Consensus: RAFT

COS 418: Distributed Systems
Lecture 14

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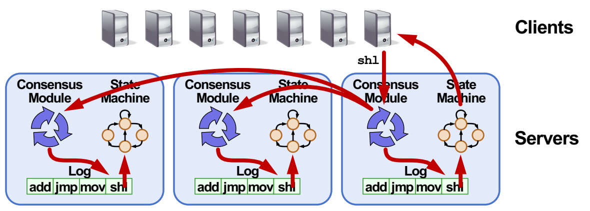
RAFT slides based on those from Diego Ongaro and John Ousterhout

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
6. Reconfiguration

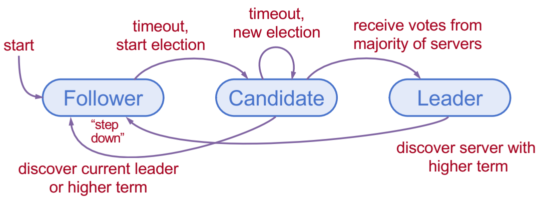
Server States

- 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

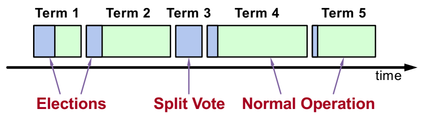
Follower Candidate Leader

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


start
timeout, start election
timeout, new election
receive votes from majority of servers
Follower
Candidate
Leader
"step down"
discover current leader or higher term
discover server with higher term

Terms (aka epochs)



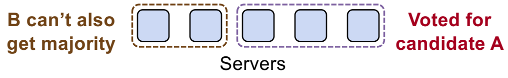
- Time divided into terms
  - Election (either failed or resulted in 1 leader)
  - Normal operation under a single leader
- Each server maintains current term value
- Key role of terms: identify obsolete information

Elections

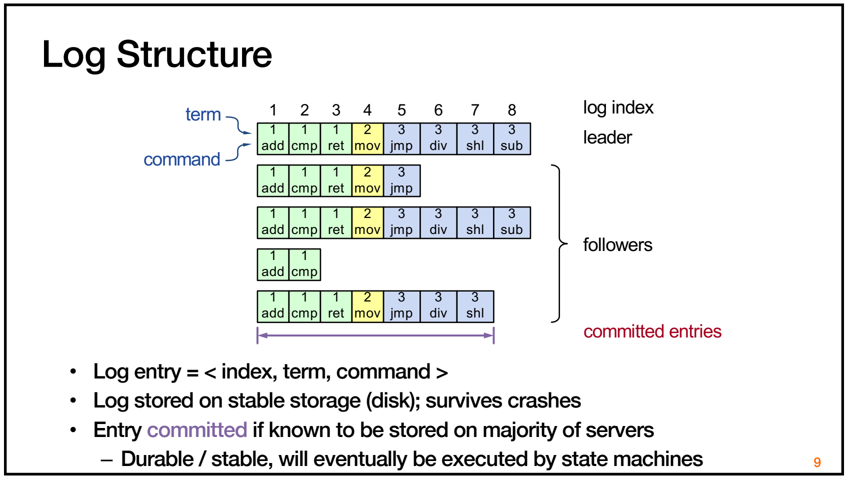
- Start election:
  - Increment current term, change to candidate state, vote for self
- Send RequestVote to all other servers, retry until either:
  1. Receive votes from majority of servers:
     - Become leader
     - Send AppendEntries heartbeats to all other servers
  2. Receive RPC from valid leader: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

Elections

- 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



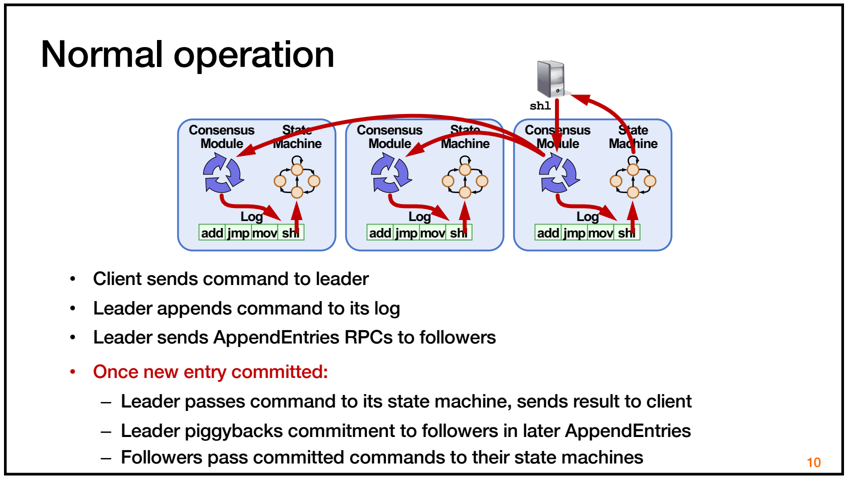
- Liveness: some candidate eventually wins
  - Each choose election timeouts randomly in [T, 2T]
  - One usually initiates and wins election before others start
  - Works well if T >> network RTT



Log Structure

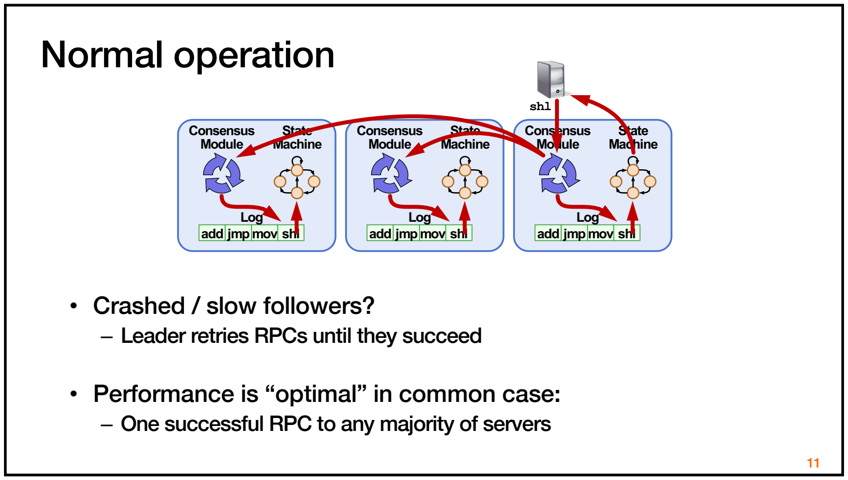
	1	2	3	4	5	6	7	8
leader	1 add	1 cmp	1 ret	2 mov	3 jmp	3 div	3 shl	3 sub
followers	1 add	1 cmp	1 ret	2 mov	3 jmp			
	1 add	1 cmp	1 ret	2 mov	3 jmp	3 div	3 shl	3 sub
	1 add	1 cmp						
	1 add	1 cmp	1 ret	2 mov	3 jmp	3 div	3 shl	

- 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 / stable, will eventually be executed by state machines



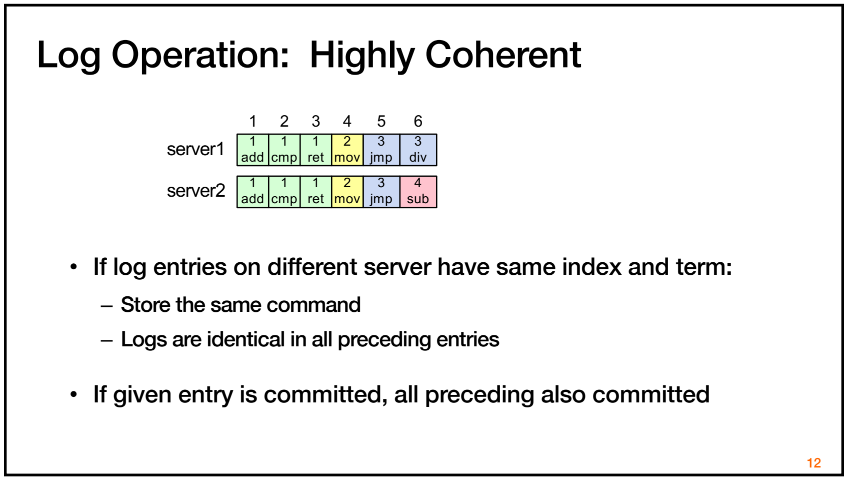
Normal operation

- 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, 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

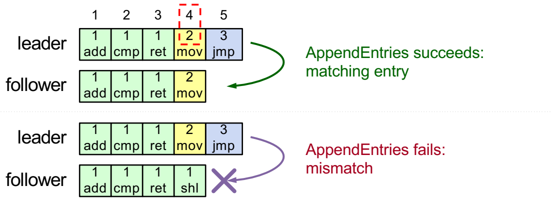


Log Operation: Highly Coherent

	1	2	3	4	5	6
server1	1 add	1 cmp	1 ret	2 mov	3 jmp	3 div
server2	1 add	1 cmp	1 ret	2 mov	3 jmp	4 sub

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

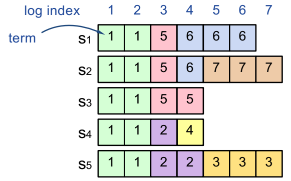
Log Operation: Consistency Check


1 2 3 4 5
leader
1 add | 1 cmp | 1 ret | 2 mov | 3 jmp
follower
1 add | 1 cmp | 1 ret | 2 mov
AppendEntries succeeds: matching entry
leader
1 add | 1 cmp | 1 ret | 2 mov | 3 jmp
follower
1 add | 1 cmp | 1 ret | 1 shl
AppendEntries fails: mismatch

- 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



log index	1	2	3	4	5	6	7
s1	1	1	5	6	6	6	
s2	1	1	5	6	7	7	7
s3	1	1	5	5			
s4	1	1	2	4			
s5	1	1	2	2	3	3	3

Safety Requirement

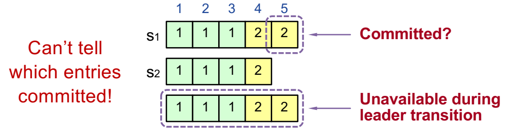
Once log entry applied to a state machine, no other state machine must apply a different value for that log entry

- 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 overwrite entries in their logs
  2. Only entries in leader's log can be committed
  3. 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

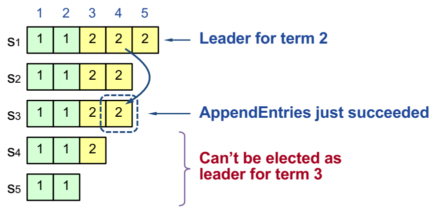


	1	2	3	4	5
s1	1	1	1	2	2
s2	1	1	1	2	
	1	1	1	2	2

Can't tell which entries committed!
Committed?
Unavailable during leader transition

- 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

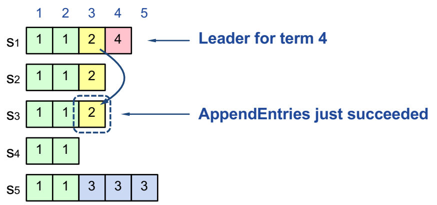


	1	2	3	4	5
s1	1	1	2	2	2
s2	1	1	2	2	
s3	1	1	2	2	
s4	1	1	2		
s5	1	1			

Leader for term 2
AppendEntries just succeeded
Can't be elected as leader for term 3

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

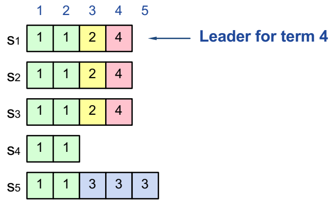
Committing Entry from Earlier Term



	1	2	3	4	5
s1	1	1	2	4	
s2	1	1	2		
s3	1	1	2		
s4	1	1			
s5	1	1	3	3	3

- Case #2: Leader trying to finish committing entry from earlier
- Entry 3 not safely committed:
  - s_5 can be elected as leader for term 5 (how?)
  - If elected, it will overwrite entry 3 on s_1, s_2, and s_3

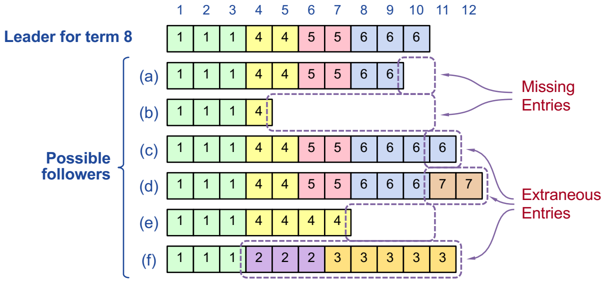
New Commitment Rules



	1	2	3	4	5
s1	1	1	2	4	
s2	1	1	2	4	
s3	1	1	2	4	
s4	1	1			
s5	1	1	3	3	3

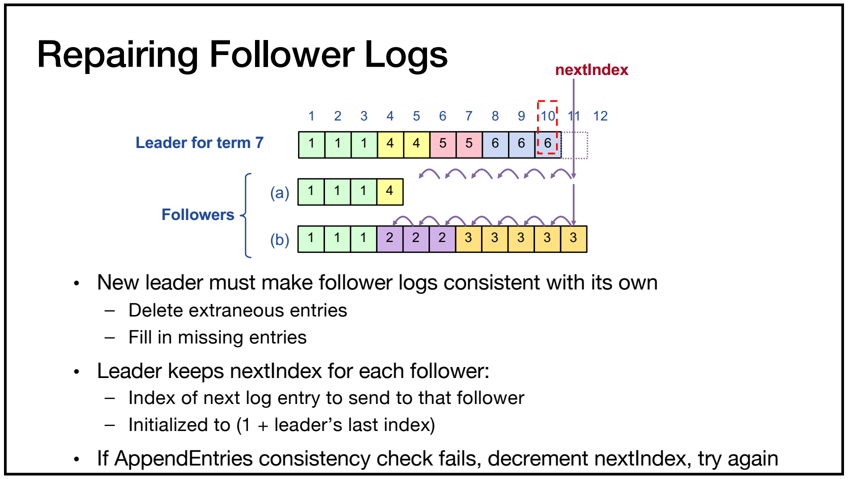
- For leader to decide entry is committed:
  1. Entry stored on a majority
  2. ≥ 1 new entry from leader's term also on majority
- Example; Once e4 committed, s_5 cannot be elected leader for term 5, and e3 and e4 both safe

Challenge: Log Inconsistencies



	1	2	3	4	5	6	7	8	9	10	11	12
Leader for term 8	1	1	1	4	4	5	5	6	6	6		
(a)	1	1	1	4	4	5	5	6	6			
(b)	1	1	1	4								
(c)	1	1	1	4	4	5	5	6	6	6	6	
(d)	1	1	1	4	4	5	5	6	6	6	7	7
(e)	1	1	1	4	4	4	4					
(f)	1	1	1	2	2	2	3	3	3	3	3	

Leader changes can result in log inconsistencies



Repairing Follower Logs

nextIndex

		1	2	3	4	5	6	7	8	9	10	11	12
Leader for term 7		1	1	1	4	4	5	5	6	6	6		
Followers	(a)	1	1	1	4								
	(b)	1	1	1	2	2	2	3	3	3	3	3	

- 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

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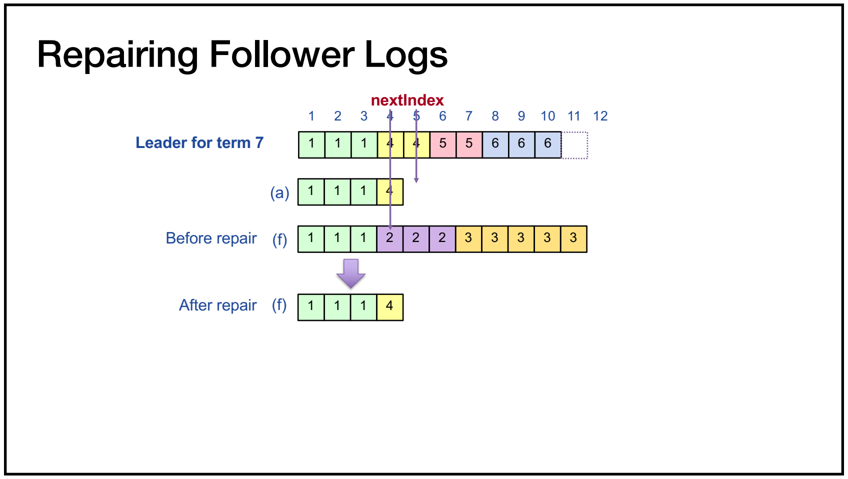

Repairing Follower Logs

nextIndex

		1	2	3	4	5	6	7	8	9	10	11	12
Leader for term 7		1	1	1	4	4	5	5	6	6	6		
	(a)	1	1	1	4								
Before repair	(f)	1	1	1	2	2	2	3	3	3	3	3	
After repair	(f)	1	1	1	4								

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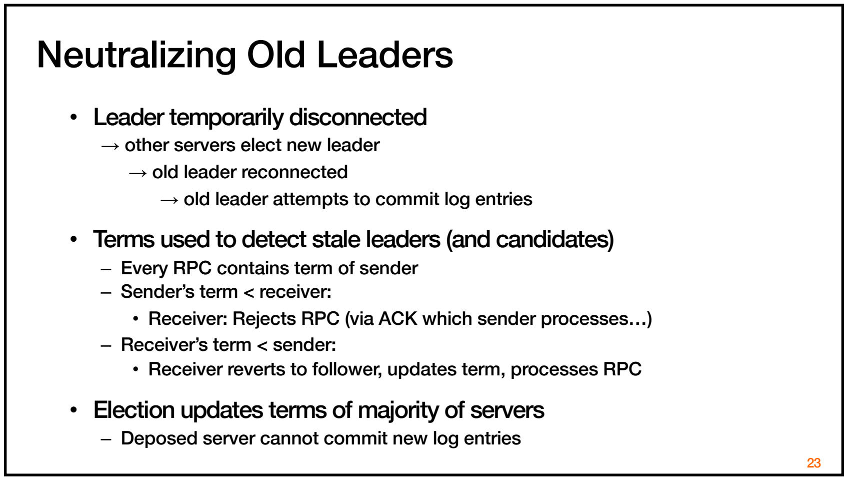

Neutralizing Old Leaders

- 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

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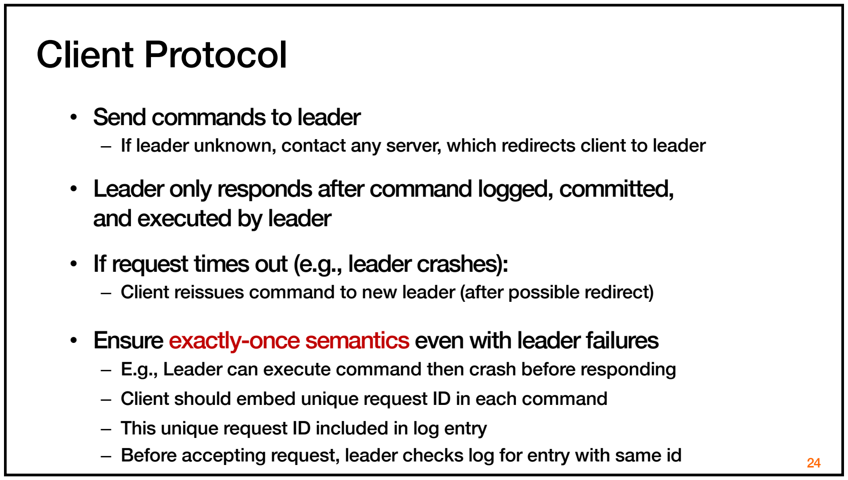

Client Protocol

- 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

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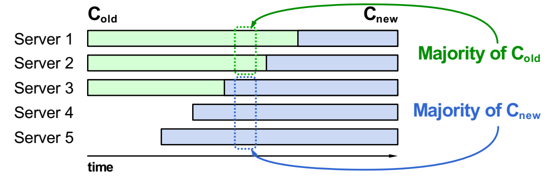
RECONFIGURATION

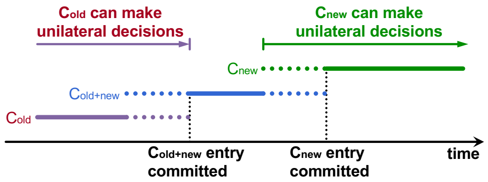
Configuration Changes

- View configuration: { leader, { members }, settings }
- Consensus must support changes to configuration: e.g., replace failed machine, change degree of replication
- Cannot switch directly from one config to another: conflicting majorities could arise



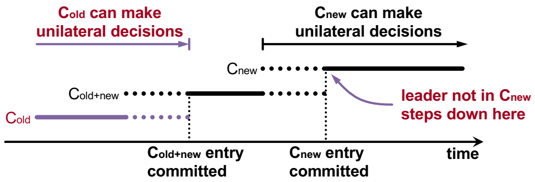
2-Phase Approach via Joint Consensus

- Joint consensus in intermediate phase: need majority of both old and new configurations for elections, commitment
- Configuration change just a log entry; applied immediately on receipt (committed or not)
- Once joint consensus is committed, begin replicating log entry for final config


C_{old} can make unilateral decisions
C_{new} can make unilateral decisions
C_{new}
$C_{old+new}$
C_{old}
$C_{old+new}$ entry committed
C_{new} entry committed
time

2-Phase Approach via Joint Consensus

- Any server from either configuration can serve as leader
- If leader not in C_{new}, must step down once C_{new} committed


C_{old} can make unilateral decisions
C_{new} can make unilateral decisions
C_{new}
$C_{old+new}$
C_{old}
leader not in C_{new} steps down here
$C_{old+new}$ entry committed
C_{new} entry committed
time