Parallelism and concurrency in Haskell

David Luposchainsky

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Concurrency vs. parallelism

Parallelism

- ► Goal: speedup
- ► Orthogonal to correctness
- Comparatively simple

Concurrency

- ▶ Affects logical structure of a program
- ▶ Heavily interleaved with correctness
- Often very complicated

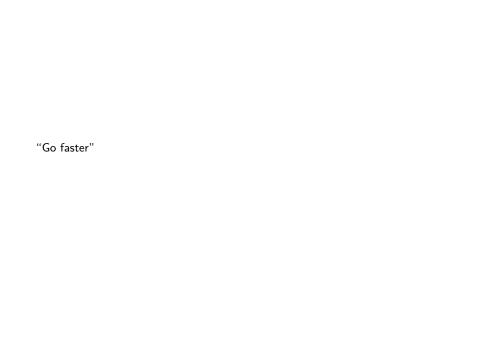
Talk outline

1. Parallelism

Excellent case for laziness

- 2. Concurrency with forks and mutable state Nice abstractions, language agnostic
- Transactional memory
 Unique to Haskell, envied by everyone else





Checking primes

```
Problem: find primes in a list (e.g. for crypto)
isPrime :: Natural -> Bool

filterPrime :: [Natural] -> [Natural]
filterPrime = filter isPrime

primesBetween lo hi = filterPrime [lo..hi]
```

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primesBetween lo hi = filterPrime [lo..hi]

Unfortunately, this won't parallelize well.
```

map is simple enough to parallelize (why?). Can we use that fact?

primesBetween lo hi = filterPrime [lo..hi]

What's in the list?

```
map (\n -> (isPrime n, n))
     (take 1e5 [1e10..])
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Thunks! Literally function applications of the lambda.

```
map (\n -> (isPrime n, n)) [1,2,3] = [ (\n -> (isPrime n, n)) 1 , (\n -> (isPrime n, n)) 2 , (\n -> (isPrime n, n)) 3 ]
```

Forcing

- ightharpoonup = Evaluation to a certain degree (e.g. WHNF)
- ▶ Primitive task that allows parallelism
- "I'll probably need this, so maybe evaluate it"

Evaluation strategies

```
-- Control.Parallel.Strategies
-- A way to evaluate 'a's
type Strategy a = a -> Eval a
withStrategy :: Strategy a -> (a -> a)
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r0 :: Strategy a -- "NOOP"
rseq :: Strategy a -- Sequential forcing
rpar :: Strategy a -- Parallel forcing
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-- Primitives
r0 :: Strategy a -- "NOOP"
rseq :: Strategy a -- Sequential forcing
rpar :: Strategy a -- Parallel forcing
-- Combining functions
evalList :: Strategy a -> Strategy [a]
evalTraversable :: Traversable t => Strategy a -> Strategy (t a)
evalTuple2 :: Strategy a -> Strategy b -> Strategy (a,b)
```

```
filterPrime =
   map snd . filter fst . map (\n -> (isPrime n, n))
   --
   -- List of thunks we'd like to force in parallel
```

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filterPrime =
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filterPrimeParallel =
    map snd . filter fst . parallelize . map (\n -> (isPrime n, n))
```

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filterPrime =
    map snd . filter fst . map (\n -> (isPrime n, n))
    -- List of thunks we'd like to force in parallel
filterPrimeParallel =
    map snd . filter fst . parallelize . map (\n -> (isPrime n, n))
 where
    parallelize :: [(a, b)] -> [(a, b)]
    parallelize = withStrategy tupleFstList
    tupleFstList :: Strategy [(a, b)]
    tupleFstList = parList parFst
    parFst :: Strategy (a,b)
    parFst = parTuple2 rseq r0
```

```
filterPrime =
    map snd . filter fst . map (\n \rightarrow (isPrime n, n))
    -- List of thunks we'd like to force in parallel
filterPrimeParallel =
    map snd . filter fst . parallelize . map (\n -> (isPrime n, n))
  where
    parallelize :: [(a, b)] -> [(a, b)]
    parallelize = withStrategy tupleFstList
    tupleFstList :: Strategy [(a, b)]
    tupleFstList = parList parFst
    parFst :: Strategy (a,b)
    parFst = parTuple2 rseq r0
filterPrimeParallel =
    map snd . filter fst . parallelize . map (\n -> (isPrime n, n))
  where
    parallelize = withStrategy (parList (parTuple2 rseq r0))
```

Demo

```
. ./run
[1 of 1] Compiling Main ( Primes.hs, Primes.o )
Linking Primes ...
Running sequentially
45.38 s
Running in parallel
16.37 s
```

Recap

 ${\tt Control.Parallel}\ for\ easy\ parallelism:$

- 1. Define strategy according to your needs
- 2. Apply strategy, done

Threads are cheap

- Couple of hundred (heap) bytes per thread
- ► Literally millions are possible
- Don't be afraid of using them!

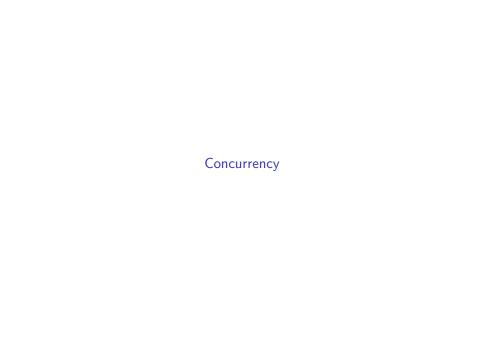
>>> time ./Main.hs 1000000 Forking 1000000 threads Start the counting cascade

Counter: 1000000

./Main.hs 1000000 4,57s user 0,50s system 100% cpu 5,032 total

Other parallelism libraries

- monad-par: Explicit dataflow networks for complicated (pure) computations
- ▶ **speculation**: the one-liner to solve all pure speculative parallelism needs



Basic primitives

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Basic primitives

```
-- Threads
forkIO :: IO () -> IO ThreadId
forkFinally :: IO a
            -> (Either SomeException a -> IO ())
            -> IO ThreadId
-- Futures/promises
async :: IO a -> IO (Async a)
wait :: Async a -> IO a
-- Inter-thread communication
data MVar a
newMVar :: a -> IO (MVar a)
takeMVar :: MVar a -> IO a
putMVar :: a -> MVar a -> IO ()
```

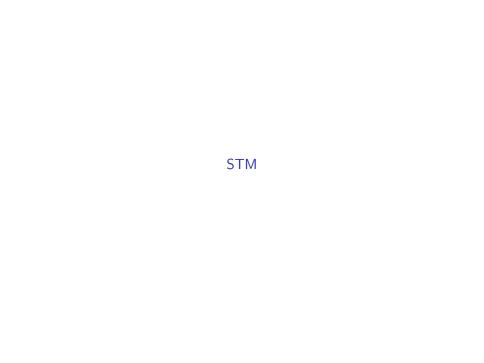
Example: network service

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```
main :: TO ()
main = do
    numClients <- newMVar 0
    forever (do
        connection <- listenOn (Port 8080)
        forkFinally (\_ -> close connection)
                     (handleClient numClients connection) )
handleClient :: MVar Integer -> Handle -> IO ()
handleClient numClients connection = do
    modifyMVar numClients (+1)
    getHttpMethod connection >>= \case
        Head -> ...
        Get -> ...
        Delete -> ...
    modifyMVar numClients (subtract 1)
```

Higher abstractions

- ► Channels: queues built with MVars
- ► Semaphores: more flexible locking
- ► Concurrent data structures



Transactional memory

```
modifyMVar :: (a -> a) -> MVar a -> IO ()
modifyMVar f mVar = do
   value <- takeMVar mVar
   putMVar mVar (f value)</pre>
```

Transactional memory

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modifyMVar :: (a -> a) -> MVar a -> IO ()
modifyMVar f mVar = do
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```

What happens when another thread fills the MVar between the take and put?

MVar API

```
data IO a
instance Monad TO where ...
data MVar a
newMVar :: a -> IO (MVar a)
takeMVar :: MVar a -> IO a
putMVar :: MVar a -> a -> IO ()
modifyMVar :: (a -> a) -> MVar a -> IO () -- Dangerous
block
       :: IO a
whenBlockedThen :: IO a -> IO a -> IO a
throw :: Exception e => e -> IO a
catch :: Exception e \Rightarrow IO \ a \rightarrow (e \rightarrow IO \ a) \rightarrow IO \ a
```

TVar API

```
data STM a
instance Monad STM where ....
data TVar a
newTVar :: a -> STM (TVar a)
takeTVar :: TVar a -> STM a
putTVar :: TVar a -> a -> STM ()
modifyTVar :: (a -> a) -> TVar a -> STM ()
retry :: STM a
orElse :: STM a -> STM a -> STM a
throwSTM :: Exception e => e -> STM a
catchSTM :: Exception e => STM a -> (e -> STM a) -> STM a
atomically :: STM a -> IO a
```

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retry :: STM a
orElse :: STM a -> STM a -> STM a
throwSTM :: Exception e => e -> STM a
catchSTM :: Exception e => STM a -> (e -> STM a) -> STM a
atomically :: STM a -> IO a
modifyTVar :: (a -> a) -> TVar a -> STM ()
modifyTVar f tVar = do
    value <- readTVar tVar
    writeTVar tVar (f value)
```

How does it work?

- STM actions write to a log of changes
- ▶ atomically attempts to commit the log
- ▶ Changed circumstances lead to retrying the action
- ► Repeat until successful

Should I use STM?

Pros

- ▶ No deadlocks by design
- ► Guaranteed atomicity

Cons

- ► Livelocks still possible
- Stampending herd
- ► No fairness guarantees
- ▶ Long transactions undesirable



'I think this is the answer		
so I'll continue with that assump and verify it in parallel"	tion	

... is a one-liner

spec :: Eq a => a -> $(a \rightarrow b) \rightarrow a \rightarrow b$ spec g f a = let s = f g in s `par` if g == a then s else f a in spec ... is a one-liner

```
spec :: Eq a => a -> (a \rightarrow b) \rightarrow a \rightarrow b
spec g f a = let s = f g in s `par` if g == a then s else f a in spec
```

- par is an old version of rpar from Control.Parallel
- Implemented by Edward Kmett
- ▶ ...after reading a 12-page paper attempting the same in C#
- ...in a Reddit comment

Add two minor modifications,

spec = specBy (==)

- ▶ Parametrize over the equality function
- ► No speculation with only one thread

```
-- Copied verbatim from the `speculation` package

specBy :: (a -> a -> Bool) -> a -> (a -> b) -> a -> b

specBy cmp guess f a

| numCapabilities == 1 = f $! a
| otherwise = speculation `par`

if cmp guess a

then speculation
else f a

where speculation = f guess

spec :: Eq a => a -> (a -> b) -> a -> b
```

How does it work?

- ► Threads are heap objects
- ► Heap objects are tracked by the GC
- Obsolete threads are simply GC'd
- ▶ Fork as long as you have memory and CPU free

Things not covered

- Exceptions
- Debugging
- ▶ async library
- ▶ FFI integration ▶ Distributed processes
- Data parallel computations
- ▶ GPGPU
- ▶ Other semiautomatic parallelization libs

