   { return end; }
   ... // Remainder omitted
}
```

The problem: Date is mutable

```
// Attack the internals of a Period instance
Date start = new Date();  // (The current time)
Date end   = new Date();  //    "      "       "
Period p = new Period(start, end);
end.setYear(78);   // Modifies internals of p!
```

The solution: *defensive copying*

```
// Original constructor
public Period(Date start, Date end) {
   if (start.after(end))
      throw new IllegalArgumentException(start + " > " + end);
   this.start = start;
   this.end   = end;
}
```

```
// Repaired constructor - defensively copies parameters
public Period(Date start, Date end) {
   this.start = new Date(start.getTime());
   this.end   = new Date(end.getTime());
   if (this.start.after(this.end))
     throw new IllegalArgumentException(start + " > "+ end);
}
```

A few important details

- Copies made *before* checking parameters
- Validity check performed on copies
- Eliminates *window of vulnerability* between parameter check and copy
- Thwarts multithreaded TOCTOU attack
  - Time-Of-Check-To-Time-Of-U

```
// BROKEN - Permits multithreaded attack!
public Period(Date start, Date end) {
    if (start.after(end))
        throw new IllegalArgumentException(start + " > " + end);
    // Window of vulnerability
    this.start = new Date(start.getTime());
    this.end   = new Date(end.getTime());
}
```

Another important detail

- Used constructor, not `clone`, to make copies
  - Necessary because `Date` class is nonfinal
  - Attacker could implement *malicious subclass*
    - Records reference to each extant instance
    - Provides attacker with access to instance list
- But who uses `clone`, anyway? [EJ Item 11]

Unfortunately, constructors are only half the battle

```
// Accessor attack on internals of Period
Period p = new Period(new Date(), new Date());
Date d = p.end();
p.end.setYear(78); // Modifies internals of p!
```

The solution: more defensive copying

```
// Repaired accessors - defensively copy fields
public Date start() {
    return new Date(start.getTime());
}
public Date end() {
    return new Date(end.getTime());
}
```

Now Period class is robust!

Summary

- Don't incorporate mutable parameters into object; make defensive copies
- Return defensive copies of mutable fields…
- Or return *unmodifiable view* of mutable fields
- **Real lesson – use immutable components**
  - Eliminates the need for defensive copying

IMMUTABILITY

Immutable classes

- **Class whose instances cannot be modified**
- Examples: `String`, `Integer`, `BigInteger`
- How, why, and when to use them

How to write an immutable class

- Don’t provide any mutators
- Ensure that no methods may be overridden
- Make all fields final
- Make all fields private
- Ensure security of any mutable components

Immutable class example

```
public final class Complex {
    private final double re, im;

    public Complex(double re, double im) {
        this.re = re;
        this.im = im;
    }

    // Getters without corresponding setters
    public double realPart()      { return re; }
    public double imaginaryPart() { return im; }

    // subtract, multiply, divide similar to add
    public Complex add(Complex c) {
        return new Complex(re + c.re, im + c.im);
    }
```

Distinguishing characteristic

- Return new instance instead of modifying
- *Functional programming*
- May seem unnatural at first
- Many advantages

Advantages

- Simplicity
- Inherently Thread-Safe
- Can be shared freely
- No need for defensive copies
- Excellent building blocks

Major disadvantage

- Separate instance for each distinct value
- Creating these instances can be costly

```
BigInteger moby = ...;  // A million bits long
moby = moby.flipBit(0); // Ouch!
```

- Problem magnified for multistep operations
  - Well-designed immutable classes provide common multistep operations as primitives
  - Alternative: mutable companion class
    - e.g., `StringBuilder` for `String`

When to make classes immutable

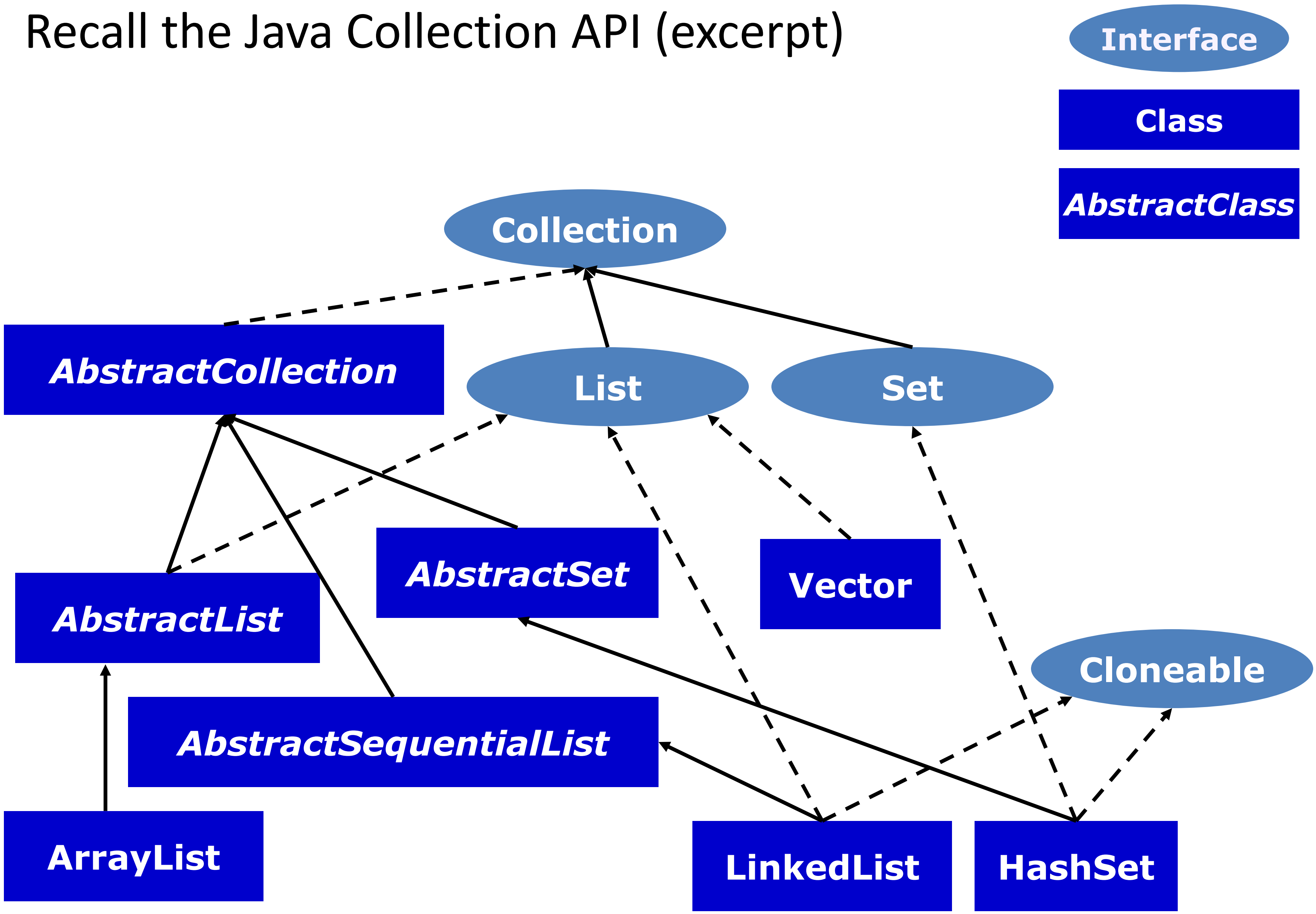
- **Always, unless there's a good reason not to**
- Always make small "value classes" immutable!
  - Examples: `Color`, `PhoneNumber`, `Unit`
  - `Date` and `Point` were mistakes!
  - Experts often use `long` instead of `Date`

When to make classes mutable

- Class represents entity whose state changes
  - Real-world - `BankAccount`, `TrafficLight`
  - Abstract - `Iterator`, `Matcher`, `Collection`
  - Process classes - `Thread`, `Timer`
- If class must be mutable, *minimize mutability*
  - Constructors should fully initialize instance
  - Avoid `reinitialize` methods

PARAMETRIC POLYMORPHISM (GENERICS)

Recall the Java Collection API (excerpt)



Consider the `java.util.Stack`

```
public class Stack {
    public void push(Object obj) { … }
    public Object pop() { …}
}
```

- Some possible client code:

```
Stack stack = new Stack();
String s = "Hello!";
stack.push(s);
String t = stack.pop();
```

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- Some possible client code:

```
Stack stack = new Stack();
String s = "Hello!";
stack.push(s);
String t = (String) stack.pop();
```

To fix the type error with a downcast (urgs!)

Parametric polymorphism via Java Generics

- *Parametric polymorphism* is the ability to define a type generically to allow static type-checking without fully specifying types
- The `java.util.Stack` instead
  - A stack of some type *T*:

```
public class Stack<T> {
    public void push(T obj) { … }
    public T pop() { … }
}
```

- Improves typechecking, simplifies(?) client code:

```
Stack<String> stack = new Stack<String>();
String s = "Hello!";
stack.push(s);
String t = stack.pop();
```

Many Java Generics details

- Can have multiple type parameters
  - e.g., `Map<Integer,String>`
- Wildcards
  - e.g., `ArrayList<?>` or `ArrayList<? extends Animal>`
- Subtyping
  - `ArrayList<String>` is a subtype of `List<String>`
  - `ArrayList<String>` is not a subtype of `ArrayList<Object>`
- Cannot create Generic arrays

```
List<String>[] foo = new List<String>[42];  // won't compile
```

- Type erasure
  - Generic type info is compile-time only
    - Cannot use `instanceof` to check generic type
      - But shouldn't use instanceof anyway

ITERATOR PATTERN

Traversing a collection

- Since Java 1.0:

```
List<String> arguments = …;
for (int i = 0; i < arguments.size(); ++i) {
  System.out.println(arguments.get(i));
}
```

- Java 1.5: for-each loop

```
List<String> arguments = …;
for (String s : arguments) {
  System.out.println(s);
}
```

- For-each loop works for every implementation of `Iterable`

```
public interface Iterable<E> {
  public Iterator<E> iterator();
}
```

The `Iterator` interface

```
public interface java.util.Iterator<E> {
  boolean hasNext();
  E next();
  void remove();  // removes previous returned item
}                 // from the underlying collection
```

- To use explicitly, e.g.:

```
List<String> arguments = …;
for (Iterator<String> it = arguments.iterator();
     it.hasNext();  ) {
  String s = it.next();
  System.out.println(s);
}
```

Getting an Iterator

```
public interface Collection<E> extends Iterable<E> {
  boolean      add(E e);
  boolean      addAll(Collection<? extends E> c);
  boolean      remove(Object e);
  boolean      removeAll(Collection<?> c);
  boolean      retainAll(Collection<?> c);
  boolean      contains(Object e);
  boolean      containsAll(Collection<?> c);
  void         clear();
  int          size();
  boolean      isEmpty();
  Iterator<E>  iterator();
  Object[]     toArray()
  <T> T[]      toArray(T[] a);
  …
}
```

Defines an interface for creating an Iterator, but allows Collection implementation to decide which Iterator to create.

An Iterator implementation for Pairs

```
public class Pair<E> {
  private final E first, second;
  public Pair(E f, E s) { first = f; second=s;}







}
```

```
Pair<String> pair = new Pair<String>("foo", "bar");
for (String s : pair) { … }
```

An Iterator implementation for Pairs

```java
public class Pair<E> implements Iterable<E> {
  private final E first, second;
  public Pair(E f, E s) { first = f; second=s;}
  public Iterator<E> iterator() {
    return new PairIterator();
  }
  private class PairIterator implements Iterator<E> {
    private boolean seenFirst = false, seenSecond = false;
    public  boolean hasNext() { return !seenSecond; }
    public  E next() {
      if (!seenFirst)  { seenFirst  = true; return first;  }
      if (!seenSecond) { seenSecond = true; return second; }
      throw new NoSuchElementException();
    }
    public void remove() {
      throw new UnsupportedOperationException();
    }
  }
}
```

```java
Pair<String> pair = new Pair<String>("foo", "bar");
for (String s : pair) { … }
```

Iterator design pattern

- Problem: Clients need uniform strategy to access all elements in a container, independent of the container type
  - Order is unspecified, but access every element once
- Solution: A strategy pattern for iteration
- Consequences:
  - Hides internal implementation of underlying container
  - Easy to change container type
  - Facilitates communication between parts of the program

Using a `java.util.Iterator<E>`: A warning

- The default Collections implementations are mutable…
- …but their `Iterator` implementations assume the collection does not change while the `Iterator` is being used
  - You will get a `ConcurrentModificationException`

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- …but their `Iterator` implementations assume the collection does not change while the `Iterator` is being used
  - You will get a `ConcurrentModificationException`
  - If you simply want to remove an item:

```
List<String> arguments = …;
for (Iterator<String> it = arguments.iterator();
     it.hasNext();  ) {
  String s = it.next();
  if (s.equals("Charlie"))
    arguments.remove("Charlie"); // runtime error
}
```

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```
List<String> arguments = …;
for (Iterator<String> it = arguments.iterator();
     it.hasNext();  ) {
  String s = it.next();
  if (s.equals("Charlie"))
    it.remove();
}
```