Strong consistency and consensus

COS 518: Advanced Computer Systems
Lecture 4
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RAFT slides heavily based on those from Diego Ongaro and John Ousterhout

Recall: Linearizability (Strong Consistency)

• Provide behavior of a single copy of object:
  – Read should return the most recent write
  – Subsequent reads should return same value, until next write

• Telephone intuition:
  1. Alice updates Facebook post
  2. Alice calls Bob on phone: “Check my Facebook post!”
  3. Bob read’s Alice’s wall, sees her post

ALL ops must be totally ordered

• Isn’t sufficient to return value of third node:
  It doesn’t know precisely when op is “globally” committed
• Instead: Need to actually order read operation

ALL ops must be totally ordered

• Once write completes, all later reads (by wall-clock start time) should return value of that write or value of later write.
• Once read returns particular value, all later reads should return that value or value of later write.
Two phase commit protocol

1. C → P: “request write X”
2. P → A, B: “prepare to write X”
3. A, B → P: “prepared” or “error”
4. P → C: “result write X” or “failed”
5. P → A, B: “commit write X”

This is more general than reads/writes

- Any server is essentially a state machine
  - Operations transition between states

- Need an op to be executed on all replicas, or none at all
  - i.e., we need distributed all-or-nothing atomicity
  - If op is deterministic, replicas will end in same state

What if primary fails?
Backup fails?

“Okay” (i.e., op is stable) if written to > ½ backups
**Two phase commit protocol**

- Commit sets always overlap $\geq 1$
- Any $>\frac{1}{2}$ nodes guaranteed to see committed op
- …provided set of nodes consistent

**View changes on failure**

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

**Consensus**

Definition:

1. A general agreement about something
2. An idea or opinion that is shared by all the people in a group

Origin: Latin, from *consentire*
Consensus used in systems

Group of servers attempting:
- Make sure all servers in group receive the same updates in the same order as each other
- Maintain own lists (views) on who is a current member of the group, and update lists when somebody leaves/fails
- Elect a leader in group, and inform everybody
- Ensure mutually exclusive (one process at a time only) access to a critical resource like a file

Paxos: the original consensus protocol

- Safety
  - Only a single value is chosen
  - Only a proposed value can be chosen
  - Only chosen values are learned by processes
- Liveness ***
  - Some proposed value eventually chosen if fewer than half of processes fail
  - If value is chosen, a process eventually learns it

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

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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

![Transition Diagram](image)

### 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

![Timeline Diagram](image)

### 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

![Flowchart Diagram](image)

### 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**

- **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**

- **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 \( <\text{index}, \text{term}> \) 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

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

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 \( \rightarrow \) Present in future leaders’ logs

Restrictions on commitment

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

**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
  - If elected, it will overwrite entry 3 on $s_1$, $s_2$, and $s_3$

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**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: e3 is only committed by leader $s_1$ (term 4) once e4 can be committed, at which case $s_5$ cannot be elected leader for term 5, and e3 and e4 both safe
**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

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

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

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

![Diagram showing joint consensus and phase approach via joint consensus]
Viewstamped Replication:
A new primary copy method to support highly-available distributed systems

Oki and Liskov, PODC 1988

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

Monday lecture

1. Consensus papers
2. From single register consistency to multi-register transactions