CSE 114A: Fall 2021 Introduction to Functional Programming

Higher-Order Functions

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Based on course materials developed by Nadia Polikarpova

Plan for this week

Last week:

- user-defined *data types*
 - and how to manipulate them using *pattern matching* and *recursion*
- how to make recursive functions more efficient with *tail recursion*

This week:

- code reuse with *higher-order functions* (HOFs)
- some useful HOFs: map, filter, and fold

Recursion is good

- Recursive code mirrors recursive data
 - Base constructor -> Base case
 - Inductive constructor -> Inductive case (with recursive call)
- But it can get kinda repetitive!

Example: evens

Let's write a function evens:

-- evens [] ==> [] -- evens [1,2,3,4] ==> [2,4] evens :: [Int] -> [Int] evens [] = ... evens (x:xs) = ...

Example: four-letter words

Let's write a function fourChars:

-- fourChars [] ==> []
-- fourChars ["i","must","do","work"] ==> ["must","work"]
fourChars :: [String] -> [String]
fourChars [] = ...
fourChars (x:xs) = ...

Yikes, Most Code is the Same!

foo [] = []

foo (x:xs)

| length x == 4 = x : foo xs
| otherwise = foo xs

Only difference is condition

• x mod 2 == 0 vs length x == 4

Moral of the day

D.R.Y. Don't Repeat Yourself!

Can we

- reuse the general pattern and
- *substitute in* the custom condition?

HOFs to the rescue!

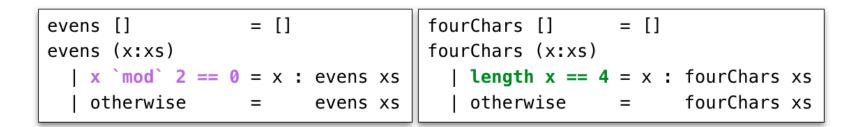
General Pattern

- expressed as a higher-order function
- takes customizable operations as *arguments*

Specific **Operation**

• passed in as an argument to the HOF

The "filter" pattern



Use the filter pattern to avoid duplicating code!

The "filter" pattern

General Pattern

- HOF filter
- Recursively traverse list and pick out elements that satisfy a predicate

Specific **Operation**

• Predicates is Even and is Four

evens = fil where	lter isEven	fourChars where	= filter	isFour
isEven x = x `	mod` 2 == 0		k = length	x == 4

```
-- evens [1,2,3,4] ==> [2,4]

evens :: [Int] -> [Int]

evens xs = filter isEven xs

where

isEven :: Int -> Bool

isEven x = x `mod` 2 == 0

filter :: ???
```

```
-- evens [1,2,3,4] ==> [2,4]

evens :: [Int] -> [Int]

evens xs = filter isEven xs

where

isEven :: Int -> Bool

isEven x = x `mod` 2 == 0

filter :: ???
```

```
-- fourChars ["i", "must", "do", "work"] ==> ["must", "work"]
fourChars :: [String] -> [String]
fourChars xs = filter isFour xs
  where
    isFour :: String -> Bool
    isFour x = length x == 4
filter :: ???
```

Uh oh! So what's the type of filter?

filter :: (Int -> Bool) -> [Int] -> [Int] -- ???

filter :: (String -> Bool) -> [String] -> [String] -- ???

- It *does not care* what the list elements are
 - as long as the predicate can handle them
- It's type is **polymorphic** (generic) in the type of list elements
- -- For any type `a`
- -- if you give me a predicate on `a`s
- -- and a list of `a`s,
- -- I'll give you back a list of `a`s

filter :: (a -> Bool) -> [a] -> [a]

Example: all caps

Lets write a function shout:

-- shout [] ==> []
-- shout ['h','e','L','L','o'] ==> ['H','E','L','L','O']
shout :: [Char] -> [Char]
shout [] = ...
shout (x:xs) = ...

Example: squares

Lets write a function squares:

-- squares [] ==> []
-- squares [1,2,3,4] ==> [1,4,9,16]
squares :: [Int] -> [Int]
squares [] = ...
squares (x:xs) = ...

Yikes, Most Code is the Same!

Lets rename the functions to foo:

-- shout foo [] = [] foo (x:xs) = toUpper x : foo xs -- squares foo [] = [] foo (x:xs) = (x * x) : foo xs

Lets refactor into the common pattern

pattern = ...

The "map" pattern

shout	[]	=	[]				
shout	(x:xs)	=	toUpper	X	:	shout	xs

squares	[]	=	[]			
squares	(x:xs)	=	(x*x)	:	squares	xs

map f [] = []
map f (x:xs) = f x : map f xs

The map Pattern

General Pattern

- HOF map
- Apply a transformation **f** to each element of a list

Specific Operations

• Transformations to Upper and $x \rightarrow x * x$

The "map" pattern

map f [] = [] map f (x:xs) = f x : map f xs Lets refactor shout and squares

shout = map ...

squares = map ...

shout = map ($x \rightarrow toUpper x$)

squares = map (\x -> x*x)

QUIZ

What is the type of map? *

map f [] = []
map f (x:xs) = f x : map f xs

(A) (Char -> Char) -> [Char] -> [Char]

(B) (Int -> Int) -> [Int] -> [Int]

(C) (a -> a) -> [a] -> [a]

(D) (a -> b) -> [a] -> [b]

(E) (a -> b) -> [c] -> [d]



http://tiny.cc/cse116-map-ind

QUIZ

What is the type of map? *

map f [] = []
map f (x:xs) = f x : map f xs

(A) (Char -> Char) -> [Char] -> [Char]

(B) (Int -> Int) -> [Int] -> [Int]

(C) (a -> a) -> [a] -> [a]

- (D) (a -> b) -> [a] -> [b]
- (E) (a -> b) -> [c] -> [d]



http://tiny.cc/cse116-map-grp

The "map" pattern

Type says it all!

• The only meaningful thing a function of this type can do is apply its first argument to elements of the list (Hoogle it!)

Things to try at home:

- can you write a function map' :: (a -> b) -> [a] -> [b] whose behavior is different from map?
- can you write a function map':: (a -> b) -> [a] -> [b] such that map' f xs returns a list whose elements are not in map f xs?

QUIZ

What is the value of quiz? *

map :: (a -> b) -> [a] -> [b]

quiz = map (\(x, y) -> x + y) [1, 2, 3]

(A) [2, 4, 6]

(B) [3, 5]

(C) Syntax Error

(D) Type Error

(E) None of the above



http://tiny.cc/cse116-quiz-ind

QUIZ

What is the value of quiz? *

map :: (a -> b) -> [a] -> [b]

quiz = map (\(x, y) -> x + y) [1, 2, 3]

(A) [2, 4, 6]

(B) [3, 5]

(C) Syntax Error

(D) Type Error

(E) None of the above



http://tiny.cc/cse116-quiz-grp

Don't Repeat Yourself

Benefits of **factoring** code with HOFs:

- Reuse iteration pattern
 - think in terms of standard patterns
 - less to write
 - easier to communicate
- Avoid bugs due to repetition

Recall: length of a list

-- Len [] ==> 0 -- Len ["carne", "asada"] ==> 2 len :: [a] -> Int len [] = 0 len (x:xs) = 1 + len xs

Recall: summing a list

-- sum [] ==> 0 -- sum [1,2,3] ==> 6 sum :: [Int] -> Int sum [] = 0 sum (x:xs) = x + sum xs

Example: string concatenation

Let's write a function cat:

-- cat [] ==> ""
-- cat ["carne", "asada", "torta"] ==> "carneasadatorta"
cat :: [String] -> String
cat [] = ...
cat (x:xs) = ...

Can you spot the pattern?

-- Len

foo [] = 0 foo (x:xs) = 1 + foo xs

-- sum foo [] = 0 foo (x:xs) = x + foo xs

-- cat

foo [] = "" foo (x:xs) = x ++ foo xs

pattern = ...

len [] = 0	sum [] = 0	cat [] = ""
len (x:xs) = $1 + len xs$	sum(x:xs) = x + sum xs	cat (x:xs) = x ++ sum xs

foldr f b [] = b
foldr f b (x:xs) = f x (foldr f b xs)

The foldr Pattern

General Pattern

- Recurse on tail
- Combine result with the head using some binary operation

foldr f b [] = b
foldr f b (x:xs) = f x (foldr f b xs)

Let's refactor sum, len and cat:

sum = foldr ...

cat = foldr ...

len = foldr ...

Factor the recursion out!

len = foldr $(x n \rightarrow 1 + n)$ 0

sum = foldr (\x n -> **x + n**) 0

cat = foldr (\x s -> x ++ n) ""

You can write it more clearly as

sum = foldr (+) 0
cat = foldr (++) ""

len = foldr $(x n \rightarrow 1 + n)$ 0

sum = foldr (\x n -> **x + n**) 0

cat = foldr (\x s -> x ++ n) ""

You can write it more clearly as

sum = foldr (+) 0
cat = foldr (++) ""

QUIZ

What does this evaluate to? *

```
foldr f b [] = b
foldr f b (x:xs) = f x (foldr f b xs)
```

```
quiz = foldr (:) [] [1,2,3]
```

(A) Type error

(B) [1,2,3]

(C) [3,2,1]

(D) [[3],[2],[1]]

(E) [[1],[2],[3]]



http://tiny.cc/cse116-foldeval-ind

QUIZ

What does this evaluate to? *

foldr f b [] = b
foldr f b (x:xs) = f x (foldr f b xs)

```
quiz = foldr (:) [] [1,2,3]
```

(A) Type error

(B) [1,2,3]

(C) [3,2,1]

(D) [[3],[2],[1]]

(E) [[1],[2],[3]]



http://tiny.cc/cse116-foldeval-grp

foldr f b [] = b
foldr f b (x:xs) = f x (foldr f b xs)

The "fold-right" pattern

```
foldr f b [x1, x2, x3, x4]
==> f x1 (foldr f b [x2, x3, x4])
==> f x1 (f x2 (foldr f b [x3, x4]))
==> f x1 (f x2 (f x3 (foldr f b [x4])))
==> f x1 (f x2 (f x3 (f x4 (foldr f b []))))
==> f x1 (f x2 (f x3 (f x4 b)))
```

Accumulate the values from the right

For example:

What is the most general type of foldr? *

foldr f b [] = b
foldr f b (x:xs) = f x (foldr f b xs)

(A) (a -> a -> a) -> a -> [a] -> a

(B) (a -> a -> b) -> a -> [a] -> b

- (C) (a -> b -> a) -> b -> [a] -> b
- (D) (a -> b -> b) -> b -> [a] -> b
- (E) (b -> a -> b) -> b -> [a] -> b



http://tiny.cc/cse116-foldtype-ind

What is the most general type of foldr? *

foldr f b [] = b
foldr f b (x:xs) = f x (foldr f b xs)

(A) (a -> a -> a) -> a -> [a] -> a

(B) (a -> a -> b) -> a -> [a] -> b

- (C) (a -> b -> a) -> b -> [a] -> b
- (D) (a -> b -> b) -> b -> [a] -> b
- (E) (b -> a -> b) -> b -> [a] -> b



http://tiny.cc/cse116-foldtype-grp

The "fold-right" pattern

Is foldr tail recursive?

Answer: No! It calls the binary operations on the results of the recursive call

Let's write tail-recursive Sum!

```
sumTR :: [Int] -> Int
sumTR = ...
```

```
Let's write tail-recursive SUM!
```

```
sumTR :: [Int] -> Int
sumTR xs = helper 0 xs
where
helper acc [] = acc
helper acc (x:xs) = helper (acc + x) xs
```

Lets run SUMTR to see how it works

sumTR	[1,2,3]						
==>	helper 0	[1,2,3]					
==>	helper 1	[2,3]	 0	+	1	==>	1
==>	helper 3	[3]	 1	+	2	==>	3
==>	helper 6	[]	 3	+	3	==>	6
==>	6						

Note: helper directly returns the result of recursive call!

Let's write tail-recursive cat!

```
catTR :: [String] -> String
catTR = ...
```

```
Let's write tail-recursive cat!
catTR :: [String] -> String
catTR xs = helper "" xs
where
helper acc [] = acc
helper acc (x:xs) = helper (acc ++ x) xs
```

Lets run catTR to see how it works

catTR			["carne",	"asada",	"torta"]
==>	helper		["carne",	"asada",	"torta"]
==>	helper	"carne"		["asada",	"torta"]
==>	helper	"carneasa	ada"		["torta"]
==>	helper	"carneasadatorta"			[]
==>	==> "carneasadatorta"				

Note: helper directly returns the result of recursive call!

Can you spot the pattern?

```
-- sumTR
foo xs = helper 0 xs
where
helper acc [] = acc
helper acc (x:xs) = helper (acc + x) xs
```

```
-- catTR
foo xs = helper "" xs
where
helper acc [] = acc
helper acc (x:xs) = helper (acc ++ x) xs
```

```
pattern = ...
```

The "fold-left" pattern

sum xs	= helper 0 xs	cat xs	= helper "" xs
where		where	
helper acc []	= acc	helper acc []	= acc
helper acc (x:xs)	= helper ($acc + x$) xs	helper acc (x:xs)	= helper (<mark>acc ++ x</mark>) xs

foldl <mark>f b</mark> xs		= helper <mark>b</mark> xs	
where			
helper acc	[]	= acc	
helper acc	(x:xs)	<pre>= helper (f acc x) xs</pre>	

The foldl Pattern

General Pattern

- Use a helper function with an extra accumulator argument
- To compute new accumulator, combine current accumulator with the head using some binary operation

The "fold-left" pattern

foldl f b xs = helper b xs
where
helper acc [] = acc
helper acc (x:xs) = helper (f acc x) xs

Let's refactor SUMTR and catTR:

sumTR = foldl ...

catTR = foldl ...

Factor the tail-recursion out!

What does this evaluate to? *

```
foldl f b xs = helper b xs
where
helper acc [] = acc
helper acc (x:xs) = helper (f acc x) xs
```

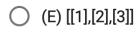
```
quiz = foldl (:) [] [1,2,3]
```

(A) Type error

(B) [1,2,3]

(C) [3,2,1]

(D) [[3],[2],[1]]





http://tiny.cc/cse116-foldl-ind

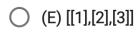
What does this evaluate to? *

```
foldl f b xs = helper b xs
where
helper acc [] = acc
helper acc (x:xs) = helper (f acc x) xs
```

```
quiz = foldl (:) [] [1,2,3]
```

(A) Type error

- (B) [1,2,3]
- (C) [3,2,1]
- (D) [[3],[2],[1]]





http://tiny.cc/cse116-foldl-grp

What does this evaluate to? *

foldl f b xs = helper b xs
where
helper acc [] = acc
helper acc (x:xs) = helper (f acc x) xs

quiz = foldl (\xs x -> x : xs) [] [1,2,3]

(A) Type error

(B) [1,2,3]

(C) [3,2,1]

(D) [[3],[2],[1]]

(E) [[1],[2],[3]]



http://tiny.cc/cse116-foldl2-ind

What does this evaluate to? *

foldl f b xs = helper b xs
where
helper acc [] = acc
helper acc (x:xs) = helper (f acc x) xs

quiz = foldl (\xs x -> x : xs) [] [1,2,3]

(A) Type error

(B) [1,2,3]

(C) [3,2,1]

(D) [[3],[2],[1]]

(E) [[1],[2],[3]]



http://tiny.cc/cse116-foldl2-grp

The "fold-left" pattern

Accumulate the values from the left

For example:

foldl	(+) 0	[1, 2, 3, 4]
==>	helper 0	[1, 2, 3, 4]
==>	helper (0 + 1)	[2, 3, 4]
==>	helper $((0 + 1) + 2)$	[3, 4]
==>	helper $(((0 + 1) + 2) + $	+ 3) [4]
==>	helper $((((0 + 1) + 2))$	+ 3) + 4) []
==>	((((0 + 1) + 2) + 3) +	4)

Left vs. Right

foldl f b [x1, x2, x3] ==> f (f (f b x1) x2) x3 -- Left foldr f b [x1, x2, x3] ==> f x1 (f x2 (f x3 b)) -- Right For example: fold1 (+) 0 [1, 2, 3] ==> ((0 + 1) + 2) + 3 -- Left foldr (+) 0 [1, 2, 3] ==> 1 + (2 + (3 + 0)) -- Right Different types! foldl :: (b -> a -> b) -> b -> [a] -> b -- Left foldr :: (a -> b -> b) -> b -> [a] -> b -- *Right*

Useful HOF: flip

-- you can write foldl (\xs x -> x : xs) [] [1,2,3]

-- more concisely like so:
foldl (flip (:)) [] [1,2,3]
What is the type of flip?

flip :: (a -> b -> c) -> b -> a -> c

Useful HOF: compose

```
-- you can write
map (\x -> f (g x)) ys
```

-- more concisely like so: map (f . g) ys What is the type of (.)?

(.) :: (b -> c) -> (a -> b) -> a -> c

Higher Order Functions

Iteration patterns over collections:

- Filter values in a collection given a *predicate*
- Map (iterate) a given *transformation* over a collection
- Fold (reduce) a collection into a value, given a *binary operation* to combine results

Useful helper HOFs:

- Flip the order of function's (first two) arguments
- Compose two functions

Higher Order Functions

HOFs can be put into libraries to enable modularity

- Data structure **library** implements map, filter, fold for its collections
 - generic efficient implementation
 - o generic optimizations: map f (map g xs) --> map
 (f.g) xs
- Data structure **clients** use HOFs with specific operations
 - no need to know the implementation of the collection

Enabled the "big data" revolution e.g. *MapReduce*, *Spark*

That's all folks!