Concurrency control abstractions
(PDCS 9, CPE 5*)

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* Concurrent Programming in Erlang, by J. Armstrong, R. Virding, C. Wikström, M. Williams
Operational Semantics of Actors

\[
\frac{e \rightarrow_{\lambda} e'}{\alpha, [R \triangleright e \triangleright]_a \parallel \mu \quad \frac{[\text{fun}:a]}{} \quad \alpha, [R \triangleright e' \triangleright]_a \parallel \mu}
\]

\[
\alpha, [R \triangleright \text{new}(b) \triangleright]_a \parallel \mu \quad \frac{[\text{new}:a,a']}{\alpha, [R \triangleright a' \triangleright]_a, [\text{ready}(b)]_{a'} \parallel \mu}
\]

\[a' \text{ fresh}\]

\[
\alpha, [R \triangleright \text{send}(a', v) \triangleright]_a \parallel \mu \quad \frac{[\text{snd}:a]}{} \quad \alpha, [R \triangleright \text{nil} \triangleright]_a \parallel \mu \uplus \{\langle a' \leftarrow v \rangle\}
\]

\[
\alpha, [R \triangleright \text{ready}(b) \triangleright]_a \parallel \{\langle a \leftarrow v \rangle\} \uplus \mu \quad \frac{[\text{rcv}:a,v]}{} \quad \alpha, [b(v)]_a \parallel \mu
\]

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AMST Semantics Example

\[ k_0 = [\text{send}(\text{new}(b5), a)]_a \ || \ \{} \]
\[ k_6 = [\text{nil}]_a, [\text{ready}(b5)]_b \ || \ \{ < a \leq 5 > \} \]

\[
\begin{array}{cccc}
  k_0 & \xrightarrow{[\text{new}:a,b]} & k_1 & \xrightarrow{[\text{snd}:a]} & k_2 & \xrightarrow{[\text{rcv}:b,a]} & k_3 & \xrightarrow{[\text{fun}:b]} & k_4 \\
  k_4 & \xrightarrow{[\text{snd}:a,5]} & k_5 & \xrightarrow{[\text{fun}:b]} & k_6
\end{array}
\]

This sequence of (labeled) transitions from \( k_0 \) to \( k_6 \) is called a computation sequence.

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k_0 = [\text{ready(cell(0))}]_a  
\ || \ \{<a=s(7)>, <a=s(2)>, <a=g(c)>\}

Three receive transitions are enabled at k_0.

Multiple enabled transitions can lead to \textit{nondeterministic} behavior.

The set of all computations sequences from k_0 is called the \textit{computation tree} \( \tau(k_0) \).
Actors/SALSA

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

- **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
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.
module cell;

behavior CellTester {

 void act( String[] args ) {
   Cell c = new Cell(0);
   c <- set(2);
   c <- set(7);
   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.
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.
Message handlers
State change.

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

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

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

\[ B_{\text{treeprod}} = \]
\[ \text{rec}(\lambda b. \lambda m. \]
\[ \text{seq}(\text{if}(\text{isnat}(\text{tree}(m))], \]
\[ \text{send}(\text{cust}(m), \text{tree}(m)), \]
\[ \text{let newcust} = \text{new}(B_{\text{joincont}}(\text{cust}(m))), \]
\[ \text{lp} = \text{new}(B_{\text{treeprod}}), \]
\[ \text{rp} = \text{new}(B_{\text{treeprod}}) \text{ in} \]
\[ \text{seq}(\text{send}(\text{lp}, \]
\[ \text{pr}(\text{left}(\text{tree}(m)), \text{newcust})), \]
\[ \text{send}(\text{rp}, \]
\[ \text{pr}(\text{right}(\text{tree}(m)), \text{newcust}))), \]
\[ \text{ready}(b)) \]
Join Continuation in AMST

$$B_{\text{joincont}} = \lambda \text{cust.} . \lambda \text{firstnum.} . \text{ready}(\lambda \text{num.} . \text{seq}(\text{send}(\text{cust}, \text{firstnum} \times \text{num}), \text{ready}(\text{sink})))$$
Sample Execution

(a)\[f(\text{tree, cust})\]

(b)\[\begin{align*} &f(\text{left(tree, JC)}) \\
&f(\text{right(tree, JC)})\end{align*}\]
Sample Execution

f(left(tree),JC)

cust

firstnum

cust

(c)

firstnum

cust

(d)

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Sample Execution

(e) Cust

(f) Cust

num

firstnum

firstnum * num
module treeprod;

behavior TreeProduct {

  void compute(Tree t, UniversalActor c) {
    if (t.isLeaf()) c <- result(t.value());
    else {
      JoinCont newCust = new JoinCont(c);
      TreeProduct lp = new TreeProduct();
      TreeProduct rp = new TreeProduct();
      lp <- compute(t.left(), newCust);
      rp <- compute(t.right(), newCust);
    }
  }
}

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module treeprod;
behavior JoinCont {

  UniversalActor cust;
  int first;
  boolean receivedFirst;

  JoinCont(UniversalActor cust){
    this.cust = cust;
    this.receivedFirst = false;
  }

  void result(int v) {
    if (!receivedFirst){
      first = v; receivedFirst = true;
    } else // receiving second value
      cust <- result(first*v);
  }
}

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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>
Actor Languages Summary

- Actors are concurrent entities that react to messages.
  - State is completely encapsulated. There is no shared memory!
  - Message passing is asynchronous.
  - Actors can create new actors. 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.
- SALSA extends an object-oriented programming language (Java) with universal actors. State is explicit, encapsulated in instance variables. Control loop is implicit: ending a message handler, signals readiness to receive a new message. Actors are garbage-collected.
- 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. Ending a function denotes process (actor) termination.
Causal order

• In a sequential program all execution states are totally ordered

• In a concurrent program all execution states of a given actor are totally ordered

• The execution state of the concurrent program as a whole is partially ordered
Total order

- In a sequential program all execution states are totally ordered.

sequential execution

computation step
In a concurrent program all execution states of a given actor are totally ordered.

The execution state of the concurrent program is partially ordered.

Diagram:
- Create new actor
- Send a message
- Computation step

Actor A1
Actor A2
Actor A3
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 asynchronous message passing
  – Messages can arrive or be processed in an order different from the sending order.
Example of nondeterminism

Actor a can receive messages $m_1$ and $m_2$ in any order.
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 a third-party 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().*
Causal order in the actor model

1. Receive a message with a token
2. Bind a token
3. Create a new actor
4. Computation step

actors: A1, A2, A3
Deterministic Cell Tester
Example

```java
module cell;

behavior TokenCellTester {
    void act(String[] args) {
        Cell c = new Cell(0);
        standardOutput <- print("Initial Value:") @
        c <- get() @
        standardOutput <- println(token) @
        c <- set(2) @
        standardOutput <- print("New Value:") @
        c <- get() @
        standardOutput <- println(token);
    }
}
```

@ syntax enforces a sequential order of message execution.

token can be optionally used to get the return value (completion proof) of the previous message.
Cell Tester Example with Named Tokens

module cell;

behavior NamedTokenCellTester {
    void act(String args[]){

        Cell c = new Cell(0);
        token p0 = standardOutput <- print("Initial Value:");
        token t0 = c <- get();
        token p1 = standardOutput <- println(t0):waitfor(p0);
        token t1 = c <- set(2):waitfor(t0);
        token p2 = standardOutput <- print("New Value:"):waitfor(p1);
        token t2 = c <- get():waitfor(t1);
        standardOutput <- println(t2):waitfor(p2);
    }
}

We use p0, p1, p2 tokens to ensure printing in order.

We use t0, t1, t2 tokens to ensure cell messages are processed in order.
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:

```java
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.*
Example: Acknowledged Multicast

\[
\text{join\{ a}_1 \leftarrow \text{m}_1(); \ a_2 \leftarrow \text{m}_2(); \ \ldots \ a_n \leftarrow \text{m}_n(); \ } \ \@ \ 
\text{cust} \leftarrow \text{n}(\text{token});
\]
## Lines of Code Comparison

<table>
<thead>
<tr>
<th>Acknowledged Multicast</th>
<th>Java</th>
<th>Foundry</th>
<th>SALSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>168</td>
<td>100</td>
<td>31</td>
</tr>
</tbody>
</table>
First Class Continuations

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

• For example:

```c
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.
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);
    }
}

delm Calvin

fib(15)

is syntactic sugar for:

    self <- fib(15)
Fibonacci Example

```java
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);
}
```

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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

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module treeprod;

behavior JoinTreeProduct { 
    int add(int[] results) {
        return results[0] + results[1];
    }

    int compute(Tree t) {
        if (t.isLeaf()) return t.value();
        else {
            JoinTreeProduct lp = new JoinTreeProduct();
            JoinTreeProduct rp = new JoinTreeProduct();
            join {
                lp <- compute(t.left());
                rp <- compute(t.right());
            } @ add(token) @ currentContinuation;
        }
    }
}

Notice we use token-passing continuations (@, token), a join block (join), and a first-class continuation (currentContinuation).
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.
Example program and mailbox (head at top):

```plaintext
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

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.)
counter(Val) ->
    receive
    increment -> counter(Val+1);
    {From,value} ->
        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, value 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

In this example, a binary tree is represented as a tuple
  {Left, Right}, or as a Number, e.g.,
  {{{5, 6}, 2}, {3, 4}}

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

```plaintext
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

```erlang
goto 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

```hrl
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
    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.

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46. Download and execute the reference cell and tree product examples in SALSA and Erlang.

47. Write a solution to the Flavius Josephus problem in SALSA and Erlang. A description of the problem is at CTM Section 7.8.3 (page 558).

48. PDCS Exercise 9.6.6 (page 204).

49. How would you implement token-passing continuations, join blocks, and first-class continuations in Erlang?

50. How would you implement selective receive in SALSA?