Principles of Software Construction:
Objects, Design, and Concurrency

Part 2: Class-level design

Behavioral subtyping, design for reuse

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Administrivia

- Homework 1 graded soon
- Reading assignment due today: Effective Java Items 17 + 50
  - Optional reading due Thursday
  - Required reading due next Tuesday
- Homework 2 due Thursday 11:59 p.m.

Design goals for your Homework 1 solution?

Functional correctness	Adherence of implementation to the specifications
Robustness	Ability to handle anomalous events
Flexibility	Ability to accommodate changes in specifications
Reusability	Ability to be reused in another application
Efficiency	Satisfaction of speed and storage requirements
Scalability	Ability to serve as the basis of a larger version of the application
Security	Level of consideration of application security

Source: Braude, Bernstein, Software Engineering. Wiley 2011

Key concepts from last Thursday

Key concepts from last Thursday

- Specifying program behavior: contracts
- Testing
  - Continuous integration
  - Coverage metrics, statement coverage
- The `java.lang.Object` contracts

Selecting test cases

- Write tests based on the specification, for:
  - Representative cases
  - Invalid cases
  - Boundary conditions
- Write stress tests
  - Automatically generate huge numbers of test cases
- Think like an attacker
- Other tests: performance, security, system interactions, …

Methods common to all objects

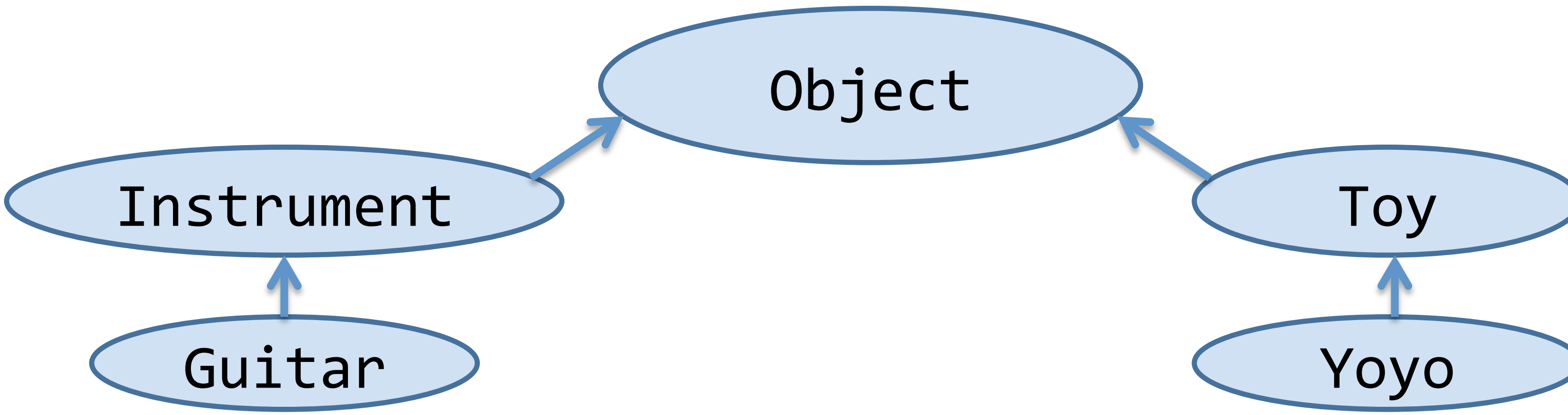
- How do collections know how to test objects for equality?
- How do they know how to hash and print them?
- The relevant methods are all present on `Object`
  - **`equals`** - returns true if the two objects are "equal"
  - **`hashCode`** - returns an `int` that must be equal for equal objects, and is likely to differ on unequal objects
  - **`toString`** - returns a printable string representation

Today

- Behavioral subtyping
  - Liskov Substitution Principle
- Design for reuse: delegation and inheritance

The class hierarchy

- The root is `Object` (all non-primitives are `Object`s)
- All classes except `Object` have one parent class
  - Specified with an `extends` clause:
    `class Guitar extends Instrument { ... }`
  - If `extends` clause is omitted, defaults to `Object`
- A class is an instance of all its superclasses



Behavioral subtyping

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

- 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

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- 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
- Also applies to specified behavior. Subtypes must have:
  - Same or stronger invariants
  - Same or stronger postconditions for all methods
  - Same or weaker preconditions for all methods

This is called the *Liskov Substitution Principle*.

LSP example: `Car` is a behavioral subtype of `Vehicle`

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

  //@ invariant speed < limit;

  //@ requires speed != 0;
  //@ ensures speed < \old(speed)
  abstract 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

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LSP example: Hybrid is a behavioral subtype of Car

```
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() { … }
}
```

```
class Hybrid extends Car {
  int charge;
  //@ invariant charge >= 0;
  //@ invariant …
  //@ 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 {
    int h, w;

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

    //methods
}
```

```
class Square extends Rectangle {
    Square(int w) {
        super(w, w);
    }
}
```


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Is this Square a behavioral subtype of Rectangle?

```
class Rectangle {
    int h, w;

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

    //methods
}
```

```
class Square extends Rectangle {
    Square(int w) {
        super(w, w);
    }
}
```

(Yes.)

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);
    }
}
```


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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.)

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);
     }
}
```


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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.)

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);
     }
}
```

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 scaleW(Rectangle r, int f) {
        r.setWidth(r.getWidth() * f);
    }
}
```

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

(Yes! But the Square is not a square…)

This Square is *not* 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;
   //@ ensures w==neww
             && h==old.h;
    void setWidth(int neww) {
        w=neww;
    }
}
```

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

   //@ requires neww > 0;
   //@ ensures w==neww
            && h==neww;
   @Override
   void setWidth(int neww) {
      w=neww;
      h=neww;
   }
}
```


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Behavioral subtyping summary

- When subtyping, design and implement carefully
  - Subtype must be substitutable anywhere the supertype could be used

Today

- Behavioral subtyping
  - Liskov Substitution Principle
- Design for reuse: delegation and inheritance

Recall our earlier sorting example:

Version A:

```
static void sort(int[] list, boolean ascending) {
   …
   boolean mustSwap;
   if (ascending) {
      mustSwap = list[i] > list[j];
   } else {
      mustSwap = list[i] < list[j];
   }
   …
}
```

Version B':

```
interface Order {
  boolean lessThan(int i, int j);
}
final Order ASCENDING =  (i, j) -> i < j;
final Order DESCENDING = (i, j) -> i > j;

static void sort(int[] list, Order cmp) {
  …
  boolean mustSwap =
    cmp.lessThan(list[i], list[j]);
  …
}
```

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 `Order`
- Judicious delegation enables code reuse

```
interface Order {
  boolean lessThan(int i, int j);
}
final Order ASCENDING =  (i, j) -> i < j;
final Order DESCENDING = (i, j) -> i > j;

static void sort(int[] list, Order cmp) {
  …
  boolean mustSwap =
    cmp.lessThan(list[i], list[j]);
  …
}
```

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 `Order`
- Judicious delegation enables code reuse
  - `Sorter` can be reused with arbitrary sort orders
  - `Order`s can be reused with arbitrary client code that needs to compare integers

```
interface Order {
  boolean lessThan(int i, int j);
}
final Order ASCENDING =  (i, j) -> i < j;
final Order DESCENDING = (i, j) -> i > j;

static void sort(int[] list, Order cmp) {
  …
  boolean mustSwap =
    cmp.lessThan(list[i], list[j]);
  …
}
```

Using delegation to extend functionality

- Consider the `java.util.List` (excerpted):

```
public interface List<E> {
  public boolean add(E e);
  public E       remove(int index);
  public void    clear();
  …
}
```

- Suppose we want a list that logs its operations to the console…

Using delegation to extend functionality

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

- One solution:

```
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);
  }
  …
```


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Delegation and design

- Small interfaces with clear contracts
- Classes to encapsulate algorithms, behaviors
  - E.g., the `Order`

Today

- Behavioral subtyping
  - Liskov Substitution Principle
- Design for reuse: delegation and inheritance

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Consider: types of bank accounts

```
public interface CheckingAccount {
    public long getBalance();
    public void  deposit(long amount);
    public boolean withdraw(long amount);
    public boolean transfer(long amount, Account??? target);
    public long getFee();
}


public interface SavingsAccount {
    public long getBalance();
    public void  deposit(long amount);
    public boolean withdraw(long amount);
    public boolean transfer(long amount, Account??? target);
    public double getInterestRate();
}
```

Interface inheritance for an account type hierarchy

```
public interface Account {
    public long getBalance();
    public void  deposit(long amount);
    public boolean withdraw(long amount);
    public boolean transfer(long amount, Account target);
    public void monthlyAdjustment();
}

public interface CheckingAccount extends Account {
    public long getFee();
}

public interface SavingsAccount extends Account {
    public double getInterestRate();
}

public interface InterestCheckingAccount
                      extends CheckingAccount, SavingsAccount {
}
```

The power of object-oriented interfaces

- Subtype polymorphism
  - Different kinds of objects can be treated uniformly by client code
  - Each object behaves according to its type
    - e.g., if you add new kind of account, client code does not change:

```
If today is the last day of the month:
   For each acct in allAccounts:
      acct.monthlyAdjustment();
```

Implementation inheritance for code reuse

```
public abstract class AbstractAccount
        implements Account {
   protected long balance = 0;
   public long getBalance() {
        return balance;
   }
   abstract public void monthlyAdjustment();
   // other methods…
}

public class CheckingAccountImpl
        extends AbstractAccount
        implements CheckingAccount {
   public void monthlyAdjustment() {
        balance -= getFee();
   }
   public long getFee() { … }
}
```


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Implementation inheritance for code reuse

```
public abstract class AbstractAccount
        implements Account {
    protected long balance = 0;
    public long getBalance() {
        return balance;
    }
    abstract public void monthlyAdjustment();
    // other methods…
}

public class CheckingAccountImpl
        extends AbstractAccount
        implements CheckingAccount {
    public void monthlyAdjustment() {
        balance -= getFee();
    }
    public long getFee() { … }
}
```

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

protected elements are visible in subclasses

an abstract method is left to be implemented in a subclass

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

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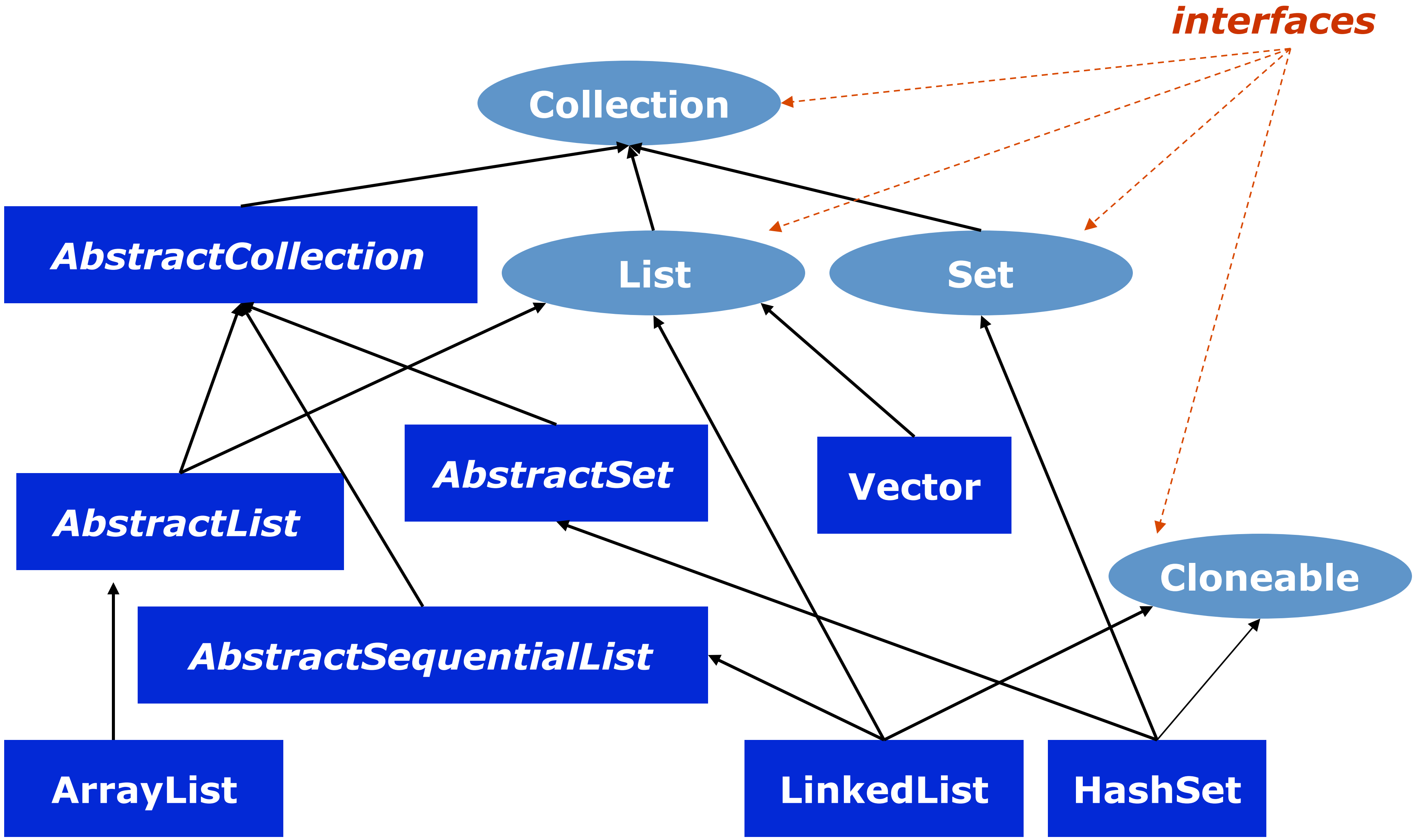
Inheritance: a glimpse at the hierarchy

- Examples from Java
  - `java.lang.Object`
  - Collections library

Java Collections API (excerpt)



Benefits of inheritance

- Reuse of code
- Modeling flexibility

Inheritance and subtyping

- Inheritance is for polymorphism and code reuse
  - Write code once and only once
  - Superclass features implicitly available in subclass

```
class A extends B
```

- Subtyping is for polymorphism
  - Accessing objects the same way, but getting different behavior
  - Subtype is substitutable for supertype

```
class A implements B
class A extends B
```

Typical roles for interfaces and classes

- An interface defines expectations / commitments for clients
- A class fulfills the expectations of an interface
  - An abstract class is a convenient hybrid
  - A subclass specializes a class's implementation

Delegation vs. inheritance summary

- Inheritance can improve modeling flexibility
- Usually, favor composition/delegation over inheritance
  - Inheritance violates information hiding
  - Delegation supports information hiding
- Design and document for inheritance, or prohibit it
  - Document requirements for overriding any method