

MGS 2011: FUN Lecture 3

Monads

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A Blessing and a Curse

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 “everything is explicit.”
Can add a lot of clutter, make it hard to maintain code

Conundrum

“Shall I be pure or impure?” (Wadler, 1992)

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- Absence of effects
 - facilitates understanding and reasoning
 - makes lazy evaluation viable
 - allows choice of reduction order, e.g. parallel
 - enhances modularity and reuse.

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“Shall I be pure or impure?” (Wadler, 1992)

- Absence of effects
 - facilitates understanding and reasoning
 - makes lazy evaluation viable
 - allows choice of reduction order, e.g. parallel
 - enhances modularity and reuse.
- Effects (state, exceptions, ...) can
 - help making code concise
 - facilitate maintenance
 - improve the efficiency.

Example: A Compiler Fragment (1)

Identification is the task of relating each applied identifier occurrence to its declaration or definition:

```
public class C {  
    int x, n;  
    void set(int n) { x = n; }  
}
```

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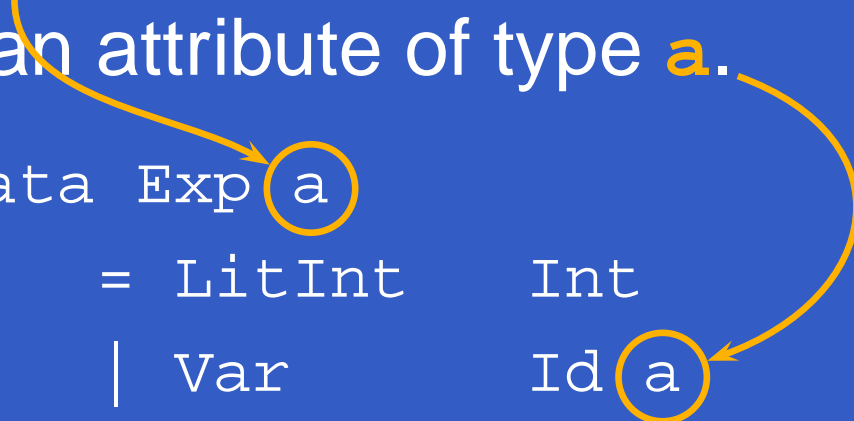


In the body of `set`, the one applied occurrence of

- `x` refers to the **instance variable** `x`
- `n` refers to the **argument** `n`.

Example: A Compiler Fragment (2)

Consider an AST `Exp` for a simple expression language. `Exp` is a parameterized type: the **type parameter** `a` allows variables to be annotated with an attribute of type `a`.



```
data Exp a
  = LitInt      Int
  | Var         Id a
  | UnOpApp     UnOp (Exp a)
  | BinOpApp    BinOp (Exp a) (Exp a)
  | If          (Exp a) (Exp a) (Exp a)
  | Let         [(Id, Type, Exp a)] (Exp a)
```

Example: A Compiler Fragment (3)

Example: The following code fragment

```
let int x = 7 in x + 35
```

would be represented like this (before identification):

```
Let [ ("x", IntType, LitInt 7) ]  
  (BinOpApp Plus  
    (Var "x" ())  
    (LitInt 35))
```


Example: A Compiler Fragment (4)

Goals of the *identification* phase:

- Annotate each applied identifier occurrence with attributes of the corresponding variable declaration.

I.e., map unannotated AST **Exp** () to annotated AST **Exp Attr**.

- **Report** conflicting variable definitions and undefined variables.

identification ::

Exp ()

->

Exp Attr,

[ErrorMsg]

Example: A Compiler Fragment (5)

Example: Before Identification

```
Let [ ("x", IntType, LitInt 7) ]  
    (BinOpApp Plus  
      (Var "x" ( ))  
      (LitInt 35))
```

Example: A Compiler Fragment (5)

Example: Before Identification

```
Let [ ("x", IntType, LitInt 7)]  
    (BinOpApp Plus  
      (Var "x" ())  
      (LitInt 35))
```

After identification:

```
Let [ ("x", IntType, LitInt 7)]  
    (BinOpApp Plus  
      (Var "x" (1, IntType))  
      (LitInt 35))
```

Example: A Compiler Fragment (6)

`enterVar` inserts a variable at the given scope level and of the given type into an environment.

- Check that no variable with same name has been defined at the same scope level.
- If not, the new variable is entered, and the **resulting environment** is returned.
- Otherwise an **error message** is returned.

```
enterVar :: Id -> Int -> Type -> Env  
         -> Either Env ErrorMessage
```



Example: A Compiler Fragment (7)

Functions that do the real work:

```
identAux ::  
  Int -> Env -> Exp ()  
  -> (Exp Attr, [ErrorMsg])
```

```
identDefs ::  
  Int -> Env -> [(Id, Type, Exp ())]  
  -> ([ (Id, Type, Exp Attr) ],  
      Env,  
      [ErrorMsg])
```

Example: A Compiler Fragment (8)

```
identDefs l env [] = ([], env, [])
identDefs l env ((i,t,e) : ds) =
  ((i,t,e') : ds', env'', ms1++ms2++ms3)
  where
    (e', ms1) = identAux l env e
    (env', ms2) =
      case enterVar i l t env of
        Left env' -> (env', [])
        Right m    -> (env, [m])
    (ds', env'', ms3) =
      identDefs l env' ds
```

Example: A Compiler Fragment (9)

Error checking and collection of error messages arguably added a lot of **clutter**. The **core** of the algorithm is this:

```
identDefs l env [] = ([], env)
identDefs l env ((i,t,e) : ds) =
  ((i,t,e') : ds', env'')
  where
    e'          = identAux l env e
    env'         = enterVar i l t env
    (ds', env'') = identDefs l env' ds
```

Errors are just a **side effect**.

Answer to Conundrum: Monads (1)

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- Monads bridges the gap: allow effectful programming in a pure setting.
- Key idea: **Computational types**: an object of type MA 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

Answer to Conundrum: Monads (2)

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- support changes to the effect structure with minimal impact on the overall program structure;

Answer to Conundrum: Monads (2)

Monads

- 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.

This Lecture

Pragmatic introduction to monads:

- Effectful computations
- Identifying a common pattern
- Monads as a *design pattern*

Example 1: 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***).

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We note:

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

Sequencing Evaluations

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

Exercise 1: Refactoring safeEval

Rewrite safeEval, case Add, using evalSeq:

```
safeEval (Add e1 e2) =
```

```
  case safeEval e1 of
```

```
    Nothing -> Nothing
```

```
    Just n1 ->
```

```
      case safeEval e2 of
```

```
        Nothing -> Nothing
```

```
        Just n2 -> Just (n1 + n2)
```

```
evalSeq ma f =
```

```
  case ma of
```

```
    Nothing -> Nothing
```

```
    Just a -> f a
```

Exercise 1: Solution

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

or

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

```
...
```

Refactored Safe Evaluator (1)

```
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)
```

Refactored Safe Evaluator (2)

```
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)
```


Inlining evalSeq (1)

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

Inlining evalSeq (1)

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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)

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safeEval (Add e1 e2) =  
  case (safeEval e1) of  
    Nothing -> Nothing  
    Just n1 -> safeEval e2 `evalSeq` (\n2 -> ...)
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Inlining evalSeq (2)

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

=

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

Inlining evalSeq (3)

=

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

Good exercise: 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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- 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.

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**.
- 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 generalize and 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)))
```

Example 2: 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?

Stateful Computations (1)

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

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- The following type synonym captures this idea:

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

(Only `Int` state for the sake of simplicity.)

Stateful Computations (1)

- 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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- When sequencing stateful computations, the resulting state should be passed on to the next computation.
- 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 (For ref.: $S\ a = Int \rightarrow (a, Int)$):

`sReturn :: a -> S a`

`sReturn a = ???`

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Computation of a value without changing the state (For ref.: $S\ a = Int \rightarrow (a, Int)$):

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Sequencing of stateful computations:

$sSeq :: S\ a \rightarrow (a \rightarrow S\ b) \rightarrow S\ b$

$sSeq\ sa\ f = ???$

Stateful Computations (3)

Computation of a value without changing the state (For ref.: $S\ a = Int \rightarrow (a, Int)$):

```
sReturn :: a -> S a
```

```
sReturn a = \n -> (a, n)
```

Sequencing of stateful computations:

```
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
(For ref.: $S\ a = Int \rightarrow (a, Int)$):

```
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

- The “plumbing” has been captured by the abstractions.

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- In particular:
 - counter no longer manipulated directly
 - no longer any risk of “passing on” the wrong version of the counter!

Comparison of the examples

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- 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

$M :: * \rightarrow *$

$M\ T$ represents computations of a value of type T .

- A polymorphic function

$return :: a \rightarrow M\ a$

for lifting a value to a computation.

- A polymorphic function

$(>>=) :: M\ a \rightarrow (a \rightarrow M\ b) \rightarrow M\ b$

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`.

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

Exercise 2: Solution

```
join :: M (M a) -> M a
```

```
join mm = mm >>= id
```

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

```
fmap f m = m >>= \a -> return (f a)
```

or:

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

```
fmap f m = m >>= return . f
```

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

```
m >>= f = join (fmap f m)
```

Monad laws

Additionally, the following **laws** must be satisfied:

$$\text{return } x \gg= f = f \ x$$

$$m \gg= \text{return} = m$$

$$(m \gg= f) \gg= g = m \gg= (\lambda x \rightarrow f \ x \gg= g)$$

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.:

$$\begin{aligned} \text{return } x >>= f &= \text{id } x >>= f \\ &= x >>= f \\ &= f \, x \end{aligned}$$

Monads in Category Theory (1)

The notion of a monad originated in Category Theory. There are several equivalent definitions (Benton, Hughes, Moggi 2000):

- ***Kleisli triple/triple in extension form:*** Most closely related to the $>>=$ version:

A ***Kleisli triple*** over a category \mathcal{C} is a triple $(T, \eta, _*)$, where $T : |\mathcal{C}| \rightarrow |\mathcal{C}|$, $\eta_A : A \rightarrow TA$ for $A \in |\mathcal{C}|$, $f^* : TA \rightarrow TB$ for $f : A \rightarrow TB$.

(Additionally, some laws must be satisfied.)

Monads in Category Theory (2)

- **Monad/triple in monoid form:** More akin to the `join/fmap` version:

A **monad** over a category \mathcal{C} is a triple (T, η, μ) , where $T : \mathcal{C} \rightarrow \mathcal{C}$ is a functor, $\eta : \text{id}_{\mathcal{C}} \rightarrow T$ and $\mu : T^2 \rightarrow T$ are natural transformations.

(Additionally, some commuting diagrams must be satisfied.)

Reading

- 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.
- *All About Monads.*
http://www.haskell.org/all_about_monads