PROGRAMMING IN HASKELL

Chapter 6 - Recursive Functions

Introduction

As we have seen, many functions can naturally be defined in terms of other functions.

```
fac :: Int → Int
fac n = product [1..n]
```

fac maps any integer n to the product of the integers between 1 and n.

Expressions are <u>evaluated</u> by a stepwise process of applying functions to their arguments.

For example:

```
  fac 4
=
  product [1..4]
=
  product [1,2,3,4]
=
  1*2*3*4
=
  24
```


Recursive Functions

In Haskell, functions can also be defined in terms of themselves. Such functions are called <u>recursive</u>.

```
fac 0 = 1
fac n = n * fac (n-1)
```

fac maps 0 to 1, and any other integer to the product of itself and the factorial of its predecessor.

For example:

```
  fac 3
=
  3 * fac 2
=
  3 * (2 * fac 1)
=
  3 * (2 * (1 * fac 0))
=
  3 * (2 * (1 * 1))
=
  3 * (2 * 1)
=
  3 * 2
=
  6
```


Note:

z fac 0 = 1 is appropriate because 1 is the identity for multiplication: 1*x = x = x*1.

z The recursive definition <u>diverges</u> on integers < 0 because the base case is never reached:

```
> fac (-1)

*** Exception: stack overflow
```

Why is Recursion Useful?

- Some functions, such as factorial, are <u>simpler</u> to define in terms of other functions.

- As we shall see, however, many functions can <u>naturally</u> be defined in terms of themselves.

- Properties of functions defined using recursion can be proved using the simple but powerful mathematical technique of <u>induction</u>.

Recursion on Lists

Recursion is not restricted to numbers, but can also be used to define functions on <u>lists</u>.

```
product :: Num a ⇒ [a] → a
product []     = 1
product (n:ns) = n * product ns
```

product maps the empty list to 1, and any non-empty list to its head multiplied by the product of its tail.

For example:

```
  product [2,3,4]
=
  2 * product [3,4]
=
  2 * (3 * product [4])
=
  2 * (3 * (4 * product []))
=
  2 * (3 * (4 * 1))
=
  24
```


Using the same pattern of recursion as in product we can define the <u>length</u> function on lists.

```
length :: [a] → Int
length []     = 0
length (_:xs) = 1 + length xs
```

length maps the empty list to 0, and any non-empty list to the successor of the length of its tail.

For example:

```
  length [1,2,3]
=
  1 + length [2,3]
=
  1 + (1 + length [3])
=
  1 + (1 + (1 + length []))
=
  1 + (1 + (1 + 0))
=
  3
```


Using a similar pattern of recursion we can define the <u>reverse</u> function on lists.

```
reverse :: [a] → [a]
reverse []     = []
reverse (x:xs) = reverse xs ++ [x]
```

reverse maps the empty list to the empty list, and any non-empty list to the reverse of its tail appended to its head.

For example:

```
  reverse [1,2,3]
=
  reverse [2,3] ++ [1]
=
  (reverse [3] ++ [2]) ++ [1]
=
  ((reverse [] ++ [3]) ++ [2]) ++ [1]
=
  (([] ++ [3]) ++ [2]) ++ [1]
=
  [3,2,1]
```


Multiple Arguments

Functions with more than one argument can also be defined using recursion. For example:

- Zipping the elements of two lists:

```
zip :: [a] → [b] → [(a,b)]
zip []     _      = []
zip _      []     = []
zip (x:xs) (y:ys) = (x,y) : zip xs ys
```


- Remove the first n elements from a list:

```
drop :: Int → [a] → [a]
drop 0 xs     = xs
drop _ []     = []
drop n (_:xs) = drop (n-1) xs
```

- Appending two lists:

```
(++) :: [a] → [a] → [a]
[]     ++ ys = ys
(x:xs) ++ ys = x : (xs ++ ys)
```


Quicksort

The <u>quicksort</u> algorithm for sorting a list of values can be specified by the following two rules:

- The empty list is already sorted;
- Non-empty lists can be sorted by sorting the tail values ≤ the head, sorting the tail values > the head, and then appending the resulting lists on either side of the head value.

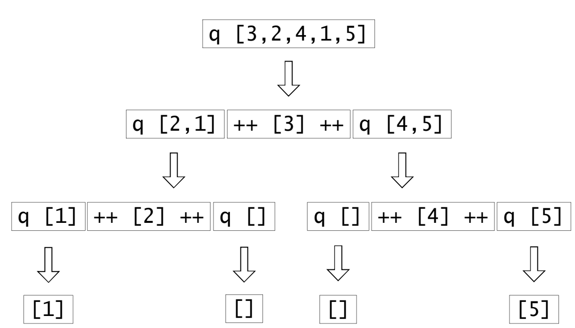
Using recursion, this specification can be translated directly into an implementation:

```
qsort :: Ord a ⇒ [a] → [a]
qsort []     = []
qsort (x:xs) =
   qsort smaller ++ [x] ++ qsort larger
   where
      smaller = [a | a ← xs, a ≤ x]
      larger  = [b | b ← xs, b > x]
```

Note:

- This is probably the <u>simplest</u> implementation of quicksort in any programming language!

For example (abbreviating qsort as q):



Exercises

(1) Without looking at the standard prelude, define the following library functions using recursion:

- Decide if all logical values in a list are true:

```
and :: [Bool] → Bool
```

- Concatenate a list of lists:

```
concat :: [[a]] → [a]
```

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- Produce a list with n identical elements:

```
replicate :: Int → a → [a]
```

- Select the nth element of a list:

```
(!!) :: [a] → Int → a
```

- Decide if a value is an element of a list:

```
elem :: Eq a ⇒ a → [a] → Bool
```

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(2) Define a recursive function

```
merge :: Ord a ⇒ [a] → [a] → [a]
```

that merges two sorted lists of values to give a single sorted list. For example:

```
> merge [2,5,6] [1,3,4]

[1,2,3,4,5,6]
```

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(3) Define a recursive function

```
msort :: Ord a ⇒ [a] → [a]
```

that implements merge sort, which can be specified by the following two rules:

- Lists of length ≤ 1 are already sorted;
- Other lists can be sorted by sorting the two halves and merging the resulting lists.

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