High-Performance Haskell

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Welcome!

A few things about this tutorial:

- Stop me and ask questions—early and often
- I assume *no* prior Haskell exposure

Sequential performance is still important

Parallelism is not a magic bullet:

- The speedup of a program using multiple processors is limited by the time needed for the sequential fraction of the program. (Amdahl's law)
- We want to make *efficient* use of every core.

Caveats

The usual caveats about performance optimizations:

- Improvements to the compiler might make some optimizations redundant. Write benchmarks to detect these cases.
- Some optimizations are compiler (i.e. GHC) specific

That being said, many of these optimizations have remained valid over a number of GHC releases.

Software prerequisites

The Haskell Platform:

- Download installer for Windows, OS X, or Linux here:
- `http://hackage.haskell.org/platform`

The Criterion benchmarking library:

```
cabal install -f-Chart criterion
```

Outline

- Introduction to Haskell
- Lazy evaluation
- Reasoning about space usage
- Benchmarking
- Making sense of compiler output
- Profiling

Haskell in 10 minutes

Our first Haskell program sums a list of integers:

```
sum :: [Int] -> Int
sum []     = 0
sum (x:xs) = x + sum xs

main :: IO ()
main = print (sum [1..10000])
```

Type signatures

Definition

A type signature describes the type of a Haskell expression:

```
sum :: [Int] -> Int
```

- **Int** is an integer.
- [a] is a list of as
  - So [**Int**] is a list of integers
- −> denotes a function.
- So **sum** is a function from a list of integers to an integer.

Defining a function

Functions are defined as a series of equations, using *pattern matching*:

```
sum []       = 0
sum (x:xs)   = x + sum xs
```

The list is defined recursively as either

- an empty list, written as [], or
- an element x, followed by a list xs.

[] is pronounced “nil” and : is pronounced “cons”.

Function application

Function application is indicated by *juxtaposition*:

```
main = print (sum [1..10000])
```

- [1..10000] creates a list of 10,000 integers from 1 to 10,000.
- We apply the **sum** function to the list and then apply the result to the print function.

We say that we *apply* rather then *call* a function:

- Haskell is a lazy language
- The result may not be computed immediately

Compiling and running our program

Save the program in a file called Sum.hs and then compile it using ghc:

```
$ ghc -O --make Sum.hs
[1 of 1] Compiling Main             ( Sum.hs, Sum.o )
Linking Sum ...
```

Now lets run the program

```
$ ./Sum
50005000
```

Defining our own data types

Data types have one or more *constructors*, each with zero or more *arguments* (or *fields*).

```
data Shape = Circle Double
           | Rectangle Double Double
```

And a function over our data type, again defined using pattern matching:

```
area :: Shape -> Double
area (Circle r)        = r * r * 3.14
area (Rectangle w h) = w * h
```

Constructing a value uses the same syntax as pattern matching:

```
area (Rectangle 3.0 5.0)
```

Back to our sum function

Our **sum** has a problem. If we increase the size of the input

```haskell
main = print (sum [1..10000000])
```

and run the program again

```
$ ghc -O --make Sum.hs
[1 of 1] Compiling Main             ( Sum.hs, Sum.o )
Linking Sum ...
$ ./Sum
Stack space overflow: current size 8388608 bytes.
Use `+RTS -Ksize -RTS' to increase it.
```

Tail recursion

Our function creates a stack frame for each recursive call, eventually reaching the predefined stack limit.

- Must do so as we still need to apply + to the result of the call.

Make sure that the recursive application is the last thing in the function

```
sum :: [Int] -> Int
sum xs = sum' 0 xs
  where
    sum' acc []     = acc
    sum' acc (x:xs) = sum' (acc + x) xs
```

Polymorphic functions

Many functions follow the same pattern. For example,

```
product :: [Int] -> Int
product xs = product' 1 xs
  where
    product' acc []     = acc
    product' acc (x:xs) = product' (acc * x) xs
```

is just like sum except we replace 0 with 1 and + with *. We can generalize **sum** and **product** to

```
foldl :: (a -> b -> a) -> a -> [b] -> a
foldl f z []     = z
foldl f z (x:xs) = foldl f (f z x) xs

sum = foldl (+) 0
product = foldl (*) 1
```

Summing some numbers...

Using our new definition of **sum**, lets sum all number from 1 to 1000000:

```
$ ghc -O --make Sum.hs
[1 of 1] Compiling Main             ( Sum.hs, Sum.o )
Linking Sum ...
$ ./Sum
Stack space overflow: current size 8388608 bytes.
Use ‘+RTS -Ksize -RTS’ to increase it.
```

What went wrong this time?

Laziness

- Haskell is a lazy language
- Functions and data constructors don't evaluate their arguments until they need them

```
cond :: Bool -> a -> a -> a
cond True  t e = t
cond False t e = e
```

- Same with local definitions

```
abs :: Int -> Int
abs x | x > 0     = x
      | otherwise = neg_x
  where neg_x = negate x
```

Why laziness is important

- Laziness supports *modular programming*
- Programmer-written functions instead of built-in language constructs

```
(||)  :: Bool -> Bool -> Bool
True  || _ = True
False || x = x
```

Laziness and modularity

Laziness lets us separate producers and consumers and still get efficient execution:

- Generate all solutions (a huge tree structure)
- Find the solution(s) you want

```
nextMove :: Board -> Move
nextMove b = selectMove allMoves
  where
    allMoves = allMovesFrom b
```

The solutions are generated as they are consumed.

Back to our misbehaving function

How does evaluation of this expression proceed?

sum [1 , 2 , 3]

Like this:

```
sum [1,2,3]
==> foldl (+) 0 [1,2,3]
==> foldl (+) (0+1) [2,3]
==> foldl (+) ((0+1)+2) [3]
==> foldl (+) (((0+1)+2)+3) []
==> ((0+1)+2)+3
==> (1+2)+3
==> 3+3
==> 6
```

Thunks

A *thunk* represents an unevaluated expression.

- GHC needs to store all the unevaluated $+$ expressions on the heap, until their value is needed.
- Storing and evaluating thunks is costly, and unnecessary if the expression was going to be evaluated anyway.
- **foldl** allocates n thunks, one for each addition, causing a stack overflow when GHC tries to evaluate the chain of thunks.

Controlling evaluation order

The **seq** function allows to control evaluation order.

```
seq :: a -> b -> b
```

Informally, when evaluated, the expression **seq** a b evaluates a and then returns b.

Weak head normal form

Evaluation stops as soon as a data constructor (or lambda) is reached:

```
ghci> seq (1 `div` 0) 2
*** Exception: divide by zero
ghci> seq ((1 `div` 0), 3) 2
2
```

We say that **seq** evaluates to *weak head normal form* (WHNF).

Weak head normal form

Forcing the evaluation of an expression using **seq** only makes sense if the result of that expression is used later:

```
let x = 1 + 2 in seq x (f x)
```

The expression

```
print (seq (1 + 2) 3)
```

doesn't make sense as the result of 1+2 is never used.

Exercise

Rewrite the expression

```
(1 + 2, 'a')
```

so that the component of the pair is evaluated before the pair is created.

Solution

Rewrite the expression as

```
let x = 1 + 2 in seq x (x, 'a')
```

A strict left fold

We want to evaluate the expression f z x *before* evaluating the recursive call:

```
foldl' :: (a -> b -> a) -> a -> [b] -> a
foldl' f z []     = z
foldl' f z (x:xs) = let z' = f z x
                    in seq z' (foldl' f z' xs)
```

Summing numbers, attempt 2

How does evaluation of this expression proceed?

```
foldl' (+) 0 [1,2,3]
```

Like this:

```
foldl' (+) 0 [1,2,3]
==> foldl' (+) 1 [2,3]
==> foldl' (+) 3 [3]
==> foldl' (+) 6 []
==> 6
```

Sanity check:

```
ghci> print (foldl' (+) 0 [1..1000000])
500000500000
```

Computing the mean

A function that computes the mean of a list of numbers:

```haskell
mean :: [Double] -> Double
mean xs = s / fromIntegral l
  where
    (s, l) = foldl' step (0, 0) xs
    step (s, l) a = (s+a, l+1)
```

We compute the length of the list and the sum of the numbers in one pass.

```
$ ./Mean
Stack space overflow: current size 8388608 bytes.
Use `+RTS -Ksize -RTS' to increase it.
```

Didn't we just fix that problem?!?

seq and data constructors

Remember:

- Data constructors don't evaluate their arguments when created
- **seq** only evaluates to the outmost data constructor, but doesn't evaluate its arguments

Problem: **foldl** ' forces the evaluation of the pair constructor, but not its arguments, causing unevaluated thunks build up inside the pair:

```
(0.0 + 1.0 + 2.0 + 3.0, 0 + 1 + 1 + 1)
```

Forcing evaluation of constructor arguments

We can force GHC to evaluate the constructor arguments before the constructor is created:

```
mean :: [Double] -> Double
mean xs = s / fromIntegral l
  where
    (s, l) = foldl' step (0, 0) xs
    step (s, l) a = let s' = s + a
                        l' = l + 1
                    in seq s' (seq l' (s', l'))
```

Bang patterns

A *bang patterns* is a concise way to express that an argument should be evaluated.

```
{-# LANGUAGE BangPatterns #-}

mean :: [Double] -> Double
mean xs = s / fromIntegral l
  where
    (s, l) = foldl' step (0, 0) xs
    step (!s, !l) a = (s + a, l + 1)
```

s and l are evaluated before the right-hand side of step is evaluated.

Strictness

We say that a function is *strict* in an argument, if evaluating the function always causes the argument to be evaluated.

```
null :: [a] -> Bool
null [] = True
null _  = False
```

null is strict in its first (and only) argument, as it needs to be evaluated to pick a return value.

Strictness - Example

cond is strict in the first argument, but not in the second and third argument:

```haskell
cond :: Bool -> a -> a -> a
cond True  t e = t
cond False t e = e
```

Reason: Each of the two branches only evaluate one of the two last arguments to cond.

Strict data types

Haskell lets us say that we always want the arguments of a constructor to be evaluated:

```
data PairS a b = PS !a !b
```

When a PairS is evaluated, its arguments are evaluated.

Strict pairs as accumulators

We can use a strict pair to simplify our mean function:

```
mean :: [Double] -> Double
mean xs = s / fromIntegral l
  where
    PS s l = foldl' step (PS 0 0) xs
    step (PS s l) a = PS (s + a) (l + 1)
```

Tip: Prefer strict data types when laziness is not needed for your program to work correctly.

Reasoning about laziness

A function application is only evaluated if its result is needed, therefore:

- One of the function's right-hand sides will be evaluated.
- Any expression whose value is required to decide which RHS to evaluate, must be evaluated.

By using this "backward-to-front" analysis we can figure which arguments a function is strict in.

Reasoning about laziness: example

```
max :: Int -> Int -> Int
max x y
    | x > y      = x
    | x < y      = y
    | otherwise  = x  -- arbitrary
```

- To pick one of the three RHS, we must evaluate x > y.
- Therefore we must evaluate *both* x and y.
- Therefore **max** is strict in both x and y.

Poll

```
data BST = Leaf | Node Int BST BST

insert :: Int -> BST -> BST
insert x Leaf     = Node x Leaf Leaf
insert x (Node x' l r)
    | x < x'      = Node x' (insert x l) r
    | x > x'      = Node x' l (insert x r)
    | otherwise = Node x l r
```

Which arguments is **insert** strict in?

- None
- 1st
- 2nd
- Both

Solution

Only the second, as inserting into an empty tree can be done without comparing the value being inserted. For example, this expression

```
insert (1 `div` 0) Leaf
```

does not raise a division-by-zero expression but

```
insert (1 `div` 0) (Node 2 Leaf Leaf)
```

does.

Some other things worth pointing out

- **insert** x l is not evaluated before the Node is created, so it's stored as a thunk.
- Most tree based data structures use strict sub-trees:

```
data Set a = Tip
           | Bin !Size a !(Set a) !(Set a)
```

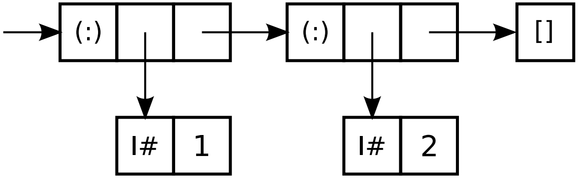
Reasoning about space usage

Knowing how GHC represents values in memory is useful because

- it allows us to approximate memory usage, and
- it allows us to count the number of indirections, which affect cache behavior.

Memory layout

Here's how GHC represents the list `[1,2]` in memory:



- Each box represents one machine word
- Arrows represent pointers
- Each constructor has one word overhead for e.g. GC information

Memory usage for data constructors

Rule of thumb: a constructor uses one word for a header, and one word for each field. So e.g.

```
data Uno = Uno a
data Due = Due a b
```

an Uno takes 2 words, and a Due takes 3.

- Exception: a constructor with no fields (like **Nothing** or **True**) takes no space, as it's shared among all uses.

Unboxed types

GHC defines a number of *unboxed* types. These typically represent primitive machine types.

- By convention, the names of these types end with a #.
- Most unboxed types take one word (except e.g. **Double**# on 32-bit machines)
- Values of unboxed types are never lazy.
- The basic types are defined in terms unboxed types e.g.

  ```
  data Int = I# Int#
  ```

- We call types such as **Int** *boxed* types

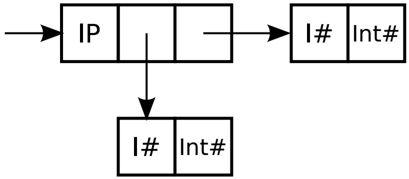
Poll

How many machine words is needed to store a value of this data type:

```
data IntPair = IP Int Int
```

- 3?
- 5?
- 7?
- 9?

IntPair memory layout



So an IntPair value takes 7 words.

Unpacking

GHC gives us some control over data representation via the UNPACK pragma.

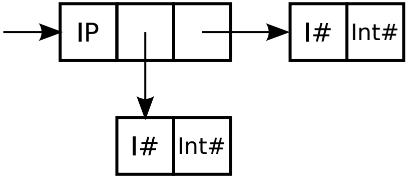
- The pragma unpacks the contents of a constructor into the field of another constructor, removing one level of indirection and one constructor header.
- Any strict, monomorphic, single-constructor field can be unpacked.

The pragma is added just before the bang pattern:

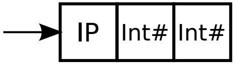
```
data Foo = Foo {-# UNPACK #-} !SomeType
```

Unpacking example

```
data IntPair = IP Int Int
```



```
data IntPair = IP {-# UNPACK #-} !Int
                  {-# UNPACK #-} !Int
```



Benefits of unpacking

When the pragma applies, it offers the following benefits:

- Reduced memory usage (4 words in the case of IntPair)
- Fewer indirections

Caveat: There are cases where unpacking hurts performance e.g. if the fields are passed to a non-strict function.

Benchmarking

In principle, measuring code-execution time is trivial:

1. Record the start time.
2. Execute the code.
3. Record the stop time.
4. Compute the time difference.

A naive benchmark

```
import time

def bench(f):
  start = time.time()
  f()
  end = time.time()
  print (end - start)
```

Benchmarking gotchas

Potential problems with this approach:

- The clock resolution might be too low.
- The measurement overhead might skew the results.
- The compiler might detect that the result of the function isn't used and remove the call completely!
- Another process might get scheduled while the benchmark is running.
- GC costs might not be completely accounted for.
- Caches might be warm/cold.

Statistically robust benchmarking

The Criterion benchmarking library:

- Figures out how many times to run your function
- Adjusts for measurement overhead
- Computes confidence intervals
- Detects outliers
- Graphs the results

```
cabal install -f-Chart Criterion
```

Benchmarking our favorite function

```
import Criterion.Main

fib :: Int -> Int
fib 0 = 0
fib 1 = 1
fib n = fib (n-1) + fib (n-2)

main = defaultMain [
       bench "fib 10" (whnf fib 10)
    ]
```

Benchmark output, part 1

```
$ ./Fibber
warming up
estimating clock resolution...
mean is 8.638120 us (80001 iterations)
found 1375 outliers among 79999 samples (1.7%)
  1283 (1.6%) high severe
estimating cost of a clock call...
mean is 152.6399 ns (63 iterations)
found 3 outliers among 63 samples (4.8%)
  3 (4.8%) high mild
```

Benchmark output, part 2

```
benchmarking fib 10
collecting 100 samples, 9475 iterations each, in
estimated 863.8696 ms
bootstrapping with 100000 resamples
mean: 925.4310 ns, lb 922.1965 ns, ub 930.9341 ns,
ci 0.950
std dev: 21.06324 ns, lb 14.54610 ns, ub 35.05525 ns,
ci 0.950
found 8 outliers among 100 samples (8.0%)
  7 (7.0%) high severe
variance introduced by outliers: 0.997%
variance is unaffected by outliers
```

Evaluation depth

```
bench "fib␣10" (whnf fib 10)
```

- whnf evaluates the result to weak head normal form (i.e. to the outmost data constructor).
- If the benchmark generates a large data structure (e.g. a list), you can use nf instead to force the generation of the whole data structure.
- It's important to think about what should get evaluated in the benchmark to ensure your benchmark reflects the use case you care about.

Benchmark: creating a list of 10k elements

```
import Criterion.Main

main = defaultMain [
    bench "whnf" (whnf (replicate n) 'a')
  , bench "nf" (nf (replicate n) 'a')
  ]
  where n = 10000
```

The expression **replicate** n x creates a list of n copies of x.

The difference between whnf and nf

```
$ ./BuildList
benchmarking whnf
mean: 15.04583 ns, lb 14.97536 ns, ub 15.28949 ns, ...
std dev: 598.2378 ps, lb 191.2617 ps, ub 1.357806 ns, ...

benchmarking nf
mean: 158.3137 us, lb 158.1352 us, ub 158.5245 us, ...
std dev: 993.9415 ns, lb 834.4037 ns, ub 1.242261 us, ...
```

Since **replicate** generates the list lazily, the first benchmark only creates a single element

A note about the whnf function

The whnf function is somewhat peculiar:

- It takes the function to benchmark, applied to its first n-1 arguments, as its first argument
- It takes the last, *n*th, argument as its second argument

For example:

```
bench "product" (whnf (foldl (*) 1) [1..10000])
```

By separating the last arguments from the rest, Criterion tries to prevent GHC from evaluating the function being benchmarked only once.

Exercise: foldl vs foldl'

Benchmark the performance of **foldl** (+) 0 [1..10000] and **foldl** ' (+) 0 [1..10000] . Start with:

```
import Criterion.Main
import Prelude hiding (foldl)

foldl, foldl' :: (a -> b -> a) -> a -> [b] -> a
foldl f z = ...
foldl' f z = ...

main = defaultMain [
    bench "foldl" ...
  , bench "foldl'" ...
  ]
```

Compiling and running:

```
$ ghc -O --make Fold.hs && ./Fold
```

Solution

```haskell
import Criterion.Main
import Prelude hiding (foldl)

foldl, foldl' :: (a -> b -> a) -> a -> [b] -> a

foldl f z []     = z
foldl f z (x:xs) = foldl f (f z x) xs

foldl' f z []     = z
foldl' f z (x:xs) = let z' = f z x
                    in seq z' (foldl' f z' xs)

main = defaultMain [
    bench "foldl" (whnf (foldl (+) 0) [1..10000])
  , bench "foldl'" (whnf (foldl' (+) 0) [1..10000])
  ]
```

Solution timings

```
benchmarking foldl
mean: 493.6532 us, lb 488.0841 us, ub 500.2349 us, ...
std dev: 31.11368 us, lb 26.20585 us, ub 42.98257 us, ...

benchmarking foldl'
mean: 121.3693 us, lb 120.8598 us, ub 122.6117 us, ...
std dev: 3.816444 us, lb 1.889005 us, ub 7.650491 us, ...
```

GHC Core

- GHC uses an intermediate language, called “Core,” as its internal representation during several compilation stages
- Core resembles a subset of Haskell
- The compiler performs many of its optimizations by repeatedly rewriting the Core code

Why knowing how to read Core is important

Reading the generated Core lets you answer many questions, for example:

- When are expressions evaluated
- Is this function argument accessed via an indirection
- Did my function get inlined

Convincing GHC to show us the Core

Given this “program”

```
module Sum where

import Prelude hiding (sum)

sum :: [Int] -> Int
sum []       = 0
sum (x:xs)   = x + sum xs
```

we can get GHC to output the Core by adding the `-ddump-simpl` flag

```
$ ghc -O --make Sum.hs -ddump-simpl
```

A first taste of Core, part 1

```
Sum.sum :: [GHC.Types.Int] -> GHC.Types.Int
GblId
[Arity 1
 Worker Sum.$wsum
 NoCafRefs
 Str: DmdType Sm]
Sum.sum =
  __inline_me (\ (w_sgJ :: [GHC.Types.Int]) ->
    case Sum.$wsum w_sgJ of ww_sgM { __DEFAULT ->
    GHC.Types.I# ww_sgM
    })
```

A first taste of Core, part 2

```
Rec {
Sum.$wsum :: [GHC.Types.Int] -> GHC.Prim.Int#
GblId
[Arity 1
 NoCafRefs
 Str: DmdType S]
Sum.$wsum = \ (w_sgJ :: [GHC.Types.Int]) ->
    case w_sgJ of _ {
      [] -> 0;
      : x_ade xs_adf ->
        case x_ade of _ { GHC.Types.I# x1_agv ->
        case Sum.$wsum xs_adf of ww_sgM { __DEFAULT ->
        GHC.Prim.+# x1_agv ww_sgM
        }
        }
    }
end Rec }
```

Reading Core: a guide

- All names a fully qualified (e.g. GHC.Types.**Int** instead of just **Int**)
- The parts after the function type declaration and before the function definition are annotations e.g.

  ```
  GblId
  [Arity ...]
  ```

  We'll ignore those for now
- Lots of the names are generated by GHC (e.g. w_sgJ).

Note: The Core syntax changes slightly with new compiler releases.

Tips for reading Core

Three tips for reading Core:

- Open and edit it in your favorite editor to simplify it (e.g. rename variables to something sensible).
- Use the ghc-core package on Hackage
- Use the GHC Core major mode in Emacs (ships with haskell-mode)

Cleaned up Core for sum

```
$wsum :: [Int] -> Int#
$wsum = \ (xs :: [Int]) ->
  case xs of _
    [] -> 0
    : x xs' -> case x of _
      I# x# -> case $wsum xs' of n#
        __DEFAULT -> +# x# n#

sum :: [Int] -> Int
sum = __inline_me (\ (xs :: [Int]) ->
        case $wsum xs of n#
          __DEFAULT -> I# n#)
```

Core for sum explained

- Convention: A variable name that ends with # stands for an unboxed value.
- GHC has split **sum** into two parts: a wrapper, `sum`, and a worker, `$wsum`.
- The worker returns an unboxed integer, which the wrapper wraps in an I# constructor.
- +# is addition for unboxed integers (i.e. a single assembler instruction).
- The worker is not tail recursive, as it performs an addition after calling itself recursively.
- GHC has added a note that `sum` should be inlined.

Core, case, and evaluation

In core, `case` always means "evaluate". Read

```
case xs of _
  [] -> ...
  : x xs' -> ...
```

as: evaluate `xs` and then evaluate one of the branches.

- Case statements are the only place where evaluation takes place.
- *Except* when working with unboxed types where e.g.

  ```
  f :: Int# -> ...
  f (x# +# n#)
  ```

  should be read as: evaluate `x# +# n#` and then apply the function `f` to the result.

Tail recursive sum

```haskell
module TRSum where

import Prelude hiding (sum)

sum :: [Int] -> Int
sum = sum' 0
  where
    sum' acc []     = acc
    sum' acc (x:xs) = sum' (acc + x) xs
```

Compiling:

```
$ ghc -O --make TRSum.hs -ddump-simpl
```

Core for tail recursive sum

```
sum1 :: Int; sum1 = I# 0

$wsum’ :: Int# -> [Int] -> Int#
$wsum’ = \ (acc# :: Int#) (xs :: [Int]) ->
  case xs of _
    [] -> acc#
    : x xs’ -> case x of _
      I# x# -> $wsum’ (+# acc# x#) xs’

sum_sum’ :: Int -> [Int] -> Int
sum_sum’ = __inline_me (\ (acc :: Int) (xs :: [Int]) ->
  case acc of _
    I# acc# -> case $wsum’ acc# xs of n#
      __DEFAULT -> I# n#)

sum :: [Int] -> Int
sum = __inline_me (sum_sum’ sum1)
```

Core for tail recursive sum explained

- `$wsum`'s first argument is an unboxed integer, which will be passed in a register if one is available.
- The recursive call to `$wsum` is now tail recursive.

Polymorphic functions

In Core, polymorphic functions get an extra argument for each type parameter e.g.

```haskell
id :: a -> a
id x = x
```

becomes

```
id :: forall a. a -> a
id = \ (@ a) (x :: a) -> x
```

This parameter is used by the type system and can be ignored.

Exercise

Compare the Core generated by foldl and foldl' and find where they differ. Start with:

```
module FoldCore where

import Prelude hiding (foldl)

foldl, foldl' :: (a -> b -> a) -> a -> [b] -> a
foldl = ...
foldl' = ...
```

Compile with:

```
$ ghc -O --make FoldCore.hs -ddump-simpl
```

Solution

The difference is in the recursive call:

- **foldl** ':

```
: x xs ->
  case f z x of z'
      __DEFAULT -> foldl' f z'
```

- **foldl**:

```
: x xs -> foldl f (f z x) xs
```

Profiling

- Profiling lets us find performance hotspots.
- Typically used when you already have performance problems.

Using profiling to find a space leak

```haskell
import System.Environment

main = do
    [d] <- map read `fmap` getArgs
    print (mean [1..d])

mean :: [Double] -> Double
mean xs = sum xs / fromIntegral (length xs)
```

Compiling:

```
$ ghc -O --make SpaceLeak.hs -rtsopts
```

Simple garbage collector statistics

```
$ ./SpaceLeak 1e7 +RTS -sstderr
./SpaceLeak 1e7 +RTS -sstderr
5000000.5
     763,231,552 bytes allocated in the heap
     656,658,372 bytes copied during GC
     210,697,724 bytes maximum residency (9 sample(s))
       3,811,244 bytes maximum slop
             412 MB total memory in use (3 MB lost due
                 to fragmentation)

  Generation 0:  1447 collections,     0 parallel,
                 0.43s,  0.44s elapsed
  Generation 1:     9 collections,     0 parallel,
                 0.77s,  1.12s elapsed
```

Simple garbage collector statistics cont.

```
INIT  time    0.00s  (  0.00s elapsed)
MUT   time    0.54s  (  0.54s elapsed)
GC    time    1.20s  (  1.56s elapsed)
EXIT  time    0.00s  (  0.00s elapsed)
Total time    1.74s  (  2.10s elapsed)

%GC time      69.0%  (74.1% elapsed)

Alloc rate    1,417,605,200 bytes per MUT second

Productivity  30.9% of total user, 25.6% of total
              elapsed
```

The important bits

- The program used a maximum of 412 MB of heap
- The were 1447 minor collections
- The were 9 major collections
- 69% of the time was spent doing garbage collection!

Time profiling

```
$ ghc -O --make SpaceLeak.hs -prof -auto-all -caf-all \
  -fforce-recomp
$ ./SpaceLeak 1e7 +RTS -p
Stack space overflow: current size 8388608 bytes.
Use `+RTS -Ksize -RTS' to increase it.
```

Lets increase the stack size to make the program finish

```
$ ./SpaceLeak 1e7 +RTS -p -K400M
```

Time profiling results

```
COST CENTRE    MODULE       %time %alloc

CAF:main_sum   Main          81.0   29.6
mean           Main          14.3    0.0
CAF            GHC.Double     4.8   70.4
```

The information isn't conclusive, but it seems like the runtime is due to the **sum** function and the allocation of lots of **Double**s.

Space profiling

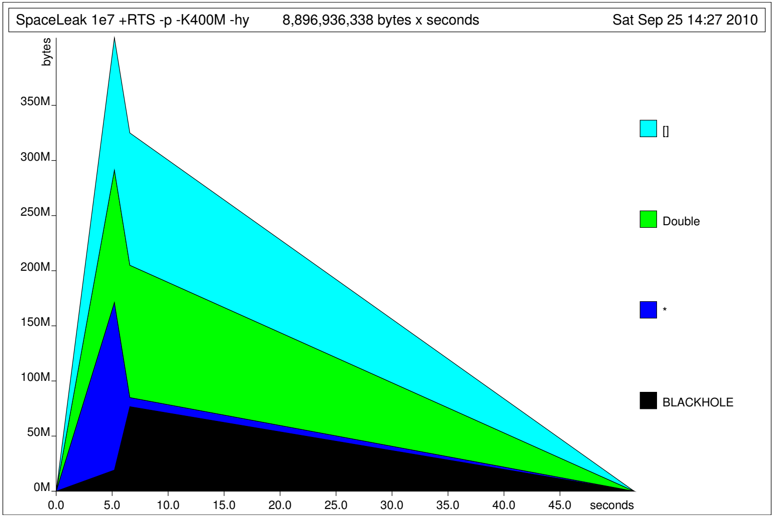
Lets take another perspective by profiling the program space usage:

```
$ ./SpaceLeak 1e7 +RTS -p -K400M -hy
```

Generate a pretty graph of the result:

```
$ hp2ps -c SpaceLeak.hp
```

Space usage graph



Space leak explained

From the graph we can confirm that a list of **Double**s are being allocated but not freed immediately. The culprit is our formulation of mean

```
mean :: [Double] -> Double
mean xs = sum xs / fromIntegral (length xs)
```

sum causes the list xs to be generated, but the list elements cannot be freed immediately as it's needed later by **length**.

Space leak fix

We've already seen the solution: compute the sum and the length at the same time:

```
mean :: [Double] -> Double
mean xs = s / fromIntegral l
  where
    (s, l) = foldl' step (0, 0) xs
    step (!s, !l) a = (s+a, l+1)
```

Writing high-performance code

1. Profile to find performance hotspots
2. Write a benchmark for the offending function
3. Improve the performance, by adjusting evaluation order and unboxing
4. Look at the generated Core
5. Run benchmarks to confirm speedup
6. Repeat

References / more content

- The Haskell Wiki:
  http://www.haskell.org/haskellwiki/Performance
- Real World Haskell, chapter 25
- My blog: http://blog.johantibell.com/

Bonus: Argument unboxing

- Strict function arguments are great for performance.
- GHC can often represents these as unboxed values, passed around in registers.
- GHC can often infer which arguments are stricts, but can sometimes need a little help.

Making functions stricter

As we saw earlier, **insert** is not strict in its first argument.

```
data BST = Leaf | Node Int BST BST

insert :: Int -> BST -> BST
insert x Leaf     = Node x Leaf Leaf
insert x (Node x' l r)
     | x < x'     = Node x' (insert x l) r
     | x > x'     = Node x' l (insert x r)
     | otherwise = Node x l r
```

The first argument is represented as a boxed **Int** value.

Core for insert

```
insert :: Int -> BST -> BST
insert = \ (x :: Int) (t :: BST) ->
  case t of _
    Leaf -> Node x Leaf Leaf
    Node x’ l r ->
      case x of _
        I# x# -> case x’ of _
          I# x’# -> case <# x# x’# of _
            False -> case ># x# x’# of _
              False -> Node x l r
              True -> Node x’ l (insert x r)
            True -> Node x’ (insert x l) r
```

Making functions stricter, part 2

We can make **insert** strict in the firsst argument by using a bang pattern.

```
{-# LANGUAGE BangPatterns #-}

insert :: a -> BST a -> BST a
insert !x Leaf  = Node x Leaf Leaf
insert x (Node x' l r)
    | x < x'    = Node x' (insert x l) r
    | x > x'    = Node x' l (insert x r)
    | otherwise = Node x l r
```

Now both equations always cause x to be evaluated.

Core for stricter insert

```
$winsert :: Int# -> BST -> BST
$winsert = \ (x# :: Int#) (t :: BST) ->
  case t of _
    Leaf -> Node (I# x#) Leaf Leaf
    Node x' l r -> case x' of _
      I# x'# -> case <# x# x'# of _
        False -> case ># x# x'# of _
          False -> Node (I# x#) l r
          True -> Node x' l ($winsert x# r)
        True -> Node x' ($winsert x# l) r
```

Benefits of strict functions

There are two main benefits of to making functions strict:

- No indirections when accessing arguments
- Less allocation