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 evaluated 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:

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

- The recursive definition diverges 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]
```

Problem of <u>reverse</u>: it is slow.

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

- It is NOT tail-recursive
- (++) for each element!

Can we do better?

A fast reverse

```
fastRev :: [a] → [a]
fastRev xs = fastRev’ xs []
  where
    fastRev’ :: [a] -> [a] -> [a]
    fastRev’ [] acc = acc
    fastRev’ (x:xs) acc = fastRev’ xs (x:acc)
```

- ✓ It is tail-recursive
- ✓ Avoids (++) for each element, uses cons (:)

Testing timing in GHCi

Turn on timing with :set s+ command

```
ghci Reverse.hs
Prelude>:set +s
Prelude>head $ reverse [1..10000000]
(9.11 secs, 2,904,957,752 bytes)
Prelude>head $ fastRev [1..10000000]
(6.38 secs, 1,840,072,168 bytes)
```

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)
```

Mutual Recursion

We can define recursion also mutually with more than one function. For example:

- Testing for even / odd

```
even :: Int -> Bool
even 0 = True
even n = odd (n-1)

odd :: Int -> Bool
odd 0 = False
odd n = even (n-1)
```

Quicksort

The quicksort 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 $\leq$ 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):

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

q [2,1] ++ [3] ++ q [4,5]

q [1] ++ [2] ++ q []        q [] ++ [4] ++ q [5]

[1]          []              []              [5]
```

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]
```

- 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
```

(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]
```

(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.