UNIVERSITY of VIRGINIA

CS4740
CLOUD COMPUTING

Consensus (Contd.)

Prof. Chang Lou, UVA CS, Spring 2024

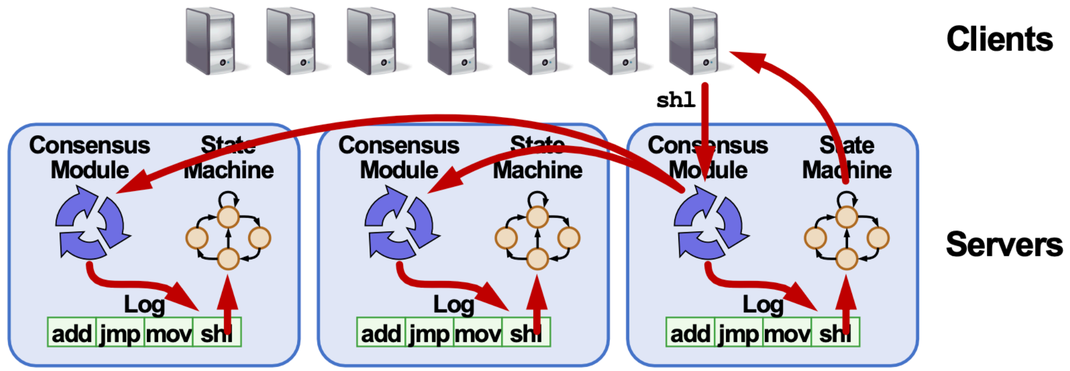
CONTEXT

— Today we continue talking about Raft, but in more details.

GAME: CONSENSUS (REVENGE)!

- Each student votes on an integer between 1 - 100.
  - Can only vote once, repeated votes become invalid.
- **Win**: if the majority of voters have chosen the same number, everyone in the quorum gets extra credits in the final.
- **Lose**: no quorum reached.
- **Extra**: before checking results, Chang can void a number.
- **Extra2**: n **malicious** students have joined the game.
  - Their goal is to create a split and fail the quorum.
- You have 5 min to discuss a strategy.
- Submit your votes to https://shorturl.at/jCT15

GOAL: REPLICATED LOG



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

RAFT OVERVIEW

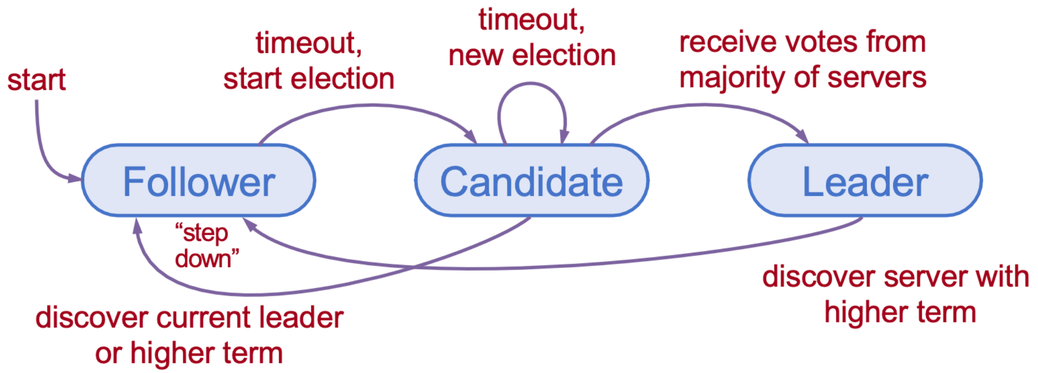
- 1. Leader election
- 2. Normal operation (basic log replication)
- 3. Safety and consistency after leader changes
- 4. Neutralizing old leaders
- 5. Client interactions

SERVER STATES

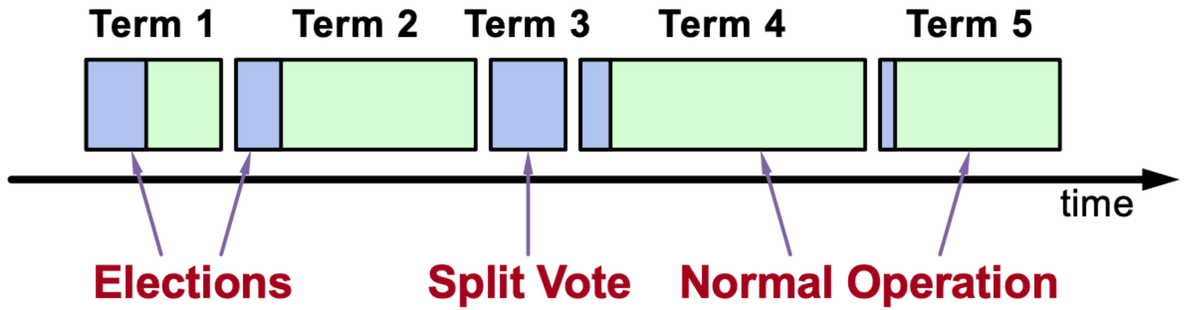
- At any given time, each server is either:
  - Leader: handles all client interactions, log replication
  - Follower: completely passive
  - Candidate: used to elect a new leader
- Normal operation: 1 leader, N-1 followers
  - Exercise: how to states transit to others?

STATE TRANSITION

- 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



TERMS (AKA EPOCHS)



- Time divided into terms
  - Election (either failed or resulted in 1 leader)
  - Normal operation under a single leader
- Each server maintains current term value
- Key role of terms: identify obsolete information

ELECTIONS

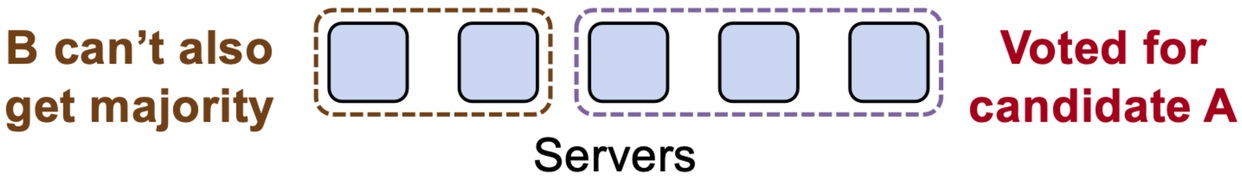
- Start election:
  - Increment current term, change to candidate state, vote for self
- Send Request Vote to all other servers, retry until either:
  - 1. Receive votes from majority of servers:
    - Become leader
    - Send AppendEntries heartbeats to all other servers
  - 2. Receive RPC from valid leader:
    - Return to follower state
  - 3. No-one win selection (election timeout elapses):
    - Increment term, start new election

TWO PROPERTIES

- **Safety**
  - only good things happen
- **Liveness**
  - good things will eventually happen

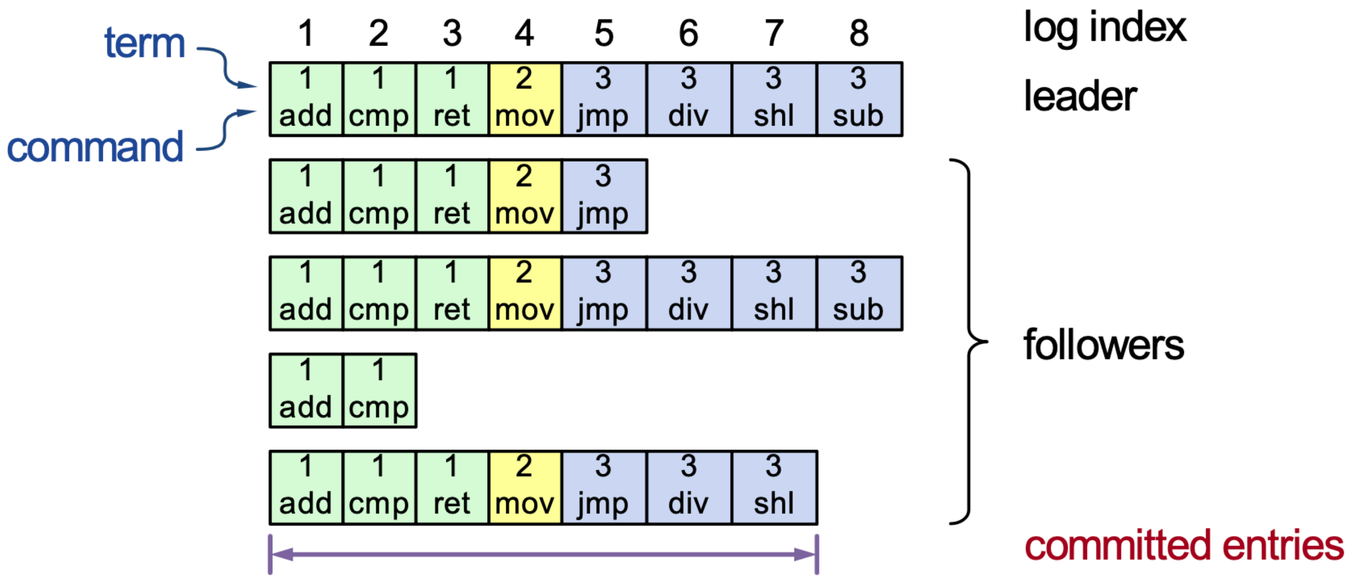
ELECTIONS

- 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 choose election timeouts randomly in [T, 2T]
  - One usually initiates and wins election before others start
  - Works well if T >> network RTT

LOG STRUCTURE



- Log entry = < index, term, command >
- Log stored on stable storage (disk); survives crashes
- Entry committed -> stored on majority of servers
  - Durable / stable, will eventually be executed by state machines

NORMAL OPERATION

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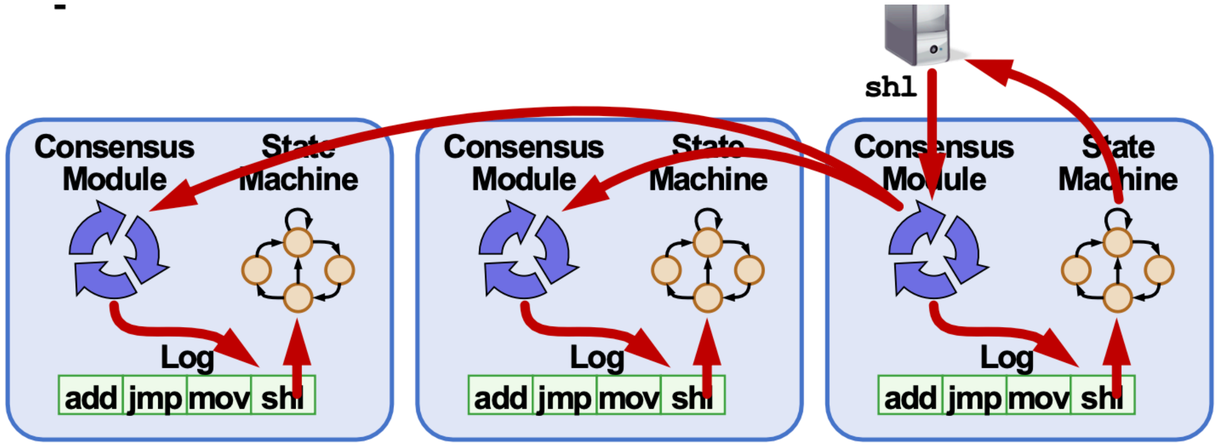
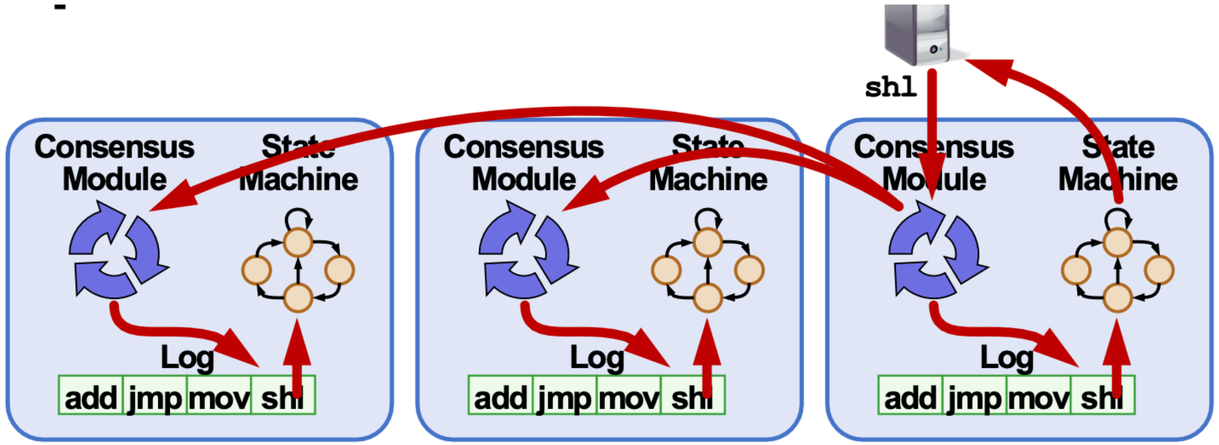


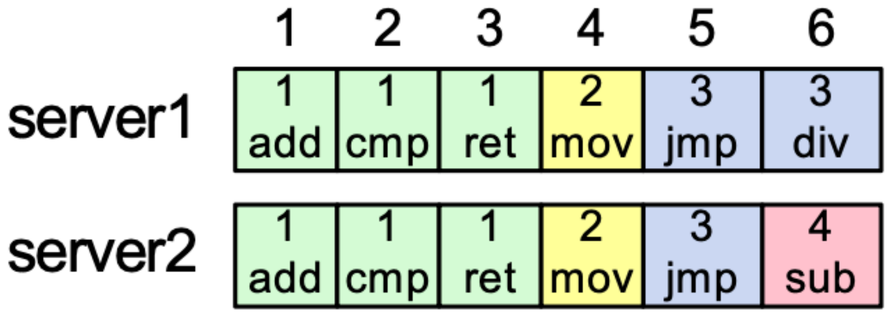
- Client sends command to leader
- Leader appends command to its log
- Leader sends AppendEntries RPCs to followers
- Once new entry committed:
  - Leader passes command to its state machine, sends result to client
  - Leader piggybacks commitment to followers in later AppendEntries
  - Followers pass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

NORMAL OPERATION



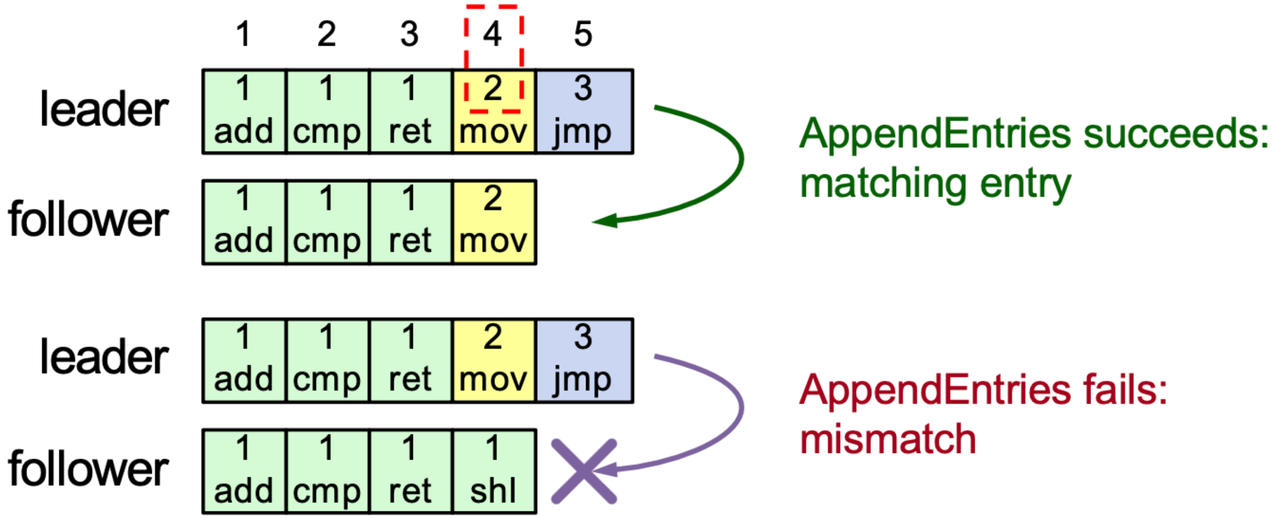
- Crashed / slow followers?
- Performance is “optimal” in common case:
  - Leader retries RPCs until they succeed
  - One successful RPC to any majority of servers
  - Followers pass committed commands to their state machines

LOG OPERATION: HIGHLY COHERENT



- If log entries on different server have same index and term:
  - Store the same command => one leader, one entry, one index, one term + log position never change
  - Logs are identical in all preceding entries => consistency check
- If given entry is committed, all preceding also committed

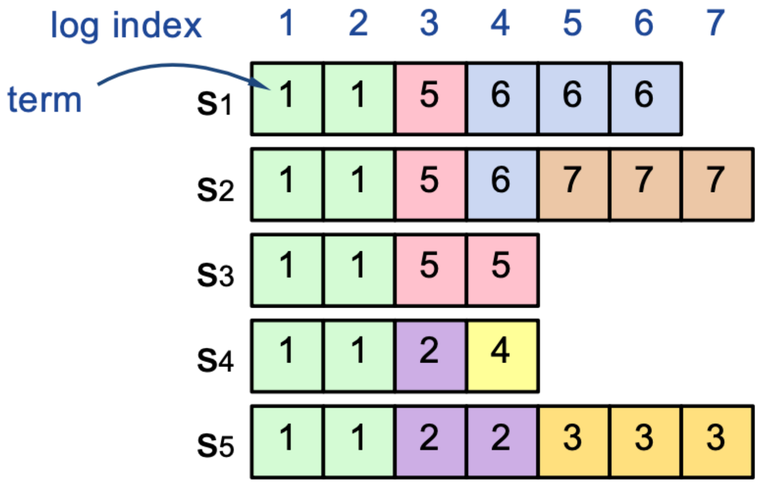
LOG OPERATION: CONSISTENCY CHECK



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

LEADER CHANGES

- New leader's log is truth, no special steps, start 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 (?)

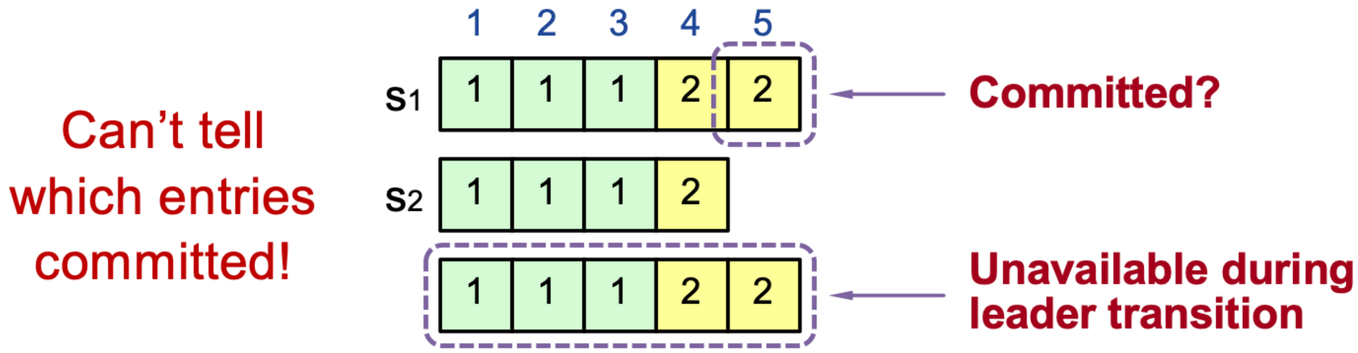


SAFETY REQUIREMENT

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

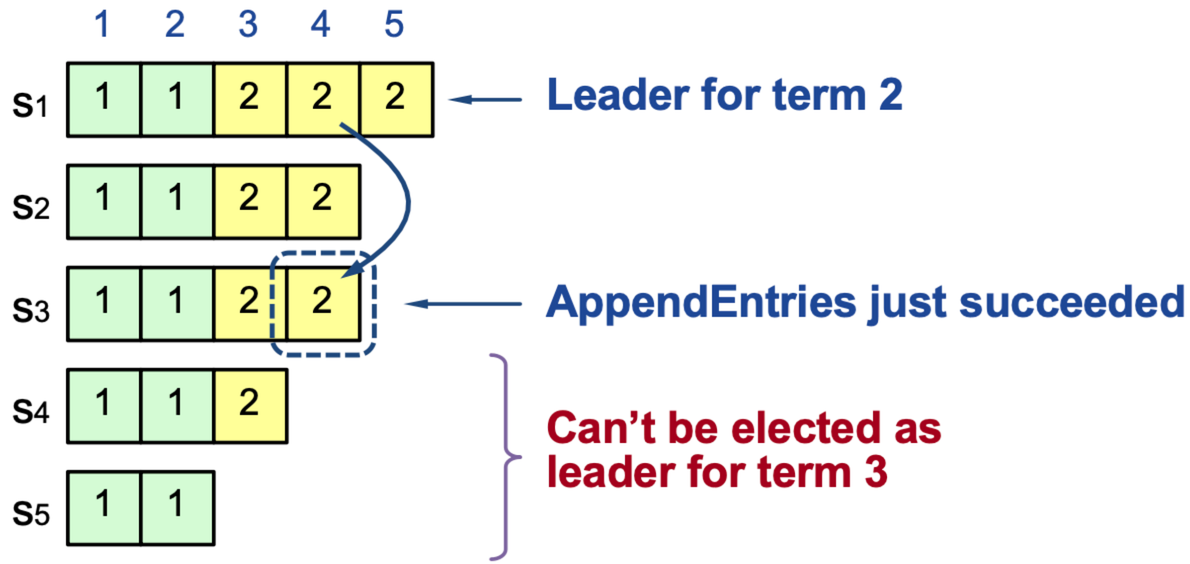
- Raft safety property: If leader has decided log entry is committed, entry will be present in logs of all future leaders
- Why does this guarantee higher-level goal?
  - 1. Leaders never over write entries in their logs
  - 2. Only entries in leader's log can be committed
  - 3. Entries must be committed before applying to state machine

PICKING THE BEST LEADER



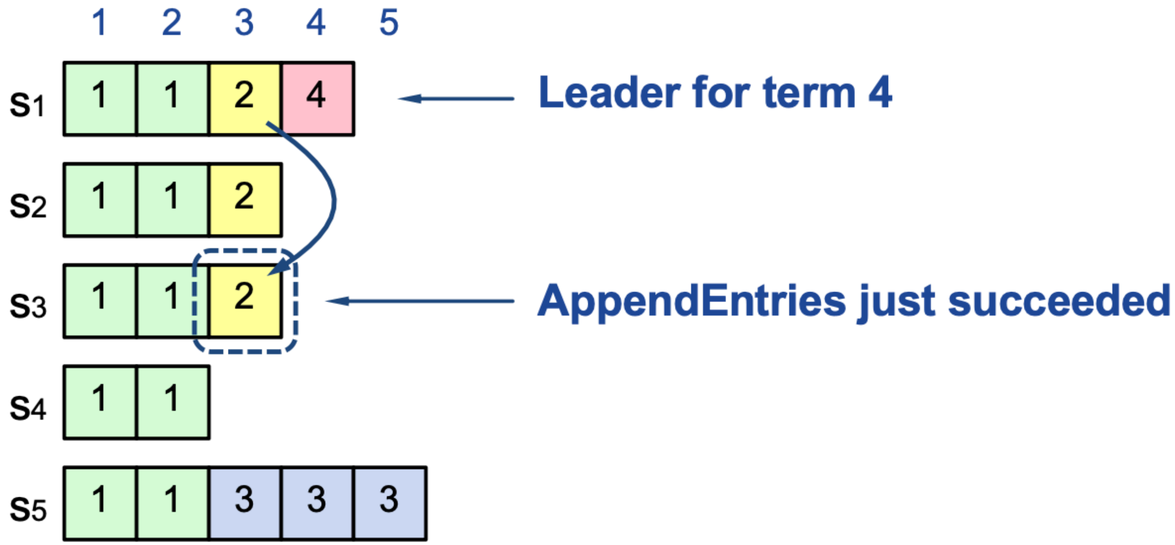
- Elect candidate most likely to contain all committed entries
  - In RequestVote, candidates incl. index + term of last log entry
  - Voter V denies vote if its log is "more complete": (newer term) or (entry in higher index of same term)
  - Leader will have "most complete" log among electing majority

COMMITTING ENTRY FROM CURRENT TERM



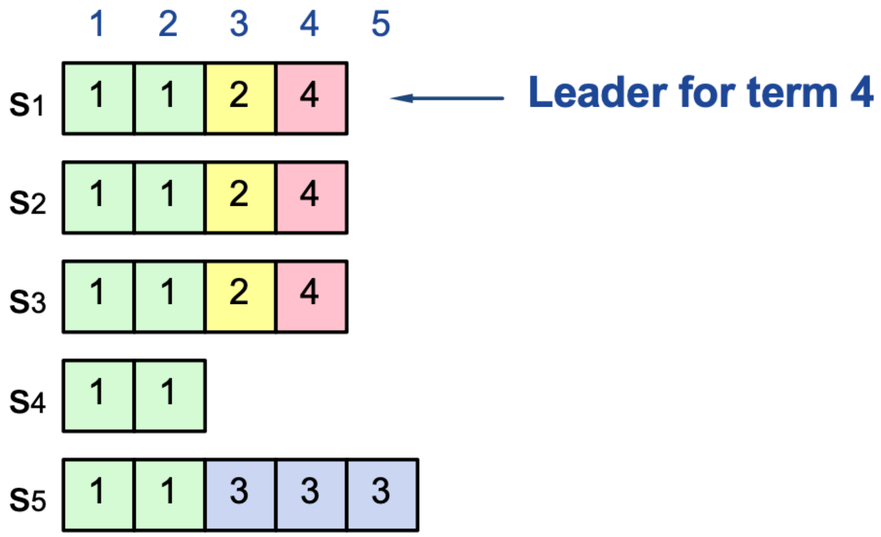
- Case #1: Leader decides entry in current term is committed
- Safe: leader for term 3 must contain entry 4

COMMITTING ENTRY FROM EARLIER TERM



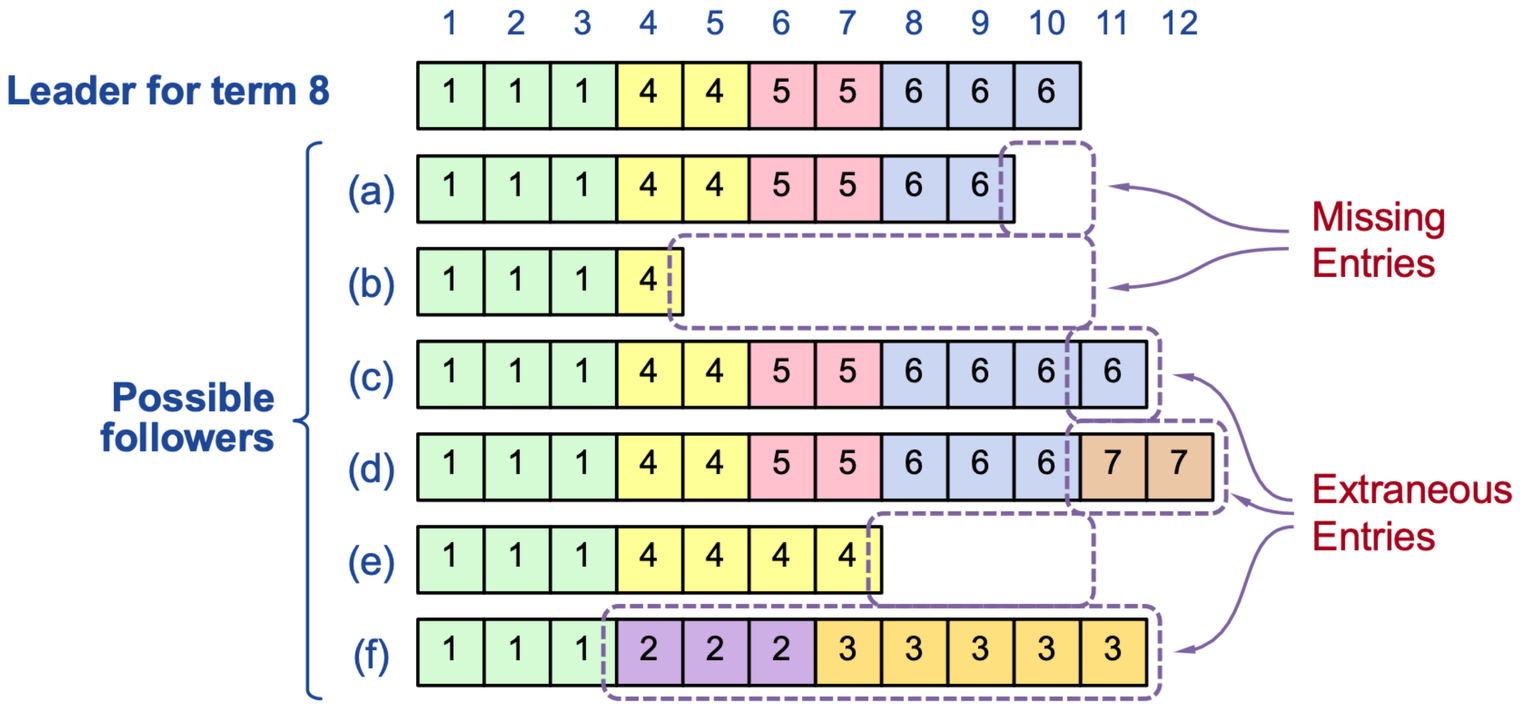
- Case #2: Leader trying to finish committing entry from earlier
- Entry 3 not safely committed:
  - s5 can be elected as leader for term 5 (how?)
  - If elected, it will overwrite entry 3 on s1, s2, and s3

NEW COMMITMENT RULES



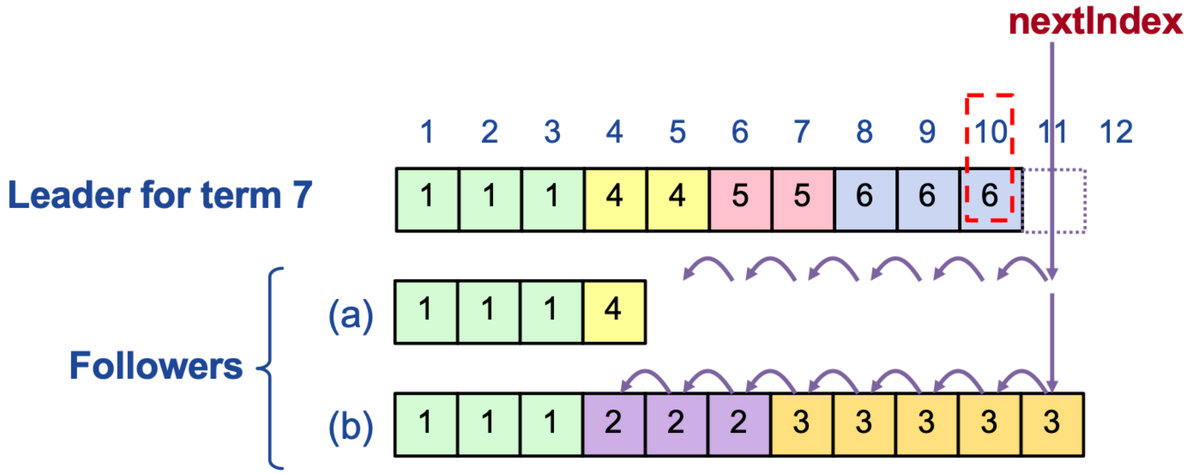
- Storing on a majority does not mean the entry is committed!
- For leader to decide entry is committed:
  - Entry stored on a majority
  - ≥1 new entry from leader's term also on majority
- Example; Once e4 committed, s5 cannot be elected leader for term 5, and e3 and e4 both safe

CHALLENGE: LOG INCONSISTENCIES



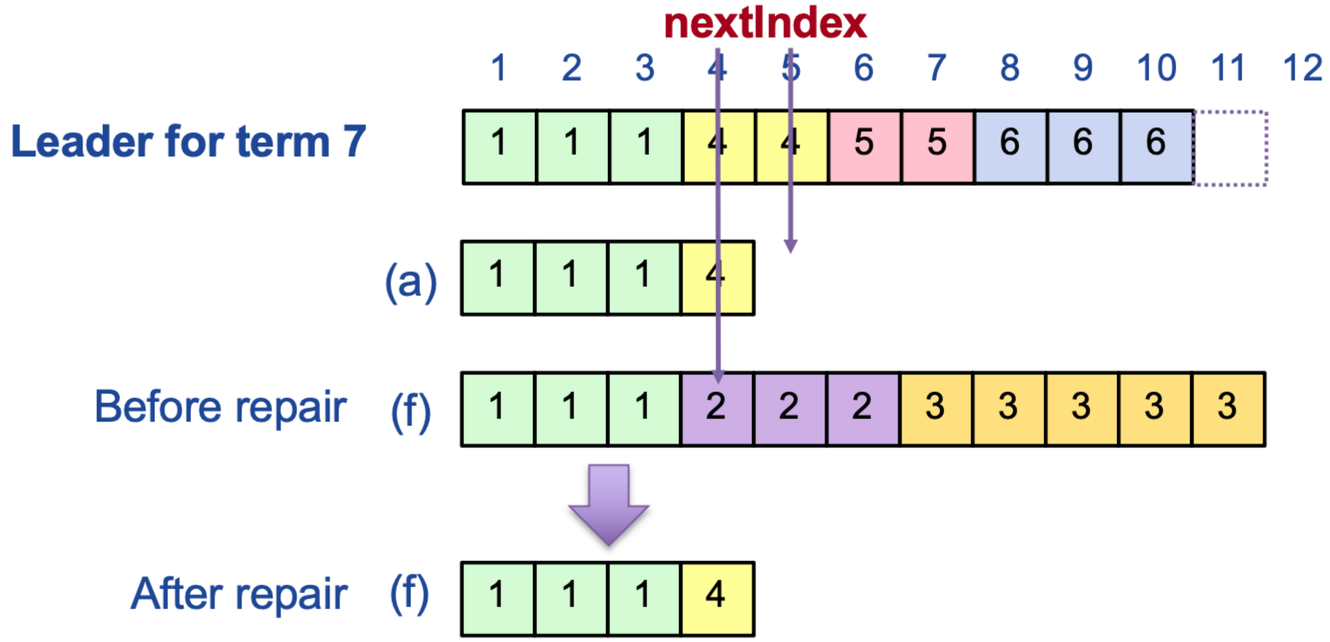
— Leader changes can result in log in consistencies

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)
- If AppendEntries consistency check fails, decrement nextIndex, try again

REPAIRING FOLLOWER LOGS



NEUTRALIZING OLD LEADERS

- Leader temporarily disconnected
  - other servers elect new leader
    - old leader reconnected
      - old leader attempts to commit log entries
- Terms used to detect stale leaders (and candidates)
  - Every RPC contains term of sender
  - Sender's term < receiver:
    - Receiver: Rejects RPC (via ACK which sender processes...)
  - Receiver's term < sender:
    - Receiver reverts to follower, updates term, processes RPC
- 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, which redirects client to leader
- Leader only responds after command logged, committed, and executed by leader
- If request times out(e.g., leader crashes):
  - Client reissues command to new leader (after possible redirect)
- Ensure exactly-once semantics even with leader failures
  - E.g., Leader can execute command then crash before responding
  - Client should embed unique request ID in each command
  - This unique request ID included in log entry
  - Before accepting request, leader checks log for entry with same id

GAME: CONSENSUS RESULT

— https://shorturl.at/jCT15

TAKEAWAYS

- Node roles: Leader, Candidate, Follower
- Terms: to identify obsolete information
- Committed log: durable on the majority of nodes (+ new entry rule)
- Repair logs: Delete extraneous entries + Fill in missing entries
- Next class: **Midterm Review**.
- Mon 3/11 Hacker Day, **no class**, 3/12 Lab2A **Deadline**.

ACKNOWLEDGEMENT

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THIS SLIDES INCLUDES CONTENTS FROM PROF. DAN PORTS' DISTRIBUTED SYSTEMS COURSE (UW)