Programming Languages (CSCI 4430/6430)

Part 2: Concurrent Programming: Summary

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Overview of concurrent programming

- There are four main approaches:
  - Sequential programming (no concurrency)
  - Declarative concurrency (streams in a functional language)
  - Message passing with active objects (Erlang, SALSA)
  - Atomic actions on shared state (Java, C++)
- The atomic action approach is the *most difficult*, yet it is the one you will probably be most exposed to!
- But, if you have the choice, which approach to use?
  - Use the simplest approach that does the job: sequential if that is ok, else declarative concurrency if there is no observable nondeterminism, otherwise use actors and message passing.

Actors/SALSA

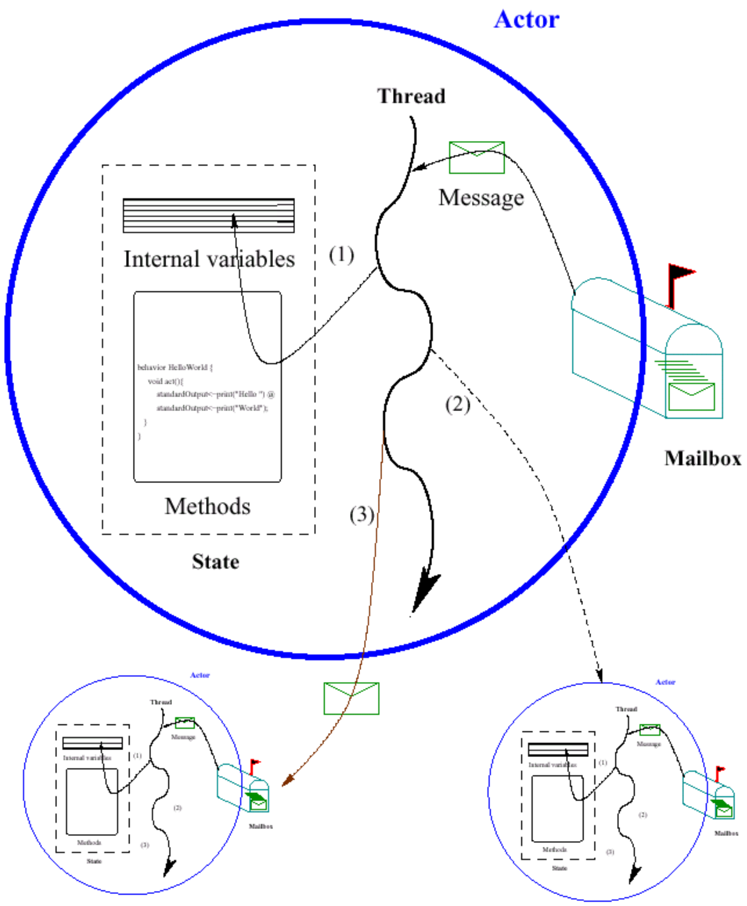
- Actor Model
  - A reasoning framework to model concurrent computations
  - Programming abstractions for distributed open systems

  G. Agha, *Actors: A Model of Concurrent Computation in Distributed Systems.* MIT Press, 1986.

  Agha, Mason, Smith and Talcott, "A Foundation for Actor Computation", *J. of Functional Programming*, 7, 1-72, 1997.

- SALSA
  - Simple Actor Language System and Architecture
  - An actor-oriented language for mobile and internet computing
  - Programming abstractions for internet-based concurrency, distribution, mobility, and coordination

  C. Varela and G. Agha, "Programming dynamically reconfigurable open systems with SALSA", *ACM SIGPLAN Notices, OOPSLA 2001,* 36(12), pp 20-34.



```
behavior HelloWorld {
    void act(){
        standardOutput<-print("Hello ") @
        standardOutput<-print("World");
    }
}
```

Agha, Mason, Smith & Talcott

1. Extend a functional language (call-by-value λ calculus + `if`s and `pair`s) with actor primitives.

2. Define an operational semantics for actor configurations.

3. Study various notions of equivalence of actor expressions and configurations.

4. Assume fairness:
   - Guaranteed message delivery.
   - Individual actor progress.

λ-Calculus as a Model for Sequential Computation

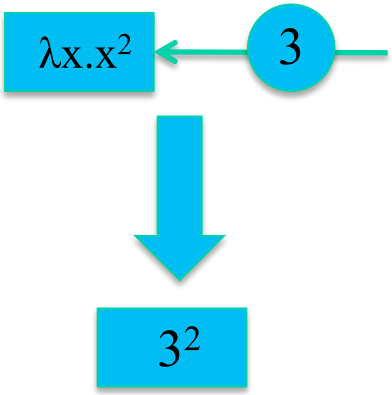
Syntax:

e	::=	v	*variable*
	|	λv.e	*function*
	|	e(e)	*application*

Example of beta-reduction:

$$\lambda x.x^2(3)$$

$$\longrightarrow \quad x^2\{3/x\}$$



Actor Primitives

- `send(a,v)`
  - Sends value ***v*** to actor ***a***.
- `new(b)`
  - Creates a new actor with behavior ***b*** (a λ-calculus functional abstraction) and returns the identity/name of the newly created actor.
- `ready(b)`
  - Becomes ready to receive a new message with behavior ***b***.

AMST Actor Language Examples

```
b5 = rec(λy.λx.seq(send(x,5),ready(y)))
```

receives an actor name ***x*** and sends the number 5 to that actor, then it becomes ready to process new messages with the same behavior ***y*** ***(b5)***.

Sample usage:

```
send(new(b5), a)
```

A *sink,* an actor that disregards all messages:

```
sink = rec(λb.λm.ready(b))
```

Reference Cell

```
cell =
rec(λb.λc.λm.if(get?(m),
                seq(send(cust(m),c),
                    ready(b(c))),
                if(set?(m),
                   ready(b(contents(m))),
                   ready(b(c)))))
```

Using the cell:

```
let a = new(cell(0)) in seq(send(a,mkset(7)),
                            send(a,mkset(2)),
                            send(a,mkget(c)))
```

Join Continuations

Consider:

```
treeprod = rec(λf.λtree.
                if(isnat(tree),
                   tree,
                   f(left(tree))*f(right(tree))))
```

which multiplies all leaves of a tree, which are numbers.

You can do the “left” and “right” computations concurrently.

Tree Product Behavior

```
$B_{treeprod}$ =
  rec(λb.λm.
      seq(if(isnat(tree(m)),
             send(cust(m),tree(m)),
             let newcust=new($B_{joincont}$(cust(m))),
                  lp = new($B_{treeprod}$),
                  rp = new($B_{treeprod}$) in
             seq(send(lp,
                  pr(left(tree(m)),newcust)),
                 send(rp,
                  pr(right(tree(m)),newcust)))),
          ready(b)))
```

Tree Product (continued)

```
B_joincont =
  λcust.λfirstnum.ready(λnum.
                 seq(send(cust,firstnum*num),
                                 ready(sink)))
```

Operational Semantics of AMST Actor Language

- Operational semantics of actor language as a labeled transition relationship between actor configurations:

$$\mathbf{k_1} \xrightarrow{\textbf{[label]}} \mathbf{k_2}$$

- Actor configurations model open system components:
  - Set of individually named actors
  - Messages "en-route"

Actor Configurations

$$\mathbf{k} = \boldsymbol{\alpha} \parallel \boldsymbol{\mu}$$

$\boldsymbol{\alpha}$ is a function mapping actor names (represented as free variables) to actor states.

$\boldsymbol{\mu}$ is a multi-set of messages "en-route."

Labeled Transition Relation

$$\frac{e \to_{\lambda} e'}{\alpha, [\mathsf{R} \blacktriangleright e \blacktriangleleft]_a \parallel \mu \xrightarrow{[\mathbf{fun}:a]} \alpha, [\mathsf{R} \blacktriangleright e' \blacktriangleleft]_a \parallel \mu}$$

$$\alpha, [\mathsf{R} \blacktriangleright \mathtt{new}(b) \blacktriangleleft]_a \parallel \mu \xrightarrow{[\mathbf{new}:a,a']} \alpha, [\mathsf{R} \blacktriangleright a' \blacktriangleleft]_a, [\mathtt{ready}(b)]_{a'} \parallel \mu$$

a' *fresh*

$$\alpha, [\mathsf{R} \blacktriangleright \mathtt{send}(a', v) \blacktriangleleft]_a \parallel \mu \xrightarrow{[\mathbf{snd}:a]} \alpha, [\mathsf{R} \blacktriangleright \mathtt{nil} \blacktriangleleft]_a \parallel \mu \uplus \{\langle a' \Leftarrow v \rangle\}$$

$$\alpha, [\mathsf{R} \blacktriangleright \mathtt{ready}(b) \blacktriangleleft]_a \parallel \{\langle a \Leftarrow v \rangle\} \uplus \mu \xrightarrow{[\mathbf{rcv}:a,v]} \alpha, [b(v)]_a \parallel \mu$$

Semantics example summary

$$k_0 = [\texttt{send(new(b5),a)}]_a \parallel \{\}$$

$$k_6 = [\texttt{nil}]_a, [\texttt{ready(b5)}]_b \parallel \{< a \texttt{<=} 5 >\}$$

$$\mathbf{k}_0 \xrightarrow{[\mathbf{new}:a,b]} \mathbf{k}_1 \xrightarrow{[\mathbf{snd}:a]} \mathbf{k}_2 \xrightarrow{[\mathbf{rcv}:b,a]} \mathbf{k}_3 \xrightarrow{[\mathbf{fun}:b]} \mathbf{k}_4$$

$$\mathbf{k}_4 \xrightarrow{[\mathbf{snd}:a,5]} \mathbf{k}_5 \xrightarrow{[\mathbf{fun}:b]} \mathbf{k}_6$$

This sequence of (labeled) transitions from $\mathbf{k}_0$ to $\mathbf{k}_6$ is called a *computation sequence*.

Asynchronous communication

$$\begin{aligned} k_0 = {} & [\mathtt{ready(cell(0))}]_a \\ & \parallel \{<a<=s(7)>,\ <a<=s(2)>,\ <a<=g(c)>\} \end{aligned}$$

Three receive transitions are enabled at k_0.

Multiple enabled transitions can lead to *nondeterministic* behavior

$$\mathbf{k_0} \xrightarrow{[\mathbf{rcv}:a,s(7)]} \mathbf{k_1}$$

$$\mathbf{k_0} \xrightarrow{[\mathbf{rcv}:a,s(2)]} \mathbf{k_1}'$$

$$\mathbf{k_0} \xrightarrow{[\mathbf{rcv}:a,g(c)]} \mathbf{k_1}''$$

The set of all computations sequences from $\mathbf{k_0}$ is called the *computation tree* $\tau(\mathbf{k_0})$.

Nondeterministic behavior (1)

$$k_0 = [\mathtt{ready(cell(0))}]_a$$
$$\quad \| \ \{\langle a \Leftarrow s(7)\rangle,\ \langle a \Leftarrow s(2)\rangle,\ \langle a \Leftarrow g(c)\rangle\}$$

$$k_1 \rightarrow^* [\mathtt{ready(cell(7))}]_a$$
$$\quad \| \ \{\langle a \Leftarrow s(2)\rangle,\ \langle a \Leftarrow g(c)\rangle\}$$

Customer **c** will get **2** or **7**.

$$k_1' \rightarrow^* [\mathtt{ready(cell(2))}]_a$$
$$\quad \| \ \{\langle a \Leftarrow s(7)\rangle,\ \langle a \Leftarrow g(c)\rangle\}$$

$$k_1'' \rightarrow^* [\mathtt{ready(cell(0))}]_a$$
$$\quad \| \ \{\langle a \Leftarrow s(7)\rangle,\ \langle a \Leftarrow s(2)\rangle,\ \langle c \Leftarrow 0\rangle\}$$

Customer **c** will get **0**.

Nondeterministic behavior (2)

$$\begin{aligned} \mathtt{k}_0 &= \mathtt{[ready(cell(0))]}_{\mathtt{a}} \\ &\quad \| \ \{\langle a \Leftarrow s(7) \rangle,\ \langle a \Leftarrow s(2) \rangle,\ \langle a \Leftarrow g(c) \rangle\} \end{aligned}$$

Order of three receive transitions determines final state, e.g.:

$$\mathbf{k}_0 \xrightarrow{[\mathbf{rcv}:a,g(c)]} \mathbf{k}_1 \rightarrow^* \xrightarrow{[\mathbf{rcv}:a,s(7)]} \mathbf{k}_2 \rightarrow^* \xrightarrow{[\mathbf{rcv}:a,s(2)]} \mathbf{k}_3$$

$$\mathtt{k}_f = \mathtt{[ready(cell(2))]}_{\mathtt{a}} \ \| \ \{\langle c \Leftarrow 0 \rangle\}$$

Final cell state is 2.

Nondeterministic behavior (3)

$$k_0 = [\mathtt{ready(cell(0))}]_a \\ \quad \| \; \{\langle a \Leftarrow s(7)\rangle, \langle a \Leftarrow s(2)\rangle, \langle a \Leftarrow g(c)\rangle\}$$

Order of three receive transitions determines final state, e.g.:

$$\mathbf{k_0} \xrightarrow{[\mathbf{rcv}:a,s(2)]} \mathbf{k_1} \to^{*} \xrightarrow{[\mathbf{rcv}:a,g(c)]} \mathbf{k_2} \to^{*} \xrightarrow{[\mathbf{rcv}:a,s(7)]} \mathbf{k_3}$$

$$k_f = [\mathtt{ready(cell(7))}]_a \; \| \; \{\langle c \Leftarrow 2\rangle\}$$

Final cell state is 7.

Erlang support for Actors

- Actors in Erlang are modeled as *processes*. Processes start by executing an arbitrary *function*. Related functions are grouped into *modules*.

- Messages can be any Erlang *terms*, *e.g.*, atoms, tuples (fixed arity), or lists (variable arity). Messages are sent asynchronously.

- State is modeled implicitly with function arguments. Actors explicitly call receive to get a message, and must use tail-recursion to get new messages, *i.e.*, control loop is explicit.

Reference Cell in Erlang

```
-module(cell).
-export([cell/1]).

cell(Content) ->
  receive
    {set, NewContent} -> cell(NewContent);
    {get, Customer}   -> Customer ! Content,
                         cell(Content)
  end.
```

Encapsulated state **`Content`.**

State change.

Message handlers

Explicit control loop: Actions at the end of a message need to include tail-recursive function call. Otherwise actor (process) terminates.

Reference Cell in Erlang

```
-module(cell).
-export([cell/1]).

cell(Content) ->
  receive
    {set, NewContent} -> cell(NewContent);
    {get, Customer}   -> Customer ! Content,
                         cell(Content)
  end.
```

`Content` is an argument to the `cell` function.

`{set, NewContent}` is a tuple *pattern*. `set` is an atom. `NewContent` is a variable.

Messages are checked one by one, and for each message, first pattern that applies gets its actions (after ->) executed. If no pattern matches, messages remain in actor’s mailbox.

Cell Tester in Erlang

```
-module(cellTester).
-export([main/0]).

main() -> C = spawn(cell,cell,[0]),
          C!{set,7},
          C!{set,2},
          C!{get,self()},
          receive
             Value ->
                io:format("~w~n”,[Value])
          end.
```

Actor creation (**spawn**)

Message passing (**!**)

receive waits until a message is available.

Cell Tester in Erlang

```
-module(cellTester).
-export([main/0]).

main() -> C = spawn(cell,cell,[0]),
          C!{set,7},
          C!{set,2},
          C!{get,self()},
          receive
             Value ->
                io:format("~w~n",[Value])
          end.
```

`[0]` is a *list* with the arguments to the module's function. General form:

`spawn(module, function, arguments)`

`self()` is a *built-in function (BIF)* that returns the process id of the current process.

Function calls take the form:
`module:function(args)`

SALSA support for Actors

- Programmers define *behaviors* for actors. Actors are instances of behaviors.

- Messages are modeled as potential method invocations. Messages are sent asynchronously.

- State is modeled as encapsulated objects/primitive types.

- Tokens represent future message return values. Continuation primitives are used for coordination.

Reference Cell Example

```
module cell;

behavior Cell {
   Object content;

   Cell(Object initialContent) {
         content = initialContent;
    }

   Object get() { return content; }

   void set(Object newContent) {
       content = newContent;
   }
}
```

Encapsulated state `content`.

Actor constructor.

Message handlers.

State change.

Reference Cell Example

```
module cell;

behavior Cell {
   Object content;

   Cell(Object initialContent) {
         content = initialContent;
   }

   Object get() { return content; }

   void set(Object newContent) {
       content = newContent;
   }
}
```

return asynchronously sets **token** associated to **get** message.

Implicit control loop: End of message implies ready to receive next message.

Cell Tester Example

```
module cell;

behavior CellTester {

    void act( String[] args ) {

        Cell c = new Cell(0);
        c <- set(7);
        c <- set(2);
        token t = c <- get();
        standardOutput <- println( t );
    }
}
```

Actor creation (`new`)

Message passing (`<-`)

`println` message can only be processed when *token* `t` from `c's get()` message handler has been produced.

Cell Tester Example

```
module cell;

behavior CellTester {

   void act( String[] args ) {

        Cell c = new Cell(0);
        c <- set(7);
        c <- set(2);
        token t = c <- get();
        standardOutput <- println( t );
   }
}
```

All message passing is asynchronous.

`println` message is called *partial* until *token* `t` is produced. Only *full* messages (with no pending tokens) are delivered to actors.

Tree Product Behavior in Erlang

```
-module(treeprod).
-export([treeprod/0,join/1]).

treeprod() ->
  receive
    {{Left, Right}, Customer} ->
       NewCust = spawn(treeprod,join,[Customer]),
       LP = spawn(treeprod,treeprod,[]),
       RP = spawn(treeprod,treeprod,[]),
       LP!{Left,NewCust},
       RP!{Right,NewCust};
    {Number, Customer} ->
       Customer ! Number
  end,
  treeprod().

join(Customer) -> receive V1 -> receive V2 -> Customer ! V1*V2 end end.
```

Tree Product Sample Execution

```
2> TP = spawn(treeprod,treeprod,[]).
<0.40.0>
3> TP ! {{{{5,6},2},{3,4}},self()}.
{{{{5,6},2},{3,4}},<0.33.0>}
4> flush().
Shell got 720
ok
5>
```

Tree Product Behavior in SALSA

This code uses token-passing continuations (`@`,`token`), a join block (`join`), and a first-class continuation (`currentContinuation`).

```
module treeprod;
import tree.Tree;

behavior TreeProduct {

    int multiply(Object[] results){
      return (Integer) results[0] * (Integer) results[1];
    }
    int compute(Tree t){
      if (t.isLeaf()) return t.value();
      else {
        TreeProduct lp = new TreeProduct();
        TreeProduct rp = new TreeProduct();
        join {
          lp <- compute(t.left());
          rp <- compute(t.right());
        } @ multiply(token) @ currentContinuation;
      }
    }
}
```

Tree Product Tester

```
module treeprod;
import tree.Tree;

behavior TreeProductTester {

    void act( String[] args ) {
        Tree t = new Tree(new Tree(new Tree(5,6),new Tree(2)),
                          new Tree(3,4));
        TreeProduct tp = new TreeProduct();
        tp <- compute(t) @ standardOutput <- println(token);
    }
}
```

```
Use as follows:
% javac tree/Tree.java
% salsac treeprod/*
% salsa treeprod/TreeProductTester
720
```

Actor Languages Summary

- Actors are concurrent entities that react to messages.
  - State is completely encapsulated. There is no shared memory!
  - Message passing is asynchronous.
  - Actor run-time has to ensure fairness.
- AMST extends the call by value lambda calculus with actor primitives. State is modeled as function arguments. Actors use `ready` to receive new messages.
- Erlang extends a functional programming language core with processes that run arbitrary functions. State is implicit in the function's arguments. Control loop is explicit: actors use `receive` to get a message, and tail-form recursive call to continue.
- SALSA extends an object-oriented programming language (Java) with universal actors. State is encapsulated in instance variables. Control loop is implicit: ending a message handler, signals readiness to receive a new message.

Concurrency Control in SALSA

- SALSA provides three main coordination constructs:
  - Token-passing continuations
    - To synchronize concurrent activities
    - To notify completion of message processing
    - Named tokens enable arbitrary synchronization (data-flow)
  - Join blocks
    - Used for barrier synchronization for multiple concurrent activities
    - To obtain results from otherwise independent concurrent processes
  - First-class continuations
    - To delegate producing a result to another message, or actor

Token Passing Continuations

- Ensures that each message in the continuation expression is sent after the previous message has been **processed**. It also enables the use of a message handler return value as an argument for a later message (through the token keyword).

  - Example:

```
a1 <- m1() @
a2 <- m2( token );
```

Send `m1` to `a1` asking `a1` to forward the result of processing `m1` to `a2` (as the argument of message `m2`).

Token Passing Continuations

- `@` syntax using `token` as an argument is syntactic sugar.
  - Example 1:

```
a1 <- m1() @
a2 <- m2( token );
```

is syntactic sugar for:

```
token t = a1 <- m1();
a2 <- m2( t );
```

  - Example 2:

```
a1 <- m1() @
a2 <- m2();
```

is syntactic sugar for:

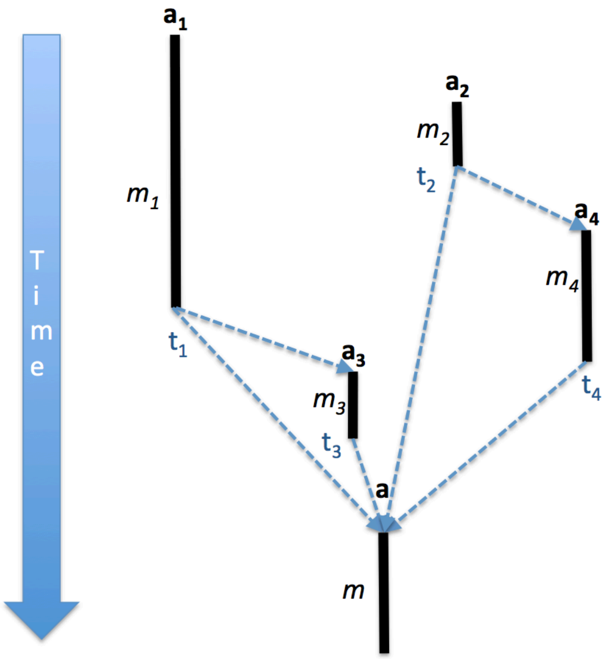
```
token t = a1 <- m1();
a2 <- m2():waitfor( t );
```

Named Tokens

- Tokens can be named to enable more loosely-coupled synchronization
  - Example:

```
token t1 = a1 <- m1();
token t2 = a2 <- m2();
token t3 = a3 <- m3( t1 );
token t4 = a4 <- m4( t2 );
a <- m(t1,t2,t3,t4);
```

Sending `m(…)` *to* `a` *will be delayed until messages* `m1()..m4()` *have been processed.* `m1()` *can proceed concurrently with* `m2()`.



Join Blocks

- Provide a mechanism for synchronizing the processing of a set of messages.
- Set of results is sent along as a *token* containing an array of results.
  - Example:

```
UniversalActor[] actors = { searcher0, searcher1,
                            searcher2, searcher3 };
join {
  for (int i=0; i < actors.length; i++){
     actors[i] <- find( phrase );
  }
} @ resultActor <- output( token );
```

Send the `find( phrase )` *message to each actor in* `actors[]` *then after all have completed send the result to* `resultActor` *as the argument of an* `output( … )` *message.*

First Class Continuations

- Enable actors to delegate computation to a third party independently of the processing context.

- For example:

```
int m(…){
    b <- n(…) @ currentContinuation;
}
```

Ask (delegate) actor `b` *to respond to this message* `m` *on behalf of current actor (*`self`*) by processing* `b`*'s message* `n`*.*

Delegate Example

`fib(15)`

is syntactic sugar for:

`self <- fib(15)`

```
module fibonacci;

behavior Calculator {

   int fib(int n) {
        Fibonacci f = new Fibonacci(n);
        f <- compute() @ currentContinuation;
   }
   int add(int n1, int n2) {return n1+n2;}

   void act(String args[]) {
        fib(15) @ standardOutput <- println(token);
        fib(5) @ add(token,3) @
        standardOutput <- println(token);
   }
}
```

Fibonacci Example

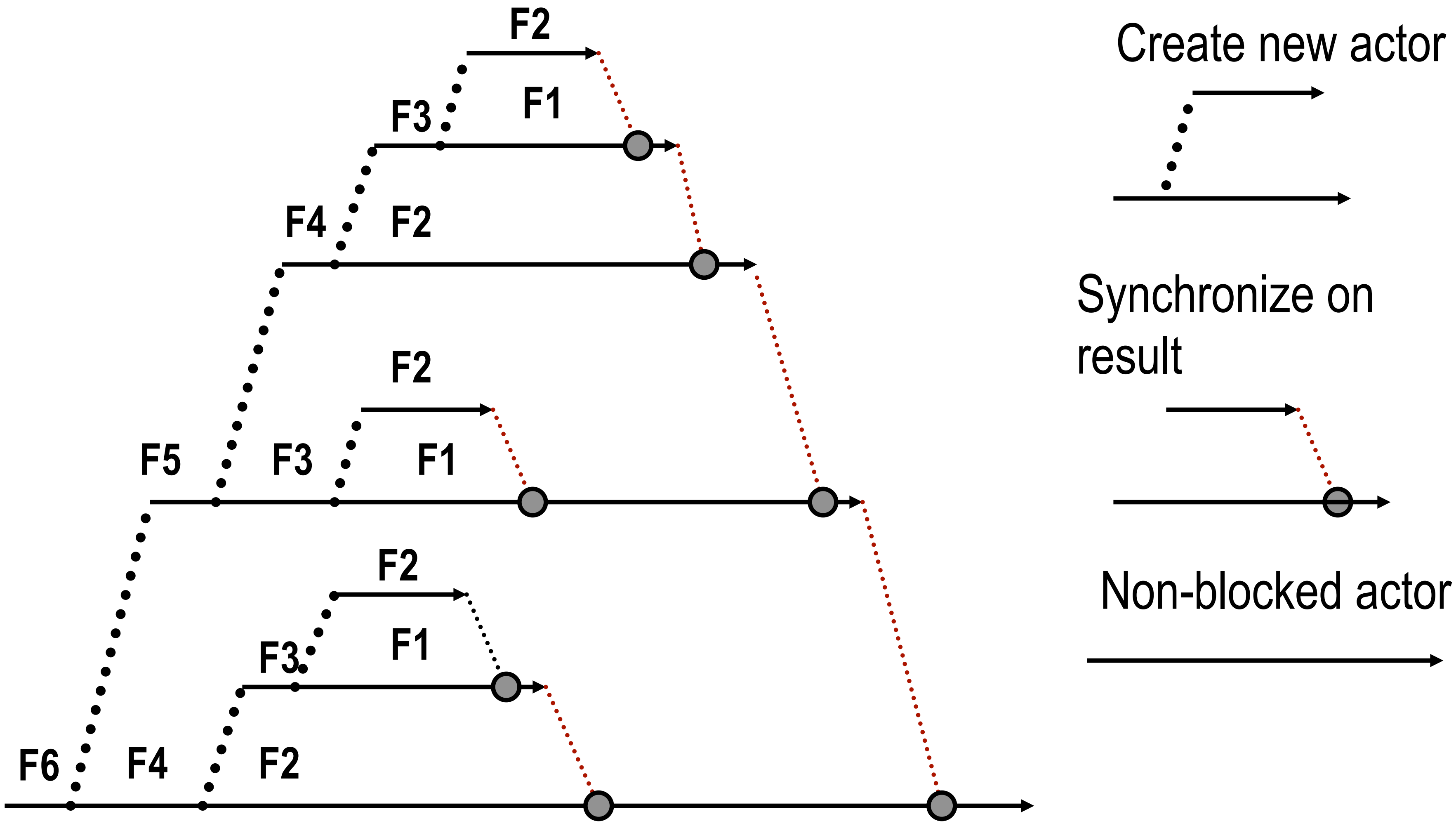
```
module fibonacci;

behavior Fibonacci {
    int n;

    Fibonacci(int n)          { this.n = n; }

    int add(int x, int y) { return x + y; }

    int compute() {
          if (n == 0)         return 0;
          else if (n <= 2)    return 1;
          else {
                    Fibonacci fib1 = new Fibonacci(n-1);
                    Fibonacci fib2 = new Fibonacci(n-2);
                    token x = fib1<-compute();
                    token y = fib2<-compute();
                    add(x,y) @ currentContinuation;
          }
    }

    void act(String args[]) {
          n = Integer.parseInt(args[0]);
          compute() @ standardOutput<-println(token);
    }
}
```

Fibonacci Example 2

```
module fibonacci2;

behavior Fibonacci {

   int add(int x, int y) { return x + y; }

   int compute(int n) {
        if (n == 0)       return 0;
        else if (n <= 2) return 1;
        else {
                Fibonacci fib = new Fibonacci();
                token x = fib <- compute(n-1);
                compute(n-2) @ add(x,token) @ currentContinuation;
        }
   }

   void act(String args[]) {
        int n = Integer.parseInt(args[0]);
        compute(n) @ standardOutput<-println(token);
   }
}
```

`compute(n-2)` is a message to `self`.

Execution of `salsa Fibonacci 6`



Create new actor

Synchronize on result

Non-blocked actor

Concurrency control in Erlang

- Erlang uses a *selective receive* mechanism to help coordinate concurrent activities:
  - Message patterns and guards
    - To select the next message (from possibly many) to execute.
    - To receive messages from a specific process (actor).
    - To receive messages of a specific kind (pattern).
  - Timeouts
    - To enable default activities to fire in the absence of messages (following certain patterns).
    - To create timers.
  - Zero timeouts (`after 0`)
    - To implement priority messages, to flush a mailbox.

Selective Receive

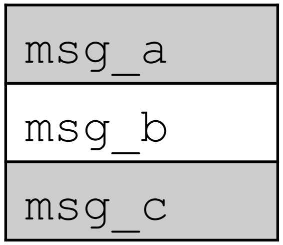
```
receive
    MessagePattern1 [when Guard1] ->
       Actions1 ;
    MessagePattern2 [when Guard2] ->
       Actions2 ;
    …
end
```

`receive` suspends until a message in the actor's mailbox matches any of the patterns including optional guards.

- Patterns are tried in order. On a match, the message is removed from the mailbox and the corresponding pattern's actions are executed.
- When a message does not match any of the patterns, it is left in the mailbox for future `receive` actions.

Selective Receive Example

Example program and mailbox (head at top):



msg_a

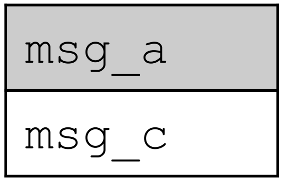
msg_b

msg_c

```
receive
    msg_b -> …
end
```

`receive` tries to match `msg_a` and fails. `msg_b` can be matched, so it is processed. Suppose execution continues:

```
receive
    msg_c -> …
    msg_a -> …
end
```



msg_a

msg_c

The next message to be processed is `msg_a` since it is the next in the mailbox and it matches the 2nd pattern.

Receiving from a specific actor

```
Actor ! {self(), message}
```

`self()` is a Built-In-Function (BIF) that returns the current (executing) process id (actor name). Ids can be part of a message.

```
receive
    {ActorName, Msg} when ActorName == A1 ->
        …
end
```

`receive` can then select only messages that come from a specific actor, in this example, `A1`. (Or other actors that know A1's actor name.)

Receiving a specific kind of message

```
counter(Val) ->
  receive
    increment -> counter(Val+1);
    {From,get} ->
      From ! {self(), Val},
      counter(Val);
    stop -> true;
    Other -> counter(Val)
  end.
```

`increment` is an atom whereas `Other` is a variable (that matches anything!).

`counter` is a behavior that can receive `increment` messages, `get` request messages, and `stop` messages. `Other` message kinds are ignored.

Order of message patterns matters

```
receive
    {{Left, Right}, Customer} ->
       NewCust = spawn(treeprod,join,[Customer]),
       LP = spawn(treeprod,treeprod,[]),
       RP = spawn(treeprod,treeprod,[]),
       LP!{Left,NewCust},
       RP!{Right,NewCust};
    {Number, Customer} ->
       Customer ! Number
end
```

`{Left,Right}` is a more specific pattern than `Number` is (which matches anything!). Order of patterns is important.

In this example, a binary tree is represented as a tuple `{Left, Right}`, or as a `Number`, e.g.,

`{{{5,6},2},{3,4}}`

Selective Receive with Timeout

```
receive
    MessagePattern1 [when Guard1] ->
       Actions1 ;
    MessagePattern2 [when Guard2] ->
       Actions2 ;
    …
    after TimeOutExpr ->
       ActionsT
end
```

`TimeOutExpr` evaluates to an integer interpreted as *milliseconds.*

If no message has been selected within this time, the timeout occurs and `ActionsT` are scheduled for evaluation.

A timeout of `infinity` means to wait indefinitely.

Timer Example

```
sleep(Time) ->
         receive
             after Time ->
                 true
         end.
```

`sleep(Time)` suspends the current actor for `Time` milliseconds.

Timeout Example

```
receive
    click ->
       receive
           click ->
             double_click
       after double_click_interval() ->
             single_click
       end
    ...
end
```

`double_click_interval` evaluates to the number of milliseconds expected between two consecutive mouse clicks, for the receive to return a `double_click`. Otherwise, a `single_click` is returned.

Zero Timeout

```
receive
    MessagePattern1 [when Guard1] ->
       Actions1 ;
    MessagePattern2 [when Guard2] ->
       Actions2 ;
    …
    after 0 ->
       ActionsT
end
```

A timeout of 0 means that the timeout will occur immediately, but Erlang tries all messages currently in the mailbox first.

Zero Timeout Example

```
flush_buffer() ->
       receive
          AnyMessage ->
             flush_buffer()
          after 0 ->
             true
       end.
```

`flush_buffer()` completely empties the mailbox of the current actor.

Priority Messages

```
priority_receive() ->
       receive
          interrupt ->
             interrupt
          after 0 ->
             receive
                AnyMessage ->
                   AnyMessage
             end
       end.
```

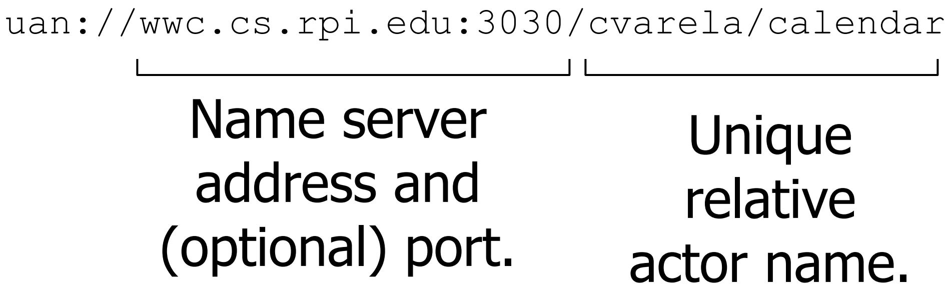
`priority_receive()` will return the first message in the actor’s mailbox, except if there is an `interrupt` message, in which case, `interrupt` will be given priority.

Overview of programming distributed systems

- It is harder than concurrent programming!
- Yet unavoidable in today’s information-oriented society, e.g.:
  - Internet, mobile devices
  - Web services
  - Cloud computing
- Communicating processes with independent address spaces
- Limited network performance
  - Orders of magnitude difference between WAN, LAN, and intra-machine communication.
- Localized heterogeneous resources, e.g, I/O, specialized devices.
- Partial failures, e.g. hardware failures, network disconnection
- Openness: creates security, naming, composability issues.

Universal Actor Names (UAN)

- Consists of *human readable* names.
- Provides location transparency to actors.
- Name to locator mapping updated as actors migrate.
- UAN servers provide mapping between names and locators.
  - Example Universal Actor Name:

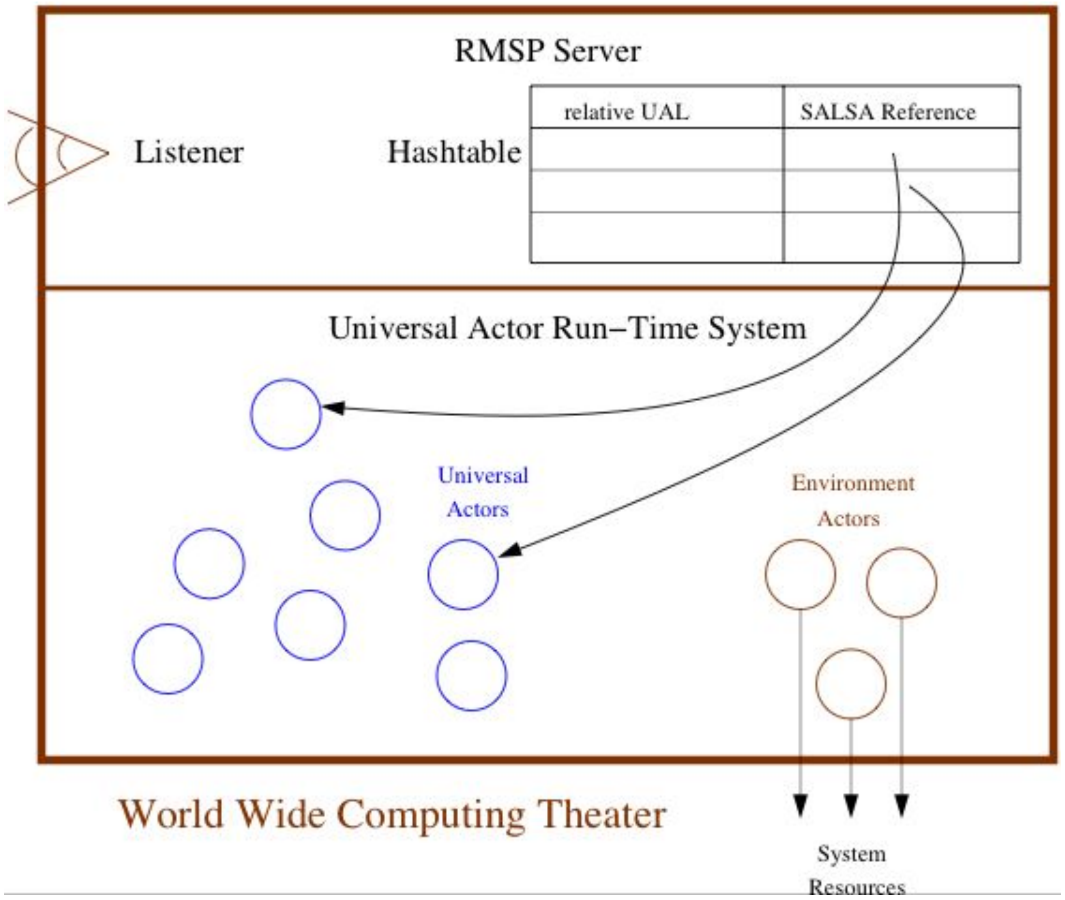


```
uan://wwc.cs.rpi.edu:3030/cvarela/calendar
```

Name server address and (optional) port.

Unique relative actor name.

WWC Theaters



Universal Actor Locators (UAL)

- Theaters provide an execution environment for universal actors.
- Provide a layer beneath actors for message passing and migration.
- When an actor migrates, its UAN remains the same, while its UAL changes to refer to the new theater.
- Example Universal Actor Locator:

$\texttt{rmsp://}\underbrace{\texttt{wwc.cs.rpi.edu:4040}}_{\text{Theater's IP address and (optional) port.}}$

SALSA Language Support for Worldwide Computing

- SALSA provides linguistic abstractions for:
  - Universal naming (UAN & UAL).
  - Remote actor creation.
  - Location-transparent message sending.
  - Migration.
  - Coordination.
- SALSA-compiled code closely tied to WWC run-time platform.

Universal Actor Creation

- To create an actor locally

```
TravelAgent a = new TravelAgent();
```

- To create an actor with a specified UAN and UAL:

```
TravelAgent a = new TravelAgent() at (uan, ual);
```

- To create an actor with a specified UAN at current location:

```
TravelAgent a = new TravelAgent() at (uan);
```

Message Sending

```
TravelAgent a = new TravelAgent();

a <- book( flight );
```

Message sending syntax is the same (<-), independently of actor's location.

Remote Message Sending

- Obtain a remote actor reference by name.

```
TravelAgent a = (TravelAgent)
  TravelAgent.getReferenceByName(“uan://myhost/ta”);

a <- printItinerary();
```

Reference Cell Service Example

```
module dcell;

behavior Cell implements ActorService{

   Object content;

   Cell(Object initialContent) {
         content = initialContent;
   }

   Object get() {
        standardOutput <- println (“Returning: ”+content);
        return content;
   }

   void set(Object newContent) {
        standardOutput <- println (“Setting: ”+newContent);
        content = newContent;
   }
}
```

`implements ActorService` signals that actors with this behavior are not to be garbage collected.

Reference Cell Tester

```
module dcell;

behavior CellTester {

    void act( String[] args ) {

      if (args.length != 2){
         standardError <- println(
              “Usage: salsa dcell.CellTester <UAN> <UAL>”);
         return;
      }

     Cell c = new Cell(0) at (new UAN(args[0]), new UAL(args[1]));

      standardOutput <- print( “Initial Value:” ) @
      c <- get() @ standardOutput <- println( token );
    }
}
```

Reference Cell Client Example

```
module dcell;

behavior GetCellValue {

   void act( String[] args ) {
      if (args.length != 1){
         standardOutput <- println(
            “Usage: salsa dcell.GetCellValue <CellUAN>”);
         return;
      }

      Cell c = (Cell) Cell.getReferenceByName(args[0]);

      standardOutput <- print(“Cell Value:”) @
      c <- get() @
      standardOutput <- println(token);
   }
}
```

Address Book Service

```
module addressbook;
import java.util.*

behavior AddressBook implements ActorService {
   Hashtable name2email;
   AddressBook() {
        name2email = new HashTable();
   }
   String getName(String email) { … }
   String getEmail(String name) { … }
   boolean addUser(String name, String email) { … }

   void act( String[] args ) {
      if (args.length != 0){
        standardOutput<-println("Usage: salsa -Duan=<UAN> -Dual=<UAL>
                                          addressbook.AddressBook");
      }
   }
}
```

Address Book Add User Example

```
module addressbook;

behavior AddUser {
   void act( String[] args ) {
      if (args.length != 3){
         standardOutput<-println(“Usage: salsa
           addressbook.AddUser <AddressBookUAN> <Name> <Email>”);
         return;
      }
      AddressBook book = (AddressBook)
         AddressBook.getReferenceByName(new UAN(args[0]));
      book<-addUser(args(1), args(2));
   }
}
```

Address Book Get Email Example

```
module addressbook;

behavior GetEmail {
    void act( String[] args ) {
      if (args.length != 2){
          standardOutput <- println(“Usage: salsa
            addressbook.GetEmail <AddressBookUAN> <Name>”);
          return;
       }
       getEmail(args(0),args(1));
    }

    void getEmail(String uan, String name){
          try{
             AddressBook book = (AddressBook)
                    AddressBook.getReferenceByName(new UAN(uan));
             standardOutput <- print(name + “’s email: “) @
             book <- getEmail(name) @
             standardOutput <- println(token);
          } catch(MalformedUANException e){
             standardError<-println(e);
          }
    }
}
```

Erlang Language Support for Distributed Computing

- Erlang provides linguistic abstractions for:
  - Registered processes (actors).
  - Remote process (actor) creation.
  - Remote message sending.
  - Process (actor) groups.
  - Error detection.
- Erlang-compiled code closely tied to Erlang *node* run-time platform.

Erlang Nodes

- To return our own node name:

```
node()
```

- To return a list of other known node names:

```
nodes()
```

- To monitor a node:

```
monitor_node(Node, Flag)
```

If `flag` is true, monitoring starts. If false, monitoring stops. When a monitored node fails, `{nodedown, Node}` is sent to monitoring process.

Actor Creation

- To create an actor locally

`travel` is the module name,
`agent` is the function name,
`Agent` is the actor name.

```
Agent = spawn(travel, agent, []);
```

- To create an actor in a specified remote node:

```
Agent = spawn(host, travel, agent, []);
```

`host` is the node name.

Actor Registration

`ta` is the registered name (an atom),
`Agent` is the actor name (PID).

- To register an actor:

```
register(ta, Agent)
```

- To return the actor identified with a registered name:

```
whereis(ta)
```

- To remove the association between an atom and an actor:

```
unregister(ta)
```

Message Sending

```
Agent = spawn(travel, agent, []),
register(ta, Agent)

Agent ! {book, Flight}
ta ! {book, Flight}
```

Message sending syntax is the same (`!`) with actor name (`Agent`) or registered name (`ta`).

Remote Message Sending

- To send a message to a remote registered actor:

```
{ta, host} ! {book, Flight}
```

Reference Cell Service Example

```
-module(dcell).
-export([cell/1,start/1]).

cell(Content) ->
  receive
    {set, NewContent} -> cell(NewContent);
    {get, Customer}   -> Customer ! Content,
                         cell(Content)
  end.

start(Content) ->
  register(dcell, spawn(dcell, cell, [Content]))
```

Reference Cell Tester

```
-module(dcellTester).
-export([main/0]).

main() -> dcell:start(0),
          dcell!{get, self()},
          receive
             Value ->
                io:format(”Initial Value:~w~n”,[Value])
          end.
```

Reference Cell Client Example

```
-module(dcellClient).
-export([getCellValue/1]).

getCellValue(Node) ->
          {dcell, Node}!{get, self()},
          receive
             Value ->
                io:format(”Initial Value:~w~n”,[Value])
          end.
```

Address Book Service

```
-module(addressbook).
-export([start/0,addressbook/1]).

start() ->
    register(addressbook, spawn(addressbook, addressbook, [[]])).

addressbook(Data) ->
  receive
    {From, {addUser, Name, Email}} ->
       From ! {addressbook, ok},
       addressbook(add(Name, Email, Data));
    {From, {getName, Email}} ->
       From ! {addressbook, getname(Email, Data)},
       addressbook(Data);
    {From, {getEmail, Name}} ->
       From ! {addressbook, getemail(Name, Data)},
       addressbook(Data)
  end.

add(Name, Email, Data) -> …
getname(Email, Data) -> …
getemail(Name, Data) -> …
```

Address Book Client Example

```
-module(addressbook_client).
-export([getEmail/1,getName/1,addUser/2]).

addressbook_server() -> 'addressbook@127.0.0.1'.

getEmail(Name) -> call_addressbook({getEmail, Name}).
getName(Email) -> call_addressbook({getName, Email}).
addUser(Name, Email) -> call_addressbook({addUser, Name, Email}).

call_addressbook(Msg) ->
    AddressBookServer = addressbook_server(),
    monitor_node(AddressBookServer, true),
    {addressbook, AddressBookServer} ! {self(), Msg},
    receive
       {addressbook, Reply} ->
           monitor_node(AddressBookServer, false),
           Reply;
       {nodedown, AddressBookServer} ->
           no
    end.
```

Advanced Features of Actor Languages

- SALSA and Erlang support the basic primitives of the actor model:
  - Actors can create new actors.
  - Message passing is asynchronous.
  - State is encapsulated.
  - Run-time ensures fairness.
- SALSA also introduces advanced coordination abstractions: tokens, join blocks, and first-class continuations; SALSA supports distributed systems development including actor mobility and garbage collection. Research projects have also investigated load balancing, malleability (IOS), scalability (COS), and visualization (OverView).
- Erlang introduces a selective receive abstraction to enforce different orders of message delivery, including a timeout mechanism to bypass blocking behavior of `receive` primitive. Erlang also provides error handling abstractions at the language level, and dynamic (hot) code loading capabilities.

Moving Cell Tester Example

```
module dcell;

behavior MovingCellTester {

    void act( String[] args ) {

     if (args.length != 3){
         standardError <- println(“Usage:
           salsa dcell.MovingCellTester <UAN> <UAL1> <UAL2>”);
         return;
     }

     Cell c = new Cell(“Hello”) at (new UAN(args[0]), new UAL(args[1]));

     standardOutput <- print( ”Initial Value:” ) @
     c <- get() @ standardOutput <- println( token ) @
     c <- set(“World”) @
     standardOutput <- print( ”New Value:” ) @
     c <- get() @ standardOutput <- println( token ) @
     c <- migrate(args[2]) @
     c <- set(“New World”) @
     standardOutput <- print( ”New Value at New Location:” ) @
     c <- get() @ standardOutput <- println( token );
   }
}
```

Address Book Migrate Example

```
module addressbook;

behavior MigrateBook {
   void act( String[] args ) {
      if (args.length != 2){
        standardOutput<-println(“Usage: salsa
          addressbook.MigrateBook <AddressBookUAN> <NewUAL>”);
        return;
      }
      AddressBook book = (AddressBook)
        AddressBook.getReferenceByName(new UAN(args[0]));
      book<-migrate(args(1));
   }
}
```

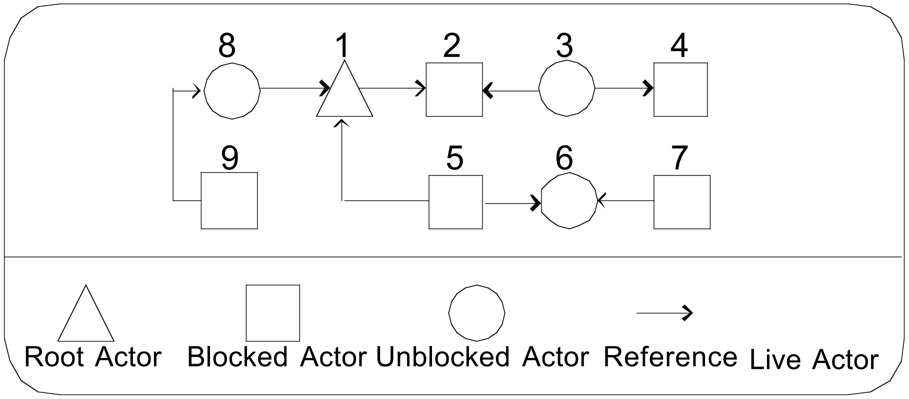
Actor Garbage Collection

- Implemented since SALSA 1.0 using *pseudo-root* approach.
- Includes distributed cyclic garbage collection.
- For more details, please see:

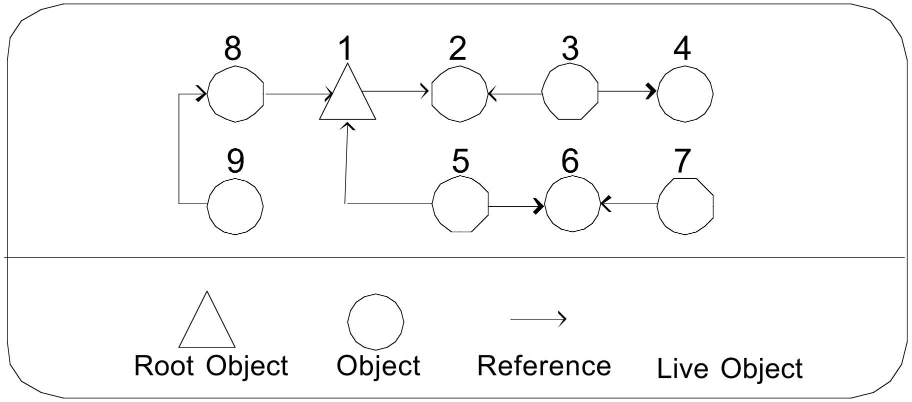
Wei-Jen Wang and Carlos A. Varela. Distributed Garbage Collection for Mobile Actor Systems: The Pseudo Root Approach. In *Proceedings of the First International Conference on Grid and Pervasive Computing (GPC 2006),* Taichung, Taiwan, May 2006. Springer-Verlag LNCS.

Wei-Jen Wang, Carlos Varela, Fu-Hau Hsu, and Cheng-Hsien Tang. Actor Garbage Collection Using Vertex-Preserving Actor-to-Object Graph Transformations. In *Advances in Grid and Pervasive Computing*, volume 6104 of *Lecture Notes in Computer Science*, Bologna, pages 244-255, May 2010. Springer Berlin / Heidelberg.

Actor GC vs. Object GC



Actor Reference Graph



Passive Object Reference Graph

IOS: Load Balancing and Malleability

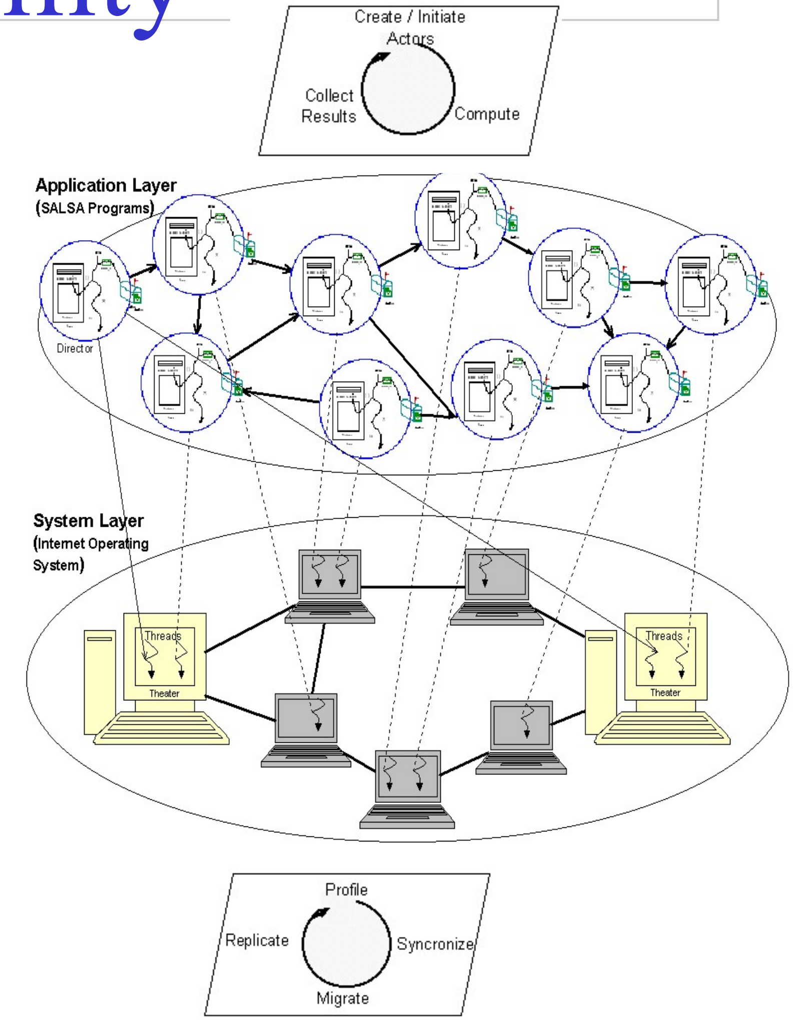
- Middleware
  - A software layer between distributed applications and operating systems.
  - Alleviates application programmers from directly dealing with distribution issues
    - Heterogeneous hardware/O.S.s
    - Load balancing
    - Fault-tolerance
    - Security
    - Quality of service

- Internet Operating System (IOS)
  - A decentralized framework for adaptive, scalable execution
  - Modular architecture to evaluate different distribution and reconfiguration strategies

K. El Maghraoui, T. Desell, B. Szymanski, and C. Varela, "The Internet Operating System: Middleware for Adaptive Distributed Computing", ***International Journal of High Performance Computing and Applications***, 2006.

K. El Maghraoui, T. Desell, B. Szymanski, J. Teresco and C. Varela, "Towards a Middleware Framework for Dynamically Reconfigurable Scientific Computing", ***Grid Computing and New Frontiers of High Performance Processing***, Elsevier 2005.

T. Desell, K. El Maghraoui, and C. Varela, "*Load Balancing of Autonomous Actors over Dynamic Networks*", HICSS-37 Software Technology Track, Hawaii, January 2004. 10pp.



Component Malleability

- New type of reconfiguration:
  - Applications can dynamically change component granularity
- Malleability can provide many benefits for HPC applications:
  - Can more adequately reconfigure applications in response to a dynamically changing environment:
    - Can scale application in response to dynamically joining resources to improve performance.
    - Can provide soft fault-tolerance in response to dynamically leaving resources.
  - Can be used to find the ideal granularity for different architectures.
  - Easier programming of concurrent applications, as parallelism can be provided transparently.

Component Malleability

- Modifying application component granularity dynamically (at run-time) to improve scalability and performance.
- SALSA-based malleable actor implementation.
- MPI-based malleable process implementation.
- IOS decision module to trigger split and merge reconfiguration.
- For more details, please see:

El Maghraoui, Desell, Szymanski and Varela,"Dynamic Malleability in MPI Applications", *CCGrid 2007*, Rio de Janeiro, Brazil, May 2007, **nominated for Best Paper Award**.

Distributed Systems Visualization

- Generic online Java-based distributed systems visualization tool
- Uses a declarative Entity Specification Language (ESL)
- Instruments byte-code to send events to visualization layer.
- For more details, please see:

T. Desell, H. Iyer, A. Stephens, and C. Varela. OverView: A Framework for Generic Online Visualization of Distributed Systems. In *Proceedings of the European Joint Conferences on Theory and Practice of Software (ETAPS 2004), eclipse Technology eXchange (eTX) Workshop*, Barcelona, Spain, March 2004.

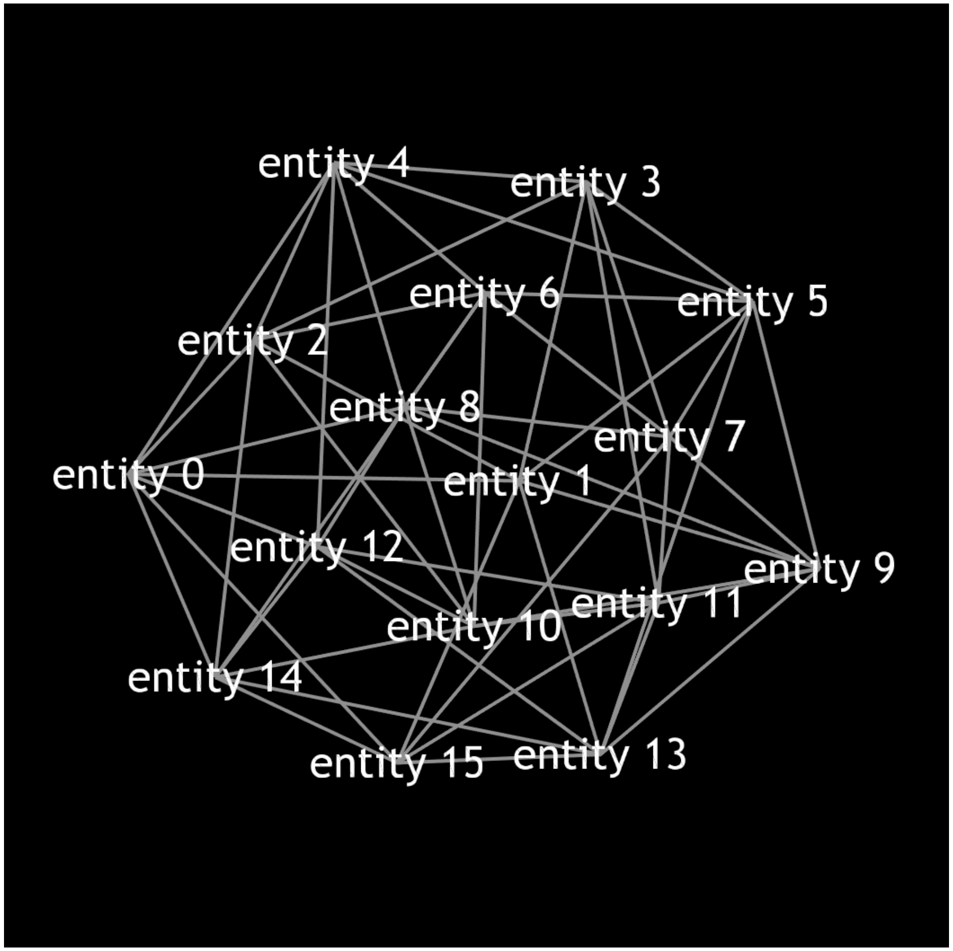
Gustavo A. Guevara S., Travis Desell, Jason Laporte, and Carlos A. Varela. Modular Visualization of Distributed Systems. *CLEI Electronic Journal*, 14:1-17, April 2011. Note: **Best papers from CLEI 2010.**

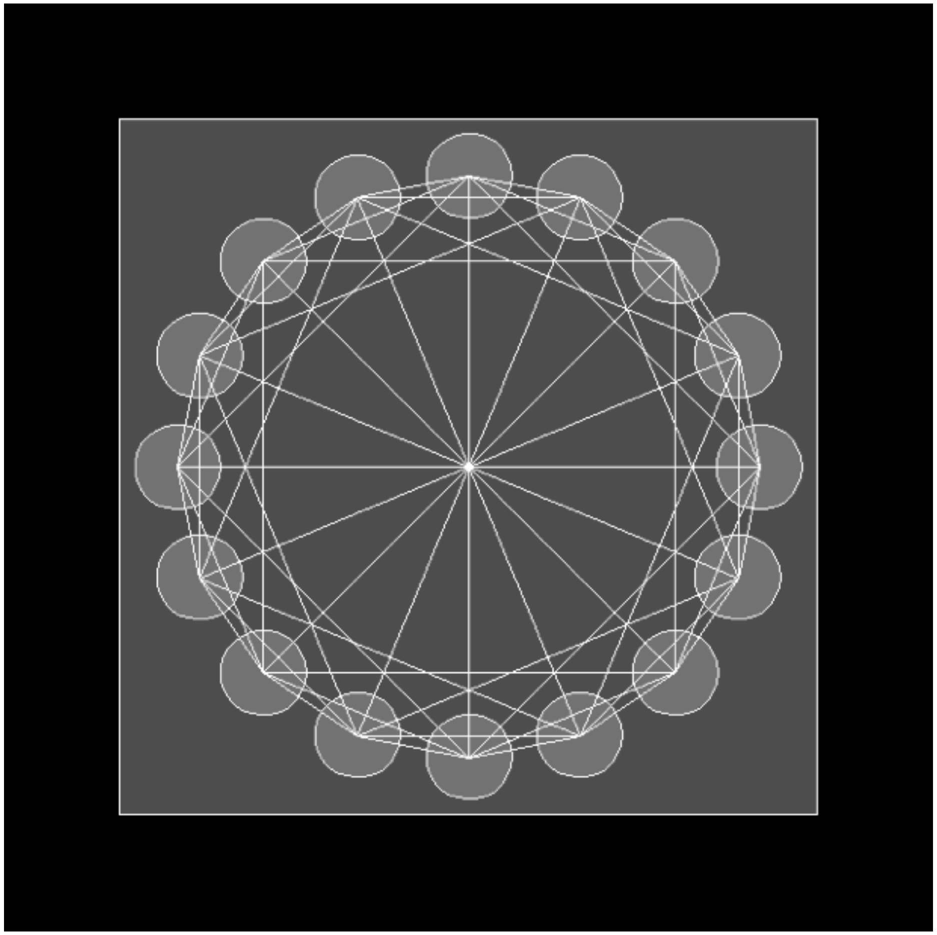
Example Specifications for SALSA

```
entity UniversalActor is salsa.language.UniversalActor$State {
        when start putMessageInMailbox(salsa.language.Message message)
                -> communication(message.getSource().getId(),
                                       message.getTarget().getId());
        when finish finalize()
                -> deletion(this.getId());
}
```

```
entity WWCSystem is wwc.messaging.WWCSystem$State {
        when start createActor(salsa.naming.UAN uan,
                             salsa.naming.UAL ual,
                             java.lang.String className)
                -> creation(uan.getId(), ual.getHostAndPort());

        when start addActor(salsa.language.Actor actor)
                -> migration(actor.getUAN().getId(),
                                actor.getUAL().getHostAndPort());
}
```

Chord application topology





Open Source Code

- Consider to contribute!
- Visit our web pages for more info:
  - SALSA: http://wcl.cs.rpi.edu/salsa/
  - IOS: http://wcl.cs.rpi.edu/ios/
  - OverView: http://wcl.cs.rpi.edu/overview/
  - COS: http://wcl.cs.rpi.edu/cos/
  - PILOTS: http://wcl.cs.rpi.edu/pilots/
  - MilkyWay@Home: http://milkyway.cs.rpi.edu/

Erlang Language Support for Fault-Tolerant Computing

- Erlang provides linguistic abstractions for:
  - Error detection.
    - Catch/throw exception handling.
    - Normal/abnormal process termination.
    - Node monitoring and exit signals.
  - Process (actor) groups.
  - Dynamic (hot) code loading.

Exception Handling

- To protect sequential code from errors:

```
catch Expression
```

If failure does not occur in **`Expression`** evaluation, **`catch Expression`** returns the value of the expression.

- To enable non-local return from a function:

```
throw({ab_exception, user_exists})
```

Address Book Example

```
-module(addressbook).
-export([start/0,addressbook/1]).

start() ->
    register(addressbook, spawn(addressbook, addressbook, [[]])).

addressbook(Data) ->
  receive
    {From, {addUser, Name, Email}} ->
       From ! {addressbook, ok},
       addressbook(add(Name, Email, Data));
    …
end.

add(Name, Email, Data) ->
    case getemail(Name, Data) of
       undefined ->
         [{Name,Email}|Data];
       _ -> % if Name already exists, add is ignored.
         Data
    end.
getemail(Name, Data) -> …
```

Address Book Example with Exception

```
addressbook(Data) ->
  receive
    {From, {addUser, Name, Email}} ->
       case catch add(Name, Email, Data) of
         {ab_exception, user_exists} ->
            From ! {addressbook, no},
            addressbook(Data);
         NewData->
            From ! {addressbook, ok},
            addressbook(NewData)
       end;
    …
end.

add(Name, Email, Data) ->
    case getemail(Name, Data) of
       undefined ->
         [{Name,Email}|Data];
       _ ->      % if Name already exists, exception is thrown.
         throw({ab_exception,user_exists})
    end.
```

Normal/abnormal termination

- To terminate an actor, you may simply return from the function the actor executes (without using tail-form recursion). This is equivalent to calling:

```
exit(normal).
```

- Abnormal termination of a function, can be programmed:

```
exit({ab_error, no_msg_handler})
```

equivalent to:

```
throw({'EXIT',{ab_error, no_msg_handler}})
```

- Or it can happen as a run-time error, where the Erlang run-time sends a signal equivalent to:

```
exit(badarg)           % Wrong argument type
exit(function_clause)  % No pattern match
```

Address Book Example with Exception and Error Handling

```
addressbook(Data) ->
  receive
    {From, {addUser, Name, Email}} ->
       case catch add(Name, Email, Data) of
         {ab_exception, user_exists} ->
            From ! {addressbook, no},
            addressbook(Data);
         {ab_error, What} -> …  % programmer-generated error (exit)
         {’EXIT’, What} -> …    % run-time-generated error
         NewData->
            From ! {addressbook, ok},
            addressbook(NewData)
       end;
    …
end.
```

Node monitoring

- To monitor a node:

```
monitor_node(Node, Flag)
```

If **`flag`** is true, monitoring starts. If false, monitoring stops. When a monitored node fails, **`{nodedown, Node}`** is sent to monitoring process.

Address Book Client Example with Node Monitoring

```
-module(addressbook_client).
-export([getEmail/1,getName/1,addUser/2]).

addressbook_server() -> 'addressbook@127.0.0.1'.

getEmail(Name) -> call_addressbook({getEmail, Name}).
getName(Email) -> call_addressbook({getName, Email}).
addUser(Name, Email) -> call_addressbook({addUser, Name, Email}).

call_addressbook(Msg) ->
    AddressBookServer = addressbook_server(),
    monitor_node(AddressBookServer, true),
    {addressbook, AddressBookServer} ! {self(), Msg},
    receive
       {addressbook, Reply} ->
           monitor_node(AddressBookServer, false),
           Reply;
       {nodedown, AddressBookServer} ->
           no
    end.
```

Process (Actor) Groups

- To create an actor in a specified remote node:

```
Agent = spawn(host, travel, agent, []);
```

- To create an actor in a specified remote node and create a link to the actor:

```
Agent = spawn_link(host, travel, agent, []);
```

An 'EXIT' signal will be sent to the originating actor if the host node does not exist.

Group Failure

- Default error handling for linked processes is as follows:
  - Normal exit signal is ignored.
  - Abnormal exit (either programmatic or system-generated):
    - Bypass all messages to the receiving process.
    - Kill the receiving process.
    - Propagate same error signal to links of killed process.
- All linked processes will get killed if a participating process exits abnormally.

Dynamic code loading

- To update (module) code while running it:

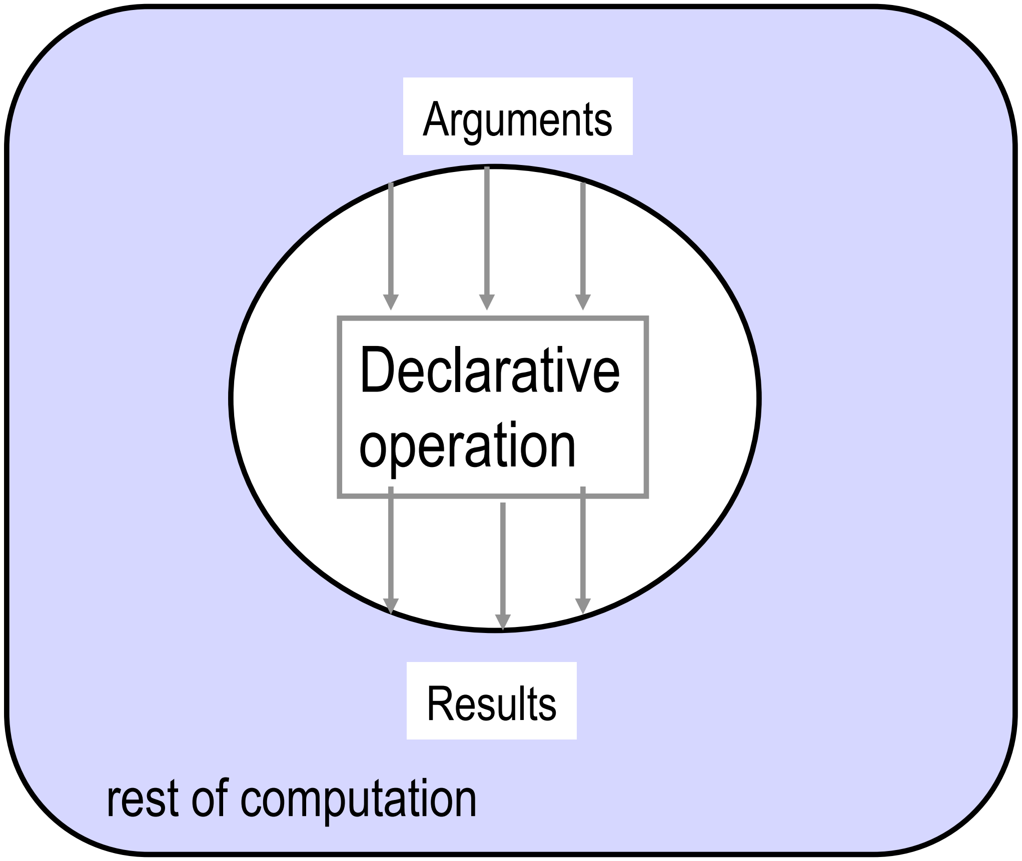
```
-module(m).
-export([loop/0]).

loop() ->
    receive
        code_switch ->
            m:loop();
        Msg -> ...
            loop()
    end.
```

`code_switch` message dynamically loads the new module code. Notice the difference between **`m:loop()`** and **`loop()`**.

Declarative operations (1)

- An operation is *declarative* if whenever it is called with the same arguments, it returns the same results independent of any other computation state
- A declarative operation is:
  - *Independent* (depends only on its arguments, nothing else)
  - *Stateless* (no internal state is remembered between calls)
  - *Deterministic* (call with same operations always give same results)
- Declarative operations can be composed together to yield other declarative components
  - All basic operations of the declarative model are declarative and combining them always gives declarative components

Declarative operations (2)



Why declarative components (1)

- There are two reasons why they are important:
- *(Programming in the large)* A declarative component can be written, tested, and proved correct independent of other components and of its own past history.
  - The complexity (reasoning complexity) of a program composed of declarative components is the *sum* of the complexity of the components
  - In general the reasoning complexity of programs that are composed of nondeclarative components explodes because of the intimate interaction between components
- *(Programming in the small)* Programs written in the declarative model are much easier to reason about than programs written in more expressive models (e.g., an object-oriented model).
  - Simple algebraic and logical reasoning techniques can be used

Why declarative components (2)

- Since declarative components are mathematical functions, algebraic reasoning is possible i.e. substituting equals for equals
- The declarative model of CTM Chapter 2 guarantees that all programs written are declarative
- Declarative components can be written in models that allow stateful data types, but there is no guarantee

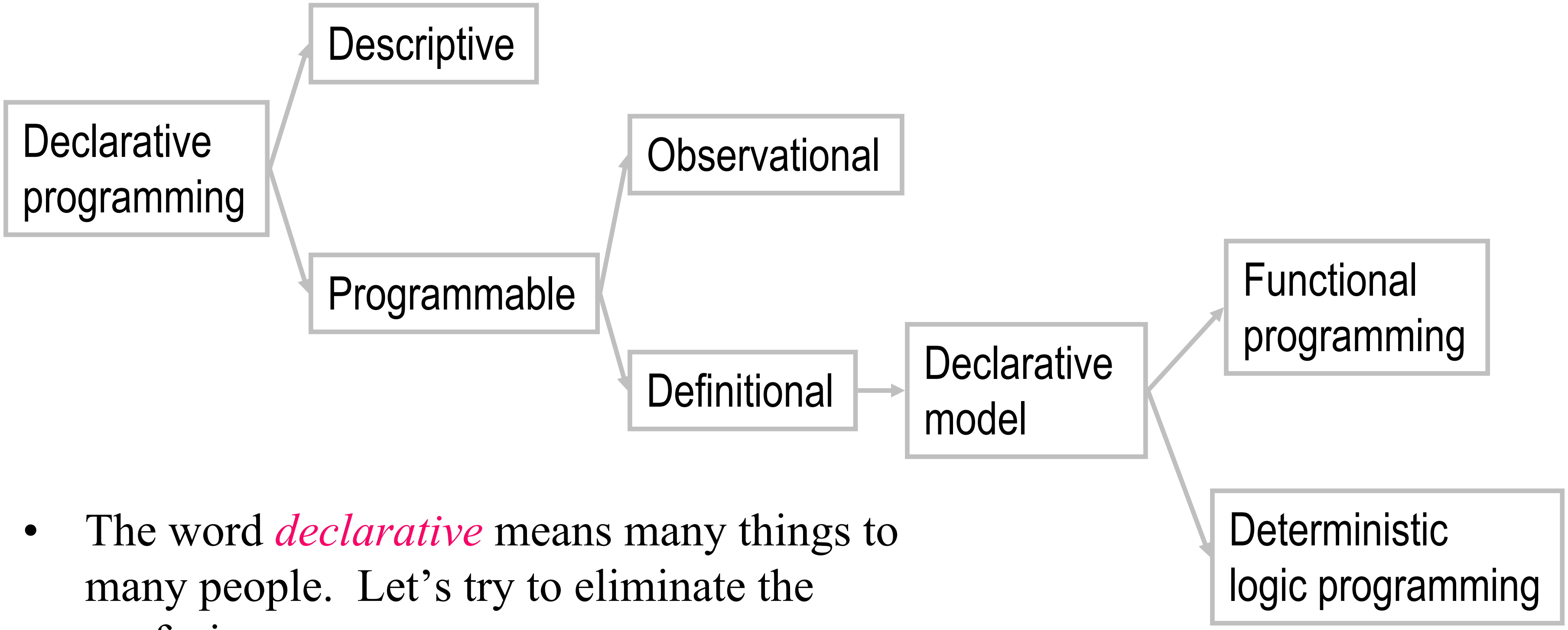
Given

$f(a) = a^2$

We can replace $f(a)$ in any other equation

$b = 7f(a)^2$ becomes $b = 7a^4$

Classification of declarative programming



- The word *declarative* means many things to many people. Let's try to eliminate the confusion.
- The basic intuition is to program by defining the *what* without explaining the *how*

Oz kernel language

The following defines the syntax of a statement, $\langle s \rangle$ denotes a statement

$\langle s \rangle$	::=	skip	*empty statement*
	|	$\langle x \rangle = \langle y \rangle$	*variable-variable binding*
	|	$\langle x \rangle = \langle v \rangle$	*variable-value binding*
	|	$\langle s_1 \rangle \ \langle s_2 \rangle$	*sequential composition*
	|	local $\langle x \rangle$ in $\langle s_1 \rangle$ end	*declaration*
	|	proc ’{’$\langle x \rangle$ $\langle y_1 \rangle$ … $\langle y_n \rangle$ ’ }’ $\langle s_1 \rangle$ end	*procedure introduction*
	|	if $\langle x \rangle$ then $\langle s_1 \rangle$ else $\langle s_2 \rangle$ end	*conditional*
	|	’ {’ $\langle x \rangle$ $\langle y_1 \rangle$ … $\langle y_n \rangle$ ’ }’	*procedure application*
	|	case $\langle x \rangle$ of $\langle \text{pattern} \rangle$ then $\langle s_1 \rangle$ else $\langle s_2 \rangle$ end	*pattern matching*

Why the Oz KL is declarative

- All basic operations are declarative
- Given the components (sub-statements) are declarative,
  - sequential composition
  - local statement
  - procedure definition
  - procedure call
  - if statement
  - case statement

are all declarative (independent, stateless, deterministic).

What is state?

- State is a sequence of values in time that contains the intermediate results of a desired computation
- Declarative programs can also have state according to this definition
- Consider the following program

```
fun {Sum Xs A}
   case Xs
   of X|Xr then {Sum Xr A+X}
   [] nil then A
   end
end

{Browse {Sum [1 2 3 4] 0}}
```

What is implicit state?

The two arguments Xs and A represent an implicit state

Xs	A
[1 2 3 4]	0
[2 3 4]	1
[3 4]	3
[4]	6
nil	10

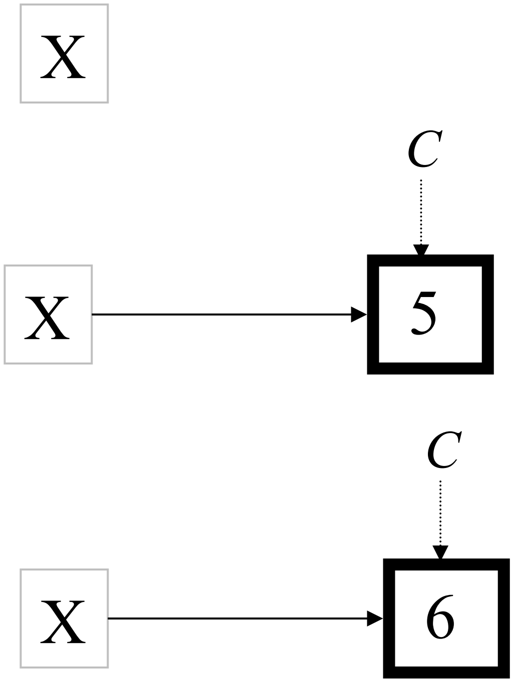
```
fun {Sum Xs A}
   case Xs
   of X|Xr then {Sum Xr A+X}
   [] nil then A
   end
end

{Browse {Sum [1 2 3 4] 0}}
```

What is explicit state: Example?

An unbound variable

A cell *C* is created with initial value 5
X is bound to *C*

The cell C, which X is bound to, is assigned the value 6



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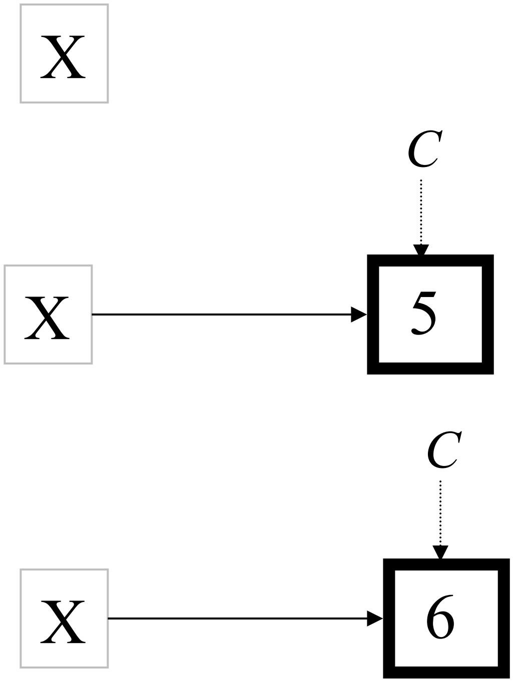


- The cell is a value container with a unique **identity**
- X is really bound to the **identity** of the cell
- When the cell is assigned, X does not change

What is explicit state?

- **X = {NewCell I}**
  - Creates a cell with initial value I
  - Binds X to the identity of the cell
- Example: X = {NewCell 0}
- **{Assign X J}**
  - Assumes X is bound to a cell C (otherwise exception)
  - Changes the content of C to become J
- **Y = {Access X}**
  - Assumes X is bound to a cell C (otherwise exception)
  - Binds Y to the value contained in C

The stateful model

⟨s⟩::= **skip**	*empty statement*
| $\langle s_1 \rangle$ $\langle s_2 \rangle$	*statement sequence*
| **...**	
| {NewCell ⟨**x**⟩ ⟨**c**⟩}	***cell creation***
| {Exchange ⟨**c**⟩ ⟨**x**⟩ ⟨**y**⟩}	***cell exchange***

Exchange: bind ⟨**x**⟩ to the old content of ⟨**c**⟩ and set the content of the cell ⟨**c**⟩ to ⟨**y**⟩

The stateful model

| {NewCell ⟨**x**⟩ ⟨**c**⟩} ***cell creation***
| {Exchange ⟨**c**⟩ ⟨**x**⟩ ⟨**y**⟩} ***cell exchange***

Exchange: bind ⟨**x**⟩ to the old content of ⟨**c**⟩ and set the content of the cell ⟨**c**⟩ to ⟨**y**⟩

```
proc {Assign C X} {Exchange C _ X} end
fun {Access C} X in{Exchange C X X}X end
```

C := X is syntactic sugar for **{Assign C X}**
@C is syntactic sugar for **{Access C}**
X=C:=Y is syntactic sugar for **{Exchange C X Y}**

Abstract data types (revisited)

- For a given functionality, there are many ways to package the ADT. We distinguish three axes.
- Open vs. secure ADT: is the internal representation visible to the program or hidden?
- Declarative vs. stateful ADT: does the ADT have encapsulated state or not?
- Bundled vs. unbundled ADT: is the data kept together with the operations or is it separable?
- Let us see what our stack ADT looks like with some of these possibilities

Stack:
Secure, stateful, and *bundled*

- This is the simplest way to make a secure stateful stack:

```
proc {NewStack ?Push ?Pop ?IsEmpty}
        C={NewCell nil}
in
        proc {Push X} {Assign C X|{Access C}} end
        fun {Pop}  case {Access C} of X|S then {Assign C S}  X  end end
        fun {IsEmpty} {Access C} ==nil end
end
```

- Compare the declarative with the stateful versions: the declarative version needs two arguments per operation, the stateful version uses higher-order programming (instantiation)
- With some syntactic support, this is *object-based programming*

Four ways to package a stack

- Open, declarative, and unbundled: the usual declarative style, e.g., in Prolog and Scheme
- Secure, declarative, and unbundled: use wrappers to make the declarative style secure
- Secure, stateful, and unbundled: an interesting variation on the usual object-oriented style
- Secure, stateful, and bundled: the usual object-oriented style, e.g., in Smalltalk and Java
- Other possibilities: there are four more possibilities! **Exercise**: Try to write all of them.

Object-oriented programming

- Supports
  - Encapsulation
  - Compositionality
  - Instantiation
- Plus
  - Inheritance

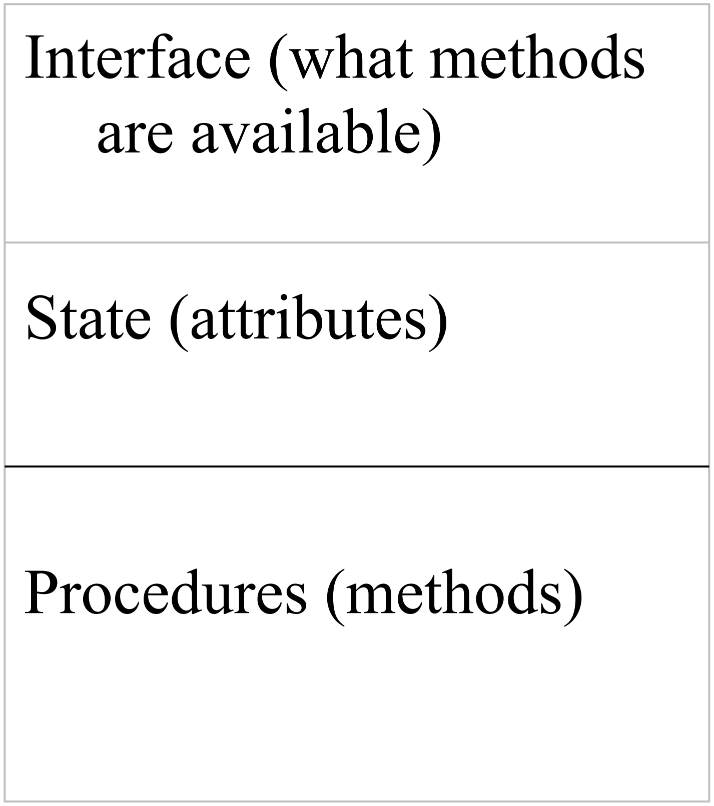
Inheritance

- Programs can be built in hierarchical structure from ADT's that depend on other ADT's (Components)
- Object-oriented programming (inheritance) is based on the idea that ADTs have so much in common
- For example, sequences (stacks, lists, queues)
- Object oriented programming enables building ADTs incrementally, through *inheritance*
- An ADT can be defined to *inherit* from another abstract data type, substantially sharing functionality with that abstract data type
- Only the difference between an abstract datatype and its ancestor has to be specified

What is object-oriented programming?

- OOP (Object-oriented programming) = encapsulated state + inheritance
- Object
  - An entity with unique identity that encapsulates state
  - State can be accessed in a controlled way from outside
  - The access is provided by means of methods (procedures that can directly access the internal state)
- Class
  - A specification of objects in an incremental way
  - Incrementality is achieved inheriting from other classes by specifying how its objects (instances) differ from the objects of the inherited classes

Instances (objects)



Interface (what methods are available)

State (attributes)

Procedures (methods)

Classes (simplified syntax)

A class is a statement

```
class ⟨ClassVariable⟩
   attr
      ⟨AttrName1⟩
         :
      ⟨AttrNameN⟩
   meth ⟨Pattern1⟩  ⟨Statement⟩  end
                 :
   meth ⟨PatternN⟩  ⟨Statement⟩  end
end
```

Classes in Oz

The class Counter has the syntactic form

```
class Counter
    attr val
    meth display
        {Browse @val}
    end
    meth inc(Value)
        val := @val + Value
    end
    meth init(Value)
        val := Value
    end
end
```

Example

- An object is created from a class using the procedure **`New/3`**, whose first argument is the class, the second is the initial method, and the result is the object (such as in the functor and procedure approaches)
- **`New/3`** is a generic procedure for creating objects from classes.

```
declare C = {New Counter init(0)}
{C display}
{C inc(1)}
{C display}
```

Summary

- A class *X* is defined by:
  - `class X ... end`
- Attributes are defined using the attribute-declaration part before the method-declaration part:
  - `attr` A_1 ... A_N
- Then follows the method declarations, each has the form:
  - `meth E S end`
- The expression *E* evaluates to a method head, which is a record whose label is the method name.

Summary

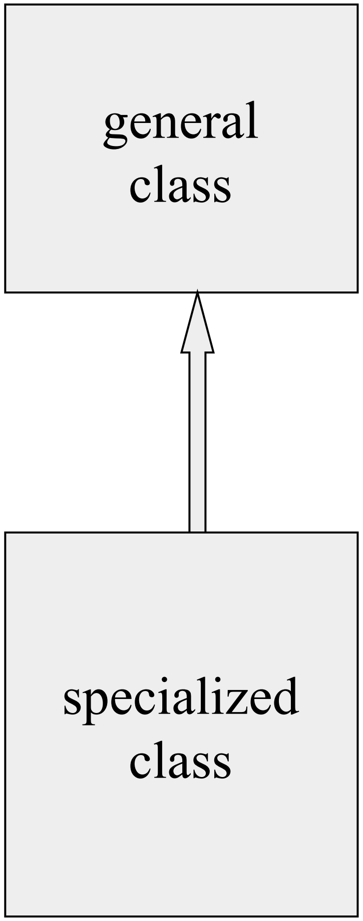
- An attribute `A` is accessed using `@A`.
- An attribute is assigned a value using `A := E`
- A class can be defined as a value:
- `X = class $ ... end`

Classes as incremental ADTs

- Object-oriented programming allows us to define a class by extending existing classes
- <u>Three things have to be introduced</u>
  - How to express inheritance, and what does it mean?
  - How to access particular methods in the new class and in preexisting classes
  - Visibility – what part of the program can see the attributes and methods of a class
- The notion of delegation as a substitute for inheritance

Inheritance

- Inheritance should be used as a way to specialize a class *while retaining the relationship between methods*
- In this way it is a just an extension of an ADT
- The other view is inheritance is just a (lazy) way to construct new abstract data types !
- No relationships are preserved



Inheritance

```
class Account
   attr balance:0
   meth transfer(Amount)
      balance := @balance+Amount
   end
   meth getBal(B)
      B = @balance
   end
end

A={New Account transfer(100)}
```

Inheritance II

The class VerboseAccount has the methods:
transfer, getBal, and verboseTransfer

Conservative extension

```
class VerboseAccount
   from Account
   meth verboseTransfer(Amount)
            ...
   end
end
```

Inheritance II

Non-Conservative extension

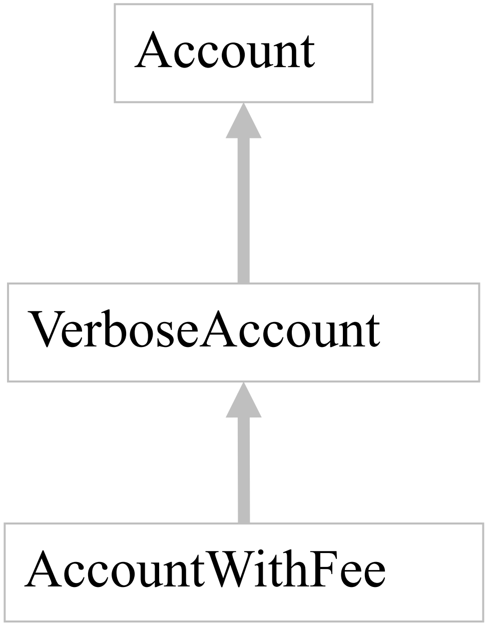
```
class AccountWithFee
  from VerboseAccount
  attr fee:5
  meth transfer(Amount)
     ...
  end
end
```

The class AccountWithFee has the methods:
transfer, getBal, and verboseTransfer
The method transfer has been redefined (overridden) with another definition

Inheritance II

Non-Conservative extension

```
class AccountWithFee
   from VerboseAccount
   attr fee:5
   meth transfer(Amount)
      ...
   end
end
```



Account

VerboseAccount

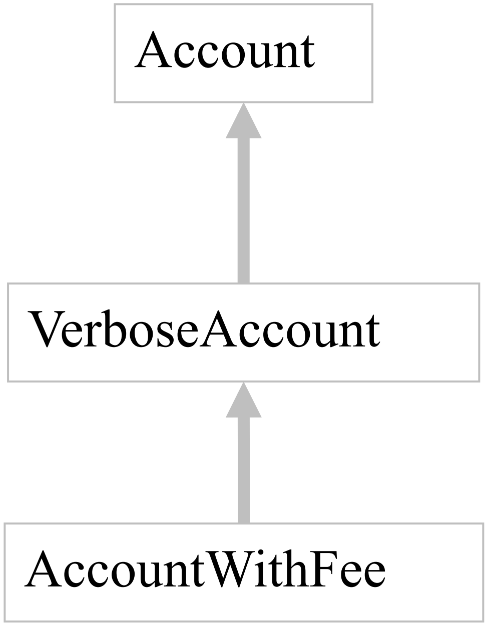
AccountWithFee

Polymorphism

The ability for operations to take objects (instances) of different types.

For example, the transfer method can be invoked in account object instances of three different classes.

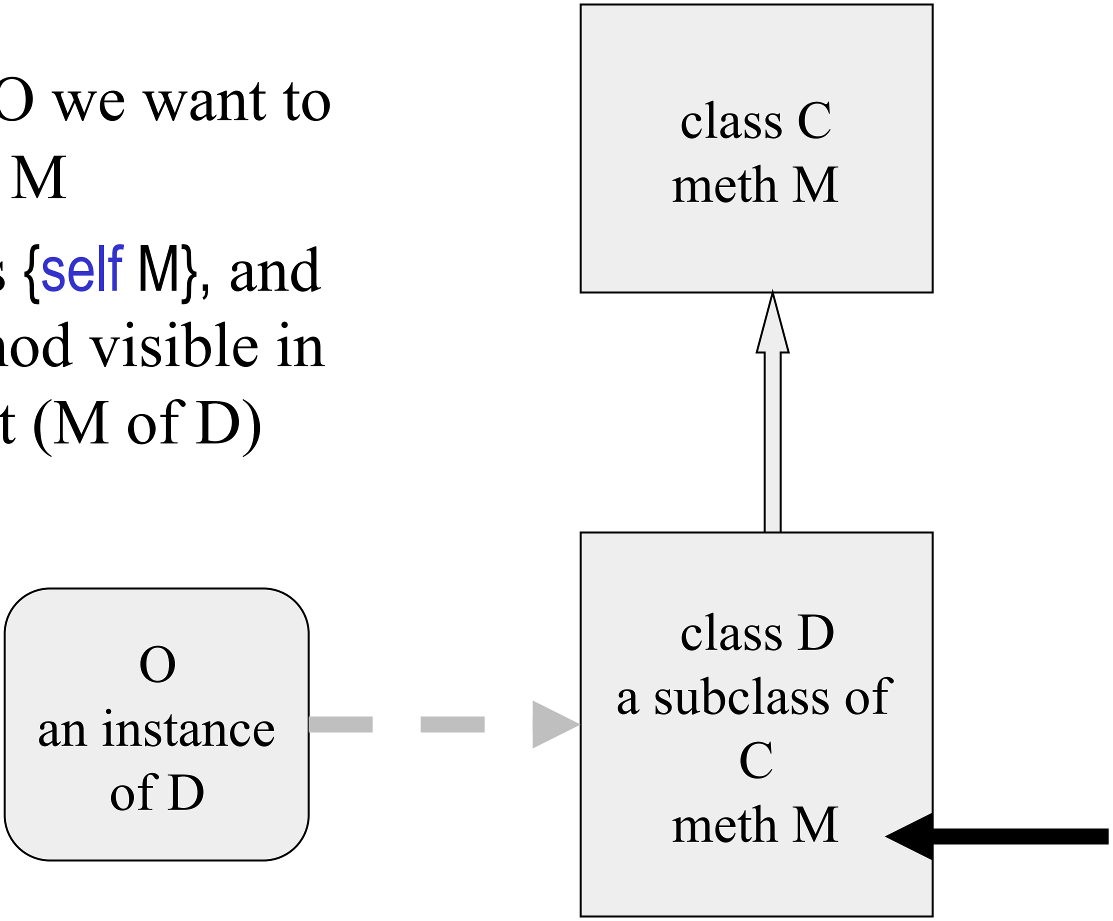
The most specific behavior should be executed.



Static and dynamic binding

Dynamic binding

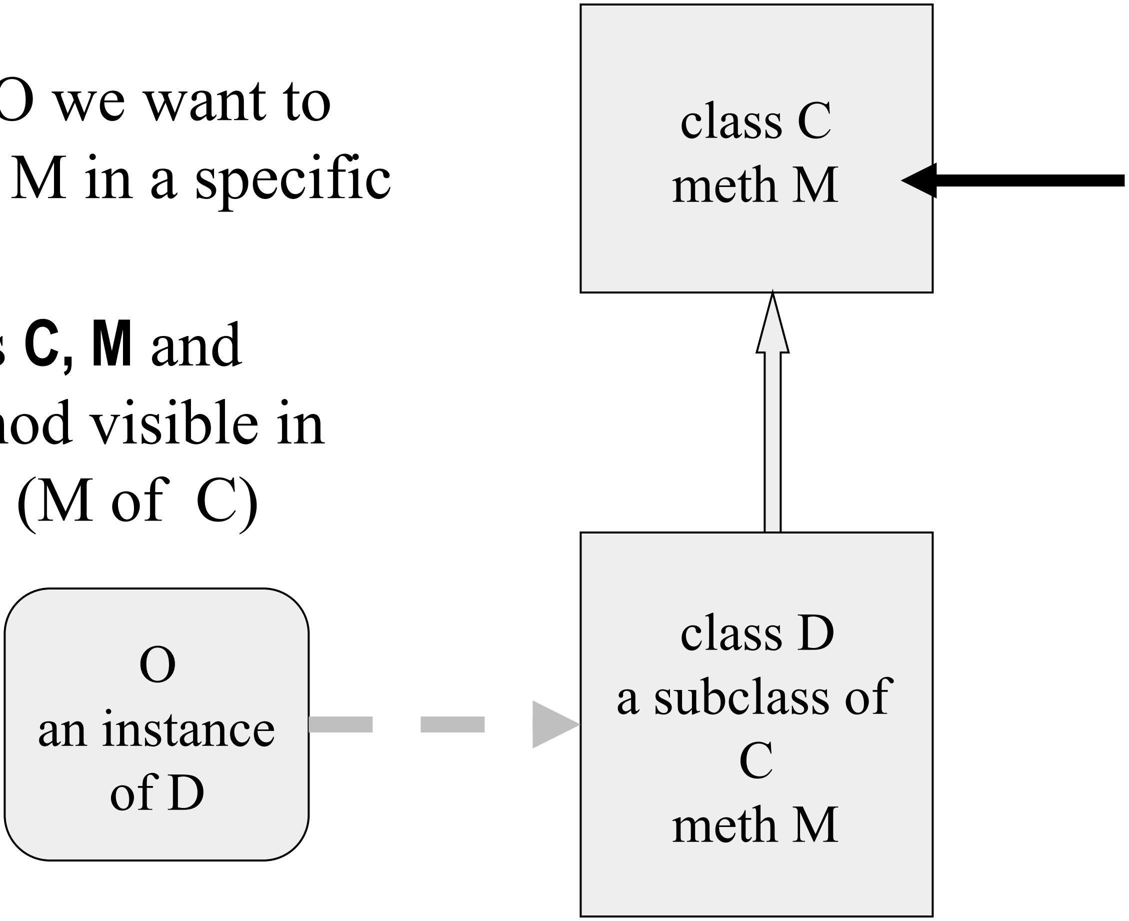
- Inside an object O we want to invoke a method M
- This is written as {self M}, and chooses the method visible in the current object (M of D)



Static and dynamic binding

Static binding

- Inside an object O we want to invoke a method M in a specific (super) class
- This is written as **C, M** and chooses the method visible in the super class C (M of C)



Static method calls

- Given a class and a method head m(…), a static method-call has the following form:

      C, m(…)

- Invokes the method defined in the class argument.
- A static method call can only be used inside class definitions.
- The method call takes the current object denoted by **self** as implicit argument.
- The method m could be defined in the class C, or inherited from a super class.

Review of concurrent programming

- There are four basic approaches:
  - Sequential programming (no concurrency)
  - Declarative concurrency (streams in a functional language, Oz)
  - Message passing with active objects (Erlang, SALSA)
  - Atomic actions on shared state (Java)
- The atomic action approach is the *most difficult*, yet it is the one you will probably be most exposed to!
- But, if you have the choice, which approach to use?
  - Use the simplest approach that does the job: sequential if that is ok, else declarative concurrency if there is no observable nondeterminism, else message passing if you can get away with it.

Concurrency

- How to do several things at once
- Concurrency: running several activities each running at its own pace
- A *thread* is an executing sequential program
- A program can have multiple threads by using the thread instruction
- {Browse 99*99} can immediately respond while Pascal is computing

```
thread
  P in
  P = {Pascal 21}
  {Browse P}
end
{Browse 99*99}
```

State

- How to make a function learn from its past?
- We would like to add memory to a function to remember past results
- Adding memory as well as concurrency is an essential aspect of modeling the real world
- Consider {FastPascal N}: we would like it to remember the previous rows it calculated in order to avoid recalculating them
- We need a concept (memory cell) to store, change and retrieve a value
- The simplest concept is a (memory) cell which is a container of a value
- One can create a cell, assign a value to a cell, and access the current value of the cell
- Cells are not variables

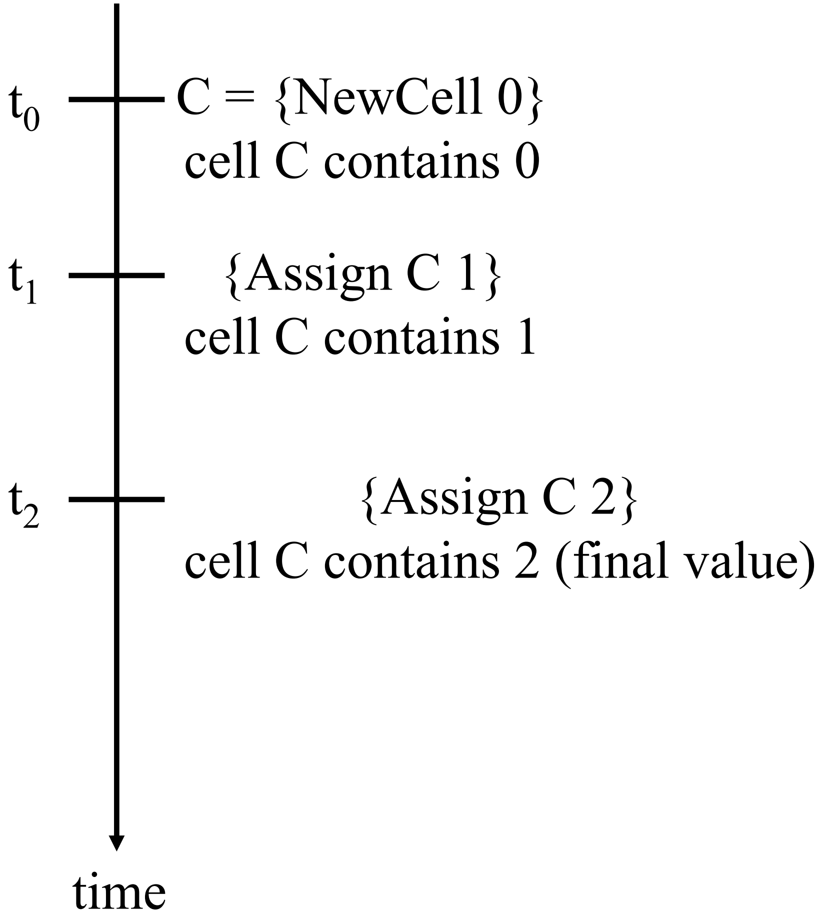
```
declare
C = {NewCell 0}
{Assign C {Access C}+1}
{Browse {Access C}}
```

Nondeterminism

- What happens if a program has both concurrency and state together?
- This is very tricky
- The same program can give different results from one execution to the next
- This variability is called *nondeterminism*
- Internal nondeterminism is not a problem if it is not observable from outside

Nondeterminism (2)

```
declare
C = {NewCell 0}

thread {Assign C 1} end
thread {Assign C 2} end
```



t_0 C = {NewCell 0}
cell C contains 0

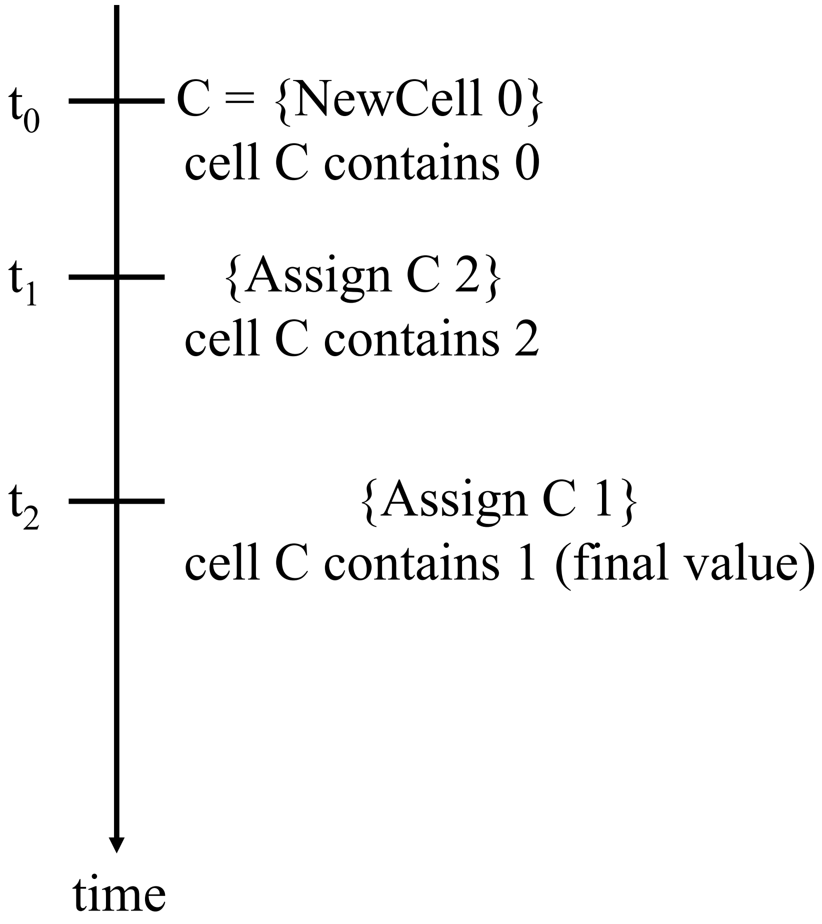
t_1 {Assign C 1}
cell C contains 1

t_2 {Assign C 2}
cell C contains 2 (final value)

time

Nondeterminism (3)

```
declare
C = {NewCell 0}

thread {Assign C 1} end
thread {Assign C 2} end
```



t_0 C = {NewCell 0}
cell C contains 0

t_1 {Assign C 2}
cell C contains 2

t_2 {Assign C 1}
cell C contains 1 (final value)

time

Nondeterminism (4)

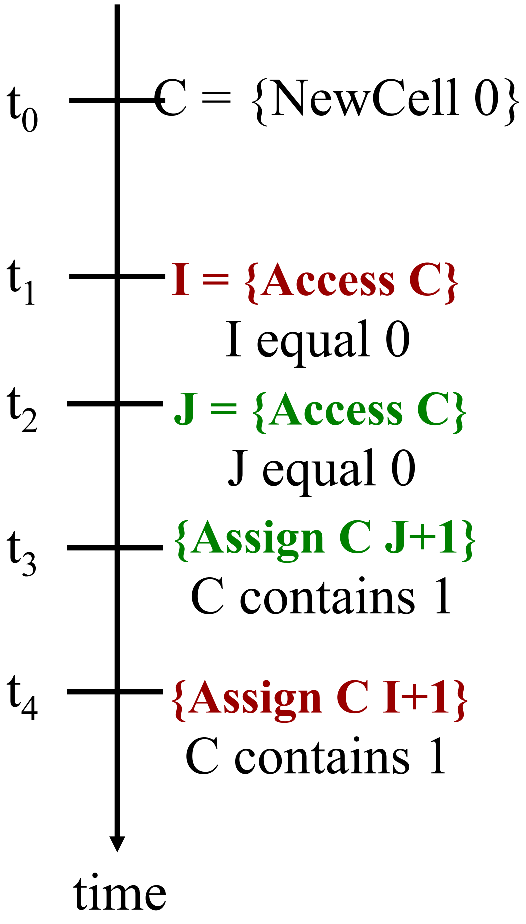
```
declare
C = {NewCell 0}

thread I in
    I = {Access C}
    {Assign C I+1}
end
thread J in
    J = {Access C}
    {Assign C J+1}
end
```

- What are the possible results?
- Both threads increment the cell C by 1
- Expected final result of C is 2
  - Is that all?

Nondeterminism (5)

- Another possible final result is the cell C containing the value 1

```
declare
C = {NewCell 0}
thread I in
   I = {Access C}
   {Assign C I+1}
end
thread J in
   J = {Access C}
   {Assign C J+1}
end
```



t_0 C = {NewCell 0}

t_1 **I = {Access C}**
I equal 0

t_2 **J = {Access C}**
J equal 0

t_3 **{Assign C J+1}**
C contains 1

t_4 **{Assign C I+1}**
C contains 1

time

Lessons learned

- Combining concurrency and state is tricky
- Complex programs have many possible *interleavings*
- Programming is a question of mastering the interleavings
- Famous bugs in the history of computer technology are due to designers overlooking an interleaving (e.g., the Therac-25 radiation therapy machine giving doses thousands of times too high, resulting in death or injury)

1. If possible try to avoid concurrency and state together
2. Encapsulate state and communicate between threads using dataflow
3. Try to master interleavings by using *atomic operations*

Atomicity

- How can we master the interleavings?
- One idea is to reduce the number of interleavings by programming with coarse-grained atomic operations
- An operation is *atomic* if it is performed as a whole or nothing
- No intermediate (partial) results can be observed by any other concurrent activity
- In simple cases we can use a *lock* to ensure atomicity of a sequence of operations
- For this we need a new entity (a lock)

Atomicity (2)

```
declare
L = {NewLock}
```

```
lock L then
  sequence of ops 1
end
```

Thread 1

```
lock L then
sequence of ops 2
end
```

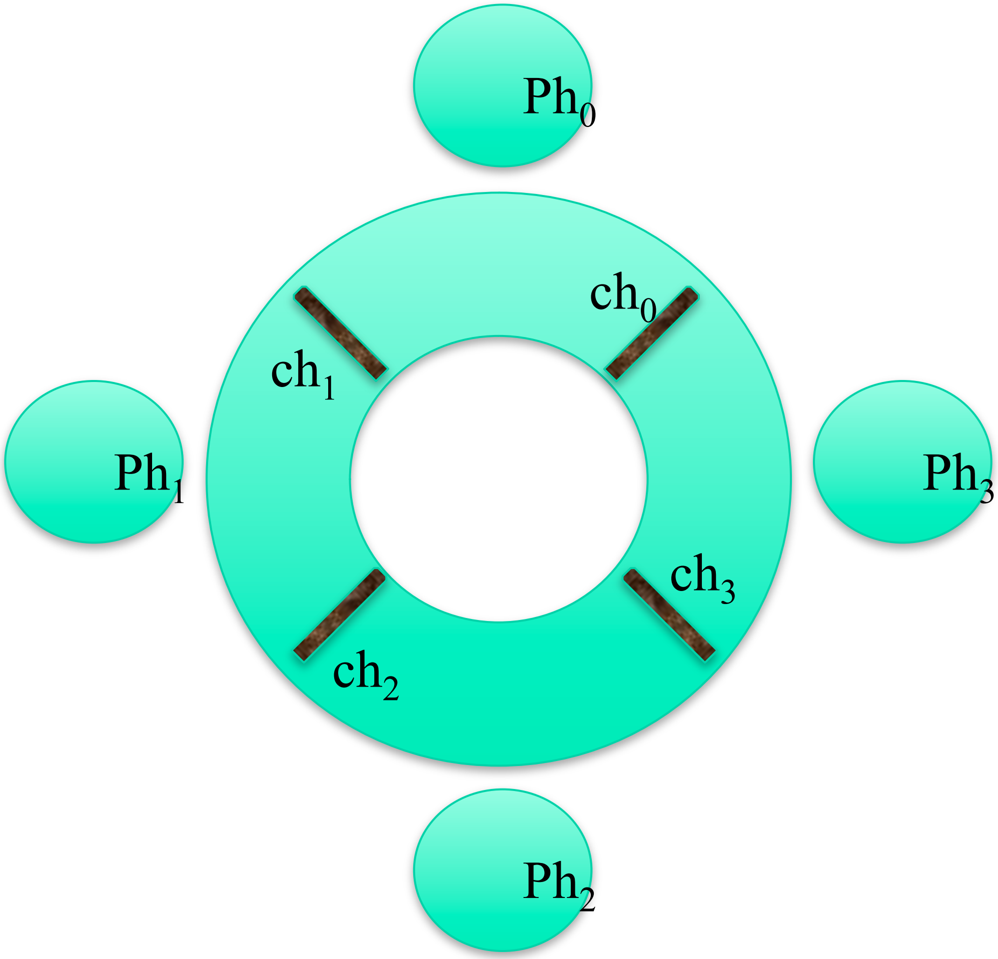
Thread 2

The program

```
declare
C = {NewCell 0}
L = {NewLock}

thread
   lock L then I in
      I = {Access C}
      {Assign C I+1}
   end
end
thread
   lock L then J in
      J = {Access C}
      {Assign C J+1}
   end
end
```

The final result of C is always 2

Locks and Deadlock: Dining Philosophers



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Declarative Concurrency

- This lecture is about declarative concurrency, programs with no observable nondeterminism, the result is a function
- Independent procedures that execute on their pace and may communicate through shared dataflow variables

Single-assignment Variables

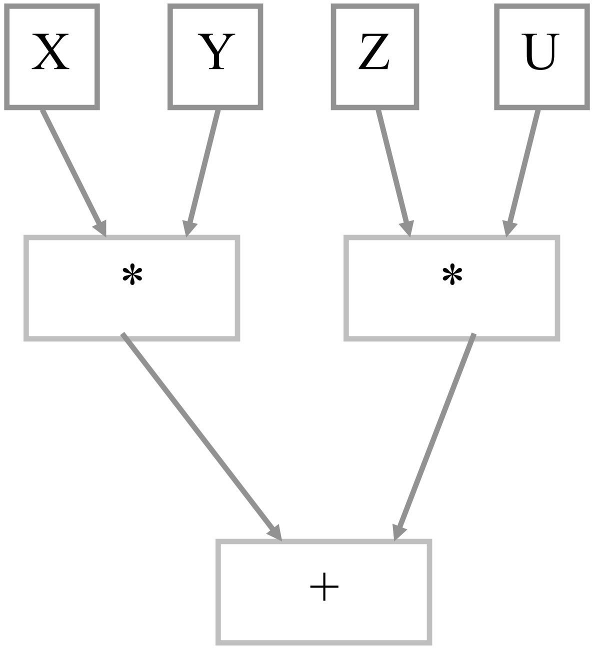
- Variables are short-cuts for values, they cannot be assigned more than once

```
declare
V = 9999*9999
{Browse V*V}
```

- Variable identifiers: is what you type
- Store variable: is part of the memory system
- The **declare** statement creates a store variable and assigns its memory address to the identifier 'V' in the environment

Dataflow

- What happens when multiple threads try to communicate?
- A simple way is to make communicating threads synchronize on the availability of data (data-driven execution)
- If an operation tries to use a variable that is not yet bound it will wait
- The variable is called a *dataflow variable*



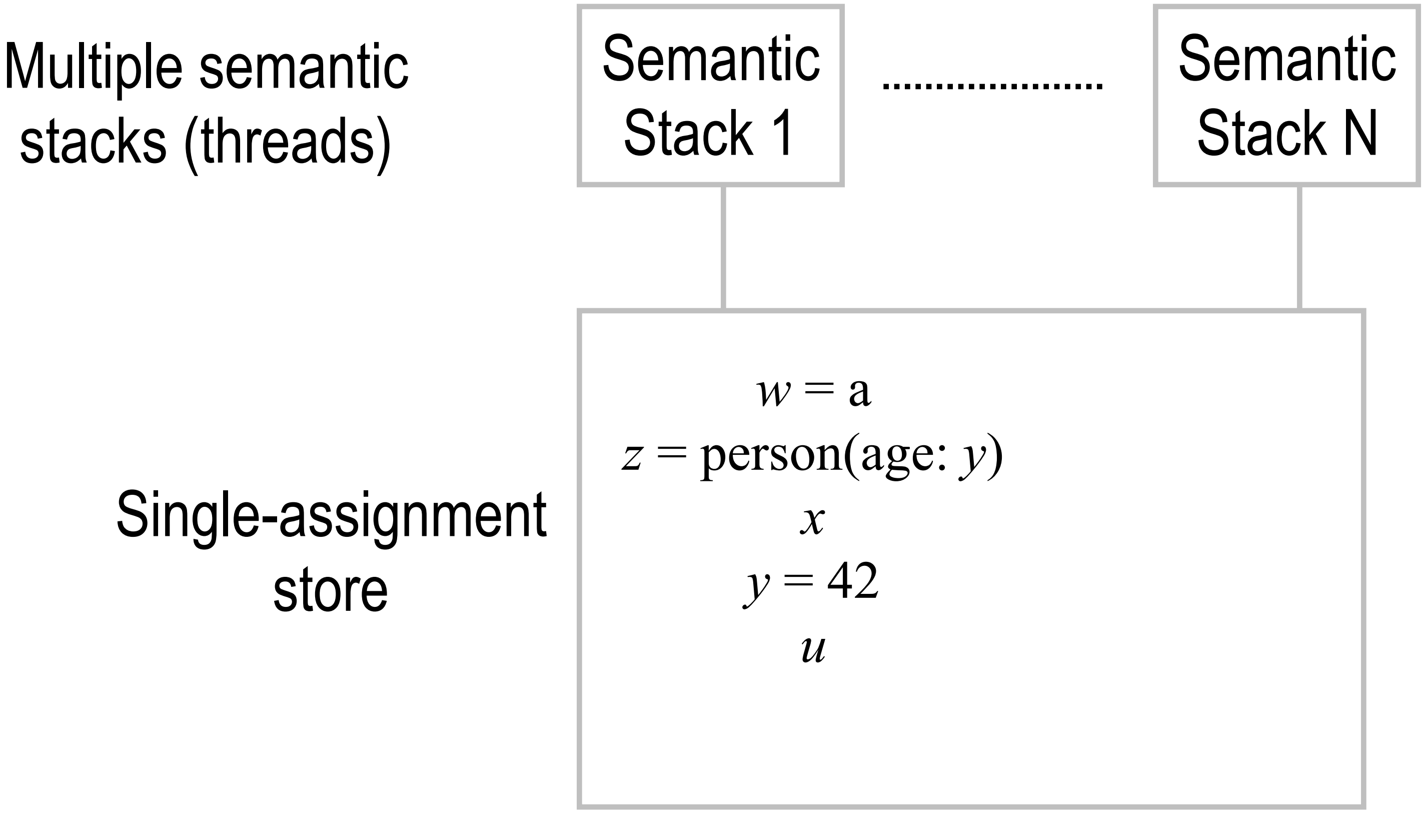
Dataflow (II)

- Two important properties of dataflow
  - Calculations work correctly independent of how they are partitioned between threads (concurrent activities)
  - Calculations are patient, they do not signal error; they wait for data availability
- The dataflow property of variables makes sense when programs are composed of multiple threads

```
declare X
thread
{Delay 5000} X=99
end
{Browse ‘Start’} {Browse X*X}
```

```
declare X
thread
{Browse ‘Start’} {Browse X*X}
end
{Delay 5000} X=99
```

The concurrent model



Multiple semantic stacks (threads)

Semantic Stack 1

……………………

Semantic Stack N

Single-assignment store

w = a

z = person(age: y)

x

y = 42

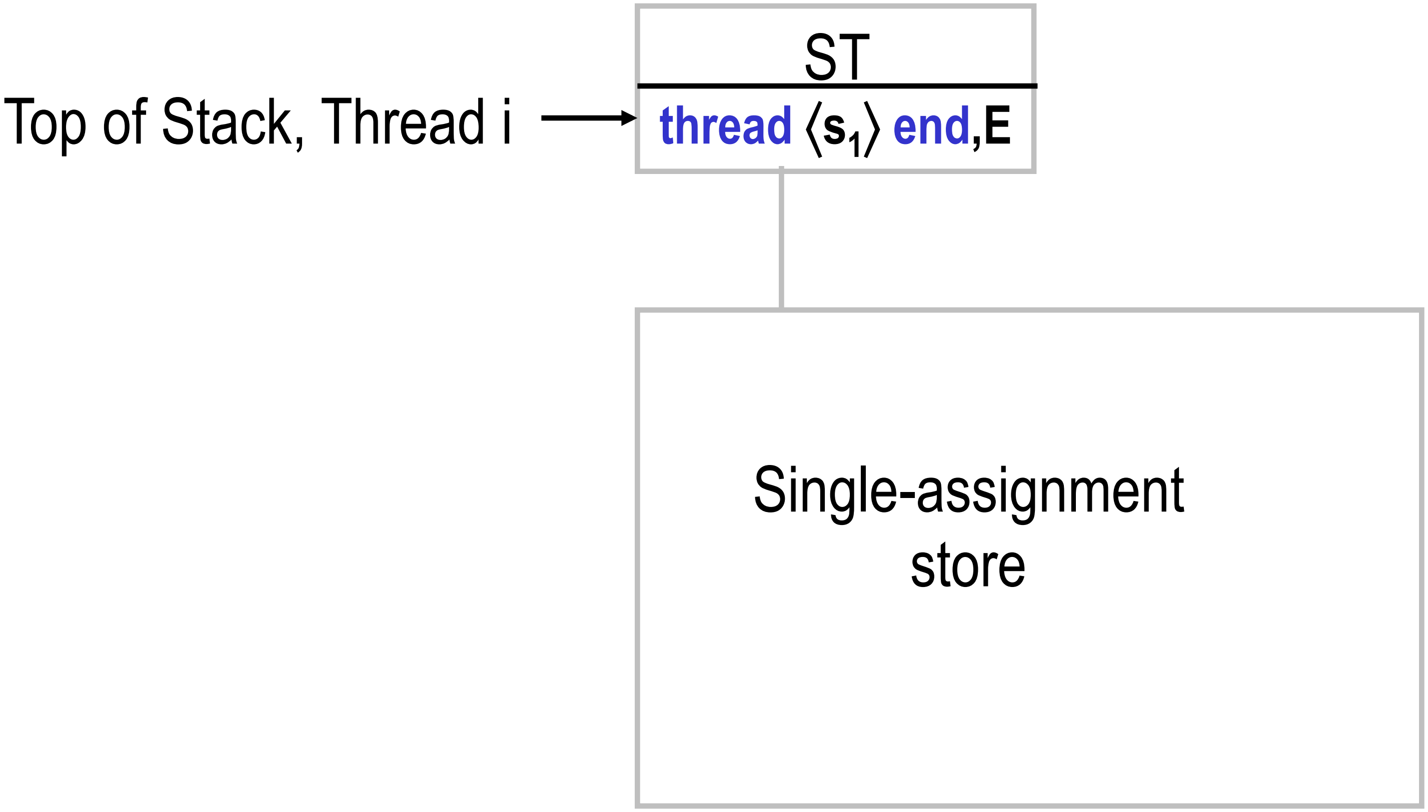
u

Concurrent declarative model

The following defines the syntax of a statement, ⟨s⟩ denotes a statement

⟨s⟩ ::= skip	*empty statement*
| ⟨x⟩ = ⟨y⟩	*variable-variable binding*
| ⟨x⟩ = ⟨v⟩	*variable-value binding*
| ⟨s$_1$⟩ ⟨s$_2$⟩	*sequential composition*
| local ⟨x⟩ in ⟨s$_1$⟩ end	*declaration*
| proc {⟨x⟩ ⟨y$_1$⟩ … ⟨y$_n$⟩ } ⟨s$_1$⟩ end	*procedure introduction*
| if ⟨x⟩ then ⟨s$_1$⟩ else ⟨s$_2$⟩ end	*conditional*
| { ⟨x⟩ ⟨y$_1$⟩ … ⟨y$_n$⟩ }	*procedure application*
| case ⟨x⟩ of ⟨pattern⟩ then ⟨s$_1$⟩ else ⟨s$_2$⟩ end	*pattern matching*
| **thread ⟨s$_1$⟩ end**	***thread creation***

The concurrent model



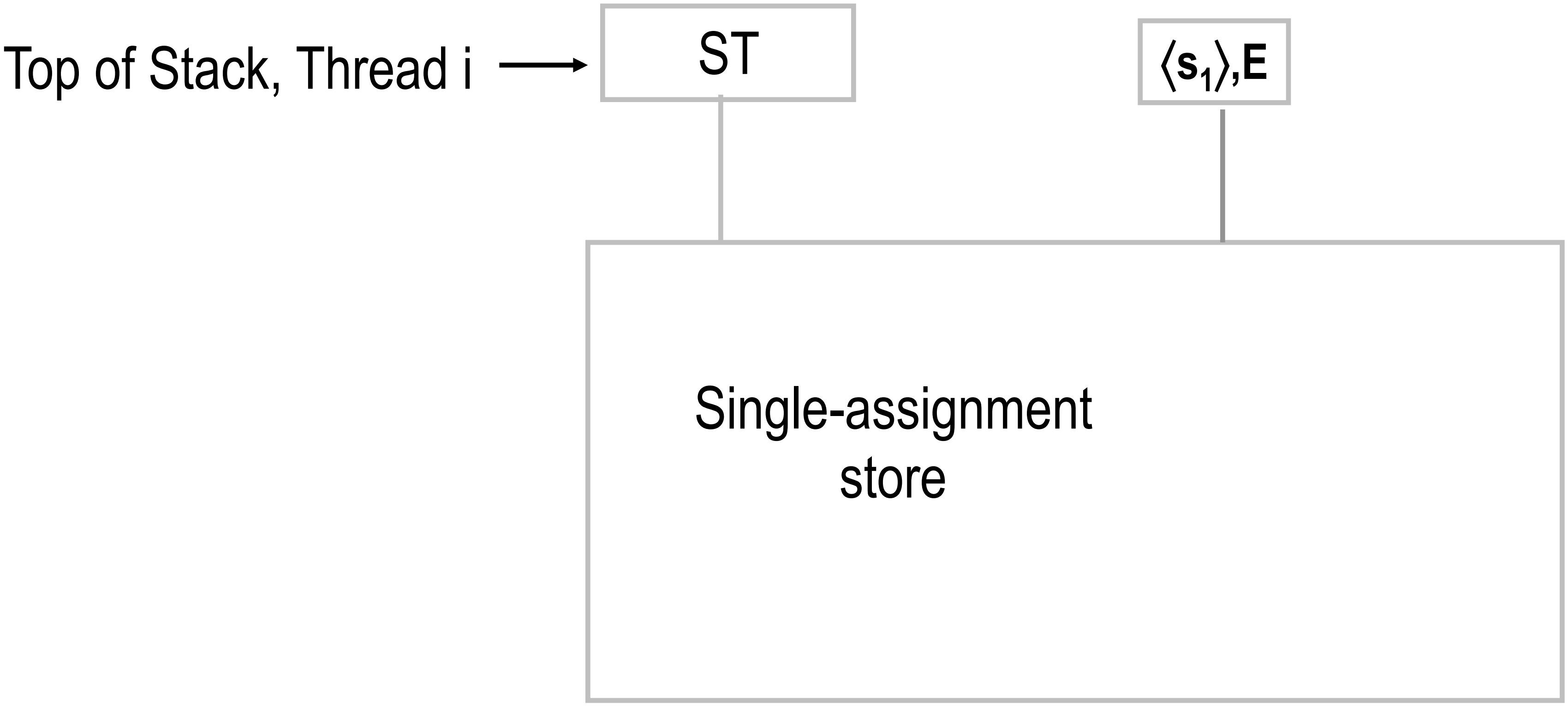
ST

Top of Stack, Thread i

thread ⟨s_1⟩ **end**,E

Single-assignment store

The concurrent model



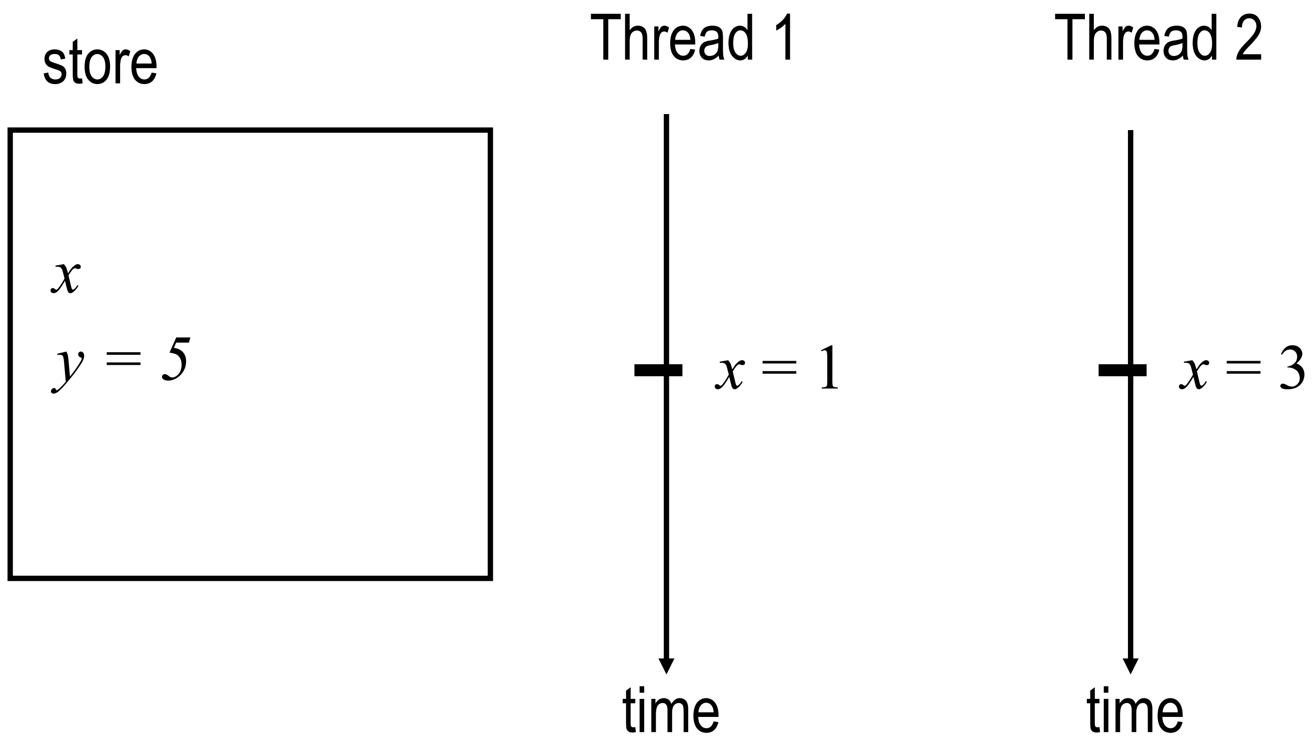
Basic concepts

- The model allows multiple statements to execute ”at the same time”
- Imagine that these threads really execute in parallel, each has its own processor, but share the same memory
- Reading and writing different variables can be done simultaneously by different threads, as well as reading the same variable
- Writing the same variable is done sequentially
- The above view is in fact equivalent to an *interleaving execution*: a totally ordered sequence of computation steps, where threads take turns doing one or more steps in sequence

Nondeterminism

- An execution is nondeterministic if there is a computation step in which there is a choice what to do next
- Nondeterminism appears naturally when there is concurrent access to shared state

Example of nondeterminism



store

x

$y = 5$

Thread 1

$x = 1$

time

Thread 2

$x = 3$

time

The thread that binds x first will continue, the other thread will raise an exception

Nondeterminism

- An execution is nondeterministic if there is a computation step in which there is a choice what to do next
- Nondeterminism appears naturally when there is concurrent access to shared state
- In the concurrent declarative model when there is only one binder for each dataflow variable or multiple compatible bindings (e.g., to partial values), the nondeterminism is not observable on the store (i.e. the store develops to the same final results)
- This means for correctness we can ignore the concurrency

Scheduling

- The choice of which thread to execute next and for how long is done by a part of the system called the *scheduler*
- A thread is *runnable* if its next statement to execute is not blocked on a dataflow variable, otherwise the thread is *suspended*
- A scheduler is fair if it does not starve a runnable thread, i.e. all runnable threads eventually execute
- Fair scheduling makes it easy to reason about programs and program composition
- Otherwise some correct program (in isolation) may never get processing time when composed with other programs

Example of runnable threads

```
proc {Loop P N}
  if N > 0 then
    {P} {Loop P N-1}
  else skip end
end
thread {Loop
           proc {$} {Show 1} end
          1000}
end
thread {Loop
           proc {$} {Show 2} end
           1000}
end
```

- This program will interleave the execution of two threads, one printing 1, and the other printing 2
- We assume a fair scheduler

Dataflow computation

- Threads suspend on data unavailability in dataflow variables
- The **{Delay X}** primitive makes the thread suspends for X milliseconds, after that, the thread is runnable

```
declare X
{Browse X}
local Y in
thread {Delay 1000} Y = 10*10 end
X = Y + 100*100
end
```

Illustrating dataflow computation

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

- Enter incrementally the values of X0 to X3
- When X0 is bound the thread will compute Y0=X0+1, and will suspend again until X1 is bound

Concurrent Map

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

- This will fork a thread for each individual element in the input list
- Each thread will run only if both the element X and the procedure F is known

Concurrent Map Function

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

- What this looks like in the kernel language:

```
proc {Map Xs F Rs}
      case Xs
      of nil then Rs = nil
      [] X|Xr then R Rr in
         Rs = R|Rr
         thread {F X R} end
         {Map Xr F Rr}
      end
end
```

How does it work?

- If we enter the following statements:

  ```
  declare F X Y Z
  {Browse thread {Map X F} end}
  ```

- A thread executing Map is created.
- It will suspend immediately in the case-statement because X is unbound.
- If we thereafter enter the following statements:

  ```
  X = 1|2|Y
  fun {F X} X*X end
  ```

- The main thread will traverse the list creating two threads for the first two arguments of the list

How does it work?

- The main thread will traverse the list creating two threads for the first two arguments of the list:

  thread {F 1} **end**, and **thread** {F 2} **end**,

After entering:

```
Y = 3|Z
Z = nil
```

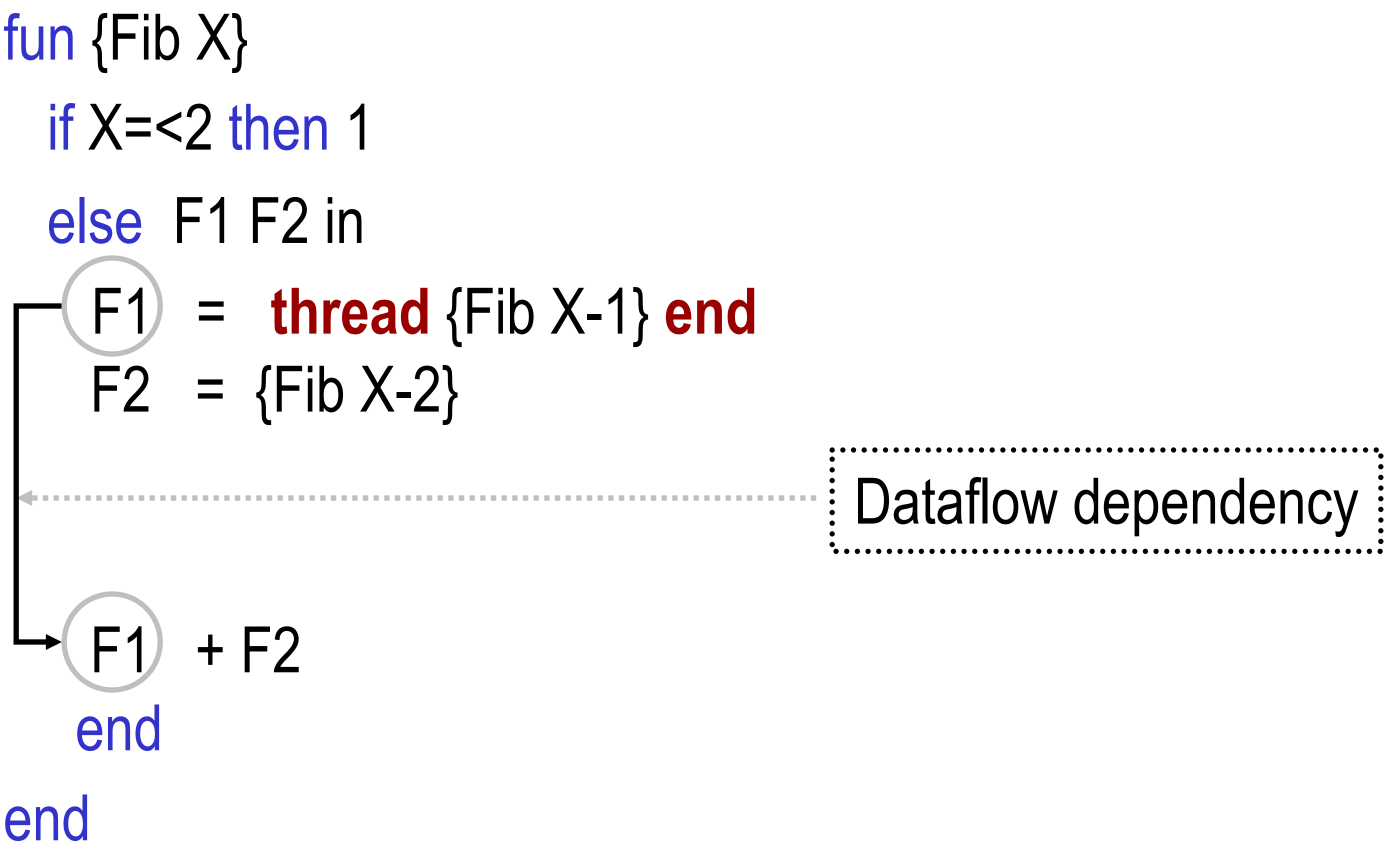
the program will complete the computation of the main thread and the newly created thread **thread** {F 3} **end**, resulting in the final list [1 4 9].

Simple concurrency with dataflow

- Declarative programs can be easily made concurrent
- Just use the thread statement where concurrency is needed

```
fun {Fib X}
   if X=<2 then 1
   else
      thread {Fib X-1} end + {Fib X-2}
   end
end
```

Understanding why

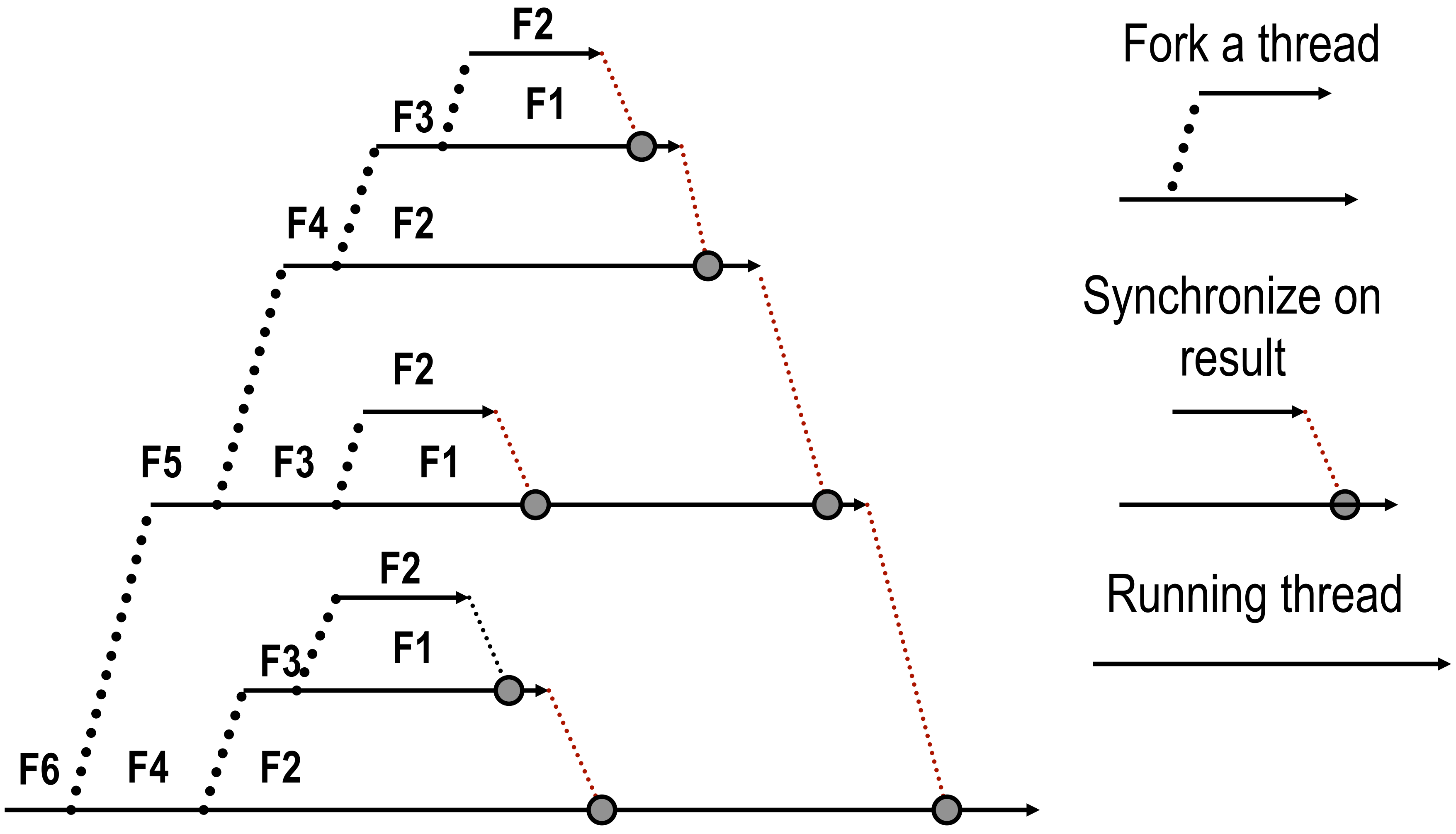


```
fun {Fib X}
   if X=<2 then 1
   else  F1 F2 in
      F1  =  thread {Fib X-1} end
      F2  =  {Fib X-2}

      F1  + F2
    end
end
```

Dataflow dependency

Execution of {Fib 6}



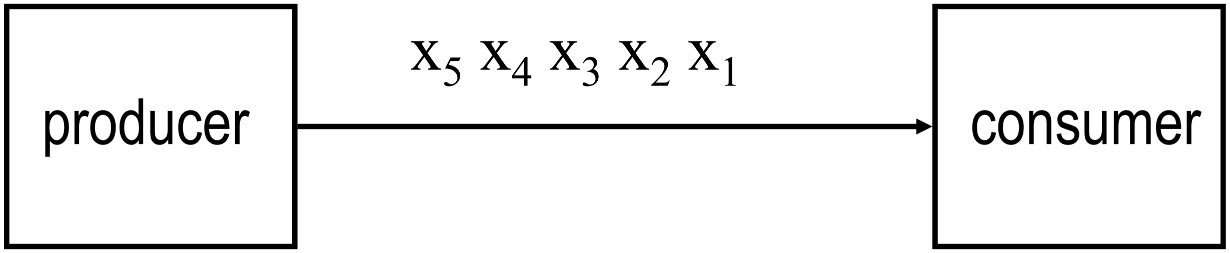
Fork a thread

Synchronize on result

Running thread

Streams

- A stream is a sequence of messages
- A stream is a First-In First-Out (FIFO) channel
- The producer augments the stream with new messages, and the consumer reads the messages, one by one.

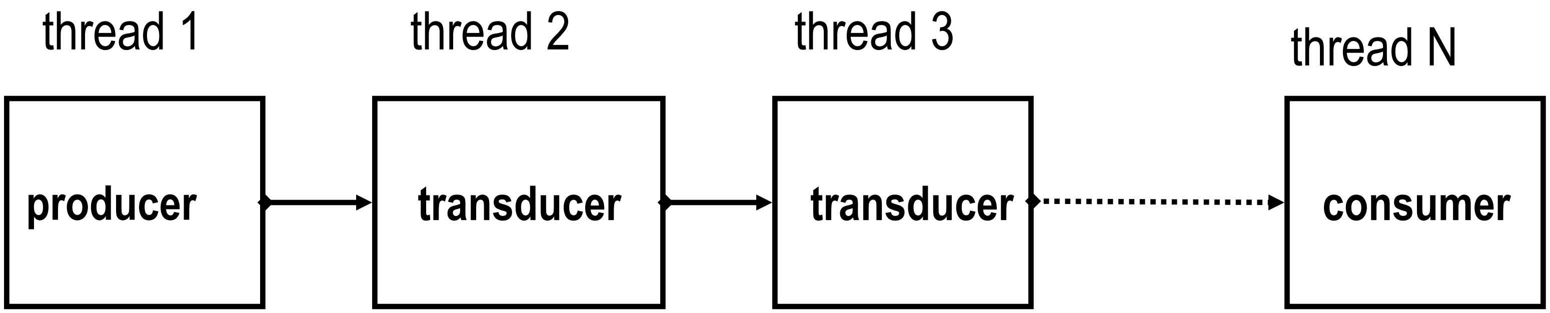


Stream Communication I

- The data-flow property of Oz easily enables writing threads that communicate through streams in a producer-consumer pattern.
- A stream is a list that is created incrementally by one thread (the producer) and subsequently consumed by one or more threads (the consumers).
- The consumers consume the same elements of the stream.

Stream Communication II

- **Producer**, produces incrementally the elements
- **Transducer**(s), transform(s) the elements of the stream
- **Consumer**, accumulates the results



Stream communication patterns

- The producer, transducers, and the consumer can, in general, be described by certain program patterns
- We show various patterns

Producer

```
fun {Producer State}
    if {More State} then
        X = {Produce State} in
        X | {Producer {Transform State}}
    else nil end
end
```

- The definition of *More*, *Produce*, and *Transform* is problem dependent
- State could be multiple arguments
- The above definition is not a complete program!

Example Producer

```
fun {Generate N Limit}
   if N=<Limit then
      N | {Generate N+1 Limit}
   else nil end
end
```

```
fun {Producer State}
   if {More State} then
      X = {Produce State} in
      X | {Producer {Transform State}}
   else nil end
end
```

- The State is the two arguments N and Limit
- The predicate More is the condition N=<Limit
- The Produce function is the identity function on N
- The Transform function (N,Limit) ⇒ (N+1,Limit)

Consumer Pattern

```
fun {Consumer State InStream}
  case InStream
  of nil then {Final State}
  [] X | RestInStream then
    NextState = {Consume X State} in
    {Consumer NextState RestInStream}
  end
end
```

The consumer suspends until InStream is either a cons or a nil

- *Final* and *Consume* are problem dependent

Example Consumer

```
fun {Sum A Xs}
   case Xs
   of nil then A
   [] X|Xr then {Sum A+X Xr}
   end
end
```

```
fun {Consumer State InStream}
   case InStream
   of nil then {Final State}
   [] X | RestInStream then
      NextState = {Consume X State} in
      {Consumer NextState RestInStream}
   end
end
```

- The State is A
- `Final` is just the identity function on State
- `Consume` takes X and State ⇒ X + State

Transducer Pattern 1

```
fun {Transducer State InStream}
   case InStream
   of nil then nil
   [] X | RestInStream then
      NextState#TX = {Transform X State}
      TX | {Transducer NextState RestInStream}
   end
end
```

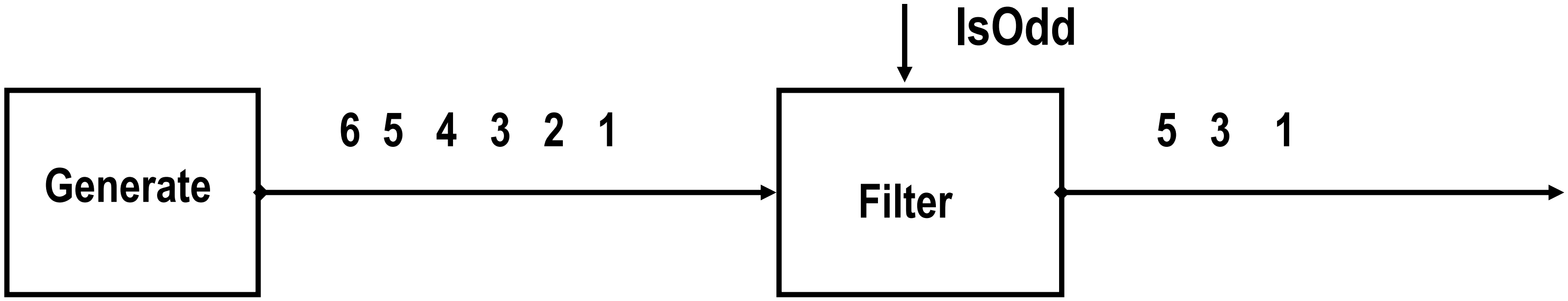
- A transducer keeps its state in State, receives messages on InStream and sends messages on OutStream

Transducer Pattern 2

```
fun {Transducer State InStream}
  case InStream
  of nil then nil
  [] X | RestInStream then
     if {Test X#State} then
        NextState#TX = {Transform X State}
        TX | {Transducer NextState RestInStream}
    else {Transducer State RestInStream} end
  end
end
```

- A transducer keeps its state in State, receives messages on InStream and sends messages on OutStream

Example Transducer



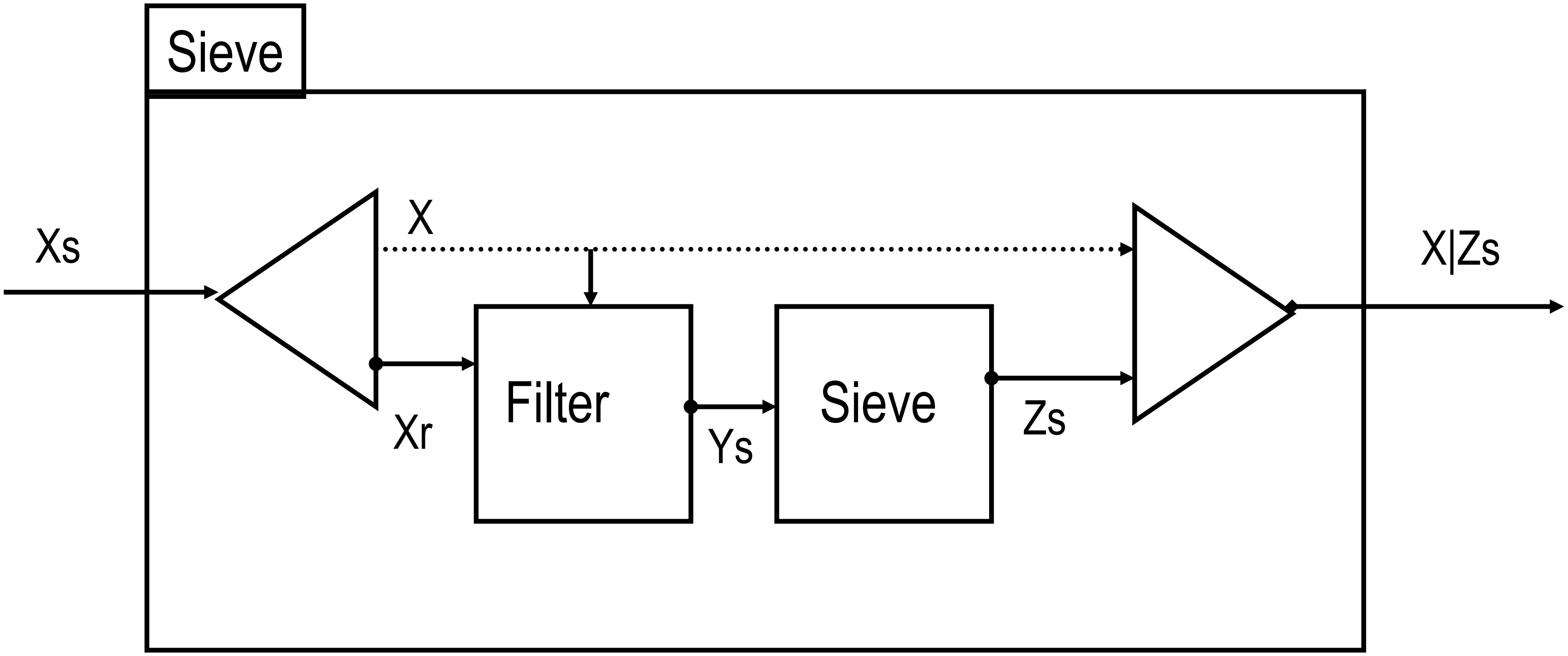
```
fun {Filter Xs F}
  case Xs
  of nil then nil
  [] X|Xr then
    if {F X} then X|{Filter Xr F}
    else {Filter Xr F} end
  end
end
```

Filter is a transducer that takes an Instream and incremently produces an Outstream that satisfies the predicate F

```
local Xs Ys in
thread Xs =  {Generate 1 100} end
thread Ys = {Filter Xs IsOdd} end
thread {Browse Ys} end
end
```

Larger example: The sieve of Eratosthenes

- Produces prime numbers
- It takes a stream 2...N, peals off 2 from the rest of the stream
- Delivers the rest to the next sieve



C. Varela; Adapted with permission from S. Haridi and P. Van Roy

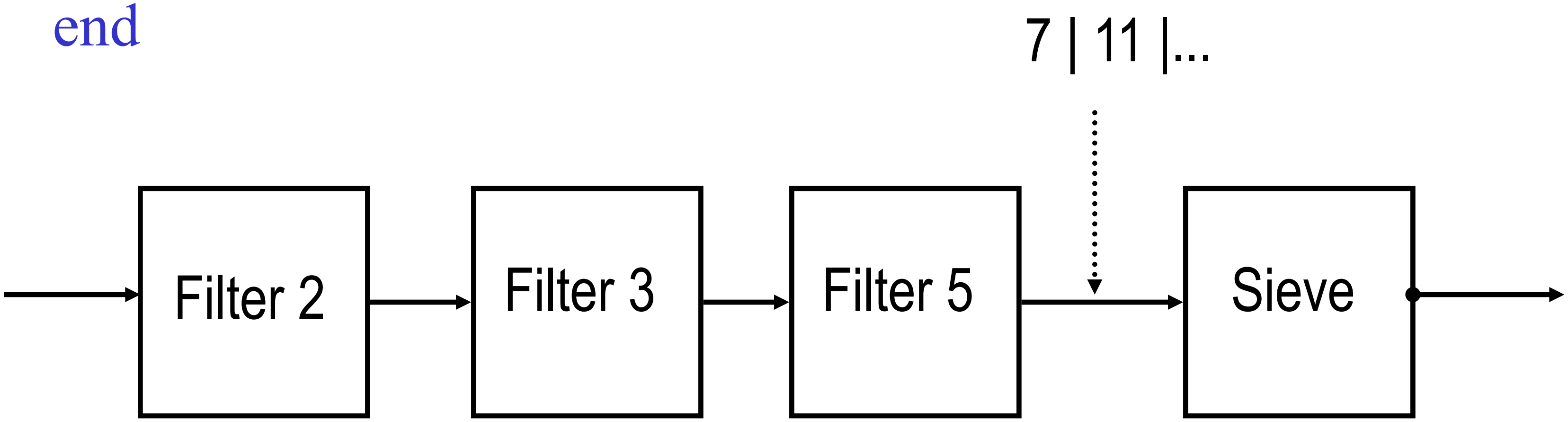
Sieve

```
fun {Sieve Xs}
  case Xs
  of nil then nil
  [] X|Xr then Ys in
    thread Ys = {Filter Xr fun {$ Y} Y mod X \= 0 end} end
    X | {Sieve Ys}
  end
end
```

- The program forks a filter thread on each sieve call

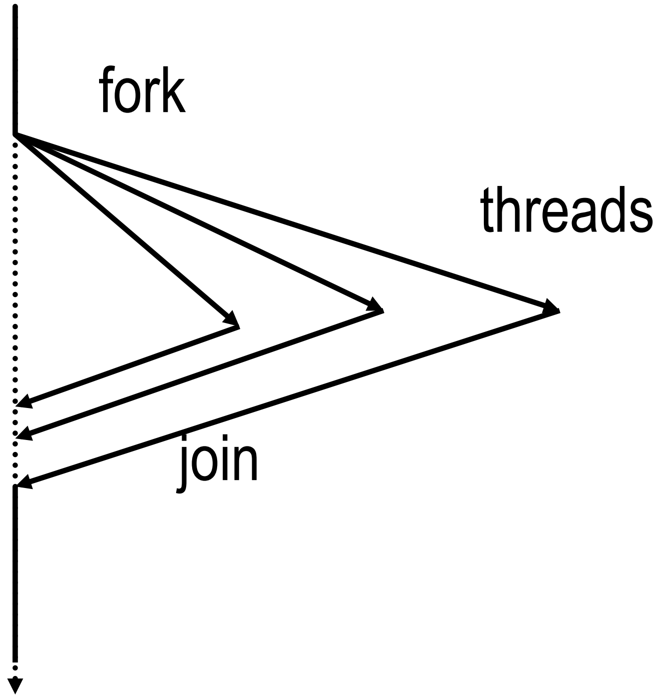
Example call

```
local Xs Ys in
   thread Xs =  {Generate 2 100000} end
   thread Ys = {Sieve Xs} end
   thread for Y in Ys do {Show Y} end end
end
```



Concurrent control abstraction

- We have seen how threads are forked by ’thread ... end’
- A natural question to ask is: how can we join threads?



Termination detection

- This is a special case of detecting *termination of multiple threads*, and making another thread wait on that event.
- The general scheme is quite easy because of dataflow variables:

```
thread ⟨S1⟩  X1 = unit  end
thread ⟨S2⟩   X2 = X1  end
  ...
thread ⟨Sn⟩  Xn = Xn-1 end
{Wait Xn}
% Continue main thread
```

- When all threads terminate the variables X_1 … X_N will be merged together labeling a single box that contains the value **unit**.
- {Wait X_N} suspends the main thread until X_N is bound.

Concurrent Composition

conc S_1 **[]** S_2 **[]** … **[]** S_n **end**

```
{Conc     [ proc{$} S1 end
            proc{$} S2 end
                ...
            proc{$} Sn end]  }
```

- Takes a single argument that is a list of nullary procedures.
- When it is executed, the procedures are forked concurrently. The next statement is executed only when all procedures in the list terminate.

Conc

```
local
  proc {Conc1 Ps I O}
    case Ps of P|Pr then
      M in
      thread {P} M = I end
      {Conc1 Pr M O}
    [] nil then O = I
    end
  end
in
  proc {Conc Ps}
   X in  {Conc1 Ps unit X}
   {Wait X}
   end
end
```

This abstraction takes
a list of zero-argument
procedures and terminate
after all these threads have
terminated

Example

```
local
  proc {Ping N}
    for I in 1..N do
        {Delay 500} {Browse ping}
    end
    {Browse 'ping terminate'}
  end
  proc {Pong N}
    for I in 1..N do
       {Delay 600} {Browse pong}
    end
    {Browse 'pong terminate'}
  end
in .... end
```

```
local
....
in
{Browse 'game started'}
{Conc
[ proc {$} {Ping 1000} end
proc {$} {Pong 1000} end ]}
{Browse ’game terminated’}
end
```

Futures

- A **future** is a read-only capability of a single-assignment variable. For example to create a future of the variable `X` we perform the operation `!!` to create a future `Y`: `Y = !!X`
- A thread trying to use the value of a future, e.g. using `Y`, will suspend until the variable of the future, e.g. `X`, gets bound.
- One way to execute a procedure lazily, i.e. in a demand-driven manner, is to use the operation `{ByNeed +P ?F}`.
- `ByNeed` takes a zero-argument function `P`, and returns a future `F`. When a thread tries to access the value of `F`, the function `{P}` is called, and its result is bound to `F`.
- This allows us to perform demand-driven computations in a straightforward manner.

Example

-
  ```
  declare Y
  {ByNeed fun {$} 1 end Y}
  {Browse Y}
  ```

- we will observe that `Y` becomes a future, i.e. we will see `Y<Future>` in the Browser.

- If we try to access the value of `Y`, it will get bound to `1`.

- One way to access `Y` is by perform the operation `{Wait Y}` which triggers the producing procedure.

Summary of concurrent programming

- There are four basic approaches:
  - Sequential programming (no concurrency)
  - Declarative concurrency (streams in a functional language, Oz)
  - Message passing with active objects (Erlang, SALSA)
  - Atomic actions on shared state (Java)
- The atomic action approach is the *most difficult*, yet it is the one you will probably be most exposed to!
- But, if you have the choice, which approach to use?
  - Use the simplest approach that does the job: sequential if that is ok, else declarative concurrency if there is no observable nondeterminism, else message passing if you can get away with it.