Keep Your Laziness In Check

Being lazy is fun and useful, but...

...sometimes it leads to unintended consequences.

- Kenny:
- Enqueue O(1), Dequeue O(1) NOT AMORTIZED because of laziness!
- Guarantees valid persistently; thunks are only evaluated once
- How do we know we have implemented the Okasaki Queues correctly?
- Correctness != functional correctness or micro-benchmark performance:
- == the right amount of lazy

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Wouldn't it be nice to QuickCheck laziness?

- QuickCheck gives functional correctness
- But laziness can't be observed by QuickCheck
- What if we make it observable? Then it's just part of functional correctness!

Wouldn't it be nice to QuickCheck laziness?

Traditional property-based testing (such as QuickCheck):

- ✓ Great for testing functional correctness
- ✓ Write a specification, fuzz inputs to functions to automatically test against that specification
- ✗ Can't observe (or even specify) properties beyond functional correctness

If we were able to **specify** and **observe** laziness, we could treat it *just like* functional correctness.

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Observing strictness (part I)

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```haskell
instrumentListWithRef :: IORef Int -> [a] -> [a]
instrumentListWithRef _     []       = []
instrumentListWithRef count (a : as) =
  unsafePerformIO $ do
    modifyIORef' count (\x -> x + 1)
    return (a : instrumentListWithRef count as)
```

- Hengchu:
- `instrumentListWithRef` injected a snippet of code at every cons cell
- and it returns a new "loaded" list
- the injected code is executed as the "loaded" list gets pattern-matched on

Strictness doesn't exist in a vacuum

Strictness doesn't exist in a vacuum

```haskell
type Context a = a -> ()
-----------------------------------------------
lazy, whnf, spineStrict :: Context [a]
lazy        = \xs -> const () xs
whnf        = \xs -> case xs of
                       []    -> ()
                       (_:_) -> ()
spineStrict =
  \xs -> whnf (foldl' (\ys y -> y : ys)) [] xs)
```

- The context type gives a function that returns a trivial value of the unit type
- It might look like there's only one such function `const ()`
- There can actually be all kinds of varying strictness behavior
- Forcing the unit value triggers the strictness behavior on the input a
- This gives us an easy way to observe the strictness behavior of a context

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Demanding an answer, lazily

Demanding an answer, lazily

```haskell
evaluate :: () -> IO ()
evaluate () = return ()

demandCount :: Context b -> ([a] -> b) -> [a] -> Int
demandCount c f as =
  unsafePerformIO $ do
    count <- newIORef 0
    let observableList =
          instrumentListWithRef count as
    evaluate ((c . f) observableList)
    readIORef count
```

- The seemingly trivial evaluate function forces the unit value returned by a context, thus triggering evaluation of the demanded part of observableList
- `demandCount` takes a context, and a function that operates over lists and the input list
- it applies instrumentListWithRef on the input list, producing an observableList, and applies the function and context over the observableList, triggering the injected instrumentation code

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Examples of `demandCount`


```
ghci> let f = take 6
ghci> demandCount lazy f [1..5]
0
ghci> demandCount whnf f [1..5]
1
ghci> demandCount spineStrict f [1..5]
5
```

- Just some examples showing demandCount
- Note that we simply treat `f` as a black box
- We don't need to know anything more about `f` other than the fact it typechecks with demandCount!

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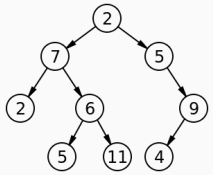
Beyond lists and numbers



?

- Kenny:
- This gives us a bare example that counts the number of cons cells forced, but what if we want more fine grained information of arbitrary algebraic data types?
- Numbers can't directly capture the structure of a tree, so it can't capture the nodes of a tree that get forced in a computation

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ListDemand

```
ListDemand

data List a =
    Cons a (List a)
  | Nil

data Thunk a = T | E a

data ListDemand d =
    ConsD (Thunk d)
          (Thunk (ListDemand d))
  | NilD

data IntDemand = IntD
```

- Now, we can exactly characterize the demand on a list of Ints by composing the type ListDemand and IntDemand

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Examples

Examples

```
data ListDemand d =
    ConsD (Thunk d)
          (Thunk (ListDemand d))
  | NilD

data IntDemand = IntD
-------------------------------------------------------
ConsD T
  (ConsD (E IntD)
    (ConsD T T))

ConsD (E IntD)
  (ConsD T
    (ConsD (E IntD) (E NilD)))
```

- The 2nd Int is forced, and we force 3 cons cells, we don't force anything in the rest of the list
- The 1st and 3rd Int is forced, and the list's spine is forced
- Note that these represent concrete observations instrumented on given inputs, they do not represent the general behavior of contexts

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TreeDemand

TreeDemand

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

data TreeDemand d =
    NodeD (Thunk (TreeDemand d))
          (Thunk d)
          (Thunk (TreeDemand d))
  | LeafD
```

- The demand type for a binary Tree
- We can either demand the value at an internal node, or one of the subtrees
- The demand type represents all of the possible prefixes/subshapes of its corresponding data type

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ListDemand vs TreeDemand

```
ListDemand vs TreeDemand
```

```
data ListDemand d =
    ConsD (Thunk d)
          (Thunk (ListDemand d))
  | NilD

data TreeDemand d =
    NodeD (Thunk (TreeDemand d))
          (Thunk d)
          (Thunk (TreeDemand d))
  | LeafD
```

- Notice the similarity between ListDemand and TreeDemand with their corresponding data types
- In general, the demand type of a data type simply interleaves a `Thunk` at every constructor field

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Computing demand, generically

```
demandList :: Context b -> ([Int] -> b)
           -> [Int]
           -> (b, Thunk (ListDemand IntDemand))

demandTree :: Context b -> (Tree Int -> b)
           -> Tree Int
           -> (b, Thunk (TreeDemand IntDemand))
-----------------------------------------------
demand     :: Context b -> (a -> b) -> a
           -> (b, Thunk (Demand a))
```

- FIX THE MARGIN ISSUES
- There is a generic transformation between a data type and its corresponding data type representing a demand upon it
- `Demand` is a type level function that calculates the demand type
- We return a `Thunk` of demand because the input might not be demanded at all
- As the input value is traversed by the function, which is driven by the context, the evaluation of each thunk builds a pointer based data structure which is isomorphic to the demand data type, which is then frozen into a demand representation

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Generic `Demand` calculation

Generic `Demand` calculation

```
type family Demand (x :: *) :: * where
 Demand (a -> b)  = FuncDemand
 Demand (a :+: b) = Demand a :+: Demand b
 Demand (a :*: b) = Thunk (Demand a) :*: Thunk (Demand b)
```

- For simplicity, we speak of types in terms of sums and products
- `FuncDemand` is isomorphic to IntDemand in that it only captures whether the function was used at all

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First-order specifications


```haskell
-- uncurried take
take     :: (Int, [a]) -> [a]

takeSpec :: Int -> [a]
         -> Demand [a]
         -> (Thunk (Demand Int), Thunk (Demand [a]))
```

- Having demonstrated how to reify demand behaviors into value, we now need to figure out how to write down a specification to check if whether a particular run of the program has the specified laziness according to the specification
- Specifications goings backwards from demands on the output to demands on the inputs of the function. This is because how much input is demanded depends on how much output is demanded, hence the arrows go the other way.
- Note that `takeSpec` takes the same inputs as `take` would. This is necessary in general because the demand behavior of programs can depend on their inputs, as it is the case for `take`!

PLACEHOLDER FOR PICTURE

- To QuickCheck `takeSpec`, we use mechanisms from QuickCheck to fuzz an Int and a [a] as inputs for `take`
- We use the `CoArbitrary` mechanism to generate random contexts that exerts non-trivial demand on the output values of `take`
- We use the generic `demand` function to kick off the entire computation
- We have now observed the demand on the input and also the demand on the output of take, so we can just straightforwardly compare that to what the specification expects.
- If we find a counterexample, we shrink the inputs first, and then shrink the reified demand, and re-exert that new demand on the output.

PLACEHOLDER FOR PICTURE

Higher-order specifications

- There is in fact also a mechanical transformation between the type of a function to the type of its demand specification
- Moreover, this transformation works even with high-order functions
- Higher-order specifications will take specification of their input functions because their demand behavior is parameterized over the demand behavior of their input functions
- At testing time, these specifications can be fuzzed through the same `CoArbitrary` mechanism

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Contributions

Contributions

With **StrictCheck**, you will be able to:

- **Observe** laziness from within Haskell
- **Specify** laziness properties as Haskell functions
- **Test** implementations against those specifications
- **For all types**,[1] including higher-order functions and data types containing functions

The implementation is a work in progress.

[1] Simple (i.e. non-indexed, non-existential) types

StrictCheck is a lightweight tool that adds a very small overhead for instrumentation and observation of functional programs in Haskell. It also provides infrastructure for writing specifications and checking