

CSE 114A: Fall 2023

**Foundations of Programming
Languages**

Intro to Haskell

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Based on course materials developed by Nadia Polikarpova

What is Haskell?

- A **typed, lazy, purely functional** programming language
 - Haskell = λ -calculus +
 - Better syntax
 - Types
 - Built-in features
 - Booleans, numbers, characters
 - Records (tuples)
 - Lists
 - Recursion
 - ...

Why Haskell?

- Haskell programs tend to be *simple* and *correct*
- ***Quicksort in Haskell***

```
sort []      = []
sort (x:xs) = sort ls ++ [x] ++ sort rs
  where
    ls      = [ l | l <- xs, l <= x ]
    rs      = [ r | r <- xs, x <  r ]
```

- ***Goals for this week***
 - Understand the above code
 - Understand what **typed**, **lazy**, and **purely functional** means (and why you care)

Haskell vs λ -calculus: Programs

- A program is an expression (not a sequence of statements)
- It evaluates to a value (it does not perform actions)
 - λ :
 $(\lambda x \rightarrow x) \text{ apple} \quad \text{--} \text{=} \text{~} \text{>} \text{ apple}$
 - Haskell:
 $(\lambda x \rightarrow x) \text{ "apple"} \quad \text{--} \text{=} \text{~} \text{>} \text{ "apple"}$

Haskell vs λ -calculus: Functions

- **Functions are first-class values:**
 - can be *passed as arguments* to other functions
 - can be *returned as results* from other functions
 - can be *partially applied* (arguments passed *one at a time*)

```
(\x -> (\y -> x (x y))) (\z -> z + 1) 0  -- =~> 2
```

- **BUT:** unlike λ -calculus, not everything is a function!

Haskell vs λ -calculus: top-level bindings

- Like in Elsa, we can name terms to use them later
- **Elsa:**

```
let T      = \x y -> x
```

```
let F      = \x y -> y
```

```
let PAIR = \x y -> \b -> ITE b x y
```

```
let FST  = \p -> p T
```

```
let SND  = \p -> p F
```

```
eval fst:
```

```
FST (PAIR apple orange)
```

```
=~> apple
```

Haskell vs λ -calculus: top-level bindings

- Like in Elsa, we can name terms to use them later

- **Haskell:**

```
haskellIsAwesome = True
```

```
pair = \x y -> \b -> if b then x else y
```

```
fst = \p -> p haskellIsAwesome
```

```
snd = \p -> p False
```

```
-- In GHCi:
```

```
> fst (pair "apple" "orange") -- "apple"
```

- **The names are called top-level variables**
- **Their definitions are called top-level bindings**

Syntax: Equations and Patterns

- You can define function bindings using **equations**:

```
pair x y b = if b then x else y -- pair = \x y b -> ...
fst p      = p True             -- fst = \p -> ...
snd p      = p False            -- snd = \p -> ...
```


Syntax: Equations and Patterns

- A single function binding can have *multiple* equations with different **patterns** of parameters:

```
pair x y True = x  -- If 3rd arg matches True,  
                  -- use this equation;  
pair x y False = y -- Otherwise, if 3rd arg matches  
                   -- False, use this equation.
```

- The first equation whose pattern matches the actual arguments is chosen
- For now, a pattern is:
 - a variable (matches any value)
 - or a value (matches only that value)

Syntax: Equations and Patterns

- A single function binding can have *multiple* equations with different **patterns** of parameters:

```
pair x y True = x -- If 3rd arg matches True,  
                -- use this equation;  
pair x y False = y -- Otherwise, if 3rd arg matches  
                    -- False, use this equation.
```

- Same as:

```
pair x y True = x -- If 3rd arg matches True,  
                -- use this equation;  
pair x y b = y -- Otherwise use this equation.
```

Syntax: Equations and Patterns

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                    -- False, use this equation.
```

- Same as:

```
pair x y True = x  -- If 3rd arg matches True,  
                  -- use this equation;  
pair x y _   = y  -- Otherwise use this equation.
```

QUIZ: Pair

Which of the following definitions of pair is incorrect? *

A. `pair x y = \b -> if b then x else y`

B. `pair x = \y b -> if b then x else y`

C.

```
pair x _ True = x
```

```
pair _ y _   = y
```

D.

```
pair x y b   = x
```

```
pair x y False = y
```

E. all of the above



<http://tiny.cc/cse116-pair-ind>

QUIZ: Pair

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pair x _ True = x
```

```
pair _ y _ = y
```

D.

```
pair x y b = x
```

```
pair x y False = y
```

E. all of the above



<http://tiny.cc/cse116-pair-grp>

Equations with guards

- An equation can have multiple guards (Boolean expressions):

```
cmpSquare x y | x > y*y = "bigger :)"  
              | x == y*y = "same :|"  
              | x < y*y = "smaller :("
```

- Same as:

```
cmpSquare x y | x > y*y = "bigger :)"  
              | x == y*y = "same :|"  
              | otherwise = "smaller :("
```

Recursion

- Recursion is built-in, so you can write:

```
sum n = if n == 0
        then 0
        else n + sum (n - 1)
```

- Or you can write:

```
sum 0 = 0
sum n = n + sum (n - 1)
```

Scope of variables

- Top-level variables have global scope

```
message = if haskellIsAwesome -- this var defined below
          then "I love CSE 130"
          else "I'm dropping CSE 130"
haskellIsAwesome = True
```

- Or you can write:

```
-- What does f compute?
f 0 = True
f n = g (n - 1) -- mutual recursion!
g 0 = False
g n = f (n - 1) -- mutual recursion!
```

- Answer: f is isEven, g is isOdd

Scope of variables

- Is this allowed?

```
haskellIsAwesome = True
```

```
haskellIsAwesome = False -- changed my mind
```

- Answer: no, a variable can be defined once per scope; no mutation!

Local variables

- You can introduce a *new* (local) scope using a **let**-expression

```
sum 0 = 0
sum n = let n' = n - 1
        in n + sum n'  -- the scope of n'
                       -- is the term after in
```

- Syntactic sugar for nested **let**-expressions:

```
sum 0 = 0
sum n = let
        n'   = n - 1
        sum' = sum n'
        in n + sum'
```

Local variables

- If you need a variable whose scope is an equation, use the **where** clause instead:

```
cmpSquare x y | x > z = "bigger :)"
              | x == z = "same :|"
              | x < z = "smaller :("
where z = y*y
```

Types

- What would *Elsa* say?

```
let FNORD = ONE ZERO
```

- **Answer:** Nothing. When evaluated, it will crunch to *something*, but it will be nonsensical.
 - λ -calculus is **untyped**.

Types

- What would *Python* say?

```
def fnord():  
    return 0(1)
```

- **Answer:** Nothing. When evaluated will cause a run-time error.
 - Python is **dynamically typed**

Types

- What would *Java* say?

```
void fnord() {  
    int zero;  
    zero(1);  
}
```

- **Answer:** Java compiler will reject this.
 - Java is **statically typed**.

Types

- In *Haskell* every expression either **has a type** or is **ill-typed** and rejected statically (at compile-time, before execution starts)
 - like in Java
 - unlike λ -calculus or Python

```
fnord = 1 0      -- rejected by GHC
```

Type Annotations

- You can annotate your bindings with their types using `::`, like so:

```
-- | This is a Boolean:  
haskellIsAwesome :: Bool  
haskellIsAwesome = True
```

```
-- | This is a string  
message :: String  
message = if haskellIsAwesome  
          then "I love CMPS 112"  
          else "I'm dropping CMPS 112"
```


Type Annotations

```
-- | This is a word-size integer
rating :: Int
rating = if haskellIsAwesome then 10 else 0
```

```
-- | This is an arbitrary precision integer
bigNumber :: Integer
bigNumber = factorial 100
```

- If you omit annotations, GHC will infer them for you
 - Inspect types in GHCi using `:t`
 - You should annotate all top-level bindings anyway! (Why?)

Function Types

- Functions have **arrow types**
 - $\lambda x \rightarrow e$ has type **A** \rightarrow **B**
 - If e has type **B**, assuming x has type **A**
- For example:
 - > `:t (\lambda x -> if x then 'a' else 'b')`
 - `(\lambda x -> if x then 'a' else 'b') :: Bool -> Char`

Function Types

- You should annotate your function bindings:

```
sum :: Int -> Int
```

```
sum 0 = 0
```

```
sum n = n + sum (n - 1)
```

- With multiple arguments:

```
pair :: String -> (String -> (Bool -> String))
```

```
pair x y b = if b then x else y
```

- Same as:

```
pair :: String -> String -> Bool -> String
```

```
pair x y b = if b then x else y
```

QUIZ: Type of Pair

With `pair :: String -> String -> Bool -> String`, what would GHCi say

```
>:t pair "apple" "orange"
```

- A. Syntax error
- B. The term is ill-typed
- C. `String`
- D. `Bool -> String`
- E. `String -> String -> Bool -> String`



<http://tiny.cc/cse116-tpair-ind>

QUIZ: Type of Pair

With `pair :: String -> String -> Bool -> String`, what would GHCi say

```
>:t pair "apple" "orange"
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- A. Syntax error
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- C. `String`
- D. `Bool -> String`
- E. `String -> String -> Bool -> String`



<http://tiny.cc/cse116-tpair-grp>

Lists

- A list is
 - either an *empty list*
`[]` -- pronounced "nil"
 - or a *head element* attached to a *tail list*
`x:xs` -- pronounced "x cons xs"

Terminology: constructors and values

```
[]          -- A list with zero elements

1:[]        -- A list with one element: 1

(:) 1 []    -- Same thing: for any infix op,
             -- (op) is a regular function!

1:(2:(3:(4:[]))) -- A list with four elements: 1, 2, 3, 4

1:2:3:4:[]  -- Same thing (: is right associative)

[1,2,3,4]   -- Same thing (syntactic sugar)
```

Lists

- `[]` and `(:)` are called the list **constructors**
- We've seen constructors before:
 - **True** and **False** are **Bool** constructors
 - **0**, **1**, **2** are... well, it's complicated, but you can think of them as **Int** constructors
 - these constructions didn't take any parameters, so we just called them *values*
- In general, a **value** is a constructor applied to *other values* (e.g., *list values* on previous slide)

Type of a list

- A list has type `[A]` if each one of its elements has type `A`
- Examples:

```
myList :: [Int]
```

```
myList = [1,2,3,4]
```

```
myList' :: [Char]           -- or :: String
```

```
myList' = ['h', 'e', 'l', 'l', 'o'] -- or = "hello"
```

```
myList'' = [1, 'h'] -- Type error: elements have  
-- different types!
```

```
myList''' :: [t] -- Generic: works for any type t!
```

```
myList''' = []
```

Functions on lists: range

```
-- | List of integers from n upto m
upto :: Int -> Int -> [Int]
upto n m
  | n > m      = []
  | otherwise = n : (upto (n + 1) m)
```

- There is also syntactic sugar for this!

```
[1..7]      -- [1,2,3,4,5,6,7]
[1,3..7]    -- [1,3,5,7]
```

Functions on lists: length

```
-- | Length of the list
```

```
length :: ???
```

```
length xs = ???
```

Pattern matching on lists

```
-- | Length of the list
length :: [Int] -> Int
length []      = 0
length (_:xs) = 1 + length xs
```

- ~~A pattern is either a *variable* (incl. `_`) or a *value*~~
- A pattern is
 - either a *variable* (incl. `_`)
 - or a *constructor* applied to other *patterns*
- **Pattern matching** attempts to match *values* against *patterns* and, if desired, *bind* variables to successful matches.

QUIZ: Patterns

Which of the following is not a pattern? *

- A. (1 : xs)
- B. (_ : _ : _)
- C. [x]
- D. [1+2, x, y]
- E. all of the above



<http://tiny.cc/cse116-pattern-ind>

QUIZ: Patterns (wrong url)

Which of the following is not a pattern? *

- A. (1 : xs)
- B. (_ : _ : _)
- C. [x]
- D. [1+2, x, y]
- E. all of the above



<http://tiny.cc/cse116-pattern-grp>

Some useful library functions

```
-- | Is the list empty?
```

```
null :: [t] -> Bool
```

```
-- | Head of the list
```

```
head :: [t] -> t    -- careful: partial function!
```

```
-- | Tail of the list
```

```
tail :: [t] -> [t] -- careful: partial function!
```

```
-- | Length of the list
```

```
length :: [t] -> Int
```

```
-- | Append two lists
```

```
(++) :: [t] -> [t] -> [t]
```

```
-- | Are two lists equal?
```

```
(==) :: [t] -> [t] -> Bool
```

You can search for library functions (by type!) at hoogle.haskell.org

Pairs

```
myPair :: (String, Int) -- pair of String and Int
myPair = ("apple", 3)
```

- (,) is the pair constructor

```
-- Field access using library functions:
whichFruit = fst myPair -- "apple"
howMany    = snd myPair -- 3
```

```
-- Field access using pattern matching:
isEmpty (x, y) = y == 0
```

```
-- same as:
isEmpty      = \ (x, y) -> y == 0
```

```
-- same as:
isEmpty p    = let (x, y) = p in y == 0
```

You can use pattern matching not only in equations, but also in λ -bindings and `let`-bindings!

Pattern matching with pairs

- Is this pattern matching correct? What does this function do?

```
f :: String -> [(String, Int)] -> Int
```

```
f _ [] = 0
```

```
f x ((k,v) : ps)
```

```
  | x == k      = v
```

```
  | otherwise = f x ps
```

Pattern matching with pairs

- Is this pattern matching correct? What does this function do?

```
f :: String -> [(String, Int)] -> Int
f _ [] = 0
f x ((k,v) : ps)
  | x == k = v
  | otherwise = f x ps
```

- **Answer:** a list of pairs represents key-value pairs in a dictionary; f performs lookup by key

Tuples

- Can we implement triples like in λ -calculus?
- Sure! But Haskell has native support for n -tuples:

```
myPair    :: (String, Int)
myPair    = ("apple", 3)
```

```
myTriple  :: (Bool, Int, [Int])
myTriple  = (True, 1, [1,2,3])
```

```
my4tuple  :: (Float, Float, Float, Float)
my4tuple  = (pi, sin pi, cos pi, sqrt 2)
```

```
...
```

```
-- And also:
```

```
myUnit    :: ()
myUnit    = ()
```

List comprehensions

- A convenient way to construct lists from other lists:

```
[toUpper c | c <- s] -- Convert string s to upper case
```

```
[(i,j) | i <- [1..3],  
         j <- [1..i] ] -- Multiple generators
```

```
[(i,j) | i <- [0..5],  
         j <- [0..5],  
         i + j == 5] -- Guards
```

Quicksort in Haskell

```
sort []      = []
sort (x:xs) = sort ls ++ [x] ++ sort rs
  where
    ls      = [ l | l <- xs, l <= x ]
    rs      = [ r | r <- xs, r > x ]
```

What is Haskell?

- A **typed, lazy, purely functional** programming language

Haskell is statically typed

- Every expression either has a type, or is *ill-typed* and rejected at compile time
- **Why is this good?**
 - catches errors early
 - types are contracts (you don't have to handle ill-typed inputs!)
 - enables compiler optimizations

Haskell is purely functional

- **Functional** = functions are *first-class values*
- **Pure** = a program is an expression that evaluates to a value
 - No side effects! unlike in Python, Java, etc:

```
public int f(int x) {  
    calls++;           // side effect!  
    System.out.println("calling f"); // side effect!  
    launchMissile();  // side effect!  
    return x * 2;  
}
```

- in Haskell, a function of type `Int -> Int` computes a *single integer output* from a *single integer input* and **does nothing else**

Haskell is purely functional

- **Referential transparency:** The same expression always evaluates to the same value
 - More precisely: In a scope where x_1, \dots, x_n are defined, all occurrences of e with $FV(e) = \{x_1, \dots, x_n\}$ have the same value
- **Why is this good?**
 - easier to reason about (remember $x++$ vs $++x$ in C?)
 - enables compiler optimizations
 - especially great for parallelization ($e_1 + e_2$: we can always compute e_1 and e_2 in parallel!)

Haskell is lazy

- An expression is evaluated only when its result is needed
- **Example:** `take 2 [1 .. (factorial 100)]`

```
      take 2 (    upto 1 (factorial 100))
=>      take 2 (    upto 1 933262154439...)
=>      take 2 (1:(upto 2 933262154439...)) -- def upto
=> 1:    (take 1 (    upto 2 933262154439...)) -- def take 3
=> 1:    (take 1 (2:(upto 3 933262154439...)) -- def upto
=> 1:2:(take 0 (    upto 3 933262154439...)) -- def take 3
=> 1:2:[]                                     -- def take 1
```

-

Haskell is lazy

- **Why is this good?**

- Can implement cool stuff like infinite lists: `[1..]`

```
-- first n pairs of co-primes:
```

```
take n [(i,j) | i <- [1..],  
               j <- [1..i],  
               gcd i j == 1]
```

- encourages simple, general solutions
- but has its problems too :(

That's all folks!
