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Exceptional Actors

Implementing Exception Handling for Encore

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Abstract

Exceptional Actors: Implementing Exception Handling for Encore

Sahand Shamal Taher

Encore is an object-oriented programming language which uses the actor model as its concurrency model, and is specifically aimed at implementing concurrent and parallel systems. Communication between actors is done via asynchronous method calls, which store their results in futures, placeholder objects for later storing the result of an computation. Encore currently lacks an exception handling mechanism, which is an important part of programming languages, and helps programmers create more fault tolerant and robust software. This thesis presents an exception handling implementation for Encore, in which futures are used to propagate errors between actors. The implementation uses a modified version of the open-source library Exceptions4C as a basis, and enables basic exception handling through try-catch-finally expressions. It uses type-based matching that also considers subtyping, and allows the programmer to define and throw custom exception types. A pull-model is used to enable inter-process communication of exceptions, where receiving actors can choose to handle exceptions at any point by consuming associated futures. The implementation is a good first step, but there are Encore features such as streams which it does not yet support. Furthermore, it brings an overhead to programs, which can be reduced by redesigning parts of the exception handling model.

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1. Introduction

Exception handling is an important feature of programming languages and helps programmers create more fault tolerant and robust software. As distributed processing has gained increased attention, new concurrency models and exception handling models have emerged. The *actor model* is a concurrency model that is gaining increased attention [1, 4, 10, 14, 19–21, 36], and has been implemented for languages such as JAVA [18] and SCALA [30], and in the .NET framework [7]. Some languages, such as DART [8] and ERLANG [3, 4], are even built with the actor model as the default concurrency model.

ENCORE, developed by the programming language group at Uppsala University, is an object-oriented programming language which uses the actor model as its concurrency model, and is specifically aimed at implementing concurrent and parallel systems [9]. Communication between actors is done via asynchronous method calls, which store their results in *futures*, placeholder objects for later storing the result of an computation [5, 24]. The ENCORE compiler is written in HASKELL and translates ENCORE code to C code, which links with a runtime system written in C.

Goal The ENCORE language currently lacks an exception handling mechanism, providing the programmer no help in recovering from errors. To solve this, ENCORE needs an exception handling mechanism which fits in with the concurrency model of ENCORE and preserves the semantics of existing language while using a reasonable amount of resources. As a starting point for ENCORE's exception handling, the ENCORE team has suggested a JAVA-inspired model to handle exceptions in synchronous settings, and to use futures to communicate exceptions asynchronously, inspired by the paper *Fault in the Future* [22].

The goal of this thesis is to implement an exception handling mechanism for ENCORE, based on the suggestions of the ENCORE team. A JAVA-inspired model for exception handling in synchronous settings will be provided, and futures be utilized to communicate exceptions in asynchronous settings.

Contributions Concretely, this thesis makes the following contributions to the design and implementation of the ENCORE programming language:

1. It extends ENCORE with a new mechanism for raising and handling exceptions using a `throw` and `try-catch-finally` mechanism. The imple-

mented `try-catch-finally` are expressions which return values.

2. It extends Encore with a family of exceptions which can be extended by a programmer. This allows distinguishing between different types of exceptions.

3. It extends Encore with an exception, representing an instance of a thrown exception. The exception objects give the programmer access to exception data, and a method for rethrowing the exception.

4. It provides exception handling in asynchronous settings by extending Encore's futures and the `get` mechanism. The futures are modified to store exceptions, and the `get` operation to rethrow exceptions in futures. The context swapping mechanism is extended to support exception handling contexts, which contain message level exception handling information.

5. It provides Encore with support to deal with exceptions in functional settings. An `Either`-object encapsulates a value, and either contains a normal value or an exception. Programs can distinguish between the normal and exceptional value through pattern matching.

In Chapter 2 relevant background information is presented, providing a basic understanding of Encore, exception handling and exception handling in existing languages. The exception handling model implemented in this work is presented in Chapter 3, where new language constructs are introduced, and the use of futures during exception handling is explained. Implementation details for exception handling model are outlined in Chapter 4, where code generation for new language constructs is shown, an exception class is introduced, and changes to the runtime and context swapping is explained. In Chapter 5, the exception handling implementation is evaluated in terms of expressiveness, performance, and limitations. A conclusion of the work is given in Chapter 6, along with a discussion about the results and future work.

2. Background

This chapter introduces Encore and its concurrency model (Section 2.1) and basic exception handling (Section 2.2). Basic exception handling in C is discussed in Section 2.2.1, and a C library for exception handling used in this work presented in Section 2.2.2. Exception handling in related programming languages and works is discussed in (Section 2.3).

2.1 Encore

Encore is an object-oriented programming language which uses the actor model as its concurrency model, and is specifically aimed at implementing concurrent and parallel systems [9]. Like regular objects, Encore's actors have encapsulated fields and methods that operate on those fields. Unlike objects, however, a thread of control is associated with each actor, which is the only thread able to access the actor's fields [9]. Communication between actors is done via asynchronous method calls, which store their results in futures (Section 2.1.1), placeholders for later storing the result of a method call [5, 24]. The Encore compiler is written in Haskell and translates Encore code to C code, which links with a runtime system written in C. Encore's runtime runs on top of the runtime of the Pony programming language [25], which is an actor-based, object-oriented programming language. The Pony runtime provides an implementation of the actor model and garbage collection, which Encore builds on.

The rest of this section details different parts of Encore's concurrency model that are relevant when implementing exception handling for Encore. Message passing and futures, which provide a means for asynchronous communication, are explained in Section 2.1.1, and cooperative scheduling primitives and their affect on actors in Section 2.1.2. Section 2.1.3 discusses Encore's threads and how they are scheduled.

2.1.1 Message Passing and Futures

Communication between actors is done via asynchronous method calls, or message sends, by using the "`!`" operator. Asynchronous method calls immediately return, optionally with a future, which is used for synchronization and make blocking operations possible (Figure 2.2). Upon finishing a method, the called actor fulfills or resolves a future with the computed result, which the caller can later retrieve from the future. Each actor has its own inbox, where messages to the actor are placed, each message corresponding to running some method. Actors can only execute one message at a time, though several messages may be running concurrently (explained in Section 2.1.3).

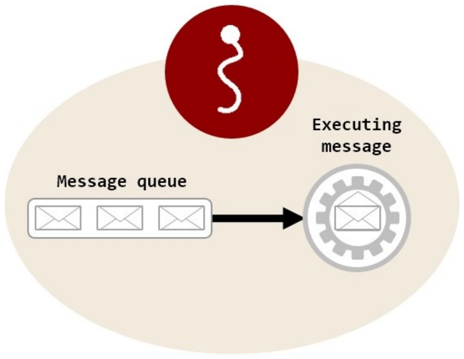


Figure 2.1: The message queue and currently executing message.

2.1.2 Cooperative Scheduling Primitives

The constructs `await`, `get` and `suspend` are cooperative scheduling primitives. The `await` and `get` mechanisms are used for synchronization, whereas `suspend` only affects scheduling. The `get` operation can be used to at any time retrieve a result in a future. This blocks the actor until the future is resolved and then returns the computed value.

```
active class MyActor
 def foo() : unit
  var fut = otherActor ! doThings()
  get(fut)
 end
end
```

Listing 2.1: Using the `get` operation on futures without blocking the underlying thread. The actor is blocked if the future is not resolved, and does not execute messages in the meantime if so.

The `await` operation can be used on a future to block the currently executing message, and not the entire actor, until a future is resolved. This allows the actor to process other messages in the meantime.

```
active class MyActor
 def foo() : unit
  var fut = otherActor ! doThings()
  await(fut)
  -- Blocking the executing message. The actor may
  -- execute other messages in the meantime.
```

```
    get(fut)
    -- The actor is not blocked, since the use of 'await'
    -- guarantees that the future is fulfilled.
  end
end
```

Listing 2.2: Using the `await` operation to block an executing message

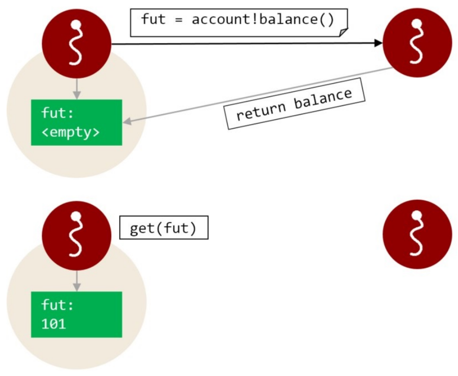


Figure 2.2: Using futures to allow blocking on an asynchronous operation. A message is sent to the account actor that then stores the result in a future. The caller is blocked if it tries to get the result before the future has been resolved.

The `suspend` command suspends an actor indefinitely. After `suspend`, either another message is executed or the suspended message is immediately resumes.

```
active class MyActor
  def foo() : unit
    var fut = otherActor ! doThings()
    this.suspend() -- Suspend actor indefinitely
    get(fut)
  end
end
```

Listing 2.3: Using the `get` operation on futures

2.1.3 Threads and Scheduling

Encore is implemented on top of Pthreads [27], and each Encore program is by default assigned one pthread per CPU core to run the user program. Each pthread can run multiple Encore threads or run messages for many actors, and actors can migrate between pthreads. Pthread local actor data is stored as an actor runs, which the scheduler swaps once the actor is finished or a cooperative scheduling primitive is used. Although actors only execute one message at a time, several messages may be running concurrently, in the sense that a message may be awaiting on a future or be suspended, while another of the actor's messages is executing. Also, if an actor migrates after an `await`, `get` or `suspend` operation, messages can be resumed on a different pthread (Figure 2.3).

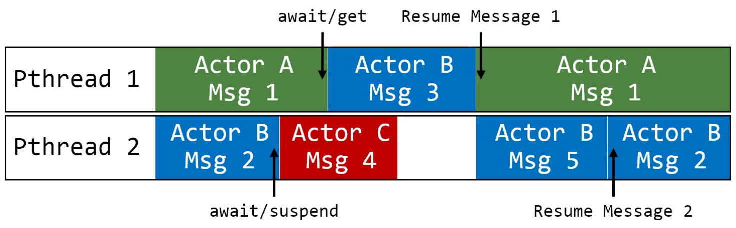


Figure 2.3: Interleaved execution of messages. After an `await` or `suspend` in Message 2, actor B executes other messages. Before resuming Message 2, the actor will have executed a message on a different thread as well as one on the same thread.

2.2 Exceptions

There are different kinds of errors that can occur in the context of computer programs. A program may compile and execute successfully, but behave in an unexpected way due to a bug, a *logic error*. On the other hand, the program may not at all compile due to incorrect syntax or failed type checking, a *compile time error*. An error that occurs while the program is running is called a *runtime error*, and can crash the program unless handled.

Exceptions can be thought of as unexpected or unusual events during the flow of a program, and are in this work synonymous with runtime errors. A common idiom for exceptions is that they can be raised somewhere in the program, which causes the program to transfer control to a different point, where the exception can be handled and recovered from [17, 33]. By enclosing code in exception handling expressions, the programmer can define error handlers for different kinds of errors. When an error occurs and an exception is raised, the program transfers control to the nearest enclosing corresponding handler, while skipping handlers designated to other kinds of exceptions (Figure 2.4). If no handler is designated to the exception, the exception is said to be uncaught, typically leading to the program exiting.

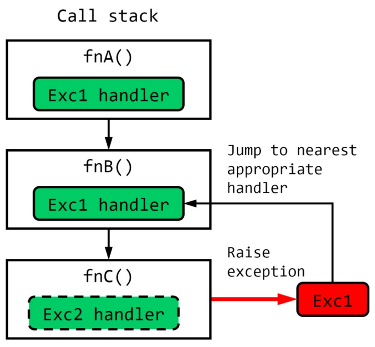


Figure 2.4: The basic idea behind exception handling.

To allow program to release resources in the event of errors, many exception handlers provide finalization or clean-up clauses, which allow some code to be executed whether or not an exception occurred in the exception handling expression. Using common terminology, an exception is raised when it is thrown, code that is enclosed in exception handling expression is put inside a `try` block, `catch` blocks define exception handlers, and `finally` blocks define finalizers.

Throughout this thesis there a distinction is made between exception handling in synchronous and asynchronous settings. Asynchronous exception handling involves passing exceptions between different threads of control, through futures or other mechanisms. To save time an open source C library for exception handling, presented in Section 2.2.2, is used in the implementation. To provide an understanding of how exception handling is implemented in the exception handling library, the next section first introduces basic exception handling in C.

2.2.1 Exception Handling in C

Basic exception handling in C can be implemented with help of the `setjmp.h` library [11, 33], which provides functions for saving and restoring stack contexts. The `setjmp` function saves the current context in a buffer (`jmp_buf`), and when called directly returns `0`. The `longjmp` function restores the last saved context and jumps to the position where the context was saved. After a `longjmp` subsequent calls of `setjmp` return a nonzero value assigned by the last `longjmp`.

An example of basic `try-catch` functionality is shown in Listing 2.4, where a conditional statement determines the program status. The first branch of the conditional represents the `try` block, and subsequent branches exception handlers (`catch` blocks). An initial `setjmp` prepares the program to run the `try` code. After the `throw`, a jump is made to the `setjmp` statement and the conditional is re-entered, this time ending up in an exceptional branch.

```
#include <stdio.h>
#include <setjmp.h>
static jmp_buf buf;
int main() {
```

```
int returncode = setjmp(buf); /* longjmp will jump here */
switch(returncode) {
case  0: puts("try-code");
         longjmp(buf, 1); /*threw exc. 1*/  break;
case  1: puts("exception handler 1");       break;
default: puts("default exception handler"); break;
}
return 0;
}
```

Listing 2.4: Basic exception handling with `setjmp.h`

For added functionality, a simple data structure with exception info, such as an error message and non-int exception types can be also created. To provide support for nested exception handlers an exception stack, consisting of a set of frames, is needed [33]. Each frame in the exception stack corresponds to one `try-catch` statement (Figure 2.5), and contains a `jmp_buf` and possibly information to be used for control flow. When an exception is thrown, the necessary exception handler is found by unwinding the exception stack, and if none exists, the exception is uncaught and the program exits.

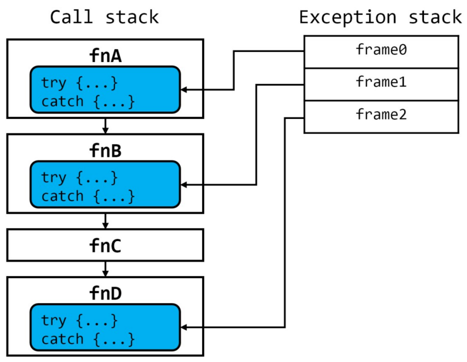


Figure 2.5: An exception stack to track `try-catch` statements.

2.2.2 The Exceptions4C Library

Several unknowns made it hard to estimate how much would be needed to provide an exception handling basis. Beyond applying the techniques described in the previous section, the basis needed to work with ENCORE's concurrency model. To save time and avoid reinventing the wheel, an open-source library for exception handling, EXCEPTIONS4C, is used in this work.

EXCEPTIONS4C (E4C) is a small, portable, open source exception handling library that brings exception handling semantics C programs. The library is written by Guillermo Calvo[1], had its first release in 2009, and uses the techniques in Section 2.2.1 along with more advanced techniques to provide extended

[1]The EXCEPTIONS4C library can be found at http://guillermocalvo.github.io/exceptions4c

functionality. There are two versions of the library, a minimal and straightforward light version, E4C light, and a more complex regular version, E4C regular, with extended exception handling functionality such as PTHREADS support. This PTHREADS support is the only feature of E4C regular that is of interest with regards to this thesis, and is explored when implementing exception handling in multithreaded settings (Section 4.5).

E4C features the language constructs `try`, `catch`, and `finally`, for finalization code, which are made available through macros. Macros for declaring exception types, and throwing and retrieving exceptions are also provided. E4C supports nested exception handlers, which are implemented through stack frames with dynamic scope. Thrown exceptions are represented as a C struct with an exception type, a message, a line number, and a file name. The exception types allow the programmer to use multiple exception handlers (`catch` clauses following a `try` block), instead of just a single universal handler, whereas the remaining data is primarily for debugging or logging purposes.

```
#include <stdio.h>
#include <e4c_lite.h>

E4C_EXCEPTION(Exception1,"A message",RuntimeException);

int main() {
 E4C_TRY {
  print("running try-code\n");
  E4C_THROW(Exception1,"Woops!");
 } E4C_CATCH(Exception1) {
  printf("exception handler 1\n");
 } E4C_CATCH(RuntimeException) {
  printf("default exception handler\n");
 } E4C_FINALLY { /* Finalize */ };
 return 0;
}
```

Listing 2.5: Basic exception handling with EXCEPTIONS4C

Exception Contexts E4C stores important exception handling data in exception contexts. The exception contexts contain an array of frames, an array for `jmp_buf`s, the last thrown exception, a variable for tracking the number of used frames, and more.

```
struct e4c_context {
 jmp_buf jump[E4C_MAX_FRAMES];
 struct e4c_exception err;
 struct{unsigned char stage; unsigned char uncaught;} frame[
    E4C_MAX_FRAMES + 1];
 int frames;
};
```

Listing 2.6: Exception contexts in E4C light.

Frames and jump buffers more or less have a one-to-one relationship, where the former simply provides additional information for control flow. Together, they, along with a frame number provide enough information for jumping to appropriate code points during exception handling (Figure 2.6). E4C light and E4C regular, without PTHREADS enabled, use one global exception context, whereas E4C regular with PTHREADS enabled uses thread local contexts.

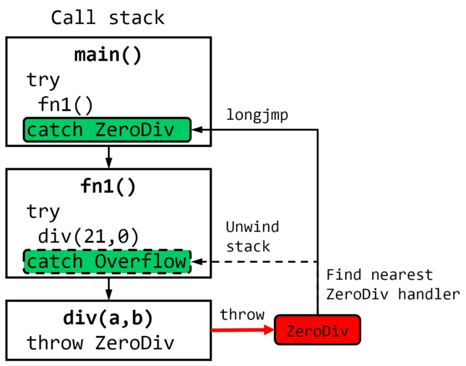


Figure 2.6: Using frames during exception handling

2.3 Related Work

There are numerous works on exception handling in languages with asynchronous method calls. A subset of these are discussed in this section, with focus on works in which futures are part of the exception handling model.

Dart DART is a programming language developed by Google, used to build web, server and mobile applications [8, 23]. The language is object-oriented, class-based, and supports actor-style concurrency through *isolates*, which communicate through message passing via futures or streams. DART streams produce a sequence of values and through the `yield` statement adds a value to the sequence [13].

DART provides `try` statements for exception handling using the keywords `try`, `on`, `catch`, and `finally`. DART's exceptions are objects, thrown using the `throw` keyword, and the user may create new exception classes. The `on` keyword prefixes exception handling code and allows catching exceptions of a specific class and may be combined with the `catch` keyword, which catches an exception of unspecified class and gives access to the underlying exception object [13].

```
try { throw new Exception1(...); }
on Exception1 { ... }
on Exception2 catch(e) { print(e); }
catch(e) { print(e); }
finally { ... }
```

Listing 2.7: Exception handling in DART

Exceptions when using futures can be handled using `try` statements, or by registering a callback function `catchError` to method calls [23].

```
class Exception1 extends
    RuntimeException {}

class X {
 ...
 ReturnType method() {
  try { throw new Exception1()
    ; }
  catch(Exception1 e) { ... }
  catch(RuntimeException e) {
    ... }
  finally { ... }
 }
}
```

(a) `try-catch-finally` statements, custom exception classes

```
// Exception1 is checked
void foo() throws Exception1
    {...}

void bar() {
 try { foo(); }
 // This handler must exist
 // for the program to compile
    .
 catch(Exception1) { ... }
}
```

(b) Checked exceptions

Listing 2.7: Exception handling in JAVA

```
Future<String> f = foo();
f.then((String s) => print(s))
 .catchError((Error e) => handle(e));
```

Listing 2.8: Exception handling with futures in DART

Java JAVA is one of the most popular object-oriented programming languages of today, and has numerous libraries and frameworks to provide concurrency. There are two types of exceptions in JAVA, checked exceptions and unchecked exceptions [32]. The much debated checked exceptions must be explicitly handled in the program (Listing 2.7b), something that the compiler guarantees through a compile time check. Unchecked exceptions are not checked at runtime, may be left uncaught, and have `RuntimeException` as root class. Users can create custom exception classes by extending existing ones, and handle exceptions with `try-catch-finally` statements (Listing 2.7a).

The library `java.util.concurrent` provides many classes for concurrency, among others an implementation of futures [29, 36]. The `get` method of futures is a synchronization mechanism that blocks the running task and retrieves the computed value once available. Futures also have a cancellation method, which attempts to cancel a task. The `get` method can throw `CancellationException`, `ExecutionException` and `InterruptedExeption`, which can be handled by wrapping the method in a `try` statement (Listing 2.9).

```
Future f = ...
try {  f.get(); }
catch(ExecutionException e) { ... }

Future f2 = ...
f2.cancel();
try { f2.get(); }
```

```
catch(CancellationException e) { ... }
```

Listing 2.9: Exception handling with futures in Java

The Google Guava project contains concurrency libraries and extends Java JDK's `Future` class with `ListenableFuture` [6]. `ListenableFuture` allows the programmer to register callbacks to be run when the task is completed, which provide one method that is invoked upon a failed computation, and another that is invoked upon a successful computation.

Scala Scala is a Java-inspired programming language that features both object-oriented and functional programming [28, 30]. Exception handling is similar to that of Java, in that `try-catch-finally` blocks are used, exceptions are objects, and that custom exception classes can be created. Scala's exception handling statements are however expressions, and its `catch` blocks define exception handlers through pattern matching anonymous functions.

Scala's `Try` type (`scala.util.Try`) is used to represents a computation that may either be successful, or result in an exception [34]. This type is useful in functional programming, and is similar to the `Either` type of Scala as well programming languages such as Haskell [31]. The result of a `Try` can be accessed through pattern matching, or through status and getter methods (Listing 2.10).

```
val result = Try( throw new Exception1 )
result match {
 case Success(s) => { println(s); }
 case Failure(e) => {
   e match {
    case e: Exception1 => ...
    case e: Exception2 => ...
    }
  }
}
// Without pattern matching
if (result.isSuccess) { println(result.get) }
else { println(result.failed.get) }
```

Listing 2.10: Exception handling in Scala

The Scala standard library provides an abstract implementation of future objects through (`scala.concurrent.Future`). There are multiple ways to handle exceptions in futures. One way is to use the callback function `recover`, which is applied when an exception occurs in the callee. The programmer can define `recover`, and can through pattern matching specify exception handling behaviours for different exception classes (Listing 2.8a). Similarly the callback `onComplete` can be defined, which is applied when the future is completed and takes a `Try` object, instead of an exception, as argument (Listing 2.8b).

An alternative approach is to use the blocking synchronization mechanism `Await.result`, which waits until the future is ready and rethrows exception objects when the computation failed (Listing 2.8c).

```
val f = Future {...}
f.recover {
 case e: Exception1 => ...
 case e: Exception2 => ...
}
```

(a) Defining the callback `recover`

```
val f = Future {...}
f.onComplete {
 case Success(s) => ...
 case Failure(e) => ...
}
```

(b) Defining the callback `onComplete`

```
val f = Future {...}
try { Await.result(f, 1 second) }
catch {...}
```

(c) Enclosing `Await` in a `try` expressions

Listing 2.8: Exception handling with futures in SCALA

Actor-based concurrency in SCALA is provided through the AKKA framework (`akka.actors`), which is presented next.

Akka The AKKA framework provides actor-based concurrency for both JAVA and SCALA, and is used for building concurrent and distributed applications [18].

Similar to actors in ENCORE, the framework's actors are objects with their own state and behaviour, and communicate through message passing. Actors communicate exceptions through futures, allowing the usual idioms of JAVA or SCALA to be used during exception handling.

Another layer in AKKA's fault handling model is actor supervision. Actors are linked to another actor, a supervisor, with a fault handling strategy [2]. When a child actor throws an exception, the supervisor applies one of four supervision directives to the child:

- `resume` keeps the child's internal state and resumes the child's execution.
- `restart` clears the child's internal states and restarts the child.
- `stop` permanently stops or kills the child.
- `escalate` fails the supervisor itself, and escalates the exception to a higher level supervisor.

There is a mapping from exception class to supervision directive, meaning the choice of directive depends on the exception class. Furthermore, the supervisor either applies the directive to just the one child (the `OneForOneStrategy`), or to the child as well as its siblings (the `AllForOneStrategy`). Note that actors form a hierarchy in AKKA, something which ENCORE's actors do not.

Erlang ERLANG is a concurrent, functional programming language designed from the ground up to create distributed, fault-tolerant, real-time systems that in principle never stop [3]. The language's concurrency model is based on the actor model, with message passing between lightweight processes, the Erlang equivalent to actors.

Fault-tolerance and error recovery is a high priority in Erlang, which has robust error handling mechanisms for both sequential and concurrent programs, the latter of which will only be briefly touched upon. Sequential errors occur in three classes:

- Runtime errors are produced when the program crashes, and have a reason such as `badarg`, `badarith` or `undef` attached. Though they are automatically raised, runtime errors can be emulated with `error(Reason)` or `error(Reason, Args)`.
- Exit errors are generated errors, and occur when the code has a call to `exit(Term)`.
- Throw errors are also generated, and indicate errors that the caller may want to catch. The code for throwing is `throw(Term)`.

```
throw_fn() -> throw(exception1).
exit_fn() ->  exit("goodbye").
error_fn() -> error(badarg).
```

Listing 2.11: Error classes in Erlang

Exception handling happens in `try` expressions or `catch` expressions [15]. The former is built up of `try`, `catch` and `after` blocks, where `after` blocks enclose finalization code. Through pattern matching and guards, errors of specific classes and terms can be handled with `try` expressions (Listing 2.12).

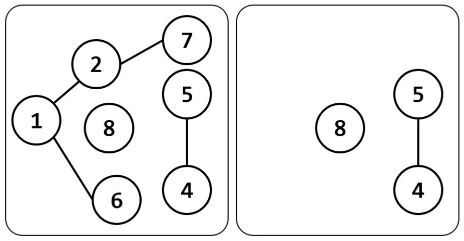
```
try_fn() ->
 try some_error_fn()
 catch
  throw:Term when Term == exception1 -> ...;
  throw:Term -> ...;
  exit:Term  -> ...;
  error:Reason -> ...
 after
  io:fwrite("finalizing\n")
 end.
```

Listing 2.12: `try` expressions in Erlang

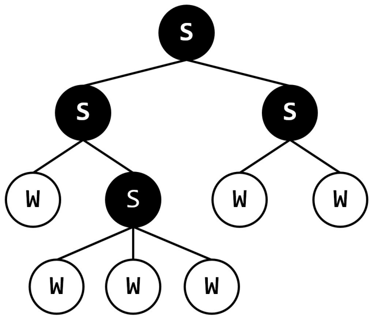
The `catch` expression, not to be confused with `catch` blocks of `try` expressions, returns the value of run code is returned unless an exception occurs. Exceptions are caught, and returned along with additional information depending on the error class.

```
> catch 1+1.
2
> catch 1+a.
{'EXIT',{badarith,[...]}}
> catch throw(exception1).
exception1
```

Listing 2.13: `catch` expressions in Erlang



(a) Links. As process 2 dies, so do the linked processes 1 and 7, as well as 6.



(b) Supervision trees, hierarchies of supervisors and workers.

Listing 2.9: Connected processes in Erlang

Error Handling in Concurrent Programs The philosophy behind Erlang's error handling in concurrent programs is to let processes crash, and let other processes fix the problem [3]. Letting processes crash leads to less time spent writing defensive code, less resources spent trying to recover from errors, and serves to decouple error handling from application logic. Process have unique IDs, which can be used to connect them in different ways, so they can observe each other and take appropriate action when connected processes die.

There are three built-in ways to connect processes in Erlang, *links*, *monitors* and *supervision trees*. When a set of processes are linked and one process die, all linked processes are informed and also die (with some exceptions), throughout the entire connected graph (Figure 2.9a).

Monitors allow processes to be connected in a unidirectional way. When a monitored process dies, its parent, the monitor, is informed of this, but does not die. Monitors can thus handle errors when their child processes, as opposed to links that die in groups. Supervision trees allow hierarchical application structures to be created. A supervision tree consists of supervisors processes with child processes below them, which they supervise (Figure 2.9b). Like in Akka, supervisors have different strategies for handling errors in children, a *restart strategy*. One-for-one supervision trees restart just the single child when one dies, whereas one-for-all supervision trees kill and then restart all siblings when any child dies. Supervisors also carry specifications for each of their children, which includes information about how to start as well as shut down a child, when to restart a terminated child, and more.

Wrap-Up All mentioned languages support exception raising and handling, either imperatively (e.g. `try-catch` statements) or functionally (e.g. `Either` types representing successful or failed computations). Erlang and Dart were built ground up with the actor-model, whereas Java and Scala utilize frameworks such as Akka for actor-based concurrency. Erlang's takes a different approach in that it encourages the programmer to let processes crash and let connecting processes, e.g. supervisors and monitors, fix the problem. ERLANG does not have futures whereas the other languages do, though they are a recent addition in JAVA and SCALA. The futures of these languages are similar to those of ENCORE, and provide exception handling through callback functions or through `try-catch` statements wrapped around retrieval of the future value.

The next chapter introduces the exception handling model that has been implemented for ENCORE.

3. Exception Handling in Encore

This chapter describes how exception handling works in Encore, using the implementation in this thesis. The exceptions handling model allows exceptions to be communicated in both synchronous and asynchronous settings. Section 3.1 introduces language constructs for raising exceptions of different types and exception handling expressions, which allow exceptions to be handled in synchronous settings. Asynchronous exception handling is exception handling that involves inter-process communication, communication of exceptions between actors, and is covered in Section 3.2.

3.1 Synchronous Exceptions

The exception handling mechanisms used in synchronous settings is inspired by Java, and features exception raising and handling. The exception handling mechanism uses type-based matching that also considers subtyping, and allows the programmer to create custom exception types. Statically checked exceptions, as found in Java [35], are not supported in this implementation, since compile time errors are outside of the scope of this thesis. Furthermore, an argument can be made that statically checked exceptions are not programmer-friendly due to the programming overhead.

Raising Exceptions: `throw` Exceptions are raised with `throw` statements, which are applied to an exception type and take an optional message.

```
throw MyException("Optional message")
throw MyException
```

Listing 3.1: Raising exceptions in Encore

Exception Handling Expressions: `try` Exceptions are handled through `try-catch`, `try-finally` or `try-catch-finally` expressions (Listing 3.1a). The `try` block encloses code that may raise an exception, and `catch` blocks define exception handlers for the possibly exceptional code. Multiple `catch` blocks may follow the `try` block, each one handling an exceptions of a different type, and optionally storing the exception to a variable when caught (Listing 3.1b).

```
try
 ...
catch
 -- catch any exception
finally
 ...
end
```

(a) Basic exception handling expressions

```
try
 ...
catch Exception1
 ...
catch e2 : Exception2
 -- save exception to "e2"
catch e : RuntimeException
 -- catch remaining exception
    types
end
```

(b) Catching and saving exceptions of different types

Listing 3.1: Exception handling expressions

The `finally` block represents finalization code, and must be the final clause in any exception handling expression. Finalization code executes at the end of the exception handling process, and does so whether or not an exception was raised.

Just like with ENCORE's `if-else` expressions, the result of an exception handling expression can be stored to a variable (Listing 3.2). Note that the result of the expression will not be set to the result of the `finally` block, but to the result of the `try` block or a `catch` block.

```
x =
 try
  throw MyException("")
  1
 catch MyException
  -1
 finally
  -20
 end
 -- Note: x == 1 or x == -1,
```

Listing 3.2: Evaluating `try` expressions

Custom Exception Types: `exception` The programmer can define custom exception types, which then become available to the exception handling mechanism (Listing 3.3). The new exception types are not available outside of exception handling, the way that `int` or `string` is usable. Each exception type is associated with a supertype and has a default message, and exceptions form a hierarchy, which gives the programmer freedom to handle exceptions through "umbrella types", or specific types. The exception type `RuntimeException` is built-in, and is the root of the exception type hierarchy. Instances of a particular exception type can be thrown with a message, which, if omitted, is replaced by the default message of the exception type.

An important consideration is the scope of exception types. Class local exceptions were first considered, but as exceptions are often be communicated between objects of different classes, they are not supported. Instead, Encore exception types simply have a global scope.

```
exception MyException("Default message", RuntimeException)

fun foo() : unit
 throw MyException("Woops!")
end
```

Listing 3.3: Defining exception types

Exception instances are objects of an exception class, with fields for exception data (Listing 3.4).

```
try
 throw MyException("Woops!")
catch e : RuntimeException
 print(e.type)      -- "MyException"
 print(e.message)   -- "Woops!"
end
```

Listing 3.4: Accessing exception data.

3.2 Asynchronous Exceptions

Actors need to be able to communicate exceptions to each other somehow. In the chosen exception handling model, exceptions are handled non-locally, and are propagated to the caller thread. A pull-model is used, where sender actors can handle exceptions when they see fit (Figure 3.2). This can be contrasted with using a push-model, where the receiver instead determines when exceptions should be handled. Any actor with a reference to an exception then needs to handle it, and not just the sender. This is relevant when an exception object is passed around by the sender.

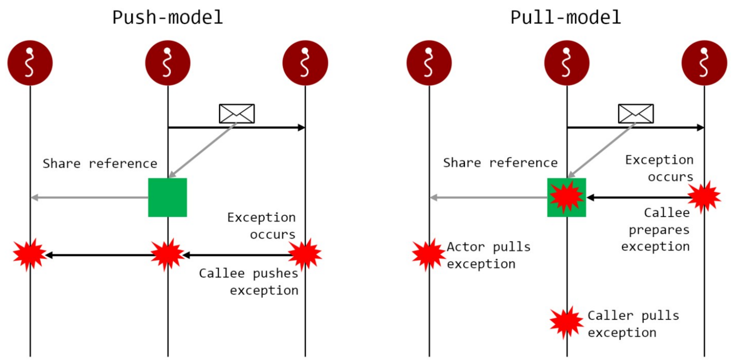
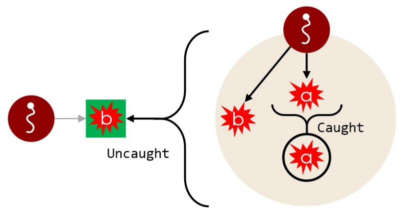


Figure 3.2: Push vs. Pull-model for exception handling.

Following the design suggested in *Fault in the Future* [22], futures are used to communicate exceptions between actors. Futures can thus hold exceptions



(a) Fulfilling futures with exceptions. Exception `a` is handled locally. Exception `b` has no local handler, and is propagated to a future.

```
val fut1 = actor ! foo()
val fut2 = actor ! foo()
var result = 0
await(fut2)
try
 result = get(fut1)
 get(fut2)
catch RuntimeException
 -- fut1/fut2 exceptional
end
```

(b) Handling exceptional futures

Figure 3.3: Futures and exceptions

on top of normal values, and are fulfilled with an exception when the callee throws an exception without catching it (Figure 3.3a). This ends the execution of the callee's currently running message, as if the message ran to completion, and allows the callee to execute other messages. If the executing message is a one-way message, where the caller is not requesting a return value, any uncaught exception are simply discarded.

Note that the `main` method, the entry point to every program, is not treated the same as other methods regarding exception handling. If an exception is thrown and left uncaught within the execution of `main`, it will remain uncaught and the program will crash. This is a conscious decision, and users must wrap possibly exceptional code in `try` expressions to protect against a crash.

As per the pull-model, the caller can handle the exceptional future at any time by using `get`. When retrieving a result from an exceptional future, `get` rethrows the exception. This means that any application of `get` on an exceptional future needs to be wrapped in an exception handling expression, (Figure 3.3b), or else the exception gets propagated again. If an exceptional futures or an exceptions is shared with other actors, they can in turn also handle the exception when they see fit. The mechanisms `await` and `suspend` remain unaffected from the programmers view, and can be used like normal.

This concludes the description of the exception handling model. In the next chapter, the implementation of the described model is explained.

4. Implementation

This chapter details the implementation details for the exception handling model (Chapter 3). Code generation is implemented for the new language constructs, and maps Encore code to C code that interacts with E4C in the runtime. An exception class is used to give users access to exception data, and to store in futures (Section 4.2). Actor communication through futures and changes to the `get` operation is explained in Section 4.3. To make sure that exceptions during do not enter the Pony runtime, and allow futures to be fulfilled with exceptions, the runtime and dispatch mechanism is modified (Section 4.4). Finally, Encore's context swapping and E4C are modified in order to provide exception contexts in the appropriate scope (Section 4.5).

4.1 Language Constructs

This section outlines the implementation details of language construct specified in the exception handling model, with focus on code generation. Implementing these constructs will not involve any modifications to the Encore or Pony runtime, but requires changes throughout the compiler. in this section

E4C light is well suited as a basis for synchronous exception handling, as it features C equivalents of the constructs specified in the exception handling model (Section 3). Once the language constructs are implemented, users will be able to use basic exception handling functionality in synchronous settings, and a base will be ready on which asynchronous exception handling will built. At this point E4C regular is given consideration, as it has built-in Pthreads support.

Custom Exception Types: `exception` The first language construct to implement is the `exception` keyword, which is used to declare an exception type. The generated C code is an E4C macro, which in turn expands to the initialization of a struct (Listing 4.1). In E4C, thrown exceptions include a reference to an exception type struct, and supertypes are references to such a struct.

To give exception types a global scope, the `exception` keyword is added as a top level construct, similar to the `class` keyword. This ensures that exception types can only be declared in the top level of the code. The generated C code

```
throw Exception1
throw Exception2("foo")
```

```
E4C_THROW(Exception1,"");
E4C_THROW(Exception2,"foo");
```

Listing 4.1: Code generation: Throwing exceptions

```
try
 ...
catch MyException
 ...
catch
 -- Catch any exception
finally
 ...
end
```

```
E4C_TRY{
 ...
}E4C_CATCH(MyException){
 ...
}E4C_CATCH(RuntimeException){
 /* Catch any exception */
}E4C_FINALLY{
 ...
};
```

Listing 4.2: Code generation: Exception handling expressions

for all exception types is placed in a shared C file, which also ensures the same exception type is only declared once.

```
exception MyException("Default msg", RuntimeException)
```

Listing 4.1: Code generation: Encore code when defining exception types.

```
E4C_DEFINE_EXCEPTION(MyException, RuntimeException);

// Expansion of the macro
const struct e4c_exception_type MyException =
 {"MyException", "Default msg", &RuntimeException};
```

Listing 4.2: Code generation: C code when defining exception types.

Raising Exceptions: `throw` Exception classes are thrown using the `throw` statement, which can take an optional message. The Encore code is translated to an invocation of the `E4C_THROW` macro.

Exception Handling Expressions: `try` The next construct is exception handling expressions (Listing 4.2), which are translated to C code in a straightforward manner thanks to the macros of the E4C library. Note that catch-all clauses are simply syntactic sugar for catch `RuntimeException`.

To allow the result of the exception handling expression to stored, a variable outside of the expression is used. At the end of the `try` block and `catch` blocks, the result variable is then set to the returned value (Listing 4.3). Note that this variable is not set in a `finally` block, adhering to the semantics of the language construct.

```
x = try
 throw MyException("")
  1
 catch MyException
  -1
 finally
  -2
 end
```

```
E4C_TRY{
  E4C_THROW(MyException,"");
  result = 1;
}E4C_CATCH(MyException){
  result = -1;
}E4C_FINALLY{
  x = -2;
}; x = result;
```

Listing 4.3: Code generation: Saving the result of exception handling expressions

4.2 Exception Objects

When exceptions are thrown, they are stored as C structs in the exception contexts of E4C. Each exception contexts stores only one exception, and they reside on the callee's stack. Encore does not preserve the callee stack after a future is fulfilled, which means that accessing exceptions stored in futures is not memory safe (Figure 4.4).

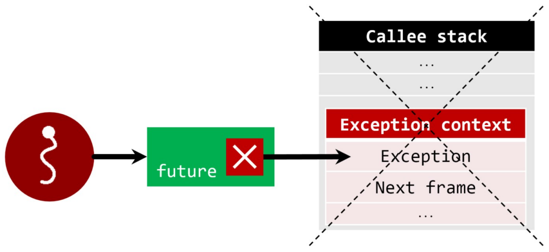


Figure 4.4: The callee stack is destroyed after a fulfill. References to the callee stack, are thus unsafe.

To solve this problem and also allow the programmer to access the exception data in Encore, an exception class, `ExceptionWrapper` is created. It represents a thrown exception instance, and holds copies of the data in the E4C exception. This makes exceptions first class objects, and allow any amount of thrown exceptions to safely be stored in the user program.

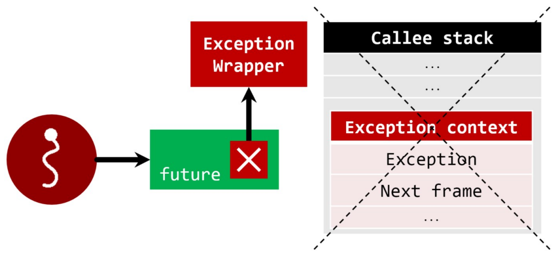


Figure 4.5: By modifying exceptional fulfills to copy the exception residing in the callee stack, the exception can safely be propagated to the future.

`ExceptionWrapper`s are created when a future is fulfilled (Section 4.4.2) or when an exception is caught, by simply desugaring `catch` clauses to fetch E4C data through embedded C code, and then passing it to the exception object constructor (Listing 4.3). The `ExceptionWrapper`s are not shared between fulfilled futures and `catch` clauses, a limitation that is discussed in Section 6.1.1.

```
try
 ...
catch e : MyException
 -- Desugar catch clause by adding the following lines
 Type type = EMBED E4C_EXCEPTION.type END
 int line  = EMBED E4C_EXCEPTION.line END
 -- Allocate string objects for 'char *' data
 String msg  = new String(EMBED E4C_EXCEPTION.message END)
 String file = new String(EMBED E4C_EXCEPTION.file END)
 -- Pass fetched values to exception object constructor
 ExceptionWrapper e = new ExceptionWrapper(type, msg, line, file)
 -- User code
 ...
end
```

Listing 4.3: Creating exceptions objects in `catch` clauses.

Note that an `ExceptionWrapper` is allocated on the heap, and the same exception data exists in parallel on the stack until overwritten. A possible workaround to this duality is to modify E4C to use `ExceptionWrapper`s and pass these by references, instead of using the single C struct. However, this adds an overhead to parts of the runtime, ENCORE's dispatch mechanism (Section 4.4.2), which makes the chosen solution preferable.

Rethrowing Exceptions A rethrow method is created for the `ExceptionWrapper` class. This method simply calls E4C's throw function, but uses the data of the `ExceptionWrapper` as arguments.

```
class ExceptionWrapper
 ...
 def rethrow() : unit
  -- Not using 'E4C_THROW' to pass file and line.
  EMBED(unit)
   e4c_throw(e4c_ctx(), #{this.e4c_type},
    #{this.cfile.getData()}, #{this.cline},
    #{this.message.getData()});
  END
 end
end
```

Listing 4.4: Rethrowing exceptions.

When the exception is later caught, new `ExceptionWrapper`s are allocated with the same data as the rethrown exception. Just like with future fulfills and `catch` clauses, exception objects are not re-used during rethrows (also discussed in Section 5.3).

4.3 Communicating Exceptions Between Actors

As explained in Section 3.2, futures allow actors to share memory and communicate synchronously. To enable exceptions to be communicated between actors, futures are modified to be able to hold exceptions, on top of normal values. The future data structure is extended to store a pointer to exceptional data in the form of an `ExceptionWrapper`, and a flag that indicates whether they are fulfilled with an exceptional or normal value. The `get` is the only future operation which needs modification to accommodate for these changes. If a future is exceptional, `get` re-throws the exceptional value when operating on the future, and otherwise returns the value, as usual.

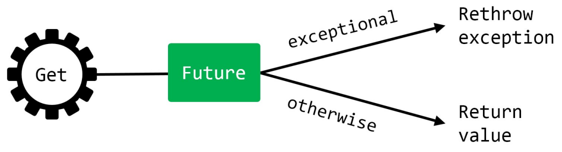


Figure 4.6: The new `get` operation.

4.4 Protecting the Runtime and Future Fulfills

When an asynchronous method call results in an exception, `E4C` will kick in and carry out a non-local. However, no exception handler exists outside of the user code, which means the exception will propagate down to the Pony runtime and crash the program. A crash is only desired when the main method leaves an exception uncaught, for all other asynchronous method calls the exception must be caught in order to prevent a crash, and fulfill a possible future with the exception. The following sections give a background to Encore's dispatch mechanism (Section 4.4.1) and presents a new version (Section 4.4.2), which protects the runtime and can fulfill futures with exceptions.

4.4.1 Encore's Dispatch Mechanism

A dispatch mechanism looks up which version of a method or function to call. Encore uses *single dynamic dispatch*, where the properties of a single actor is used to find the proper function to run [26]. Under the hood, Encore's dispatch mechanism also runs methods different ways depending a one-way or regular message is being processed (Section 2.1.1). To achieve this, each message in an actor's inbox carries with it an ID that indicates the method to call and in what way. The dispatch mechanism then uses the message ID in a switch statement with one case per ID, and stores the result in the future of the message. This mechanism allows actors to postpone the execution of asynchronous method calls to any later point.

```
void dispatch_MyClass(...) {
 switch (msg_id) {
  case REGULAR_MSG_method1: fulfill(future, method1(...)); break;
  case ONEWAY_MSG_method1:  method1(...);                  break;
  ... } }
```

Listing 4.5: Dispatch function of an Encore class. The dispatch function consists of a conditional, with multiple branches for each method. one corresponding to a different kind of call on the same method. Branches for regular messages involve fulfilling a future, whereas those of one-way messages are just a method call.

4.4.2 Modifying the Dispatch Mechanism

To deal with exceptions during asynchronous method calls, and store exceptional results in futures when processing regular messages, Encore's dispatch mechanism needs to be modified. Currently, exceptional method calls, run from the dispatch function (Listing 4.5), do not have a fallback exception frame. When an exception is thrown and uncaught in the methods corresponding runtime function, the exception stack will be empty, leading E4C to exit the program.

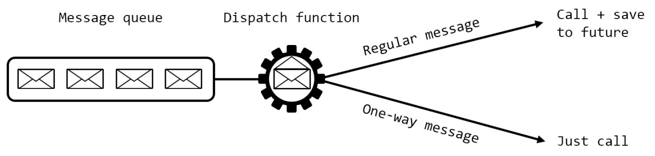


Figure 4.7: With Encore's current dispatch mechanism, exceptional method calls result in the program exiting.

The dispatch mechanism has be modified to create a fallback exception frame, so that exceptions are caught when occurring in asynchronous method calls. This involves wrapping each call to the generated C functions of the methods in an exception handling statement, and adding additional in each switch case.

In switch cases of regular messages, the future is fulfilled with an `ExceptionWrapper` if an exception is caught, and the future's `exceptional` flag (Section 3.2) is set to `true` by passing the value to a modified version of the fulfill function. In switch cases of one-way messages, caught exceptions are ignored since there is no return value, not letting the caller know what has happened. Alternative ways of dealing with exceptions in one-way message sends are discussed in Section 6.

```
void dispatch_MyClass(...) {
 switch (msg_id) {
  case REGULAR_MSG_method1:
   E4C_TRY { fulfill(future, method1(...), 0); }
   E4C_CATCH { fulfill(future, the_exception(), 1); }; break;
  case ONEWAY_MSG_method1:
   E4C_TRY { method1(...); }
   E4C_CATCH { /*do nothing*/ }; break;
  ... } }
```

Listing 4.6: Modifying dispatch to support exceptions. A boolean is passed to fulfill to indicate whether the value is exceptional. All method calls are enclosed by `try` expressions, in case an exception is left uncaught in the method.

4.5 Scope of Exception Contexts

Exception contexts carry crucial data which, if not preserved can lead to undefined behaviour in E4C. When context swapping occurs in Encore, another message or actor is takes over a thread, and if exception contexts are not swapped as Encore's exception swapping mechanism is triggered, they will become corrupted. This section outlines modifications needed to ENCORE's context swapping mechanism and E4C in order to provide exception contexts at the correct level.

E4C regular's provides built in support for PTHREADS, which enables each pthread to have its own exception context. However, exceptions on the level of pthreads will not work for ENCORE, where each pthread runs messages for many actors, and actors can migrate between pthreads as well as execute messages in an interleaving fashion (Section 2.1.3).

To properly preserve exception handling information during ENCORE's context swaps, both actor blocking and interleaving of messages need to be considered. If only actor blocking occurred, then actors would process messages sequentially and only need an actor level exception context. However, with interleaved message execution, where message level information can be stored and resumed, each message needs its own exception context.

Note that message level exception contexts are needed in both multithreaded and single threaded settings. Consider the program in Listing 4.7, where a `suspend` is used during exception handling. If another actor then runs and creates an exception frame, the exception frame of the first actor is overwritten, leading to undefined behaviour.

```
class SeeFood
 def is_hotdog(s : String) : unit
  try
   suspend()
   if not s.equals("hotdog") then throw RuntimeException end
   println("Hotdog: {}", s)
  catch
   println("Not hotdog: {}", s)
  end
 end
end

class Main
 def main() : unit
  val fut_a = new SeeFood ! is_hotdog("avocado")
  val fut_h = new SeeFood ! is_hotdog("hotdog")
  get(fut_a)
  get(fut_h)
 end
end
```

Listing 4.7: Message level exception contexts in single threaded settings.

Solution Since the PTHREADS support of E4C regular is not useful for ENCORE, E4C light is used in combination with ENCORE's built in PTHREADS support. The ENCORE thread is extended with an `e4c_context` pointer, and a getter function is created to simplify accessing the new field. `e4c_context`s are created and stored on messages' stack as soon as they starts running, and the new field of the ENCORE thread is set to the address of the stored `e4c_context`.

To make sure E4C functions use the message level exception context instead of a global or thread local one, E4C functions and macros are modified to take a pointer argument to an `e4c_context`. By simply passing the message local `e4c_context` to the functions, E4C will use the correct exception context. The same exception context will naturally be used in the dispatch function (Section 4.4.2), and elsewhere in the runtime.

When the execution of a message resumes, the address of the message's `e4c_context`, stored somewhere on its stack, has been lost, as the ENCORE thread now has a pointer to the `e4c_context` of the previous, possibly finished, message. To solve this and properly resume messages, a pointer to the `e4c_context` is created right before the context swap, and is then used to refresh the exception data when the a message resumes execution.

5. Evaluation

This section presents an evaluation of the exception handling implementation, and consists of an overview of its features (Section 5.1) and performance experiments (Section 5.2). Finally, some limitations of the implementation are discussed in Section 5.3.

5.1 Expressiveness

This section demonstrates features of the exception handling implementation, and how they simplify propagation and handling of errors in Encore. Note that basic testing has been successfully carried out on all demonstrated language constructs, to ensure that they behave as expected in both synchronous and asynchronous settings.

5.1.1 Synchronous exceptions

The exception handling mechanism simplifies error handling circumstances by allowing the programmer to use `try-catch` expressions and `throw` statements (Listing 5.1a). Without this implementation, the programmer needs to add extra logic to the program for propagating and handling exceptional values. As an example, objects of the `Either` type of Encore can be used to represent a computation that is either successful or a failure, and have to be handled in a match statement in order to mimic exception handling behaviour (Listing 5.1b).

Custom exception types can be defined by the user, and can then be used to distinguish between different kinds of exceptions. Furthermore, exceptions form a hierarchy, which allows the programmer to arbitrarily group exception types during exception handling (Listing 5.2b). To distinguish between different kinds of exceptions without the implemented exception handling mechanism, the programmer would have to map values to exceptions and use conditional statements (Listing 5.2b). Handling exception hierarchies properly would require even more control logic.

With the implemented exception handling mechanism, exceptions can also be saved to variables when caught, giving the user access to additional information (Listing 5.1). The saved exception is a first class object that can be passed around, and provides a `rethrow` method.

```
try
 if all_is_fine then
  1
 else
  throw RuntimeException
 end
catch
 -- error
end
```

(a) The implemented `try` expressions

```
val result =
 if all_is_fine then
  Right[int,int](1)
 else
  Left[int,int](-1)
 end

match result with
 case Right(x) =>
  ...
 end
 case Left(e) =>
  -- error
 end
end
```

(b) Mimicking `try` functionally

Listing 5.1: Evaluation of `try` expressions

```
exception IOExc("",
  RuntimeException)
exception AccessDenied("",
  IOExc)
exception DirNotFound("",
  IOExc)
exception FileNotFound("",
  IOExc)


...
 try
  if all_is_fine then
   1
  else
   if accessdenied then
    throw AccessDenied
   else
    throw IOExc
   end
  end
 catch AccessDenied
  request_access()
 catch IOExc
  ask_for_new_path()
 end
```

(a) With exception types

```
val result =
 if all_is_fine then
  Right[int,int](1)
 else
  if accessdenied then
   Left[int,int](-11)
  else -- bad path
   Left[int,int](-10)
  end
 end

match result with
 case Right(x) =>
  x
 end
 case Left(x) =>
  match e with
   case -11 =>
    request_access()
   end
   case -10 =>
    ask_for_new_path()
   end
  end
 end
end
```

(b) With complex control logic

Listing 5.2: Distinguishing between different types of errors.

```
val fut = actor ! foo()
try
 get(fut)
catch
 -- handle
end
```

(a) Through `get` and `try-catch`

```
val res = get(actor ! foo())
match res with
 case Right(x) =>
  ...
 end
 case Left(x) =>
  -- handle
 end
end
```

(b) Functionally through `Either` types

```
val fut = actor ! foo()
await(fut)
this.suspend()
try
 println(get(fut))
catch
 -- fut contained exception
end
```

(c) Cooperative scheduling primitives are used like usual.

Listing 5.3: Handling exceptions in asynchronous settings

```
fun exceptional(x : int) : unit
 try
  if x > 0 then throw RuntimeException("neg") end
   print(x)
 catch e : Exception1
  print("Message: {}", e.message)
  e.rethrow()
 end
end
```

Listing 5.1: Accessing exception objects.

5.1.2 Asynchronous Exceptions

In this implementation, there is no significant difference between how exceptions are handled asynchronously and synchronously. Futures are used as a middle-man, and the `get` operation, which now rethrows exceptions in futures, has to be wrapped in `try-catch` expressions in order to handle the exception. Without these changes, `Either` would have to be used, like in the synchronous case (Listing 5.3b). The cooperative scheduling primitives `await`, `get` and `suspend` all work as expected, without requiring any extra work on the programmer side (Listing 5.3c).

5.2 Performance

This section presents CPU running time experiments for the implemented exception handling mechanism. The first motivation behind the experiments was to get a rough idea about the runtime overhead caused by Encore's passive use of exception handling (e.g. during context swapping and dispatch). The second motivation was to see how programs scale as more exception handling related operations are executed. Section 5.2.1 presents performance experiments mainly aimed at learning more about the overhead of the exception handling mechanism, and Section 5.2.2 at learning how well the mechanism scales. The results and concluding remarks about the experiments are presented in Section 5.2.3.

All tests were run under Ubuntu 14.04 64-bit through VirtualBox on a Windows 8.1 host. The host had a 2.00 GHz Intel Core i7 4510U with 512 kB L2 cache and 8 GB RAM, out of which 1.5 GB was made available to the guest environment. Running times of programs were measured with the Linux `time` command, and each test configuration was run at least three times. The time was calculated by averaging the `user` and `sys` measurements output by `time`. Profiling data of programs was also gathered, using the GNU profiler `gprof`, and was used to pinpoint resource hogs. Different test programs were run under slightly different circumstances, and the figures are not meant to be used in to compare the test programs, but to compare runs of the same test program with varying parameters.

5.2.1 Runtime Overhead Experiments

Even when user programs do not use exception handling, it is used by Encore when messages are run, during context swapping, and in dispatch. To get a rough idea about the runtime overhead several test programs are executed on a version of Encore where exception handling is disabled, and on a version where exception handling is enabled. The running time of the test runs are then measured, and compared.

Basic Message Send Tests The first set of programs do basic message sends from the main actor to one of four actors. Main calls the method `foo` of the actors, which simply returns 1. The call to `foo` is done in three ways, in Test1 it is a simple one-way message send, in Test2 the result is saved to a future, and in Test3 the result is retrieved with `get` (Listing 5.2). Every program is run with varying values for the `times` parameter.

```
active class A
 def foo() : int
  1
 end
end

active class Main
 def main(args:[String]) : unit
  var times = get_times(args)
  var nactors = 4
  var a = new [A](nactors)
  repeat i <- nactors do
   a(i) = new A()
  end

  repeat i <- times do
   -- Test 1: One-way message sends
   a(i%nactors) ! foo()
   -- Test 2: Regular messages
   var f = a(i % nactors) ! foo()
   -- Test 3: Synchronizing with `get`
   get(a(i%nactors) ! foo())
  end
 end
end
```
Listing 5.2: Three basic performance tests that do not use exception handing.

Savina Tests The second set of programs are existing stress tests from the Encore test suite (found as appendices in Chapter A), and involve more complex interactions than the basic message send tests. Some of the Savina tests mainly do one-way message sends in the end, whereas others involve a lot of regular message sends and object allocation. Only one of configuration for each Savina programs is run.

5.2.2 Scalability Experiments

The performance experiments in this section are meant to show how well a program performs as more exception handling operations are executed. The programs do basic message sends from the main actor to one of four actors. Main wraps the method call in a `try-catch` expression and either calls `foo`, which simply returns 1, or `throw_`, which throws an exception. One of five programs is run, each of which use exception handling mechanisms in a slightly different way (Listing 5.4). Each program is run with varying values for the `times` parameter.

5.2.3 Results

Given the results from Test 1, as well as some of the Savina tests, there seems to be a significant overhead when exception handling is not utilized. On Test 1, exception handling causes a 13% slow down with 40 M message sends, and a 28% slow down with 100 M message sends, and the running time seems to increases exponentially (Table 5.1). Similarly, the Savina tests Pingpong, Counting, Chamaneos and Big also indicate that there is significant overhead with exception handling enabled (Table 5.3).

On the other hand, experiments on Tests 2 and 3 did not result in as severe overheads, but these programs could only be executed with a maximum of 1 M message sends (Figure 5.2). The reason for this limitation is that these programs

```
active class A
 def foo() : int
  1
 end
 def throw_() : int
  throw RuntimeException
  1
 end
end

active class Main
 def main(args:[String]) :
    unit
  var times = get_times(args)
  var nactors = 4
  var a = new [A](nactors)
  repeat i <- nactors do
   a(i) = new A()
  end
  repeat i <- times do
   -- Some test
  end
 end
end
```

```
try
  -- Test 4
 a(i%nactors) ! foo()
 1
  -- Test 5
 get(a(i%nactors) ! foo())
  -- Test 6
 a(i%nactors) ! throw_()
 1
  -- Test 7
 get(a(i%nactors) ! throw_())
catch
 -1
end

-- Test 8
try
 get(a(i%nactors) ! throw_())
catch e : RuntimeException
 -1
end
```

Listing 5.4: Basic test programs where exception handling is used within the user program. Tests 4 through 7 catch without saving. Test 8 is like Test 7, but saves caught exceptions.

Messages (millions)	**6**	**8**	**10**	**20**	**40**	**60**	**80**	**100**
Test 1: No exceptions [s]	1.4	1.9	2.2	4.5	8.8	13.2	18.0	22.8
Test 1: Exceptions [s]	1.4	1.9	2.3	4.6	9.9	15.5	21.8	29.3
Overhead	1%	4%	5%	3%	13%	18%	21%	28%

Table 5.1: Test1 running time (in seconds, rounded up) with and without exceptions enabled, for varying amounts of message sends, and the calculated overhead. The test sends one-way messages, and does thus not involve allocation of any futures. A noticeable overhead is observed when exception handling is enabled, which seems to increase exponentially.

Messages (thousands)	**400**	**600**	**800**	**900**	**1000**
Test 2: No exceptions [s]	0.6	0.8	1.1	1.2	1.5
Test 2: Exceptions [s]	0.6	0.9	1.1	1.3	1.5
Overhead	5%	16%	5%	6%	2%
Test 3: No exceptions [s]	1.4	2.1	2.8	3.1	3.5
Test 3: Exceptions [s]	1.5	2.2	2.9	3.4	3.8
Overhead	5%	7%	5%	9%	7%

Table 5.2: Test2 and Test3 running time (in seconds, rounded up) with and without exceptions enabled, for varying amounts of message sends, and the calculated overhead. Both tests involve sending regular messages, where futures are created. Test2 involves messages such as `var f = a!foo()`, and Test3 `get(var f = a!foo())`

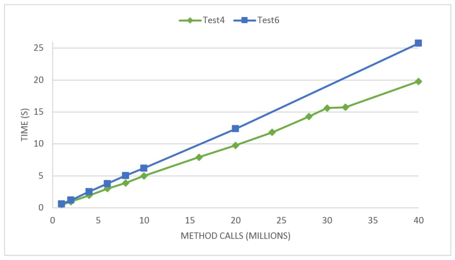
.

allocate a future for every message, and quickly cause garbage collection to trigger. Tests 5, 7 and 8 are similar, in that they allocate a future for every message, and also hit a roof at around 1 M messages. Tests 4 and 6 are similar to Test 1, in that they send one-way messages (Figure 5.5a). One thing to notice is that Test 6, which also throws exceptions, has a significantly higher running time than Test 4.

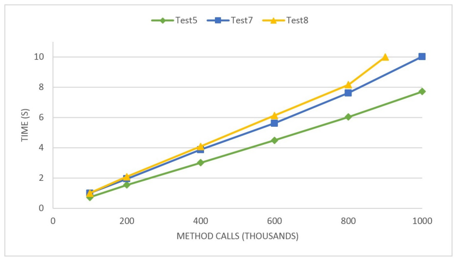
The profiling data verifies that large amounts of regular messages trigger garbage collection, and also shows that the stack unwinding of the exception handler (`try-catch` in Encore's dispatch) causes much slow down. Note that these tests are worst-case in the sense of only executing trivial behaviours (e.g. directly returning an integer). This means exception handling, context switching, queuing messages, handling messages, carrying out function calls, and so on, have a huge overhead from a percentage point of view. As an example, the gprof data shows that Test 4 spends around 30% of the time queuing and handling messages, 5% dispatching functions, and over 9% on exception handling. In real applications, methods are commonly more long-running, meaning the fraction of time spent managing exceptions will be reduced.

Test **Argument**	**Pingpong** **300 K**	**Counting** **50 M**	**Fib** **26**	**Chameneos** **800 K**	**Big** **-**	**BndBuffer** **-**
Exceptions [s]	6.7	10.0	2.9	14.7	22.0	16.9
No exceptions [s]	7.3	15.4	2.7	16.9	30.8	16.9
Overhead	10%	54%	-8%	15%	40%	0%

Table 5.3: Savina tests running time (in seconds, rounded up) with and without exceptions enabled, for a fixed number of operations, and the calculated overhead.



(a) Tests 4 and 6



(b) Tests 5, 7 and 8

Figure 5.5: Results of Tests 4 through 8, tests program with involving exception handling.

As a last minute alternative, a modification was made to avoid stack-unwinding when exceptions were not in use. Instead of non-local jumps when throwing exceptions to dispatch, a flag within the exception context is set to indicate that the exception was not propagated, and the method call returns as usual. Dispatch then knows whether an exception was raised by checking the propagation flag, and if so fulfills with the exception. The profiling data of the modified version looks promising, and spends significantly less time with exception handling functions, though thorough analysis has not yet been carried out.

5.3 Limitations

This section discusses limitation of the implementation and doubles as a future work within the scope of the chosen exception handling model. Future work outside of the exception handling model, as well as suggestions for optimization are brough up in Section 6.1.

Some of the trivial compiler level issues, relating to syntax and code generation, are brought up in Section 5.3.1. Streaming methods and future chaining, two Encore mechanisms which the exception handling library does not yet support, are discussed in Section 5.3.2. The last limitation in the implementation relates to a limit on the number of exception frames, and is discussed in Sections 5.3.3.

5.3.1 Compiler Level Issues and Refactoring

Below is a list of issues related to code generation, syntax and more, most of which are trivial to solve. Though the issues may be trivial, they are useful for the Encore team to know about.

- Exception types are not known to Encore, but only exist in the underlying C code. To fix this, Encore's program table needs to be modified to hold information about exception types. Each use of the `exception` construct will then add the new exception type to the program table. Exception objects currently hold references to an E4C exception type represented by a C struct. This reference can be replaced with a reference to the exception type in the modified program table.
- The `throw` statement can only be passed string literals `throw MyException ("Goodbye world!")` and not string objects or expressions `throw MyException (msgString)`. Fixing this requires modifying `throw` to take an expression, instead of string literal, as second argument, and during typechecking make sure that the expression evaluates to a string.
- The function name of the `ExceptionWrapper` constructor is hard coded in constructor calls, which is not very robust. If possible, the function name should be generated by the compiler.
- Exception type definitions can be more expressive by making arguments optional. The supertype could default to `RuntimeException` and the default message to the name of the exception type.
  `exception MyExc1`
  would become desugared to
  `exception MyExc1("MyExc1", RuntimeException).`

5.3.2 Streaming Methods and Future Chaining

Due to time constraints, streaming methods and future chaining have been ignored in this thesis, which need to be dealt with at some point. In short, streaming methods return streams, which represents a sequence of values that will be produced. The `yield` statement is used to generate one value at a time in the stream's sequence. Streams are used in a similar manner to futures, but also have the `eos` operation which checks if the stream has reached its end, and the `getNext` operation, which returns the next value in the stream's sequence.

```
active class MyStreamer
 stream even() : int
  var i = 0
  while i < 10 do
   yield(i)  -- add i to sequence
   i = i + 2 -- prepare next value
  end
 end
end
```

```

active class Main
 def main() : unit
  var even = new MyStreamer ! even()
  while not(eos(even)) do
   println(get(even))
   even = getNext(even)
  end
 end
end
```

Listing 5.3: A basic use case of streams.

One possible solution to get exception handling to work with streaming methods is to modify streams to how futures have been modified. The stream is then extended to carry exceptions and an indicator flag, and the `get` (and perhaps `getNext`) operation of streams is modified to rethrow exceptional values. The `put` operation, which is the stream equivalent of fulfill, is modified to take an extra argument that indicate that a produced value is exceptional. Finally, dispatch clauses of stream methods, similarly to those in regular or future asynchronous method calls, is wrapped in an exception handling statement.

A possible solution for allowing exception handling to work with future chaining is to modify the `chain` operation in a similar manner to dispatch clauses of regular messages. Function calls are then wrapped in a exception handling statement, and if caught, the future is fulfilled with an exception. This is possibly the only change that is needed.

5.3.3 Exception Frame Limit

E4C's exception contexts store exception frames in an array, which means that the depth of nested exception handling statements in executing messages must not exceed some fixed value, currently five. This is not problematic from a practical standpoint as it is unusual and unnecessary that a program, in the context of one message, recursively handles exceptions to a significant depth. If exceptions need to be handled in a deep recursion, it is enough to use a single exception handler accompanied with control logic.

Having a fixed number of exception frames leads to an memory overhead when all exception frames are not used. The size of all frames is $stack\_limit * (jmp\_buf\_size + 2)$ bytes. Assuming a $jmp\_buf\_size = 200$ bytes, there is a 202 byte overhead for each unused frame. The depth of five is arbitrary, and could perhaps be reduced by a level or two, though it is uncertain whether this is a meaningful optimization. Perhaps it is possible to use a dynamic data structure instead, circumventing both the depth and memory overhead issue.

6. Conclusion

Encore now has a basic exception handling mechanism that is suitable for its concurrency model. The exception handling mechanisms used in synchronous settings is inspired by Java, and features exception raising and handling, through `try-catch-finally` expressions. It uses type-based matching that also considers subtyping, and allows the programmer to define and throw custom exception types. Thrown exceptions can be accessed in the form of objects of class `ExceptionWrapper`, which are assigned exception types, carry messages, can be shared between actors, and can be rethrown.

A pull-model of exception handling is used for inter-process communication of exceptions, allowing exceptions to be propagated from one actor to another through futures, and only need handling when the `get` mechanism is applied on a future.

A modified version of the open-source C library Exceptions4C serves as basis for the exception handling implementation, and provides non-local jumping functionality. Exceptions4C carries exception data in the form of exception contexts, which if not preserved leads to undefined program behaviour. Due to Encore's scheduling constructs `await` and `suspend`, each running message must store its own exception context, which adds to the complexity of the exception handling mechanism. Each message carries an exception context in its stack, and Encore's context swapping mechanism swaps message contexts whenever a message continues execution, or when the aforementioned scheduling constructs are applied.

The exception handling implementation works as intended, but carries a certain overhead, even when not directly used in a program. The main cause behind this is possibly `try-catch` functionality used in Encore's dispatch mechanism, which occurs whether or not the program uses exceptions. In worst-case test programs, in the sense of only executing trivial, short-running methods (e.g. directly returning an integer), the overhead of the exception handling implementation was often over 10%. In other test programs, where a lot of futures were used to propagate results, the overhead was far less noticable. It is hard to predict an overhead for real applications, but it will be low in programs with long-running methods or that are memory intensive, and high when there is lots of inter-thread communication and short-running methods.

In hindsight, dealing with exception contexts may seems easy, but reaching this point required learning a lot about Encore's concurrency model and scheduler. Some important questions in reaching the solution are:

- How do threads work in the language?
- Is there a one to one mapping between actors and threads?
- Do running messages keep a stack, or do they share an actor level stack?
- What constructs can control scheduling in ENCORE, and what are their semantics? (This includes synchronization mechanisms.)
- When does context swapping occur in the language, and how does this related to the scheduling constructs?

In the case of ENCORE, actors do not map to threads, and because of the non-blocking synchronization `await` or the `suspend` operation, context swapping can occur in the middle of message execution. Each message must thus have its own stack, and exception contexts must be saved individually for each message.

6.1 Future Work

Section 6.1.1 outlines an optimization for allocation of `ExceptionWrapper`s, which is currently done in a wasteful manner, and Section 6.1.2, two approaches to letting users attach data to exceptions.

6.1.1 Redundant Allocation of Exception Objects

To avoid needlessly allocating objects, exceptions exist as C structs in the runtime when thrown, and occur as ENCORE objects (`ExceptionWrapper`s) in the user program only to provide user accesses and fulfill futures with an exceptional value. However, this design choice along with time constraints of this thesis has led to some limitations in exception objects, one of which can be remedied while keeping this duality, and another which requires a fundamental redesign to be fixed.

`ExceptionWrapper`s, are not re-used or shared between futures, `catch` clauses and rethrows (Section 4.2), but redundant copies are created at each point an exception is moved from a future to a `catch` clause, or from a `rethrow` to a future. To re-use exception objects and optimize the exception handling runtime, an `ExceptionWrapper` pointer can be added to the E4C context, which the rethrow method, dispatch clauses and `catch` clauses interact with. The rethrow method sets the pointer to the address of the target `ExceptionWrapper`, before throwing an exception as usual.

```
class ExceptionWrapper
 ...
 def rethrow() : unit
  EMBED(unit)
   -- set ExceptionWrapper pointer to address of this object.
   e4c_set_exceptionwrapepr(#{this});
```

```
    e4c_throw(...);
   END
  end
end
```

Listing 6.1: Modifying the rethrow method to share the current `ExceptionWrapper`

Dispatch and `catch` clauses can then be modified to re-use the pointer, unless `NULL`, instead of allocating new `ExceptionWrapper`s.

```
void dispatch_MyClass(...) {
 switch (msg_id) {
  case REGULAR_MSG_method1:
   E4C_TRY { fulfill(future, method1(...), 0); }
   E4C_CATCH {
    if ew_exists() { fulfill(future, current_ew(), 1); }
    else { fulfill(future, current_exception(), 1); }
   }; break;
  ... } }
```

Listing 6.2: Modifying the dispatch to re-use existing `ExceptionWrapper`s.

```
try
 ...
catch e : MyException
 -- Desugar catch clause by adding the following lines
 ExceptionWrapper e =
  if EMBED (bool) exception_wrapper_exists(); END then
   EMBED (ExceptionWrapper) current_exception_wrapper(); END
  else
    -- allocate new ExceptionWrapper as usual
  end
  -- User code
end
```

Listing 6.3: Modifying `catch` clauses to re-use existing `ExceptionWrapper`s.

6.1.2 Custom Data in Exceptions

Users may want to attach custom data to exceptions, which is not possible in the current implementation. Two approaches to this problem are discussed, both with the prerequisite that the runtime can re-use exception objects as explained in Section 6.1.1.

Approach 1: Adding a Data Member to Exception Objects Taking inspiration from .NET exception's `Data` property [12], a dynamic data structure along with getter and setter methods is added to the `ExceptionWrapper` class. To attach custom data to an exception, users create the exception object before throwing it through the `ExceptionWrapper` constructor. Data is added with the setter method, and the `rethrow` method is then used to throw it.

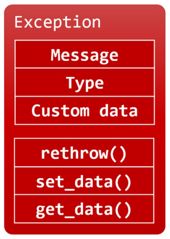


Figure 6.1: A custom data field in exception objects, along with a getter and setter method.

Approach 2: User Defined Exception Classes Another approach is to allow user to throw instances of user defined exception classes, as in JAVA [29] and C#, instead of the current exception types. In ENCORE this can be achieved through *traits*, which provides a set of methods, and also describe a set of required methods and fields to be included in any class that wish to include the trait [9]. By creating a trait `throwable`, the shared fields and methods of exceptions can be required, and methods such as `rethrow` can be provided, allowing the runtime to interact with the custom exception class in a predictable way. Users can then add any custom fields and methods to their exception class, which can be used for any purposes during exception handling. Note that the supertype matching may turn out to be problematic with this approach.

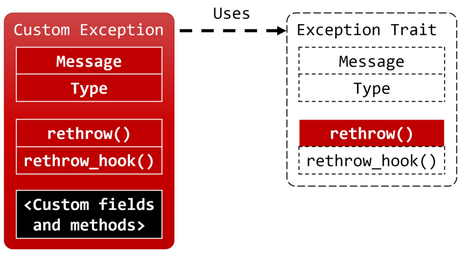


Figure 6.2: A trait for custom exceptions classes.

6.1.3 The Exception Handling Model

In languages such as DART, JAVA and SCALA, callbacks for exception handling can be registered to futures or method calls. One problem with ENCORE's one-way messages is that there is no way for the caller to know whether or not the called method was successfully executed. Allowing callbacks to be defined and run when methods fail or succeed, could elegantly solve this problem.

Exceptions for Parallel Types ENCORE offers support for parallel types, which are collections of data operated on in parallel [16]. The operations applied to elements of collections are functional, and among others include mapping a function to each element, filtering, and returning the first available result followed by killing all other parallel computations. Exception handling for parallel types can be implemented by providing new operations that work on an `Either` data type provided in this thesis, which is a data structure containing a normal value or an exception. The new operations can allow failing the parallel if an element fails, replacing failed elements with a default values, filtering failed elements, and more.

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Appendices

A. Savina Tests

A.1 Pingpong

Listing A.1: 1.pingpong/Main.enc

```
active class PingActor
  var pingsLeft : int

  def init(count : int, pong : PongActor) : unit
    this.pingsLeft = count
    pong!sendPing(this)
    this.pingsLeft = this.pingsLeft - 1
  end

  def sendPong(pong : PongActor) : unit
    if this.pingsLeft > 0 then
      pong!sendPing(this)
      this.pingsLeft = this.pingsLeft - 1
    end
  end
end

active class PongActor
  var pongCount : int
  def init() : unit
    this.pongCount = 0
  end
  def sendPing(ping : PingActor) : unit
    print("Got ping {}\n", this.pongCount)
    ping!sendPong(this)
    this.pongCount = this.pongCount + 1
  end
end

active class Main
  def main(args : [String]) : unit
    if |args| != 2 then
      print("input required: number of pings not specified\n")
    else
      let
        N = match (args(1)).to_int() with
              case Just(result) =>
                result
              end
              case Nothing =>
                0
              end
            end
      in
        new PingActor(N, new PongActor())
        print("done")
      end
    end
  end
end
```

A.2 Counting

Listing A.2: 3.Counting/Count.enc

```
active class Counter
  var count : int
  def init() : unit
    this.count = 0
  end
  def increment() : unit
    this.count = this.count + 1
  end
  def retrieve(p : Producer) : unit
    p!resultMessage(this.count)
  end
end
active class Producer
  var counter : Counter
  var iterations : int
  def init(counter : Counter, iterations : int) : unit
    this.counter = counter
    this.iterations = iterations
  end
  def increment(max : int) : unit
    var i = 0
    while i < max do
      this.counter!increment()
      i = i + 1
    end
    this.counter!retrieve(this)
  end
  def resultMessage(count : int) : unit
    if this.iterations != count then
      print("ERROR: expected : {}, found: {}", this.iterations,
    count)
    else
      print("SUCCESS! received: {}", count)
    end
  end
end
active class Main
```

```
  def main(args : [String]) : unit
    if |args| != 2 then
      print("number of pings not specified\n")
    else
      let
        n = match (args(1)).to_int() with
              case Just(result) =>
                result
              end
              case Nothing =>
                print("number of pings not specified\n")
                0
              end
            end
        counter = new Counter()
        producer = new Producer(counter, n)
      in
        producer!increment(n)
      end
    end
  end
end
```

A.3 Fib

Listing A.3: 6.Fib/fib.enc

```
import Std

linear trait Action
  require var msg : String
  require var number : int
  def getMsg() : String
    this.msg
  end
  def setNumber(n : int) : unit
    this.number = n
  end
  def getNumber() : int
    this.number
  end
end

active class Main
  def main(args : [String]) : unit
    if |args| != 2 then
      print("input required: number-th of fibo not specified\n")
    else
      let
        N = match (args(1)).to_int() with
              case Just(result) =>
                result
              end
              case Nothing =>
              0
            end

          end
      in
        let
          fjRunner = new FibonacciActor(Nothing)
        in
          fjRunner!process(new Request(N))
        end
      end
    end
  end
end

linear class Request : Action
  var msg : String
  var number : int
  def init(n : int) : unit
    this.msg = "Request"
    this.number = n
  end
  def request(n : int) : unit
    this.number = n
  end
end

linear class Response : Action
  var msg : String
  var number : int
  def init(value : int) : unit
    this.msg = "Response"
    this.number = value
  end
  def response_one() : unit
    this.number = 1
  end
end

active class FibonacciActor
  var result : int
  var respReceived : int
  var parent : Maybe[FibonacciActor]
  def init(parent : Maybe[FibonacciActor]) : unit
    this.result = 0
    this.respReceived = 0
    this.parent = parent
  end
  def process(msg : Action) : unit
    match msg.getMsg() with
      case "Request" =>
        if msg.getNumber() <= 2 then
          this.result = 1
          this!processResult(new Response(1))
        else
          var request = new Request(msg.getNumber() - 1)
          val f1 = new FibonacciActor(Just(this))
          f1!process(consume request)
          var request = new Request(msg.getNumber() - 2)
          val f2 = new FibonacciActor(Just(this))
          f2!process(consume request)
        end
        ()
      end
      case "Response" =>
        this.respReceived = this.respReceived + 1
        this.result = this.result + msg.getNumber()
        if this.respReceived == 2 then
          this!processResult(new Response(this.result))
        end
      end

    end
  end
  def processResult(var response : Response) : unit
    match this.parent with
      case Just(p) => { p!process(consume response); (); }
      case Nothing => print(" Result = {}\n", this.result)
    end
  end
end
```

A.4 Chameneos

Listing A.4: 7.Chameneos/Chameneos.enc

```
-- Colour convention:
-- Blue   = 1
-- Red    = 2
-- Yellow = 3

import List

fun doCompliment(c1 : int, c2 : int) : int
  if c1 == 1 && c2 == 1 then
    1
  else if c1 == 1 && c2 == 2 then
    3
  else if c1 == 1 && c2 == 3 then
    2
  else if c1 == 2 && c2 == 1 then
    3
  else if c1 == 2 && c2 == 2 then
    2
  else if c1 == 2 && c2 == 3 then
    1
  else if c1 == 3 && c2 == 1 then
    2
  else if c1 == 3 && c2 == 2 then
    1
  else if c1 == 3 && c2 == 3 then
```

```
    3
  else
    abort("This should never happen!")
  end
end

fun lookup(n : int) : String
  if n == 0 then
    "zero"
  else if n == 1 then
    "one"
  else if n == 2 then
    "two"
  else if n == 3 then
   "three"
  else if n == 4 then
    "four"
  else if n == 5 then
    "five"
  else if n == 6 then
    "six"
  else if n == 7 then
    "seven"
  else if n == 8 then
    "eight"
  else if n == 9 then
    "nine"
  else
    abort("this should not happen!")
  end
end

fun spell(n : int) : List[String]
  val spelledList = new List[String]()
  if n == 0 then
    spelledList.prepend(lookup(n))
    spelledList
  else
    var remaining = n
    while remaining > 0 do
      spelledList.prepend(lookup(remaining % 10))
      remaining = remaining / 10
    end
    spelledList
  end
end

fun spellAndPrint(n : int) : unit
  val spelledList = spell(n)
  var cursor = spelledList.first
  while cursor != null do
    print("{} ", cursor.getData().getValue())
    cursor = cursor.getNextLink()
  end
end

active class Creature
```

```
  var place : MeetingPlace
  var colour : int
  var id : int
  var sameCount : int
  var count : int
  var silent : bool

  def init(place : MeetingPlace, colour : int, id : int, silent :
    bool) : unit
    this.place = place
    this.colour = colour
    this.id = id
    this.sameCount = 0
    this.count = 0
    this.silent = silent
  end

  def meet(id : int, colour : int) : unit
    this.count = this.count + 1
    this.colour = colour
    if this.id == id then
      this.sameCount = this.sameCount + 1
    end
    this.place!meet(this, this.id, this.colour)
  end

  def stop() : unit
    unless this.silent then
      print("{} {}\n", this.count, this.sameCount)
    end
    this.place!sumMeetings(this.count)
  end

  def run() : unit
    this.place!meet(this, this.id, this.colour)
  end
end

active class MeetingPlace
  var meetingsLeft : int
  var firstColour : int
  var firstID : int
  var firstChameneos : Maybe[Creature]
  var meetings : int
  var amountOfCreaturesDone : int
  var numberOfCreatures : int
  var main : Main
  var firstRun : bool
  var started : bool

  def start() : unit
    this.started = true
  end

  def init(meetingsLeft : int, main : Main, numberOfCreatures :
    int, firstRun : bool) : unit
    this.meetingsLeft = meetingsLeft
    this.firstColour = -1
    this.firstID = 0
    this.firstChameneos = Nothing
    this.amountOfCreaturesDone = 0
    this.main = main
    this.numberOfCreatures = numberOfCreatures
    this.firstRun = firstRun
    this.started = false
  end

  def sumMeetings(meetings : int) : unit
    this.meetings = this.meetings + meetings
    this.amountOfCreaturesDone = this.amountOfCreaturesDone + 1
    if this.amountOfCreaturesDone == this.numberOfCreatures then
      spellAndPrint(this.meetings)
      if this.firstRun then
        this.main!runSecondScenario()
      end
    end
  end

  def meet(chameneos : Creature, id : int, c : int) : unit
    if not(this.started) then
      this!meet(chameneos, id, c)
    else if this.meetingsLeft == 0 then
      chameneos!stop()
    else if this.firstColour == -1 then
      this.firstChameneos = Just(chameneos)
      this.firstColour = c
      this.firstID = id
    else
      val newColour = doCompliment(c, this.firstColour)
      this.firstColour = -(1)
      this.meetingsLeft = this.meetingsLeft - 1
      chameneos!meet(this.firstID, newColour)
      match this.firstChameneos with
        case Just(cham) => cham!meet(id, newColour)
        case Nothing    => abort("ERR. There is not initial
    chameneos")
      end
    end
  end
end

active class Main
  var meetings : int

  def runSecondScenario() : unit
    val colours = [1, 2, 3, 2, 3, 1, 2, 3, 2, 1]
    this!runDefault(this.meetings, colours, false)
  end

  def runDefault(n : int, colours : [int], firstRun : bool) : unit
    val  place = new MeetingPlace(n, this, |colours|, firstRun)
    repeat i <- |colours| do
      print("{} ", colours(i))
    end
    println("")
    repeat i <- |colours| do
      val colour = colours(i)
      val creature = new Creature(place, colour, i, false)
      creature!run()
    end
    place!start()
  end

  def run(meetings : int, creatureAmount : int) : unit
    val place = new MeetingPlace(meetings, this, creatureAmount,
    false)
    repeat i <- creatureAmount do
      val colour = i % 3 + 1
      val creature = new Creature(place, colour, i, true)
      creature!run()
    end
    place!start()
  end

  def printColoursAux(c1 : int, c2 : int) : unit
    print("{} + {} -> {}\n", c1, c2, doCompliment(c1, c2))
  end

  def printColours() : unit
    this.printColoursAux(1, 1)
    this.printColoursAux(1, 2)
    this.printColoursAux(1, 3)
    this.printColoursAux(2, 1)
    this.printColoursAux(2, 2)
    this.printColoursAux(2, 3)
    this.printColoursAux(3, 1)
    this.printColoursAux(3, 2)
    this.printColoursAux(3, 3)
    print("\n")
  end

  def extractor(maybe : Maybe[int]) : int
    match maybe with
      case Nothing => -1
      case Just(i) => i
    end
  end

  def main(argv : [String]) : unit
    if |argv| == 1 then
      -- This was written because the results are not
    deterministic and the CI
      -- should at least check that it compiles
      println("Please supply arguments. Defaults should be
    '800000' for first argument")
      exit(0)
    end
    val colours = [1, 2, 3]
    val  numberOfMeetings = if |argv| > 1 then
                               this.extractor((argv(1)).to_int())
                             else
```

```
                              800000
                            end
    val numberOfCreatures = if |argv| > 2 then
                              this.extractor((argv(2)).to_int())
                            else
                              -1
                            end
    this!printColours()
    this.meetings = numberOfMeetings
    if numberOfCreatures != -1 then
      this!run(numberOfMeetings, numberOfCreatures)
    else
      this!runDefault(numberOfMeetings, colours, true)
    end
  end
end
```

Listing A.5: 7.Chameneos/List.enc

```
module List

import Std

read class Data[t] : Id
  val elem : t
  def init(elem : t) : unit
    this.elem = elem
  end
  def getValue() : t
    this.elem
  end
end

local class Link[t] : Id
  var data : Data[t]
  var next : Link[t]
  def init(elem : t, next : Link[t]) : unit
    let
      data = new Data(elem)
    in
      data.elem = elem
      this.data = data
      this.next = next
    end
  end
  def getData() : Data[t]
    this.data
  end
  def getNextLink() : Link[t]
    this.next
  end
  def show() : unit
    print("TBI")
    if this.next != null then
      this.next.show()
    else
      ()
    end
  end
end

local class List[t]: Id
  var first : Link[t]
  var size : int
  def init() : unit
    this.first = null : Link[t]
    this.size = 0
  end
  def prepend(elem : t) : unit
    let
      newFirst = new Link[t](elem, this.first)
    in
      this.first = newFirst
    end
    this.size = this.size + 1
  end
  def nth(var n : int) : Data[t]
    var cursor = this.first
    while n > 0 do
      cursor = cursor.getNextLink()
      n = n - 1
    end
    cursor.getData()
  end
  def pop() : Data[t]
    let
      head = this.first
    in
      this.first = this.first.getNextLink()
      this.size = this.size - 1
      head.getData()
    end
  end
  def show() : unit
    this.first.show()
  end
end
```

A.5 Big

Listing A.6: 8.Big/Big.enc

```
import Random

active class BigActor
  var id : int
  var numMessages : int
  var sinkActor : SinkActor
  var numPings : int
  var expPinger : int
  var neighbors : [BigActor]
  def init(id : int, numMessages : int, sinkActor : SinkActor) :
    unit
    this.id = id
    this.numMessages = numMessages
    this.sinkActor = sinkActor
    this.numPings = 0
    this.expPinger = -(1)
  end
  def ping(id : int) : unit
    ((this.neighbors)(id))!pong(this.id)
  end
  def pong(id : int) : unit
    if id != this.expPinger then
      print("ERROR: Expected: {} but received ping from {}\n",
    this.expPinger, id)
    end
    this.numPings = this.numPings + 1
    if this.numPings == this.numMessages then
      this.sinkActor!exit()
    else
      this!sendPing()
    end
  end
  def setNeighbors(neighbors : [BigActor]) : unit
    this.neighbors = neighbors
  end
  def sendPing() : unit
    let
      target = random(|this.neighbors|)
      targetActor = (this.neighbors)(target)
    in
      this.expPinger = target
      targetActor!ping(this.id)
    end
  end
end
active class SinkActor
  var numWorkers : int
  var numMessages : int
  def init(numWorkers : int) : unit
    this.numWorkers = numWorkers
    this.numMessages = 0
  end
  def exit() : unit
    this.numMessages = this.numMessages + 1
    if this.numMessages == this.numWorkers then
      print("Everything should be done now!\n")
    end
  end
end
active class Main
  def extractor(maybe : Maybe[int]) : int
    match maybe with
      case Nothing =>
        -(1)
      end
      case Just(i) =>
```

```
        i
      end
    end
  end

  def main(argv : [String]) : unit
    -- TODO: the original number of messages is 16 * 1024.
    --       we had to reduce the size of numMessages because
    --       it uses too much memory, and the process was killed
    --       by OS before exiting. More information can be found
    at
    --       https://github.com/parapluu/encore/issues/743
    let
      numMessages = 1024 --16 * 1024
      numActors = if |argv| > 1 then
                    this.extractor((argv(1)).to_int())
                  else
                    8 * 1024
                  end
      sinkActor = new SinkActor(numActors)
      chunkSize = 1 * 1024
      chunks = if numActors >= chunkSize then
                 numActors / chunkSize
               else
                 1
               end
    in
      var counter = 1
      while counter < chunks + 1 do
        let
          arraySize = if chunkSize * counter + 1 > numActors then
                        if numActors > chunkSize then
                          chunkSize + numActors % chunkSize
                        else
                          numActors
                        end
                      else
                        chunkSize
                      end
          bigActors = new [BigActor](arraySize)
        in
          repeat i <- |bigActors| do
            bigActors(i) = new BigActor(i, numMessages, sinkActor)
          end
          repeat i <- |bigActors| do
            (bigActors(i))!setNeighbors(bigActors)
          end
          repeat i <- |bigActors| do
            (bigActors(i))!pong(-(1))
          end
        end
        counter = counter + 1
      end
    end
  end
end
```

A.6 BndBuffer

Listing A.7: 11.BndBuffer/main.enc

```
import Manager

active class Main
  def main() : unit
    let
      bufferSize           = 50
      numProducers         = 40
      numConsumers         = 40
      numItemsPerProducer  = 1000
      produce_cost         = 25
      consume_cost         = 25
    in
      new Manager(bufferSize, numProducers, numConsumers,
    numItemsPerProducer, produce_cost, consume_cost)
    end
  end
end
```

Listing A.8: 11.BndBuffer/Consumer.enc

```
module Consumer

import Manager
import Random

fun math_log(x:real) : real
  EMBED (real) log(#{x}); END
end

fun math_abs(a:int) : int
  if a < 0 then
    0-a
  else
    a
  end
end

fun processItem(curTerm:real, cost:int) : real
  val max = 4000000000
  var res = curTerm
  if cost > 0 then
    repeat i <- cost do
      repeat j <- 100 do
        res = res + math_log(math_abs(random(max)) + 0.01)
      end
    end
  else
    res = res + math_log(math_abs(random(max)) + 0.01)
  end
  -- print ("Consumer is processing items")
  res
end
```

```

active class Consumer
  val id : int
  val manager : Manager
  val consCost : int
  var consItem : real

  def init(id:int, manager:Manager, consCost:int) : unit
    this.id = id
    this.manager = manager
    this.consCost = consCost
    -- print("Consumer {} created\n", id)
  end

  def doConsume(data: real) : unit
    this.consItem = processItem(this.consItem + data, this.
    consCost)
  end

  def process(data: real) : unit
    this.doConsume(data)
    this.manager ! consumerAvailable(this)
  end
end
```

Listing A.9: 11.BndBuffer/HackyQueue.enc

```
module HackyQueue

import Std

local class HackyQueue[t]: Id
  val head : HackyQueueLink[t]
  var tail : HackyQueueLink[t]
  var size : int

  def init(null_element : t) : unit
    this.head = new HackyQueueLink[t](null_element)
    this.tail = this.head
  end

  def append(element : t) : unit
    this.tail.next = new HackyQueueLink[t](element)
    this.tail = this.tail.next
    this.size = this.size + 1
  end

  def take() : t
    var dummy = this.head
    if dummy.next == null then
      dummy.element
    else
      this.size = this.size - 1

      val first = dummy.next
      dummy.next = first.next

      if this.tail == first then
        this.tail = this.head
      end

      first.element
    end
  end

  def size() : int
    this.size
  end

  def is_empty() : bool
    this.size == 0
  end
end

subord class HackyQueueLink[t] : Id
  val element : t
  var next : HackyQueueLink[t]

  def init(element : t) : unit
    this.element = element
  end
end
```

Listing A.10: 11.BndBuffer/Manager.enc

```
module Manager

import HackyQueue
import Producer
import Consumer

active class Manager
  val adjusted_buffer_size : int
  val available_producers : HackyQueue[Producer]
  val available_consumers : HackyQueue[Consumer]
  val pending_data : HackyQueue[real]

  def init(buffer_size: int, num_producers: int, num_consumers:
    int, items_per_producer: int, produce_cost:int, consume_cost:
    int) : unit
    this.adjusted_buffer_size = buffer_size - num_producers
    this.available_producers = new HackyQueue[Producer](null)
    this.available_consumers = new HackyQueue[Consumer](null)
    this.pending_data = new HackyQueue[real](-1)

    var producers = new [Producer](num_producers)
    repeat i <- num_producers do
      let p = new Producer(i, this, items_per_producer,
    produce_cost) in
        this.available_producers.append(p)
        producers(i) = p
      end
    end
    repeat i <- num_consumers do
      this.available_consumers.append(new Consumer(i, this,
    consume_cost))
    end

    for p <- producers do
      p ! produce()
    end
    -- print("Hello, I am your new manager\n")
  end

  def dataItem(data:real, from:Producer) : unit
    if this.available_consumers.is_empty() then
      this.pending_data.append(data)
    else
      this.available_consumers.take() ! process(data)
      -- print("Consumed {} litres\n", data)
    end

    if this.pending_data.size() >= this.adjusted_buffer_size then
      this.available_producers.append(from)
    else
      from ! process()
    end
  end

  def consumerAvailable(consumer : Consumer) : unit
    if this.pending_data.is_empty() then
      this.available_consumers.append(consumer)
    else
      consumer ! process(this.pending_data.take())
    end

    if not this.available_producers.is_empty() then
      this.available_producers.take() ! process()
    end
  end
end
```

Listing A.11: 11.BndBuffer/Producer.enc

```
module Producer

import Manager
import Util

active class Producer
  val id : int
  val manager : Manager
  var prodItem : real
  var itemsProduced : int
  val prodCost : int
  val numItemsToProduce : int

  def init(id: int, manager: Manager, numItemsToProduce: int,
    prodCost:int) : unit
    this.id = id
    this.manager = manager
    this.numItemsToProduce = numItemsToProduce
    this.prodCost = prodCost

    -- print("Producer {} created\n", id)
  end

  def produce() : unit
    this.prodItem = processItem(this.prodItem, this.prodCost)
    this.manager ! dataItem(this.prodItem, this)
    this.itemsProduced = this.itemsProduced + 1
  end

  def process() : unit
    if this.itemsProduced <= this.numItemsToProduce then
      this.produce()
    end
  end
end
```

Listing A.12: 11.BndBuffer/RandomNewSyntax.enc

```
-- This module could be removed once the new syntax is merged in
    the development branch.
module Random

EMBED
BODY
__thread unsigned seed;
END

-- Random number generator with thread-local seed
fun random(max:int) : int
  EMBED (int)
    if (seed == 0)
      {
        seed = (unsigned) time(NULL);
      }
    rand_r(&seed) % #{max};
  END
end

-- Simple random number generator encapsulating a seed of its own
read class Random
  val seed:EMBED unsigned int END
  -- Trace function required because of the embed type of seed
  def Random_trace() : unit
    ()
  end

  -- Initialisation always with a seed in [0..2^32)
  def init(seed:int) : unit
    assertFalse(seed < 0)
    assertFalse(seed > 4294967295)  -- for want of an Encore 2^32
    operator
    EMBED (unit)
      _this->_enc__field_seed = (unsigned) #{seed};
    END
  end

  -- Returns random % max where max [0..2^32)
  def random(max:int) : int
    EMBED (int)
      rand_r((unsigned *) &(_this->_enc__field_seed)) % #{max};
    END
  end
end
```

Listing A.13: 11.BndBuffer/Util.enc

```
module Util

import Random

fun math_log(x:real) : real
  EMBED (real)
    log(#{x});
  END
end

fun math_abs(a:int) : int
  if a < 0 then 0-a else a end
end

fun processItem(curTerm:real, cost:int) : real
   val max = 4000000000
   var res = curTerm
   if cost > 0 then
     repeat i <- cost do
       repeat j <- 100 do
         res = res + math_log(math_abs(random(max)) + 0.01)
       end
     end
   else
      res = res + math_log(math_abs(random(max)) + 0.01)
   end
   res
end
```