

Concepts of Object-Oriented Programming

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Chair of Programming Methodology

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5. Information Hiding and Encapsulation

5.1 Information Hiding

5.2 Encapsulation

Information Hiding

- Definition

Information hiding is a technique for reducing the dependencies between modules:

- *The intended client is provided with all the information needed to use the module **correctly**, and **with nothing more***
 - *The client uses only the (publicly) available information*
- Information hiding deals with programs, that is, with static aspects
- Contracts are part of the exported interfaces

Objectives

- Establish strict interfaces
- Hide implementation details
- Reduce dependencies between modules
 - Classes can be studied and understood in isolation
 - Classes interact only in simple, well-defined ways

```
class Set {  
    ...  
    // contract or documentation  
    public void insert( Object o )  
        { ... }  
}
```

```
class BoundedSet {  
    Set rep;  
    int maxSize;  
  
    public void insert( Object o ) {  
        if ( rep.size( ) < maxSize )  
            rep.insert( o );  
    }  
}
```

The Client Interface of a Class

- Class name
- Type parameters and their bounds
- Super-class
- Super-interfaces
- Signatures of exported methods and fields
- Client interface of direct superclass

```
class SymbolTable
    extends Dictionary<String,String>
    implements Map<String,String> {
    public int size;

    public void add( String key, String value )
    { put( key, value ); }

    public String lookup( String key )
        throws IllegalArgumentException {
        return atKey( key );
    }
}
```

Other Interfaces

- Subclass interface
 - Efficient access to superclass fields
 - Access to auxiliary superclass methods

```
public class DList {  
    protected Node first, last;  
    private int modCount;  
    protected void modified( )  
        { modCount++; }  
    ...  
}
```

Other Interfaces

- Subclass interface
 - Efficient access to superclass fields
 - Access to auxiliary superclass methods
- Friend interface
 - Mutual access to implementations of cooperating classes
 - Hiding auxiliary classes

```
package coop.util;  
public class DList {  
    protected Node first, last;  
    private int modCount;  
    protected void modified( )  
        { modCount++; }  
  
    ...  
}
```

```
package coop.util;  
/* default */ class Node {  
    /* default */ Object elem;  
    /* default */ Node next, prev;  
    ... }  
}
```

Other Interfaces

- Subclass interface
 - Efficient access to superclass fields
 - Access to auxiliary superclass methods
- Friend interface
 - Mutual access to implementations of cooperating classes
 - Hiding auxiliary classes
- And others

```
package coop.util;  
public class DList {  
    protected Node first, last;  
    private int modCount;  
    protected void modified( )  
        { modCount++; }  
  
    ...  
}
```

```
package coop.util;  
/* default */ class Node {  
    /* default */ Object elem;  
    /* default */ Node next, prev;  
    ... }  
}
```


Expressing Information Hiding

- Java: Access modifiers
 - **public** client interface
 - **protected** subclass + friend interface
 - Default access friend interface
 - **private** implementation

- Eiffel: Clients clause in feature declarations
 - **feature** { ANY } client interface
 - **feature** { T } friend interface for class T
 - **feature** { NONE } implementation (only “**this**”-object)
 - All exports include subclasses

Safe Changes

- Consistent renaming of hidden elements

Safe Changes

- Consistent renaming of hidden elements

```
package coop.util;

public class DList {

    protected Node first, last;

    private int modCount;
    protected void incrModCount( )
        { modCount++; }

    ...
}
```

Safe Changes

- Consistent renaming of hidden elements

```
package coop.util;

public class DList {

    protected Node first, last;

    private int version;
    protected void incrModCount( )
        { version++; }

    ...
}
```

Safe Changes

- Consistent renaming of hidden elements
- Modification of hidden implementation as long as exported functionality is preserved

```
package coop.util;

public class DList {

    protected Node first, last;

    private int version;
    protected void incrModCount( )
    { version++; }

    ...
}
```

Safe Changes

- Consistent renaming of hidden elements
- Modification of hidden implementation as long as exported functionality is preserved
- Access modifiers and clients clauses specify what classes might be affected by a change

```
package coop.util;

public class DList {

    protected Node first, last;

    private int version;
    protected void incrModCount( )
        { version++; }
    ...
}
```

Safe Changes

- Consistent renaming of hidden elements
- Modification of hidden implementation as long as exported functionality is preserved
- Access modifiers and clients clauses specify what classes might be affected by a change

```
package coop.util;

public class DList {

    protected Node first, last;

    private int version;
    protected void modified( )
        { version++; }
    ...
}
```

Exchanging Implementations

```
class Coordinate {  
    private double x,y;  
    ...  
    public double distOrigin( )  
        { return Math.sqrt( x*x + y*y ); }  
}
```

```
class Coordinate {  
    private double radius, angle;  
    ...  
    public double distOrigin( )  
        { return radius; }  
}
```


Exchanging Implementations

- Observable behavior must be preserved

```
class Coordinate {  
    private double x,y;  
    ...  
    public double distOrigin( )  
        { return Math.sqrt( x*x + y*y ); }  
}
```

```
class Coordinate {  
    private double radius, angle;  
    ...  
    public double distOrigin( )  
        { return radius; }  
}
```

Exchanging Implementations

- Observable behavior must be preserved
- Exported fields limit modifications severely
 - Use getter and setter methods instead

```
class Coordinate {  
    private double x,y;  
    ...  
    public double distOrigin( )  
        { return Math.sqrt( x*x + y*y ); }  
}
```

```
class Coordinate {  
    private double radius, angle;  
    ...  
    public double distOrigin( )  
        { return radius; }  
}
```

Exchanging Implementations

- Observable behavior must be preserved
- Exported fields limit modifications severely
 - Use getter and setter methods instead
- Modifications are critical
 - Fragile baseclass problem
 - Object structures

```
class Coordinate {  
    private double x,y;  
    ...  
    public double distOrigin( )  
        { return Math.sqrt( x*x + y*y ); }  
}
```

```
class Coordinate {  
    private double radius, angle;  
    ...  
    public double distOrigin( )  
        { return radius; }  
}
```

Method Selection in Java (JLS1)

```
class T {  
    public void m( ) { ... }  
}
```

```
class S extends T {  
    public void m( ) { ... }  
}
```

```
class U extends S { }
```

```
T v = new U( );  
v.m( );
```

Method Selection in Java (JLS1)

- At compile time:
 1. Determine static declaration

```
class T {  
    public void m( ) { ... }  
}
```

```
class S extends T {  
    public void m( ) { ... }  
}
```

```
class U extends S { }
```

```
T v = new U( );  
v.m( );
```

Method Selection in Java (JLS1)

- At compile time:
 1. Determine static declaration
 2. Check accessibility

```
class T {  
    public void m( ) { ... }  
}
```

```
class S extends T {  
    public void m( ) { ... }  
}
```

```
class U extends S { }
```

```
T v = new U( );  
v.m( );
```

Method Selection in Java (JLS1)

- At compile time:
 1. Determine static declaration
 2. Check accessibility
 3. Determine invocation mode (virtual / nonvirtual)

```
class T {  
    public void m( ) { ... }  
}
```

```
class S extends T {  
    public void m( ) { ... }  
}
```

```
class U extends S { }
```

```
T v = new U( );  
v.m( );
```

Method Selection in Java (JLS1)

- At compile time:
 1. Determine static declaration
 2. Check accessibility
 3. Determine invocation mode (virtual / nonvirtual)
- At run time:
 4. Compute receiver reference

```
class T {  
    public void m( ) { ... }  
}
```

```
class S extends T {  
    public void m( ) { ... }  
}
```

```
class U extends S { }
```

```
T v = new U( );  
v.m( );
```


Method Selection in Java (JLS1)

- At compile time:
 1. Determine static declaration
 2. Check accessibility
 3. Determine invocation mode (virtual / nonvirtual)

- At run time:
 4. Compute receiver reference
 5. Locate method to invoke (based on dynamic type of receiver object)

```
class T {  
    public void m( ) { ... }  
}
```

```
class S extends T {  
    public void m( ) { ... }  
}
```

```
class U extends S { }
```

```
T v = new U( );  
v.m( );
```

Rules for Overriding: Access

Rules for Overriding: Access

```
class Super {  
    ...  
    protected void m( ) { ... }  
}
```

```
class Sub extends Super {  
    void m( ) { ... }  
}
```

Rules for Overriding: Access

```
class Super {  
    ...  
    protected void m( ) { ... }  
}
```

```
class Sub extends Super {  
    void m( ) { ... }  
}
```

```
In class Super or Sub:  
public void test( Super v ) {  
    v.m( );  
}
```

Rules for Overriding: Access

- **Access Rule:**
The access modifier of an overriding method must provide **at least as much access** as the overridden method

```
class Super {  
    ...  
    protected void m( ) { ... }  
}
```

```
class Sub extends Super {  
    void m( ) { ... }  
}
```

```
In class Super or Sub:  
public void test( Super v ) {  
    v.m( );  
}
```

Rules for Overriding: Access

- **Access Rule:**

The access modifier of an overriding method must provide **at least as much access** as the overridden method

Default access

protected

public

```
class Super {  
    ...  
    protected void m( ) { ... }  
}
```

```
class Sub extends Super {  
    void m( ) { ... }  
}
```

In class Super or Sub:
public void test(Super v) {
 v.m();
}

Rules for Overriding: Access

- **Access Rule:**
The access modifier of an overriding method must provide **at least as much access** as the overridden method

Default access

protected

public

```
class Super {  
    ...  
    protected void m( ) { ... }  
}
```

```
class Sub extends Super {  
    public void m( ) { ... }  
}
```

```
In class Super or Sub:  
public void test( Super v ) {  
    v.m( );  
}
```

Rules for Overriding: Hiding

```
class Super {  
    ...  
    private void m( )  
        { System.out.println("Super"); }  
    public void test( Super v )  
        { v.m( ); }  
}
```

```
class Sub extends Super {  
    public void m( )  
        { System.out.println("Sub"); }  
}
```


Rules for Overriding: Hiding

```
class Super {  
    ...  
    private void m( )  
        { System.out.println("Super"); }  
    public void test( Super v )  
        { v.m( ); }  
}
```

```
class Sub extends Super {  
    public void m( )  
        { System.out.println("Sub"); }  
}
```

```
Super v = new Sub( );  
v.test( v );
```

Rules for Overriding: Hiding

- **Override Rule:**
A method Sub.m **overrides** the superclass method Super.m only if Super.m is **accessible from Sub**
- If Super.m is not accessible from Sub, it is **hidden** by Sub.m
- Private methods cannot be overridden

```
class Super {  
    ...  
    private void m( )  
        { System.out.println("Super"); }  
    public void test( Super v )  
        { v.m( ); }  
}
```

```
class Sub extends Super {  
    public void m( )  
        { System.out.println("Sub"); }  
}
```

```
Super v = new Sub( );  
v.test( v );
```

Problems with Default Access Methods

```
package PT;  
public class T {  
    void m( ) { ... }  
}
```

```
package PS;  
public class S extends PT.T {  
    public void m( ) { ... }  
}
```

```
In package PT:  
T v = new PS.S( );  
v.m( );
```

Problems with Default Access Methods

- S.m does not override T.m (T.m is not accessible in S)
- T.m and S.m are **different methods** with same signature
- **Static** declaration for invocation is **T.m**
- At run time, **S.m is** selected and **invoked**

```
package PT;  
public class T {  
    void m( ) { ... }  
}
```

```
package PS;  
public class S extends PT.T {  
    public void m( ) { ... }  
}
```

```
In package PT:  
T v = new PS.S( );  
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Corrected Method Selection (JLS2)

- Dynamically selected method **must override** statically determined method

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- Dynamically selected method **must override** statically determined method

- At compile time:
 1. Determine static declaration
 2. Check accessibility
 3. Determine invocation mode (virtual / nonvirtual)
- At run time:
 4. Compute receiver reference
 5. Locate method to invoke **that overrides statically determined method**

Problems with Protected Methods

```
package PT;  
public class T {  
    protected void m( ) { ... }  
}
```

```
package PS;  
public class S extends PT.T {  
    protected void m( ) { ... }  
}
```

```
package PT;  
public class C {  
    public void foo( ) {  
        T v = new PS.S( );  
        v.m( );  
    }  
}
```


Problems with Protected Methods

- S.m overrides T.m
- **Static declaration** is T.m, which is **accessible for C**
- **At run time**, S.m is selected, which is **not accessible for C**
- **protected** does not always “**provide at least as much access**” as **protected**

```
package PT;  
public class T {  
    protected void m( ) { ... }  
}
```

```
package PS;  
public class S extends PT.T {  
    protected void m( ) { ... }  
}
```

```
package PT;  
public class C {  
    public void foo( ) {  
        T v = new PS.S( );  
        v.m( );  
    }  
}
```

Problems with Protected Methods

- S.m overrides T.m
- **Static declaration** is T.m, which is **accessible for C**
- **At run time**, S.m is selected, which is **not accessible for C**
- **protected** does not always “**provide at least as much access**” as **protected**

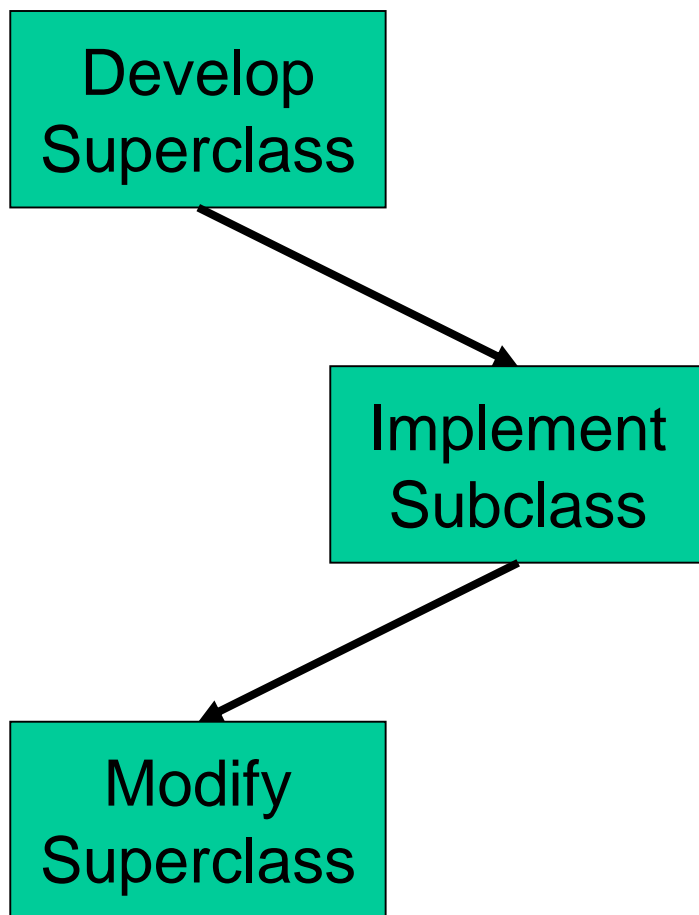
```
package PT;  
public class T {  
    protected void m( ) { ... }  
}
```

```
package PS;  
public class S extends PT.T {  
    protected void m( ) { ... }  
}
```

public would
be safe

```
package PT;  
public class C {  
    public void foo( ) {  
        T v = new PS.S( );  
        v.m( );  
    }  
}
```

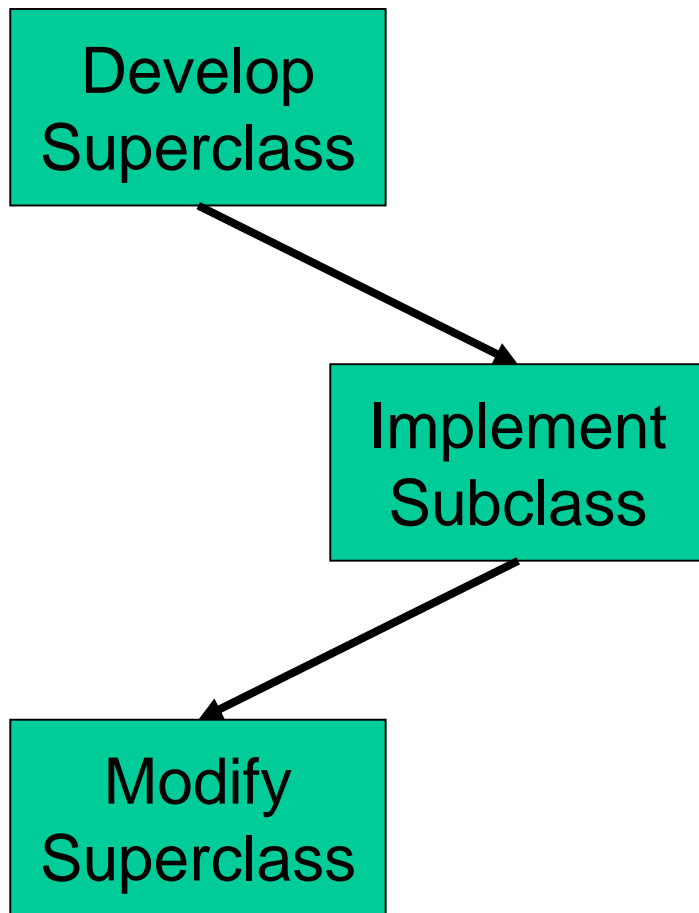
Another Fragile Baseclass Problem



```
class C {  
    int x;  
    public    void inc1( )  
        { this.inc2( ); }  
    private  void inc2( )  
        { x++; }  
}
```

```
class CS extends C {  
    public    void inc2( )    { inc1( ); }  
}
```

Another Fragile Baseclass Problem

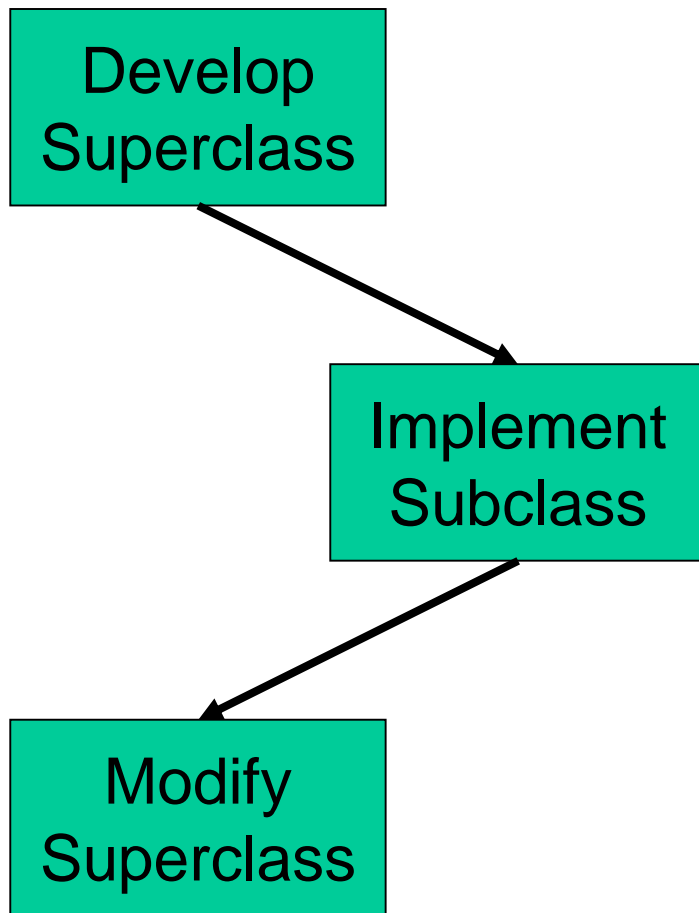


```
class C {  
    int x;  
    public    void inc1( )  
        { this.inc2( ); }  
    private  void inc2( )  
        { x++; }  
}
```

```
class CS extends C {  
    public    void inc2( )    { inc1( ); }  
}
```

```
CS cs = new CS( 5 );  
cs.inc2( );  
System.out.println( cs.x );
```

Another Fragile Baseclass Problem



```
class C {  
    int x;  
    public void inc1( )  
        { this.inc2( ); }  
    protected void inc2( )  
        { x++; }  
}
```

```
class CS extends C {  
    public void inc2( ) { inc1( ); }  
}
```

```
CS cs = new CS( 5 );  
cs.inc2( );  
System.out.println( cs.x );
```

5. Information Hiding and Encapsulation

5.1 Information Hiding

5.2 Encapsulation

Objective

- A well-behaved module operates according to its specification in any context, in which it can be reused
- Implementations rely on consistency of internal representations
- Reuse contexts should be prevented from violating consistency

Objective

- A well-behaved module operates according to its specification in any context, in which it can be reused
- Implementations rely on **consistency of internal representations**
- Reuse contexts should be prevented from violating consistency

```
class Coordinate {  
    public double radius, angle;  
    // invariant 0 <= radius &&  
    // 0 <= angle && angle < 360  
    ...  
    // ensures 0 <= result  
    public double distOrigin( )  
        { return radius; }  
}
```

```
Coordinate c = new Coordinate( );  
c.radius = -10;  
Math.sqrt( c.distOrigin( ) );
```


Encapsulation

- Definition

Encapsulation is a technique for structuring the state space of executed programs. Its objective is to guarantee data and structural consistency by establishing capsules with clearly defined interfaces.

- Encapsulation deals mainly with dynamic aspects
- Information hiding and encapsulation are often used synonymously in the literature; here, encapsulation is a more specific concept

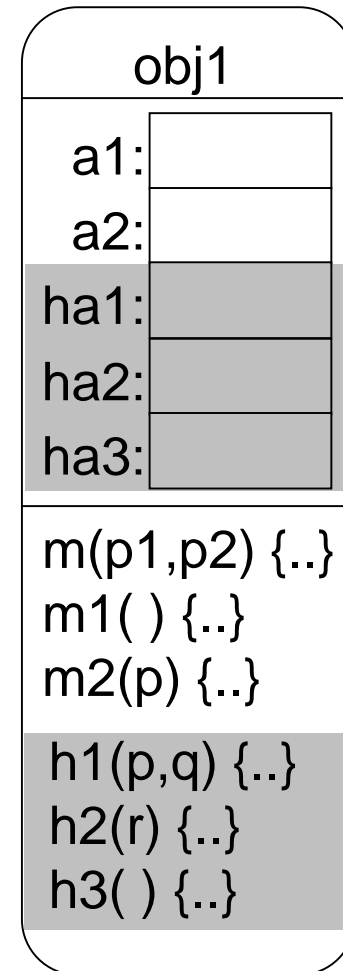
Levels of Encapsulation

- Capsules can be
 - Individual objects
 - Object structures
 - A class (with all of its objects)
 - All classes of a subtype hierarchy
 - A package (with all of its classes and their objects)

- Encapsulation requires a definition of the boundary of a capsule and the interfaces at the boundary

Consistency of Objects

- Objects have (external) interfaces and an (internal) representation
- Consistency can include
 - Properties of one execution state
 - Relations between execution states
- The internal representation of an object is encapsulated if it can be manipulated only by using the object's interfaces



Example: Breaking Consistency (1)

```
class Coordinate {  
    public double radius, angle;  
    // invariant 0 <= radius &&  
    // 0 <= angle && angle < 360  
  
    ...  
    // ensures 0 <= result  
    public double distOrigin( )  
    { return radius; }  
}
```

```
Coordinate c = new Coordinate( );  
c.radius = -10;  
Math.sqrt( c.distOrigin( ) );
```

Example: Breaking Consistency (1)

- Problem:
Exported fields allow
objects to manipulate
the state of other objects

```
class Coordinate {  
    public double radius, angle;  
    // invariant 0 <= radius &&  
    // 0 <= angle && angle < 360  
    ...  
    // ensures 0 <= result  
    public double distOrigin( )  
    { return radius; }  
}
```

```
Coordinate c = new Coordinate( );  
c.radius = -10;  
Math.sqrt( c.distOrigin( ) );
```

Example: Breaking Consistency (1)

- **Problem:**
Exported fields allow objects to manipulate the state of other objects
- **Solution:**
Apply proper information hiding

```
class Coordinate {  
    public double radius, angle;  
    // invariant 0 <= radius &&  
    // 0 <= angle && angle < 360  
    ...  
    // ensures 0 <= result  
    public double distOrigin( )  
        { return radius; }  
}
```

```
Coordinate c = new Coordinate( );  
c.radius = -10;  
Math.sqrt( c.distOrigin( ) );
```

Example: Breaking Consistency (1)

Use
private

- Problem:
Exported fields allow objects to manipulate the state of other objects
- Solution:
Apply proper information hiding

```
class Coordinate {  
    public double radius, angle;  
    // invariant 0 <= radius &&  
    // 0 <= angle && angle < 360  
    ...  
    // ensures 0 <= result  
    public double distOrigin( )  
        { return radius; }  
}
```

```
Coordinate c = new Coordinate( );  
c.radius = -10;  
Math.sqrt( c.distOrigin( ) );
```

Example: Breaking Consistency (2)

```
class Coordinate {  
    protected double radius, angle;  
    // invariant 0 <= radius &&  
    //          0 <= angle && angle < 360  
    ...  
    public double getAngle( )  
    { return angle; }  
}
```


Example: Breaking Consistency (2)

```
class Coordinate {  
    protected double radius, angle;  
    // invariant 0 <= radius &&  
    //           0 <= angle && angle < 360  
    ...  
    public double getAngle( )  
    { return angle; }  
}
```

```
class BadCoordinate  
    extends Coordinate {  
    public void violate( )  
    { angle = -1; }  
}
```

Example: Breaking Consistency (2)

```
class Coordinate {  
    protected double radius, angle;  
    // invariant 0 <= radius &&  
    //           0 <= angle && angle < 360  
    ...  
    public double getAngle( )  
        { return angle; }  
}
```

```
BadCoordinate c =  
    new BadCoordinate( );  
c.violate( );  
Math.sqrt( c.getAngle( ) );
```

```
class BadCoordinate  
    extends Coordinate {  
    public void violate( )  
        { angle = -1; }  
}
```

Example: Breaking Consistency (2)

- **Problem:**
Subclasses can introduce (new or overriding) methods that break consistency

```
BadCoordinate c =  
    new BadCoordinate( );  
c.violate( );  
Math.sqrt( c.getAngle( ) );
```

```
class Coordinate {  
    protected double radius, angle;  
    // invariant 0 <= radius &&  
    //           0 <= angle && angle < 360  
    ...  
    public double getAngle( )  
        { return angle; }  
}
```

```
class BadCoordinate  
    extends Coordinate {  
    public void violate( )  
        { angle = -1; }  
}
```

Example: Breaking Consistency (2)

- Problem:
Subclasses can introduce (new or overriding) methods that break consistency
- Solution:
Behavioral subtyping

```
BadCoordinate c =  
    new BadCoordinate( );  
c.violate( );  
Math.sqrt( c.getAngle( ) );
```

```
class Coordinate {  
    protected double radius, angle;  
    // invariant 0 <= radius &&  
    //           0 <= angle && angle < 360  
    ...  
    public double getAngle( )  
        { return angle; }  
}
```

```
class BadCoordinate  
    extends Coordinate {  
    public void violate( )  
        { angle = -1; }  
}
```

Achieving Consistency of Objects

1. Apply information hiding:
Hide internal representation wherever possible
2. Make consistency criteria explicit:
Use contracts or informal documentation to express consistency criteria (e.g., invariants)
3. Check interfaces:
Make sure that all exported operations of an object – including subclass methods – preserve all documented consistency criteria

Invariants

- Invariants express consistency properties
- The invariant of object o has to hold in:
 - Prestates of o's methods
 - Poststates of o's methods
- Temporary violations possible

```
class Redundant {  
    private int a, b;  
    // invariant a == b  
    ...  
    public void set( int v ) {  
        // prestate: invariant holds  
        a = v;  
        // invariant does not hold  
        b = v;  
        // poststate: invariant holds  
    }  
}
```

Checks for Invariants: Textbook Solution

- Assume that all objects o are capsules
 - Only methods executed on o can modify o 's state
 - The invariant of object o refers only to the encapsulated fields of o
- For each invariant, we have to show
 - That all exported methods preserve the invariants of the receiver object
 - That all constructors establish the invariants of the new object

Object Consistency in Java

```
class Redundant {  
    private int a, b;  
    private Redundant next;  
    // invariant a == b  
  
    ...  
    public void set( int v ) { ... }  
  
    public void violate( ) {  
        // all invariants hold  
        next.a = next.b + 1;  
        // invariant of next does not hold  
    }  
}
```


Object Consistency in Java

- Declaring all fields **private** does not guarantee encapsulation on the level of individual objects

```
class Redundant {  
    private int a, b;  
    private Redundant next;  
    // invariant a == b  
    ...  
    public void set( int v ) { ... }  
  
    public void violate( ) {  
        // all invariants hold  
        next.a = next.b + 1;  
        // invariant of next does not hold  
    }  
}
```

Object Consistency in Java

- Declaring all fields **private** does not guarantee encapsulation on the level of individual objects
- Objects of same class can break the invariant

```
class Redundant {  
    private int a, b;  
    private Redundant next;  
    // invariant a == b  
    ...  
    public void set( int v ) { ... }  
  
    public void violate( ) {  
        // all invariants hold  
        next.a = next.b + 1;  
        // invariant of next does not hold  
    }  
}
```

Object Consistency in Java

- Declaring all fields **private** does not guarantee encapsulation on the level of individual objects
- Objects of same class can break the invariant
- Eiffel supports encapsulation on the object level
 - **feature { NONE }**

```
class Redundant {  
    private int a, b;  
    private Redundant next;  
    // invariant a == b  
    ...  
    public void set( int v ) { ... }  
  
    public void violate( ) {  
        // all invariants hold  
        next.a = next.b + 1;  
        // invariant of next does not hold  
    }  
}
```

Invariants for Java (Simple Solution)

- Assumption: The invariants of object *o* may refer only to **private fields** of *o*
- For each invariant, we have to show
 - That all exported methods **and constructors of class T** preserve the invariants **of all objects of T**
 - That all constructors **in addition** establish the invariants of the new object

References

- James Gosling, Bill Joy, Guy Steele, Gilad Bracha, and Alex Buckley: *The Java Language Specification*. 2013
<http://docs.oracle.com/javase/specs/>
- Peter Müller and Arnd Poetzsch-Heffter: *Kapselung und Methodenbindung: Javas Designprobleme und ihre Korrektur*. Java-Informationen-Tage, 1998 (in German)