Distributed Programming with

Cloud Haskell

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The Haskell Consultants

Overview

- Introduction
- Haskell
- Cloud Haskell
- Communication
- Going distributed
- Towards Map-Reduce

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Introduction

What is Cloud Haskell?

- Framework (a number of related packages) for Haskell
- Message-passing distributed concurrency (Erlang, actors)
- All in libraries; no (specific) compiler support required

Features

- Global view on a distributed program
- Single program runs in potentially many places
- Processes and nodes are first class entities
- Communication via (typed) messages
- Functions can be sent
- Programmable serialization
- Easy to monitor processes (and recover from failure)
- (Draft of) formal semantics

Multicore in Haskell

Many approaches

Different problems have different requirements / cost models.

Multicore in Haskell

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Different problems have different requirements / cost models.

Concurrency

- threads and locks (`MVar` s)
- aynchronous computations (`Async` s)
- software transactional memory
- …

Multicore in Haskell

Many approaches

Different problems have different requirements / cost models.

(Deterministic) Parallelism

- evaluation strategies
- dataflow-based task parallelism
- flat and nested data parallelism
- ...

Multicore in Haskell

Many approaches

Different problems have different requirements / cost models.

Distributed Concurrency

- Cloud Haskell
- …

Freedom of choice

- Haskell is great for embedded domain-specific languages.
- GHC has a very capable run-time system.
- You can pick whatever suits the needs of your task.
- All the approaches can be combined!

Freedom of choice

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Lesson

Rather than picking a language based on the model you want, pick a library based on the problem you have.

Cloud Haskell Example

```
server :: Process ()
server = forever $ do
  () ← expect
  liftIO $ putStrLn "ping"

client :: ProcessId → Process ()
client serverPid = forever $ do
  send serverPid ()
  liftIO $ threadDelay (1 * 10^6)

main :: IO ()
main = do
  Right t ← createTransport "127.0.0.1" "201306"
                           defaultTCPParameters
  node    ← newLocalNode t initRemoteTable
  runProcess node $ do
    serverPid ← getSelfPid
    spawnLocal $ client serverPid
    server
```

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Haskell

Pure Functions

$$\mathrm{dist} :: \mathrm{Floating}\ a \Rightarrow a \to a \to a$$
$$\mathrm{dist}\ x\ y = \mathrm{sqrt}\ (x * x + y * y)$$

Pure Functions

$$\mathsf{dist} :: \mathsf{Floating}\ \mathsf{a} \Rightarrow \mathsf{a} \to \mathsf{a} \to \mathsf{a}$$
$$\mathsf{dist}\ \mathsf{x}\ \mathsf{y} = \mathsf{sqrt}\ (\mathsf{x} * \mathsf{x} + \mathsf{y} * \mathsf{y})$$

$$\mathbf{data}\ \mathsf{Tree}\ \mathsf{a} = \mathsf{Leaf}\ \mathsf{a} \mid \mathsf{Node}\ (\mathsf{Tree}\ \mathsf{a})\ (\mathsf{Tree}\ \mathsf{a})$$

$$\mathsf{size} :: \mathsf{Tree}\ \mathsf{a} \to \mathsf{Int}$$
$$\mathsf{size}\ (\mathsf{Leaf}\ \mathsf{n}) \quad = 1$$
$$\mathsf{size}\ (\mathsf{Node}\ \mathsf{l}\ \mathsf{r}) = \mathsf{size}\ \mathsf{l} + \mathsf{size}\ \mathsf{r}$$

Pure Functions

```haskell
dist :: Floating a => a -> a -> a
dist x y = sqrt (x * x + y * y)
```

```haskell
data Tree a = Leaf a | Node (Tree a) (Tree a)
size :: Tree a -> Int
size (Leaf n)   = 1
size (Node l r) = size l + size r
```

```haskell
search :: Eq a => Tree a -> a -> Bool
search (Leaf n)   x = n == x
search (Node l r) x = search l x || search r x
```

Type signatures

```
dist   :: Floating a ⇒ a → a → a
size   :: Tree a → Int
search :: Eq a ⇒ Tree a → a → Bool
```

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Function calls

```
dist :: Floating a ⇒ a → a → a
```

```
dist x y
dist 2 3
dist (2 + x) (3 + x)
```

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IO

```haskell
conversation :: IO ()
conversation = do
  putStrLn "Who are you?"
  name ← getLine
  putStrLn $ "Hi " ++ name ++ ". Where are you from?"
  loc ← getLine
  putStrLn $
    if loc == "Munich"
    then "Oh, I love Munich!"
    else "Sorry, where is " ++ loc ++ "?"
```

IO

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conversation = do
  putStrLn "Who are you?"
  name ← getLine
  putStrLn $ "Hi " ++ name ++ ". Where are you from?"
  loc ← getLine
  putStrLn $
    if loc == "Munich"
    then "Oh, I love Munich!"
    else "Sorry, where is " ++ loc ++ "?"
```

```haskell
readNLines :: Int → IO [String]
readNLines n = replicateM n getLine
```

Monads

```
Maybe    a      -- possibly failing
State s  a      -- state-maintaining
Random   a      -- depending on a PRNG
Signal   a      -- time-changing
Par      a      -- annotated for parallelism
IO       a      -- arbitrary side effects
STM      a      -- logged transactions
Process  a      -- Cloud Haskell processes
...
```

Monads

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```

“Semicolon” is overloaded

You can define your own “monads”. You can decide what the semantics of sequencing in your application should be.

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Concurrency

forkIO :: IO () $\rightarrow$ IO ThreadId

Concurrency

```
forkIO :: IO () → IO ThreadId
```

```
threadDelay :: Int → IO ()
forever     :: Monad m ⇒ m a → m b   -- here:  IO a → IO b
```

Concurrency

```haskell
forkIO :: IO () → IO ThreadId
```

```haskell
threadDelay :: Int → IO ()
forever     :: Monad m ⇒ m a → m b   -- here:  IO a → IO b
```

```haskell
printForever :: String → IO ()
printForever msg = forever $ do
  putStrLn msg
  threadDelay (1 ∗ 10^6)

main :: IO ()
main = do
  forkIO $ printForever "child 1"
  forkIO $ printForever "child 2"
  printForever "parent"
```

Cloud Haskell

Cloud Haskell example revisited

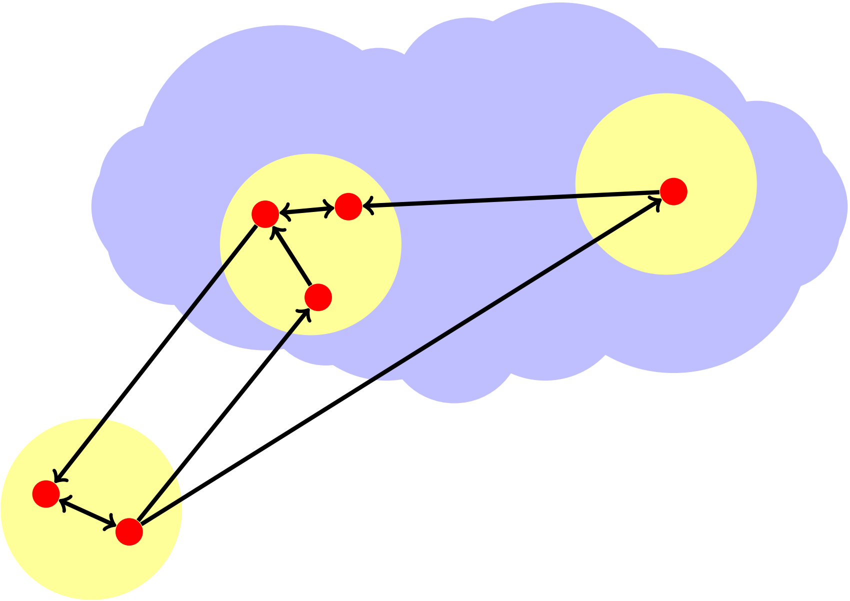
```haskell
server :: Process ()
server = forever $ do
  () ← expect
  liftIO $ putStrLn "ping"

client :: ProcessId → Process ()
client serverPid = forever $ do
  send serverPid ()
  liftIO $ threadDelay (1 * 10^6)

main :: IO ()
main = do
  Right t ← createTransport "127.0.0.1" "201306"
                           defaultTCPParameters
  node    ← newLocalNode t initRemoteTable
  runProcess node $ do
    serverPid ← getSelfPid
    spawnLocal $ client serverPid
    server
```

Layered architecture

Over-simplified:

User application
Higher-level libraries
Distributed process core library
Backend (simplelocalnet, Azure, EC2, . . .)
Transport (TCP, in-memory, SSH, ZeroMQ, . . .)
System libraries

Nodes, Processes, Communication



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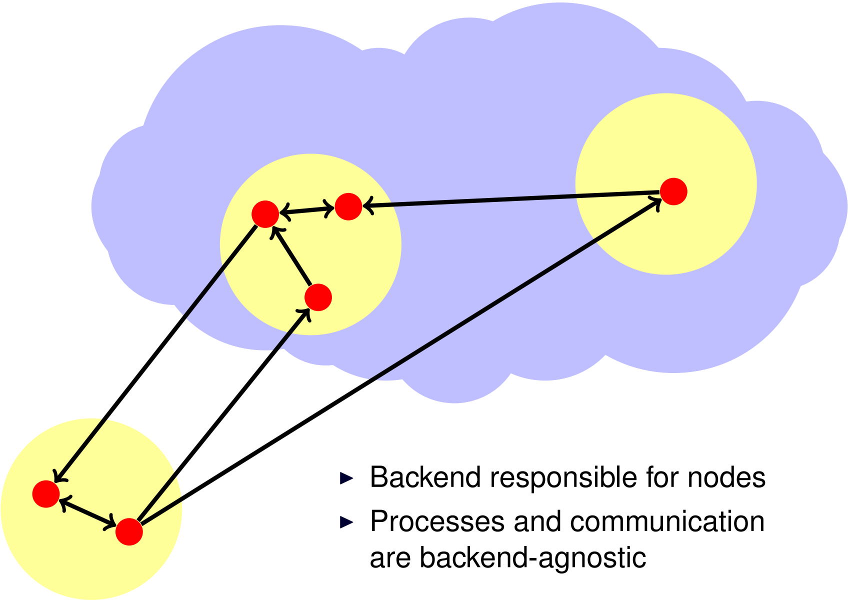
Nodes, Processes, Communication



- Backend responsible for nodes
- Processes and communication are backend-agnostic

Spawning and running processes

```
spawnLocal :: Process () → Process ProcessId
spawn      :: NodeId → Closure (Process ())
                     → Process ProcessId
```

For the main process:

```
runProcess :: LocalNode → Process () → IO ()
```

Sending and receiving messages

Ad-hoc:

```
send          :: Serializable a ⇒ ProcessId → a → Process ()
expect        :: Serializable a ⇒ Process a
expectTimeout :: Serializable a ⇒ Int → Process (Maybe a)
```

Sending is asynchronous. Receiving blocks.

Sending and receiving messages

Ad-hoc:

$$
\begin{array}{ll}
\mathsf{send} & :: \mathsf{Serializable\ a} \Rightarrow \mathsf{ProcessId} \rightarrow \mathsf{a} \rightarrow \mathsf{Process\ ()} \\
\mathsf{expect} & :: \mathsf{Serializable\ a} \Rightarrow \mathsf{Process\ a} \\
\mathsf{expectTimeout} & :: \mathsf{Serializable\ a} \Rightarrow \mathsf{Int} \rightarrow \mathsf{Process\ (Maybe\ a)}
\end{array}
$$

Sending is asynchronous. Receiving blocks.

Typed channels:

$$
\begin{array}{ll}
\mathsf{newChan} & :: \mathsf{Serializable\ a} \Rightarrow \mathsf{Process\ (SendPort\ a, ReceivePort\ a)} \\
\mathsf{sendChan} & :: \mathsf{Serializable\ a} \Rightarrow \mathsf{SendPort\ a} \rightarrow \mathsf{a} \rightarrow \mathsf{Process\ ()} \\
\mathsf{receiveChan} & :: \mathsf{Serializable\ a} \Rightarrow \mathsf{ReceivePort\ a} \rightarrow \mathsf{Process\ a} \\
\ldots &
\end{array}
$$

Serializable

$$\text{Serializable a} = (\text{Typeable a}, \text{Binary a})$$

Serializable

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```
Typeable a      -- has a run-time type representation
Binary a        -- has a binary representation
```

Static and dynamic typing

Haskell's typing discipline

Haskell is a statically typed language, but can be dynamically typed locally, on demand.

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Haskell's typing discipline

Haskell is a statically typed language, but can be dynamically typed locally, on demand.

$$
\begin{array}{ll}
\mathsf{typeOf} & :: \mathsf{Typeable\ a} \Rightarrow \mathsf{a} \to \mathsf{TypeRep} \\
\mathsf{toDyn} & :: \mathsf{Typeable\ a} \Rightarrow \mathsf{a} \to \mathsf{Dynamic} \\
\mathsf{fromDynamic} & :: \mathsf{Typeable\ a} \Rightarrow \mathsf{Dynamic} \to \mathsf{Maybe\ a}
\end{array}
$$

GHC can "derive" an instance of Typeable for any datatype automatically.

Binary representation

$$\mathsf{encode} :: \mathsf{Binary}\ a \Rightarrow a \rightarrow \mathsf{ByteString}$$
$$\mathsf{decode} :: \mathsf{Binary}\ a \Rightarrow \mathsf{ByteString} \rightarrow a$$

- Haskell has no built-in serialization.
- Automatic generation of sane Binary instances for many datatypes possible via datatype-generic or meta-programming.
- Programmer has control – instances can deviate from simply serializing the in-memory representation.

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Communication

How to reply

Idea

Messages can include process ids and channel send ports.

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Old server:

```
server :: Process ()
server = forever $ do
  () ← expect
  liftIO $ putStrLn "ping"
```

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How to reply

Idea

Messages can include process ids and channel send ports.

New server:

```
server :: Process ()
server = forever $ do
  clientPid ← expect
  liftIO $ putStrLn $ "ping " ++ show clientPid
  send clientPid ()
```

Adapting the client

Old client:

```
client :: ProcessId → Process ()
client serverPid =
  forever $ do
    send serverPid ()
    liftIO $ threadDelay (1 * 10^6)
```

Adapting the client

Old client:

```
client :: ProcessId → Process ()
client serverPid =

  forever $ do
    send serverPid ()


    liftIO $ threadDelay (1 * 10^6)
```

Adapting the client

New client:

```
client :: ProcessId → Process ()
client serverPid = do
  clientPid ← getSelfPid
  forever $ do
    send serverPid clientPid
    () ← expect
    liftIO $ putStrLn "pong"
    liftIO $ threadDelay (1 ∗ 10^6)
```

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More about replying

- We can send ids of other processes.
- Forwarding, redirection, broadcasting.

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- We can send ids of other processes.
- Forwarding, redirection, broadcasting.

For typed channels:

- We can serialize `SendPort`.
- But we cannot serialize `ReceivePort`.

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Conversations

Some rules about exchanging messages:

- only one mailbox per process;
- we can expect a particular type;
- we can receiveWait for specific messages;
- typed channels are separate;
- sane ordering of messages;
- messages may remain undelivered.

Going distributed

Distributed ping-pong

No changes to server and client are needed.

Old main:

```
main :: IO ()
main = do
  Right t ← createTransport "127.0.0.1" "201306"
                            defaultTCPParameters
  node    ← newLocalNode t initRemoteTable
  runProcess node $ do
    serverPid ← getSelfPid
    spawnLocal $ client serverPid
    server
```

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Distributed ping-pong

No changes to server and client are needed.

New main (using `distributed-process-simplelocalnet`):

```
main :: IO ()
main = do
  args ← getArgs
  let rtbl = __remoteTable initRemoteTable
  case args of
    ["master", port] → do
      backend ← initializeBackend "127.0.0.1" port rtbl
      startMaster backend master
    ["slave" , port] → do
      backend ← initializeBackend "127.0.0.1" port rtbl
      startSlave  backend
```

Automatic detection of slaves

$$\text{startSlave} \quad :: \text{Backend} \rightarrow \text{IO}\ () \qquad \text{-- does nothing}$$
$$\text{startMaster} :: \text{Backend} \rightarrow ([\text{NodeId}] \rightarrow \text{Process}\ ()) \rightarrow \text{IO}\ ()$$

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Automatic detection of slaves

```
startSlave  :: Backend → IO ()    -- does nothing
startMaster :: Backend → ([NodeId] → Process ()) → IO ()
```

Master gets node ids of all slaves.

Spawning functions remotely

```
master :: [NodeId] → Process ()
master slaves = do
  serverPid ← getSelfPid
  forM_ slaves $
    λnid → spawn nid ($(mkClosure 'client) serverPid)
  server
```

Spawning functions remotely

```
master :: [NodeId] → Process ()
master slaves = do
  serverPid ← getSelfPid
  forM_ slaves $
    λnid → spawn nid ($(mkClosure 'client) serverPid)
  server
```

Spawns a function call on a remote node.

Serializing functions

- "Single program assumption"
- Top-level functions are easy
- (Partially) applied functions are turned into closures

Serializing functions

- "Single program assumption"
- Top-level functions are easy
- (Partially) applied functions are turned into closures

- Currently based on a bit of meta-programming.
- In the future perhaps using a (small) compiler extension.

Towards Map-Reduce

Distributing actual work

```
master :: [Input] → [NodeId] → Process ()
master inputs workers = do
  masterPid  ← getSelfPid
  workerPids ← forM workers $
    λnid → spawn nid ($(mkClosure 'worker) masterPid)
  forM_ (zip inputs (cycle workerPids)) $
    λ(input, workerPid) → send workerPid input
  r ← collectResults (length inputs)
  liftIO $ print r
```

Distributing actual work

```
master :: [Input] → [NodeId] → Process ()
master inputs workers = do
  masterPid  ← getSelfPid
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    λnid → spawn nid ($(mkClosure 'worker) masterPid)
  forM_ (zip inputs (cycle workerPids)) $
    λ(input, workerPid) → send workerPid input
  r ← collectResults (length inputs)
  liftIO $ print r
```

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Workers

```
...
  workerPids ← forM workers $
    λnid → spawn nid ($(mkClosure 'worker) masterPid)
...
```

```
worker :: ProcessId → Process ()
worker serverPid = forever $ do
  x ← expect    -- obtain function input
  send serverPid (expensiveFunction x)
```

The `expensiveFunction` is “mapped” over all inputs.

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Collecting results

```
...
  r ← collectResults (length inputs)
  liftIO $ print r
...
```

```
collectResults :: Int → Process Result
collectResults = go emptyResult
  where
    go :: Result → Int → Process Result
    go !acc 0 = return acc
    go !acc n = do
      r ← expect   -- obtain one result
      go (combineResults acc r) (n − 1)
```

In go we “reduce” the results.

Abstraction and variation

- Abstracting from `expensiveFunction`, `emptyResult`, `combineResults` (and `inputs`) yields a simple map-reduce function.
- Can easily use other ways to distribute work, for example work-stealing rather than work-pushing.
- Can use a hierarchy of distribution and reduction processes.

Conclusions

Aspects we hardly talked about:

- User-defined message types
- Matching of messages
- Embrace failure! (Linking and monitoring)
- Combination with other multicore frameworks

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Conclusions

Aspects we hardly talked about:

- User-defined message types
- Matching of messages
- Embrace failure! (Linking and monitoring)
- Combination with other multicore frameworks

Remember:

- Cloud Haskell is a library (easy to change, extend, adapt)
- Cloud Haskell is ongoing work
- All of Haskell plus distributed programming
- Watch for exciting new backends and higher-level libraries

Want to try it?

`http://haskell-distributed.github.io/`

Mini-tutorial blog series by Duncan Coutts and Edsko de Vries:

`http://www.well-typed.com/blog/70`