FP101x - Functional Programming

Programming in Haskell – The Countdown Problem

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Challenge the future

What Is Countdown?

- A popular quiz programme on British television that has been running since 1982.

- Based upon an original French version called "Des Chiffres et Des Lettres".

- Includes a numbers game that we shall refer to as the countdown problem.

Example

Using the numbers

1 3 7 10 25 50

and the arithmetic operators

+ - * ÷

construct an expression whose value is 765

Rules

- All the numbers, including intermediate results, must be positive naturals (1,2,3,…).

- Each of the source numbers can be used at most once when constructing the expression.

- We abstract from other rules that are adopted on television for pragmatic reasons.

For our example, one possible solution is

$\boxed{(25-10) * (50+1)} = \boxed{765}$

Notes:

- There are 780 solutions for this example.
- Changing the target number to $\boxed{831}$ gives an example that has no solutions.

Evaluating Expressions

Operators:

```
data Op = Add | Sub | Mul | Div
```

Apply an operator:

```
apply            :: Op → Int → Int → Int
apply Add x y  = x + y
apply Sub x y  = x - y
apply Mul x y  = x * y
apply Div x y  = x `div` y
```

Decide if the result of applying an operator to two positive natural numbers is another such:

```
valid            :: Op → Int → Int → Bool
valid Add _ _    = True
valid Sub x y    = x > y
valid Mul _ _    = True
valid Div x y    = x `mod` y == 0
```

Expressions:

```
data Expr = Val Int | App Op Expr Expr
```

Return the overall value of an expression, provided that it is a positive natural number:

```
eval                  :: Expr → [Int]
eval (Val n)        = [n | n > 0]
eval (App o l r) = [apply o x y | x ← eval l
                                 , y ← eval r
                                 , valid o x y]
```

Either succeeds and returns a singleton list, or fails and returns the empty list.

Formalising The Problem

Return a list of all possible ways of choosing zero or more elements from a list:

```
choices :: [a] → [[a]]
```

For example:

```
> choices [1,2]

[[],[1],[2],[1,2],[2,1]]
```

Return a list of all the values in an expression:

```
values                :: Expr → [Int]
values (Val n)         = [n]
values (App _ l r) = values l ++ values r
```

Decide if an expression is a solution for a given list of source numbers and a target number:

```
solution          :: Expr → [Int] → Int → Bool
solution e ns n = elem (values e) (choices ns)
                  && eval e == [n]
```

Brute Force Solution

Return a list of all possible ways of splitting a list into two non-empty parts:

```
split :: [a] → [([a],[a])]
```

For example:

```
> split [1,2,3,4]

[([1],[2,3,4]),([1,2],[3,4]),([1,2,3],[4])]
```

Return a list of all possible expressions whose values are precisely a given list of numbers:

```
exprs      :: [Int] → [Expr]
exprs []    = []
exprs [n]   = [Val n]
exprs ns    = [e | (ls,rs) ← split ns
                 , l       ← exprs ls
                 , r       ← exprs rs
                 , e       ← combine l r]
```

The key function in this lecture.

Combine two expressions using each operator:

```
combine     :: Expr → Expr → [Expr]
combine l r =
   [App o l r | o ← [Add,Sub,Mul,Div]]
```

Return a list of all possible expressions that solve an instance of the countdown problem:

```
solutions     :: [Int] → Int → [Expr]
solutions ns n = [e | ns' ← choices ns
                    , e   ← exprs ns'
                    , eval e == [n]]
```

How Fast Is It?

System:	1.2GHz Pentium M laptop
Compiler:	GHC version 6.4.1
Example:	`solutions [1,3,7,10,25,50] 765`
One solution:	0.36 seconds
All solutions:	43.98 seconds

Can We Do Better?

- Many of the expressions that are considered will typically be invalid - fail to evaluate.
- For our example, only around 5 million of the 33 million possible expressions are valid.
- Combining generation with evaluation would allow earlier rejection of invalid expressions.

Fusing Two Functions

Valid expressions and their values:

```
type Result = (Expr,Int)
```

We seek to define a function that fuses together the generation and evaluation of expressions:

```
results    :: [Int] → [Result]
results ns = [(e,n) | e ← exprs ns
                    , n ← eval e]
```

This behaviour is achieved by defining

```
results []  = []
results [n] = [(Val n,n) | n > 0]
results ns  =
   [res | (ls,rs) ← split ns
        , lx      ← results ls
        , ry      ← results rs
        , res     ← combine' lx ry]
```

where

```
combine' :: Result → Result → [Result]
```

Combining results:

```
combine' (l,x) (r,y) =
   [(App o l r, apply o x y)
      | o ← [Add,Sub,Mul,Div]
      , valid o x y]
```

New function that solves countdown problems:

```
solutions'      :: [Int] → Int → [Expr]
solutions' ns n =
   [e | ns'    ← choices ns
      , (e,m) ← results ns'
      , m == n]
```

How Fast Is It Now?

Example: `solutions' [1,3,7,10,25,50] 765`

One solution: 0.04 seconds

All solutions: 3.47 seconds

Around 10 times faster in both cases.

Can We Do Better?

- Many expressions will be essentially the same using simple arithmetic properties, such as:

$$\boxed{x * y} = \boxed{y * x}$$

$$\boxed{x * 1} = \boxed{x}$$

- Exploiting such properties would considerably reduce the search and solution spaces.

Exploiting Properties

Strengthening the valid predicate to take account of commutativity and identity properties:

```
valid          :: Op → Int → Int → Bool
valid Add x y  = x ≤ y
valid Sub x y  = x > y
valid Mul x y  = x ≤ y && x ≠ 1 && y ≠ 1
valid Div x y  = x `mod` y == 0 && y ≠ 1
```

How Fast Is It Now?

Example: `solutions'' [1,3,7,10,25,50] 765`

Valid: 250,000 expressions

Around 20 times less.

Solutions: 49 expressions

Around 16 times less.

One solution: 0.02 seconds

Around 2 times faster.

All solutions: 0.44 seconds

Around 7 times faster.

More generally, our program usually produces a solution to problems from the television show in an instant, and all solutions in under a second.

Happy Hacking!