CS 410/510: Advanced Programming

Profiling in Haskell

Mark P Jones
Portland State University

What makes a good program?

- Qualitative factors:
  - Correctness
  - Maintainability, readability, understandability, portability, flexibility, …
  - Use of appropriate abstractions and idioms
  - …
- Quantitative factors:
  - Performance, Predictability, …
  - Time, Memory, Disk, Bandwidth, …

Understanding Program Behavior:

- High-level languages abstract away from the underlying machine
- This can make it very difficult to understand what is happening when a program executes
- Analytic techniques can predict asymptotic trends
- Hard to model complexities of memory, timing, stack, cache, disk, buffers, network, latencies, bandwidth, concurrency, branch prediction, …

Profiling Tools:

- Two broad approaches:
  - Instrumentation
  - Sampling
- Standard Advice:
  - Focus on writing qualitatively good code first
  - Once that's working, use profiling tools to identify performance hot-spots and obtain quantitatively good code

Form Follows Function:

```
expr, term, atom :: Parser Int

expr    = term "+" expr            -- return (l+r)
         | term "-" expr           -- return (l-r)
         | term

term    = atom "*" term            -- return (l*r)
         | atom "/" term           -- return (l`div`r)
         | atom

atom    = "-" atom                 -- return (negate x)
         | "(" expr ")"            -- return n
         | number
```

Form Follows Function:

```
expr, term, atom :: Parser Int

expr   = do l <- term; string "+"; r <- expr; return (l+r)
       ||| do l <- term; string "-"; r <- expr; return (l-r)
       ||| term

term   = do l <- atom; string "*"; r <- term; return (l*r)
       ||| do l <- atom; string "/"; r <- term; return (l`div`r)
       ||| atom

atom   = do string "-"; x <- atom; return (negate x)
       ||| do string "("; n <- expr; string ")"; return n
       ||| number
```

Parsing Examples:

```
Parsing> parse expr "1+2"
[3]
Parsing> parse expr "(1+2) * 3"
[]
Parsing> parse expr "(1+2)*3"
[9]
Parsing> parse expr "((1+2)*3)+1"
[10]
Parsing> parse expr "(((1+2)*3)+1)*8"
[80]
Parsing> parse expr "((((1+2)*3)+1)*8)"
[80]
Parsing>
```

Execution Statistics in Hugs:

- Mechanisms:
  - Enable the collection of execution statistics using :set +s
  - Turn on messages when garbage collection occurs using :set +g
  - Change total heap size (when loading Hugs) using hugs –hSize

- Measures:
  - **Cells**: a chunk of memory
  - **Reductions**: a single rewrite step

Collecting Statistics:

```
Parsing> :set +s
Parsing> 1
1
(22 reductions, 32 cells)
Parsing> 2
2
(22 reductions, 32 cells)
Parsing> 3
3
(22 reductions, 32 cells)
Parsing> 1+2
3
(26 reductions, 36 cells)
Parsing> length "hello"
5
(56 reductions, 75 cells)
Parsing> length "world"
5
(56 reductions, 75 cells)
Parsing> id 1
1
(22 reductions, 32 cells)
Parsing> (\x -> x) 1
1
(23 reductions, 32 cells)
Parsing>
```

Observing Garbage Collection:

```
Parsing> :set
TOGGLES: groups begin with +/- to turn options on/off resp.
s    Print no. reductions/cells after eval
...
OTHER OPTIONS: (leading + or - makes no difference)
hnum Set heap size (cannot be changed within Hugs)
...
Current settings: +squR -tgl.QwkIT -h1000000 -p"%s> " -r$$ -c40
...
Parsing> length [1..200000]
{{Gc:979946}}{{Gc:979945}}{{Gc:979947}}{{Gc:979946}}{{Gc:
979947}}200000
(4200043 reductions, 5598039 cells, 5 garbage collections)
{{Gc:979983}}Parsing>
```

Observing Garbage Collection:

```
$ hugs -h100000 +gs
...
Hugs> length [1..200000]
{{Gc:86831}}{{Gc:86830}}{{Gc:86832}}{{Gc:86833}}{{Gc:86828}}...
{{Gc:86828}}{{Gc:86829}}{{Gc:86828}}{{Gc:86828}}200000
(4200054 reductions, 5598125 cells, 64 garbage collections)
{{Gc:86866}}Hugs> :q

$ hugs -h8M +gs
...
Hugs> length [1..200000]
200000
(4200054 reductions, 5598125 cells)
{{Gc:7986866}}Hugs>:q
```

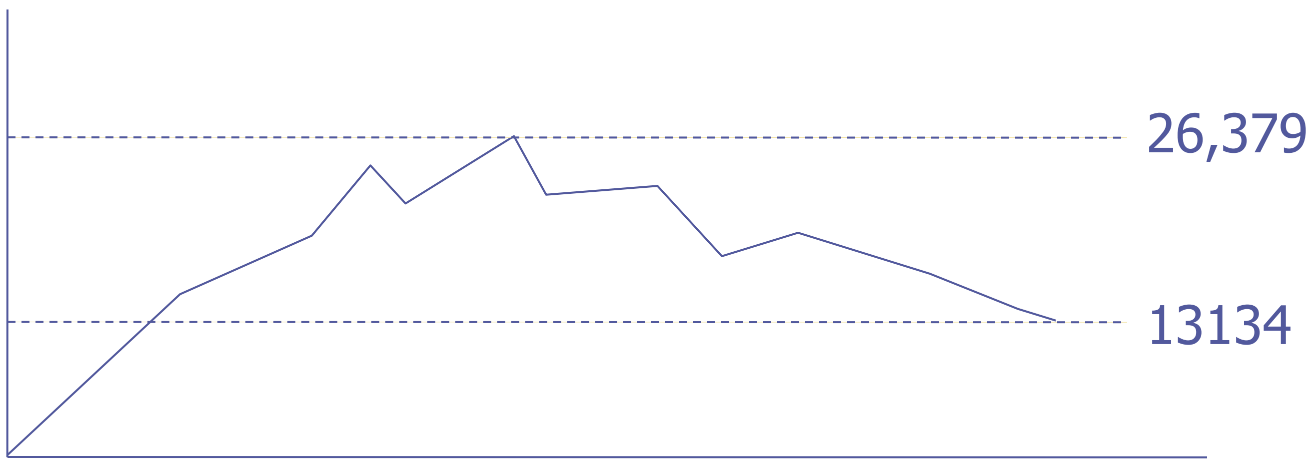
Observing Garbage Collection:

```
$ hugs -h26378
...
ERROR "/Users/user/local/lib/hugs/packages/hugsbase/Hugs/Prelude.hs"
- Garbage collection fails to reclaim sufficient space
FATAL ERROR: Unable to load Prelude

$ hugs -h26379
...
Hugs> :set +sg
Hugs> length [1..200000]
{{Gc:13208}}{{Gc:13213}}{{Gc:13208}}{{Gc:13205}}{{Gc:13209}}...
{{Gc:13203}}{{Gc:13209}}200000
(4200054 reductions, 5598125 cells, 424 garbage collections)
{{Gc:13245}}Hugs>
```

Observations:

- Note that: 100000 – 86866 = 13134 = 26379 – 13245
- So we can conclude that Hugs:
  - uses 13134 cells for internal state
  - needs at least 26379 cells to load

- Possible profile of memory usage during startup:



Heap size, Residency, Allocation:

- **Heap size** measures maximum capacity
- **Residency** measures amount of memory that is actually in use at any given time
- Haskell programs allocate constantly (and, simultaneously, create garbage)
- **Total allocation** may exceed heap size

Back to Parsing:

Parentheses seem to be part of the problem, so let’s stress test:

```
addParens n s = if n==0
                then s
                else "(" ++ addParens (n-1) s ++ ")”
```

```
Parsing> [ addParens n "1" | n <-[0..5] ]
["1","(1)","((1))","(((1)))","((((1))))","(((((1)))))"]
Parsing>
```

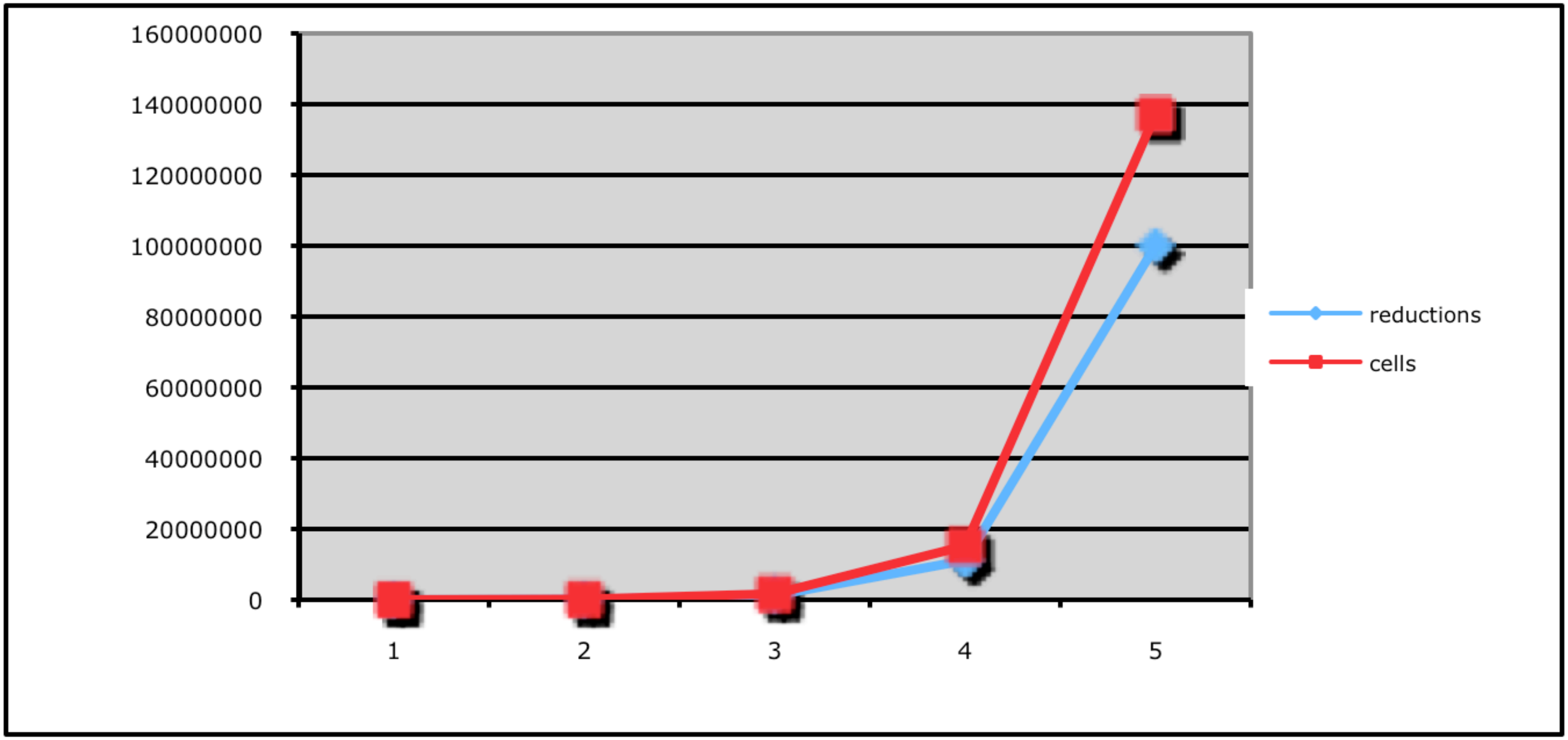
Rapid increases in reductions and cell counts

```
Parsing> :set +s
Parsing> parse expr (addParens 1 "1")
[1]
(15060 reductions, 20628 cells)
Parsing> parse expr (addParens 2 "1")
[1]
(137062 reductions, 187767 cells)
Parsing> parse expr (addParens 3 "1")
[1]
(1234954 reductions, 1691736 cells, 1 garbage collection)
Parsing> parse expr (addParens 4 "1")
[1]
(11115840 reductions, 15227127 cells, 15 garbage collections)
Parsing> parse expr (addParens 5 "1")
[1]
(100043656 reductions, 137045268 cells, 139 garbage collections)
Parsing>
```

Memory is not the problem here:

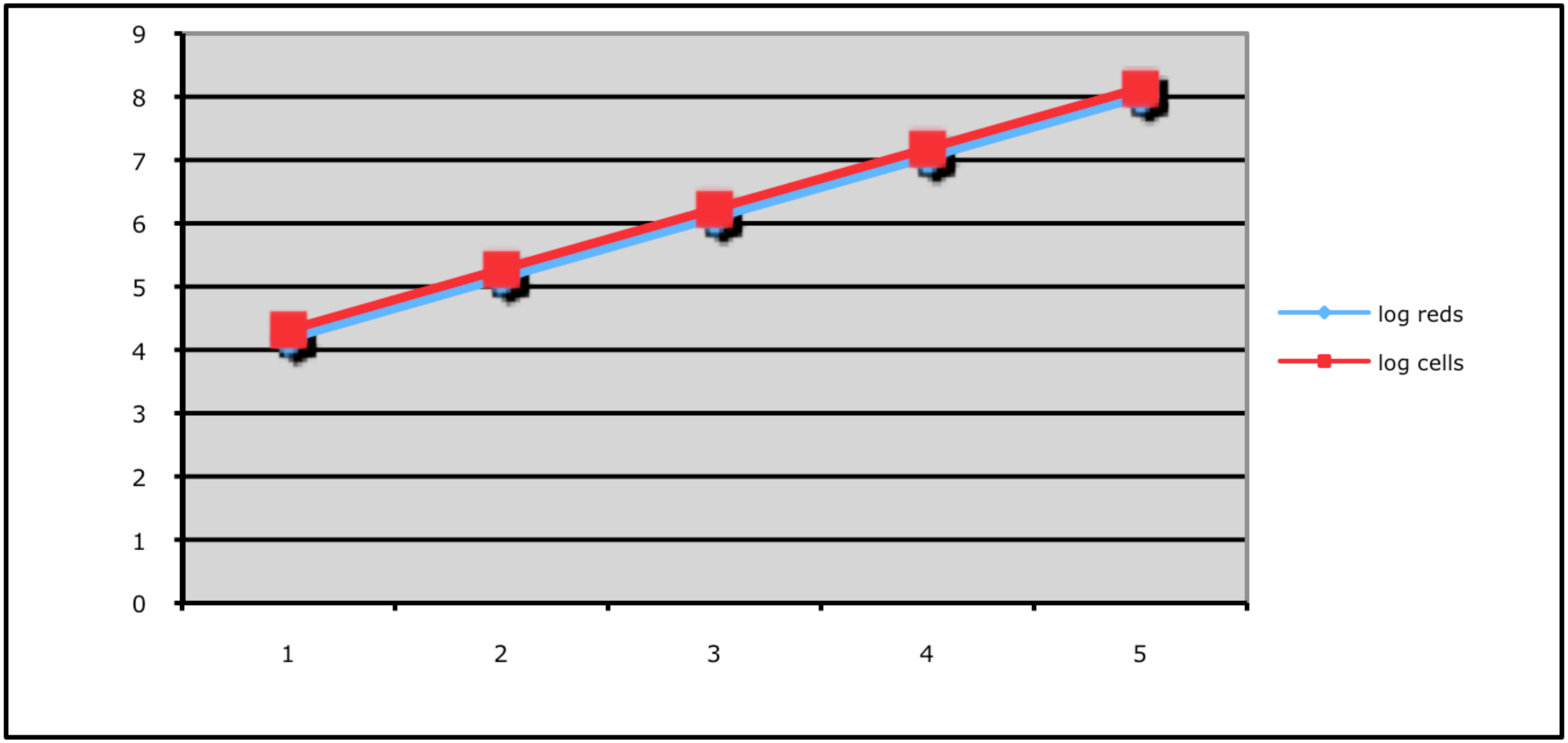
```
$ hugs -h26379 +sg
Hugs> :l altParsing.lhs
Parsing> :gc
Garbage collection recovered 6462 cells
Parsing> parse expr "1"
[1]
(1367 reductions, 1881 cells)
{{Gc:6304}}Parsing> parse expr (addParens 1 "1")
{{Gc:6218}}{{Gc:6213}}{{Gc:6217}}[1]
(15073 reductions, 20665 cells, 3 garbage collections)
{{Gc:6281}}Parsing> parse expr (addParens 5 "1")
{{Gc:6044}}{{Gc:6072}}{{Gc:6066}}{{Gc:6076}}{{Gc:6072}}{{Gc:
6081}}{{Gc:6063}}{{Gc:6085}}{{Gc:6068}}{{Gc:6090}}{{Gc:6062}}...
{{Gc:6113}}{{Gc:6078}}{{Gc^C:6048}}{Interrupted!}

(16505831 reductions, 22610720 cells, 3713 garbage collections)
{{Gc:6048}}Parsing>
```

Analysis (1):



parens	reductions	cells
1	15060	20628
2	137062	187767
3	1234954	1691736
4	11115840	15227127
5	100043656	137045268

Analysis (2):



parens	reductions	cells	log reds	log cells
1	15060	20628	4.177824972	4.314457123
2	137062	187767	5.136917065	5.273619267
3	1234954	1691736	6.091650781	6.228332591
4	11115840	15227127	7.045942287	7.18261797
5	100043656	137045268	8.000189554	8.136864044

Why Exponential Behavior?

Recall this grammar ...

```
expr, term, atom :: Parser Int

expr   = do l <- term; string "+"; r <- expr; return (l+r)
       ||| do l <- term; string "-"; r <- expr; return (l-r)
       ||| term

term   = do l <- atom; string "*"; r <- term; return (l*r)
       ||| do l <- atom; string "/"; r <- term; return (l`div`r)
       ||| atom

atom   = do string "-"; x <- atom; return (negate x)
       ||| do string "("; n <- expr; string ")"; return n
       ||| number
```

Matching "1" as an term:

- First, we match it as a term … and then find that it's not followed by a "+"

  do **l <- term**; string "+"; r <- expr; return (l+r)

- So then we match it again as a term … and find that it's not followed by a "-"

  do **l <- term**; string "-"; r <- expr; return (l-r)

- Then, finally we can match it as a term without any following characters

  term

- So we will match "1" as a term three times before we succeed … or as an atom nine times … or …

Refactoring the Grammar:

```
expr, term, atom :: Parser Int

expr    = do l <- term
             do string "+"; r <- expr; return (l+r)
              ||| do string "-"; r <- expr; return (l-r)
              ||| return l

term    = do l <- atom
             do string "*"; r <- term; return (l*r)
              ||| do string "/"; r <- term; return (l`div`r)
              ||| return l

atom    = ... as before ...
```

A Step Forward:

```
Parsing> :set +s
Parsing> parse expr (addParens 10 "1")
[1]
(3624 reductions, 6091 cells)
Parsing> parse expr (addParens 100 "1")
[1]
(42414 reductions, 83491 cells)
Parsing> parse expr (addParens 1000 "1")
[1]
(1321314 reductions, 3530491 cells, 3 garbage collections)
Parsing> parse expr (addParens 10000 "1")

(3899701 reductions, 11445375 cells, 12 garbage collections)
ERROR - Control stack overflow
Parsing>
```

Profiling with GHC:

- GHC provides a much broader and more powerful range of profiling tools than Hugs
- We have to identify a main program:

```
module Main where
main = print (parse expr "(((((1)))))")
```

- Compiling: ghc --make altParsing.lhs
- Running: ./altParsing +RTS –sstderr
- Still slow!

```
$ ./altParsing +RTS -sstderr
[1]
848,494,732 bytes allocated in the heap
  1,506,284 bytes copied during GC (scavenged)
          0 bytes copied during GC (not scavenged)
     24,576 bytes maximum residency (1 sample(s))

       1619 collections in generation 0 (  0.02s)
          1 collections in generation 1 (  0.00s)

          1 Mb total memory in use

  INIT  time    0.00s  (  0.00s elapsed)
  MUT   time    1.01s  (  1.03s elapsed)
  GC    time    0.02s  (  0.02s elapsed)
  EXIT  time    0.00s  (  0.00s elapsed)
  Total time    1.03s  (  1.06s elapsed)

  %GC time       1.7%  (2.3% elapsed)

  Alloc rate    836,673,373 bytes per MUT second

  Productivity  98.2% of total user, 96.0% of total elapsed

$
```

Profiling Options:

- For more serious work, compile with the –prof flag

  ghc --make -prof altParsing.lhs

- Opens up possibilities for:
  - Time and allocation profiling
  - Memory profiling
  - Coverage Profiling
  - …
- Profiling code has overheads; not for production use

Cost Center Profiling:

- A technique for distributing costs during program execution
- Programmer creates "cost centers":
  - by hand {-# SCC "name" #-}
  - for all top-level functions: -auto-all
- Program maintains runtime stack of cost centers
- RTS samples behavior at regular intervals
- Produce a summary report of statistics at the end of execution

In Practice:

```
$ ghc --make -prof -auto-all altParsing.lhs
$ ./altParsing +RTS -p
[1]
$ ls
altParsing*      altParsing.hi    altParsing.lhs
altParsing.o     altParsing.prof
$
```

```
 Time and Allocation Profiling Report  (Final)

          altParsing +RTS -p -RTS

       total time  =        0.54 secs   (27 ticks @ 20 ms)
       total alloc = 803,275,236 bytes  (excludes profiling overheads)

COST CENTRE              MODULE        %time %alloc

CAF                      Main          100.0  100.0


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

MAIN          MAIN                1           0    0.0    0.0   100.0  100.0
 CAF          Main              154          19  100.0  100.0   100.0  100.0
 CAF          GHC.Handle         92           4    0.0    0.0     0.0    0.0
```

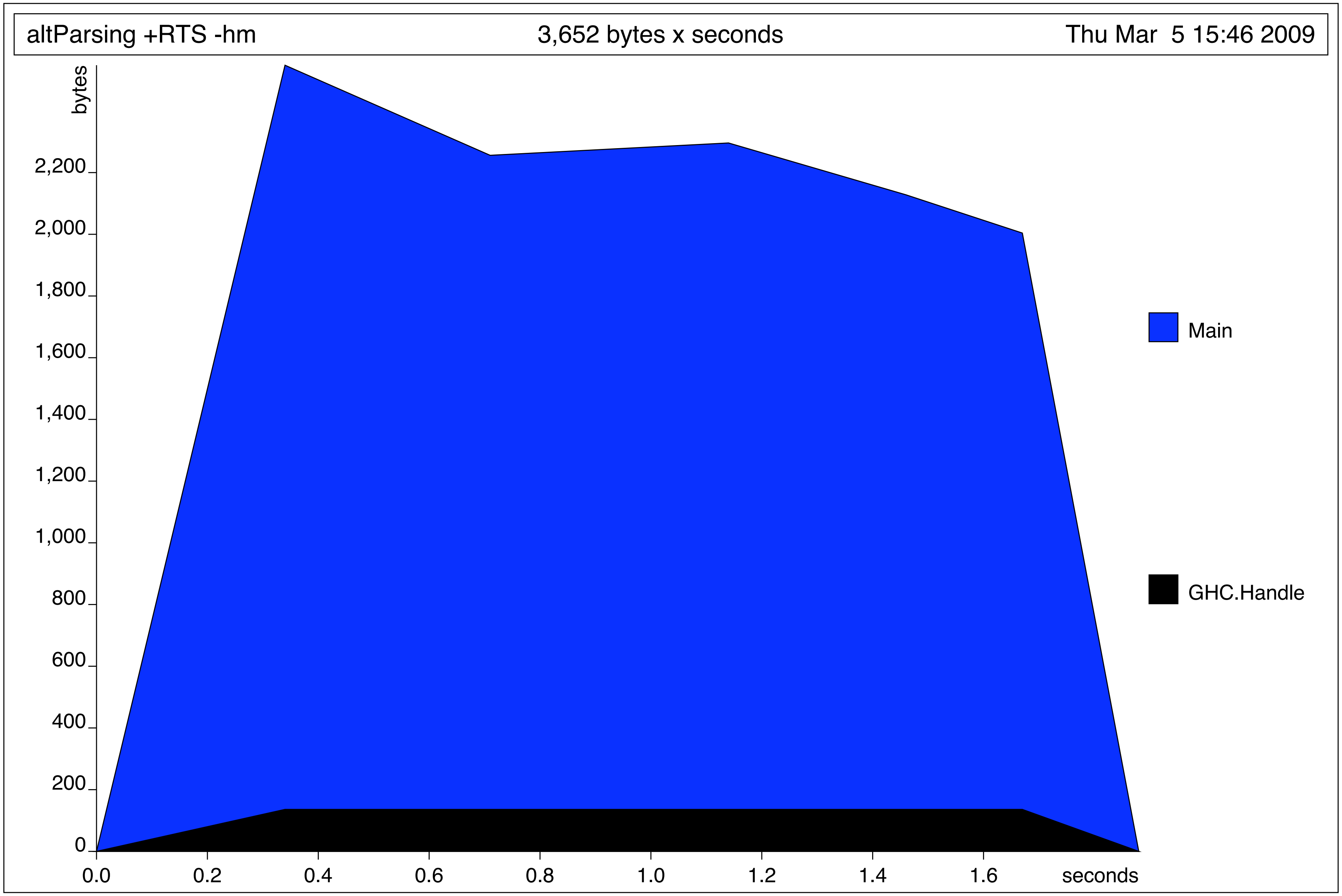
Alas, not a very insightful report,
in this case …

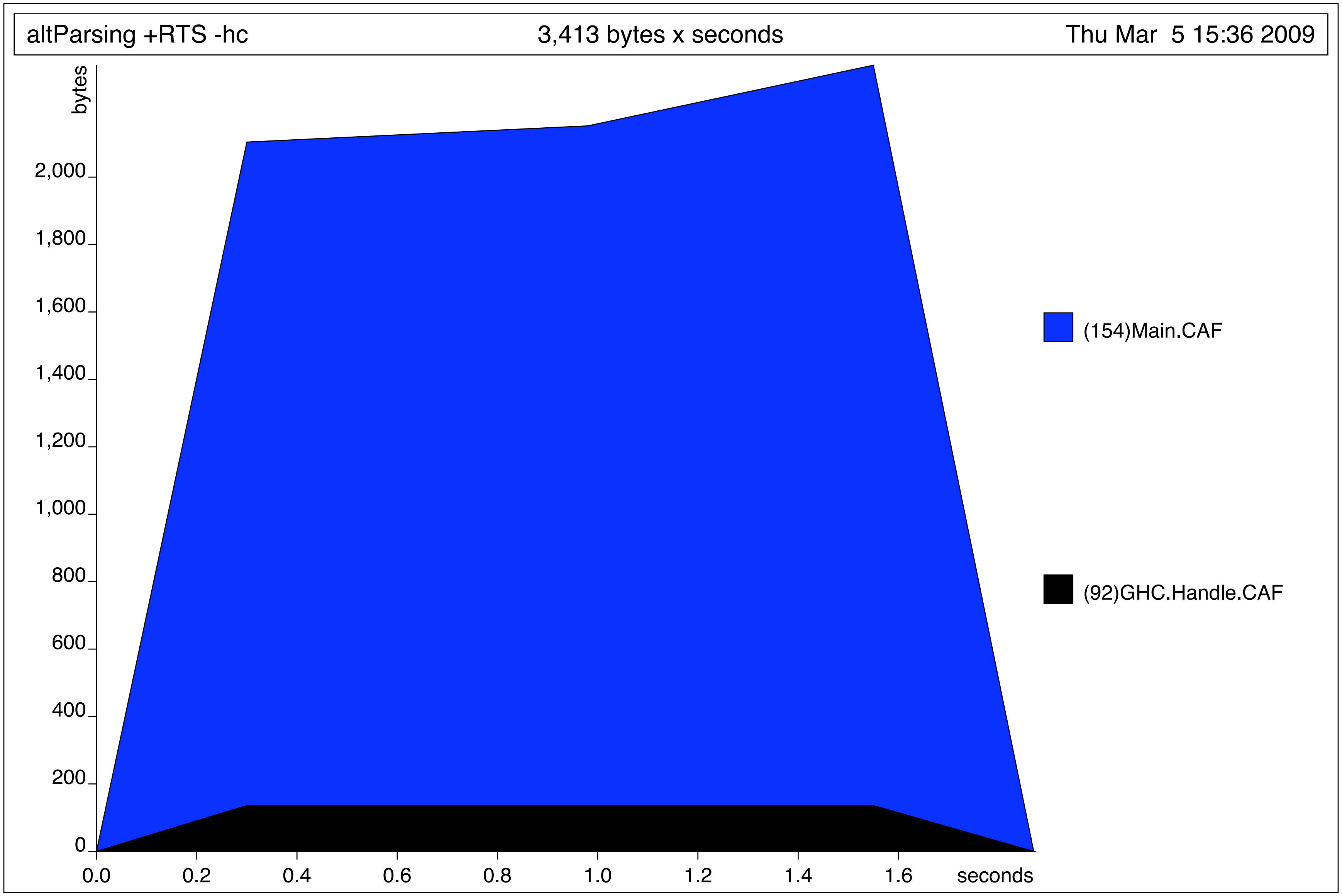
Heap Profiling:

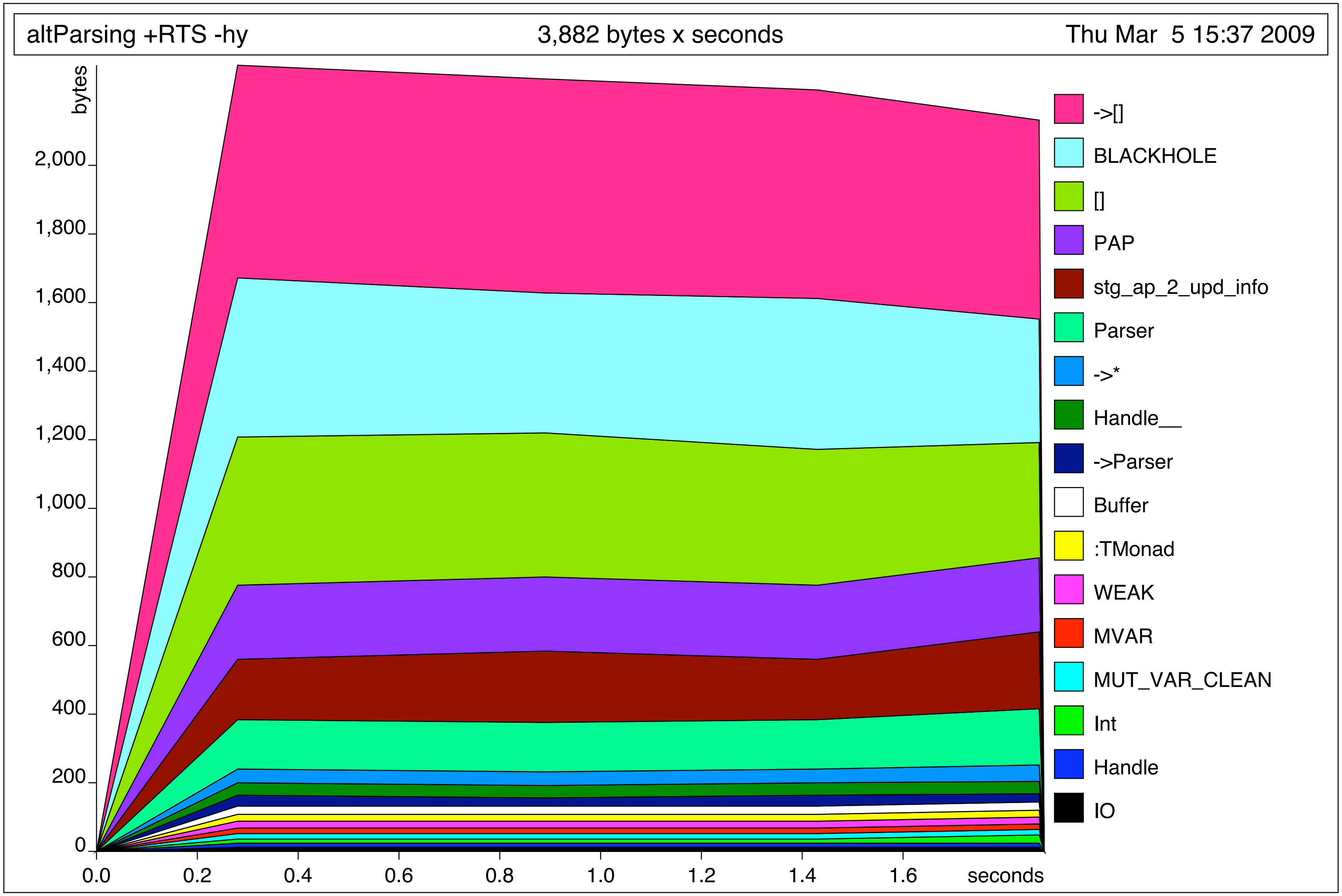
- A technique for measuring heap usage during program execution
- Compile code for profiling and run with argument +RTS option where option is:
  - -hc   by function
  - -hm   by module
  - -hy   by type
  - -hb   by thunk behavior
- Generates output.hp text file
- Produce a graphical version using hp2ps utility

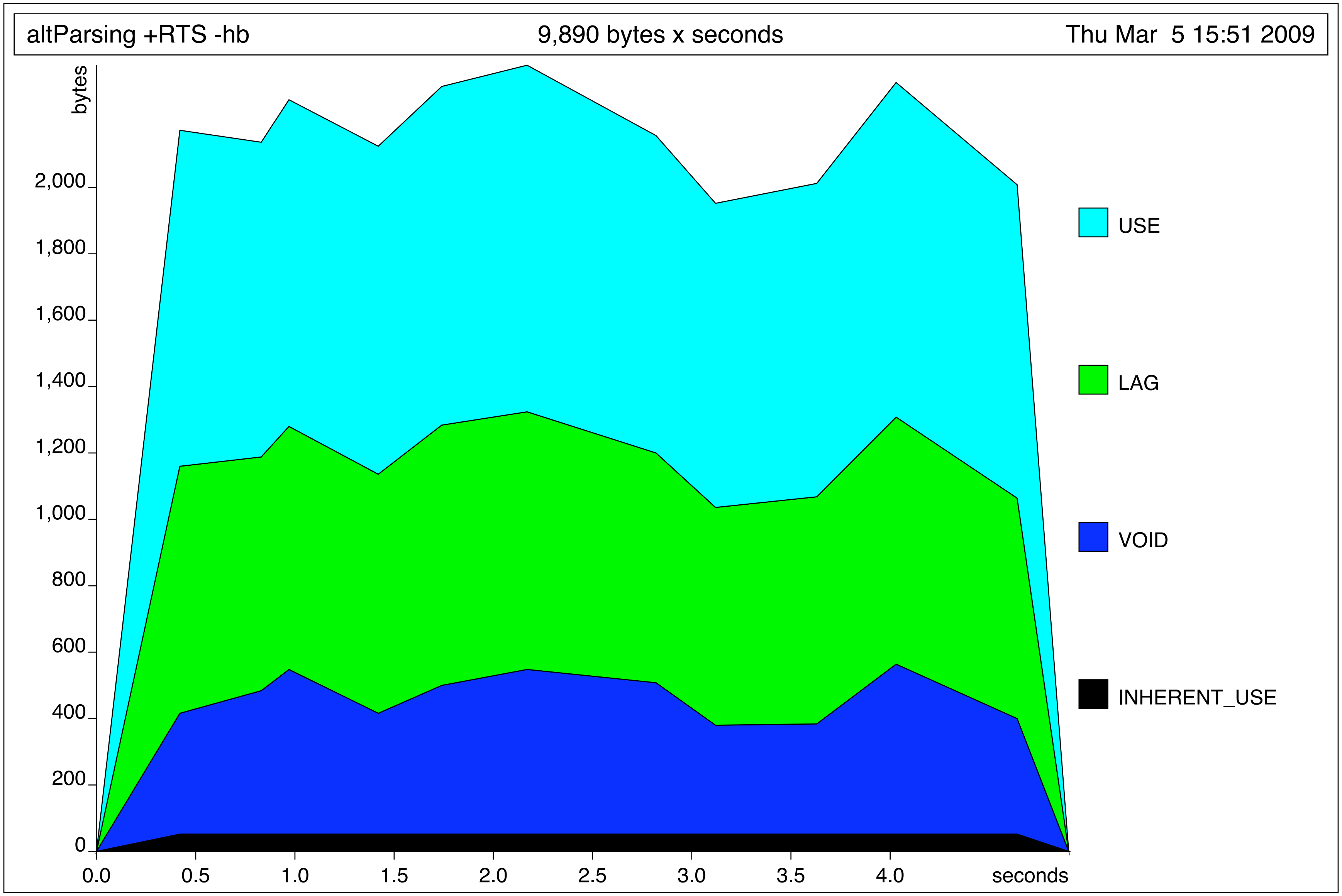
In Practice:

```
$ ghc --make –prof altParsing.lhs
$ ./altParsing +RTS -hc
[1]
$ ls
altParsing*      altParsing.hi    altParsing.lhs
altParsing.o     altParsing.hp
$ hp2ps –c altParsing.hp
$ open altParsing.ps
$
```


altParsing +RTS -hm
3,652 bytes x seconds
Thu Mar 5 15:46 2009
bytes
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
seconds
Main
GHC.Handle


altParsing +RTS -hc
3,413 bytes x seconds
Thu Mar 5 15:36 2009
bytes
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
seconds
(154)Main.CAF
(92)GHC.Handle.CAF


altParsing +RTS -hy
3,882 bytes x seconds
Thu Mar 5 15:37 2009
bytes
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
seconds
->[]
BLACKHOLE
[]
PAP
stg_ap_2_upd_info
Parser
->*
Handle__
->Parser
Buffer
:TMonad
WEAK
MVAR
MUT_VAR_CLEAN
Int
Handle
IO


altParsing +RTS -hb
9,890 bytes x seconds
Thu Mar 5 15:51 2009
bytes
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
seconds
USE
LAG
VOID
INHERENT_USE

Biographical Profiling (-hb):

- LAG phase: object created but not yet used
- USE: objects is in use
- DRAG: object has been used for the last time, but is still referenced
- VOID: an object is never used

Coverage Profiling:

- Used to determine which parts of a program have been exercised during any given run

- Works by instrumenting code to get exact results

- Provides two kinds of coverage:
  - Source coverage
    - Yellow – not executed
  - Boolean guard coverage
    - Green always true
    - Red always false

In Practice:

```
$ ghc --make –fhpc altParsing.lhs
$ ./altParsing
[1]
$ ls
altParsing*      altParsing.hi    altParsing.lhs
altParsing.o     altParsing.tix
$
```

In Practice:

```
$ hpc report altParsing
33% expressions used (138/409)
  0% boolean coverage (0/1)
     100% guards (0/0)
       0% 'if' conditions (0/1), 1 unevaluated
     100% qualifiers (0/0)
 66% alternatives used (4/6)
  0% local declarations used (0/6)
 54% top-level declarations used (18/33)
$
```

In Practice:

```
$ hpc markup altParsing
Writing: Main.hs.html
Writing: hpc_index.html
Writing: hpc_index_fun.html
Writing: hpc_index_alt.html
Writing: hpc_index_exp.html
$ open Main.hs.html
$ open hpc_index.html
$
```

Coverage of altParser:

```

> number :: Parser Int
> number   = many1 digit
>                  *** foldl1 (\a x -> 10*a+x)

A parser that evaluates arithmetic expressions:

> expr, term, atom :: Parser Int

> expr     = do l <- term; string "+"; r <- expr; return (l+r)
>          ||| do l <- term; string "-"; r <- expr; return (l-r)
>          ||| term

> term     = do l <- atom; string "*"; r <- term; return (l*r)
>          ||| do l <- atom; string "/"; r <- term; return (l`div`r)
>          ||| atom

> atom     = do string "-"; x <- atom; return (negate x)
>          ||| do string "("; n <- expr; string ")"; return n
>          ||| number

```

Summary:

- Profiling tools help us to understand the complex operational behavior of code

- Expert use of profiling tools requires significant use and experience

- But, even with limited experience, it is still possible to gain some interesting into what our programs really do!