CSEP505: Programming Languages
Lecture 8: Haskell, Laziness, IO Monad

Dan Grossman
Autumn 2016

Acknowledgments

- Slide-and-code content *liberally* appropriated with permission from Kathleen Fisher, Tufts University
- She in turn acknowledges Simon Peyton Jones, Microsoft Research, Cambridge "for many of these slides"
- And then I probably introduced errors and weaknesses as I changed them…

References

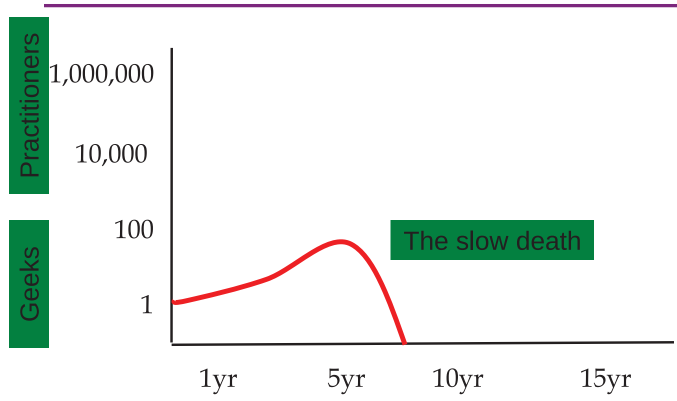
- "Real World Haskell",
  - Particularly Chapters 0 & 7
  - http://book.realworldhaskell.org/
- "Tackling the Awkward Squad"
  - Particularly Sections 1 & 2
  - http://research.microsoft.com/~simonpj/papers/marktoberdorf/mark.pdf

Haskell

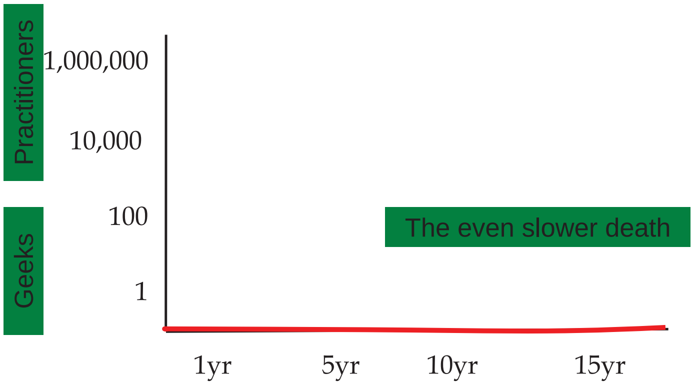
- Haskell is a programming language that is:
  - Similar to ML: general-purpose, strongly typed, higher-order, functional, supports type inference, …
  - Different from ML: purely functional core, lazy evaluation, monadic IO, type classes, …
  - These differences are why we will use it for Homework 5 and what we will focus on
- Designed by committee in 1980s and 1990s to unify research efforts in lazy languages. Continues to evolve.
  - Haskell 1.0 in 1990, Haskell '98, Haskell' ongoing.
  - "A History of Haskell: Being Lazy with Class" HOPL 3

These "graphs" aren't mine and aren't based on real data, but they're fun [and make a meta-point ?]

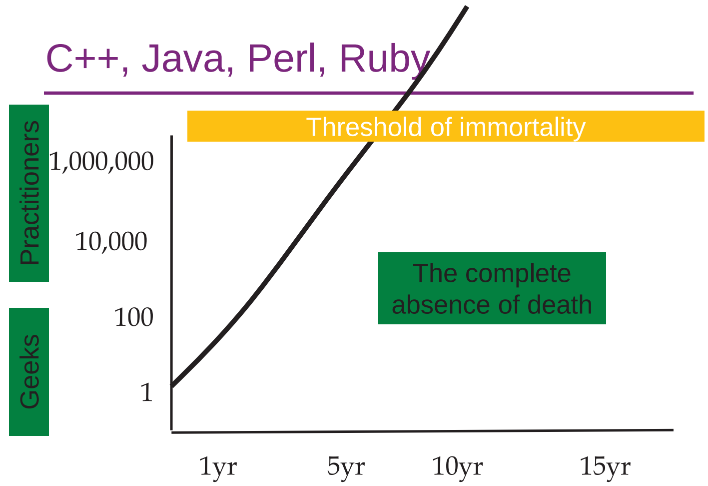
Successful Research Languages



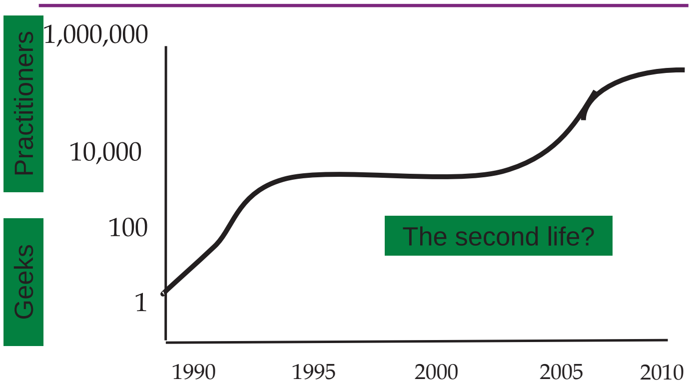
Committee languages



C++, Java, Perl, Ruby



Haskell



Function types mean more

Thanks to *purity*, a function type is a stronger spec in Haskell:

- If `f :: A -> B`, then for every `e :: A`, we know `f e`
  - *Equals* some `v :: B`, or
  - Does not terminate [hand-wave exceptions, …]
- If e1 = e2, then f e1 = f e2
  - A "bigger deal than it looks" – "no side effects or implicit state"
  - `let x = f e in (x,x)`
    is indistinguishable from `(f e, f e)`

Ah, xkcd

http://xkcd.com/1312/

Syntax differences from OCaml

- `x :: Int` means "`x` has type `Int`"
- `y : ys` means "cons `y` onto list `ys`"
- `\x -> x + 1` "\" means lambda
- Required upper/lowercase:
  - Expression identifiers are lowercase
  - Type constructors (names) are uppercase
  - Type variables are lower case (and no `'`)
- Comments:
  - `--` to end of line
  - `{- … -}`
- At top-level no "`let`" for bindings
- In other scopes, `let` or `where` with latter common
- Whitespace relevant (no | on case branches, …)

List comprehensions

- "Not a big deal" but convenient syntax for maps, filters, and zips
  - Could "desugar"

```
myData = [1,2,3,4,5,6,7]
twiceData = [2 * x | x <- myData]
-- [2,4,6,8,10,12,14]
twiceEvenData = [2 * x| x <- myData, x `mod` 2 == 0]
-- [4,8,12]
crossProductDataEvens =
   [(i,j)| i <- myData, j <- myData,
           (i+j) `mod` 2 == 0]
-- [(1,1),(1,3),(1,5),(1,7),(2,2),(2,4),…]
```


Laziness

- Haskell is a **lazy** language
- Functions (and data constructors) do not evaluate their arguments until they need them
  - Then "store the result" to avoid re-execution
  - By default this happens "everywhere"
- Theoretical "best approach" in pure language
  - Humans struggle to determine "when evaluation happens"
  - But thanks to purity it doesn't matter (!)
  - And laziness is powerful for "infinite data structures"

If OCaml vs. Haskell

```
if' :: Bool -> a -> a -> a
if' b e1 e2 = case b of True -> e1 | False -> e2
```

```
(* WRONG: always evaluates e1 and e2 *)
let if' b e1 e2 = match b with true -> e1
                             | false -> e2
(* RIGHT but no memoization (fine here) and caller
   must thunk *)
let if' b e1 e2 = match b with true -> e1 ()
                             | false -> e2 ()
(* using Lazy library (but avoiding special syntax)
and caller must thunk and use Lazy.from_fun *)
let if' b e1 e2 = match b with true -> Lazy.force e1
                             | false -> Lazy.force e2
```


Implmenting OCaml lazy

- Lazy module no big deal:

```
type 'a t1 = Done of 'a | NotDone of unit -> 'a
type 'a t = 'a t1 ref (* export abstractly *)
let from_fun f = ref (NotDone f)
let force p = match !p with
                  Done v -> v
                  NotDone f -> p := Done (f());
                               force p
```

- The point is this is *the semantics* in Haskell for every function call and data argument (forced only when its known that "result of program" needs it)

Examples

```
loop x = loop x
xs = 3+2 : loop 7 : 1+4 : []
x1 = head xs
x2 = (head (tail xs))
x3 = (head (tail (tail xs)))
three = length xs
prefix_sums acc ys =
   case ys of
    [] -> []
    y : ys -> (acc+y) : prefix_sums (acc+y) ys
five = head (prefix_sums 0 xs)
main :: IO a
   print x1; print x3; print three; print five
   -- ; print x2
```

Lazy programming

- Do not worry about creating (thunks that create) large, even infinite data structures
  - Then use only what you need
- Example: *streams*

```
ones = 1 : ones
nats = prefix_sums 0 ones
a_few = tail (take 7 nats)
```

- Example: search problems [not shown]
  - "Natural" separation between "generator" of [potentially-infinite] moves and "consumer" (search strategy)

Back to purity

- Pure functions are easy to test – "no side effects"
- Example: If `xs = reverse(reverse xs)`, then you can replace one with the other with high confidence
- And testing this property cannot depend on *any* state because if `reverse` is pure (and everything in "core Haskell" is pure), then it cannot depend on that state

Purity is beautiful

- Like in OCaml:
  higher-order functions, algebraic data types, parametric polymorphism, ...
- Plus equational reasoning due to "no side effects" and "only needed computations evaluated"
  – If `x = y`, then `f x = f y`
  – Order of evaluation is irrelevant, so don't have to "think about it being lazy" except for termination/performance

… and the beast

- But to be *useful* as well as *beautiful*, a language must manage the "Awkward Squad":
  – Input/Output
  – Imperative update
  – Error recovery (e.g., timing out, catching divide by zero, etc.)
  – Foreign-language interfaces
  – Concurrency

The whole point of a running a program is to affect the real world, an "update in place" of something

Direct approach

- Could allow side effects "the usual way" and discourage them
  – Example: `putchar :: Char -> ()`
  – And similar for references, exceptions, ffi, concurrency
- In practice, this works fine in an eager language (cf. OCaml) but is unworkable in a lazy language
  – Makes evaluation order relevant again
  – And laziness is hard to reason about
  – And compiler wants freedom to optimize away laziness when it can tell "it won't matter"
- This *also* doesn't work at the semantics level if we *define our language* to have "undefined evaluation order" rather than lazy
  – As Haskell does…

Examples

Evaluation order of function arguments and data constructor arguments does not matter (and isn't defined) when functions are pure.

Example:
```
((\x y. y) (putchar 'w') [putchar 'x', putchar 'y']
```

With lazy *implementation* output still depends on how result is used

By the way:
  – What about exceptions?
  – Non-deterministic evaluation order "so any exception might happen" works okay in practice
  – Example: `y = [3 `div` 0, head (tail [4])]`

Tackling the "Awkward Squad"

- Laziness and side effects are *incompatible*
- Side effects are important!
- For a long time, this tension was *embarrassing* to the lazy functional programming community
  – [will skip earlier solutions that "worked okay for I/O in terms of lazy streams"]
- In early 90's, a surprising solution – the *monad* -- emerged from an unlikely source (category theory)
- Haskell's **IO monad** provides a way of tackling the awkward squad: I/O, imperative state, exceptions, foreign functions, & concurrency.

Monadic I/O: The Key Idea

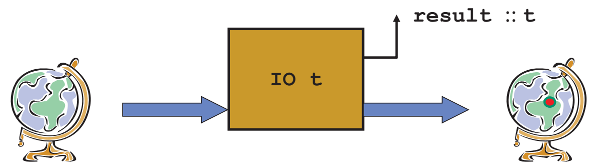
- `IO` is a type constructor
  - `IO t` is a type where `t` is a type
- Think of `IO t` as describing an "action" or "computation" that *when performed* produces a result of type `t`
- Now manipulate values of type `IO t` in your pure lazy language
  - Pass them around, combine them, etc.
    - With helpful functions and sugar
    - But cannot "do an IO action" inside a program
  - Only `main :: IO a`, can be "performed"
    - By "running the program"

A helpful picture

- `IO` is an *abstract* type constructor, but *think of it* as:

```
type IO t = World -> (t, World)
```

  - "An action" that, when performed, takes "a world" and returns "a t and a [new] world"

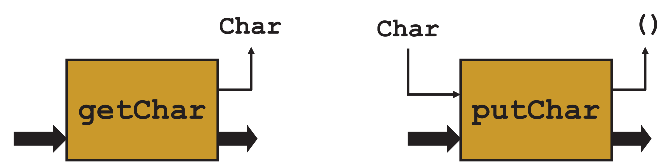


- Thanks to abstraction, there is no way to "get a world", so you can't "store or copy a world" (woah!!)

Actions are first class

- Evaluating an `IO t` produces an action
  - Evaluation has no side effects
  - Does not perform-the-action, which [probably] has side effects

Simple I/O



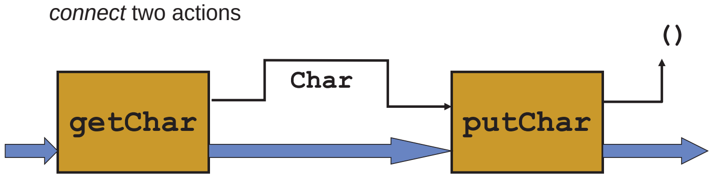

```
getChar :: IO Char
putChar :: Char -> IO ()

main :: IO ()
main = putChar 'x'
```

Main program is an action of type `IO ()` (and it is performed)

Connection actions

- To read a character and then write it back out, we need to *connect* two actions



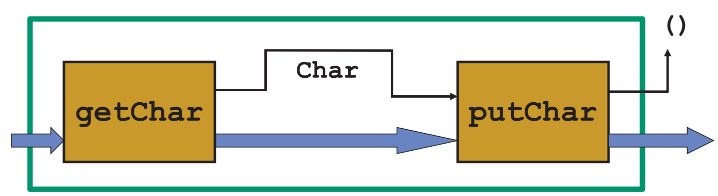
- This is done with the *bind combinator*…

Bind

- "Provided" (as are `getChar` and `putChar` are)

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

- Semantics is exactly "the compound sequenced action" you would expect from the type

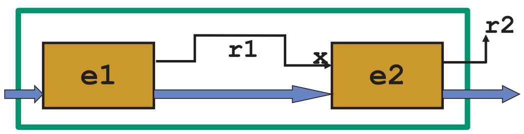



```
echo :: IO ()
echo = getChar >>= putChar
```

More on >>=

- Called bind because it *binds* the result of the left-hand action in the action on the right
- The result of calling >>= is an action that, when performed:
  - Performs the action on the left, producing result *r1*
  - Applies the function on the right to *r1* to get another action
  - Applies that action, to get another result *r2*
  - Returns *r2*

```
e1 >>= \x -> e2
```



Printing a character twice

```
echoDup :: IO ()
echoDup = getChar    >>= (\c ->
          putChar c >>= (\() ->
          putChar c))
```

- Parentheses are optional for usual lambda-concrete-syntax reasons
- "Do notation" is syntactic sugar for exactly the same thing
  - Designed to "look imperative"; will extend it soon
  - It's just sugar for creating actions with bind, not performing them!

```
echoDup :: IO ()
echo = do { c  <- getChar;
            () <- putChar c;
            putChar c; }
```


More sugar / helper functions

- The "then" combinator sequences actions when there is no value to pass forward

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

```
echoDup :: IO ()
echoDup = getChar    >>= (\c ->
          putChar c >>
          putChar c)
```

```
echoDup :: IO ()
echoDup = do { c  <- getChar;
               putChar c;
               putChar c; }
```


Getting Two Characters

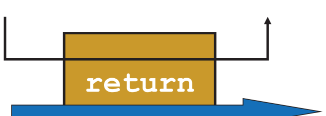
```
getTwoChars :: IO (Char,Char)
getTwoChars = getChar >>= (\c1 ->
              getChar >>= (\c2 ->
              ????
```

- `(c1,c2) :: (Char, Char)` but we need the ???? to be replaced with something of type `IO (Char, Char)`
- Need a way to convert "plain" values into IO actions
  - Should be fine: "performing the action in a world" is just "evaluate the expression" [ignoring the world]

The return combinator

- [I won't try to justify the name "return" – it's not what you think even though it sorta kinda sounds right]
- The "action" `return v` just produces result v (no side effects)

```
return :: a -> IO a
```




```
getTwoChars :: IO (Char,Char)
getTwoChars = getChar >>= (\c1 ->
              getChar >>= (\c2 ->
              return (c1,c2)
```


Yet more sugar

- Can omit braces for do-notation
- Can use indentation instead of semicolons
- … some more
- But the simple stuff is "just":
  - `x <- e1; e2` for `e1 >>= \x. e2`
  - `e1; e2` for `e1 >> e2`
  - `return e` [not necessarily just at end because it's *not* the "return" you are used to]

Bigger Example

- [Of course in practice, you would provide this as a faster primitive]
- Key points:
  - Recursion as usual ☺
  - "Mixing in" regular code that produces actions

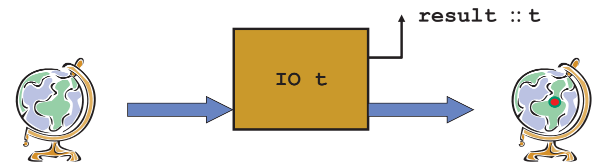
```
getLine :: IO [Char]
getLine = do { c <- getChar ;
               if c == '\n' then
                    return []
               else
                    do { cs <- getLine;
                         return (c:cs) }}
```


A helpful picture [again]

- IO is an *abstract* type constructor, but *think of it* as:

```
type IO t = World -> (t, World)
```

  - "An action" that, when performed, takes "a world" and returns "a `t` and a [new] world"



- Thanks to abstraction, there is no way to "get a world", so you can't "store or copy a world" (woah!!)
  - Enforces "single path" through a sequence of actions

Control Structures

- More examples showing how "first-class actions" can be composed to build your own control structures
  - Think: treating code [actions] as data and building up compound data that can later be 'run'

```
forever :: IO () -> IO ()
forever a = a >> forever a

repeatN :: Int -> IO () -> IO ()
repeatN n a = if n=0
              then return ()
              else a >> repeatN (n-1) a
```

  - Example use:

```
repeatN 5 (putChar '#')
```


More first-class fun

- Showing general idea of "first-class actions" lets the programmer define structures of [arbitrary] actions
  - No need to bake more than `>>=` and `return` into the language

```
sequence :: [IO a] -> IO [a]
sequence xs =
   case xs of
     [] -> return []
     y:ys= do { r  <- y;
                rs <- sequence ys;
                return (r:rs) }
```

  - Example use:

```
sequence [getLine, putChar '>' >> return [], getLine]
```


Growing the IO monad

- The IO monad is "built-in" to Haskell via `main :: IO()`
- It is "one-stop shopping" for "all the stuff that needs a well-defined sequence when performed"
  - a.k.a. "the sin bin" combined with "the outside world"
- Just a flavor:

```
openFile :: FilePath -> IOMode -> IO Handle
hPutStr  :: Handle -> String -> IO ()
hGetLine :: Handle -> IO String
hClose   :: Handle -> IO ()

data IORef a   -- Abstract type
newIORef    :: a -> IO (IORef a)
readIORef   :: IORef a -> IO a
writeIORef :: IORef a -> a -> IO ()
```


So we have an imperative language

So now you *could* write this

```
count :: (a -> Bool) -> [a] -> IO Int
count f xs = do { r <- newIORef 0; help r xs }
  where
     help r xs =
       case xs of
         [] -> readIORef r
       | x:xs -> if f x
                 then do { old <- readIORef r;
                           writeIORef r (old+1);
                           help r xs }
                 else help r xs
```

But…

- Just because you *can* write imperative code doesn't mean you *should*

```
count :: (a -> Bool) -> [a] -> Int
count f xs =
    case xs of
        [] -> 0
       | x:xs -> (if f x then 1 else 0)
                     + count f xs
-- previous slide's count
--     :: (a -> Bool) -> [a] -> IO Int
-- can get an IO Int with
--    return (count f xs)
```


The Roach Motel ☺

- "Once you get in to the IO monad, you can't get out"
  - Bind lets you use a value "in there" but "leaves you in there"
  - Return "gets anything you want in there"
- So you find yourself "wanting to cheat", looking for a `magic_escape :: IO a -> a`
- The presence of such a function would "break everything" because it would have to "perform the action" [no other way it could find an `a`, but then we have side effects in allegedly pure code, which was *the whole thing we were trying to avoid*]

Examples with this problem

- Suppose you want to read some configuration options from a file but treat the values as "pure constants"

```
configFileContents :: [String]
configFileContents = lines (readFile "config") --NO!
useOptimization :: Bool
useOptimization = elem "optimize" configFileContents
```

- This doesn't and shouldn't type-check: `readFile :: String->IO String`
- Leaves only two options:
  - Put all code depending on file contents in IO monad
  - Cheat

The Cheat Exists (!)

- They call it unsafePerformIO not magic_escape
  `magic_escape :: IO a -> a`
- Any code that uses it has an obligation to "know" that "it doesn't matter"
  - When we perform the IO action
  - How many times we perform the IO action
  - Relative order of performing this action vs. other actions

  [Notice: Reading a read-only, accessible file meets this obligation]
- The operator has a deliberately long to discourage its use

BTW, It really is a cheat

- You can use unsafePerformIO to circumvent the type system arbitrarily
  - Exact same issue arises in OCaml without "the value restriction"
  - OCaml has to avoid this; Haskell can say "unsafePerformIO is unsafe"

```
r :: forall a. IORef a    -- This is bad!
r =  unsafePerformIO (newIORef (error "urk"))

cast :: b -> c
cast x = unsafePerformIO (do {writeIORef r x;
                              readIORef r     })
```


Implementation

- The compiler front-end and optimizer doesn't know that the IO monad is special
  - It can be restrained by using an unkown "World" type that is "threaded through"
- Then the back-end code generator can convert the "World"-y code to in-place imperative operations

```
type IO t = World -> (t, World) -- in compiler front
return :: a -> IO a
return a = \w -> (a,w)
(>>=) :: IO a -> (a -> IO b) -> IO b
(>>=) m k = \w -> case m w of (r,w') -> k r w'
```

Summary

- A Haskell program is a single IO action called **`main`**. Inside the IO monad, evaluation order is defined
- Big IO actions are built by gluing together smaller ones with bind (**`>>=`**) and by converting pure code into actions with **`return`**
- IO actions are first-class
  - They can be passed to functions, returned from functions, and stored in data structures
  - So it is easy to define new "glue" combinators
- The IO Monad allows Haskell to be pure while efficiently supporting side effects
- The type system separates the pure from the effectful code

A Monadic "Outer Layer"

- In languages like ML or Java, the fact that the language is in the IO monad is baked into the language
  - There is no need to mark anything in the type system because it is everywhere.
- In Haskell, the programmer can choose when to live in the IO monad and when to live in the realm of pure functional programming
- So it is not Haskell that lacks imperative features, but rather the other languages that lack the ability to have a statically distinguishable pure subset

Now from here [time permitting]

- There are lots of other monads
  - All monads have **`>>=`** and **`return`**
  - They can differ on "what else they have"
  - Do-notation can be used with "any monad"
- You can write code that is "generic over" "which monad"
  - Ridiculously powerful idiom for "threading things" without syntactic clutter (cf. when I showed you "state monad" in OCaml)
- Monad is a "typeclass"
  - Haskell supports "other [user-defined] typeclasses too"
  - Integrates overloading with polymorphic lambda calculus