# Distributed Algorithms
## Raft Consensus

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Acknowledgement: Diego Ongaro and John Ousterhout

# Contents

# Paxos History

1989 Leslie Lamport developed a new consensus protocol called Paxos; it was published as DEC SRC Technical Report 49. 42 pages!

## Abstract

Recent archaeological discoveries on the island of Paxos reveal that the parliament functioned despite the peripatetic propensity of its part-time legislators. The legislators maintained consistent copies of the parliamentary record, despite their frequent forays from the chamber and the forgetfulness of their messengers. The Paxon parliament's protocol provides a new way of implementing the state-machine approach to the design of distributed systems — *an approach that has received limited attention because it leads to designs of insufficient complexity.*

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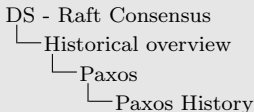it was published as DEC SRC Technical Report 49. 42 pages!

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From `http://the-paper-trail.org/blog/consensus-protocols-paxos/`

- Just to remember: the FLP result has been published in 1985. The first paper on failure detectors has been published in 1991.

- **The Part-time Parliament**. The original paper. Once you understand the protocol, you might well really enjoy this presentation of it. Contains proofs of correctness which the 'Paxos Made Simple' paper does not.

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1990 Submitted to ACM Trans. on Comp. Sys. (TOCS). Rejected.

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  ▶ Because Lampson *got tired of everyone saying how difficult it was to understand the Paxos algorithm*
  ▶ Abstract: "*The Paxos algorithm, when presented in plain English, is very simple*"
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From `http://the-paper-trail.org/blog/consensus-protocols-paxos/`

- **How To Build a Highly Available System Using Consensus**. Butler Lampson demonstrates how to employ Paxon consensus as part of a larger system. This paper was partly responsible for ensuring the success of Paxos by popularizing it within the distributed systems community.

- **Paxos Made Simple**. Presents Paxos in a ground-up fashion as a consequence of the requirements and constraints that the protocol must operate within. Short and very readable, it should probably be your first visit after this article.

  If each command is the result of a single instance of the Basic Paxos protocol a significant amount of overhead would result. This paper defines Paxos to be what is commonly called "Multi-Paxos" which in steady state uses a distinguished leader to coordinate an infinite stream of commands. A typical deployment of Paxos uses a continuous stream of agreed values acting as commands to update a distributed state machine.
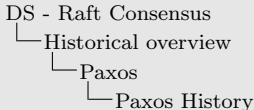
# Paxos History

Paxos optimizations and extensions

2004 Leslie Lamport and Mike Massa. "Cheap Paxos". DSN'04,
     Florence, Italy

2005 Leslie Lamport. "Generalized Consensus and Paxos". Technical
     Report MSR-TR-2005-33, Microsoft Research

2006 Leslie Lamport. "Fast Paxos". *Distributed Computing* 19(2):79-103

An important milestone

2007 T. D. Chandra, R. Griesemer, J. Redstone. Paxos made live: an
     engineering perspective. PODC 2007, Portland, Oregon.

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From http://the-paper-trail.org/blog/consensus-protocols-paxos/

- **Cheap Paxos and Fast Paxos**. Two papers that present some optimizations on the original protocol.

- **Paxos Made Live**.

    – This paper from Google bridges the gap between theoretical algorithm and working system. There are a number of practical issues to consider when implementing Paxos that you might well not have imagined. If you want to build a system using Paxos, you should read this paper beforehand.
    – It describes how Paxos is used in Chubby - the Google lock manager.

# Paxos implementations

- Google uses the Paxos algorithm in their Chubby distributed lock service. Chubby is used by BigTable, which is now in production in Google Analytics and other products

- Amazon Web Services uses the Paxos algorithm extensively to power its platform

- Windows Fabric, used by many of the Azure services, make use of the Paxos algorithm for replication between nodes in a cluster

- Neo4j HA graph database implements Paxos, replacing Apache ZooKeeper used in previous versions.

- Apache Mesos uses Paxos algorithm for its replicated log coordination

# The sad state of Paxos

### About publications...

"The dirty little secret of the NSDI community is that at most five people really, truly understand every part of Paxos ;-)." – NSDI reviewer

### About implementations...

"There are significant gaps between the description of the Paxos algorithm and the needs of a real-world system. . . the final system will be based on an unproven protocol." – Chubby authors

# Raft Consensus Protocol

### An algorithm to build real systems

- Must be correct, complete, and perform well
- Must be understandable

### Key design ideas

- What would be easier to understand or explain?
- Less complexity in state space
- Less mechanisms

### Bibliography

- D. Ongaro and J. Ousterhout. In search of an understandable consensus algorithm.
  In *2014 USENIX Annual Technical Conference*, pages 305–319, Philadelphia, PA, June 2014. USENIX Association.
  http://www.disi.unitn.it/~montreso/ds/papers/raft.pdf

# Raft implementations

## Actual deployments

- HydraBase by Facebook (replacement for Apache HBase)
- Consul by HashiCorp (datacenter management)
- Rafter by Basho (NOSQL key-value store called Riak)

## Open-source projects: 82 total (May 2016)

| Language | Numbers | Language | Numbers |
|----------|---------|------------|---------|
| Java | 17 | Javascript | 6 |
| Go | 8 | Python | 5 |
| Ruby | 8 | Clojure | 4 |
| Scala | 7 | Rust | 3 |
| Erlang | 6 | Bloom | 3 |
| C/C++ | 6 | Others | 9 |

# Introduction

Two approaches to consensus:

- Symmetric, leader-less, active replication:
  - ▶ All servers have equal roles
  - ▶ Clients can contact any server

- Asymmetric, leader-based, passive replication:
  - ▶ At any given time, one server is in charge, others accept its decisions
  - ▶ Clients communicate with the leader

Raft is leader-based

- Decomposes the problem (normal operation, leader changes)
- Simplifies normal operation (no conflicts)
- More efficient than leader-less approaches

# Raft overview

1. Leader election:
   - Select one of the servers to act as leader
   - Detect crashes, choose new leader

2. Normal operation
   - Basic log replication

3. Safety and consistency after leader changes

4. Neutralizing old leaders

5. Client interactions
   - Implementing linearizeable semantics

6. Configuration changes
   - Adding and removing servers

# Server states

| LEADER | Handles all client interactions, log replication |
|---|---|
| | At most 1 viable leader at a time |
| FOLLOWER | Completely passive (issues no RPCs, responds to incoming RPCs) |
| CANDIDATE | Used to elect a new leader |
| | Normal operation: 1 leader, N-1 followers |
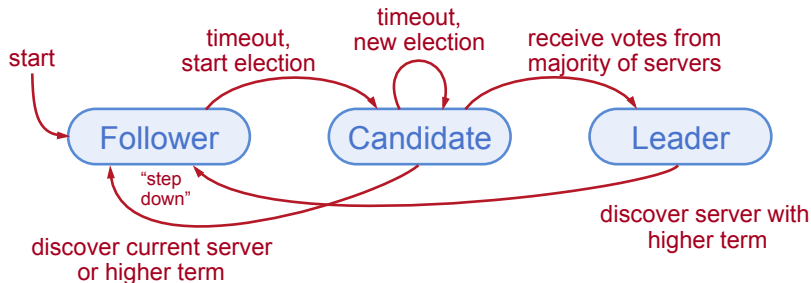
# Terms
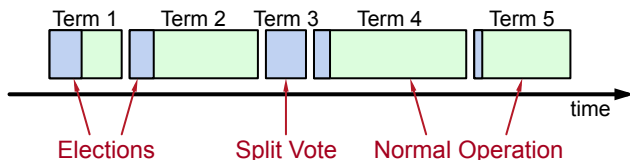


- Time divided into terms:
  - ▶ Election
  - ▶ Normal operation under a single leader

- At most one leader per term

- Some terms have no leader (failed election)

- Each server maintains current term value

- Key role of terms: identify obsolete information

# Server state

**Persistent state**

Each server persists the following variables to stable storage synchronously before responding to RPCs:

| | |
|---|---|
| *currentTerm* | Latest term server has seen (initialized to 0 on first boot) |
| *votedFor* | ID of the candidate that received vote in current term (or null if none) |
| *log*[ ] | Log entries: <table><tr><td>*term*</td><td>term when entry was received by leader</td></tr><tr><td>*command*</td><td>command for state machine</td></tr></table> |

# Server state

**Non-persistent state**

| *state* | Current state taken from LEADER, CANDIDATE, FOLLOWER |
|---------|------------------------------------------------------|
| *leader* | ID of the leader |
| *commitIndex* | index of highest log entry known to be committed |
| *nextIndex*[] | index of next log entry to send to peer |
| *matchIndex*[] | index of highest log entry known to be replicated |

**Initialization**

$currentTerm \leftarrow 1$ 

$votedFor \leftarrow$ **nil**

$log \leftarrow \{\}$

$state \leftarrow$ FOLLOWER

$leader \leftarrow$ **nil**

$commitIndex \leftarrow 0$

$nextIndex = \{1, 1, \ldots, 1\}$

$matchIndex = \{0, 0, \ldots, 0\}$

# RPCs

Communication between leader and servers happen through two RPCs:

- APPENDENTRIES
  - ▶ Add an entry to the log, *or*
  - ▶ Empty messages used as heartbeats
  - ▶ Message tags: APPENDREQ, APPENDREP

- VOTE
  - ▶ Message used by candidates to ask votes and win elections
  - ▶ Message tags: VOTEREQ, VOTEREP

# Hearthbeats and timeouts

- Servers start up as followers

- Followers expect to receive RPCs from leaders or candidates

- Leaders must send empty APPENDENTRIES RPCs to maintain authority

- If $\Delta_{election}$ time units elapse with no RPCs:
  - Follower assumes leader has crashed
  - Follower starts new election
  - Timeouts typically 100-500ms

# Election basics - Election start

① Set new timeout in range $[\Delta_{election}, 2 \cdot \Delta_{election}]$

② Increment current term

③ Change to Candidate state

④ Vote for self

⑤ Send VOTE RPCs to all other servers, retry until either:
- ► Receive votes from majority of servers:
  - ★ Become Leader
  - ★ Send APPENDENTRIES heartbeats to all other servers
- ► Receive APPENDENTRIES from valid leader:
  - ★ Return to Follower state
- ► No one wins election (election timeout elapses):
  - ★ Start new election

# Election - Pseudocode

---

Election code - executed by process $p$

---

**on timeout** $\langle \textsc{ElectionTimeout} \rangle$ **do**
    **if** $state \in \{\textsc{follower}, \textsc{candidate}\}$ **then**
        $t \leftarrow \mathsf{random}(1.0, 2.0) \cdot \Delta_{election}$
        **set timeout** $\langle \textsc{ElectionTimeout} \rangle$ **at** $\mathsf{now}() + t$
        $currentTerm \leftarrow currentTerm + 1$
        $state \leftarrow \textsc{candidate}$
        $votedFor \leftarrow p$
        $votes \leftarrow \{p\}$
        **foreach** $q \in \Pi$ **do**
            **cancel timeout** $\langle \textsc{RpcTimeout}, q \rangle$
            **set timeout** $\langle \textsc{RpcTimeout}, q \rangle$ **at** $\mathsf{now}()$

---

# Election - Pseudocode

---

RPC timeout code - executed by process $p$

---

**on timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **do**

    **if** $state = \text{CANDIDATE}$ **then**

        **set timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **at** $\text{now}() + \Delta_{vote}$

        **send** $\langle \text{VOTEREQ}, currentTerm \rangle$ **to** $q$

---

# Election - Pseudocode

---

Election code - executed by process $p$

---

**on receive** $\langle \text{VOTEREQ}, term \rangle$ **from** $q$ **do**

    **if** $term > currentTerm$ **then**

        stepdown($term$)

    **if** $term = currentTerm$ **and** $votedFor \in \{q, \mathbf{nil}\}$ **then**

        $votedFor \leftarrow q$

        $t \leftarrow \mathsf{random}(1.0, 2.0) \cdot \Delta_{election}$

        **set timeout** $\langle \text{ELECTIONTIMEOUT} \rangle$ **at** $\mathsf{now}() + t$

    **send** $\langle \text{VOTEREP}, term, votedFor \rangle$

---

# Election - Pseudocode

---

Election code - executed by process $p$

---

**on receive** $\langle \text{VOTEREP}, term, vote \rangle$ **from** $q$ **do**

    **if** $term > currentTerm$ **then**

        stepdown($term$)

    **if** $term = currentTerm$ **and** $state = \text{CANDIDATE}$ **then**

        **if** $vote = p$ **then**

            $votes \leftarrow votes \cup \{q\}$

        **cancel timeout** $\langle \text{RPCTIMEOUT}, q \rangle$

        **if** $|votes| > |\Pi|/2$ **then**

            $state \leftarrow \text{LEADER}$

            $leader \leftarrow p$

            **foreach** $q \in P - \{p\}$ **do**

                sendAppendEntries($q$)

---

# Election - Pseudocode

---

**procedure** stepdown($term$)
 $currentTerm \leftarrow term$
 $state \leftarrow$ FOLLOWER
 $votedFor \leftarrow$ **nil**
 $t \leftarrow$ random$(1.0, 2.0) \cdot \Delta_{election}$
 **set timeout** $\langle$ELECTIONTIMEOUT$\rangle$ **at** now$() + t$

---

# Election - Correctness

**Safety**: allow at most one winner per term

- Each server gives out only one vote per term (persist on disk)
- Two different candidates can't accumulate majorities in same term



B can't also get majority

Servers

Voted for candidate A
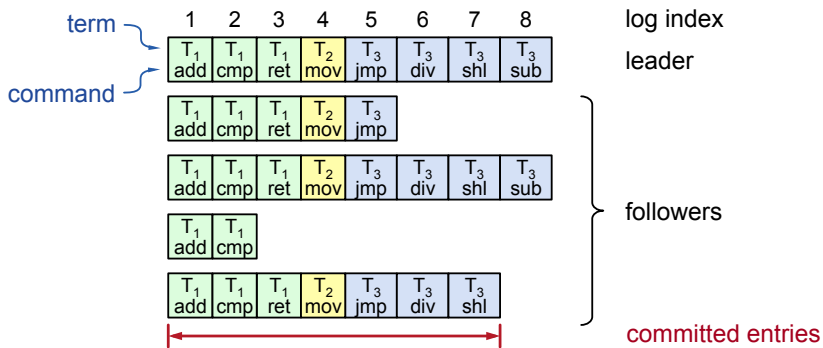
**Liveness**: some candidate must eventually win

- Choose election timeouts randomly in $[\Delta_{election}, 2 \cdot \Delta_{election}]$
- One server usually times out and wins election before others wake up
- Works well if $\Delta_{election} >>$ broadcast time

# Randomize timeouts

- How much randomization is needed to avoid split votes?
- Conservatively, use random range $\approx 10\times$ network latency
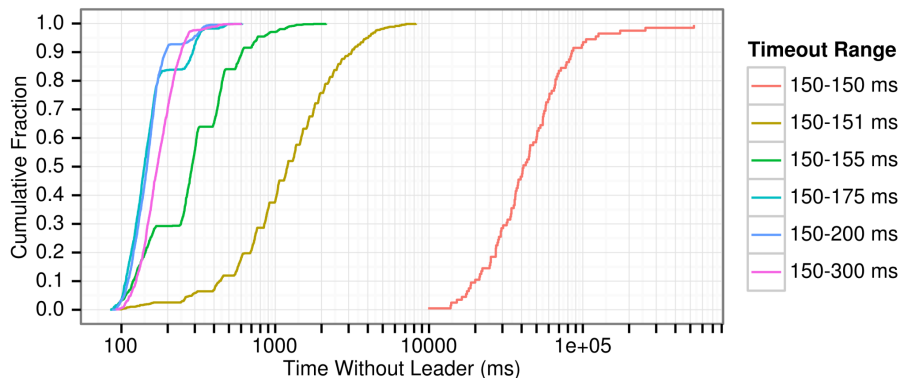
# Log structure



- Log stored on stable storage (disk); survives crashes
- Entry committed if known to be stored on majority of servers
- Durable, will eventually be executed by state machines

# Normal operation

- Client sends command to leader

- Leader appends command to its log

---

Normal operation code executed by process $p$

---

**upon receive** $\langle$ REQUEST, *command* $\rangle$ **from** client **do**
  **if** $state =$ LEADER **then**
   $log$.append($currentTerm$, *command*)
   **foreach** $q \in P - \{p\}$ **do**
    sendAppendEntries($q$)

---

# Normal operation

- Leader sends APPENDENTRIES RPCs to followers

- Once new entry committed:
  - Leader passes command to its state machine, returns result to client
  - Leader notifies followers of committed entries in subsequent AppendEntries RPCs
  - Followers pass committed commands to their state machines

- Crashed/slow followers?
  - Leader retries RPCs until they succeed
  - Performance is optimal in common case: one successful RPC to any majority of servers

# Normal operation

---

RPC timeout code executed by process $p$

**on timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **do**

    **if** $state = \text{CANDIDATE}$ **then**

        **set timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **at** $\text{now}() + \Delta_{vote}$

        **send** $\langle \text{VOTEREQ}, currentTerm \rangle$ **to** $q$

    **if** $state = \text{LEADER}$ **then**

        sendAppendEntries($q$)

---

# How to send append entries

---

**procedure** sendAppendEntries($q$)

    **set timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **at** $\text{now}() + \Delta_{election}/2$

    $lastLogIndex \leftarrow$ choose in$[nextIndex[q], log.\text{len}()]$

    $nextIndex[q] = lastLogIndex$

    **send** $\langle term, lastLogIndex - 1, log[lastLogIndex[q] - 1].term$

            $log[lastLogIndex \ldots log.\text{len}()], commitIndex \rangle$ **to** $q$

---

# Log consistency

## Consistency in logs

- If log entries on different servers have same index and term:
  - They store the same command
  - The logs are identical in all preceding entries

- If a given entry is committed, all preceding entries are also committed

# APPENDENTRIES Consistency Check

- Each APPENDENTRIES RPC contains index, term of entry preceding new ones
- Follower must contain matching entry; otherwise it rejects request
- Implements an induction step, ensures coherency



AppendEntries succeeds:
matching entry

AppendEntries fails:
mismatch

# APPENDENTRIES Consistency Check

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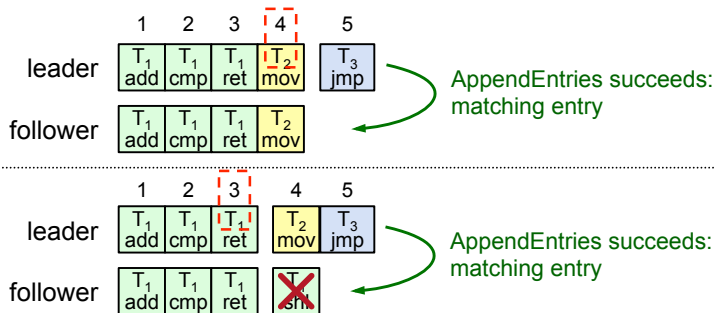
# Normal operation - Pseudocode

---

Normal operation code - executed by process $p$

---

**on receive** $\langle$AppendReq, $term$, $prevIndex$, $prevTerm$, $entries$, $commitIndex\rangle$
**from** $q$ **do**

   **if** $term > currentTerm$ **then**
      stepdown($term$)

   **if** $term < currentTerm$ **then**
      **send** $\langle$AppendRep, $currentTerm$, **false**$\rangle$ **to** $q$
   **else**

      $index \leftarrow 0$
      $success \leftarrow prevIndex = 0$ **or** ($prevIndex \leq log$.len() **and**
       $log[prevIndex].term = prevTerm$)
      **if** $success$ **then**
         storeEntries($prevIndex$, $entries$, $commitIndex$)
      **send** $\langle$AppendRep, $currentTerm$, $success$, $index\rangle$

# At beginning of new leader's term

- Old leader may have left entries partially replicated
- No special steps by new leader: just start normal operation
- Leader's log is "the truth"
- Will eventually make follower's logs identical to leader's
- Multiple crashes can leave many extraneous log entries
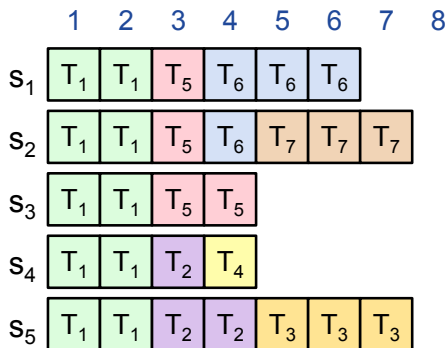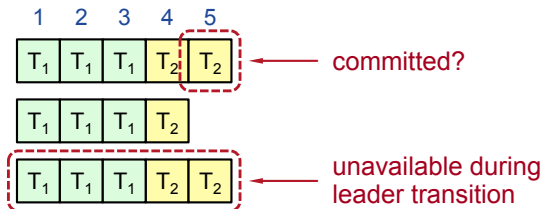
# Safety Requirement

> Once a log entry has been applied to a state machine, no other state machine must apply a different value for that log entry

- Raft safety property:
  - If a leader has decided that a log entry is committed, that entry will be present in the logs of all future leaders
  - This guarantees the safety requirement

- Leaders never overwrite entries in their logs
  - Only entries in the leader's log can be committed
  - Entries must be committed before applying to state machine

**Committed → Present in future leaders' logs**

Restrictions on
commitment

Restrictions on
leader election

# Picking the Best Leader

- Can't tell which
  entries are committed!



- During elections, choose candidate with log most likely to contain all committed entries

    ▸ Candidates include index & term of last log entry in VoteReq

    ▸ Voting server $V$ denies vote if its log is "more complete":
      $(lastLogTerm_C < lastLogTerm_V)$ **or**
      $(lastLogTerm_C = lastLogTerm_V$ **and** $lastLogIndex_C < lastLogIndex_V)$

    ▸ Leader will have "most complete" log among electing majority

# Election - Modified pseudocode

---

RPC timeout code - executed by process $p$

---

**on timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **do**

    **if** $state = \text{CANDIDATE}$ **then**

        **set timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **at** $\text{now}() + \Delta_{vote}$

        $lastLogTerm \leftarrow log[log.\text{len}()].term$

        $lastLogIndex \leftarrow log.\text{len}()$

        **send** $\langle \text{VOTEREQ}, currentTerm, lastLogTerm, lastLogIndex \rangle$ **to** $q$

    **if** $state = \text{LEADER}$ **then**

        **set timeout** $\langle \text{RPCTIMEOUT}, q \rangle$ **at** $\text{now}() + \Delta_{election}/2$

        sendAppendEntries($q$)

---

# Election - Modified pseudocode

---

Election code - executed by process $p$

---

**on receive** $\langle$VOTEREQ, $term$, *lastLogTerm, lastLogIndex*$\rangle$ **from** $q$ **do**

    **if** $term > currentTerm$ **then**

        stepdown($term$)

    **if** $term = currentTerm$ **and** $votedFor \in \{q, \mathbf{nil}\}$ **and**

      $(lastLogTerm > log[log.\mathsf{len}()].term$ **or**

      $(lastLogTerm = log[log.\mathsf{len}()].term$ **and** $lastLogIndex \geq log.\mathsf{len}())$ )

    **then**

        $votedFor \leftarrow q$

        $t \leftarrow \mathsf{random}(1.0, 2.0) \cdot \Delta_{election}$

        **set timeout** $\langle$ELECTIONTIMEOUT$\rangle$ **at** $\mathsf{now}() + t$

    **send** $\langle$VOTEREP, $term$, $votedFor\rangle$

---

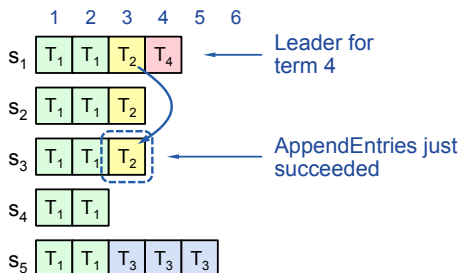# Committing Entry from Current Term

Case 1/2: Leader decides entry in current term is committed
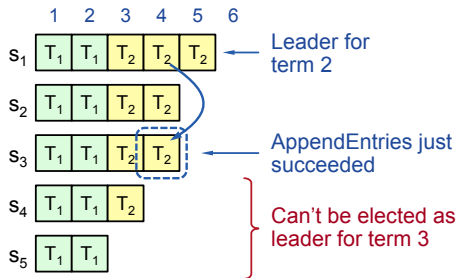


Safe: leader for term $T_3$ must contain entry $T_4$

# Committing Entry from Earlier Terms

Case 2/2: Leader is trying to commit entry from an earlier term



Unsafe: Entry 3 not safely committed

- $s_5$ can be elected as leader for term $T_5$
- If elected, it will overwrite entry 3 on $s_1$, $s_2$, and $s_3$!

# New commitment rule

- For a leader to decide that an entry is committed:
  - ▶ Must be stored on a majority of servers
  - ▶ At least one new entry from leader's term must also be stored on majority of servers

- Once entry 4 committed:
  - ▶ $s_5$ cannot be elected leader for term $T_5$
  - ▶ Entries 3 and 4 both safe
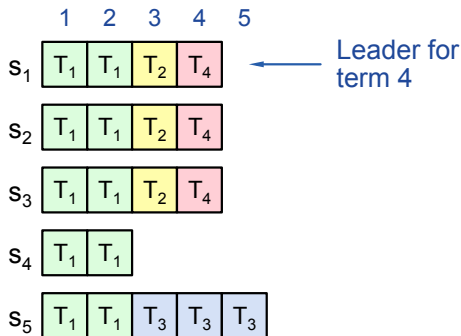


Combination of election rules and commitment rules makes Raft safe

# Log inconsistencies

## Leader changes can result in log inconsistencies:
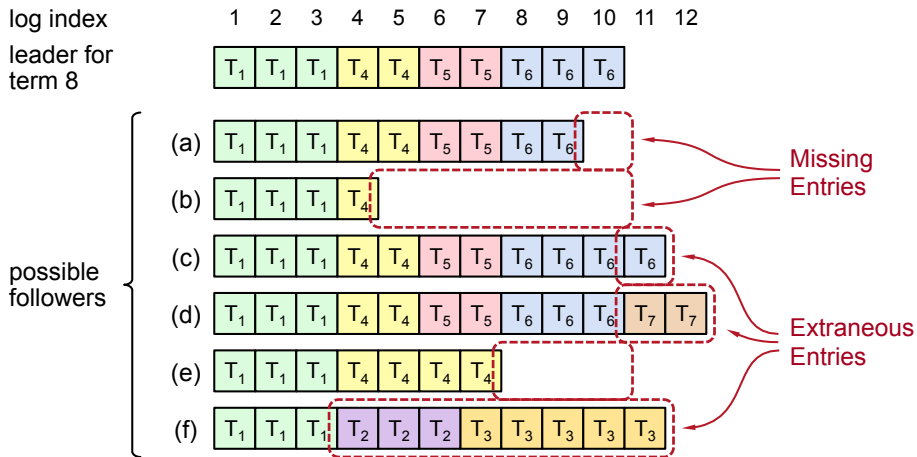
# Repairing follower log

- New leader must make follower logs consistent with its own
  - Delete extraneous entries
  - Fill in missing entries

- Leader keeps *nextIndex* for each follower:
  - Index of next log entry to send to that follower
  - Initialized to (1 + leader's last index)

- When ApPENDENTRIES consistency check fails, decrement *nextIndex* and try again
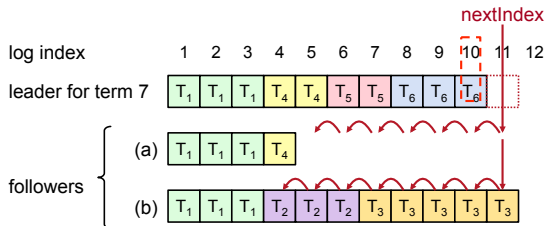
# Repairing follower log – Pseudocode

---

Normal operation code - executed by process $p$

**upon receive**$\langle$APPENDREP, $term$, $success$, $index\rangle$ **from** $q$ **do**

 **if** $term > currentTerm$ **then**

  stepdown($term$)

 **else if** $state =$ LEADER **and** $term = currentTerm$ **then**

  **if** $success$ **then**

   $nextIndex[q] \leftarrow index + 1$

  **else**

   $nextIndex[q] \leftarrow \mathsf{max}(1, nextIndex - 1)$

  **if** $nextIndex[q] \leq \log.\mathsf{len}()$ **then**

   sendAppendEntries($q$)

---

# Repairing follower log

When follower overwrites inconsistent entry, it deletes all subsequent entries
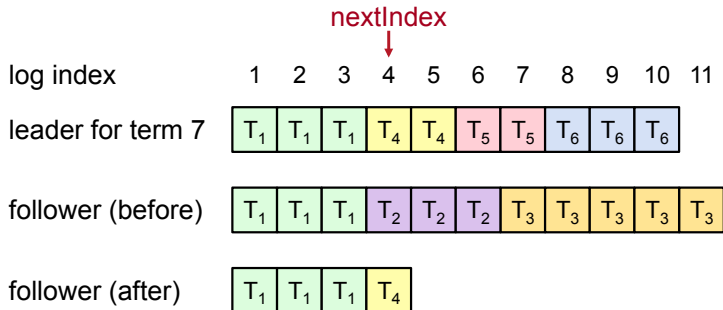
# Repairing follower log

---

**procedure** storeEntries ($prevIndex, entries, c$)

    $index \leftarrow prevIndex$

    **for** $j \leftarrow 1$ **to** $entries$.len() **do**

        $index \leftarrow index + 1$

        **if** $log[index].term \neq entries[j].term$ **then**

            $log = log[1 \ldots index - 1] + entries[j]$

    $commitIndex \leftarrow$ min($c, index$)

    **return** $index$

---

# Neutralizing Old Leaders

Deposed leader may not be dead

- Temporarily disconnected from network
- Other servers elect a new leader
- Old leader becomes reconnected, attempts to commit log entries

Terms used to detect stale leaders (and candidates)

- Every RPC contains term of sender
- If sender's term is older, RPC is rejected, sender reverts to follower and updates its term
- If receiver's term is older, it reverts to follower, updates its term, then processes RPC normally

Election updates terms of majority of servers

- Deposed server cannot commit new log entries

# Neutralizing Old Leaders

---

Normal operation code - executed by process $p$

---

**on receive** $\langle \text{AppendReq}, \textit{term}, \textit{prevIndex}, \textit{prevTerm}, \ldots \rangle$ **from** $q$ **do**

    **if** $\textit{term} > \textit{currentTerm}$ **then**

         stepdown($\textit{term}$)

    **if** $\textit{term} < \textit{currentTerm}$ **then**

         **send** $\langle \text{AppendRep}, \textit{currentTerm}, \textbf{false} \rangle$ **to** $q$

    **else**

         [. . .]

---

# Client protocol

Clients sends commands to leader:

- If leader unknown, contact any server
- If contacted server not leader, it will redirect to leader

Leader responds when:

- command has been logged
- command has been committed
- command has been executed by leader's state machine

If request times out (e.g., leader crash):

- Client re-issues command to some other server
- Eventually redirected to new leader
- Retry request with new leader

# Client protocol

What if leader crashes after executing command, but before responding?

- Must not execute command twice

Solution: client embeds a unique id in each command

- Server includes id and response in log entry
- Before accepting command, leader checks its log for entry with that id
- If id found in log, ignore new command, return response from old command

Result: exactly-once semantics as long as client doesn't crash

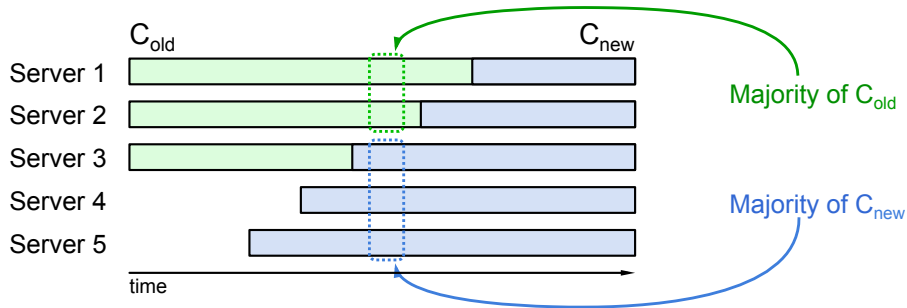# Configuration

## System configuration
- ID, address for each server
- Determines what constitutes a majority

Consensus mechanism must support changes in the configuration

- Replace failed machine
- Change degree of replication

# Configuration changes

Cannot switch directly from one configuration to another:
conflicting majorities could arise

# Joint consensus

Raft uses a 2-phase approach

- Intermediate phase uses joint consensus (need majority of both old and new configurations for elections, commitment)

- Once joint consensus is committed, begin replicating log entry for final configuration
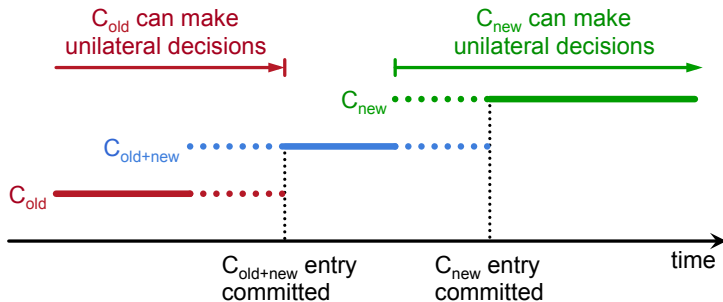
# Reading Material

- D. Ongaro and J. Ousterhout. In search of an understandable consensus algorithm.

  In *2014 USENIX Annual Technical Conference*, pages 305–319, Philadelphia, PA, June 2014. USENIX Association.

  http://www.disi.unitn.it/~montreso/ds/papers/raft.pdf