Pro Scala: Monadic Design Patterns for the Web

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Preface

The book you hold in your hands, Dear Reader, is not at all what you expected...

Chapter 1

Motivation and Background

Where are we; how did we get here; and where are we going?

With apologies to Italo Calvino You've just picked up the new book by Greg Meredith, Pro Scala. Perhaps you've heard about it on one of the mailing lists or seen it advertised on the `Scala` site or at Amazon. You're wondering if it's for you. Maybe you've been programming in functional languages or even `Scala` for as long as you can remember. Or maybe you've been a professional programmer for quite some time. Or maybe you're a manager of programmers, now and you're trying to stay abreast of the latest technology. Or, maybe you're a futurologist who looks at technology trends to get a sense of where things are heading. Whoever you are, if you're like most people, this book is going to make a lot more sense to you if you've already got about five to ten thousand hours of either `Scala` or some other functional language programming under your belt. There may be nuggets in here that provide some useful insights for people with a different kind of experience; and, of course, there are those who just take to the ideas without needing to put in the same number of hours; but, for most, that's probably the simplest gauge of whether this book is going to make sense to you at first reading.

On the other hand, just because you've got that sort of experience under your belt still doesn't mean this book is for you. Maybe you're just looking for a few tips and tricks to make `Scala` do what you want for the program you're writing right now. Or maybe you've got a nasty perf issue you want to address and are looking here for a resolution. If that's the case, then maybe this book isn't for you because this book is really about a point of view, a way of looking at programming and computation. In some sense this book is all about programming and complexity management because that's really the issue that the professional programmer is up against, today. On average the modern programmer building an Internet-based

application is dealing with no less than a dozen technologies. They are attempting to build applications with nearly continuous operation, 24x7 availability servicing 100's to 1000's of concurrent requests. They are overwhelmed by complexity. What the professional programmer really needs are tools for complexity management. The design patterns expressed in this book have been developed for nearly *fifty* years to address exactly those concerns. Since `Scala` isn't nearly fifty years old you can guess that they have origins in older technologies, but `Scala`, it turns out, is an ideal framework in which both to realize them and to talk about their ins and outs and pros and cons. However, since they don't originate in `Scala`, you can also guess that they have some significant applicability to the other eleven technologies the modern professional programmer is juggling.

1.1   Where are we

1.1.1   The concurrency squeeze: from the hardware up, from the web down

It used to be fashionable in academic papers or think tank reports to predict and then bemoan the imminent demise of Moore's law, to wax on about the need to "go sideways" in hardware design from the number of cores per die to the number of processors per box. Those days of polite conversation about the on-coming storm are definitely in our rear view mirror. Today's developer knows that if her program is commercially interesting at all then it needs to be web-accessible on a 24x7 basis; and if it's going to be commercially significant it will need to support at least 100's if not thousands of concurrent accesses to its features and functions. Her application is most likely hosted by some commercial outfit, a Joyent or an EngineYard or an Amazon EC3 or ... who are deploying her code over multiple servers each of which is in turn multi-processor with multiple cores. This means that from the hardware up and from the web down today's intrepid developer is dealing with parallelism, concurrency and distribution.

Unfortunately, the methods available in in mainstream programming languages of dealing with these different aspects of simultaneous execution are not up to the task of supporting development at this scale. The core issue is complexity. The modern application developer is faced with a huge range of concurrency and concurrency control models, from transactions in the database to message-passing between server components. Whether to partition her data is no longer an option, she's thinking hard about *how* to partition her data and whether or not this "eventual consistency" thing is going to liberate her or bring on a new host of programming nightmares. By comparison threads packages seem like quaint relics from a time

when concurrent programming was a little hobby project she did after hours. The modern programmer needs to simplify her life in order to maintain a competitive level of productivity.

Functional programming provides a sort of transition technology. On the one hand, it's not that much of a radical departure from mainstream programming like Java. On the other it offers simple, uniform model that introduces a number of key features that considerably improve productivity and maintainability. Java brought the C/C++ programmer several steps closer to a functional paradigm, introducing garbage collection, type abstractions such as generics and other niceties. Languages like `OCaml`, `F#` and `Scala` go a step further, bringing the modern developer into contact with higher order functions, the relationship between types and pattern matching and powerful abstractions like monads. Yet, functional programming does not embrace concurrency and distribution in its foundations. It is not based on a model of computation, like the actor model or the process calculi, in which the notion of execution that is fundamentally concurrent. That said, it meshes nicely with a variety of concurrency programming models. In particular, the combination of higher order functions (with the ability to pass functions as arguments and return functions as values) together with the structuring techniques of monads make models such as software transactional memory or data flow parallelism quite easy to integrate, while pattern-matching additionally makes message-passing style easier to incorporate.

1.1.2 Ubiquity of robust, high-performance virtual machines

Another reality of the modern programmer's life is the ubiquity of robust, high-performance virtual machines. Both the `Java` Virtual Machine (`JVM`) and the Common Language Runtime (`CLR`) provide managed code execution environments that are not just competitive with their unmanaged counterparts (such as `C` and `C++`), but actually the dominant choice for many applications. This has two effects that are playing themselves out in terms of industry trends. Firstly, it provides some level of insulation between changes in hardware design (from single core per die to multi-core, for example) that impacts execution model and language level interface. To illustrate the point, note that these changes in hardware have impacted hardware memory models. This has a much greater impact on the `C/C++` family of languages than on `Java` because the latter is built on an abstract machine that not only hides the underlying hardware memory model, but more importantly can hide changes to the model. One may, in fact, contemplate an ironic future in which this abstraction alone causes managed code to outperform `C/C++` code because of `C/C++`'s faulty assumptions about best use of memory that percolate all through application code. Secondly, it completely changes the landscape for language development. By provid-

ing a much higher level and more uniform target for language execution semantics it lowers the barrier to entry for contending language designs. It is not surprising, therefore, that we have seen an explosion in language proposals in the last several years, including `Clojure`, `Fortress`, `Scala`, `F#` and many others. It should not escape notice that all of the languages in that list are either functional languages, object-functional languages, and the majority of the proposals coming out are either functional, object-functional or heavily influenced by functional language design concepts.

1.1.3   Advances in functional programming, monads and the awkward squad

Perhaps chief among the reasons for the popularity of developing a language design based on functional concepts is that the core of the functional model is inherently simple. The rules governing the execution of functional programs (the basis of an abstract evaluator) can be stated in half a page. In some sense functional language design is a "path of least resistance" approach. A deeper reason for adoption of functional language design is that the core model is *compositional*. Enrichment of the execution semantics amounts to enrichment of the components of the semantics. Much more can be said about this, but needs to be deferred to a point where more context has been developed. Deep simplicity and compositionality are properties and principles that take quite some time to appreciate while some of the practical reasons that recent language design proposals have been so heavily influenced by functional language design principles is easily understood by even the most impatient of pragmatic of programmers: functional language design has made significant and demonstrable progress addressing performance issues that plagued it at the beginning.

Since the mid '80's when `Lisp` and it's progeny were thrown out of the industry for performance failures a lot of excellent work has gone on that has rectified many of the problems those languages faced. In particular, while `Lisp` implementations tried to take a practical approach to certain aspects of computation, chiefly having to do with side-effecting operations and i/o, the underlying semantic model did not seem well-suited to address those kinds of computations. And yet, not only are side-effecting computations and especially i/o ubiquitous, using them led (at least initially) to considerably better performance. Avoiding those operations (sometimes called functional purity) seemed to be an academic exercise not well suited to writing "real world" applications.

However, while many industry shops were throwing out functional languages, except for niche applications, work was going on that would reverse this trend.

One of the key developments in this was an early bifurcation of functional language designs at a fairly fundamental level. The `Lisp` family of languages are untyped and dynamic. In the modern world the lack of typing might seem egregiously unmaintainable, but by comparison to `C` it was more than made up for by the kind of dynamic meta-programming that these languages made possible. Programmers enjoyed a certain kind of productivity because they could "go meta" – writing programs to write programs (even dynamically modify them on the fly) – in a uniform manner. This sort of feature has become mainstream, as found in `Ruby` or even `Java`'s reflection API, precisely because it is so extremely useful. Unfortunately, the productivity gains of meta-programming available in `Lisp` and it's derivatives were not enough to offset the performance shortfalls at the time.

There was, however, a statically typed branch of functional programming that began to have traction in certain academic circles with the development of the `ML` family of languages – which today includes `OCaml`, the language that can be considered the direct ancestor of both `Scala` and `F#`. One of the very first developments in that line of investigation was the recognition that data description came in not just one but *two* flavors: types and *patterns*. The two flavors, it was recognized, are dual. Types tell the program how data is built up from its components while patterns tell a program how to take data apart in terms of its components. The crucial point is that these two notions are just two sides of the same coin and can be made to work together and support each other in the structuring and execution of programs. In this sense the development – while an enrichment of the language features – is a reduction in the complexity of concepts. Both language designer and programmer think in terms of one thing, description of data, while recognizing that such descriptions have uses for structuring and de-structuring data. These are the origins of elements in `Scala`'s design like **case class**es and the **match** construct.

The `ML` family of languages also gave us the first robust instantiations of parametric polymorphism. The widespread adoption of generics in `C/C++`, `Java` and `C#` say much more about the importance of this feature than any impoverished account the author can conjure here. Again, though, the moral of the story is that this represents a significant reduction in complexity. Common container patterns, for example, can be separated from the types they contain, allowing for programming that is considerably DRYer.

Still these languages suffered when it came to a compelling and uniform treatment of side-effecting computations. That all changed with Haskell. In the mid-80's a young researcher by the name of Eugenio Moggi observed that an idea previously discovered in a then obscure branch of mathematics (called category theory) offered a way to *structure* functional programs to allow them to deal with side-effecting computations in uniform and compelling manner. Essentially, the notion of a monad (as it was called in the category theory literature) provided a language

level abstraction for structuring side-effecting computations in a functional setting. In today's parlance, he found a domain specific language, a DSL, for organizing side-effecting computations in an ambient (or hosting) functional language. Once Moggi made this discovery another researcher, Phil Wadler, realized that this DSL had a couple of different "presentations" (different concrete syntaxes for the same underlying abstract syntax) that were almost immediately understandable by the average programmer. One presentation, called comprehensions (after it's counter part in set theory), could be understood directly in terms of a very familiar construct **SELECT** ... **FROM** ... **WHERE** ...; while the other, dubbed **do**-notation by the `Haskell` community, provided operations that behaved remarkably like sequencing and assignment. `Haskell` offers syntactic sugar to support the latter while the former has been adopted in both `XQuery`'s FLWOR-expressions and Microsoft's `LINQ`.

Of course, to say that `Haskell` offers syntactic sugar hides the true nature of how monads are supported in the language. There are actually three elements that come together to make this work. First, expressing the pattern at all requires support for parametric polymorphism, generics-style type abstraction. Second, `Haskell`'s typeclass mechanism (the `Haskell` equivalent to `Scala`'s **trait**) another mechanism is required to make the pattern itself polymorphic. Then there is the **do**-notation itself and the syntax-driven translation from that to `Haskell`'s core syntax. Taken together, these features allow the compiler to work out which interpretations of sequencing, assignment and return are in play – without type annotations. The simplicity of the design sometimes makes it difficult to appreciate the subtlety, or the impact it has had on modern language design, but this was the blueprint for the way `Scala`'s **for**-comprehensions work.

With this structuring technique (and others like it) in hand it becomes a lot easier to spot (often by type analysis alone) situations where programs can be rewritten to equivalent programs that execute much better on existing hardware. This is one of the central benefits of the monad abstraction, and these sorts of powerful abstractions are among the primary reasons why functional programming has made such progress in the area of performance. As an example, not only can `LINQ`-based expressions be retargeted to different storage models (from relational database to `XML` database) they can be rewritten to execute in a data parallel fashion. Results of this type suggest that we are really just at the beginning of understanding the kinds of performance optimizations available through the use of monadic programming structuring techniques.

It turns out that side-effecting computations are right at the nub of strategies for using concurrency as a means to scale up performance and availability. In some sense a side-effect really represents an interaction between two systems (one of which is viewed as "on the side" of the other, i.e. at the boundary of some central locus of

computation). Such an interaction, say between a program in memory and the I/O subsystem, entails some sort of synchronization. Synchronization constraints are the central concerns in using concurrency to scale up both performance and availability. Analogies to traffic illustrate the point. It's easy to see the difference in traffic flow if two major thoroughfares can run side-by-side versus when they intersect and have to use some synchronization mechanism like a traffic light or a stop sign. So, in a concurrent world, functional purity – which insists on no side-effects, i.e. no synchronization – is no longer an academic exercise with unrealistic performance characteristics. Instead computation which can proceed without synchronization, including side-effect-free code, becomes the gold standard. Of course, it is not realistic to expect computation never to synchronize, but now this is seen in a different light, and is perhaps the most stark way to illustrate the promise of monadic structuring techniques in the concurrent world programmers find themselves. They allow us to write in a language that is largely familiar to most programmers and yet analyze what's written and rewrite it to optimize for the concurrent setting.

In summary, functional language design improved in terms of

- extending the underlying mechanism at work in how types work on data exposing the duality between type conformance and pattern-matching

- extending the reach of types to parametric polymorphism

- providing a framework for cleaning up the semantics of side-effecting or stateful computations and generalizing them

Taken together with the inherent simplicity of functional language design and its compositional nature we have the makings of a revolution in complexity management. This is the real dominating trend in the industry. Once `Java` was within 1.4X the speed of `C/C++` the game was over because `Java` offered such a significant reduction in application development complexity which turned into gains in both productivity and manageability. Likewise, the complexity of `Java` [1] development and especially `Java` development on Internet-based applications has become nearly prohibitive. Functional languages, especially languages like `Scala` which run on the `JVM` and have excellent interoperability with the extensive `Java` legacy, and have performance on par with `Java` are poised to do to `Java` what `Java` did to `C/C++`.

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[1] and here we are not picking on `Java`, specifically, the same could be said of `C#`

1.2   Where are we going

With a preamble like that it doesn't take much to guess where all this is heading. More and more we are looking at trends that lead toward more functional and functionally-based web applications. The growing popularity of frameworks like `Lift` is really the tip of the iceberg.

1.2.1   A functional web

TBD

1.2.2   DSL-based design

It has become buzz-word du jour to talk about DSL-based design. So much so that it's becoming hard to understand what the term means. In the functional setting the meaning is really quite clear and since the writing of the Structure and Interpretation of Computer Programs (one of the seminal texts of functional programming and one of the first to pioneer the idea of DSL-based design) the meaning has gotten considerably clearer. In a typed functional setting the design of a collection of types tailor-made to model and address the operations of some domain is the basis is effectively the design of an abstract syntax of a language for computing over the domain.

To see why this must be so, let's begin from the basics. If we want to know what DSL-based design means in practical terms, eventually we have to ask what goes into the specification of a language. The commonly received wisdom is that a language is comprised of a *syntax* and a *semantics*. The syntax carries the structure of the expressions of the language while the semantics says how to evaluate those expressions to achieve a result – typically either to derive a meaning for the expression (such as this expression denotes that value) or perform an action or computation indicated by the expression (such as print this string on the console). Focusing, for the moment, on syntax as the more concrete of the two elements, we note that syntax is governed by *grammar*. Whether we're building a concrete syntax, like the `ASCII` strings one types to communicate `Scala` expressions to the compiler or building an abstract syntax, like the expression trees of `LINQ`, syntax is governed by grammar.

Now, think about building a parser. A parser is essentially a transformer from concrete syntax to abstract syntax. We know how describe the grammar of the concrete syntax, this is input to a parser generator, often a variant of `EBNF`. How do we describe the grammar of the abstract syntax? In a typed functional setting this

is given by *the definitions of the types of the abstract syntax*. That is, in a typed functional setting the type system plays the role of `EBNF` providing a grammar for the specification of grammars governing some abstract syntax. Then the collection of types comprising the model of some domain is then nothing other than the grammar of an abstract syntax, by definition, and whether or not there is a concrete syntax in front of it.

1.3 How are we going to get there

1.3.1 Leading by example

The principal technique throughout this book is leading by example. What this means in this case is that the ideas are presented primarily in terms of a coherent collection of examples that work together to do something. Namely, these examples function together to provide a prototypical web-based application with a feature set that resonates with what application developers are building today and contemplating building tomorrow.

Let's illustrate this in more detail by telling a story. We imagine a cloud-based editor for a simple programming language, not unlike `Mozilla's bespin`. A user can register with the service and then create an application project which allows them

- to write code in a structured editor that understands the language;

- manage files in the application project;

- compile the application;

- run the application

Our toy language

For our example we'll need a toy language. Fittingly for a book about `Scala` we'll use the λ-calculus as our toy language. The core *abstract* syntax of the lambda calculus is given by the following *EBNF* grammar.

MENTION
$M, N ::= x$

ABSTRACTION
$\mid \lambda x.M$

APPLICATION
$\mid MN$

To this core let us add some syntactic sugar.

PREVIOUS
$M, N ::= ...$

LET
$\mid let x = M$

SEQ
$\mid M; N$

Now let's wrap this up in concrete syntax.

MENTION
$M, N ::= x$

ABSTRACTION
$\mid (x_1, ..., x_k) \texttt{=>} M$

APPLICATION
$\mid M(N_1, ..., N_k)$

LET
$\mid \texttt{val} x \texttt{=} M$

SEQ
$\mid M; N$

GROUP
$\mid$ `M`

Chapter 2

Toolbox

Notation and terminology

TBD

2.1 Introduction to notation and terminology

While we defer to the rich and growing body of literature on Scala to provide a more complete set of references for basic Scala notation, to be somewhat self-contained in this section we review the notation and terminology we will need for this book.

2.2 Introduction to core design patterns

2.3 Variations in presentation

2.3.1 A little history

Haskell was the first programming language to popularize the notion of monad as a structuring technique for functional programming. There were several key ideas that went into the `Haskell` packaging of the idea. One was to treat the core elements that make up a monad more or less *directly* without appeal to category theory – which was where the notion originated. This is considerably easier to do in a functional programming language because the ambient language can be thought of as a category; thus, for the average programmer there is no need to refer to

categories, in general, but only to the "universe" of programs that can be written
in the language at hand. Then, because Haskell already has a notion of parametric
polymorphism (which we can think of as as generics in the context of this discussion),
a monad's most central piece of data is a parametric type constructor, say T.

Given such a type constructor, you only need a pair of maps (one of which is
higher order). Thus, in `Haskell` a monad is presented in terms of the following data

- a parametric type constructor, T a

- a **return** map enjoying the signature **return** :: a −> T a

- a bind map enjoying the signature bind : T a −> (a −> T b) −> T b

In `Haskell` these elements can be collected inside a typeclass. Resulting in a
declaration of the form

```
typeclass Monad T a where
 return :: a -> T a
 bind :: T a -> (a -> T b ) -> T b
```
<div align="center">Listing 2.1: monad typeclass</div>

Now, it's not enough to simply have this collection of pieces. The pieces have
to fit together in a certain way; that is, they are subject to the following laws:

- **return** (bind a f) ≡ f a

- bind m **return** ≡ m

- bind (bind m f) g ≡ bind m (\ x −> bind (f x) g)

Unlike `Haskell`, `Scala` did not reify the notion of monad under a **trait**, the
language's equivalent of `Haskell`'s typeclass. Instead the systematic means of de-
sugaring **for**-notation and polymorphic interpretations of flatMap, etc are the effec-
tive definitions of the notion in `Scala`.

2.3.2   A little more history

If one were to reify the notion in `Scala` there are several design choices – all of which
endure some desiderata. Following the original presentation developed in category
theory, however, has some crucial advantages:

- intuition

- correspondence to previously existing structures

- decomposition of the requirements

which we explore in some detail here.

Intuition: Monad as container

As we will see the notion of monad maps nicely onto an appropriately parametric notion of container. From this point of view we can imagine a container "API" that has three basic operations.

Shape of the container   The first of these is a *parametric* specification of the *shape* of the container. Examples of container shapes include: List [A], Set [A], Tree[A], etc. At the outset we remain uncommitted to the particular shape. The API just demands that there is some shape, say S[A].

Putting things into the container   The next operation is very basic, it says how to put things into the container. To align with a very long history, we will refer to this operation by the name unit. Since the operation is supposed to allow us to put elements of type A into containers of shape S[A], we expect the signature of this operation to be unit : A $=>$ S[A].

Flattening nested containers   Finally, we want a generic way to flatten nested containers. Just like there's something fundamentally the same about the obvious way to flatten nested lists and nested sets, we ask that the container API provide a canonical way to flatten nested containers. If you think about it for a moment, if a container is of shape, S[A], then a nested container will be of shape, S[S[A]]. If history demands that we call our flattening operation mult, then our generic flatten operation will have signature, mult : S[S[A]] $=>$ S[A].

Preserving connection to existing structure: Monad as generalization of monoid

Programmers are very aware of data structures that support a kind of concatenation operation. The data type of String is a perfect example. Every programmer expects that the concatenation of a given String, say s, with the empty String, "" will

return a result string equal to the original. In code, s.equals(s + ””) **==true** .
Likewise, string concatenation is insensitive to the order of operation. Again, in
code, ((s + t) + u).equals(s + (t + u)) **==true** .

Most programmers have noticed that these very same laws survive polymorphic
interpretations of +, equals and the "empty" element. For example, if we substituted
the data type Integer as the base type and used integer addition, integer equality,
and 0 as the empty element, these same code snippets (amounting assertions) would
still work.

Many programmers are aware that there is a very generic underlying data type,
historically referred to as a *monoid* defined by these operations and laws. In code,
we can imagine defining a **trait** in Scala something like

Decomposition of monad requirements

The constraints on any given monad candidate are well factored into three different
kinds of requirements – operating at different levels of the "API": functoriality,
naturality and coherence. Often these can be mechanically verified, and when they
can't there are natural ways to generate spot-checks that fit well with tools such as
ScalaCheck.

A categorical way to look at monads

In category theory the monad is presented in terms of the following data

- a "unit" map enjoying the signature $unit : A \to T[A]$

- a "mult" map enjoying the signature $mult : T[T[A]] \to T[A]$

subject to the following laws:

- $T(id_A) = id_{T[A]}$

-
  - $unit(f) \circ unit_A = unit_B \circ unit(B)$
  - $mult(f) \circ mult_{T[A]} = mult_{T[B]} \circ mult(B)$

Coherence
  - $mult \circ Tmult = mult \circ multT$
  - $mult \circ Tunit = multunitT$

These two definitions are interchangeable. That's what makes them "presentations" of the same underlying idea.

One of the reasons for the difference in presentation is that `Haskell` doesn't treat the Monad type class as a Functor. The refactoring of the *mult* map into the *bind* map is that it builds functoriality into definition. The other reason is the do notation.

`Scala` follows `Haskell`, though the same notation is called for-notation. The basic construct looks like

and the de-sugaring looks like

This means, therefore, that we have the following correspondence

Chapter 3

An IO-monad for http streams

Code first; questions later

TBD

3.1 Code first, questions later

TBD

3.1.1 An HTTP-request processor

3.1.2 What we did

3.2 Synchrony, asynchrony and buffering

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3.3 State, statelessness and continuations

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Zippers and contexts and URI's, oh my!

Zippers are not just for Bruno anymore

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6.1 Zippers are not just for Bruno anymore

TBD

6.2 Constructing contexts and zippers from data types

TBD

6.3 Mapping URIs to zipper-based paths and back

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A review of collections as monads

Where are we; how did we get here; and where are we going?

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7.2   Monads and take-out

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