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CLOUD HASKELL

Haskell support for the development of distributed applications

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1. Abstract

The following paper tries to familiarize the reader with the basic concepts of distributed applications, concurrency and the improvements brought by Haskell to this branch of computer science. Over ten chapters has been presented a birds eye view of Haskell and functional programming as a whole, concurrency and distributed applications and have dived into the building and usage of various libraries of *Cloud Haskell Platform* which offers open source implementations of distributed computing interfaces, allowing processes to communicate with one other through explicit message passing rather than shared memory.

2. Use of functional programming - Haskell

Haskell is a computer programming language (Jones, 2013). In particular, it is a polymorphically statically typed, lazy, purely functional language, quite different from most other programming languages. The language is named for Haskell Brooks Curry, whose work in mathematical logic serves as a foundation for functional languages. Haskell is based on the lambda calculus, hence the lambda we use as a logo.

2.1. Why use Haskell?

Writing large software systems, that work, is difficult and expensive. Maintaining those systems is even more difficult and expensive. Functional programming languages, such as Haskell, can make it easier and cheaper.

Haskell offers:

- Substantially increased programmer productivity (Ericsson measured an improvement factor of between 9 and 25 using Erlang, a functional programming language similar to Haskell, in one set of experiments on telephony software).
- Shorter, clearer, and more maintainable code.
- Fewer errors, higher reliability.
- A smaller "semantic gap" between the programmer and the language.
- Shorter lead times.

Haskell is a wide-spectrum language, suitable for a variety of applications. It is particularly suitable for programs which need to be highly modifiable and maintainable.

Much of a software product's life is spent in *specification*, *design* and *maintenance*, and not in *programming*. Functional languages are superb for writing specifications which can actually be executed (and hence tested and debugged). Such a specification then *is* the first prototype of the final program.

Functional programs are also relatively easy to maintain, because the code is shorter, clearer, and the rigorous control of side effects eliminates a huge class of unforeseen interactions.

2.2. What's good about functional programming?

Spreadsheets and SQL are both fairly specialized languages. Functional programming languages take the same ideas and move them into the realm of general-purpose programming. To get an idea of what a functional program is like, and the expressiveness of functional languages, look at the following quicksort programs. They both sort a sequence of numbers into ascending order using a standard method called "quicksort". The first program is written in Haskell and the second in C.

Whereas the C program describes the particular steps the machine must make to perform a sort -- with most code dealing with the low-level details of data manipulation -- the Haskell program encodes the sorting algorithm at a much higher level, with improved brevity and clarity as a result (at the cost of efficiency unless compiled by a very smart compiler.

3. Distributed Applications

Distributed applications (distributed apps) are applications or software that runs on multiple computers within a network at the same time and can be stored on servers or with cloud computing. Unlike traditional applications that run on a single system, distributed applications run on multiple systems simultaneously for a single task or job.

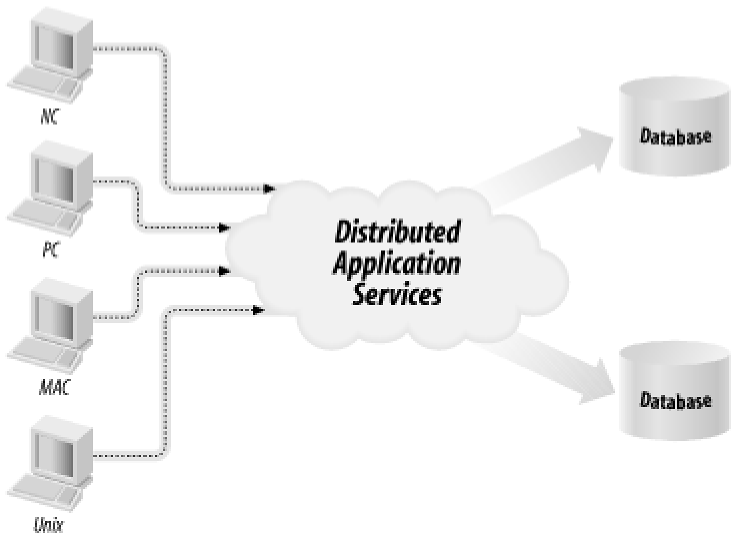


Figure 1- Distributed application services

Distributed apps can communicate with multiple servers or devices on the same network from any geographical location. The distributed nature of the applications refers to data being spread out over more than one computer in a network.

Distributed applications are broken up into two separate programs: the client software and the server software. The client software or computer accesses the data from the server or cloud environment, while the server or cloud processes the data. Cloud computing can be used instead of servers or hardware to process a distributed application's data or programs. If a distributed application component goes down, it can failover to another component to continue running.

Failover is a backup operational mode in which the functions of a system component (such as a processor, server, network, or database, for example) are assumed by secondary system components when the primary component becomes unavailable through either failure or scheduled down time. Used to make systems more fault-tolerant, failover is typically an integral part of mission-critical systems that must be constantly available. The procedure involves automatically offloading tasks to a standby system component so that the procedure is as seamless as possible to the end user. Failover can apply to any aspect of a system: within a personal computer, for example, failover might be a mechanism to protect against a failed processor; within a network, failover can apply to any network component or system of components, such as a connection path, storage device, or Web server.

Distributed applications allow multiple users to access the apps at once. Many developers, IT professionals or enterprises choose to store distributed apps in the cloud because of cloud's elasticity and scalability, as well as its ability to handle large applications or workloads.

4. Cloud Haskell Platform

(Cloud Haskell)

Cloud Haskell is a set of libraries that bring *Erlang-style concurrency* and distribution to Haskell programs. This project is an implementation of that distributed computing interface, where processes communicate with one another through explicit message passing rather than shared memory.

The term *Erlang-style concurrency* does not have an authoritative definition. Many authors have described their own vision of this term, but the necessary conditions that an application has to fulfill in order to be qualified as an Erland-style application are the following:

- Fast process creation/destruction
- Ability to support >> 10 000 concurrent processes with largely unchanged characteristics
- Fast asynchronous message passing
- Copying message-passing semantics (share-nothing concurrency)
- Process monitoring
- Selective message reception

4.1.Asynchronous message passing

It has been argued that synchronous message passing is a better building block than asynchronous message passing. It is probably true that synchronous message passing is much easier to reason about, but asynchronous communication ("send and pray") feels more intuitive in a distributed environment (in which case environments based on synchronous message passing will resort to some form of asynchronous communication as well). Anyway, it is reasonable to argue that asynchronous communication is a defining characteristic of Erlang-style Concurrency.

4.2.Copying semantics

Note that this doesn't necessarily mean that messages must be copied, but they must act as if they were. There are several reasons why this is important:

- For reliability reasons, processes must not share memory
- In the distributed case, copying is inevitable, and we want as similar semantics as possible between local and distributed message passing

It is perhaps too strong to require that processes share nothing, as this would rule out Erlang-style concurrency in most existing languages (even languages like Scala make it possible to share data between processes). Let's just say that the Erlang style is to make it easier to use share-nothing concurrency than to use sharing.

4.3.Process monitoring

This is the enabler of “out-of-band” error handling, or the “let it crash” philosophy, which is very typical for Erlang. The idea is that you program for the correct case, and rely on supervising processes for error handling. This has turned out to be a beautiful way of handling fault tolerance in large systems.

4.4.Selective message reception

There are many ways to achieve selective message reception, but for complex multi-way concurrency, you have to support at least one of them. This is something often overlooked when approaching concurrency. It’s not obviously needed in simple programs, but when it is needed, you will suffer complexity explosion if you don’t have it.

The ability to support selective message reception is sufficient for Erlang-style concurrency. It can be done either by matching on a single message queue (Erlang, OSE Delta), or by using different mailboxes/channels (Haskell, .NET, UNIX sockets).

Originally described by the joint Towards Haskell in the Cloud (Jeff Epstein) paper, Cloud Haskell has be re-written from the ground up and supports a rich and growing number of features for:

- building concurrent applications using asynchronous message passing
- building distributed computing applications
- building fault tolerant systems
- running Cloud Haskell nodes on various network transports
- working with several network transport implementations (and more in the pipeline)
- supporting static values (required for remote communication)

Cloud Haskell comprises the following components, some of which are complete, others experimental.

- distributed-process: Base concurrency and distribution support
- distributed-process-platform: The Cloud Haskell Platform - APIs
- distributed-static: Support for static values
- rank1dynamic: Like `Data.Dynamic` and `Data.Typeable` but supporting polymorphic values
- network-transport: Generic `Network.Transport` API
- network-transport-tcp: TCP realisation of `Network.Transport`
- network-transport-inmemory: In-memory realisation of `Network.Transport` (incomplete)
- network-transport-composed: Compose two transports (very preliminary)
- distributed-process-simplelocalnet: Simple backend for local networks
- distributed-process-azure: Azure backend for Cloud Haskell (proof of concept)

One of Cloud Haskell’s goals is to separate the transport layer from the *process layer*, so that the transport backend is entirely independent. In fact, other projects can and do reuse the transport layer, even if they don’t use or have their own process layer

Abstracting over the transport layer allows different protocols for message passing, including TCP/IP, UDP, MPI, CCI, ZeroMQ, SSH, MVars, Unix pipes, and more. Each of these transports provides its own implementation of the `Network.Transport` API and provides a means of creating new connections for use within `Control.Distributed.Process`.

The following diagram shows dependencies between the various subsystems, in an application using Cloud Haskell, where arrows represent explicit directional dependencies.

```
+------------------------------------------------------------+
|                        Application                         |
+------------------------------------------------------------+
             |                               |
             V                               V
+-------------------------+   +------------------------------+
|      Cloud Haskell      |<--|    Cloud Haskell Backend     |
|  (distributed-process)  |   | (distributed-process-...)    |
+-------------------------+   +------------------------------+
             |           ______/             |
             V           V                   V
+-------------------------+   +------------------------------+
|   Transport Interface   |<--|   Transport Implementation   |
|   (network-transport)   |   |   (network-transport-...)    |
+-------------------------+   +------------------------------+
                                             |
                                             V
                              +------------------------------+
                              | Haskell/C Transport Library  |
                              +------------------------------+
```

Figure 2 - Dependencies in Cloud Haskell application

In this diagram, the various nodes roughly correspond to specific modules:

```
Cloud Haskell                : Control.Distributed.Process
Cloud Haskell                : Control.Distributed.Process.*
Transport Interface          : Network.Transport
Transport Implementation     : Network.Transport.*
```

Figure 3 - Cloud Haskell Modules

An application is built using the primitives provided by the Cloud Haskell layer, provided by the `Control.Distributed.Process` module, which defines abstractions such as nodes and processes.

The application also depends on a Cloud Haskell Backend, which provides functions to allow the initialization of the transport layer using whatever topology might be appropriate to the application.

It is, of course, possible to create new Cloud Haskell nodes by using a Network Transport Backend such as `Network.Transport.TCP` directly.

The Cloud Haskell interface and backend make use of the Transport interface provided by the `Network.Transport` module. This also serves as an interface for the Network.Transport.* module, which provides a specific implementation for this transport, and may, for example, be based on some external library written in Haskell or C.

5. Network Transport Abstraction Layer

Cloud Haskell's generic network-transport API is entirely independent of the concurrency and messaging passing capabilities of the *process layer*. Cloud Haskell applications are built using the primitives provided by the *process layer* (i.e., distributed-process), which provides abstractions such as nodes and processes. Applications must also depend on a Cloud Haskell backend, which provides functions to allow the initialization of the transport layer using whatever topology might be appropriate to the application.

`Network.Transport` is a network abstraction layer geared towards specific classes of applications, offering the following high level concepts:

- Nodes in the network are represented by `EndPoint`s. These are heavyweight stateful objects.
- Each `EndPoint` has an `EndPointAddress`
- Connections can be established from one `EndPoint` to another using the `EndPointAddress` of the remote end
- The `EndPointAddress` can be serialized and sent over the network, whereas `EndPoint`s and connections cannot
- Connections between `EndPoint`s are unidirectional and lightweight
- Outgoing messages are sent via a `Connection` object that represents the sending end of the connection
- Incoming messages for **all** of the incoming connections on an `EndPoint` are collected via a shared receive queue
- In addition to incoming messages, `EndPoint`s are notified of other `Event`s such as new connections or broken connections

This design was heavily influenced by the design of the Common Communication Interface (CCI). Important design goals are:

- Connections should be lightweight: it should be no problem to create thousands of connections between endpoints
- Error handling is explicit: every function declares as part of its type which errors it can return (no exceptions are thrown)
- Error handling is "abstract": errors that originate from implementation specific problems (such as "no more sockets" in the TCP implementation) get mapped to generic errors ("insufficient resources") at the Transport level

For the purposes of most Cloud Haskell applications, it is sufficient to know enough about the `Network.Transport` API to instantiate a backend with the required configuration and pass the returned opaque handle to the Node API in order to establish a new, connected, running node. More involved setups are, of course, possible.

The simplest use of the API is:

```
main :: IO
main = do
  Right transport <- createTransport "127.0.0.1" "10080" defaultTCPParameters
  node1 <- newLocalNode transport initRemoteTable
```

Figure 4 - Use of NetworkTransport API

Here we can see that the application depends explicitly on the `defaultTCPParameters` and `createTransport` functions from `Network.Transport.TCP`, but little else. The application *can* make use of other `Network.Transport` APIs if required, but for the most part this is irrelevant and the application will interact with Cloud Haskell through the *Process Layer* and *Platform*.

6. Concurrency and Distribution

The *Process Layer* is where Cloud Haskell's support for concurrency and distributed programming are exposed to application developers.

The core of Cloud Haskell's concurrency and distribution support resides in the distributed-process library. As well as the APIs necessary for starting nodes and forking processes on them, we find all the basic primitives required to:

- spawn processes locally and remotely
- send and receive messages, optionally using typed channels
- monitor and/or link to processes, channels and other nodes

We focus on the essential *concepts* behind the process layer. A concurrent process is somewhat like a Haskell thread - in fact it is a forkIO thread - but one that can send and receive messages through its *process mailbox*. Each process can send messages asynchronously to other processes, and can receive messages synchronously from its own mailbox. The conceptual difference between threads and processes is that the latter do not share state, but communicate only via message passing.

Code that is executed in this manner must run in the Process monad. Our process will look like any other monad code, plus we provide an instance of MonadIO for Process, so you can liftIO to make IO actions available.

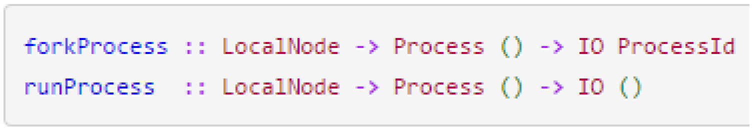
Processes reside on nodes, which in our implementation map directly to the `Control.Distributed.Processes.Node` module. Given a configured `Network.Transport` backend, starting a new node is fairly simple:

```
newLocalNode :: Transport -> IO LocalNode
```

Figure 5 - Node Creation

Once this function returns, the node will be *up and running* and able to interact with other nodes and host processes. It is possible to start more than one node in the same running program, though if you do this they will continue to send messages to one another using the supplied `Network.Transport` backend.

Given a new node, there are two primitives for starting a new process.



```
forkProcess :: LocalNode -> Process () -> IO ProcessId
runProcess  :: LocalNode -> Process () -> IO ()
```

Figure 6 - Primitives for Stating a Process

Once we've spawned some processes, they can communicate with one another using the messaging primitives provided by [distributed-processes][distributed-processes], which are well documented in the haddocks.

7. What is Serializable?

Processes can send data if the type implements the Serializable typeclass, which is done indirectly by implementing Binary and deriving Typeable. Implementations are already provided for primitives and some commonly used data structures. As programmers, we see the messages in nice high-level form (e.g., Int, String, Ping, Pong, etc), however these data have to be encoded in order to be sent over a communications channel.

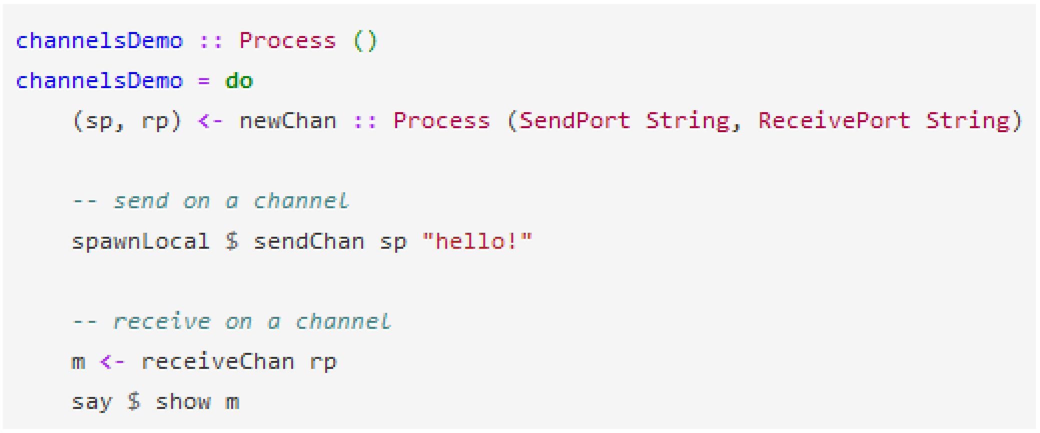
Not all types are Serializable, for example concurrency primitives such as MVar and TVar are meaningless outside the context of threads with a shared memory. Cloud Haskell programs remain free to use these constructs within processes or within processes on the same machine though. If you want to pass data between processes using *ordinary* concurrency primitives such as STM then you're free to do so. Processes spawned locally can share types such as TMVar just as normal Haskell threads would.

8. Typed Channels

Channels provide an alternative to message transmission with send and expect. While send and expect allow us to transmit messages of any `Serializable` type, channels require a uniform type. Channels work like a distributed equivalent of Haskell's `Control.Concurrent.Chan`, however they have distinct ends: a single receiving port and a corollary send port.

Channels provide a nice alternative to *bare send and receive*, which is a bit *un-Haskell-ish*, since our process' message queue can contain messages of multiple types, forcing us to undertake dynamic type checking at runtime.

We create channels with a call to `newChan`, and send/receive on them using the `{send,receive}Chan` primitives:



```haskell
channelsDemo :: Process ()
channelsDemo = do
    (sp, rp) <- newChan :: Process (SendPort String, ReceivePort String)

    -- send on a channel
    spawnLocal $ sendChan sp "hello!"

    -- receive on a channel
    m <- receiveChan rp
    say $ show m
```

Figure 7 - Create channel by Call/Send/Receive Chan primitives

Channels are particularly useful when you are sending a message that needs a response, because we know exactly where to look for the reply.

Channels can also allow message types to be simplified, as passing a `ProcessId` for the reply isn't required. Channels aren't so useful when we need to spawn a process and send a bunch a messages to it, then wait for replies however; we can't send a `ReceivePort` since it is not `Serializable`.

`ReceivePorts` can be merged, so we can listen on several simultaneously. In the latest version of distributed-process, we can listen for *regular* messages and multiple channels at the same time, using `matchChan` in the list of allowed matches passed `receiveWait` and `receiveTimeout`.

8.1.Linking and monitoring

Processes can be linked to other processes, nodes or channels. Links are unidirectional, and guarantee that once the linked object *dies*, the linked process will also be terminated. Monitors do not cause the *listening* process to exit, but rather they put a `ProcessMonitorNotification` into the process' mailbox. Linking and monitoring are foundational tools for *supervising* processes, where a top level process manages a set of children, starting, stopping and restarting them as necessary.

8.2.Stopping Processes

Because processes are implemented with `forkIO` we might be tempted to stop them by throwing an asynchronous exception to the process, but this is almost certainly the wrong thing to do. Firstly, processes might reside on a remote node, in which case throwing an exception is impossible. Secondly, if we send some messages to a process' mailbox and then dispatch an exception to kill it, there is no guarantee that the subject will receive our message before being terminated by the asynchronous exception.

To terminate a process unconditionally, we use the kill primitive, which dispatches an asynchronous exception (killing the subject) safely, respecting remote calls to processes on disparate nodes and observing message ordering guarantees such that `send pid "hello" >> kill pid "goodbye"` behaves quite unsurprisingly, delivering the message before the kill signal.

Exit signals come in two flavours however - those that can be caught and those that cannot. Whilst a call to kill results in an *un-trappable* exception, a call to `exit :: (Serializable a) => ProcessId -> a -> Process ()` will dispatch an exit signal to the specified process that can be caught. These *signals* are intercepted and handled by the destination process using `catchExit`, allowing the receiver to match on the `Serializable` datum tucked away in the *exit signal* and decide whether to oblige or not.

9. Rethinking the Task Layer

Towards Haskell in the Cloud describes a multi-layered architecture, in which manipulation of concurrent processes and message passing between them is managed in the *process layer*, whilst a higher level API described as the *task layer* provides additional features such as

- automatic recovery from failures
- data centric processing model
- a promise (or *future*) abstraction, representing the result of a calculation that may or may not have yet completed

The distributed-process-platform library implements parts of the *task layer*, but takes a very different approach to that described in the original paper and implemented by the remote package. In particular, we diverge from the original design and defer too many of the principles defined by Erlang's Open Telecom Platform, taking in some well-established Haskell concurrency design patterns along the way.

In fact, distributed-process-platform does not really consider the *task layer* in great detail. We provide an API comparable to remote's Promise in `Control.Distributed.Process.Platform.Async`. This API however, is derived from Simon Marlow's Control.Concurrent.Async package, and is not limited to blocking queries on Async handles in the same way. Instead our API handles both blocking and non-blocking queries, polling and working with lists of Async handles. We also eschew throwing exceptions to indicate asynchronous task failures, instead handling *task* and connectivity failures using monitors. Users of the API need only concern themselves with the `AsyncResult`, which encodes the status and (possibly) outcome of the computation simply.

```haskell
demoAsync :: Process ()
demoAsync = do
  -- spawning a new task is fairly easy - this one is linked
  -- so if the caller dies, the task is killed too
  hAsync :: Async String
  hAsync <- asyncLinked $ (expect >>= return) :: Process String

  -- there is a rich API of functions to query an async handle
  AsyncPending <- poll hAsync   -- not finished yet

  -- we can cancel the task if we want to
  -- cancel hAsync

  -- or cancel it and wait until it has exited
  -- cancelWait hAsync

  -- we can wait on the task and timeout if it's still busy
  Nothing <- waitTimeout (within 3 Seconds) hAsync

  -- or finally, we can block until the task is finished!
  asyncResult <- wait hAsync
  case asyncResult of
      (AsyncDone res) -> say (show res)  -- a finished task/result
      AsyncCancelled  -> say "it was cancelled!?"
      AsyncFailed (DiedException r) -> say $ "it failed: " ++ (show r)
```

Figure 8 - Asynchronous Application Example

Unlike remote's task layer, we do not exclude IO, allowing tasks to run in the Process monad and execute arbitrary code. Providing a monadic wrapper around Async that disallows side effects is relatively simple, and we do not consider the presence of side effects a barrier to fault tolerance and automated process restarts. Erlang does not forbid *IO* in its processes, and yet that doesn't render supervision trees ineffective. They key is to provide a rich enough API that stateful processes can recognize whether or not they need to provide idempotent initialization routines.

The utility of preventing side effects using the type system is, however, not to be sniffed at. A substrate of the ManagedProcess API is under development that provides a *safe process* abstraction in which side effect free computations can be embedded, whilst reaping the benefits of the framework.

Work is also underway to provide abstractions for managing asynchronous tasks at a higher level, focusing on workload distribution and load regulation.

The kinds of task that can be performed by the async implementations in distributed-process-platform are limited only by their return type: it **must** be `Serializable` - that much should've been obvious by now. The type of asynchronous task definitions comes in two flavors, one for local nodes which require no remote-table or static serialization dictionary, and another for tasks you wish to execute on remote nodes.

```
-- | A task to be performed asynchronously.
data AsyncTask a =
    AsyncTask
      {
        asyncTask :: Process a -- ^ the task to be performed
      }
  | AsyncRemoteTask
      {
        asyncTaskDict :: Static (SerializableDict a)
          -- ^ the serializable dict required to spawn a remote process
      , asyncTaskNode :: NodeId
          -- ^ the node on which to spawn the asynchronous task
      , asyncTaskProc :: Closure (Process a)
          -- ^ the task to be performed, wrapped in a closure environment
      }
```

Figure 9 - Asynchronously performed task

9.1.Managed Processes

The main idea behind a ManagedProcess is to separate the functional and non-functional aspects of an actor. By functional, we mean whatever application specific task the actor performs, and by non-functional we mean the concurrency or, more precisely, handling of the process' mailbox and its interaction with other actors (i.e., clients).

Looking at typed channels, we noted that their insistence on a specific input domain was more haskell-ish than working with bare send and receive primitives. The Async sub-package also provides a type safe interface for receiving data, although it is limited to running a computation and waiting for its result.

The Control.Distributed.Processes.Platform.ManagedProcess API provides a number of different abstractions that can be used to achieve similar benefits in your code. It works by introducing a standard protocol between your process and the world outside, which governs how to handle request/reply processing, exit signals, timeouts, sleeping/hibernation with threadDelay and even provides hooks that terminating processes can use to clean up residual state.

The API documentation is quite extensive, so here we will simply point out the obvious differences. A process implemented with ManagedProcess can present a type safe API to its callers although that's not its primary benefit. For a very simplified example:

```haskell
add :: ProcessId -> Double -> Double -> Process Double
add sid x y = call sid (Add x y)

divide :: ProcessId -> Double -> Double
          -> Process (Either DivByZero Double)
divide sid x y = call sid (Divide x y )

launchMathServer :: Process ProcessId
launchMathServer =
  let server = statelessProcess {
      apiHandlers = [
          handleCall_   (\(Add    x y) -> return (x + y))
        , handleCallIf_ (input (\(Divide _ y) -> y /= 0)) handleDivide
        , handleCall_   (\(Divide _ _) -> divByZero)
        ]
    }
  in spawnLocal $ start () (statelessInit Infinity) server >> return ()
  where handleDivide :: Divide -> Process (Either DivByZero Double)
        handleDivide (Divide x y) = return $ Right $ x / y

        divByZero :: Process (Either DivByZero Double)
        divByZero = return $ Left DivByZero
```

Figure 10 - Process implemented with ManagedProcess

Apart from the types and the imports, that is a complete definition. Whilst it's not so obvious what's going on here, the key point is that the invocation of call in the client facing API functions handles all of the relevant waiting/blocking, converting the async result and so on. Note that the managed process does not interact with its mailbox at all, but rather just provides callback functions which take some state and either return a new state and a reply, or just a new state. The process is managed in the sense that its mailbox is under someone else's control.

10. Building Examples

10.1. Getting Started

(Tuyl, 2008)

A. In order to go through these examples, you will need a working Haskell environment. If you don't already have one, follow the instructions from the Haskell portal in order to install.

B. In order to compile the projects, you will need to install stack. Stack is a cross-platform program for developing Haskell projects. It is aimed at Haskellers both new and experienced.

Stack features:

- Installing GHC automatically, in an isolated location.
- Installing packages needed for your project.
- Building your project.
- Testing your project.
- Benchmarking your project

(Coutts, 2012)

C. To facilitate the use of Cloud Haskell the developers offer a large suite of libraries. These libraries need to be compiled. The user needs to install Cabal in order to use the built libraries.

Cabal is a system for building and packaging Haskell libraries and programs. It defines a common interface for package authors and distributors to easily build their applications in a portable way. Cabal is part of a larger infrastructure for distributing, organizing, and cataloging Haskell libraries and programs.

Specifically, the Cabal describes what a Haskell package is, how these packages interact with the language, and what Haskell implementations must to do to support packages. The Cabal also specifies some infrastructure (code) that makes it easy for tool authors to build and distribute conforming packages.

The Cabal is only one contribution to the larger goal. In particular, the Cabal says nothing about more global issues such as how authors decide where in the module name space their library should live; how users can find a package they want; how orphan packages find new owners; and so on.

(Iubomir, 2015)

D. Once you're up and running, you'll want to get hold of the distributed-process library and a choice of network transport backend. This guide will use the network-transport-tcp backend, but other backends are available on Hackage and GitHub.

10.2. Building the libraries

Once the distributed-process and the network-transport-tcp libraries are downloaded, they need to be built. By far the easiest way is to use the cabal command line tool to install a new package and its dependencies.cabal is part of the Haskell Platform, so make sure you install that first.

Once you have the tool installed, installing other packages is easy. The first thing to do is to give the command:

```
cabal update
```

Figure 11 - Cabal Update

This will download the most recent list of packages; this must be done from time to time, to get the latest version of each package, when installing.

It is advisable to use a sandbox, to prevent version incompatibility with earlier installed packages. To initiate a sandbox, give command:

```
cabal sandbox init
```

Figure 12 - Cabal sandox init

To install Cabal packages from Hackage use:

```
cabal install foo
```

Figure 13 - Cabal install

Other common variations:

```
cabal install                             Package in the current directory
cabal install foo                         Package from the Hackage server
cabal install foo-1.0                     Specific version of a package
cabal install 'foo < 2'                   Constrained package version
cabal install foo bar baz                 Several packages at once
cabal install foo --dry-run               Show what would be installed
cabal install foo --constraint=bar==1.0   Use version 1.0 of package bar
```

Figure 14 - Cabal install other variations

One thing to be especially aware of, is that the packages are installed locally by default, whereas the commands

```
runhaskell Setup configure
runhaskell Setup build
runhaskell Setup install
```

Figure 15 - runhaskell Setup

Install globally by default. If you install a package globally, the local packages are ignored. The default for cabal-install can be modified by editing the configuration file.

Help about cabal-install can be obtained by giving commands like:

```
cabal --help
cabal install --help
```

Figure 16 - Cabal commands

10.3. Setting up the project

Starting a new Cloud Haskell project using stack is as easy as

```
$ stack new
```

Figure 17 - stack new

in a fresh new directory. This will populate the directory with a number of files, chiefly `stack.yaml` and `*.cabal` metadata files for the project. You'll want to add `distributed-process` and `network-transport-tcp` to the `build-depends` stanza of the executable section.

10.4. Create a node

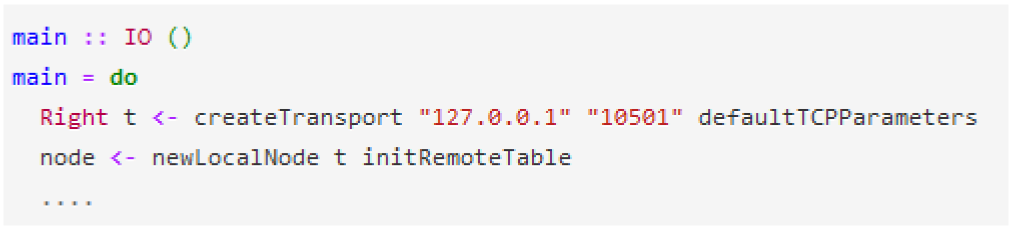
Cloud Haskell's lightweight processes reside on a "node", which must be initialized with a network transport implementation and a remote table. The latter is required so that physically separate nodes can identify known objects in the system (such as types and functions) when receiving messages from other nodes. We will look at inter-node communication later, for now it will suffice to pass the default remote table, which defines the built-in types that Cloud Haskell needs at a minimum in order to run.

In app/Main.hs, we start with our imports:

```haskell
import Network.Transport.TCP (createTransport, defaultTCPParameters)
import Control.Distributed.Process
import Control.Distributed.Process.Node
```

Figure 18 - Library import into Main.hs

Our TCP network transport backend needs an IP address and port to get started with:



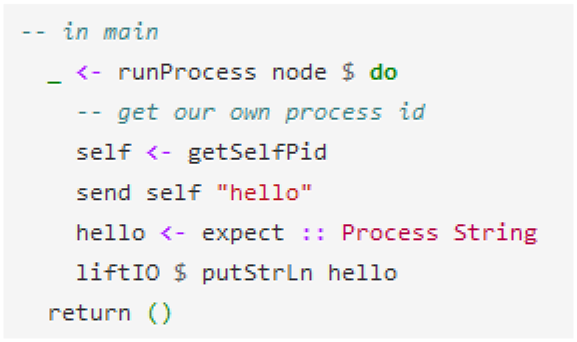
```haskell
main :: IO ()
main = do
  Right t <- createTransport "127.0.0.1" "10501" defaultTCPParameters
  node <- newLocalNode t initRemoteTable
  ....
```

Figure 19 - Set IP and port for Network Transport Backend

And now we have a running node.

10.5. Sending messages

We start a new process by evaluating runProcess, which takes a node and a Process action to run, because our concurrent code will run in the Process monad. Each process has an identifier associated to it. The process id can be used to send messages to the running process - here we will send one to ourselves!



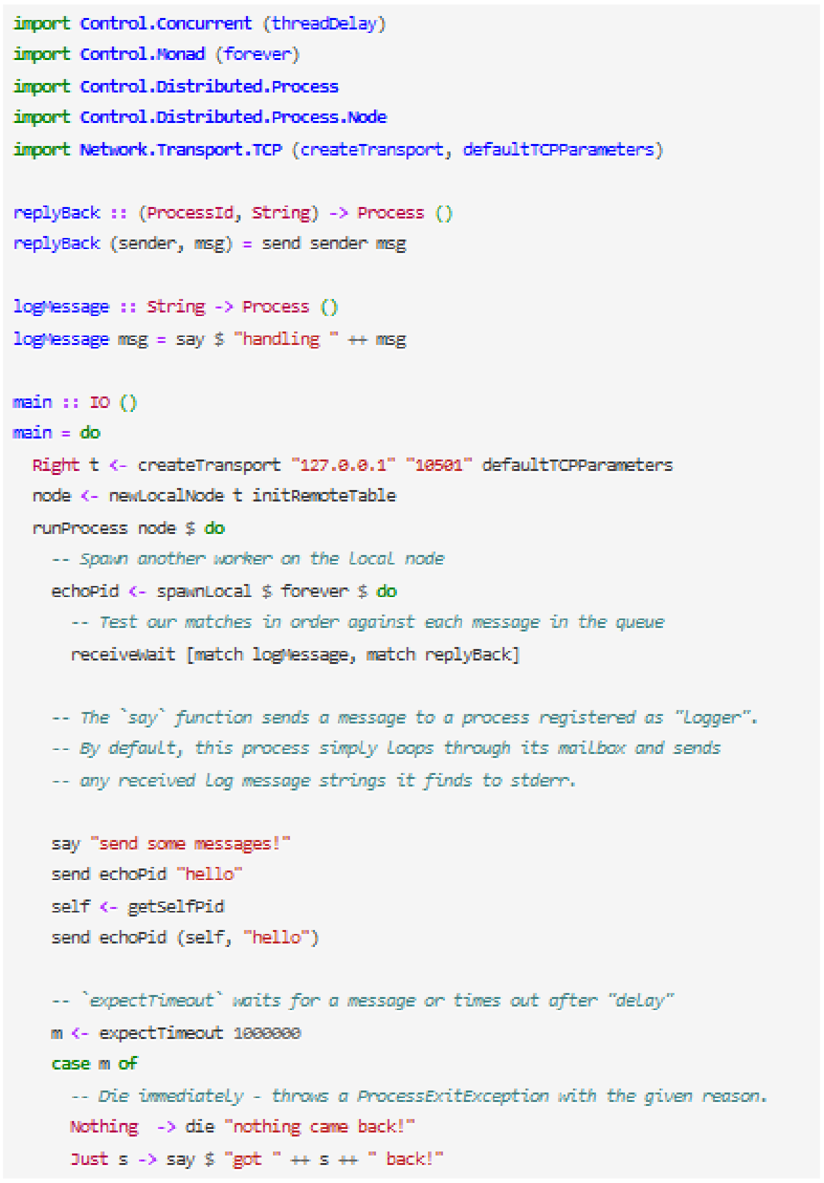
```haskell
-- in main
  _ <- runProcess node $ do
    -- get our own process id
    self <- getSelfPid
    send self "hello"
    hello <- expect :: Process String
    liftIO $ putStrLn hello
  return ()
```

Figure 20 - Start new process

Note that we haven't deadlocked our own thread by sending to and receiving from its mailbox in this fashion. Sending messages is a completely asynchronous operation - even if the recipient doesn't exist, no error will be raised and evaluating send will not block the caller, even if the caller is sending messages to itself.

Each process also has a mailbox associated with it. Messages sent to a process are queued in this mailbox. A process can pop a message out of its mailbox using expect or the receive* family of functions. If no message of the expected type is in the mailbox currently, the process will block until there is. Messages in the mailbox are ordered by time of arrival.

Let's spawn two processes on the same node and have them talk to each other:



```haskell
import Control.Concurrent (threadDelay)
import Control.Monad (forever)
import Control.Distributed.Process
import Control.Distributed.Process.Node
import Network.Transport.TCP (createTransport, defaultTCPParameters)

replyBack :: (ProcessId, String) -> Process ()
replyBack (sender, msg) = send sender msg

logMessage :: String -> Process ()
logMessage msg = say $ "handling " ++ msg

main :: IO ()
main = do
  Right t <- createTransport "127.0.0.1" "10501" defaultTCPParameters
  node <- newLocalNode t initRemoteTable
  runProcess node $ do
    -- Spawn another worker on the local node
    echoPid <- spawnLocal $ forever $ do
      -- Test our matches in order against each message in the queue
      receiveWait [match logMessage, match replyBack]

    -- The `say` function sends a message to a process registered as "logger".
    -- By default, this process simply loops through its mailbox and sends
    -- any received log message strings it finds to stderr.

    say "send some messages!"
    send echoPid "hello"
    self <- getSelfPid
    send echoPid (self, "hello")

    -- `expectTimeout` waits for a message or times out after "delay"
    m <- expectTimeout 1000000
    case m of
      -- Die immediately - throws a ProcessExitException with the given reason.
      Nothing  -> die "nothing came back!"
      Just s -> say $ "got " ++ s ++ " back!"
```

Figure 21 - Message sending application demo

Note that we've used `receiveWait` this time around to get a message. `receiveWait` and similarly named functions can be used with the Match data type to provide a range of advanced message processing capabilities. The match primitive allows you to construct a "potential message handler" and have it evaluated against received (or incoming) messages. Think of a list of Matches as the distributed equivalent of a pattern match. As with expect, if the mailbox does not contain a message that can be matched, the evaluating process will be blocked until a message arrives which *can* be matched.

In the *echo server* above, our first match prints out whatever string it receives. If the first message in our mailbox is not a String, then our second match is evaluated. Thus, given a tuple `t :: (ProcessId, String)`, it will send the String component back to the sender's `ProcessId`. If neither match succeeds, the echo server block until another message arrives and tries again.

10.6. Serializable data

Processes may send any datum whose type implements the Serializable type class, defined as:

```
class (Binary a, Typeable) => Serializable a
instance (Binary a, Typeable a) => Serializable a
```

Figure 22 - Serializable type class

That is, any type that is Binary and Typeable is Serializable. This is the case for most of Cloud Haskell's primitive types as well as many standard data types. For custom data types, the Typeable instance is always given by the compiler, and the Binary instance can be auto-generated too in most cases, e.g.:

```
{-# LANGUAGE DeriveDataTypeable #-}
{-# LANGUAGE DeriveGeneric #-}

data T = T Int Char deriving (Generic, Typeable)

instance Binary T
```

Figure 23 - Use of Typable instance

10.7. Spawning Remote Processes

We saw above that the behaviour of processes is determined by an action in the Process monad. However, actions in the Process monad, no more serializable than actions in the IO monad. If we can't serialize actions, then how can we spawn processes on remote nodes?

The solution is to consider only static actions and compositions thereof. A static action is always defined using a closed expression (intuitively, an expression that could in principle be evaluated at compile-time since it does not depend on any runtime arguments). The type of static actions in Cloud Haskell is Closure (Process a). More generally, a value of type Closure b is a value that was constructed explicitly as the composition of symbolic pointers and serializable values.

Values of type Closure b are serializable, even if values of type b might not. For instance, while we can't in general send actions of type Process (), we can construct a value of type Closure (Process ()) instead, containing a symbolic name for the action, and send that instead. So long as the remote end understands the same meaning for the symbolic name, this works just as well. A remote spawn then, takes a static action and sends that across the wire to the remote node.

Static actions are not easy to construct by hand, but fortunately Cloud Haskell provides a little bit of Template Haskell to help. If f :: T1 -> T2 then:

```
$(mkClosure 'f) :: T1 -> Closure T2
```

Figure 24 - Use of mkClosure

You can turn any top-level unary function into a Closure using mkClosure. For curried functions, you'll need to uncurry them first (i.e. "tuple up" the arguments). However, to ensure that the remote side can adequately interpret the resulting Closure, you'll need to add a mapping in a so-called remote table associating the symbolic name of a function to its value. Processes can only be successfully spawned on remote nodes of all these remote nodes have the same remote table as the local one.

We need to configure our remote table (see the API reference for more details) and the easiest way to do this, is to let the library generate the relevant code for us.

For example:

```
sampleTask :: (TimeInterval, String) -> Process ()
sampleTask (t, s) = sleep t >> say s

remotable ['sampleTask]
```

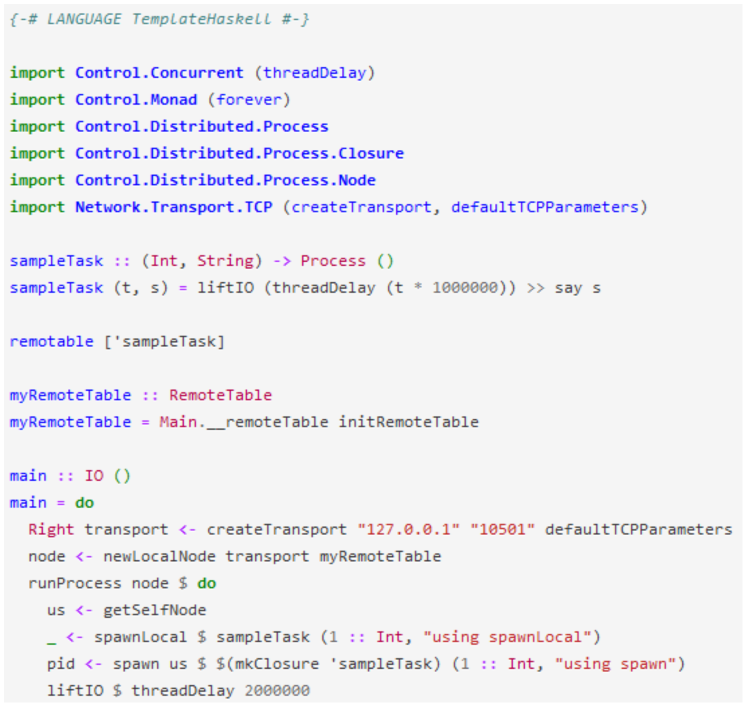
Figure 25 - Configuration of remote table

The last line is a top-level Template Haskell splice. At the call site for spawn, we can construct a Closure corresponding to an application of sampleTask like so:

```
($(mkClosure 'sampleTask) (seconds 2, "foobar"))
```

Figure 26 - Use of sample task

The call to `remotable` implicitly generates a remote table by inserting a top-level definition `__remoteTable :: RemoteTable -> RemoteTable` in our module for us. We compose this with other remote tables in order to come up with a final, merged remote table for all modules in our program:



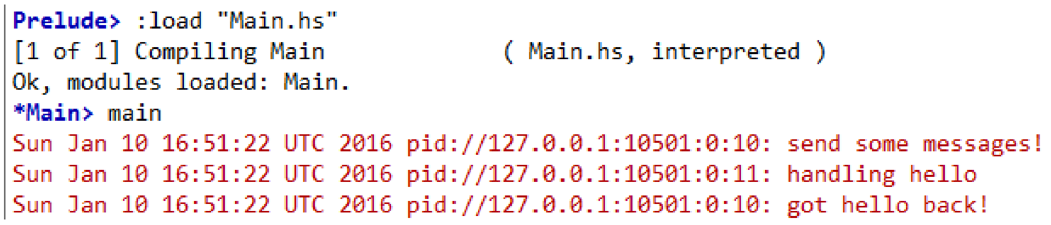
```haskell
{-# LANGUAGE TemplateHaskell #-}

import Control.Concurrent (threadDelay)
import Control.Monad (forever)
import Control.Distributed.Process
import Control.Distributed.Process.Closure
import Control.Distributed.Process.Node
import Network.Transport.TCP (createTransport, defaultTCPParameters)

sampleTask :: (Int, String) -> Process ()
sampleTask (t, s) = liftIO (threadDelay (t * 1000000)) >> say s

remotable ['sampleTask]

myRemoteTable :: RemoteTable
myRemoteTable = Main.__remoteTable initRemoteTable

main :: IO ()
main = do
  Right transport <- createTransport "127.0.0.1" "10501" defaultTCPParameters
  node <- newLocalNode transport myRemoteTable
  runProcess node $ do
    us <- getSelfNode
    _ <- spawnLocal $ sampleTask (1 :: Int, "using spawnLocal")
    pid <- spawn us $ $(mkClosure 'sampleTask) (1 :: Int, "using spawn")
    liftIO $ threadDelay 2000000
```

Figure 27 - Generation of a remote call table

In the above example, we spawn sampleTask on node us in two different ways:

- using spawn, which expects some node identifier to spawn a process on along for the action of the process
- using spawnLocal, a specialization of spawn to the case when the node identifier actually refers to the local node (i.e. us). In this special case, no serialization is necessary, so passing an action directly rather than a Closure works just fine

Running the above code will result in printing of the data exchange between the server and the client:



```
Prelude> :load "Main.hs"
[1 of 1] Compiling Main             ( Main.hs, interpreted )
Ok, modules loaded: Main.
*Main> main
Sun Jan 10 16:51:22 UTC 2016 pid://127.0.0.1:10501:0:10: send some messages!
Sun Jan 10 16:51:22 UTC 2016 pid://127.0.0.1:10501:0:11: handling hello
Sun Jan 10 16:51:22 UTC 2016 pid://127.0.0.1:10501:0:10: got hello back!
```

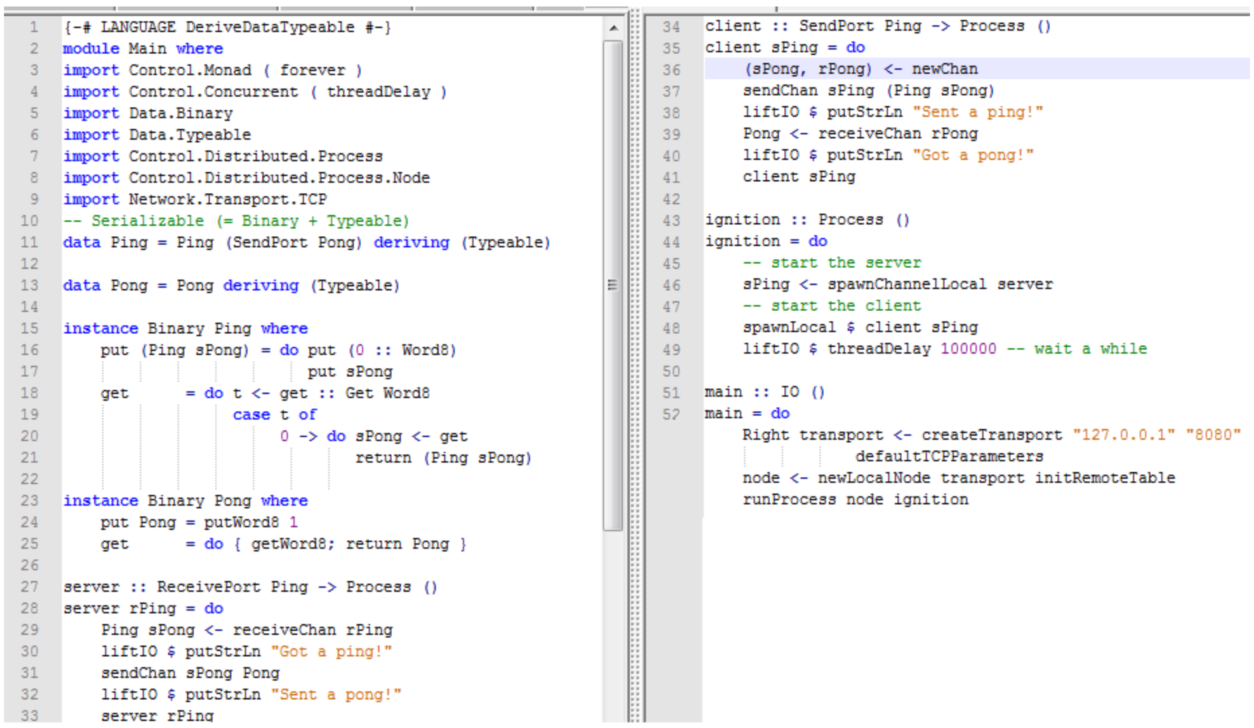
Figure 28 - Running the code

10.8. Classic Ping Pong Example

The above example does nothing more than printing the request and response from client/server. The next example, based on the first one, respects the so called “ping-pong” principle.

We assume that there are two threads *A* and *B*. The thread *A* sends a text (in our example, but in real life applications this may vary from a variable to a very large and complex request), let’s say *Ping* and pauses himself after that. Another thread *B* waits for this text, ‘awakes’ himself, sends the text *Pong* and then goes back to ‘sleep’ allowing thread *A* to restart this process.

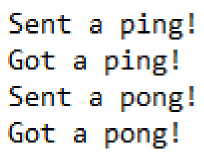
This thread synchronization procedure, it may seem without reason but it’s a very important and basic example of concurrency and must be understood by every developer that wishes to approach more complex and large algorithms:



```haskell
{-# LANGUAGE DeriveDataTypeable #-}
module Main where
import Control.Monad ( forever )
import Control.Concurrent ( threadDelay )
import Data.Binary
import Data.Typeable
import Control.Distributed.Process
import Control.Distributed.Process.Node
import Network.Transport.TCP
-- Serializable (= Binary + Typeable)
data Ping = Ping (SendPort Pong) deriving (Typeable)

data Pong = Pong deriving (Typeable)

instance Binary Ping where
    put (Ping sPong) = do put (0 :: Word8)
                          put sPong
    get       = do t <- get :: Get Word8
                   case t of
                        0 -> do sPong <- get
                                return (Ping sPong)

instance Binary Pong where
    put Pong = putWord8 1
    get       = do { getWord8; return Pong }

server :: ReceivePort Ping -> Process ()
server rPing = do
    Ping sPong <- receiveChan rPing
    liftIO $ putStrLn "Got a ping!"
    sendChan sPong Pong
    liftIO $ putStrLn "Sent a pong!"
    server rPing
client :: SendPort Ping -> Process ()
client sPing = do
    (sPong, rPong) <- newChan
    sendChan sPing (Ping sPong)
    liftIO $ putStrLn "Sent a ping!"
    Pong <- receiveChan rPong
    liftIO $ putStrLn "Got a pong!"
    client sPing

ignition :: Process ()
ignition = do
    -- start the server
    sPing <- spawnChannelLocal server
    -- start the client
    spawnLocal $ client sPing
    liftIO $ threadDelay 100000 -- wait a while

main :: IO ()
main = do
    Right transport <- createTransport "127.0.0.1" "8080"
                           defaultTCPParameters
    node <- newLocalNode transport initRemoteTable
    runProcess node ignition
```

Figure 29 - Ping Pong algorithm

Running the above algorithm will result in a synchronized print of *Got a ping!* and *Sent a pong!* messages:



```
Sent a ping!
Got a ping!
Sent a pong!
Got a pong!
```

Figure 30 - Ping Pong algorithm print

Due to the speed of Haksell computation and the relative slow speed of message printing, sometimes, this messages will be scrambled, proving the computing speed and efficiency of this Haskell algorithm.

11. Final conclusions

Understanding these two basic examples can make every Haskell developer or enthusiast understand, or at least get a grasp of what concurrency is like under this procedural language. *Cloud Haskell Platform* offers complete libraries that support concurrency and proves once again the computing power of Haskell and its versatility. Adding to this statement, other open source packages like *stack* or *cabal* are important tools to know and have for every Haskell developer.

In conclusion, this paper can serve every Haskell enthusiast in their effort to familiarize with the suite offered by *Cloud Haskell Platform*, with the tools used for building various libraries for Haskell or with the theoretical aspects of concurrency and distributed programming.

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