Lazy and Parallel Evaluation

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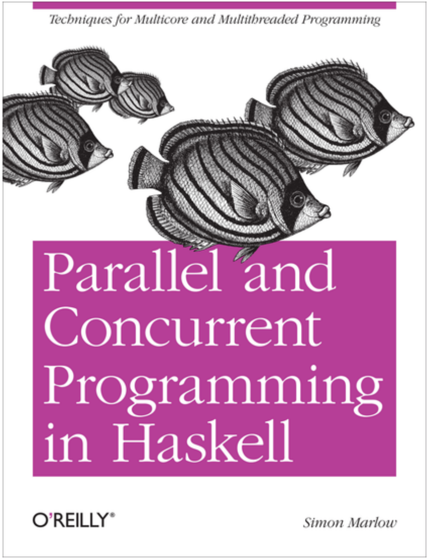
Laziness

- Forcing Evaluation with seq
- Weak Head Normal Form

Parallelism

- ThreadScope
- Sparking Parallelism with par
- Sparks
- Limiting Granularity



This material adapted from

Simon Marlow's book

https://simonmar.github.io/pages/pcph.html

Mary Sheeran and John Hughes's class

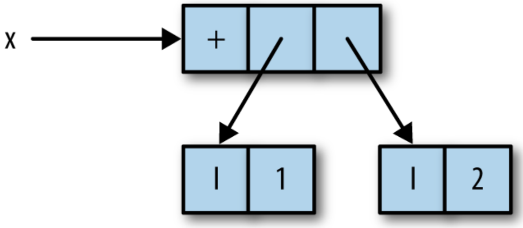
http://www.cse.chalmers.se/edu/year/2018/course/DAT280_Parallel_Functional_Programming/lectures.html

Laziness in Haskell

Haskell follows a *call-by-need*† evaluation strategy in which expressions are evaluated only when their values are needed and at most once.

Thunk Crood

```
Prelude> let x = 1 + 2 :: Int
Prelude> :t x
x :: Int
Prelude> :sprint x
x = _
Prelude> x + 1
4
Prelude> :sprint x
x = 3
```



[Marlow, Figure 2–1]

_ denotes an unevaluated "thunk"

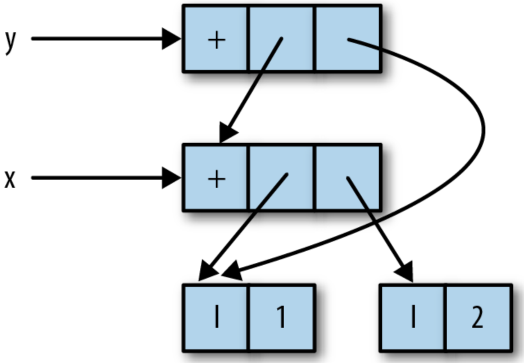
†C, Java, etc. are *call-by-value*: arguments are evaluated before a function call; Algol-68 is *call-by-name*: arguments are (re)evaluated at each reference

Thunks all the way down: *seq* also forces evaluation

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

`seq x y` = evaluate x and y; return y

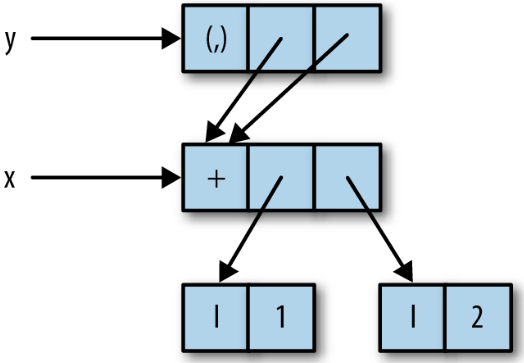
```
Prelude> let x = 1 + 2 :: Int
Prelude> let y = x + 1
Prelude> :sprint x
x = _
Prelude> :sprint y
y = _
Prelude> seq y ()
()
Prelude> :sprint x
x = 3
Prelude> :sprint y
y = 4
```



[Marlow, Figure 2–2]

Weak Head Normal Form: Lazy Data Structures

```
Prelude> let x = 1 + 2 :: Int
Prelude> let y = (x, x)
Prelude> let swap(a, b) = (b, a)
Prelude> let z = swap (x,x+1)
Prelude> :sprint z
z = _
Prelude> seq z ()
()
Prelude> :sprint z
z = (_,_)
Prelude> seq x ()
()
Prelude> :sprint z
z = (_,3)
```



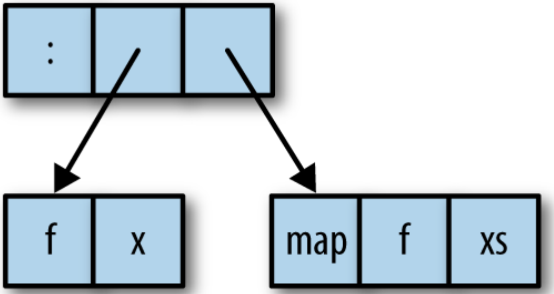
[Marlow, Figure 2–3]

Weak head normal form: top is data constructor or lambda, not application

Functions Build Thunks

```
Prelude> let xs =
   map (+1) [1..10] :: [Int]
Prelude> :sprint xs
xs = _
Prelude> seq xs ()
()
Prelude> :sprint xs
xs = _ : _
Prelude> seq (tail xs) ()
()
Prelude> :sprint xs
xs = _ : _ : _
Prelude> length xs
10
Prelude> :sprint xs
xs = [_,_,_,_,_,_,_,_,_,_]
```

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



[Marlow, Figure 2–4]

Let's Speed Up a Dumb† Program

```
nfib1 :: Integer -> Integer
nfib1 n | n < 2 = 1
nfib1 n = nfib1 (n-1) + nfib1 (n-2) + 1

main :: IO ()
main = print (nfib1 40)
```

n	nfib n
10	177
20	21891
25	242785
30	2692537
35	29860703
40	331160281

```
$ stack ghc -- -O2 \             # Optimize
               -threaded \       # Enable parallel execution
               -rtsopts \        # Enable run-time system flags +RTS
               -eventlog \       # Enable parallel profiling
               nfib1.hs
```

†This should be iterative, not recursive

Running the Program

```
$ TIMEFORMAT="real %Rs"         # for bash time builtin
$ time ./nfib1
331160281
real 9.984s
$ time ./nfib1 +RTS -N1         # +RTS = Run Time System, -N1 = 1 core
331160281
real 9.994s
$ time ./nfib1 +RTS -N4         # -N4 = use 4 cores
331160281
real 10.214s
$ time ./nfib1 +RTS -N4 -ls     # -ls = Record events in nfib1.eventlog
331160281
real 10.378s
```

ThreadScope

ThreadScope: the Haskell parallel execution event log viewer

Under Ubuntu, I was able to install it using Aptitude:

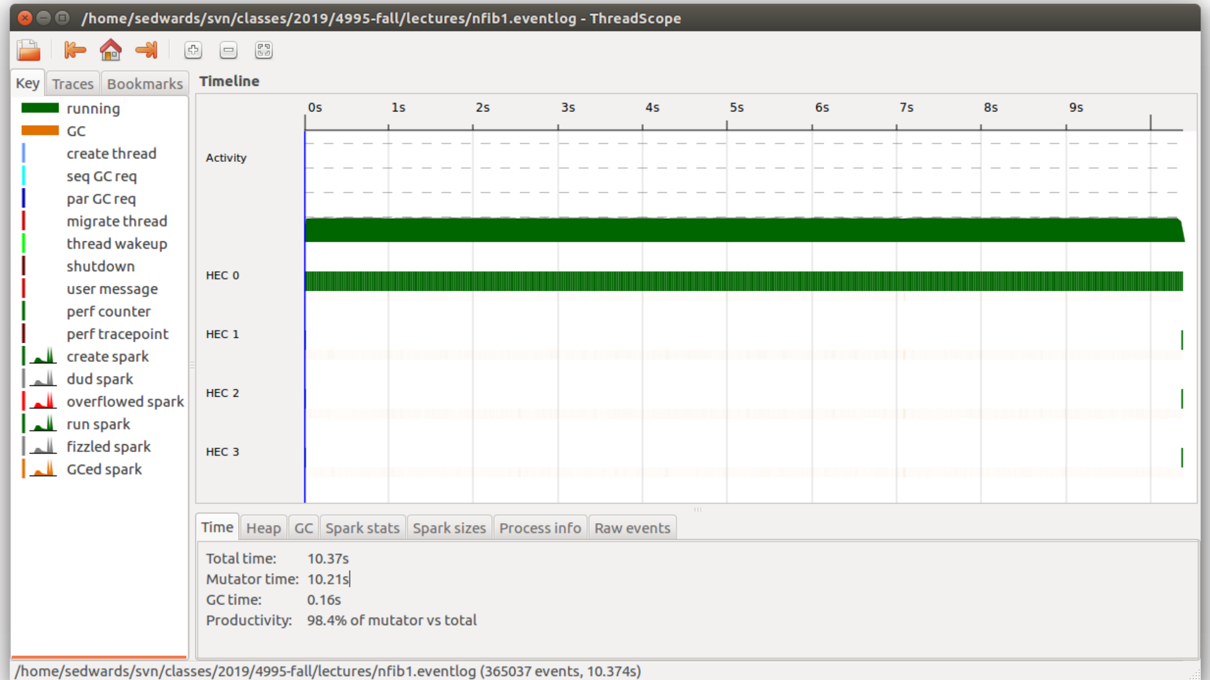
```
$ sudo apt install threadscope
```

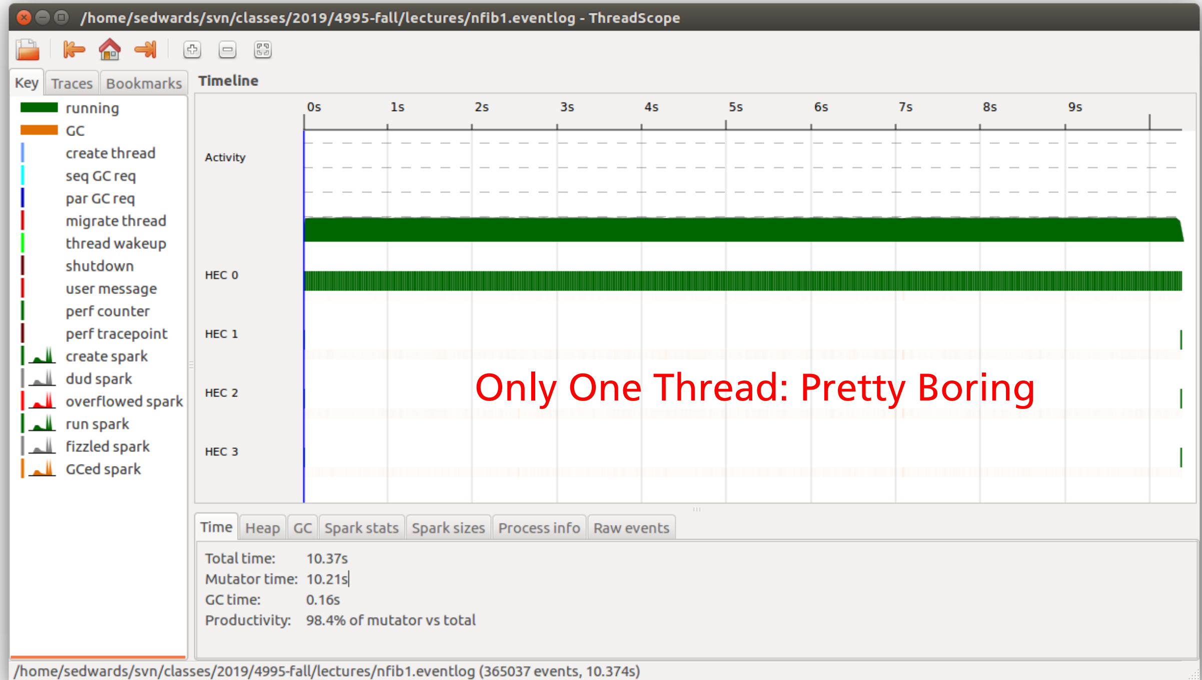
The Haskell stack may also be able to install it (`stack install threadscope`), but it didn't work automatically on my machine

A Haskell executable compiled with `-rtsopts` enables the `+RTS` ... `-RTS` syntax for passing arguments to the Haskell runtime system

The `-l` option enables event logging (in a binary file *executable*.eventlog); `s` includes scheduler events

Google "Haskell Runtime Control" or look in the GHC User Guide


/home/sedwards/svn/classes/2019/4995-fall/lectures/nfib1.eventlog - ThreadScope
Key
Traces
Bookmarks
Timeline
running
GC
create thread
seq GC req
par GC req
migrate thread
thread wakeup
shutdown
user message
perf counter
perf tracepoint
create spark
dud spark
overflowed spark
run spark
fizzled spark
GCed spark
0s
1s
2s
3s
4s
5s
6s
7s
8s
9s
Activity
HEC 0
HEC 1
HEC 2
HEC 3
Time
Heap
GC
Spark stats
Spark sizes
Process info
Raw events
Total time: 10.37s
Mutator time: 10.21s
GC time: 0.16s
Productivity: 98.4% of mutator vs total
/home/sedwards/svn/classes/2019/4995-fall/lectures/nfib1.eventlog (365037 events, 10.374s)


/home/sedwards/svn/classes/2019/4995-fall/lectures/nfib1.eventlog - ThreadScope
Key
Traces
Bookmarks
running
GC
create thread
seq GC req
par GC req
migrate thread
thread wakeup
shutdown
user message
perf counter
perf tracepoint
create spark
dud spark
overflowed spark
run spark
fizzled spark
GCed spark
Timeline
0s
1s
2s
3s
4s
5s
6s
7s
8s
9s
Activity
HEC 0
HEC 1
HEC 2
HEC 3
Only One Thread: Pretty Boring
Time
Heap
GC
Spark stats
Spark sizes
Process info
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Asking for Parallelism

In Control.Parallel, (`stack install parallel`)

```
par : a -> b -> b
```

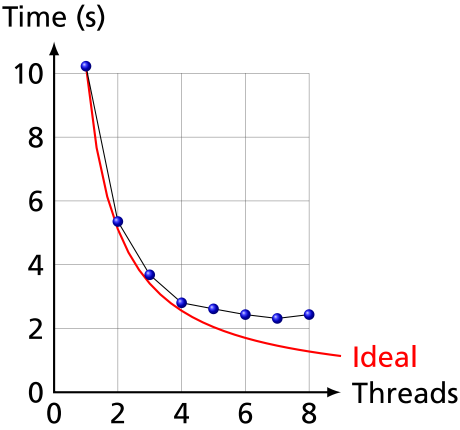
`par` *x y* “sparks” the evaluation of *x* in parallel with *y*; returns *y*.

The run-time system *may* convert a spark into work for a thread

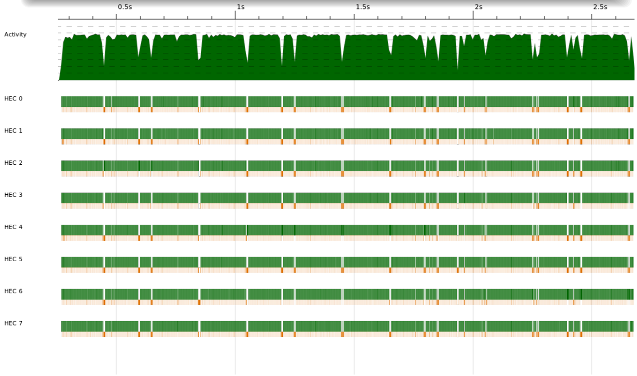
```
import Control.Parallel(par)

nfib2 :: Integer -> Integer
nfib2 n | n < 2 = 1
nfib2 n = par nf (nf + nfib2 (n-2) + 1)
  where nf = nfib2 (n-1)
```

Performance of nfib2 (using par)

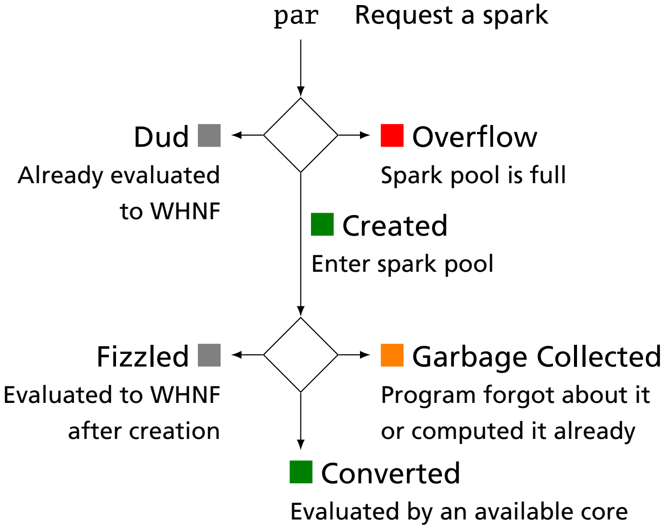



```
$ time ./nfib2 +RTS -N8 -ls
331160281
real 2.604s
```



A speedup of 7.44: Pretty good for a first try

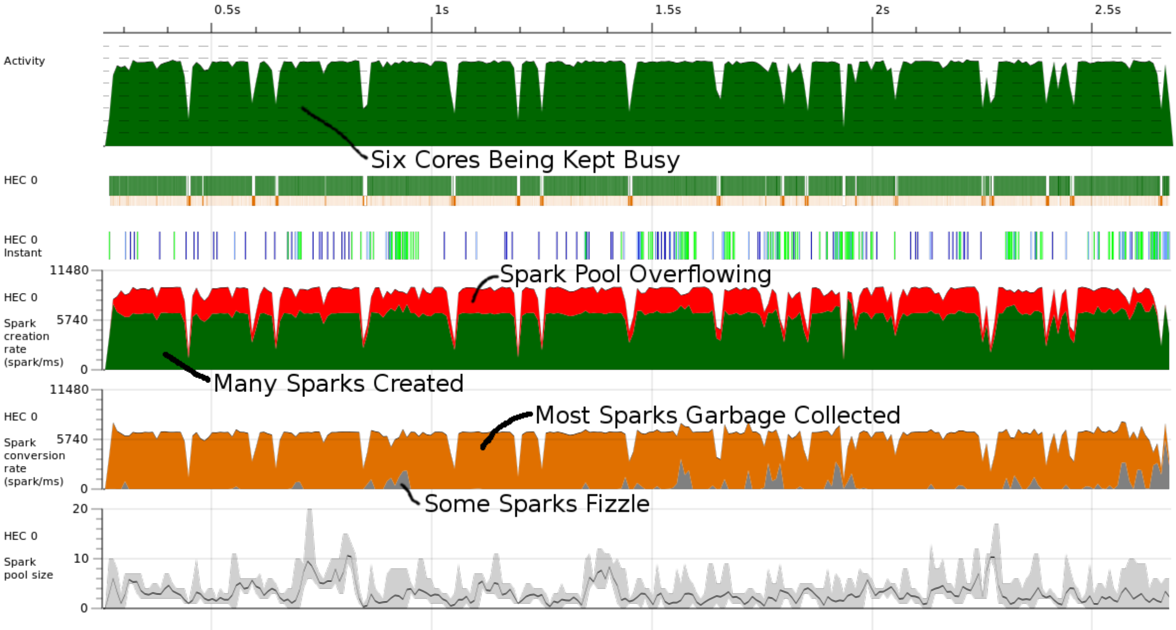
Sparks




```
$ ./nfib2 +RTS -N8 -s
331160281
SPARKS:
166651588 total
     1210 converted,
 47083668 overflowed,
        0 dud,
117359879 GC'd,
  2206831 fizzled
```

Conclusion: Far too many sparks created; majority were garbage collected; 25% didn't even fit in the spark pool. Only 1210 (0.0007%) did useful work.

From `https://wiki.haskell.org/ThreadScope_Tour`



0.5s
1s
1.5s
2s
2.5s
Activity
Six Cores Being Kept Busy
HEC 0
HEC 0
Instant
11480
HEC 0
Spark creation rate (spark/ms)
5740
0
Spark Pool Overflowing
Many Sparks Created
11480
HEC 0
Spark conversion rate (spark/ms)
5740
0
Most Sparks Garbage Collected
Some Sparks Fizzle
20
HEC 0
Spark pool size
10
0

Asking more precisely for parallelism

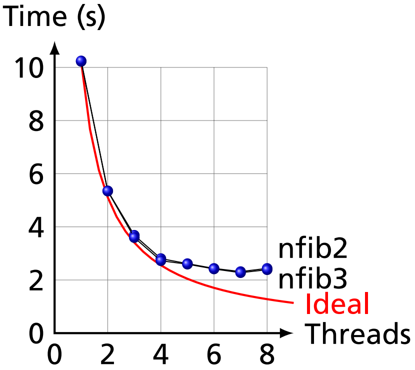
Also in Control.Parallel,

```
pseq : a -> b -> b
```

Like seq, but only strict in its first argument. pseq *x y* means "make sure *x* is evaluated before starting on *y*"

```
import Control.Parallel(par, pseq)

nfib3 :: Integer -> Integer
nfib3 n | n < 2 = 1
nfib3 n = nf1 `par` nf2 `pseq` nf1 + nf2 + 1
  where nf1 = nfib3 (n-1)
        nf2 = nfib3 (n-2)
```



No visible change in performance; the compiler may have automatically done this for us

Controlling Granularity

We are creating a *lot* of sparks, most of which are pointless:

```
./nfib3 +RTS -N8 -s
SPARKS: 168073361 (
             2351 converted,
         48159769 overflowed,
                0 dud,
        115072423 GC'd,
          4838818 fizzled)
```

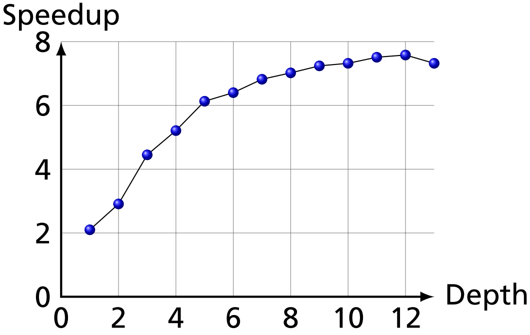
It doesn’t make sense to be creating 168 million pieces of work when we only have 8 cores on which to do work; only 2351 ever did useful work.

Idea: let’s go parallel only to a certain depth

Running Parallel to a Certain Depth

```
nfib4 :: Int -> Int -> Integer
nfib4 0 n          = nfib n
nfib4 _ n | n < 2 = 1
nfib4 d n = nf1 `par` nf2 `pseq`
            nf1 + nf2 + 1
  where nf1 = nfib4 (d-1) (n-1)
        nf2 = nfib4 (d-1) (n-2)

nfib :: Int -> Integer
nfib n | n < 2 = 1
nfib n = nfib (n-1) +
         nfib (n-2) + 1
```



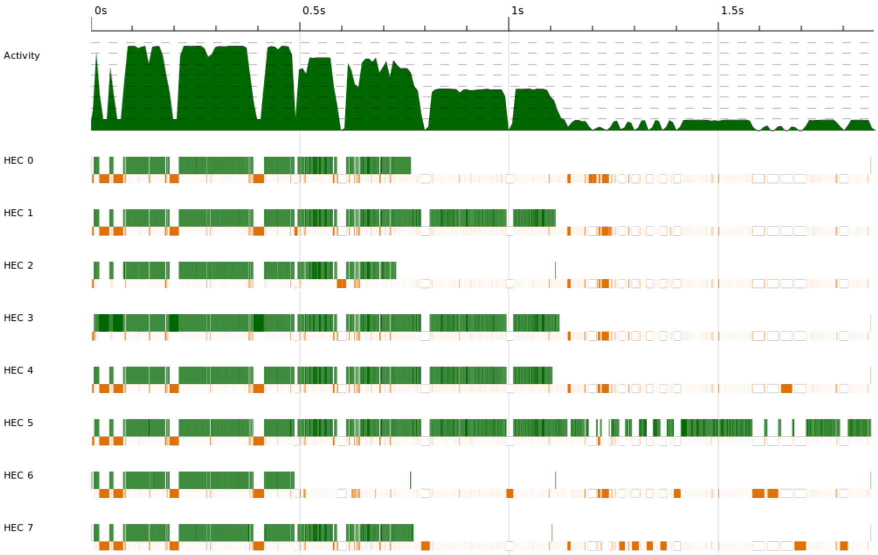
Computing nfib4 40 on an 8-thread i7

Depth	Sparks				Time (s)		Speedup
	total	converted	GC'ed	fizzled	total	elapsed	
1	1	1	0	0	8.00	3.80	2.10
2	3	3	0	0	6.80	2.34	2.91
3	7	7	0	0	8.83	1.98	4.45
4	15	12	0	2	7.89	1.51	5.21
5	31	19	0	11	7.58	1.24	6.13
6	63	30	0	32	8.14	1.27	6.40
7	127	39	0	87	8.62	1.26	6.82
8	256	48	1	206	7.51	1.07	7.02
9	511	78	0	432	7.57	1.05	7.24
10	1026	98	4	923	7.53	1.03	7.32
11	2052	162	49	1840	7.33	0.98	7.51
12	4106	160	436	3509	7.04	0.93	7.58
13	8226	249	2109	5867	7.62	1.04	7.32
25	30 833 310	2855	28 605 093	398 402	10.17	1.50	6.77

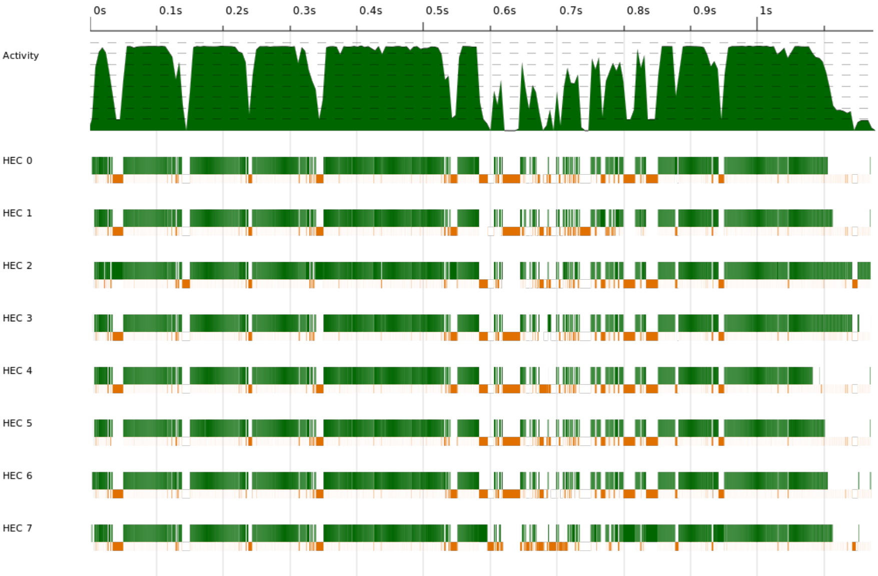
3.6 GHz 4-core, 8-thread i7-3820, `+RTS -N8 -s`, 4-run averages, `-O2 -threaded -rtsopts`

Depth = 1: Only two-way parallelism

Depth = 4: 16-way parallelism but unbalanced



Depth = 7: 32 sparks, better balancing



Depth = 12: 4000+ sparks, excellent balancing