



Functional Programming

Lecture 4

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Topics

abstract data types, algebraic data types, binary search trees, combinator parsing, efficiency, encoding data types as lambda-terms, evaluation strategies, formal verification, first steps, guarded recursion, Haskell introduction, higher-order functions, historical overview, induction, infinite data structures, input and output, lambda-calculus, lazy evaluation, list comprehensions, lists, modules, pattern matching, polymorphism, property-based testing, reasoning about functional programs, recursive functions, sets, strings, tail recursion, trees, tupling, type checking, type inference, types, types and type classes, unification, user-defined types

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Overview

- Intermediate Wrap-Up
- User-Defined Types
- Trees
- Input and Output

Intermediate Wrap-Up

Functions You Should Know

- infix operators and special syntax

`(<=)`, `(<)`, `(==)`, `(>=)`, `(>)`, `(||)`, `(-)`, `(,)`, `(:)`, `(/=)`, `(.)`,
`(*)`, `(&&)`, `(+)`, `(++)`, `[]`, `[m..n]`

- other `Prelude` functions

`abs`, `compare`, `concat`, `const`, `div`, `drop`, `error`, `even`,
`filter`, `foldr`, `foldr1`, `fromInteger`, `fst`, `head`, `init`, `last`,
`length`, `lines`, `map`, `max`, `min`, `mod`, `negate`, `not`, `null`,
`product`, `putStr`, `putStrLn`, `read`, `replicate`, `reverse`, `show`,
`showList`, `showsPrec`, `signum`, `snd`, `splitAt`, `sum`, `tail`, `take`,
`unlines`, `unwords`, `words`, `zip`, `zipWith`

- other `Prelude` constants

`False`, `otherwise`, `True`

- other functions

`Data.Char.isDigit`, `System.Environment.getArgs`

Syntax You Should Recognize

- **anonymous functions** / functions without names

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`(+)` = `(\x y -> x + y)` infix to prefix

`x `f` y = f x y` prefix to infix

`(a >)` = `(\x -> a > x)` argument smaller than **a**?

`(> b)` = `(\x -> x > b)` argument greater than **b**?

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headIfPositive xs = case xs of
    x:_ | x > 0 -> x
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headIfPositive xs = case xs of
    x:_ | x > 0 -> x
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- list comprehensions

```
filter p xs == [x | x <- xs, p x]
```

```
map f xs == [f x | x <- xs]
```

```
concat (map f xs) == [y | x <- xs, y <- f x]
```

```
concat $ map (\x -> map ((,) x) ys) xs ==
```

```
[(x, y) | x <- xs, y <- ys]
```

Types and Type Classes

- **type signatures** – annotate functions by types

```
range :: Int -> Int -> [Int]
```

```
range m n | m > n      = []
```

```
          | otherwise = m : range (m + 1) n
```

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- type synonyms – mnemonic names for types

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type Height = Int
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- **type classes** and **class constraints** – for every function **f**, specific to class **C**, type inference adds a **C**-constraint to type

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Example – Type Constraints

- without type signature, we get

```
ghci> :t range
```

```
range :: (Ord a, Num a) => a -> a -> [a]
```

- $m > n$, hence m and n of class Ord and m and n of same type
- $m + 1$, hence m of class Num
- m and n of same type, hence n of class Num

Equational Reasoning

- a function definition in Haskell is a (set of conditional) equation(s)
- if conditions are met, we may “replace equals by equals”
- in this way we may **evaluate** function calls by applying equations stepwise, until we reach final result

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Kinds of Conditions

- “**if** b **then** t **else** e ” is t , when b is true; and e , otherwise
- “**case** e **of** { $p_1 \rightarrow e_1$; ... ; $p_n \rightarrow e_n$ }” is e_i , if e first matches p_i

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Primitive Operations

- for primitive operations (like $(+)$, $(*)$, ...), we assume predefined equations
- e.g., $1 + 2 = 3$, $0 * 10 = 0$, ...

Examples – Equational Reasoning

- definition

```
zip (x:xs) (y:ys) = (x, y) : zip xs ys
```

```
zip _      _      = []
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            | otherwise = n * factorial (n - 1)
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- definitions

```
null xs = case xs of { [] -> True; _ -> False }
tail xs = case xs of _:ys -> ys
prod xs = if null xs then 1
          else head xs * prod (tail xs)
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- evaluate `prod [5,6]`

User-Defined Types

Data Declarations – Algebraic Data Types

- new types are introduced by

$$\begin{array}{rcl} \mathbf{data} \ T \ \alpha_1 \ \cdots \ \alpha_n & = & C_1 \ \tau_{11} \ \cdots \ \tau_{1m_1} \\ & & | \ \vdots \\ & & | \ C_k \ \tau_{k1} \ \cdots \ \tau_{km_k} \end{array}$$

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Examples

- `data Bool = False | True`
- `data List a = Nil | Cons a (List a)`
- `data Pair a b = Pair a b`

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constructors and type names
live in different name spaces

Automatically Deriving Type Class Instances

- for some type classes it is possible to automatically derive instances for algebraic data types
- e.g.,

```
data List a = Nil | Cons a (List a)
  deriving (Eq, Show, Read)
```
- now, we are able to use `(==)`, `show`, and `read` for `Lists`

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Examples

```
ghci> Nil == Cons 1 Nil
False
ghci> show (Cons 1 (Cons 2 Nil))
"Cons 1 (Cons 2 Nil)"
ghci> read it :: List Int
Cons 1 (Cons 2 Nil)
```

Trees

Definition – Tree

- (rooted) tree $T = (N, E)$
- with set of nodes/vertices N
- and set of edges $E \subseteq N \times N$
- unique root of T ($root(T) \in N$) without predecessor
- all other nodes have exactly one predecessor

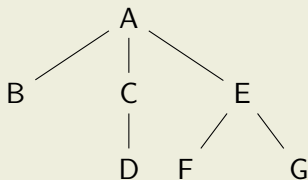
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Example

- $N = \{A, B, C, D, E, F, G\}$
- $E = \{(A, B), (A, C), (A, E), (C, D), (E, F), (E, G)\}$
- $root(T) = A$

- $T =$



Trees in Haskell

- possible type for trees with arbitrary nodes
`data Tree a = Empty | Node a [Tree a]`
- a tree is either empty (0 nodes) or there is at least one node with content of type `a` and an arbitrary number of successor trees

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Examples

Empty

1

Node 1 []

1

2

Node 1 [Node 2 []]

1

2

3

Node 1 [Node 2 [], Node 3 []]

Binary Trees

- restrict number of successors (maximum 2)
- type

```
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Functions on Binary Trees

- size – number of nodes

```
size :: BTree a -> Integer
```

```
size Empty          = 0
```

```
size (Node _ l r) = size l + size r + 1
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size (Node _ l r) = size l + size r + 1
```

- height – length of longest path from root to some leaf

```
height :: BTree a -> Integer
```

```
height Empty        = 0
```

```
height (Node _ l r) = max (height l) (height r) + 1
```

Creating Trees from Lists

- the easy way

```
fromList [] = Empty
```

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fromList (x:xs) = Node x Empty (fromList xs)
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- the balanced way

```
make [] = Empty
```

```
make xs = Node z (make ys) (make zs)
```

where

```
    m          = length xs `div` 2
```

```
    (ys, z:zs) = splitAt m xs
```

Creating Trees from Lists

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fromList []      = Empty
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```
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  where
    m          = length xs `div` 2
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```

- the orderly way

```
searchTree = foldr insert Empty
  where
    insert x Empty = Node x Empty Empty
    insert x (Node y l r)
      | x < y      = Node y (insert x l) r
      | otherwise = Node y l (insert x r)
```

Transforming Trees into Lists

```
flatten Empty          = []  
flatten (Node x l r) = flatten l ++ [x] ++ flatten r
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A Sorting Algorithm for Lists

```
sort = flatten . searchTree
```

Input and Output

An Initial Example

- write the file `welcomeIO.hs`

```
main = do
```

```
    putStrLn "Greetings! What's your name?"
```

```
    name <- getLine
```

```
    putStrLn (
```

```
        "Welcome to Haskell's IO, " ++ name ++ "!")
```

- compile it with GHC via

```
$ ghc --make welcomeIO.hs
```

- and run it

```
$ ./welcomeIO
```

```
Greetings! What's your name?
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Notes

- `putStrLn` – prints string followed by newline
- `getLine` – reads line from standard input
- new syntax: `do` and `<-`

IO and the Type System

- consider

```
ghci> :load welcomeIO.hs
```

```
ghci> :t putStrLn
```

```
putStrLn :: String -> IO ()
```

```
ghci> :t getLine
```

```
getLine :: IO String
```

```
ghci> :t main
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```
main :: IO ()
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- `IO a` is type of IO actions delivering results of type `a` (in addition to their IO operations)

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Examples

- `String -> IO ()` – after supplying a string, we obtain an IO action (in case of `putStrLn`, “printing”)
- `IO ()` – just IO (in case of `main`, run our program)
- `IO String` – do some IO and deliver a string (in case of `getLine`, user-input)

Further Notes

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- inside IO actions, `x <- action` (where `action :: IO a`) may be used to bind result of `action` (which has type `a`) to name `x` (but seriously, this is actually only done, once execution starts)

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Implications

- once we are inside an IO action, we cannot escape
- strict separation between purely functional code and IO
- when `IO a` does not appear inside type signature, we can be absolutely sure that no IO (“side-effect”) is performed

Using Pure Code Inside IO Actions

- consider program `reply.hs`

```
reply :: String -> String
reply name =
  "Pleased to meet you, " ++ name ++ ".\n" ++
  "Your name contains " ++ n ++ " characters."
  where
    n = show $ length name
```

```
main :: IO ()
main = do
  putStrLn "Greetings again. What's your name?"
  name <- getLine
  let niceReply = reply name
  putStrLn niceReply
```

- that is, we may use `let x = e` (there is no `in` here!) to bind result of pure expression `e` to name `x`

Some Simple IO Functions

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- `getChar :: IO Char` – read single character from stdin
- `getLine :: IO String` – read line (excluding newline)
- `interact :: (String -> String) -> IO ()` – use function that gets input as string and produces output as string

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Notes

- `getArgs :: IO [String]` is in `System.Environment`
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Do Some IO Action for Each Argument

```
foreach :: [a] -> (a -> IO ()) -> IO ()
```

- `foreach [] io = return ()`
`foreach (a:as) io = do { io a; foreach as io }`

- better `cat.hs`

```
main = do
  files <- getArgs
  if null files then interact id else do
    foreach files readAndPrint
  where readAndPrint file = do
        s <- readFile file
        putStr s
```

Homework (for November 23rd)

1. Read Chapter 7 of [Real World Haskell](#).
2. Evaluate the function call `take 4 (iterate tail [1..3])` by equational reasoning using the definitions:
`iterate f x = x : iterate f (f x)`
`tail (_:xs) = xs`
`take n xs | n <= 0 || null xs = []`
`take n (x:xs) = x : take (n-1) xs`
3. Define a new type `Cmd` of commands that work with respect to an implicit stack and allow us to push an `Int` on top, pop the top element, and add the topmost elements by popping both and pushing the result on top. Moreover, implement a function `exec :: Cmd -> Stack Int -> Stack Int` that executes a single command on a given stack.
4. Implement a function `levels :: BTree a -> [[a]]` that returns the list of nodes at each level of a binary tree.

Example:

```
levels (Node 1 (Node 2 Empty Empty)
           (Node 3 Empty Empty)) = [[1], [2,3]]
```

Homework (for November 23rd, continued)

5. Implement a program `NL.hs` that echoes every line of its standard input with line numbers added.

Example: `echo -e "what\nup?" | ./NL`

```
1 what
```

```
2 up?
```

6. Implement a simple stack-based calculator that outputs the internal stack in each iteration, reads commands from standard input (until the string `exit` is observed) and executes them on the internal stack.

Example: `./Calc`

```
stack: []
```

```
> Push 1
```

```
stack: [1]
```

```
> Push 2
```

```
stack: [2,1]
```

```
> Add
```

```
stack: [3]
```

```
> exit
```