Programming Paradigms

Lecture 11

Slides are from Prof. Chin Wei-Ngan from NUS

More on Declarative Concurrency

Agents and
Message Passing Concurrency

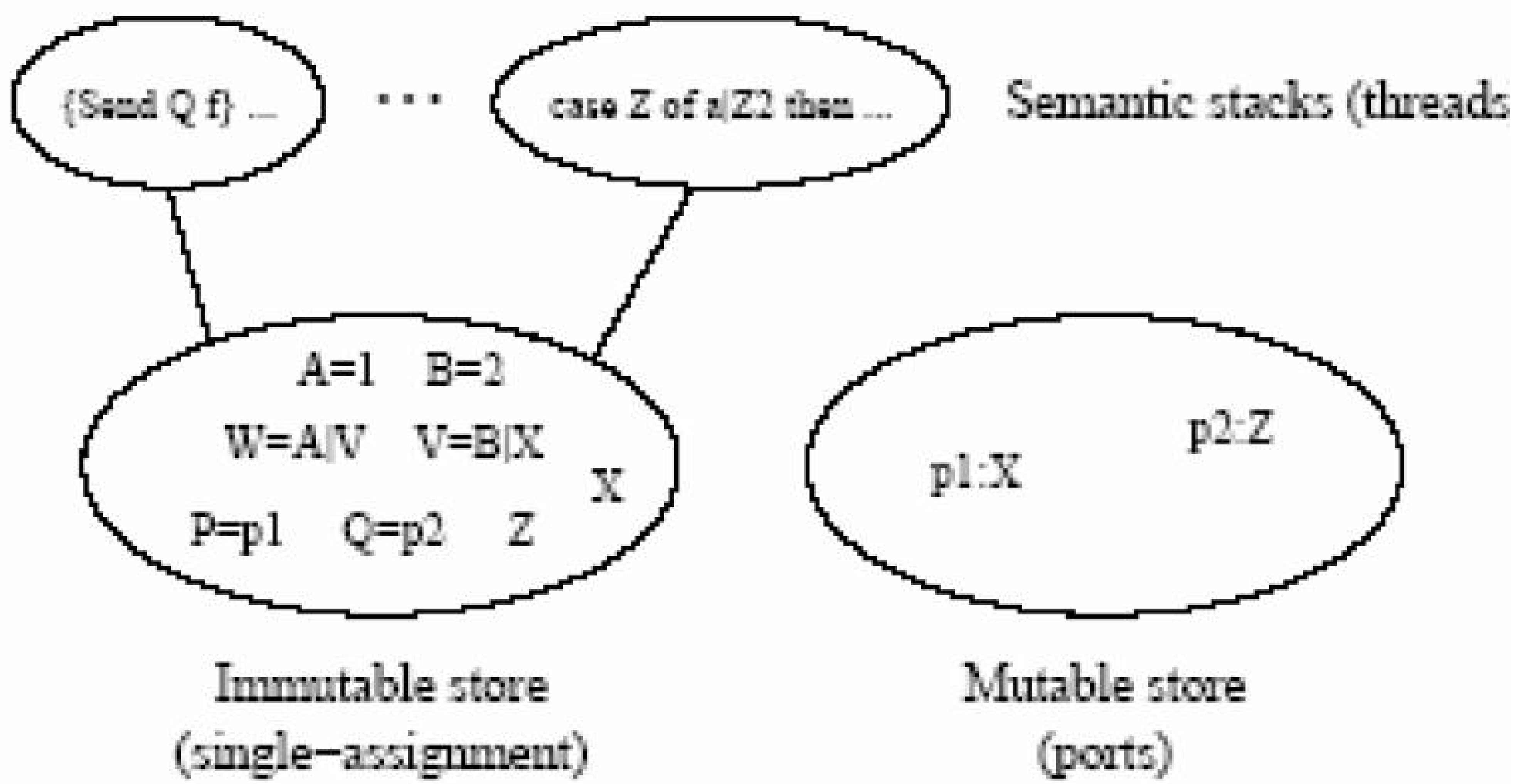
Ports

- A **port** is an ADT with two operations:
  - `{NewPort S P}` or equivalently `P={NewPort S}`: create a new port with entry point (channel) `P` and stream `S`.
  - `{Send P X}`: append `X` to the stream corresponding to the entry point `P`.
- Successive sends from the same thread appear on the stream in the same order in which they were executed.
- This property implies that a port is an asynchronous FIFO (first-in, first-out) communication channel.

Semantics of Ports

- Extend the execution state of the declarative model by adding a **mutable store** μ
- This store contains ports, i.e. pairs of the form $x : y$, where x and y are variables of the single-assignment store (x is the channel's name and y is the *current last position of stream*).
- The mutable store is initially empty.
- The semantics guarantees that x is *always bound* to a name value that represents a port and that y is *unbound*.
- The execution state becomes a triple (MST, σ, μ) (or (MST, σ, μ, τ) if the trigger store is considered).

The Message-Passing Concurrent Mode



The `NewPort` Operation

- The semantics of ({NewPort <x> <y>}, *E*) is:
  - Create a **fresh port name** (also called **unique address**) *n*.
  - Bind *E*(<y>) and *n* in the store.
  - If the binding is successful, then add the pair *E*(<y>) : *E*(<x>) to the mutable store μ.
  - If the binding fails, then raise an error condition.

The `Send` Operation

- The semantics of (`{Send` <x> <y>`}`,*E*) is:
  - If the activation condition is `true` (*E*(<x>) is determined), then:
    - If *E*(<x>) is not bound to the name of a port, then raise an error condition.
    - If the mutable store contains *E*(<x>) : ***z***, then:
      - Create a new variable ***z0*** in the store.
      - Update the mutable store to be *E*(<x>) : ***z0***.
      - Create a new list pair *E*(<y>) | ***z0*** and bind ***z*** with it in the store.
  - If the activation condition is `false`, then suspend execution.

Question

```
declare S P
P={NewPort S}
{Browse S}
thread {Send P a} end
thread {Send P b} end
```

- What will the Browser show?
- Note that each `{Send P …}` is in a separate thread

Question

```
declare S P
P={NewPort S}
{Browse S}
thread {Send P a} end
thread {Send P b} end
```

- Which will the Browser show?
- Either
  - `a|b|_<future>` or
  - `b|a|_<future>`
- non-determinism: we can't say what

Answering Messages

- Traditional view

- Include the entry port `P'` of the sender in the message:

  `{Send P pair(Message P')}`

- Receiver sends answer message to `P'`

  `{Send P' AnsMessage}`

Answering Messages

- Do not reply by address, use something like pre-addressed reply envelope
  - dataflow variable!!!
- `{Send P pair(Message Answer)}`
- Receiver can bind `Answer`!

Port Objects

- A **port object** is a combination of one or more ports and a stream object.
- This *extends stream objects* in two ways:
  - First, many-to-one communication is possible: many threads can reference a given port object and send to it independently.
    - This is not possible with a stream object because it has to know where its next message will come from.
  - Second, port objects can be embedded inside data structures (including messages).
    - This is not possible with a stream object because it is referenced by a stream that can be extended by just one thread.

Stream Object

accumulator

input

output

```
proc {StreamObject S1 X1 ?T1}
   case S1 of M|S2 then N X2 T2 in
        {NextState M X1 N X2}
        T1 = N|T2  {StreamObject S2 X2 T2}
     [] nil then T1=nil end
end
```

StreamObject :: [A], B, [C] → ()
NextState :: A,B, C,A → ()

```
declare S0 X0 T0
thread {StreamObject S0 X0 T0} end
```

Port Objects. Distributed Algorithm

```
declare P1 P2 ... Pn in
local S1 S2 ... Sn in
   {NewPort S1 P1}
   {NewPort S2 P2}
   ...
   {NewPort Sn Pn}
  thread {RP S1 S2 ... Sn} end
end
```

- The thread contains a recursive procedure `RP` that reads the port streams and performs some action for each message received.
- Sending a message to the port object is just sending a message to one of the ports.
- Similar terms: **agent**, **process** (Erlang), **active object**

A Math Agent

```
proc {Math E}
   case E
   of add(N M Answer) then Answer=N+M
   [] mul(N M Answer) then Answer=N*M
   [] int(Formula Answer) then
      Answer = ...
   end
end
```

- **Remark:** `Answer` is included in the stream's element `X` of `{Send EntryPoint X}`

Making the Agent Work (Port Creation)

```
local S in
  MP = {NewPort S}
  proc {MathProcess Ms}
    case Ms of M|Mr then
      {Math M}
      {MathProcess Mr}
    end
  end
  thread {MathProcess S} end
end
```

- `MathProcess` is a recursive procedure that reads the port streams and performs some action for each message received.

Making the Agent Work (Sending a Message

```
declare A B
thread % client 1
   {Send MP add(2 3 A)}
   {Browse A}
end
thread % client 2
   {Send MP mul(2 3 B)}
   {Browse B}
end
```

- `A` and `B` are two dataflow variables which will be bound in port `MP`

Recall Higher-Order Construct

ForAll :: {[X], X→()} → ()

```
proc {ForAll Xs P}
   case Xs
   of nil  then skip
   [] X|Xr then {P X} {ForAll Xr P}
   end
end
```

- Call procedure `P` for all elements in `Xs`

Smells of Higher-Order…

- Using `ForAll`, we have

```
proc {MathProcess Ms}
   {ForAll Ms Math}
end
```

Making the Agent Work

```
declare MP in
local S in
  MP = {NewPort S}
  thread {ForAll S Math} end
end
```

Making the Agent Work

```
declare MP in
local S in
  MP = {NewPort S}
  thread for M in S do {Math M} end end
end
```

- The stream `S` is private (`local`) to the port.
- `Math` is associated to the port `MP`
- `MP` and `Math` can become arguments of a generic function.

Smells Even Stronger…

- Programming with port objects can be abstracted into a function

```
fun {NewAgent Process}
   Port Stream
in
   Port={NewPort Stream}
   thread {ForAll Stream Process} end
   Port
end
```

NewAgent :: {X→()} → Port X

- So, the previous port creation is equivalent with:

```
MP = {NewAgent Math}
```

Why Do Agents/ Processes Matter?

- Model to capture communicating entities
- Each agent is simply defined in terms of how it replies to messages
- Each agent has a thread of its own
  - no screw-up with concurrency
  - we can easily extend the model so that each agent has a state (encapsulated)
- ***Extremely useful to model distributed systems!***

Summary so far

- Ports for message sending
  - use stream (list of messages) as mailbox
  - port serves as unique address
- Use agent abstraction
  - combines port with thread running agent
  - simple concurrency scheme
- Introduces non-determinism… and state!

Protocols

Protocols

- **Protocol**: is a set of rules for sending and receiving messages
  - programming with agents
- Most well-known protocols:
  - the Internet protocols (TCP/IP, HTTP, FTP, etc.)
  - LAN (Local Area Network) protocols such as Ethernet and DHCP (Dynamic Host Connection Protocol), …

RMI (Remote Method Invocation)

- It seems to be the most popular of the simple protocols.
- It allows an object to call another object in a different operating system process, either on the same machine or on another machine connected by a network.
- **RMI** is a descendant of the **RPC** (Remote Procedure Call), which was invented in 1980, before object-oriented programming became popular.
- RMI became popular once objects started replacing procedures as the remote entities to be called.
- We assume that a "*method*" is simply what a port object does when it receives a particular message.

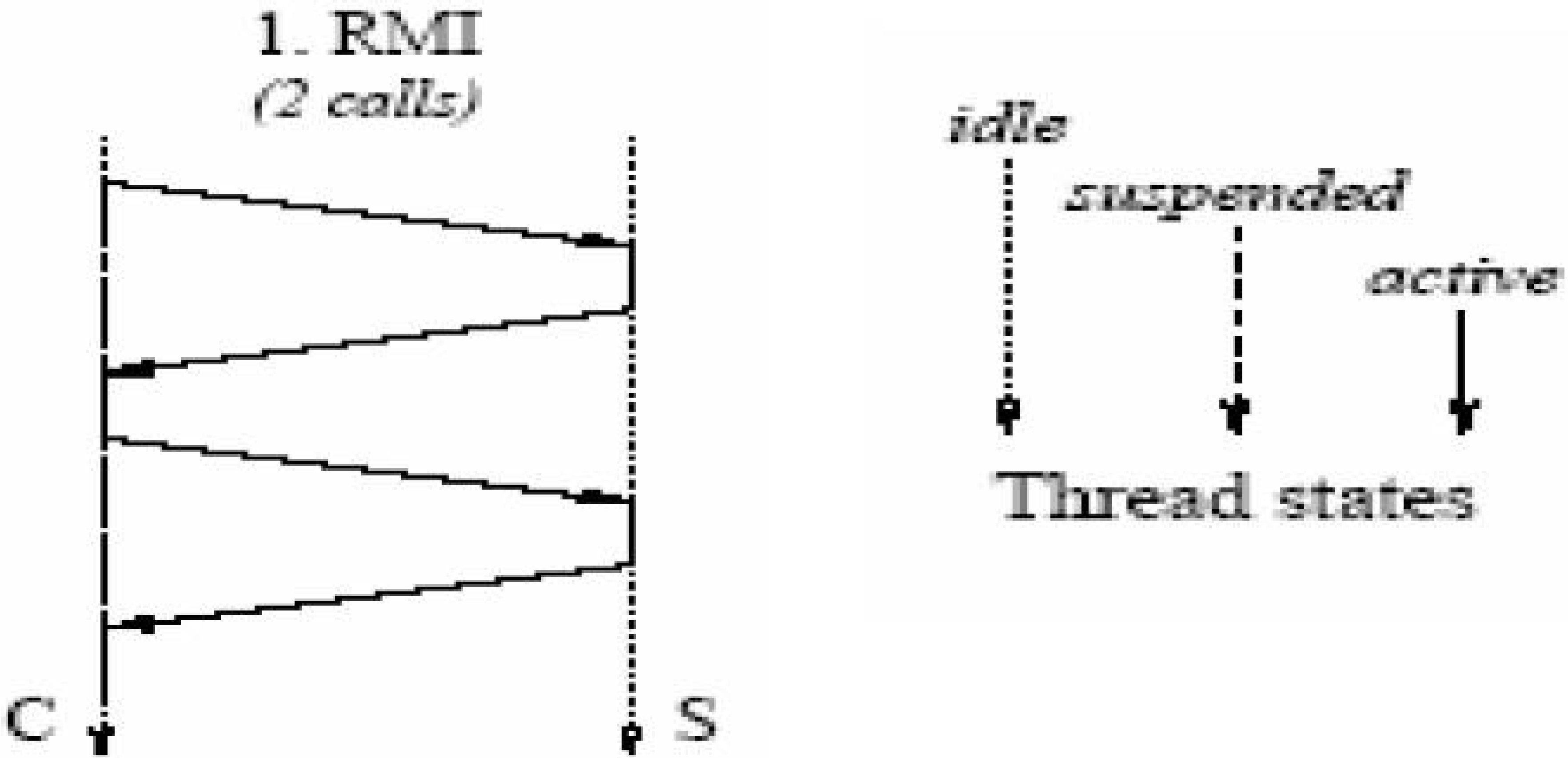
Differences between RPC and RMI

RPC

- Faster than RMI
- Depends on the platform
- Has to convert the arguments between architectures so that each computer can use its native datatype

RMI

- Is part of Java's object-oriented approach
- Allows multiple-concurrent method invocation
- Is portable (doesn't depend on the operating system)
- Good security system
- To call outside methods, RMI needs JNI, JDBC, RMI-IIOP, RMI-IDL, etc.



- A client sends a request to a server and then waits for the server to send back a reply.
- C stands for client, S for server, *idle* means "available to service requests", *suspended* means "not available".

The Server as a Port Object

```
declare
proc {ServerProc Msg}
   case Msg
   of calc(X Y) then
      Y = X * X + 1.0
   end
end
Server={NewAgent ServerProc}
```

- The second argument `Y` of calc is bound by the server.
- The server computes the polynomial `X * X + 1.0`

What is `NewAgent`? (Reminder)

```
fun {NewAgent Process}
   Port Stream
in
   Port={NewPort Stream}
   thread {ForAll Stream Process} end
   Port
end
```

The Client (using RMI)

```
declare
proc {ClientProc Msg}
   case Msg
   of work(Y) then
      Y1 Y2 in
      {Send Server calc(1.0 Y1)}
      {Wait Y1}
      {Send Server calc(2.0 Y2)}
      {Wait Y2}
      Y = Y1 + Y2
   end
end
Client={NewAgent ClientProc}
```

The Client as a Port Object II

```
local X in
    {Send Client work(X)}
    {Browse X}
end
```

- Difference between the client and server:
    - The client definition references the server directly but the server definition does not know its clients.
    - The server gets a client reference indirectly, through the argument `Y`, i.e. the dataflow variable that is bound to the answer by the server.
    - The client waits until receiving the reply before continuing.

What is `Wait`?

- `{Wait X}` suspends the thread until `X` becomes determined, i.e. also called *explicit synchronization* on variable `X`

```
declare Y
{ByNeed proc {$ X} X=1 end Y}
{Browse Y}
{Wait Y}
<statement>
```

- Display `Y` in the Browser.
- To access `Y`, the operation `{Wait Y}` will trigger the producing procedure.
- `<statement>` will be executed only after `Y` is bound

Characteristics of RMI

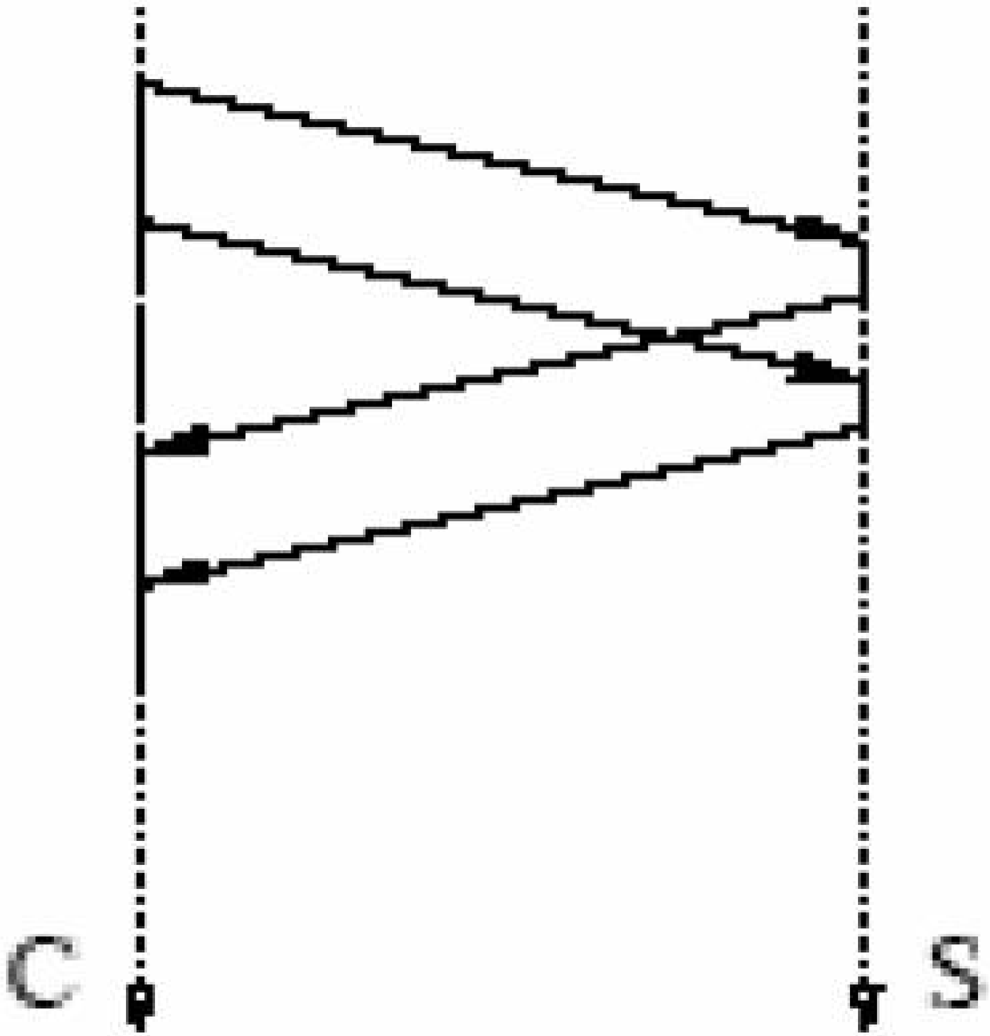
- In the previous example, all messages are executed sequentially by the server.
- In practice, some RMI implementations do things somewhat differently, i.e. they allow multiple calls from different clients to be processed concurrently.
- May use different languages and different OS.

Asynchronous RMI

- Similar to RMI, except that the client continues execution immediately after sending the request.
- The client is informed when the reply arrives.
- So, two requests can be done in rapid succession.
- **Motivation**: If communications between client and server are slow, then this will give a large performance advantage over RMI.

2. Asynchronous RMI

(2 calls)



The Asynchronous RMI Client

```
declare
proc {ClientProc Msg}
   case Msg
   of work(Y) then Y1 Y2 in
      {Send Server calc(1.0 Y1)}
      {Send Server calc(2.0 Y2)}
      Y = Y1 + Y2
   end
end
Client={NewAgent ClientProc}
local X in
   {Send Client work(X)}
   {Browse X}
end
```

Characteristics of Asynchronous RMI

- Message sends overlap. Client waits for both results `Y1` and `Y2` before doing the addition `Y1+Y2`.
- The server is the same as with standard RMI. It still receives messages one by one and executes them sequentially.
- Requests are handled by the server in the same order as they are sent and the replies arrive in that order as well.

RMI with Callback

- Server may need to call back client to fulfill request, e.g. check on some special values.

```
proc {ServerProc Msg}
   case Msg
   of calc(X ?Y Client) then X1 D in
      {Send Client delta(D)}
       X1=X+D
      Y = X * X + 1.0
   end
end
Server={NewAgent ServerProc}
```

callback

RMI with Callback

```
proc {ClientProc Msg}
   case Msg
   of work(?Z) then Y in
      {Send Server calc(10.0 Y Client)}
      Z=Y+100.0
   [] delta(?D) then D=1.0
   end
end
Client={NewAgent ClientProc}
{Browse {Send Client work($)}}
```

- Does this work?

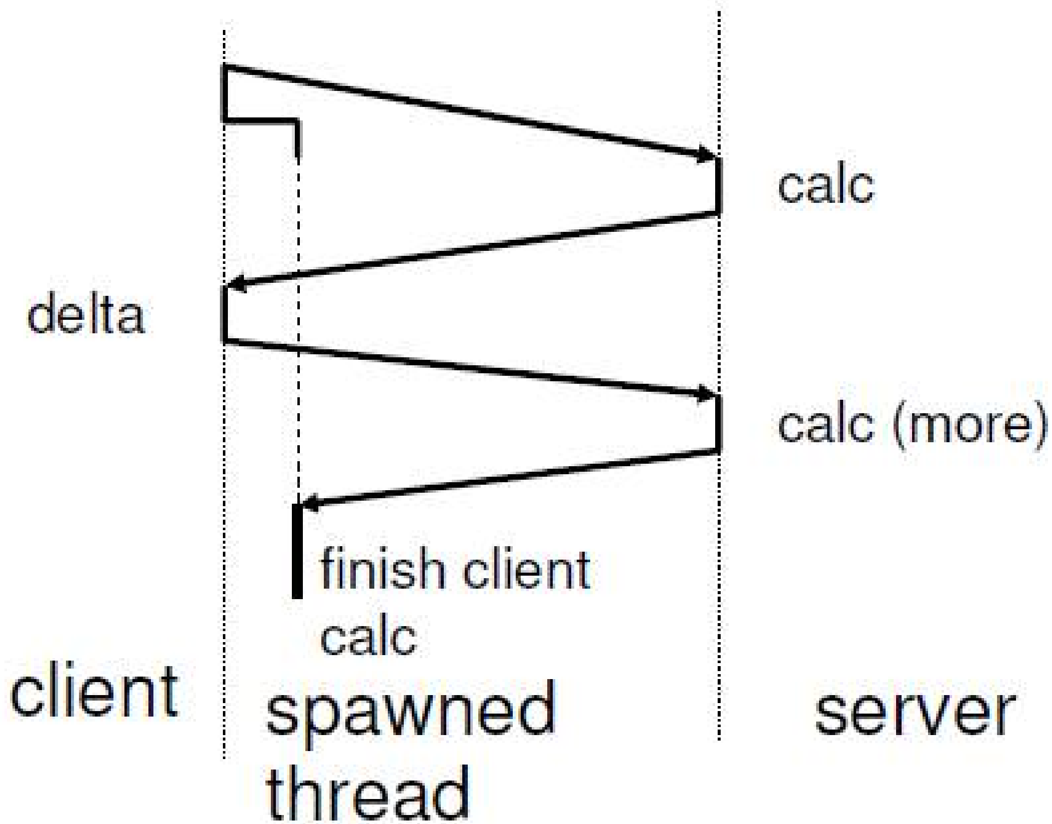
No! It deadlocks as server and client waiting for each other.

Solution – Use Thread

```
proc {ClientProc Msg}
   case Msg
   of work(?Z) then Y in
      {Send Server calc(10.0 Y Client)
      thread Z=Y+100.0 end
   [] delta(?D) then D=1.0
   end
end
```

add thread to allow client to proceed.

RMI with Callback (using thread)



RMI with Callback (using continuation)

- Possible to avoid thread.

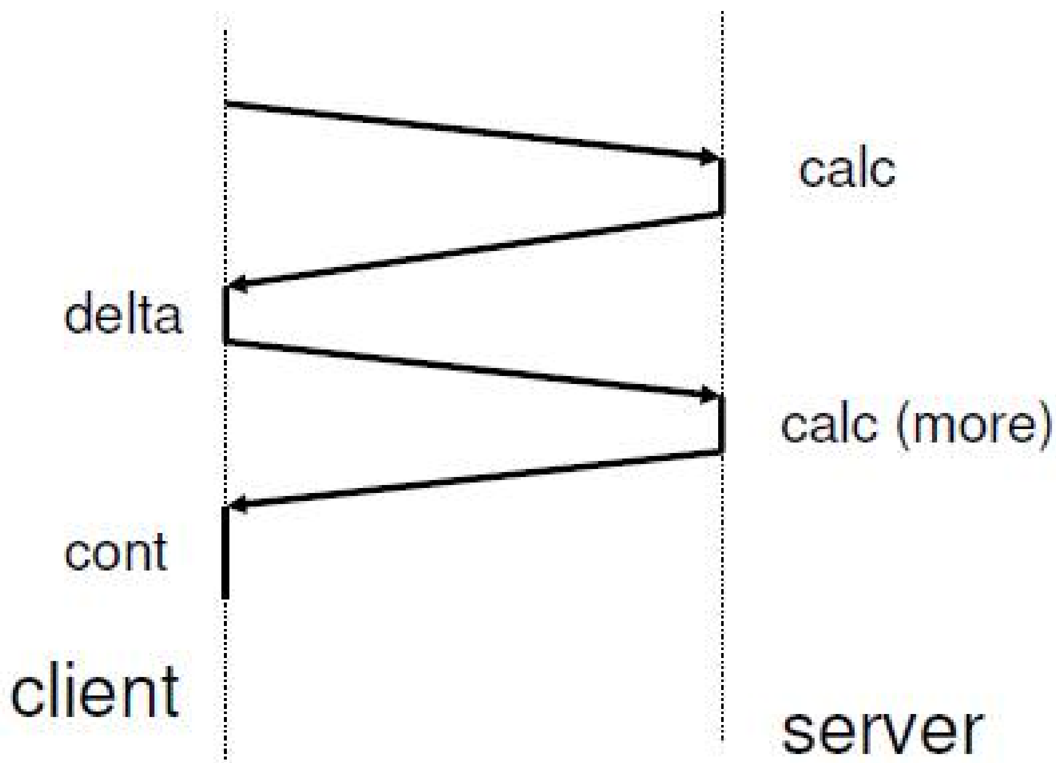
```
proc {ServerProc Msg}
    case Msg
    of calc(X Client Cont) then X1 D Y in
        {Send Client delta(D)}
         X1=X+D
         Y = X * X + 1.0
        {Send Client Cont#Y}
    end
end
Server={NewAgent ServerProc}
```

continuation

Solution – Using Continuation Record

```
proc {ClientProc Msg}
   case Msg
   of work(?Z) then Y in
      {Send Server calc(10.0 Client cont(Z))}
   [] cont(Z)#Y then Z=Y+100.0
   [] delta(?D) then D=1.0
   end
end
Client={NewAgent ClientProc}
{Browse {Send Client work($)}}
```

RMI with Callback (using continuation record)



Erlang

Erlang

- Developed by Ericsson for telecoms application.
- Features : fine grain parallelism, extreme reliability, hot code updates.
- Functional core – dynamically typed strict functional language.
- Message-passing extension – processes communicate by sending messages asynchronously in FIFO order.

Functions in Erlang

- Uses pattern-matching and Prolog syntax

```
factorial(0) -> 1;

factorial(N) when N>0 -> N*factorial(N-1).
```

Pattern-Matching with Tuple

```
area({square, Side}) -> Side*Side;

area({rectangle,X,Y}) -> X*Y;

area({circle, R}) -> 3.14159*R*R;

area({triangle, A,B,C}) -> … ;
```

tuple

Concurrency and Message Passing

- `spawn(M,F,A)` creates a new process and returns its `Pid` . Note that M-module, F-initial function, A-argument list.

- Send operation (written as `Pid!msg`) is an asynchronous message sending.

- `receive` operation removes message from a mailbox. It uses pattern-matching to select messages for removal

An Erlang Process

```
-module(areaserver)
-export([start/0, loop/0]

start() -> spawn(areaserver, loop, []).

loop() -> receive
            {From, Shape} ->
               From!area(Shape),
               loop()
             end.
```

spawn

receive

send

Receive Construct

```
receive
  Pattern1 [when Guard1] -> Body1;
     :
  PatternN [when GuardN] -> BodyN;
 [after Expr -> BodyT;]
end
```

This expression blocks until a message matching one of patterns arrives or when timeout occurs

Summary

- Stream Object
- Thread Module and Composition
- Soft Real-Time Programming
- Agents and Message Passing
- Protocols
- Erlang