Towards Formalising Erlang Failure and Failure Detection

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Declaration

I, the undersigned, declare that the dissertation entitled:

Towards Formalising Erlang Failure and Failure Detection

submitted is my work, except where acknowledged and referenced.

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27 May 2011

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Abstract

Lately, more emphasis is being put on building fault-tolerant parallel systems. This fact can be clearly seen from the number of companies that are opting to develop their systems in Erlang; a parallel language which is renowned for its error handling capabilities. A sound understanding of a system's behaviour when errors occur is the key to developing truly fault-tolerant software.

This dissertation investigates Erlang's error handling mechanisms so as to better understand how Erlang behaves in the presence of errors. A formal model is defined in order to provide a precise and unambiguous description of the behaviour of these mechanisms. The correctness of the model is evaluated by considering a number of Erlang programs and comparing the behaviour as described by the model with that of actual Erlang. Ultimately, the defined model is animated through an evaluator.

Contents

List of Figures

List of Tables

1. Introduction

In the past few years, there has been cosiderable interest in concurrent programming languages such as Erlang. This fact is clearly reflected in the increasing number of companies that are opting to use Erlang in their systems. Among such systems one finds Facebook's chat service, Amazon's SimpleDB and Yahoo's bookmarking service Delicious. Undoubtedly, one of the driving factors behind Erlang's success lies in the fact that it enables developers to build fault-tolerant systems using really simple constructs.

Understanding the behaviour of Erlang systems in the presence of errors may not always be an easy feat. This is even more so when considering the fact that due to the parallel nature of Erlang systems the interleaving of processes may result in different outputs even when the same error occurs at consecutive executions of a system. Nonetheless, a sound understanding of a system's error handling behaviour is the cornerstone to the development of truly reliable software.

Experience has shown that lack of understanding of a system's behaviour in the presence of errors is one of the contributing factors behind many system failures. One classic example is the Ariane 5 space shuttle which was shred to pieces due to an unhandled exception[4]. Additionally, [5] claims that 50% of all system failures in telephone switching applications are caused by faults in exception handling algorithms.

In order to ensure a higher degree of reliability, the computing community has lately started to adopt formal methods for system specification and modelling. The main goal of a model is to faithfully mirror the behaviour of a system. One of the strengths in models stems from the fact that they are able to abstract away from the complex details of a system illustrating only the relevant aspects which need to be checked. For instance, whereas programs are concerned with language syntax and resource allocation, when building models these details are ignored and more emphasis is put on interactions, actions and concurrency[1]. The simpler nature of the model makes it much easier to reason about the behaviour of the system in various situations. Besides that, the reduction in complexity also provides a better understanding of the program's behaviour.

Ideally a model is specified before a new programming language is implemented since this yields a better language design. In addition, the simplistic nature of the model provides future language learners a clearer definition of what the programming constructs are expected to do. However, in most cases no language models are specified prior to the implementation of a new programming language. Such was the case when Erlang was born.

As a result, even though Erlang makes use of really simple error handling constructs, sometimes it may not be easy to reason about the behaviour of Erlang systems in the presence of errors. This is mainly due to the fact that Erlang's error handling mechanisms differ significantly from the ones found in mainstream programming languages.

One distinct characteristic of Erlang's error handling behaviour lies in the fact that apart from handling errors locally, Erlang is also able to handle errors remotely. When using Erlang's local error handling mechanisms, errors are handled by the same process in which they occur. This is done by using the try-catch statement, as shown in the following program:

```
try
    %% ****code****
catch
    %% error handling code
end.
```

Listing 1.1: Local Error Handling

When using remote error handling, two seperate processes are used. One process will be responsible to execute the `*** code ****` part. If an error occurs, this process would simply fail without attempting to recover from the error. The error would then be handled by another different process. A simple program which makes use of Erlang's remote error handling constructs is the following:

```
%% spawn a new process to handle errors
spawn_link(?MODULE,errorHandler,[Pid]),

%% *** code ****.
```

Listing 1.2: Remote Error Handling

In this case, Erlang will first spawn a new process which will be responsible of handling any errors that might occur while executing the `*** code ****` part. After spawning the “error handling” process, the system continues to execute the rest of the program.

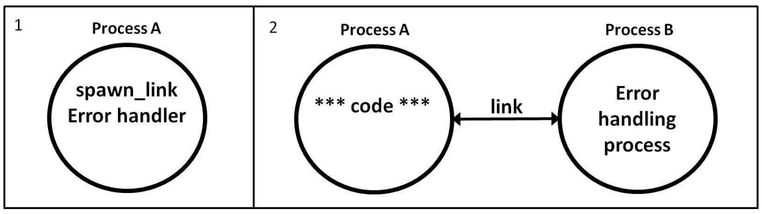


Figure 1.1: System implemented in 1.2

Here, it is important to note that extra attention must be given when building systems which make use of the remote error handling constucts. This is because the parallel nature of these systems may sometimes yield to unexpected behaviour. For instance, let’s consider the two programs that have been presented so far. At first glance, the program described in Listing 1.1 gives the impression that it should always behave in the exact same way as the one described in Listing 1.2. However, in truth there exist some subtle differences between the two programs.

At this point, it is nigh on impossible to identify the underlying cause that leads the two programs to behave differently. This problem brings to light the fact that even though both programs make use of really simple constructs understanding the behaviour of such systems in the presence of errors is not as straightforward as it might seem. Hence, defining a model for Erlang’s error handling constructs would definitely provide a valuable tool to correctly understand the behaviour of such systems.

1.1 Aims and Objectives

The primary aim of this project is to study the mechanisms behind Erlang's renowned error handling capabilities. Ultimately, a model is defined so as to get a better understanding of Erlang's distinct error handling mechanisms. The underlying reasons behind defining such model, is that a model is able to :

Offer a better insight - The simplistic nature of the defined model makes it easier to reason about the behaviour of Erlang's error handling constructs. This is because, through the model, it becomes really straightforward to get a detailed step-by-step description of how systems which make use of these constructs might behave. Even though the primary aim of models is to serve as a tool upon which analysis and verification can be performed, even the act itself of defining the model may reveal certain subtleties which may lead to unexpected behaviour.

Explain the cause of unexpected behaviour - The model is also capable of describing the cause of why a system behaved in an unexpected way. This is because it enables us to analyse what went wrong through a retracing of the system in execution.

Predict system's behaviour - Through the model it becomes possible to foresee how a particular system will behave. Exhaustive analysis of the model is able to surface any faults that could arise while the system is running. Moreover, since the model is able to provide a step-by-step description of how an Erlang system behaves it enables us to identify those sequences of events that may lead to any faulty behaviour.

Lay the foundations for a semantic theory - One of the strengths of a formal model is that it provides an accurate and unambiguous description of the behaviour of specific constructs. Therefore, whereas informal semantics definitions fall short in ensuring that two different syntactic systems behave in the same way, a model is able to ascertain if the two different systems are truly equivalent or not.

1.2 Methodology

The main focus of this work is to define a model for Erlang's error handling constructs. The steps taken to achieve this goal are the following:

1. Obtain a good understanding of Erlang's error handling mechanisms focusing on the different constructs that are used to build fault-tolerant systems.
2. Define a mathematical model to faithfully describe the different error handling constructs that are incorporated within Erlang.
3. Animate the defined model through an evaluator.
4. Evaluate the correctness of the defined model. This is done by considering a number of different Erlang systems and comparing the behaviour as described by the model with the way the program behaves when run on the Erlang VM.

1.3 Dissertation Overview

This dissertation is organized as follows:

Chapter 2 descibes the most basic concepts needed to fully understand the motivation behind this work. Primarily, it outlines those characteristics that make Erlang an ideal language for implementing fault-tolerant systems. It then gives a brief overview of the Erlang language, introducing those constructs for which a formal semantic definition is defined in this project. A number of pairs of simple Erlang programs which seem to have identical behaviour are considered.

Chapter 3 presents a formal description of Erlang's error handling constructs. These formal rules are then used to show if the examples described in the previous chapter are truly equivalent or not.

Chapter 4 describes how the formal semantic rules defined in Chapter 3 are ultimately animated through an evaluator. The main design choices that were taken when developing the evaluator are discussed.

Chapter 5 illustrates the evaluation strategy used to see to what degree the aims set forth in the beginning of this project have been met. It also mentions the main limitations of the defined semantic rules and of the designed evaluator.

Chapter 6 states the results that have been achieved through this project. It also proposes some future work that could be done.

2. Background

2.1 Introduction

The scope of this chapter is to present a general overview of some basic concepts which are key in understanding the motivation behind this work. Primarily, it outlines the main reasons why more emphasis is being put on parallel languages. The different models of parallel languages are identified highlighting the strengths and weaknesses of each model. Subsequently, some light is shed on Erlang, the language whose error handling behaviour will be ultimately defined formally.

2.2 The Need for Parallel Languages

The primary goal of this project is to study the fault recovery mechanisms integrated within a parallel language. Perhaps at this point one might ask: "Why are we considering a parallel language in the first place? Maybe the best way to address this question is to first present some facts describing the situation that we are currently in.

Way back in 1965, Gordon Moore had predicted that the number of transistors on an integrated circuit would double every couple of years[6]. For a long time there seemed to be a direct relationship between the number of transistors and software performance. However, in the last decade, the rate of improvement in software performance has slowed significantly. The whole problem stems from the fact that instead of increasing the clock speed we are now increasing the number of cores. One major downside of this approach is that most software is not capable of fully exploiting the benefits of multi-core processors. Doubling the number of cores in a CPU does not necessary lead to doubling the performance as was the case when doubling the clock speed.

Therefore, whereas before all software benefited instantly from the gradual improvement in computer performance, now we are facing a situation where existing software is finding it hard to keep pace with hardware. Nonetheless, the world is still expecting that the computing community continues providing software with improved performance. Consequently, in order to quench the thirst for more powerful software, a shift to parallel computing is required. This is because, by adopting a parallel paradigm, software would be able to improve in performance as a result of to the increased number of cores, similar to the way, systems were able to become more efficient due to an increase in clock speed.

2.3 Message Passing Languages

Currently, the programming languages which support concurrent processes can be categorized into two main classes: those that support interprocess communication through shared memory communication and those that are able to exchange data and information through message passing. The main difference, between these two models is the fact that in the former model, processes communicate by accessing the same instance of data which is physically found in memory. In contrast, when using the message passing model, processes access different instances of the same data, rather than the actual data itself.

The message passing model, is usually preferred when transferring small amounts of data between processes[7]. This is due to the fact, that when accessing shared memory one has to use locks in order to ensure that no two processes are writing simultaneously at the same memory location, since this may inherently result in a race condition. On the other hand, when using message passing mechanisms, the risk of race conditions is reduced since data is sent directly between processes[10]. Moreover, message-passing systems tend to have a simpler system design since one does not need to include any locks when accessing data.

Another major benefit of message passing is the fact that it increases the degree of isolation between processes which guarantees that an error which occurs in one process does not propagate to other processes[8]. This is not the case, when using shared memory. A case in point is when a process crashes while updating the shared memory. As a result, incorrect data might be stored in memory, which may subsequently affect the behaviour of other processes accessing this erroneous data. On the other hand, message passing ensures that such cases will never occur.

Perhaps one downside of message passing model is the fact that systems adopting this model tend to be slower since all accesses to memory are implemented using system calls in contrast to shared memory systems[7]. Nonetheless, in some systems it is ideal to trade off efficiency in order to obtain a much simpler system design which is able to handle errors in a much cleaner way.

One can appreciate even more the benefits of message passing over shared memory through Nyström's work in [9]. In his paper, Nyström compares the shared memory model adopted by Java threads with Erlang's message passing model. He argues how Erlang offers much better parallelisation tools when compared to Java and shows how this can be easily seen from the different ways in which Erlang and Java presented their views with respect to the parallelisation mechanisms they offer. He mentions that in one of Sun's tutorials threads were introduced in the following way:

> The first rule of using threads is this: avoid them if you can. Threads can be difficult to use, and they tend to make programs harder to debug.

Conversely, Erlang presented the use of parallel processes to its users in the following way:

> Use one parallel process to model each truly concurrent activity in the real world
>
> If there is a one-to-one mapping between the number of parallel processes and the number of truly parallel activities in the real world, the program will be easy to understand.

This striking contrast between the two statements seems to hint that Erlang users should be much more confident when building parallel system.

2.4 Mailbox Based Languages

The term message passing embraces both channel and mailbox/actor-model communication. The primary difference between the two is that whilst a mailbox is associated with a particular process, a channel is independent from any process. In a mailbox system, a process is able to send messages to either its own mailbox or to another process' mailbox. However, it may only read messages from its own mailbox. Another aspect of mailboxes is the fact that once a process terminates, its mailbox will automatically no longer be available to other processes.

When using the channel mechanism, all processes in a system are able send and receive to/from the same channel. In contrast to the mailbox mechanism the channel is not associated with the pid of any of the processes. Consequently, if for instance process A terminates, Process B should still be able to send/receive messages from a particular channel. In actual fact, a channel may still be available even when all processes in a system terminate unless it is destroyed by some process.

Therefore, one major benefit of mailboxes over channels is that mailboxes from their very nature guarantee that resources used to store messages are released immediately upon a process failure. On the other hand, when using channels, another process must be responsible of releasing any resources. As a result, mailboxes can be considered as providing a cleaner recovery from errors since redundant resources are released immediately.

2.5 Erlang

This section will delve deeper into one particular actor-based language, Erlang; the language whose error handling mechanisms will be studied in this project. Firstly, Erlang's most basic constructs will be introduced. These constructs will serve as the main building blocks to implement simple Erlang systems in later stages of this project. Subsequently, Erlang's error handling constructs will be described so as to get a clear picture of the constructs for which a formal semantics will be defined later on.

Here it is important to note that for the purpose of this project only a subset of Erlang will be considered. The underlying reason is that defining a formal semantics for all of Erlang's constructs would be infeasible since this would result in a rather cumbersome semantics. In addition, the chosen subset is close to the one defined in [2] which describes a complete subset of Erlang, and therefore it should be able to represent most of the systems written in Erlang.

2.5.1 Basic Erlang

Here some light will be shed on a number of different Erlang constructs. Primarily, we will first look at those constructs that are needed to build sequential Erlang systems. Then the constructs needed to build parallel Erlang systems will be outlined.

2.5.1.1 Erlang Values

In the chosen subset, Erlang values may consist of atoms, integer, variables, pids and lists. A new unique pid can only be assigned to a process once a new process is created i.e. a user cannot assign a specific pid to a process. The pid of a new process will be returned to the parent process once a process creation function such as (spawn or spawn_link) has been evaluated. Communication with a particular process can only take place if its pid is known by the process wishing to establish communication.

2.5.1.2 Single Assignment

The term *single assignment* refers to the fact that in Erlang once a variable becomes bound to a value it cannot become bound to a different value. This practice has been adopted in various functional programming languages such as F# and Haskell because of side effects. To better understand what the single assignment term actually refers to let's consider the following piece of Erlang code:

```
Value = [0],
Value = [Value,1],
...
```

Given the fact that variables can be bound only once, the above code will result in a runtime error. This is because when evaluating the second expression (`Value = [Value,1]`), Value has already been bound to [0] and therefore, the system will fail when it attempts to bind Value to `[Value,1]`. In Erlang, the correct way to implement to above code is by introducing a fresh new variable name:

```
Value = [0],
Value1 = [Value,1],
...
```

2.5.2 Case Expression

The case statement behaves in the same way as in conventional programming languages. A very simple example is :

```
case Number of
          1 -> hello;
          2 -> bye
end.
```

which returns hello if Number is equal to 1 or bye if Number is equal to 2.

In the chosen subset, the case statement also serves as an alternative to Erlang's *single assignment*. For instance, let's consider the assignment statement :

```
Value = [0]
```

When evaluating this expression Value will become bound to [0]. The same behaviour can be obtained by using the following expression :

```
case [0] of Value -> ... end
```

When evaluating the above expression, [0] is successfully pattern matched against Value. As a result, Value becomes bound to [0]. Therefore, it is quite clear that the above case statement behaves just like the assignment statement. Here, it is noteworthy the fact that in Erlang the case statement is not a scoping construct and hence any bindings that occur through this construct will hold even after the end keyword. Thus, consecutive assignemnt statments can be expressed in terms of the case statement as shown hereunder:

```
Value  = [0],
Value1 = [Value,1],      ⇔    case [0] of Value -> ok end,
...                           case Value1 of [Value,1] -> end
```

2.5.2.1 Spawning New Processes

The spawn(m,f,a) function is the primary Erlang construct that creates new processes. This function expects three arguments as input - (module name, function name, arguments). The second argument indicates which function the newly created process will start executing once it has been created. The third argument refers to the values that are passed to the functions and the module name indicates the module where the function definition is found. Once the spawn function is evaluated it returns the pid of the new process so that the parent process will be able to communicate with its child process. Therefore, when evaluating the following expression:

```
Pid = spawn(math,sum,[[1,2,3]])
```

a new process will be created and Pid will become bound to the pid of the newly spawned process. This new process will start executing sum([1,2,3]). The function definition of sum should be found in the math module.

2.5.2.2 Sending and Receiving Messages

Sending of messages is done by using the infix construct ! . This construct expects two arguments, the recipient's pid and the message to be sent. For instance, in order to send a [*msg,hello*] message to a process the following expression is used:

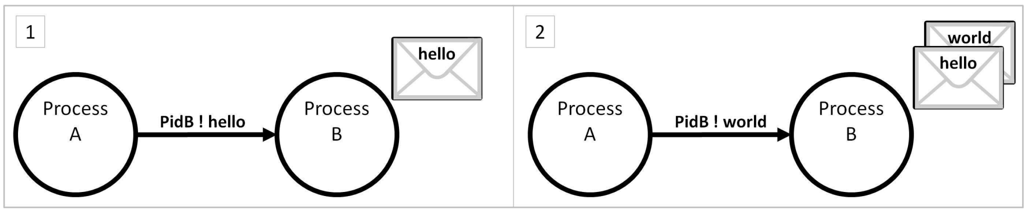
```
Pid ! [msg,hello].
```

Once this construct is evaluated the [*msg,hello*] message is appended to the mailbox of the process identified by Pid. The latter process can then read the message by using the receive construct as shown hereunder:

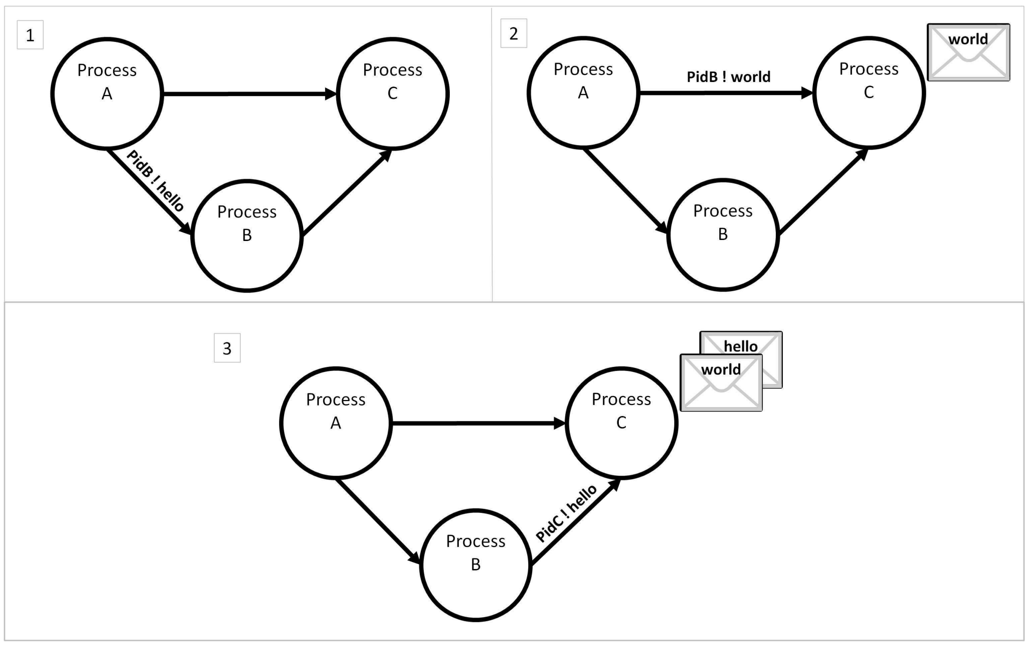
```
 receive
        [msg,Text] -> Text
end
```

The above code will cause the process to block until a message consisting of a two element list, whose first element is the atom `msg` is received. Upon receipt of such message, `Text` will become bound to the second element of the list. For instance, in this case once the [*msg,hello*] message is received, it is successfully pattern-matched against [msg,Text], and as a result `Text` will become bound to the atom *hello*.

Here it is worth pointing out that in Erlang, the order of messages between a pair of processes is guaranteed. Therefore, if say a process A sends two consecutive messages to another process, say process B:

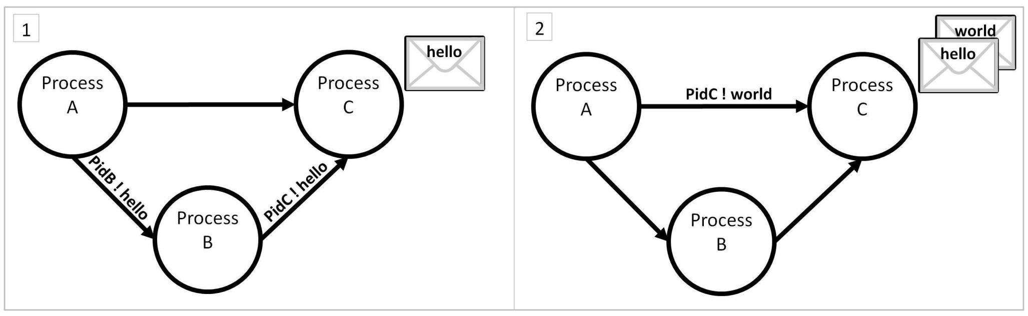


it may never be the case that process B receives the *world* message prior to receiving the *hello* message. However, order of messages can only be guaranteed between a *pair* of processes. With regards to message ordering between different processes it may not always be possible to guarantee that messages will be received in one specific order. A case in point is the following system.



In this system, process A sends two messages; it first sends the *hello* message to process B and then it will send the *world* message to process C. When process B receives the *hello* message, it will forward the received message to process C.

The above diagram illustrates that process C will receive the *world* message prior to the *hello* message. However, in this particular system it may also be the case that process C receives the messages in a different order. This may happen if the following sequence of events takes place:



Just the same in both cases, process C is still able to select which of the two messages to read/remove from the mailbox first. This can be done by using the following coding:

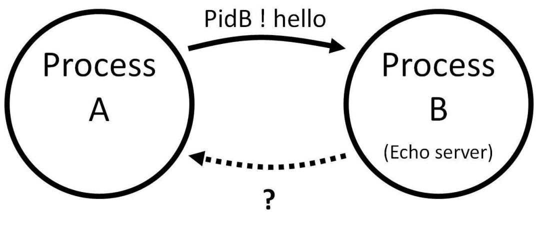
```
receive
   hello -> ...
end,

receive
   world -> ....
end,
```

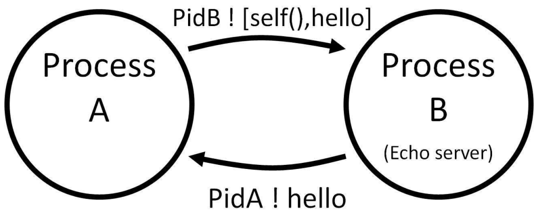
In this code excerpt, the `hello` and `world` atoms are used as patterns against which, messages in the process' mailbox will be pattern matched. In this case, since the first receive statment is only able to read messages consisting solely of the `hello` atom, the process will be suspended until the *hello* message is received in its mailbox. Only then can the process proceed to read the *world* message.

2.5.2.3 Process Pid

The pid of a process is known by its parent process and by its owner. A parent process will be informed about the pid of its child process, immediately after the creation of its child. For instance, the spawn function always returns the pid of the newly created process. A process is able of discovering its own pid by using the self() built-in function. One example where the self() function may be used is the following:



In this case process A spawns process B. Process B will act as an echo server, echoing back any messages that it receives. As mentioned in the previous section, in order for a process to send a message, it must know the pid of the recipient. In this particular case, process A will be able to communicate with process B by using the pid that is returned by the spawn function. However, since process B does not know A's pid it is not able to echo back A's message. In order for process B to be able to send messages, process A must include its own pid with the messages it sends.



In this case, the self() function will evaluate down to PidA. Process B will then be able to send back messages by using the received pid.

2.5.3 Error Handling in Erlang

Errors are likely to occur during a system's runtime. This is even more so when considering the fact that Erlang systems are not statically type checked and therefore type errors have to be handled during runtime. If systems were to be build using solely the constructs described so far, an exception or an error will immediately result in a whole system failure. In this section Erlang's simple yet powerful error handling constructs will be introduced so as to get acquainted with the constructs for which ultimately a formal semantics will be defined.

2.5.4 Recovering from Errors

Before describing the actual error handling constructs, we will consider a simple system so as to get a clear overview of the different ways Erlang may recover from errors. The considered system accepts as input two lists and returns the sum of the first list, and the product of the second list. Error handling mechanisms are used so as to handle the cases when non-numeric data is found in any of the input lists.

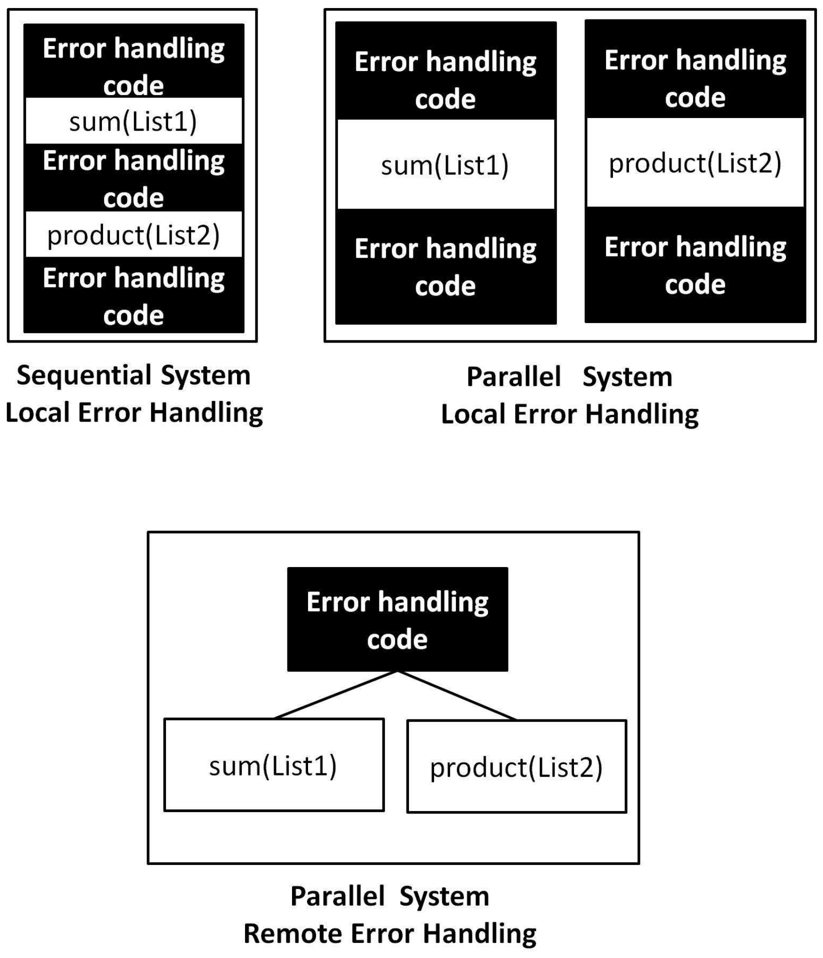


Figure 2.1: SumNProduct System

Diagram 2.1 describes the different ways in which the system may be implemented. It clearly demonstrates that when implementing the system sequentially, each process is made up of coding surrounded by error handling coding. In the second version of the system, the system experiences an improvement in efficiency since the sum and product of the list are being carried out by two separate processes. However, just as in the previous case, the process' coding is cluttered up with error handling code. This downside is overcome by adopting the design shown in the last version of the system. In this case, thanks to remote error handling the system enjoys a higher degree of seperation of concerns since every process is only responsible of carrying out one particular task either calculating the sum or the product or recovering from errors. In the following sections, we will take a closer look into each of the different versions of the system outlining the constructs that are needed to implement them.

2.5.5 Local Error Handling

2.5.5.1 Exceptions in Erlang

In Erlang there are three classes of exceptions:

- error
- throw
- exit

Exceptions of class error are usually caused due to some unforeseen error such as calling an undefined functions or attempting to perform arithmetic operations on non-numeric values. throw exceptions are generated by calling the throw(Reason) built-in function. These types of exceptions are often used within a try-catch blocks. exit exceptions can be generated by using the exit(Reason) built-in function. The purpose of this exception is to terminate the process immediately.

2.5.5.2 Try-catch

The try-catch construct has a similar behaviour to the one found in mainstream programming languages. As mentioned in the previous section, there are three types of exception classes that can be caught exit, throw and error. When catching exceptions, the name of the exception class precedes the name of the exception (errorClass:errorName). For instance, a divide by zero exception which is of class error or a throw exception can be caught in the following way:

```
try
    10/0
catch
    error:badarith-> 'div by 0'
end.
```

```
try
     throw(stop)
catch
   throw:stop -> 'exception caught'
end.
```

2.5.5.3 SumNProduct - Sequential Version

The Erlang constructs that have been introduced so far, enable us to write the sequential version of the sumNProduct system.

```
sum([])    -> 0;                    product([])     -> 1;
sum([H|T]) -> H+sum(T).             product([H|T])  -> H * product(T).

sumNProduct(List1,List2) ->
       Sum = try
                %% calculate sum of given list
                sum(List1)
             catch
                %% if error occurs return invalid
                error:badarith -> invalid
             end,

       Product = try
                    %% calculate product of given list
                    product(List2)
                 catch
                    %% if error occurs return invalid
                    error:badarith -> invalid
                 end,

       [Sum,Product].
```

Listing 2.1: SumNProduct - Sequential Version

In this case, the try-catch statement will be used so as to recover from errors that might arise if non-numeric data is input. In both cases if an exception is raised, the system will return the atom `invalid`. Here it is worth pointing out that since the two computations have no side-effect actions it is preferable that they are carried out in parallel. In the next section, the sumNProduct system will be implemented using Erlang's parallel constructs and the two different implementations will be compared.

2.5.5.4 SumNProduct - Parallel Version

```
sumNProduct(List1,List2) ->
   %% spawn a process to compute the sum of List1
   spawn(math,sumProcess,[self(),List1]),

   %% spawn another process to compute the sum of List2
   spawn(math,productProcess,[self(),List2]),
    %% receive the sum value}
    receive
        [sum,Value1] ->
             %% receive the product value
             receive
                [product,Value2] -> [Value1,Value2]
             end
    end.
```

```
sumProcess(Pid,List) ->
   Sum =
    try
      %% calculate sum of given list
      sum(List)
    catch
       %% if error occurs return invalid
       error:badarith -> invalid
   end,

   %% return Sum to parent process
   Pid ! [sum,Sum].
```

```
productProcess(Pid,List) ->
  Product =
   try
    %% calculate product of given list
     product(List)
   catch
      %% if error occurs  return invalid
      error:badarith -> invalid
  end,

  %% return Product to parent process
  Pid ! [product,Product].
```

Listing 2.3: SumNProduct Example - Parallel Version

The above program will spawn two processes; one process will compute the sum and another will compute the product. This is done through the following spawn calls:

```
%% spawn a process to compute the sum of List1
spawn(math,sumProcess,[self(),List1]),

%% spawn another process to compute the sum of List2
spawn(math,productProcess,[self(),List2]),
```

Listing 2.4: Spawning new processes

When evaluating these calls, Erlang will first create a new process which will start evaluating the sumProcess function. Subsequently a new process is created which will start evaluating the productProcess function. Here, it is important to note that the sumProcess/productProcess function apart from the list of numbers, will also expect the pid of the parent process(self() will evaluate down to the parent's pid). This pid is needed so that the newly created process will be able to send back the sum or product of the input list once it completes its computation as shown hereunder.

```
Pid ! [sum,Sum].              Pid ! [product,Product].
```

These are the last statements that are found in the sumProcess/ productProcess function. One point worth pointing out at this point is that the first element of the list to be sent(i.e. either `sum` or `product` atom) acts as a tag, so that the parent process will be able to distinguish between the sum and product result. In fact, when the parent process reads the received results, it will pattern match against a two element list whose first element is either the `sum` or `product` atom.

```
%% receive the sum value
receive
    [sum,Value1] ->
         %% receive the product value
         receive
            [product,Value2] -> [Value1,Value2]
         end
end.
```

Listing 2.5: Receiving Results of Sum and Product

When comparing the parallel version to its sequential counterpart, surely one major benefit of the parallel one is that it may result in a significant improvement in performance especially if the input lists are considerably large. Yet, in the above implementation, errors are still handled locally and therefore code is still cluttered up with error handling coding. In the next section, we will be introduced to Erlang's remote error handling constructs which will make it possible to make an external process handle any generated errors.

2.5.6 Remote Error Handling

On the strength in Erlang when compared to mainstream programming languages lies in the fact that it has adopted the notion of remote error handling. In order to better understand what this term actually refers to let's consider a very simple system. In this example the system's task is to compute the sum of two input numbers. Error handling mechanisms need to be used in order to handle errors that might arise due to invalid input data.

When using remote error handling two distinct processes are created:

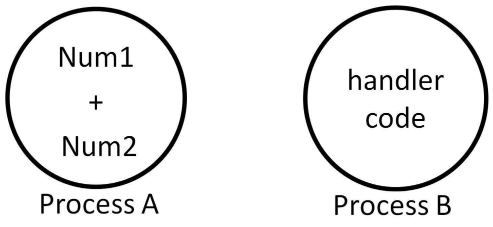


Figure 2.2: Remote Error Handling

Process A's task is to compute the sum of the two input numbers. If invalid data has been input, Process A would simply fail without attempting to recover from the error. Process B's task is to handle any error which might occur. One here can appreciate how the "let it fail" philosophy adopted by Erlang makes it possible to implement systems having a higher degree of separation of concerns. This is due to the fact that when using this approach the code responsible for computing the sum of input data is not cluttered up with any exception handling code. This yields a much cleaner and thus clearer coding.

The three main factors behind Erlang's error handling mechanisms are:

- *links*: these can be seen as bidirectional paths between two processes along which error signals travel. Each Erlang process has a link set which consists of the pids to whom the process is linked. Whenever a process, say process A links to another process say process B, B is added to A's link set and A is added to B's link set. Once a process terminates it sends an error signal to all processes found in its link set. Here it is worth noticing that due to their bidirectional nature, two linked processes are guaranteed to be notified about the termination of the other process irrespective of which process created the link.

- *error signals*: these are the signals that are sent along the links. Whenever a process terminates, error signals are sent to all linked processes to notify them about its termination. Apart from being sent upon process termination these signals can also be generated explicitly by using the exit/2 built-in function. In the latter case these signals are used to fake the termination of the process sending the signal.

- *system processes*: processes in Erlang can be classified in two distinct categories; system processes and non-system processes. The key difference between the two is how they behave upon receipt of an abnormal error signal. A system process will translate the error signal into a normal message and add it to the processes mailbox. On the other hand, a non-system process will terminate upon receipt of an abnormal error signal. If a process wishes to become a system process it can set its flag by using the expression shown hereafter:

  ```
  process_flag(trap_exit,true)
  ```

  Similarly, a process may unset its process_flag as follows:

  ```
  process_flag(trap_exit,false)
  ```

  By default, the process_flag is not set and therefore a process will terminate immediately on receipt of a process failure notification. If the process_flag has been set to true, the received notification will be added to the process' mailbox and the process will be notified about a process' termination by reading the message from its own mailbox.

Let's consider a very simple example of how these concepts are actually used. In the following diagrams links are represented as straight lines and system processes are represented as double-lined circles.

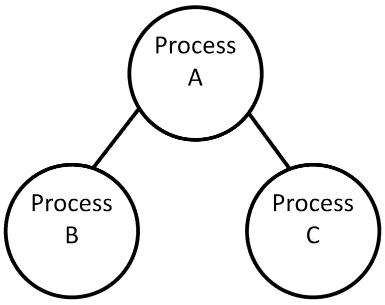


Figure 2.3: Erlang system

In the system described in 2.3 process A is linked to both process B and C. Since all three processes are non-system processes, whenever any of them receives an error signal they will terminate. Therefore, if process B terminates abnormally, the following actions will follow.

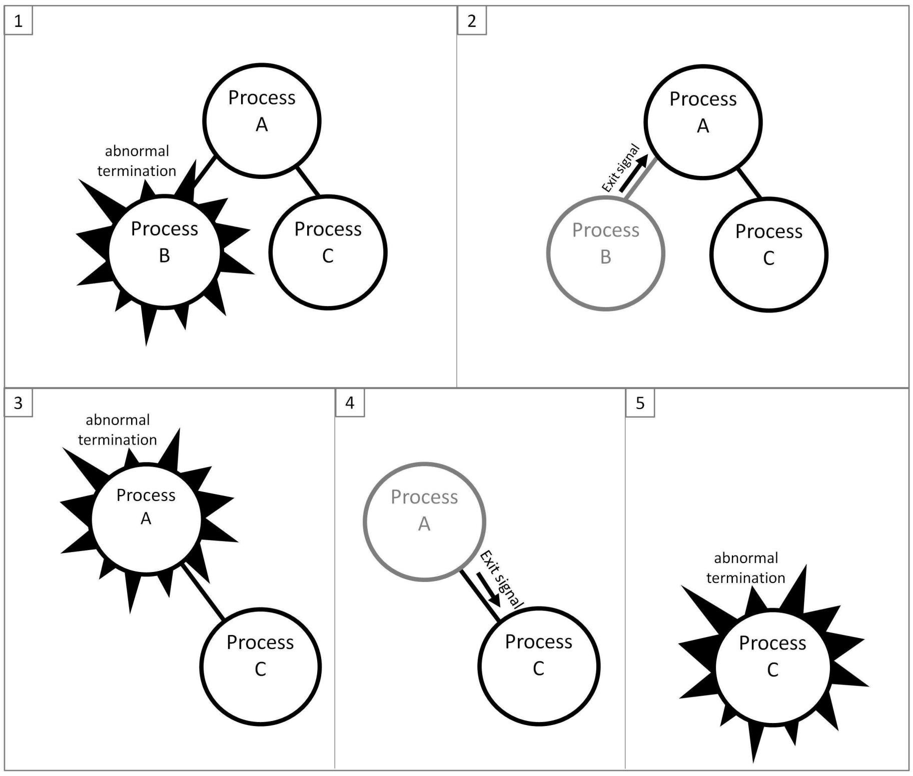


Figure 2.4: Error propagation

Now let's consider the same system, modifying Process A to a system process.

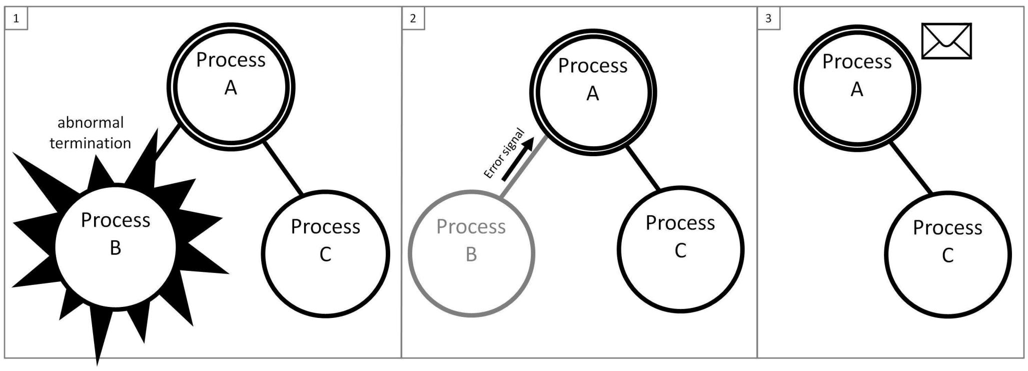


Figure 2.5: Error propagation

In this case the error signal sent by Process B is translated into an error message and added to Process A's mailbox. Process C is not notified about Process B's termination since there is no direct link between Process B and Process C. System processes are highly used when building fault-tolerant systems and recovery actions need to be done upon a process failure. For instance, in the above case, process A could be programmed to restart a copy of Process B again once it receives process B's error message.

2.5.6.1 Monitoring

Monitors are very similar in concept to links. Monitors are created by using the monitor built-in function. For instance, if a process wishes to monitor another process whose pid is bound to Pid then the `monitor(process,Pid)` expression is used. The key difference between monitors and links is that monitors are unidirectional in contrast to links which are bidirectional. In addition, a monitor will never terminate abruptly if the process it is monitoring fails. Instead, upon process termination a message is added to the monitor's mailbox. To better understand the difference in behaviours between monitors and links let's consider the following diagrams.

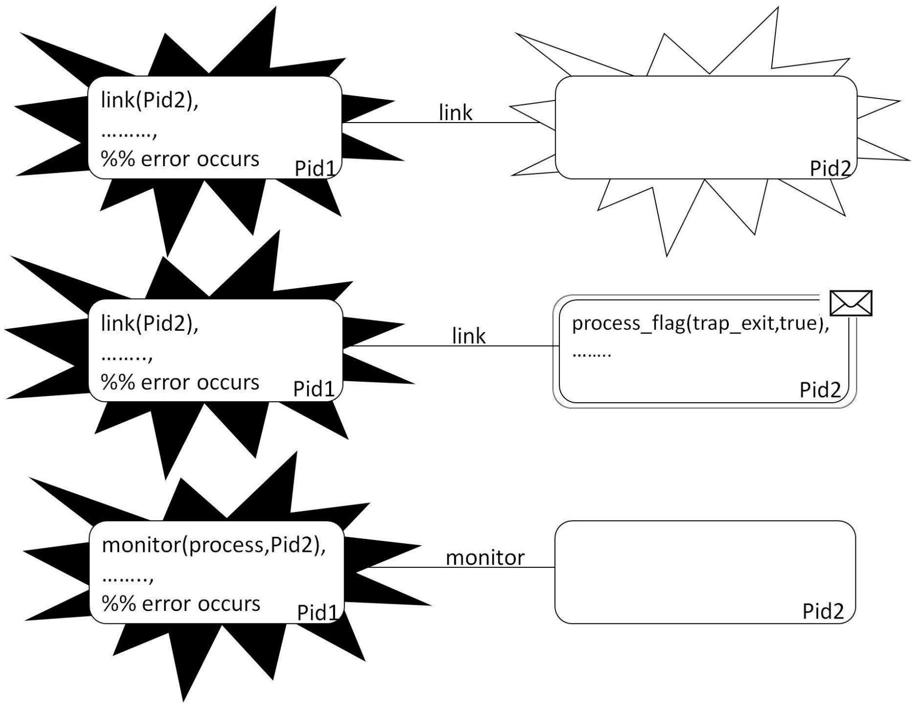


Figure 2.6: Links & Monitors - Process Pid1 terminates

Figure 2.5.6.1 demonstrates the different ways in which the linked/monitored process(i.e. Pid2) behaves when the process creating the link/monitor fails. It clearly illustrates that since links are bidirectional a failure in Pid1 will immediately be propagated to Pid2. On the other hand, in case 3 since monitors are unidirectional, Pid2 will not be notified of Pid1's failure.

Now let's consider the case when process Pid2 terminates abnormally. As shown in the diagrams below an error in Pid2, will be immediately propagated to Pid1 both in the case when using monitors and links.

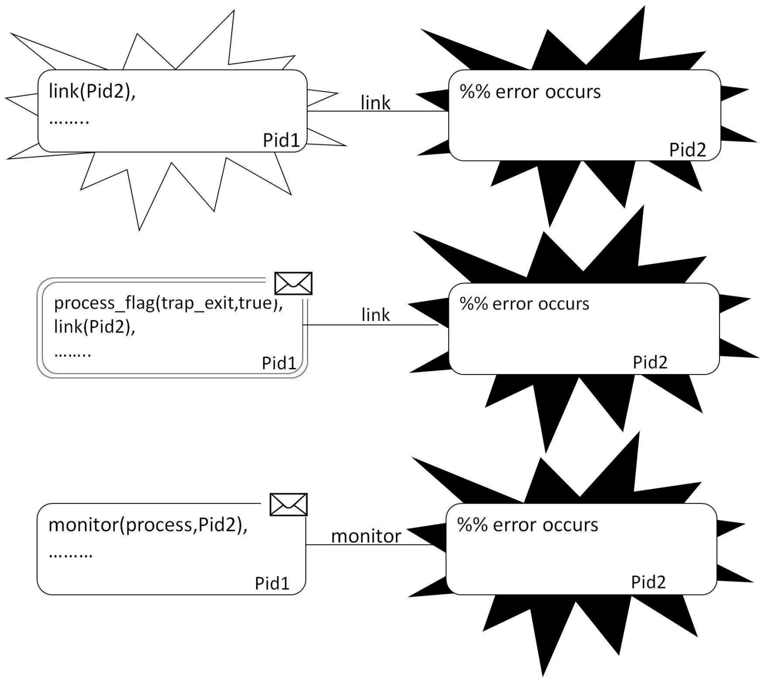


Figure 2.7: Links & Monitors - Process Pid2 terminates

When comparing the behaviour of linked and monitored processes one question that may spring to mind is if it is possible to define monitors in terms of links as described hereafter:

Process A

```
monitor(process,Pid2),
 ....

%%error occurs - reason = stop
```

Process B

```
...
```

Process A

```
process_flag(trap_exit,true),
link(PidB),
...
%%error occurs - reason = stop
```

Process B

```
process_flag(trap_exit,true),
...
```

Listing 2.6: Monitors & Links

The previous diagrams show that there is an overlapping behaviour between monitors and links - case 2 and 3 of both figures give the impression that by trapping exit signals, links are able to act just like monitors. However, at this point it is quite impossible to determine if these two behaviours are truly equivalent or not. Most surely this is one problem which the defined semantics will be able to tackle. This is due to the fact that the formal definitions will be able to give us a clear cut answer to this problem.

2.5.6.2 spawn_link, spawn_monitor

The spawn_link and spawn_monitor functions are used to create and link or monitor the process as one atomic action. Perhaps here one might ask if the spawn_link construct is simply syntactic sugaring for spawn() followed by link().

```
spawn_link(module,function,[args]),    ?   Pid = spawn(module,function,[args]),
                                       ⇔   link(Pid),
```

Listing 2.7: spawn_link & spawn() + link ()

The only possible way to answer such a problem is through a formal semantic definition of these constructs.

2.5.6.3 Explicit Error Signals

So far, we have seen that the primary source of error signals is the failure of a linked/monitored process. An additional way how error signals can be generated is by using the exit(pid,reason) built-in function(In the following sections, this function will be referred to exit/2 so as to be able to dinstinguish this function from the exit function described in Section 2.5.5.1). This construct expects two arguments, the Pid to whom the error signal is to be sent and the reason describing the cause of the error. The behaviour of the receiving process depends mainly on two things:

- The reason passed as the second argument
- The recipient's process flag

If the reason is equal to kill, the recipient process will terminate immediately with reason *killed*, irrespective if it is trapping exit signals or not. Otherwise, the behaviour of the recipient process will be determined by whether or not the recipient is trapping the received exit signals as clearly illustrated in the diagram shown hereafter.

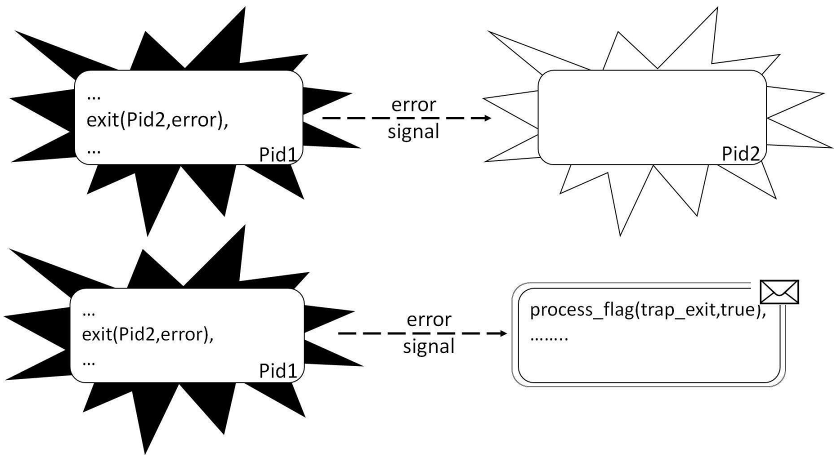


Figure 2.8: Explicit error signals

One here cannot help noticing the striking similarity between the exit/2 construct and the behaviour of error propagation through links(see Figure 2.5.6.1). Perhaps at this point one might question if it is possible in some cases to implement the link behaviour by using only the exit/2 construct. For instance, in the following case, will the two processes always behave in an identical way?

Process 1		Process 2

`link(ProcessB),`
`link(ProcessC),`
`...`
`exit(badarg),`
	$\overset{?}{\Leftrightarrow}$	`exit(ProcessB,badarg),`
		`exit(ProcessC,badarg),`
		`exit(badarg),`

Listing 2.8: Links & Explicit Exit Signals

At the moment it is quite difficult to ensure if the behaviour of these two processes is truly identical or not. This is due to the fact that, even though the definitions given so far seem to hint that these two processes are equivalent, there is no way to guarantee that they will always behave in the same way. Undoubtedly a formal semantic definition of these constructs is key to check if the same behaviour can actually be obtained by using these two different constructs.

Apart from sending explicit error signals to other processes, the exit/2 function can also be used to send error signals to the calling process. This can be done by passing the calling process' pid as a first argument:

```
exit(self(), Reason)
```

This generated exit signal may cause the calling process to terminate with reason Reason. One question that springs to mind here is if the behaviour of self-sent exit signals is equivalent to the exit(Reason) statement. This is due to the fact that the exit(Reason) expression may also cause the process to terminate with reason Reason (see Section 2.5.5.1).

$$\texttt{exit(reason)} \quad \overset{?}{\Leftrightarrow} \quad \texttt{exit(self(),reason)}$$

Listing 2.9: exit(Reason) & exit(self(),Reason)

Certainly, this is yet another interesting problem that the formal semantics should be able to solve.

2.5.6.4 SumNProduct - Remote Error Handling

```
sumNProduct(List1,List2) ->
   %% set process flag to true to trap any error signals
   process_flag(trap_exit,true),

   %% spawn process to compute Sum
   SumPid = spawn_link(math,sumProcess,[self(),List1]),

   %% spawn process to compute Product
   ProductPid = spawn_link(math,productProcess,[self(),List2]),

   %% receive Sum and Product value
   Sum = receiveValue(SumPid,sum),
   Product = receiveValue(ProductPid,product),

   [Sum,Product].
```

```
%% calculates sum of List
sumProcess(Pid,List) -> Pid ! [sum,sum(List)].


%% calculates product of List
productProcess(Pid,List) -> Pid ! [product,product(List)].
```

```
%% check if the linked process terminated normally or not
receiveValue(Pid,Tag)->
   receive
        %% if linked process terminated normally
        %% then read result from mailbox
        {'EXIT',Pid,normal} ->
              receive
                   [Tag,Value] -> Value
              end;

        %% otherwise if process terminated abnormally
        %% return invalid
        {'EXIT',Pid,{badarith,Stack}} -> invalid
   end.
```

Listing 2.11: SumNProduct - Remote Error Handling

In this version of the sumNProduct system, Erlang will first set the process_flag to true. This is done so that the process will be able to trap any errors that might occur in any of the processes with whom it will become linked later on. Erlang will then spawn_link two separate processes; one to calculate the sum and the other to calculate the product.

```
process_flag(trap_exit,true),

SumPid = spawn_link(math,sumProcess,[self(),List1]),

ProductPid = spawn_link(math,productProcess,[self(),List2]),
```

Listing 2.12: Parent process

Here, it is worth pointing out that since both processes are linked and the process_flag is set to true, the parent process will receive an exit notification message once the linked processes have terminated. If the linked process completed its task normally, the parent process will receive an `{'EXIT',Pid, normal}` message. On the other hand, if the linked process terminated abnormally due to non-numeric data it will receive a `{'EXIT',Pid,{badarith, Stack}}` message. In both cases the `Pid`, refers to the pid of the terminated process. After creating the two processes, the parent process will then suspend until it receives the results of the two processes.

```
receiveValue(Pid,Tag)->
   receive
        {'EXIT',Pid,normal} ->
                    receive
                         [Tag,Value] -> Value
                    end;
        {'EXIT',Pid,{badarith,Stack}} -> invalid
   end.
```

Listing 2.13: Receiving Results from processes

What the `receiveValue` function essentially does is that it first checks if the process terminated either normally(an `{'EXIT', Pid,normal}` message was received) or abnormally(an `{'EXIT',Pid,{badarith,Stack}}` was received). If the linked process terminated normally, then it will read the result of the process' computation i.e. either the sum or the product. The `Tag` variable can be either the `sum` or `product` atom and is used to indicate which of the two result should be read. If the linked process terminated abnormally, the system will return the atom `invalid`.

Perhaps one major benefit of adopting the notion of remote error handling lies in the fact that sumProcess function and the productProcess function do not include any error handling code. In fact if we had to compare the sumProcess function with the one used in the parallel version of the system it becomes clear that through remote error handling the system enjoys a higher degree of separation of concerns.

Local Error Handling

```
sumProcess(Pid,List) ->
   Sum =
      try
          sum(List)
      catch
          error:badarith -> invalid
      end,

   Pid ! [sum,Sum].
```

Remote Error Handling

```
sumProcess(Pid,List) ->
    Pid ! [sum,sum(List)].
```

Listing 2.14: Seperation of Concerns

Through this simple example it becomes clear how remote error handling enables us to write fault-tolerant systems which are not cluttered up with exception handling coding. As a result, the number of lines related to error recovery within the system has been reduced. Even though the reduction in this simple system was minimal, one can easily imagine the significant reduction that can be achieved when this concept is applied to larger parallel systems. In fact in his book, Cesarini claimed that a particular system which was formerly implemented in C++ experienced an amazing 85% reduction in code when implemented in Erlang. One of the main contributors to this dramatic reduction was Erlang's error handling mechanisms since as stated in [12] " 27% of the C++ code consisted of defensive programming". It is a well-known known fact that the number of bugs within a system is directly proportional to the number of lines of code. Therefore, this reduction plays an important role in reducing drastically the presence of bugs within a system.

2.6 Conclusion

This chapter has taken a closer look at the main constructs incorporated within Erlang. A simple example was used to acquaint us with Erlang's error handling mechanisms. It was illustrated how Erlang enables us to handle errors locally through the try-catch construct similar to the way other conventional programming languages handle errors. The chosen example, was also implemented using Erlang's remote handling mechanisms. This helped to bring out certain benefits that remote error handling has over local error handling namely reduction in lines of code and a higher degree of separation of concerns.

However, one recurrent dilemma when describing these Erlang constructs was if some constructs could actually be implemented in terms of other constructs. One particular case was for instance that of monitors and trap-exit links. In addition, even though the sumNProduct system was implemented in different ways there was no way one could actually guarantee that the system really maintained its semantic definition. The next chapter attempts to solve these problems by presenting a formal semantic definition for these constructs. These definition will make it possible to indicate if two syntactically different systems have similar behaviour or not.

3. Formal Semantics

3.1 Introduction

The main focus of this chapter is to get a better understanding of Erlang's error handling behaviour by presenting a formal model for Erlang's error handling constructs. In order to better appreciate the usefulness of this model, a number of Erlang systems are considered and the behaviour of these systems is described in terms of the model.

3.2 The need for Formal Semantics in Erlang

More often than not, the semantics of a language are more likely to be defined through informal description rather than through a formal one. However, lately more emphasis is being put on formal semantics, mainly due to the number of benefits they offer over their informal counterparts. In this section, the main drawbacks of using informal semantics to describe the behaviour of Erlang's error handling constructs are discussed so as to better understand the need of a formal model.

One major downside of using informal descriptions stems from the fact that they leave scope for ambiguity and therefore, as clearly shown in the previous chapter, they are not able to show if two different programs will actually behave in the same way or not. In contrast, formal semantics are able to present an unambiguous and more accurate description of a system's behaviour. Consequently, when using these semantics it becomes much more straightforward to show if the behaviour of two different programs is actually equivalent or not.

Another, drawback of informal descriptions is that in certain cases, they may fall short of accurately describing how the different Erlang constructs might interact. As a result, it may become relatively challenging to understand a system's behaviour through these semantics. This is even more so, when considering the fact that due to the parallel nature of Erlang systems, the interleaving of processes may result in different behaviour at consecutive executions of the same system. Thus, describing how parallel systems may behave by using informal semantics may result in really lengthy and cumbersome descriptions. On the other hand, through formal semantics it becomes much easier to reason about the behaviour of parallel systems. This is because, from their very nature they are able to provide concise but detailed descriptions of how a particular system might behave.

3.3 Current Formal Semantics in Erlang

Due to the fact that Erlang was conceived in industry, it was primarily defined in terms of its implementation[13]. However, given the significant role that formal semantics play in reasoning about the behaviour of systems, it was evident that defining such semantics for Erlang was key in understanding soundly the behaviour of Erlang programs. This is even more so, when considering the fact that Erlang systems are highly dynamic and concurrent and therefore, they tend to become quite challenging to fully reason about their behaviour. Erlang's current formal semantics can be classified in three categories[16]:

- functional semantics
- process semantics
- node semantics

The functional semantics, as the name itself implies, deals with the functional part of Erlang such as pattern matching and function evaluation whilst the process semantics deals with the process rules for instance, process termination, message passing and links. The semantics defined in these two categories, are used to describe the behaviour of systems found on a single machine[14]. On the other hand, the behaviour of multi-node systems can be described through the node semantics[13]. The term *multi-node* system refers to the fact that a particular

Erlang system may sometimes be composed of multiple runtime systems communicating with each other. In Erlang each of these runtime systems is called a node. Multi-node systems are oftenly used when implementing distributed systems.

3.3.1 Differences Between Current Semantics and Defined Model

One of the most noticeable difference between the current semantics and the defined model lies in the fact that whereas all current formal semantics of Erlang[14, 13] are defined by using an LTS semantics in this project the formal rules are defined by using a reduction semantics. By adopting this approach, the semantics are able to provide a clearer picture of how communication between processes is carried out. This is because, when using a reduction semantics both the sender and receiver of a signal are included in the rule definition. As a result, it becomes easier to see how a particular action has effected the receiving process. Additionally, the syntax of the reduction semantic definitions is somewhat closer to the way in which these semantics may be implemented through an evaluator.

Another benefit of reduction semantics is that they enable us to describe some Erlang behaviours through less formal rules. For instance, when defining message delivery through an LTS semantics three different rules are needed:

- one rule describes the behaviour of a process when a message is sent

$$\frac{i \neq pid}{i[pid!v,\ q,\ l,\ b\,] \xrightarrow{pid!v} i[v,\ q,\ l,\ b\,]}\ \text{SEND}$$

- another rule to describe how the a process behaves on receipt of a message

$$\frac{pid = i}{i[e,\ q,\ l,\ b\,] \xrightarrow{pid?v} i[e,\ q \mathbin{+\!\!+} v,\ l,\ b\,]}\ \text{RCV}$$

- a rule to describe how delivery of messages occurs

$$\frac{s_1 \xrightarrow{pid!v} {s_1}' \qquad s_2 \xrightarrow{pid?v} {s_2}'}{s_1 \mid\mid s_2 \xrightarrow{\tau} {s_1}' \mid\mid {s_2}'}\ \text{COMM}$$

In contrast, when describing the delivery of messages through reduction semantics only one rule is used:

$$\frac{i \neq pid}{\begin{array}{l} i[j!v,\ q,\ l,\ b\,]\ ||\ j[e,\ q_j,\ l_j,\ b_j\,] \longrightarrow \\ \qquad\qquad\qquad i[v,\ q,\ l,\ b\,]\ ||\ j[e,\ q_j +\!\!\!+\, v,\ l_j,\ b_j\,] \end{array}}\ \text{SEND}$$

Another fact worth mentioning with respect to the current Erlang semantics, is that the formal semantic definition of certain mechanisms is somewhat inaccurate since it does not faithfully mirror the behaviour of actual Erlang. A case in point is the way the current semantics defines the behaviour of Erlang when a link failure occurs. According to these semantics whenever a process attempts to link to a terminated process, an exit signal is immediately sent to the process attempting to create the link. However, as clearly described in [18] a link failure may not necessary cause the system to behave in this way. The model presented in this chapter addresses this inaccuracy and defines a more accurate description of how Erlang behaves in the case of link failure.

The current semantics also fall short of describing the way a process may behave when it sends an explicit exit signal to itself(by using the exit(self(), Reason) expression). In fact, the current semantics are only able to describe soundly the way a system behaves when an explicit exit signal is sent to another different process. In the formal semantics described in this project some rules were defined to faithfully describe the way a process behaves when an explicit exit signal is sent to itself(see section 3.11.4).

Another improvement over the current semantics is that the presented model is able to describe both the linking and monitoring mechanisms in Erlang whereas the current semantics are only able to describe the linking behaviour. It is important to note that even though in [3] it was claimed that monitors can be implemented in terms of links, in truth there exist some subtle differences between the two mechanisms. As a result, implementing monitors in terms of links may not be as easy as it might seem. This fact is discussed in more depth in section 3.11.5, where a simple example is considered to highlight the main differences that exist between monitoring and linking.

The next sections presents the formal model defined in this project whose aim is to accurately describe the behaviour of Erlang systems in the presence of errors.

3.4 Erlang System

Here a formal description of an Erlang system will be given together with some fundamental rules that will be used as the foundation for the defined semantics.

An Erlang system can be composed of one or more processes. In the defined semantics an Erlang system is represented as a set of processes. A system which is composed of three processes is expressed as:

$$\mathrm{P} \mid\mid \mathrm{Q} \mid\mid \mathrm{R}$$

Some important rules within the defined semantics are the following:

$$\mathrm{P} \mid\mid \mathrm{Q} \equiv \mathrm{Q} \mid\mid \mathrm{P} \quad (\textsc{comm}) \qquad \mathrm{P}||(\mathrm{Q}||\mathrm{R}) \equiv (\mathrm{P}||\mathrm{Q})||\mathrm{R} \quad (\textsc{assoc})$$

$$\frac{P \equiv P' \quad P \longrightarrow Q \quad Q \equiv Q'}{P' \longrightarrow Q'}\ \textsc{struct} \qquad \frac{s_1 \longrightarrow s_1'}{s_1||s_2 \longrightarrow s_1'||s_2}\ \textsc{interleave}$$

Table 3.1: System rules

In this semantics it is assumed that Erlang systems are well-formed and therefore every process in a system has a unique pid. This assumption made it possible to define the following relation:

$$\mathit{pid} \times \mathit{system} \longrightarrow \mathit{process}$$

3.5 Erlang Subset

Erlang has a relatively large number of constructs. Hence, defining a formal semantics for all these constructs would be rather infeasible since this would result in a rather cumbersome semantics. Therefore, for this work a reduced subset of Erlang (Table 3.2) was chosen.

$digit$	$::= 0 \mid \cdots \mid 9$
$uppercase$	$::= A \mid \cdots \mid Z$
$lowercase$	$::= a \mid \cdots \mid z$
$digitletter$	$::= digit \mid uppercase \mid lowercase \mid \_ \mid @$
$number$	$::= digit^{+}$
$unquotedatom$	$::= lowercase\ digitletter^{*}$
$quotedatom$	$::= '(digitletter \mid whitespace)^{+}\,'$
$atom$	$::= unquotedatom \mid quotedatom$
var	$::= uppercase\ digitletter^{*}$
$value(v)$	$::= atom$
	$\mid\ int$
	$\mid\ pid$
	$\mid\ [\,]$
$compound\ value\ (cv)$	$::= v \mid [cv_1 \mid cv_2]$
$expression\ (e)$	$::= v \mid [e_1 \mid e_2]$
	$\mid\ var$
	$\mid\ built\text{-}in\ function$
	$\mid\ e_1, e_2$
	$\mid$ case e of m end
	$\mid$ try e catch m end
	$\mid$ receive m end
	$\mid\ e_1!e_2$
$pattern(p)$	$::= cv \mid var \mid [p_1 \mid p_2]$
$matchPtrn\ (m)$	$::= p_1 \rightarrow e_1; \cdots ; p_n \rightarrow e_n$
$built\text{-}in\ functions(b)$	$::=$ self()
	$\mid$ spawn(e, e, e)
	$\mid$ link(e)
	$\mid$ monitor(e, e)
	$\mid$ spawn_link(e, e, e)
	$\mid$ spawn_monitor(e, e, e)
	$\mid$ process_flag(e, e)
	$\mid$ error(e)
	$\mid$ throw(e)
	$\mid$ exit(e)
	$\mid$ exit(e, e)

Table 3.2: Erlang's subset

When expressing the formal definitions of Erlang's constructs some minor syntactic modifications were made to Erlang's syntax. This was done so as to represent expressions in a neater way. These modifications are primarily the following:

- a sequence of Erlang expressions will be delimeted by a $\cdot$ instead of a comma.

This is because the comma will act as a delimeter for separating the different elements in the tuple representing an Erlang process.

- the concept of modules will not be present in the defined semantics since the notion of modules does not in any way affect Erlang's error handling behaviour. As a result, built-in functions such as spawn, spawn_link and spawn_monitor do not expect the module name parameter.

3.6 Contextual Rules

The formal rules presented in this project are only able to describe the behaviour of expressions for the case when all parameters of an expression have already been evaluated down to a value. As a result, the reduction context rules are necessary in order to define the way a subexpression is evaluated with respect to a bigger context.

$$\frac{i[e,\ m,\ l,\ f\ ] \longrightarrow i[e',\ m',\ l',\ f'\ ]}{i[c[e],\ m,\ l,\ f\ ] \longrightarrow i[c[e'],\ m',\ l',\ f'\ ]}\ \text{CONTEXT}_0$$

$$\frac{i[e,\ m,\ l,\ f\ ] \longrightarrow i[ex,\ m',\ l',\ f'\ ]}{i[c[e],\ m,\ l,\ f\ ] \longrightarrow i[ex,\ m',\ l',\ f'\ ]}\ \text{CONTEXT}_1$$

Table 3.3: Contextual rules

A reduction context, c[] defines a subexpression position such that, if a subexpression e performs an action and reduces down to e_1, than the whole expression can perform the same action and only the subexpression e is changed. For instance, when evaluating the following case statement

$$\mathsf{case}\ e\ \mathsf{of}\ m\ \mathsf{end}$$

the model will first try to reduce expression e. If e reduces down to e_1, then the whole expression reduces down to

$$\mathsf{case}\ e_1\ \mathsf{of}\ m\ \mathsf{end}.$$

$$
\begin{array}{rll}
\mathrm{c}[\cdot] ::= & \cdot & \\
 & \mid \mathrm{funName}(..., v_{n-1}, c[\cdot], e_{n+1}, ...) & n > 0 \\
 & \mid [..., v_{n-1}, c[\cdot], e_{n+1}] & n > 0 \\
 & \mid \mathrm{c}[\cdot]!\mathrm{e} \quad \mid \quad \mathrm{v}!\mathrm{c}[\cdot] & \\
 & \mid \mathsf{case}\ \mathrm{c}[\cdot]\ \mathsf{of}\ mt\ \mathsf{end} &
\end{array}
$$

What the c[·] definition essentially states is that when reducing a function call Erlang will evaluate the functions paramenters from left to right. Elements in a list are also evaluated from left to right. When evaluating a send statement, Erlang will first evaluate the expression on the left hand side, and subsequently it will start evaluating the expression found after the ! operator. The last part of the definition describes the fact that when evaluating a case statement Erlang will first evaluate the expression found between the case and of keywords.

3.7 Erlang Process

In this section the notion of an Erlang process is formalised. In this semantics processes may be in one of two states, either alive or terminated. Here, it is worth mentioning the fact that terminated processes cannot be considered as dead or useless processes. This is due to the fact that terminated processes will still have some tasks to carry out such as informing all processes found in their link set about their termination. Additionally, terminated processes are also used when defining the behaviour of the linking mechanism.

A live process is represented as

$$p[e, m, l, f]$$

pid(p)	- a unique process identifier
expression(e)	- the expression the process is executing
mailbox(m)	- a list of received messages that are waiting to be read
links(l)	- the set of pids to which the process is linked
flag(f)	- a boolean value indicating if a process is trapping exit signals or not

A terminated process is expressed as

$$p[\text{r,l}]$$

pid(p)	- a unique process identifier
reason(r)	- reason describing process termination
links(l)	- the set of pids found in the link set

A live Erlang process may terminate either normally or abnormally.

$$\frac{}{i[v,\ m,\ l,\ f\ ] \longrightarrow\ i[normal, l]}\ \text{TERM}_0$$

$$\frac{}{i[ex,\ m,\ l,\ f\ ] \longrightarrow\ i[reason(ex), l]}\ \text{TERM}_1$$

Table 3.4: Process Termination Rules

TERM$_0$ states that when a process completes its task, it will terminate with reason *normal*. Otherwise, the reason will describe the error that caused the process to terminate(TERM$_1$).

3.8 Case Statement

$$\frac{\exists I.((result\ v\ mt_I\ e) \wedge \forall J.J < I \Rightarrow \neg(matches\ v\ mt_J))}{i[\textsf{case}\ v\ \textsf{of}\ mt\ \textsf{end},\ m,\ l,\ f\ ] \longrightarrow\ i[e,\ m,\ l,\ f\ ]}\ \text{CASE}_0$$

$$\frac{\forall I.\neg(matches\ v\ mt_I)}{i[\textsf{case}\ v\ \textsf{of}\ mt\ \textsf{end},\ m,\ l,\ f\ ] \longrightarrow\ i[\textsf{error:}\{case\_clause, v\},\ m,\ l,\ f\ ]}\ \text{CASE}_1$$

Table 3.5: Case rules

Before describing what these rules state, the *matches* and *result* functions will be defined. (The definition of these two function is very similar to the one defined in [14].)

The *matches* function is defined as:

$$matches\ v\ (p \rightarrow e) \triangleq\ \exists\widetilde{V}.(v = p\{\widetilde{V}/\widetilde{fv(p)}\})$$

The *matches* function is given two parameters, a value(v) and a ($pattern \rightarrow expression$). This function returns true if pattern p is identical to value$v$ once the substitution($p\{\widetilde{V}/\widetilde{fv(p)}\}$) is done. Two functions used in this substitution are the:

- $\widetilde{V}$: returns all the values found in v. For example, if $v = [1, 2, 3, 4]$ then $\widetilde{V} = 1, 2, 3, 4$.
- $fv(p)$: returns all the free variables found in pattern p. For instance, $fv([a, B, c, D]) = [B, D]$.

What the $p\{\widetilde{V}/\widetilde{fv(p)}\}$ substitution essentially does is that it replaces variables according to their position in the list. For instance, let's consider the case when:

$$\begin{array}{rlrl} v = & [1,2,3,4] & p = & [a,X,c,Y] \\ \widetilde{V} = & 1,2,3,4 & fv(p) = & X,Y \end{array}$$

In this case, when evaluating $p\{\widetilde{V}/\widetilde{fv(p)}\}$, free variable X, the second element of p, is replaced by 2, the second element of v, and free variable Y, the fourth element of p is replaced by 4, the fourth element of v:

$$p\{\widetilde{V}/\widetilde{fv(p)}\} = [a, 2, c, 4]$$

If p and v have different arities no replacements are done.

The *result* function is defined as:

$$result\ v\ (p \rightarrow e)\ e' \triangleq \exists\widetilde{V}.(v = p\{\widetilde{V}/\widetilde{fv(p)}\} \wedge e' = e\{\widetilde{V}/\widetilde{fv(p)}\})$$

The *result* function is very similar to the *matches* function. The only difference is that this function has an extra parameter e'. This parameter represents the corresponding body of the pattern which successfully pattern matched against the given value. For instance, in the following case, this predicate will return true:

$$\begin{array}{ll} v & = [text, hello] \\ p \rightarrow e & = [text, Value] \rightarrow Value \\ & \\ e' & = hello \end{array}$$

Now let's move on to describe the behaviour of the case statement as defined in these rules. The first rules states that the system will try to pattern match the value against the patterns found in $mt(\mathrm{CASE}_0)$. The patterns in mt are sequentially matched against the value v found between the case and of keywords. The described reduction step is done if

$$\exists I.((result\ v\ mt_I\ e) \wedge \forall J.J < I \Rightarrow \neg(matches\ v\ mt_J))$$

What the above predicate essentially states is that a case statement will return the expression e if

- one of the elements in mt, say $(p_1 \rightarrow e)$, consists of a pattern p_1 that can be successfully pattern matched against v and
- all the elements prior to $(p_1 \rightarrow e)$ fail to pattern match against v

Therefore, if we evaluate the following case statement according to CASE_0:

```
case [a,b,c] of

     [X,Y]   -> first;
     [X,Y,Z] -> second;
      X      -> third

end.
```

the system first tries to pattern match $[a, b, c]$ against $[X, Y]$ and it fails. Subsequently, it attempts to pattern match $[a, b, c]$ against $[X, Y, Z]$ and it succeeds. As a result, it returns the atom *second*. Note that the value $[a, b, c]$ can be also successfully pattern matched against the last pattern X. However, the defined rule states that the case statement should always return the body of the $first$ pattern against which $[a, b, c]$ is successfully pattern matched.

The second rule states that if the value fails to pattern match against any of the patterns in $mt(\forall I.\neg(matches\ v\ mt_I))$, then an exception is raised(CASE_1).

3.9 Local Error Handling - try-catch

$$\frac{}{i[\mathsf{try}\ v\ \mathsf{catch}\ mt\ \mathsf{end},\ m,\ l,\ f\ ] \longrightarrow i[v,\ m,\ l,\ f\ ]}\ \mathrm{TRY}_0$$

$$\frac{i[e,\ m,\ l,\ f\ ] \longrightarrow i[e',\ m',\ l',\ f'\ ]}{i[\mathsf{try}\ e\ \mathsf{catch}\ mt\ \mathsf{end},\ m,\ l,\ f\ ] \longrightarrow i[\mathsf{try}\ e'\ \mathsf{catch}\ mt\ \mathsf{end},\ m',\ l',\ f'\ ]}\ \mathrm{TRY}_1$$

$$\frac{\begin{array}{c} i[e,\ m,\ l,\ f\ ] \longrightarrow i[ex,\ m,\ l,\ f\ ] \\ \exists I.((result\ ex\ mt_I\ e') \wedge \forall J.J < I \Rightarrow \neg(matches\ ex\ mt_J)) \end{array}}{i[\mathsf{try}\ e\ \mathsf{catch}\ mt\ \mathsf{end},\ m,\ l,\ f\ ] \longrightarrow i[e',\ m,\ l,\ f\ ]}\ \mathrm{TRY}_2$$

$$\frac{\begin{array}{c} \forall I.\neg(matches\ ex\ mt_I) \\ i[e,\ m,\ l,\ f\ ] \longrightarrow i[ex,\ m,\ l,\ f\ ] \end{array}}{i[\mathsf{try}\ e\ \mathsf{catch}\ mt\ \mathsf{end},\ m,\ l,\ f\ ] \longrightarrow i[ex,\ m,\ l,\ f\ ]}\ \mathrm{TRY}_3$$

Table 3.6: Rules for local error handling

These rules describe that Erlang will first try to evaluate the expression between the try and catch statement(TRY$_1$). If this expression evaluates down to a value than that value is returned(TRY$_0$). If the expression raises an exception, the system will try to pattern match the exception against the patterns found in *mt* and if the exception pattern matches, the corresponding error handling code is returned(TRY$_2$). Otherwise, if the exception is not caught the try expression will return the raised exception. (TRY$_3$).

3.9.1 sumNProduct Example(Sequential version)

Using the rules defined so far it is now possible to get a step-by-step description of how the example explained in section 2.5.5.3 is evaluated. Here, only the reduction steps related to the evaluation of sum(List1)will be shown.

```
try sum(List1) catch error:badarith  -> 0 end,...
```

The evaluation of

```
... try product(List2) catch error:badarith  -> 0 end.
```

is almost identical. First, let's consider the case when the input list is the numeric list `[12,5]`. By using rule TRY$_1$ the system will first evaluate `sum([12,5])` :

$$i[\mathsf{try}\ sum([12,5])\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{try}\ 12 + sum([5])\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \quad (\mathsf{TRY}_1)$$

$$\longrightarrow\ i[\mathsf{try}\ \ 12 + 5\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \quad (\mathsf{TRY}_1)$$

$$\text{where } e_1 = \mathsf{try}\ product([12,5])\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end}\cdot [Sum, Product]$$

Since the expression between the try and catch block evaluated down to a value, by rule TRY$_0$ the whole try-catch construct will evaluate down to 17.

$$\longrightarrow\ i[\mathsf{try}\ 17\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \quad (\mathsf{TRY}_1)$$

$$\longrightarrow\ i[17 \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \quad (\mathsf{TRY}_0)$$

$$\longrightarrow\ i[e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \quad (\mathsf{SEQ}_1)$$

The system will then continue to evaluate e_1.

One here can appreciate that the defined rules make it possible to ascertain that the system will always return the sum of the input list whenever valid numbers are input since there does not exist any other possible sequences of steps that may lead to a different result.

Now let's consider the case where the input list contains a non-numeric value; [a,12]. As in the previous case the system will first evaluate the expression found within the try catch block:

$$i[\mathsf{try}\ sum([a,12])\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{try}\ a + sum([12])\ \mathsf{catch}\ error : badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ (\mathsf{TRY}_1)$$

$$\longrightarrow\ i[\mathsf{try}\ a + 12\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \quad (\mathsf{TRY}_1)$$

$$\text{where } e_1 = \mathsf{try}\ product([12,5])\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end}\cdot [Sum, Product]$$

When the system attempts to add a to 12 a *badarith* exception is raised:

$$\longrightarrow\ i[\mathsf{try\ error}{:}badarith\ \mathsf{catch\ error}{:}badarith \rightarrow invalid\ \mathsf{end} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{TRY}_1)$$

The generated exception is caught and therefore the output of this computation will be the atom *invalid*.

$$\longrightarrow\ i[invalid \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{TRY}_2)$$

$$\longrightarrow\ i[e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{SEQ}_1)$$

The system will then continue to evaluate e_1.

3.10 Parallel Erlang

$$\frac{fresh(j)}{i[\mathsf{spawn}(f, args),\ m,\ l,\ f\ ] \longrightarrow \quad i[j,\ m,\ l,\ f\ ]||j[f(args),\ \epsilon,\ \emptyset,\ \mathsf{false}\ ]}\ \text{SPAWN}$$

$$\frac{i = j}{i[j!v,\ m,\ l,\ f\ ] \longrightarrow\ i[v,\ m +\!\!+ v,\ l,\ f\ ]}\ \text{SEND}_0$$

$$\frac{i \neq j}{i[j!v,\ m_i,\ l_i,\ f_i\ ]\ ||\ j[e_j,\ m_j,\ l_j,\ f_j\ ] \longrightarrow \quad i[v,\ m_i,\ l_i,\ f_i\ ]\ ||\ j[e_j,\ m_j +\!\!+ v,\ l_j,\ f_j\ ]}\ \text{SEND}_1$$

$$\frac{i \neq j}{i[j!v,\ m_i,\ l_i,\ f_i\ ]\ ||\ j[reason, \{pids\}]\ \longrightarrow \quad i[v,\ m_i,\ l_i,\ f_i\ ]\ ||\ j[reason, \{pids\}]}\ \text{SEND}_2$$

$$\frac{\exists I.((result\ v\ mt_I\ e) \wedge \forall J.J < I \Rightarrow \neg(matches\ v\ mt_J))}{i[?mt,\ m_1 +\!\!+ v +\!\!+ m_2,\ l_i,\ f_i\ ] \longrightarrow\ i[e,\ m_1 +\!\!+ m_2,\ l,\ f\ ]}\ \text{RCV}$$

Table 3.7: Process rules

The SPAWN rule states that whenever a new process is created, its identifier must be unique($fresh(j)$). It also illustrates that the new process will have an empty mailbox and link set. Additionally, by default it will not be trapping any exit signals since its process_flag is set to false.

With regards to message delivery, it was assumed that all messages arrive in their destination instantaneously. In fact, in actual Erlang when dealing with single-node systems it is guaranteed message delivery is immediate. The instantaneous message delivery is described by the three SEND rules. SEND_0 describes the fact that when a process sends a message to itself, the message is immediately appended to the process' mailbox. When a process sends a message to another process, say process j then this message is appended immediately to process j's mailbox(SEND_1). The last send rule describes the fact that when a message is sent to terminated process j then the message is not appended to process j's mailbox(SEND_2).

What the RCV rule states is that the receive construct will attempt to pattern match sequentially the patterns found in mt with the messages found in the mailbox. The body of the first pattern to pattern match against one of the messages in the mailbox will be returned. This fact is described through the following predicate:

$$\exists I.((result\ v\ mt_I\ e) \wedge \forall J.J < I \Rightarrow \neg(matches\ v\ mt_J))$$

For this predicate to hold:

- one of the patterns in mt must pattern match against the message v which is currently found in the process' mailbox described as $[m_1 +\!\!+ v +\!\!+ m_2]$
- all messages found in the mailbox prior to v i.e. in $[m_1]$ do not pattern match against any of the patterns found prior to mt_I.

Once a message has been pattern matched it is removed from the mailbox. Note that if no messages pattern match against any of the patterns in mt than the system will block. This is the main reason why there is no reduction rule defined to cater for this particular case.

3.10.1 sumNProduct Example(Parallel Version)

Through these rules, it is now possible to describe the behaviour of the sumN-Product system(parallel version). In this version, two seperate processes are used to calculate the sum and product of the input lists. We will first consider the case when two valid lists are input; for this example both input lists are [12,5].

Firstly, the system will spawn a new process whose task is to calculate the sum of [12,5]. The pid of the newly created process, in this case j will be returned to the parent process i.

$$i[\mathsf{spawn}(sumProcess, [i, [12, 5]]) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[j \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ j[sumProcess(i, [12, 5]),\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{SPAWN})$$

$$\longrightarrow\ i[e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ j[sumProcess(i, [12, 5]),\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{SEQ}_1)$$

$$\text{where } e_1 = \mathsf{spawn}(productProcess, [i, [12, 5]])\ \cdot\ ?[sum, Value1] \rightarrow ?[product, Value2] \rightarrow [Value1, Value2].$$

Process i will then spawn another process whose task is to calculate the product of [12,5].

$$\longrightarrow\ i[k \cdot e_2,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ k[productProcess(i, [12, 5]),\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ j[sumProcess(i, [12, 5]),\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{SPAWN})$$

$$\text{where } e_2 = ?[sum, Value1] \rightarrow ?[product, Value2] \rightarrow [Value1, Value2].$$

Once the sum of the list has been calculated, the *sumProcess* functions will evaluate the $i![sum, 17]$ expression. When evaluating this expression, process j will send a message containing the sum result to process i. The sent message will be appended to process i's mailbox.

$$\equiv\ j[i![sum, 17]),\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ i[e_2,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ s_k$$

$$\longrightarrow\ j[[sum, 17],\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ i[e_2,\ [[sum, 17]],\ \emptyset,\ \mathsf{false}]\ ||\ s_k \qquad (\mathsf{SEND}_1)$$

$$\text{where } s_k = k[productProcess(i, [12, 5]),\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

Similarly, once the product of the list has been calculated, the *productProcess* functions will evaluate the $i![product, 60]$ expression. When evaluating this expression, process k will send the product result to process i. This will be also appended to process i's mailbox.

$$\equiv\ k[i![product,60]),\ \epsilon,\ \emptyset,\ \mathsf{false}]\ \|\ i[e_2,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ \|\ s_j$$

$$\longrightarrow\ k[[product,60],\ \epsilon,\ \emptyset,\ \mathsf{false}]\ \|\ i[e_2,\ [[sum,17],[product,60]],\ \emptyset,\ \mathsf{false}]\ \|\ s_j \qquad (\mathsf{SEND_1})$$

where $s_j = j[[sum,17],\ \epsilon,\ \emptyset,\ \mathsf{false}]$

Process i will then start reading the received messages. It will first read the sum Value. Once this message is read it will be removed from the mailbox.

$$\equiv\ i[?[sum,Value1]\rightarrow ?[product,Value2]\rightarrow,\ [[sum,17],[product,60]],\ \emptyset,\ \mathsf{false}]\ \|\ s_j\ \|\ s_k$$

$$\longrightarrow\ i[?[product,Value2]\ \rightarrow\ [17,Value2],\ [[product,60]],\ \emptyset,\ \mathsf{false}]\ \|\ s_j\ \|\ s_k \qquad (\mathsf{RCV})$$

Subsequently, process i reads the received product result. Once this message is read it is also removed from the mailbox. The system will then return a list containing the sum and product of the input lists.

$$\longrightarrow\ i[[17,60],\ \epsilon,\ \emptyset,\ \mathsf{false}]\ \|\ s_j\ \|\ s_k \qquad (\mathsf{RCV})$$

The above steps show only one possible sequence of reductions that leads to the expected output i.e.[17,60]. One fact worth pointing out here is that in truth there a several other possible interleavings which can lead to the same output. For instance, process j could have sent the [sum,17] message before process i spawned process k. In fact, even though this system consists only of three processes there are relatively many different possible interleavings. Nonetheless, the defined semantic rules enable us to check that given the same input there does not exist any possible interleaving that may lead to a different output. Here one can appreciate even more how such simple rules have in actual fact paved the way to show such an essential fact.

In order to check if the parallel version of sumNProduct is semantically equivalent to the sequential version we will need to check the case when invalid data is passed. Though it will not be illustrated here(since the reduction steps are highly similar to the ones described in the sequential version of the sumNProduct example), through these semantics it is possible to show that in fact the system will always evaluate down to $[invalid, invalid]$ when given non-numeric data. Therefore, it can be concluded that the parallel version of sumNProduct is semantically equivalent to its sequential version.

3.11 Remote Error Hadling

3.11.1 Links and System Processes

$$\frac{}{\begin{array}{l} i[\mathsf{link}(j),\ m_i,\ l_i,\ f_i\ ]\ ||\ j[e_j,\ m_j,\ l_j,\ f_j\ ] \longrightarrow \\ \qquad i[\mathsf{true},\ m_i,\ l_i \cup \{j\},\ f_i\ ]\ ||\ j[e_j,\ m_j,\ l_j \cup \{i\},\ f_j\ ] \end{array}}\ \text{LINK}_0$$

$$\frac{f = \mathsf{true}}{\begin{array}{l} i[\mathsf{link}(j),\ m,\ l,\ f\ ]\ ||\ j[v,l] \longrightarrow \\ \qquad i[true,\ m +\!\!+ [{}'EXIT',j,noproc],\ l,\ f\ ]\ ||\ j[v,l] \end{array}}\ \text{LINK}_1$$

$$\frac{f = \mathsf{false}}{\begin{array}{l} i[\mathsf{link}(j),\ m,\ l,\ f\ ]\ ||\ j[v,l] \longrightarrow \\ \qquad i[\text{error:}noproc,\ m,\ l,\ f\ ]||j[v,l] \end{array}}\ \text{LINK}_2$$

$$\frac{}{\begin{array}{l} i[\mathsf{process\_flag}(trap\_exit, flag_1),\ m,\ l,\ f_2\ ] \longrightarrow \\ \qquad i[f_2,\ m,\ l,\ flag_1\ ] \end{array}}\ \text{PROC\_FLAG}$$

Table 3.8: Process rules for linking and system processes

As already described in section 2.5.6 links are the underlying factor behind Erlang's remote handling mechanisms. These three rules bring to light the fact that the link expression can be also used as a ping. This is because the link(Pid) expression is able to indicate if the process identified by Pid is alive(LINK_0) or dead(LINK_1 or LINK_2). Rule LINK_0 describes Erlang's behaviour when a process successfully links to another process. Here, it is worth mentioning the fact that since in this semantics links are expressed as a set, it is ensured that whenever a process attempts to link to a process which is already found in its link set nothing actually happens. This guarantees that the defined rules are faithful to the behaviour of actual Erlang.

The last two rules describe Erlang's behaviour when a process tries to link to a terminated process. LINK_1 describes link failure when the process calling link is trapping exit signals i.e. the process_flag is set to true. In this case a link failure will result in a message to be appended to the calling process' mailbox. LINK_2 describes the case when the calling process is not trapping exit signals. In this case a link failure evaluate down to an exception. Interestingly enough all semantics which have attempted to describe Erlang's error handling mechanisms so far, always describe a link failure in the following way:

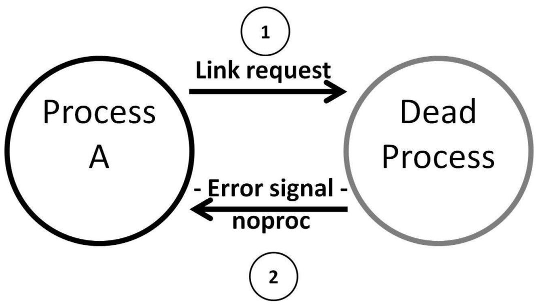


Figure 3.1: Link Failure as described by Current Semantic Definitions

As shown in the above diagram, according the these semantics a link failure will always trigger the terminated process to send an exit signal with reason noproc. Consequently, since process A is not trapping exit signals, the sent signal will cause process A to terminate with reason *noproc*.

However, according to Erlang's reference manual [23], a link failure may result in either of the following:

> - If the calling process is not trapping exits, and checking Pid is cheap – that is, if Pid is local – link/1 fails with reason noproc.
>
> - Otherwise, if the calling process is trapping exits, and/or Pid is remote, link/1 returns true, but an exit signal with reason noproc is sent to the calling process.

All previous semantic definitions seem to ignore the fact that a link call may also evaluate down to an exception with reason *noproc*. Perhaps the reason why this was deemed to be correct was that the generated exception, if uncaught, may still terminate the calling process with reason *noproc*. Nevertheless, this semantic definition is not capable of describing correctly the behaviour of actual Erlang when a link failure occurs within a try-catch block. For instance, let's consider the following case:

```
try
   link(Pid)
catch
   error:noproc -> 'process is dead'
end,

Pid2!hello.
```

Listing 3.1: Link Failure Program

In the above case, the exception generated due to link failure will be caught. As a result, the process will still be able to send the *hello* message to Pid2. However, if the above coding is evaluated using the previous semantic definitions, the link failure will cause the calling process to terminate immediately with reason noproc. This is so, because a try-catch is only capable of catching exceptions(i.e. exit signals cannot be caught by using the try-catch construct). When considering this example it becomes clear that the previous semantic definition of link failure is somewhat inaccurate to the behaviour of actual Erlang.

The last rule described in Table linkProcFlag is the PROC_FLAG rule. This rules states the behaviour of a system process upon receipt of an exit signal. Once a process receives an exit signal it may either terminate abruptly or else it may translate the received signal into a normal message which is appended it to its own mailbox. One of the main factors which decides which course of actions to take is the process_flag. If the process_flag, (which in our semantics is expressed as the last element of the process tuple) is set to true, then the received exit signal will not cause the process to terminate immediately. Conversely, if the process_flag is set to false, the process may terminate immediately upon receipt of an exit signal. The process_flag function's second argument is a boolean value which determines if the flag should be set or unset. As stated in the PROC_FLAG rule, once the function is evaluated the previous flag value (i.e. flag_0) will be returned.

3.11.2 Error Propagation

$$\frac{v = normal \quad \wedge \quad f = \mathsf{false} \quad \wedge \quad j \in pids}{i[v, pids] \;||\; j[e, m, l, f] \;\longrightarrow\; i[v, pids \setminus \{j\}] \;||\; j[e, m, l \setminus \{i\}, f]}\ \text{EXIT}_0$$

$$\frac{v \neq normal \quad \wedge \quad f = \mathsf{false} \quad \wedge \quad j \in pids}{i[v, pids] \;||\; j[e, m, l, f] \;\longrightarrow\; i[v, pids \setminus \{j\}] \;||\; j[v, l \setminus \{i\}]}\ \text{EXIT}_1$$

$$\frac{f = \mathsf{true} \quad \wedge \quad j \in pids}{\begin{array}{l} i[v, pids] \;||\; j[e, m, l, f] \;\longrightarrow \\ \qquad\qquad i[v, pids \setminus \{j\}] \;||\; j[e, m \mathbin{+\!\!+} [\text{EXIT}, i, v], l \setminus \{i\}, f] \end{array}}\ \text{EXIT}_2$$

Table 3.9: Error propagation

The above rules state the behaviour of Erlang processes on receipt of an error signal. To better understand the relation between these rules and the behaviour of Erlang's error propagation let's consider the following diagram:

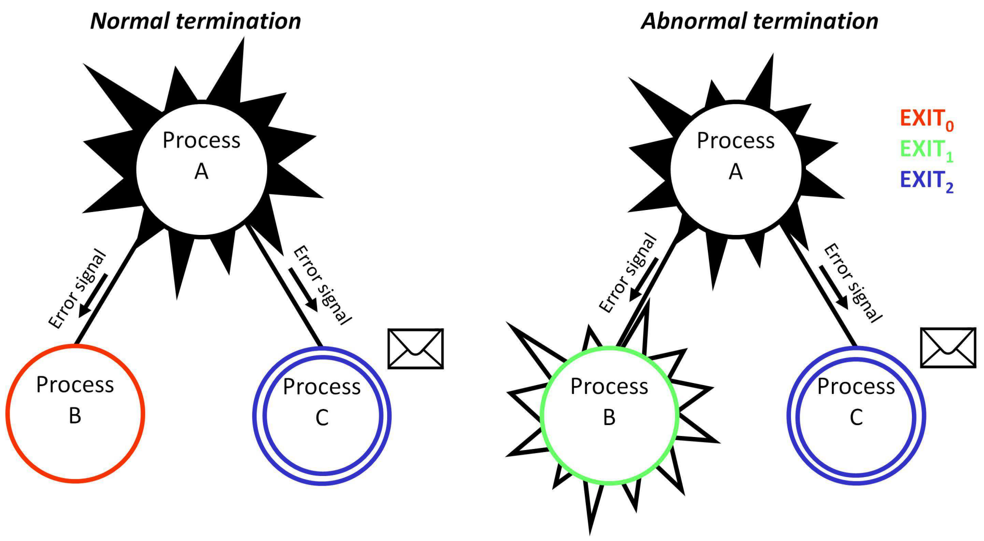


Figure 3.2: Exit propagation through links

Figure 3.2 depicts a system which is composed of three processes. Process A is linked to Process B and Process C. When process A terminates, an error signal will be sent to both linked processes. The main difference between the two processes is that process C is a system process (i.e. it is trapping exit signals) while process B is not. Through this diagram it becomes quite evident that the behaviour of a process on receipt of an error signal depends mainly on two things

- if a process is a system process
- if the reason of the received exit signal is equal to normal or not

As clearly illustrated in the diagram a normal termination(v = normal) will never cause a linked process to terminate immediately. Therefore, if a process which is not trapping exit signals receives an exit signal where reason is equal to normal, the receiving process will ignore this signal(EXIT$_0$). Instant termination of a linked process can only happen as a result of an abnormal termination of a linked process(EXIT$_1$). If a linked process is trapping exit signals, the received exit signal will be translated into a message and appended to the process' mailbox(EXIT$_2$).

In our semantics a terminated process is expressed as $pid[v, linkSet]$. Therefore, in the above case process A will be expressed as $A[v, \{B, C\}]$. The receiving process will be able to identify the cause of process termination by reading v; if the process has terminated normally the value of v will be equal to normal. Otherwise, v will describe the error which occured for instance *badarith*.

Here, it is worth pointing out that the fact, that the group of linked pids are expressed as a set is key. This is mainly due to the fact that sets from their very nature:

- do not determine order between elements
- do not store duplicates

The first point guarantees that the sending of error signals in our semantics is not done in any particular order. This ensures that these rules faithfully describe the behaviour error propagation since in actual Erlang the order in which error signals are sent is not determined. For instance, if we consider the following piece of code

```
link(Pid1),
link(Pid2),
.....,
%%error occurs
```

even though Pid1 is added to the link set prior to Pid2, it is not guaranteed that an error signal will be first sent to Pid1. In actual fact, since the order is not determined, it may very well be the case that the same system will sometimes first send an error signal to Pid1 and at other times first send an error signal to Pid2. The fact that sets do not store duplicates also plays a crucial role in ensuring that the defined semantics is loyal to the behaviour of actual Erlang. For instance, in the following case:

```
link(Pid1),
link(Pid1),
.....,
%%error occurs
```

even though the process attempted to create a link to Pid1 twice, Pid1 will still be found once in the process' link set. As a result, when sending error signals to all processes found in the link set only one error signal will be sent to Pid1. Additionally, in the defined rules the set of linked processes is updated immediately ($pids \setminus \{j\}$) once an error signal has been sent so as to ensure that no duplicate error signals are sent.

3.11.3 Spawn_link

$$\frac{}{\begin{array}{l} i[\mathsf{spawn\_link}(f, args),\ m,\ l,\ f\ ] \longrightarrow \\ \qquad\qquad i[j,\ m,\ \{l \cup j\},\ f\ ] || j[f(args),\ \epsilon,\ \{i\},\ \mathsf{false}\ ] \end{array}}\ \text{SPAWN\_LINK}$$

Table 3.10: Spawn_link rule

As stated by this rule, the spawn_link primarily consists of a function which creates a new process and links to it as one atomic action. Perhaps one question that may come to mind at this point is whether it is possible to define spawn_link in terms of spawn followed by link. For instance, let'consider the following system:

```
%% this function will cause the process to terminate
%% with reason badarith
doError(Pid) -> Pid ! a + a.

processA() ->
  process_flag(trap_exit,true),
  %% spawn_link new process
  spawn_link(moduleName,doError,[self()]),
  %% wait for result from the spawned process
  receive
       [value,Result] -> Result;
       {'EXIT',Pid,badarith} -> 'invalid operation'
  end.
```

Listing 3.2: Spawn_link - Example A

By using the defined rules, it is possible to ascertain that the above system will be always return the same result. The below description gives one possible interleaving how this result can be achieved.

The system will first set its process_flag so as to be able to trap any received exit signals.

$$i[\text{process\_flag}(trap\_exit, \mathsf{true}) \cdot e,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{false} \cdot e,\ \epsilon,\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{PROC\_FLAG})$$

where $e = \mathsf{spawn\_link}(doError, [i]\cdot$
$?[value, Result] \rightarrow Result;$
$[EXIT, Pid, badarith] \rightarrow' invalid\ operation'.$

Subsequently, a new process is created and a link between the two processes is set up instantaneously.

$$\longrightarrow\ i[\mathsf{spawn\_link}(doError, [\mathsf{self}()]) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}]$$

$$\longrightarrow\ i[j \cdot e_1,\ \epsilon,\ \{j\},\ \mathsf{true}]\ \|\ j[doError(i),\ \epsilon,\ \{i\},\ \mathsf{false}] \qquad (\mathsf{SPAWN\_LINK})$$

where $e_1 = ?[value, Result] \rightarrow Result;$
$[EXIT, Pid, badarith] \rightarrow' invalid\ operation'.$

When the new process(process j), attempts to evaluate the $doError()$ function it fails. The uncaught exception, will cause the process to terminate with reason $badarith$.

$$j[\mathsf{error} : badarith,\ \epsilon,\ \{i\},\ \mathsf{false}] \longrightarrow\ j[badarith, \{i\}] \qquad (\mathsf{TERM}_1)$$

Upon process j's termination, an error signal is sent to process i. This signal is trapped and translated into a normal message. The error notification message,

$[EXIT, j, badarith]$ is appended to process i's mailbox.

$$\longrightarrow\ j[badarith, \{i\}]\ \ ||\ i[e_1,\ \epsilon,\ \{i\},\ \mathsf{true}]$$

$$\longrightarrow\ j[badarith, \emptyset]\ \ ||\ \ i[e_1,\ [[EXIT, j, badarith]],\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{EXIT}_2)$$

The trapped error signal will be read, and the atom *'invalid operation'* will be returned.

$$\equiv\ \ i[e_1,\ [[EXIT, j, badarith]],\ \emptyset,\ \mathsf{true}]\ \ ||\ \ j[badarith, \emptyset]$$

$$\longrightarrow\ i['invalid\,operation',\ \epsilon,\ \{j\},\ \mathsf{true}]\ \ ||\ \ j[badarith, \emptyset] \qquad (\mathsf{RCV})$$

Now let's consider the same system, but replacing spawn_link by spawn followed by a link as follows:

```
%% this function will cause the process to terminate
%% with reason badarith
doError(Pid) -> Pid ! a + a.

processA() ->
   process_flag(trap_exit,true),
   %% create new process
   Pid = spawn(moduleName,doError,[self()]),

   %% link to new process
   link(Pid),

   receive
      [value,Result] -> Result
      {EXIT,Pid,badarith} -> 'invalid operation'
   end.
```

Listing 3.3: Spawn_link - Example B

Even though the above system may still evaluate down to *'invalid operation'* it is also possible that the system returns a different result. This may occur if the following sequence of steps occurs.
The system sets its process flag and creates the new process.

$$i[\text{process\_flag}(trap\_exit, \mathsf{true}) \cdot spawn(doError, [i]) \cdot link(j) \cdot e,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{false}\cdot spawn(doError,[i])\cdot link(j)\cdot e,\ \epsilon,\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{PROC\_FLAG})$$

$$\longrightarrow\ i[\mathsf{spawn}(doError,[i])\cdot link(j)\cdot e,\ \epsilon,\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{SEQ_1})$$

$$\longrightarrow\ i[j\cdot link(j)\cdot e,\ \epsilon,\ \emptyset,\ \mathsf{true}]\ ||\ j[doError([i]),\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{SPAWN})$$

where $e = ?[value, Result] \to Result;$
$[EXIT, Pid, badarith] \to' invalid\ operation'.$

Process j will then attempt to evaluate doError and it fails. As a result, process j terminates. Note however, that since there are no pids in its link set no error signals will be sent.

$$j[\mathsf{error} : badarith,\ \epsilon,\ \emptyset,\ \mathsf{false}] \longrightarrow\ j[badarith, \emptyset] \qquad (\mathsf{TERM_1})$$

Subsequently, process i will attempt to link to process j. Since process j has terminated it receives an error signal with reason noproc.

$$\longrightarrow\ i[\mathrm{link}(j)\cdot e,\ \epsilon,\ \emptyset,\ \mathsf{true}]\ ||\ j[badarith, \emptyset] \qquad (\mathsf{TERM_1})$$

$$\longrightarrow\ i[\mathrm{true},\ q +\!\!+ ['EXIT', j, noproc],\ \emptyset,\ \mathsf{true}]\ ||\ j[badarith, \epsilon] \qquad (\mathsf{LINK_1})$$

Due to the fact that the receive construct is only able to read exit message with reason *badarith*, process j will then block indefinitely since no messages in its mailbox pattern match against the provided patterns .

This really simple example illustrates that by calling a spawn followed by a link, the system may sometimes evaluate to unwanted results. Perhaps this is one of the main reasons why as mentioned in [17], the link call is rarely used in actual Erlang systems. In fact, Erlang developers more often than not, opt to use solely the spawn_link function since this guarantees that the link is always carried out instantly, ensuring that no error signals are lost.

3.11.4 Explicit error signals

$$\frac{i \neq j \ \wedge \ v = kill}{i[exit(j,v),\ m_i,\ l_i,\ f_i\,]\ ||\ j[e_j,\ m_j,\ l_j,\ f_j\,] \longrightarrow i[\mathsf{true},\ m_i,\ l_i,\ f_i\,]\ ||\ j[killed, l_j]}\ \text{EXIT}_3$$

$$\frac{i \neq j \ \wedge \ v \neq kill \ \wedge \ v \neq normal \ \wedge \ f_j = \mathsf{false}}{i[exit(j,v),\ m_i,\ l_i,\ f_i\,]\ ||\ j[e_j,\ m_j,\ l_j,\ f_j\,] \longrightarrow i[\mathsf{true},\ m_i,\ l_i,\ f_i\,]\ ||\ j[v, l_j]}\ \text{EXIT}_4$$

$$\frac{i \neq j \ \wedge \ v = normal \ \wedge \ f_j = \mathsf{false}}{i[exit(j,v),\ m_i,\ l_i,\ f_i\,]\ ||\ j[e_j,\ m_j,\ l_j,\ f_j\,] \longrightarrow i[\mathsf{true},\ m_i,\ l_i,\ f_i\,]\ ||\ j[e_j,\ m_j,\ l_j,\ f_j\,]}\ \text{EXIT}_5$$

$$\frac{i \neq j \ \wedge \ v \neq kill \ \wedge \ f_j = \mathsf{true}}{i[exit(j,v),\ m_i,\ l_i,\ f_i\,]\ ||\ j[e_j,\ m_j,\ l_j,\ f_j\,] \longrightarrow i[\mathsf{true},\ m_i,\ l_i,\ f_i\,]\ ||\ j[e_j,\ m_j +\!\!+ [EXIT, i, v],\ l_j,\ f_j\,]}\ \text{EXIT}_6$$

$$\frac{}{i[exit(j,v),\ m_i,\ l_i,\ f_i\,]\ ||\ j[v, l_j] \longrightarrow i[\mathsf{true},\ m_i,\ l_i,\ f_i\,]\ ||\ j[v, l_j]}\ \text{EXIT}_7$$

Table 3.11: Explicit exit signals

$$\frac{i = j \ \wedge \ v = kill}{i[exit(j,v), m, l, f] \ \longrightarrow \ i[killed, l]}\ \text{EXIT}_8$$

$$\frac{i = j \ \wedge \ v \neq kill \ \wedge \ f = \mathsf{false}}{i[exit(j,v), m, l, f] \ \longrightarrow \ i[v, l]}\ \text{EXIT}_9$$

$$\frac{i = j \ \wedge \ v \neq kill \ \wedge \ f = \mathsf{true}}{i[exit(j,v), m, l, f] \ \longrightarrow \ i[\mathsf{true}, m +\!\!+ [EXIT, i, v], l, f]}\ \text{EXIT}_{10}$$

Table 3.12: Self-sent exit signals

The above rules state how processes behave on receipt of an error signal which is explicitly sent by another process. The diagram shown hereafter illustrates how these rules relate to the behaviour of actual Erlang.

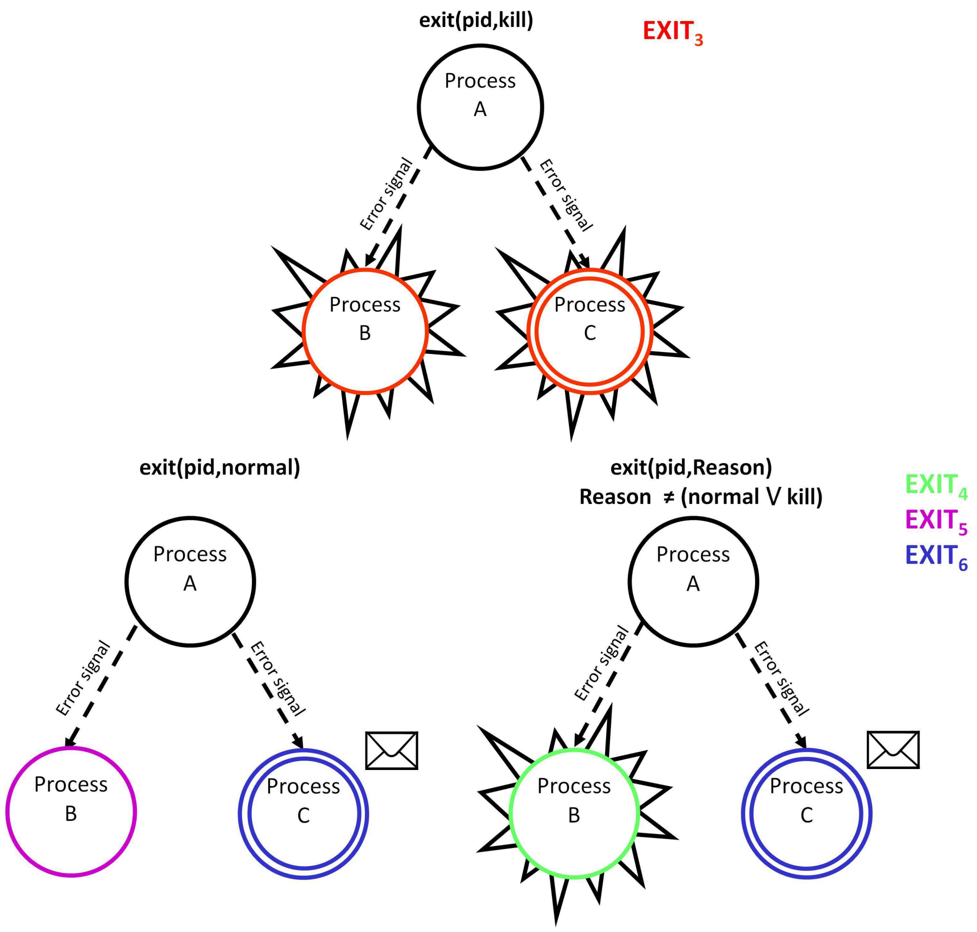


Figure 3.3: Exit propagation through explicit error signals

In the above diagram Process A is the process which is generating the explicit error signal by calling the exit(pid,Reason) built-in function. Here note, that process A is calling the exit function twice i.e. exit(B,Reason), exit(C,Reason). The key difference between process B and process C, is that process C is a system process(process_flag is set) while process B is not.

Perhaps the most noticeable difference between explicitly generated error signals and error propagation through links is when the reason of the generated signal is *kill*. In this case, as stated in rule EXIT$_3$, the receiving process will terminate immediately with reason *killed* irrespective of whether it is trapping exit signals or not. Rules EXIT$_4$ and EXIT$_5$ describe the way the system behaves whenever an exit signal is sent to a process which is not trapping exit signals. Rule EXIT$_4$ states that when an exit signal with reason R(where R $\neq$ to *kill* or *normal*) is sent to a process which is not trapping exit signals, the receiving process will terminate with reason R. Otherwise, if an exit signal with reason *normal* is sent to a process which is not trapping exit signals then this process will not terminate(EXIT_5). Rule EXIT_6 states that when an exit signal is sent to a process which is trapping exit signal, then the received signal is translated into an exit message and appended to the process' mailbox. Rule EXIT_7 states that if an exit signal is sent to a terminated process, then the exit signal is ignored.

Given the high degree of similarity between explicitly generated error signals and error propagation through links, at this point it is worth considering if it is possible to imitate the behaviour of links by sending explicit error signals. For example, can the following two pieces of code be considered as semantically equivalent?

Process i:

```
link(j),
link(k),
...
exit(badarg),
```

$$\overset{?}{\Leftrightarrow}$$

Process i :

```
exit(j,badarg),
exit(k,badarg),
exit(badarg),
```

Listing 3.4: Exit propagation & Explicitly sent exit signals

At first glance, they seem to have identical behaviour - in both cases an exit signal with reason *badarg* will be sent to process j and process k. However, there is one subtle difference. In the first case process i will terminate prior to sending any error signals whereas in the second case process j will send all error signals before its termination. In order to better understand the consequence of such a slight difference let's consider the case where an external process, say process l sends an exit signal with reason *stop* just after process i has sent an error signal to process j.

First we will consider the piece of code shown on the left hand side. In this case after linking to process j and process k, process i will terminate with reason *badarg*.

$$i[\mathsf{link}(j)\cdot\mathsf{link}(k)\cdot\ldots\mathsf{exit}(badarg),\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ j[e_j,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ k[e_k,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{link}(k)\cdot\mathsf{exit}(badarg),\ \epsilon,\ \{j\},\ false]\ ||\ j[e_j,\ \epsilon,\ \{j\},\ \mathsf{false}]\ ||\ k[e_k,\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{LINK}_0)$$

$$\longrightarrow\ i[\mathsf{exit}(badarg),\ \epsilon,\ \{j,k\},\ false]\ \ ||\ \ j[e_j,\ \epsilon,\ \{j\},\ \mathsf{false}]\ \ ||\ \ k[e_k,\ \epsilon,\ \{k\},\ \mathsf{false}] \qquad (\mathsf{LINK}_0)$$

$$\longrightarrow\ i[badarg, \{j,k\}]\ \ ||\ \ j[e_j,\ \epsilon,\ \{j\},\ \mathsf{false}]\ \ ||\ \ k[e_k,\ \epsilon,\ \{k\},\ \mathsf{false}] \qquad (\mathsf{TERM}_1)$$

After its termination, process i will start sending error signals to all processes found in its link set; i.e. process j and process k. Here it is worth pointing out that process i may first send an error signal to either process j or k since as mentioned in Section 3.11.2 the order in which error signals are sent upon process termination is undetermined. In the following steps process i will first send an error signal to process j. Since process j is not trapping exit signals it will terminate with reason *badarg*.

$$i[badarg, \{j,k\}]\ ||\ j[e,\ \epsilon,\ \{i\},\ false] \longrightarrow\ i[badarg, \{k\}]\ ||\ j[badarg, \emptyset] \qquad (\mathsf{EXIT}_2)$$

After the error signal has been sent, another different process l, sends an error signal with reason *stop* to process i. Since process i has already terminated this error signal will be ignored.

$$l[stop, \{i\}]\ ||\ i[badarg, \{k\}]\ \longrightarrow\ l[stop, \emptyset]\ ||\ i[badarg, \{k\}] \qquad (\mathsf{EXIT}_7)$$

Process i, will then continue sending error signals to the remaining processes found in its link set i.e. process k. On receipt of the error signal process k will also terminate with reason *badarg*.

$$i[badarg, \{k\}]\ ||\ k[e,\ \epsilon,\ \{i\},\ false] \longrightarrow\ i[badarg, \emptyset]\ ||\ k[badarg, \{i\}] \qquad (\mathsf{EXIT}_2)$$

Now let's consider the scenario where no links are used. In this case process i will first send an error signal to process j and just as before process j will terminate with reason *badarg*.

$$i[\text{exit}(j, badarg),\ \epsilon,\ \emptyset,\ false]||\ j[e,\ \epsilon,\ \{i\},\ false] \longrightarrow \\ i[\text{true},\ \epsilon,\ \emptyset,\ false]\ ||\ j[badarg, \emptyset] \qquad (\mathsf{EXIT}_4)$$

Then process i will receive the error signal from process l. Since process i is not trapping exit signals, this will cause process i to terminate immediately.

$$l[stop, \{i\}] \mid\mid i[\text{true},\ \epsilon,\ \emptyset,\ false] \longrightarrow l[stop, \emptyset] \mid\mid i[stop, \emptyset] \qquad (\mathsf{EXIT}_2)$$

As a result process i would never be able to send the remaining error signal to process k. This which may potentially result in a memory leak, if for instance process k is blocked waiting for some message from process i. This particular example proves that the behaviour of error propagation through links cannot always be imitated by using explicit error signals.

Another major difference between links and explicit error signals is that an explicit error signal can be sent to the process generating the signal itself. This is done if the first argument of the exit built-in functions is set to the calling process pid, $exit(self(), Reason)$. In the case of links this behaviour cannot be obtained, a process cannot be linked to oneself. The rules defining the behaviour of processes when exit signals are sent to oneself are described in Table 3.11.4.

What these rules essentially state is that when sending error signals to oneself the behaviour of the process will depend mainly on two factors:

- the reason describing the cause of the error signal
- the process's process_flag

If the reason of the error signal is equal to *kill*, the process will die irrespective of whether it is trapping exit signals or not(EXIT_8). Otherwise, if the process is trapping exit signals, the generated error signal will be trapped and a message is appended to the process' mailbox(EXIT_{10}). If the process is not trapping exit signals, the process will terminate immediately with the reason being the one set by the explicitly generated error signal(EXIT_9). Here it is worth highlighting the fact that the process will still terminate even if the reason is set to *normal*.

In fact this is one minor improvement over Fredlund's semantic definition of explicitly generated error signals[14]. In his work, Fredlund does not define rules to describe the behaviour of processes when error signals are sent to oneself. Consequently, when trying to evaluate exit(self(),Reason) it is impossible to see how the system will behave. For instance, let's consider the case when the expression exit(self(),*normal*) is evaluated. At first one might think that when evaluating this expression the process will not terminate. This is because non-system processes will only terminate upon receipt of an abnormal error signal (i.e. reason $\neq$ *normal*). However, in truth when evaluating this expression using actual Erlang the system will terminate immediately with reason *normal*.

One problem mentioned in the previous chapter with respect to self-sent error signals was if the function call exit(Reason) can be considered to be semantically equivalent to exit(self(), Reason). Through the above semantics it becomes evident that there are some major difference between the two. For instance, let's consider the following two code excerpts:

```
process_flag(trap_exit,true),          ?      process_flag(trap_exit,true),
....                                   ⇔      ....
exit(reason),                                 exit(self(),reason),
```

Listing 3.5: exit(Reason) & exit(self(),Reason) - Case A

When trying to evaluate the code excerpt found on the left using the defined semantics the *exit*(*reason*) will be first reduced to an exception. This exception will then cause the process to terminate with reason *reason*.

$$i[exit : reason,\ \epsilon,\ \emptyset,\ \mathsf{true}] \longrightarrow\ i[reason, \emptyset] \qquad (\mathsf{TERM}_1)$$

If we attempt to evaluate the code excerpt found on the right hand side the end process will be different. This is due to the fact that the $exit(self(), reason)$ will not cause the process to terminate. Instead an error signal notification is added to its mailbox.

$$i[\text{exit}(\text{self}(), reason),\ \epsilon,\ \emptyset,\ true] \longrightarrow$$
$$i[true,\ [EXIT, i, reason],\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{EXIT}_{10})$$

This scenario shows that the exit(Reason) function cannot be considered to be semantically equivalent to exit(self(),Reason). Nonetheless, the above case only illustrates that these two expressions are not equivalent when called from within a system process. What if the process_flag is set to false just before calling the exit(self(), Reason)? In this case will the two expressions always behave in the same way? In order to be able to tackle this problem let's consider the following code excerpts:

```
try                                         try
   process_flag(trap_exit,false),              process_flag(trap_exit,false),
   exit(reason),                       ?       exit(self(),reason),
catch                                  ⇔    catch
   exit:reason -> caught                       exit:reason -> caught
end                                         end
```

Listing 3.6: exit(Reason) & exit(self(),Reason) - Case B

Using the defined semantics, the exit(reason) will be first reduced to an exception. Since this is found within a try-catch block the generated exception will not cause the process to terminate. As a result, the process will not terminate.

$$i[\mathsf{try}\ \ \mathsf{exit} : reason\ \ \text{catch}\ \mathsf{exit} : reason \rightarrow caught\ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{false}] \longrightarrow \\ i[caught,\ \epsilon,\ \emptyset,\ \mathsf{false}] \qquad (\mathsf{TRY}_2)$$

In the second case, the exit(self(),reason) expression will send an exit signal to itself. Due to the fact that the try-catch block is only capable of catching exceptions, the sent exit signal will immediately cause the process to terminate.

$$i[\mathsf{exit}(\mathsf{self}(), reason),\ \epsilon,\ \emptyset,\ \mathsf{false}] \longrightarrow\ i[reason, \emptyset] \qquad (\mathsf{EXIT}_9)$$

Therefore, even though at first it might seem that exit(self(), Reason) and exit(Reason) will always behave in the same way when used by a non-system process, this case proves that in truth this may not always be the case.

3.11.5 Monitors

$$\frac{}{\begin{array}{c} i[\mathsf{monitor}(process, j),\ m_i,\ l_i,\ f_i\ ]||j[e_j,\ m_j,\ l_j,\ f_j\ ] \longrightarrow \\ i[true,\ m_i,\ l_i,\ \mathsf{true}\ ]\ ||\ j[e_j,\ m_j,\ l_j \cup \{i\},\ f_j\ ] \end{array}}\ \text{MON}_0$$

$$\frac{}{\begin{array}{c} i[\mathsf{monitor}(process, j),\ m,\ l,\ f\ ]\ ||\ j[v, l] \longrightarrow \\ i[true,\ m +\!\!+ \{'EXIT', j, down\},\ l,\ f\ ]\ ||\ j[v, l] \end{array}}\ \text{MON}_1$$

These rules state that when a process calls the monitor function, a one directional link is created between the calling process and the specified pid(MON$_0$). If the process specified by the pid terminates abnormally, a notification message about its termination will be sent. When the calling process, attempts to monitor a terminated process, a notification message is immediately sent to the calling process(MON$_1$).

One point worth mentioning here is that these rules have two main limitiations:

- In actual Erlang, when a process calls the monitor function consecutive times, multiple monitors are created. For instance, in the following example

```
monitor(process, Pid1),
monitor(process, Pid1)
```

two monitors will be created. As a result when the process terminates, two message notifications will be received. In our semantics, only one message will be received since the link set will only contain one instance of the monitor's pid. (due to the fact that sets are not able to store duplicates)

- In actual Erlang, when a process calls the monitor function it will only be able to trap error signals from the process which it is monitoring. For instance, in the case shown hereafter:

```
monitor(process, Pid1),
link(Pid2)
```

the calling process is only able of trapping error signals from Pid1. If process Pid2 fails abnormally, than the calling process will also fail. However, by using the defined rules, it is not possible to faithfully describe this behaviour. In fact the defined rules assume that there will only be monitor calls within one process.

Using the defined rules, we are now able to tackle another problem mentioned in the previous chapter - Can the monitor behaviour be implemented using links as illustrated in the following diagram?

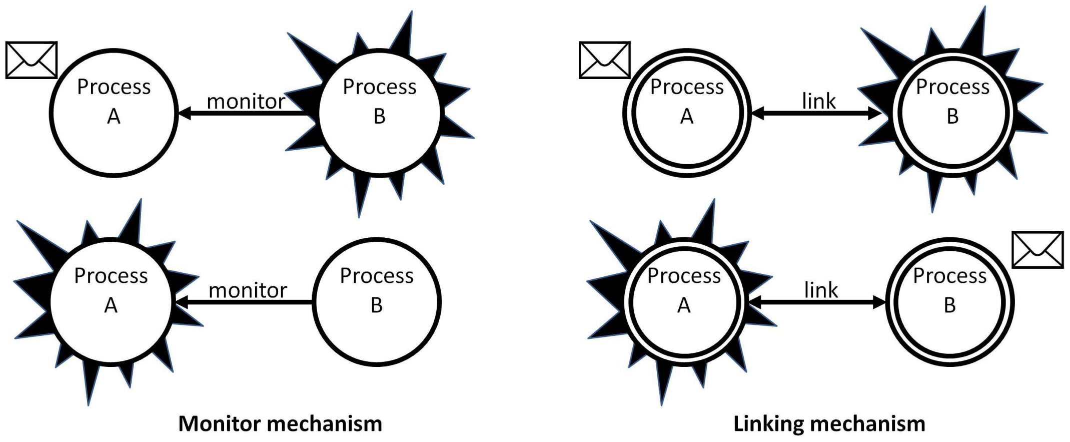


Figure 3.4: Monitor and Links

The following two code excerpts, illustrate how the above two systems are implemented in Erlang.

Process i

```
monitor(process,Pid2),
 ....
%%error occurs - reason = stop
```

Process j

```
...
```

Process i

```
process_flag(trap_exit,true),
link(PidB),
...
%%error occurs - reason = stop
```

Process j

```
process_flag(trap_exit,true),
...
```

Listing 3.7: Monitors & Links

The two systems seem to be semantically equivalent. In both cases if process j fails, process i will be notified through an error messages. Additionally, a failure in process i should never cause process j to terminate since:

- in the case of monitors, an error signal will not be sent given that process j is not included in process i's links set.
- in the case of links, process j should be able to trap the received exit signal.

Nonetheless, by using the defined rules it is possible to see that this last statement is not entirely true since in reality when using links, process j may actually fail to trap the received exit signal. This occurs, if the following sequence of reductions take place.

After setting its process_flag, process i creates a link to process j.

$$i[\mathsf{link}(j) \cdot \mathsf{exit(stop)},\ \epsilon,\ \emptyset,\ \mathsf{true}] \mid\mid j[e,\ \epsilon,\ \{i\},\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{true} \cdot \mathsf{exit(stop)},\ \epsilon,\ \{j\},\ \mathsf{true}] \mid\mid j[e,\ \epsilon,\ \{i\},\ \mathsf{false}] \qquad (\mathsf{LINK}_0)$$

where $e = \mathsf{process\_flag}(trap\_exit, \mathsf{true}) \cdot ...$

Process i, then terminates abnormally with reason *stop*. Upon termination it sends an error signal to process j. Since process j has not set its process_flag yet, the sent error signal will cause it to terminate immediately.

$$\longrightarrow\ i[stop, \{j\}] \mid\mid j[e,\ \epsilon,\ \{i\},\ \mathsf{true}] \qquad (\mathsf{TERM}_1)$$

$$\longrightarrow\ i[stop, \emptyset] \mid\mid j[stop, \emptyset] \qquad (\mathsf{EXIT}_2)$$

Therefore, this proves that even though at first it might seem that the two code excerpts are equivalent in actual fact they are not. Here one can appreciate the fact, that thanks to the defined rules it was possible to clearly identify the subtle difference between the two mechanisms.

3.11.6 sumNProduct Example(Remote error handling)

Using this rule it is now possible to describe the behaviour of sumNProduct which makes use of the remote handling mechanisms as described in 3.11.2. Here, it is important to note that in the following descriptions only the main reduction steps are described. This is due to the fact that if all the reduction steps were to be mentioned, the system's description may result in a rather lengthy one.

First, we will consider the case when the both input lists consists are set to [12,5]. First the parent process sets its flag so that it will be able to trap any received error signals.

$$i[\mathsf{process\_flag}(trap\_exit, \mathsf{true}) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{false} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{PROC\_FLAG})$$

$$\begin{aligned}\text{where } e_1 = {} & \mathsf{spawn\_link}(sumProcess, [i, [12, 5]]) \cdot \mathsf{spawn\_link}(productProcess, [i, [12, 5]]) \cdot \\ & ?[sum, Sum] \to Sum; [EXIT, j, badarith] \to invalid \cdot \\ & ?[product, Product] \to Product; [EXIT, k, badarith] \to invalid \cdot \\ & \ [Sum, Product]\end{aligned}$$

Two seperate processes are then created. Since the spawn_link function is used a link between the child and parent process is set up immediately. First the process which is responsible to compute the sum is spawned:

$$\longrightarrow\ i[\mathsf{spawn\_link}(sumProcess, [i, [12, 5]]) \cdot e_2,\ \epsilon,\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{SEQ}_1)$$

$$\longrightarrow\ i[j \cdot e_2,\ \epsilon,\ \{j\},\ \mathsf{true}] \mid\mid j[i![sum, 12 + 5]),\ \epsilon,\ \{i\},\ \mathsf{false}] \qquad (\mathsf{SPAWN\_LINK})$$

$$\begin{aligned}\text{where } e_2 = &\,\mathsf{spawn\_link}(\mathit{productProcess}, [i, [12, 5]])\cdot\\ &?[\mathit{sum}, \mathit{Sum}] \to \mathit{Sum}; [\mathit{EXIT}, j, \mathit{badarith}] \to \mathit{invalid}\cdot\\ &?[\mathit{product}, \mathit{Product}] \to \mathit{Product}; [\mathit{EXIT}, k, \mathit{badarith}] \to \mathit{invalid}\cdot\\ &\ [\mathit{Sum}, \mathit{Product}]\end{aligned}$$

Subsequently, another process is spawned to calculate the product of the input list.

$$\begin{aligned}\longrightarrow\ & i[\mathsf{spawn\_link}(\mathit{productProcess}, [i, [12, 5]]) \cdot e_3,\ \epsilon,\ \{j\},\ \mathsf{true}]\ \ ||\\ & k[i![\mathit{product}, 12 * 5],\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid s_j \qquad (\mathsf{SEQ}_1)\end{aligned}$$

$$\longrightarrow\ i[k \cdot e_3,\ \epsilon,\ \{k\},\ \mathsf{true}]\ \ ||\ \ k[i![\mathit{product}, 12 * 5],\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid s_j \qquad (\mathsf{SPAWN\_LINK})$$

$$\longrightarrow\ i[e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}] \mid\mid k[i![\mathit{product}, 12 * 5],\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid s_j \qquad (\mathsf{SEQ}_1)$$

$$\begin{aligned}\text{where } s_j &= j[i![\mathit{sum}, 12 + 5]),\ \epsilon,\ \{i\},\ \mathsf{false}]\\ e_3 &= ?[\mathit{sum}, \mathit{Sum}] \to \mathit{Sum}; [\mathit{EXIT}, j, \mathit{badarith}] \to \mathit{invalid}\cdot\\ &\quad ?[\mathit{product}, \mathit{Product}] \to \mathit{Product}; [\mathit{EXIT}, k, \mathit{badarith}] \to \mathit{invalid}\cdot\\ &\quad\ [\mathit{Sum}, \mathit{Product}]\end{aligned}$$

Process j, the process calculating the sum will then send its result.

$$\equiv\ \ j[i![\mathit{sum}, 12 + 5]),\ \epsilon,\ \{i\},\ \mathsf{false}]\ \ ||\ \ i[e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}]\ \ ||\ \ s'_k$$

$$\longrightarrow\ j[[\mathit{sum}, 17],\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid i[e_3,\ [[\mathit{sum}, 17]],\ \{j, k\},\ \mathsf{true}] \mid\mid s'_k \qquad (\mathsf{SEND}_1)$$

Subsequently process k will send the the product of the input list.

$$\equiv\ \ k[i\ !\ [\mathit{product}, 60],\ \epsilon,\ \{i\},\ \mathsf{false}]\ \ ||\ \ i[e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}]\ \ ||\ \ s'_j$$

$$\longrightarrow\ \ k[[\mathit{product}, 17],\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid i[e_3,\ [[\mathit{sum}, 17], [\mathit{product}, 60]],\ \{j, k\},\ \mathsf{true}] \mid\mid s'_j \qquad (\mathsf{SEND}_1)$$

$$\begin{aligned}\text{where } s'_k &= k[i![\mathit{product}, 12 * 5]),\ \epsilon,\ \{i\},\ \mathsf{false}]\\ s'_j &= j[[\mathit{sum}, 17],\ \epsilon,\ \{i\},\ \mathsf{false}]\end{aligned}$$

The two results are then read from the mailbox. First process i will read the sum value.

$$\equiv\ i[?[sum, Sum] \rightarrow Sum; [EXIT, j, badarith] \rightarrow invalid \cdot e_4,$$
$$[[sum, 17], [product, 60]],\ \{j, k\},\ \mathsf{true}]\ \|\ s''_j\ \|\ s''_k$$

$$\longrightarrow\ i[17 \cdot e_4,\ [[product, 60]],\ \{j, k\},\ \mathsf{true}]\ \|\ s''_j\ \|\ s''_k \qquad \textsf{(RCV)}$$

$$\begin{aligned} \text{where } e_4 &= ?[product, Value] \rightarrow Value; [EXIT, k, badarith] \rightarrow invalid \\ &\quad \cdot[17, Product] \\ s''_k &= k[[product, 60],\ \epsilon,\ \{i\},\ \mathsf{false}] \\ s''_j &= j[[sum, 17],\ \epsilon,\ \{i\},\ \mathsf{false}] \end{aligned}$$

Then process i will then read the product value. The two read values i.e. [17,60] are then returned.

$$\longrightarrow\ i[?[product, Product] \rightarrow Product; [EXIT, k, badarith] \rightarrow invalid$$
$$\cdot[17, Product],\ [[product, 60]],\ \{j, k\},\ \mathsf{true}]\ \|\ s''_j\ \|\ s''_k$$

$$\longrightarrow\ i[[17, 60],\ \epsilon,\ \{j, k\},\ \mathsf{true}]\ \|\ s''_j\ \|\ s''_k \qquad \textsf{(RCV)}$$

The above reduction steps are only one possible sequence of steps that can lead to the expected output. As mentioned in a previous section, when dealing with a parallel system there may be various different interleavings which still lead to the same output. Nonetheless, through the defined rules it is possible to check that all possible interleavings lead to the same result.

We will now consider the case when invalid list of data is input - [a,12]. Note that here only the main reduction steps are highlighted. These will give an idea how the defined rules can be used to describe the behaviour of a system. Similar to the previous case, process i will first set its process flag.

$$i[\mathsf{process\_flag}(trap\_exit, \mathsf{true}) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{false} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}] \qquad \textsf{(PROC\_FLAG)}$$

$$\begin{aligned} \text{where } e_1 = &\ \mathsf{spawn\_link}(sumProcess, [i, [a, 12]]) \cdot \mathsf{spawn\_link}(productProcess, [i, [a, 12]]) \cdot \\ &\ ?[sum, Sum] \rightarrow Sum; [EXIT, j, badarith] \rightarrow invalid \cdot \\ &\ ?[product, Product] \rightarrow Product; [EXIT, k, badarith] \rightarrow invalid \cdot \\ &\ [Sum, Product] \end{aligned}$$

Then it will spawn the two processes, one to calculate the sum and another to calculate the product.

$$\longrightarrow\ i[\mathsf{spawn\_link}(sumProcess, [i, [a, 12]]) \cdot e_2,\ \epsilon,\ \emptyset,\ \mathsf{true}] \qquad (\mathsf{SEQ}_1)$$

$$\longrightarrow\ i[j \cdot e_2,\ \epsilon,\ \{j\},\ \mathsf{true}] \,||\, j[i![sum, a + 12]),\ \epsilon,\ \{i\},\ \mathsf{false}] \qquad (\mathsf{SPAWN\_LINK})$$

$$\begin{aligned} \text{where } e_2 = {} & \mathsf{spawn\_link}(productProcess, [i, [a, 12]])\cdot \\ & ?[sum, Sum] \rightarrow Sum; [EXIT, j, badarith] \rightarrow invalid\cdot \\ & ?[product, Product] \rightarrow Product; [EXIT, k, badarith] \rightarrow invalid\cdot \\ & \ [Sum, Product] \end{aligned}$$

Subsequently, another process is spawned to calculate the product of the input list.

$$\begin{aligned} \longrightarrow\ & i[\mathsf{spawn\_link}(productProcess, [i, [a, 12]]) \cdot e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}] \ || \\ & \quad k[i![product, a * 12],\ \epsilon,\ \{i\},\ \mathsf{false}] \,||\, s_j \qquad (\mathsf{SEQ}_1) \end{aligned}$$

$$\longrightarrow\ i[k \cdot e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}] \ \ || \ \ k[i![product, a * 12],\ \epsilon,\ \{i\},\ \mathsf{false}] \,||\, s_j \qquad (\mathsf{SPAWN\_LINK})$$

$$\longrightarrow\ i[e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}] \,||\, k[i![product, a * 12],\ \epsilon,\ \{i\},\ \mathsf{false}] \,||\, s_j \qquad (\mathsf{SEQ}_1)$$

$$\begin{aligned} \text{where } s_j &= j[i![sum, a + 12]),\ \epsilon,\ \{i\},\ \mathsf{false}] \\ e_3 &= ?[sum, Sum] \rightarrow Sum; [EXIT, j, badarith] \rightarrow invalid\cdot \\ & \quad ?[product, Product] \rightarrow Product; [EXIT, k, badarith] \rightarrow invalid\cdot \\ & \quad\ [Sum, Product] \end{aligned}$$

When processes j attempts to calculate the sum of the received list it will fail with reason *badarith*. Afterwards, it will send an error signal to process i.

$$\equiv\ \ j[i![sum, a + 12]),\ \epsilon,\ \{i\},\ \mathsf{false}] \ \ || \ \ i[e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}] \ \ || \ \ s'_k$$

$$\longrightarrow\ j[\mathsf{error} : badarith,\ \epsilon,\ \{i\},\ \mathsf{false}] \ \ || \ \ i[e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}] \,||\, s'_k$$

$$\longrightarrow\ j[badarith, i] \,||\, i[e_3,\ \epsilon,\ \{j, k\},\ \mathsf{true}] \,||\, s'_k \qquad (\mathsf{TERM}_1)$$

$$\longrightarrow\ j[badarith, \emptyset] \,||\, i[e_3,\ [[EXIT, j, badarith]],\ \{k\},\ \mathsf{true}] \,||\, s'_k \qquad (\mathsf{EXIT}_2)$$

$$\text{where } s'_k = k[i![product, a * 12]),\ \epsilon,\ \{i\},\ \mathsf{false}]$$

Process i will then read the received error notification

$$\equiv\ i[?[sum, Sum] \to Sum; [EXIT, j, badarith] \to invalid \cdot e_4,$$
$$[[EXIT, j, badarith]],\ \{k\},\ \mathsf{true}]\ ||\ j[badarith, \emptyset]\ ||\ s'_k$$

$$\longrightarrow\ i[invalid \cdot e_4,\ \epsilon,\ \{k\},\ \mathsf{true}]\ ||\ j[badarith, \emptyset]\ ||\ s'_k \qquad (\mathsf{RCV})$$

where $e_4 = ?[product, Value] \to Value; [EXIT, k, badarith] \to invalid$
$\cdot[invalid, Product]$

Similarly, process k will also terminate with reason *badarith*. The received error notification will be appended to process i's mailbox.

$$\equiv\ k[i![product, 12 * 5],\ \epsilon,\ \{i\},\ \mathsf{false}]\ ||\ i[invalid \cdot e_4,\ \epsilon,\ \{k\},\ \mathsf{true}]\ ||\ s'_j$$

$$\longrightarrow\ k[\mathsf{error}{:}badarith,\ \epsilon,\ \{i\},\ \mathsf{false}]\ ||\ i[invalid \cdot e_4,\ \epsilon,\ \{k\},\ \mathsf{true}]\ ||\ s'_j$$

$$\longrightarrow\ k[badarith, \{i\}]\ ||\ i[invalid \cdot e_4,\ \epsilon,\ \{k\},\ \mathsf{true}]\ ||\ s'_j \qquad (\mathsf{TERM}_1)$$

$$\longrightarrow\ k[badarith, \emptyset]\ ||\ i[e_4,\ [[EXIT, k, badarith]],\ \emptyset,\ \mathsf{true}]\ ||\ s'_j \qquad (\mathsf{EXIT}_2)$$

where $s'_j = j[badarith, \emptyset]$

Process i will read the error notification sent from process k.

$$\longrightarrow\ i[?[product, Product] \to Product; [EXIT, k, badarith] \to invalid \cdot [invalid, Product],$$
$$[[EXIT, k, badarith]],\ \emptyset,\ \mathsf{true}]\ ||\ s'_k\ ||\ s'_j$$

$$\longrightarrow\ i[[invalid, invalid],\ \epsilon,\ \emptyset,\ \mathsf{true}]\ ||\ s'_k\ ||\ s'_j \qquad (\mathsf{RCV})$$

where $s'_k = k[badarith, \emptyset]$

The above steps show that in the case of invalid input, this version of sumNProduct will also return $[invalid, invalid]$ just like its sequential and other parallel version. By using the defined rules it is also possible to show that even by changing the order in which the events happen the system will still return the same output if given the same input. Therefore, it is possible to conclude that this version of sumNProduct is semantically equivalent to its previous versions.

3.12 Conclusion

This chapter presented a formal semantic definition of Erlang's error handling mechanisms. These formal definitions provided us a better insight of how Erlang systems behave in the presence of errors. In fact, by using these rules it became possible to get a step-by-step description of how Erlang systems are executed, bringing to light any unexpected sequences of events that may lead to unwanted results. Additionally, these rules were also able to show that in some cases, two syntactically different systems can actually have semantically equivalent behaviour. However, when dealing with parallel system it was much more challenging to ensure semantic equivalence of two systems. This is due to the fact that the number of possible interleavings is exponential to the size of the given system. This latter fact, is the motivation behind the next chapter. In order to facilitate the task of exhaustively analysing a system's behaviour, the defined semantic rules will be animated through an evaluator.

4. Implementation Framework

4.1 Introduction

The main motivation behind defining a formal semantics for the error handling constructs was to be able to correctly reason about Erlang systems. Through the rules defined in the previous chapter it became possible to give a detailed description of how a particular Erlang system is expected to behave. The aim of this chapter is to give a high-level description of the system which was designed so as to be able to check the behaviour of a system under all possible interleavings in a more efficient way. The main components of the designed system will be outlined highlighting any choices that were taken whilst designing the system.

4.2 System Design

The system was implemented in Haskell and as illustrated in Figure 4.1, it consists mainly of three main modules. The first module is responsible for parsing the input text. The parsed input is then fed to the evaluator which will describe all possible ways the input system may behave according to the previously defined semantic rules. The last module's task is to present in an understandable way, a step-by-by description of these different behaviours. In the following sections we will take a deeper look at hwoeach of these modules.

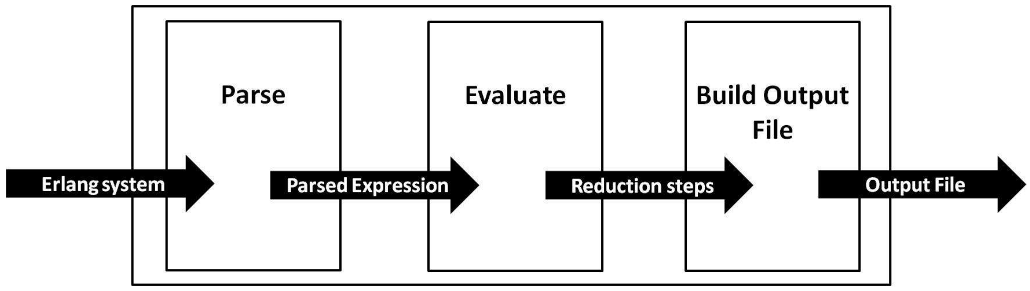


Figure 4.1: System's design

4.3 Input

The designed system asks the user to enter three inputs:

1. name of the module file - The module file should contain the function definitions that are called by the Erlang system. Even though in actual Erlang one system can call functions, whose definitions are found within different modules in the designed system, all function definitions have to be found within the same file. The expressions of this file will be parsed according to the BNF described in Table 3.2. The only difference is that the spawn, spawn_link, and spawn_monitor functions do not expect the module name parameter.

2. name of the input file - this file will contain the input expression that in actual Erlang is input into the shell. This expression will be also parsed according to the BNF described in Table 3.2 and as in the previous case the spawn, spawn_link and spawn_monitor functions do not expect the module name parameter.

3. name of the output file - this will determine the name of the file where the results of the evaluator will be stored.

4.4 Parsing

The first module is composed of two distinct sub-modules; the lexer and the parser. The purpose why the parsing analysis was divided into two stages is that this approach helps in ensuring a less complex design for the parser.

4.4.1 Lexer

The lexer used within the system was adapted from the one found in [20]. As input the lexer will be fed text upon which it performs the following taks:

- remove comments
- remove white spaces
- detect any lexical errors
- recognise any keywords or operators
- recognise atoms and integers

For example, if the lexer is given the following input:

```
%% this is an example

[1,20,Hello,world]
```

it will tokenize the input text and return the following list of tokens.

```
[Tok "["     3  2 Keyword,
 Tok "1"     3  3 Number,
 Tok ","     3  4 Keyword,
 Tok "10"    3  5 Number,
 Tok ","     3  7 Keyword,
 Tok "Hello" 3  8 Variable,
 Tok ","     3 13 Keyword,
 Tok "world" 3 14 UnquotedAtom,
 Tok "]"     3 19 Keyword,
 Tok ""      3 20 EndToken]
```

Each token has a string containing the exact substring from the source file followed by the line and column where the token is found in source file and the token's class such as Number or Variable. This tokenized list is then passed to the parser.

4.4.2 Parser Combinators

The parser was implemented using parser combinators rather than a parser generator. One major benefit of using parser combinators is that one need not generate the whole parser every time a minor modification is done to the parser as is the case when using a parser generator. The fundamental principle behind parser combinators is that a parser is written in bottom-up fashion, similar to the way that one would define a language grammar.

In fact, when implementing the parser for this project the most elementary parser were first defined. These parsers were then “joined” together so as to get the main parser which is able to parse all of the expressions found in the chosen subset of Erlang. The most basic parser within the designed system is the `token` parser.

```
token ([]) = ParseError "Unexpected eof"
token (x:xs) = Expression (x,xs)
```

Listing 4.1: Basic Parser

The task of this simple parser is to return as the parsed expression, the head of the token’s list that is passed to the main parser. Apart from the `token` parser, several other elementary parsers were defined. These all combined the token parser described above with another function in order to produce a new parser. One such parser is the `keyword` parser.

```
keyword str = token <=> (isKeyword str)
```

Listing 4.2: Keyword parser

Here, the `<=>` combinator, checks if the function given on the right hand side, `(isKeyword str)`, returns true when applied to the parsed expression that is produced when using the parser on the left hand side `(token)`. The `keyword` parser was then combined to other elementary parsers which are needed to parse the Erlang expressions that are found in the chosen subset. Two such expression parsers are the following:

```
caseExp =  (keyword "case") <-+>
            expression      <+->
           (keyword "of")   <+>
            erlangMatch
```

```
tryExp = (keyword "try")   <-+>
          sequence         <+->
         (keyword "catch") <+>
          exceptionsCatch
```

Listing 4.3: Parser Combinators

These parsers make use of three different parser combinators. The `<+>` combinator joins two parsers using the ‘and’ type operator. The `<-+>` combinator is similar to the `<+>` combinator but does not return the output of the parser on the left hand side of the combinator. On the other hand, the `<+->` combinator does not return the output of the parser defined on the right hand side. For instance, when applying the caseExp parser to a tokenized list representing the following expressions:

```
case Value of 1 -> hello; 2 -> bye end

try A+B catch error:Desc -> Desc end
```

the Erlang expression parser returns the expression

```
Case (Var "Value") Match [(1,Atom "hello"),(2,(Atom "bye")]

Try  (Add (Var A) (Var B)) Match [Exception Error (Var Desc)]
```

In order to be able to parse all the expressions in the subset, a different simple parser were defined for each Erlang expression. Here, only the `tryExp` and `caseExp` parsers were described. However, the other parsers were defined similar to the way in which these two parsers have been defined.

The main parser then "combined" all of these expression parser by using the `<|>` combinator whose task is to join any two elementary parsers using the 'or' type operator.

```
prefixExp :: Parser ErlangExp
prefixExp =
            caseExp
      <|> receiveExp
      <|> tryExp
      <|> builtInFun
      <|> functionCall
      <|> list
      <|> atom
      <|> number
      <|> var
```

Listing 4.4: Expressions Parser

The above parser is used to parse the Erlang expressions found in the chosen subset. Once again, through this example one cannot help noticing the fact parser combinators made it possible to define the parser using really neat syntax. Moreover the parser's syntax is highly similar to the BNF definition. In fact, by looking at the parser definitions in 4.4 one can immediately understand what expression a particular parser is expected to parse since the parser function is almost identical to the BNF definition.

Another reason why it was opted to implement the parser through parser combinators lies in the fact that this approach allows incremental development. Therefore, if for instance the parser were to be extended so as to be able to parse Erlang tuples it would be relatively easy to carry out such modification. This is because in order to extend the parser one need only define a simple parser to parse Erlang tuples. The simple parser is then "joined" to the main parser as described in Listing 4.5

```
prefixExp :: Parser ErlangExp
prefixExp  =
                 caseExp
          <|>    receiveExp
          <|>    tryExp
          <|>    builtInFun
          <|>    functionCall
          <|>    list
          <|>    atom
          <|>    number
          <|>    var
          <|>    tuple
```

Listing 4.5: Expression Parser Extended

This simple example brings to light the fact that when using parser combinators, no major modifications need to be done in order to increase the number of expressions that the parser is able to parse. Therefore, with regards to this work, even though the parser was defined for a subset of Erlang, it will be quite straightforward to extend the parser so as to be able to accept an increased subset of Erlang. In fact, if a parser were to be defined to accept a larger subset of Erlang there will not be a need to implement the new parser from scratch as is the case when parser generators are used. This is because the parser implemented for this project may serve as the basis upon which the larger parser is built.

4.5 Evaluator

The primary aim of the evaluator is to give a clear and accurate description of how a particular Erlang system behaves. This is done by going through all possible sequences of reduction steps that the system might take, possibly revealing any unexpected ways in which an Erlang system might behave. Undoubtedly, one of the major benefits of the designed evaluator is that it makes the task of checking the behaviour of a system under all possible interleavings much more efficient. One here should be aware that the total number of interleavings can be considerably large even when the input system is extremely simple. This can be clearly seen if we consider the following really simple system:

```
processA() ->
  %% create a new process send the value 3
  case spawn_link(processB,[]) of
     %% send the value 3 to the new process
     Pid -> Pid ! 3
  end.

processB() ->
     %% bind the sum of 1+2 to Total
     case 1+2 of Total ->

           %% add the received Value to Total
           receive
             Value -> Total + Value
           end
     end.
```

Listing 4.6: Erlang Program

The following two lists identify all the small subtasks that are carried out by each process when the system is executed. Each of these tasks corresponds to exactly one reduction step.

Process A :	Process B :
A1 : spawn new process	**B1 :** compute sum of 1+2
A2 : bind Pid to pid of new process	**B2 :** bind Total to the result
A3 : send message to process B	**B3 :** receive message
	B4 : add Total to the received Value

Table 4.1: Actions to be performed when executing program 4.6

Diagram 4.2 illustrates the different sequences of reduction steps that this particular system may take before it returns its final output.

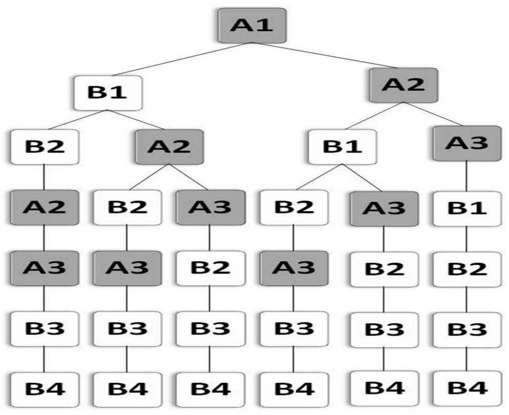


Figure 4.2: Different interleavings

In the above diagram the actions that are done by process A are indicated by gray coloured boxes, whereas actions that are carried out by process B are indicated by white boxes.

One here may notice that in all cases, process A will send the message to process B, and process B will always evaluate down to 6. Therefore, all cases can be considered to have identical behaviour even though the sequence of steps that led the system to achieve its final result are slightly different. Through this diagram it becomes clear that one extra reduction step in any of the given process, will increase the number of possible interleavings drastically.

In order to reduce the number of interleavings that the evaluator needs to go through, it was decided that sequences of reduction steps that do not cause any side effects, such as evaluation of addition followed by binding of variables should be considered as one single operation. This is due to the fact, that the order in which non-side effect reduction steps occurs may never yield to a different system's behaviour. For instance, let's consider again the program described in 4.6. In this case, as described in 4.1 the majority of the actions that are carried out by the two processes are non-side effect actions. In fact, the only side-effect action is A3.

Therefore, it does not make any real difference if B1 is computed before A2, or vice versa. This is because, non-side effect actions may only effect the local state of the process. By adopting such a practice, the number of interleavings is reduced substantially. This fact, is quite evident through Diagram 4.3 which shows the reduced number of different interleavings that the evaluator will check when using this approach.

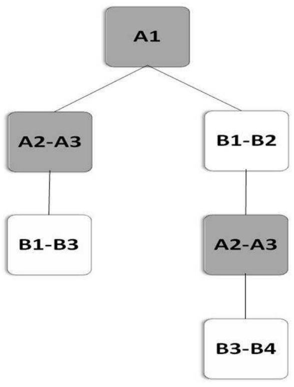


Figure 4.3: Different interleavings

In order to better appreciate how this approach made it possible to reduce the number of interleavings but still be able to represent all the different ways in which the system may behave, let's consider another simple system.

Process A :	Process B :
A1 : spawn new process	**B1 :** compute sum of 1+2
A2 : bind Pid to pid of new process	**B2 :** bind Total to the result
A3 : send exit signal to process B	**B3 :** send Total to process C

Table 4.2: Actions to be performed

In this case, the different interleavings, may result in a different behaviour. This is because, if action **A3** is executed before **B3** then the *Total* message will never reach process C. This may occur if any of these interleavings occur:

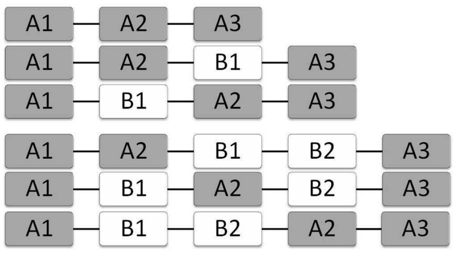


Figure 4.4: Possible Interleavings of System in 4.2: process B fails to send message

By analysing these interleavings it becomes evident that in actual fact all these interleavings are expressing the same behaviour i.e. the behaviour of the system when the exit signal is received before process B sends the *Total* message to process C. Here, it is worth highlighting the fact that in Erlang systems once a process dies, all the information stored within local variables is lost. As a result, with regards to this example, it does not really matter if the exit signal is received after executing step **B1** or just after executing **B2**. This is because, upon process B's termination all information stored in variables is lost.

Now, let's consider the case when codeCommB3 is evaluated before **A3** and therefore the *Total* message will be successfully sent to process C. As in the previous case, there are several possible different interleavings that may lead process B to eventually send the *Total* message. These interleavings are described in Figure 4.5.

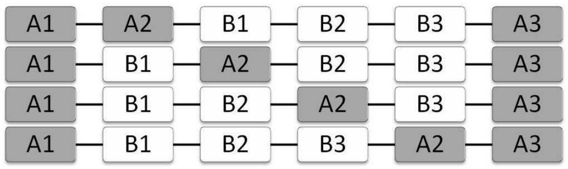

A1 — A2 — B1 — B2 — B3 — A3
A1 — B1 — A2 — B2 — B3 — A3
A1 — B1 — B2 — A2 — B3 — A3
A1 — B1 — B2 — B3 — A2 — A3

Figure 4.5: Possible Interleavings of System in 4.2: process B sends message

Through this example it became evident that an Erlang system due to its parallel nature may take different interleavings to complete its task. However, the behaviour of a system is really determined by the order in which the side-effect actions take place. For instance, with respect to this system, what really matters is if the exit message is received before or after the *Total* message is sent to process C. Therefore, all the different behaviours in which this particular system may behave can be represented through the following two interleavings.

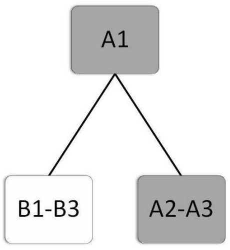


Figure 4.6: Possible Interleavings of System 4.2

Here, it is important to note that even though the number of interleavings to be checked are reduced substantially, the different interleavings are still able to represent all the possible ways in which a system may behave.

One of the major benefits of reducing the number of possible interleavings was that the evaluator experienced a slight improvement in efficiency. Just the same, the number of possible interleavings in some cases is considerably large especially when dealing with systems in which processes may terminate abnormally. This is due the fact that the order in which exit signals are sent is undefined. For instance, if a process is linked to 3 other processes, say process A, process B and process C then there are a total of six different orderings in which the exit signal may be sent. (since the failed process may send its exit signals either to A then to B and then to C, or first to B, then to A and then to C ...) Let's consider the following example, to better understand how the order in which exit signals are sent may increase significantly the number of possible interleavings:

```
...
%% spawn and link to process A
spawn_link(waitError,[Pid,ProcessB]),

%% spawn and link process B
spawn_link(waitError,[Pid,ProcessC]),

%% process terminates abnormally
%% with reason 'error occured'
exit('error occured').
```

```
waitError(Pid,Name) ->
    %% start trapping exit signals
    process_flag(trap_exit,true),

     %% wait for error message
     receive
        Error -> Pid ! Name
     end.
```

Listing 4.9: Erlang Program using Remote Error Handling Mechanisms

Each process in the above system, needs to execute the following steps:

Process A :	Process B :
A1 : spawn_link process B	**B1 :** set process flag
A1 : spawn_link process C	**B2 :** receive error message and send result to Pid
A3b : send error signal to B	
A3c : send error signal to C	Process C :
	C1 : set process flag
	C2 : receive error message and send result to Pid

Table 4.3: Actions to be performed when executing program 4.9

In this case process A is linked to both process B and process C and therefore it needs to send an exit signal to both processes. The evaluator needs to cover both when A sends its exit signal first to process B and when process A sends its exit signal first to process C. This factor, is one major contributor to the increase in the number of sequences that need to be checked by the evaluator. To get a better idea, how large this number can actually get, let's consider the following diagram which describes the different interleavings that the system described above may take:

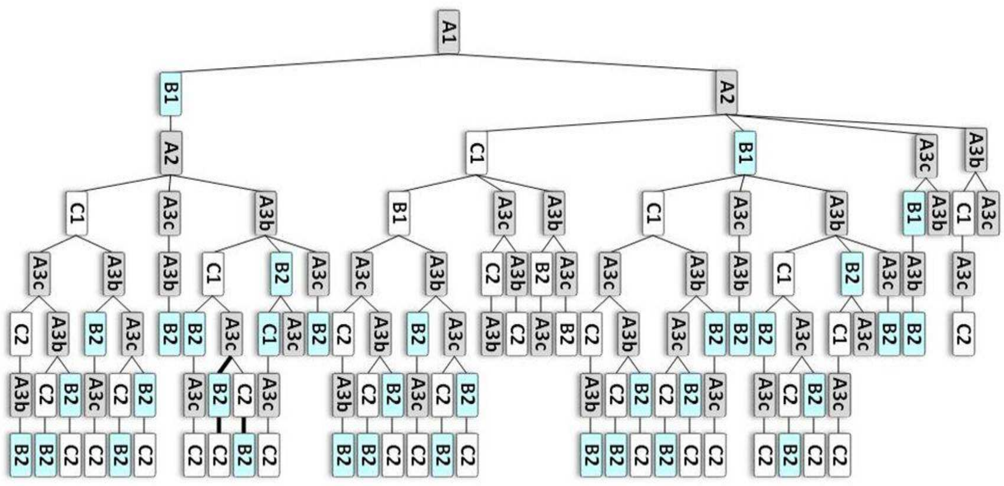


Figure 4.7: Error handling - possible interleavings

Given the fact, that the number of different sequences may become considerably large, it was decided that in the final output the evaluator only includes the different end result the system might reach and one sequence that may lead to this end result. For instance, in the above system, since the system may end in five different ways in the output file only five sequence of reductions steps are included, even though there are more different interleavings that the system may take.

4.6 Building the Output File

Once the evaluator has gone through all the interleavings, an output file is built decribing the different ways in which the input system may behave. The output file consists of a pdf file, which is composed primarily of four sections

- function definitions
- shell input
- different end systems
- sequence of reduction steps that have led to the above end systems

In order to build the pdf file, the output of the evaluator is translated into a latex file. This is then parsed by using the pdflatex command. Once the output file has been built, the system will automatically open the file so that the user may view the result of the evaluator.

4.7 Conclusion

This chapter gave a brief overview of the main components found within the designed system. It also illustrated why parallel systems may go through several different sequences of reduction steps before completing their task. As a result, it became evident that when dealing with parallel systems the use of an evaluator is key in order to identify those sequences of steps that may lead to unexpected behaviour.

5. Evaluation

5.1 Introduction

The aim of this chapter is to measure to what degree the objectives set forth in the beginning of this project have been met. These objectives were primarily that the defined model should be able to:

- offer a better insight into Erlang's error handling mechanisms
- explain better those circumstances that lead to unexpected results
- predict a system's behaviour
- lay foundations for a semantic theory

In the first section of this chapter the evaluation strategy that is used is explained. Subsequently, the described evaluation strategy is applied to a number of Erlang systems in order to evaluate to what extent the initial objectives have been achieved. Finally, the results of the evaluation are discussed.

5.2 Evaluation Strategy

Since the semantics were defined post-hoc, it was important to ensure that the presented definitions are loyal to the behaviour of actual Erlang. The correctness of the defined model was measured by adopting the strategy described in Figure 5.1.

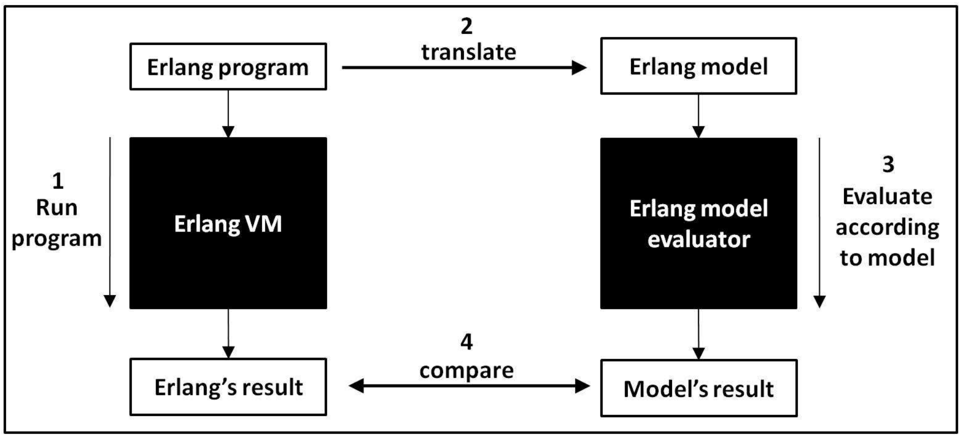


Figure 5.1: Evaluation Strategy

The correctness of the model was analysed by considering a number of different Erlang programs.

1. Each program was first run on the Erlang VM. In order to get a clearer picture of how a program is evaluated, Erlang's trace built-in function was used. This function returns a step-by-step description of how a program has been evaluated by Erlang, hence indicating the order in which side-effect actions such as linking and delivery of exit signals took place.

2. The same Erlang program was then translated in terms of the model.

3. Subsequently, the translated Erlang program was input into the evaluator. The evaluator returned sequences of reduction steps describing the different ways the input program may be evaluated according to the defined model.

4. The output generated by Erlang's tracer and the output of the evaluator are compared to analyse if the defined rules are capable of faithfully describing Erlang's behaviour.

5.3 Assessing the Defined Model

In this section, the evaluation strategy is applied to several Erlang programs. The programs were selected in such a way to evaluate all the rules which were defined to describe Erlang's error handling behaviour.

5.3.1 Test Case 1 : Local Error Handling

In order to evaluate the correctness of the formal rules describing Erlang's local error handling mechanisms, several programs which make use of the try-catch expression were considered. Two of the programs which were considered were the following:

Test case 1A:

```
fun1() ->
   try
      hello
   catch
      throw:stop ->
              'error caught'
   end.
```

Test case 1B:

```
fun1() ->
   try
      abc + def,
   catch
      error:badarith ->
                 'sum error'
   end.
```

In all cases it was found that the model is able to mirror correctly the behaviour of Erlang both when no exceptions were raised within the try-catch block(as in test case 1A), and also when exceptions were raised and needed to be handled by the try-catch statement(as in test case 1B).

One of the most interesting test cases with regards to local error handling was the following program which consists of two nested try-catch statements.

```
fun1(Pid,A,B) ->
        try
             try
               Pid ! A + B
             catch
               error:badarith -> Pid ! invalid
             end,

        catch
           error:badarg -> invalidPid
        end.
```

Listing 5.1: Nested try-catch statements

In this program, the innermost try-catch can only handle *badarith* exceptions, i.e. exceptions that occur when non-numeric data is passed as the second and third argument. The outermost try-catch statement is used to handle *badarg* exceptions, i.e. those exceptions which arise if invalid pids are passed to the function.

Here, we will consider the case when the first argument, i.e. the value bound to Pid is not a valid pid. As a result, when evaluating the `Pid ! A + B` an exception of type *badarg* is raised. The trace that was generated when evaluating the

```
fun1(nonPid,1,2)
```

expression was the following:

```
ln1 : {trace,<0.161.0>,send,3,invalidPid}

ln2 : {trace,<0.161.0>,exit,normal}
```

The above trace list shows that Erlang will first attempt to send the sum of the two input numbers i.e. 3 (`ln1`). Since in this case the first argument is bound to the atom *invalidPid* the send expression fails. This can be seen from the fact that in the trace list there is no tuple to show that the message has been received. At this point, it is important to note that the raised *badarg* exception does not cause the process to terminate abnormally since as shown in `ln2` the process will terminate with reason *normal.* This fact indicates that the generated exception must have been handled by one of the try-catch statements. In fact, when running the program, the system returned the atom *invalidPid* which shows that the generated exception was handled by the outermost try-catch statement.

This program was then evaluated by using to the defined semantics rules. According to the defined rules the system first evaluates the expression found within the try-catch block(which in the following reduction step is represented by e_1).

$$i[\mathsf{try}\ e_1\ \mathsf{catch\ error}{:}badarg \rightarrow\ invalidPid\ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

where $e_1 = \mathsf{try}\ nonPid\ !\ 1 + 2\ \mathsf{catch\ error}{:}badarg \rightarrow\ invalidPid\ \mathsf{end}$

When evaluating the try-catch statement found in e_1 a *badarg* exception is raised. Since, the try-catch statement is only able to handle *badarith* exceptions, e_1 will evaluate down to a *badarg* exception as shown in the following reduction step:

Evaluating subexpression e_1:

$$i[\textsf{try}\ nonPid\,!\,1+2\ \textsf{catch error:}badarith \rightarrow\ Pid!invalid\ \textsf{end},\ \epsilon,\ \emptyset,\ \textsf{false}]$$

$$\longrightarrow\ i[\textsf{error:}badarg\ ,\ \epsilon,\ \emptyset,\ \textsf{false}]$$

The raised exception is then handled by the outermost try-catch statement and the atom $invalidPid$ is returned.

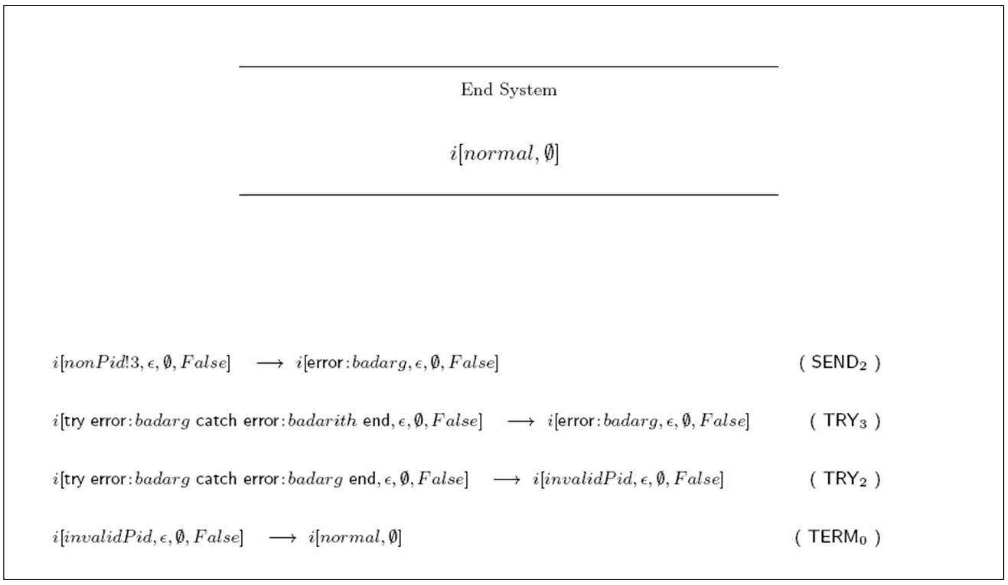
$$i[\textsf{try error:}badarg\ \textsf{catch error:}badarg \rightarrow\ invalidPid\ \textsf{end}\ ,\ \epsilon,\ \emptyset,\ \textsf{false}]$$

$$\longrightarrow\ i[invalidPid\ ,\ \epsilon,\ \emptyset,\ \textsf{false}]$$

Subsequently, since there is no other expression to evaluate after the try-catch statement the process terminates normally.

$$\longrightarrow\ i[normal, \emptyset]$$

The same behaviour was described when the program was input into the evaluator:



End System

$i[normal, \emptyset]$

$i[nonPid!3, \epsilon, \emptyset, False] \longrightarrow i[\textsf{error}:badarg, \epsilon, \emptyset, False]$ ($\textsf{SEND}_2$)

$i[\textsf{try error}:badarg\ \textsf{catch error}:badarith\ \textsf{end}, \epsilon, \emptyset, False] \longrightarrow i[\textsf{error}:badarg, \epsilon, \emptyset, False]$ ($\textsf{TRY}_3$)

$i[\textsf{try error}:badarg\ \textsf{catch error}:badarg\ \textsf{end}, \epsilon, \emptyset, False] \longrightarrow i[invalidPid, \epsilon, \emptyset, False]$ ($\textsf{TRY}_2$)

$i[invalidPid, \epsilon, \emptyset, False] \longrightarrow i[normal, \emptyset]$ ($\textsf{TERM}_0$)

Figure 5.2: Local error handling - evaluator's output

As seen in Figure 5.2, the evaluator described the fact that the raised exception is handled by the outermost try-catch statement(TRY_2). Subsequently, the process terminates with reason *normal*(TERM$_0$).

With regards to the output generated by the evaluator, here it is important to note that the expression in each reduction step only describes the innermost evaluating expression. For instance, in the first reduction step, only the `nonPid!3` expression found in process i is shown even though in actual fact this expression is found within a try-catch statement. The main reason why it was opted to only show the innermost evaluating expression was to prevent the reduction steps descriptions from becoming too cumbersome.
Here, it is evident that the reduction steps describe a behaviour which is identical to the one of actual Erlang. Therefore, it is clear that in this particular test case the defined model is able to faithfully describe the behaviour of actual Erlang. We will now move on to see if the behaviour of Erlang's remote error handling mechanisms as described by the model is completely faithful to the behaviour of Erlang.

5.3.2 Test Case 2 : Remote Error Handling - Links

In Erlang whenever a process, say process A terminates with reason R then an exit signal is sent to all of A's linked processes. Upon receipt of this exit signal, the linked process, say process B may behave in either of the following way:

case A: if process B's process_flag is set, an exit notification is appended to process B's mailbox
case B: if process B's process_flag is unset and R is *normal*, then the process B ignores the received signal
case C: if process B's process_flag is unset and R is not equal to *normal*, then the receiving process terminates with reason R

In order to check if the error propagation behaviour as described by the model is correct, the test cases were chosen in such a way to cater for all the three different ways a process might behave on receipt of an exit signal due to the termination of a linked process. Here, only the evaluation of case A is described since the evaluation carried out for each of the other cases is quite similar to the one described here.

In the chosen program, one process is used to handle the generated exception whereas another seperate process is responsible to compute the summation of the two input numbers.

```
fun1(Num1, Num2) ->
        %% set process flag
        process_flag(trap_exit,true),

        %% create new process to compute sum of numbers
        Pid = spawn_link(?MODULE,sum,[self(),Num1,Num2]),
        receive
              {'EXIT',Pid,Error} -> invalid;
              Result -> Result
        end.


sum(Pid,Num1,Num2) -> Pid ! Num1 + Num2.
```

Listing 5.2: Remote Error Handling Example

When running this test case, the fun1() function was passed non-numeric data *(aa,bb)* so as to see how the system will behave when incorrect data is input. The generated trace list was as follows:

```
ln1 : {trace,<0.125.0>,spawn,<0.126.0>,{links,sum,[<0.125.0>,aa,bb]}}
ln2 : {trace,<0.125.0>,link,<0.126.0>}

ln3 : {trace,<0.126.0>,exit,{badarith,[{links,sum,3}]}}

ln4 : {trace,<0.125.0>,'receive',{'EXIT',<0.126.0>,
      {badarith,[{links,sum,3}]}}}

ln5 : {trace,<0.125.0>,getting_unlinked,<0.126.0>}

ln6 : {trace,<0.125.0>,exit,normal}
```

In the above trace list, each side-effect action is represented by a tuple. The second element of every tuple identifies the Pid of the process performing the action. The third element gives the name of the side effect action that has been done. In the case of spawning the fourth element shows the Pid of the new process, whilst the fifth element shows the arguments passed to the spawn function basically {moduleName, functionName, arguments}. In the case of linking, the third element refers to the pid of the process with whom the link will be done.

When the process terminates the third tuple is set to exit and the fourth tuple indicates the reason with which the process terminated.

Here, one can appreciate how the trace list made it possible to get a really clear picture of how this particular program is evaluated. In order to better understand Erlang's behaviour as described by the trace list let's consider the following diagram.

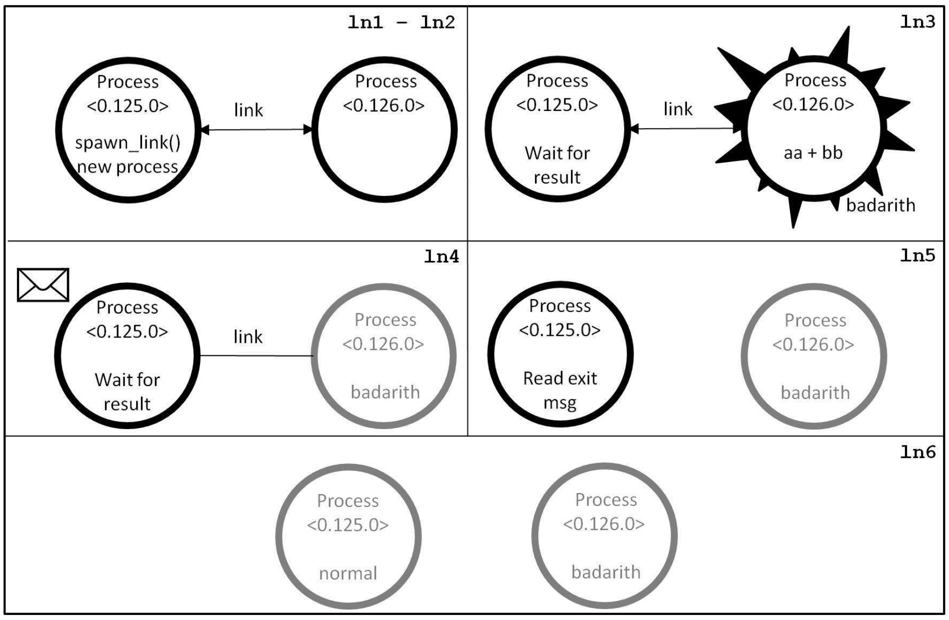

ln1 - ln2
Process <0.125.0> spawn_link() new process
link
Process <0.126.0>
ln3
Process <0.125.0> Wait for result
link
Process <0.126.0> aa + bb
badarith
ln4
Process <0.125.0> Wait for result
link
Process <0.126.0> badarith
ln5
Process <0.125.0> Read exit msg
Process <0.126.0> badarith
ln6
Process <0.125.0> normal
Process <0.126.0> badarith

Figure 5.3: Remote error handling - Trace list's output

The trace list describes the fact that the parent process (`<0.125.0>`) first spawns and links to a new process(`<0.126.0>`)(`ln1 - ln2`). The task of the new process is to compute the sum of *aa* and *bb*. Since the new process fails to compute the sum of *aa* and *bb* it terminates with reason *badarith*(`ln3`). Once process `<0.126.0>` terminates, an exit message is appended to process `<0.125.0>`'s mailbox(`ln4`). The link which was found between the two processes is removed(`ln5`). Subsequently, process `<0.125.0>` reads the exit message and terminates normally(`ln6`).

When the same system was input into the evaluator, the following sequence of reductions was described. The parent process(process *i*), will first set its process_flag to true so as to trap any received exit signals.

$$i[\mathsf{process\_flag}(trap\_exit, \mathsf{true}) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{false} \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}]$$

$$\begin{aligned}\text{where } e_1 = {} & \mathsf{spawn\_link}(sum, [i, aa, bb]),\\ & ?['EXIT', Pid, Error] \rightarrow invalid; Result \rightarrow Result\ \mathsf{end}.\end{aligned}$$

Process i then starts evaluating e_1. It spawn_links a process(process j) whose task will be to compute the sum of the input parameters i.e. aa and bb.

$$\longrightarrow\ i[\mathsf{spawn\_link}(sum, [i, aa, bb]) \cdot e_1',\ \epsilon,\ \emptyset,\ \mathsf{true}]$$

$$\longrightarrow\ i[j \cdot e_1',\ \epsilon,\ \{j\},\ \mathsf{true}]\ \|\ j[i!aa + bb,\ \epsilon,\ \{i\},\ \mathsf{false}]$$

$$\text{where } e_1' = ?['EXIT', Pid, Error] \rightarrow invalid; Result \rightarrow Result\ \mathsf{end}.$$

When process j attempts to calculate the sum of the two input numbers it fails and a *badarith* exception is raised. This causes process j to terminate with reason *badarith.*

$$\longrightarrow\ i[j \cdot e_1',\ \epsilon,\ \{j\},\ \mathsf{true}]\ \|\ j[\mathsf{error}{:}badarith,\ \epsilon,\ \{i\},\ \mathsf{false}]$$

$$\longrightarrow\ i[j \cdot e_1',\ \epsilon,\ \{j\},\ \mathsf{true}]\ \|\ j[\mathsf{error}{:}badarith, \{i\}]$$

Upon termination, an error signal is sent to process i. Since process i is trapping exit signals, the received signal is translated into an exit notification and appended to process i's mailbox.

$$\equiv\ j[\mathsf{error}{:}badarith, \{i\}]\ \|\ i[j \cdot e_1',\ \epsilon,\ \{j\},\ \mathsf{true}]$$

$$\longrightarrow\ j[\mathsf{error}{:}badarith, \emptyset]\ \|\ i[j \cdot e_1',\ [['EXIT', j, badarith]],\ \emptyset,\ \mathsf{true}]$$

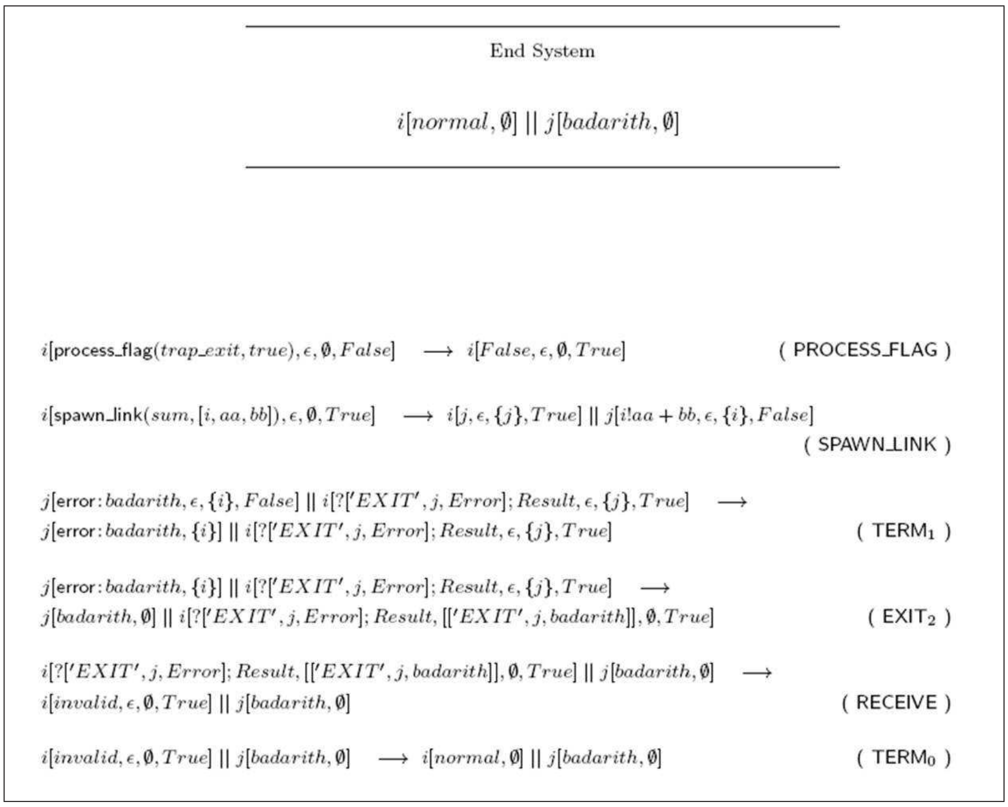
Process i then moves on to evaluate expression e_1' which consists of a receive statement. The received exit message is read from the process' mailbox and process i terminates with reason *normal.*

$$\begin{aligned}\longrightarrow\ & j[\mathsf{error}{:}badarith, \emptyset]\ \|\\ & i[\ ?['EXIT', Pid, Error] \rightarrow invalid; Result \rightarrow Result\ \mathsf{end}.\ ,\\ & \quad [['EXIT', j, badarith]],\ \emptyset,\ \mathsf{true}]\end{aligned}$$

$\longrightarrow j[\mathsf{error}\colon badarith, \emptyset] \;||\; i[invalid\;,\; \epsilon,\; \emptyset,\; \mathsf{true}]$

$\longrightarrow j[\mathsf{error}\colon badarith, \emptyset] \;||\; j[normal, \emptyset]$

The same behaviour was described by the evaluator:



End System

$$i[normal, \emptyset] \;||\; j[badarith, \emptyset]$$

$i[\mathsf{process\_flag}(trap\_exit, true), \epsilon, \emptyset, False] \longrightarrow i[False, \epsilon, \emptyset, True]$ (PROCESS_FLAG)

$i[\mathsf{spawn\_link}(sum, [i, aa, bb]), \epsilon, \emptyset, True] \longrightarrow i[j, \epsilon, \{j\}, True] \;||\; j[i!aa + bb, \epsilon, \{i\}, False]$
(SPAWN_LINK)

$j[\mathsf{error}\colon badarith, \epsilon, \{i\}, False] \;||\; i[?['EXIT', j, Error]; Result, \epsilon, \{j\}, True] \longrightarrow$
$j[\mathsf{error}\colon badarith, \{i\}] \;||\; i[?['EXIT', j, Error]; Result, \epsilon, \{j\}, True]$ (TERM_1)

$j[\mathsf{error}\colon badarith, \{i\}] \;||\; i[?['EXIT', j, Error]; Result, \epsilon, \{j\}, True] \longrightarrow$
$j[badarith, \emptyset] \;||\; i[?['EXIT', j, Error]; Result, [['EXIT', j, badarith]], \emptyset, True]$ (EXIT_2)

$i[?['EXIT', j, Error]; Result, [['EXIT', j, badarith]], \emptyset, True] \;||\; j[badarith, \emptyset] \longrightarrow$
$i[invalid, \epsilon, \emptyset, True] \;||\; j[badarith, \emptyset]$ (RECEIVE)

$i[invalid, \epsilon, \emptyset, True] \;||\; j[badarith, \emptyset] \longrightarrow i[normal, \emptyset] \;||\; j[badarith, \emptyset]$ (TERM_0)

Figure 5.4: Remote error handling - Evaluator's output

Through this example it becomes evident how Erlang's trace function made it easier to compare the behaviour of actual Erlang to the one described by the model. This is because, the trace list brings to light the order in which the side effect actions took place and as a result it becomes really straightforward to compare the sequence of reduction steps as described by the model to the sequence of steps as described by the trace list.

5.3.3 Test Case 3 : Remote Error Handling - Monitors

In this section, the degree up to which the defined model is able to mirror the behaviour of one-way linking (also known as monitoring) is evaluated. A number of different programs were considered to evaluate the correctness of the model. Table 5.1 describes the way monitors are expected to behave according to the defined model.

Test case description	Behaviour according to model
Process A starts monitoring process B. Process A terminates.	Process B is not affected.
Process A starts monitoring process B. Process B terminates.	An exit message is appended to process A's mailbox.
Process A creates two monitors of process B. Process B terminates.	Process A receives only one exit message describing B's termination.

Table 5.1: Monitors - Behaviour as described by model

One point worth mentioning here is that when the behaviour as described by the model was compared to the behaviour of actual Erlang only the first two test cases were found to be faithful to Erlang's behaviour. In the last case the model fell short of describing correctly Erlang's behaviour. In order to better understand why in the third case the behaviour of the model was found not to be loyal to that of actual Erlang let's consider the following program:

```
fun1(Pid) ->
     erlang:monitor(process,Pid),
     erlang:monitor(process,Pid),

     exit(Pid,stop),

     receive
          Msg1 -> '1st msg'
     end,
     receive
          Msg2 -> '2nd msg'
     end.
```

Listing 5.3: Monitor Example

In this program two monitors are created to monitor the process indentified by *Pid*. An exit signal is then sent to process *Pid*. Subsequently, the program will wait for two messages describing process *Pid* termination. When evaluating the above program, Erlang returned the following trace list:

```
ln1:{trace,<0.224.0>,exit,stop}

ln2:{trace,<0.226.0>,'receive',{'DOWN',#Ref<0.0.0.1065>,process,<0.224.0>,
     stop}}

ln3:{trace,<0.226.0>,'receive',{'DOWN',#Ref<0.0.0.1064>,process,<0.224.0>,
     stop}}

ln4:{trace,<0.226.0>,exit,normal}
```

The above trace list indicates that since the monitor function is called twice, the process creating the monitor(process `<0.226.0>`) receives two exit messages when the monitored process(process `<0.224.0>`) terminates(`ln2 - ln3`). In contrast, when the above system is described through the model only one exit message is received.

According to the defined rules, this program is evaluated in the following way. In these reduction steps, the process creating the monitors is identified as process i whereas the process which is going to be monitored is process j. Process i will first evaluate the first monitor expression.

$$i[\mathsf{monitor}(process, j) \cdot monitor(process, j) \cdot exit(j, stop) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid j[e,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{monitor}(process, j) \cdot exit(j, stop) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}] \mid\mid j[e,\ \epsilon,\ \{i\},\ \mathsf{false}]$$

where $e_1 = ?Msg1 \rightarrow' 1st\ msg'\ \mathsf{end} \cdot ?Msg2 \rightarrow' 2nd\ msg'\ \mathsf{end}$.

It then moves on to evaluate the next monitor expression. Note however, that when executing this statement, process j's state is not affected in any way since no links are added to its link set.

$$\longrightarrow\ i[exit(j, stop) \cdot e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}] \mid\mid j[e,\ \epsilon,\ \{i\},\ \mathsf{false}]$$

An exit signal is then sent to process j. This exit signal causes process j to terminate immediately.

$$\longrightarrow\ i[e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}] \mid\mid j[stop, \{i\}]$$

Process j then starts sending exit signals to those processes found in its link set, in this case process i. Since process i is trapping exit signals, the received signal is translated into an exit message and appended to its mailbox. Here, it is important to note that since process i's pid was only found once in process j's link set, only one exit message is sent to process i.

$$\equiv \; j[stop, \{i\}] \mid\mid i[e_1,\ \epsilon,\ \emptyset,\ \mathsf{true}]$$

$$\longrightarrow \; j[stop, \emptyset] \mid\mid i[e_1,\ [{'EXIT'}, j, stop],\ \emptyset,\ \mathsf{true}]$$

Process i will then read the exit message it received.

$$\equiv \; i[?Msg1 \rightarrow{'}\ 1st\ msg'\ \mathsf{end}\cdot ?Msg2 \rightarrow{'}\ 2nd\ msg'\ \mathsf{end},\ [{'EXIT'}, j, stop],\ \emptyset,\ \mathsf{true}] \mid\mid j[stop, \emptyset]$$

$$\longrightarrow \; i[[{'EXIT'}, j, stop]\cdot ?Msg2 \rightarrow{'}\ 2nd\ msg'\ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{true}] \mid\mid j[stop, \emptyset]$$

Since only one message was found in process i's mailbox, process i will block indefinetly waiting for the second message.

$$\longrightarrow \; i[?Msg2 \rightarrow{'}\ 2nd\ msg'\ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{true}] \mid\mid j[stop, \emptyset]$$

Therefore, by analysing the behaviour as described by the model, it becomes clear that with respect to the behaviour of monitors, the model's description is not completely faithful to the behaviour of actual Erlang.

5.3.4 Test Case 4 : Explicit Exit Signals

In this section, the correctness of the model with respect to the behaviour of explicitly sent exit signal is analysed. During the evaluation stage, a number of Erlang programs which make use of the exit(Pid,R) expression were considered. In the following table, there is a summary of the different behaviours that the model was able to describe when a process, say process A sent an exit signal to another process, say process B.

Reason (R)	Is process B trapping signals?	Model's Result
normal	yes	exit message appended to process B's mailbox
normal	no	process B ignored the signal
$\neq$ normal	yes	exit message appended to process B's mailbox
$\neq$ normal	no	process B dies with reason R
kill	yes	process B died with reason *killed*
kill	no	process B died with reason *killed*

Table 5.2: Explicit exit signals - Behaviour as described by model

In all of the above cases, the model was found to be loyal to the behaviour of actual Erlang.

Apart from sending explicit signals to external processes, an Erlang process is also able to send explicit exit signals to itself through the following expression exit(self(),R). In order to ensure that the model is also able to describe the behaviour of Erlang when explicit exit signals are sent to the calling process, a number of other programs were considered to cover all possible situations in which an exit(self(),R) may be used. The results obtained are described in the following table.

Reason (R)	Is process trapping signals?	Model's Result
normal	yes	exit message is appended to process A's mailbox
normal	no	process A terminates with reason *normal*
$\neq$ normal	yes	exit message is appended to process A's mailbox
$\neq$ normal	no	process A dies with reason R
kill	yes	process A dies with reason *killed*
kill	no	process A dies with reason *killed*

Table 5.3: Explicit exit signals - Behaviour as described by model

When the model's behaviour was compared to the one of actual Erlang it was found that in all cases the model was able to faithfully describe the behaviour of Erlang whenever a process sends an explicit exit signals to itself. Therefore, it was concluded that the model is able to correctly describe Erlang's behaviour whenever explicit exit signals are used.

5.3.5 Test Case 5 : Order of Signal Evaluation

When dealing with single-node Erlang systems message delivery is guaranteed to be carried out instantaneously[3]. In order to check if the order in which received signals are evaluated is loyal to the behaviour of actual Erlang, a number of systems which make use of side effect signals, primarily:

- sending of message e.g. Pid ! hello
- linking signals e.g. link(Pid)
- explicit exit signals e.g. exit(Pid,stop)

were considered. In the initial test cases, consecutive side effect actions of the same type (i.e. either consecutive linking signals or exit signals or ordinary messages) were carried out between a pair of processes. Through these test cases it became clear that in Erlang the receiving process always evaluated the signals in the same order in which they were sent. For instance, if a process, evaluated the following code:

```
B ! message1,
B ! message2
```

then it was always the case that process B received `message1` prior to `message2`. Similarly, when a process evaluated the following code:

```
exit(B,stop1),
exit(B,stop2)
```

then it was always the case that process B received the `stop1` exit signal prior to receiving the `stop2` signal. This kind of behaviour was correctly described by the defined model. Therefore, the model was found to be faithful to the behaviour of actual Erlang with regards to the order in which “same-type” signals are evaluated.

After checking that the model can correctly describe Erlang’s behaviour when consecutive “same-type” signals are sent between a pair of processes it was checked if the model could also faithfully describe the behaviour of actual Erlang when signals of different types were sent between a pair of processes. One of the considered programs was the following:

```
init() -> Pid = spawn(?MODULE,wait,[]),

          %% send first signal - an exit signal
          exit(Pid,stop),

          %% send second signal - a link signal
          link(Pid),

          wait().

wait() -> receive
             noMsg -> ok
         end.
```

Listing 5.4: Order of signal evaluation - test case

In this program two different signals; an exit signal followed by a link signal are sent to a particular process. The generated trace list when running this program was :

```
ln 1 : {trace,<0.806.0>,spawn,<0.807.0>,{system3,wait,[]}}

ln 2 : {trace,<0.806.0>,link,<0.807.0>}
ln 3 : {trace,<0.807.0>,getting_linked,<0.806.0>}

ln 4 : {trace,<0.807.0>,exit,stop}

ln 5 : {trace,<0.806.0>,exit,stop}
```

The above trace list reveals the fact that although the process creating the link(`<0.806.0>`), sends the exit signal before sending the link signal, Erlang will actually create the link(`ln 2`) before the other process terminates due to the received exit signal(`ln 4`). Consequently, when process `<0.807.0>` terminates with reason *stop*, it will send an exit signal to its newly linked process. The latter process will then also terminate with reason *stop*(`ln 5`).

This example shows that even though in Erlang, all signals between a pair of processes are guaranteed to be ordered, there is no guarantee that all signals will be evaluated in the same order in which they are sent. This is because, whereas link signals were evaluated instantly, other signals such as the exit signals were not. In fact, it seems that the exit signals are evaluated when the system schedules some time for the receiving process. In order to better understand this latter statement let's consider Figure 5.5 which describes how actual Erlang is evaluating this particular system. The process in green indicates the process which is currently in running state whereas the black process is currently waiting for the scheduler to give it a time slice.

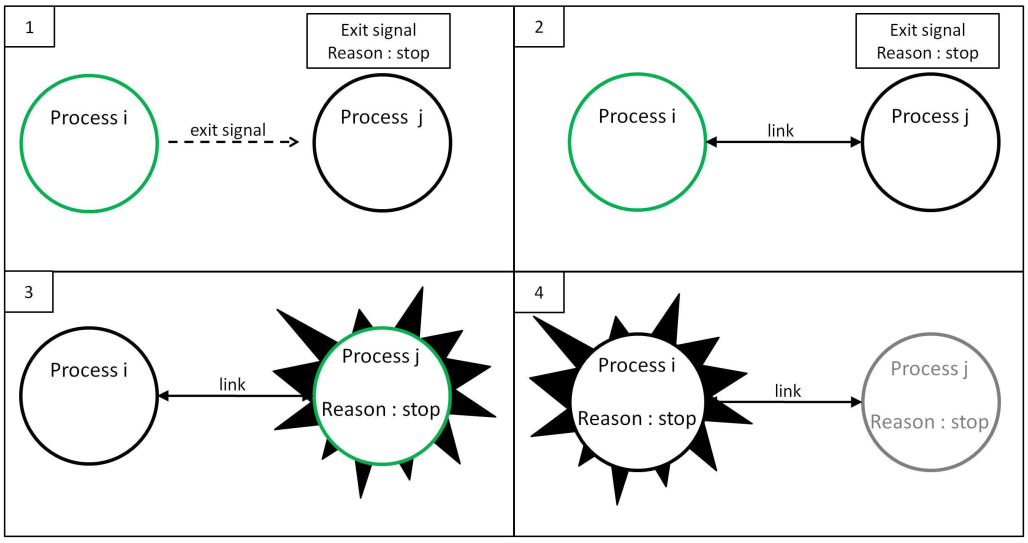


Figure 5.5: Order of signal evaluation

When evaluating this particular system, actual Erlang first sends an exit signal to process j. Note how this signal does not cause process j to terminate immediately(1). Instead, the received signal seems to be put into some sort of queue. Subsequently, process i sends a link signal to process j. Here, it is important to highlight the fact that the link signal is not put into a queue as was the case with the exit signal. In contrast, this signal is evaluated instantly and a link is created between the two processes(2). When the time scheduler assigns some time to process j, this process will first evaluate the received exit signal and terminate(3). Upon termination it will send an exit signal to its linked process, process i(4).

When the behaviour of this program was described using the defined rules, it fell short of describing the behaviour of actual Erlang. This is because in the defined semantics all signals are received and evaluated instantaneously. As a result, according to the defined rules, the system will be evaluated in the following way:

The parent process(process i) will first spawn its child process(process j).

$$i[\mathsf{spawn}(wait, []) \cdot \mathsf{exit}(j, stop) \cdot \mathsf{link}(j) \cdot wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[j \cdot \mathsf{exit}(j, stop) \cdot \mathsf{link}(j) \cdot wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid j[wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

Process i, will then send an exit signal to process j. This will cause process j to terminate with reason *stop*.

$$\longrightarrow\ i[\mathsf{exit}(j, stop) \cdot \mathsf{link}(j) \cdot wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}]\ \mid\mid\ j[wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[\mathsf{true} \cdot \mathsf{link}(j) \cdot wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid j[stop, \emptyset]$$

Process i, then attempts to link to process j. However, since process j has terminated, the link call fails and a *noproc* exception is raised.

$$\longrightarrow\ i[\mathsf{link}(j) \cdot wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid j[stop, \emptyset]$$

$$\longrightarrow\ i[\mathsf{error}{:}noproc \cdot wait(),\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid j[stop, \emptyset]$$

$$\longrightarrow\ i[\mathsf{error}{:}noproc,\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid j[stop, \emptyset]$$

The raised exception causes process i to terminate with reason *noproc*.

$$\longrightarrow\ i[noproc, \emptyset] \mid\mid j[stop, \emptyset]$$

Therefore, whereas in Erlang both processes terminated with reason *stop*, according to the defined rules the two processes will terminate with different reasons. Perhaps at this point one question that comes to mind is, if it is the case that the defined model has described a behaviour which can never occur in actual Erlang. In order to answer this question a time delay was inserted between the exit() and link() expression as shown in Listing 5.5. This was done to see if Erlang will evaluate the received signals in the same order in which they are sent.

```
init() ->  Pid = spawn(?MODULE,wait,[]),
              exit(Pid,stop),
              %% 1 second delay
              link(Pid),
              wait().
```

```
wait() -> receive
              noMsg -> ok
          end.
```

Listing 5.5: Order of signal evaluation - one second delay

In this case the generated trace list is as follows:

```
ln1 : {trace,<0.198.0>,spawn,<0.199.0>,{system3,wait,[]}}

ln2 : {trace,<0.199.0>,exit,stop}

ln3 : {trace,<0.198.0>,link,<0.199.0>}

ln4 : {trace,<0.198.0>,exit,{noproc,[{erlang,link,[<0.199.0>]},
        {system3,init,0}]}}
```

As shown in the trace list, in this case the child process(process `<0.199.0>`) will terminate before its parent process(process `<0.199.0>`) attempts to create the link(`ln2`). In fact, when the link expression is evaluated an exception is raised. This fact is illustrated by the fact that the parent process terminated with reason *noproc* (`ln4`). In order to get a clearer picture of what is happening in this case let's consider Figure 5.6

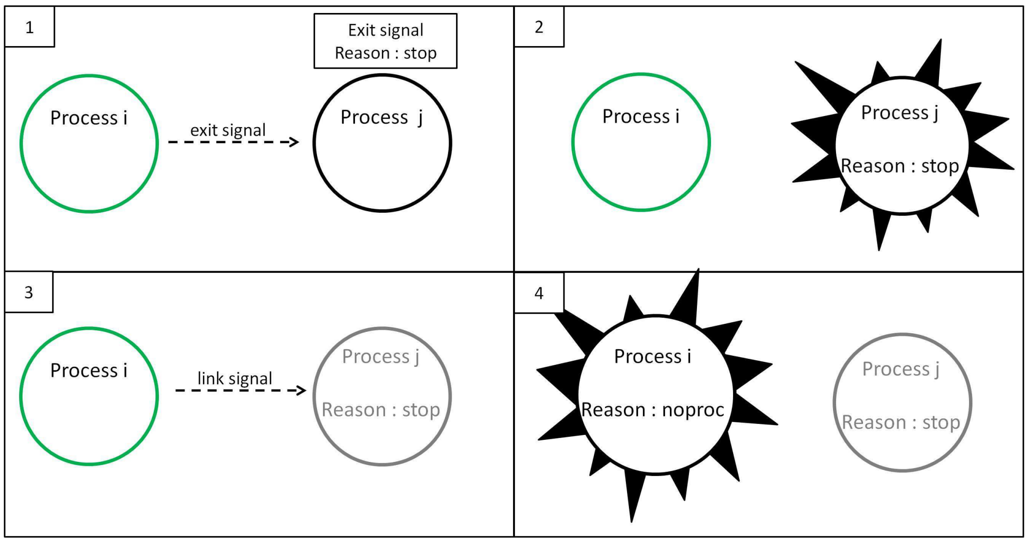


Figure 5.6: Order of signal evaluation

This latter behaviour is identical to the one described by the model and therefore it shows that the model did not describe a behaviour which may never occur in reality.

Nonetheless, through test case 2 it became clear that in actual Erlang signals are not delivered and evaluated instantly. This fact was also brought to light through the following test case. In this case, two different processes, Pid1 and Pid2 are spawned. Subsequently an error signal is first sent to Pid2 and then another exit signal is sent to Pid1.

```
init() -> Pid1 = spawn(?MODULE,wait,[]),
          Pid2 = spawn(?MODULE,wait,[]),

          exit(Pid2,'first signal'),
          exit(Pid1,'second signal'),

          wait().

 wait() -> receive
                noMsg -> ok
            end.
```

Listing 5.6: Order of evaluation of exit signals

The generated trace list shows that even though an exit signal is first sent to *Pid2*(in the below trace list indicated by Pid `<0.966.0>`), the first process to terminate due to received exit signal is the process indicated by *Pid1*(in the below trace list indicated by Pid `<0.964.0>`).

```
{trace,<0.963.0>,spawn,<0.964.0>,{system4,wait,[]}}
{trace,<0.963.0>,spawn,<0.965.0>,{system4,wait,[]}}

{trace,<0.964.0>,exit,'second signal'}
{trace,<0.965.0>,exit,'first signal'}
```

In order to better understand what is actually happening let's consider the following diagram. The green processes, represent those processes which are in a running state whereas the black processes are in a waiting state.

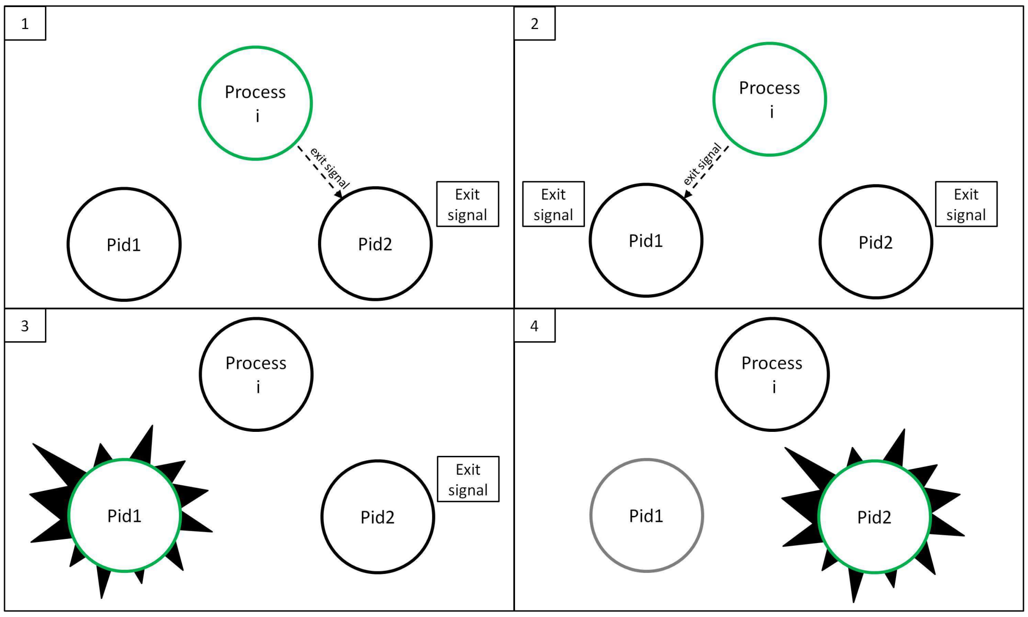


Figure 5.7: Order of signal evaluation

This diagram shows that even though an exit signal is first sent to process Pid2, the first process to terminate is process Pid1. Conversely, according to the defined semantic rules, the order in which the two processes will terminate is defined by the order in which the exit signals are sent i.e. according to the defined rules process $Pid2$'s termination will always occur prior to that of $Pid1$. Therefore, through this case it seems that the defined semantics are not totally faithful to the behaviour of actual Erlang.

Nonetheless, it was decided that the defined rules should just the same assume that signals will be evaluated instantly. The main underlying reason, is that this prevents from having a state explosion when going through all possible sequence of states that the system may take. Additionally, in most cases, it is still possible to predict accurately the behaviour of actual Erlang by using the defined semantic rules.

5.3.6 Test Case 6: Handling Errors Locally or Remotely

In the initial chapter of this dissertation, a simple example was considered so as to illustrate why understanding the behaviour of Erlang's error handling constructs may not always be as straightforward as it might seem. In fact, even though the two programs described in Chapter 1 seemed to have identical behaviour, when they were run on Erlang it became evident that this was not the case. This is because, whereas the program which handled errors locally was always able to handle the raised exceptions, the one which made use of remote error handling constructs sometimes failed to handle the exceptions which occured.

In this section the defined model is applied to both systems so as to see to what degree the defined model is able to provide a better understanding of how these systems behave hopefully revealing the underlying cause of this different behaviour. The first system to be considered is the one in which errors are handled locally:

```
processI(Pid,Num1,Num2) ->
           try
               Pid ! A + B
           catch
               error:badarith -> Pid ! invalid
           end.


processJ() ->
           receive
             Result -> Result
           end.
```

Listing 5.7: Local Error Handling Example

In this example, the system is composed of two different processes.

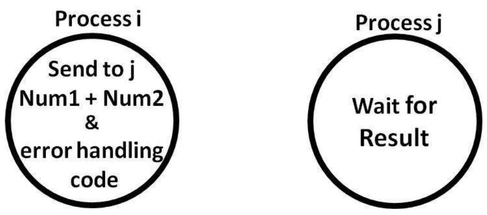


Figure 5.8: Local Error Handling Example

Process *i*'s task is to compute the sum of the two input numbers. The result of this computation is then sent to the process *j*. Error handling constructs are used so that if an error occurs when computing the sum of the two numbers, the atom *invalid* is sent to process *j*.

When this program was run by Erlang it gave the expected results both when valid data or invalid data was input. When the behaviour of this system was described through the defined model it became evident that this program will always behave as expected. In fact, the model was able to ensure that some value will always reache process j since there does not exist any other possible sequence of reductions they may cause process j to block indefinitely waiting for the result. This is because when valid data is input, the sum of the input numbers is received and when invalid data is input the atom *invalid* is received.

Here, the case when the pid of process j and non-numeric data 1 and a is passed to the processI() function will be considered so as to be able to better appreciate how the model was able to provide a detailed description of this system's behaviour in the case when exceptions are raised.

According to the defined rules, the system first attempts to calculate the sum of 1 and a. This raises a *badarith* exception.

$$i[\mathsf{try}\ j\ !\ 1 + a\ \mathsf{catch\ error} : badarith \rightarrow j!invalid\ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ s_j$$

$$\longrightarrow\ i[\mathsf{try\ error} : badarith\ \mathsf{catch\ error} : badarith \rightarrow j!invalid\ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ s_j$$

where $s_j = j[?Result \rightarrow Result\ \mathsf{end}],\ \epsilon,\ \emptyset,\ \mathsf{false}]$

The raised exception is caught by the try-catch block and as a result, the atom *invalid* is sent to process j.

$$\longrightarrow\ i[j!invalid,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ j[?Result \rightarrow Result\ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

$$\longrightarrow\ i[invalid,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ j[?Result \rightarrow Result\ \mathsf{end},\ [invalid],\ \emptyset,\ \mathsf{false}]$$

Process j then reads the received message.

$$\longrightarrow\ i[invalid,\ \epsilon,\ \emptyset,\ \mathsf{false}]\ ||\ j[invalid,\ \epsilon,\ \emptyset,\ \mathsf{false}]$$

Through these reduction steps it became clear why in this case the system always behaves as expected. Now let's consider the case when the same system was implemented using remote error handling constructs. In this case the system is composed of three different processes as shown hereunder:

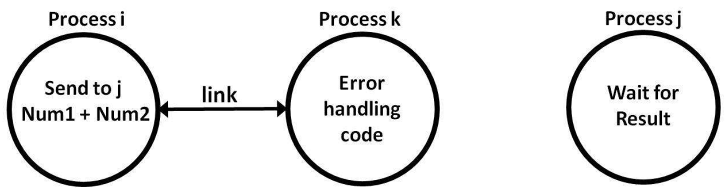


Figure 5.9: Remote Error Handling Example - System

Process *i*'s task is to compute the sum of the input numbers. The result is then sent to process *j*. If an error occurs when computing the sum, process *i* will terminate and the error is expected to be handled by process *k*. The task of process *k* is to send the atom *invalid* to process *j* if any errors occur whilst computing the sum of the two numbers. The system described in Figure 5.9 was implemented in the following way:

```
processB(Pid,Num1,Num2) ->
      %% spawn_link a new process to handle errors
      %% the new process will start evaluating the errorHandler function
      spawn_link(?MODULE,errorHandler,[Pid]),

      Pid ! Num1 + Num2.

errorHandler(Pid) ->
     %% make this process a system process
     process_flag(trap_exit,true),

     %% receive the trapped exit signal
     receive
       %% if process terminated normally then do nothing
       {'EXIT',Pid1,normal} -> ok;

       %% otherwise send 'invalid' to the process identified by Pid
       {'EXIT',Pid1,{badarith,stack}} -> Pid ! invalid
end.
```

Listing 5.8: Remote Error Handling Example

When the system was evaluated according to the defined rules it became clear why in some cases the system was not handling the error which occurs while computing the sum of the two numbers. In fact, the defined rules revealed the fact that due to the different interleavings that the system might take, the system may terminate in either of these two states when invalid data is input.

Case 1: $i[badarith, \emptyset] \mid\mid j[normal, \emptyset] \mid\mid k[normal, \emptyset]$

Case 2: $i[badarith, \emptyset] \mid\mid j[?Result \rightarrow Result \ \mathsf{end},\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid k[badarith, \emptyset]$

Case 1 describes the case when the error handling process(process k) successfully handled the generated error. As a result, the atom *invalid* is successfully sent to process j. Process j reads the sent message and terminates normally. This kind of behaviour is identical to the one where local error handling is used since the generated exception was successfully handled by the error handling process.

Case 2 describes the case when the error handling process(process k) failed to handle the error and therefore, no message was sent to process j. As a result, process j remains blocked waiting for the result of the computation. In order to better understand the cause of such behaviour let's consider the trace of execution(as described by the model) that has led the system to behave in this way.

According to the defined model the parent process(process i) will first spawn_link the error handling process(process k).

$$i[\mathsf{spawn\_link}(errorHandler, [j]) \cdot j \ ! \ 1 + a,\ \epsilon,\ \emptyset,\ \mathsf{false}] \mid\mid s_j$$

$$\begin{aligned} \longrightarrow\ & i[k \cdot j \ ! \ 1 + a,\ \epsilon,\ \{k\},\ \mathsf{false}] \mid\mid \\ & k[\mathsf{process\_flag}(trap\_exit, true) \cdot e_1,\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid s_j \end{aligned}$$

$$\begin{aligned} \text{where } s_j &= j[?Result \rightarrow Result \ \mathsf{end}],\ \epsilon,\ \emptyset,\ \mathsf{false}] \\ e_1 &= ?['EXIT', Pid, normal] \rightarrow ok; ['EXIT', Pid, badarith] \rightarrow Pid!invalid \end{aligned}$$

Subsequently, when process i attempts to compute the sum of a and 1, a *badarith* exception is raised.

$$\begin{aligned} \longrightarrow\ & i[j \ ! \ 1 + a,\ \epsilon,\ \{k\},\ \mathsf{false}] \mid\mid \\ & k[\mathsf{process\_flag}(trap\_exit, true) \cdot e_1,\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid s_j \end{aligned}$$

$$\begin{aligned} \longrightarrow\ & i[\mathsf{error} : badarith,\ \epsilon,\ \{k\},\ \mathsf{false}] \mid\mid \\ & k[\mathsf{process\_flag}(trap\_exit, true) \cdot e_1,\ \epsilon,\ \{i\},\ \mathsf{false}] \mid\mid s_j \end{aligned}$$

The raised exception will cause process i to terminate with reason *badarith*.

$$\longrightarrow\ i[badarith, \{k\}] \;||\; k[\mathsf{process\_flag}(trap\_exit, true) \cdot e_1,\ \epsilon,\ \{i\},\ \mathsf{false}] \;||\; s_j$$

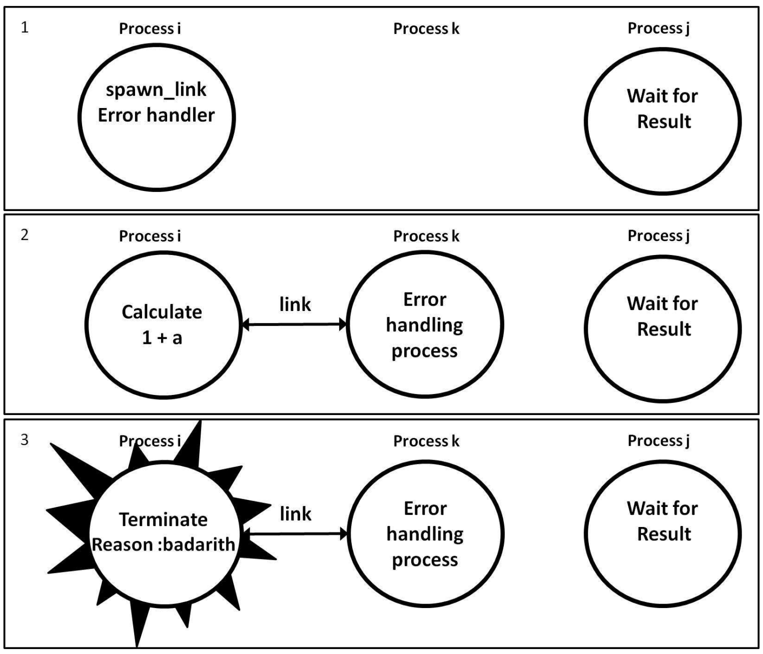
Upon termination, process i starts sending exit signals to all its linked processes, in this case process k. Note that since process k(the error handling process), has not set its process_flag yet, it will fail to trap the exit signal. As a result, instead of carrying out the needed error handling code process k would terminate immediately upon receipt of the exit signal.

$$\longrightarrow\ i[badarith, \{k\}] \;||\; k[\mathsf{process\_flag}(trap\_exit, true) \cdot e_1,\ \epsilon,\ \{i\},\ \mathsf{false}] \;||\; s_j$$

$$\longrightarrow\ i[badarith, \emptyset] \;||\; k[badarith, \emptyset] \;||\; s_j$$

Here it is worth pointing out that process j, is still alive waiting to receive the result of the computation.

Through these reductions it became clear why this system does not have an identical behaviour to the one which uses local error handling. The main reason behind this faulty behaviour lies in the fact that an error might occur before the error handling process has set its process_flag. As a result, it is not able to trap the received exit signal so as to recover from the received signal. The sequence of steps that led to such behaviour are described in Figure 5.10



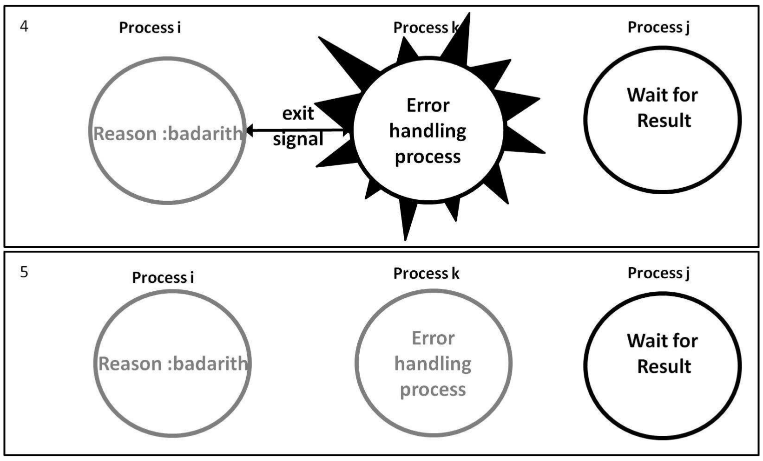
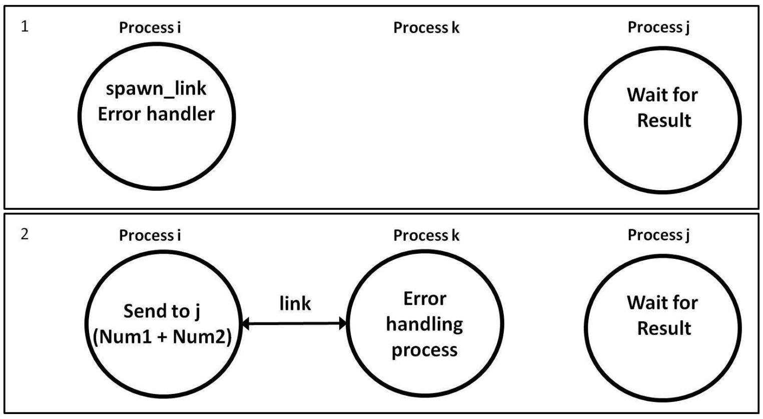


Figure 5.10: Remote Error Handling Example - Unexpected Behaviour(1)

This example proved that the model is truly capable of providing a better insight into how a system might behave. Moreover, through the model it became much easier to identify the sequence of events that led to this behaviour.

It is also worth mentioning, that even though the two programs considered in Chapter 1, seemed to have identical behaviour when valid data is input, when the model was applied to this program it revealed that in effect this is not true. This is because, when using remote error handling it may be the case that process k will block indefinitely. This may happen if the sequence of steps described in the Figure 5.11 takes place.



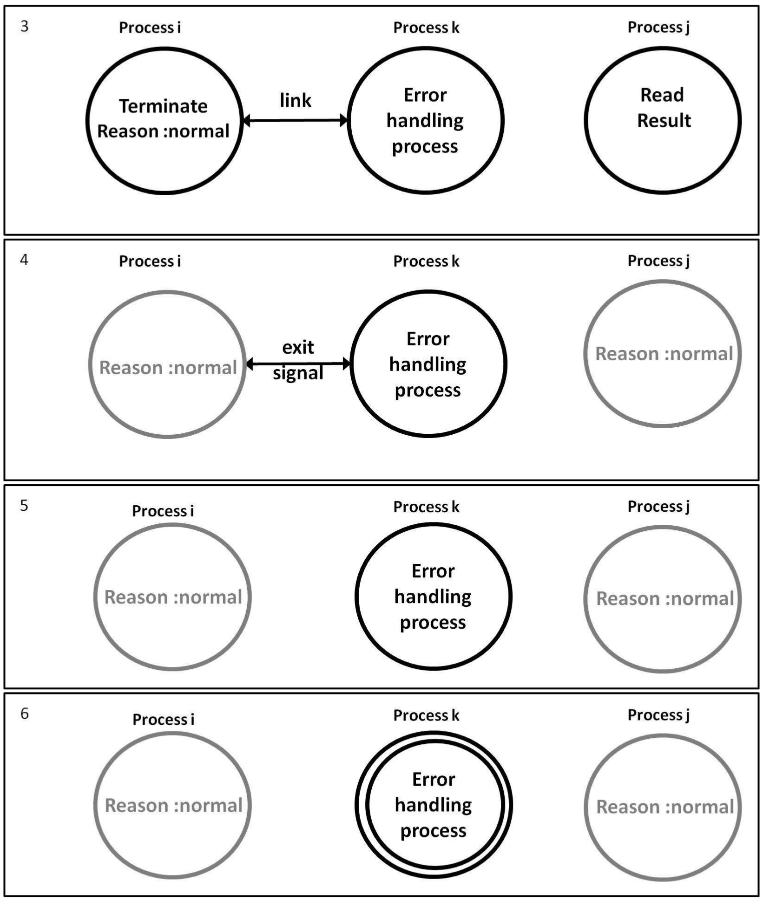


Figure 5.11: Remote Error Handling Example - Unexpected Behaviour(2)

In the above diagram, process i terminates before process k has set its process_flag(4). Since the reason is set to *normal*, the received signal is ignored(5). After receiving the signal, process k will set its process_flag to true(6). Given the fact that both process i and process j have terminated, process k will then remain blocked waiting for the message describing the way process i terminates.

Through this simple case study, it became evident that the defined model is able to provide a better insight into Erlang's both local and remote error handling constructs. As a result, whereas before it was somewhat difficult to truly reason about Erlang's behaviour in the presence of errors through the model it became much easier to understand such behaviour. Moreover, the step-by-step description of how Erlang programs are evaluated greatly helped to reveal the cause of unexpected behaviour.

5.4 Evaluation Results

This last section, outlines some facts that were observed during the evaluation stage of this project. Primarily, it first gives a summary describing the results that were obtained when measuring to what degree the model is faithful to actual Erlang. Subsequently, the main limitations of the work done in this project are discussed.

5.4.1 Accomplishments

In this section a table is presented summarizing all the different aspects of the model that have been analysed in this chapter. Primarily it shows, if the model is sound and/or complete with respect to the behaviour of actual Erlang. The term soundness refers to the fact that the model can never describe a behaviour which may never occur in reality. Completeness refers to the fact that the model is able to represent all the possible ways actual Erlang may behave when using that particular mechanism.

Erlang mechanism	Model	
	Sound	Complete
Local Error Handling - try-catch	✓	✓
Error Propagation - linking	✓	✓
Error Propagation - monitoring	✓	
Explicit Error Signals	✓	✓
Order of Signal Evaluation	✓	

Table 5.4: Soundness & Completeness of Model

Here, it is important to note that since in this project the evaluation approach was not a formal one, the ✓ symbol does not necessary imply that a particular mechanism is 100% guaranteed to be sound or complete. However, the several examples which were considered during the evaluation stage gave us a good indication if the behaviour of a specific Erlang mechanism as described by the model is sound and/or complete.

This table shows that the defined model was found to be able to describe soundly the behaviour of all the Erlang mechanisms that were considered. This is because when carrying out the evaluation it was never the case that the model described a behaviour which can never occur in actual Erlang.

With respect to the model's completeness, in some cases the model fell short to describe all the possible ways an Erlang system may behave. For instance, when using monitors, the model was not able to completely describe the behaviour of actual Erlang when one particular process created multiple monitors of another process. The model was also found not to be complete when it came to describing the ordering in which sent signals are evaluated. This is because, whereas the model assumes that all signals are evaluated in the same order in which they are sent, in reality Erlang may sometimes evaluate the sent signals in a different order.

However, even though the model is not complete through the evaluation stage it became evident that by using the model we are now able to get a better insight into how Erlang's error handling mechanisms behave. In this chapter, this fact became even more clear through the several number of test cases which were carried out. In all these test cases the model was able to give a precise description of how particular constructs behave.

Through the model it also became possible to get a good indication if two systems are expected to behave in a similar way or not. For instance, in the last case study, the model was able to show that although the program which adopted remote error handling seemed to have an identical behaviour to the one using local error handling, in truth the two programs may behave in a different way.

5.4.2 Limitations

Even though, in most cases the defined semantics and designed evaluator are able to faithfully mirror the behaviour of actual Erlang through the evaluation stage it became apparent that they still suffer from some limitations.

5.4.2.1 A Single-node Semantics

One main limitation of the defined semantics is that they are only able of describing all possible behaviors of *single-node* systems. If these semantics were to be used to describe the behaviour of distributed Erlang systems, the rules may not be able to describe completely the different ways in which the system might behave. This is because, as claimed by [3], when dealing with distributed Erlang systems, signal delivery is not immediate. In contrast, the defined semantics assumes that all signals are received instantaneously. In order to better understand, the implications of this latter fact let's consider the following case:

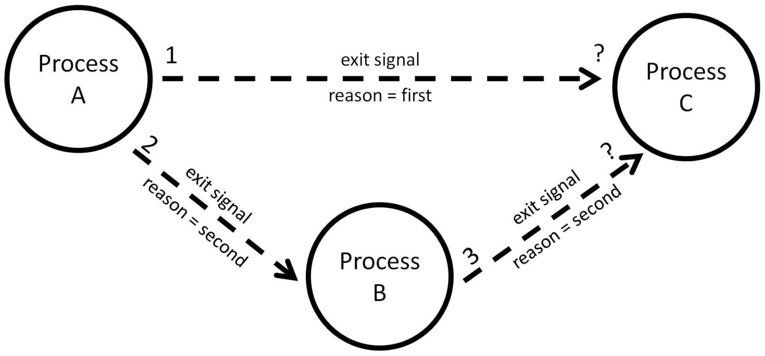


Figure 5.12: Error signals - Distributed Systems

In the above system Process A, first sends an explicit exit signal to process C. Subsequently, an error signal is sent to process B. Once process B receives the exit signal it will terminate and an exit signal is sent to process C.

According to the defined semantics, process C will always terminate with reason *'first'* and process B will always terminate with reason *'second'*. This is because in the defined semantics all exit signals are received and evaluated immediately. However, in actual Erlang if all three processes were to be found on different nodes, the exit signal delivery is not guaranteed to be instantaneous. Therefore, even though process A will send the exit signal *'first'* to process C prior to sending an exit signal *'second'* to process B, it is not guaranteed that the *'first'* signal arrives at C prior to the exit signal *'second'*. In actual fact, it may very well be the case that process C terminates with reason *'second'*. This kind of behaviour cannot be described through the presented semantics.

5.4.2.2 Simulation Time

Perhaps one of the main limitations of the designed evaluator is that in some cases it may take a considerably long time to produce an output describing the different ways the system may behave. The underlying cause lies in the fact that the number of different interleavings that need to be checked will grow exponentially to the size of the input system. As a result, the designed evaluator is only able to simulate the behaviour of small systems in a reasonable amount of time.

5.5 Conclusion

This chapter evaluated the different aspects of this project. This was done by considering a number of Erlang systems and comparing the behaviour of these programs as described by the model against the way the same programs behaved when run on the Erlang VM. This evalution strategy gave us a clear indication to what extent the model is able to faithfully mirror the behaviour of actual Erlang. Additionally, it also helped to expose the main benefits and limitations of the defined model and evaluator.

6. Conclusion and Future Work

In this final chapter the benefits that have been achieved through this project will be outlined. Subsequently, some improvements that could be done to the work presented in this project are suggested.

6.1 Benefits Achieved

The following points outline the main results that were accomplished through the defined semantic rules.

Offer a better insight - In the initial stage of this project it was not quite clear how Erlang systems, especially those which made use of the remote error handling constructs might behave. For instance, in Chapter 1, it was rather unclear why the program which made use of the remote error handling constructs(Listing 1.2) does not always behave in the same way as the one which uses local error handling constructs(Listing 1.1). The model defined in this work has successfully addressed these type of problems by providing precise and unambigious description of Erlang's error handling constructs. As a result, as shown in the Evaluation chapter, by applying the model on a particular Erlang systems it is now possible to understand immediately why a system is behaving in a certain way.

Explain the cause of unexpected behaviour - The defined rules are capable of providing a step-by-step description of how a system is evaluated possibly revealing sequences of steps that may lead to unexpected outcomes. For instance, with respect to the example described in Chapter 1, it is now clear why sometimes the system which makes use of remote error handling constructs behaves in an unexpected way and thus fails to handle any raised exceptions. This is because through the defined model it is now possible to retrace the sequence of steps that may cause the system to behave in an unexpected way.

Predict system's behaviour - Prior to defining the model, the only way a user could see how an Erlang system might behave was by executing it on the Erlang VM. In fact, in the initial stage of this project, the difference in behaviour between Listing 1.1 and Listing 1.2 could only be noted after the two systems were run on the Erlang VM. Conversely, through the defined rules it has became possible to see that the two systems might behave in different ways, without the need of actually running the systems on the Erlang VM.

Lay the foundations of a semantic theory - This model is able to give a good indication of whether or not a pair of systems are expected to have identical behaviour. For instance, even though the pair of systems described in Chapter 1 seemed to have identical behaviour, the model was able to show that in actual fact this was not the case. In fact, when the model was applied to the pair of programs, it was able to bring to light the subtle difference that existed between them. This fact indicates that the defined rules can act as a basis for defining notions of equivalence such as testing equivalence[26] and reduction barbed congruence, which can later be justified through labelled transition systems and bisimulations[24, 25].

6.2 Suggestions for Future Work

Even though the main objectives of this project have been met, there is still room for improvement. In this section a number of suggestions that may be considered for future work are presented.

6.2.1 Distributed-node Semantics

Following up this work, it would be interesting to study the behaviour of Erlang's error handling mechanisms when used in distributed systems. The rules defined in this project are only able to accurately describe the behaviour of single-node systems. Therefore, when considering the fact that in these days more emphasis is being put on building distributed systems it would be quite beneficial to extend the semantic rules defined here so as to be able to cater also for distributed systems.

6.2.2 Extend chosen Erlang Subset

Another improvement that could be done to the semantics, is to modify Erlang's chosen subset so as to accept all constructs found in Core Erlang[2]. As claimed in [3], Core Erlang represents a complete core fragment of Erlang. Therefore, if the semantics is modified to operate on Core Erlang, it would be a great step towards defining a complete semantics for Erlang. In addition, since there already exists a compiler(HiPE compiler) which can automatically translate Erlang programs in terms of Core Erlang, it will become possible to modify the designed evaluator to accept ordinary Erlang programs instead of programs consisting only of constructs found in the chosen subset. This is because the HiPE compiler could then be used to translate the input fed to the evaluator in terms of Core Erlang prior to simulating Erlang's behaviour according to the defined semantics.

6.2.3 Improve Evaluator's Efficiency

One major downside of the designed evaluator is that it may be rather slow when simulating the behaviour of input systems. Even though some techniques have already been adopted in order to improve its efficiency, it would be ideal to further explore other modifications that could be made to make it more efficient. Perhaps, one possible improvement would be that given the fact that the simulation of different traces is independent of each other, they could easily be carried out in parallel.

6.2.4 A semantic theory based around notions of equivalence

The model defined in this work only provides the basis of a semantic theory. Therefore, it would be interesting to extend this work so that given any two Erlang systems it would be able to show if they are truly semantically equivalent or not.

6.3 Conclusion

This project gave a closer insight into Erlang's error handling mechanisms. A formal semantic definition for these mechanisms was presented providing an accurate and unambigious description of Erlang's behaviour when dealing with errors. These definitions have been animated through an evaluator which returns a detailed description of all the possible different ways a particular Erlang system may behave.

In order to better appreciate the usefulness of these formal definitions, the behaviour of a number of different Erlang systems was described according to the defined semantics. These descriptions were found to be really helpful in understanding why sometimes certain systems behaved in an unexpected way. In addition, these descriptions were also able to approximate whether two syntactically different systems were truly semantically equivalent or not.

A.

Here are some steps that need to be followed in order to use the designed evaluator.

A.1 Prerequisites

- pdf reader eg. Acrobat Reader
- implementation of LaTeX eg. MiKTeX (listings package needed)

A.2 Using the Evaluator

In order to use the evaluator

1. Copy Evaluator Folder onto your computer.
2. Run the Evaluator.bat file.
3. In the command prompt enter the path where the “functions” file is found. This file should contain the necessary function definitions that are needed when running the Erlang system. The syntax of the input file should be quite similar to the one used when writing an Erlang module. In fact the only differences between an ordinary Erlang module file and the input accepted by the evaluator are that in the input file:
   - the `module` and `export` constructs need not be included
   - definitions of functions which share the same function name are not delimeted by a ; but by a .
   - the spawn_link, spawn_monitor and spawn functions do not expect the module name parameter
   - only the subset of Erlang as defined in Table 3.2 can be successfully parsed

Following there is a simple Erlang module and how it can be expressed in terms of the evaluator's input. The code in green, highlights the parts which need to be removed or modified before an Erlang module is fed to the evaluator.

Erlang Module:

```
-module(example1).
-export([init/1,sum/1,getSum/2]).

sum([]) -> 0;
sum([H|T]) -> H + sum(T).

getSum(Pid,List) -> Pid ! sum(List).

init(List) ->
 spawn_link(?MODULE,getSum,[self(),List]),
 receive
    Sum -> Sum
 end.
```

Evaluator's input:

```
sum([]) -> 0.
sum([H|T]) -> H + sum(T).

getSum(Pid,List) -> Pid ! sum(List).

init(List) ->
   spawn_link(getSum,[self(),List]),
   receive
      Sum -> Sum
   end.
```

4. After entering the functions file path, enter the path of the file containing the expression that in actual Erlang is input into Erlang's shell.

5. In the command prompt then enter the name of the output file.

6. The system will then automatically create and open a pdf file containing a detailed description of the different ways the system may behave.

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