Mobility, garbage collection, load balancing, visualization (SALSA)  
Fault-tolerance, hot code loading (Erlang)  
(PDCS 9; CPE 7*)

Carlos Varela  
Rensselaer Polytechnic Institute

October 22, 2021

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

C. Varela
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.
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.
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:

  rmosp://wwc.cs.rpi.edu:4040

  Theater’s IP address and (optional) port.
Migration

• Obtaining a remote actor reference and migrating the actor.

TravelAgent a = (TravelAgent) TravelAgent.getReferenceByName("uan://myhost/ta");

a <- migrate("yourhost:yourport") @ a <- printItinerary();
module migrate;

behavior Migrate {

    void print() {
        standardOutput<-println( "Migrate actor is here." );
    }

    void act( String[] args ) {

        if (args.length != 3) {
            standardError<-println("Usage: salsa migrate.Migrate <UAN> <srcUAL> <destUAL>");
            return;
        }

        UAN uan = new UAN(args[0]);
        UAL ual = new UAL(args[1]);

        Migrate migrateActor = new Migrate() at (uan, ual);

        migrateActor<-print() @
        migrateActor<-migrate( args[2] ) @
        migrateActor<-print();
    }
}
Migration Example

• The program must be given *valid* universal actor name and locators.
  – Appropriate name server and theaters must be running.
  – Theater must be run from directory with access to the code for the migrating actor’s behavior.

• After remotely creating the actor. It sends the `print` message to itself before migrating to the second theater and sending the message again.
Compilation and Execution

```
$ salsac migrate/Migrate.salsa
SALSA Compiler Version 1.0: Reading from file Migrate.salsa . . .
SALSA Compiler Version 1.0: SALSA program parsed successfully.
SALSA Compiler Version 1.0: SALSA program compiled successfully.
$ salsa migrate.Migrate
Usage: salsa migrate.Migrate <UAN> <srcUAL> <destUAL>
```

1. **Compile** `Migrate.salsa` file into `Migrate.java`, and then **bytecode** (`class` files.)

2. **Execute** Name Server

3. **Execute** Theater 1 and Theater 2 (with access to `migrate` directory)

4. **Execute** Migrate in any computer with Internet access
Migration Example

The actor will print "Migrate actor is here." at theater 1 then at theater 2.
# World Migrating Agent Example

<table>
<thead>
<tr>
<th>Host</th>
<th>Location</th>
<th>OS/JVM</th>
<th>Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td>yangtze.cs.uiuc.edu</td>
<td>Urbana IL, USA</td>
<td>Solaris 2.5.1 JDK 1.1.6</td>
<td>Ultra 2</td>
</tr>
<tr>
<td>vulcain.ecoledoc.lip6.fr</td>
<td>Paris, France</td>
<td>Linux 2.2.5 JDK 1.2pre2</td>
<td>Pentium II 350Mhz</td>
</tr>
<tr>
<td>solar.isr.co.jp</td>
<td>Tokyo, Japan</td>
<td>Solaris 2.6 JDK 1.1.6</td>
<td>Sparc 20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local actor creation</td>
<td>386(us)</td>
</tr>
<tr>
<td>Local message sending</td>
<td>148(us)</td>
</tr>
<tr>
<td>LAN message sending</td>
<td>150-160 ms</td>
</tr>
<tr>
<td>WAN message sending</td>
<td>20-30 s</td>
</tr>
<tr>
<td>LAN minimal actor migration</td>
<td>2-3 s</td>
</tr>
<tr>
<td>LAN 100Kb actor migration</td>
<td>240-250 ms</td>
</tr>
<tr>
<td>WAN minimal actor migration</td>
<td>3-7 s</td>
</tr>
<tr>
<td>WAN 100Kb actor migration</td>
<td>25-30 s</td>
</tr>
</tbody>
</table>
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.
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 );
  }
}

C. Varela
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");
        }
    }
}
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:


Challenge 1: Actor GC vs. Object GC

Actor Reference Graph

Passive Object Reference Graph
Challenge 2: Non-blocking communication

- Following references to mark live actors is not safe!

An example of mutation and asynchronous delivery of message
Challenge 2: Non-blocking communication

- Following references to mark live actors is not safe!
- What can we do?
  - We can *protect the reference from deletion* and *mark the sender live* until the sender knows the message has arrived.
Challenge 2: Non-blocking communication (continued)

- How can we guarantee the safety of an actor referenced by a message?
- The solution is to *protect the reference from deletion* and *mark the sender live* until the sender knows the message has arrived.
Challenge 3: Distribution and Mobility

• What if an actor is remotely referenced?

  – We can *maintain an inverse reference list* (only visible to the garbage collector) to indicate whether an actor is referenced.

  – Three operations change inverse references: *actor creation*, *reference passing*, and *reference deletion*.

  – The inverse reference registration must be based on *non-blocking* and *non-First-In-First-Out* communication!
The Pseudo Root Approach

• Pseudo roots:
  – Treat unblocked actors, migrating actors, and roots as pseudo roots.
  – Map *in-transit messages and references* into *protected references* and *pseudo roots*
  – Use inverse reference list (only visible to garbage collectors) to identify remotely referenced actors

• Actors which are not reachable from any pseudo root are garbage.
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


Middleware Architecture

Application Layer
- Component
- Component
- Component

Virtual Network Layer (IOS Agent)
- Profiling Module
  - Component Monitor
  - Local Profiling Information

- Protocol Module
  - CPU Monitor
  - Network Monitor
  - Join/Leave Protocol
  - Communication Protocol

- Decision Module
  - Split/Merge Strategies
  - Migration Strategies
  - Replication Strategies

Physical Layer
- CPU
- Network
- Memory

Component Profiling API
- Component Profiling

Reconfiguration Requests
- Inter-IOS Agent Communication

Carlos Varela
IOS Architecture

• IOS middleware layer
  
  – A Resource Profiling Component
    • Captures information about actor and network topologies and available resources
  
  – A Decision Component
    • Takes migration, split/merge, or replication decisions based on profiled information
  
  – A Protocol Component
    • Performs communication with other agents in virtual network (e.g., peer-to-peer, cluster-to-cluster, centralized.)
A General Model for Weighted Resource-Sensitive Work-Stealing (WRS)

- Given:
  A set of resources, \( R = \{ r_0 \ldots r_n \} \)
  A set of actors, \( A = \{ a_0 \ldots a_n \} \)
  \( \omega \) is a weight, based on importance of the resource \( r \) to the performance of a set of actors \( A \)

\[
0 \leq \omega(r,A) \leq 1
\]
\[
\sum_{r}^{\text{all}} \omega(r,A) = 1
\]

\( \alpha(r,f) \) is the amount of resource \( r \) available at foreign node \( f \)
\( \nu(r,l,A) \) is the amount of resource \( r \) used by actors \( A \) at local node \( l \)
\( M(A,l,f) \) is the estimated cost of migration of actors \( A \) from \( l \) to \( f \)
\( L(A) \) is the average life expectancy of the set of actors \( A \)

- The predicted increase in overall performance \( \Gamma \) gained by migrating \( A \) from \( l \) to \( f \), where \( \Gamma \leq 1 \):

\[
\Delta(r,l,f,A) = (\alpha(r,f) - \nu(r,l,A)) / (\alpha(r,f) + \nu(r,l,A))
\]
\[
\Gamma = \sum_{r}^{\text{all}} (\omega(r,A) * \Delta(r,l,f,A)) - M(A,l,f)/(10+\log L(A))
\]

- When work requested by \( f \), migrate actor(s) \( A \) with greatest predicted increase in overall performance, if positive.
Impact of Process/Actor Granularity

Experiments on a dual-processor node (SUN Blade 1000)
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:

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:


Overview Architecture

Java Source

Java Compiler

Java Bytecode  Entity Specification File

OVI

Compile Time

Instrumented Bytecode  Instrumented Bytecode  Instrumented Bytecode

OVD

Run Time

OVP  OVP  OVP

Visualization Module  Visualization Module
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 WWCSys is wwc.messaging.WWCSys$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
2D-Mesh application topology
Hypercube application topology
Visualizing distribution and mobility
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})
-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 -> 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.
  ...
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
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.

C. Varela 42
Node monitoring

- To monitor a node:

  \[
  \text{monitor\_node}(\text{Node}, \text{Flag})
  \]

  If `Flag` is true, monitoring starts. If false, monitoring stops. When a monitored node fails, \{\text{nodedown}, \text{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:

  \[
  \text{Agent} = \text{spawn}(\text{host}, \text{travel}, \text{agent}, []);
  \]

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

  \[
  \text{Agent} = \text{spawn\_link}(\text{host}, \text{travel}, \text{agent}, []);
  \]

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:

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

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

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

57. Download and execute the `Migrate.salsa` example.

58. Download OverView and visualize a Fibonacci computation in SALSA. Observe garbage collection behavior.

59. Download social networking example (PDCS Chapter 11) in SALSA and execute it in a distributed setting.

60. PDCS Exercise 11.8.2 (page 257).

61. Create a ring of linked actors in Erlang.
   a. Cause one of the actors to terminate abnormally and observe default group failure behavior.
   b. Modify default error behavior so that upon an actor failure, the actor ring reconnects.

62. Modify the cell example, so that a new “get_and_set” operation is supported. Dynamically (as cell code is running) upgrade the cell module code to use your new version.