# Explicit concurrent programming in high-level languages

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# Outline

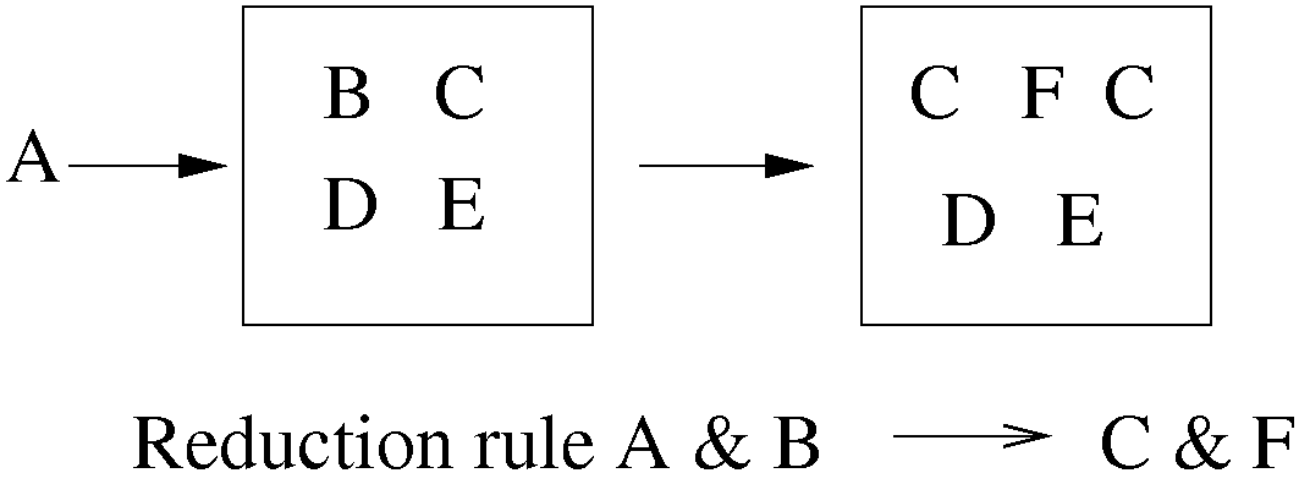
# Explicit parallelism

- In languages that use explicit parallelism the programmer must explicitely define which parts should be executed as independent parallel tasks
- The programmer has complete control over the parallel execution
- This is opposite to implicit parallelism where the system decides automatically which parts to run in parallel

# Join calculus

- Join calculus aims to support asynchronous, distributed and mobile programming
- Join operational semantics are specified as a reflexive chemical abstract machine (CHAM)
- Using CHAM the state of a system is represented as a "chemical soup"
  - active definitions
  - running processes
  - a set of reduction rules
- Join calculus can be seen as a functional language with Join patterns (provides synchronization between elements in the "soup")

# CHAM example



# JoCaml

- JoCaml = Objective Caml + Join calculus
- The programs are made of processes and expressions
- Channels (also called port names) are the main new primitive values compared to Objective Caml
- Processes can send messages on channels

# Channels and processes

- Channels are created with a def binding

```
#def echo(x) = print_int x; 0
```

- echo is an asynchronous channel → sending a message on it is a nonblocking operation and it cannot be said when the printing actually happens
- Processes are created with a keyword spawn
- There can be concurrency inside processes as well

```
#spawn echo(1) & echo(2)
#spawn begin
    print_int 1; print_int 2; 0
 end
```

# Channels and processes

- The process created by sending messages are called guarded processes and they can spawn new messages

```
#def echo_twice(x) = echo(x) & echo(x)
```

- Channels can take tuples as arguments and even other channels as well

```
#def foo(x,y) = echo(x) & echo(x+y)

#def twice(f,x) = f(x) & f(x)
#spawn twice(echo, 5)
```

# Synchronous channels

- Synchronous channels can be used to define processes that return values
- Synchronous channels use reply/to constructs

```
#def fib(n) =
    if n <= 1 then reply 1 to fib
    else reply fib(n-1) + fib(n-2) to fib

#print_int (fib 10)
>89
```

- In the example above the synchronous channel behaves like a function but the real value of them comes apparent when used with join patterns

# Join patterns

- Join patterns define multiple channels and specifies a synchronization pattern between them

```
#def foo() & bar(x) = do_something(x) ; 0
```

- In the example above messages to both foo and bar must be sent before the guarded process is executed

```
#def a() & c() = print_string "ac" ; 0
  or b() & c() = print_string "bc" ; 0

#spawn a() & b() & c()
```

- The example above illustrates a composite join definition
- Channel c is defined only once and can take part in either synchronizations

# Mutual exclusion example

- Using both asynchronous and synchronous channels allows us to define many concurrent data structures such as the counter bellow

```
#def count(n) & inc() = count(n+1) & reply to inc
  or count(n) & get() = count(n) & reply n to get
#spawn count(0)
```

- A safer way to define a counter would be:

```
#let create_counter () =
  def count(n) & inc0() = count(n+1) & reply to inc0
   or count(n) & get0() = count(n) & reply n to get0 in
  spawn count(0) ;
  inc0, get0
#let inc,get = create_counter()
```

# Control structures

- Many common synchronization primitives can be expressed with Join patterns
- Locks:

```
#let new_lock () =
  def free() & lock() = reply to lock
  and unlock() = free() & reply to unlock in
  spawn free() ;
  lock, unlock
#let my_lock,my_unlock = new_lock()
```

# Control structures

- Barriers:

```
#def join1 () & join2 () = reply to join1 & reply to join2

#spawn begin
    (print_int 1 ; join1 (); print_string "a" ; 0)
  & (join2() ; print_string "b" ; 0)
 end
```

- Asynchronous loops:

```
#def loop(a,x) = if x > 0 then (a() & loop(a,x-1))
```

# Timeouts

- The following example illustrates how we do not have to wait for a result of some computation if it takes too long

```
#let timeout t f x =
  def wait() & finished(r) = reply Some r to wait
  or  wait() & timeout() = reply None to wait in
  spawn begin
    finished(f x) &
    begin Thread.delay t; timeout() end
  end ;
  wait()
```

- In this example the computation of f does not stop after the timeout. Exceptions could be used to archieve this.

# Other languages

- Join calculus has been incorporated into other languages as well, e.g., Join Java and Polyphonic C#
- Join Java adds Join patterns and a new signal return type to Java

```
final class SimpleJoinPattern {
    int A() & B() & C(int x) {
        return x;
    }
}
final class SimpleJoinThread {
    signal athread(int x) {
        ...
    }
}
```

# Actor model

- In Actor model all the computation is done by actors.
- Actors can concurrently
  - send messages to other actors
  - create new actors
  - designate the behavior that is used when the next message is received
- All communication is done asynchronously
- Actors are identified by addresses and messages can only be sent to known addresses

# Actor model

- There is no requirement that the messages arrive in the order they are sent
- In this sense sending messages is similar to sending IP packets
- As different processes communicate only using message passing, there is no need for locks
- Actor model (or some of its variations) is employed in multiple programming languages
  - Erlang
  - Act 1, 2 and 3
  - ActorScrip
  - etc.

# Erlang

- Erlang is a general purpose functional programming language that uses Actor model for concurrency
- It was designed by Ericsson to support distributed, fault-tolerant, soft-real-time, non-stop applications
- Erlang processes are lightweight processes (not operating system processes or threads) that have no shared state between them
- Supports hot code loading

# Processes

- A process is a complete virtual machine
- A process can create another one using keyword spawn

```
Pid2 = spawn(Mod, Func, Args)
```

- Pid2 is the identifier of the new process and it is known only to the creating process
- self() can be used to return the identifier of the executing process

# Message passing

- In the example bellow, Msg is a variable and is bound when a message is received
- Variables can be bound only once
- Note that Pid2 in receive part has already been bound

```
-module(echo).
-export([go/0, loop/0).
go() ->
        Pid2 = spawn(echo, loop, []),
        Pid2 ! {self(), hello},
        receive
                {Pid2, Msg} ->
                  io::format("P1 ~w~n", [Msg])
        end,
        Pid2 ! stop.
```

# Message passing

[example continued from the previous slide]

```
loop() ->
        receive
                {From, Msg} ->
                  From ! {self(), Msg},
                  loop();
                stop ->
                  true
        end.
```

# More on message passing

- Lets assume that two processes send messages a and b to a third process (a and b are atoms, Msg is a variable)
- To receive a before b (regardless of the send order):

```
receive
    a -> do_something(a);
end,
receive
    b -> do_something(b);
end
```

- To process the first message to arrive:

```
receive
    Msg -> do_something(Msg);
end
```

# Registered processes

- Keyword register can be used to register a process identifier with an alias
- Any process can send messages to a registered process

```
start() ->
        Pid = spawn(num_anal, server, [])
        register(analyser, Pid).
analyse(Seq) ->
        analyser ! (self(), {analyse,Seq}},
        receive
            {analysis_result, R} ->
                R
        end
```

# Timeouts

- The example bellow performs do_something if a message is received before T ms has elapsed

```
time_example(T) ->
        receive Msg -> do_something(Msg);
        after T -> do_something_else();
end.
```

- The message buffer can be flushed followingly

```
flush ->
      receive Any -> flush();
      after 0 -> true
end.
```

# Data-flow programming

- Data-flow programming provides automatic synchronization by introducing (concurrent) logic variables and futures (the names may vary from one language to another)
- Logic variables are initially unbound
- Accessing an unbounded logic variable automatically suspends the executing thread
- It is not possible to change the value of a logic variable after it has been bound
- A future is a read only capability of a logic variable
- Data-flow programming allows programmers to focus on what needs to be synchronized

# Flow-Java

- Flow-Java is a conservative extension of Java
- Adds single assignment variables (variant of logic variables) and futures
- Overhead for the runtime is in most cases between 10% and 40%
- Single assignments are introduced with the type modifier single
- A single assignment variable can be bound by using `@=`
- Aliasing is possible and equality testing has also been extended

```
single Object s;
Object o = new Object();
s @= o;
```

# Example

```
class Spawn implements Runnable {
   private single Object result;
   private Spawn(single Object r) {
      result = r;
   }
   public void run() {
      result @= computation();
   }
}
public static void main (String[] args) {
   single Object r;
   new Thread(new Spawn(r)).start();
   System.out.println(r);
}
```

# Futures

- In the previous example, the main thread can unintentionally bind the result
- To prevent this, futures can be used
- The future of a single assignment variable is obtained by a conversion from single t to t
- Implicit conversion allows integration with normal Java

```
public static Object spawn() {
    single Object r;
    new Thread(new Spawn(r)).start();
    return r;
}
```

# Barrier example

```
class Barrier implements Runnable {
   private single Object left;
   private single Object right;
   private Barrier(single Object l, single Object r) {
      left = l; right = r;
   }
   public void run() {
      computation();
      left @= right;
   }

[continues on the next slide...]
```

# Barrier example

```
public static void spawn(int n) {
   single Object first; single Object prev = first;
   for(int i = 0; i < n; i++) {
      single Object t;
      new Thread(new Barrier(prev, t)).start();
      prev = t;
   }
   first == prev;
}
```

# Oz

- All variables in Oz are logic variables (also called dataflow variables)
- Executing a statement in Oz proceeds only when all real dataflow dependencies on the variables involved are resolved
- Oz is a concurrency-oriented language
- Threads are cheap to create in Mozart (60 times faster than in Java 1.2)
- All threads are run by Oz emulator (the main system thread of the process)
- Mozart Programming System is an implementation of Oz

# A simple example

- **thread** ... **end** forks a new thread

```
declare X0 X1 X2 X3 in
thread
   local Y0 Y1 Y2 Y3 in
      Y0 = X0+1
      Y1 = X1+Y0
      Y2 = X2+Y1
      Y3 = X3+Y2
      {Browse [Y0 Y1 Y2 Y3]}
   end
end
```

# A concurrent map function

- The following function generates a new list by mapping function F to its each element
- Each element is processes in a new thread

```
fun {Map Xs F}
   case Xs
   of nil then nil
   [] X|Xr then thread {F X} end | {Map Xr F}
   end
end
```

# Streams

- Threads can communicate through streams in a producer-consumer way

```
fun {Generator N}
   if N > 0 then N|{Generator N-1}
   else nil end
end
local
   fun {Sum1 L A}
      case L
      of nil then A
      [] X|Xs then {Sum1 Xs A+X}
      end
   end
in fun {Sum L} {Sum1 L 0} end
end
{Browse thread {Sum thread {Generator 100} end} end}
```

# Synchronizing the streams

- In the previous example the communication was asynchronous
- If the producer works faster than the consumer, more and more memory is needed for the buffering
- One way to solve this is to use futures and ByNeed primitive
- ByNeed takes a one-argument procedure as argument and returns a future
- If this future is accessed, the procedure given for ByNeed is used to bind a value to the future

# Example with futures

```
local
   proc {Producer Xs}
      Xr in
      Xs = volvo|{ByNeed {Producer Xr} $}
   end
   proc {Consumer N Xs}
      if N>0 then
         case Xs of X|Xr then
            if X==volvo then
               {Consumer N-1 Xr}
            else {Consumer N Xr} end
         end
      end
   end
in
   {Consumer 1000000 thread {Producer $} end}
end
```

Questions?