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

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.

\[
\text{Prelude}> \text{let } x = 1 + 2 \text{ :: Int}
\]
\[
\text{Prelude}> :t \; x
\]
\[
\text{x :: Int}
\]
\[
\text{Prelude}> :\text{sprint} \; x
\]
\[
\text{x = _}
\]
\[
\text{Prelude}> x + 1
\]
\[
4
\]
\[
\text{Prelude}> :\text{sprint} \; x
\]
\[
\text{x = 3}
\]

_ 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: \texttt{seq} also forces evaluation

\begin{verbatim}
\texttt{seq :: a -> b -> b}
\texttt{seq x y = evaluate x and y; return y}
\end{verbatim}

Prelude> \texttt{let x = 1 + 2 :: Int}
Prelude> \texttt{let y = x + 1}
Prelude> \texttt{:sprint x}
x = _
Prelude> \texttt{:sprint y}
y = _
Prelude> \texttt{seq y ()}
()  
Prelude> \texttt{:sprint x}
x = 3  
Prelude> \texttt{:sprint y}
y = 4
\end{verbatim}

[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 = [_,_,_,_,_,_,_,_,_,_]
```

\[
\text{map} :: (a \rightarrow b) \rightarrow [a] \rightarrow [b]
\text{map } f \; [] = []
\text{map } f \; (x:xs) = \text{let } x' = f \; x
\quad \text{xs}' = \text{map } f \; \text{xs}
\quad \text{in } x' : \text{xs}'
\]

[Marlow, Figure 2–4]
Let’s Speed Up a Dumb† Program

\[
\text{nfib1 :: Integer } \rightarrow \text{ Integer} \\
nfib1 \ n \ | \ n < 2 = 1 \\
nfib1 \ n = nfib1 (n-1) + nfib1 (n-2) + 1 \\
\]

\[
\text{main :: IO ()} \\
\text{main = print (nfib1 40)} \\
\]

<table>
<thead>
<tr>
<th>(n)</th>
<th>(\text{nfib n})</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>177</td>
</tr>
<tr>
<td>20</td>
<td>21891</td>
</tr>
<tr>
<td>25</td>
<td>242785</td>
</tr>
<tr>
<td>30</td>
<td>2692537</td>
</tr>
<tr>
<td>35</td>
<td>29860703</td>
</tr>
<tr>
<td>40</td>
<td>331160281</td>
</tr>
</tbody>
</table>

\[
\text{$ \$ stack ghc -- -O2 \ \\
\text{-threaded \ \
\text{-rtsopts \ \
\text{-eventlog \ \
\text{nfib1.hs}}}
\]

# Optimize
# Enable parallel execution
# Enable run–time system flags +RTS
# Enable parallel profiling

†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: the Haskell parallel execution event log viewer

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

```bash
$ 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`); it includes scheduler events.

Google “Haskell Runtime Control” or look in the GHC User Guide.
Only One Thread: Pretty Boring
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

par Request a spark

Overflow Spark pool is full

Created Enter spark pool

Dud Already evaluated to WHNF

Created Entered spark pool

Fizzled Evaluated to WHNF after creation

Garbage Collected Program forgot about it or computed it already

Converted Evaluated by an available core

$ ./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
Asking more precisely for parallelism

Also in Control.Parallel,

\[
pseq : a \rightarrow b \rightarrow b
\]

Like \texttt{seq}, but only strict in its first argument. \texttt{pseq x y} means “make sure \texttt{x} is evaluated before starting on \texttt{y}”

\[
\text{import Control.Parallel(par, pseq)}
\]

\[
nfib3 :: \text{Integer} \rightarrow \text{Integer}
\]

\[
nfib3 \ n \mid n < 2 = 1
\]

\[
nfib3 \ n = \text{nf1 `par` nf2 `pseq` nf1 + nf2 + 1}
\]

\[
\text{where nf1 = nfib3 (n-1)}
\]

\[
nf2 = \text{nfib3 (n-2)}
\]

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

![Graph showing time (s) vs threads for nfib2 and nfib3. Ideal line indicates linear scaling with threads.](image)
Controlling Granularity

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

```bash
./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

\[
\text{nfib4 :: Int} \rightarrow \text{Int} \rightarrow \text{Integer} \\
nfib4 \ 0 \ n \ = \ \text{nfib} \ n \\
nfib4 \ - \ n \ | \ n < 2 = 1 \\
nfib4 \ d \ n = \text{nfl} \ `\text{par}` \ \text{nf2 `pseq`} \\
\quad \text{where} \ \text{nf1} = \text{nfib4} \ (d-1) \ (n-1) \\
\quad \text{nf2} = \text{nfib4} \ (d-1) \ (n-2) \\
\]

\[
\text{nfib :: Int} \rightarrow \text{Integer} \\
nfib \ n \ | \ n < 2 = 1 \\
nfib \ n = \text{nfib} \ (n-1) + \\
\quad \text{nfib} \ (n-2) + 1 \\
\]

Diagram:
- Vertical axis: Speedup
- Horizontal axis: Depth
- Title: Speedup Depth
- Note: Computing \text{nfib4 40} on an 8-thread i7
<table>
<thead>
<tr>
<th>Depth</th>
<th>Sparks</th>
<th>Time (s)</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>converted</td>
<td>GC’ed</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>63</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>127</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
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<tr>
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</tr>
<tr>
<td>10</td>
<td>1026</td>
<td>98</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>2052</td>
<td>162</td>
<td>49</td>
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<td>12</td>
<td>4106</td>
<td>160</td>
<td>436</td>
</tr>
<tr>
<td>13</td>
<td>8226</td>
<td>249</td>
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<tr>
<td>25</td>
<td>308333310</td>
<td>2855</td>
<td>28605093</td>
</tr>
</tbody>
</table>

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