Putting it all together for SMR:

Two-Phase Commit, Leader Election

RAFT

COS 418: *Distributed Systems*
Lecture 13

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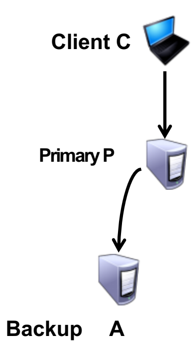
RAFT slides heavily based on those from Diego Ongaro and John Ousterhout

Recall: Primary-Backup

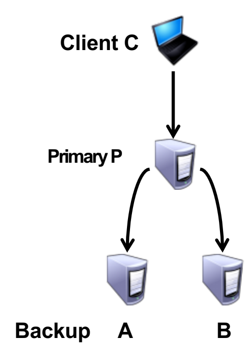
- **Mechanism:** Replicate and separate servers
- **Goal #1:** Provide a highly reliable service
- **Goal #2:** Servers should behave just like a single, more reliable server

Extend PB for high availability



- Primary gets ops, orders into log
- Replicates log of ops to backup
- Backup executes ops in same order
- Backup takes over if primary fails
- But what if network partition rather than primary failure?
  - "View" server to determine primary
  - But what if view server fails?
    - "View" determined via consensus!

PB high availability via 2PC

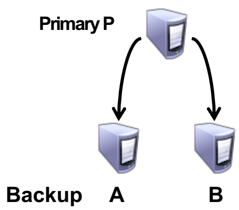


1. **C → P:** *"request <op>"*
2. **P → A, B:** *"prepare <op>"*
3. **A, B → P:** *"prepared"* or *"error"*
4. **P → C:** *"result exec<op>" or "failed"*
5. **P → A, B:** *"commit <op>"*

"Okay" (i.e., op is stable) if written to > ½ backups

View changes on failure

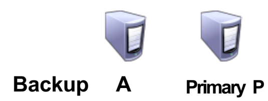
1. Backups monitor primary
2. If a backup thinks primary failed, initiate View Change (leader election)



View changes on failure

1. Backups monitor primary
2. If a backup thinks primary failed, initiate View Change (leader election)
3. Inituitive safety argument:
   - View change requires *f+1* agreement
   - Op committed once written to *f+1* nodes
   - At least one node both saw write and in new view
4. More advanced: Adding or removing nodes ("reconfiguration")

Requires ***2f + 1*** nodes to handle ***f*** failures



Basic fault-tolerant Replicated State Machine (RSM) approach

1. Consensus protocol to elect leader
2. 2PC to replicate operations from leader
3. All replicas execute ops once committed

Why bother with a leader?

Not necessary, but …

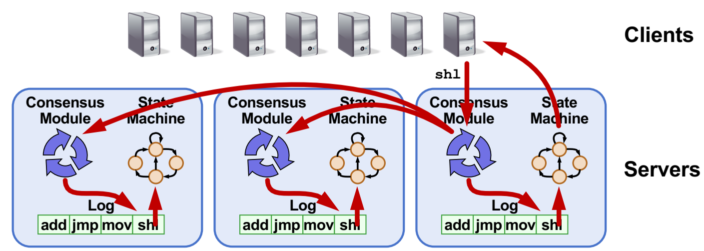
- Decomposition: normal operation vs. leader changes
- Simplifies normal operation (no conflicts)
- More efficient than leader-less approaches
- Obvious place to handle non-determinism

Raft: A Consensus Algorithm for Replicated Logs

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

Raft Overview

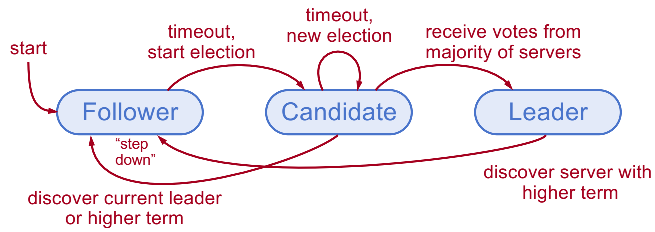
1. **Leader election**
2. **Normal operation (basic log replication)**
3. **Safety and consistency after leader changes**
4. **Neutralizing old leaders**
5. **Client interactions**
6. **Reconfiguration**

Server States

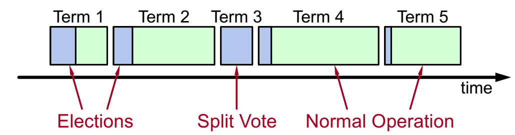
- At any given time, each server is either:
  - Leader: handles all client interactions, log replication
  - Follower: completely passive
  - Candidate: used to elect a new leader
- Normal operation: 1 leader, N-1 followers

Liveness Validation

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



Terms (aka epochs)



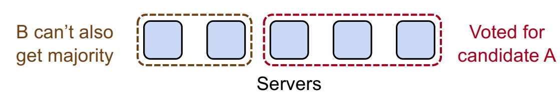
- Time divided into terms
  - Election (either failed or resulted in 1 leader)
  - Normal operation under a single leader
- Each server maintains current term value
- Key role of terms: identify obsolete information

Elections

- **Start election:**
  - Increment current term, change to candidate state, vote for self
- **Send 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 must eventually win**
  - Each choose election timeouts randomly in [T, 2T]
  - One usually initiates and wins election before others start
  - Works well if T >> network RTT

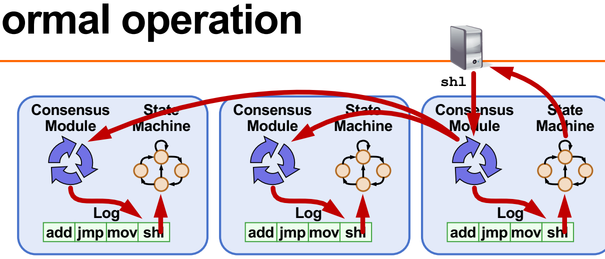
Log Structure

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

term (upper number), command (lower text); committed entries: 1–7

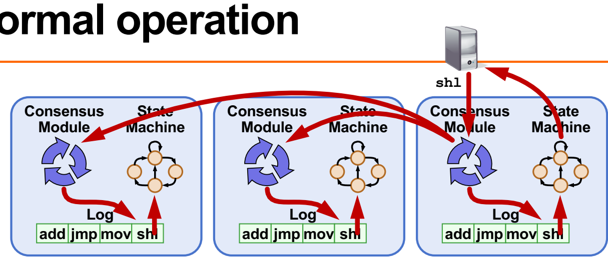
- Log entry = < index, term, command >
- Log stored on stable storage (disk); survives crashes
- Entry committed if known to be stored on majority of servers
  - Durable / stable, will eventually be executed by state machines

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



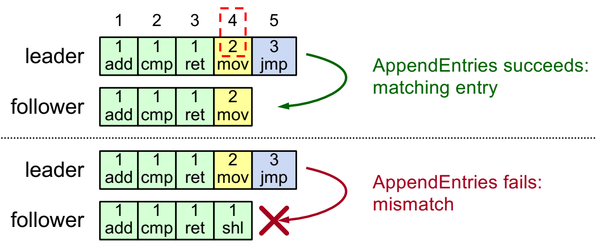
- Crashed / slow followers?
  - Leader retries RPCs until they succeed
- Performance is optimal in common case:
  - One successful RPC to any majority of servers

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

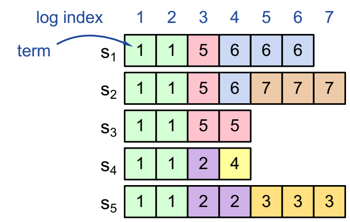
Log Operation: Consistency Check



- 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

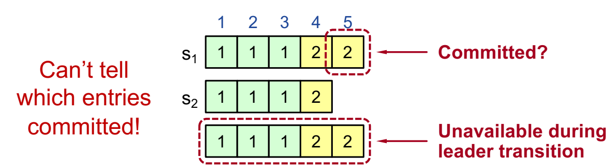
- **Raft safety property:** If leader has decided log entry is committed, entry will be present in logs of all future leaders
- Why does this guarantee higher-level goal?
  1. Leaders never overwrite entries in their logs
  2. Only entries in leader's log can be committed
  3. Entries must be committed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

Committed → Present in future leaders' logs

Restrictions on commitment

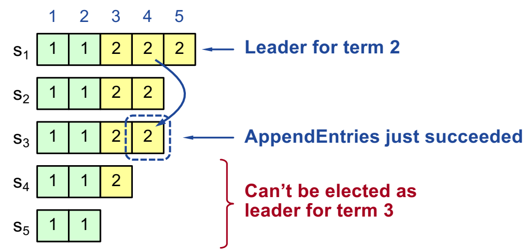
Restrictions on leader election

Picking the Best Leader



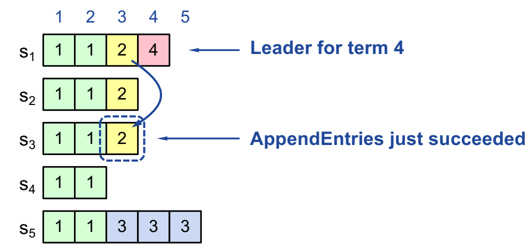
- Elect candidate most likely to contain all committed entries
  - In RequestVote, candidates incl. index + term of last log entry
  - Voter V denies vote if its log is "more complete": (newer term) or (entry in higher index of same term)
  - Leader will have "most complete" log among electing majority

Committing Entry from Current Term



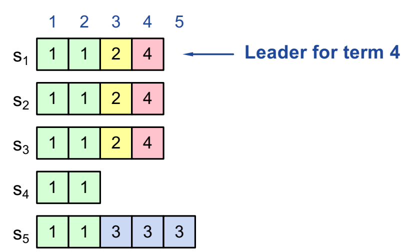
- **Case #1:** Leader decides entry in current term is committed
- Safe: leader for term 3 must contain entry 4

Committing Entry from Earlier Term



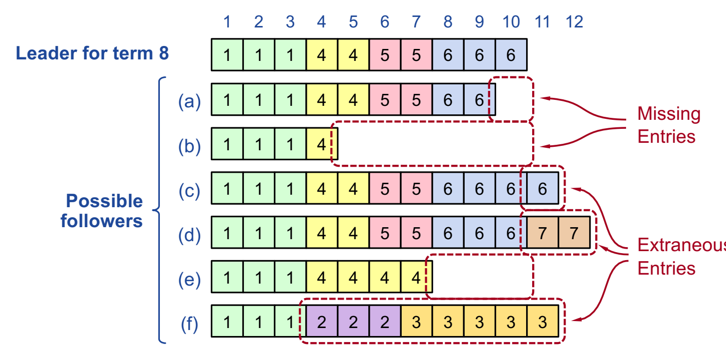
- **Case #2:** Leader trying to finish committing entry from earlier
- Entry 3 not safely committed:
  - s_5 can be elected as leader for term 5 (how?)
  - If elected, it will overwrite entry 3 on s_1, s_2, and s_3

New Commitment Rules



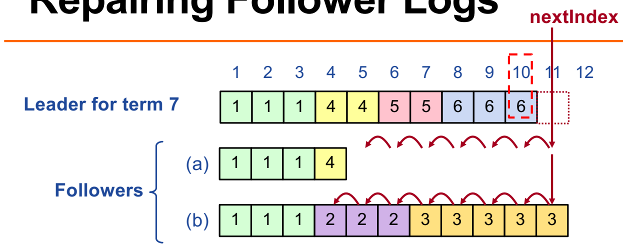
- **For leader to decide entry is committed:**
  1. Entry stored on a majority
  2. ≥ 1 new entry from leader's term also on majority
- Example; Once e4 committed, s_5 cannot be elected leader for term 5, and e3 and e4 both safe

Challenge: Log Inconsistencies



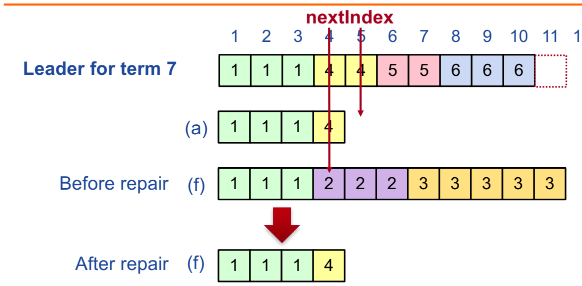
Leader changes can result in log inconsistencies

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)
- 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

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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 ID in each command
  - This client ID included in log entry
  - Before accepting request, leader checks log for entry with same id

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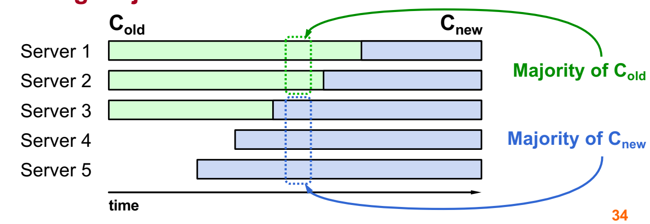
Reconfiguration

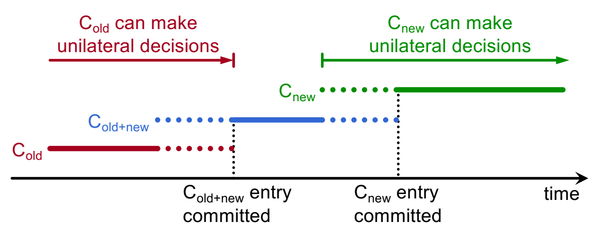
Configuration Changes

- **View configuration: { leader, { members }, settings }**
- **Consensus must support changes to configuration**
  - Replace failed machine
  - Change degree of replication
- **Cannot switch directly from one config to another: conflicting majorities could arise**



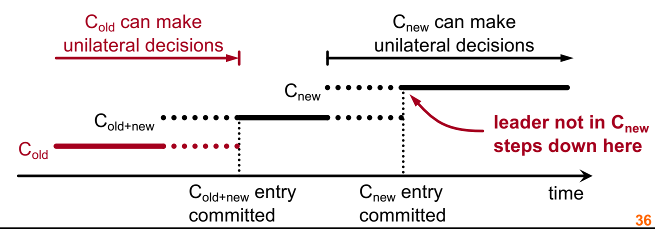
2-Phase Approach via Joint Consensus

- 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 configuration



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



Viewstamped Replication:

A new primary copy method to support highly-available distributed systems

Oki and Liskov, PODC 1988

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Raft vs. VR

- Strong leader
  - Log entries flow only from leader to other servers
  - Select leader from limited set so doesn't need to "catch up"
- Leader election
  - Randomized timers to initiate elections
- Membership changes
  - New joint consensus approach with overlapping majorities
  - Cluster can operate normally during configuration changes

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