

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
 - ...

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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)

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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 :
`(\x -> x) apple -- ==> apple`
 - Haskell:
`(\x -> x) "apple" -- ==> "apple"`

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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!

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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
```

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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**

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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 -> ...
```

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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)

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Syntax: Equations and Patterns

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```
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.
```

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Syntax: Equations and Patterns

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- Same as:

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

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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>

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QUIZ: Pair

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D.

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```

E. all of the above



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

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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 :("
```

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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)
```

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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

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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!

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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'
```

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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
```

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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**.

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Types

- What would *Python* say?

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

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

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Types

- What would *Java* say?

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

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

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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
```

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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"
```

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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?)

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Function Types

- Functions have **arrow types**
 - `\x -> e` has type `A -> B`
 - If `e` has type `B`, assuming `x` has type `A`
- For example:

```
> :t (\x -> if x then 'a' else 'b')
(\x -> if x then 'a' else 'b') :: Bool -> Char
```

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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
```

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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>

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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-grp>

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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"

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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)
```

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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)

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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''' = []
```

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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]
```

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Functions on lists: length

```
-- | Length of the list
length :: ???
length xs = ???
```

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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.

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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>

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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>

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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

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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!

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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
```

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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

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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  = ()
```

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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
```

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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 ]
```

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What is Haskell?

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

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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

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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++;
    System.out.println("calling f");
    launchMissile();
    return x * 2;
}
```

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

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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!)

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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
```

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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 :(

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That's all folks!
