Introducing Monads

Lecture 3,
Designing and Using Combinators
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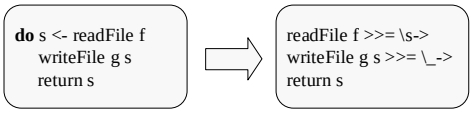
Example



Common ”Look and Feel”

We have already seen that **do** and return can be used with many different DSELs:

•Parsers, Wash/CGI

•IO, ST s

These are all examples of *monads*.

A monad is something that supports **do** and return!

What are the Types?

A monad is always associated with a *parameterised type*, e.g. IO or ST s, the type of *actions*.

Call it m.

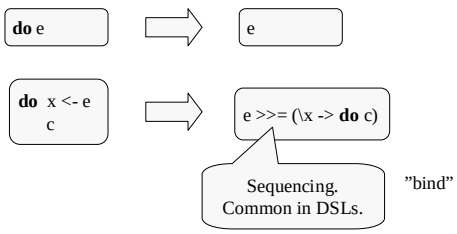
return :: a -> m a

```
readFile f >>= \s->
writeFile g s >>= \_->
return s
```

What is the type of >>=?

The **do** Syntactic Sugar

The **do** syntax is just sugar for using an overloaded operator:



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(>>=) :: m a -> … -> …

First arg is an action

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```

What is the type of >>=?

(>>=) :: m a -> (a -> …) -> …

Second arg receives result of first

The Monad Class

Monad operations are overloaded (hence can be used with many libraries).

```
class Monad m where
    return :: a -> m a
    (>>=) :: m a -> (a -> m b) -> m b
```

instance Monad IO …

instance Monad (ST s) …

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class Monad m where
    return :: a -> m a
    (>>=) :: m a -> (a -> m b) -> m b
```

instance Monad Parser …

instance Monad CGI …

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A monad is always associated with a *parameterised type*, e.g. IO or ST s, the type of *actions*.

Call it m.

return :: a -> m a

```
readFile f >>= \s->
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return s
```

What is the type of >>=?

(>>=) :: m a -> (a -> m b) -> m b

Result is an action returning result of second arg.

Why Use Monads?

Why Use Monads?

•A *shared interface* to many libraries

•allows a common ”look and feel” -- familiarity!

•allows *shared code*

```
liftM :: Monad m => (a->b) -> m a -> m b
sequence :: Monad m => [m a] -> m [a]
do syntactic sugar!
```

Standard library Monad

•functionality the DSEL implementor need not implement

•… and which users already know how to use.

Systematic Monad Implementation

•Start with an *underlying* monad (e.g. IO, ST)

•Add features (e.g. state, exceptions, concurrency) one by one.

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•A *design guideline*: no need to spend intellectual effort on the design of sequencing operations.

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Why Use Monads?

•A *shared interface* to many libraries

•A *design guideline*: no need to spend intellectual effort on the design of sequencing operations.

•A *systematic implementation*: saves intellectual effort, encourages code reuse.

The Identity Monad

The ”vanilla” monad, supporting no special features.

```
newtype Id a = Id a

instance Monad Id where
    return x = Id x
    Id x >>= f = f x
```

An abstract type: represented by an a, but a different type.

Note (in passing) that >>= is *lazy* -- it doesn’t need its first argument unless f does.

Monadic ”sequencing” doesn’t imply sequencing in time…

Adding Features: Monad Transformers

A *monad transformer* transforms an existing monad (without a particular feature) into a new monad which has it.

A *parameterised monad* -- represent by a parameterised type!

```
class (Monad m, Monad (t m)) =>
        MonadTransformer t m where
  …
```

What should the method(s) be?

The State Monad

How can we add a state to actions?

Let actions take the state as an argument, and deliver a new state as a result.

```
newtype State s m a = State (s -> m (s,a))
```

Parameterised on both the state and the underlying monad.

Adding Features: Monad Transformers

A *monad transformer* transforms an existing monad (without a particular feature) into a new monad which has it.

A *parameterised monad* -- represent by a parameterised type!

```
class (Monad m, Monad (t m)) =>
        MonadTransformer t m where
  lift :: m a -> t m a
```

Anything we can do in the old monad, we can also do in the new…

The State Monad

```
newtype State s m a = State (s -> m (s,a))
```

The monad operations just pass the state along.

```
instance Monad m => Monad (State s m) where
  return x = State $ \s -> return (s,x)
  State f >>= h = State $ \s ->
      do (s',a) <- f s
         let State g = h a
         g s'
```

Example: Adding State

Consider adding a *state* feature: actions may depend on, and change, a state.

```
class Monad m => StateMonad s m | m -> s where
  update :: (s -> s) -> m s
```

```
readState = update id
writeState s = update (\_->s)
```

```
tick :: StateMonad Integer m
    => m Integer
tick = do n <- readState
          writeState (n+1)
          return n
```

The State Monad is a StateMonad

```
newtype State s m a = State (s -> m (s,a))
```

Of course, we can implement update:

```
instance Monad m => StateMonad s (State s m)
  where
    update f = State $ \s ->
      let s' = f s in
        return (s',s')
```

State is a Monad Transformer

```
newtype State s m a = State (s -> m (s,a))
```

Can we ”lift” actions in the underlying monad?

Yes -- they don’t change the state!

```
instance MonadTransformer (State s) m where
    lift a = State $ \s ->
        do x <- a
           return (s,x)
```

Another Example: Failure

Add a possibility for actions to *fail*, and to handle failure.

```
class Monad m => FailureMonad m where
    failure :: m a
    handle :: m a -> m a -> m a
```

Applications in search and backtracking programs.

Example:

divide x y = **if** y==0 **then** return (x/y) **else** failure

Last Step: Run Functions

We must be able to *observe the result* of an action -- otherwise the action is useless!

(The only exception is the IO monad, which is observable at the top level).

We define a *run function* for every monad (c.f. runST).

```
runId (Id a) = s
runState s (State f) =
    let (s’,a) = f s in a
```

```
Main> runId $ runState 0 $
            sequence [tick,tick,tick]
[0,1,2]
Main>
```

Actions with Failure

Allow actions to deliver a special result, meaning ”I failed”.

```
newtype Failure m a = Failure (m (Maybe a))
```

```
data Maybe a = Just a
             | Nothing
```

Summary: How to Add a Feature

- Define a class representing the feature to be added (StateMonad).
- Define a *type parameterised on an underlying monad* to represent actions supporting the feature (State).
- Define sequencing of actions (**instance** Monad).
- Define how it supports the feature (**instance** StateMonad).
- Define how to lift underlying actions (**instance** MonadTransformer).
- Define how to observe the result of an action (runState).

Sequencing Failure

Sequencing must *check if the first action failed*, and if so abort the second.

```
instance Monad m => Monad (Failure m)
    where
        return x = Failure (return (Just x))
        Failure m >>= h = Failure $
            do a <- m
               case a of
                   Nothing -> return Nothing
                   Just x -> let Failure m’ = h x in m’
```

Supporting Failure

```
instance Monad m => FailureMonad m where

    failure = Failure $ return Nothing

    Failure m ‘handle‘ Failure h = Failure $
          do x <- m
             case x of
                Nothing -> h
                Just a -> return (Just a)
```

Observing Result of a Failure

```
runFailure :: Failure m a -> m a
runFailure (Failure m) =
    do Just a <- m
       return a
```

What happens if the result is Nothing? Should runFailure handle this?

NO! Handle failures in the monad!

```
Main> runId $ runFailure $ failure ‘handle‘ return 3
3
```

Lifting Actions to Failure

Lifting an action just makes it succeed (return Just something).

```
instance Monad m =>
   MonadTransformer Failure m where
        lift m = Failure $ do x <- m
                              return (Just x)
```

Combining Features

Suppose we want to add State *and* Failure to a monad.

```
example ::
   (StateMonad Integer m,
    FailureMonad m)
        => m Integer
example = do tick
             failure
          ‘handle‘
             do tick
```

We can build a suitable monad in two ways:

- Failure (State Integer m)
- State Integer (Failure m)

Need new instances:
- FailureMonad (State s m)
- StateMonad (Failure m) s

Observing Result of a Failure

```
runFailure :: Failure m a -> m a
runFailure (Failure m) =
    do Just a <- m
       return a
```

What happens if the result is Nothing? Should runFailure handle this?

NO! Handle failures in the monad!

```
Main> runId $ runFailure $ return 2 ‘handle‘ return 3
2
```

Sample Runs

```
example ::
   (StateMonad Integer m,
    FailureMonad m)
        => m Integer
example = do tick
             failure
          `handle`
             do tick
```

```
Main> runId $ runState 0 $ runFailure $ example
1
Main> runId $ runFailure $ runState 0 $ example
0
```

Sample Runs

```
example ::
  (StateMonad Integer m,
   FailureMonad m)
      => m Integer
example = do tick
             failure
          `handle`
             do tick
```

Failure (State Integer Id)

```
Main> runId $ runState 0 $ runFailure $ example
1
Main> runId $ runFailure $ runState 0 $ example
0
```

State Integer (Failure Id)

Example: Parsing

- A parser can fail -- we handle failure by trying an alternative.
- A parser *consumes input* -- has a state, the input to parse.
- A failing parse should not change the state.

```
type Parser m tok a = State [tok] (Failure m) a
```

Type *synonym* -- not abstract

We get for free:

- return x -- accept no tokens & succeed
- **do** syntax -- for sequencing
- failure -- the failing parser

What are the types?

- Failure (State s m) a ≅ s -> m (s, Maybe a)

Always yields a final state

- State s (Failure m) a ≅ s -> m (Maybe (s, a))

No state on failure

Failure (State Integer Id)

```
Main> runId $ runState 0 $ runFailure $ example
1
Main> runId $ runFailure $ runState 0 $ example
0
```

State Integer (Failure Id)

Parsing a Token

```
satisfy p = do s<-readState
               case s of
                 [] -> failure
                 x:xs -> if p x then do writeState xs
                                        return x
                         else failure

literal tok = satisfy (==tok)
```

Why the Different Behaviour?

Compare the instances of `handle`:

```
instance FailureMonad m => FailureMonad (State s m) where
State m `handle` State m' = State $ \s ->
      m s `handle` m' s
```

Same state in handler.

```
instance Monad m => FailureMonad (Failure m) where
   Failure m `handle` Failure m' =
      Failure (do x <- m
                  case x of
                    Nothing -> m'
                    Just a -> return (Just a))
```

M is a state monad

So state changes

Completing the Library

```
p ||| q = p `handle` q
many p = some p ||| return []
some p = liftM2 (:) p (many p)

runParser p input =
    runFailure $ runState input $ p
```

This completes the basic parsing library we saw in the previous lecture.

Summary

• Monads provide *sequencing*, and offer a general and uniform interface to many different DSELs.

• Monad transformers provide a systematic way to design and implement monads.

• Together with generic monadic code, they provide a lot of functionality “for free” to the DSEL implementor.