The Raft Consensus Protocol

CSE 486/586: Distributed Systems

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The Raft Consensus Protocol

Raft [5, 4] is a relatively new consensus protocol.

It uses a suite of inter-related protocols to provide:

- Membership
- Leader election
- Consensus on a sequence of values

Raft was designed specifically to be understandable.

Paxos

Prior to Raft, the most-used consensus algorithm was Paxos [2].

Paxos is notoriously hard to understand.

It was often implemented partially, or incorrectly, or just badly.

This is partly due to complexity, and partly due to presentation.
(It's a Lamport story paper.)

Raft was a specific reaction to this problem!

We'll probably see Paxos later.

Decomposition

Raft simplifies consensus by decomposing it into smaller problems.

Proving the safety of each part individually is sufficient.

Raft elects a leader to handle consensus at any given time.

If the leader is correctly elected, its decisions will be final.

The leader coordinates many of the details of consensus.

Goals

Raft provides:

- A log of values agreed upon by all processes
- Availability in the face of failures
- Robustness to asynchronous message delays and losses

Raft does not handle Byzantine failures!

All Raft participants must operate in good faith.

Servers

Raft participants are called servers.

Every server has the same capabilities.

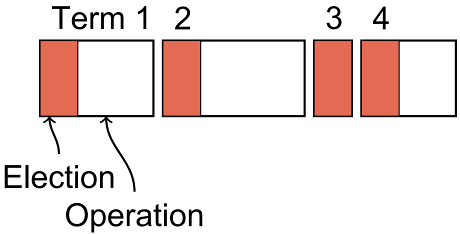
Not all servers perform all actions at all times.

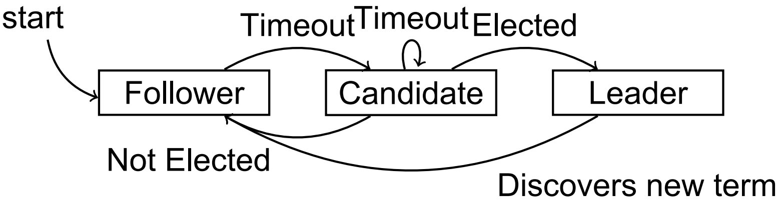
Servers occupy three states:

- Follower: Followers replicate and store the agreed-upon log.
- Candidate: Candidates emerge to replace failed leaders.
- Leader: The (unique at any given time!) leader appends new entries to the log.

Leaders are elected for a term, typically after failure.

Server States





Quorum

Raft is based on quorum.

Quorum is a legal term; from Merriam-Webster:

the number (such as a majority) of officers or members of a body that when duly assembled is legally competent to transact business

Quorum systems appeared in the late 1970s [1].

Quorum provides consensus with failures.

The Quorum Model

Quorum ensures that no two incompatible changes can be made.

It does this by requiring that some subset of processes agree.

Unlike other consensus we've seen, not all processes must agree.

A change that hasn't reached enough processes is provisional.

Any change that has reached enough processes is committed.

Achieving Quorum in Raft

Quorum is required in three places in Raft:

- Election
- Commitment
- Membership changes

For each of these actions, a quorum of servers must approve.

A quorum in Raft is 50% of servers + 1 server.

Servers can refuse only elections; others may be delayed.

Safety

50% + 1 server ensures that a change is permanent if:

- No server “forgets” what it has done
- No more than half of the servers fail

By contradiction:

- Assume that 50% + 1 servers agree on X
- Assume that 50% + 1 servers agree on $\neg X$
- Contradiction: At least one server agreed on $X \cup \neg X$!

The Raft State Machine

Raft emulates a state machine.
(This is common; recall Lamport Clocks [3].)

Every server replicates the state machine.

Raft is indifferent to the properties of the state machine.

It merely assumes that:

- There is some starting state
- Deterministic changes are made to that state as log entries are committed

State Transitions

Notionally, every log entry is a state change.

Any server can replay its log to arrive at the current state.

If every server has the same log, every server has the same state.

We often think of state changes as assignments.

They can, however, be arbitrarily complex commands!

Commitment

A log entry is committed once a quorum of servers records it.

A committed entry will always persist, even with failure.

If no more than 50% of servers fail, some server will record it.

The rules of raft ensure that that server will propagate it.

The set of committed states defines the consensus state.

Uncommitted states may be different between servers.

Leaders and Terms

Time is divided into terms in Raft.

Each term is the tenure of a leader.

- It begins with election of the leader
- It ends with (perceived) failure of the leader

Only one server can be leader at a time.

Only the leader can append to the log.

If a leader sees a term higher than its own, it becomes a follower.

The Logical Clock

Terms form a logical clock.

Each term is numbered.

Higher numbers replace lower numbers, with restrictions.

Any decisions made by the leader of term *T* following *S*:

- Preserve every log entry committed as of the end of *S*
- Are superseded by any decisions made in *U* following *T* subject to the same rules

Elections

After leader failure, one or more servers become candidates.

Servers may vote for only one server per term.

This means that no more than one server can win an election.

It is possible that no server wins an election!

In this case, the term will conclude with a new election.

Heartbeats

The current leader sends a heartbeat to all servers.

It contains:

- The current term
- The first log entry the leader believes this server needs
- The previous log entry's index and term

If a follower does not hear a heartbeat within a timeout interval, it starts an election.

The election is for the next term.

Starting an Election

A server that starts an election:

- Immediately votes for itself
- Sends a message to every other server asking for votes
- Starts an election timer

The election ends when either:

- The server receives a quorum of votes
- The timer expires

In the first case, it starts sending heartbeats.

In the second, it starts another election.

Voting

A server *A* will only vote for a server *B* if:

- *A* has not voted during this term
- *B*'s log is at least as up-to-date as *A*'s

A log is more up-to-date if:

- It contains a later term
- It ends with the same term but is longer

Election Safety

These rules guarantee that the elected leader:

- Knows about every committed log entry
  - More than half of the servers voted for it
  - It was at least as up-to-date as the servers that voted for it
- Is unique in a given term
  - More than half the servers voted for it
  - Servers vote only once per term

Log Management

Only the elected leader can append to the log.

Requests for state change are submitted by clients.

The leader confirms the request only once the entry commits.

An entry may not be on all servers when the leader confirms.

Appending an Entry

To append an entry:

1. A client request arrives at the leader
2. The leader sends the entry to every up-to-date server
3. When the entry commits, the leader confirms to the client
4. Updates are retried until every server eventually commits

The highest committed index is on every heartbeat.

Servers apply committed entries to their state machine.

Commitment

An entry commits when either:

- It propagates to a quorum within the term it is proposed
- It is in a leader's log when a later entry is committed

If an entry fails to commit during its term, it may be lost.

When the leader learns that an entry commits, it updates its heartbeat.

Safety does not depend on any server hearing that heartbeat!

Primacy of the Leader

When a leader is elected, it starts appending to its own log.

Other servers may:

- Have newer log entries
- Be missing log entries
- Have both newer and missing log entries

All newer log entries on other servers must be:

- Uncommitted
- From earlier terms

The new leader's log becomes the canonical log.

Processing Heartbeats

Recall that heartbeats contain:

- The current term
- The newest entry the leader believes a server needs
- The previous entry's term and index

A server applies the update if:

- Its current term is no larger than the heartbeat
- It has a log entry with the index and term of the heartbeat's predecessor

Newer Entries

If a server has newer entries than an accepted heartbeat

- They must not have achieved quorum
- They are not committed

Therefore they can be discarded.

The server will replace all later entries with the new entry.

Received: Index 2 Term 3 PrevTerm 1

Old: | 1 | 1 | 2 | 2 |

New: | 1 | 1 | 3 |

Missing Entries

If a server does not know the predecessor of a heartbeat:

- It rejects the heartbeat
- The leader backs up one entry

Received: Index 2 Term 3 PrevTerm 1

Old: [1]

New: [1]

Received: Index 1 Term 1 PrevTerm 1

Old: [1]

New: [1][1]

Safety

Election rules ensure that the leader knows every committed entry.

The leader always sends the term of the previous entry.

The leader only proposes one entry at any index.

The leader’s history replaces any conflicting entries.

Configuration Changes

Raft maintains membership as a configuration of servers.

Changing configurations requires:

- A quorum of the old configuration
- A quorum of the new configuration

Configuration changes are special log entries.

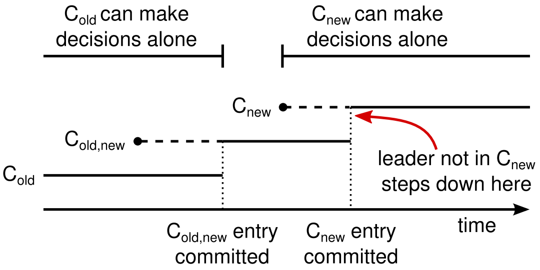
Transition

The configuration change requires two phases:

- A quorum of old servers acknowledge the new configuration
- A quorum of old + new servers adopt the new configuration

This ensures that there is never a time with two leaders.

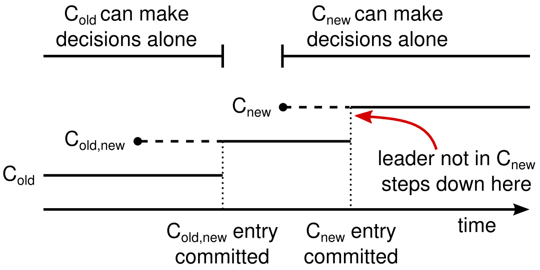
Phase 1



In the first phase, the leader is either:

- In the old configuration
- Elected by a majority of the union of the old and new members

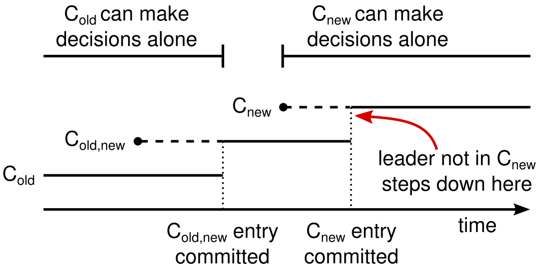
Phase 1



A leader in the old configuration proposes a union configuration.

When it commits, all servers that commit it use it for quorum.

Phase 2



After the union configuration commits, the leader proposes the new configuration

When it commits, a leader from the new configuration must be elected.

Safety

The union configuration provides safety.

A quorum of old servers must adopt the union configuration.

A quorum of both old and new servers must agree to remove outgoing servers.

This prevents a minority from receiving quorum at any point.

Avoiding Impossibility

Raft doesn't contravene FLP.

It is technically possible to have eternal elections.

In this case, nothing commits.

Raft uses randomized timeouts to reduce the window for this.

If server failures are several orders of magnitude less frequent than the timeout interval, consensus is likely.

Timeouts are $\ll$ 1 s, failures are > 1 month!

More Information

Some really great resources on Raft are:

- The USENIX presentation by Diego Ongaro [4]
- The Raft web site at `https://raft.github.io/`
- The Secret Lives of Data at `http://thesecretlivesofdata.com/raft/`

The extended version [6] may help clear up details.

Summary

- Raft provides consensus through quorum.
- Almost half of the participants can fail without losing consensus.
- Decomposing elections, membership changes, and log manipulation makes Raft easier to understand.

References I

Required Readings

[5] Diego Ongaro and John Ousterhout. "In Search of an Understandable Consensus Algorithm". In: *Proceedings of USENIX Annual Technical Conference*. USENIX, June 2014, pp. 305–319. URL: https://www.usenix.org/system/files/conference/atc14/atc14-paper-ongaro.pdf.

Optional Readings

[1] David K. Gifford. *Weighted Voting for Replicated Data*. Tech. rep. CSL-79-14. Xerox PARC, Sept. 1979. URL: http://bitsavers.org/pdf/xerox/parc/techReports/CSL-79-14_Weighted_Voting_for_Replicated_Data.pdf.

References II

[2] Leslie Lamport. "The Part-Time Parliament". In: *ACM Transactions on Computing Systems* 16.2 (May 1998), pp. 133–169. DOI: 10.1145/279227.279229. URL: https://www.microsoft.com/en-us/research/uploads/prod/2016/12/The-Part-Time-Parliament.pdf.

[3] Leslie Lamport. "Time, Clocks, and the Ordering of Events in a Distributed System". In: 21.7 (July 1978). Ed. by R. Stockton Gaines, pp. 558–565. URL: http://lamport.azurewebsites.net/pubs/time-clocks.pdf.

References III

[4] Diego Ongaro. *In Search of an Understandable Consensus Algorithm*. USENIX ATC '14 Presentation. 2014. URL: https://youtube.com/watch?v=no5Im1daS-o.

[6] Diego Ongaro and John Ousterhout. *In Search of an Understandable Consensus Algorithm (Extended Version)*. Tech. rep. Stanford University, May 2014.