Monads by Example

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# What are Monads?

It is entirely reasonable that this is the first question that anyone learning Monads asks, and it is also entirely reasonable that anyone who is teaching Monads tries to answer it. However, Monads are a complex concept that cannot be explained in a single sentence or even a single paragraph; to understand Monads you must simultaneously understand the problem they are trying to solve, their implementation, the interface for working with them, and the theoretical computational background. Therefore, I will not try and answer this question in a single phrase; my explanation of what Monads are is the entirety of this paper.

I would like to take a few moments and clear up one possible misconception. Monads are not special. They are a data structure, just like a Linked List or a Dictionary. They have methods that you can call, and they store data in the same way. They don't have a common sounding name, so they seem scary, and people have a tendency to define them using complex math or weird analogies, but I firmly believe that Monads aren't actually any more complicated than the run of the mill data structures that programmers use every day.

# Our First Monads

In this section, we'll explore a common problem surrounding how to report errors to the caller of a function.

## Error Handling in Plain Python

Python usually uses Exception raising and catching to report errors that happen within code. It's a desirable feature to have in a scripting language, but it is less useful in systems languages, like C, Go, or Rust, because exceptions are expensive in terms of memory and CPU time. It's also less useful in functional languages like Haskell or Scala, which use types and abstract data structures to make code more predictable and safer, a goal which is undermined when code can throw exceptions that crash the whole program. In the following section, I'll be exploring ways to handle errors in Python without throwing exceptions and without using Monads.

### Division

def division(x, y):  
 return x / y

Consider the above code fragment. This is a very simple function; one that is so simple it hardly deserves to exist. However, if y is zero, this function can throw a ZeroDevisionError. It's possible that we want to recover from this error gracefully; check the inputs and see if an error will occur, and return some error code instead of raising an exception.

However, we must decide what the error code should be. We can't choose 0.0, because that is correctly returned by division(0.0,1.0). We can't choose -1.0, because that is correctly returned by division(-1.0,1.0). In fact, this function can return any possible floating point number, so we can't choose a floating point number as our error code. One solution is to return a float on success, but None on failure.

def division(x, y):  
 if y == 0:  
 return None  
 return x / y

Now we've written a function that checks whether or not division is possible, and performs division if it is, but returns an error code if it is not.

### Indexing

def index(ls, i):  
 return ls[i]

The above code is similar to the last example; it will perform an index lookup into a list, and return the item from the list if it can. If it can't, we're still left with the problem that it throws an exception if the index is out of bounds. Let's try and do the same thing as above; rewrite this function so that it doesn't throw an error, but instead uses an error code to signal something has gone wrong.

Our first guess might be to have our error code be the same as above, and just return None. However, this isn't possible, because the code index([None], 0) would also return None. In fact, python lets any value be inside of a list; there is no possible error code we can return that can't also be in the list. Luckily, python lets us use multiple return values.

def index(ls, i):  
 if i < 0 or i >= len(ls):  
 return True, None  
 return False, ls[i]

This allows us to actually check whether or not this function has failed, without worrying about receiving an exception. This allows us to handle errors from outside of the function in a logical way:

failed, value = index([1,2,3],0)  
if failed:  
 print("Oh no, we failed")  
else:  
 print(value)

### Combining The Above

def divide\_elements(ls, i1, i2):  
 return ls[i1]/ls[i2]

Now, we've combined the two operations in python which might lead to an exception, and we've done it in a way that allows for three different operations to result in an exception. We can rewrite this function so that it won't throw any errors, by checking after each step for an error code.

def index(ls, i):  
 if i < 0 or i >= len(ls):  
 return True, None  
 return False, ls[i]  
  
def division(x, y):  
 if y == 0:  
 return None  
 return x / y  
  
def divide\_elements(ls, i1, i2):  
 failure, v1 = index(ls, i1)  
 if failure:  
 return None  
   
 failure, v2 = index(ls, i2)  
 if failure:  
 return None  
   
 return division(v1, v2)

This code works nicely; you can throw two types of errors at it, and it returns None when either error would occur.

### Other Programming Languages

Python has been very nice to us so far; in Python, it is easy to write a function that returns two values, or returns different types in different scenarios. Python also has other features, such as Exceptions, which make this rewriting we've been dong sort of useless. The most Pythonic way of writing the above would probably be to catch the exceptions, writing:

def divide\_elements(ls, i1, i2):  
 try:  
 return ls[i1]/ls[i2]  
 except (IndexError, ZeroDivisionError):  
 return None

Other languages have their own ways of dealing with the errors we discussed above, and they all have their own benefits. In C, the common pattern is to have the actual return value of the function be a number that indicates whether an error occurred, and if one did, what the error was. To get the meaningful result from the function, you pass a pointer to a block of memory into the function, and that function writes the answer you want into that block of memory. This is much faster and simpler than having to write all of the infrastructure required to deal with throwing exceptions and allowing someone above you to catch that exception.

In many modern languages, including Rust, Scala, and Haskell, the solution of choice is to use Monads.

## The Option Monad

The Option Monad, also called the Maybe Monad in many programming languages, is a way of representing the result of a function or computation that might result in an error and produce no meaningful output. We call an Option Monad that has a value and represents a successful computation Some, and we call one that doesn't have a value and represents a failed computation Nothing.

These are really easy to write in programming languages like Haskell, Scala, or Rust, but I'm going to write it in Python to help avoid any confusion about the inner workings of the Monad. In the end, all Monads are just objects, like trees, lists, or dictionaries.

class Option:  
 def \_\_init\_\_(self, failed, value):  
 self.\_failed = failed  
 self.\_value = value  
  
 def \_\_repr\_\_(self):  
 if self.\_failed:  
 return 'Nothing'  
 else:  
 return 'Some({})'.format(self.\_value)  
   
 def is\_some(self):  
 if self.\_failed:  
 return False  
 return True  
  
 def is\_none(self):  
 return not self.is\_some()  
  
 def unwrap(self):  
 if self.\_failed:  
 raise Exception('This Option has no value')  
 else:  
 return self.\_value  
   
 @classmethod  
 def some(cls, x):  
 return cls(False, x)  
   
 @classmethod  
 def none(cls):  
 return cls(True, None)

This is the longest piece of code we've had so far, so let me break it down bit by bit.

class Option:  
 def \_\_init\_\_(self, failed, value):  
 self.\_failed = failed  
 self.\_value = value  
   
 def \_\_repr\_\_(self):  
 if self.\_failed:  
 return 'Nothing'  
 else:  
 return 'Some({})'.format(self.\_value)

The \_\_init\_\_ function is the constructor or initializer function for classes in python. Here all we do is create a boolean that indicates whether or not we have failed the computation or not, and if we haven't failed it, we store the result of the computation in \_value. Note that if \_failed is True, then we don't care what is in \_value, because the computation has failed and that value has no meaning. I will note that the users of this class will probably never call \_\_init\_\_ themselves, as we will later write alternate constructors that are easier for people to use.

The \_\_repr\_\_ function simply tells python how this object should be printed.

def is\_some(self):  
 if self.\_failed:  
 return False  
 return True  
   
 def is\_none(self):  
 return not self.is\_some()  
  
 def unwrap(self):  
 if self.\_failed:  
 raise Exception('This Option has no value')  
 else:  
 return self.\_value

These three functions are the meat of the Option Monad; these are the ways we interact with it. The is\_some function returns True when there is a meaningful return value, and False if the computation failed. is\_none does the opposite. unwrap returns the value of the Option Monad *if there is a value to be returned*, otherwise it throws an error. In order to use the unwrap function without an error, you must first check and see whether the computation succeeded or failed.

@classmethod  
 def some(cls, x):  
 return cls(False, x)  
   
 @classmethod  
 def none(cls):  
 return cls(True, None)

These functions, decorated with @classmethod, aren't methods of the object. Instead, they're methods that exist as part of the class itself; here, we use them as alternate constructors.

At this point, let me rewrite our exception-free code from above using the Option Monad.

def division(x, y):  
 if y == 0:  
 return Option.none()  
 return Option.some(x / y)  
  
def index(ls, i):  
 if i < 0 or i >= len(ls):  
 return Option.none()  
 return Option.some(ls[i])  
  
def divide\_elements(ls, i1, i2):  
 res1 = index(ls, i1)  
 if res1.is\_none():  
 return Option.none()  
   
 res2 = index(ls, i2)  
 if res2.is\_none():  
 return Option.none()  
   
 return division(res1.unwrap(), res2.unwrap())

The above code is the exact same length in lines; and already has some benefits. First, these functions have a return type that can be determined just be looking at the code - not as useful in python as in other languages, but they are very useful in statically typed languages. Second, we don't have to remember the convention for every function. Before, we had to remember that division returned None for an error, but index returned False, None for an error. Despite these benefits, it's not that much of an improvement.

And that's because we haven't yet implemented the most important function for a Monad. This is the most important but also the most complicated part of the Option Monad, so I am going to insert a header for this.

## The Bind and Fmap Functions

def bind(self, function):  
 if self.is\_none():  
 return self  
   
 val = self.unwrap()  
 return function(val)

The bind function is higher order function. That means it's a function that takes another function as an argument, and does something with that function. If you look in the end of the previous section, we repeated this piece of code two times:

res = index(ls, i1)  
 if res.is\_none():  
 return Option.none()

We were checking whether or not a function had successfully computed a value, or whether an error had occurred. If the value existed, we later passed that value into a function. If the value did not exist, then we simply returned the indication of failure, an Option.none() object.

Looking at bind, we can see it does exactly that. res.bind(function) checks whether or not res is a successfully computed value, in which case it passes that value into function, or if it is a failed computation, in which case it simply returns itself, passing the failed computation forward.

def fmap(self, function):  
 if self.is\_none():  
 return self  
  
 val = self.unwrap()  
 return Option.some(function(val))

fmap does something similar to bind; whereas the function passed to bind might fail, and therefore returns an Option Monad, a function passed to fmap will always succeed, and therefore the return value needs to be wrapped in an Option Monad again. fmap and bind serve very similar purposes, but they are useful in different contexts.

So, with fmap and bind in mind, let's consider the our code again.

def division(x, y):  
 if y == 0:  
 return Option.none()  
 return Option.some(x / y)  
  
def index(ls, i):  
 if i < 0 or i >= len(ls):  
 return Option.none()  
 return Option.some(ls[i])  
  
def divide\_elements(ls, i1, i2):  
 res1 = index(ls, i1)  
 res2 = index(ls, i2)  
   
 partial = lambda x: lambda y: division(x,y)  
   
 return res2.bind(res1.bind(partial))

I've changed a few things, so go back and look at what I've done. There's this new line partial = lambda x: lambda y: division(x,y). This is a way of defining an inline function in python; here, I have a function of x that returns a function of y, that itself returns division(x,y). This makes it so that instead of calling this function with two arguments, I instead call it with one argument twice. Here's an example of using a similar lambda function:

partial = lambda x: lambda y: x/y  
  
two\_over = partial(2)  
two\_over(3) # same as 2 / 3  
two\_over(5) # same as 2 / 5  
  
ten\_over = partial(10)  
ten\_over(50) # same as 10 / 50  
  
partial(3)(4) # same as 3 / 4

What I do on the return statement line is I use bind to apply the function to these arguments; the function division will fail drastically if it gets an Option Monad in as an argument; it would fail on the comparison to zero and it would also fail on trying to divide two Option Monads. By using bind, I am telling the Options to apply the function to themselves if they have a value, or returning Nothing if they don't have a value. This wraps the error handling into the data structure that represents errors without me having to ever write an explicit if x.is\_some(): check.

You may still think this sort of thing is useless; and in python, for such a simple example, it kinda is! But as we continue to explore Monads, we will encounter some examples of things that get more and more complex without Monads, but that Monads make simpler. Oh hey look, that's the next section.

## A More Complex Example

In order to give a more illustrative example of where the Option Monad can be more useful, consider the following problem; open a file, and read the first whitespace separated word from the beginning of the file, and parse it into an integer if possible. This problem is fairly easy to do with built in Python functions, but the Option Monad can make error handling easier. However, none of Python's built in functions use the Option Monad, so we will have to rewrite them so that they do. In languages with the Option Monad as a star player, such as Rust, Haskell, or Scala, this isn't an issue.

def option\_open(filename, mode='r'):  
 try:  
 fd = Option.some(open(filename, mode=mode))  
 except Exception:  
 fd = Option.none()  
 return fd  
  
def option\_read(fd, size=-1):  
 try:  
 data = Option.some(fd.read(size))  
 except Exception:  
 data = Option.none()  
 return data  
  
import re  
  
def option\_match(pattern, string):  
 match = re.match(pattern, string)  
 if match:  
 match = Option.some(match)  
 else:  
 match = Option.none()  
 return match  
  
def option\_get\_group(match, group):  
 try:  
 g = match.group(group)  
 except Exception:  
 g = None  
  
 if g == None:  
 g = Option.none()  
 else:  
 g = Option.some(g)  
   
 return g  
  
def option\_int(s):  
 try:  
 i = Option.some(int(s))  
 except Exception:  
 i = Option.none()  
  
 return i

These functions perform the exact same operations as their Python counterparts, but they return Some if the computation succeeds and Nothing if it fails, instead of throwing an error or using some other return code. This will allow us to use bind to chain these functions.

result = (Option.some('text.txt')  
 .bind(option\_open)  
 .bind(option\_read)  
 .bind(lambda x: option\_match(r'\s\*(\S\*)', x))  
 .bind(lambda x: option\_get\_group(x, 1))  
 .bind(option\_int))

This code opens a text file, reads the entire file from it, looks at the first word in the file, and tries to read it in as an integer. Using the Option Monad is useful because if an error happens at any time during the computation, it just passes a Nothing Option through the rest of the bind functions.

We can make this look cooler by choosing an infix operator to overload. By convention, >>= is used, but that's hard to to do in python, so we are going to use >>. We can override that operator in python with the following code:

def \_\_rshift\_\_(self, function):  
 return self.bind(function)

Now, let's rewrite the above option code as the following.

result = (  
 Option.some('text.txt')  
 >> option\_open  
 >> option\_read  
 >> (lambda x: option\_match(r'\s\*(\S\*)', x))  
 >> (lambda x: option\_get\_group(x, 1))  
 >> option\_int  
 )

Consider the same operation in regular Python. We can write it in one expression, in which case this is impossible to read, or we can split it up, over many lines, creating a bunch of temporary variables that we use once and then never again.

# one expression  
result = int(  
 re.match(  
 r'\s\*(\S\*)',  
 open('text.txt').read()  
 ).group(1)  
 )  
  
# with temporary variables  
temp1 = open('text.txt').read()  
temp2 = re.match(r'\s\*(\S\*)', temp1).group(1)  
result = int(temp2)

The first example is unreadable. The functions used have no meaningful order, so it becomes an act of mental gymnastics to figure out what happens when. The functions appear in the order int, match, open, read, and group. int comes first, despite being called last, and open, the first function to be called, appears randomly in the middle.

The second example is the shortest version where all the functions appear in the source code in the order they are called, and so it is pretty readable, but once again we've got the problem of errors!

This code could blow up if the wrong information is passed into it, and it can blow up in approximately 5 places. Even worse, because .group() can return None if it fails, and int(None) == 0, you can get a wrong answer from this code without an error being thrown. In order to guarantee that this code doesn't fail, this is the sort of code you would need to write in Python.

try:  
 temp1 = open('text.txt').read()  
 temp2 = re.match(r'\s\*(\S\*)', temp1).group(1)  
 if temp2 == None:  
 result = None  
 else:  
 result = int(temp2)  
except Exception:  
 result = None

The above code now won't throw any errors or produce erroneous results, and will set result to None if the code fails. Now, compare that safe version without Monads to the version that is safe with Monads.

result = (  
 Option.some('text.txt')  
 >> option\_open  
 >> option\_read  
 >> (lambda x: option\_match(r'\s\*(\S\*)', x))  
 >> (lambda x: option\_get\_group(x, 1))  
 >> option\_int  
 )

The Monad version is simpler, just as safe, and even a line shorter (two if you don't count the line with a single closing parenthesis). Not to mention cooler by far.

## The Result Monad

There is one major problem with the Option monad above; if our code fails, we have no way to know how or when. With the standard python example, we could print an error message to the screen or to a file that would let us know what kind of error occurred. There is another Monad, called the Result Monad, that allows us to do that while still having the power of the Option Monad. I won't reproduce the entire code here (it is in the appendix) but I will go over a few of the changes, as we will use the Result Monad in the next section.

The Result Monad uses slightly different names; a value is Ok if it is a successful computation, and it is an Error if it has failed. The functions to check this status are self.is\_ok() and self.is\_error().

def \_\_init\_\_(self, failed, value, message):  
 self.\_failed = failed  
 self.\_message = message  
 self.\_value = value

Our \_\_init\_\_ function now takes an additional argument; an error message. Now, we have a value that indicates whether or not our computation has failed, a value that stores the result of the computation (if the computation succeeded), and a value that stores the error message (if the computation failed).

In order to access the error message, we add a new function like unwrap.

def error\_msg(self):  
 if self.is\_error():  
 return self.\_message  
 else:  
 raise Exception('This Result is Ok')

This function checks whether or not we have failed, and returns the error message if it is an Error. Just like unwrap, it throws an Exception if there is no error message.

bind has not changed at all, but it is nice to note that when you return self in the case of the error, the error message stays the same.

def bind(self, function):  
 if self.is\_error():  
 return self  
   
 val = self.unwrap()  
 return function(val)

I'm also adding another function that is sort of like bind, but instead, provides a simple way for Monadic computations to check for errors, and if they've occurred, to replace the computed value with a default value.

def recover(self, function):  
 if self.is\_error():  
 return function()  
   
 return self

This function allows you to perform an operation like getting a value from a configuration file, but using a default value if it fails, with Monads. The following snippet, for example, uses results to open, read, and parse some number from a file, and then it checks whether the operation failed at any level, and uses the value of 10 if it failed.

config = (  
 result\_open('config.txt')  
 >> result\_read  
 >> result\_parse  
 ).recover(lambda: Result.ok(10))

The equivalent in plain Python would be the following.

try:  
 temp1 = open('config.txt').read()  
 config = parse(temp1)  
except Exception:  
 config = 10

We've already seen these used above, but for completeness here are the two constructors for the Result Monad.

@classmethod  
 def ok(cls, val):  
 return cls(False, val, None)  
   
 @classmethod  
 def error(cls, msg):  
 return cls(True, None, msg)

# A Parsing Monad

We're now going to talk about a Monad called the Parsing Combinator, which basically recreates and improves upon regular expressions using Monads. Here we see the truth of the oft said but little understood aphorism that Monads represent computation; here, they represent the computation of regular expressions.

It's also worth noting that there are many python Parsing Combinator libraries on the python package index, and those will have faster, more powerful implementations than the one below.

## The Code

Unlike the Option Monad, I'm not going to go over the entire codebase for the Parsing Combinator. I hope to provide enough context so that the inner workings aren't mysterious, but there is a lot of code (all in the appendix) and it is frankly quite dull at times.

class Parser:  
 def \_\_init\_\_(self, function):  
 self.\_function = function  
   
 def \_\_call\_\_(self, text, index):  
 return self.\_function(text, index)

The basic idea behind our Parsing Combinator is that the Monad holds a function that takes a string, which we're going to call text, and it returns a Result Monad. If the result is a success, the Result Monad holds a tuple of the text that has matched the current parser, and the remainder of text. In order to make this a bit easier for us, we will implement the special method \_\_call\_\_, so that we can write stuff like self(text) instead of self.\_function(text) in the future.

Before we jump into all of the super complex functions, let's look at a basic constructor for this Parser Monad.

@classmethod  
 def char(cls, val):  
  
 def match\_char(text):  
 try:  
 current = text[0]  
 except IndexError:  
 return Result.error('End of String encountered, but ' +  
 '{} is still expected'.format(repr(val)))  
   
 if current == val:  
 return Result.ok((text[0], text[1:]))  
 else:  
 return Result.error('Failed to match character {} at {}'  
 .format(repr(val), repr(text)))  
  
 return Parser(match\_char)

This constructor creates a Parser with the function match\_char. If we look at match\_char, despite its length, it is a very simple function. First, it tries to see what the first character in the string (current) is, checking for an error (and returning an Error Result Monad) if there is one. Then, it compares current to the value that was passed into the constructor, and sees if it matches. If it does match, then it returns an Ok Result, with the parsed value being the character, and the remaining text being the rest of the text, from the parsed character on.

Now that we've seen a way to construct this Monad, let's look at how to combine simple Parsing Combinators into more complex ones.

def combine(self, other, function):  
   
 def combine\_func(match, rest):  
 res = other(rest)  
 if res.is\_ok():  
 other\_match, rest = res.unwrap()  
 new\_match = function(match, other\_match)  
 return Result.ok((new\_match, rest))  
 else:  
 return res  
   
 return (  
 Parser(lambda text: self(text)  
 .bind(lambda res: combine\_func(\*res)))  
 )

combine is the most useful function for us; it takes two parsers (self and other) and a function. It creates a new parser that first executes self on the input text, and then it executes other on the remaining text after self's match. Then it uses function to combine the two matches, and returns that combination along with the remaining text. We're also going to define a few functions that call combine with a particular function.

def concat(self, other):  
 return self.combine(other, lambda x,y: x + y)  
   
 def first(self, other):  
 return self.combine(other, lambda x,y: x)  
   
 def last(self, other):  
 return self.combine(other, lambda x,y: y)  
   
 def tuple(self, other):  
 return self.combine(other, lambda x,y: (x,y))

These functions are the most common choices for what you might want to use to combine the two matches. Most common is concat, which simply concatenates the two strings; this is the default regex behavior. Then there is first and last, which instead of combining the two values, instead discard one of the values. We will see later why this is useful. Finally, we can put the two values into a tuple instead of concatenating them. This is mostly useful when used in conjunction with bind, which we will discuss later. However, I've provided a few examples of working with these functions.

match\_a = Parser.char('a')  
match\_b = Parser.char('b')  
  
# This will match the string 'ab' and return the string 'ab'  
match\_a.concat(match\_b)  
  
# This will match the string 'ab' and return the string 'a'  
match\_a.first(match\_b)  
  
# This will match the string 'ab' and return the string 'b'  
match\_a.last(match\_b)  
  
# This will match the string 'ab' and return the tuple ('a','b')  
match\_a.tuple(match\_b)

We also have a few other important functions that we use to build more complex parsers. I haven't included their code here, because I think that understanding combine is the most important code here, and I don't want to get bogged down in too many details.

choice implements the ability to try one parser, and if it fails, recover by trying another. Be careful with this one, because it only operates locally. If you try and match **x** or **y**, and **x** succeeds in matching the text but puts you in a corner that causes failure later on, it won't backtrack and try **y**. It will only backtrack and try **y** if matching **x** fails.

many is perhaps the most complicated constructor. What we want to do is continually match one parser, using a function to combine the results, until a failure occurs; but when a failure occurs, we want to ignore the failure and return that previous match. We also implement many1 that matches one or more examples of an object, not zero or more like many.

There is also a variant of many called many\_list, which instead of combining them by concatenating them, like many does, simply collects a list of all of the many matches.

def optional(self):  
 return self.choice(Parser.empty())

Finally, optional tries to match the input text with self, but if it fails, it matches nothing and finishes.

Finally, we add symbolic versions of many of the above functions. This is purely for ease of reading the expressions we will write; you will see that they can get pretty complex, and this.concat(that) is harder to understand at a glance than this + that.

Now we can move on to the Monadic functions.

def bind(self, function):  
   
 def bind\_func(result):  
 function(result[0]).bind(lambda x:  
 Result.ok(x, result[1]))  
  
 return Parser(lambda text: self(text).bind(bind\_func))

bind is, of course, the star of the show. Lets break this down into steps, starting from the the return statement and moving back.

* We're creating a new Parser, so we're passing in a function that takes text, and should return a Result Monad holding (matched value, remainder of text).
* The first thing this function does is pass text through the current parser's function. This should result in a Result Monad holding (matched value, remainder of text).
* Then, we call bind on that result, passing in bind\_func. bind\_func is going to get a tuple as it's only argument, and should return a Result Monad holding (matched value, remainder of text).
* bind\_func takes the result, and passes the matched value through the function passed in to the Parser's bind function. This gives us a Result Monad, and we pull out it's value (if it exists).
* Then we build the new Result Monad holding (matched value, remainder of text), except now the matched value is the result of function.

We're also going to use bind to define fmap.

def fmap(self, function):  
 return self.bind(lambda x: Result.ok(function(x)))

The high level understanding of bind and fmap comes from the view of the Parsing Combinator as holding both an already parsed value, and the remainder of the string to be parsed. bind and fmap operate on the already parsed value, and don't alter the remaining string to be parsed.

Here is a full table of which functions I have bound to which symbols:

|  |  |
| --- | --- |
| symbol | function |
| + | concat |
| <= | first |
| => | last |
| & | tuple |
| >> | bind |
| > | fmap |

There are also many constructors available, so here's a list of them and a brief description of what they do.

|  |  |
| --- | --- |
| constructor | description |
| char | Matches the character that is passed into it |
| oneof | Matches any one of the characters passed in as a string or list |
| empty | Matches nothing |
| noneof | Matches any character not passed in as a string or list |

## Using the Parser Combinator

Now we have a powerful enough Parser Monad to recreate all of the flexibility and power of regular expressions. We can combine parsers to make more complex ones, we can define functions that return parsers that recreate common regular expressions syntax, so let's try parsing something simple; let's try and write a Parser Combinator that parses numbers.

A number can be as simple as 12 or as complex as 12.00123e45, so we're going to need to build up a complex parser. Let's start with creating a parser that parses 1 or more of consecutive digits.

digits = Parser.oneof('0123456789').many1()

Now, we need to express an optional decimal place, followed by one of more digits. Remember, the + will parse one, and then the other, and then concatenate their results.

decimal = (Parser.char('.') + digits).optional()

Now, we need an exponent part, which is pretty simple given the above. However, we do need one additional component, a sign. The | symbol will parse one or the other of the two things on either side of it.

sign = (Parser.char('+') | Parser.char('-')).optional()  
exponent = ((Parser.char('e') | Parser.char('E'))  
 + sign + digits).optional()

Finally, we can put these three together to get:

number = sign + digits + decimal + exponent

Here's our finished code, and it's results on some possible inputs:

digits = Parser.oneof('0123456789').many1()  
decimal = (Parser.char('.') + digits).optional()  
sign = (Parser.char('+') | Parser.char('-')).optional()  
exponent = ((Parser.char('e') | Parser.char('E'))  
 + sign + digits).optional()  
number = sign + digits + decimal + exponent  
  
Parser.parse\_total(number, '12')  
 # Ok('12')  
Parser.parse\_total(number, '12e10')  
 # Ok('12e10')  
Parser.parse\_total(number, '2.12345e100')  
 # Ok('2.12345e100')  
Parser.parse\_total(number, 'hello world')  
 # Error(Failed to match one of  
 # ['0', '1', '2', '3', '4', '5', '6', '7', '8', '9'])  
Parser.parse\_total(number, '99 bottles of beer on the wall')  
 # Error(The match did not consist of the entire string:  
 # ' bottles of beer on the wall' was left over)  
Parser.parse\_total(number, '')  
 # Error(End of String encountered)

Furthermore, we can use a result-oriented version of python's float function, along with our bind operator, to cast these results to be floats instead of strings.

def result\_float(x):  
 try:  
 return Result.ok(float(x))  
 except Exception:  
 return Result.error('Failed to cast to a float')  
  
Parser.parse\_total(number, '7.22345e10') >> result\_float  
 # Ok(72234500000.0)

## Going Further

Everything we've done so far can basically be done in the exact same way by regular expressions. However, because of the way we've defined the Parsing Combinator, we can use bind and fmap inside of Parsing Combinator expressions. This allows us to parse complex expressions into fully formed and entirely arbitrary python objects.

### List of Numbers Parser

number = (sign + digits + decimal + exponent) >> result\_float

As above, we can put the cast to a float inside of the number parser, and it will automatically do the conversion whenever something is parsed. We can also take this further:

whitespace = Parser.oneof(' \n').many1()  
  
# without infix operators  
many\_numbers = (  
 (whitespace.optional().last(number))  
 ).many\_list()  
  
# with infix operators  
many\_numbers = (  
 (whitespace.optional() >= number)  
 ).many\_list()

Let me take this text and expand it into English. This reads 'If there's any whitespace, match it and discard it, and parse a number following it. Then, put that number in a list, and repeat until parsing fails. Then combine all of the lists (via concatenation), and return that.' And this works perfectly, in pure and standard python, with no eval or exec statements. And it is simpler than doing this with regular expressions.

text = '2.12345e+100 2.1e10 1223 13.5 100e100'  
print(Parser.parse\_total(many\_numbers, text))  
# Ok([2.12345e+100, 21000000000.0, 1223.0, 13.5, 1e+102])

### CSV Parser

Parsing Combinators can be used to write powerful, modular, readable, and concise parsers for any format of text. For example, here is a CSV parser in 5 lines of code.

expression = Parser.noneof(',\n').many1()  
comma = Parser.char(',')  
newline = Parser.char('\n')  
line = (expression <= comma.optional()).many\_list()  
csv = (line <= newline.optional()).many\_list()  
  
# Example  
text = '''1,2,3,4,5  
hello world, my, good, friends, 5  
0,1,2,3,4'''  
  
print(csv.parse\_total(text))  
# Ok(  
# [  
# ['1', '2', '3', '4', '5'],  
# ['hello world', ' my', ' good', ' friends', ' 5'],  
# ['0', '1', '2', '3', '4']  
# ]  
# )

### Abstract Syntax Tree Parser

And finally, here is a full arithmetic expression parser. This is more powerful than the power of regular expressions to break a string into tokens. It constructs the full AST from a purely textual input, just using a Parser Combinator. You'll notice that at this point, I need to define a function and pass that in to a Parser; we need to do this because this is a recursive expression we are parsing. However, it doesn't actually add to the complexity too much.

from collections import namedtuple  
from enum import Enum, auto  
  
class Op(Enum):  
 PLUS = auto()  
 MINUS = auto()  
 TIMES = auto()  
 DIV = auto()  
  
Expr = namedtuple('Expr', ['Op','e1','e2'])  
  
openp = Parser.char('(') + whitespace.optional()  
closep = whitespace.optional() + Parser.char(')')  
plus = whitespace.optional() + Parser.char('+')  
 + whitespace.optional()  
minus = whitespace.optional() + Parser.char('-')  
 + whitespace.optional()  
times = whitespace.optional() + Parser.char('\*')  
 + whitespace.optional()  
div = whitespace.optional() + Parser.char('/')  
 + whitespace.optional()  
  
Plus = lambda x: Expr(Op.PLUS, x[0], x[1])  
Minus = lambda x: Expr(Op.MINUS, x[0], x[1])  
Times = lambda x: Expr(Op.TIMES, x[0], x[1])  
Div = lambda x: Expr(Op.DIV, x[0], x[1])  
  
def expr(text):  
 # rec stands for recursive  
 rec\_plus = ((openp >= Parser(expr))  
 & (plus >= Parser(expr))) <= closep  
 rec\_minus = ((openp >= Parser(expr))  
 & (minus >= Parser(expr))) <= closep  
 rec\_times = ((openp >= Parser(expr))  
 & (times >= Parser(expr))) <= closep  
 rec\_div = ((openp >= Parser(expr))  
 & (div >= Parser(expr))) <= closep  
   
 full = (  
 (rec\_plus > Plus)  
 | (rec\_minus > Minus)  
 | (rec\_times > Times)  
 | (rec\_div > Div)  
 | number  
 )  
  
 return full(text)  
  
text = '((1+2) \* (9 - 11))'  
  
print(Parser(expr).parse\_total(text))  
# Ok(  
# Expr(  
# Op=<Op.TIMES: 3>,  
# e1=Expr(  
# Op=<Op.PLUS: 1>,  
# e1=1.0,  
# e2=2.0  
# ),  
# e2=Expr(  
# Op=<Op.MINUS: 2>,  
# e1=9.0,  
# e2=11.0  
# )  
# )  
# )

I decided to reproduce this sort of code using standard regular expressions; Not only did that version have twice as many lines, it was a much more fragile program. I didn't thoroughly test it, but its behavior when given wrong input wasn't well defined, and there were edge cases that might result in malformed results. The Parsing Combinator above, however, is short and will always return an Error Result with a sensible error message if an error happens.

# Theory of Monads

Now that we've seen a few examples of what a Monad is, we can talk about the formal definition. This is going to be the most abstract section of the text, but I'll try and keep any statements from category theory or abstract algebra from appearing here.

## Defining Monads

Monads are a special type of object that contains with in it a value and a context. Our Option and Result Monads contained the result of a computation, along with contextual information regarding whether the operation had succeeded or failed. This allowed us to write programs that could detect failure elegantly. Our Parsing Monad contained the result of the parsing so far, as well as the rest of the text remaining to be parsed. Whenever you see a Monad, you can sum up its operation by asking "What is the value in this Monad, and what is the context?". Many people, when confronted with Monads, want a way to get the value out of the Monad. But this causes problems, because you've taken the value out of context, and it becomes significantly more useless.

In order to interact with the values without taking them out of their context, we have a function called fmap. fmap takes the value, and applies the function to that value, and puts the result of he function back into context. In our Option and Result Monads, it applied the function to the value if our computation was successful, or it simply bypassed the function if our computation had failed. In our parsing combinator, it applied the function to the result of our computation, while leaving the remainder of the text to be parsed alone.

However, this meant that we couldn't use functions on the values in our Monad if the functions themselves returned Monads. For our Option and Result Monads, that means that we couldn't use a function that could fail (a function that returned an Option or Result Monad) on our Monad with fmap. If we did that, we could end up with a recursive Monad, like Some(None) or Some(Some(3)). This is annoying, and there's two ways to fix this weirdness.

The first way, which we used in the previous section, is to use a function called bind. bind is the same as fmap, but instead of putting the return value of the function passed to bind back into the same context, it expects that bind will return a new value and context (a Monad of some kind).

The second way is an alternative to bind; you don't need both, and it's more common to have bind as the one to use, so I haven't bothered talking about it yet. This function is called join, and it takes a recursive Monad and flattens it from two layers to one layer. For example:

Option.some(Option.some(x)).join() == Option.some(x)  
Option.some(Option.none()).join() == Option.none()  
Option.none().join() == Option.none()

We can show that join isn't any less useful than bind by actually writing bind using only join and fmap.

def bind(monad, function):  
 return monad.fmap(function).join()

This does the same thing as bind usually does; it applies the function to the inside value if the Monad isn't Nothing, and then it returns Nothing if either the function returns or the Monad is Nothing, or it returns Some(value) if the function succeeds and the Monad had a value to pass into the function.

We can also show a way to write fmap and join solely using bind:

def fmap(monad, function):  
 monad.bind(lambda x: Option.some(function(x)))  
  
def join(monad):  
 monad.bind(lambda x: x.unwrap() if x.is\_some() else x)

This means, for our purposes, for something to be a Monad, we require it to either have both fmap *and* join, or bind.

## Monad Laws

Now, Monads have three laws, or rules, they have to follow; this is just to make sure Monads don't have any unexpected behavior, but we should go over those rules anyway.

First of all, if you fmap over a Monad with the identity function (a function that returns its inputs unchanged), the value in the Monad doesn't change.

Monad(x).fmap(lambda x: x) == Monad(x)

Secondly, if you fmap two functions in a row, it should be the same as simply fmaping the function which does the equivalent of those two functions in order.

m.fmap(lambda x: x+1).fmap(lambda x: x+2) == m.fmap(lambda x: x+3)

Finally, if you apply a function to a value and then stick it in a Monad, it is the same as putting that value in a Monad and fmaping that function.

Monad(x).fmap(f) == Monad(f(x))

If you want, you can put these rules into equivalent forms using bind instead of fmap.

These might seem common sense, and if they are, that's good! The only reason that we require that these rules are followed is so that somebody doesn't create a Monad that behaves weirdly and it screws up our program. If they don't seem common sense, that's okay; you don't really have to understand them.They basically boil down to "Monads should behave sensibly when you fmap functions over them".

# The Zeroth Monad

Our first section was titled 'Our First Monad'. However, we are computer scientists, and therefore we start counting at zero, not at one. So let's talk about another Monad that everyone reading this document has probably used, but never noticed that it was a Monad. It turns out that a list is a Monad.

How is a list a Monad? Well, from the previous section, a Monad is really just anything with a bind function, or with a fmap and a join function. And while not every programming language has these functions built in, we can easily write these functions for a list.

# python has a built in function, 'map' that does this.  
def fmap(ls, function):  
 new = []  
 for item in ls:  
 new.append(function(item))  
 return new  
  
# this is sometimes called 'flatten'  
def join(ls):  
 new = []  
 for sublist in ls:  
 for item in sublist:  
 new.append(item)  
 return new  
  
# bind can be defined entirely with the other two!  
def bind(ls, function):  
 return join(fmap(ls, function))

This is all nice and well that we now have these functions, but it explains little conceptually. So let's try and describe Monads conceptually, and see how that can be applied to lists.

Our first Monads, the Option Monad and the Result Monad, both represented some sort of computation result that required more context than a simple value; in particular, they represented a computation result that could either succeed, producing a value, or fail, producing no meaningful value.

Lists can be thought of in a similar way; instead of representing either zero or one meaningful return value, lists can represent computations that can return zero, one, or any possible number of return values. For example, consider the following contrived example.

def less\_than\_abs(x):  
 if x == 0:  
 return []  
 ls = [0]  
 for i in range(1,x):  
 ls.append(i)  
 ls.append(-i)  
 return ls  
  
from math import sqrt  
  
def sqrts(x):  
 if x < 0:  
 return []  
 elif x == 0:  
 return [0.0]  
 else:  
 return [sqrt(x), -sqrt(x)]  
  
bind(  
 bind(  
 [3],  
 less\_than\_abs  
 ),  
 sqrts  
)  
# [0.0, 1.0, -1.0, 1.4142135623730951, -1.4142135623730951]

In this case, we execute two functions in series, getting all of the valid results to our question in one list; but the number of results isn't the same for all inputs, so we need a Monad to represent this computational uncertainty.

# Code: The Result Monad

class Result:  
 def \_\_init\_\_(self, failed, value, message):  
 self.\_failed = failed  
 self.\_message = message  
 self.\_value = value  
  
 def \_\_repr\_\_(self):  
 if self.\_failed:  
 return 'Option.error({})'.format(repr(self.\_message))  
 else:  
 return 'Option.ok({})'.format(repr(self.\_value))  
  
 def \_\_str\_\_(self):  
 if self.\_failed:  
 return 'Error({})'.format(self.\_message)  
 else:  
 return 'Ok({})'.format(self.\_value)  
  
 def is\_ok(self):  
 if self.\_failed:  
 return False  
 return True  
  
 def is\_error(self):  
 return not self.is\_ok()  
   
 def unwrap(self):  
 if self.is\_ok():  
 return self.\_value  
 else:  
 raise Exception('This Result is an Error')  
   
 def error\_msg(self):  
 if self.is\_error():  
 return self.\_message  
 else:  
 raise Exception('This Result is Ok')  
   
 def bind(self, function):  
 if self.is\_error():  
 return self  
   
 val = self.unwrap()  
 return function(val)  
   
 def fmap(self, function):  
 if self.is\_error():  
 return self  
   
 val = self.unwrap()  
 return Result.ok(function(val))  
   
 def recover(self, function):  
 if self.is\_error():  
 return function()  
   
 return self  
   
 def \_\_rshift\_\_(self, function):  
 return self.bind(function)  
  
 @classmethod  
 def ok(cls, val):  
 return cls(False, val, None)  
   
 @classmethod  
 def error(cls, msg):  
 return cls(True, None, msg)  
  
# The following are built in functions  
# rewritten to work with the Result Monad  
  
def result\_open(filename, mode='r'):  
 try:  
 fd = Result.ok(open(filename, mode=mode))  
 except Exception:  
 fd = Result.error("Failed to open the file")  
 return fd  
  
def result\_read(fd, size=-1):  
 try:  
 data = Result.ok(fd.read(size))  
 except Exception:  
 data = Result.error("Failed to read from the file")  
 return data  
  
import re  
  
def result\_match(pattern, string):  
 match = re.match(pattern, string)  
 if match:  
 match = Result.ok(match)  
 else:  
 match = Result.error("Failed to match the pattern")  
 return match  
  
def result\_get\_group(match, group):  
 try:  
 g = match.group(group)  
 except Exception:  
 g = None  
  
 if g == None:  
 g = Result.error("Failed to get the group from the match")  
 else:  
 g = Result.ok(g)  
   
 return g  
  
def result\_int(s):  
 try:  
 i = Result.ok(int(s))  
 except Exception:  
 i = Result.error("Failed to parse into an integer")  
 return i  
  
  
result = (  
 Result.ok('text.txt')  
 >> result\_open  
 >> result\_read  
 >> (lambda x: result\_match(r'\s\*(\S\*)', x))  
 >> (lambda x: result\_get\_group(x, 1))  
 >> result\_int  
 )  
  
print(result)

# Code: The Parsing Combinator

class Parser:  
 def \_\_init\_\_(self, function):  
 self.\_function = function  
   
 def \_\_call\_\_(self, text):  
 x = self.\_function(text)  
 return x  
  
 def \_\_repr\_\_(self):  
 return '<Parsing Combinator>'  
   
 def bind(self, function):  
   
 def bind\_func(result):  
 return function(result[0]).bind(lambda x: Result.ok((x, result[1])))  
  
 return Parser(lambda text: self(text).bind(bind\_func))  
   
 def fmap(self, function):  
 return self.bind(lambda x: Result.ok(function(x)))  
   
 def combine(self, other, function):  
   
 def combine\_func(match, rest):  
 res = other(rest)  
 if res.is\_ok():  
 other\_match, rest = res.unwrap()  
 new\_match = function(match, other\_match)  
 return Result.ok((new\_match, rest))  
 else:  
 return res  
   
 return Parser(lambda text: self(text).bind(lambda res: combine\_func(\*res)))  
   
 def concat(self, other):  
 return self.combine(other, lambda x, y: x + y)  
   
 def choice(self,other):  
   
 def choice\_func(text):  
 return self(text).recover(lambda: other(text))  
   
 return Parser(choice\_func)  
   
 def many(self, function=lambda x,y: x + y):  
   
 def repeat\_func(text):  
 res = self(text)  
   
 if res.is\_error():  
 return Result.ok(('',text))  
   
 match = res.unwrap()[0]  
 rest = res.unwrap()[1]  
   
 res = self(rest)  
   
 while res.is\_ok():  
 match = function(match, res.unwrap()[0])  
 rest = res.unwrap()[1]  
 res = self(rest)  
   
 return Result.ok((match, rest))  
   
 return Parser(repeat\_func)  
   
 def many\_list(self):  
   
 def repeat\_func(text):  
 res = self(text)  
   
 if res.is\_error():  
 return Result.ok(('',text))  
   
 match = [res.unwrap()[0]]  
 rest = res.unwrap()[1]  
   
 res = self(rest)  
   
 while res.is\_ok():  
 match = match + [res.unwrap()[0]]  
 rest = res.unwrap()[1]  
 res = self(rest)  
   
 return Result.ok((match, rest))  
   
 return Parser(repeat\_func)  
   
 def many1(self, function=lambda x,y: x + y):  
 return self.combine(self.many(function), function)  
   
 def many1\_list(self):  
 return self.combine(self.many\_list(function), function)  
   
 def optional(self):  
 return self | Parser.empty()  
   
 def first(self, other):  
 return self.combine(other, lambda x,y: x)  
   
 def last(self, other):  
 return self.combine(other, lambda x,y: y)  
   
 def tuple(self, other):  
 return self.combine(other, lambda x,y: (x,y))  
  
 def \_\_rshift\_\_(self, function):  
 return self.bind(function)  
   
 def \_\_gt\_\_(self, function):  
 return self.fmap(function)  
   
 def \_\_ge\_\_(self, other):  
 return self.last(other)  
   
 def \_\_le\_\_(self, other):  
 return self.first(other)  
   
 def \_\_add\_\_(self, other):  
 return self.concat(other)  
   
 def \_\_or\_\_(self, other):  
 return self.choice(other)  
  
 def \_\_and\_\_(self, other):  
 return self.tuple(other)  
  
 @classmethod  
 def char(cls, val):  
  
 def match\_char(text):  
 try:  
 current = text[0]  
 except IndexError:  
 return Result.error('End of String encountered, but ' +  
 '{} is still expected'.format(repr(val)))  
   
 if current == val:  
 return Result.ok((text[0], text[1:]))  
 else:  
 return Result.error('Failed to match character {} at {}'  
 .format(repr(val), repr(text)))  
  
 return Parser(match\_char)  
  
 @classmethod  
 def empty(cls):  
  
 def match\_empty(text):  
 return Result.ok(('', text))  
  
 return Parser(match\_empty)  
  
 @classmethod  
 def oneof(cls, charls):  
  
 def match\_charls(text):  
 try:  
 current = text[0]  
 except IndexError:  
 return Result.error('End of String encountered, but one of ' +  
 '{} is still expected'.format(list(charls)))  
  
 if current in charls:  
 return Result.ok((text[0], text[1:]))  
 else:  
 return Result.error('Failed to match one of {} at {}'  
 .format(list(charls), repr(text)))  
  
 return Parser(match\_charls)  
  
 @classmethod  
 def noneof(cls, charls):  
  
 def none\_charls(text):  
 try:  
 current = text[0]  
 except IndexError:  
 return Result.error('End of String encountered, but none of ' +  
 '{} is still expected'.format(repr(text)))  
  
 if current not in charls:  
 return Result.ok((text[0], text[1:]))  
 else:  
 return Result.error('Found one of {} at {} '  
 +'when there should be none of'.format(list(charls), repr(text)))  
  
 return Parser(none\_charls)  
  
 def parse\_prefix(self, string):  
 return self(string)  
  
 def parse\_total(self, string):  
   
 def check\_full(tup):  
 if tup[1] == '':  
 return Result.ok(tup[0])  
 else:  
 return Result.error('The match did not consist of the entire ' +  
 'string: {} was left over'.format(repr(tup[1])))  
   
 return self(string) >> check\_full