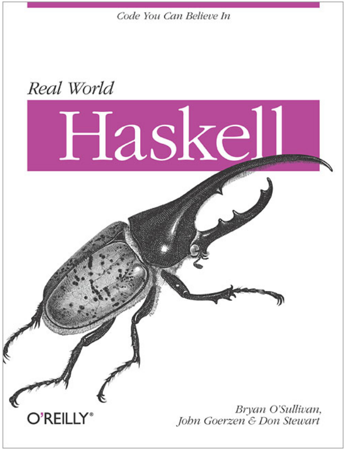
Profiling and Optimization



Stephen A. Edwards

Columbia University

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After Chapter 25 of O'Sullivan, Goerzen, and Stewart

Artificial example program to optimize:

Calculate the average value of a list of Doubles [1,2,3,...] by summing their values and dividing by the length

```haskell
import System.Environment (getArgs)
import Text.Printf (printf)

main :: IO ()
main = do
  [d] <- map read <$> getArgs
  printf "%f\n" $ mean [1..d]

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

```
$ stack ghc -- --make -O2 -Wall prof1.hs
[1 of 2] Compiling Main             ( prof1.hs, prof1.o )
[2 of 2] Linking prof1
$ /usr/bin/time -f "elapsed %e s" ./prof1 1e5
50000.5
elapsed 0.03 s
$ /usr/bin/time -f "elapsed %e s" ./prof1 1e6
500000.5
elapsed 0.12 s
$ /usr/bin/time -f "elapsed %e s" ./prof1 1e7
5000000.5
elapsed 1.19 s
$ /usr/bin/time -f "elapsed %e s" ./prof1 1e8
50000000.5
elapsed 10.24 s
$ /usr/bin/time -f "elapsed %e s" ./prof1 1e9
Command terminated by signal 9
elapsed 200.01 s
```

Scales linearly, but this exhausted memory on a 64 GB machine

What is actually going on?

How do we make this work in bounded memory?

```
$ ./prof1 1e8 +RTS -s
50000000.5
  12,800,142,880 bytes allocated in the heap
  10,020,680,440 bytes copied during GC
   2,517,947,400 bytes maximum residency (13 sample(s))
     431,184,888 bytes maximum slop
            5718 MiB total memory in use (0 MB lost due to fragmentation)

                                     Tot time (elapsed)  Avg pause  Max pause
  Gen  0      3039 colls,     0 par    2.278s   2.286s     0.0008s    0.0038s
  Gen  1        13 colls,     0 par    5.422s   5.431s     0.4178s    2.1034s

  INIT    time    0.001s  (  0.001s elapsed)
  MUT     time    2.068s  (  2.059s elapsed)
  GC      time    7.699s  (  7.717s elapsed)
  EXIT    time    0.000s  (  0.003s elapsed)
  Total   time    9.768s  (  9.780s elapsed)

  %GC     time       0.0%  (0.0% elapsed)

  Alloc rate    6,190,156,893 bytes per MUT second

  Productivity  21.2% of total user, 21.1% of total elapsed
```

MUT = "mutator" = useful work

GC = "garbage collection"

Spending about 79% of its time doing garbage collection

%GC time is wrong

```
$ stack ghc -- --make -O2 prof1.hs \
  -rtsopts \                         Enable more +RTS options
  -prof \                            Enable profiling
  -fprof-auto                        Profile every top-level function
[1 of 2] Compiling Main             ( prof1.hs, prof1.o )
[2 of 2] Linking prof1 [Objects changed]
```

```
$ /usr/bin/time -f "elapsed %e s" ./prof1 1e6 +RTS -p
500000.5
elapsed 0.16 s      # vs. 0.12 s without profiling
```

Generates prof1.prof file because of -p option

```
      Thu Nov  2 16:41 2023 Time and Allocation Profiling Report  (Final)

         prof1 +RTS -p -RTS 1e6

      total time  =        0.06 secs   (62 ticks @ 1000 us, 1 processor)
      total alloc = 128,107,088 bytes  (excludes profiling overheads)

COST CENTRE MODULE SRC                   %time %alloc

main        Main   prof1.hs:(5,1)-(7,29)   77.4   99.9
mean        Main   prof1.hs:10:1-43        22.6    0.0
                                                                      individual     inherited
COST CENTRE MODULE               SRC                    no. entries  %time %alloc   %time %alloc

MAIN        MAIN                 <built-in>             129       0    0.0    0.0   100.0  100.0
 CAF        Main                 <entire-module>        257       0    0.0    0.0     0.0    0.0
  main      Main                 prof1.hs:(5,1)-(7,29)  258       1    0.0    0.0     0.0    0.0
 CAF        GHC.Conc.Signal      <entire-module>        250       0    0.0    0.0     0.0    0.0
 CAF        GHC.Float            <entire-module>        244       0    0.0    0.0     0.0    0.0
 CAF        GHC.IO.Encoding      <entire-module>        237       0    0.0    0.0     0.0    0.0
 CAF        GHC.IO.Encoding.Iconv <entire-module>       235       0    0.0    0.0     0.0    0.0
 CAF        GHC.IO.Handle.FD     <entire-module>        227       0    0.0    0.0     0.0    0.0
 CAF        GHC.Read             <entire-module>        212       0    0.0    0.0     0.0    0.0
 CAF        Text.Printf          <entire-module>        193       0    0.0    0.0     0.0    0.0
 main       Main                 prof1.hs:(5,1)-(7,29)  259       0   77.4   99.9   100.0   99.9
  mean      Main                 prof1.hs:10:1-43       260       1   22.6    0.0    22.6    0.0
```

```haskell
main :: IO ()
main = do
  [d] <- map read <$> getArgs
  printf "%f\n" $ mean [1..d]

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

```
COST CENTRE MODULE SRC                          %time %alloc

main        Main   prof1.hs:(5,1)-(7,29)         79.4   99.9
mean        Main   prof1.hs:10:1-43              20.6    0.0
```

Most allocation is for the list of Doubles (in main)

Only 20% of the time is spent traversing the list

`-fprof-auto` gives unsufficient precision; need to define smaller *cost centers*

SCC : "Set Cost Center" annotation in a `{-# SCC id #-}` comment.

id may be a Haskell identifier or a quoted string

```
import System.Environment (getArgs)
import Text.Printf (printf)
main :: IO ()
main = do [d] <- map read <$> getArgs
          printf "%f\n" $ mean ({-# SCC list #-} [1..d])

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

```
$ stack ghc -- --make -O2 prof2.hs -prof -fprof-auto
[1 of 2] Compiling Main             ( prof2.hs, prof2.o )
[2 of 2] Linking prof2
$ /usr/bin/time -f "elapsed %e s" ./prof2 1e6 +RTS -p
500000.5
elapsed 0.19 s
```

```haskell
main = do [d] <- map read <$> getArgs
          printf "%f\n" $ mean ({-# SCC list #-} [1..d])
mean xs =                    ({-# SCC sum    #-} sum    xs) /
          fromIntegral ({-# SCC length #-} length xs)
```

```
      Thu Nov  2 17:24 2023 Time and Allocation Profiling Report  (Final)
         prof2 +RTS -p -RTS 1e6
      total time  =        0.06 secs   (59 ticks @ 1000 us, 1 processor)
      total alloc = 128,107,104 bytes  (excludes profiling overheads)

COST CENTRE MODULE SRC                %time %alloc
list        Main   prof2.hs:6:50-55    72.9   99.9
sum         Main   prof2.hs:9:44-52    13.6    0.0
length      Main   prof2.hs:10:44-52   13.6    0.0

                                                                   individual      inherited
COST CENTRE  MODULE                 SRC                  no.     entries  %time %alloc   %time %alloc

MAIN         MAIN                   <built-in>           129           0    0.0    0.0   100.0  100.0
 CAF         Main                   <entire-module>      257           0    0.0    0.0     0.0    0.0
  main       Main                   prof2.hs:(5,1)-(6,56) 258          1    0.0    0.0     0.0    0.0
 CAF         GHC.Conc.Signal        <entire-module>      250           0    0.0    0.0     0.0    0.0
 CAF         GHC.Float              <entire-module>      244           0    0.0    0.0     0.0    0.0
 CAF         GHC.IO.Encoding        <entire-module>      237           0    0.0    0.0     0.0    0.0
 CAF         GHC.IO.Encoding.Iconv  <entire-module>      235           0    0.0    0.0     0.0    0.0
 CAF         GHC.IO.Handle.FD       <entire-module>      227           0    0.0    0.0     0.0    0.0
 CAF         GHC.Read               <entire-module>      212           0    0.0    0.0     0.0    0.0
 CAF         Text.Printf            <entire-module>      193           0    0.0    0.0     0.0    0.0
 main        Main                   prof2.hs:(5,1)-(6,56) 259          0    0.0    0.0   100.0   99.9
  list       Main                   prof2.hs:6:50-55     260           1   72.9   99.9    72.9   99.9
  mean       Main                   prof2.hs:(9,1)-(10,53) 261         1    0.0    0.0    27.1    0.0
   length    Main                   prof2.hs:10:44-52    263           1   13.6    0.0    13.6    0.0
   sum       Main                   prof2.hs:9:44-52     262           1   13.6    0.0    13.6    0.0
```

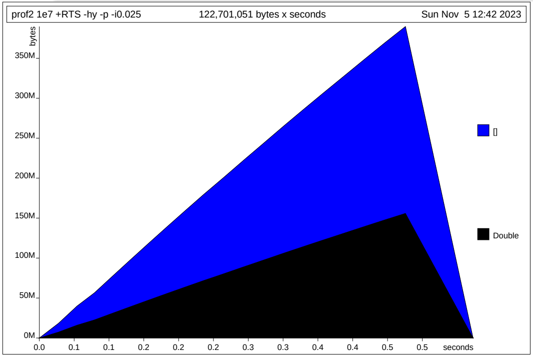
```haskell
main = do [d] <- map read <$> getArgs
          printf "%f\n" $ mean ({-# SCC list #-} [1..d])
mean xs =                 ({-# SCC sum    #-} sum    xs) /
          fromIntegral ({-# SCC length #-} length xs)
```

```
      Thu Nov  2 17:24 2023 Time and Allocation Profiling Report  (Final)
         prof2 +RTS -p -RTS 1e6
      total time  =        0.06 secs   (59 ticks @ 1000 us, 1 processor)
      total alloc = 128,107,104 bytes  (excludes profiling overheads)

COST CENTRE MODULE SRC                %time %alloc
list        Main   prof2.hs:6:50-55    72.9   99.9
sum         Main   prof2.hs:9:44-52    13.6    0.0
length      Main   prof2.hs:10:44-52   13.6    0.0
```

The list is virtually all of the memory allocated

Sum and length are both taking a fair amount of time (to traverse the list)

```
$ stack ghc -- --make -O2 prof2.hs -prof -fprof-auto -rtsopts
[1 of 2] Compiling Main             ( prof2.hs, prof2.o )
[2 of 2] Linking prof2
$ /usr/bin/time -f "elapsed %e s" ./prof2 1e7 +RTS -hy -p -i0.025
5000000.5
elapsed 3.22 s
$ hp2ps prof2.hp     # Creates prof2.ps
```



`-hy` Profile heap by type into prof2.hp

`-i0.025` Sample heap size every 0.025 s

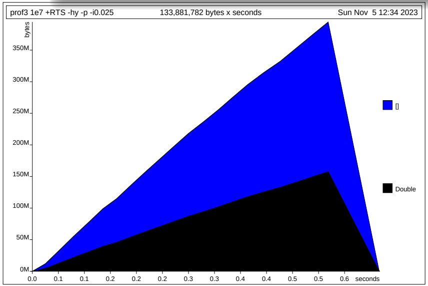
1e7 element list:
160e6 bytes of Doubles (16 bytes ea.);
240e6 bytes of Cons cells (24 bytes ea.)

List is being created slowly (lazily) then deallocated as it's being traversed again

Laziness doesn't reduce memory because the list needs to be traversed *twice*.

Idea: make two equivalent lists

```haskell
main = do
  [d] <- map read <$> getArgs
  printf "%f\n" $ mean [1..d] [1..d]

mean :: [Double] -> [Double] -> Double
mean xs1 xs2 = sum xs1 / fromIntegral (length xs2)
```



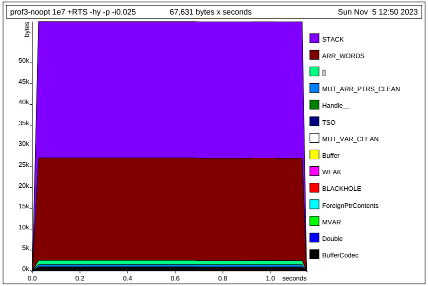

```
$ ghc --make -O2 prof3.hs \
    -prof -fprof-auto -rtsopts
$ ./prof3 1e7 +RTS -hy -p -i0.025
5000000.5
elapsed 6.66 s
```

No luck: compiler recognized that `[1..d]` and `[1..d]` are identical and merged

Laziness doesn't reduce memory because the list needs to be traversed *twice*.

Idea: make two equivalent lists

```
main = do
  [d] <- map read <$> getArgs
  printf "%f\n" $ mean [1..d] [1..d]

mean :: [Double] -> [Double] -> Double
mean xs1 xs2 = sum xs1 / fromIntegral (length xs2)
```



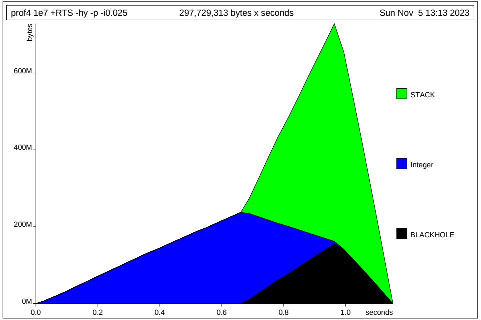

```
$ ghc --make prof3.hs -o prof3-noopt \
    -prof -fprof-auto -rtsopts
$ ./prof3-noopt 1e7 +RTS -hy -p -i0.025
5000000.5
elapsed 1.17 s
```

6× speedup from *disabling* optimization

This is what we want but…yuck

Sum the list and assess its length simultaneously:

```
mean :: [Double] -> Double
mean xs = total / fromIntegral count
  where (count, total) = foldl step (0, 0) xs
        step (n, s) x = (n + 1, s + x)
```




```
$ ghc --make -O2 prof4.hs \
    -prof -fprof-auto -rtsopts
$ /usr/bin/time -f "elapsed %e s" \
    ./prof4 1e7 +RTS -hy -p -i0.025
5000000.5
elapsed 12.51 s
```

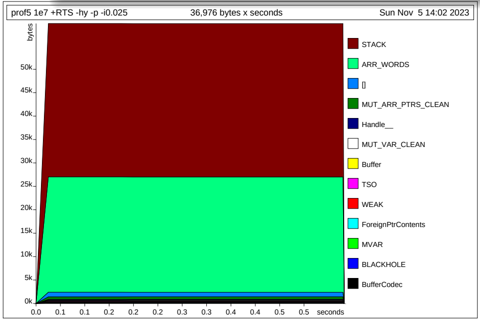
We traded 400M of heap for 700M of stack

The whole computation remains lazy: each call of *step* remains a thunk on the stack

That there are a lot of *Integer*-type objects is a hint: these are complex data structures being evaluated lazily.

Force the use of *Ints*:

```
mean :: [Double] -> Double
mean xs = total / fromIntegral count
  where (count, total) = foldl step (0::Int, 0) xs
        step (n, s) x = (n + 1, s + x)
```




```
$ ghc --make -O2 prof5.hs \
    -prof -fprof-auto -rtsopts
$ /usr/bin/time -f "elapsed %e s" \
    ./prof5 1e7 +RTS -hy -p -i0.025
5000000.5
elapsed 0.68 s
```

Much, much better

Initial version:

```
1,280,142,368 bytes allocated
1,070,855,432 bytes copied by GC

670 MiB total memory in use

INIT    time    0.001s
MUT     time    0.208s
GC      time    0.831s
EXIT    time    0.000s
Total   time    1.040s

Productivity  20.0%
```

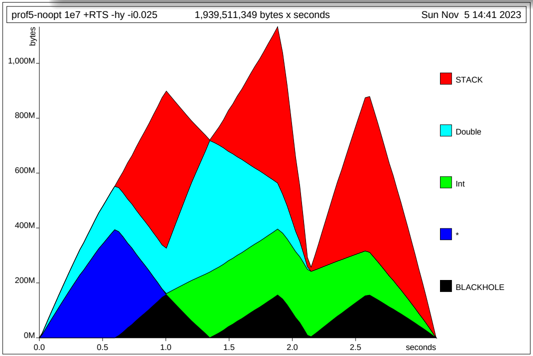
Using *foldl* with *Ints*

```
1,280,142,368 bytes allocated
       35,520 bytes copied by GC

6 MiB total memory in use

INIT    time    0.001s
MUT     time    0.184s
GC      time    0.002s
EXIT    time    0.000s
Total   time    0.187s

Productivity  98.3%
```

5× speedup: GC 400× faster

However, without optimization, we get

```
$ ghc --make prof5.hs -o prof5-noopt -prof -rtsopts
$ ./prof5-noopt 1e7 +RTS -hy -i0.025 -s
MUT      time     3.099s
GC       time    37.322s
```



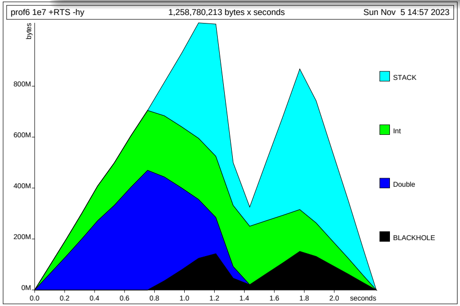
Using an enormous amount of stack space, building a big Double list

It's being too lazy

For this simple example –O2 was able to do strictness analysis to eliminate needless laziness; we won't always be so lucky

First trick: use *Data.List.foldl'*, which accumulates state strictly

```haskell
import Data.List (foldl')

mean :: [Double] -> Double
mean xs = total / fromIntegral count
  where (count, total) = foldl' step (0::Int, 0) xs
        step (n, s) x = (n + 1, s + x)
```



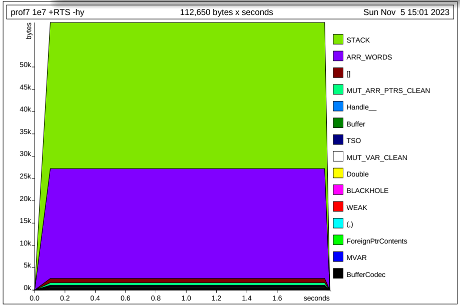

```
$ ghc --make prof6.hs -prof -rtsopts
$ ./prof6 1e7 +RTS -hy
```

Better than before, but it's still too lazy

Problem is that *foldl'* is only strict to WHNF: the accumulated pair state is left unevaluated

Second trick: use *seq* to force strict evaluation of the components of the pair

```
mean :: [Double] -> Double
mean xs = total / fromIntegral count
  where (count, total) = foldl' step (0, 0) xs
        step (n, s) x = n `seq` s `seq` (n + 1, s + x)
```



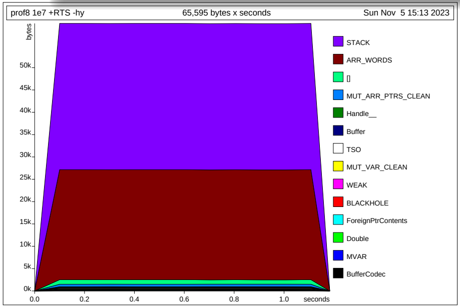

```
$ ghc --make prof7.hs -prof -rtsopts
$ ./prof7 1e7 +RTS -hy
```

Back to a very fast, constant-memory implementation

Another approach: force the accumulated state datatype to be strict

Adding ! to fields forces them to be strict

```haskell
data Pair = Pair !Int !Double

mean :: [Double] -> Double
mean xs = total / fromIntegral count
  where Pair count total = foldl' step (Pair 0 0) xs
        step (Pair n s) x = Pair (n + 1) (s + x)
```



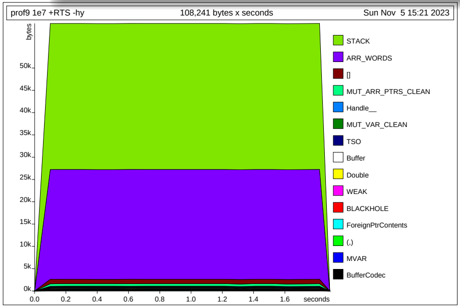

```
$ ghc --make prof8.hs -prof -rtsopts
$ ./prof8 1e7 +RTS -hy
```

Similar effect as using *seq*; slightly less intrusive

The BangPatterns language extension is another way to force strictness

Adding ! to patterns forces arguments to be strict

```haskell
{-# LANGUAGE BangPatterns #-}

mean :: [Double] -> Double
mean xs = total / fromIntegral count
  where (count, total) = foldl' step (0::Int, 0) xs
        step (!n, !s) x = (n + 1, s + x)
```




```
$ ghc --make prof9.hs -prof -rtsopts
$ ./prof9 1e7 +RTS -hy
```

Even less intrusive than using a different data type