Concurrency control abstractions
(PDCS 9, CPE 5*)

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October 17, 2017

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

\[
\begin{align*}
\frac{e \rightarrow^{\lambda} e'}{\alpha, [R \triangleright e \leftarrow]_a || \mu \quad \xrightarrow{\text{fun:a}} \quad \alpha, [R \triangleright e' \leftarrow]_a || \mu}
\end{align*}
\]

\[
\begin{align*}
\alpha, [R \triangleright \text{new}(b) \leftarrow]_a || \mu \quad \xrightarrow{\text{new:a,a'}} \quad \alpha, [R \triangleright a' \leftarrow]_a, [\text{ready}(b)]_{a'} || \mu
\end{align*}
\]

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

\[
\alpha, [R \triangleright \text{ready}(b) \leftarrow]_a || \{\langle a \leftarrow v \rangle\} \cup \mu \quad \xrightarrow{\text{rcv:a,v}} \quad \alpha, [b(v)]_a || \mu
\]
AMST Semantics Example

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

This sequence of (labeled) transitions from \(k_0\) to \(k_6\) is called a \textit{computation sequence}. 
Nondeterministic Behavior

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

Three receive transitions are enabled at \( k_0 \).

Multiple enabled transitions can lead to nondeterministic behavior.

The set of all computations sequences from \( k_0 \) is called the 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
Reference Cell Example

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

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

**Encapsulated state Content.**

**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])  % receive waits until a message is available.
  end.

Actor creation (spawn)
Message passing (!)
Join Continuations

Consider:

\[
\text{treeprod} = \text{rec}(\lambda f. \lambda \text{tree}.
\quad \text{if}(\text{isnat}(\text{tree}),
\quad \quad \text{tree},
\quad \quad f(\text{left}(\text{tree}))*f(\text{right}(\text{tree})))
\]

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

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

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

(a) $f(\text{tree}, \text{cust})$

(b) $f(\text{left(tree)}, \text{JC})$, $f(\text{right(tree)}, \text{JC})$
Sample Execution

$$f(\text{left(tree)},JC)$$

(c)  

(d)
Sample Execution

(e) Cust

(f) firstnum * num
module jctreeprod;

import tree.Tree;

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);
        }
    }
}
module jctreeprod;

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.

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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
Causal order in the actor model

- In a concurrent program all execution states of a given actor are totally ordered.
- The execution state of the concurrent program is partially ordered.
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`).*
• @ 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

create new actor

bind a token

receive a message with a token

computation step
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 <- println("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.
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 cell messages are processed in order.

We use t0, t1, t2 tokens to ensure printing 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:

```
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

\[ \text{join}\{ a_1 \leftarrow m_1(); \ a_2 \leftarrow m_2(); \ \ldots \ a_n \leftarrow m_n(); \} \ @ \]
\[ \text{cust} \leftarrow n(\text{token}); \]
## 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);
    }
}

fib(15)

is syntactic sugar for:

self <- fib(15)
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);
  }
}
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
Tree Product Behavior Revisited

module treeprod;
import tree.Tree;

behavior JoinTreeProduct {

    int multiply(Object[] results){
        return (Integer) results[0] * (Integer) 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());
            } @ multiply(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.
Selective Receive Example

Example program and mailbox (head at top):

```
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 2\textsuperscript{nd} 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
  \{\text{Left, Right}, \text{Customer}\} \to
  \text{NewCust} = \text{spawn}(\text{treeprod}, \text{join}, [\text{Customer}]),
  \text{LP} = \text{spawn}(\text{treeprod}, \text{treeprod}, []),
  \text{RP} = \text{spawn}(\text{treeprod}, \text{treeprod}, []),
  \text{LP}!\{\text{Left}, \text{NewCust}\},
  \text{RP}!\{\text{Right}, \text{NewCust}\};
  \{\text{Number, Customer}\} \to
  \text{Customer} ! \text{Number}
end

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

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

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

sleep(Time) suspends the current actor for Time milliseconds.
receive
click ->
  receive
    click ->
      double_click
    after double_click_interval() ->
      single_click
  end
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.
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
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.
Exercises

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?