

Cloud Haskell Semantics (DRAFT)

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1 Introduction

Cloud Haskell brings Erlang-style concurrency to Haskell in the form of a library.¹ The original publication [Epstein et al., 2011] is a good introduction to Cloud Haskell, and is accompanied by an ever-growing number of resources, collected on the Haskell Wiki.² The current document augments the original publication about Cloud Haskell by giving a precise semantics to the Cloud Haskell primitives. It is meant as a reference, not an introduction.

The original Cloud Haskell paper stipulates that messages are “asynchronous, reliable, and buffered”, but does not describe how this can be achieved. Understanding “reliable” to mean “reliable ordered” (or “TCP-like”), the reliability of message delivery comes from the reliability of the underlying network protocol—up to a point.

The problem is that the underlying network protocol is connection-oriented, but Cloud Haskell is not. Intuitively, when P sends a message to Q , we open a reliable-ordered connection from P to Q . Reliability of message delivery now follows from reliability of the network protocol, until P somehow gets disconnected from Q . If P now sends another message to Q , the implementation cannot simply reconnect: after all, some messages that were sent on the first connection might not have been delivered. This means that P might send m_1, m_2, m_3 to Q , but Q will receive m_1, m_3 .³

One (non-)solution is for P to buffer all messages it sends to Q , and remove messages from this buffer only when Q acknowledges that it received them. On a reconnect P must ask which message Q last received, and retransmit the rest. This means that when P gets disconnected from Q , it must infinitely buffer all messages sent to Q (until a connection is reestablished). However, infinite buffering is too strong a requirement; moreover, this is unsatisfactory because it means implementing a reliable protocol on top of the underlying reliable network protocol. We would like a different solution.

Instead, Cloud Haskell does *not* attempt to reconnect automatically, but provides a `reconnect` primitive which gives programmers the option of reconnecting manually. This is an explicit acknowledgement from the programmer that message loss might occur, and forces them to consider how such loss might be dealt with.

The semantics we present is based on [Svensson et al., 2010], which we will refer to as the “Unified” semantics. However, we will present the semantics in a more “Haskell” style following the semantics for STM [Harris et al., 2008]. It differs from the Unified semantics in that

1. We introduce an explicit notion of *reconnecting* (with potential message loss)
2. We simplify the semantics: we “flatten” sets of nodes of processes as sets of processes (but assume a mapping from process identifiers to node identifiers), do not have per-process mailboxes (but only the system queue or “ether”) and do not have an explicit concept of node controllers

Our semantics differs from the STM semantics in that we pretend that the Cloud Haskell `Process` monad is the top-level monad, and do not consider the `IO` monad at all. Current imprecisions with respect to the “real” Cloud Haskell are

1. We ignore the issue of serializability, other than to say that the semantics will get stuck when trying to send a non-serializable payload; consequently, we do not formalize `static`
2. We do not formalize all Cloud Haskell primitives (merging of ports, “advanced messaging”, and others)

¹<http://hackage.haskell.org/package/distributed-process>

²<http://www.haskell.org/haskellwiki/Cloud.Haskell>

³Indeed, message passing in Erlang is ordered but unreliable for the same reason [Svensson and Fredlund, 2007].

| | | | |
|--|----------------|--|------------------|
| $\frac{\llbracket M \rrbracket = V \quad M \neq V}{M \rightarrow V} \text{EVAL}$ | | $\frac{M \rightarrow N}{\langle \mathbb{P}[M]_{pid}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[N]_{pid}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle} \text{ADMIN}$ | |
| $\text{return } N \gg= M \rightarrow M N$ | BIND | $\text{catch } (\text{return } M) N \rightarrow \text{return } M$ | CATCH_1 |
| $\text{throw } N \gg= M \rightarrow \text{throw } N$ | THROW | $\text{catch } (\text{throw } M) N \rightarrow N M$ | CATCH_2 |

Figure 1: Administrative Transitions

3. Some of the concepts that we do formalize are lower-level concepts; for instance, the primitive `spawn` that we formalize is asynchronous (following the Unified semantics); a synchronous construct can be derived.

2 Preliminaries

Cloud Haskell Processes run on *nodes*. Processes communicate by sending messages to each other (directly or using typed channels). Processes can also send messages to nodes (for instance, a request to spawn or monitor a process).

We assume disjoint countable sets `NodeId`, `ProcessId`, and `ChannelId`, changed over by *nid*, *pid* and *cid* respectively, and representing process identifiers, node identifiers, and (typed) channel identifiers. We assume the existence of total functions

$$\begin{aligned} \text{node} &: (\text{ProcessId} \uplus \text{ChannelId}) \rightarrow \text{NodeId} \\ \text{process} &: \text{ChannelId} \rightarrow \text{ProcessId} \end{aligned}$$

and define

$$\text{Identifier} = \text{NodeId} \uplus \text{ProcessId} \uplus \text{ChannelId}$$

and let *id* range over `Identifier`.

We represent a process as a pair M_{pid} of a term *M* and a process ID *pid*. We will denote a set of processes as

$$M_{pid} \parallel \dots \parallel N_{pid'}$$

A *system* $\langle \mathcal{P}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle$ is a tuple containing a set \mathcal{P} of processes, a *system queue* \mathcal{Q} , a *blacklist* \mathcal{B} , and a set of monitors \mathcal{M} . The set of monitors \mathcal{M} is a set of tuples $(id_{to}, pid_{fr}, nid, ref)$ which records that node *nid* knows that process pid_{fr} is monitoring id_{to} (*ref* is the monitor reference). The system queue is a set of triples $(id_{to}, id_{fr}, message)$ of messages that have been sent but not yet processed. The blacklist records disconnections and is represented as a of pairs (id_{to}, id_{fr}) .

3 Semantics

We follow the STM semantics as closely as possible. The language is the same except for the primitives considered, and we use the same concept of evaluation contexts:

$$\begin{aligned} \text{value} \quad V & ::= id \mid \lambda x. M \mid \text{return } M \mid M \gg= N \mid \text{throw } M \mid \text{catch } M N \mid \\ & \quad \text{expect} \mid \text{send } pid \ M \mid \text{spawn } nid \ M \mid \text{monitor } id \\ \text{term} \quad M, N & ::= x \mid V \mid MN \mid \dots \\ \text{Evaluation} \quad \mathbb{E} & ::= [] \mid \mathbb{E} \gg= M \mid \text{catch } \mathbb{E} \ M \\ \text{context} \quad \mathbb{P}_{pid} & ::= \mathbb{E} []_{pid} \parallel \mathcal{P} \end{aligned}$$

Indeed, the “administrative” transitions are identical (Figure 1).

3.1 Disconnect and Reconnect

Figure 2 gives the semantics for disconnecting and reconnecting. Rule `DISCONNECT` models random network disconnect between nodes nid_1 and nid_2 . We assume that entire *nodes* get disconnected from each other, not individual processes. *Reconnecting* however is on a per process basis (`RECON-EX`). Connections to and from node controllers can be implicitly reconnected (`RECON-IM1` and `RECON-IM2`).

$$\begin{array}{c}
\frac{nid_1 \neq nid_2}{\langle \mathcal{P}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathcal{P}; \mathcal{Q}; \mathcal{B} \cup (\overline{nid_1} \times \overline{nid_2}); \mathcal{M} \rangle} \text{DISCONNECT} \\
\frac{}{\langle \mathbb{P}[\text{reconnect } id_{to}]_{pid_{fr}}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[\text{return } ()]_{pid}; \mathcal{Q}; \mathcal{B} \setminus (id_{to}, pid_{fr}); \mathcal{M} \rangle} \text{RECON-EX} \\
\frac{}{\langle \mathcal{P}; \mathcal{Q}; \mathcal{B}, (nid_{to}, id_{fr}); \mathcal{M} \rangle \rightarrow \langle \mathcal{P}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle} \text{RECON-IM}_1 \quad \frac{}{\langle \mathcal{P}; \mathcal{Q}; \mathcal{B}, (id_{to}, nid_{fr}); \mathcal{M} \rangle \rightarrow \langle \mathcal{P}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle} \text{RECON-IM}_2
\end{array}$$

where

$$\overline{nid} \subset \text{Identifier} = \{nid\} \cup \{pid \mid \text{node}(pid) = nid\} \cup \{cid \mid \text{node}(cid) = nid\}$$

Figure 2: Disconnect and Reconnect

$$\begin{array}{c}
\frac{}{\langle \mathbb{P}[\text{send } pid_{to} \ M]_{pid_{fr}}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[\text{return } ()]_{pid_{fr}}; \mathcal{Q} \triangleright_{\mathcal{B}} (pid_{to}, pid_{fr}, M); \mathcal{B}; \mathcal{M} \rangle} \text{SEND} \\
\frac{id_{fr} \notin \text{senders}(\mathcal{Q})}{\langle \mathbb{P}[\text{expect}]_{pid_{to}}; \mathcal{Q}, (pid_{to}, id_{fr}, M), \mathcal{Q}'; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[\text{return } M]_{pid_{to}}; \mathcal{Q}, \mathcal{Q}'; \mathcal{B}; \mathcal{M} \rangle} \text{EXPECT} \\
\frac{cid \text{ fresh} \quad \text{process}(cid) = pid}{\langle \mathbb{P}[\text{newChan}]_{pid}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[\text{return } (cid^s, cid^r)]_{pid}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle} \text{NEWCHAN} \\
\frac{}{\langle \mathbb{P}[\text{sendChan } cid_{to}^s \ M]_{pid_{fr}}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[\text{return } ()]_{pid_{fr}}; \mathcal{Q} \triangleright_{\mathcal{B}} (cid_{to}, pid_{fr}, M); \mathcal{B}; \mathcal{M} \rangle} \text{SENDCHAN} \\
\frac{pid_{fr} \notin \text{senders}(\mathcal{Q})}{\langle \mathbb{P}[\text{receiveChan } cid_{to}^r]_{pid}; \mathcal{Q}, (cid_{to}, pid_{fr}, M), \mathcal{Q}'; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[\text{return } M]_{pid}; \mathcal{Q}, \mathcal{Q}'; \mathcal{B}; \mathcal{M} \rangle} \text{RECEIVECHAN} \\
\frac{ref \text{ fresh}}{\langle \mathbb{P}[\text{spawn } nid \ M]_{pid}; \mathcal{Q}; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathbb{P}[\text{return } ref]_{pid}; \mathcal{Q} \triangleright_{\mathcal{B}} (nid, pid, \text{spawn } ref \ M); \mathcal{B}; \mathcal{M} \rangle} \text{SPAWN-ASYNC} \\
\frac{pid \notin \text{senders}(\mathcal{Q}) \quad pid' \text{ fresh} \quad \text{node}(pid') = nid}{\langle \mathcal{P}; \mathcal{Q}, (nid, pid, \text{spawn } ref \ M), \mathcal{Q}'; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle \mathcal{P} \parallel M_{pid'}; \mathcal{Q}, \mathcal{Q}' \triangleright_{\mathcal{B}} (pid, nid, \text{spawned } ref \ pid'); \mathcal{B}; \mathcal{M} \rangle} \text{SPAWN-EXEC}
\end{array}$$

where

$$\begin{array}{ll}
\mathcal{Q} \triangleright_{\mathcal{B}} (id_{to}, id_{fr}, M) = \mathcal{Q}, (id_{to}, id_{fr}, M) & \text{if } (id_{to}, id_{fr}) \notin \mathcal{B} \\
\mathcal{Q} \triangleright_{\mathcal{B}} (id_{to}, id_{fr}, M) = \mathcal{Q} & \text{otherwise}
\end{array}$$

($\triangleright_{\mathcal{B}}$) is only defined for serializable payloads.

Figure 3: Basic Primitives

3.2 Communication

The semantics for the basic primitives are listed in Figure 3. Once a connection has been blacklisted, no further messages can be sent across that connection (until an explicit or implicit reconnect).

Message passing is ordered but only for a given sender and receiver; no ordering guarantees exist between messages sent by different processes. For that reason rules EXPECT, RECEIVECHAN and SPAWN-EXEC choose the *first* message of a *randomly chosen* sender.

Since the semantics is not type-driven, we represent typed channels simply as an identifier with an annotation whether it is the send-end (cid^s) or the receive end (cid^r) of the channel (rules NEWCHAN, SENDCHAN and RECEIVECHAN).

Spawning finally is asynchronous. When process P spawns process Q on node nid (rule SPAWN-ASYNC) a message is sent to node nid (which may, of course, never arrive). When the remote node receives the message and actually spawns Q (rule SPAWN-EXEC) it sends a message back to P with Q 's process ID. In Cloud Haskell this primitive is called `spawnAsync`, and the Cloud Haskell `spawn` primitive is defined in terms of `spawnAsync` (we do not consider the synchronous version in this document).

| | |
|---|-------------|
| $\frac{nid_{fr} = \text{node}(pid_{fr}) \quad nid_{to} = \text{node}(id_{to}) \quad \text{ref fresh}}{\langle P[\text{monitor } id_{to}]_{pid_{fr}}; Q; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle P[\text{return ref}]_{pid_{fr}}; Q \triangleright_{\mathcal{B}} (nid_{to}, pid_{fr}, \text{monitor ref } id_{to}); \mathcal{B}; \mathcal{M}, (id_{to}, pid_{fr}, nid_{fr}, \text{ref}) \rangle}$ | MON-LOC |
| $\frac{pid_{fr} \notin \text{senders}(Q)}{\langle P; Q, (nid_{to}, pid_{fr}, \text{monitor ref } id_{to}), Q'; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle P; Q, Q'; \mathcal{B}; \mathcal{M}, (id_{to}, pid_{fr}, nid_{to}, \text{ref}) \rangle}$ | MON-REM |
| $\frac{nid_{fr} = \text{node}(pid_{fr}) \quad (id_{to}, pid_{fr}) \in \mathcal{B}}{\langle P; Q; \mathcal{B}; \mathcal{M}, (id_{to}, pid_{fr}, nid_{fr}, \text{ref}) \rangle \rightarrow \langle P; Q, (pid_{fr}, id_{to}, \text{discon ref}); \mathcal{B}; \mathcal{M} \rangle}$ | MON-DIS |
| $\frac{\text{node}(pid) = nid}{\langle (\text{return } ())_{pid} \parallel P; Q; \mathcal{B}; \mathcal{M}, (pid, pid', nid, \text{ref}) \rangle \rightarrow \langle (\text{return } ())_{pid} \parallel P; Q \triangleright_{\mathcal{B}} (pid', nid, \text{died ref}); \mathcal{B}; \mathcal{M} \rangle}$ | MON-RET |
| $\frac{\text{node}(pid) = nid}{\langle (\text{throw } M)_{pid} \parallel P; Q; \mathcal{B}; \mathcal{M}, (pid, pid', nid, \text{ref}) \rangle \rightarrow \langle (\text{throw } M)_{pid} \parallel P; Q \triangleright_{\mathcal{B}} (pid', nid, \text{exc ref } M); \mathcal{B}; \mathcal{M} \rangle}$ | MON-THROW |
| $\frac{\text{node}(pid) = nid \quad pid \notin \mathcal{P}}{\langle P; Q; \mathcal{B}; \mathcal{M}, (pid, pid', nid, \text{ref}) \rangle \rightarrow \langle P; Q \triangleright_{\mathcal{B}} (pid', nid, \text{unknown ref}); \mathcal{B}; \mathcal{M} \rangle}$ | MON-UNKNOWN |

Figure 4: Monitoring

| | |
|---|----------|
| $\frac{\text{node}(pid) = nid \quad \nexists pid', \text{ref} \cdot (pid', pid, nid, \text{ref}) \in \mathcal{M}}{\langle (\text{return } ())_{pid} \parallel P; Q; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle P; Q; \mathcal{B}; \mathcal{M} \rangle}$ | TERMRET |
| $\frac{\text{node}(pid) = nid \quad \nexists pid', \text{ref} \cdot (pid', pid, nid, \text{ref}) \in \mathcal{M}}{\langle (\text{throw } M)_{pid} \parallel P; Q; \mathcal{B}; \mathcal{M} \rangle \rightarrow \langle P; Q; \mathcal{B}; \mathcal{M} \rangle}$ | TERMTROW |

Figure 5: Process Termination

3.3 Monitoring

When process P on node nid_P wants to monitor process Q on node nid_Q both nodes must be notified. The local node it notified immediately, and a message is sent to the remote node (rules MON-LOC and MON-REM). As with all messages, the message to the remote node might be lost. When P is disconnected from Q it is the responsibility of P 's local node nid_P to notify P (MON-DIS); when Q terminates (MON-RET) or crashes (MON-THROW) it is the responsibility of the remote node nid_Q to notify P .

3.4 Process Termination

The rules for normal and abnormal process termination are defined in Figure 5. When a process crashes it dies silently, unless monitors are setup.

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