MGS 2007: ADV Lectures 1 & 2

Monads and Monad Transformers

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Monads (1)

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  - makes programs easier to understand and reason about
  - make lazy evaluation viable
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"Shall I be pure or impure?" (Wadler, 1992)

- Absence of effects
  - makes programs easier to understand and reason about
  - make lazy evaluation viable
  - enhances modularity and reuse.
- Effects (state, exceptions, . . .) can
  - yield concise programs
  - facilitate modifications
  - improve the efficiency.

Monads (2)

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- Key idea: ***Computational types***: an object of type $M\,A$ denotes a ***computation*** of an object of type A.
- ***Thus we shall be both pure and impure, whatever takes our fancy!***
- Monads originated in Category Theory.
- Adapted by
  - Moggi for structuring denotational semantics
  - Wadler for structuring functional programs

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- promote disciplined use of effects since the type reflects which effects can occur;
- allow great flexibility in tailoring the effect structure to precise needs;
- support changes to the effect structure with minimal impact on the overall program structure;
- allow integration into a pure setting of “real” effects such as
  - I/O
  - mutable state.

First Two Lectures

- Effectful computations: motivating examples
- Monads
- The Haskell do-notation
- Some standard monads
- Monad transformers

Example: A Simple Evaluator

```
data Exp = Lit Integer
         | Add Exp Exp
         | Sub Exp Exp
         | Mul Exp Exp
         | Div Exp Exp

eval :: Exp -> Integer
eval (Lit n)     = n
eval (Add e1 e2) = eval e1 + eval e2
eval (Sub e1 e2) = eval e1 - eval e2
eval (Mul e1 e2) = eval e1 * eval e2
eval (Div e1 e2) = eval e1 ‘div‘ eval e2
```

Making the evaluator safe (1)

```
data Maybe a = Nothing | Just a

safeEval :: Exp -> Maybe Integer
safeEval (Lit n) = Just n
safeEval (Add e1 e2) =
    case safeEval e1 of
        Nothing -> Nothing
        Just n1 ->
            case safeEval e2 of
                Nothing -> Nothing
                Just n2 -> Just (n1 + n2)
```

Making the evaluator safe (2)

```
safeEval (Sub e1 e2) =
    case safeEval e1 of
        Nothing -> Nothing
        Just n1 ->
            case safeEval e2 of
                Nothing -> Nothing
                Just n2 -> Just (n1 - n2)
```

Making the evaluator safe (3)

```
safeEval (Mul e1 e2) =
    case safeEval e1 of
        Nothing -> Nothing
        Just n1 ->
            case safeEval e2 of
                Nothing -> Nothing
                Just n2 -> Just (n1 * n2)
```

Making the evaluator safe (4)

```
safeEval (Div e1 e2) =
    case safeEval e1 of
        Nothing -> Nothing
        Just n1 ->
            case safeEval e2 of
                Nothing -> Nothing
                Just n2 ->
                    if n2 == 0
                    then Nothing
                    else Just (n1 `div` n2)
```

Any common pattern?

Clearly a lot of code duplication!
Can we factor out a common pattern?

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We note:

- ***Sequencing*** of evaluations (or ***computations***).
- If one evaluation fails, fail overall.
- Otherwise, make result available to following evaluations.

Example: Numbering trees

```
data Tree a = Leaf a | Node (Tree a) (Tree a)

numberTree :: Tree a -> Tree Int
numberTree t = fst (ntAux t 0)
    where
        ntAux :: Tree a -> Int -> (Tree Int,Int)
        ntAux (Leaf _)      n = (Leaf n, n+1)
        ntAux (Node t1 t2) n =
            let (t1', n')  = ntAux t1 n
            in let (t2', n'') = ntAux t2 n'
               in (Node t1' t2', n'')
```

Observations

- Repetitive pattern: threading a counter through a ***sequence*** of tree numbering ***computations***.

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Can we do better?

Sequencing evaluations (1)

Sequencing is common to both examples, with the outcome of a computation ***affecting*** subsequent computations.

```
evalSeq :: Maybe Integer
           -> (Integer -> Maybe Integer)
           -> Maybe Integer
evalSeq ma f =
    case ma of
        Nothing -> Nothing
        Just a  -> f a
```

Sequencing evaluations (2)

```
safeEval :: Exp -> Maybe Integer
safeEval (Lit n) = Just n
safeEval (Add e1 e2) =
    safeEval e1 ‘evalSeq‘ (\n1 ->
    safeEval e2 ‘evalSeq‘ (\n2 ->
    Just (n1 + n2)))
safeEval (Sub e1 e2) =
    safeEval e1 ‘evalSeq‘ (\n1 ->
    safeEval e2 ‘evalSeq‘ (\n2 ->
    Just (n1 - n2)))
```

Sequencing evaluations (3)

```
safeEval (Mul e1 e2) =
    safeEval e1 `evalSeq` (\n1 ->
    safeEval e2 `evalSeq` (\n2 ->
    Just (n1 - n2)))
safeEval (Div e1 e2) =
    safeEval e1 `evalSeq` (\n1 ->
    safeEval e2 `evalSeq` (\n2 ->
    if n2 == 0
    then Nothing
    else Just (n1 `div` n2)))
```

Aside: Scope rules of λ-abstractions

The scope rules of λ-abstractions are such that parentheses can be omitted:

```
safeEval :: Exp -> Maybe Integer
...
safeEval (Add e1 e2) =
    safeEval e1 `evalSeq` \n1 ->
    safeEval e2 `evalSeq` \n2 ->
    Just (n1 + n2)
...
```

Inlining `evalSeq` (1)

```
safeEval (Add e1 e2) =
  safeEval e1 `evalSeq` \n1 ->
  safeEval e2 `evalSeq` \n2 ->
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```

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```
safeEval (Add e1 e2) =
  safeEval e1 `evalSeq` \n1 ->
  safeEval e2 `evalSeq` \n2 ->
  Just (n1 + n2)
```

$=$

```
safeEval (Add e1 e2) =
  case (safeEval e1) of
    Nothing -> Nothing
    Just a -> (\n1 -> safeEval e2 ...) a
```

Inlining `evalSeq` (2)

=

```
safeEval (Add e1 e2) =
  case (safeEval e1) of
    Nothing -> Nothing
    Just n1 -> safeEval e2 `evalSeq` (\n2 -> ...)
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Inlining `evalSeq` (3)

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```
safeEval (Add e1 e2) =
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Excercise 1: Verify the other cases.

`Maybe` viewed as a computation (1)

- Consider a value of type `Maybe a` as denoting a ***computation*** of a value of type `a` that ***may fail***.

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- I.e. ***failure is an effect***, implicitly affecting subsequent computations.

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- Consider a value of type `Maybe a` as denoting a ***computation*** of a value of type `a` that ***may fail***.
- When sequencing possibly failing computations, a natural choice is to fail overall once a subcomputation fails.
- I.e. ***failure is an effect***, implicitly affecting subsequent computations.
- Let's adopt names reflecting our intentions.

Maybe viewed as a computation (2)

Successful computation of a value:

```
mbReturn :: a -> Maybe a
mbReturn = Just
```

Sequencing of possibly failing computations:

```
mbSeq :: Maybe a -> (a -> Maybe b) -> Maybe b
mbSeq ma f =
    case ma of
        Nothing -> Nothing
        Just a  -> f a
```

`Maybe` viewed as a computation (3)

Failing computation:

```
mbFail :: Maybe a
mbFail = Nothing
```

The safe evaluator revisited

```
safeEval :: Exp -> Maybe Integer
safeEval (Lit n) = mbReturn n
safeEval (Add e1 e2) =
    safeEval e1 ‘mbSeq‘ \n1 ->
    safeEval e2 ‘mbSeq‘ \n2 ->
    mbReturn (n1 + n2)
...
safeEval (Div e1 e2) =
    safeEval e1 ‘mbSeq‘ \n1 ->
    safeEval e2 ‘mbSeq‘ \n2 ->
    if n2 == 0 then mbFail
    else mbReturn (n1 ‘div‘ n2)))
```

Stateful Computations (1)

- A ***stateful computation*** consumes a state and returns a result along with a possibly updated state.

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type S a = Int -> (a, Int)
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(Only `Int` state for the sake of simplicity.)

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- A ***stateful computation*** consumes a state and returns a result along with a possibly updated state.
- The following type synonym captures this idea:

```
type S a = Int -> (a, Int)
```

  (Only `Int` state for the sake of simplicity.)
- A value (function) of type `S a` can now be viewed as denoting a stateful computation computing a value of type `a`.

Stateful Computations (2)

- When sequencing stateful computations, the resulting state should be passed on to the next computation.

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- I.e. ***state updating is an effect***, implicitly affecting subsequent computations.
  (As we would expect.)

Stateful Computations (3)

Computation of a value without changing the state:

```
sReturn :: a -> S a
sReturn a = ???
```

Stateful Computations (3)

Computation of a value without changing the state:

```
sReturn :: a -> S a
sReturn a = \n -> (a, n)
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Sequencing of stateful computations:

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Computation of a value without changing the state:

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Sequencing of stateful computations:

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sSeq :: S a -> (a -> S b) -> S b
sSeq sa f = \n ->
    let (a, n') = sa n
    in f a n'
```

Stateful Computations (4)

Reading and incrementing the state:

```
sInc :: S Int
sInc = \n -> (n, n + 1)
```

Numbering trees revisited

```
data Tree a = Leaf a | Node (Tree a) (Tree a)

numberTree :: Tree a -> Tree Int
numberTree t = fst (ntAux t 0)
    where
        ntAux :: Tree a -> S (Tree Int)
        ntAux (Leaf _)  =
            sInc ‘sSeq‘ \n -> sReturn (Leaf n)
        ntAux (Node t1 t2) =
            ntAux t1 ‘sSeq‘ \t1’ ->
            ntAux t2 ‘sSeq‘ \t2’ ->
            sReturn (Node t1’ t2’)
```

Observations

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- In particular, there is no longer any risk of “passing on” the wrong version of the state!

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Comparison of the examples

- Both examples characterized by sequencing of effectful computations.
- Both examples could be neatly structured by introducing:
  - A type denoting computations
  - A function constructing an effect-free computation of a value
  - A function constructing a computation by sequencing computations
- In fact, both examples are instances of the general notion of a ***MONAD***.

Monads in Functional Programming

A monad is represented by:

- A type constructor

  `M :: * -> *`

  `M T` represents computations of a value of type `T`.

- A polymorphic function

  `return :: a -> M a`

  for lifting a value to a computation.

- A polymorphic function

  `(>>=) :: M a -> (a -> M b) -> M b`

  for sequencing computations.

Exercise 2: `join` and `fmap`

Equivalently, the notion of a monad can be captured through the following functions:

```
return :: a -> M a
join :: (M (M a)) -> M a
fmap :: (a -> b) -> (M a -> M b)
```

`join` “flattens” a computation, `fmap` “lifts” a function to map computations to computations.

Define `join` and `fmap` in terms of >>= (and `return`), and >>= in terms of `join` and `fmap`.

Exercise 2: Solution

```
join :: M (M a) -> M a
join mm = mm >>= id

fmap :: (a -> b) -> M a -> M b
fmap f m = m >>= \x -> return (f x)

(>>=) :: M a -> (a -> M b) -> M b
m >>= f = join (fmap f m)
```

Monad laws

Additionally, the following laws must be satisfied:

$$
\begin{aligned}
\texttt{return}\ x \mathbin{\texttt{>>=}} f &= f\ x \\
m \mathbin{\texttt{>>=}} \texttt{return} &= m \\
(m \mathbin{\texttt{>>=}} f) \mathbin{\texttt{>>=}} g &= m \mathbin{\texttt{>>=}} (\lambda x \rightarrow f\ x \mathbin{\texttt{>>=}} g)
\end{aligned}
$$

I.e., `return` is the right and left identity for >>=, and >>= is associative.

Exercise 3: The Identity Monad

The ***Identity Monad*** can be understood as representing ***effect-free*** computations:

```
type I a = a
```

1. Provide suitable definitions of `return` and `>>=`.
2. Verify that the monad laws hold for your definitions.

Exercise 3: Solution

```
return :: a -> I a
return = id

(>>=) :: I a -> (a -> I b) -> I b
m >>= f = f m
-- or: (>>=) = flip ($)
```

Simple calculations verify the laws, e.g.:

$$\begin{aligned} \texttt{return}\ x \mathbin{\texttt{>>=}} f &= \texttt{id}\ x \mathbin{\texttt{>>=}} f \\ &= x \mathbin{\texttt{>>=}} f \\ &= f\ x \end{aligned}$$

Monads in Haskell (1)

In Haskell, the notion of a monad is captured by a ***Type Class***:

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

This allows the names of the common functions to be overloaded, and the sharing of derived definitions.

Monads in Haskell (2)

The Haskell monad class has two further methods with default instances:

```
(>>) :: m a -> m b -> m b
m >> k = m >>= \_ -> k

fail :: String -> m a
fail s = error s
```

The Maybe monad in Haskell

```
instance Monad Maybe where
    -- return :: a -> Maybe a
    return = Just

    -- (>>=) :: Maybe a -> (a -> Maybe b)
                -> Maybe b
    Nothing  >>= _ = Nothing
    (Just x) >>= f = f x
```

Exercise 4: A state monad in Haskell

Haskell 98 does not permit type synonyms to be instances of classes. Hence we have to define a new type:

```
newtype S a = S (Int -> (a, Int))

unS :: S a -> (Int -> (a, Int))
unS (S f) = f
```

Provide a `Monad` instance for `S`.

Exercise 4: Solution

```
instance Monad S where
    return a = S (\s -> (a, s))

    m >>= f = S $ \s ->
        let (a, s') = unS m s
        in unS (f a) s'
```

Monad-specific operations (1)

To be useful, monads need to be equipped with additional operations specific to the effects in question. For example:

```
fail :: String -> Maybe a
fail s = Nothing

catch :: Maybe a -> Maybe a -> Maybe a
m1 `catch` m2 =
    case m1 of
        Just _  -> m1
        Nothing -> m2
```

Monad-specific operations (2)

Typical operations on a state monad:

```
set :: Int -> S ()
set a = S (\_ -> ((), a))

get :: S Int
get = S (\s -> (s, s))
```

Moreover, there is often a need to “run” a computation. E.g.:

```
runS :: S a -> a
runS m = fst (unS m 0)
```

The do-notation (1)

Haskell provides convenient syntax for programming with monads:

```
do
    a <- exp₁
    b <- exp₂
    return exp₃
```

$$\texttt{do}\quad \texttt{a <- } exp_1;\ \texttt{b <- } exp_2;\ \texttt{return } exp_3$$

is syntactic sugar for

$$exp_1\ \texttt{>>= \textbackslash a ->}$$
$$exp_2\ \texttt{>>= \textbackslash b ->}$$
$$\texttt{return}\ exp_3$$

The do-notation (2)

Computations can be done solely for effect, ignoring the computed value:

```
do
    exp1
    exp2
    return exp3
```

$$\texttt{do} \quad exp_1 \quad exp_2 \quad \texttt{return}\ exp_3$$

is syntactic sugar for

exp_1 `>>= \_ ->`
exp_2 `>>= \_ ->`
`return` exp_3

The `do`-notation (3)

A `let`-construct is also provided:

```
do
    let a = exp1
        b = exp2
    return exp3
```

is equivalent to

```
do
    a <- return exp1
    b <- return exp2
    return exp3
```

Numbering trees in do-notation

```
numberTree :: Tree a -> Tree Int
numberTree t = runS (ntAux t)
    where
        ntAux :: Tree a -> S (Tree Int)
        ntAux (Leaf _) = do
            n <- get
            set (n + 1)
            return (Leaf n)
        ntAux (Node t1 t2) = do
            t1' <- ntAux t1
            t2' <- ntAux t2
            return (Node t1' t2')
```

Nondeterminism: The list monad

```
instance Monad [] where
    return a = [a]
    m >>= f  = concat (map f m)
    fail s   = []
```

Example:

```
do
    x <- [1, 2]
    y <- ['a', 'b']
    return (x,y)
```

Result: `[(1,'a'),(1,'b'),(2,'a'),(2,'b')]`

Environments: The reader monad

```
instance Monad ((->) e) where
    return a = const a
    m >>= f  = \e -> f (m e) e

getEnv :: ((->) e) e
getEnv = id
```

The Haskell IO monad

In Haskell, IO is handled through the IO monad.
IO is ***abstract***! Conceptually:

```
newtype IO a = IO (World -> (a, World))
```

Some operations:

```
putChar     :: Char -> IO ()
putStr      :: String -> IO ()
putStrLn    :: String -> IO ()
getChar     :: IO Char
getLine     :: IO String
getContents :: String
```

Monad Transformers (1)

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For example: State and Error/Partiality?

We could implement a suitable monad from scratch:

```
newtype SE s a = SE (s -> Maybe (a, s))
```

Monad Transformers (2)

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- Not always obvious how: e.g., should the combination of state and error have been

```
newtype SE s a = SE (s -> (Maybe a, s))
```

- Duplication of effort: similar patterns related to specific effects are going to be repeated over and over in the various combinations.

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- A ***monad transformer*** transforms a monad by adding support for an additional effect.
- A library of monad transformers can be developed, each adding a specific effect (state, error, . . .), allowing the programmer to mix and match.

Monad Transformers (3)

Monad Transformers can help:

- A ***monad transformer*** transforms a monad by adding support for an additional effect.
- A library of monad transformers can be developed, each adding a specific effect (state, error, . . .), allowing the programmer to mix and match.
- A form of ***aspect-oriented programming***.

Monad Transformers in Haskell (1)

- A monad transformer maps monads to monads. This is represented by a type constructor of the following kind:

  ```
  T :: (* -> *) -> (* -> *)
  ```

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- A monad transformer maps monads to monads. This is represented by a type constructor of the following kind:

```
T :: (* -> *) -> (* -> *)
```

- Additionally, we require monad transformers to ***add*** computational effects. Thus we require a mapping from computations in the underlying monad to computations in the transformed monad:

```
lift :: M a -> T M a
```

Monad Transformers in Haskell (2)

- These requirements are captured by the following (multi-parameter) type class:

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

Classes for Specific Effects

A monad transformer adds specific effects to any monad. Thus there can be many monads supporting the same operations. Introduce classes to handle the overloading:

```
class Monad m => E m where
    eFail :: m a
    eHandle :: m a -> m a -> m a

class Monad m => S m s | m -> s where
    sSet :: s -> m ()
    sGet :: m s
```

The Identity Monad

We are going to construct monads by successive transformations of the identity monad:

```
newtype I a = I a
unI (I a) = a

instance Monad I where
    return a = I a
    m >>= f = f (unI m)

runI :: I a -> a
runI = unI
```

The Error Monad Transformer (1)

```
newtype ET m a = ET (m (Maybe a))
unET (ET m) = m

instance Monad m => Monad (ET m) where
    return a = ET (return (Just a))

    m >>= f = ET $ do
        ma <- unET m
        case ma of
            Nothing -> return Nothing
            Just a  -> unET (f a)
```

The Error Monad Transformer (2)

We need the ability to run transformed monads:

```
runET :: Monad m => ET m a -> m a
runET etm = do
    ma <- unET etm
    case ma of
        Just a -> return a
```

ET is a monad transformer:

```
instance Monad m => MonadTransformer ET m wher
    lift m = ET (m >>= \a -> return (Just a))
```

The Error Monad Transformer (3)

Any monad transformed by ET is an instance of E:

```
instance Monad m => E (ET m) where
    eFail = ET (return Nothing)
    m1 `eHandle` m2 = ET $ do
        ma <- unET m1
        case ma of
            Nothing -> unET m2
            Just _  -> return ma
```

The Error Monad Transformer (4)

A state monad transformed by ET is a state monad:

```
instance S m s => S (ET m) s where
    sSet s = lift (sSet s)
    sGet = lift sGet
```

Exercise 5: Running transf. monads

Let

```
ex1 = eFail ‘eHandle‘ return 1
```

1. Suggest a possible type for `ex1`.
2. How can `ex1` be run, given your type?

Exercise 5: Solution

```
ex1 :: ET I Int
ex1 = eFail ‘eHandle‘ return 1

ex1r :: Int
ex1r = runI (runET ex1)
```

The State Monad Transformer (1)

```
newtype ST s m a = ST (s -> m (a, s))
unST (ST m) = m

instance Monad m => Monad (ST s m) where
    return a = ST (\s -> return (a, s))

    m >>= f = ST $ \s -> do
        (a, s') <- unST m s
        unST (f a) s'
```

The State Monad Transformer (2)

We need the ability to run transformed monads:

```
runST :: Monad m => ST s m a -> s -> m a
runST stf s0 = do
    (a, _) <- unST stf s0
    return a
```

ST is a monad transformer:

```
instance Monad m =>
         MonadTransformer (ST s) m where
    lift m = ST (\s -> m >>= \a ->
                           return (a, s))
```

The State Monad Transformer (3)

Any monad transformed by ST is an instance of S:

```
instance Monad m => S (ST s m) s where
    sSet s = ST (\_ -> return ((), s))
    sGet   = ST (\s -> return (s, s))
```

An error monad transformed by ST is an error monad:

```
instance E m => E (ST s m) where
    eFail = lift eFail
    m1 ‘eHandle‘ m2 = ST $ \s ->
        unST m1 s ‘eHandle‘ unST m2 s
```

Exercise 6: Effect ordering

Consider the code fragment

```
ex2a :: ST Int (ET I) Int
ex2a= (sSet 3 >> eFail) ‘eHandle‘ sGet
```

Note that the exact same code fragment also can be typed as follows:

```
ex2b :: ET (ST Int I) Int
ex2b = (sSet 42 >> eFail) ‘eHandle‘ sGet
```

What is

```
runI (runET (runST ex2a 0))
runI (runST (runET ex2b) 0)
```

Exercise 6: Solution

$$\texttt{runI (runET (runST ex2a 0))} = \texttt{0}$$
$$\texttt{runI (runST (runET ex2b) 0)} = \texttt{3}$$

Exercise 7: Alternative ST?

To think about.

Could ST have been defined in some other way, e.g.

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

or perhaps

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

Reading (1)

- Philip Wadler. The Essence of Functional Programming. *Proceedings of the 19th ACM Symposium on Principles of Programming Languages (POPL'92)*, 1992.
- Nick Benton, John Hughes, Eugenio Moggi. Monads and Effects. In *International Summer School on Applied Semantics 2000*, Caminha, Portugal, 2000.

Reading (2)

- Sheng Liang, Paul Hudak, Mark Jones. Monad Transformers and Modular Interpreters. In *Proceedings of the 22nd ACM Symposium on Principles of Programming Languages (POPL'95)*, January 1995, San Francisco, California
- Nomaware. *All About Monads.* `http://www.nomaware.com/monads`