MGS 2009: FUN Lecture 2
Purely Functional Data Structures

Henrik Nilsson

University of Nottingham, UK

Purely Functional Data structures (1)

Why is there a need to consider purely functional data structures?

- The standard implementations of many data structures assume imperative update. To what extent truly necessary?

- Purely functional data structures are ***persistent***, while imperative ones are ***ephemeral***:
    - Persistence is a useful property in its own right.
    - Can't expect added benefits for free.

Purely Functional Data structures (2)

This lecture draws from:

> Chris Okasaki. *Purely Functional Data Structures*. Cambridge University Press, 1998.

We will look at some examples of how **_numerical representations_** can be used to derive purely functional data structures.

Numerical Representations (1)

Strong analogy between lists and the usual representation of natural numbers:

```
data List a =                              data Nat =
      Nil                                        Zero
    | Cons a (List a)                          | Succ Nat


tail (Cons _ xs) = xs                      pred (Succ n) = n


append Nil          ys = ys            plus Zero n        = n
append (Cons x xs) ys =                plus (Succ m) n =
     Cons x (append xs ys)                    Succ (plus m n)
```

Numerical Representations (2)

This analogy can be taken further for designing container structures because:

- inserting an element resembles incrementing a number

- combining two containers resembles adding two numbers

etc.

Thus, representations of natural numbers with certain properties induce container types with similar properties. Called *Numerical Representations*.

Random Access Lists

We will consider **Random Access Lists** in the following. Signature:

```
data RList a

empty    :: RList a
isEmpty  :: RList a -> Bool
cons     :: a -> RList a -> RList a
head     :: RList a -> a
tail     :: RList a -> RList a
lookup   :: Int -> RList a -> a
update   :: Int -> RList a -> RList a
```

Positional Number Systems (1)

- A number is written as a **sequence** of **digits** $b_0 b_1 \ldots b_{m-1}$, where $b_i \in D_i$ for a fixed family of digit sets given by the positional system.

- b_0 is the **least significant** digit, b_{m-1} the **most significant** digit (note the ordering).

- Each digit b_i has a **weight** w_i. Thus:

$$\text{value}(b_0 b_1 \ldots b_{m-1}) = \sum_{0}^{m-1} b_i w_i$$

where the fixed sequence of weights w_i is given by the positional system.

Positional Number Systems (2)

- A number is written written in **base** B if $w_i = B^i$ and $D_i = \{0, \ldots, B - 1\}$.

- The sequence w_i is usually but not necessarily increasing.

- A number system is **redundant** if there is more than one way to represent some numbers (disallowing trailing zeroes).

- A representation of a positional number system can be **dense**, meaning including zeroes, or **sparse**, eliding zeroes.

Exercise 1: Positional Number Systems

Suppose $w_i = 2^i$ and $D_i = \{0, 1, 2\}$. Give three different ways to represent 17.

Exercise 1: Solution

- 10001, since $\mathrm{value}(10001) = 1 \cdot 2^0 + 1 \cdot 2^4$

- 1002, since $\mathrm{value}(1002) = 1 \cdot 2^0 + 2 \cdot 2^3$

- 1021, since $\mathrm{value}(1021) = 1 \cdot 2^0 + 2 \cdot 2^2 + 1 \cdot 2^3$

- 1211, since
  $\mathrm{value}(1211) = 1 \cdot 2^0 + 2 \cdot 2^1 + 1 \cdot 2^2 + 1 \cdot 2^3$

From Positional System to Container

Given a positional system, a numerical representation may be derived as follows:

- for a container of size n, consider a representation $b_0 b_1 \ldots b_{m-1}$ of n,

- represent the collection of n elements by a sequence of trees of size w_i such that there are b_i trees of that size.

For example, given the positional system of exercise 1, a container of size 17 might be represented by 1 tree of size 1, 2 trees of size 2, 1 tree of size 4, and 1 tree of size 8.

What Kind of Trees?

The kind of tree should be chosen depending on needed sizes and properties. Two possibilities:

- ***Complete Binary Leaf Trees***

  ```
  data Tree a = Leaf a
              | Node (Tree a) (Tree a)
  ```

  Sizes: $2^n, n \geq 0$

- ***Complete Binary Trees***

  ```
  data Tree a = Leaf a
              | Node (Tree a) a (Tree a)
  ```

  Sizes: $2^{n+1} - 1, n \geq 0$

Binary Random Access Lists (1)

Binary Random Access Lists are induced by

- the usual binary representation, i.e. $w_i = 2^i$, $D_i = \{0, 1\}$
- complete binary leaf trees

Thus:

```
data Tree a = Leaf a
            | Node Int (Tree a) (Tree a)
data Digit a = Zero | One (Tree a)
type RList a = [Digit a]
```

The `Int` field keeps track of tree size for speed.

Binary Random Access Lists (2)

The increment function on dense binary numbers:

```
inc [] = [One]
inc (Zero : ds) = One : ds
inc (One  : ds) = Zero : inc ds  -- Carry
```

Binary Random Access Lists (3)

Inserting an element first in a binary random access list is analogous to `inc`:

```
cons :: a -> RList a -> RList a
cons x ts = consTree (Leaf x) ts


consTree :: Tree a -> RList a -> RList a
consTree t []             = [One t]
consTree t (Zero : ts)    = (One t : ts)
consTree t (One t' : ts) =
    Zero : consTree (link t t') ts
```

Binary Random Access Lists (4)

The utility function `link` joins two equally sized trees:

```
-- t1 and t2 are assumed to be the same size
link t1 t2 = Node (2 * size t1) t1 t2
```

Exercise 2: `unconsTree`

The decrement function on dense binary numbers:

```
dec [One] = []
dec (One  : ds) = Zero : ds
dec (Zero : ds) = One : dec ds  -- Borrow
```

Define `unconsTree` following the above pattern:

```
unconsTree :: RList a -> (Tree a, RList a)
```

And then `head` and `tail`:

```
head :: RList a -> a
tail :: RList a -> RList a
```

Exercise 2: Solution (1)

```
unconsTree :: RList a -> (Tree a, RList a)
unconsTree [One t]       = (t, [])
unconsTree (One t : ts) = (t, Zero : ts)
unconsTree (Zero  : ts) = (t1, One t2 : ts')
    where
        (Node _ t1 t2, ts') = unconsTree ts
```

Note: partial operation.

Exercise 2: Solution (2)

```
head :: RList a -> a
head ts = x
    where
        (Leaf x, _) = unconsTree ts


tail :: RList a -> RList a
tail ts = ts'
    where
        (_, ts') = unconsTree ts
```

Binary Random Access Lists (5)

Lookup is done in two stages: first find the right tree, then lookup in that tree:

```
lookup :: Int -> RList a -> a
lookup i (Zero : ts) = lookup i ts
lookup i (One t : ts)
    | i < s        = lookupTree i t
    | otherwise  = lookup (i - s) ts
    where
        s = size t
```

Note: partial operation.

Binary Random Access Lists (6)

```
lookupTree :: Int -> Tree a -> a
lookupTree _ (Leaf x) = x
lookupTree i (Node w t1 t2)
    | i < w `div` 2 =
        lookupTree i t1
    | otherwise =
        lookupTree (i - w `div` 2) t2
```

The operation `update` has exactly the same
structure.

Binary Random Access Lists (7)

Time complexity:

- `cons`, `head`, `tail`, perform $O(1)$ work per digit, thus $O(\log n)$ worst case.

- `lookup` and `update` take $O(\log n)$ to find the right tree, and then $O(\log n)$ to find the right element in that tree, so $O(\log n)$ worst case overall.

Binary Random Access Lists (7)

Time complexity:

- `cons, head, tail,` perform $O(1)$ work per digit, thus $O(\log n)$ worst case.

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Time complexity for `cons, head, tail` disappointing: can we do better?

Skew Binary Numbers (1)

Skew Binary Numbers:

- $w_i = 2^{i+1} - 1$ (rather than 2^i)

- $D_i = \{0, 1, 2\}$

Representation is redundant. But we obtain a *canonical form* if we insist that only the least significant non-zero digit may be 2.

Note: The weights correspond to the sizes of *complete* binary trees.

Skew Binary Numbers (2)

Theorem: Every natural number n has a unique skew binary canonical form.

Proof sketch. By induction on n.

- Base case: the case for 0 is direct.

Skew Binary Numbers (3)

- Inductive case. Assume n has a unique skew binary representation $b_0 b_1 \dots b_{m-1}$
  - If the least significant non-zero digit is smaller than 2, then $n + 1$ has a unique skew binary representation obtained by adding 1 to the least significant digit b_0.
  - If the least significant non-zero digit b_i is 2, then note that $1 + 2(2^{i+1} - 1) = 2^{i+2} - 1$. Thus $n + 1$ has a unique skew binary representation obtained by setting b_i to 0 and adding 1 to b_{i+1}.

Exercise 3: Skew Binary Numbers

- Give the canonical skew binary representation for 31, 30, 29, and 28.

- Assume a *sparse* skew binary representation of the natural numbers

  ```
  type Nat = [Int]
  ```

  where the integers represent the *weight* of each non-zero digit. Assume further that the integers are stored in increasing order, except that the first two may be equal indicating that the smallest non-zero digit is 2. Implement a function `inc` to increment a natural number.

Exercise 3: Solution

- 00001, 0002, 0021, 0211

- ```
  inc :: Nat -> Nat
  inc (w1 : w2 : ws)
       | w1 == w2 = w1 * 2 + 1 : ws
  inc ws           = 1 : ws
  ```

Skew Binary Random Access Lists (1)

```haskell
data Tree a = Leaf a | Node (Tree a) a (Tree a)
type RList a = [(Int, Tree a)]


empty :: RList a
empty = []


cons :: a -> RList a -> RList a
cons x ((w1, t1) : (w2, t2) : wts) | w1 == w2 =
    (w1 * 2 + 1, Node t1 x t2) : wts
cons x wts = ((1, Leaf x) : wts)
```

Skew Binary Random Access Lists (2)

```
head :: RList a -> a
head ((_, Leaf x)       : _) = x
head ((_, Node _ x _) : _) = x


tail :: RList a -> RList a
tail ((_, Leaf _): wts) = wts
tail ((w, Node t1 _ t2) : wts) =
     (w', t1) : (w', t2) : wts
    where
        w' = w `div` 2
```
Note: again, partial operations.

Skew Binary Random Access Lists (3)

```
lookup :: Int -> RList a -> a
lookup i ((w, t) : wts)
    | i < w       = lookupTree i w t
    | otherwise   = lookup (i - w) wts
lookupTree :: Int -> Int -> Tree a -> a
lookupTree _ _ (Leaf x) = x
lookupTree i w (Node t1 x t2)
    | i == 0      = x
    | i < w'      = lookupTree (i - 1) w' t1
    | otherwise   = lookupTree (i - w' - 1) w' t2
    where
        w' = w `div` 2
```

Skew Binary Random Access Lists (4)

Time complexity:

- `cons, head, tail:` $O(1)$.

- `lookup` and `update` take $O(\log n)$ to find the right tree, and then $O(\log n)$ to find the right element in that tree, so $O(\log n)$ worst case overall.

Skew Binary Random Access Lists (4)

Time complexity:

- `cons, head, tail`: $O(1)$.

- `lookup` and `update` take $O(\log n)$ to find the right tree, and then $O(\log n)$ to find the right element in that tree, so $O(\log n)$ worst case overall.

Okasaki:

Although there are better implementations of lists, and better implementations of (persistent) arrays, none are better at both.