Fun With Haskell: Fast Haskell

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Metadata
Overview of today

Today I want to give an overview of some of the plumbing used in at-scale Haskell programs.

- `bytestring` for chunked handling of strings.
- Builders (e.g. `blaze-builder`) for efficient construction of output.
- `conduit` package for managing streaming data.
  - (Replacement for `enumerator`.)

(In particular, all of these are used by Yesod.)

ByteString

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ByteString

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- Not a crazy goal: lots of bytes out there.

ByteString
What's wrong with String?

- Recall: `type String = [Char]`.
- What is `Char`, anyway?

```
> import Data.Char
> minBound :: Char
'\NUL'
> ord maxBound
1114111
```

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- What is *that*?
- `0x10FFFF`.

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    - It's great for what it is, but:
    - No canonical mapping to/from reality.

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- Recall: `type String = [Char]`.
- What is `Char`, anyway?
- It's an abstract *unicode code point*.
- Unicode is sort of a figment of everybody's imagination.
    - It's great for what it is, but:
    - No canonical mapping to/from reality.
- Importantly: it's not a byte.

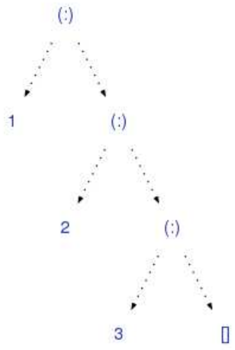
ByteString
What's wrong with `[Word8]`, then?

- Haskell has `Data.Word`.
- So: use `[Word8]`?
- What does a list look like, anyway?

ByteString

What's wrong with ***[Word8]****, then?*

Consider [1,2,3]:



- Each node here is a separate thing on the heap!
- Each arrow is a pointer, maybe with bad locality.
- *5 machine words* of data *for each byte*!

ByteString
What's wrong with `[Word8]`, then?

OW!

ByteString
What's wrong with `[Word8]`, then?

Probably fine for toy programs. What do we want for real?

- A structure with *good cache performance*:
- Amortize pointer overhead and chases by giving us lots of data each time.

ByteString
Strict ByteStrings

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- Maybe even a structure that doesn't use pointers internally?
- (Strict) Arrays!
- Since they're strings we also want offset and length information.
- Behold! A `Data.ByteString`:

```
data ByteString = PS
 {-# UNPACK #-} !(ForeignPtr Word8) -- payload
 {-# UNPACK #-} !Int                -- offset
 {-# UNPACK #-} !Int                -- length
```

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```

- Lots of fanciness we haven't covered (sorry!)
- But: this is essentially just what you'd do in C.
    - Pointer to memory
    - Current position
    - Total length
- Implemented using all kinds of neat IO tricks.
- Hidden behind a much nicer interface.

ByteString
Strict ByteStrings

- OK, scary stuff off the screen.
- `ByteStrings` are `Eq`, `Ord`, `Show`, so on.
- Constructors and destructors; `empty` and `singleton` and

```
pack :: [Word8] -> ByteString
unpack :: ByteString -> [Word8]
```

- API has everything we might want: maps, folds, search by `Word8`, search by substring, IO, etc.

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- Do a lot of copying to maintain purity.
- Suggestions for what we might do instead?
- List of array chunks!
- Behold: `Data.ByteString.Lazy`!

```
import qualified Data.ByteString.Internal as S
data ByteString =
   Empty
 | Chunk {-# UNPACK #-} S.ByteString ByteString
```

ByteString
Lazy ByteStrings

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data ByteString =
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```

- Ah ha, a *lazy* list of *strict* ByteString `Chunks`.

ByteString
Lazy ByteStrings

- Same API as last time, but different complexities for calls.
- Most $O(n)$ now down to $O(n/c + c)$.
- `length` a little more expensive, but that's OK.

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  - A strict `ByteString`: $O(n)$ copies of at least $O(n)$ data.
  - A list? $O(n)$ copies of $O(n)$ data.
  - A lazy `ByteString`? Also quadratic.

ByteString
Do these solve all our problems?

- Strict byte strings are *great* if you can get them.
  - They might stink to build, however.
  - Managing lots of long-lived ones might lead to leaks.
- Lazy byte strings a little better:
  - Stink a little less to build.
  - Can produce them chunk-at-a-time, lazily.
  - Can collect them in pieces.

ByteString
Do these solve all our problems?

- Often, really need to do lots of appends.
- Especially of small objects!
    - Implies a lot of copies of arrays and/or list spines.
- What are we to do?
    - Those imperative people are laughing at us. :(

Builder
Difference Lists

- Wait, we do have a trick up our sleeve!
- Function composition! :)

Builder
Difference Lists

- Why is (++) quadratic in the first place?
- Consider `x = ([1,2] ++ [3,4]) ++ [5]`.
- Recall (++):

```
(++) []     ys = ys
(++) (x:xs) ys = x : xs ++ ys
```

Builder
Difference Lists

```
(++) (x:xs) ys = x : xs ++ ys


(([1,2] ++ [3,4]) ++ [5])
(1:([2] ++ [3,4]) ++ [5])    -- visit 1
(1:2:([] ++ [3,4]) ++ [5])  -- visit 2
(1:2:[3,4] ++ [5])
1:(2:[3,4] ++ [5])           -- visit 1 again
1:2:([3,4] ++ [5])           -- visit 2 again
1:2:3:([4] ++ [5])           -- visit 3
1:2:3:4:([] ++ [5])          -- visit 4
1:2:3:4:[5]
```

Builder
Difference Lists

- So: want to avoid visiting things over and over.
- Try this:
  - Build a *function* which takes the "rest of the list" and returns the "whole list"
  - A *prefix-concatenation* function.
  - `:: [a] -> [a]`
- `[1,2] == (\t -> 1:2:t) []`

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  - `:: [a] -> [a]`
- `[1,2] == (\t -> 1:2:t) []`
- Easy to append:

```
append da db t = da (db t)
```

Builder
Difference Lists

- So what happens when we evaluate this one?

```
append (\t -> 1:2:t)
       (append (\t -> 3:4:t) (\t -> 5:t))
       x
```

- It turns out to be pretty quick!

```
append (\t -> 1:2:t)
       (append (\t -> 3:4:t) (\t -> 5:t))
       x
1:2:(append (\t -> 3:4:t) (\t -> 5:t) x)
1:2:3:4:((\t -> 5:t) x)
1:2:3:4:5:x
```

Builder

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- So, what did we want, again?
- Fast concatenation of small objects.
- But big buffers for amortization (e.g. syscalls).
- Builders capture this for us.

Builder

- There are a few lurking around Hackage.
- `blaze-builder` currently popular.
    - Provides `Blaze.ByteString.Builder` modules.
    - Uses UTF-8 encodings to get bytes.

- Once you have built your recipe, you run it with

```
toLazyByteString :: Builder -> ByteString
toByteString :: Builder -> ByteString
-- other, more fancy forms
```

Builder

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- `blaze-builder` currently popular.
  - Provides `Blaze.ByteString.Builder` modules.
  - Uses UTF-8 encodings to get bytes.
  - (Likely replaced by a new builder in the `bytestring` library in the next release.)
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Builder
Building Builders

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Builder
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- OK, so...
- Oh right, appending them.
- `Builder` is a `Monoid`, so use

```
mappend :: Monoid a => a -> a -> a
```

- or a `Writer` monad (transformer).

Builder
Building Builders

- Ah, getting one in the first place.
- `Blaze.ByteString.Builder.Char.Utf8`:

```
fromChar :: Char -> Builder
fromString :: String -> Builder
fromShow :: Show a => a -> Builder
```

- `Blaze.ByteString.Builder.Int`:

```
fromInt8 :: Int8 -> Builder
{- ... -}
fromInt64sle :: [Int64] -> Builder
```

- Other builtins, and mechanisms for adding your own.

Builder
Building Builders

BuilderTest.hs

```
import Data.Char
import Data.Monoid
import Blaze.ByteString.Builder
import Blaze.ByteString.Builder.Char.Utf8

main = print $ toByteString $
  fromString "I would like to show you: "
    `mappend`
  fromShow (6*5)
    `mappend`
  fromInt8 (fromIntegral $ ord '!')
```

More on This

If this has piqued your interest, and you want more detail:

- Real World Haskell [2, ch. 8,13].
- Simon Meier's Guided Tour Through The ByteString Library [1].
- Hackage documentation for `ByteString` and `blaze-builder`.
- The upcoming `ByteString-builder` in ByteString `0.10.0.0`.

Conduit
What are they?

"[a] solution to the streaming data problem" [3]. What's the problem?

- Imagine writing the `zgrep` tool.
- Need to read a chunk of compressed data, expand it, and grep through it.
- And: don't forget the boundary cases.
- Who thinks manual buffer management is fun? (more than once?)

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"[a] solution to the streaming data problem" [3]. What's the problem?

- Imagine writing the `zgrep` tool.
- Need to read a chunk of compressed data, expand it, and grep through it.
- And: don't forget the boundary cases.
- Who thinks manual buffer management is fun? (more than once?)
- Want, instead, a logical abstraction of streams of data:
  - grep asks the decompressor for data
  - the decompressor asks the file for data
  - Eventually, maybe, grep is done and closes the stream or the file ends.

Conduit
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  - Transformations in the middle: gzip, UTF-8 codec, ...
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  - All in a relatively simple API.

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  - Generic `Source` and `Sink` abstractions.
  - Transformations in the middle: gzip, UTF-8 codec, ...
  - *Deterministic* resource management (e.g. file descriptors)
  - All in a relatively simple API.
- Disclaimer: I am "borrowing" from Michael Snoyman's (the package author) blog. [4] and prior in the series.

Conduit
What are they?

Glossary:

- `Source`: whence data comes.
- `Sink`: whither data goes.
- `Conduit`: A (stateful) data manipulation function.
    - Looks like a sink on one side, and a source on the other.
- `Fuse`: The act of combining a conduit to ...
    - a source; results in a source. `($=)`
    - a sink; results in a sink. `(=$)`
    - a conduit; results in a conduit. `(=$=)`
- `Combine`: Joining a source and a sink `($$)`; causes data to flow until either (or both) are done.

Conduit
What are they?

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Conduit
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- Conduits might also!
- Want to close files as soon as we're done with them (don't want to wait for all references to go away and the GC to run "finalizers").
- Want to free resources on exceptions.
    - Including asynchronous exceptions, so we can kill off long-running threads by timeouts, etc.

Conduit
Sources

- Sources are relatively simple:

```
data SourceResult a = Open a | Closed
data PreparedSource m a = PreparedSource
  { sourcePull :: ResourceT m (SourceResult a)
  , sourceClose :: ResourceT m ()
  }
```

- Only two things you can do to `PreparedSources`:
  - Close the source
  - Ask for more data ("pull")

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- Only two things you can do to `PreparedSources`:
    - Close the source
    - Ask for more data ("pull")
- The source will respond to a pull either with data (`Open a`) or by signaling the end.

Conduit
Sources

Consider a source which forever returns the same piece of data:

```
repeat :: Monad m => a -> PreparedSource m a
repeat a = PreparedSource
  { sourcePull = return $ Open a
  , sourceClose = return ()
  }
```

What would the source `eof` which never returned any data look like?

Conduit
Sources

Invariants of the system for `Sources`

- Won't ask for another pull after one returns `Closed`.
- Don't close a source after it has said it was closed.
- Don't close a source multiple times.

(These invariants are not enforced but may be assumed by all `Sources` and should be maintained by all other bits of code.)

Conduit
Sources with State

- The source "methods" are monadic actions.
- Suppose we want a source which streams all Nats:
- Make a `PreparedSource` that closes over an `IORef`:

```
mkNatSource = do
  r <- newRef 0 -- provided by ResourceT
  return $ PreparedSource
         { sourceClose = return ()
         , sourcePull = do
             next <- readRef r
             writeRef r (next+1)
             return next
         }
```

Conduit
Sources with State

- Very frequently have a monadic action to make a `PreparedSource`.
- Conduit calls these actions Sources:

```
newtype Source m a = Source
  { prepareSource :: ResourceT m
                       (PreparedSource m a) }
```

- So should have

```
mkNatSource = Source $ do
    {- ... -}
```

Conduit
Sources with State

- Utility function for stateful sources:

```
sourceState :: Resource m
  => state
  -> (state -> ResourceT m (state
                           ,SourceResult output))
  -> Source m output
```

- And one for IO state:

```
sourceIO :: ResourceIO m
  => IO state              -- open
  -> (state -> IO ())      -- close
  -> (state -> m (SourceResult output))
  -> Source m output
```

Conduit
Sources with State

These curious `ResourceT` and such are how `conduit` manages to track and free resources.

- Register some cleanup action:

```
register :: IO () -> ResourceT IO ReleaseKey
```

- Explicitly call some cleanup (guaranteed to happen at most once):

```
release :: ReleaseKey -> ResourceT IO ()
```

- Run a computation ensuring that everything gets released:

```
runResourceT :: ResourceT IO a -> IO a
```

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```

- (Actually more polymorphic than slideware allows)

Conduit
Sinks

- OK, now we can produce data.
- Could actually use sources directly in monadic code (call `sourcePull` and `sourceClose` ourselves).
- Sinks take a *stream of input* and produce *exactly one output*.
- As with sources, sinks can be in two states:

```
data SinkResult in out =
   Processing
 | Done (Maybe in) out
```

- (When it's `Done` it may have some input left over.)

Conduit
Sinks

- Sinks come in one of two flavors:

```
data PreparedSink in m out =
    SinkNoData out
  | SinkData
    { sinkPush :: in
               -> ResourceT m (SinkResult in out)
    , sinkClose :: ResourceT m out
    }
```

- Some sinks are trivial and need no data.
- The rest need to be fed some input.
    - May return a result before the end of the stream.
    - Obligated to return a result when the stream ends.

Conduit
Sinks

- And, as before, a Sink is really a monadic computation returning a prepared Sink:

```
newtype Sink in m out = Sink
  { prepareSink :: ResourceT m
                   (PreparedSink in m out) }
```

Conduit
Sinks

A simple sink which counts the number of inputs:

```
count = Sink $ do
  r <- newRef 0
  return $ PreparedSink
         { sinkClose = readRef r
         , sinkPush _ = do
             n <- readRef r
             writeRef r (n+1)
             return Processing
         }
```

Conduit
Sinks

- Helpers for state state and IO. e.g.:

```
sinkState :: Resource m
  => s
  -> (s -> in -> ResourceT m
                (s, SinkResult in out))
  -> (s -> ResourceT m out)
  -> Sink in m out
```

- So:

```
count' = sinkState 0
  (\s _ -> return (s+1,Processing))
  (\s -> return s)
```

Conduit
Sinks

- The `Data.Conduit.List` module provides a useful source:

```
sourceList :: Resource m => [a]
                         -> Source m a
```

- and many useful sinks, such as

```
fold :: Resource m => (b -> a -> b)
                   -> b -> Sink a m b
take :: Resource m => Int -> Sink a m [a]
drop :: Resource m => Int -> Sink a m ()
```

Conduit
Sinks

And (ta-da): `Sinks` are `Monads`!

- What does that even mean?

Conduit
Sinks

And (ta-da): `Sinks` are `Monads`!

- What does that even mean?
- It means we can compose sinks together!

SinkMonadEx.hs

```
import Data.Conduit.List as CL
foo b = do
  xs <- CL.take 5
  CL.drop 5
  CL.fold (+) (foldr (*) b xs)
```

Conduit
Combining Sources and Sinks

A first example: sum up the entries in a list. (`ConduitSumList.hs`)

- Source: `sourceList`.
- Sink:

```
sinkSum = CL.fold (+) 0
```

- Glue them together with `($$)`:

```
pipe l = sourceList l $$ sinkSum
```

- Then run it:

```
main = runResourceT $ (pipe [1,2,3])
        >>= print
```

Conduit
Conduits

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Conduit
Conduits

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- Maybe
    - Read from a file.
    - Decode UTF-8.
    - Chunk file into lines.
    - Accumulate each Int into the total
    - Write the stream of totals to file.

Conduit
Conduits

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- Maybe
    - Read from a file.
    - Decode UTF-8.
    - Chunk file into lines.
    - Accumulate each Int into the total
    - Write the stream of totals to file.
- Middle three stages are *data transformers*, or `Conduits`.

Conduit
Conduits

Let's look at the types:

```
data ConduitResult i o =
   Producing [o] | Finished (Maybe i) [o]

data PreparedConduit i m o = PreparedConduit
  { conduitPush :: i
                -> ResourceT m (ConduitResult i o)
  , conduitClose :: ResourceT m [o] }

newtype Conduit i m o = Conduit
  { prepareConduit :: ResourceT m
                        (PreparedConduit i m o) }
```

Conduit
Conduits

- A pass-through conduit is straightforward:

```
pt = Conduit $ return $ PreparedConduit
  { conduitPush = \i -> return (Producing [i])
  , conduitClose = return [] }
```

- So is a one-to-one mapper:

```
mapM f = Conduit $ return $ PreparedConduit
  { conduitPush = \i -> do
        fi <- lift $ f i
        return (Producing [fi])
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```

- Available as `map` in `Data.Conduit.List`.

Conduit
Conduits

- But conduits may produce many outputs for a given input:
    - Consider taking a stream of strings and producing a stream of characters.
- Or may require many inputs for a given output.
    - Such as a filter

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    - Consider taking a stream of strings and producing a stream of characters.
- Or may require many inputs for a given output.
    - Such as a filter
- That's why they produce *lists* of output.

Conduit
Conduits

- Even better: conduits can maintain *state*.
- And we have the usual helper functions `conduitState` and `conduitIO`.
- And, of course, the libraries often save us.
- Longer, out-of-slide example: `ConduitSumFile.hs`

Conduit
Buffered Sources

Summary of the world thus far:

- Traditional I/O monad:
  - Open a file.
  - Read a line from the file.
  - Do something to that line and adjust state.
  - Do those for a while.
  - Close the file.
- Conduits:
  - Write a custom sink, source, or conduit.
  - Glue it into a pipeline.
  - Run the pipeline.

Conduit
Buffered Sources

But there's a problem:

- Go back to our easier example:

```
pipe l = sourceList l $$ sinkSum
```

- What if `sinkSum` stops after, say, the sum is ≥ 5?

Conduit
Buffered Sources

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Conduit
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Conduit
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- What if `sinkSum` stops after, say, the sum is ≥ 5?
- There might be stuff left in the list!
- Maybe even stuff we care about!
- How do we get at it?

Conduit
Buffered Sources

Enter `BufferedSources`.

```
data BufferedSource m a = BufferedSource
  { bsourcePull :: ResourceT m (SourceResult a)
  , bsourceUnpull :: a -> ResourceT m ()
  , bsourceClose :: ResourceT m ()
    }
```

- Just like sources, but now with *unpull*.

Conduit
Buffered Sources

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```

- Just like sources, but now with *unpull*.
- Puts things back so that they will be read next.

Conduit
Buffered Sources

- If we run two pipelines on a buffered source,
- And the first stops early,
- We'll get the left-over data on the second.

```
runResourceT $ do
    bsrc <- bufferSource $ sourceList [1,2,3]
    bsrc $$ drop 2
    x <- bsrc $$ take 1
    print x
```

Next time

- Web development using Yesod.
  - I will send out instructions tonight for bringing the stack up to “hello world” stage.
  - (I will also bring enough power strips to class for everybody to plug in.)
- Intended to be a mixture of lecture and workshop.
  - Rough plan: walk through mechanics of Yesod.
  - Then you guys group up or work alone and I float around answering questions.
- Seem reasonable?

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