

Higher-order Functions

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Fall 2025

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Table of Contents

Recurring Patterns

Functions as First Class Values

Higher-order Functions

Functions as Return Values

Doubling a LList

Let's write a function `doubleList` that takes a `LList` of numbers and returns a new `LList` that is the result of multiplying every number in the given `LList` by two.

```
def doubleList(l):  
    if isEmpty(l):  
        return empty()  
    return cons(2*first(l), doubleList(rest(l)))
```

Recalling leetSpeak

Now, let's recall our leetSpeak function.

```
def leetSpeak(s):  
    if s == "":  
        return ""  
    return convertChar(s[0]) + leetSpeak(s[1:])
```

Generalizing recursive solutions

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These two functions are performing the same general task.

- Each function is repeatedly applying some binary function f to each value of the sequence and the result of the recursion
- Each function is producing a base value when the base case is reached

Folding a sequence

Both of these functions are *folding* these sequences. A *fold* of a sequence is exactly the procedure of applying a binary function f to each value of the sequence and each subsequent result of the function f .

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$f(v_2,$

\dots

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Folding a sequence

$f(v_0,$
 $f(v_1,$
 $f(v_2,$
 \dots
 $f(v_{n-1},$
 $f(v_n, ???))))))\dots$

What value is used for the second argument when the fold is applying the given function to the final value of the sequence?

Folding a sequence

$$\begin{aligned} &f(v_0, \\ &\quad f(v_1, \\ &\quad\quad f(v_2, \\ &\quad\quad\quad \dots \\ &\quad\quad\quad\quad f(v_{n-1}, \\ &\quad\quad\quad\quad\quad f(v_n, ???))))))\dots \end{aligned}$$

What value is used for the second argument when the fold is applying the given function to the final value of the sequence?

In the case of our recursions this would be the value we produce when the base case is reached!

Folding a sequence

$$f(v_0, f(v_1, f(v_2, \dots f(v_{n-1}, f(v_n, base))))))...$$

What value is used for the second argument when the fold is applying the given function to the final value of the sequence?

In the case of our recursions this would be the value we produce when the base case is reached!

One may argue that both our functions `leetSpeak` and `doubleList` do not apply just a single function f .

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For example, one may argue `leetSpeak` both calls the function `convertChar` and uses the `append` operation to build the final result from the recursive result.

Finding f

One may argue that both our functions `leetSpeak` and `doubleList` do not apply just a single function f .

For example, one may argue `leetSpeak` both calls the function `convertChar` and uses the `append` operation to build the final result from the recursive result.

However while that may be the case as we've written it we can easily rewrite both of these functions so that their recursive result is simply the result of applying some function to their first value and their recursive result.

Rewriting leetSpeak

Consider the following rewrite of leetSpeak

```
def lc(c, s):  
    return convertChar(c) + s  
  
def leetSpeak(s):  
    if s == "":  
        return ""  
    return lc(s[0], leetSpeak(s[:1]))
```

Rewriting leetSpeak

Consider the following rewrite of leetSpeak

```
def lc(c, s):  
    return convertChar(c) + s  
  
def leetSpeak(s):  
    if s == "":  
        return ""  
    return lc(s[0], leetSpeak(s[:1]))
```

Now our function leetSpeak is simply the result of folding lc over a string!

Rewriting doubleList

Consider the following rewrite of doubleList

```
def dc(num, l):  
    return cons(2*num, l)  
  
def doubleList(l):  
    if isEmpty(l):  
        return empty()  
    return dc(first(l), doubleList(rest(l)))
```


Rewriting doubleList

Consider the following rewrite of doubleList

```
def dc(num, l):  
    return cons(2*num, l)  
  
def doubleList(l):  
    if isEmpty(l):  
        return empty()  
    return dc(first(l), doubleList(rest(l)))
```

Now our function doubleList is simply the result of folding dc over a LList of numbers!

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",  
        lc("e",
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",  
        lc("e",  
            lc("a",
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",  
        lc("e",  
            lc("a",  
                lc("t", ""))))))
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",  
        lc("e",  
            lc("a",  
                "7")))))
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

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lc("g",  
    lc("r",  
        lc("e",  
            lc("a", "7")))))
```


Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",  
        lc("e",  
            "47"))))
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",  
        lc("e", "47"))))
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r",  
        "347"))))
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    lc("r", "347"))
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g",  
    "r347")
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

```
lc("g", "r347")
```

Consider the function call `leetSpeak("great")` and how it would be evaluated.

`"gr347"`

Now consider the function call `doubeList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

`dc(1,`

Now consider the function call `doubeList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

```
dc(1,  
    dc(2,
```

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```
dc(1,  
    dc(2,  
        dc(3,
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```
dc(1,  
    dc(2,  
        dc(3,  
            dc(4,
```

Visualizing doubleList

Now consider the function call `doubeList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

```
dc(1,  
    dc(2,  
        dc(3,  
            dc(4,  
                dc(5, ())))))
```

Visualizing doubleList

Now consider the function call `doubleList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

```
dc(1,  
    dc(2,  
        dc(3,  
            dc(4,  
                (10))))))
```

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Now consider the function call `doubleList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

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dc(1,  
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            dc(4, (10))))))
```

Now consider the function call `doubeList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

```
dc(1,  
    dc(2,  
        dc(3,  
            (8, 10))))
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Now consider the function call `doubleList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

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dc(1,  
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        dc(3, (8, 10))))
```


Now consider the function call `doubleList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

```
dc(1,  
    dc(2,  
        (6, 8, 10))))
```

Now consider the function call `doubeList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

```
dc(1,  
    dc(2, (6, 8, 10)))
```

Now consider the function call `doubeList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

```
dc(1,  
    (4, 6, 8, 10))
```

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dc(1, (4, 6, 8, 10))
```

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(2, 4, 6, 8, 10)

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By rewriting both functions and examining how they evaluate it is clear they are both performing exactly the same procedure (the fold) and the only ways they differ are their binary function and their base value!

Visualizing doubleList

Now consider the function call `doubeList(LC(1, 2, 3, 4, 5))` and how it would be evaluated.

(2, 4, 6, 8, 10)

By rewriting both functions and examining how they evaluate it is clear they are both performing exactly the same procedure (the fold) and the only ways they differ are their binary function and their base value!

Now that we've observed these similarities how can we take advantage of them?

Table of Contents

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Functions as Return Values

In programming, and particularly functional programming, we define a concept known as *first class functions* to discuss the behaviours of some programming languages.

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- Functions may be used as arguments in function calls¹

¹A corollary of this is that functions may be bound to identifiers

First class values

In programming, and particularly functional programming, we define a concept known as *first class functions* to discuss the behaviours of some programming languages.

We will define a programming language to have functions as first class values if the following conditions are true:

- Functions may be used as arguments in function calls¹
- Functions may be the return value of a function call

Python does have first class functions!

¹A corollary of this is that functions may be bound to identifiers

Table of Contents

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Functions as Return Values

Higher-order functions

We now know that functions that take functions themselves as the values to substitute for their parameters, or even produce a function as their return value!

Functions that operate on functions (as their parameters or their return value) are called *higher-order functions*.

We will now define our first higher-order function! This function will be the one that abstracts away the differences between functions like `leetSpeak` and `doubleList`.

Defining the fold operation

We have now defined the behaviour of folding over a sequence. For now we will focus just on folding LLists and write a function `fold` that takes an LList, a function `combine`, and a base value `base` and performs the fold operation we defined earlier.

Defining the fold operation

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```
def fold(l, combine, base):
```

It is important to note that the *type* of `combine` here is a *function*!

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```
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It is important to note that the *type* of `combine` here is a *function*!

Now, we define our base case. For an LList this will be when it is empty, and when that is the case we should produce the base value we were given

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```
def fold(l, combine, base):  
    if isEmpty(l):  
        return base
```

Now, we need only to apply the `combine` operation to both the first of our LList and the recursive result.

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```
def fold(l, combine, base):  
    if isEmpty(l):  
        return base  
    return combine(first(l), ???)
```

But what is the recursive result in the case of `fold`?

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But what is the recursive result in the case of `fold`?

The result of folding the operation over the rest of the LList!

Defining the fold operation

We have now defined the behaviour of folding over a sequence. For now we will focus just on folding LLists and write a function `fold` that takes an LList, a function `combine`, and a base value `base` and performs the fold operation we defined earlier.

```
def fold(l, combine, base):  
    if isEmpty(l):  
        return base  
    return combine(first(l), fold(rest(l), combine, base))
```

Function specifications for higher-order function

Let us write the function specification for `fold`

Function specifications for higher-order function

Let us write the function specification for fold

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l  
    with the base value acting as our final  
    second operand.  
  
    l          - LList  
    combine    -  
    base       -  
    returns    -  
    '''
```

How do we define the type of combine?

A notation for function types

We will choose to represent the *type* of a function as the types of its parameters and return types.

For example, we would write the type of a function that takes one string and one integer parameter and returns a float as the following `(str int -> float)`.

The same as the way the text `LList` means the type `LList`, the text enclosed in the parentheses above means the type of “a function that takes a string and integer parameter and returns a float”.

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Now that we know how to write the type of a function, can we complete the specification for `fold`?

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        base value acting as our final second operand.  
  
        l          - LList  
        combine    -  
        base       -  
        returns    -  
    '''
```

What is the type of the function combine though? We know it takes two parameters, but what types are they? What is its return type?

Function specifications for higher-order function

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def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine    - (any any -> any)  
    base       -  
    returns    -  
    '''
```

We could try writing any, to indicate that combine can operate on anything.

Function specifications for higher-order function

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        base value acting as our final second operand.  
  
        l          - LList  
        combine    - (any any -> any)  
        base       - any  
        returns    -  
    '''
```

Then what is our base type? It is one of the values operated on by combine, so it must also be any?

Function specifications for higher-order function

Now that we know how to write the type of a function, can we complete the specification for fold?

```
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    '''  
        fold folds the function combine over the LList l with the  
        base value acting as our final second operand.  
  
        l          - LList  
        combine    - (any any -> any)  
        base       - any  
        returns    - any  
    '''
```

What about our return type? It ultimately is the value produced by combine, so it must also be any?

Using our fold function

Let's now try using our fold function.

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First let us try fold with the dc function we wrote!

Using our fold function

Let's now try using our fold function.

First let us try fold with the dc function we wrote!

```
fold(LL(1, 2, 3, 4, 5), dc, empty()) -> (2, 4, 6, 8, 10)
```


Using our fold function

Let's now try using our fold function.

Consider the following fold application — what does it do?

Using our fold function

Let's now try using our fold function.

Consider the following fold application — what does it do?

```
def add(x, y):  
    return x + y
```

```
fold(LL(1, 2, 3, 4, 5), add, 0)
```

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Consider the following fold application — what does it do?

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def add(x, y):  
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```
fold(LL(1, 2, 3, 4, 5), add, 0)
```

This computes the summation of a LList, all in one line!

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Using our fold function

Let's now try using our fold function.

Consider the following fold application — what does it do?

```
def mul(x, y):  
    return x*y
```

```
fold(LL(1, 2, 3, 4, 5), mul, 1)
```

Using our fold function

Let's now try using our fold function.

Consider the following fold application — what does it do?

```
def mul(x, y):  
    return x*y
```

```
fold(LL(1, 2, 3, 4, 5), mul, 1)
```

This computes the produce of a LList, all in one line!

Bad usage of fold

Now, we try the following use of our function fold

```
def sc(x, y):  
    # x          - a character  
    # y          - an int  
    # returns - a character  
    return chr(ord(x)-y)  
  
fold(LL("h", "e", "y"), sc, 3)
```

Bad usage of fold

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    # x          - a character  
    # y          - an int  
    # returns - a character  
    return chr(ord(x)-y)
```

```
fold(LL("h", "e", "y"), sc, 3)
```

When we try this we get an error!

```
TypeError: unsupported operand type(s)  
    for -: 'int' and 'str'
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What is the issue?

Bad usage of fold

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```

```
fold(LL("h", "e", "y"), sc, 3)
```

The issue is that the result of our fold becomes:

```
sc("h", sc("e", sc("y", 3)))
```

Bad usage of fold

Now, we try the following use of our function fold

```
def sc(x, y):  
    # x          - a character  
    # y          - an int  
    # returns - a character  
    return chr(ord(x)-y)
```

```
fold(LL("h", "e", "y"), sc, 3)
```

The issue is that the result of our fold becomes:

```
sc("h", sc("e", "v"))
```

But `sc` cannot use a string as its second parameter! However, we didn't violate the specification we wrote for our `fold` because we said these could all be any! So clearly our specification is wrong!

Fixing the fold specification

When defining higher-order functions it is often the case that there will be a relationship between the type of the function we're operating on and our other values. We can use free variables in our types to denote types that can be any, but have some relationship to other types in our specification!

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine    - (X Y -> Z)  
    base       - any  
    returns    - any  
    '''
```

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine - (X Y -> Z)  
    base      - any  
    returns  - any  
    '''
```

We will begin by changing all the values in combine to free variables, and then working out the relationships.

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine    - (X Y -> Z)  
    base       - any  
    returns    - any  
    '''
```

We will begin by changing all the values in `combine` to free variables, and then working out the relationships.

The X, Y, and, Z here are free variables that represent “some” type.

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine - (X Y -> Z)  
    base      - Y  
    returns  - any  
    '''
```

We know that the base value is used as the second argument to the call to combine. As such, the type of base should match with Y.

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine - (X Y -> Z)  
    base      - Y  
    returns   - Z  
    '''
```

Furthermore, we know that fold simply returns the result of combine in the recursive case. That means the return type of fold must be Z.

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine - (X Y -> Z)  
    base      - Y  
    returns   - Z  
    '''
```

Does this catch the problem from the above fold of our function `sc` though?

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine    - (X Y -> Z)  
    base       - Y  
    returns    - Z  
    '''
```

No it doesn't! The problem from `sc` was that `sc` returned a string, and the result of `sc` was then used as the second argument to *itself*! However `sc` expected an integer as its second argument so it didn't work!

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine - (X Y -> Y)  
    base      - Y  
    returns   - Y  
    '''
```

Since the return value of combine is going to be used as its own second argument these types must also match!

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList  
    combine    - (X Y -> Y)  
    base       - Y  
    returns    - Y  
    '''
```

Since the return value of `combine` is going to be used as its own second argument these types must also match!

This means each of `combine`'s second parameter and return type, `base`, and the return type of `fold` are all the same type!

Fixing the fold specification

```
def fold(l, combine, base):  
    '''  
    fold folds the function combine over the LList l with the  
    base value acting as our final second operand.  
  
    l          - LList of X  
    combine    - (X Y -> Y)  
    base       - Y  
    returns    - Y  
    '''
```

Lastly, since each element of `l` is used as the first argument to `combine` that means that `l` must actually be a `LList` of `X`

This function we've defined is actually known as `foldr` and performs what is known as a *right fold*.

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A more sophisticated `foldr` is available for you already in the `cmp274` module. Unlike the one we wrote together on the slides here it works on both `LLists` and strings, as well as other built-in Python sequences.

foldr and the `cmp274` module

This function we've defined is actually known as `foldr` and performs what is known as a *right fold*.

A more sophisticated `foldr` is available for you already in the `cmp274` module. Unlike the one we wrote together on the slides here it works on both `LLists` and strings, as well as other built-in Python sequences.

For example:

```
foldr("great", lc, "") -> 'gr347'
```


Knowledge Check: Consider the following function definition

```
def sub(x, y):  
    return x - y
```

What is the result of the function call
`foldr(LL(7, 10, 1, 22), sub, 0)`? Figure out the result first
by hand and then check your result by executing the code. If your
answer does not match try to figure out where you went wrong!

Practicing with foldr

Practice Problem: Write the function `parity` which takes a `BinaryStr` a parameter and returns `True` if the number of ones in the string is even, and `False` if the number of ones in the string is odd. Your function should not use explicit recursion and instead should use `foldr` to achieve any repetition necessary.

We define a `BinaryStr` as:

- The empty string `""`
- `"0" + BinaryStr`
- `"1" + BinaryStr`

As always you may write any helper functions that you like (at least one helper function will be necessary — the argument for `foldr`!)

More practice with foldr

For both of the following questions you should not use explicit recursion, and should instead only use `foldr` for necessary repetition. Note that the bodies of both functions should really just be to return the result of a call to `foldr` — the real work comes in discovering and writing the correct function to fold!

Practice Problem: We have previously solved the problem of reversing a `LList`. Write a function `foldReverse` which solves takes a single `LList` parameter and returns the reverse of that `LList`.

Practice Problem: Write a function `maxLList` that takes a single parameter that is a `LList` of numbers and returns the largest number in the `LList`.

Considering accumulative recursion

While `foldr` is very powerful in abstracting away the simple recursions we wrote early on, it doesn't aim to solve problems like `reverse` which we solved with accumulative recursion.

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While `foldr` is very powerful in abstracting away the simple recursions we wrote early on, it doesn't aim to solve problems like `reverse` which we solved with accumulative recursion.

Can we abstract away the differences between accumulative recursive functions in order to build a higher-order function that replicates their behaviour?

Considering accumulative recursion

While `foldr` is very powerful in abstracting away the simple recursions we wrote early on, it doesn't aim to solve problems like `reverse` which we solved with accumulative recursion.

Can we abstract away the differences between accumulative recursive functions in order to build a higher-order function that replicates their behaviour?

We can try, first we need to identify the commonalities and differences between accumulative recursive solutions.

Finding the last word

We are going to write a function `lastPalindrome` that takes a `LList` of strings and returns the string with the largest index that is a palindrome. That is, it returns the *last* string in order in the `LList` that is a palindrome. If no palindromes exist in the `LList` then it returns `False`.

For example, if the `LList`
(`"hello"`, `"racecar"`, `"trap"`, `"kayak"`, `"foo"`) was used as an argument the function would produce `"kayak"` and not `"racecar"` as `"kayak"` is the *last* string in the `LList` that is a palindrome.

While we can write `lastPalindrome` without accumulative recursion, accumulative recursion is a more natural way to find the last occurrence of something, as we simply have to update our accumulator with each instance we find as we recurse deeper through our `LList`. So, we will write a helper function `lastPalindromeAcc` which is the accumulative recursion solution to the problem.

```
def lastPalindromeAcc(l, lastSoFar):
```



```
def lastPalindromeAcc(l, lastSoFar):
```

Now, we must decide on our base case. Again, the empty LList is a good option. Once again as with most accumulative recursions we can simply produce our accumulator when we've reached the base case.

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar
```

Now, what must we do in our recursive case?

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar
```

Now, what must we do in our recursive case?

It depends on whether our current string is a palindrome, so we should first determine that.

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar
```

Now, what must we do in our recursive case?

It depends on whether our current string is a palindrome, so we should first determine that.

We can use string slicing to easily calculate the reverse of a string, and equality to check if it is a palindrome.

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar  
    if first(l) == first(l)[::-1]:  
        ...  
    else:  
        ...
```

Regardless of whether the current string is a palindrome or not we must recurse on the rest of the LList in case there is a later palindrome.

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar  
    if first(l) == first(l)[::-1]:  
        return lastPalindromeAcc(rest(l), ???)  
    else:  
        return lastPalindromeAcc(rest(l), ???)
```

Regardless of whether the current string is a palindrome or not we must recurse on the rest of the LList in case there is a later palindrome.

The question then is simply what to do with our accumulator in each case.

lastPalindrome

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar  
    if first(l) == first(l)[::-1]:  
        return lastPalindromeAcc(rest(l), ???)  
    else:  
        return lastPalindromeAcc(rest(l), ???)
```

By the nature of the order in which we recurse, if we have found a palindrome then it appears *later* than any we have already seen. As such, we can replace `lastSoFar` with this new palindrome. If this string is not a palindrome then we simply ignore it and our last seen palindrome remains the same.

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar  
    if first(l) == first(l)[::-1]:  
        return lastPalindromeAcc(rest(l), first(l))  
    else:  
        return lastPalindromeAcc(rest(l), lastSoFar)
```

By the nature of the order in which we recurse, if we have found a palindrome then it appears *later* than any we have already seen. As such, we can replace `lastSoFar` with this new palindrome. If this string is not a palindrome then we simply ignore it and our last seen palindrome remains the same.


```
def lastPalindrome(l):  
    return lastPalindromeAcc(l, False)
```

Finally, we must write the actual `lastPalindrome` function that wraps `lastPalindromeAcc`. What value should we use for initializing `lastSoFar` though?

Finally, we must write the actual `lastPalindrome` function that wraps `lastPalindromeAcc`. What value should we use for initializing `lastSoFar` though?

If no palindrome is ever found then the initial value is the value that will be kept as `lastSoFar` the entire recursion. As such it is clear we must initialize `lastSoFar` to the value that should be produced when no palindrome is found — `False`.

Comparing lastPalindrome and reverse

At first glance the viewer of lastPalindromeAcc and reverseHelper may think they are not all that similar!

```
def lastPalindromeAcc(l, lastSoFar):  
    if isEmpty(l):  
        return lastSoFar  
    if first(l) == first(l)[::-1]:  
        return lastPalindromeAcc(rest(l), first(l))  
    else:  
        return lastPalindromeAcc(rest(l), lastSoFar)  
  
def reverseHelper(l, asf):  
    if isEmpty(l):  
        return asf  
    return reverseHelper(rest(l), cons(first(l), asf))
```

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    else:  
        return lastPalindromeAcc(rest(l), lastSoFar)  
  
def reverseHelper(l, asf):  
    if isEmpty(l):  
        return asf  
    return reverseHelper(rest(l), cons(first(l), asf))
```

But, they are! We just need to abstract out the differences!

A supposition on accumulative recursion

We constructed `foldr` when we observed we could construct arbitrarily complex functions to represent the binary operation to fold over our sequences.

A supposition on accumulative recursion

We constructed `foldr` when we observed we could construct arbitrarily complex functions to represent the binary operation to fold over our sequences.

We then make the supposition that the same can be true for simple accumulative recursions with one accumulator. We simply need to find the right binary function to fold!

How can we rewrite the function lastPalindromeAcc so that it looks more similar to reverseHelper?

```
def reverseHelper(l, asf):  
    if isEmpty(l):  
        return asf  
    return reverseHelper(rest(l), cons(first(l), asf))
```

Rewriting lastPalindromeAcc

How can we rewrite the function `lastPalindromeAcc` so that it looks more similar to `reverseHelper`?

```
def reverseHelper(l, asf):  
    if isEmpty(l):  
        return asf  
    return reverseHelper(rest(l), cons(first(l), asf))
```

That is, we want a solution that when the base case is reached simply returns the accumulator, and when the base case is *not* reached simply returns the recursive call, replacing the accumulator with some function applied to the current item and the accumulator.

Rewriting lastPalindromeAcc

How can we rewrite the function `lastPalindromeAcc` so that it looks more similar to `reverseHelper`?

```
def lastPalindromeAcc(l, acc):  
    if isEmpty(l):  
        return acc  
    return lastPalindromeAcc(rest(l), lpCombine(first(l), asf))
```

More simply put, can we find a definition for `lpCombine` so that the above code performs the same operation as our original `lastPalindromeAcc`?

Rewriting lastPalindromeAcc

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```

More simply put, can we find a definition for lpCombine so that the above code performs the same operation as our original lastPalindromeAcc?

Yes we can!

```
def lpCombine(???, ???):
```

To find our definition for `lpCombine` we start by defining what our parameters will be.

Finding lpCombine

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```

To find our definition for `lpCombine` we start by defining what our parameters will be.

We observe that the way `lpCombine` is called is with the first of our `LList` being our first argument, and the accumulator as our second. So we should define the function as such.

```
def lpCombine(s, acc):
```

The next thing we must determine is what exactly our function should return! We note that the return value of the function is being used in `lastPalindromeAcc` as the new value of our accumulator for the next recursive call. As such, this function needs to determine what the next accumulator should be and return it.

```
def lpCombine(s, acc):
```

The next thing we must determine is what exactly our function should return! We note that the return value of the function is being used in `lastPalindromeAcc` as the new value of our accumulator for the next recursive call. As such, this function needs to determine what the next accumulator should be and return it.

But we already wrote code to determine the next accumulator in `lastPalindromeAcc`, so it is much the same here!

```
def lpCombine(s, acc):  
    if s == s[::-1]:  
        return s  
    return acc
```

If `s` is a palindrome then it is our most recent palindrome! On the other hand if it is not, then we should continue to use `acc`.

Finding lpCombine

```
def lpCombine(s, acc):  
    if s == s[::-1]:  
        return s  
    return acc
```

If `s` is a palindrome then it is our most recent palindrome! On the other hand if it is not, then we should continue to use `acc`.

This definition of `lpCombine` in combination with the new definition of `lastPalindromeAcc` yields the same behaviour we were targeting.

Comparing the new lastPalindrome and reverse

Comparing these two functions now we see they look almost identical!

```
def lastPalindromeAcc(l, acc):  
    if isEmpty(l):  
        return acc  
    return lastPalindromeAcc(rest(l), lpCombine(first(l), asf))  
  
def lastPalindrome(l):  
    return lastPalindromeAcc(l, False)
```

Comparing the new lastPalindrome and reverse

Comparing these two functions now we see they look almost identical!

```
def reverseHelper(l, asf):  
    if isEmpty(l):  
        return asf  
    return reverseHelper(rest(l), cons(first(l), asf))  
  
def reverse(l):  
    return reverseHelper(l, empty())
```

Differences between `lastPalindrome` and `reverse`

If we consider the differences between `lastPalindrome` and `reverse` we can see that there are only two ways they differ:

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If we consider the differences between `lastPalindrome` and `reverse` we can see that there are only two ways they differ:

- The function that is folded over the sequence
- The value to initialize `acc` to.

But that's the same as what we found when developing `foldr` — so how do these functions differ from those we abstracted with `foldr`?

Differences between `lastPalindrome` and `reverse`

If we consider the differences between `lastPalindrome` and `reverse` we can see that there are only two ways they differ:

- The function that is folded over the sequence
- The value to initialize `acc` to.

But that's the same as what we found when developing `foldr` — so how do these functions differ from those we abstracted with `foldr`?

To answer that we must trace out these functions much as we did with `doubleList` and `leetSpeak`

Visualizing lastPalindrome

Consider now applying the function `lastPalindrome` to the `LList` `("hello", "racecar", "trap", "kayak", "foo")` and how it would be evaluated. For space, we shorten the name of `lpCombine` to `lpc`.

```
lpc("hello", False)
```

Visualizing lastPalindrome

Consider now applying the function `lastPalindrome` to the `LList` `("hello", "racecar", "trap", "kayak", "foo")` and how it would be evaluated. For space, we shorten the name of `lpCombine` to `lpc`.

```
lpc("racecar",  
    lpc("hello", False))
```


Visualizing lastPalindrome

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```
lpc("trap",  
    lpc("racecar",  
        lpc("hello", False)))
```

Visualizing lastPalindrome

Consider now applying the function `lastPalindrome` to the `LList` `("hello", "racecar", "trap", "kayak", "foo")` and how it would be evaluated. For space, we shorten the name of `lpCombine` to `lpc`.

```
lpc("foo",  
    lpc("trap",  
        lpc("racecar",  
            lpc("hello", False))))
```

Visualizing lastPalindrome

Consider now applying the function `lastPalindrome` to the `LList` `("hello", "racecar", "trap", "kayak", "foo")` and how it would be evaluated. For space, we shorten the name of `lpCombine` to `lpc`.

```
lpc("foo",  
    lpc("trap",  
        lpc("racecar",  
            lpc("hello", False))))
```

However an observation can be made here as well — we don't need this large chain to be built up! We note that at each step both arguments of `lpc` are able to be evaluated to a final value! More on that, and its importance, later.

Visualizing lastPalindrome

Consider now applying the function `lastPalindrome` to the `LList` `("hello", "racecar", "trap", "kayak", "foo")` and how it would be evaluated. For space, we shorten the name of `lpCombine` to `lpc`.

```
lpc("foo",  
    lpc("trap",  
        lpc("racecar",  
            lpc("hello", False))))
```

However an observation can be made here as well — we don't need this large chain to be built up! We note that at each step both arguments of `lpc` are able to be evaluated to a final value! More on that, and its importance, later.

As such, a more accurate visualization would evaluate each `lpc` application immediately, replacing each call with the next call on the result of the previous one.

Consider now applying the function `reverse` to the `LList` `(1, 2, 3, 4)` and how it would be evaluated.

```
cons(1, empty())
```

Consider now applying the function `reverse` to the `LList` `(1, 2, 3, 4)` and how it would be evaluated.

```
cons(2,  
      cons(1, empty()))
```

Consider now applying the function `reverse` to the `LList` (1, 2, 3, 4) and how it would be evaluated.

```
cons(3,  
    cons(2,  
        cons(1, empty()))))
```

Consider now applying the function `reverse` to the `LList` (1, 2, 3, 4) and how it would be evaluated.

```
cons(4,  
    cons(3,  
        cons(2,  
            cons(1, empty())))))
```


Generalizing the procedure

We can see from `reverse` and `lastPalindrome` a pattern emerging that defines the procedure we are trying to abstract. Given a sequence of values of the form $(v_0, v_1, \dots, v_{n-1}, v_n)$ and binary function f and a base value b the procedure we are attempting to define is

$$f(v_0, \text{base})$$

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...

$f(v_1,$
 $f(v_0, base))\dots$

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$$\begin{aligned} &f(v_{n-1}, \\ &\quad \dots \\ &\quad f(v_1, \\ &\quad \quad f(v_0, \text{base})) \dots) \end{aligned}$$

Generalizing the procedure

We can see from `reverse` and `lastPalindrome` a pattern emerging that defines the procedure we are trying to abstract. Given a sequence of values of the form $(v_0, v_1, \dots, v_{n-1}, v_n)$ and binary function f and a base value b the procedure we are attempting to define is

$$\begin{aligned} &f(v_n, \\ &\quad f(v_{n-1}, \\ &\quad \quad \dots \\ &\quad \quad \quad f(v_1, \\ &\quad \quad \quad \quad f(v_0, \text{base})) \dots)) \end{aligned}$$

The procedure we've been trying to define is known as a *left* fold, as opposed to the *right* fold we already defined.

Defining left folds

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- The first function application that left fold evaluates is between the first element, i.e. the left-most one, and the base value.
- The first function application that right fold evaluates is between the last element, i.e. the right-most one, and the base value.

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- The first function application that left fold evaluates is between the first element, i.e. the left-most one, and the base value.
- The first function application that right fold evaluates is between the last element, i.e. the right-most one, and the base value.

As such the name of the function we want to define will be `foldl`.

Defining foldl

```
def foldl(l, f, acc):  
    '''  
    foldl performs a left fold of the function f  
    over l with the base value supplied in acc  
    acting as our first second operand.  
  
    l          - LList of X  
    f          - (X Y -> Y)  
    acc       - Y  
    returns   - Y  
    '''
```

Our parameter types for foldl are the same as they were for foldr. The major difference is that our third parameter ceases just to be our base value, but instead will be our accumulator that must be initialized to our base value when foldl is called.

Defining foldl

```
def foldl(l, f, acc):  
    '''  
    foldl performs a left fold of the function f  
    over l with the base value supplied in acc  
    acting as our first second operand.  
  
    l          - LList of X  
    f          - (X Y -> Y)  
    acc        - Y  
    returns    - Y  
    '''
```

First, our base case is the same as it was for both our accumulative recursive examples — simply return the accumulator if the base case has been reached.

Defining foldl

```
def foldl(l, f, base):  
    if isEmpty(l):  
        return acc
```

First, our base case is the same as it was for both our accumulative recursive examples — simply return the accumulator if the base case has been reached.

Defining foldl

```
def foldl(l, f, base):  
    if isEmpty(l):  
        return acc
```

Our recursive case now simply becomes recursively calling `foldl` on the rest of our `LList` and updating our accumulator to be the result of applying `f` to the current first value of our list and the accumulator.

Defining foldl

```
def foldl(l, f, base):  
    if isEmpty(l):  
        return acc  
    return foldl(rest(l), f, f(first(l), base))
```

Our recursive case now simply becomes recursively calling `foldl` on the `rest` of our `LList` and updating our accumulator to be the result of applying `f` to the current first value of our list and the accumulator.

Reversing a LList with foldl

Now that we have `foldl` we can reverse a `LList` simply by performing a left fold of the function `cons` over a `LList`! Consider:

```
foldl(LL(1, 2, 3, 4), cons, LL()) -> (4, 3, 2, 1)
```


`foldl` and the `cmp274` module

The function `foldl` is already defined for us in the `cmp274` module, so you have no need to copy this definition into your own programs if you want to use `foldl`.

Additionally, the module provided version provides support for arbitrary Python sequences and not just `LLists`.

Understanding foldl

Knowledge Check: Consider the following function definition

```
def sub(x, y):  
    return x - y
```

What is the result of the function call

`foldl(LL(7, 10, 1, 22), sub, 0)`? Figure out the result first by hand and then check your result by executing the code. If your answer does not match try to figure out where you went wrong!

Does the result differ from the same expression but using `foldr` instead of `foldl`? If so why?

Practice Question: Write a Python function `extremes` that has a single non-empty `LList` of numbers as its parameter `l`. The function returns a `LList` with exactly two elements in it, the first of which is the *minimum* element of `l`, and the second element is the *maximum* element of `l`.

You may not use any explicit recursion in solving the question, and must use `foldl` for any necessary repetition.

Hint: As with writing any `fold` application the difficulty of this question lies in finding the function to fold over the `LList` and the value to initialize your base value to.

Practice writing higher-order functions

Practice Question: A common process we need to perform in computing is to *map* a function onto a sequence. Given a unary function f and a sequence S of the form $(v_0, v_1, \dots, v_{n-1}, v_n)$ the result of mapping f onto S is the sequence:

$$(f(v_0), f(v_1), \dots, f(v_{n-1}), f(v_n))$$

Write the function `map` that takes two parameters, the first being a unary function and the second being a `LList`. Your function should return the result of mapping the given function onto the given `LList`.

Examples are given on the following slide.

Examples of `map`

```
def add3(x):  
    return x + 3
```

```
def double(x):  
    return x*2
```

Consider the two following definitions about when considering the example `map` applications below

```
map(add3, LL(0, 10, -2)) -> (3, 13, -6)
```

```
map(double, LL(0, 10, -2)) -> (0, 20, -4)
```

More practice with higher-order functions

Practice Question: Another common process we need to perform is that of *filtering* a sequence. Given a unary function f that returns a `bool` and a sequence S of the form $(v_0, v_1, \dots, v_{n-1}, v_n)$ then the result of filtering S by the predicate f is the sequence:

$$S' = (v_i, v_{i+1}, \dots)$$

Where an element $v_i \in S'$ if and only if $f(v_i) \rightarrow \text{True}$.

Write the function `filter` as defined above. Examples are given on the next slide.

Examples of filter

```
def isNegative(x):  
    return x < 0
```

```
def isShort(s):  
    return len(s) < 6
```

Consider the two following definitions about when considering the example map applications below

```
map(isNegative, LL(-10, 0, 10, -2)) -> (-10, -2)  
map(isShort, LL("abc", "zaboomafoo", "great"))  
    -> ("abc", "great")
```

Table of Contents

Recurring Patterns

Functions as First Class Values

Higher-order Functions

Functions as Return Values

Abstracting function creation

Imagine you are writing software for image editing. To do so you define a data type `Pixel`. Your `Pixel` data type is defined as follows:

A `Pixel` is a:

- `LL(CV, CV, CV)`

And you also define a `ColorValue` or `CV` as an integer in the range `[0, 255]`.

So a `Pixel` is a `LList` of three integers in the range `[0, 255]`.

The three values in your `Pixel` data type represent the *red*, *blue*, and *green* component of a colour. That is, the `LList` of a `Pixel` is of the form (R, G, B) .

For example, the Safety Orange colour used in our “Fun on Functions” slides had the RGB value $(255, 103, 0)$.

A picture can be represented by many `Pixels` in a `LList`.

Imagine as you are writing your image editing software you need to add a feature to “red shift” an image by adding 30 to the red components of each Pixel in your image.

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You observe that this is as simple as mapping a function onto your `LList of Pixels` so you write the function to map.

Colour shifting

Imagine as you are writing your image editing software you need to add a feature to “red shift” an image by adding 30 to the red components of each Pixel in your image.

You observe that this is as simple as mapping a function onto your LList of Pixels so you write the function to map.

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def redShift(p):  
    newRed = first(p) + 30  
    if newRed > 255:  
        return cons(255, rest(p))  
    return cons(newRed, rest(p))
```

We require more shifting functions

Let's say after completing the “red shift” feature your boss comes back and tells you to add “even redder shift” functionality to the program, which adds 60 to the red components of each `Pixel` in your image.

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You could go back and write a near identical function that just swap the value 60 for the value 30 in your code.

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You could go back and write a near identical function that just swap the value 60 for the value 30 in your code.

But what about when your boss comes back and asks for an “even more redder shift” function. What about one for green? and blue?

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For example why write one function for red shifting by a value of 30, another for 60, and another for 90?

Instead wouldn't it be better to write a function that is parameterized by not only the `Pixel` to shift but also the amount by which to shift it? This way we would only have to write *one* function for performing a red shift and simply provide different arguments for the amount to shift by!

Parameterized `redShift`

Consider the updated `redShift` function, that is parameterized now by the shift value.

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This function is a nice idea... but We can't use this function with map! map expects a unary function — this is a binary function!

If only we had a way to abstract away the differences between our various shift functions, so that we don't have to create several almost identical unary functions!

The solution to our problem

Recall that higher-order functions are those functions that operate *on* functions — this is not only functions whose parameters are functions, but also functions whose *return values* are functions!

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With our current knowledge of defining functions we could only write functions that produce a function we've already written — not a very helpful application. In order for functions that return functions to be useful, we need some way for those functions to create new functions when they are called.

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But how can we create a new function “on-the-fly” for our higher-order functions to return?

How to create functions

There are two main ways in which we'll be able to create new functions within existing functions.

²Often called *local* functions or *nested* functions in other languages.

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We will start by focusing on `lambda` functions.

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What are lambda functions

The name for lambda functions comes from the *lambda calculus* from which the definition originates.

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A lambda function is an *anonymous* function, which simply means that it does not have to bound to an identifier. When we learned about expressions we learned about literals. The same way that 5 is an integer literal, a lambda function is a function literal.

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A lambda function is an *anonymous* function, which simply means that it does not have to bound to an identifier. When we learned about expressions we learned about literals. The same way that 5 is an integer literal, a lambda function is a function literal.

Most programming languages that support lambda functions allow for lambda functions to be any arbitrary function. In Python the body of a lambda function must be a single expression.

Anatomy of a Python lambda

A lambda function in Python is an expression of the form

```
lambda x, y : x + y
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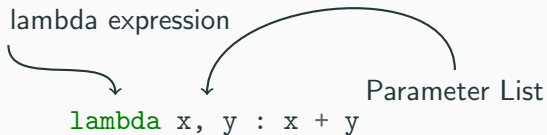


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Parameter List

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The diagram illustrates the components of a Python lambda expression. It shows the code `lambda x, y : x + y`. An arrow points from the text "Keyword to begin lambda expression" to the word `lambda`. Another arrow points from the text "Parameter List" to the parameters `x, y`. A third arrow points from the text "Parameter List" to the colon `:` that follows the parameters.

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Here we have folded the function that adds its first parameter to two times its second parameter over the `LList (1, 2, 3)` with a base value of 0. The evaluation of this is:

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Recall — function call expressions

Recall that when we defined our Python function call expressions we said they took the form of

```
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Recall that when we defined our Python function call expressions we said they took the form of

`expr(argList)`

When we made this definition we said that `expr` could be any expression that evaluated to a function. Until now the only expressions we had that could evaluate to a function were identifiers. Now, we also have lambda expressions.

Check your understanding

Knowledge Check: Consider the following expressions and state whether they are valid or not. If they are valid state what they will evaluate to, if they are not valid state why they are not.

- `(lambda x, y : x-len(y))(10, "hi")`
- `(lambda x: 3*x)("xyz")`
- `lambda x, y, z : z+x*y`
- `(lambda x : x+3)(2, 5)`

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Another use case of lambda functions is to allow us to write functions that can return functions!

Our first function returning function

We will now define the function `adderGenerator` which takes a single integer parameter n , and returns the function that takes a single integer parameter and adds n to it.

```
def adderGenerator(n):  
    return lambda x: x + n
```


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```
def adderGenerator(n):  
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```

How does this function work? When `adderGenerator` is called the value for n gets bound to the argument that was supplied. As such, in that particular function call of `adderGenerator` n has a particular value and the returned lambda function is the function that adds that particular value to its parameter x .

Example uses of `adderGenerator`

Consider the following applications of `adderGenerator` and their results

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map(adderGenerator(3), LL(0, -10, 2)) -> (3, -7, 5)
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```
adderGenerator(10)(2) -> 12
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Note: We now have yet another expression that can appear on the left-hand side of a function call expression in Python — a function call itself! If functions can return functions, then of course a function call can be an expression that evaluates to a function!

Solving the redShift problem

Now that we can write functions that return functions, can we solve our redShift problem?

Now, redShift is the function that returns a unary function which adds the given amount to its arguments red component!

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That is, can we write a function `redShift` that takes a parameter *sAmt*, and returns a function that takes a single `Pixel` parameter and adds *sAmt* to its red component, so that we can quickly construct functions to shift by an arbitrary red amount?

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Solving the redShift problem

Yes we can! Consider the following

```
def redShiftHelper(p, sAmt):  
    newRed = first(p) + sAmt  
    if newRed > 255:  
        return cons(255, rest(p))  
    return cons(newRed, rest(p))  
  
def redShift(sAmt):  
    return lambda p: redShiftHelper(p, sAmt)
```

Now, redShift is the function that returns a unary function which adds the given amount to its arguments red component!

Using redShift

Now, imagine we have an LList of Pixels bound to the identifier `img` which is the image we want to transform. We can apply any number of different `redShifts` now by simply mapping different applications of the `redShift` function over our LList.

```
map(redShift(30), img)
```

```
map(redShift(60), img)
```

```
map(redShift(90), img)
```

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Lambda limitations

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This raises the question, could we write the function `redShift` without writing our helper function `redShiftHelper`?

The fact that our `redShiftHelper` function is several statements and expressions would seem to imply that we cannot, but actually...

We can! We just need another tool in our toolbox, and a clever rewrite of the function.

The ternary operator

Many programming languages have an operator simply named the ternary operator for use in writing conditional expressions.

The ternary operator is used when you want to write an expression that operates on three values a , b , and c , and this expression evaluates to b if a is **True** and c otherwise.

Common uses of the ternary operator

Some of the most common uses of the ternary operator is to simplify code that looks like this

```
if cond:
    x = val1
else:
    x = val2
```

However, since the ternary operator is just that — an operator — it means it is very useful to allow us to write expressions in lambda functions which have conditional evaluation.

Anatomy of the ternary operator

An expression using the ternary operator takes the following form:

```
exprIfTrue if condExpr else exprIfFalse
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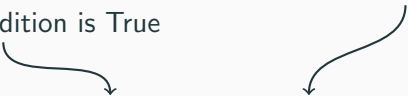
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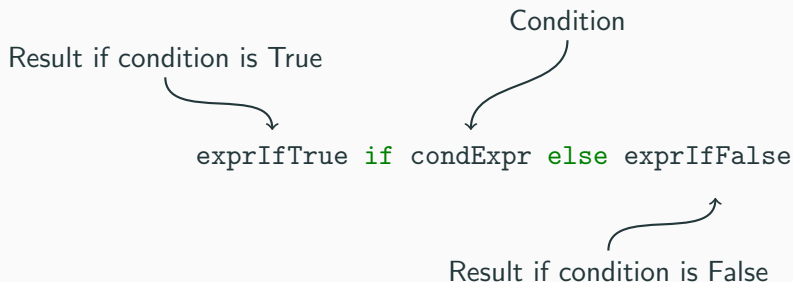
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```


Practice Question: Given that you have a `LList` of numbers bound to the identifier *lon* write a single expression that evaluates to the mean of that `LList`. You may not write any named functions, if you require a function for any reason at all it must be a lambda function. You may call the higher-order functions available in the `cmput274` module.

Practice Question: Rewrite the function `redShift` so that it does not require a helper function, and instead simply returns a lambda that produces the correct result.

That is, your lambda should no longer call another helper function as the original one calls `redShiftHelper`.