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ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA INFORMÁTICA
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Diseño de sistemas funcionales y reactivos

Functional and reactive systems design

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Abstract

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Keywords:

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Introduction

1.1 Motivation

As technology has been evolving the non functional requirements of software systems has been growing to be more demanding. Nowadays a typical cloud service is being used

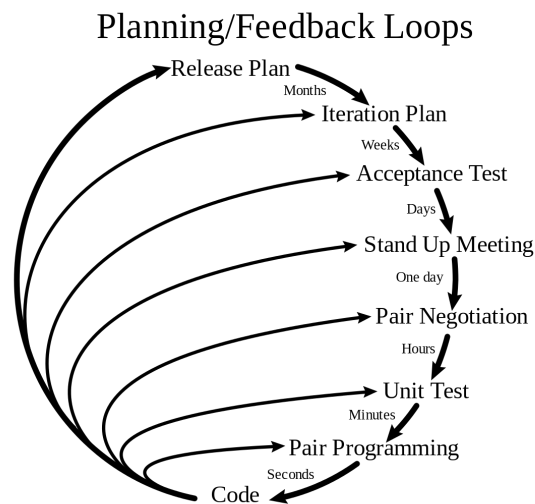


Figure 1: A diagram showing the iterations of extreme programming.

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2

Concepts of Functional Programming

2.1 Introduction

Functional programming is a programming paradigm in which programs are structured as a composition of pure functions [1].

Pure functions, in contrast to function constructs of programming languages, refer to the mathematical concept of a function. In mathematics "a function f from S to T , where S and T are non-empty sets, is a rule that associates with each element of S (the domain) a unique element of T (the codomain)" [2]. [[Include image of two related sets]].

Although this is the mathematical definition, in the domain of a programming language it could also be stated that "a pure function has no observable effect on the execution of the program other than to compute a result given its inputs" [3]

However, functions constructs in many programming languages don't have the traits of mathematical functions. As an example let's take this function written in [introduce programming language]. [Explain example].

The elements which make language functions not perform as mathematical functions are called side effects. To make differentiation functions that don't have side effects are referred to as pure functions[4] while functions that have side effects are called procedures.

Side effects that can make a function not pure are [5].

- Performing I/O
- Modifying a variable

- Modifying a data structure in place

[[Set examples of broken purity]]

2.2 Referential transparency

When treating with pure functions there is a one to one relation between a function call and the result it produces. For example we can see that the expression $2 + 2$ is the same as 4. In mathematics this is a very important property when solving equations. On the process of solving them usually both sides of it are simplified by applying operations that reduce the number of elements on each side until we get a simple expression that its trivial to solve [[Include example]].

This property is called referential transparency [6] and is a very important property of functional programming.

The reason of why referential transparency is only possible when using pure functions lies in its definition. If a function is not pure, an element of the domain may be related with multiple elements of the codomain, thus, it is not posible to know a priori which is the related element to the input. [[Include another example]]

2.2.1 Local reasoning

One of the benefits of referential transparency is local reasoning. In order to understand how a function behaves it is only necessary to understand the components of the function itself and not the context in which its placed.

When referential transparency is not present this is no longer possible. As an example consider a function which depends on a global variable `name`, and returns a greeting with that name [[Introduce the example]].

To understand the behaviour of the function it is needed to know the context in which it is called, i.e. inspect where the variable `name` is assigned and also when assignments to the variable occur previous to the function call.

But even though it is possible to analyse the behaviour at a certain point in time it is not possible to ensure that without changes to the function itself, the functionality will keep the

same, as changes in the context of the function regarding the variable name may change the behaviour of the function in the future [[Introduce new example]].

2.2.2 The substitution model and equational reasoning

When referential transparency is given, a new reasoning model for functional programs can be achieved, called equational reasoning. When reasoning about a functional program it is possible to start substituting function calls for the value they result in. To understand how a program behaves in term of its inputs the only thing its needed to do is to start changing the calls for results they produce. [[Do and follow an example of RT]]

The substitution model can be useful in multiple scenarios. For example, to debug errors, this model can be applied. The first step is to get the arguments of the misbehaving function. Once they have been acquired the next step is to start substituting. For every substitution, it is checked that the result of it is the one expected. At the moment that a function results to a non expected result the cause of the error is found.

This process can be done automatically by running a debugger which allows to evaluate expressions and also manually by calculating the results by hand. A mixed approach could be by using a REPL (Read-eval-print loop). This tool allows to import certain functions and use them interactively. Some examples are The Scala REPL and GHCi for Haskell. An example of use is shown [[Introduce example]].

2.2.3 Function Composition and safe refactoring

The substitution model can also be used to safely refactor code when repetitions occur [[Explain later]]. The main reason of why functional code can be safely refactored is because of function composition. As defined at the beginning of the section functional programs are defined by the composition of functions.

A function takes as input an element of the type of its domain (A) and produces a result of the type of its codomain (B). The notation that will be used for representing such functions will be the same as the Scala programming language uses. The function previously mentioned would be represented as $f : A \Rightarrow B$.

If we have a function $f : A \Rightarrow B$ and another function $g : B \Rightarrow C$ both can be composed by mathematical composition $g \circ f$ to create a new function $h : A \Rightarrow C$.

This way it is possible to refactor a set of expressions used within a function to a new one. This can be achieved safely as long as side effects are not present in them. [[Follow an example using this]].

This is also a corollary of the substitution principle as how the function composition mechanism works

2.3 Functional programming constructs and programming languages

The functional programming paradigm suits better in some programming languages than others. This usually lies in the constructs a language gives to create programs.

2.3.1 Statements and expressions

In imperative languages, building blocks are usually conditional and loop statements. These constructs are inherently non functional as the way they behave is by having declared variables that gets updated in these statements. This is very clear in C style for and while loops.

2.3.2 Imperative statements

A while loop evaluates an expression. If this expression is true the block of the while code is executed. In case it is false the next statement to the block is executed.

The definition of the while loop spots the lack of referential transparency. It expects that an expression can produce two different values. Some times it will be false and at least once it will be true if the loop ends.

The for statement has a similar behaviour to the while. With the addition of a first statement that will be executed previous to the first loop and a second one that will be executed at the end of each loop.

Even if the expression used in the condition of the loops was referentially transparent the statements would add no value to the programs. A condition that evaluates to true would make an infinite loop which would never produce any value and if it was false the block would never get executed.

The if/else statement of imperative languages has the problem that it does not produce any value. The code block of it has to do a side effect, like modifying a variable, in order to do

something useful.

There is one exception in which the if/else statement could produce a value while not breaking referential transparency. Which is in the case that the return of the function is done inside the if block [[Another example]].

2.3.3 Functional expressions

Functional programming languages by contrast provide construct that enable composing programs by referential transparent expressions. To provide conditional logic Scala provides an if/else expression. In contrast to the if/else statement the expression produces a value, which is the result of the expression of the block that get executed ¹.

Another expression that Scala provides is the for expression. A for expression traverses a data structure in order to produce a new one by filtering and transforming the element of it. At a later moment in the document [[Complete with chapter when ready]] for expressions will be revisited and explained in greater detail.

Along with the if and the for expressions a way to iterate and construct functional programs is by using recursion. Recursion is a useful tool in order to loop through collections without breaking referential transparency. The problem with recursion is that each nested call makes the run time allocate one extra frame in the stack to save the context in which the recursive call was made.

There is a way to overcome this, as functions in which the last expression calculated is the recursive call, called tail-recursive, can be efficiently implemented by an optimisation of the compiler which can substitute the recursive call for a goto statement without the expenses of new stack frame allocations [8] ² [[As always follow an example]]

2.3.4 Higher order functions

Higher order functions refer to functions which accept functions as parameters. In Scala functions have their own type, like `Strings` or `Ints` do. This way they are treated as other kind

¹In case that the if expression doesn't contain an else and the condition is not satisfied the returned value is the Unit [7]

²In Scala in order to tell the compiler to fail if the substitution cannot be done the `@tailrec` annotation can be used[9]

of values. As an example a string trimming function can be created. This function will iterate character by character the string and will remove the element if a specific condition is met. The predicate to remove a character is decided by the caller. [[Introduce example]]

2.4 Parametric polymorphism and Type classes

2.4.1 Parametric polymorphism

Functional programming can express polymorphism by the use of generic types in function declarations. It allow functions to take parameters with an abstract type. In Scala to use a generic type in a function, the generic must be defined between square brackets after the function name. This way the function can be defined one time but used by different types. As an example a list length function can be defined.

[[Example parriba y pabajo]]

This function will take a `List [A]` of elements of a generic type `A` and compute the length of it regardless of the actual type of the elements of the list. When the function is called the actual type `[A]` will be resolved.

2.4.2 Type classes

Although parametric polymorphism is good when the details of the generic type are irrelevant it lacks the possibility to define a behaviour that is associated with the type itself.

Type classes³ was defined in Haskell as a way to implement Ad-hoc polymorphism [10]. A type class is an abstract representation of a behaviour that types which belong to the class posses. If a type can implement the type class behaviour it becomes an instance of it and the type itself belongs to the class.

[[Present example]]

In Scala, implicit resolution was implemented as a way to have type classes resolved at compile time without the need of the function caller to provide the instance manually and have it resolved automatically by the compiler in an object oriented language [11].

Typeclasses are a very useful because they allow to decouple structure from behaviour. If a specific behaviour is desired for a given type it is not needed to modify the source of the type

³Not to be confused with Object Oriented classes

itself, a type class instance can be provided in a separate source file. This is specially useful when using third party compiled dependencies. If a new functionality it is required for them as they are compiled its source code cannot be modified. However a type class instance can be provided to enrich its capabilities.

[[Rellenar con type classes]]

2.5 Functional data structures

At the beginning of the section among the different kind of side effects one of the mentioned was *Modifying a data structure in place*. If modifying a data structure in place produces a side effect and breaks referential transparency data structures must be defined immutable by default, and as a corollary on this property, operations on them must not modify their internals but return a new one with the changes desired.

Languages that weren't designed to be functional usually define their data structures as mutable ones. In Java, the `Collection` class, root of the hierarchy of a great number of data structures defines most of its operations as mutable [12]. As an example the method `add` has the following definition `boolean add(E e)`. The returned type of the method is a `boolean`, which according to the documentation "is true if this collection changed as a result of the call". The definition implies that mutation has been done in place.

The main problem with this is that libraries that want to subclass the Java Collections API and be compatible with the standard library have to maintain this constraints. This has lead to immutable collection implementations like Google's Guava Immutable Collection library [13] serving only as immutable representations of data structures but not providing a rich set of operations to modify them.

Scala for example provides two type of collections. Immutable and Mutable ones. Scala documentation states "Scala collections systematically distinguish between mutable and immutable collections. A mutable collection can be updated or extended in place. This means you can change, add, or remove elements of a collection as a side effect. Immutable collections, by contrast, never change. You have still operations that simulate additions, removals, or updates, but those operations will in each case return a new collection and leave the old collection unchanged" [14].

3

Reactive Systems

3.1 The reactive manifesto

As mentioned in the introduction each today's systems have to handle big loads of data, coming from thousands of concurrent users, which are demanding low latency responses by terms of milliseconds and robust systems with a 100% of up time.

The reactive manifesto [15] calls Reactive Systems the ones able to cope with this expectances and gives this description: "Reactive Systems are more flexible, loosely-coupled and scalable. This makes them easier to develop and amenable to change. They are significantly more tolerant of failure and when failure does occur they meet it with elegance rather than disaster. Reactive Systems are highly responsive, giving users effective interactive feedback."

At the same time it describes what the traits of reactive systems are. This traits can be categorised hierarchically by the end goal they serve. Being responsiveness the trait which directly provides value to systems and the other three characteristics that reactive systems need to meet in order to be responsive. This relationship can be visualised in the Figure 2.

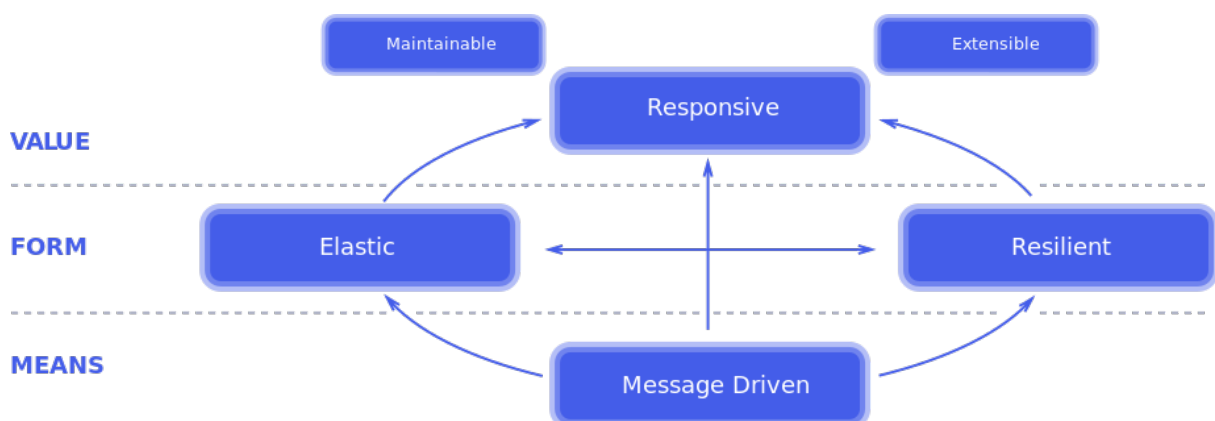


Figure 2: A hierarchical view at the reactive principles.

3.2 The reactive principles

3.2.1 Responsive

Responsiveness is the cornerstone of the reactive systems. Systems which are responsive are more comfortable to use for users as they respond faster and adapt quicker to their needs.

Google found out in 2007 that additional 0.5 seconds of load time of a search could lead to a loss of interest of on the search of a 20%.

More recently in an study developed by Akamai Technologies in 2017 other insights about consequences of pages responsiveness, being some of the most interesting.

- A 100-millisecond delay in website load time can hurt conversion rates by 7 percent
- A two-second delay in web page load time increase bounce rates by 103 percent
- 53 percent of mobile site visitors will leave a page that takes longer than three seconds to load

With that in mind is important to design systems that respond to user request with low latency in a consistent manner.

At the same responsiveness is about creating systems in which errors can be detected quickly and dealt effectively.

3.2.2 Resilient

Resilience provides a better responsiveness as systems react better to failure. A resilient system is able to operate even if parts of it are failing. As an example if a user is using a social network he should be able to see friends posts if the chat system is unavailable.

At the same time resiliency is the ability to recover from errors without manual intervention and local errors shouldn't be propagated but rather handled and managed by different parts of the system.

When designing reactive systems errors should be expected to occur. Even if all the possible applications errors could be avoided there are other elements of the applications which are out of control, such as network errors or interactions with external systems. This principle is stated in the *Design for failure* approach [[Insert reference]] which embraces the acknowledge

of possible errors, thus having to make systems which can have errors but needs to be able to recover from them.

3.2.3 Elastic

Applications traffic isn't stable. Online commerces usually have much higher demands on holidays season like Christmas. A marketing campaign can create higher traffic than usual in applications. Even an unexpected reference in a newspaper or a website may increase the number of users to an unmanageable amount with the original design.

Load balancers or more advanced orchestration systems like Kubernetes [16] can handle elasticity on the infrastructure level, allowing replicas of the application to coexist. However applications have to be designed to allow the distribution of work among the instances of the application, this is refered as the Systems scalability.

Scalability The Scalability of a system is the capacity that it has to increase its throughput respectively to its hardware resources. It is defined by the Universal Law of Computational Scalability [[Insert citation]], the formula is a variation of the Amhdalh's law [[Insert citation]] and is present in figure 3

$$C(N) = \frac{N}{1 + \alpha(N-1) + \beta N(N-1)}$$

Figure 3: The Universal Law of Computational Scalability formula

In the formula the parameter N represents the amount of concurrent process running the application. α is the time that is lost because of the need to wait for shared resources to become available. And β the time that distributed nodes take to have consistent data.

The mere act of increasing the parallelism of an application by adding more computation nodes doesn't mean that the application will scale linearly to it. Systems have to be designed in order to use efficiently the computer resources.

3.2.4 Message driven

The way to achieve Elastic and Resilient systems is by the use of asynchronous message passing by this mechanishm application are decoupled both by space and time.

If modules of the application are communicated by asynchronous messages the end location of the resource which will handle the message is transparent for the caller. A message will be delivered to a mailbox. The specific receptor of the message is not known. A load balancer can choose which will be the recipient of the message, allowing **Elasticity**.

As messages are asynchronous the sender of the message doesn't need to wait to a response of the receiver of it, and can handle other workloads or even terminate as is no longer responsible of the message.

This decoupling provides greater **resilience** because the asynchronous boundary isolate errors from being propagated. Indeed errors can be propagated as messages, having specific error handler modules which can act in consequence to avoid the collapse of the system and allow a gracefully recover of failure.

4

Functional and Reactive System designs patterns

4.1 Computational effects

In 1991 Eugenio Moggi [[Insert citation]] described a model in category theory for separating the set of values a object A could have from the notion of a computation of it, $T\ A$, which had an effect on top of this type. This computation abstracts from the type A the posible results that the computation could have. Some examples of computations mentioned on the text of interest to this topics are.

- Side effects that modify an set of possible states S : `State[A, S]`
- Exceptions where E is the set of possible exceptions: `Either[A, E]`
- Interactive Input/Output which results in an A value: `IO[A]`

From a programming point of view a very interesting finding of that article is that this effect over A can be abstracted and define operations that transform the type A regardless of the effect in which it was contained as long as the effect F is a monad.

4.1.1 Monads

A monad is category that provides two operations over a type constructor `F[_]`, `flatMap`⁴ and `pure`⁵. In the following figure the a trait that defines the `Monad` typeclass in Scala is

⁴On literature is also usually called `bind`

⁵Also known as `point` or `return`

defined.

[[Example]]

The semantics of the operations can be inferred by following the types of them. The pure function takes a value `a` and lifts it to the monad context `F`. The `flatMap` operation takes a monad `F [a]` and a function which transform an `a` into a monad with the same context but a possible different type `F [B]`. This operation maintains the monad context.

4.2 Example of monadic effects

Then some monads instances can be defined for different effects.

Option Monad The Option Monad is an effect which may have a value of a type `A` or not. An `Option[A]` has two possible values. `Some` which means that the value is present or `None` meaning that there is no value.

The function `flatMap` in this case returns a transformed `Some` if the monad in which it was applied was also a `Some` or directly returns a `None` if the monad was empty and no transformation could be applied

State Monad The State Monad is an effect which given an state of type `S` performs an state transition resulting in a value of type `A`, modeling an state machine. As state cannot be mutated in place the state transation returns both the new state and the resulting value. It can be defined this way

When using the state monad `flatMap` directly returns a monad with the new state avoiding to explicitly pass the state all along the way.

IO Monad Side effects are inherently non functional. A side effect such as reading input from the keyboard implies that every time that this operation is called the outcome may be different breaking referential transparency.

However if we look to the description of operations that do side effects they have nothing that implies a breaking of referential transparency. For example the function `read from keyboard` whould have the type `() => A` which a pure function could have.

If the side effect is abstracted from the function definition the purity is maintained. This is what the IO monad does. When a function is passed to the IO the execution is suspended. It is not executed until the programmer runs the computation, moment at which purity is lost.

If side effects execution is delayed until the very end of the execution programs can keep functional at its core and the benefits of purity are not lost until the interpretation of the side effects.

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Appendix A

Installation

Manual

Requirements:

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