Monads

CS242
Lecture 12
Evaluation Rules: Static Scope

[Var]

\[ E \vdash x \rightarrow E(x) \]

[Int]

\[ E \vdash i \rightarrow i \]

[Abs]

\[ E \vdash \lambda x. e \rightarrow \langle \lambda x. e, E \rangle \]

[App]

\[ E \vdash e_1 \rightarrow \langle \lambda x. e_0, E' \rangle \]

\[ E \vdash e_2 \rightarrow v \]

\[ E'[x: v] \vdash e_0 \rightarrow v' \]

Note: \( E[x: v] \) is the same environment as \( E, x:v \). \( E \)
is extended (or updated if \( x \) is already present) at point \( x \) to return \( v \).
Review: State

Evaluation rules have the form

\[ E, \ S \vdash \ e \rightarrow \ v, \ S' \]

Expressions evaluate to a value and update the state.
### Evaluation Rules with State

**[Var]**

\[ E, S \vdash x \rightarrow E(x), S \]

**[Int]**

\[ E, S \vdash i \rightarrow i, S \]

**[New]**

\[ l \notin \text{dom}(S) \]

\[ E, S \vdash \text{new} \rightarrow l, S[l = 0] \]

**[Abs]**

\[ E, S \vdash \lambda x. e \rightarrow (\lambda x. e, E), S \]

**[App]**

\[ E, S \vdash e_1 e_2 \rightarrow v', S \]

\[ E, S_0 \vdash e_1 \rightarrow (\lambda x. e_0, E'), S_1 \]

\[ E, S_1 \vdash e_2 \rightarrow v, S_2 \]

\[ E'[x: v], S_2 \vdash e_0 \rightarrow v', S_3 \]
Another Feature: Exceptions

Evaluation rules have one of two forms

\[
E \overset{e}{\rightarrow} v \quad \text{evaluation produces a normal value}
\]

\[
E \overset{e}{\rightarrow} \text{Exc}(v) \quad \text{evaluation produces an exception}
\]

In the second case further evaluation must be \textit{strict} in the exception: Once produced the exception propagates through all other computation until caught or it is the result of the computation.
Evaluation Rules with Exceptions

- **[Var]**
  \[ E \vdash x \rightarrow E(x) \]

- **[Int]**
  \[ E \vdash i \rightarrow i \]

- **[Abs]**
  \[ E \vdash \lambda x.e \rightarrow \langle \lambda x.e, E \rangle \]

- **[Raise]**
  \[ E \vdash \text{raise } e \rightarrow \text{Exc}(v) \]

- **[AppE1]**
  \[ E \vdash e_1 \rightarrow \text{Exc}(v) \]
  \[ E \vdash e_1 e_2 \rightarrow \text{Exc}(v) \]

- **[AppE2]**
  \[ E \vdash e_2 \rightarrow \text{Exc}(v) \]
  \[ E \vdash e_1 e_2 \rightarrow \text{Exc}(v) \]

- **[App]**
  \[ E \vdash e \rightarrow v \]
  \[ E \vdash e_2 \rightarrow v \]
  \[ E'[x: v] \vdash e_0 \rightarrow v' \]
  \[ E \vdash e_1 e_2 \rightarrow v' \]
Beyond Pure Lambda Calculus

• What do lambda calculus+state and lambda calculus+exceptions have in common?

• Three things
  • They are both lambda calculus + “side information”
  • There are new primitives for manipulating the side information
  • If the extra primitives are not used, the behavior is pure lambda calculus

• This is how programming languages are often described
  • A core functional part (lambda calculus)
  • Plus additional features that go beyond pure functions
But Why Not Pure Lambda Calculus?

- Why not make the state an explicit argument to functions?
  - A function $a \to b$ that works on state could have a type $a \times s \to b \times s$

- But this exposes the state; the programmer must explicitly manage it.

- An alternative signature: $a \to (s \to b \times s)$

- Factor out $M b = s \to b \times s$ as an abstract data type
  - $M b$ is a state transformer
Language Features

• There are many non-functional language features that have similar properties:

• Continuations
• (Certain styles of) concurrency
• Nondeterminism
• Random numbers
• ...

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Monads

• We can abstract the common part of these language features
  • Sequencing to thread the extra information through the computation

• Enables us to *program* these features in pure lambda calculus
  • In a concise way

• More general than the state transformer abstraction
  • Monads are an abstraction for defining such abstractions
Types

• A monad $M\ a$ is an abstract type
  • The implementation of $M$ is hidden

• The ``normal’’ type is $a$

• The extra information is hidden in the abstraction
Operations

return: \( a \rightarrow M\ a \)

*A function for creating an element of a monad.*

bind: \( M\ a \rightarrow (a \rightarrow M\ b) \rightarrow M\ b \)

*Sequencing: Take an element of a monad, unwrap the value inside, and apply a function returning an element of the monad with a possibly different type.*

Bind is usually written \( v >>\ f \), for monad value \( v \) and function \( f \).
Discussion

• One take: Not much here!
  • Pretty basic

• A second take: Just the right abstraction, and simple!
  • It turns out that return/bind are enough to implement many language features within the lambda calculus

• Keep in mind that return and bind are different for each monad
  • We have to find appropriate definitions
Partial Functions

• Start with a very simple monad

• An option type `Maybe(a)` is either a value of type `a` or nothing

• Useful for expressing the result of partial functions w/o exceptions

• Examples
  • `head: List(a) -> Maybe(a)` returns nothing if the list is empty
  • `div: int -> int -> Maybe(int)` returns nothing if the divisor is zero
Partial Functions

data Maybe a =
    Just a
| Nothing

Example use to compose partial functions $f$ and $g$:

$$\lambda x. \text{let } y = f \ x \text{ in}
    \case y \text{ of}
        \text{Nothing: Nothing}
        \text{Just } v: g(v)$$
Partial Functions with Monads

data Maybe a =
   Just a
   | Nothing

-- monad M = Maybe
return = Just
v >>= f = case v of
   Nothing -> Nothing
   Just x -> f x
Composing Partial Functions

Consider the composition of two partial functions \( f \) and \( g \):
\[
\lambda x. \ x >>= f >>= g
\]

The `Maybe` monad handles the `Nothing` case transparently
- The case analysis is hidden inside of `>>=`
- Automatically short-circuits the computation if \( f \) returns `Nothing`
Example

head x = case x of
  Nil: Nothing
  Cons(a,as) : Just(a)

-- take the head of the first list of a list of lists
λl. return l >>= head >>= head
The State Monad

return: \( a \rightarrow M \ a \)
return = \( \lambda v.\lambda s. (v,s) \)  

\[ \text{-- note } M \ a = s \rightarrow a \ast s \text{ where } s \text{ is the state type} \]

\text{>>=} : M \ a \rightarrow (a \rightarrow M \ b) \rightarrow M \ b 
\text{p} \text{ >>=} f = \lambda s. \text{let} (v,s') = \text{p} \ s \text{ in } f \ v \ s' \]
Example Use

-- increment a global counter each time function foo is called
-- the state is a single integer
foo = λx. return 3 >>= λv. inc >>= λz.return v
bar = reset >>= foo >>= foo

-- inc and reset are new operations that manipulate the state
inc = λi.(i+1, i+1)
reset = λi.(0,0)
Nicer Syntax ...

-- increment a global counter each time function foo is called
-- the state is just a single integer

// interpret assignment := as bind, taking a value M a
// unwrapping the value of type a

foo x = do {
    v := return 3
    z := inc
    return v
}
First Principles ...

• We want a stateful function of type \( a \rightarrow b \)
  • Which is a pure function of type \( a \rightarrow s \rightarrow (b,s) \) if we make the state explicit

• The second piece \( s \rightarrow (b,s) \) is a state transformer

• How do we compose a state transformer \( s \rightarrow (a,s) \) and a stateful function \( a \rightarrow s \rightarrow (b,s) \)?
  • This is what bind does.
Discussion

• Return & bind do just a few things:

• The e in return e is a pure computation
  • Doesn’t know about the state, can be written normally

• Bind handles the “plumbing” of the monad
  • Hides the manipulation of the state except through state primitives
  • And correctly sequences it through the computation
Exceptions

data Exceptional e a =
    Success a
    | Exception e

  -- monad M = Exceptional e
return: a → M a
return = Success

>>>=: M a → (a → M b) → M b
v >>>= f = case v of
    Exception l -> Exception l
    Success r -> f r

throw = Exception

catch e h = case e of
    Exception l -> h l
    Success r  -> Success r
Using Exceptions

Consider composition of two functions \( f \) and \( g \) that can raise exceptions:
\[
\lambda x. \text{return } x \gg= f \gg= g
\]

Easy to add a handler for \( f \):
\[
\lambda x. (\text{catch (return } x \gg= f) h) \gg= g
\]

Or for both \( f \) and \( g \):
\[
\lambda x. \text{catch (return } x \gg= f \gg= g) h
\]

The threading of the exceptions is tedious without bind.
The Continuation Monad

newtype Cont r a = (a -> r) -> r   -- r is the result type of the computation

A continuation monad $M = \text{Cont } r$
return: $a \rightarrow M a$
return $= \lambda a. \lambda k. k a$

$\gg=:\ M a \rightarrow (a \rightarrow M b) \rightarrow M b$
c $\gg= f = \lambda k. c (\lambda a. f a k)$

return 6 $\gg= \lambda i. \text{return } (7 * i)$
The Continuation Monad

• Allows building continuations by extending existing continuations
  • Continuations are composed in pieces

• Note there is no automatic translation
  • This is not a CPS transformation!

• The programmer must build up the desired continuations by hand
Discussion

• Monads are a way of programming language features

• And it’s just programming!
  • No need for a compiler
  • Can add or remove features as desired

• Examples of good uses:
  • A small part of the program needs state
    • Use the State monad just in that portion
  • Part of the program needs State and Exceptions
    • Again, just use these monads in the parts where they are needed
Comments

• Three features are important to making monads work

• Higher-order functions
  • Bind is a higher order function
  • Many of the monads wrap higher order functions (continuations)

• Type checking
  • The type checker will complain if monads are used incorrectly
  • Necessary for most programmers to avoid getting tangled up
Upsides

• Since it is "just programming", users can write their own monads
  • And they do
  • Many programming patterns are usefully abstracted as monads

• Monads are ubiquitous in Haskell
  • Where they were pioneered

• And have appeared in many other settings
  • Again, easy to adopt new ways of structuring software
  • Even in languages without monads built-in
Downsides

• Monads are not a panacea
  • “It’s just programming”

• There are three main limitations
  • Multiple monads don’t compose particularly well
    • State(Exceptions(LC)) has different semantics than Exceptions(State(LC))
    • Monads don’t commute
  • To use monads, your program must be structured using return/bind
    • Contagious: Whole program tends to end up being written monadically
    • Major hit when converting non-monadic code to monadic code
  • Performance is not what it could be if the features were built in
    • No free lunch – there is a reason compilers are large and complicated

• And the programs end up looking like C++!
A New View of Languages

• We now view languages as having a pure core and a number of monads added on

• Most languages have the monads built in
  • State, Exceptions, Concurrency, ...

• But now we realize many of these features can be implemented within a language with higher-order features
History

• Monads were first used in language semantics
  • An idea borrowed from category theory in mathematics
  • Instead of messy environments with state, exceptions, continuations, use monads to structure the execution rules

• Haskell is a pure functional language
  • The designers insisted on purity
  • But how to handle I/O with the outside world?
  • Monads provided an elegant solution
  • Built-in I/O was the first use of monads in Haskell