Parallelism and concurrency in Haskell

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Introduction

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
3. **Transactional memory**
   Unique to Haskell, envied by everyone else

Parallelism

“Go faster”

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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Unfortunately, this won't parallelize well.

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

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```
isPrime :: Natural -> Bool

filterPrime :: [Natural] -> [Natural]
filterPrime = map snd . filter fst . map (\n -> (isPrime n, n))
           -- `isPrime` isolated in `map` argument
           -- (using the decorate-operation-undecorate idiom)

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```

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

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

Evaluation strategies

```haskell
-- Control.Parallel.Strategies

-- A way to evaluate 'a's
type Strategy a = a -> Eval a
withStrategy :: Strategy a -> a -> a

-- 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)
```

Back to primes

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

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```haskell
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    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
```

Back to primes

```haskell
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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

`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!

```
. ./run
Creating thread ring of size 3000000
Passing token 3000000 times
1
Time taken: 11.46 s
```

Other parallelism libraries

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

Concurrency

Basic primitives

```haskell
forkIO :: IO () -> IO ThreadId

-- Inter-thread communication
data MVar a
newMVar  :: a -> IO (MVar a)
takeMVar :: MVar a -> IO a
putMVar  :: a -> MVar a -> IO ()
```

MVar

- “Mutable variable”
- “Lock with data attached to it”
- Fully lazy, fully polymorphic
- Either full or empty
- Potentially blocking
  - write to full MVar
  - reading from empty MVar

Example: network service

```
main :: IO ()
main = do
    numClients <- newMVar 0
    forever (do
        connection <- listenOn (Port 8080)
        forkIO (handleClient numClients connection) )

modifyMVar :: (a -> a) -> MVar a -> IO ()
modifyMVar f mVar = do
    v <- takeMVar mVar
    putMVar mVar $! f v

handleClient :: MVar Integer -> Handle -> IO ()
handleClient numClients connection =
    modifyMVar numClients (+1)
    getHttpMethod connection >>= \case
        Head -> respond connection "I'm not RFC compliant weee\r\n\r\n"
        Get -> ...
        Delete -> ...
        ...
    modifyMVar numClients (subtract 1)
    close connection
```

Higher abstractions

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

Shortcomings of forkIO

- Silent exceptions
- Returning values from forks is awkward
- Locks are hard to use, no atomicity guarantees

STM

Transactional memory

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

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

MVar API

```
data IO a -- abstract
instance Monad IO where ...

data MVar a -- abstract
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 -- doesn't exist, but might be handy sometimes
whenBlockedThen :: IO a -> IO a -> IO a -- dito

throw :: Exception e => e -> IO a
catch :: Exception e => IO a -> (e -> IO a) -> IO a
```

TVar API

```haskell
data STM a -- abstract
instance Monad STM where ...

data TVar a -- abstract
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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data STM a -- abstract
instance Monad STM where ...

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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 then 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

Speculative parallelism

“I think this is the answer

so I’ll continue with that assumption

and verify it in parallel”

… is a one-liner

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

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```haskell
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```

- 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#
- … written as a no-brainer one-liner in a Reddit comment

Add two minor modifications,

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

```haskell
-- 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
spec = specBy (==)
```

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

Questions?