301AA - Advanced Programming

Lecturer: Andrea Corradini
andrea@di.unipi.it
http://pages.di.unipi.it/corradini/

Course pages:
http://pages.di.unipi.it/corradini/Didattica/AP-18/

AP-2018-09: Reflection
Overview

• Reflection in Programming Languages: pros & cons

• Reflection in Java
  – Class objects
  – Retrieving members of a class
  – Invoking methods and constructors, accessing fields
  – Accessibility

⇒ Tutorial: The Reflection API of Java
  https://docs.oracle.com/javase/tutorial/reflect/index.html
Reflection

• **Reflection** is the ability of a program to manipulate as data something representing the state of the program during its own execution.

• A system may support reflection at different levels: from simple information on types to reflecting the entire structure of the program.

• Another dimension of reflection is if a program is allowed to **read** only, or also to **change** itself.

• **Introspection** is the ability of a program to **observe** and therefore **reason** about its own state.

• **Intercession** is the ability for a program to **modify** its own execution state or **alter its own interpretation** or meaning.

• Both aspects require a mechanism for encoding execution state as data: providing such an encoding is called **reification**.
Structural and behavioral reflection

- **Structural reflection** is concerned with the ability of the language to provide a complete \textit{reification} of both
  - the \textit{program} currently executed
  - as well as its \textit{abstract data types}.

- **Behavioral reflection** is concerned with the ability of the language to provide a complete \textit{reification} of
  - its own \textit{semantics} and \textit{implementation} (processor)
  - as well as the data and implementation of the \textit{run-time system}.
Uses of Reflection

• **Class Browsers**
  need to be able to enumerate the members of classes

• **Visual Development Environments**
  can exploit type information available in reflection to aid
  the developer in writing correct code.

• **Debuggers**
  need to be able to examine private members on classes

• **Test Tools**
  can make use of reflection to ensure a high level of code
  coverage in a test suite

• **Extensibility Features**
  An application may make use of external, user-defined
  classes by creating instances of extensibility objects
Drawbacks of Reflection

If it is possible to perform an operation without using reflection, then it is preferable to avoid using it, because Reflection brings:

• **Performance Overhead**
  Reflection involves types that are dynamically resolved, thus JVM optimizations cannot be performed, and reflective operations have slower performance than their non-reflective counterparts.

• **Security Restrictions**
  Reflection requires a runtime permission which may not be present when running under a security manager. This affects code which has to run in a restricted security context, such as in an Applet.

• **Exposure of Internals**
  Reflective code may access internals (like private fields), thus it breaks abstractions and may change behavior with upgrades of the platform, destroying portability.
Reflection in Java

• Java supports **introspection** and **reflexive invocation**, but not code modification.
• For every type (*primitive, loaded or synthesized*), the JVM maintains an associated object of class **java.lang.Class**
• This object “reflects” the type it represents
• It is the “entry point” for reflection. All relevant information about the type can be obtained from it:
  – Class name & modifiers
  – Superclass & Interfaces implemented
  – Methods, fields, constructors, etc.
• API: **java.lang.reflect**
The Reflection Logical Hierarchy in Java

- Object
- Class
- compiled class file
- Field
- Method
- Constructor
- Member
Retrieving Class Objects

• Use method `Object.getClass()`

• Examples:
  – `Class c = "foo".getClass();` // String
  – `byte[] bytes = new byte[1024];
    Class c = bytes.getClass();` // byte array
  – `Set<String> s = new HashSet<String>();
    Class c = s.getClass();` // HashSet

• Use field `.class` of a type (also primitive)
  – `Class c = String.class;`
  – `Class c = boolean.class;`
  – `Class c = int[][[]].class;`
Retrieving Class Objects (2)

• Use method `Class.forName(String)`

• Examples:
  - `Class c = Class.forName("java.util.List");`
  - `Class c = Class.forName("[D"); // double[]`
  - `Class c = Class.forName("[[Ljava.lang.String;");`
Instances of the class `Class` represent classes and interfaces in a running Java application.

Class objects are constructed automatically by the JVM as classes are loaded.

They provide access to the information read from the class file.
# Class file structure

```java
ClassFile {
    u4 magic;          \ 0xCAFEBABE  
    u2 minor_version;  \  Java Language Version  
    u2 major_version;  \  Constant Pool  
    u2 constant_pool_count;
    cp_info constant_pool[constant_pool_count–1];  \  access modifiers and other info  
    u2 access_flags;  \  References to Class and Superclass  
    u2 this_class;  
    u2 super_class;  \  References to Direct Interfaces  
    u2 interfaces_count;
    u2 interfaces[interfaces_count];  \  Static and Instance Variables  
    u2 fields_count;
    field_info fields[fields_count];  \  Methods  
    u2 methods_count;
    method_info methods[methods_count];  \  Other Info on the Class  
    u2 attributes_count;
    attribute_info attributes[attributes_count];
}
```
Inspecting a Class

- After we obtain a Class object `myClass`, we can:
  - Get the class name
    ```java
    String s = myClass.getName();
    ```
  - Get the class modifiers
    ```java
    int m = myClass.getModifiers();
    boolean isPublic = Modifier.isPublic(m);
    boolean isAbstract = Modifier.isAbstract(m);
    boolean isFinal = Modifier.isFinal(m);
    ```
  - Test if it is an interface
    ```java
    boolean isInterface = myClass.isInterface();
    ```
  - Get the interfaces implemented by a class
    ```java
    Class[] itfs = myClass.getInterfaces();
    ```
  - Get the superclass
    ```java
    Class super = myClass.getSuperClass();
    ```
public static void showType(String className) throws ClassNotFoundException {
    Class thisClass = Class.forName(className);
    String flavor = thisClass.isInterface() ? "interface" : "class";
    System.out.println(flavor + " " + className);
    Class parent = thisClass.getSuperclass();
    if (parent != null) {
        System.out.println("extends " + parent.getName());
    }
    Class[] interfaces = thisClass.getInterfaces();
    for (int i = 0; i < interfaces.length; ++i) {
        System.out.println("implements "+
                interfaces[i].getName());
    }
}
Discovering Class members

• Fields, methods, and constructors

• `java.lang.reflect.*` :
  – `Member` interface
  – `Field` class
  – `Method` class
  – `Constructor` class
## Class Methods for Locating Members

<table>
<thead>
<tr>
<th>Member</th>
<th>Class API</th>
<th>List of members?</th>
<th>Inherited members?</th>
<th>Private members?</th>
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<tr>
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<td>getDeclaredField(String)</td>
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<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Field</td>
<td>getField(String)</td>
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<td>no</td>
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<td>yes</td>
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<tr>
<td>Field</td>
<td>getFields()</td>
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<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Method</td>
<td>getDeclaredMethod(…)</td>
<td>no</td>
<td>no</td>
<td>yes</td>
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<tr>
<td>Method</td>
<td>getMethod(…)</td>
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<td>no</td>
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<tr>
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<td>getMethods()</td>
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<td>no</td>
</tr>
<tr>
<td>Constructor</td>
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<td>N/A</td>
<td>yes</td>
</tr>
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<td>getConstructors()</td>
<td>yes</td>
<td>N/A</td>
<td>no</td>
</tr>
</tbody>
</table>
Class Methods for locating Fields

- **getDeclaredField(String name)**: Returns a Field object representing the field called **name**. Must belong to the class **this** and can be private.

- **getField(String name)**: Returns a Field object representing the field called **name**. Must be public and can belong to a superinterface or superclass.

- **getDeclaredFields()**: Returns an array of Field objects reflecting all the fields declared by the class or interface represented by this Class object. This includes public, protected, default (package) access, and private fields, but excludes inherited fields.

- **getFields()**: Returns an array containing Field objects reflecting all the accessible public fields of the class or interface represented by this Class object.
Class Methods for locating Methods

- `getDeclaredMethod(String name, Class<?>... parameterTypes)`: Returns a `Method` object corresponding to the specified method, declared in this class.
- `getMethod(String name, Class<?>... parameterTypes)`: Returns a `Method` object corresponding to the public specified method.
- `getDeclaredMethods()`: Returns an array of `Method` objects reflecting all (public and private) the methods declared by the class or interface represented by this Class object.
- `getMethods()`: Returns an array containing `Method` objects reflecting all the accessible public methods of the class or interface represented by this Class object.
Class Methods for locating Constructors

- **getDeclaredConstructor** (**Class**< ? >... **parameterTypes**): Returns a Constructor object that reflects the specified constructor of the class or interface represented by this Class object. The parameterTypes parameter is an array of Class objects that identify the constructor's formal parameter types, in declared order.

- **getConstructor** (**Class**< ? >... **parameterTypes**): Returns a Constructor object that reflects the specified public constructor of the class represented by this Class object. The parameterTypes parameter is an array of Class objects that identify the constructor's formal parameter types, in declared order.

- **getDeclaredConstructors()**: Returns an array of Constructor objects reflecting all the constructors declared by the class represented by this Class object. These are public, protected, default (package) access, and private constructors. The elements in the array returned are not sorted and are not in any particular order.

- **getConstructors()**: Returns an array containing Constructor objects reflecting all the accessible public constructors
Working with Class members

• **Members**: fields, methods, and constructors

• For each member, the reflection API provides support to retrieve declaration and type information, and operations unique to the member (for example: setting the value of a field, invoking a method, creating an object)

• `java.lang.reflect.*`:
  - **Member** interface
  - **Field** class: Fields have a type and a value. The `java.lang.reflect.Field` class provides methods for accessing type information and setting and getting values of a field on a given object.
Working with Class members

- **Method** class: Methods have return values, parameters and may throw exceptions. The `java.lang.reflect.Method` class provides methods for accessing type information for return type and parameters and **invoking** the method on a given object.

- **Constructor** class: The Reflection APIs for constructors are defined in `java.lang.reflect.Constructor` and are similar to those for methods, with two differences:
  - constructors have no return values
  - the invocation of a constructor creates a new instance of an object for a given class
public class Btest
{
    public String aPublicString;
    private String aPrivateString;
    public Btest(String aString) {
        // ...
    }
    public Btest() {
        // ...
    }
    public Btest(String s1,String s2) {
        // ...
    }
    private void Op1(String s) {
        // ...
    }
    protected String Op2(int x) {
        // ...
    }
    public void Op3() {
        // ...
    }
}

public class Dtest extends Btest
{
    public int aPublicInt;
    private int aPrivateInt;
    public Dtest(int x) {
        // ...
    }
    private void OpD1(String s) {
        // ...
    }
    public String OpD2(int x){
        // ...
    }
}
Example: retrieving **public** fields

```java
// get all public fields
try{
    Class c = Class.forName("Dtest");
    Field[] publicFields = c.getFields();
    for (int i = 0; i < publicFields.length; ++i) {
        String fieldName = publicFields[i].getName();
        Class typeClass = publicFields[i].getType();
        System.out.println("Field: " + fieldName + " of type " + typeClass.getName());
    }
} catch (ClassNotFoundException e){
    System.out.println("Class not found...");
}
```

Field: aPublicInt of type int
Field: aPublicString of type java.lang.String
Example: retrieving **declared** fields

```java
Class c = Class.forName("Dtest");

// get all declared fields
Field[] publicFields = c.getDeclaredFields();
for (int i = 0; i < publicFields.length; ++i) {
    String fieldName = publicFields[i].getName();
    Class typeClass = publicFields[i].getType();
    System.out.println("Field: " + fieldName + " of type " + typeClass.getName());
}
```

Field: aPublicInt of type int
Field: aPrivateInt of type int
Example: retrieving public constructors

```java
// get all public constructors
Constructor[] ctors = c.getConstructors();
for (int i = 0; i < ctors.length; ++i) {
    System.out.print("Constructor ( ");
    Class[] params = ctors[i].getParameterTypes();
    for (int k = 0; k < params.length; ++k){
        String paramType = params[k].getName();
        System.out.print(paramType + " ");
    }
    System.out.println(")");
}
```

Constructor (int )
Example: retrieving public methods

```java
//get all public methods

Method[] ms = c.getMethods();
for (int i = 0; i < ms.length; ++i) {
    String mname = ms[i].getName();
    Class retType = ms[i].getReturnType();
    System.out.print("Method : "+mname+" returns "+retType.getName()+" parameters : ( ");
    Class[] params = ms[i].getParameterTypes();
    for (int params = 0; k < params.length; ++k) {
        String paramType = params[i].getName();
        System.out.print(paramType + " ");
    }
    System.out.println(") ");
}
Method : OpD2 returns java.lang.String parameters : ( int )
Method : Op3 returns void parameters : ()
Method : wait returns void parameters : ()
Method : wait returns void parameters : ( long int )
Method : wait returns void parameters : ( long )
Method : hashCode returns int parameters : ( )
Method : getClass returns java.lang.Class parameters : ( )
Method : equals returns boolean parameters : ( java.lang.Object )
Method : toString returns java.lang.String parameters : ( )
Method : notify returns void parameters : ( )
Method : notifyAll returns void parameters : ( )
```
//get all declared methods

Method[] ms = c.getDeclaredMethods();
for (int i = 0; i < ms.length; ++i) {
    String mname = ms[i].getName();
    Class retType = ms[i].getReturnType();
    System.out.print("Method : " + mname + " returns " + retType.getName() + " parameters : ( ");
    Class[] params = ms[i].getParameterTypes();
    for (int k = 0; k < params.length; ++k)
    {
        String paramType = params[k].getName();
        System.out.print(paramType + " ");
    }
    System.out.println(") ");
}

Method : OpD1 returns void parameters : ( java.lang.String )
Method : OpD2 returns java.lang.String parameters : ( int )
Due to Java’s erasure semantics, generic type information is not represented at run time.
Method signature and erasure (2)

```java
try {
    LinkedList<String> list = new LinkedList<String>();
    Class c = list.getClass();
    Method add = c.getMethod( "add", Object.class );
} catch( Exception e ) {
    System.out.println( "Method not found" );
}

// no exception
```
Using Reflection for Program Manipulation

• Previous examples used Reflection for Introspection only

• Reflection is a powerful tool to:
  – Creating new objects of a type that was not known at compile time
  – Accessing members (accessing fields or invoking methods) that are not known at compile time
Using Reflection for Program Manipulation

- **Object**
- **Class**
  - **Field**
  - **Method**
  - **Constructor**

compiled class file
MyNewClass.class

get/set
invoke
Creating new objects

• Using Default Constructors
  – `java.lang.reflect.Class.newInstance()`

```java
Rectangle r = new Rectangle();
Class c = Class.forName("java.awt.Rectangle") ;
Rectangle r = (Rectangle) c.newInstance();
```

• Using Constructors with Arguments
  – `java.lang.reflect.Constructor.newInstance(Object... initargs)`

```java
Rectangle r = new Rectangle(12,24);
Class c = Class.forName("java.awt.Rectangle") ;
Class[] intArgsClass = new Class[]{int.class, int.class};
Object[] intArgs = new Object[]{new Integer(12),new Integer(24)};
Constructor ctor = c.getConstructor(intArgsClass);
Rectangle r = (Rectangle) ctor.newInstance(intArgs);
```
Accessing fields

• Getting Field Values
  Rectangle r = new Rectangle(12,24) ;
  // h = r.height
  Class c = r.getClass() ;
  Field f = c.getField("height") ;
  Integer h = (Integer) f.get(r) ;

• Setting Field Values
  Rectangle r = new Rectangle(12,24) ;
  // r.width=30
  Class c = r.getClass() ;
  Field f = c.getField("width") ;
  f.set(r, new Integer(30)) ;
Invoking methods

```java
String s1 = "Hello";
String s2 = "World";
// result = s1.concat(s2);

Class c = String.class;
Class[] paramtypes = new Class[] { String.class };
Object[] args = new Object[] { s2 };
Method concatMethod =
    c.getMethod("concat",paramtypes);
String result =
    (String) concatMethod.invoke(s1,args);
```
Accessible Objects

- Certain operations are forbidden by privacy rules:
  - Changing a final field
  - Reading or writing a private field
  - Invoking a private method...
- Such operations fail also if invoked through reflection
- The programmer can request that Field, Method, and Constructor objects be "accessible."
  - Request granted if no security manager, or if the existing security manager allows it
- In this case you can invoke method or access field, even if inaccessible via privacy rules!
- **AccessibleObject** Class: the superclass of Field, Method, and Constructor
Accessible Objects (cont.)

**AccessibleObject** provides the methods:

- **boolean isAccessible( )**
  - Gets the value of the accessible flag for this object
- **void setAccessible(boolean flag)**
  - Sets the accessible flag for this object to the indicated boolean value
- **static void setAccessible(AccessibleObject[] array, boolean flag)**
  - Sets the accessible flag for an array of objects with a single security check
Accessing private fields

```java
public static String getString( Object o ) {
    if ( o == null ) return "null";
    Class toExamine = o.getClass();
    String state = "[";
    Field[ ] fields = toExamine.getDeclaredFields( );
    for ( int fi = 0; fi < fields.length; fi++ )
        try {
            Field f = fields[ fi ];
            if ( !Modifier.isStatic( f.getModifiers( ) ) )
                state += f.getName() + ":" + "\n
        } catch ( Exception e ) { return "Exception"; }
    return state + "]";
}
```

```java
class Cell {
    private int value = 5;
    ...
}
```
java.lang.reflect Class Field

```java
public Object get(Object obj)
throws IllegalArgumentException, IllegalAccessException
```

Returns the value of the field represented by this Field, on the specified object. The value is automatically wrapped in an object if it has a primitive type.

The underlying field's value is obtained as follows:

- <omissis>

- If this Field object is enforcing Java language access control, and the underlying field is inaccessible, the method throws an `IllegalAccess Exception`. If the underlying field is static, the class that declared the field is initialized if it has not already been initialized.
public static String getString( Object o ) {
    if ( o == null ) return "null";
    Class toExamine = o.getClass( );
    String state = "[";
    Field[ ] fields = toExamine.getDeclaredFields( );
    for ( int fi = 0; fi < fields.length; fi++ )
        try {
            Field f = fields[ fi ];
            f.setAccessible( true );
            if ( !Modifier.isStatic( f.getModifiers( ) ) )
                state += f.getName() + "=" + f.get( o ) + "", ";
        } catch ( Exception e ) { return "Exception"; }
    return state + "]";
}

class Cell {
    private int value = 5;
    ...
}

Cell c = new Cell( );
String s = getString( c );
System.out.println( s );
[value=5, ]
class Cell {
    int value;
    Cell( int v ) { value = v; }
    int get( ) { return value; }
    void set( int v )
    {
        value = v;
    }
    void swap( Cell c ) {
        int tmp = value;
        value = c.value;
        c.value = tmp;
    }
}

class TestCell {
    void testSet( ) { ... }
    void testSwap( ) {
        Cell c1 = new Cell( 5 );
        Cell c2 = new Cell( 7 );
        c1.swap( c2 );
        assert c1.get( ) == 7;
        assert c2.get( ) == 5;
    }
}
A generic driver; the basic mechanism behind JUnit
Conclusions

- Reflective capabilities need special support at the levels of language (APIs) and compiler

  - Language (API) level:
    - Java: java.lang.reflection
    - .NET: System.Reflection
    - Very similar hierarchy of classes supporting reflection (Metaclasses)

  - Compiler level:
    - Specific type information is saved together with the generated code (needed for type discovery and introspection)
    - The generated code must contain also code for automatically creating instances of the Metaclasses every time a new type is defined in the application code