Programming Paradigms

Lecture 9

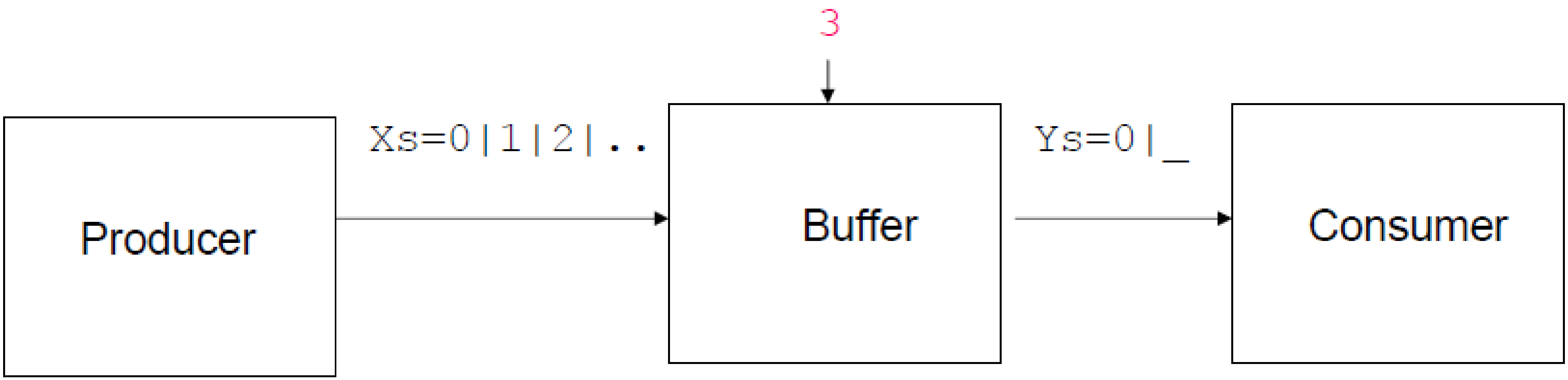
Slides are from Prof. Chin Wei-Ngan from NUS

More on Declarative Concurrency

Bounded Buffer

- *Eager – producer may run ahead*
- *Demand-driven – consumer in control but more complex execution.*
- *Compromise* : Bounded Buffer

Bounded Buffer




```
Xs={Produce 0 Limit}    {Buffer 4 Xs Ys}    S={Consume Ys 0}
```

```
local Xs Ys S in
   thread {DGenerate 0 Xs} end
   thread {Buffer 4 Xs Ys} end
   thread S={DSum Ys 0 10} end
   {Browse Xs} {Browse Ys} {Browse S}
end
```

```
proc {DGenerate N Xs}
  case Xs of X|Xr then
    X=N
    {DGenerate N+1 Xr}
  end
end

fun {DSum ?Xs A Limit}
  if Limit > 0 then
    X|Xr=Xs
  in
    {DSum Xr A+X Limit-1}
  else A end
end
```

```
proc {Buffer N ?Xs Ys}
  fun{Startup N ?Xs}
    if N==0 then Xs
    else Xr in Xs=_|Xr {Startup N-1 Xr} end
  end

  proc {AskLoop Ys ?Xs ?End}
    case Ys of Y|Yr then Xr End2 in
 Xs=Y|Xr
 End=_|End2
 {AskLoop Yr Xr End2}
    end
  end

  End={Startup N Xs}
in
  {AskLoop Ys Xs End}
end
```

Lazy Streams

- Better solution for demand-driven concurrency

  Use Lazy Streams

  That is consumer decides, so producer runs on request.

Needed Variables

- Idea:
  - start execution,
  - when value for variable needed
  - suspend on the variable
- Value for variable needed…

  …a thread suspends on variable!

Lazy Execution (Reminder)

- Up to now the execution order of each thread follows textual order.

  Each statement is executed in order strict order, whether or not its results are needed later.
- This execution scheme is called *eager execution*, or *supply-driven* execution
- Another execution order is to execute each statement only if its results **are needed** somewhere in the program
- This scheme is called **lazy evaluation**, or **demand-driven evaluation**

Lazy Execution. Reminder

```
declare
fun lazy {F1 X} 2*X end
fun {F2 Y} Y*Y end
B = {F1 3}
{Browse B}            → nothing (simply unbound B)
C = {F2 4}
{Browse C}            → display 16
A = B+C               → display 6 for B
```

- `F1` is a lazy function
- `B = {F1 3}` is executed only if its result is needed in `A = B+C`

Example

```
declare
fun lazy {F1 X} 2*X end
fun lazy {F2 Y} Y*Y end
B = {F1 3}
{Browse B} % → nothing (simply unbound B)
C = {F2 4}
{Browse C} % → nothing (simply unbound C)
```

- `F1` and `F2` are now lazy functions
- `B = {F1 3}` and `C = {F2 4}` are executed only if their results are needed in an expression, like: `A = B+C`

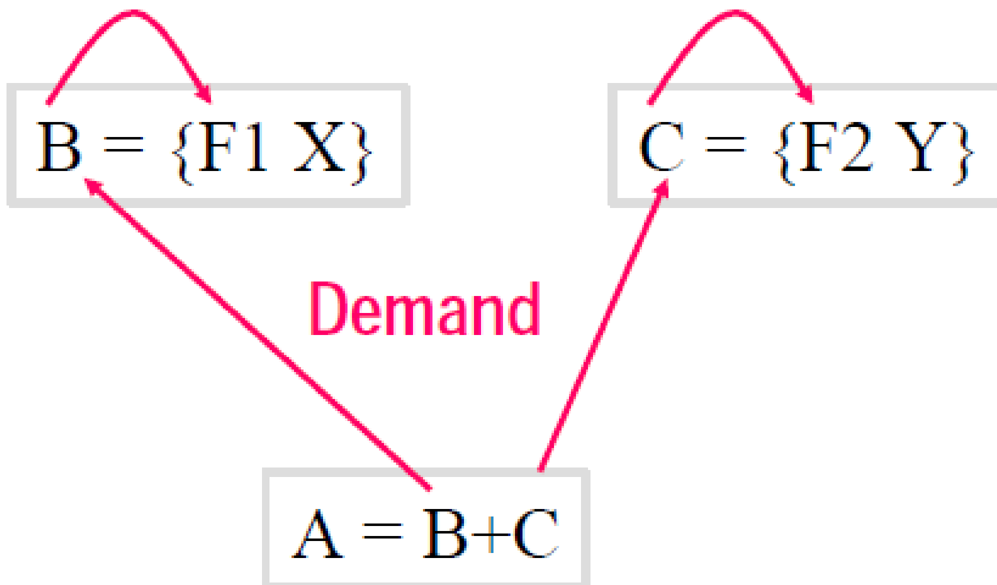
Example

```
declare
fun lazy {F1 X} 2*X end
fun lazy {F2 Y} Y*Y end
B = {F1 3}
{Browse B} % → display 6
C = {F2 4}
{Browse C} % → display 16
A = B+C
```

- `F1` and `F2` are now lazy functions
- `B = {F1 3}` and `C = {F2 4}` are executed because their results are needed in `A = B+C`

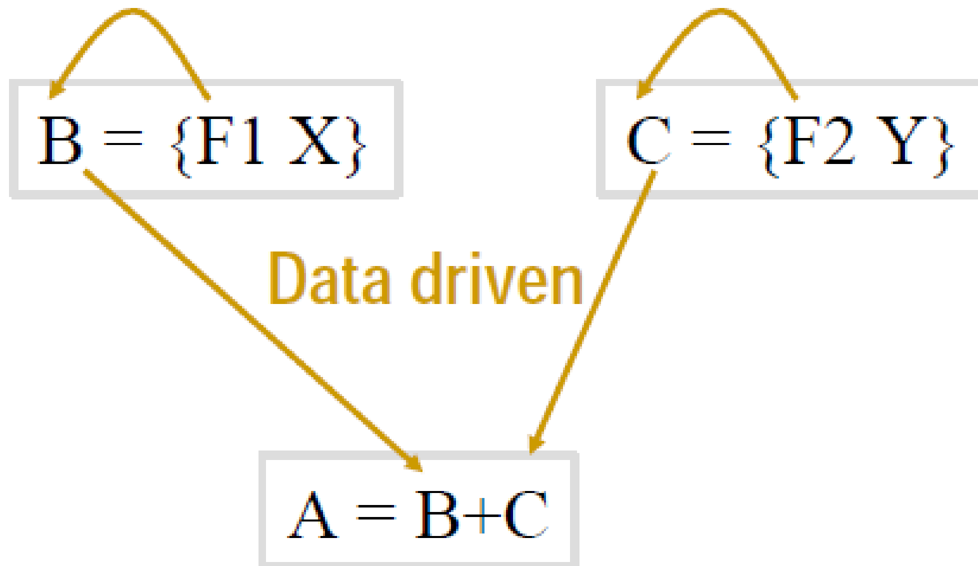
Example

- In **lazy execution**, an operation suspends until its result is needed
- Each suspended operation is triggered when another operation needs the value for its arguments
- In general, multiple suspended operations can start concurrently



Example II

- In **data-driven execution**, an operation suspends until the values of its arguments results are available
- In general, the suspended computation can start concurrently



Triggers

- A by-need trigger is a pair `(F,X)`:
  - a zero-argument function `F`
  - a variable `X`
- Trigger creation

  `X={ByNeed F}` or equivalently

  `{ByNeed (proc {$ A} A={F} end) X}`
- If `X` is needed, then `X={ByNeed F}` means:

  execute **`thread`** `X={F}` **`end`**

  delete trigger, `X` becomes a normal variable

Example 1: `ByNeed`

```
X={ByNeed fun {$} 4 end}
```

- Executing `{Browse X}`
  - Shows: `X` (meaning not yet triggered)
  - `Browse` does not need the value of `X`
- Executing `T`: `Z=X+1`
  - `X` is needed
  - current thread `T` blocks (`X` is not yet bound)
  - new thread created that binds `X` to `4`
  - thread `T` resumes and binds `Z` to `5`

Example 2: ByNeed

```
declare
fun {F1 X} {ByNeed fun {$} 2*X end} end
fun {F2 Y} {ByNeed fun {$} Y*Y end} end
B = {F1 3}
{Browse B} % simply display B
C = {F2 4}
{Browse C} % simply display C
```

Example 2: ByNeed

```
declare
fun {F1 X} {ByNeed fun {$} 2*X end} end
fun {F2 Y} {ByNeed fun {$} Y*Y end} end
B = {F1 3}
{Browse B} % display 6
C = {F2 4}
{Browse C} % display 16
A = B+C
```

Example 3: `ByNeed`

```
thread X={ByNeed fun {$} 3 end} end
thread Y={ByNeed fun {$} 4 end} end
thread Z=X+Y end
```

- Considering that each thread executes atomically, there are six possible executions.
- For lazy execution to be declarative, all of these executions must lead to equivalent stores.
- The addition will wait until the other two triggers are created, and these triggers will then be activated.

Lazy Functions

```
fun lazy {Produce N}
   N|{Produce N+1}
end
```

can be implemented with by-need triggers

```
fun {Produce N}
   {ByNeed fun {$} N|{Produce N+1} end}
end
```

Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
```

- Intuitive understanding: function executes only, if its output is needed

Example: Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
declare Ns={Produce 0}
{Browse Ns}
```

- Shows again `Ns`
  - Remember: `Browse` does not need the values of the variables

Example: Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
declare Ns={Produce 0}
```

- Execute `_=Ns.1`
  - needs the variable `Ns`
  - Browser now shows `0|_` or `0|<Future>`

Example: Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
declare Ns={Produce 0}
```

- Execute `_=Ns.2.2.1`
  - needs the variable `Ns.2.2`
  - Browser now shows `0|1|2|_`

Everything can be Lazy!

- Not only producers, but also transducers can be made lazy
- Sketch
  - consumer needs variable
  - transducer is triggered, needs variable
  - producer is triggered

Lazy Transducer. Example

```
fun lazy {Inc Xs}
    case Xs
    of X|Xr then X+1|{Inc Xr}
    end
end

declare Xs={Inc {Inc {Produce N}}}
```

Global Summary

- Declarative concurrency
- Mechanisms of concurrent program
- Streams
- Demand-driven execution
  - execute computation, if variable needed
  - need is suspension by a thread
  - requested computation is run in new thread
- By-Need triggers
- Lazy functions

More on Concurrency

Overview

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

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
```

Thread Operations

Common Operations on Thread

`{Thread.this}`	return thread id
`{Thread.state T}`	return current state of T
`{Thread.suspend T}`	suspend T
`{Thread.resume T}`	resume T
`{Thread.prempt T}`	preempt T
`{Thread.terminate T}`	terminate T
`{Thread.injectException T}`	raise E in thread T
`{Thread.setPriority T P}`	set priority of T
`{Thread.setThisPriority P}`	set priority of thread

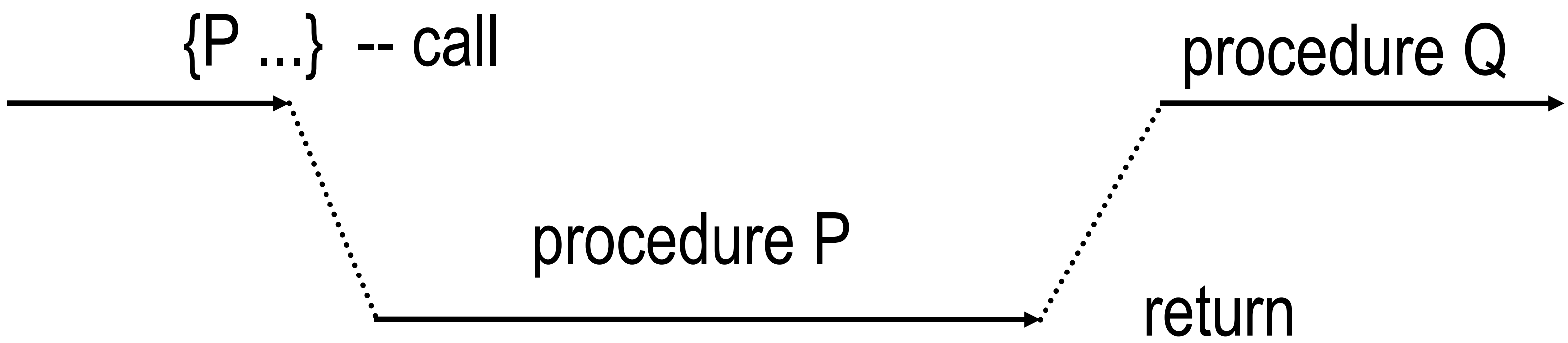
Common Property Operations

`{Property.get priorities}`	get current priority ratios
`{Property.put priorities p(high:X medium:Y)}`	set system priority ratios

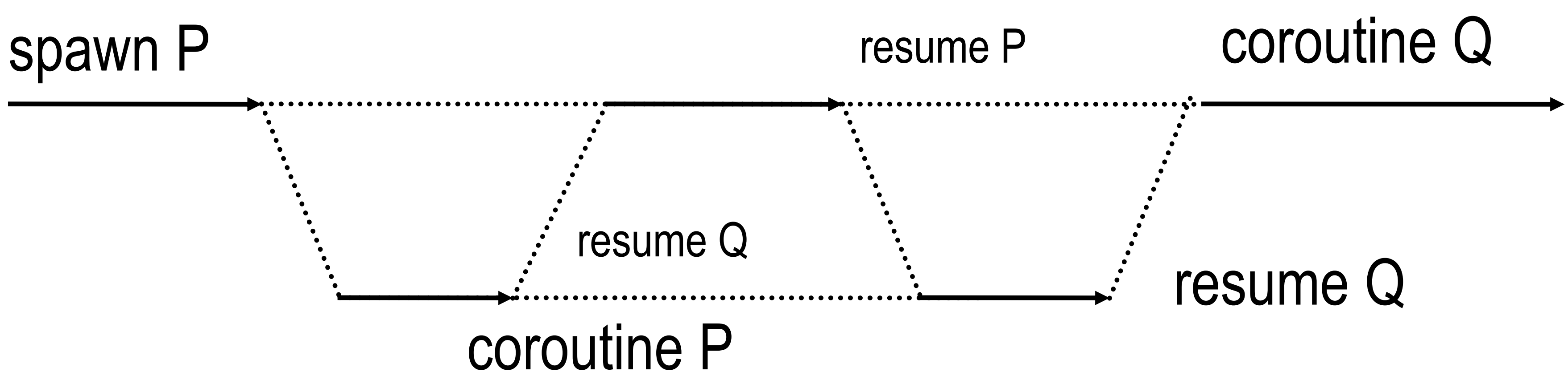
Coroutines

- Languages that do not support concurrent thread might instead support a notion called **coroutining**
- A coroutine is a nonpreemptive thread (sequence of instructions), there is no scheduler
- Switching between threads is the programmer's responsibility

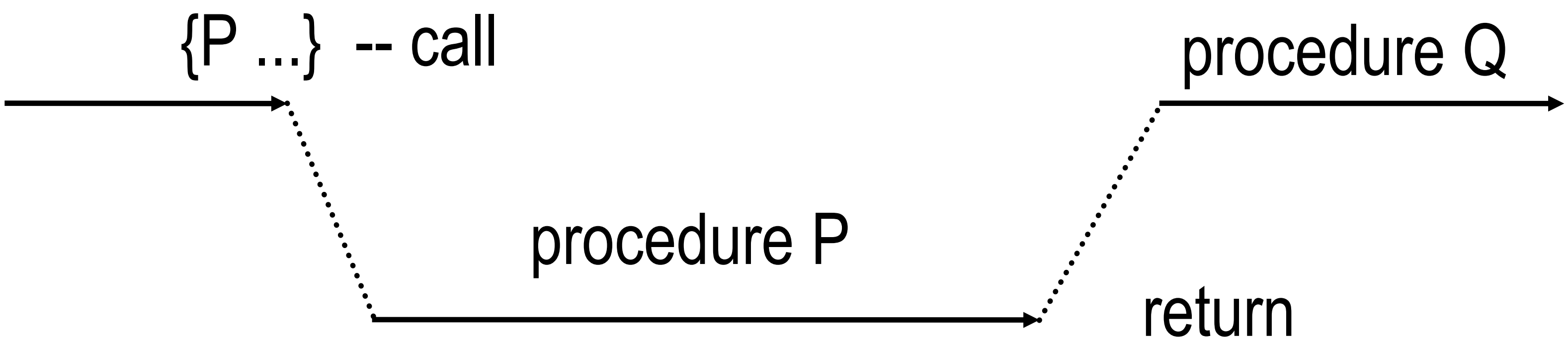
Coroutines



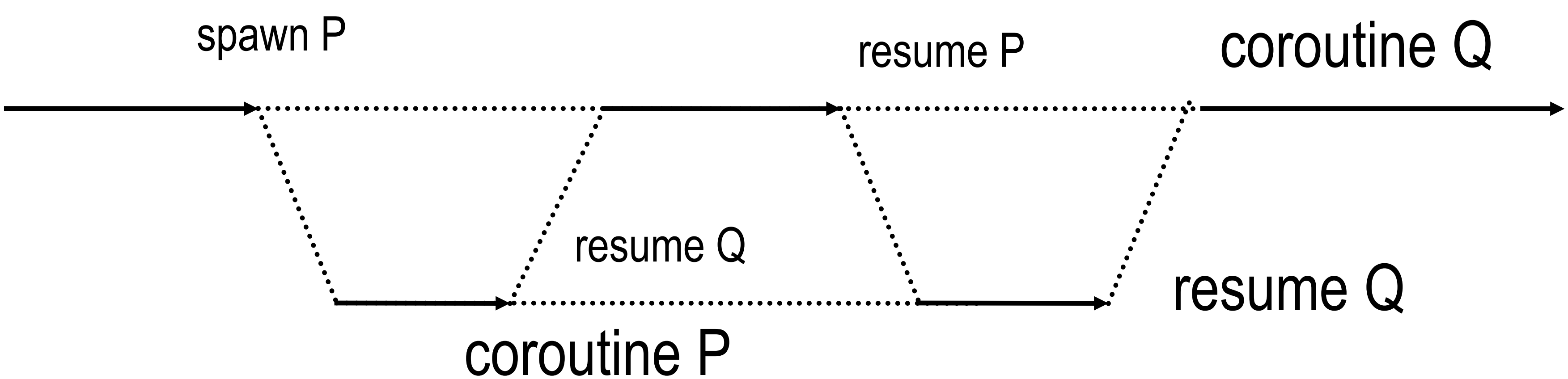
Procedures: one sequence of instructions, program transfers explicitly when terminated it returns to the caller



Coroutines

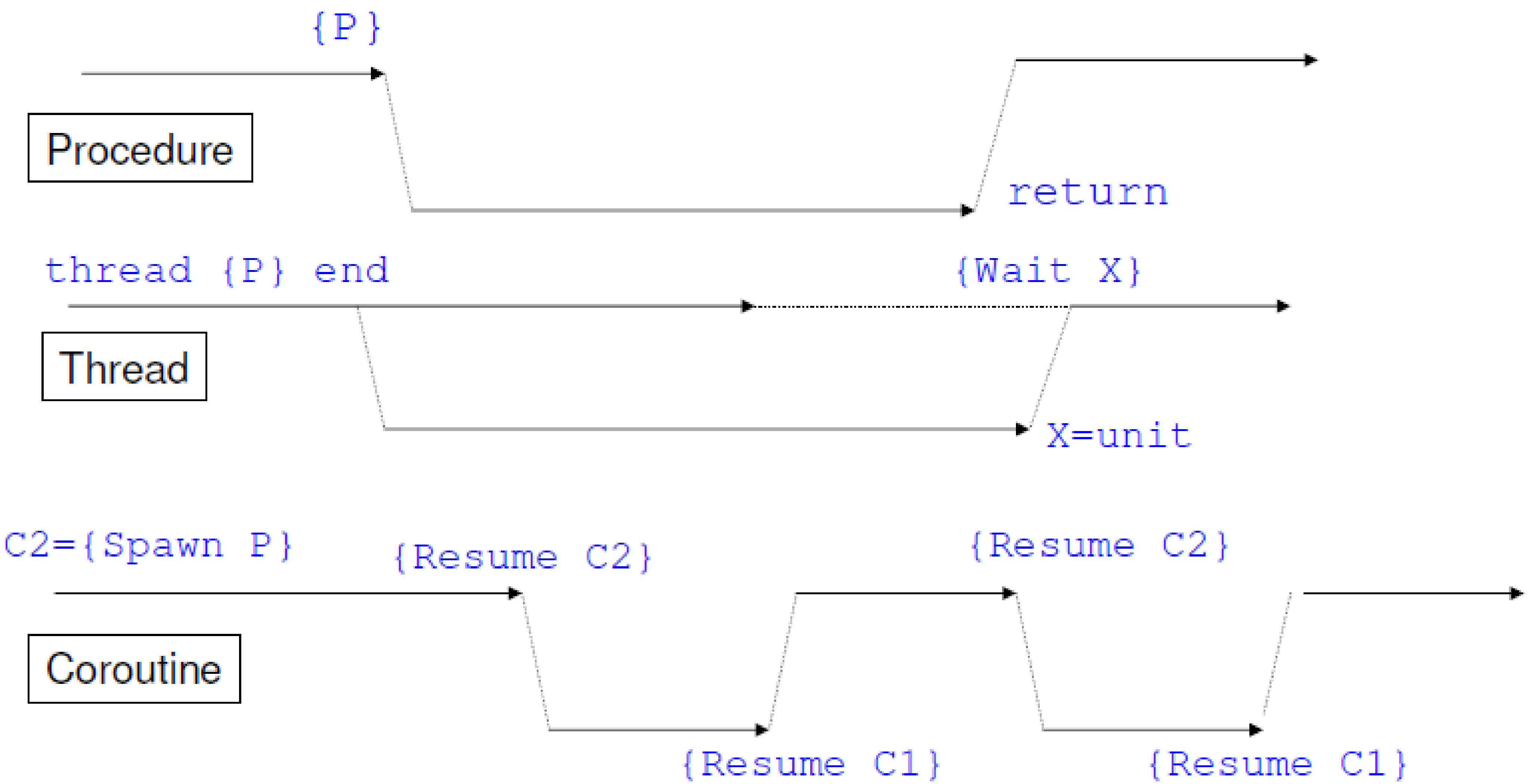


Coroutines: New sequences of instructions, programs explicitly does all the scheduling, by spawn, suspend and resume



Coroutine

A coroutine is a nonpremptive thread



Basic Mechanism for Coroutines

```
fun {Spawn P}
   PId in
   thread
       Pid={Thread.this}
       {Thread.suspend Pid}
       {P}
   end
   PId
end

proc {Resume Id}
   {Thread.resume Id}
   {Thread.suspend {Thread.this}}
end
```

Spawn :: (()→()) → Id
Resume :: Id → ()

Fork-Join for Threads

```
local X1 X2 .. Xn-1 Xn in
  thread <stmt1> X1=unit end
  thread <stmt2> X2=X1 end
      :
  thread <stmtn> Xn=Xn-1 end
  {Wait Xn}
end
```

wait for all threads to complete through variable binding

Barrier Synchronization

list of threads

```
proc {Barrier Ps}
   fun {Loop Ps L}
      case Ps of P|Pr then M in
        thread {P} M=L end
        {Loop Pr M}
      [] nil then L
      end
   end
   S={Loop Ps unit}
in
   {Wait S}
end
```

wait for all threads to complete

Soft Real-Time Programming

- Real-time
  - control computations by time
  - animations, simulations, timeouts, …
- *Hard* real-time has firm deadlines, which have to be respected all the time, without any exception (medical equipments, air traffic control, …)
- *Soft* real-time is used in less demanding situations.
  - suggested time
  - no time guarantees
  - no hard deadlines as for controllers, etc.
  - Examples: telephony, consumer electronics, …

The `Time` module

- The `Time` module contains a number of useful soft real-time operations:
  - `Delay`
  - `Alarm`
  - `Time`
- `{Delay N}` suspends the thread for `N` milliseconds
- Useful for building abstractions
  - timeouts
  - repeating actions

The `Time` module

- `{Alarm N U}` creates a new thread that binds `U` to `unit` after at least `N` milliseconds.
- `Alarm` can be implemented with `Delay`
- `{Time.time}` returns the integer number of seconds that have passed since the current year started

Soft Real-Time Programming. Example

```
functor
import
   Browser(browse:Browse)
define
   proc {Ping N}
      if N == 0 then {Browse 'ping terminated'}
      else {Delay 500} {Browse ping} {Ping N - 1} end
   end
   proc {Pong N}
      {For 1 N 1
       proc {$ I} {Delay 600} {Browse pong} end }
      {Browse 'pong terminated'}
   end
in
   {Browse 'game started'}
   thread {Ping 6} end
   thread {Pong 6} end
end
```

Soft Real-Time Programming. Example

Agents and
Message Passing Concurrency

Client-Server Architectures

- Server provides some service
  - receives message
  - replies to message
  - examples: web server, mail server, …
- Clients know address of server and use service by sending messages
- Server and clients run independently

Client-Server Applications …

- With declarative programming, it is impossible to write a client/server program where the server does not know which client will send the next message.
- **Observable *nondeterministic* behavior**: the server can receive information in any order from two independent clients.
- The server has **only** an input stream from which it reads commands.

The Message-Passing Concurrent Model

- Extends the declarative concurrent model by adding one new concept, an **asynchronous communication channel**.
- Any client can send messages to the channel at any time and the server can read all the messages from the channel (no limitations).
- A client/server program may give different results on different executions because the order of clients' sends is not fixed.
- **Message-passing model** is *nondeterministic* and therefore no longer declarative.

Peer-to-Peer Architectures

- Similar to Client-Server:
  - every client is also a server
  - communicate by sending messages to each other
- We call all these guys (client, server, peer)

  agent
- In [van Roy, Haridi; 2004] book, this is called ***portObject***

Common Features

- Agents
  - have identity — mail address
  - receive messages — mailbox
  - process messages — ordered mailbox
  - reply to messages — pre-addressed return letter

- Now how to cast into programming language?

Message Sending

- Message data structure
- Address **port**
- Mailbox stream of messages
- Reply dataflow variable in message

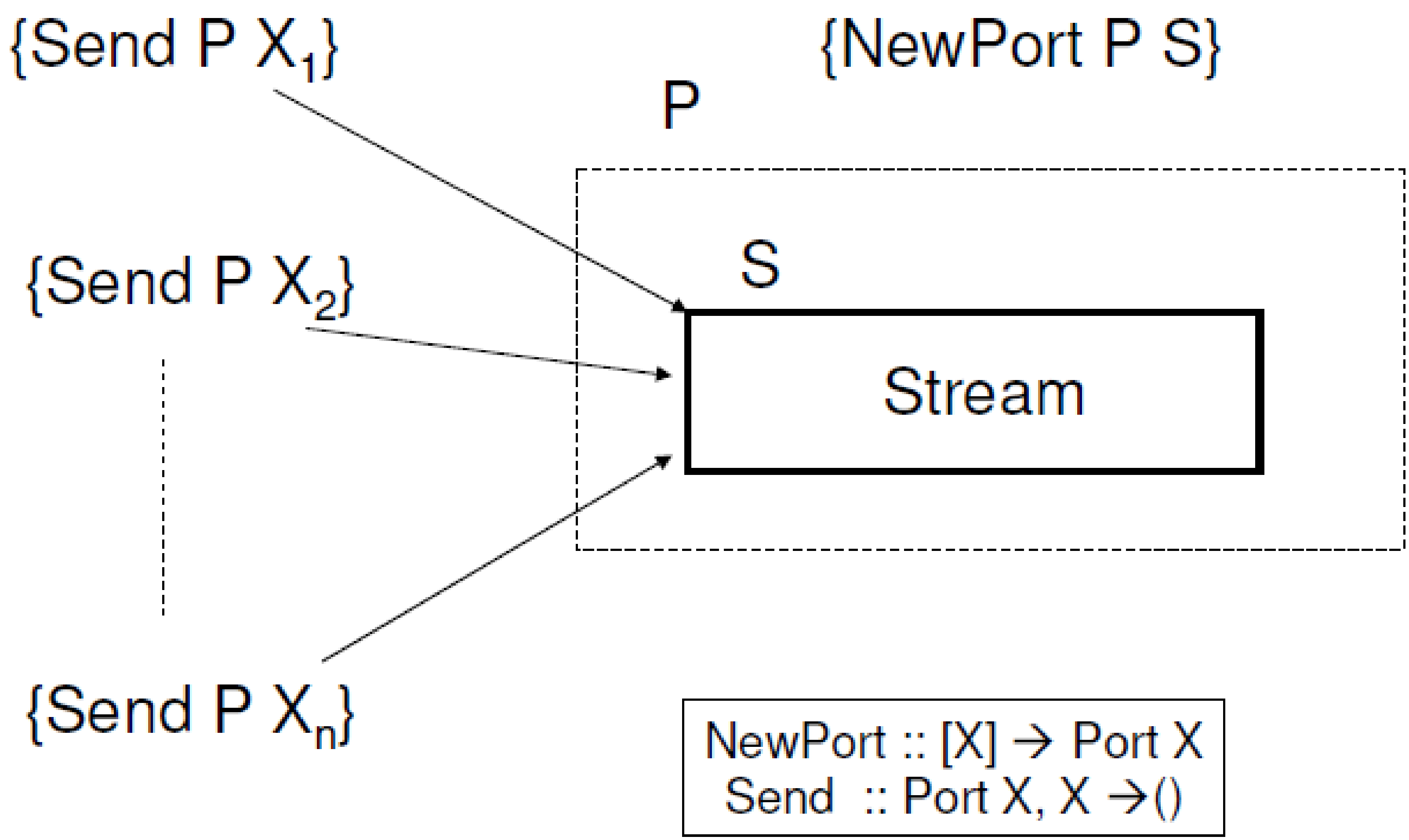
$\boxed{\text{Type :: Port X}}$

message type

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.

Port and its Stream



Ports

- **Asynchronous**: a thread can send a message at any time and it does not need to wait for any reply.
- As soon as the message is in the communication channel, the thread can continue executing.
- Communication channel can contain many pending messages, which are waiting to be handled.

Example

```
declare S P
P={NewPort S}
{Browse S}
```

- Displays initially `S<future>` (or _)

Example

```
declare S P
P={NewPort S}
{Browse S}
```

- Execute `{Send P a}`
- Shows `a|_<future>`

Example

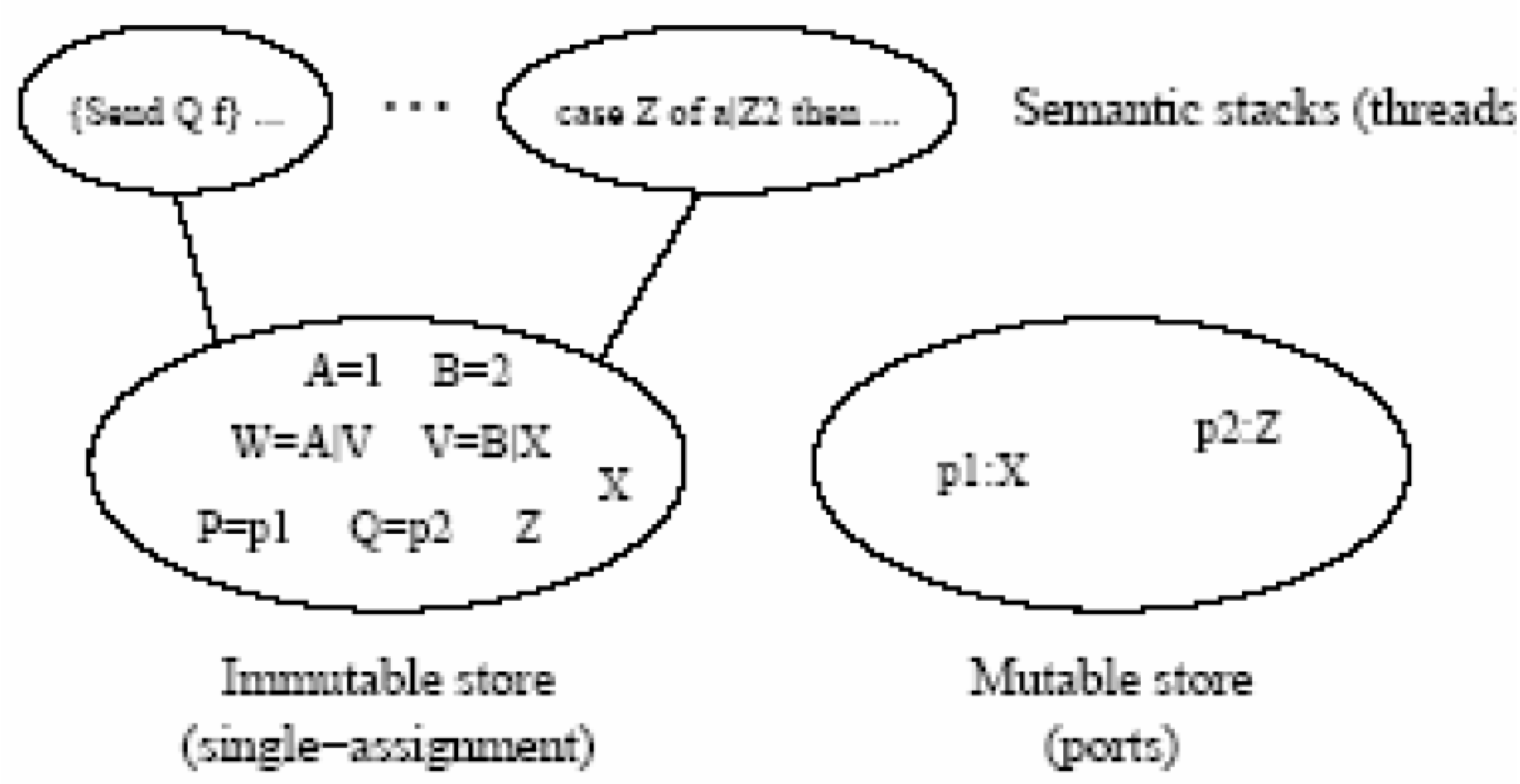
```
declare S P
P={NewPort S}
{Browse S}
```

- Execute `{Send P b}`
- Shows `a|b|_<future>`
- Note that `{Send P a}` and `{Send P b}` are in the same thread

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`!