Haskell - Concurrency and parallelism

Functional Programming

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Spring 2018

Outline

Parallelism and concurrency

Lightweight threads

STM

Data parallelism and Futhark

Concurrency

Definition: **code is split up and executed out-of-order**

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Disadvantage:

1. Race-conditions
2. Deadlocking
3. Starvation

Definition: **code is split up and executed *at the same time***

Parallelism

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Code can thus be *concurrenc* but not *parallel*. What is an example?

Concurrency vs. parallelism

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- Concurrency is when many things are happening in random order
- Parallelism is when many things happen at the same time

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- Parallelism is when many things happen at the same time

Problems of concurrency

- Not always *deterministic*
- Complicated to keep track of data flow
- Sometimes depending on concurrent processes (idle locks)

Correct parallelism is

- Deterministic (same outcome)
- High-level declarative (does not deal with synchronisation or communication)

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Haskell provides tons of tools for this

- Par Monad
- Eval Monad
- MVars
- IO Manager
- Asynchronous exceptions
- Software Transactional Memory (STM)
- Lightweight threads

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- Par Monad
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- IO Manager
- Asynchronous exceptions
- **Software Transactional Memory (STM)**
- **Lightweight threads**

- Lastly: Data parallelism and Futhark

Credits

A lot of the material in these slides have been borrowed from a course on parallel functional programming on Copenhagen University. Especially from slides on Haskell by Ken Friis Larsen.

Some of the material is also borrowed from the book on Parallel and Concurrent Programming in Haskell:
`http://shop.oreilly.com/product/0636920026365.do`

In Java:

```
import java.util.Thread;
Thread t = new Thread(() -> ...);
```

Lightweight threads

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import java.util.Thread;
Thread t = new Thread(() -> ...);
```

In Haskell:

```
import Control.Concurrent
-- forkIO :: IO () -> IO ThreadId

main = do
  threadId <- forkIO $ putStrLn "FP rocks!"
```

Communicating with Threads

Same problem as in Java: How would you get data in/out of a thread?

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Solution: external variables!

An `MVar` is exactly that: a *atomic* variable.

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```
data MVar a -- abstract

newEmptyMVar :: IO (MVar a)
readMVar :: MVar a -> IO a
takeMVar :: MVar a -> IO a
putMVar :: MVar a -> a -> IO ()
```

Threads example

```haskell
getURL :: String -> IO String
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```

```haskell
main = do
  m1 <- newEmptyMVar
  m2 <- newEmptyMVar
  forkIO $ do
    r <- getURL "http://www.wikipedia.org/wiki/Shovel"
    putMVar m1 r
  forkIO $ do
    r <- getURL "http://www.wikipedia.org/wiki/Spade"
    putMVar m2 r
  r1 <- takeMVar m1
  r2 <- takeMVar m2
  return (r1,r2)
```

```haskell
data Async a = Async (MVar a)

async :: IO a -> IO (Async a)
async action = do
  var <- newEmptyMVar
  forkIO $ action >>= putMVar var
  return $ Async var

wait :: Async a -> IO a
wait (Async var) = readMVar var
```

```haskell
main = do
  a1 <- async $
    getURL "http://www.wikipedia.org/wiki/Shovel"
  a2 <- async $
    getURL "http://www.wikipedia.org/wiki/Spade"
  r1 <- wait a1
  r2 <- wait a2
  return (r1,r2)
```

Using the async pattern

```haskell
main = do
  a1 <- async $
    getURL "http://www.wikipedia.org/wiki/Shovel"
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    getURL "http://www.wikipedia.org/wiki/Spade"
  r1 <- wait a1
  r2 <- wait a2
  return (r1,r2)
```

```haskell
getURLs :: [String] -> IO [ByteString]
getURLs sites =
  mapM (async.getURL) sites >>= mapM wait
```

Concurrency problems

Remember the concurrency problems:

1. Race-conditions
2. Deadlocking
3. Starvation

What is the root of these problems?

Parallel problems

In parallel computing we generally face two problems:

- Granularity
- Data dependency

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Solution: Think of parallelism as a series of transactions

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1. storing the current state of affairs

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Software Transactional Memory

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4. commit change if success

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This is a genious use case for monads: our monad simply *is* the state

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```haskell
import Control.Concurrent.STM

data STM a -- abstract
instance Monad STM -- among other things

atomically :: STM a -> IO a
retry :: STM a
orElse :: STM a -> STM a -> STM a

data TVar a -- abstract
newTVar :: a -> STM (TVar a)
readTVar :: TVar a -> STM a
writeTVar :: TVar a -> a -> STM ()
```

STM example: Banking

```haskell
type Amount = Int
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transfer from to amount = atomically $ do
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```haskell
deposit :: Account -> Amount -> STM ()
deposit account amount = do
  balance <- readTVar account
  writeTVar account $ balance + amount
withdraw :: Account -> Amount -> STM ()
withdraw account amount = deposit account (- amount)
```

STM example: Banking 2

```haskell
limitedWithdraw :: Account -> Amount -> STM ()
limitedWithdraw account amount = do
  balance <- readTVar account
  if amount > 0 && amount > balance
    then retry
    else writeTVar account $ balance - amount
```

```haskell
limitedWithdraw :: Account -> Amount -> STM ()
limitedWithdraw account amount = do
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  if amount > 0 && amount > balance
    then retry
    else writeTVar account $ balance - amount
```

```haskell
backupWithdraw :: Account -> Account -> Amount -> STM (
backupWithdraw acc1 acc2 amt =
  (limitedWithdraw acc1 amt)
    `orElse`
  (limitedWithdraw acc2 amt)
```

Performance

Threads and STM still have performance problems

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What about GPU acceleration you say?

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Solution: Data parallelism

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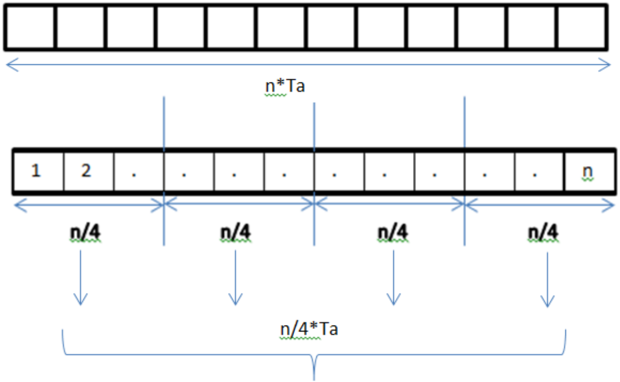
Task parallelism: Break problem into small parts, delegate to threads

Data parallelism: Break data into small parts, delegate to threads

Work versus span



Work: The amount of instructions to do, assuming a single PU
Span: The longest series of instructions, assuming infinite PU

Using data parallelism

$$\underbrace{\begin{pmatrix}1 & 2 & 3\\ 4 & 5 & 6\\ 1 & 3 & 2\end{pmatrix}}_{3 \times 3}\underbrace{\begin{pmatrix}10 & 11\\ 7 & 5\\ 2 & 4\end{pmatrix}}_{3 \times 2} = \underbrace{\begin{pmatrix}1*10+2*7+3*2 & 1*11+2*5+3*4\\ 4*10+5*7+6*2 & 4*11+5*5+6*4\\ 1*10+3*7+2*2 & 1*11+3*5+2*4\end{pmatrix}}_{3 \times 2}$$

We can compute one cell at the time, giving $O(n^3)$

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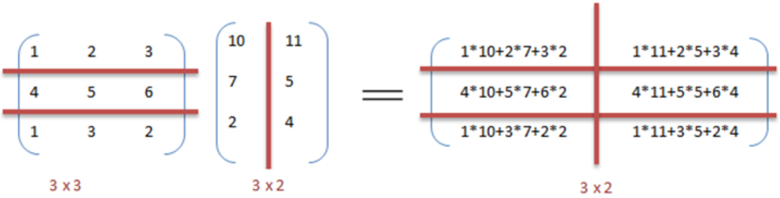

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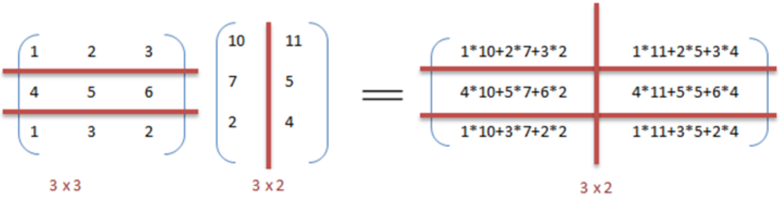
Or we can compute all cells in parallel, giving $O(1)$



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Or we can compute all cells in parallel, giving $O(1)$ (span)

GPU acceleration

This is similar to the Single Instruction Mulitiple Data `SIMD` idea

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Used in the OpenCL standard for GPUs

Futhark is a data parallel programming language developed here in Copenhagen

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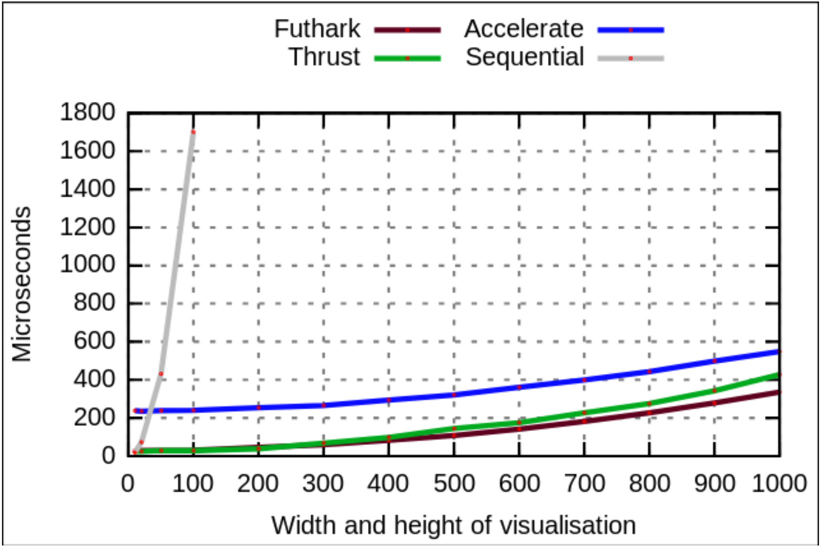
Futhark performance



Recap

- Concurrency vs. parallelism
- Lightweight threading with `forkIO`
- Software Transactional Memory (STM)
- Task parallelism versus data parallelism
- Futhark and GPU accelerated functional programming