Consensus with RAFT

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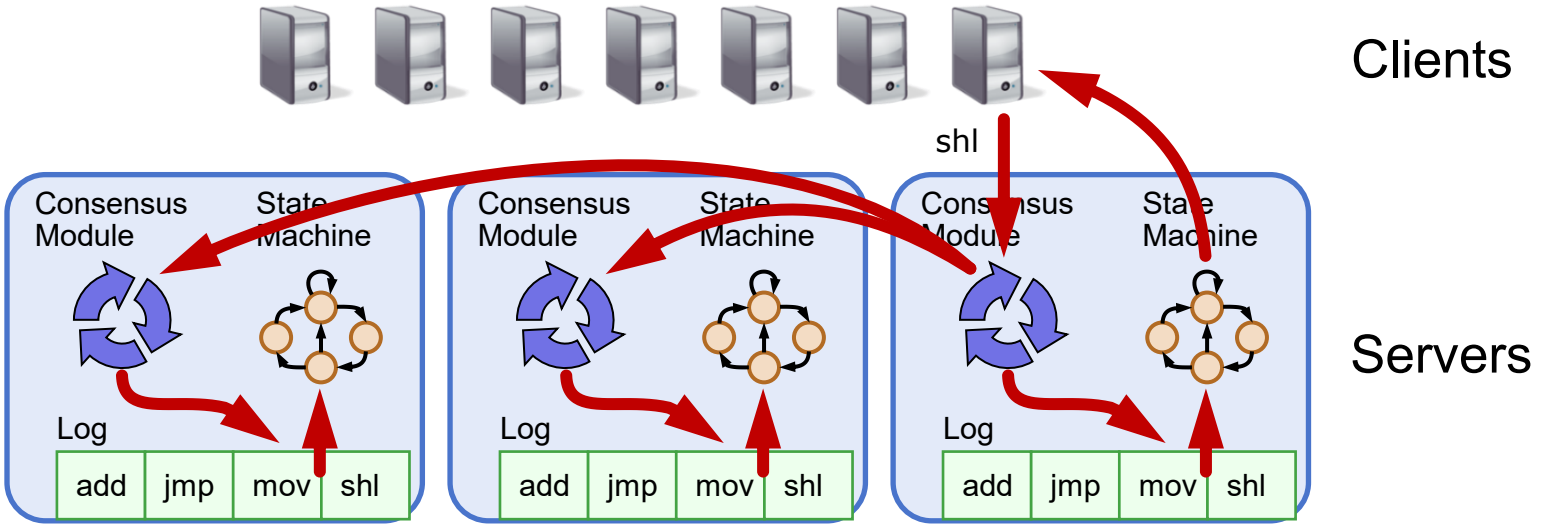
These slides are modified versions of slides from Diego Ongaro, John Ousterhout and Michael Freedman

Goal: Replicated Log



- Replicated log enables replicated state machine
  - All servers execute same commands in same order
- Consensus module ensures proper log replication

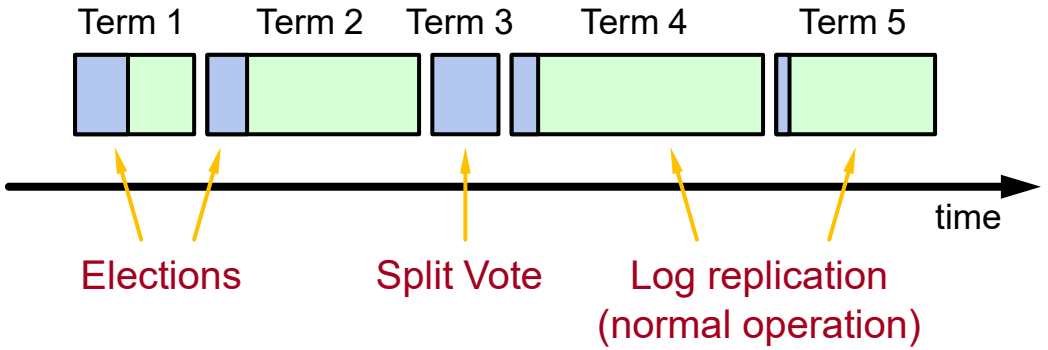
Raft Overview

- Raft is a library that uses a leader-based consensus scheme to implement fault-tolerant state machine replication

- Leader Election: ensures one leader at any time
- Log Replication: leader broadcasts messages to replicas in order (normal operation)
- Choosing Leader: ensures safety and consistency
- Client Interaction: ensures exactly-once semantics

Leader Election

Terms (aka Epochs)



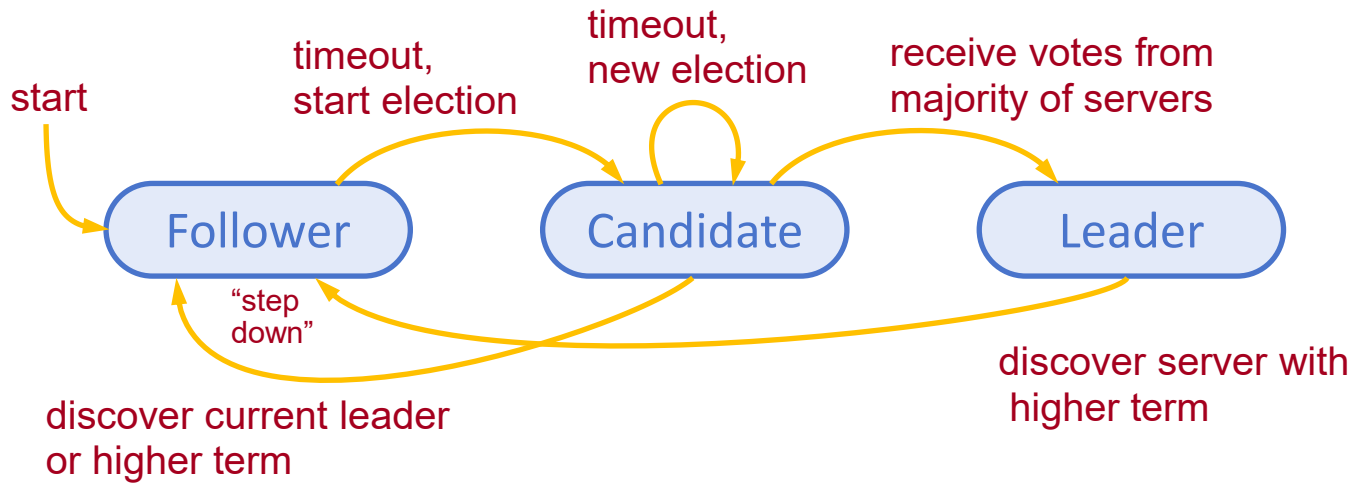
- Raft divides time into terms
- Each term starts with leader election
  - If election fails, a term has no leader (e.g., Term 3)
  - Otherwise, a term has one leader that performs log replication
- Each replica maintains latest known term value
  - Key role of terms: identify obsolete information

Server States

- At any given time, each server is either:
  - Leader: handles all client interactions, log replication
  - Follower: completely passive
  - Candidate: used to elect a new leader
- Normal operation: 1 leader, N-1 followers

Liveness Validation

- Servers start as followers
- Leaders send heartbeats (empty AppendEntries RPCs) to maintain authority over followers
- If electionTimeout elapses with no RPCs (100-500ms), follower assumes leader has crashed and starts new election

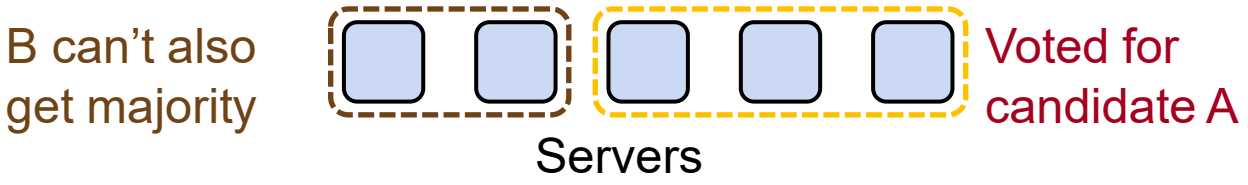


Elections

- Start election:
  - Increment current term, change to candidate state, vote for self
- Send RequestVote to all other servers, retry until either:
  - Receive votes from majority of servers:
    - Become leader
    - Send AppendEntries heartbeats to all other servers
  - Receive RPC from valid leader (with same or higher term):
    - Return to follower state
  - No-one wins election (election timeout elapses):
    - Increment term, start new election

Safety & Liveness

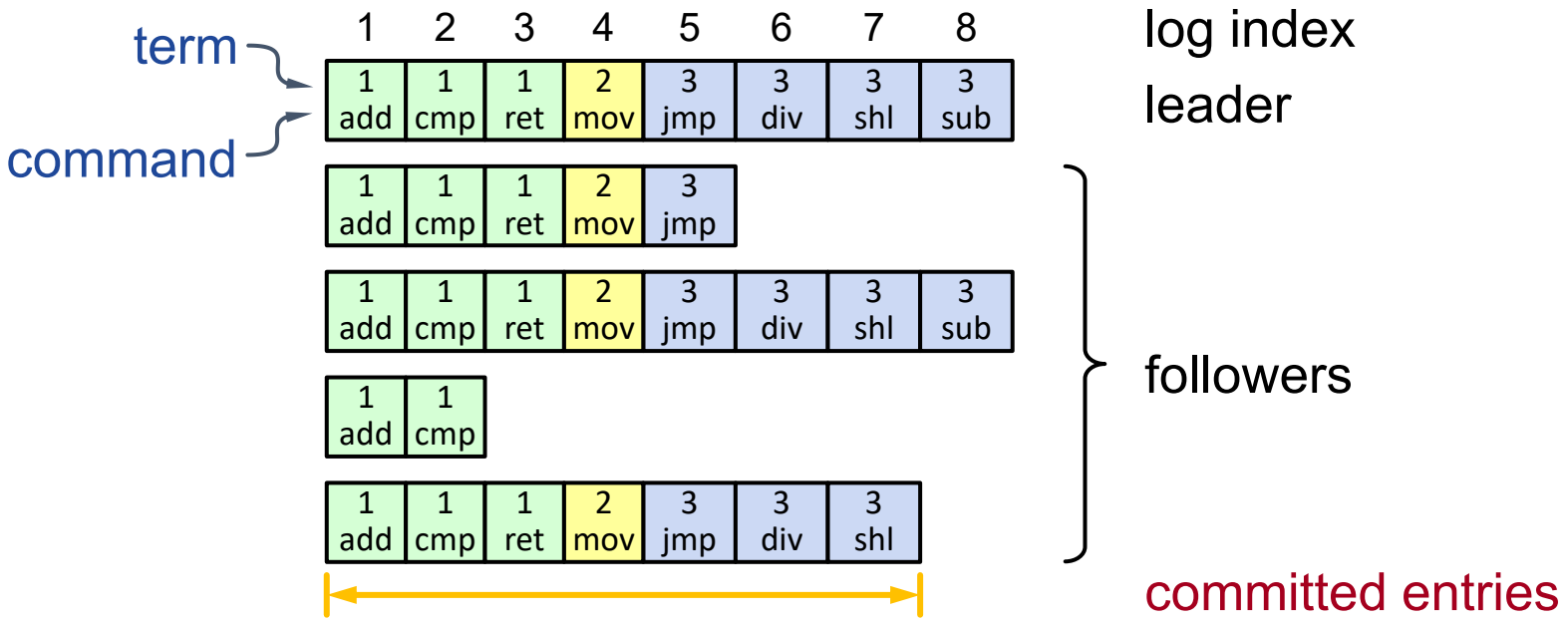
- Safety: allow at most one winner per term
  - Each server votes only once per term (persists on disk)
  - Two different candidates can't get majorities in same term



- Liveness: some candidate eventually wins
  - Each candidate chooses election timeouts randomly in [T, 2T]
  - One usually initiates and wins election before others start
  - Works well if T >> network RTT

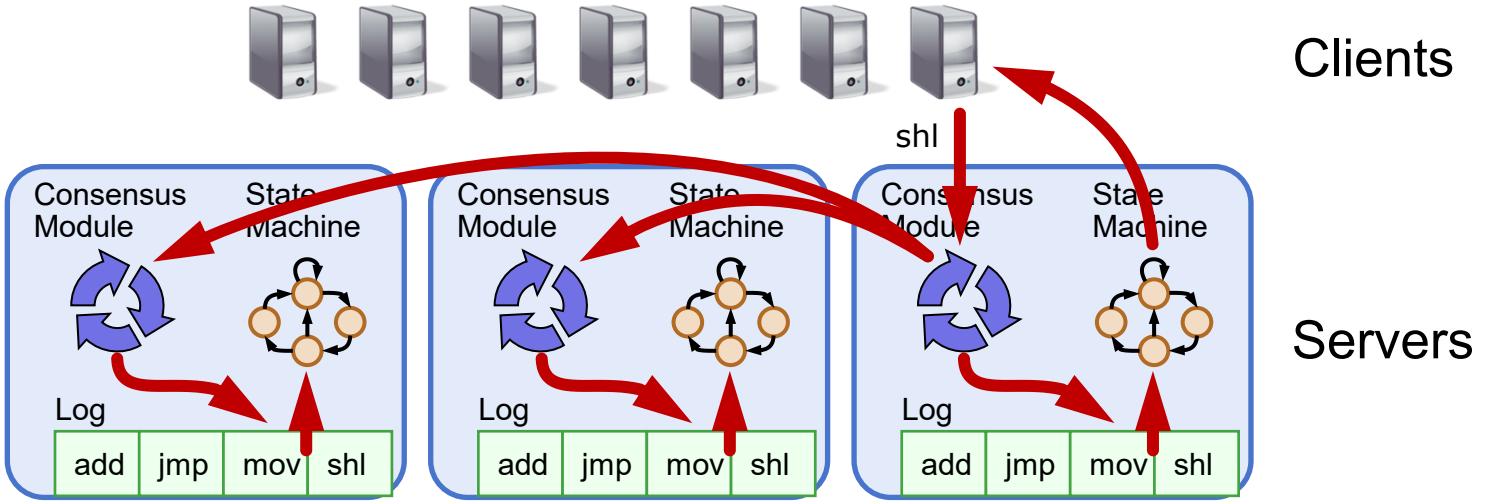
Log Replication

Log Structure



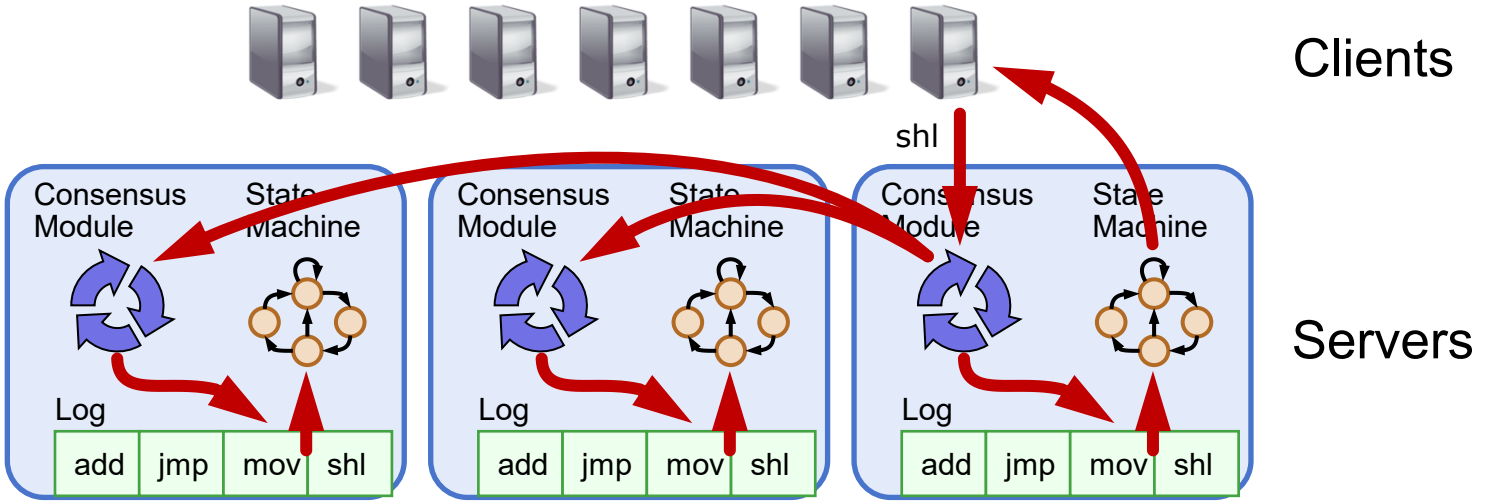
- Log entry = < index, term, command >
- Log stored on stable storage (disk); survives crashes
- Entry created in current term is committed when it is stored on majority of servers
- Committed entry stored durably, eventually executed by state machines

Normal Operation



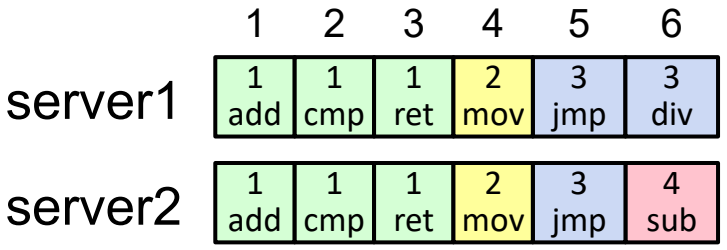
- Client sends command to leader
- Leader appends command to its log
- Leader sends AppendEntries RPCs to followers
- Once new entry committed:
  - Leader passes command to its state machine, sends result to client
  - Leader piggybacks commitment to followers in later AppendEntries
  - Followers pass committed commands to their state machines

Normal Operation



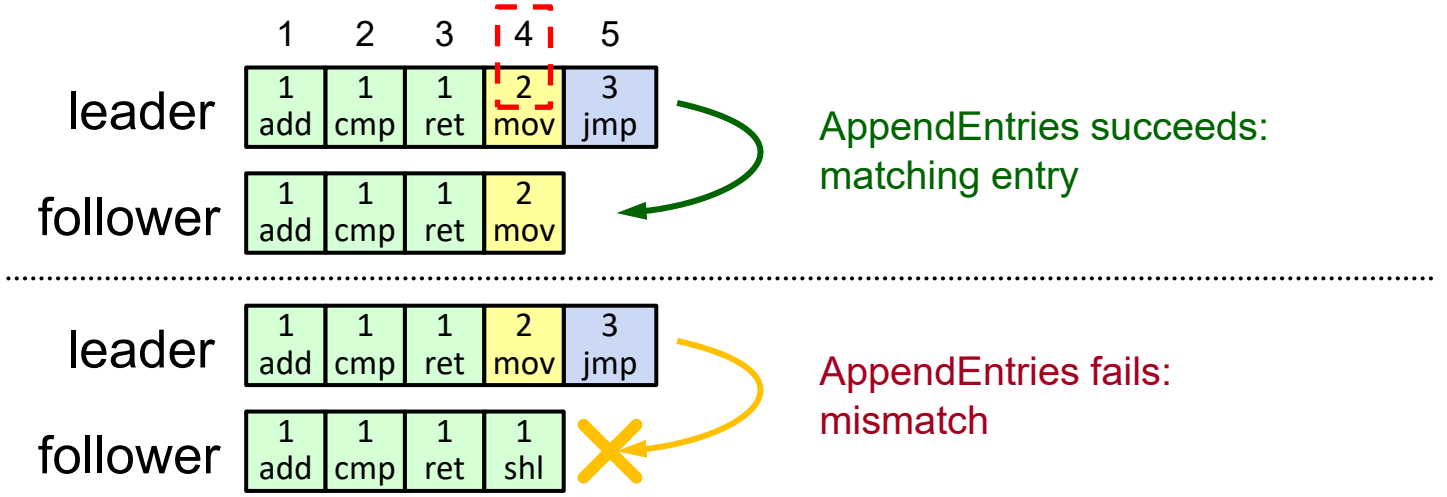
- Crashed / slow followers?
  - Leader retries RPCs until they succeed
- Performance is “optimal” in common case:
  - One successful RPC to any majority of servers

Log Operation: Highly Coherent



- If log entries on different servers have same index and term:
  - They store the same command
  - Logs are identical in all preceding entries
- If given entry is committed, all preceding entries are also committed

Log Operation: Consistency Check



- AppendEntries has <index,term> of entry preceding new ones
- Follower must contain matching entry, or else it rejects
- Implements an induction step, ensures coherency

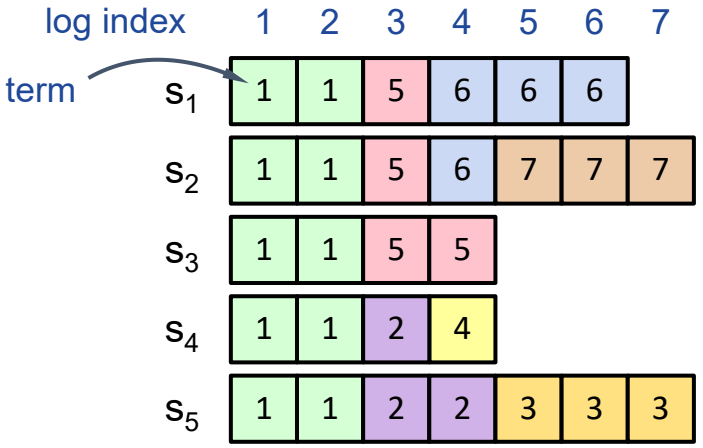
Why does Raft Work?

- Leader elected based on majority vote in a term
  - So only one leader per term
- Leader performs log replication
  - Can an old leader perform log replication? If so, how can Raft ensure logs are synchronized?
- Leader delivers message and waits for a majority before committing message
  - Intersection of the two majorities ensures that only one leader can deliver messages at a time

Choosing Leader

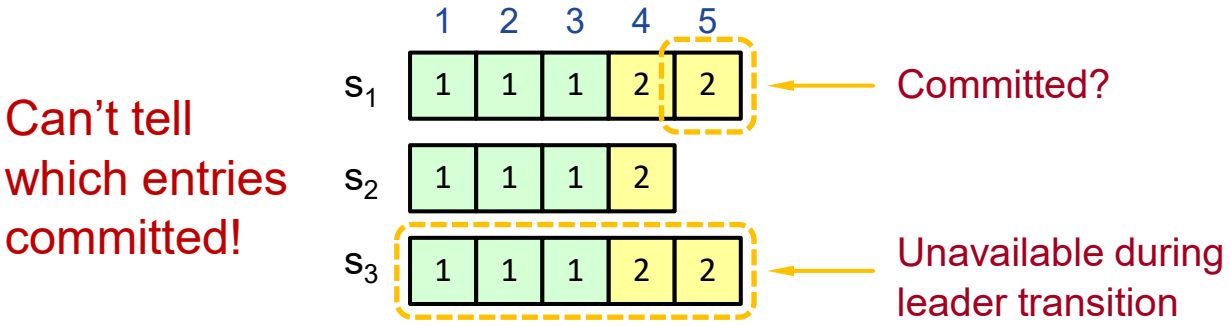
After Leader Change

- New leader's log is truth, no additional steps needed
  - Starts normal operation
  - Will eventually make follower's logs identical to leader's
  - Old leader may have left entries partially replicated
- Multiple crashes can leave many extraneous log entries



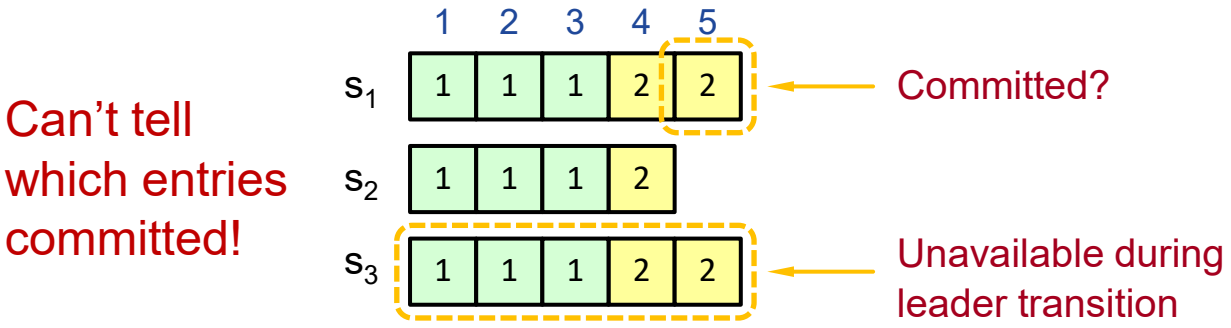
Choosing the Leader

- Raft leader completeness property: if log entry is committed in a term, entry will be present in logs of future term leaders
- Problem: how to determine which entries are committed?



Choosing the Best Leader

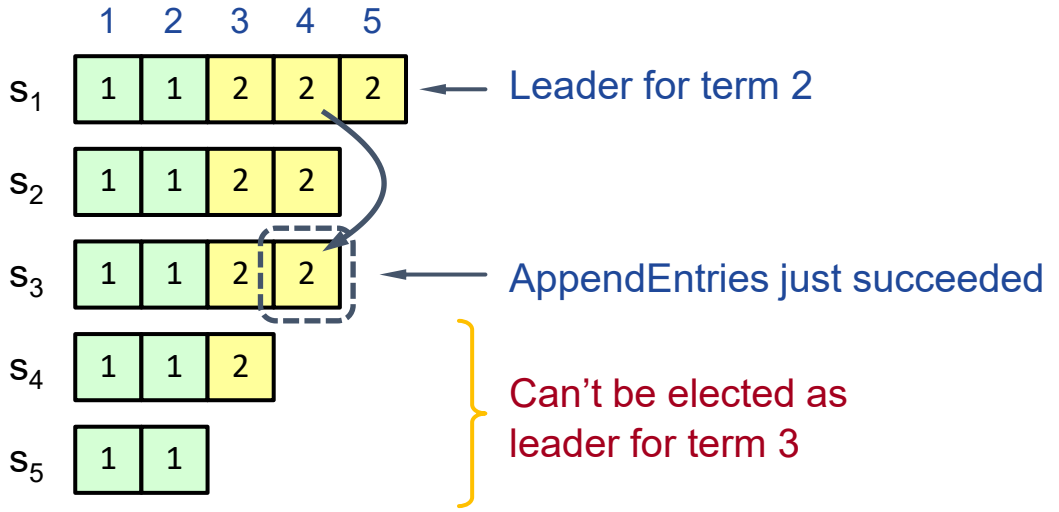
- Elect candidate that contains all potentially committed entries
  - In RequestVote, candidates incl. index + term of last log entry
  - Voter V denies vote if its log is "more complete":
    last entry has (higher term) or (higher index with same term)
  - Leader will have "most complete" log among electing majority



Leader's Commitment Rule

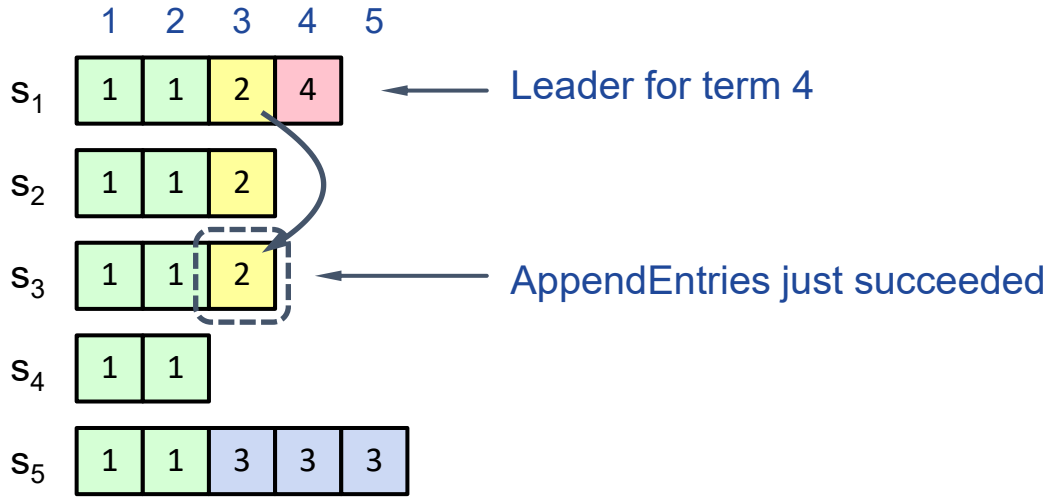
- Two cases:
  - Entries in current term
  - Entries in previous terms

Leader Commits Current Term Entry



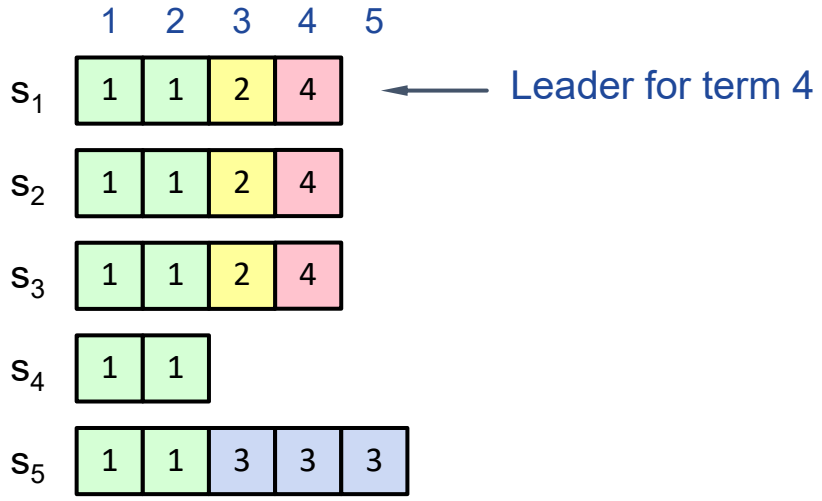
- Leader knows entry in current term is committed when it is stored durably on a majority
- This is safe because leader for Term 3 must contain Entry 4

Leader Commits Earlier Term Entry



- In Term 2, Entry 3 replicated to S1 and S2
- Leader 4 finishes replicating Entry 3 (from Term 2) to S3
  - Entry 3 is now on a majority of servers
- Is Entry 3 safely committed?
  - S5 can be elected as leader for Term 5 (how?)
  - If elected, it will overwrite Entry 3 on S1, S2, and S3

New Commit Rules



- For leader to decide that an entry (in current or previous term) is committed:
  - Entry stored on a majority
  - At least 1 new entry from leader's term is also in majority
- E.g., once Entry 4 is committed, S5 cannot be elected leader for Term 5, and Entry 3 and 4 are both safe

Client Interaction

Client Protocol

- Clients send commands to leader, if leader unknown, contact any server, which redirects client to leader
- Leader only responds after command logged (locally), committed, and executed by leader
- Problem: A leader could execute command and then fail before returning response to client
  - Client retries the same command with another leader, so command executed twice
- To ensure exactly-once semantics, state machines must perform duplicate detection
  - Client embeds unique request ID in each command
  - State machine checks request ID and returns previous result

Discussion

Q1

- A lease serves as a lock with a timeout
- Say, a leader is elected using leases as follows:
  - An external server stores
    - Server location of the current leader
    - Leader's lease, i.e, a time until which this server will serve as leader
  - Leader sends periodic heartbeats to external server
    - Each heartbeat renews the leader's lease, i.e., extends the time for which server will remain the leader
  - Other servers contact the external server to find leader
    - If the lease has expired, the first server to contact the external server becomes the leader
- What safety issues can occur with this leader election mechanism?

Q2

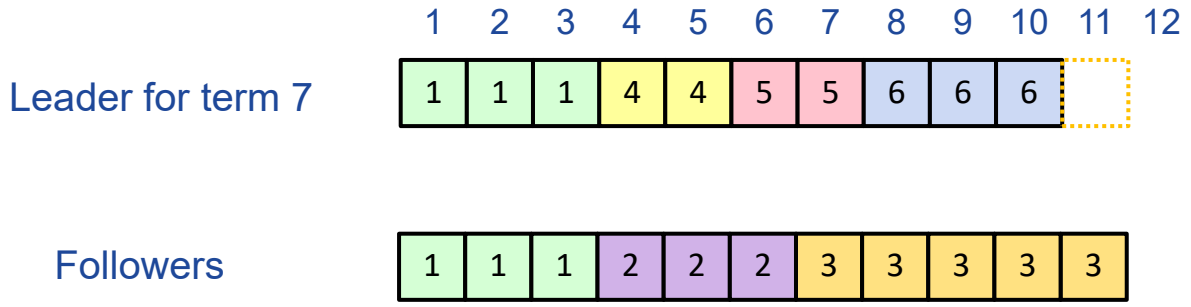
- Raft also uses heartbeats. Why doesn't it have these safety issues? Why can heartbeats cause liveness and/or availability issues?

Q3

- Besides the log, each server maintains the following persistently (on disk):
  - currentTerm (latest term that the server has seen)
  - votedFor (candidate that received vote in current term)
- Why are these values maintained on disk?

Q4

- When a new leader is elected, it may delete extraneous entries in a follower:



- Intuitively, why doesn't this cause data loss?

Q5

- What is exactly-once semantics and why is it useful? Why is it hard to enforce?