DESCRIPTION OF THE CHORD PROTOCOL USING ASMS FORMALISM

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ABSTRACT. This paper describes the overlay protocol Chord using the formalism of Abstract State Machines. The formalization concerns Chord actions that maintain ring topology and manipulate distributed keys. We define a class of runs and prove the correctness of our formalization with respect to it.

Keywords: Peer-to-peer, Chord, DHT-based Overlay Networks, Abstract State Machines, Formalization.

1. Introduction

A decentralized Peer-to-Peer system (P2P) involves many peers (nodes) which execute the same software, participate in the system having equal rights and might join or leave the system continuously. In such a framework processes are dynamically distributed to peers, with no centralized control. P2P systems have no inherent bottlenecks and can potentially scale very well. Moreover, since there are no dedicated nodes critical for systems’ functioning, those systems are resilient to failures, attacks, etc. The main applications of P2P-systems involve: file sharing, redundant storage, real-time media streaming, etc.

P2P systems are frequently implemented in a form of overlay networks, a structure that is totally independent of the underlying network that is actually connecting devices. Overlay network represents a logical look on organization of the resources. Some of the overlay networks are realized in the form of Distributed Hash Tables (DHT) that provide a lookup service similar to a hash table; (key, value) pairs are stored in a DHT, and any participating peer can efficiently retrieve the value associated with a given key. Responsibility for maintaining the mapping from keys to values is distributed among the peers, in such a way that any change in the set of participants causes a minimal amount of disruption. It allows a DHT to scale to extremely large number of peers and to handle continual node arrivals, departures, and failures. The Chord protocol is one of the first, simplest and most popular DHTs. The paper which introduces Chord has been recently awarded the SIGCOMM 2011 Test-of-Time Award.

Our aim is to describe Chord using Abstract State Machine (ASM) and to prove the correctness of the formalization, which was motivated by the obvious fact that errors in concurrent systems are difficult to reproduce and find merely by program testing. There are at least two reasons for using ASMs. The ASM-code for Chord presented in this paper has been written following one of the best implementations of the high level C++-like pseudo code from.

Recently, several non-relational database systems (NRDBMS) have been developed that are usually based on the Chord like technology. To analyze their
behavior, it might be useful to characterize situations when correctness of the underlying protocol holds. Following that idea, we have formulated several deterministic conditions that guarantee correctness of Chord, and proved the corresponding statements. This is in contrast to the approach from [17, 20–22] where a probabilistic analysis is proposed, and correctness holds with "high probability".

Most of them are based on the Chord like technology. NRDBMSs are used when a large amount of data exist and do not need frequent update. Usually, an NRDBMS does not guarantee correctness.

The main objectives of Chord are maintaining the ring topology as nodes concurrently join and leave a network, mapping keys onto nodes and distributed data handling. The formalism of ASM enables us to precisely describe a class of possible runs - so called regular runs - of the protocol, and to prove correctness of the main operations with respect to it. Moreover, several examples of runs, given in Example 3.1, that violate the constraints for the regular runs illustrate how correctness can be broken in those cases.

2. ASM Formalization of Chord

2.1. Basic Notions. Let $L$, $M$ and $K$ be three fixed positive integers, and $N = 2^M$. We will consider the following disjoint universes:

- the set $Peer = \{p_1, \ldots, p_L\}$ of all peers that might participate in the considered Chord network,
- the set $Key = \{k_1, \ldots, k_K\}$ of identifiers of objects that might be stored in the considered Chord network, and the set $Value = \{v_1, \ldots, v_K\}$ of the values of those $K$ objects,
- the set $Chord = \{0, 1, \ldots, N - 1\}$ denoting at most $N$ peers that are involved in the network in a particular moment,
- the sets $Join = \{join, skip\}$ and $Action = \{put, get, fairLeave, unfairLeave, skip\}$ which represent the actions of the peers.

Note that:

- it might be that $L > N$ ($K > N$), i.e., that there are more peers (objects to be stored in the network) than nodes, but it can never be $N > L$, and
- without any loss of generality we assume that the numbers of keys and values are the same; if there are more values than keys, all values mapped to the same key might be organized in a list.

Any peer, active in the network will be called a node. We assume that a node (Fig. 1) is represented by its identifier $id$ in the network, information on its predecessor and successor, a finger table, a pointer ($next$) to an element in the finger table which will be updated in the current stabilization cycle, and a list of $(key, value)$ pairs of the records for which the node is responsible for.

More formally, we introduce the following functions:

- $id : Peer \rightarrow Chord \cup \{undef\}$
- $successor : Chord \rightarrow Chord$,
- $predecessor : Chord \rightarrow Chord$,
- $finger : Chord \rightarrow Chord^*$,
- $next : Chord \rightarrow \{1, \ldots, M\}$, and
- $keyvalue : Chord \rightarrow (Chord \times Value)^*$,
where $\text{Chord}^*$ is the set that contains lists of nodes’ identifiers, and $(\text{Chord} \times \text{Value})^*$ is the set of lists containing pairs $\langle \text{hash}(\text{key}), \text{value} \rangle$. Each $\text{finger}(x)$ has $M$ entries ordered respect to the ring ordering.

In other words, a peer $p$, which is a node, is represented by the tuple:

$\langle \text{id}(p), \text{successor}(\text{id}(p)), \text{predecessor}(\text{id}(p)), \text{finger}(\text{id}(p)), \text{next}(\text{id}(p)), \text{keyvalue}(\text{id}(p)) \rangle$.

Table 1 shows all the other functions that will be used in the formal description of the protocol, but that do not directly change the representations of nodes. We assume that the five functions in Table 1 ($\text{hash}$, $\text{ping}$, $\text{known\_nodes}$, $\text{key\_value}$ and $\text{keys}$) are external.

The $\text{hash}$ function assigns identifiers of nodes to peers and keys:

$\text{hash} : \text{Peer} \cup \text{Key} \rightarrow \text{Chord} \cup \{\text{undef}\}$,

where $\text{undef}$ is a special value which indicates that:

- there are $N$ nodes in the network, and an identifier is requested for a new node, or
- there are $N$ keys in the network, but we try to add a new key.

The function must also guarantee that in each moment two different active peers (keys) have different hash values. However, note that it is possible that in different moments different peers have the same identifier. Also, it may happen that a peer can have different identifiers (obtained by different calls of the $\text{hash}$ function before and after a period in which the peer is not present in the network). The above mentioned $\text{id}$ function can be explained as a "local" counterpart of $\text{hash}$. 

### Table 1. Chord functions

| Function       | Description                                                                 |
|----------------|----------------------------------------------------------------------------|
| $\text{hash}$  | Maps the sets of peers and keys to $\text{Chord} \cup \{\text{undef}\}$    |
| $\text{ping}$  | Tests whether a node is reachable                                          |
| $\text{member\_pf}$ | Checks whether a node is between two nodes in $\text{Chord}$                |
| $\text{communication}$ | Realizes communication requests                                           |
| $\text{mode}$  | Determines Peer\_agent state                                              |
| $\text{known\_nodes}$ | Simulates external knowledge about existing nodes                          |
| $\text{key\_value}$ | Select a $(\text{key}, \text{value})$ for storing in the network          |
| $\text{keys}$  | Select to look for a value with particular key                            |

![Figure 1. Structure of Chord node](image)
Namely, we can assume that the values produced by hash are stored in the local memory and read and published by id to reduce the number of expensive calls of hash. In the program given below, id will be invoked with the argument Me to allow a node to identify itself in the network.

The external function ping, defined as:

\[ ping : \text{Chord} \rightarrow \{true, false\} \]

returns true or false, depending on whether the argument is reachable in the network.

The function member_of:

\[ \text{member}_of : \text{Chord} \times \text{Chord} \times \text{Chord} \rightarrow \{true, false\} \]

determines whether the first argument is between two next two arguments with respect to the ring ordering, more formally:

- if \( \text{arg}_2 = \text{arg}_3 \) always returns true,
- if \( \text{arg}_2 < \text{arg}_3 \) returns true if \( \text{arg}_2 < \text{arg}_1 \leq \text{arg}_3 \) holds,
- if \( \text{arg}_2 > \text{arg}_3 \) returns true if \( \neg (\text{arg}_3 \leq \text{arg}_1 < \text{arg}_2) \) holds,
- otherwise returns false.

The function mode:

\[ \text{mode} : \text{Peer} \rightarrow \text{Mode} \]

determines Peer agent state. Initially, for all \( p \in \text{Peer} \) value of \( \text{mode}(p) \) is set to not_connected.

The external function known_nodes:

\[ \text{known}_nodes : \text{Peer} \rightarrow \text{Chord} \]

simulates external knowledge about the nodes in the particular Chord network.

The external function key_value:

\[ \text{key}_value : \text{Peer} \rightarrow \text{Key} \times \text{Value} \]

simulates the choice of a node to store a \( \langle \text{key}, \text{value} \rangle \) pair in the Chord network.

The external function keys:

\[ \text{keys} : \text{Peer} \rightarrow \text{Key} \]

simulates the choice of a node to look if some value with particular key is stored in the Chord network.

2.2. Chord Rules. The rest of this section contains our ASM-formalization of the Chord protocol. We present the general program executed by every peer, and a high level description of the rules performed in a Chord network which corresponds to the pseudo code given in [22] (note that the rules FairLeave, UnfairLeave, Put and Get are not given there). A detailed specification of these rules is provided in Appendix ??.

2.2.1. Peer agent Module. The following main module contains actions that are executed by every peer. The mode of all peers is initially not_connected. After a node joins a network successfully, its mode is changed to connected. In each execution of a loop, a node concurrently calls the rules responsible for the ring topology maintenance (Stabilize, UpdatePredecessor, UpdateFingers) and communication (ReadMessages) and, according to a non-deterministic choice, it might also invoke one of the FairLeave, UnfairLeave, Put and Get rules.
if \( \text{mode}(Me) = \text{not\_connected} \) then
  if Choosed Action Is Join
    seq
      if There Are No Known Nodes then
        START
      else
        JOIN
      endif
      if Connection Successful then
        \( \text{mode}(Me) := \text{connected} \)
      else
        \( \text{mode}(Me) := \text{not\_connected} \)
      endif
    endseq
  endif
else
  if \( \text{mode}(Me) = \text{connected} \) then
    if \( \text{id}(Me) \) Does Not Have Communication Problems then
      par
        \text{STABILIZE}
        \text{UPDATE\_PREDECESSOR}
        \text{UPDATE\_FINGERS}
      seq
        choose action in Action
        par
          \text{LeavingActions} =
          \text{FAIR\_LEAVE} \text{Or} \text{UNFAIR\_LEAVE}
          \text{KeyValueHandling} =
          \text{PUT} \text{Or} \text{GET}
        endpar
      endseq
    else
      \( \text{mode}(Me) := \text{not\_connected} \)
    endif
  endif
endif

2.2.2. Chord Rules - High Level Description. Any node present in a Chord network can execute Get rule (ask for the value of a key). That rule does not change the actual state of the network, but we define it as:

\text{Get}\ =
\text{Invoke \text{FIND\_SUCCESSOR} For Given key}
And Check Corresponding value
During the each execution of a Peer Agent Module all the messages send to a node are processed:

Read Messages Dedicated To Me,
Change Local Variables If It Is Requested And
Clear Processed Messages

3. Correctness of the Formalization

In this section we present the correctness of our formalization with respect to the so-called regular runs.

**Definition 3.1.** Let $x_1, x_2 \in \text{Node}$ and $y_0, \ldots, y_r \in \text{Node}$ be all the nodes from a Chord network such that $x_1 = y_0 < \ldots < y_r = x_2$. The pair $\langle x_1, x_2 \rangle$ forms a stable pair in a state if the following holds:

- $y_{i+1} = \text{successor}(y_i), y_i = \text{predecessor}(y_{i+1})$, for all $i \in \{0, \ldots, r-1\}$.

A Chord network $\{x_0, \ldots, x_{k-1}\}, k \geq 1$, is stable in a state if the pair $\langle x_0, x_0 \rangle$ is stable.

Intuitively, a pair $\langle x_1, x_2 \rangle$ is stable in a state if there is no node trying to join the network through the node on the ring-interval $(x_1, x_2)$ in that state.

**Definition 3.2.** Regular runs are all runs of a distributive algebra $\mathcal{A}$ which satisfy that:

- any execution of FairLeave, UnfairLeave and Put might happen only between a stable pair of nodes.

The following example illustrates the need for the above constraint. In the example and in the rest of the paper we will graphically illustrate sequences of moves, so that $S_i$ denotes a state, the updated values are in bold, and $\diamond$ means that the rest of a network is not affected by a move.
Example 3.1. Let $S_0$ be the initial state in which the nodes $N_1$ and $N_3$ are members of a network, and the node $N_2$ wants to join. Suppose that before the pair $⟨N_1, N_3⟩$ becomes stable, $N_1$ executes the put rule with the hash 2 of a key. Since $N_1$ is not aware of $N_2$, the corresponding key will be stored in $N_3$, and not in $N_2$.

\[
\begin{array}{c|c|c}
\text{id} & 1 & 3 \\
\text{predecessor} & \diamond & 1 \\
\text{successor} & 3 & \diamond \\
\text{hash(key)} & \text{empty} & \text{empty}
\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{id} & 1 & 2 & 3 \\
\text{predecessor} & \diamond & \text{undef} & 1 \\
\text{successor} & 3 & 3 & \diamond \\
\text{hash(key)} & \text{empty} & \text{empty} & \text{empty}
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{id} & 1 & 2 \\
\text{predecessor} & \diamond & \text{undef} \\
\text{successor} & 3 & 3 \\
\text{hash(key)} & \text{empty} & \text{empty}
\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{id} & 1 & 2 & 3 \\
\text{predecessor} & \diamond & \text{undef} & 2 \\
\text{successor} & 2 & 3 & \diamond \\
\text{hash(key)} & \text{empty} & \text{empty} & 2
\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{id} & 1 & 2 & 3 \\
\text{predecessor} & \diamond & 1 & 2 \\
\text{successor} & 2 & 3 & \diamond \\
\text{hash(key)} & \text{empty} & \text{empty} & 2
\end{array}
\]

Again, assume that $S_0$ is the initial state and the network contains the nodes $N_1, N_3$ and $N_4$. If the node $N_2$ executes the join rule, and before the pair $⟨N_1, N_4⟩$ becomes stable, $N_3$ wants to leave, $N_2$ will be isolated from the rest of the network, and the other nodes will never be aware of it.

\[
\begin{array}{c|c|c|c|c}
\text{id} & 1 & 3 & 4 \\
\text{predecessor} & \diamond & 1 & 3 \\
\text{successor} & 3 & 4 & \diamond
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
\text{id} & 1 & 2 & 3 & 4 \\
\text{predecessor} & \diamond & \text{undef} & 1 \\
\text{successor} & 3 & 4 & \diamond
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
\text{id} & 1 & 2 & 4 \\
\text{predecessor} & \diamond & \text{undef} & 1 \\
\text{successor} & 4 & 3 & \diamond
\end{array}
\]

A similar example can be given for UnfairLeave.

In the sequel, we show that a stable pair of nodes in a Chord network, which executes a regular run, eventually becomes stable after adding/removing of a node.
between them (the theorems 3.1–3.6). Corollary 3.2 formulates the corresponding statement for a stable network. Finally, we prove that the proposed key-handling correctly distributes keys and answers queries (Theorem 3.7 and Corollary 3.3).

The first theorem expresses that the rule $\text{FindSuccessor}$ will terminate in a finite number of steps. It corresponds to Theorem IV.2 from [20–22].

**Theorem 3.1.** Let $n \in \text{Chord}$ be the node which fires the rule $\text{FindSuccessor}$ for $h \in \{0, 1, \ldots, N - 1\}$. Let $m'$ be the minimal element of $\text{Chord}$ such that $h \leq m'$. If the pair $\langle n, m' \rangle$ is stable in that state, the node $n$ will get the result after a finite number of moves.

Theorems 3.2–3.6 guarantee that the successor and predecessor pointers for each node will be eventually up to date after a node joins, or unfair leaves the network. In the corresponding proofs we will use some finite initial sequences of runs. Due to the fact that the $\text{Stabilize}$ and $\text{UpdatePredecessor}$ are applied periodically by all nodes in a network, we will mention only those applications which change the values of the functions $\text{predecessor}$ and $\text{successor}$.

Note that, in each proof we will consider some fixed linearization of moves, but according to Corollary ??, all linearizations of the corresponding regular run will result in the same final state.

Theorem 3.3 corresponds to Theorem IV.3 from [20–22].

**Theorem 3.2.** Let a peer join a Chord network, between two nodes which constitute a stable pair. Then, there is a number $k > 0$ of steps, such that if no other join rule happens in the meantime, the $\text{Stabilize}$ rule will bring the starting pair to be stable after $k$ steps.

**Theorem 3.3 (Concurrent joins).** Let a Chord network contain a stable pair. If a sequence of $\text{Join}$ rules is executed between the nodes which form this stable pair, interleaved with $\text{Stabilize}$, $\text{UpdatePredecessor}$ and $\text{UpdateFingers}$, then there is a number $k > 0$ of steps, such that after the last $\text{Join}$ rule, the starting pair of nodes will be stable after $k$ steps.

**Theorem 3.4.** Let a Chord network contain a stable pair and let a node between them leave the network. Then, there is a number $k \geq 0$ of steps, such that if no $\text{Join}$ rule happens at the considered part of the network in the meantime, the pair will be brought into a stable state after $k$ steps.

**Theorem 3.5.** Let a Chord network contain a stable pair. Let a node which is between those nodes leave the network following by several nodes which want to join between them. Then, there is a number $k \geq 0$ of steps, such that the considered pair will be brought into a stable state after $k$ steps.

Note that the restriction from the formulation of Theorem 3.5, that no other leave-rules are allowed after the first one, is not essential. According to the definition of regular runs, leave-rules can be executed only between nodes which constitute a stable pair, and we can consider an execution of a sequence of join rules interleaved with leave-rules, and obtain the same result. The above statement will hold for each subsequence which starts with a leave rule followed by several join rules. Thus, we have the following:

**Corollary 3.1.** Let a Chord network contain a stable pair. Let a node, which is in between those nodes, leave the network. Then, there is a number $k \geq 0$, such that the considered pair of nodes will become stable after $k$ moves.
Theorem 3.6 incorporates all previous ideas, and is the main statement concerning correctness of maintaining topological structure of Chord networks.

**Theorem 3.6.** Let a finite initial segment of a run produce the state $S$ of a Chord network. Then, for every pair of nodes $n, n' \in \text{Chord}$, there is a number $k \geq 0$, such that $\langle n, n' \rangle$ will become stable after $k$ moves.

Since a network is stable in a state if all pairs of nodes from the network are stable in that state, we have:

**Corollary 3.2.** Let a finite initial segment of a run produce the state $S$ of a Chord network. Then, there is a number $k \geq 0$, such that the network will become stable after $k$ moves.

Finally, the next two statements say that our formalization consistently manipulates distributed keys. Theorem 3.7 states that $(\text{key}, \text{value})$ pairs are properly distributed over the network. Informally, it follows from the facts that for every $n \in \text{Chord}$, $\text{hash}(\text{key}) \leq n$ for the keys for which $n$ is responsible for, and that all rules that manipulate $(\text{key}, \text{value})$ pairs invoke $\text{FINDSUCCESSOR}$ rule.

**Theorem 3.7** (Golden rule).

$$\forall((\text{key}, \text{value}) \in \text{Keys} \times \text{Values}, n \in \text{Chord})((\text{key}, \text{value}) \in \text{keyvalue}(n)$$

$$\Rightarrow \text{member}\_\text{of}(\text{hash}(\text{key}), \text{predecessor}(n), n).$$

**Corollary 3.3** follows from the definition of $\text{GET}$, and the theorems 3.1 and 3.7

**Corollary 3.3.** If $\text{GET}$ returns $\text{undef}$ for some $\text{key} \in \text{Keys}$, then there is no $\text{value} \in \text{Values}$ such that $(\text{key}, \text{value})$ pair is stored in the Chord network.

Namely, according to Theorem 3.7, all $(\text{key}, \text{value})$ pairs are stored properly, and from Theorem 3.1 $\text{GET}$ considers only the $(\text{key}, \text{value})$ pairs stored in the node $N$ which satisfy condition $\text{member}\_\text{of}(\text{hash}(\text{key}), \text{predecessor}(\text{id}(N)), \text{id}(N))$.

4. Conclusion

In this paper we have presented an ASM-based formalization of the Chord protocol. We have proved that the proposed formalization is correct with respect to the regular runs. Up to our knowledge, it is the first comprehensive formal analysis of Chord presented in the literature which concerns both maintenance of the ring topology and data distribution. We have also indicated that if we consider all possible runs, incorrect behavior of Chord protocol could appear.

Possible direction for further work is to apply similar technique to describe other DHT protocols. For example, an interesting candidate for examination in the ASM-framework could be Synapse, a protocol for information retrieval over the inter-connection of heterogeneous overlay networks defined in [18], and applied in [19].

Another challenge could be verification of the given description in one of the formal proof assistants (e.g., Coq, Isabelle/HOL). It might also produce a certified program implementation from the proof of correctness of our ASM-based specification.
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