# Keep Your Laziness In Check

**Kenny Foner**, **Hengchu Zhang**, and **Leo Lampropoulos**

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University of Pennsylvania





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## Being lazy is sometimes vital, but. . .

. . . it can lead to unintended consequences.





Being lazy is sometimes vital, but. . .
. . . it can lead to unintended consequences.

- Ubiquitous in Haskell programming, used in OCaml programming
- (FRP) In the broader world, it is intrinsic in web-based functional reactive programming
- (Spark) and in the field of big-data processing, for example, Spark

## Lazy lists

```
type 'a lazyList =
  | Cons of ('a Lazy.t *
             'a lazyList Lazy.t)
  | Nil
```





Lazy lists
type 'a lazyList =
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| Nil

- In this talk, we'll analyze functions that operate over lazy data structures
- for instance, a lazy list like this
- A lazy list is just a list with all of its parameters wrapped in a lazy computation

# Lazy queues

```
let enQ a (front,                    back) =
          (front, lazy (Cons (lazy a, back)))

let deQ (front, back) =
  match Lazy.force front with
    | Cons (a, front') -> (a, (front', back))
    | Nil ->
        let Cons (a, front') = reverseLazyList back
        in (a, (front', lazy Nil))
```





Lazy queues
let enQ a (front, back) = (front, lazy (Cons (lazy a, back)))
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- As a micro example to motivate why thinking about laziness can be non-trivial, let's look at this queue
- In this slide, we use call-by-name ML for simplicity of presentation, but it can be implemented in OCaml using the Lazy module
- This has amortized O(1) performance cost.
- This queue is lazy as long as you don't empty the front, then it is fully lazy in the structure of the back list. It only forces the spine of the back list when the front list is emptied.

# 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 only specify and check functional correctness properties

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





Wouldn't it be nice to QuickCheck laziness?
Traditional property-based testing (such as QuickCheck):
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If we were able to **specify** and **observe** laziness, we could treat it *just like* functional correctness.

- QuickCheck gives functional correctness
- But laziness can't be observed by QuickCheck
- At the 3rd bullet point, say that laziness is not generally considered part of functional correctness much like how asymptotic runtime is not part of functional correctness because they are not directly observable
- What if we make it observable? Then it's just part of functional correctness!

# StrictCheck

"We actually can do that thing."

# Observing strictness

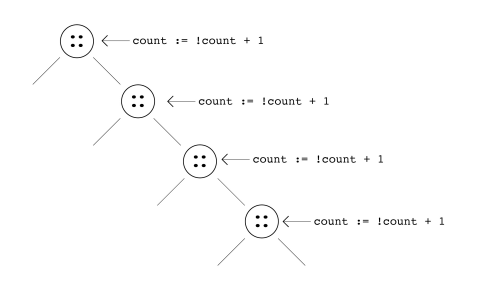


**Figure 1:** Instrumented List

```
instrumentListWithRef : int ref
                      -> 'a lazyList
                      -> 'a lazyList
```





Observing strictness
Figure 1: Instrumented List
instrumentListWithRef : int ref
-> 'a lazyList
-> 'a lazyList

- Hengchu:
- `instrumentListWithRef` clones the structure of the original list, and attaches a lazy effectful computation to each constructor in the list. So as the list is evaluated, each step of evaluation triggers one update

# Strictness doesn't exist in a vacuum

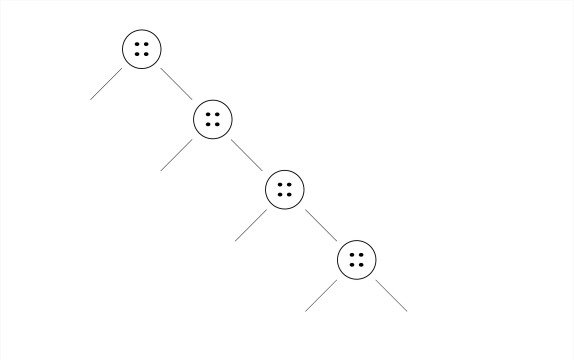

**Figure 2:** No Demand





Strictness doesn't exist in a vacuum

Figure 2: No Demand

# Strictness doesn't exist in a vacuum

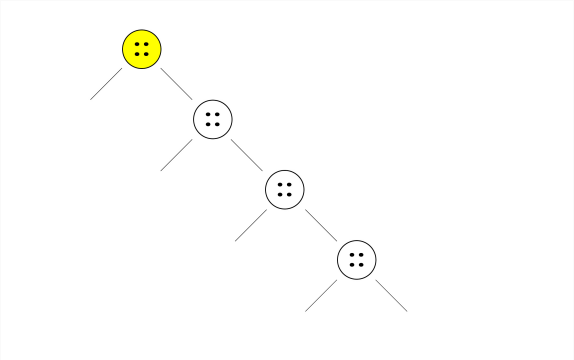

**Figure 3:** Weak Head Normal Form





Strictness doesn't exist in a vacuum

Figure 3: Weak Head Normal Form

# Strictness doesn't exist in a vacuum

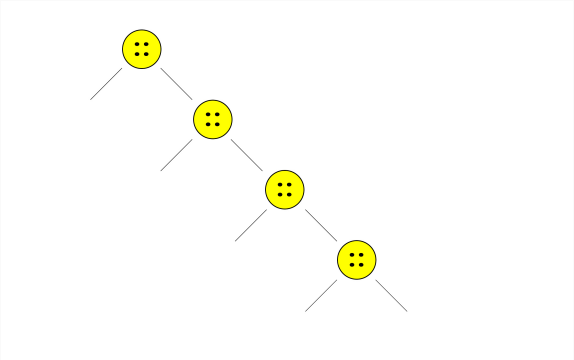

**Figure 4:** Spine Strict





Strictness doesn't exist in a vacuum

Figure 4: Spine Strict

- These pictures are illustrations of a demand context on a lazy list
- These functions have the type from list to unit
- It might look like there's only one such function (namely the lazy implementation)
- There can actually be many different demand behaviors
- 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

## Demanding an answer, lazily

```
demandCount context f xs =
    let count           = ref 0
        observableList =
          instrumentListWithRef count xs
    in context (f observableList); !count
```





Demanding an answer, lazily
demandCount context f xs =
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- `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
- context is exerting some demand on the output of f

## Examples of `demandCount`

```
> let f xs = takeLazy (lazy 6, xs)
> let list = toLazyList [1; 2; 3; 4; 5]
```





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> demandCount firstCons f list
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Examples of demandCount

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> demandCount spineStrict f list
```





Examples of demandCount

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5
```





Examples of demandCount

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> demandCount noDemand f list
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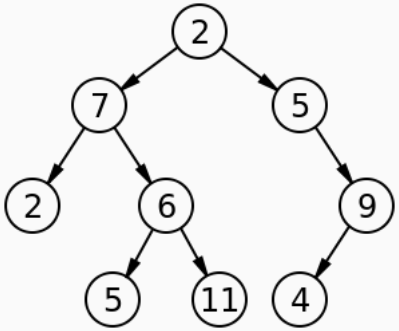
> demandCount spineStrict f list
5

- Just some examples showing demandCount
- takeLazy is a function that takes the specified number of elements from a lazy list and returns a lazyList
- 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!

# Beyond lists and numbers

TODO: erase the numbers in tree




?

- Kenny:
- Arbitrary lazy algebraic datatypes
- 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

## ListDemand

```
type 'a lazyList =
  | Cons of ('a Lazy.t *
             'a lazyList Lazy.t)
  | Nil
-----------------------------------
type 'a thunk = T | E of 'a

type 'd listDemand =
  | ConsD of ('d thunk *
              'd listDemand thunk)
  | NilD

type intDemand = IntD
```





ListDemand

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type 'a lazyList =
  | Cons of ('a Lazy.t *
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type 'a thunk = T | E of 'a

type 'd listDemand =
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  | NilD

type intDemand = IntD
```

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

## Examples

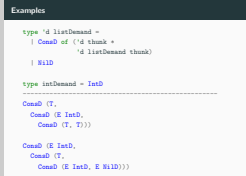
```
type 'd listDemand =
  | ConsD of ('d thunk *
              'd listDemand thunk)
  | NilD

type 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

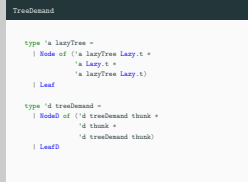
## TreeDemand

```
type 'a lazyTree =
  | Node of ('a lazyTree Lazy.t *
             'a Lazy.t *
             'a lazyTree Lazy.t)
  | Leaf

type 'd treeDemand =
  | NodeD of ('d treeDemand thunk *
              'd thunk *
              'd treeDemand thunk)
  | 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

## ListDemand vs TreeDemand

```
type 'd listDemand =
  | ConsD of ('d thunk *
              'd listDemand thunk)
  | NilD

type 'd treeDemand =
  | NodeD of ('d treeDemand thunk *
              'd thunk *
              'd treeDemand thunk)
  | LeafD
```





ListDemand vs TreeDemand

type 'd listDemand =
  | ConsD of ('d thunk *
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  | NilD

type 'd treeDemand =
  | NodeD of ('d treeDemand thunk *
              'd thunk *
              'd treeDemand thunk)
  | 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

## Computing demand, generically

```
demandList : 'b context -> (int lazyList -> 'b)
           -> int lazyList
           -> ('b * intDemand listDemand thunk)

demandTree : 'b context -> (int lazyTree -> 'b)
           -> int lazyTree
           -> ('b * intDemand treeDemand thunk)
```





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-----------------------------------------------

demand     : 'b context -> ('a -> 'b) -> 'a
           -> ('b * ('a DEMAND) thunk)
```
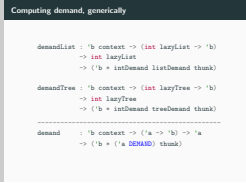




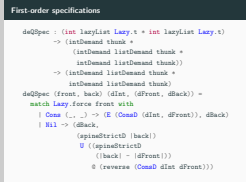

- There is a determinate relation between a lazy data structure and its demand representation
- We return a `Thunk` of demand because the input might not be demanded at all
- As the input value is traversed by the function, which is driven by the context, the evaluation of each thunk builds a pointer based data structure which is isomorphic to the demand data type, which is then frozen into a demand representation
- We expect that the 'a parameter is some kind of lazy structure, and 'b is also some kind of lazy structure
- We use generic programming to implement the DEMAND type for all algebraic data types

## First-order specifications

```
deQSpec : (int lazyList Lazy.t * int lazyList Lazy.t)
        -> (intDemand thunk *
              (intDemand listDemand thunk *
               intDemand listDemand thunk))
        -> (intDemand listDemand thunk *
              intDemand listDemand thunk)
deQSpec (front, back) (dInt, (dFront, dBack)) =
  match Lazy.force front with
    | Cons (_, _) -> (E (ConsD (dInt, dFront)), dBack)
    | Nil -> (dBack,
              (spineStrictD |back|)
               U ((spineStrictD
                    (|back| - |dFront|))
                  @ (reverse (ConsD dInt dFront))))
```

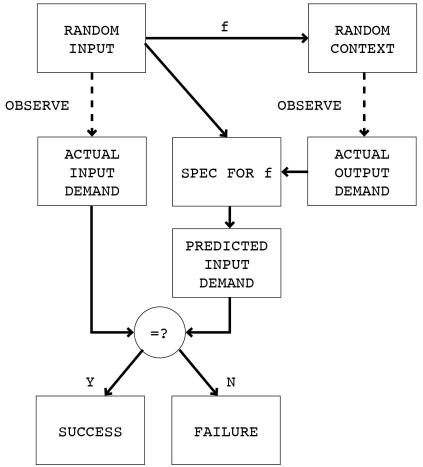






- Having demonstrated how to reify demand behaviors into value, we now need to figure out how to write down a specification to check if whether a particular run of the program has the specified laziness according to the specification
- Specifications goings backwards from demands on the output to demands 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`!

# Connecting specification with observation








Connecting specification with observation

- To QuickCheck `takeSpec`, we use mechanisms from QuickCheck to fuzz an Int and a [a] as inputs
- We can generate random contexts that exerts non-trivial demand on the output values
- 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.
- Higher-order also works! but we don't want to go into the details

## 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





Contributions

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- **Test** implementations against those specifications
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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

# Have questions?

Come ask us about . . .

- Higher-order specifications
- Generic programming
- Random generation of demand contexts
- Details of instrumentation
- What language are you actually implementing this in?
  (Hint: it's not ML)

  . . .





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