Raft

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Raft's Design Goals

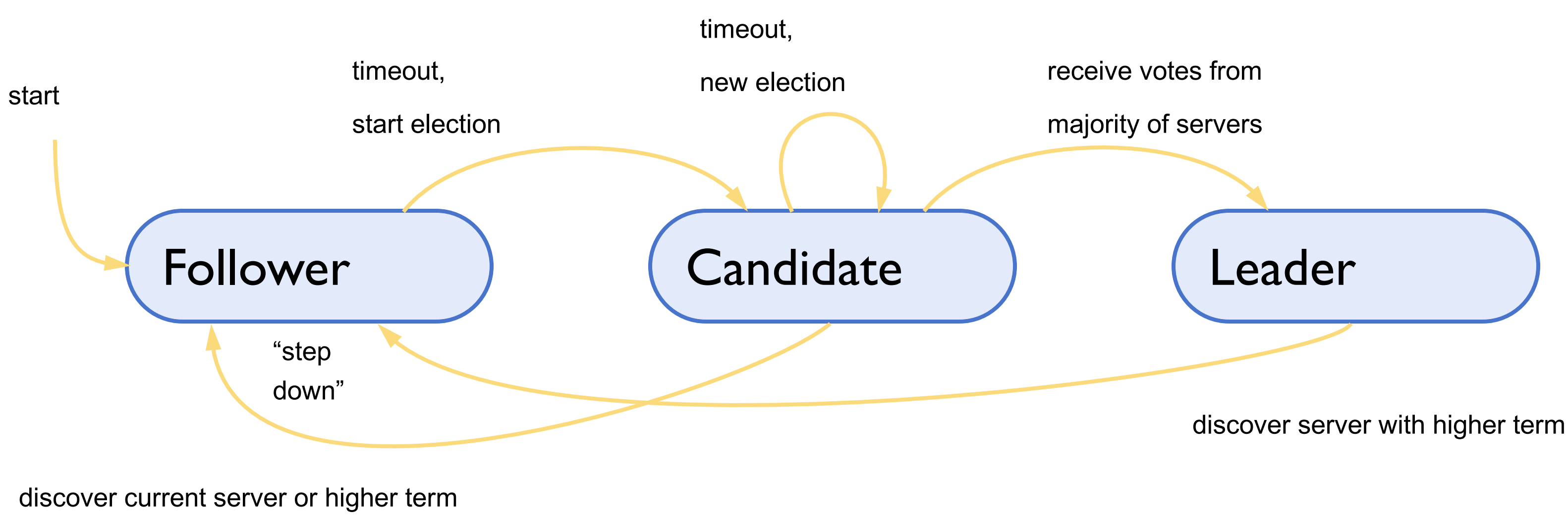
- Alternative to Paxos
  - Paxos is too complex and incomplete for real implementations
- Algorithm for building real systems
  - Must be correct, complete, and perform well
  - Must also be **understandable**
- "What would be easier to understand or explain?"
  - Fundamentally different decomposition than Paxos
  - Less complexity in state space
  - Less mechanism

Raft Overview

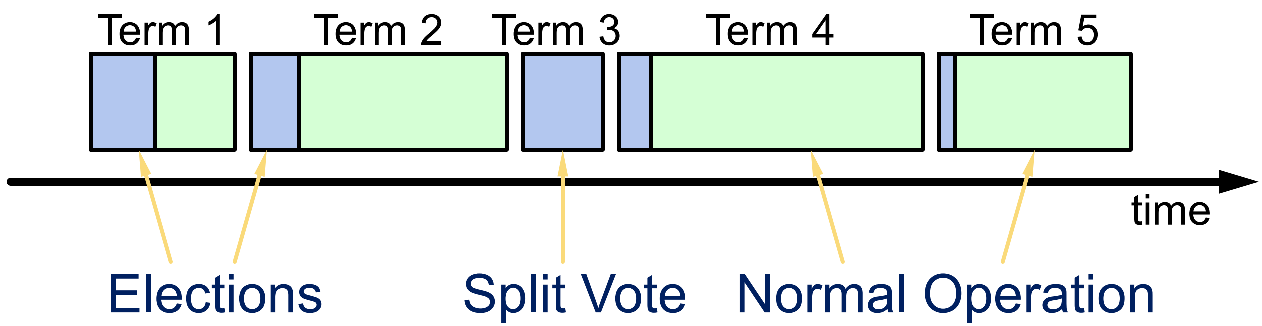
1. Leader election:
   - Select one of the servers to act as leader
   - Detect crashes, choose new leader
2. Normal operation (basic log replication)
3. Safety and consistency after leader changes
4. Neutralizing old leaders
5. Client interactions
   - Implementing linearizeable semantics
6. Configuration changes:
   - Adding and removing servers

Server States

- 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



Terms



- Time divided into terms:
  - Election
  - Normal operation under a single leader
- At most 1 leader per term
- Some terms have no leader (failed election)
- Each server maintains current term value
- Key role of terms: identify obsolete information

Heartbeats and Timeouts

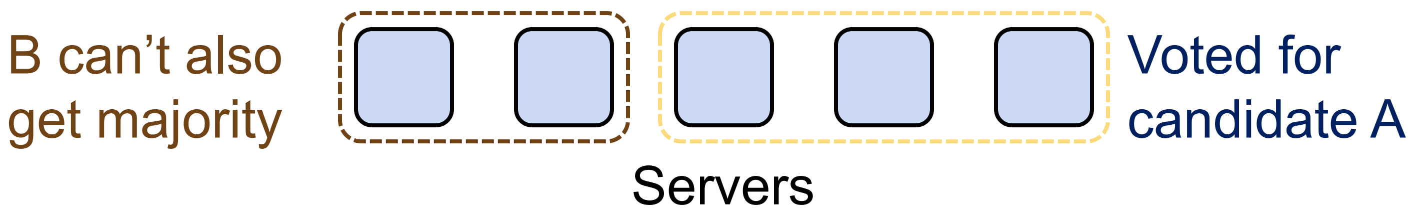
- Servers start up as followers
- Followers expect to receive RPCs from leaders or candidates
- Leaders must send **heartbeats** to maintain authority
- If **electionTimeout** elapses with no RPCs:
  - Follower assumes leader has crashed
  - Follower starts new election
  - Timeouts typically 100-500ms

Election Basics

- Increment current term
- Change to Candidate state
- Vote for self
- Send RequestVote RPCs to all other servers, retry until either:
  1. Receive votes from majority of servers:
     - Become leader
     - Send AppendEntries heartbeats to all other servers
  2. Receive RPC from valid leader:
     - Return to follower state
  3. No-one wins election (election timeout elapses):
     - Increment term, start new election

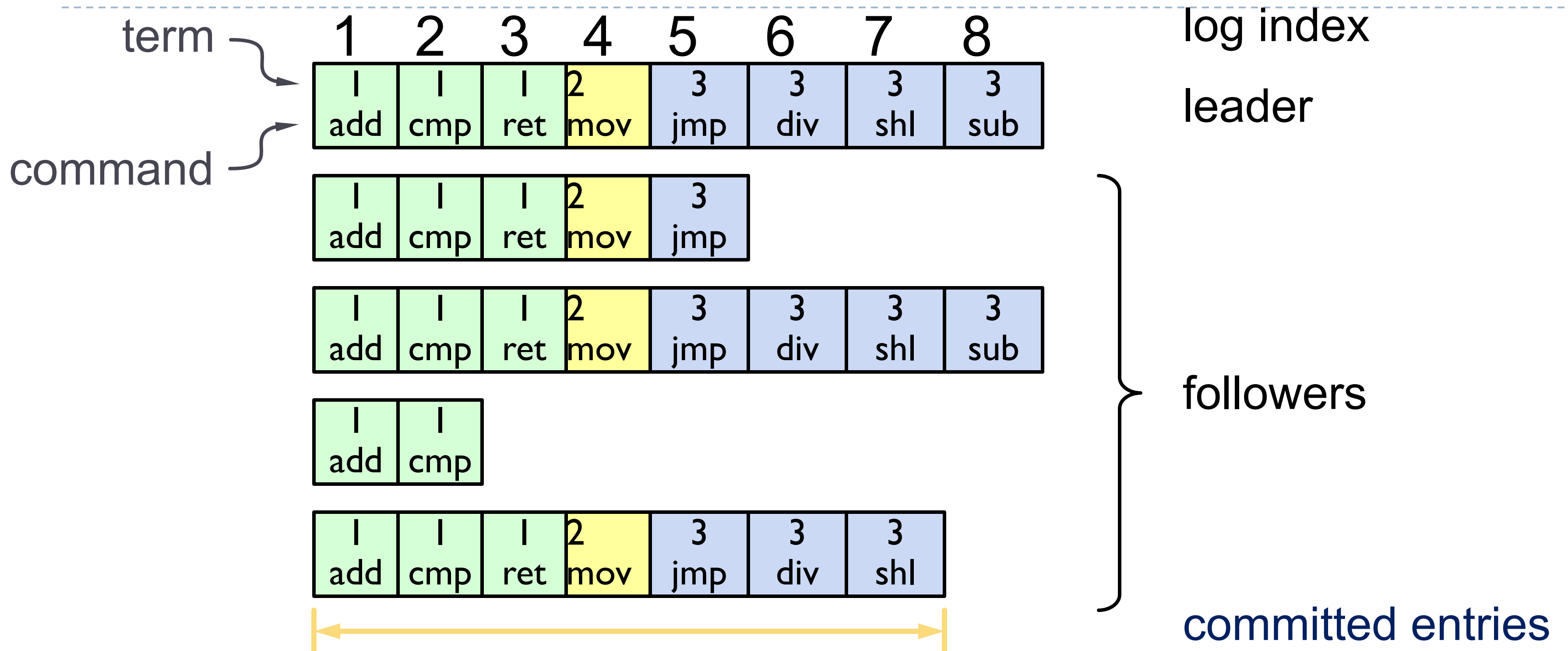
Elections, cont'd

- 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



- Liveness: some candidate must eventually win
  - Choose election timeouts **randomly** in [T, 2T]
  - One server usually times out and wins election before others wake up
  - Works well if T >> broadcast time

Log Structure



- Log entry = index, term, command
- 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
- 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

Log Consistency

High level of coherency between logs:

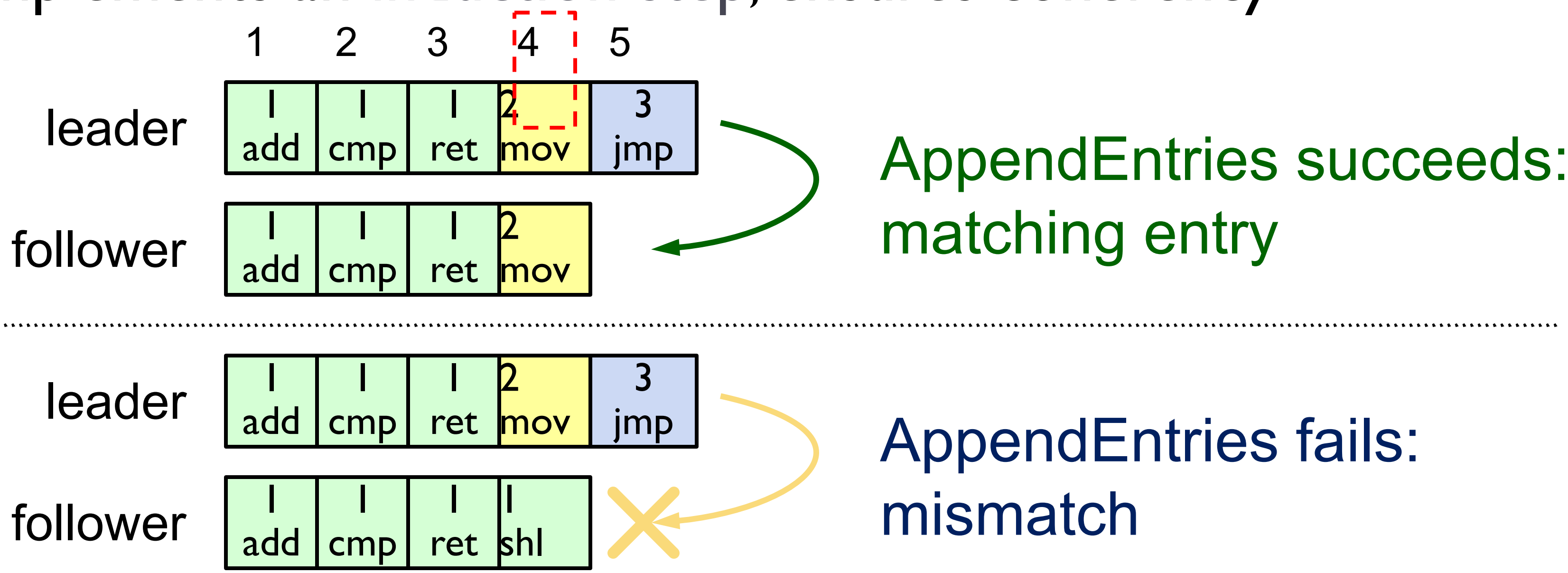
- If log entries on different servers have same index and term:
  - They store the same command
  - The logs are identical in all preceding entries

1	2	3	4	5	6
1 add	1 cmp	1 ret	2 mov	3 jmp	3 div
1 add	1 cmp	1 ret	2 mov	3 jmp	4 sub

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

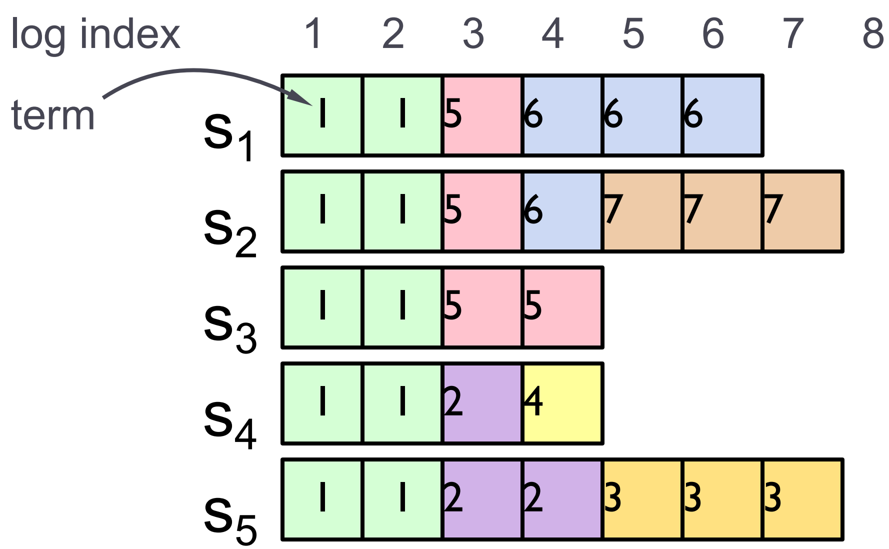
AppendEntries Consistency Check

- 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



Leader Changes

- 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

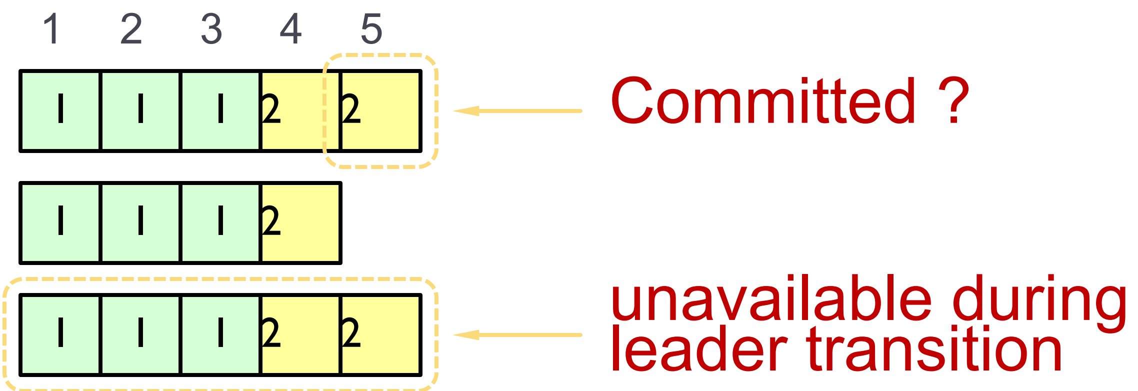
Committed → Present in future leaders' logs

Restrictions on commitment

Restrictions on leader election

Picking the Best Leader

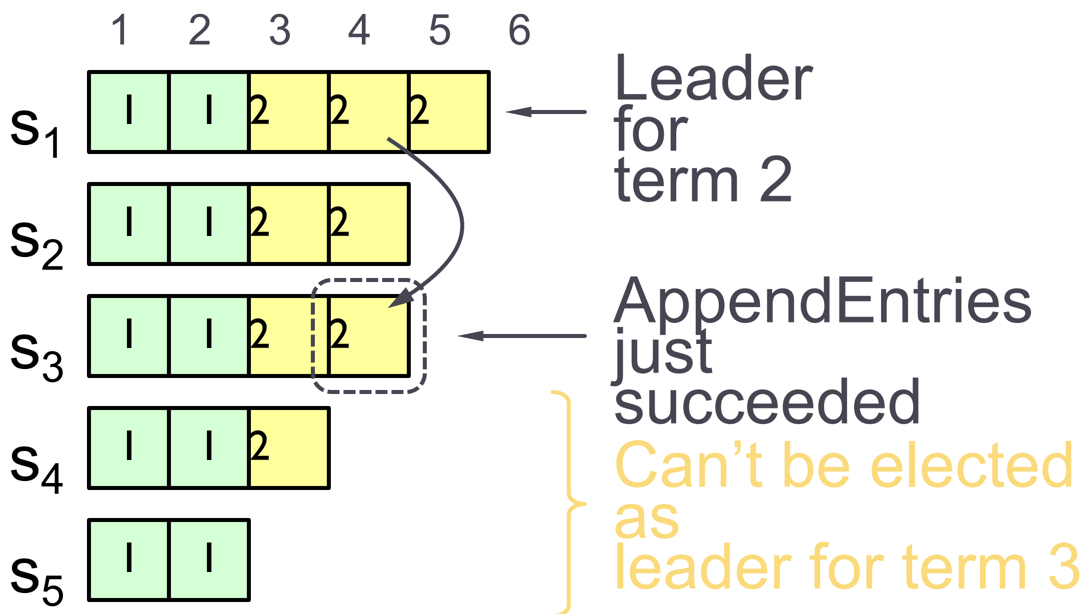
- Can't tell which entries are committed!



- During elections, choose candidate with log most likely to contain all committed entries
  - Candidates include log info in RequestVote RPCs (index & term of last log entry)
  - Voting server V denies vote if its log is "more complete": $(lastTerm_V > lastTerm_C) \ ||$ $(lastTerm_V == lastTerm_C) \ \&\& \ (lastIndex_V > lastIndex_C)$
  - Leader will have "most complete" log among electing majority

Committing Entry from Current Term

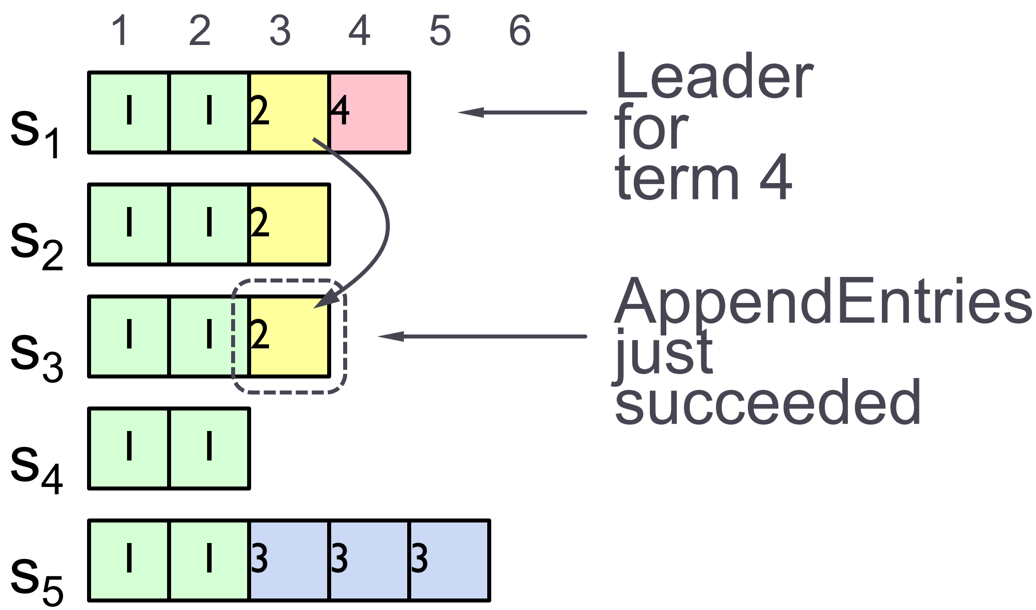
- Case #1/2: Leader decides entry in current term is committed



- Safe: leader for term 3 must contain entry 4

Committing Entry from Earlier Term

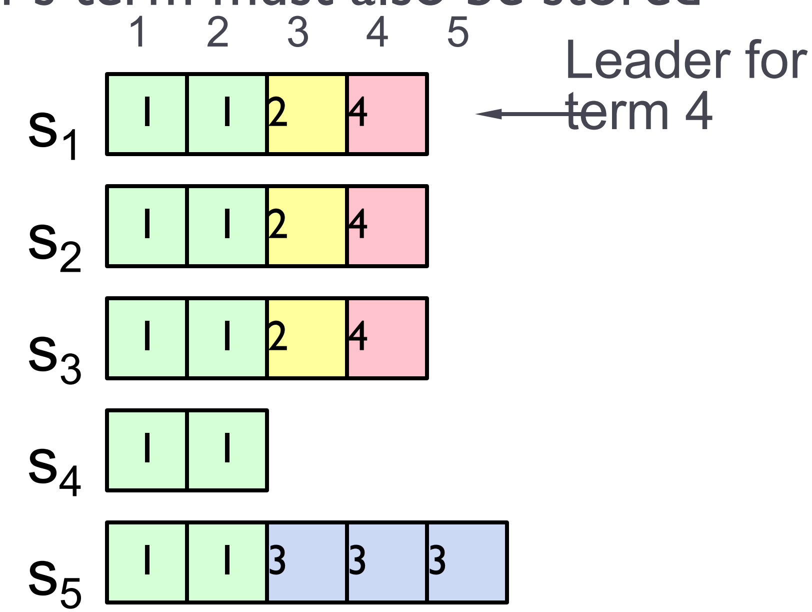
- Case #2/2: Leader is trying to finish committing entry from an earlier term



- Entry 3 not safely committed:
  - s_5 can be elected as leader for term 5
  - If elected, it will overwrite entry 3 on s_1, s_2, and s_3!

New Commitment Rules

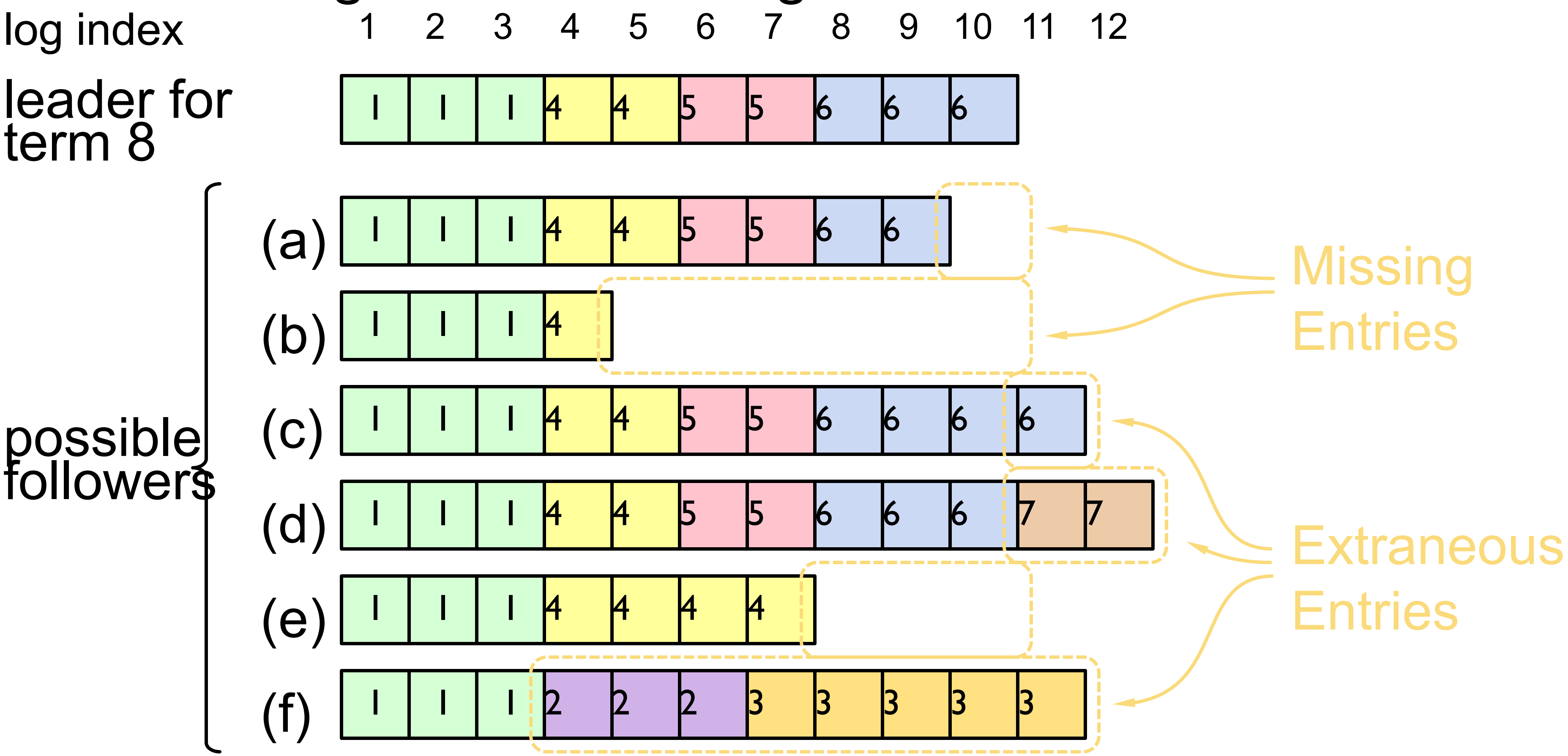
- For a leader to decide an entry is committed:
  - Must be stored on a majority of servers
  - At least one new entry from leader's term must also be stored on majority of servers
- Once entry 4 committed:
  - s_5 cannot be elected leader for term 5
  - Entries 3 and 4 both safe



Combination of election rules and commitment rules makes Raft safe

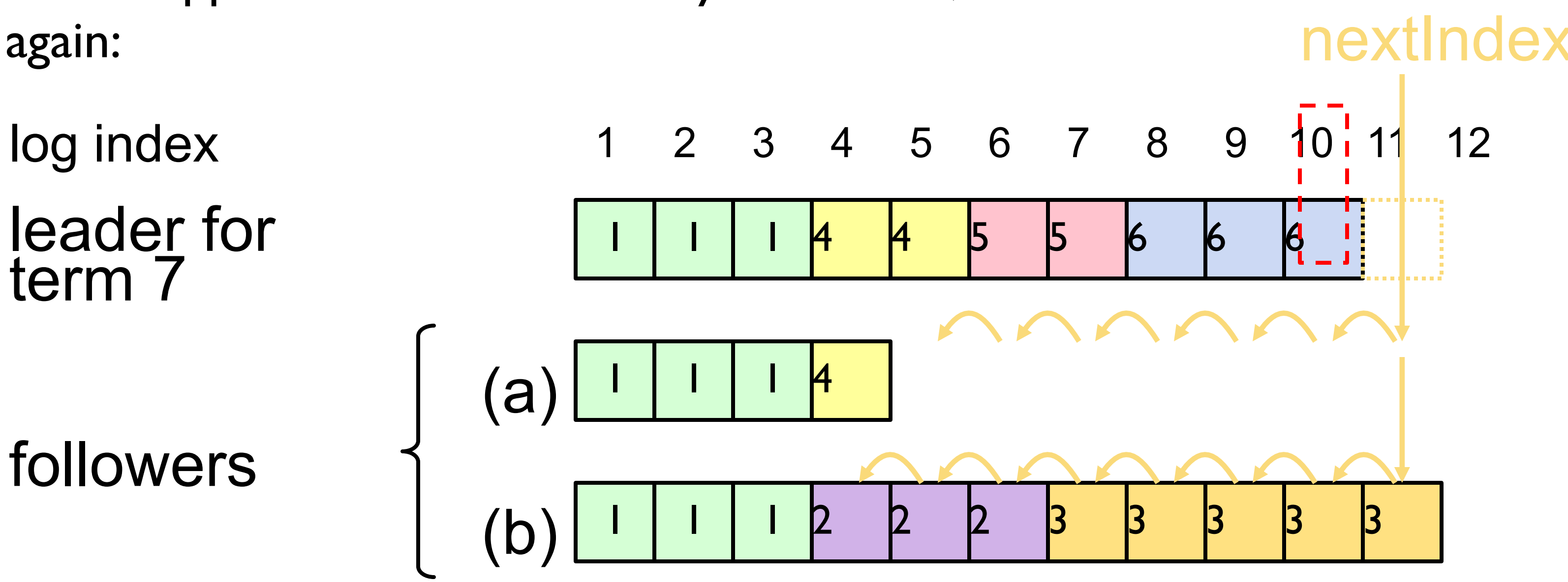
Log Inconsistencies

Leader changes can result in log inconsistencies:



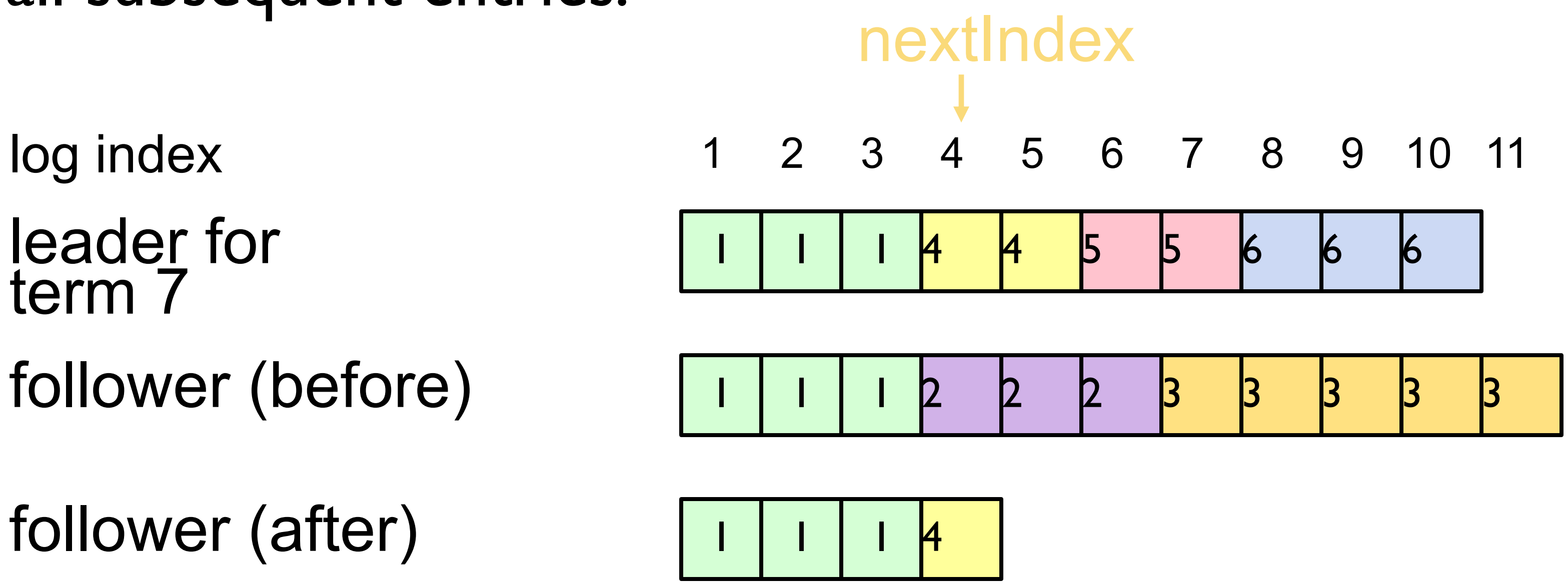
Repairing Follower Logs

- 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 Logs, cont'd

- When follower overwrites inconsistent entry, it deletes all subsequent entries:



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

Client Protocol

- Send commands to leader
  - If leader unknown, contact any server
  - If contacted server not leader, it will redirect to leader
- Leader does not respond until command has been logged, committed, and executed by leader's state machine
- If request times out (e.g., leader crash):
  - Client reissues command to some other server
  - Eventually redirected to new leader
  - Retry request with new leader

Client Protocol, cont'd

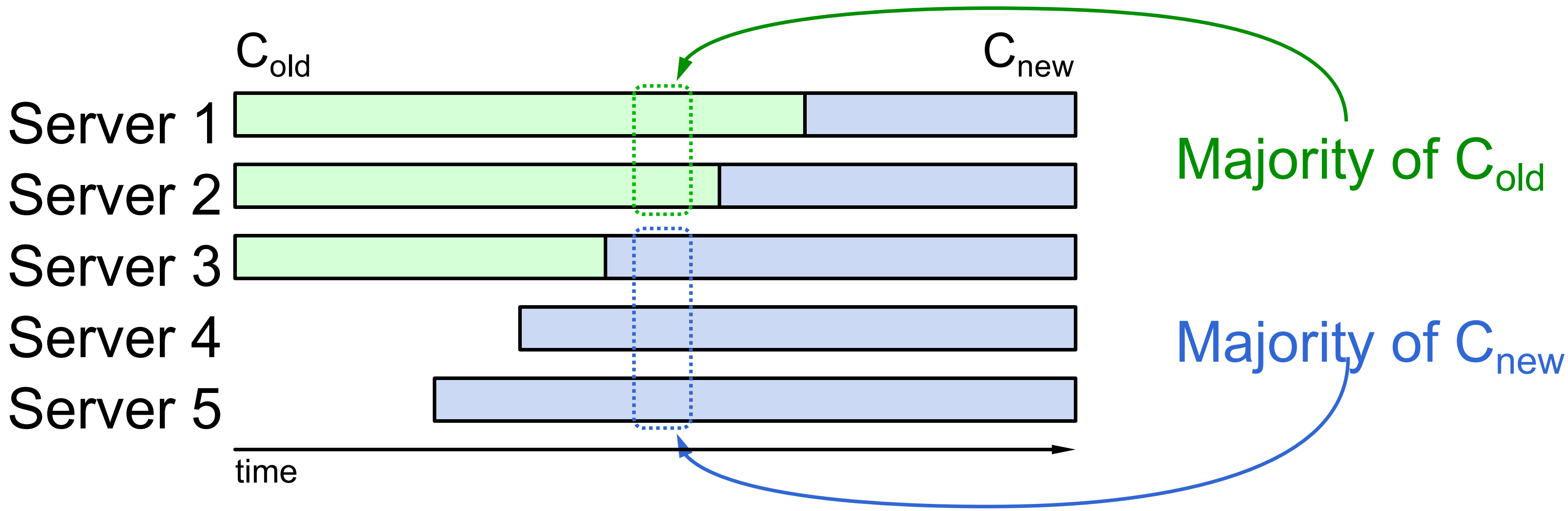
- What if leader crashes after executing command, but before responding?
  - Must not execute command twice
- Solution: client embeds a unique id in each command
  - Server includes id in log entry
  - Before accepting command, leader checks its log for entry with that id
  - If id found in log, ignore new command, return response from old command
- Result: exactly-once semantics as long as client doesn't crash

Configuration Changes

- 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

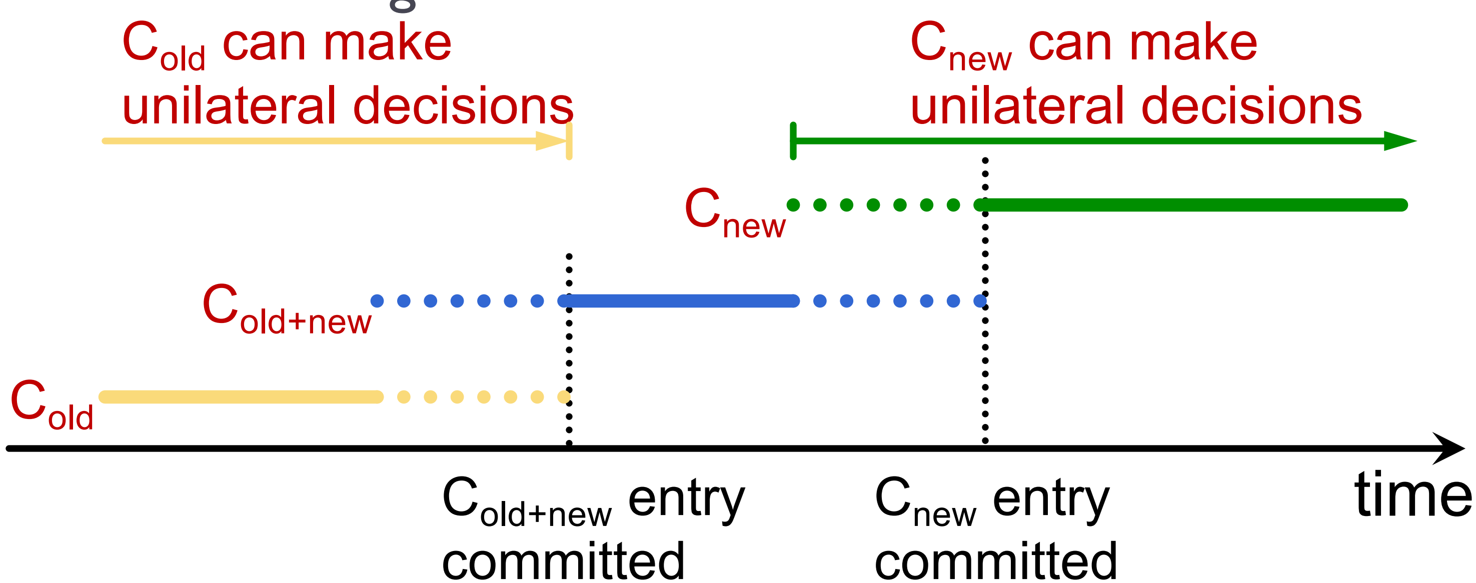
Configuration Changes, cont'd

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)
  - Configuration change is just a log entry; applied immediately on receipt (committed or not)
  - Once joint consensus is committed, begin replicating log entry for final configuration



Joint Consensus, cont'd

- Additional details:
  - Any server from either configuration can serve as leader
  - If current leader is not in C_{new}, must step down once C_{new} is committed.