Distributed Systems

CS425/ECE428

March 6 2023

Instructor: Radhika Mittal

Logistics

- MP1 is due today.
- HW2 is due on Wednesday.
- MP2 has been released.
- HW3 has been released.

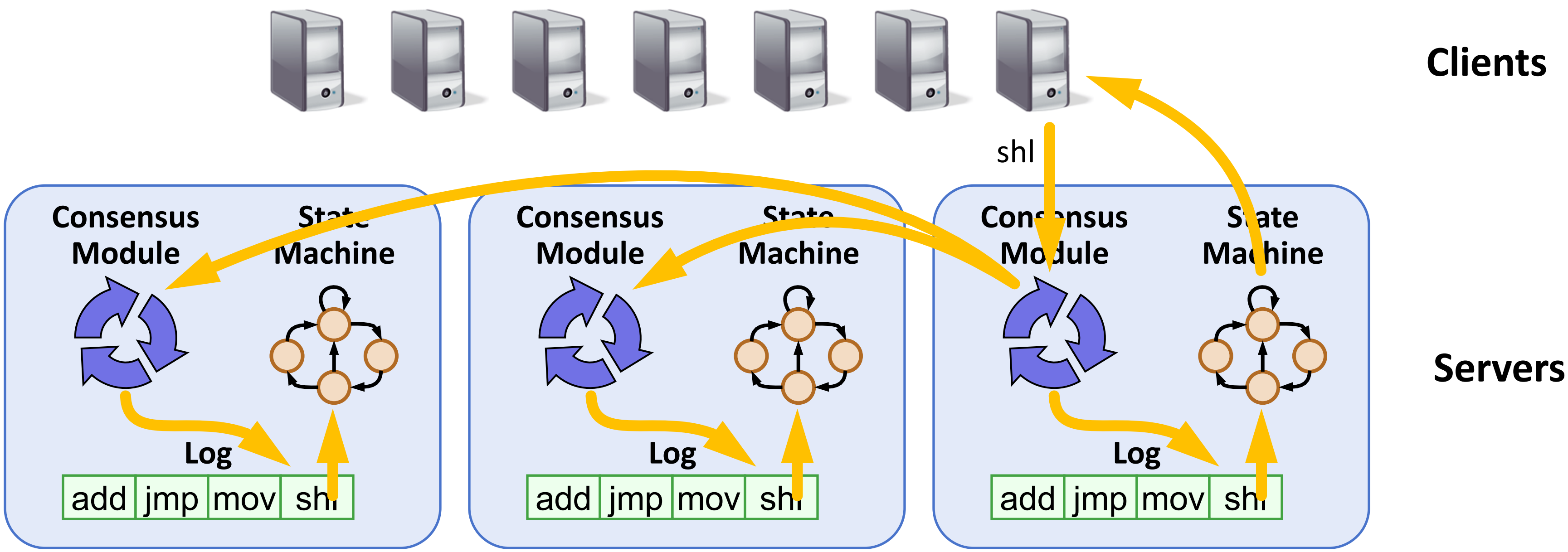
Agenda for today

- Consensus
  - Consensus in synchronous systems
    - *Chapter 15.4*
  - Impossibility of consensus in asynchronous systems
    - *We will not cover the proof in details*
  - Good enough consensus algorithm for asynchronous systems:
    - *Paxos made simple, Leslie Lamport, 2001*
  - Other forms of consensus algorithm
    - Raft (log-based consensus)
    - Block-chains (distributed consensus)

Raft: A Consensus Algorithm for Replicated Logs

Slides from Diego Ongaro and John Ousterhout, Stanford University

Goal: Replicated Log



- Replicated log => replicated state machine
  - All servers execute same commands in same order
- Consensus module ensures proper log replication
- **System makes progress as long as any majority of servers are up**
- **Failure model: fail-stop (not Byzantine), delayed/lost messages**

Raft Overview

1. Leader election:
   - Select one of the servers to act as leader
   - Detect crashes, choose new leader
2. Neutralizing old leaders
3. Normal operation (basic log replication)
4. Safety and consistency after leader changes

Raft Overview

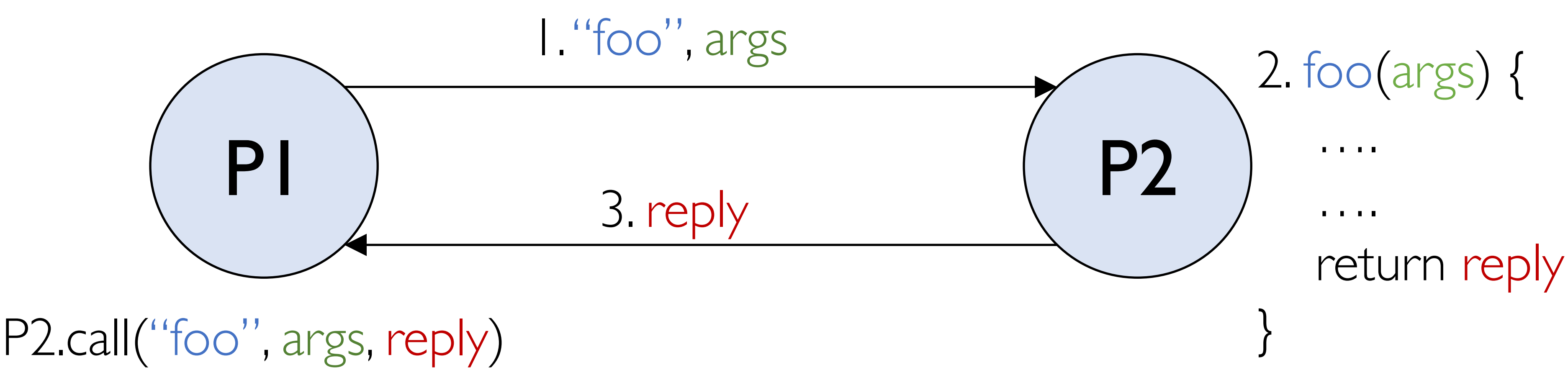
1. Leader election:
   - Select one of the servers to act as leader
   - Detect crashes, choose new leader
2. Neutralizing old leaders
3. Normal operation (basic log replication)
4. Safety and consistency after leader changes

Server States

- At any given time, each server is either:
  - Leader: handles all client interactions, log replication
    - At most 1 viable leader at a time
  - Follower: completely passive: issues no RPCs (requests), responds to incoming RPCs
  - Candidate: used to elect a new leader
- Normal operation: 1 leader, N-1 followers

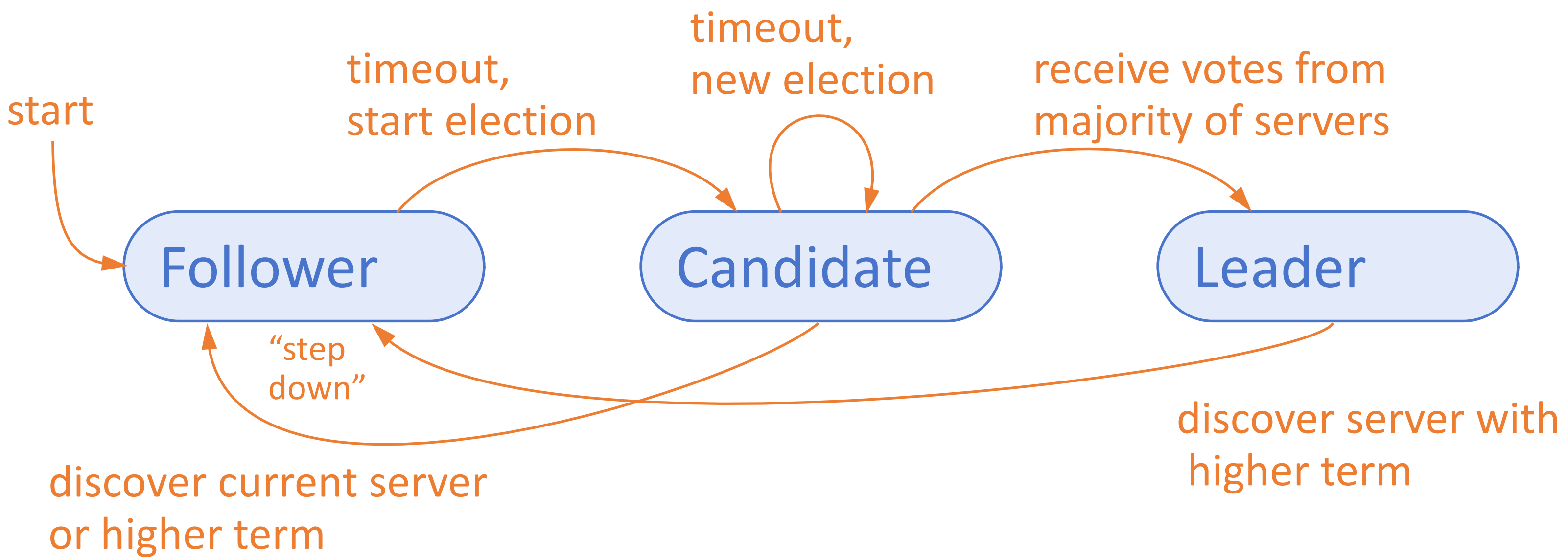
Quick Detour: RPCs

- Raft servers communicate via RPCs.
- What are RPCs?
  - Remote Procedure Calls: *procedure call between functions on different processes*
  - *Convenient programming abstraction.*

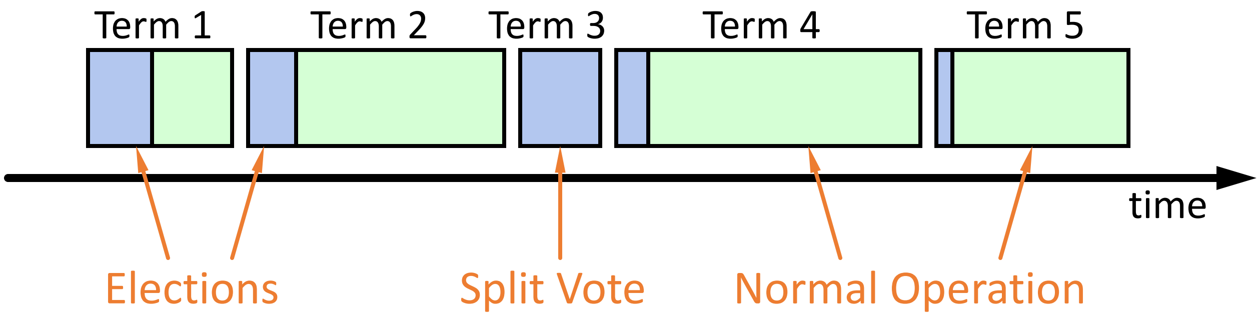


Server States

- At any given time, each server is either:
  - 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 1 leader per term
- Some terms have no leader (failed election)
- Each server maintains current term value
- Key role of terms: identify obsolete information

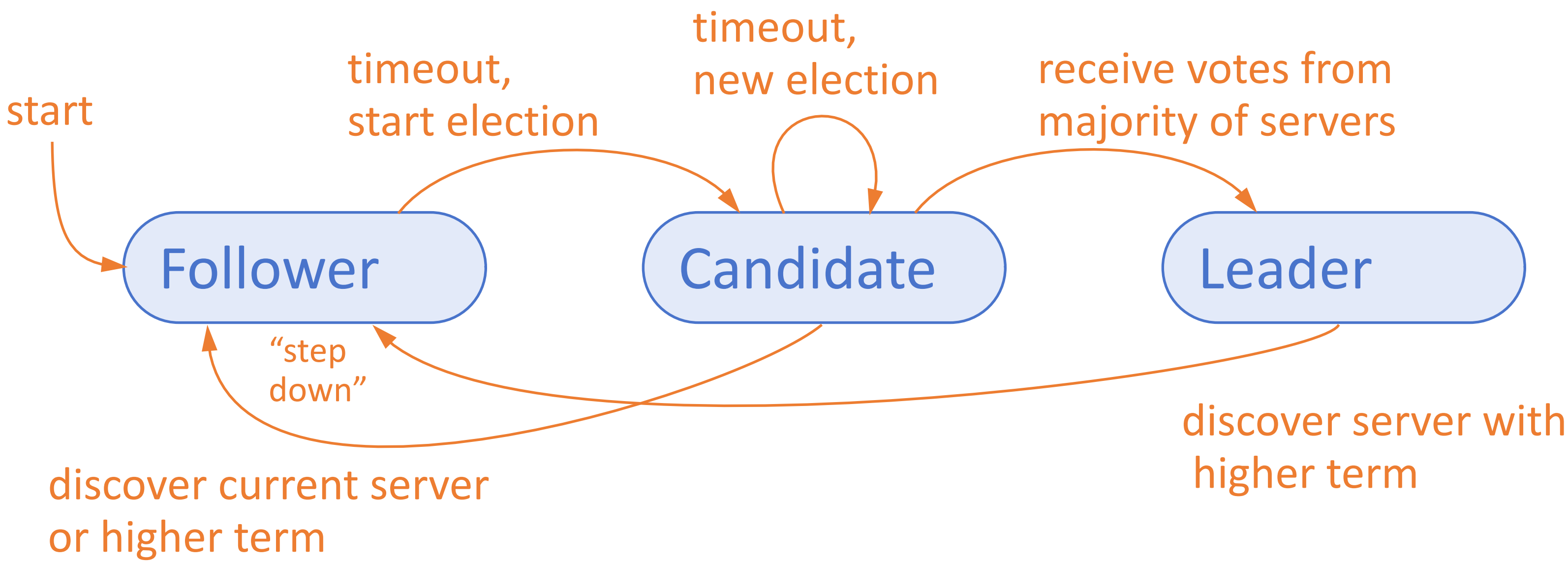
Heartbeats and Timeouts

- Servers start up as followers.
- Followers expect to receive RPCs from leaders or candidates.
- Leaders must send heartbeats (empty AppendEntries RPCs) to maintain authority.
- If electionTimeout elapses with no RPCs:
  - Follower assumes leader has crashed
  - Follower promotes itself to candidate and starts new election
  - Timeouts typically in range100-500ms
    - *Randomly* chosen in some range to reduce probability of split election.

Election Basics

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

State Diagram Revisit



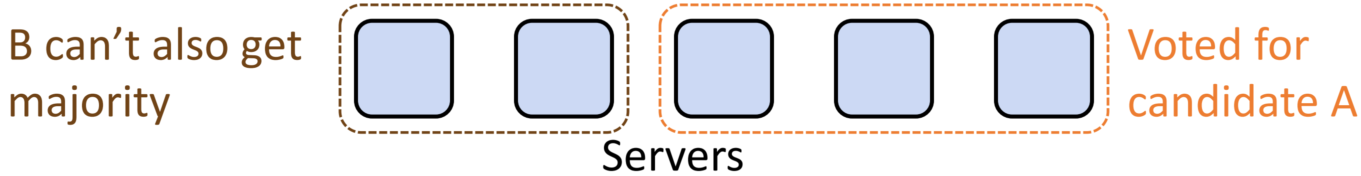
Election Basics: handling RequestVote RPCs

- Suppose a server in term currentTerm has voted for process with id votedFor in that term.
- When it receives RequestVote RPC from process candidateId with term voteRequestTerm:

```
If voteRequestTerm < currentTerm
        reply false
        return.
If voteRequestTerm > currentTerm
        currentTerm = voteRequestTerm, votedFor = null
If (votedFor is null or candidateId)*
        //should not have voted for anyone else in that term
        Grant vote, votedFor = candidateId
        *we will extend on this condition later.
```

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, kT]
  - One server usually times out and wins election before others wake up
  - Works well if T >> broadcast time
- *Safety is guaranteed. Liveness is not guaranteed.*

Implication of terms

- Each term has at most one leader (safety condition).
- Terms always increase with time.
- If the latest term has an elected leader, majority of processes must have updated themselves to the latest term.
- Only the leader of the latest term can commit log entries (we will discuss this next).

Raft Overview

1. Leader election:
   - Select one of the servers to act as leader
   - Detect crashes, choose new leader
2. Neutralizing old leaders
3. Normal operation (basic log replication)
4. Safety and consistency after leader changes

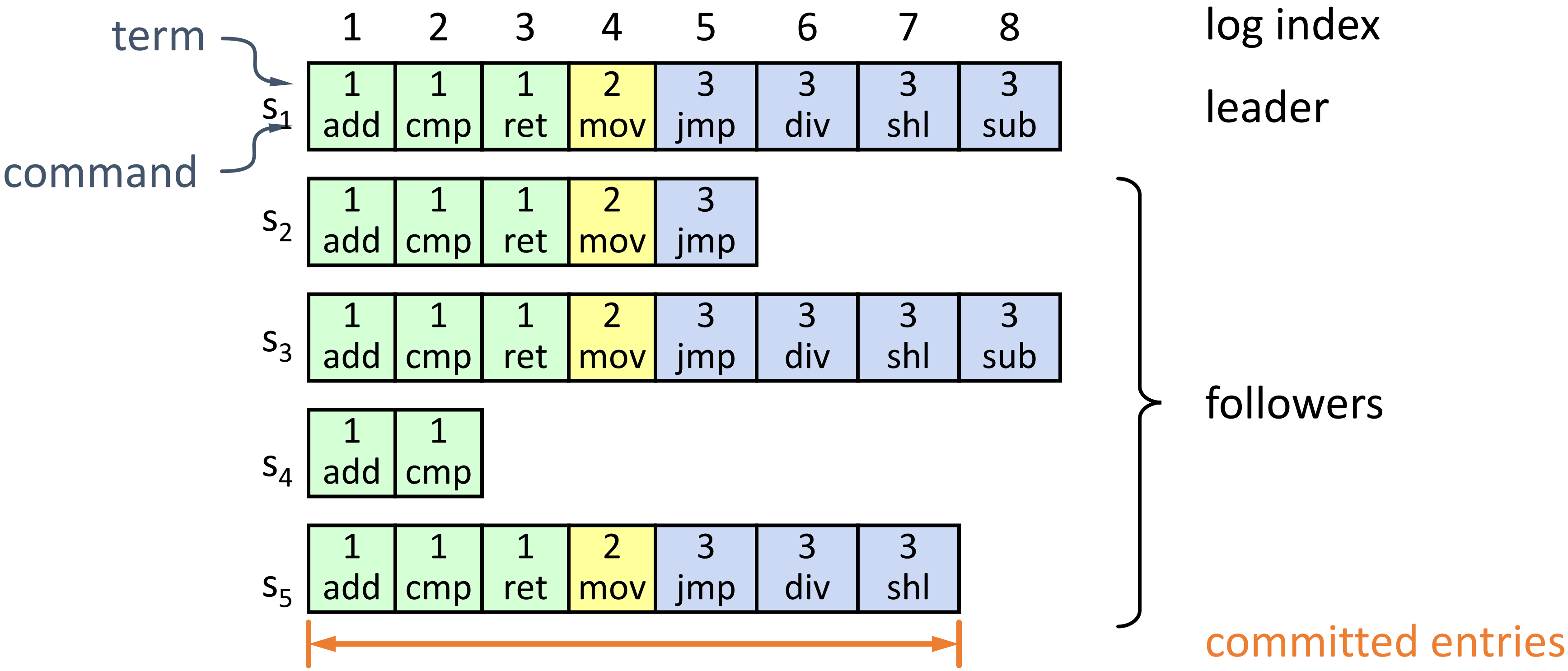
Neutralizing Old Leaders

- 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

Raft Overview

1. Leader election:
   - Select one of the servers to act as leader
   - Detect crashes, choose new leader
2. Neutralizing old leaders
3. Normal operation (basic log replication)
4. Safety and consistency after leader changes

Log Structure



- Log entry = index, term, command
- Log stored on stable storage (disk); survives crashes
- Entry is committed by the leader when certain conditions are met*.
    - Durable, will eventually be executed by state machines
    - * we will get back to this.

Normal Operation

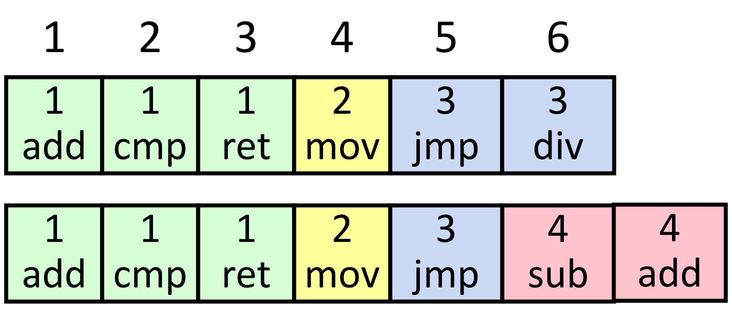
- Client sends command to leader
- Leader appends command to its log (*not yet committed*)
- Leader sends AppendEntries RPCs to followers
- Once new entry committed* (*we will discuss when and how*):
  - Leader passes command to its state machine, returns result to client
  - Leader notifies followers 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:

Raft guarantees that:

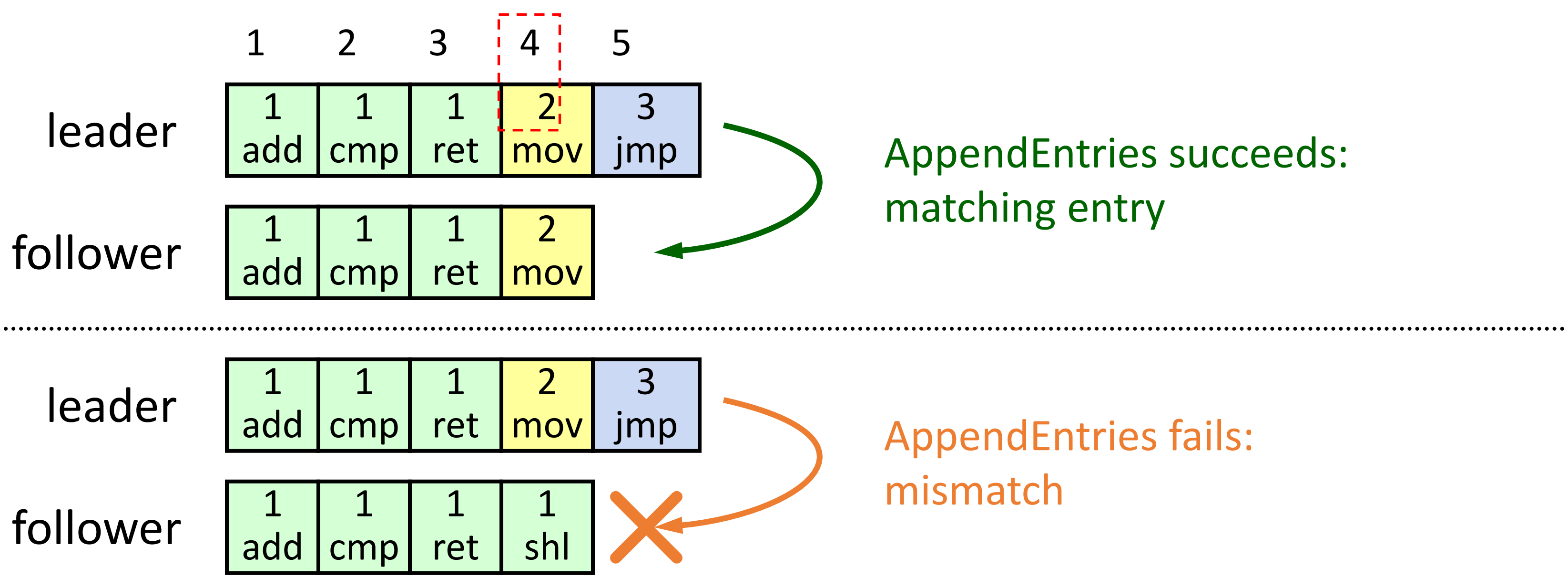
- If log entries on different servers have same index and term:
  - They store the same command
  - The logs are identical in all preceding entries



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

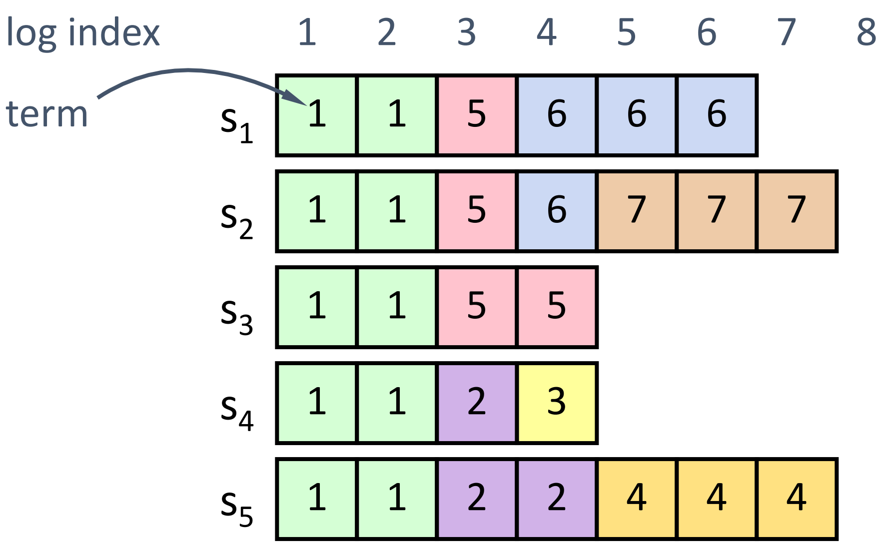
AppendEntries Consistency Check

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

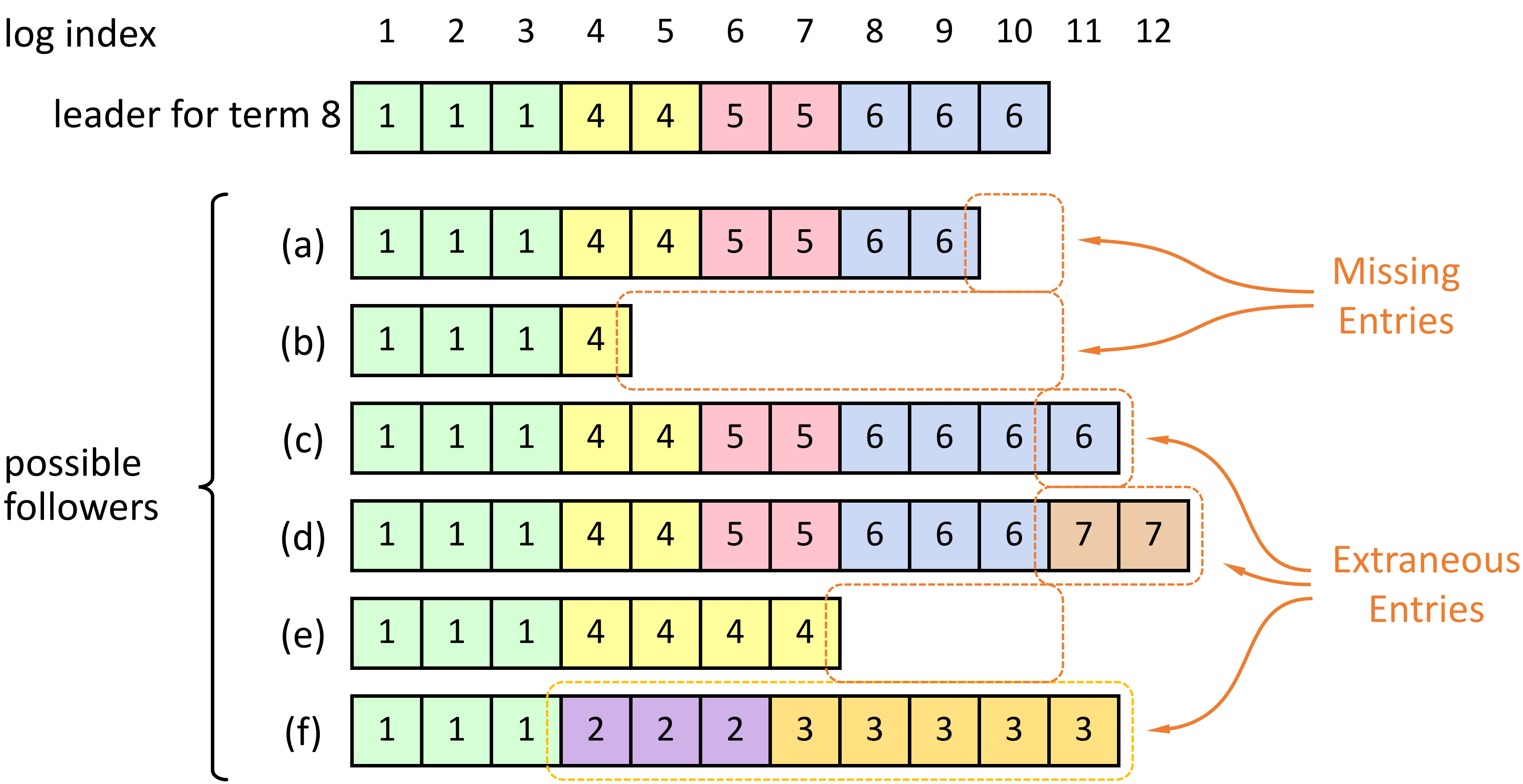


Leader Changes

- 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**
    - *Unless a new leader gets elected during the process.*
  - Multiple crashes can leave many extraneous log entries:



Log Inconsistencies



Repairing Follower Logs

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

- Next class:
  - How leader repairs logs?
  - How does Raft guarantee safety of consensus and when can a log entry be committed?

MP2: Raft Leader Election and Log Consensus

- Lead TA: Jiangran Wang

- Objective:
  - Implement a leader-based consensus protocol for replicated state machine, that maintains log consensus even when nodes crash or get temporarily disconnected.

- Task:
  - Beef up a skeleton code provided to you to implement Raft leader election and log consensus.
  - We provide an emulation framework and a test suite.
  - Strive to pass all the test cases provided in our test suite.

MP2: Logistics

- Due on April 5th.
  - Late policy: Can use part of your 168hours of grace period accounted per student over the entire semester.
- Must be implemented in Go.
  - The framework we provide is in Go.
- Read the specification and the comments in the provided code carefully.
- **Start early!!**
  - MP2 is harder than MP1.