Distributed systems abstractions (PDCS 9, CPE 6*)

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

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.

Tree Product Behavior in AMST

$B_{treeprod}$ =

```
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)))
```

Join Continuation in AMST

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

Tree Product Behavior in SALSA

```
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);
      }
   }

}
```

Join Continuation in SALSA

```
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);
    }
}
```

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.
```

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

- `@` 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 );
```

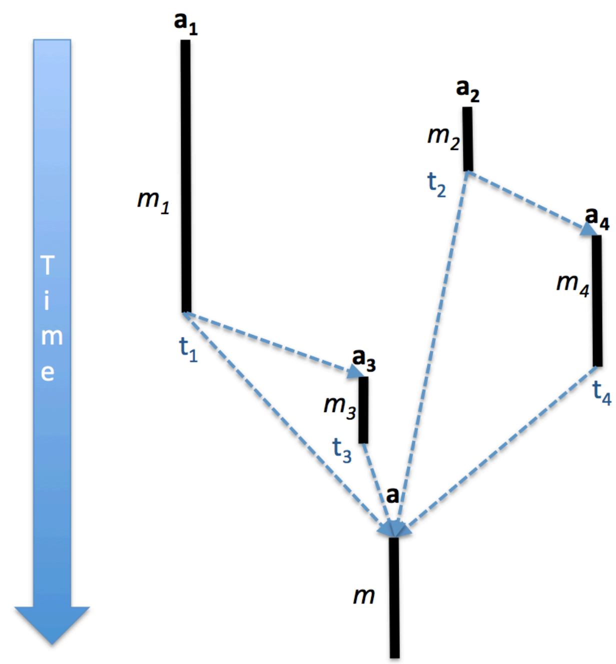
Named Tokens

- 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`.

Tree Product Behavior Revisited

Notice we use token-passing continuations (`@`,`token`), a join block (`join`), and a first-class continuation (`currentContinuation`).

```
module treeprod;

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;
      }
    }
}
```

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,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
```

`{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.

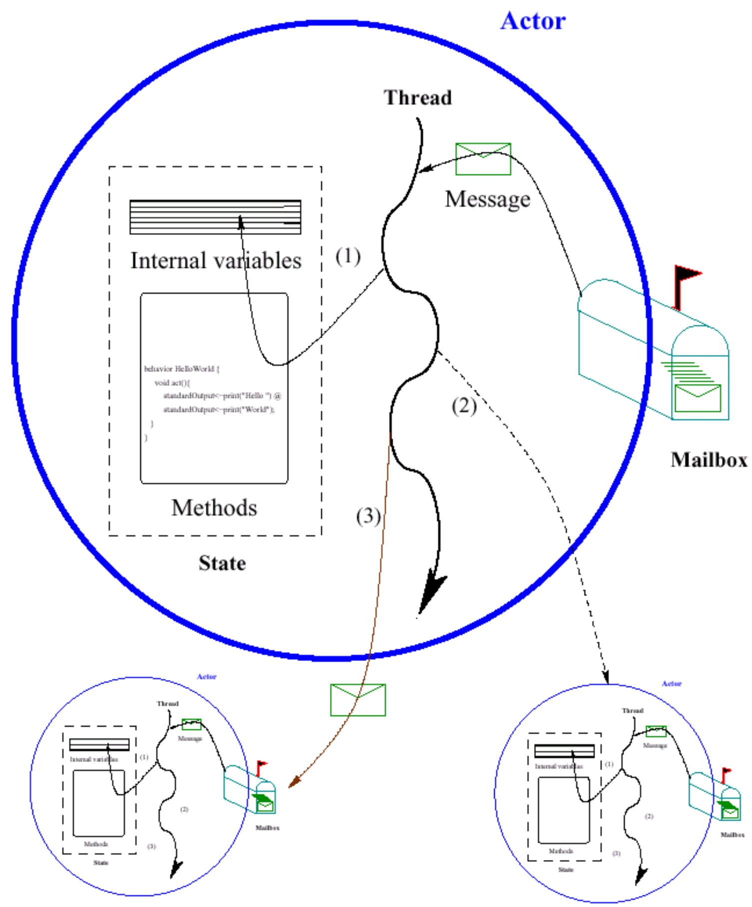
Overview of programming distributed systems

- 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.

SALSA Revisited

- 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 Intriguing Technology Track,* 36(12), pp 20-34.



- Advantages for distributed computing
  - Actors encapsulate state and concurrency:
    - Actors can run in different machines.
    - Actors can change location dynamically.
  - Communication is asynchronous:
    - Fits real world distributed systems.
  - Actors can fail independently.

World-Wide Computer (WWC)

- Distributed computing platform.
- Provides a run-time system for *universal actors*.
- Includes naming service implementations.
- Remote message sending protocol.
- Support for universal actor migration.

Abstractions for Worldwide Computing

- *Universal Actors*, a new abstraction provided to guarantee unique actor names across the Internet.

- *Theaters*, extended Java virtual machines to provide execution environment and network services to universal actors:
  - Access to local resources.
  - Remote message sending.
  - Migration.

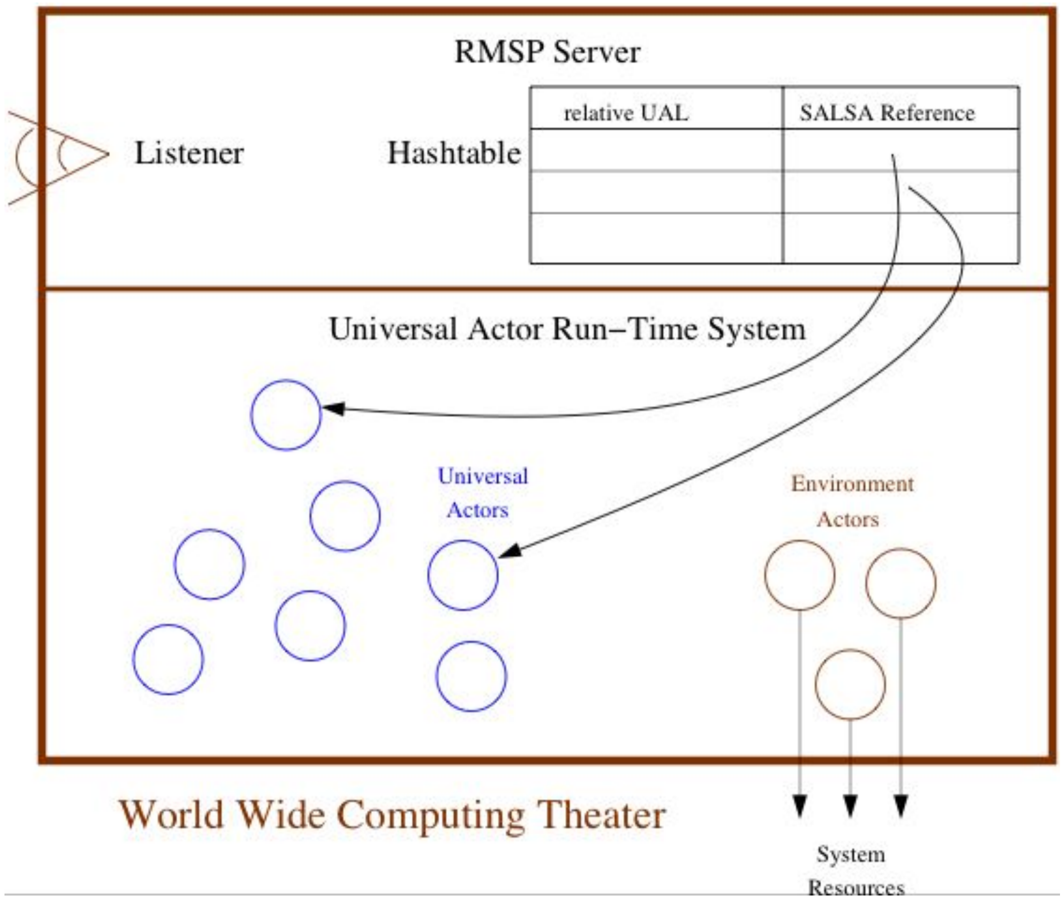
- *Naming service*, to register and locate universal actors, transparently updated upon universal actor creation, migration, garbage collection.

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:

$$\texttt{uan://}\underbrace{\texttt{wwc.cs.rpi.edu:3030}}_{\text{Name server address and (optional) port.}}\underbrace{\texttt{/cvarela/calendar}}_{\text{Unique relative actor name.}}$$

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:

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

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 (args[0], 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.
```

Exercises

51. How would you implement the join continuation linguistic abstraction considering different potential distributions of its participating actors?
52. CTM Exercise 11.11.3 (page 746). Implement the example using SALSA/WWC and Erlang.
53. PDCS Exercise 9.6.3 (page 203).
54. PDCS Exercise 9.6.9 (page 204).
55. PDCS Exercise 9.6.12 (page 204).
56. Write the same distributed programs in Erlang.