Building Distributed and Mobile Applications with IMC

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Implementing Distributed Applications & Code Mobility

- Java provides useful means for implementing distributed applications:

  and code mobility:

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- Java provides useful means for implementing distributed applications:
  - Java network library
  - language synchronization features

  and code mobility:
  - object serialization
  - dynamic class loading

Implementing Distributed Applications & Code Mobility

- Java provides useful means for implementing distributed applications:
  - Java network library
  - language synchronization features

  and code mobility:
  - object serialization
  - dynamic class loading
- These mechanisms are low-level
  - Most Java-based distributed and mobile systems re-implement from scratch components for distribution and mobility

IMC - Implementing Mobile Calculi

- Is a middleware/framework for implementing distributed and mobile code run-time systems
- Aims at simplifying the implementation of distributed mobile code applications:
  - is based on recurrent standard mechanisms and patterns
  - permits concentrating on the features that are specific of a particular language
  - can be easily extended/customized to fit language-specific requirements
- Provides components for
  - Network topology
  - Communication protocols
  - Code mobility
- We have used IMC to implement run-time systems for some mobile and distributed calculi (e.g., JDPI, KLAVA, etc.).

The MIKADO project

The IMC framework is being built within an European project (EU-FET) on *Global Computing*

Calculi for Mobility

- The main intent is to investigate new mobile code calculi linguistic features:
  - The meta theory
  - Provide prototype implementations

One of the tasks of the project was to build a framework for developing the run-time systems for mobile code languages.

Protocols

- Primitives for implementing specific protocols
  - low level protocols (protocol layers)
  - high level protocols (protocol states)
- Build a protocol starting from small components
- Make the components re-usable:
  - the components are abstract and independent from specific communication layers.

Network Topology

- Primitives for connection and disconnection (both physical and logical)
- Node creation and deletion
- Keeps track of the topology of the network
  - flat
  - hierarchical

Mobility

- Make code mobility transparent to the programmer
- All issues are dealt with by the package:
  - code collecting, marshalling
  - code dispatch
  - dynamic loading of code received from a remote site
- Provide abstract interfaces and implementations for Java byte-code mobility

Network protocols...

- Each *network protocol* is viewed as an aggregation of *protocol states*:
  - a high-level communication protocol is described as a state automaton
- Each protocol state is implemented:
  - by extending the `ProtocolState` abstract class
  - by providing the implementation for the method `enter`, which returns the next state to execute.
- The `Protocol` class:
  - aggregates the protocol states
  - provides a *template method* (`start`) that will execute each state at a time

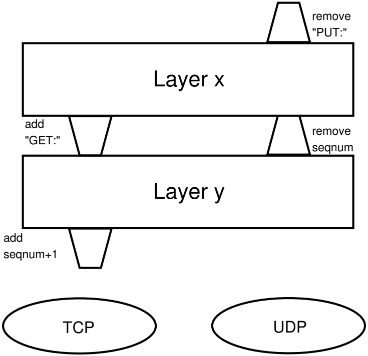
Marshalers and UnMarshalers

- Specialized streams: `Marshaler` and an `UnMarshaler` to write/read from the actual communication layer.
- They provide means to write/read any primitive data type (inherited from `DataOutput` and `DataInput`).
- They deal with code mobility (relying on the `mobility` sub-package).

```
public interface Marshaler extends
        DataOutput, Closeable, Flushable, MigratingCodeHandler {
    void writeStringLine(String s) throws IOException;
    void writeReference(Serializable o) throws IOException;
    void writeMigratingCode(MigratingCode code) throws IOException,
                                        MigrationUnsupported;
    void writeMigratingPacket(MigratingPacket packet) throws IOException;
    ...
}
```

Protocol layers

- The data in the streams can be "pre-processed" by some customized *protocol layers*
- Each protocol layer takes care of the shape of messages (*low-level* protocol)
- These layers are then composed into a `ProtocolStack` that ensures the order of preprocessing passing through all the layers in the stack.



Using a ProtocolStack

Writing

```
Marshaler m = protocolStack.createMarshaler();
m.setMigratingCodeFactory(new JavaByteCodeMigratingCodeFactory());
m.writeStringLine("obj");
m.writeInt(obj.size());
m.writeMigratingCode(obj);
protocolStack.releaseMarshaler(m);
```

Using a ProtocolStack

Writing

```
Marshaler m = protocolStack.createMarshaler();
m.setMigratingCodeFactory(new JavaByteCodeMigratingCodeFactory());
m.writeStringLine("obj");
m.writeInt(obj.size());
m.writeMigratingCode(obj);
protocolStack.releaseMarshaler(m);
```

Reading

```
UnMarshaler u = protocolStack.createUnMarshaler();
u.setMigratingCodeFactory(new JavaByteCodeMigratingCodeFactory());
s = u.readStringLine();
i = u.readInt();
obj = u.readMigratingCode();
protocolStack.releaseUnMarshaler(u);
```

How layers work

- When a marshaler is created, a new “communication” is started (using the underlying session);
- The headers (of the low-level protocol layers) are created;
- The contents written using the marshaler can be buffered (e.g., for UDP, into an UDP packet);
- When the marshaler is released the buffer is actually flushed (e.g., for UDP, the packet is actually sent).

A customized layer

The following specialized protocol layer removes a header from the input that consists of the line `"IN"`; it also adds a header to the output that consists of the line `"OUT"`:

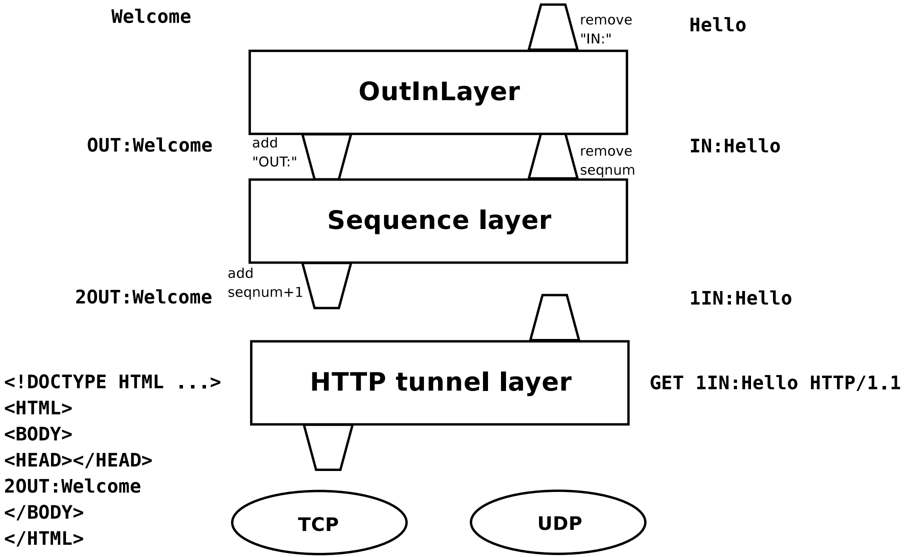
```
public class OutInLayer extends ProtocolLayer {
    protected Marshaler doCreateMarshaler(Marshaler marshaler)
        throws ProtocolException {
        marshaler.writeStringLine("OUT");
        return marshaler;
    }

    protected UnMarshaler doCreateUnMarshaler(UnMarshaler unMarshaler)
        throws ProtocolException {
        String header = unMarshaler.readStringLine();
        if (!header.equals("IN"))
            throw new ProtocolException("wrong header: " + header);
        return unMarshaler;
    }
}
```

Tunneling

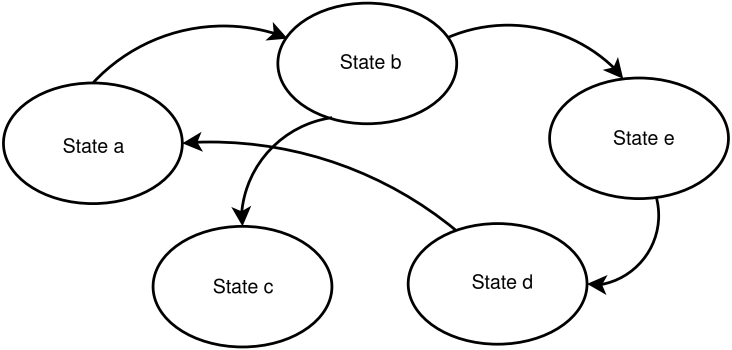
A specialized subclass, `TunnelProtocolLayer` is provided that permits to "tunnel" a protocol layer into another (high level) protocol: e.g., encapsulate a message into HTTP requests and responses.

Tunneling


Welcome
remove
"IN:"
Hello
OutInLayer
OUT:Welcome
add
"OUT:"
remove
seqnum
IN:Hello
Sequence layer
add
seqnum+1
2OUT:Welcome
1IN:Hello
<!DOCTYPE HTML ...>
<HTML>
<BODY>
<HEAD></HEAD>
2OUT:Welcome
</BODY>
</HTML>
HTTP tunnel layer
GET 1IN:Hello HTTP/1.1
TCP
UDP

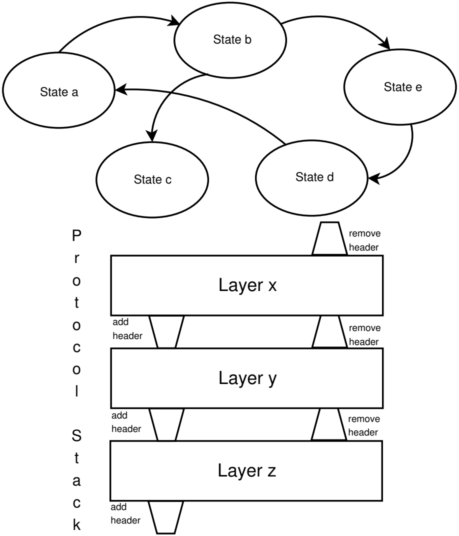
Protocol States

A high level protocol can be described as a state automaton.
The `protocols` package provides features to implement protocol states and compose them in an automaton.

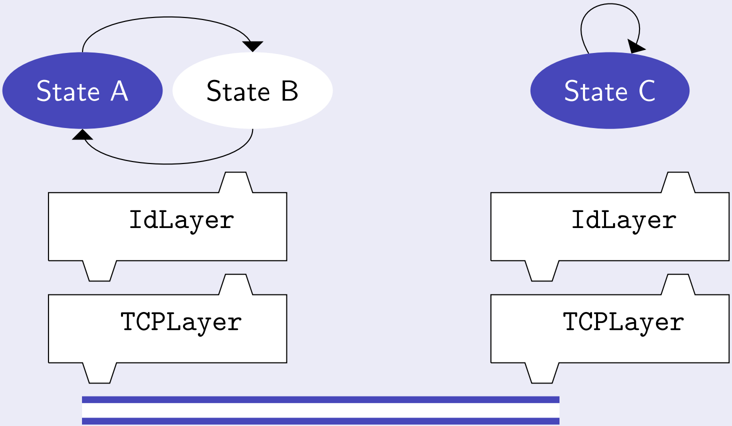


The class `Protocol`

A collection of protocol states and a reference to a protocol stack:



Communication Protocols: an example



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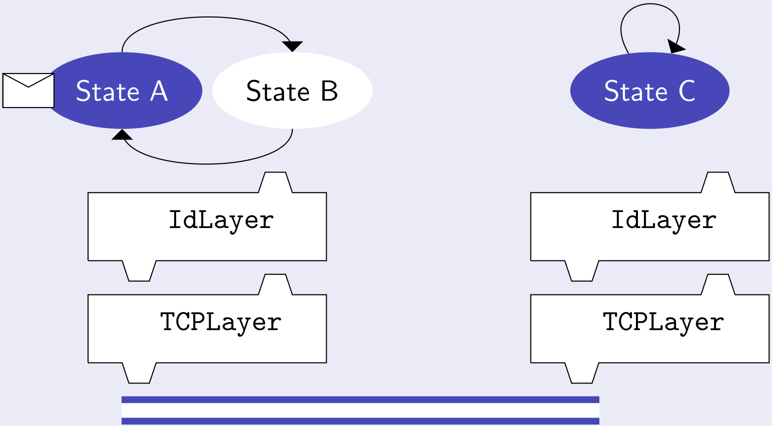

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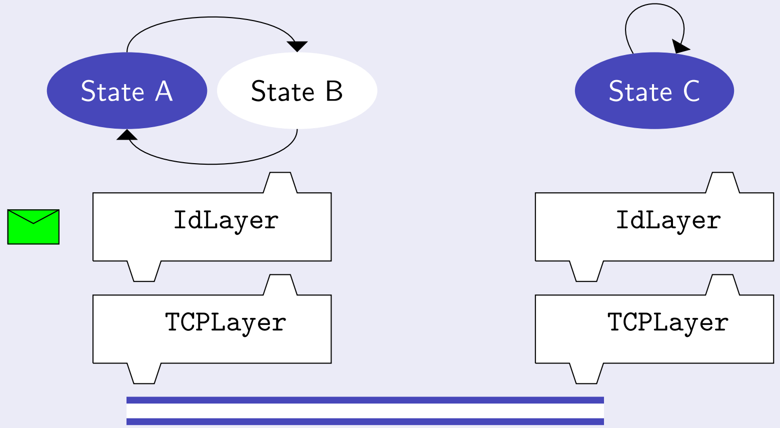

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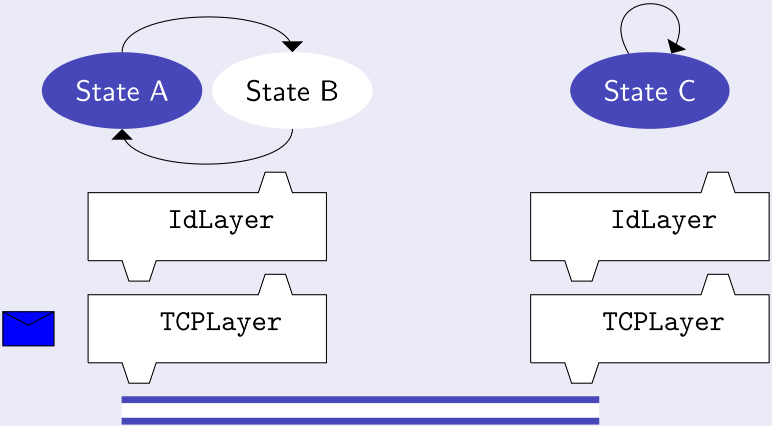

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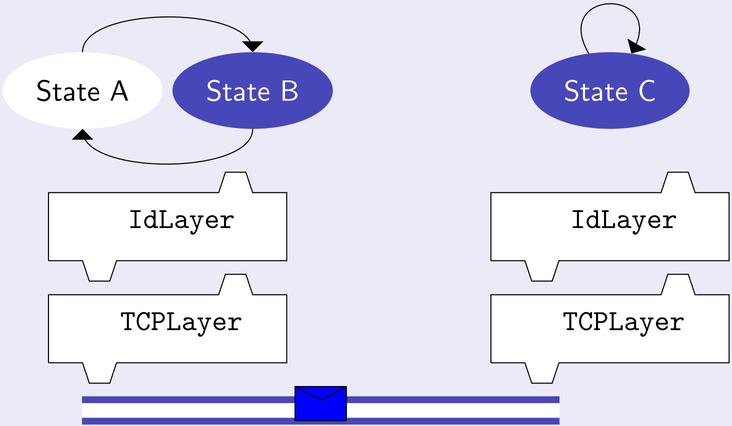

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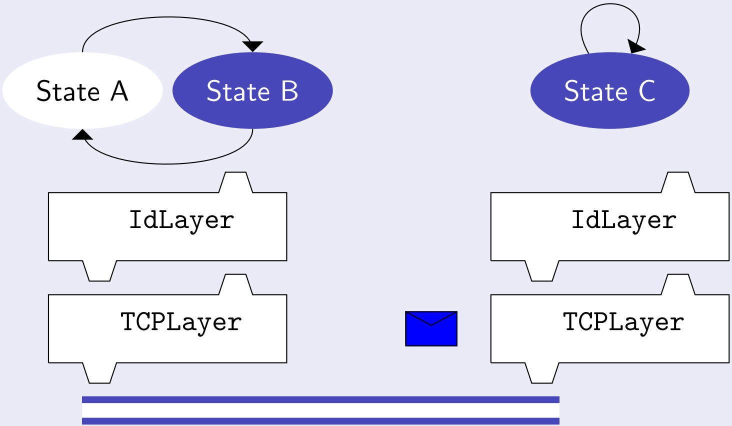

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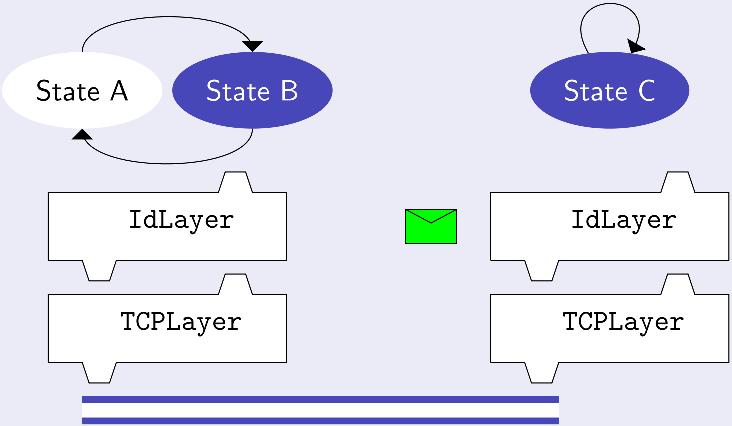

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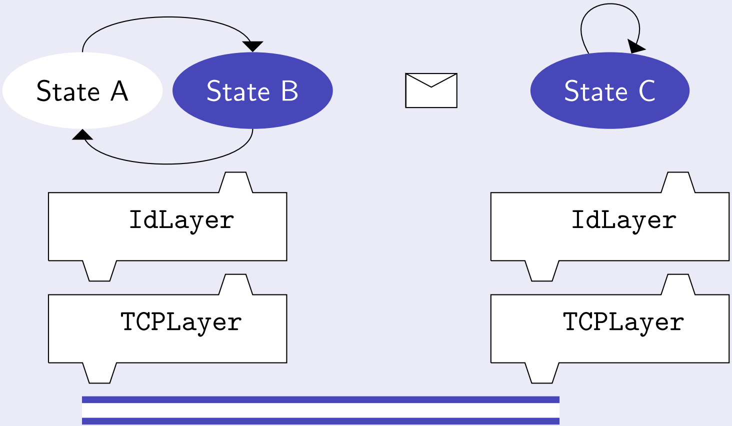

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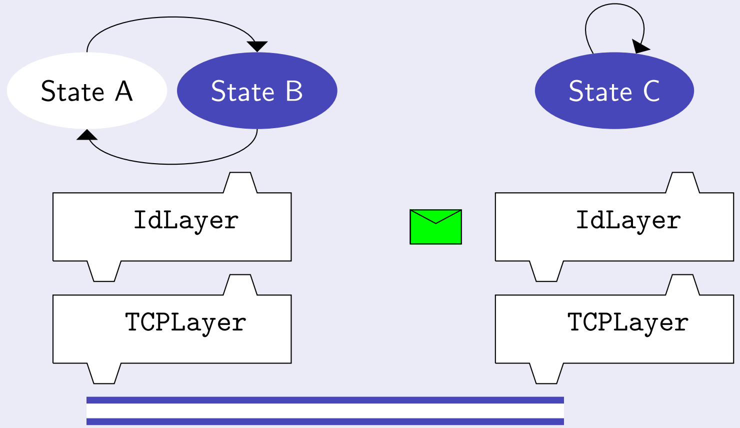

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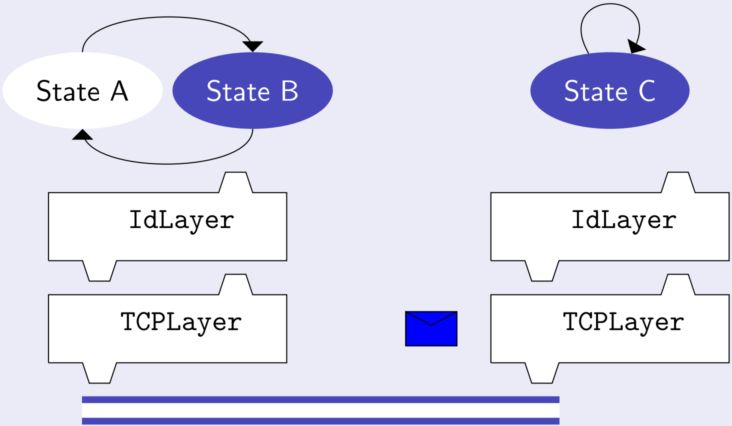

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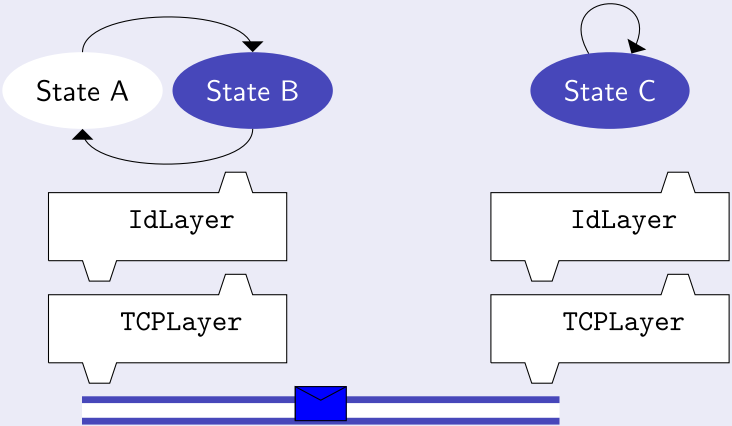

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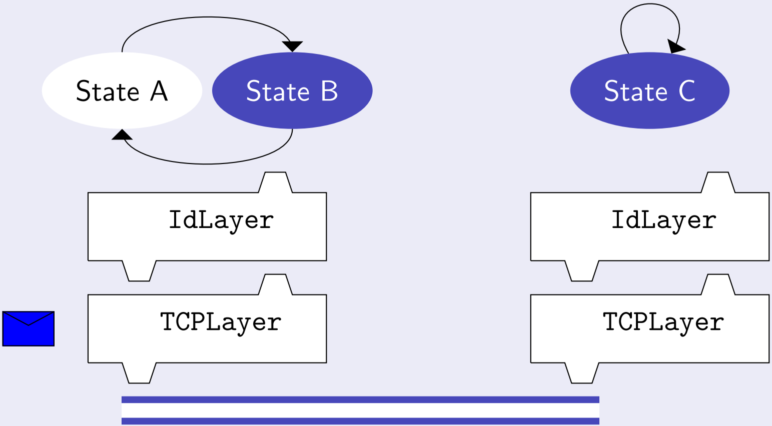

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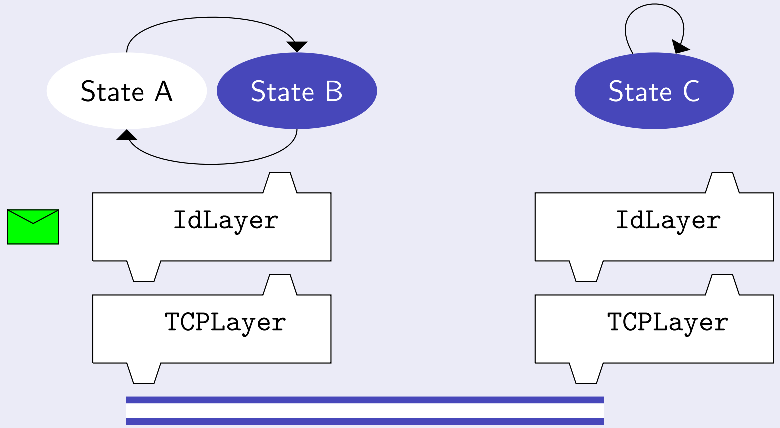

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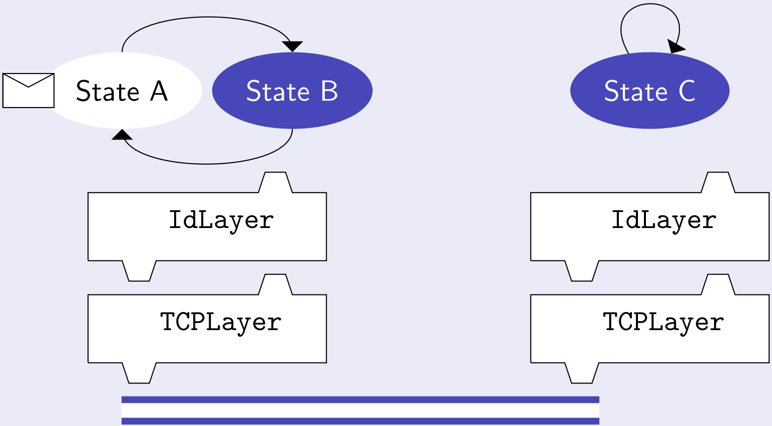

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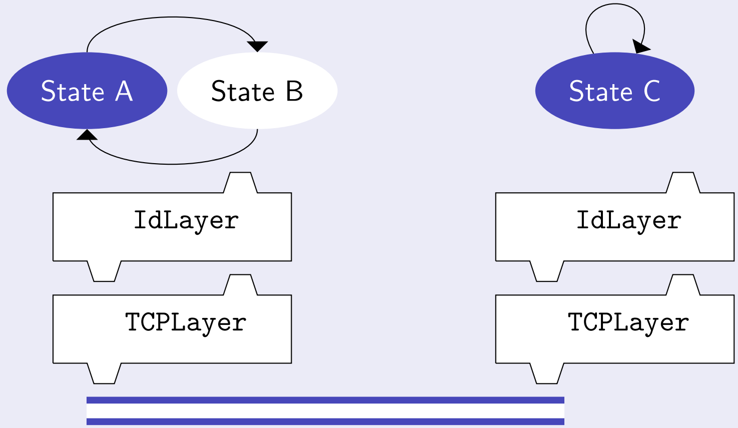

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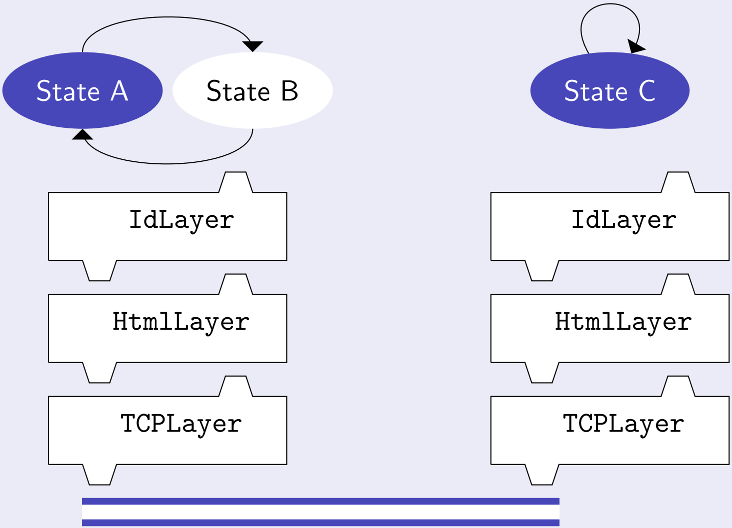

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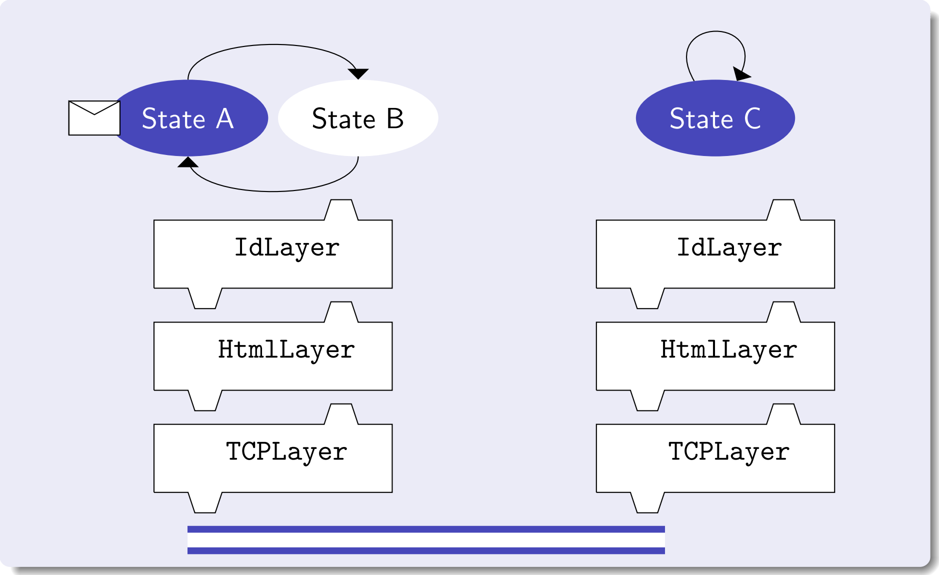

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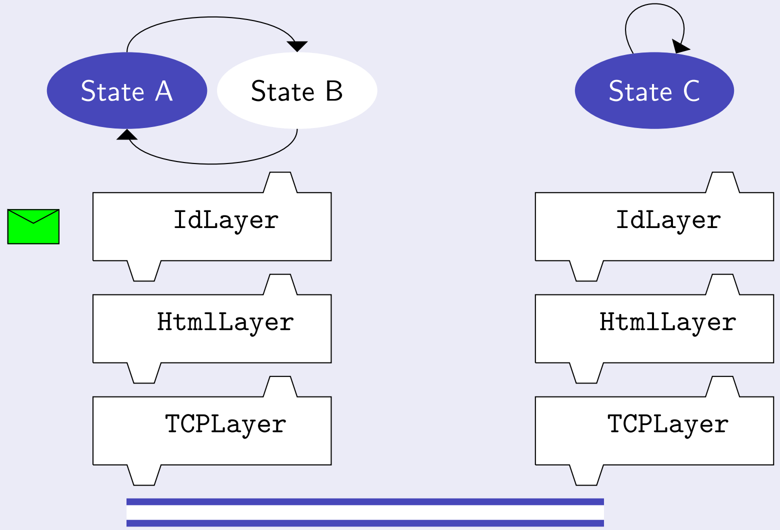

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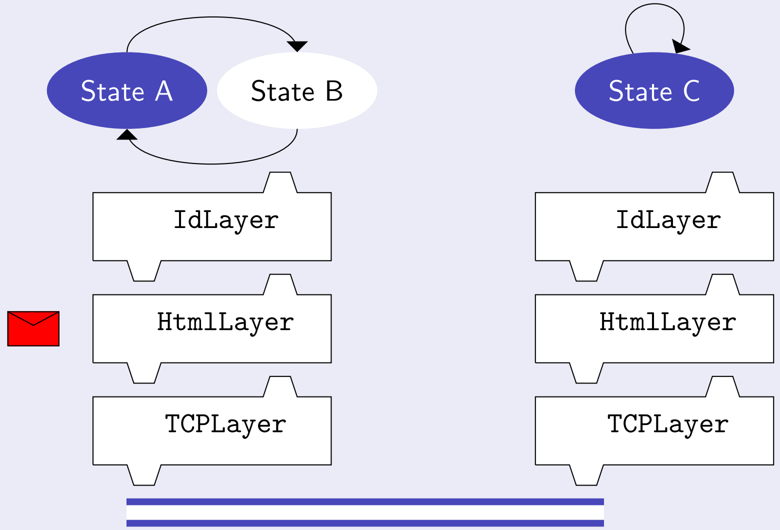

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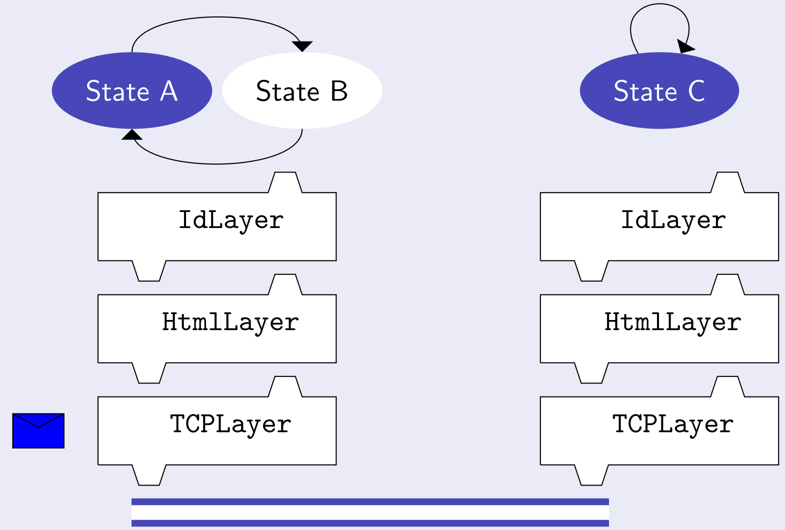

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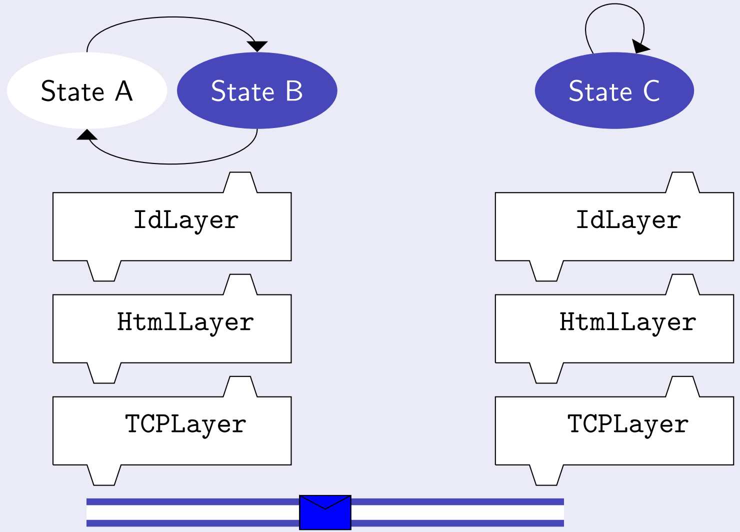

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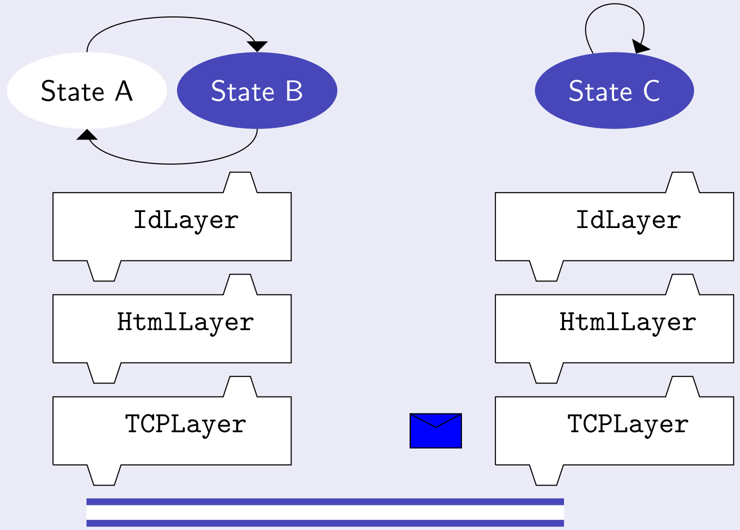

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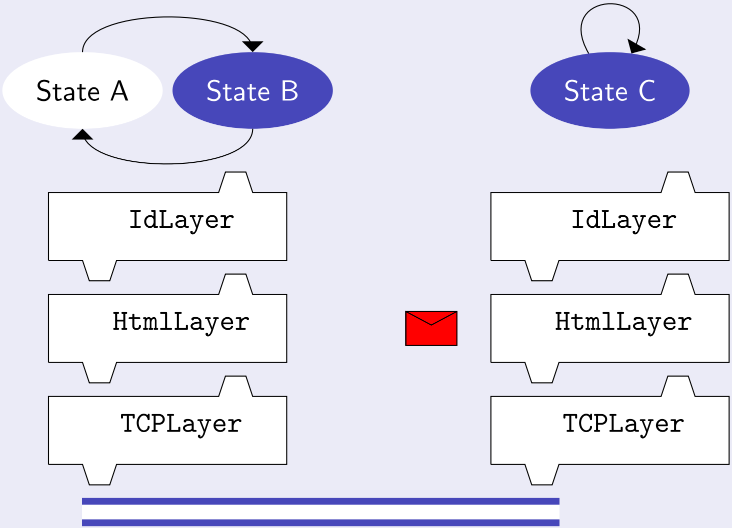

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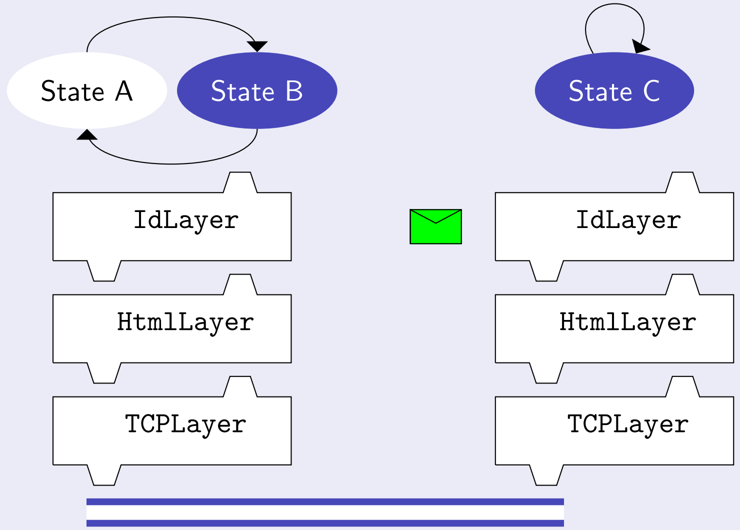

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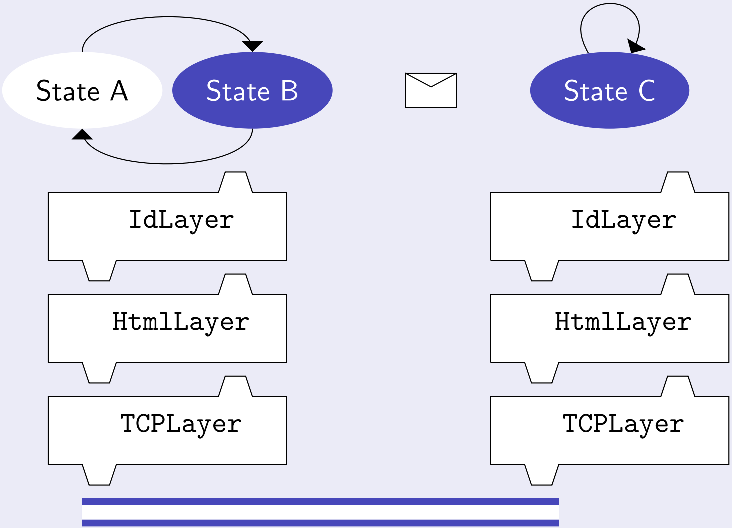

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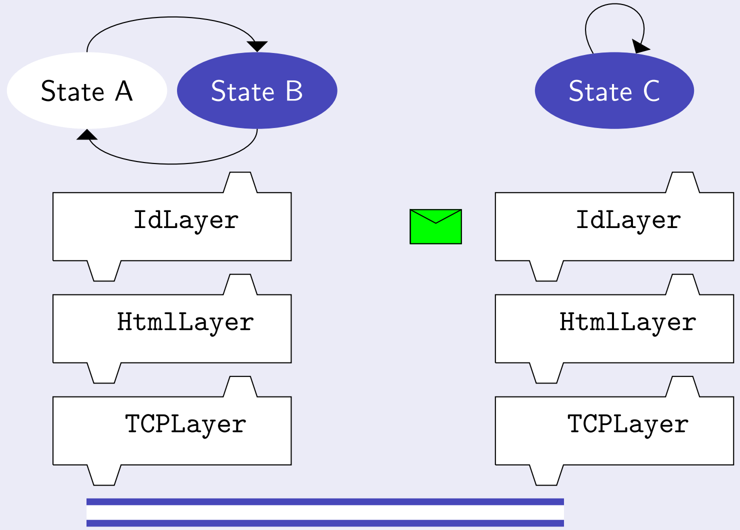

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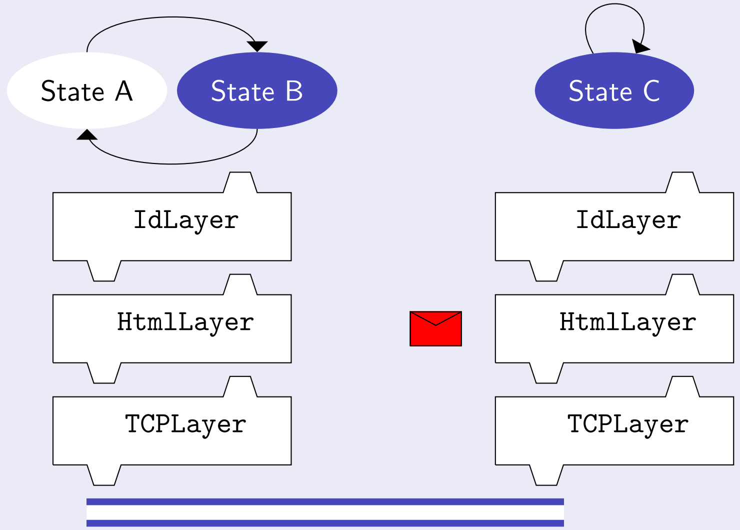

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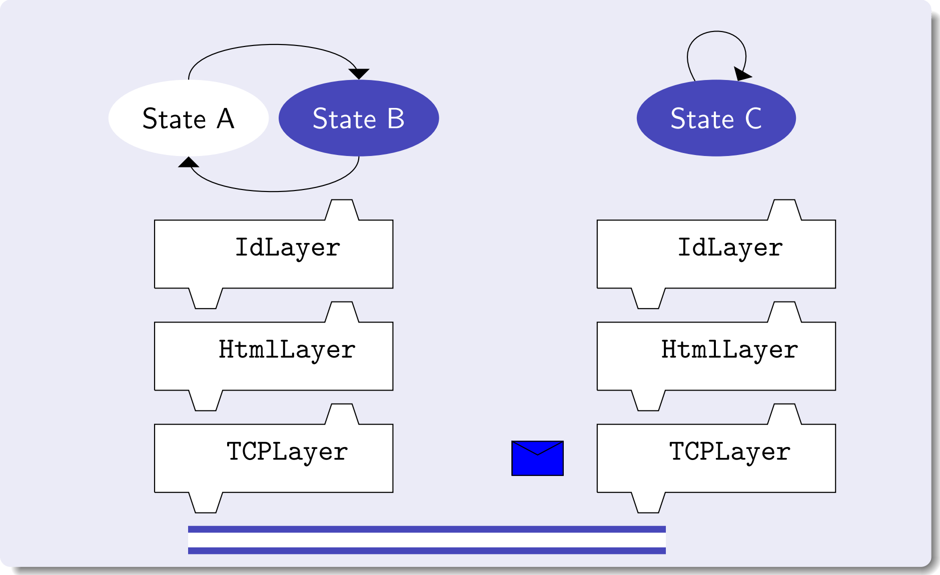

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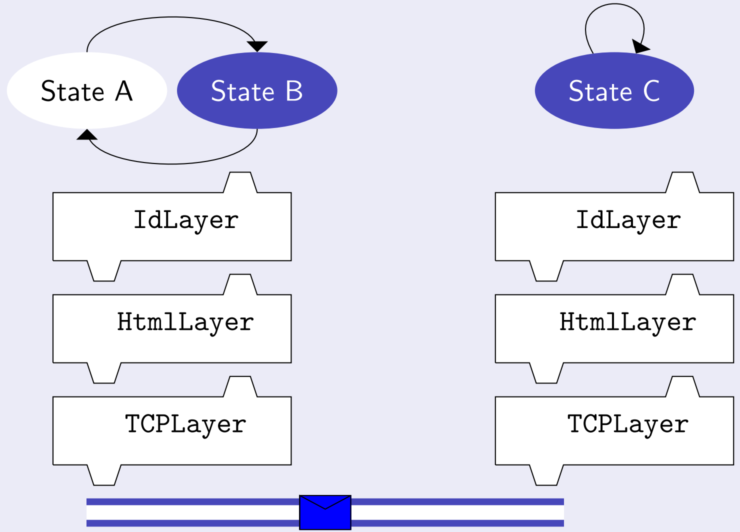

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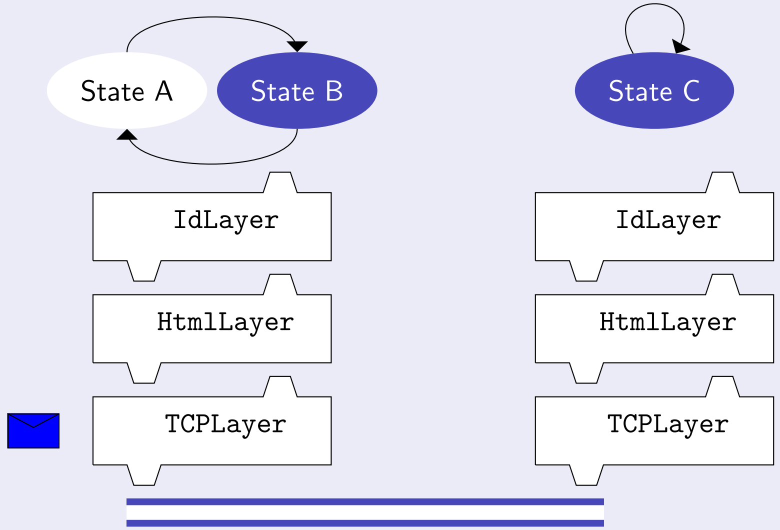

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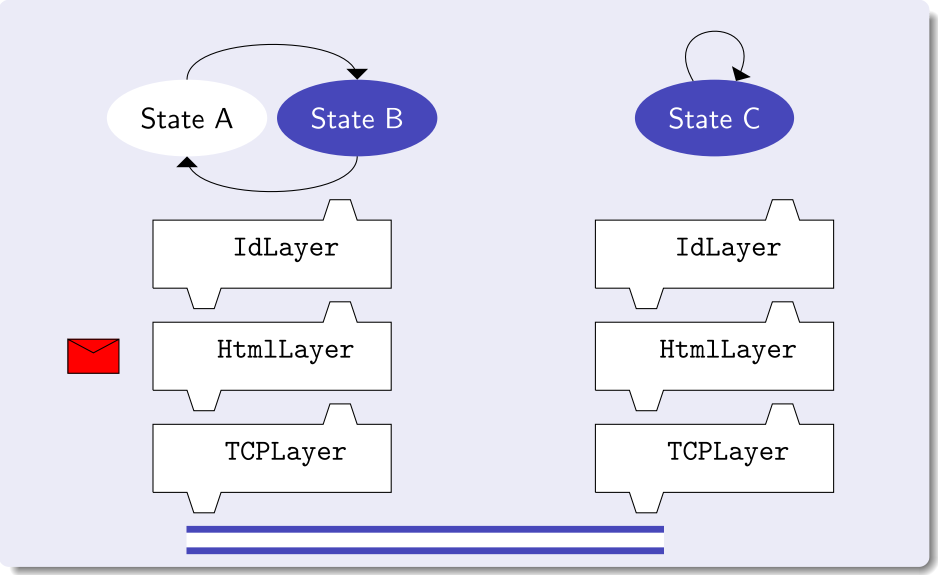

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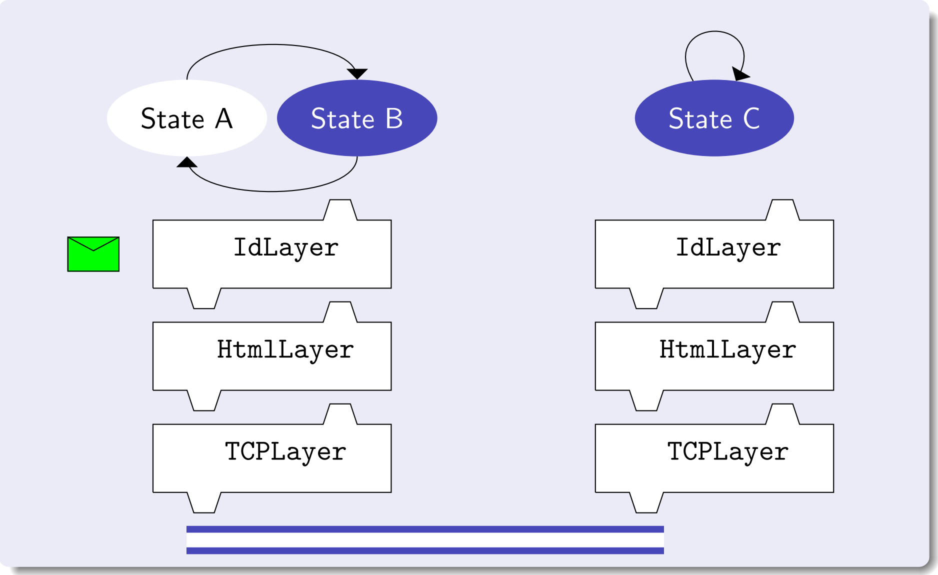

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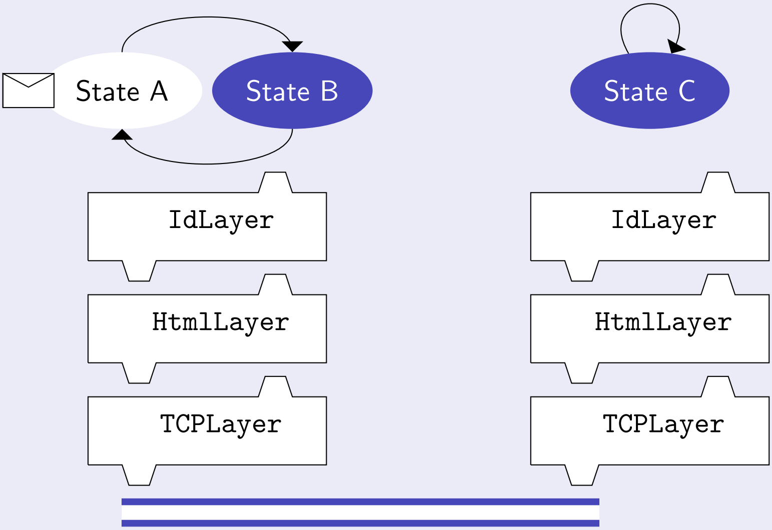

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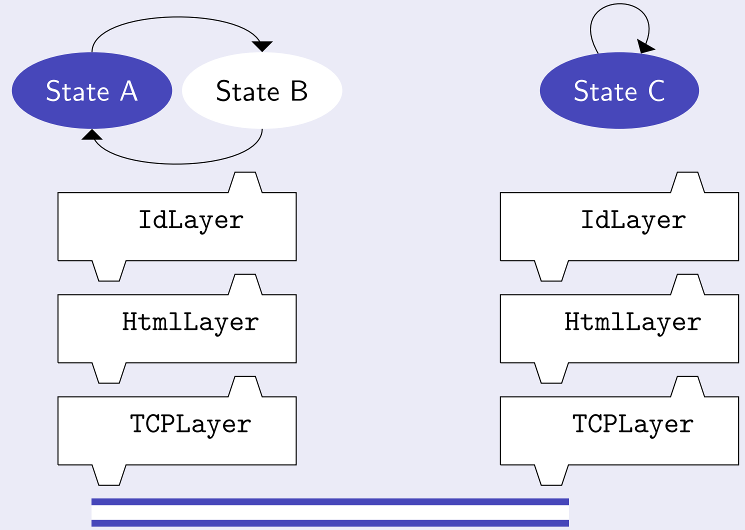

The class ProtocolState

Derive from the class `ProtocolState`; implement `enter()`

```
public class EchoProtocolState extends ProtocolStateSimple {
    public void enter(Object param, TransmissionChannel transmissionChannel)
            throws ProtocolException {
        UnMarshaler unMarshaler = createUnMarshaler();
        String line = unMarshaler.readStringLine();
        releaseUnMarshaler(unMarshaler);
        Marshaler marshaler = createMarshaler();
        marshaler.writeStringLine(line);
        releaseMarshaler(marshaler);
    }
}
```

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        marshaler.writeStringLine(line);
        releaseMarshaler(marshaler);
    }
}
```

getUnMarshaler

```
if (transmissionChannel == null || transmissionChannel.unMarshaler == null) {
    return createUnMarshaler();
else
    return transmissionChannel.unMarshaler;
```

Switch state

Avoid writing long switch statements

ProtocolSwitchState

```
protocolSwitchState.addRequestState("WRITE", new WriteState(Protocol.START));
protocolSwitchState.addRequestState("READ", new ReadState(Protocol.START));
protocolSwitchState.addRequestState("REMOVE", new ReadState(Protocol.START));
protocolSwitchState.addRequestState("QUIT", Protocol.END);
Protocol protocol = new Protocol();
protocol.setState(Protocol.START, protocolSwitchState);
```

- Each protocol state is parameterized with the next state in the automaton
- `START` and `END` are the identifiers of the special start and end states

Connectivity features

Provide basic connectivity classes:

- `Node`:
  - container of executing processes (`NodeProcess`)
  - provides features to receive and establish a session, e.g.: `accept`, `connect`
- `SessionManager`: keeps trace of all the established sessions

Connectivity features

Provide basic connectivity classes:

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Session identifiers

Sessions are logical connections and independent from the low level communication layer. Automatically chosen according to `SessionId`

- Stream connections for TCP sockets (`tcp-mysite.com:9999`)
- Logical connections if UDP packets are used (`udp-mysite.com:9999`)
- Local pipes (`pipe-foobar`)

Session Starter

SessionStarter is an abstract class for establishing a session (both client and server side):

```
public abstract class SessionStarter {
    /** Accepts an incoming session. */
    public abstract Session accept() throws ProtocolException;

    /** Establishes a session. */
    public abstract Session connect() throws ProtocolException;

    /** Closes this starter, but not sessions created through this starter. */
    protected abstract void doClose() throws ProtocolException;
}
```

Specific session starters should be provided for specific low-level communication protocols; the framework provides `TcpSessionStarter`, `UdpSessionStarter` and `LocalSessionStarter` (that uses local pipes, useful for testing).

Example: creating a TCP session, server-side

```
int port = 9999;
ProtocolStack protocolStack = new ProtocolStack();
// possibly customize stack with additional layers
System.out.println("accepting connections on port " + port);
SessionStarter sessionStarter = new TcpSessionStarter(new IpSessionId(port));
Session session = protocolStack.accept(sessionStarter);
System.out.println("established session " + session);
sessionStarter.close();
// no more accepting sessions, but the established session is still up.
UnMarshaler unMarshaler = protocolStack.createUnMarshaler();
while (true) {
  System.out.println("read line: " + unMarshaler.readStringLine());
}
```

The client side will be similar (but it will use `connect` instead of `accept`).

Abstracting from session starters

- IMCSessionStarterTable: associates a `SessionStarter` class to a specific `SessionId` identifier
  - e.g., `"tcp"` → `TcpSessionStarter`
- We can then abstract from a specific session type
- method createSessionStarter(SessionId) returns the `SessionStarter` associated to a specific session type.

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Abstraction

Switching from a session type to another is just a matter of changing the session identifier.

Binding protocols and sessions

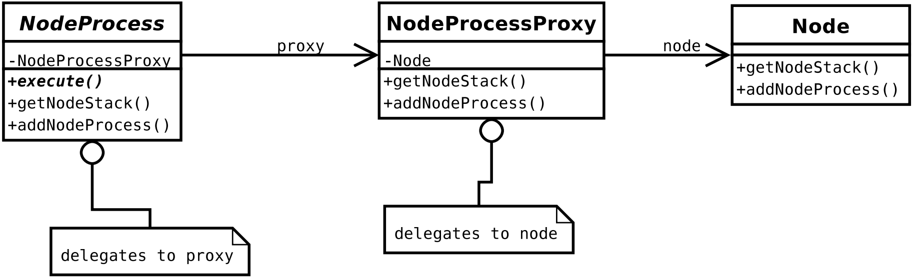
```
public class GenericServer {
    public GenericServer(String host, Protocol protocol)
            throws ProtocolException, IOException {
        SessionStarterTable sessionStarterTable = new IMCSessionStarterTable();
        SessionId sessionId = SessionId.parseSessionId(host);
        System.out.println("accepting session " + sessionId + " ...");
        ProtocolStack protocolStack = new ProtocolStack();
        Session session =
            protocolStack.accept(sessionStarterTable.createSessionStarter(sessionId));
        System.out.println("established session " + session);
        System.out.println("starting protocol... ");
        protocol.setProtocolStack(protocolStack);
        protocol.start();
        protocol.close();
        System.out.println("protocol terminated");
    }
}
```

Nodes & Processes

- A participant to a network is an instance of class Node.
- A node is a container of running processes (class NodeProcess).
  - The programmer must inherit from `NodeProcess`
  - and provide the implementation for method execute
- A process can access the resources contained in a node and migrate to other nodes.
- A node keeps track of all the processes currently in execution.

Processes & proxies

- Processes delegate most of their methods to the node they are running in.
- However, they do not have access to the node itself (to avoid security problems).
- This is achieved by using a proxy: the processes delegate to the proxy and not directly to the node.



A process example

A process running a protocol

```
public class ProtocolThread extends NodeProcess {
    /** The protocol this thread will execute. */
    protected Protocol protocol;

    public void execute() throws IMCException {
        try {
            protocol.start();
        } finally {
            close();
        }
    }

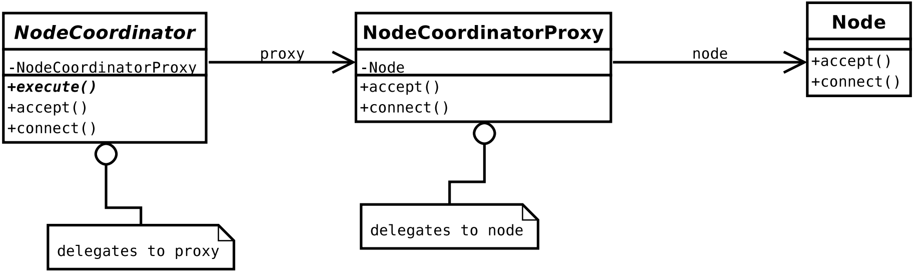
    public void close() throws IMCException {
        super.close();
        protocol.close();
    }
}
```

Node coordinators

Node coordinators are super user processes:

- Privileged processes
- can execute connection and disconnection actions
- cannot migrate

Standard processes cannot execute privileged actions.



A node coordinator example

Accepting connections

```
public class MyCoordinator extends NodeCoordinator {
    SessionId sessionId;

    public void execute() throws IMCException {
        Protocol protocol = new MyProtocol();
        accept(sessionId, protocol);
        protocol.start();
    }

    public static void main(String args[]) {
        Node node = new Node();
        node.addNodeCoordinator(new MyCoordinator());
    }
}
```

Another node coordinator example

Accepting connections (multi-threaded)

```
public class AcceptNodeCoordinator extends NodeCoordinator {
    private ProtocolFactory protocolFactory;
    private SessionId sessionId;
    private SessionStarter sessionStarter;

    public void execute() throws IMCException {
        if (sessionStarter == null)
            sessionStarter = createSessionStarter(sessionId, null);

        while (true) {
            Protocol protocol = protocolFactory.createProtocol();
            addNodeProcess(
                new ProtocolThread(accept(sessionStarter, protocol)));
        }
    }
}
```

Goals of the package `mobility`

- Package `org.mikado.imc.mobility`
- Make code mobility transparent to the programmer
- All issues are dealt with by the package:
  - code collecting, marshalling
  - code dispatch
  - dynamic loading of code received from a remote site
- Provide abstract interfaces and implementations for Java byte-code mobility
- Used internally by the IMC `protocols` package to exchange migrating objects, but can also be used as a stand-alone package

Moving code

Two possible approaches:

- Automatic: the classes needed by the migrating code are collected and delivered together with that code;
- On demand: when some classes are required by code migrated to a remote site, it is requested to the server that sent the code.

We choose automatic approach

Advantage

Comply with mobile agent paradigm:

- the agent is autonomous when migrating
- disconnected operations
- the originating computer does not need be connected after migration

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Drawback

Code that may be never used is dispatched

Kinds of mobility

Three kinds of mobility have been identified in the literature:

- *weak mobility*: the dynamic linking of code arriving from a different site;

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Kinds of mobility

Three kinds of mobility have been identified in the literature:

- *weak mobility*: the dynamic linking of code arriving from a different site;
- *strong mobility*: the movement of the code and of the execution state of a thread to a different site and the resumption of its execution on arrival;
- *full mobility*: the movement of the whole state of the running program including all threads' stacks, namespaces and other resources. This is a generalization of strong mobility that makes the migration completely transparent.

Code mobility in Java (and in IMC)

Unfortunately Java only provides *weak mobility*, since threads' execution state (stack and program counter) cannot be saved and restored

Code mobility in Java (and in IMC)

Unfortunately Java only provides *weak mobility*, since threads' execution state (stack and program counter) cannot be saved and restored

- On arrival the process is simply executed from the start
- It is up to the programmer to keep track of the execution state of the process
- However, all the process fields' values are restored on arrivale

Java byte-code mobility

Starting from these interfaces, the package `mobility` provides concrete classes that automatically deal with

- migration of Java objects together and their byte-code;
- deserializing transparently such objects by dynamically loading their transmitted byte-code.

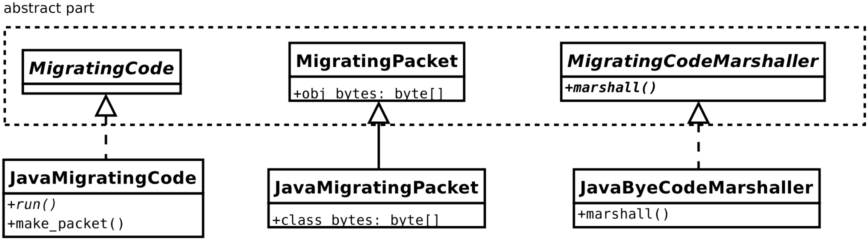

Figure: Main classes of the package

Migrating Java code

```java
public class JavaMigratingCode extends Thread implements MigratingCode {
  public void run() { /* empty */ }
  public JavaMigratingPacket make_packet() throws IOException {...}
}
```

- the serialized object
- the byte code of all the classes used by the migrating object (these classes are collected by `make_packet` using *Java Reflection API*)

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Scalable to inheritance

`make_packet` needs not be redefined in derived classes: it handles subclasses transparently and automatically.

Collecting classes

getUsedClasses

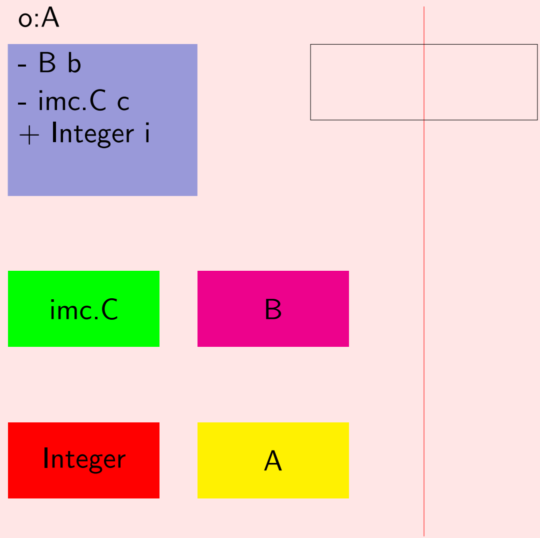
```
protected void getUsedClasses( Class c ) {
  if (c == null || ! addUsedClass( c )) return ;

  Field[] fields = c.getDeclaredFields() ;
  Constructor[] constructors = c.getDeclaredConstructors() ;
  Method[] methods = c.getDeclaredMethods() ;
  int i ;

  for ( i = 0 ; i < fields.length ; i++ )
    getUsedClasses( fields[i].getType() ) ;

  for ( i = 0 ; i < constructors.length ; i++ ) {
    getUsedClasses( constructors[i].getParameterTypes() ) ;
    getUsedClasses( constructors[i].getExceptionTypes() ) ;
  }
  ...
```

Collecting classes

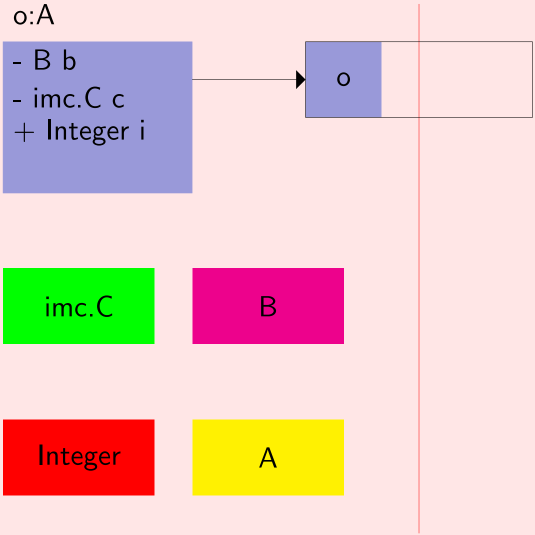
Some classes are excluded by the collection:

- Classes belonging to standard libraries
  - these classes are given additional privileges, thus they must be loaded from the local file system
- classes of specific packages (e.g., the IMC package) that must be present in the remote sites
- classes explicitly excluded by the programmer

Code Mobility: example



Code Mobility: example



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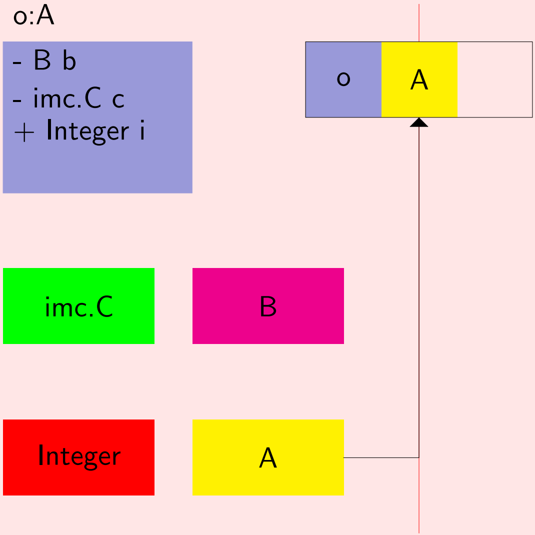

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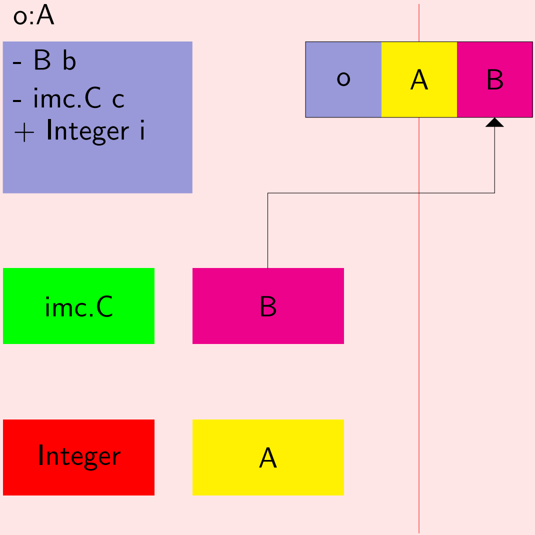

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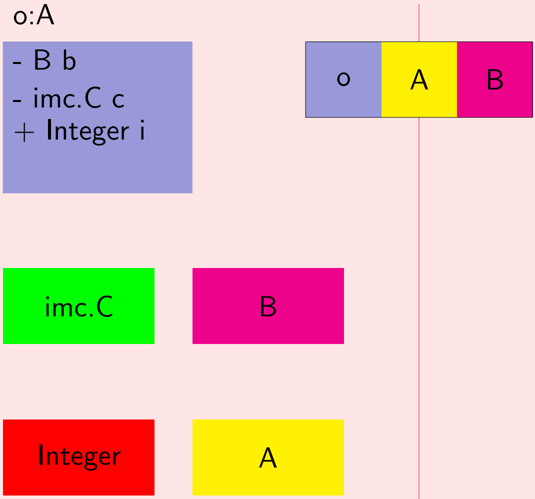

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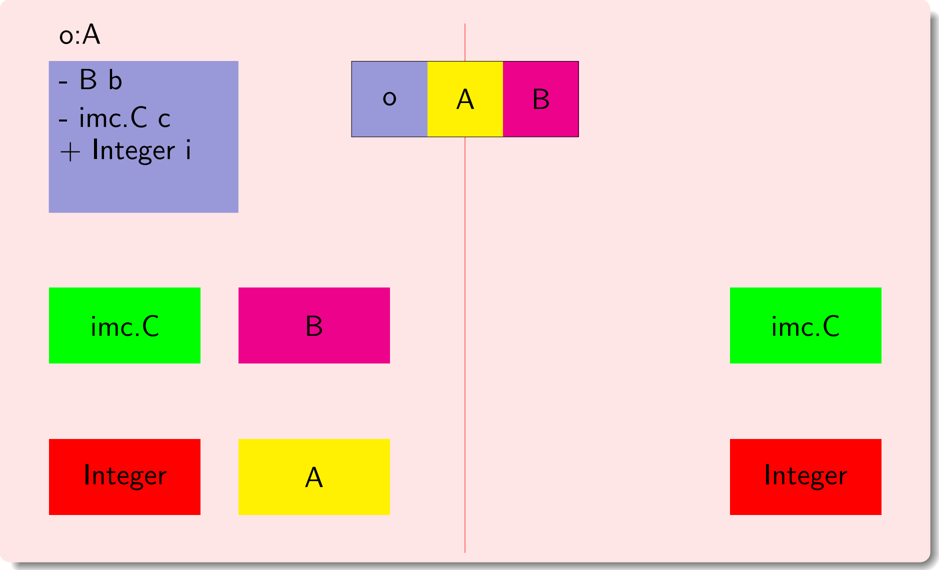

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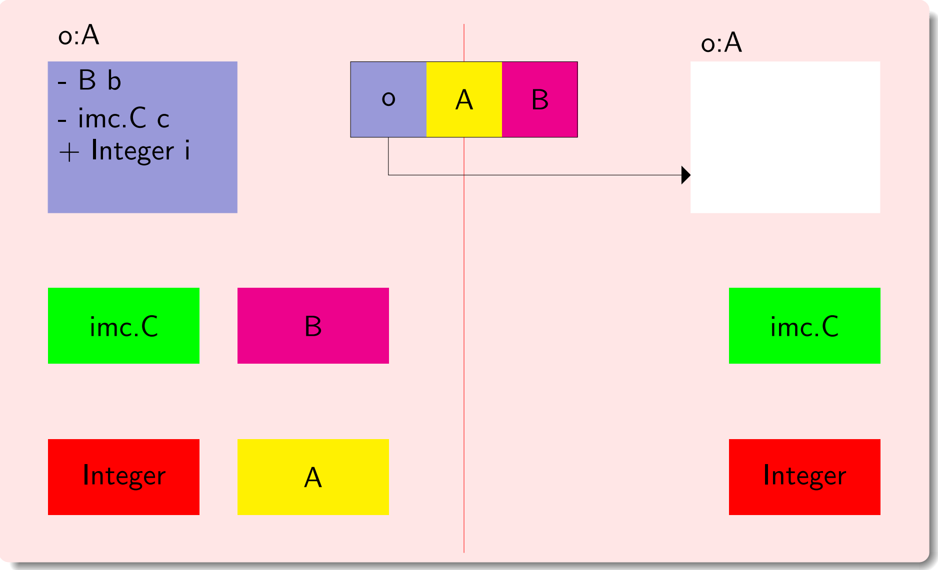

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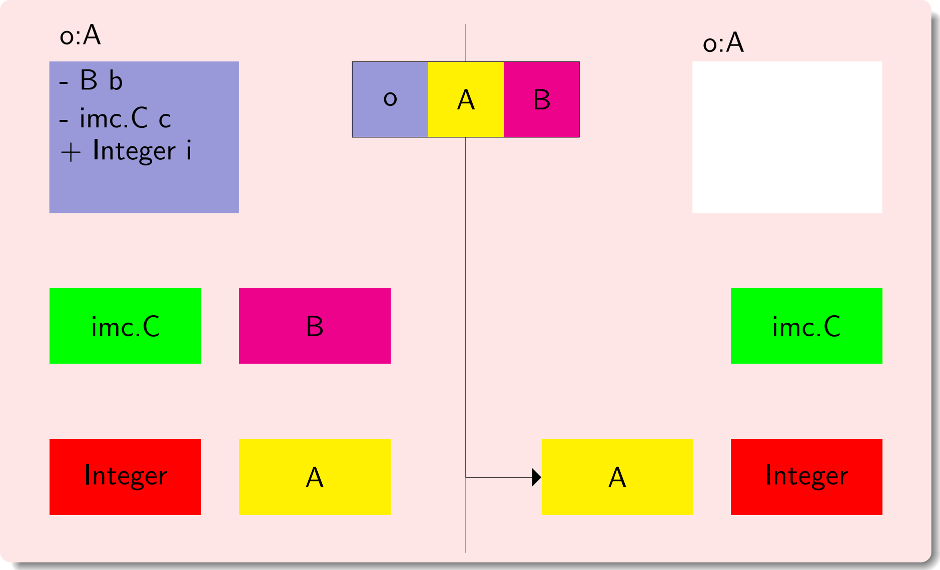

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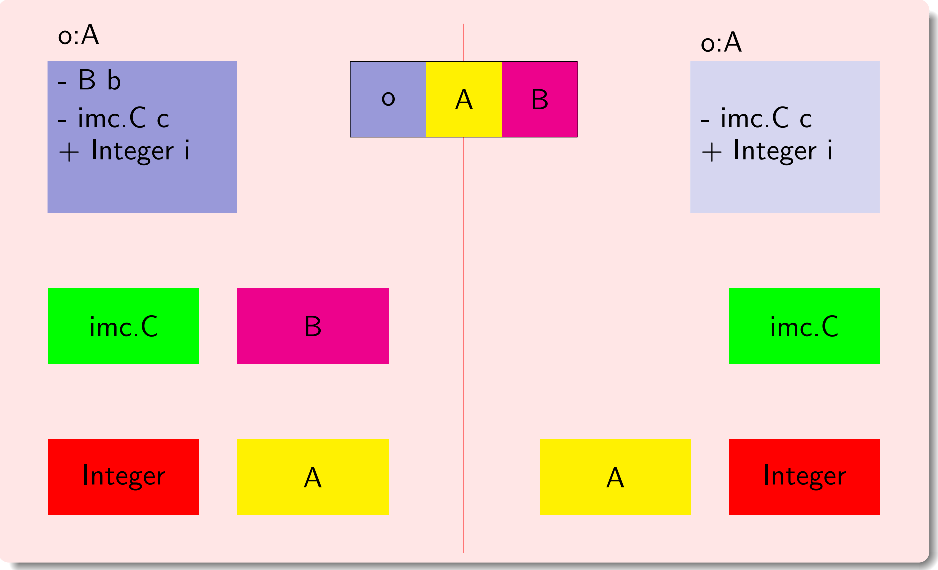

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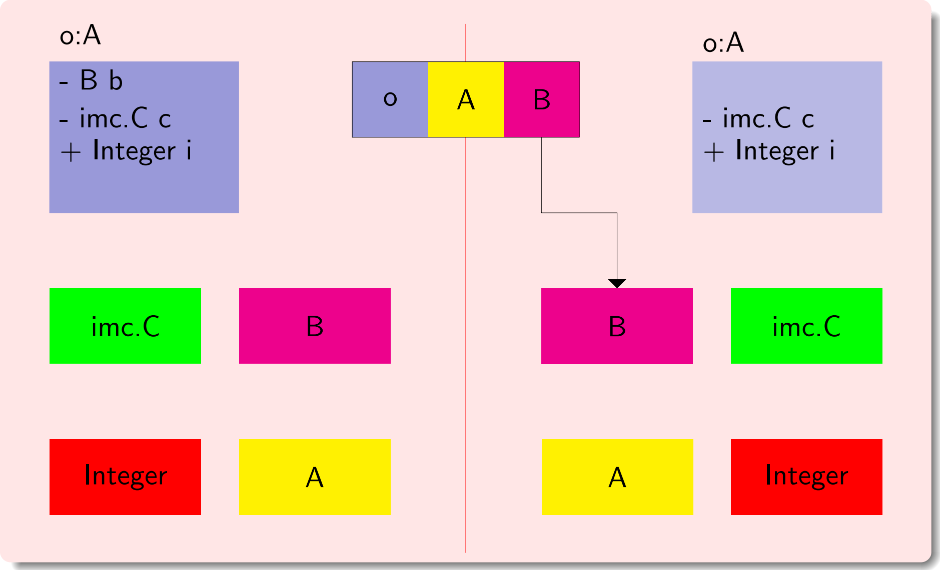

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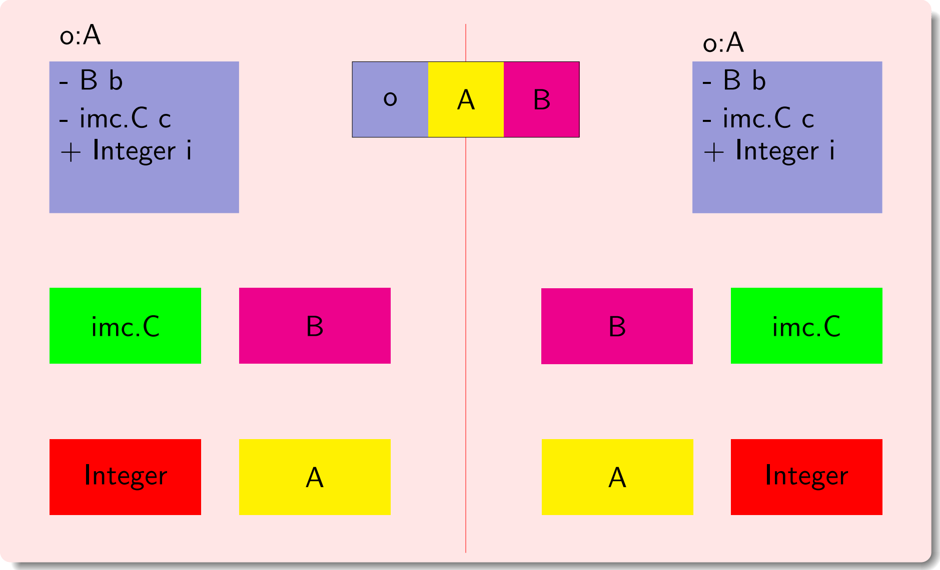

NodeClassLoader

Each site willing to accept migrating code will internally use a `NodeClassLoader` provided by the package

- When a migrating code is received from the network in a `JavaMigratingPacket`
- its classes are stored in the `NodeClassLoader` internal table
- the object is deserialized
- during deserialization, needed classes are loaded by `NodeClassLoader` from the internal class table

Retrieving class byte code

When a `MigratingPacket` is created the byte code of the collected classes is retrieved:

- by the local file system, in the originating site
- by the `NodeClassLoader` table in the other sites

This enables a migrating code to visit many sites in sequence.

DPI programming model

- DPI is a locality-based extension of π:
  - Processes are distributed over a set of nodes (or *locations*) each of which is identified by a *name* or *locality*.
- Like in π calculus, processes interact each other via message passing over *channels*.
- Only local communication is permitted
  - Two processes can interact only if they are located on the same node.
- Processes can change their execution environment performing action go .
- DPI does not assume a specific network topology
  - a variant of DPI, DPIF, considers explicit link

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DPI syntax

Systems

$$
\begin{array}{rcll}
M, N & ::= & \mathbf{0} & \text{Empty} \\
 & | & M|N & \text{Composition} \\
 & | & (\nu e).N & \text{Restriction} \\
 & | & l[\![P]\!] & \text{Agent}
\end{array}
$$

Threads

$$
\begin{array}{rcll}
P, Q, R & ::= & \mathtt{stop} & \text{Termination} \\
 & | & P|Q & \text{Composition} \\
 & | & (\nu e)P & \text{Restriction} \\
 & | & \mathtt{go}\ \ u.P & \text{Movement} \\
 & | & u!\langle v\rangle.P & \text{Output} \\
 & | & u?(X).P & \text{Input} \\
 & | & \mathtt{rec}\ A.P & \text{Recursion} \\
 & | & A & \text{Process Identifier} \\
 & | & \mathtt{if}\ u = v\ \mathtt{then}\ P\ \mathtt{else}\ Q & \text{Matching}
\end{array}
$$

JDPI implementation...

- `JDpiProtocol`:
  - implements the communication protocol between DPI nodes;
- `JDpiProcess`:
  - implements a generic DPI process;
  - is a `JavaMigratingCode`.
- `JDpiNode`:
  - implements a DPI node;
  - provides a computational environment for `JDpiProcesses`;
  - manages local channel interactions;
- `JDpiLocality`:
  - is an abstraction for *node names*
- Two kinds of topology have been implemented:
  - *flat*;
  - a la DPIF.

Implementing DPI

Node

DPI nodes provide:

- a computational environment for processes;
- functionalities for processes interactions

Implementing DPI

Node

DPI nodes provide:

- a computational environment for processes;
- functionalities for processes interactions

Implemented as...

- an extension of `org.mikado.topology.Node`;
- new methods for managing channels:
  - creation;
  - input;
  - output.

Implementing DPI

Processes

- a DPI process (`JDpiProcess`) is implemented as a subclass of the class `NodeProcess`
  - each process has to provide method *body()*;
  - implements the `JavaMigratingCode`;
  - allows to easily migrate a process to a remote site.
- Processes can be added to a node for execution with the method `addProcess`
- Each process interacts with the hosting node using a `JDpiNodeProxy`
  - provides an access to node methods;

Implementing DPI: Example 1

Processes

$$\textbf{rec } X.ex?(u).go@u.X$$

Implemented in Java

```
class MyProc extends JDpiProcess {
   public void body() {
      JDpiChannelName<JDpiLocality> inC =
         new JDpiChannelName<JDpiLocality>("ex");
      JDpiLocality u = in(inC);
      go(u);
   }
}
```

Implementing DPI: Example 2

Processes

$$\nu a.ex!a$$

Implemented in Java

```
public void body(){
    JDpiChannelName<String> a = new JDpiChannelName<String>();
    JDpiChannelName<JDpiChannelName<String>> outChannel =
        new JDpiChannelName<JDpiChannelName<String>>("ex");
    out(outChannel, a);
}
```

Implementing DPI: Example 3

An agent that migrates over a set of *electronic markets*, in search of a best price. At the end of the search, the agent migrates to locality `home` and provides its result on channel `result`.

Implemented in Java

```
public void body() {
  while (count < localities.size()) {
      JDpiChannelName<Article> c = new JDpiChannelName<Article>(art);
      Article a = in( c );
      if (( lowestPrice == 0)||(a.getPrice()<lowestPrice)) {
        locality = localities.get(count);
        lowestPrice = a.getPrice();
      }
      if (++count < localities.size())
        go(localities.get(count));
      else
        go(home);
    }
  }
}
```

Metrics

The Java implementation JDPI is composed of

- about 1000 lines of code
- only 28 classes:
  - provide 152 methods,
  - the average number of lines per method is 3.5

Ongoing works

- Implementing security policies
  - Calculus of Membranes;
  - Types for access control;
  - Logical specification of security policies;
  - ...
- Consider process interaction based on `XML`
  - query and pattern matching
- Reimplement KLAVA (the run-time system for KLAIM) using IMC
- Integration in Eclipse

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Services (project SENSORIA)

- Add features to deal with services
- Single out recurrent mechanisms of calculi for SOC (e.g., SCC, COWS, ...)

References

`http://imc-fi.sourceforge.net`

- papers
- documentation
- GPL software

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Thanks!