Building distributed systems with RMI

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Agenda

Week	Wednesday, 13:30 – 18:30
S6	*Introduction to distributed systems and middleware* (CM), S. Bouchenak, 13:30 – 15:00 *Introduction to JDBC* (CM), C. Labbé, 15:15 – 16:45
S7	**RMI-based distributed systems** (CM), S. Bouchenak , 13:30 – 15:00 RMI-based distributed systems (TD), S. Bouchenak & D. Serrano, 15:15 – 18:30
S8	Servlet-based distributed systems (CM), S. Bouchenak , 13:30 – 15:00 RMI-based distributed systems (TD), S. Bouchenak & D. Serrano, 15:15 – 18:30
S9	Interruption week
S10	Introduction to transactions (CM), C. Labbé, 13:30 – 15:00
S11	Multi-tier distributed systems (CM), S. Bouchenak , 13:30 – 15:00 Servlet-based distributed systems (TD), S. Bouchenak & D. Serrano, 15:15 – 18:30
S12	Presentation of the project (CM), S. Bouchenak , 13:30 – 15:00 Multi-tier distributed systems (TD), S. Bouchenak & D. Serrano, 15:15 – 18:30
S13	Support projet (TD), C. Labbé & D. Serrano, 15:15 – 18:30
S14	–
S15	Project, S. Bouchenak & C. Labbé & D. Serrano, 13:30 – 16:45

Motivations

- Sockets are a simple and flexible technology for data communication in distributed systems
- Sockets are restricted to the transmission of data
- Sockets leave the semantics of this data unconsidered
- Protocols which provide the semantic interpretation of the data must be developed on the application level
- The development of such protocols is often time-consuming and error-prone

Motivations (2)

- Object-oriented programming already provides a framework for semantics of data – the objects
- In local applications, objects communicate via methods
- It would be desirable, for distributed applications, to have a similar communication paradigm available
- Such a communication paradigm would permit the remote call of methods
- Java provides the Remote Method Invocation mechanism: *RMI*

Remote Procedure Call (RPC)

- RPC is a technology developed in the 80s to call procedures on remotes computers (with the procedural programming paradigm)
- RPC allows the call of procedures located in another process space on a remote computer (or on the same machine)
- Technical issues for implementing RPC
  - Different addess spaces
  - Heterogeneous machines

RPC implementation

- Different address spaces
  - In the local case:
    - Data used in a procedure call is simply passed as a reference (a pointer)
    - This reference refers to a physical memory address
    - Such a reference has no correct meaning in a different address space
  - In the distributed case:
    - The referenced data used in a remote call needs to be passed as a copy

RPC implementation (2)

- Heterogeneous machines
  - In communication between heterogeneous computer architectures, the internal representation of data on another computer may not be the same as on the original computer
  - Data sent in remote procedure calls must be converted into a platform-independent data format (e.g. XDR – eXtensible Data Representation)
  - Data received in remote procedure calls must be converted back into an internal representation of the receiver's side

Outline

1. Motivations
2. **Overview of RMI-based distributed applications**
3. A simple example
4. Methodology to build distributed applications using RMI
5. The architecture of RMI
6. A detailed example step by step

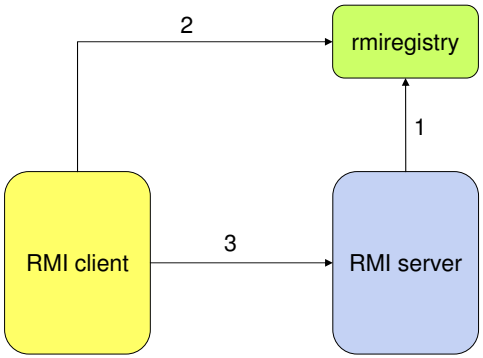
Overview of RMI-based distributed applications

- RMI applications comprise two separate programs, a server and a client
- The server program:
  - creates some remote objects,
  - makes references to these objects accessible,
  - and waits for clients to invoke methods on these objects.
- The client program:
  - obtains a remote reference to one or more remote objects on a server,
  - and then invokes methods on them.
- RMI provides the mechanism by which the server and the client communicate and pass information back and forth.

Overview of RMI-based distributed applications (2)

- Distributed object applications follow these steps:
  - Client locates remote objects on server
    - Various mechanisms to obtain references to remote objects
    - An application server can register its remote objects with RMI registry (RMI's simple naming facility)
    - An application server can return remote object references as part of other remote invocations
  - Client communicates with remote objects on server
    - To the client programmer, remote communication looks similar to regular Java method invocations
    - Details of remote communication are handled by RMI and transparent to client and server programs
  - Load class definitions for objects that are passed around
    - Because RMI enables objects to be passed back and forth, it provides mechanisms for loading an object's class definition

Overview of RMI-based distributed applications (3)



Remote objects

- Objects with methods that can be invoked across Java virtual machines are called *remote objects*
- An object becomes remote by implementing a *remote interface*, which has the following characteristics:
  - A remote interface extends the interface *java.rmi.Remote*
  - Each method of the interface declares *java.rmi.RemoteException* in its throws clause, in addition to any application-specific exceptions

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A simple example

Remote object – Interface definition

```
import java.rmi.*;


public interface Hello
    extends Remote {

    // A method provided by the
    // remore object
    public String sayHello()
          throws RemoteException;

}
```


A simple example (2)

Remote object – Interface definition

```
import java.rmi.*;


public interface Hello
    extends Remote {

    // A method provided by the
    // remore object
    public String sayHello()
          throws RemoteException;

}
```

Remote object – Class implementation

```
import java.rmi.*;
import java.rmi.server.*;

public  class HelloImp
    implements Hello {

    private String message;

    public Hello(String s) {
          message = s ;
    }

    public String sayHello ()
          throws RemoteException {
          return message ;
    }

}
```


A simple example (3)

Server

```
import java.rmi.*;
import java.rmi.server.*;
import java.rmi.registry.*;

public class HelloServer {

  public static void  main(String [] args){
     ...

     try {
        // Create a Hello remote object
        HelloImp h =
              new HelloImp ("Hello world !");
        Hello h_stub = (Hello)
        UnicastRemoteObject.exportObject(h, 0);

        // Register the remote object in RMI
        // registry with a given identifier
        Registry registry= LocateRegistry.getRegistry();
        registry.bind("Hello1", h_stub);

        System.out.println ("Server ready");

     } catch (Exception e)  {
              System.err.println("Error on server :"
              + e) ;
              e.printStackTrace();
              return;
     }
  }
}
```

A simple example (4)

Server

```
import java.rmi.*;
import java.rmi.server.*;
import java.rmi.registry.*;

public class HelloServer {

  public static void  main(String [] args){
     ...

     try {
        // Create a Hello remote object
        HelloImp h =
              new HelloImp ("Hello world !");
        Hello h_stub = (Hello)
        UnicastRemoteObject.exportObject(h, 0);

        // Register the remote object in RMI
        // registry with a given identifier
        Registry registry= LocateRegistry.getRegistry();
        registry.bind("Hello1", h_stub);

        System.out.println ("Server ready");

     } catch (Exception e)  {
              System.err.println("Error on server :"
              + e) ;
              e.printStackTrace();
              return;
     }
  }
}
```

Client

```
import java.rmi.*;
import java.rmi.registry.*;

public class HelloClient {
  public static void main(String [] args) {

     try {
     if (args.lenght < 1) {
        System.out.println("Usage:
              java HelloClient <server host>");
        return;
     }
     String host = arg[0];

     // Get remote object reference
     Registry registry =
        LocateRegistry.getRegistry(host);
     Hello h = (Hello) registry.lookup("Hello1");

     // Remote method invocation
     String res = h.sayHello();

     System.out.println(res);

     } catch (Exception e)  {
              System.err.println("Error on
              client: " + e) ;
     }
  }
}
```


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4. **Methodology to build distributed applications using RMI**
5. The architecture of RMI
6. A detailed example step by step

Steps to build distributed applications with RMI

- Using RMI to develop a distributed application involves the following general steps:
  1. Designing and implementing the components of the distributed application.
  2. Compiling sources.
  3. Making classes network accessible.
  4. Starting the application.

Designing and implementing the components of the distributed application

- Determine application architecture
  - Which components are local objects
  - And which components are remotely accessible
  - What components are servers (creators of remote objects) and which are clients (accessors to remote objects)
- Define remote interfaces
  - A remote interface specifies the methods that can be invoked remotely by a client on remote objects
  - The design of such interfaces includes the determination of the types of objects that will be used as the parameters and return values for these methods
  - If any of these interfaces or classes do not yet exist, they need to be defined as well
  - Client program accesses remote interfaces, not to the implementation classes of those interfaces

Designing and implementing the components of the distributed application (2)

- Implementing remote objects
  - Remote objects must implement one or more remote interfaces
  - The remote object class may include implementations of other interfaces and methods that are available only locally
  - If any local classes are to be used for parameters or return values of any of these methods, they must be implemented as well
- Implementing servers
  - Servers that create remote objects and provide access to them can be implemented at any time after the remote objects are implemented
- Implementing clients
  - Clients that use remote objects can be implemented at any time after the remote interfaces are defined

Steps to build distributed applications with RMI

- Using RMI to develop a distributed application involves the following general steps:
  1. Designing and implementing the components of the distributed application
  2. **Compiling sources**
  3. Making classes network accessible
  4. Starting the application

Compiling source code

- As with any Java program, use *javac* compiler to compile the source files
- The source files contain
  - the declarations of the remote interfaces
  - their implementations
  - any other server classes
  - and the client classes
- With versions prior to Java Platform, Standard Edition 5.0
  - an additional step was required to build stub classes
  - by using the *rmic* compiler
  - however, this step is no longer necessary

Steps to build distributed applications with RMI

- Using RMI to develop a distributed application involves the following general steps:
  1. Designing and implementing the components of the distributed application
  2. Compiling sources
  3. **Making classes network accessible**
  4. Starting the application

Making classes network accessible

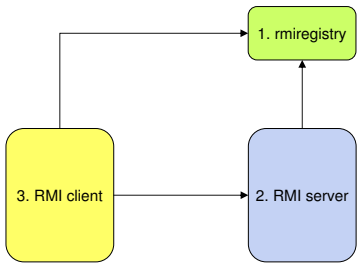
- Certain class definitions are made network accessible
  - such as the definitions for the remote interfaces
  - and their associated types,
  - and the definitions for classes that need to be downloaded to the clients or servers
- Class definitions are typically made network accessible through a web server

Steps to build distributed applications with RMI

- Using RMI to develop a distributed application involves the following general steps:
  1. Designing and implementing the components of the distributed application
  2. Compiling sources
  3. Making classes network accessible
  4. **Starting the application**

Starting the application

- Starting the application includes
  - running the RMI remote object registry
    - using the *rmiregistry* tool
  - the server
    - using the *java* tool
  - and the client
    - using the *java* tool



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5. **The architecture of RMI**
6. A detailed example step by step

The architecture of RMI

- Transparency regarding distribution
  - RMI offers full trasparency regarding distribution
  - After a first initialization, a call can be used in exactly the same way as in the local case

The architecture of RMI (2)

Server

```
import java.rmi.*;
import java.rmi.server.*;
import java.rmi.registry.*;

public class HelloServer {

  public static void  main(String [] args){
     ...

     try {
        // Create a Hello remote object
        HelloImp h =
              new HelloImp ("Hello world !");
        Hello h_stub = (Hello)
        UnicastRemoteObject.exportObject(h, 0);

        // Register the remote object in RMI
        // registry with a given identifier
        Registry registry= LocateRegistry.getRegistry();
        registry.bind("Hellol", h_stub);

        System.out.println ("Server ready");

     } catch (Exception e)  {
              System.err.println("Error on server :"
              + e) ;
              e.printStackTrace();
              return;
     }
  }
}
```

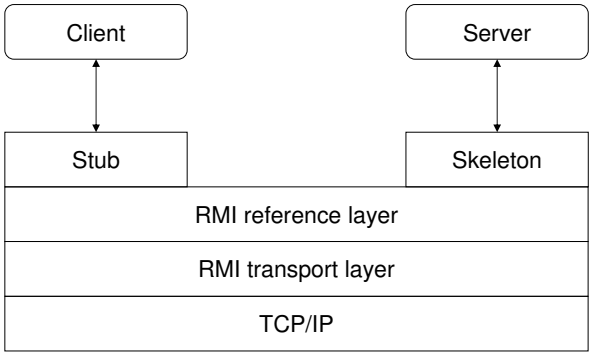
Client

```
import java.rmi.*;
import java.rmi.registry.*;

public class HelloClient {
  public static void main(String [] args) {

     try {
     if (args.lenght < 1) {
        System.out.println("Usage:
              java HelloClient <server host>"); return;
     }
     String host = arg[0];
     // Get remote object reference
     Registry registry =
        LocateRegistry.getRegistry(host);
     Hello h = (Hello) registry.lookup("Hellol");

     // Remote method invocation
     String res = h.sayHello();
     System.out.println(res);
     } catch (Exception e)  {
              System.err.println("Error on
              client: " + e) ;
     }
  }
}
```


The architecture of RMI (3)

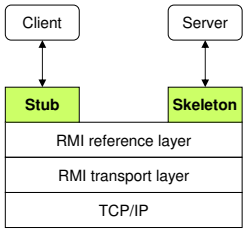
- Transparency regarding distribution
  - RMI offers full trasparency regarding distribution
  - After a first initialization, a call can be used in exactly the same way as in the local case
- RMI client and server
  - Both client and server are normal objects implemented in Java
  - The server must document the interface it provides for remote access
  - From this description, additional classes are automatically created by a special compiler
  - These classes internally take care of communication handling between client and server
  - These classes are known as *Stub* (client-side) and *Skeleton* (server-side)

Layers of RMI architecture



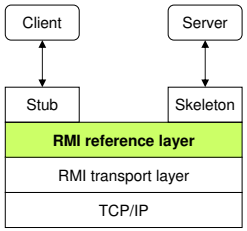
The architecture of RMI (4)

- The stub and skeleton layer in RMI
  - Stub
    - A placeholder object which offers the same interface as the server object
  - Skeleton
    - The skeleton takes the calls of the stub
    - It processes them
    - It forwards the call to the server object
    - It waits for the result
    - It sends the result back to the stub



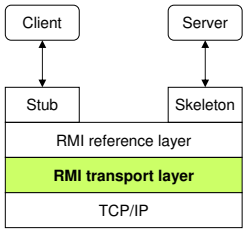
The architecture of RMI (5)

- The reference layer in RMI
  - It finds the respective communication partners
  - It includes the name service, the *registry*



The architecture of RMI (6)

- The transport layer in RMI
  - It manages communication connections
  - It handles communication
  - It must not be confused with the network transport layer (e.g. TCP/IP)



Outline

1. Motivations
2. Overview of RMI-based distributed applications
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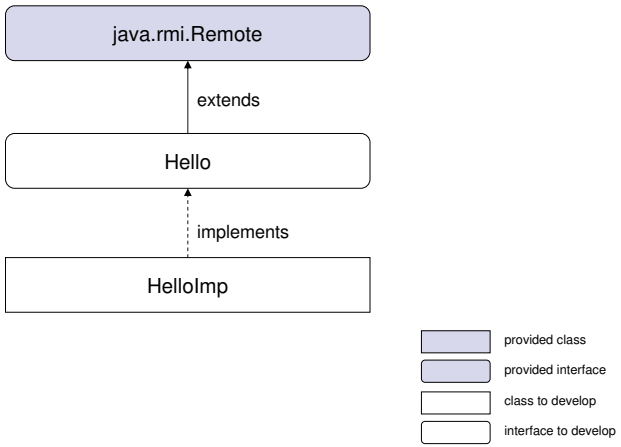
5. The architecture of RMI
   - Architecture
   - **Class hierarchy in RMI**
6. A detailed example step by step

Class hierarchy in RMI



Class hierarchy in RMI (2)

- Package ***java.rmi.server***
  - Provides classes and interfaces for supporting the server side of RMI
- Class ***java.rmi.server.RemoteObject***
  - Distributed objects do not inherit directly from *Object*
  - They inherit from *RemoteObject*
  - *RemoteObject* implements the *Object* behavior for remote objects (e.g. methods *hashCode*, *equals*, and *toString* are reimplemented)
- Class ***java.rmi.server.UnicastRemoteObject***
  - Provides support for point-to-point active object references (invocations, parameters, and results)
  - Uses TCP streams

Class hierarchy in RMI (3)

- Package ***java.rmi***
  - Provides the RMI package
- Interface ***java.rmi.Remote***
  - Identifies interfaces whose methods may be invoked from a non-local virtual machine
  - Any object that is a remote object must directly or indirectly implement this interface
  - Only those methods specified in a "remote interface“ (an interface that extends java.rmi.Remote) are available remotely
- Class ***java.rmi.RemoteException***
  - Communication-related exceptions that may occur during the execution of a remote method call
  - Each method of a remote interface (an interface that extends *java.rmi.Remote*) must list *RemoteException* in its throws clause

Class hierarchy in an example

Remote object – Interface definition

```
import java.rmi.*;


public interface Hello
    extends java.rmi.Remote {

    // A method provided by the
    // remore object
    public String sayHello()
    throws java.rmi.RemoteException;

}
```

Remote object – Class implementation

```
import java.rmi.*;
import java.rmi.server.*;

public  class HelloImp
    implements Hello {

    private String message;

    public Hello(String s)
    {
          message = s ;
    }

    public String sayHello ()
          throws java.rmi.RemoteException
    {
          return message ;
    }

}
```

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A detailed example step by step

- Main steps to create a distributed application with RMI:

Server side	Client side
Define the remote interface provided by the remote object	
Implement the remote object	
Implement the server program	Implement the client program
Compile the source files	Compile the source files
Start the RMI regsitry	
Start the server	Start the client

A detailed example step by step (2)

- Define the remote interface provided by the remote object:
  - Extends *java.rmi.Remote*
  - Defines the set of methods that can be called remotely
  - Each method must declare *java.rmi.RemoteException*

```
import java.rmi.Remote;
Import java.rmi.RemoteException;


public interface Hello extends Remote {

   // A method provided by the remore object
   public String sayHello() throws RemoteException;

}
```


A detailed example step by step (3)

- Implement the remote object in a class:
  - Declare the remote interface being implemented
  - Implement the set of methods that can be called remotely
  - Implement any other local method that can not be invoked remotely

```
import java.rmi.RemoteException;

public  class HelloImp implements Hello {
    private String message;

    public Hello(String s) {
          message = s ;
    }

    public String sayHello () throws RemoteException {
          return message ;
    }
}
```

A detailed example step by step (4)

- Implement the remote object in a class – Passing objects in RMI
  - Arguments to remote methods or return values from remote methods can be of any type
    - Primitive data types (e.g. int, float, etc.)
    - Remote objects
    - Local objects
  - Objects passed to or returned from remote methods must be *serializable*
    - They must implement the *java.io.Serializable* interface
  - Some object types do not meet any of these criteria; they cannot be passed to or returned from remote methods
    - Most of these objects, such as threads or file descriptors, encapsulate information that makes sense only within a single address space
    - Many of the core classes (e.g. classes in the packages *java.lang* and *java.util*) implement the *Serializable* interface

A detailed example step by step (5)

- How arguments and return values are passed in remote method invocations
  - Remote objects are essentially passed by reference
    - A remote object reference is a stub
    - It is a client-side proxy that implements the remote interface that the remote object implements
    - Passing a remote object by reference means that any changes made to the state of the object by remote method invocations are reflected in the original remote object
  - Local objects are passed by copy
    - Using object serialization
    - By default, all fields are copied except fields that are marked static or transient
    - Default serialization behavior can be overridden on a class-by-class basis
    - A copy of the object is created in the receiving Java virtual machine
    - Any changes to the object's state by the receiver are reflected only in the receiver's copy, not in the sender's original instance
    - Any changes to the object's state by the sender are reflected only in the sender's original instance, not in the receiver's copy

A detailed example step by step (6)

- Implement the server program:
  - Create and install a security manager
  - Create and export remote objects
  - Register remote objects with the RMI registry

```
import java.rmi.server.UnicastRemoteObject;
import java.rmi.registry.LocateRegistry;
import java.rmi.registry.Registry;

public  class HelloServer {
   public static void  main(String [] args){
     try {
        if (System.getSecurityManager() == null) { System.setSecurityManager(new SecurityManager());}
        HelloImp h = new HelloImp ("Hello world !");
        Hello h_stub = (Hello) UnicastRemoteObject.exportObject(h, 0);
        Registry registry= LocateRegistry.getRegistry();
        registry.bind("Hello", h_stub);
        System.out.println ("Server ready");
     } catch (Exception e)  {
           System.err.println("Error on server :" + e) ; e.printStackTrace(); return;
     }
   }
}
```


A detailed example step by step (7)

- Implement the server program – Create and install a Security Manager
  - The first task of the server program is to create and install a security manager
  - This protects access to system resources from untrusted downloaded code running within the Java virtual machine
  - A security manager determines whether downloaded code has access to the local file system or can perform any other privileged operations
  - If an RMI program does not install a security manager, RMI will not download classes (other than from the local class path) for objects received as arguments or return values of remote method invocations
  - This restriction ensures that the operations performed by downloaded code are subject to a security policy

A detailed example step by step (8)

- Implement the client program:
  - Create and install a security manager
  - Get a remot object reference
  - Perform remote method invocations on the remote object

```
import java.rmi.registry.LocateRegistry;
import java.rmi.registry.Registry;

public class HelloClient {
  public static void main(String [] args) {
   if (args.lenght < 1) { System.out.println("Usage: java HelloClient <server host>"); return; }
   try {
     if (System.getSecurityManager() == null) { System.setSecurityManager(new SecurityManager()); }
     String host = arg[0];
     Registry registry = LocateRegistry.getRegistry(host);
     Hello h = (Hello) registry.lookup("Hello1");

     String res = h.sayHello(); System.out.println(res);
   } catch (Exception e)  {
            System.err.println("Error on client: " + e); e.printStackTrace(); return;
   }
  }
}
```


A detailed example step by step (9)

- Compile source files
  - This example separates
    - The remote interface
    - The remote object implementation class
    - The server program class
    - The client program class
  - Compile the remote interface and build a jar file that contains it
    - **javac –d classes –classpath .:classes src/Hello.java**
    - **jar cvf lib/Hello.jar classes/Hello.class**
  - Compile the remote object implementation class and build a jar file that contains it
    - **javac –d classes –classpath .:classes:lib/Hello.jar src/HelloImp.java**
    - **jar cvf lib/HelloImp.jar classes/HelloImp.class**

A detailed example step by step (10)

- Compile and run server-side and client-side programs:
  - Server-side
    - Compile the server program
      - **javac –d classes –classpath .:classes:lib/Hello.jar:lib/HelloImp.jar src/HelloServer.java**
    - Start RMI registry
      - **rmiregistry &**
    - Start the server
      - **java –classpath .:classes:lib/Hello.jar:lib/HelloImp.jar HelloServer**
  - Client-side
    - Compile the client program
      - **javac –d classes –classpath .:classes:lib/Hello.jar src/HelloClient.java**
    - Start the client
      - **java –classpath .:classes:lib/Hello.jar HelloClient**

A detailed example step by step (11)

- A note about security
  - The server and client programs run with a security manager installed
  - When either program runs, a security policy file must be specified
  - So that the code is granted the security permissions it needs to run
  - Example of a policy file (named *server.policy*) to use with the server

```
grant codeBase "file:/home/ann/src/" {
   permission java.security.AllPermission;
};
```

  - Example of a policy file (named *client.policy*) to use with the client

```
grant codeBase "file:/home/john/src/" {
   permission java.security.AllPermission;
};
```

Agenda

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S9	Interruption week
S10	Introduction to transactions (CM), C. Labbé, 13:30 – 15:00
S11	Multi-tier distributed systems (CM), S. Bouchenak , 13:30 – 15:00 Servlet-based distributed systems (TD), S. Bouchenak & D. Serrano, 15:15 – 18:30
S12	Presentation of the project (CM), S. Bouchenak , 13:30 – 15:00 Multi-tier distributed systems (TD), S. Bouchenak & D. Serrano, 15:15 – 18:30
S13	Support projet (TD), C. Labbé & D. Serrano, 15:15 – 18:30
S14	–
S15	Project, S. Bouchenak & C. Labbé & D. Serrano, 13:30 – 16:45

References

This lecture is extensively based on:

- Sun Microsystems. *Java Tutorial on RMI*. http://java.sun.com/docs/books/tutorial/rmi/
- M. Boger. *Java in Distributed Systems: Concurrency, Distribution and Persistence*. Wiley, 2001.
- This lecture is partly based on lectures given by Sacha Krakowiak, http://sardes.inrialpes.fr/people/krakowia/