You Can Do More If You’re Lazy!

Handout #41
CS251 Lecture 36
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Overview of Today’s Lecture

- A quick introduction to Haskell, a language with lazy parameter-passing and data structures.
- Modularity problems involving lists, and their solution with lazy lists in Haskell
- Lazy trees
- Lazy data in other languages
Sample Haskell Expressions

Prelude> 2*(3+4)
14

Prelude> head [1,2,3,4]
1

Prelude> tail [1,2,3,4]
[2,3,4]

Prelude> map (2*) [1,2,3,4]
[2,4,6,8]

Prelude> foldr (+) 0 [1,2,3,4]
10

Prelude> take 2 [10,20,30,40,50]
[10,20]

Prelude> drop 2 [10,20,30,40,50]
[30,40,50]

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More Haskell Expressions

Prelude> fst (1,2)
1

Prelude> snd (1,2)
2

Prelude> zip [1,2,3] [10,20,30,40]
[(1,10),(2,20),(3,30)]

Prelude> unzip [(1,10),(2,20),(3,30)]
([1,2,3],[10,20,30])

Prelude> (\ x -> x*x) (1+2)
9

Prelude> (\ x y -> x*x) (1+2) (3/0) -- illustrates laziness
9

Prelude> (\ x y -> x*x) (3/0) (1+2)
Program error: primDivDouble 3.0 0.0
Haskell Types

Prelude> :type map
map :: (a -> b) -> [a] -> [b]

Prelude> :type foldr
foldr :: (a -> b -> b) -> b -> [a] -> b

Prelude> :type zip
zip :: [a] -> [b] -> [(a,b)]

Prelude> :type unzip
unzip :: [(a,b)] -> ([a],[b])

Prelude> :type "foo"
"foo" :: String

Prelude> :type "foo" == "bar"
"foo" == "bar" :: Bool
Qualified Types in Haskell

Prelude> :type 1+2
1 + 2 :: Num a => a

Prelude> :type [1,2,3]
[1,2,3] :: Num a => [a]

Prelude> :type 1 == 2
1 == 2 :: Num a => Bool

Prelude> :type \ x -> x*x
\ x -> x * x :: Num a => a -> a
In HUGS, definitions *must* be in a file, not at top-level!

\[ a = 2 + 3 -- \text{declare variable } a \]

\[ \text{sq} = \lambda x \to x \times x -- \text{sugared form: } \text{sq} \ x = x \times x \]

\[ \text{fact} \ 0 = 1 -- \text{recursive factorial} \]
\[ \text{fact} \ n = n \times \text{fact} \ (n-1) \]

\[ \text{factIter} \ n = \text{loop} \ n \ 1 -- \text{iterative factorial} \]
\[ \quad \text{where} \quad \text{loop} \ 0 \ \text{ans} = \text{ans} \]
\[ \quad \text{loop} \ \text{num} \ \text{ans} = \text{loop} \ (\text{num-1}) \ (\text{num} \times \text{ans}) \]

\[ \text{isEven} \ 0 = \text{True} -- \text{Mutually recursive functions isEven and isOdd} \]
\[ \text{isEven} \ m = \text{isOdd} \ (m - 1) \]

\[ \text{isOdd} \ 0 = \text{False} \]
\[ \text{isOdd} \ n = \text{isEven} \ (n - 1) \]

\[ \text{mymap} \ f \ [] = [] \]
\[ \text{mymap} \ f \ (x:\text{xs}) = (f \ x):(\text{mymap} \ f \ \text{xs}) \]
A Modularity Problem

Consider infinite sequences of integers, such as:

- *powers of 2:* 1, 2, 4, 8, 16, 32, 64, ...
- *factorials:* 1, 1, 2, 6, 24, 120, 720, ...
- *Fibonacci numbers:* 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, ...
- *primes:* 2, 3, 5, 7, 11, 13, 17, 19, 23, 29 ...

Suppose we want answers to questions like the following:

- What are the first \( n \) elements?
- What is the first element greater than 100?
- What is the (0-based) index of the first element greater than 100?
- What is the first consecutive pair whose difference is more than 25?
- What is the least index \( i \) for which the sum of elements 0 through \( i \) is more than 1000?

**Challenge:** can we answer these questions in a modular way?
-- returns list of first \( n \) Fibonacci numbers
fibsPrefix :: Integer \to [Integer]
fibsPrefix \( n \) = gen 0 0 1
    where gen i a b =
        if i \geq n then []
        else a : (gen (i + 1) b (a + b))

-- returns least Fibonacci number greater than \( \text{lim} \)
leastFibGt :: Integer \to Integer
leastFibGt \( \text{lim} \) = least 0 1
    where least a b = if a > \( \text{lim} \) then a
        else least b (a + b))

-- returns (0-based) index \( i \) such that first \( i \) Fibonacci numbers have a sum greater than \( \text{lim} \)
fibSumIndex :: Integer \to Integer
fibSumIndex \( \text{lim} \) = index 0 0 0 1
    where index i sum a b =
        if sum \geq \( \text{lim} \) then i
        else index (i+1) (sum+a) b (a + b)
**A More Modular Approach: Infinite Lists**

*Idea:* Separate the generation of the sequence elements from subsequent processing. Since we don't know how many elements we need, generate *all* of them — *lazily!*

```haskell
nats = genNats 0 where genNats n = n : genNats (n + 1)
     -- Can also be written: nats = [0..]

poss = tail nats -- the positive integers
     -- Can also be written: poss = [1..]

powers n = genPowers 1
    where genPowers x = x : (genPowers (n * x))

facts = genFacts 1 1
    where genFacts ans n = ans : (genFacts (n * ans) (n + 1))

fibs = genFibs 0 1
    where genFibs a b = a : (genFibs b (a + b))
```
Note: Assume the following functions are invoked only on infinite lists. Then we can ignore the base case of an empty list! Each function could be extended to handle the empty list as well.

-- Returns a list of the first \(n\) elements of a given list.
-- (Note: the \texttt{take} function is part of standard Haskell)
\[
\text{take } n \hspace{1em} (x:xs) \hspace{1em} = \hspace{1em} \text{if } (n == 0) \hspace{1em} \text{then } [] \hspace{1em} \text{else } x : \text{take } (n-1) \hspace{1em} xs
\]

-- Returns first element satisfying predicate \(p\)
\[
\text{firstElem } p \hspace{1em} (x:xs) \hspace{1em} = \hspace{1em} \text{if } (p \hspace{1em} x) \hspace{1em} \text{then } x \hspace{1em} \text{else } \text{firstElem } p \hspace{1em} xs
\]

-- Returns first contiguous pair satisfying predicate \(p\)
\[
\text{firstPair } p \hspace{1em} (x:y:zs) \hspace{1em} = \hspace{1em}
\text{if } (p(x,y)) \hspace{1em} \text{then } (x,y) \hspace{1em} \text{else } \text{firstPair } p \hspace{1em} (y:zs)
\]

-- Returns (0-based) index of first elt satisfying pred \(p\)
\[
\text{indexOf } p \hspace{1em} xs = \hspace{1em} \text{ind } 0 \hspace{1em} xs
\text{where } \text{ind } i \hspace{1em} (x:xs) \hspace{1em} = \hspace{1em}
\text{if } (p \hspace{1em} x) \hspace{1em} \text{then } i \hspace{1em} \text{else } (\text{ind } (i+1) \hspace{1em} xs)
\]
Modular Infinite List Processing Examples

take 10 fibs

firstElem (\ x -> x > 100) (powers 2)

indexOf (\ x -> x > 1000) facts

firstPair (\ (x,y) -> (y - x) > 25) fibs
Scanning accumulates partial results of \texttt{foldl} into a list.

\begin{verbatim}
scanl :: (a -> b -> a) -> a -> [b] -> [a]
scanl f ans (x:xs) = ans : scanl f (f ans x) xs

scanl (+) 0 (powers 2) -- be careful of initial zero!

-- alternative definition of facts
facts = scanl (*) 1 poss

-- Like scanl, but uses first elt as initial answer
scanl1 :: (a -> a -> a) -> [a] -> [a]
scanl1 f (x:xs) = scanl f x xs

indexOf (\s -> s > 1000) (scanl1 (+) fibs)
\end{verbatim}
Higher-order Infinite List Generation

iterate :: (a -> a) -> a -> [a]
iterate f x = x : iterate f (f x)

-- another way to generate the nats
nats = iterate (1 +) 0

iterate2 :: (a -> a -> a) -> a -> a -> [a]
iterate2 f x1 x2 = x1 : iterate2 f x2 (f x1 x2)

-- another way to generate the fibs
fibs = iterate2 (+) 0 1

iteratei :: (Integer -> a -> a) -> Integer -> a -> [a]
iteratei f i x = x : iteratei f (i + 1) (f i x)

-- yet another way to generate the facts
facts = iteratei (*) 1 1
Cyclic Definitions of Infinite Lists

ones = 1 : ones

-- cyclic definition of nats
nats = 0 : (map (1 +) nats)

zipWith :: (a -> b -> c) -> [a] -> [b] -> [c]
zipWith f (x:xs) (y:ys) = (f x y) : (zipWith f xs ys)

-- another cyclic definition of nats
nats = 0 : (zipWith (+) ones nats)

-- cyclic definition of facts
facts = 1 : (zipWith (*) poss facts)

-- cyclic definition of fibs
fibs = 0 : 1 : (zipWith (+) fibs (tail fibs))
Generating Primes

Idea: use the Sieve of Eratosthenes

\[
sieve \ (x:xs) = \\
x : (sieve \ (filter \ (\ y -> (rem \ y \ x) /= 0) \ xs))
\]

primes = sieve \ (tail \ (tail \ nats))
    -- start sieving at 2

Not only does this give an infinite list of primes, it does so efficiently
by avoiding unnecessary divisions.

For more examples of lazy lists in Haskell, see Chapter 17 of
Simon Thompson book *Haskell: The Craft of Functional
Programming.*
Lazy Trees

Can use laziness to perform a two-pass tree walk in a single pass:

```haskell
data Tree a = Leaf | Node (Tree a) a (Tree a) deriving Show

addMax tr = tr'
  where (tr', m) = walk tr
    walk Leaf = (Leaf, 0)
    walk (Node l n r) = (Node l' (n + m) r', max3 n ml mr)
      where (l', ml) = walk l
        (r', mr) = walk r

max3 a b c = max a (max b c)

t = (Node (Node Leaf 1 (Node Leaf 7 Leaf)) 5 (Node Leaf 4 Leaf))

-- AddMax> addMax t
-- Node (Node Leaf 8 (Node Leaf 14 Leaf)) 12 (Node Leaf 11 Leaf)

See Hughes paper *Functional Programming Matters* for compelling lazy game tree example.
```
### Streams: Lazy Lists for Scheme and Hoilec

<table>
<thead>
<tr>
<th>Scheme Lists</th>
<th>Scheme Streams</th>
<th>Hoilec Lists</th>
<th>Hoilec Streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>cons</td>
<td>cons-stream</td>
<td>prep</td>
<td>sprep</td>
</tr>
<tr>
<td>car</td>
<td>head</td>
<td>head</td>
<td>shead</td>
</tr>
<tr>
<td>cdr</td>
<td>tail</td>
<td>tail</td>
<td>stail</td>
</tr>
<tr>
<td>'()</td>
<td>the-empty-stream</td>
<td>#e</td>
<td>(sempty)</td>
</tr>
<tr>
<td>null?</td>
<td>null-stream</td>
<td>empty?</td>
<td>sempty?</td>
</tr>
</tbody>
</table>

- Scheme and Hoilec streams are lazy only in their tails, *not* in their heads!
- Can easily translate lazy list examples from Haskell to Hoilec and Scheme.
- See Section 3.5 of *Structure and Interpretation of Computer Programs (SICP)* for more Scheme stream examples.
Hoilec Streams

(sprep $E_{head}$ $E_{tail}$) returns a (potentially infinite) stream whose head is the value of $E_{head}$ and whose tail is the value of $E_{tail}$. The evaluation of $E_{tail}$ is delayed until it is needed.

(shead $E_{stream}$) returns the head element of the stream value of $E_{stream}$.

(stail $E_{stream}$) returns the tail element of the stream value of $E_{stream}$. This forces the computation of the delayed tail expression.

sempty returns the empty stream.

(seempty? $E_{stream}$) returns #t if $E_{stream}$ is the empty stream and #f otherwise.
Hoilec Stream Examples

;; Generate stream of integers starting with n
(def ints-from
  (fun (n)
      (sprep (ints-from (+ n 1))))) ; No base case!

;; Converts first n elements of infinite stream to a list
(def (sprefix n stream)
  (if (= n 0)
      #e
      (prep (shead stream)
        (sprefix (- n 1) (stail stream))))

(def ones (sprep 1 ones))

(def (smap f stream)
  (if (sempthy? stream)
      stream
      (sprep (f (shead stream)) (smap f (stail stream))))

(def nats (sprep 0 (smap (fun (x) (+ x 1)) nats)))
Implementing Lazy Data in Strict Languages

Use memoizing promises to implement lazy lists in Hoilec:

(delay E) desugars to (make-promise (fun () E))

(def (force promise) (promise))

(sprep E₁ E₂) desugars to (list E₁ (delay E₂))

(define (shead stream) (nth 1 stream))

(define (stail stream) (force (nth 2 stream)))

(define (sempty) #e)

(define (sempty? stream) (empty? stream))

Can generalize this idea to handle infinite trees.

Can similarly implement lazy lists in Scheme and OCaml.

Lazy data is very helpful, but sometimes need even more laziness (e.g. translating addMax example to Scheme or OCaml).
Java Iterators

Like streams, Java’s iterators can be conceptually infinite. For example:

```java
public class FibIterator implements Iterator<Integer> {

    private int a, b;

    public FibIterator () { a = 0; b = 1; }

    public boolean hasNext () { return true; }

    public Integer next () {
        int old_a = a; a = b; b = old_a + b;
        return new Integer(old_a); // wrap int to satisfy next() spec
    }

    public void remove () { ... ignore this ... } }
```

- Maintaining explicit state of iterator is often tricky compared to lazy list.
- Unlike streams, enumerations are not *persistent*; can’t hold on to a snapshot of the enumeration at a given point in time without copying it.
- While lazy lists are easy to adapt to trees, enumerations are inherently linear.