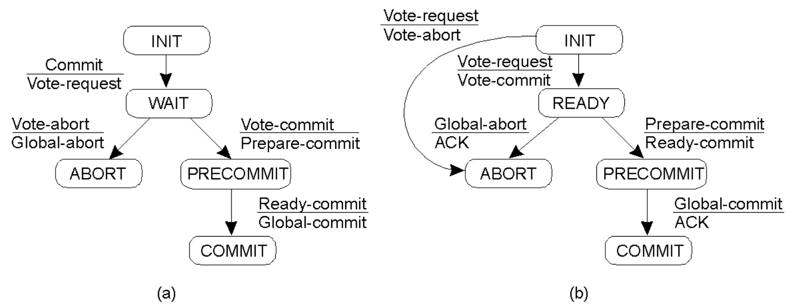
Distributed Consensus

- Part 1: Consensus
- Part 2: Paxos
- Part 3: RAFT

Three-Phase Commit



Two phase commit: problem if coordinator crashes (processes block)

Three phase commit: variant of 2PC that avoids blocking

Replication for Fault Tolerance

- Basic idea: use replicas for the server and data
- Technique 1: split incoming requests among replicas
  - If one replica fails, other replicas take over its load
  - Suitable for crash fault tolerance (each replica produces correct results when it is us).
- Technique 2: send each request to all replicas
  - Replicas vote on their results and take majority result
  - Suitable for BFT (a replica can produce wrong results)
    - 2PC, 3PC, Paxos are techniques

Consensus

- Consensus: get a group of processes to agree on something
- Consensus vs Byzantine Agreement
- Achieve reliability in presence of faulty processes
  - requires processes to agree on data value needed for computation
  - Examples: whether to commit a transaction, agree on identity of a leader, atomic broadcasts, distributed locks
- **4 Properties** of a consensus protocol with **fail-stop** failures
  - Agreement: every correct process agrees on same value
  - Termination: every correct process decides some value
  - Validity: If all propose v, all correct processes decides v
  - Integrity: Every correct process decided at most one value and if it decides v, someone must have proposed v.

2PC, 3PC Problems

- Both have problems in presence of failures
  - **Safety** is ensured but **liveness** is not
- 2PC
  - must wait for all nodes and coordinator to be up
  - all nodes must vote
  - coordinator must be up
- 3PC
  - handles coordinator failure
  - but network partitions are still an issue
- Paxos : how to reach consensus in distributed systems that can tolerate **non-malicious** failures?
  - majority rather than all nodes participate

Paxos: fault-tolerant agreement

- Paxos lets nodes agree on same value despite:
  - node failures, network failures and delays
- Use cases:
  - Nodes agree X is primary (or leader)
  - Nodes agree Y is last operation (order operations)
- General approach
  - One (or more) nodes decides to be leader (aka proposer)
  - Leader proposes a value and solicits acceptance from others
  - Leader announces result or tries again
- Proposed independently by Lamport and Liskov
  - Widely used in real systems (ZooKeeper, Chubby, Spanner)

Paxos Requirements

- Safety (Correctness)
  - All nodes agree on the same value
  - Agreed value X was proposed by some node
- Liveness (fault-tolerance)
  - If less than N/2 nodes fail, remaining nodes will eventually reach agreement
  - Liveness not guaranteed if steady stream of failures
- Why is agreement hard?
  - Network partitions
  - Leader crashes during solicitation or after deciding but before announcing results,
  - New leader proposes different value from already decided value,
  - More than one node becomes leader simultaneously....

Paxos Setup

- Entities: Proposer (leader), acceptor, learner
  - Leader proposes value, solicits acceptance from acceptors
  - Acceptors are nodes that want to agree; announce chosen value to learners
- Proposals are ordered by proposal #
  - node can choose any high number to try to get proposal accepted
  - An acceptor can accept multiple proposals
    - If prop with value v chosen, all higher proposals have value v
- Each node maintains
  - n_a, v_a: highest proposal # and accepted value
  - n_h : highest proposal # seen so far
  - my_n: my proposal # in current Paxos

Paxos operation: 3 phase protocol

- **Phase 1 (Prepare phase)**
  - A node decides to be a leader and propose
  - Leader chooses my_n > n_h
  - Leader sends <prepare, my_n> to all nodes
  - Upon receiving <prepare, n> at acceptor
    - If n < n_h
      - reply <prepare-reject> /* already seen higher # proposal */
    - Else
      - n_h = n /* will not accept prop lower than n */
      - reply <prepare-ok, n_a, v_a> /* send back previous prop, value/
      - /* can be null, if first */

Paxos operation

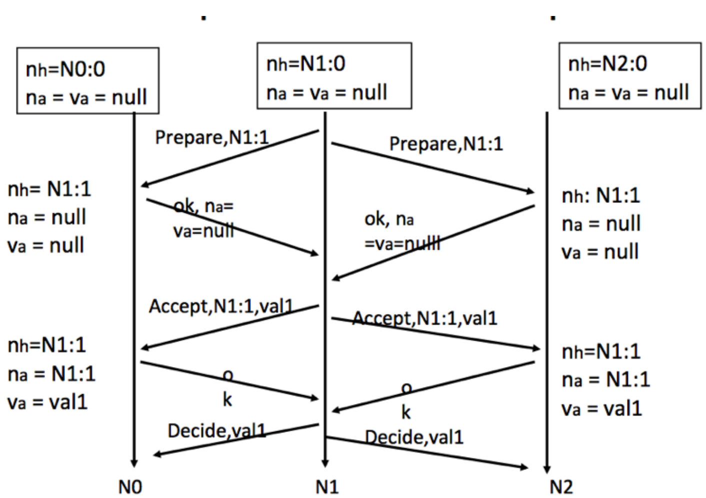
- **Phase 2 (accept phase)**
  - If leader gets prepare-ok from **majority**
    - V = non-empty value from highest n_a received
    - If V = null, leader can pick any V
    - Send <accept, my_n, V> to all nodes
  - If leader fails to get majority prepare-ok
    - delay and restart Paxos
  - Upon receiving <accept, n, V>
    - If n < n_h
      - reply with <accept-reject>
    - else
      - n_a=n ; v_a = V; n_h = h; reply <accept-ok>

Paxos Operation

- **Phase 3 (decide)**
  - If leader gets accept-ok from majority
    - Send <decide, v_a> to all learners
  - If leader fails to get accept-ok from a majority
    - Delay and restart Paxos

- **Properties**
  - P1: any proposal number is unique
  - P2: any two set of acceptors have at least one node in common
  - P3: value sent in phase 2 is value of highest numbered proposal received in responses in phase 1

Paxos Example



Issues

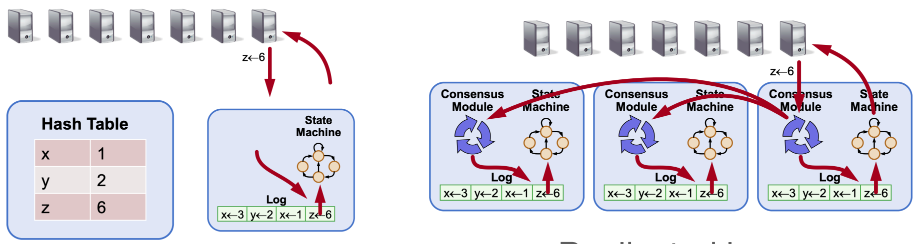
- Network partitions:
  - With one partition, will have majority on one side and can come to agreement (if nobody fails)
- Timeouts
  - A node has max timeout for each message
  - Upon timeout, declare itself as leader and restart Paxos
- Two leaders
  - Either one leader is not able to decide (does not receive majority accept-oks since nodes see higher proposal from other leader) OR
  - one leader causes the other to use it value
- Leader failures: same as two leaders or timeout occurs

Part 3: Raft Consensus Protocol

- Paxos is hard to understand (single vs multi-paxos)
- Raft - *understandable* consensus protocol
- **State Machine Replication (SMR)**
  - Implemented as a replicated log
  - Each server stores a log of commands, executes in order
  - Incoming requests —> replicate into logs of servers
  - Each server executed request log in order: stays consistent
- Raft: first elect a leader
- Leader sends requests (log entries) to followers
- If **majority** receive entry: safe to apply -> commit
  - If entry committed, all entries preceding it are committed

Log replication

- Servers maintain log of commands: order to perform ops
- Replicated log: replicated state machine (SMR)
  - all servers (replicas) execute commands in log order



Single server log

Replicated log

Fig courtesy: D. Ongaro

Consensus Approaches

- Leaderless (symmetric)
  - Client can contact any server
- Leader-based (asymmetric)
  - One server is leader and other servers follow the leader
  - Clients contact leader

- RAFT is a leader-based consensus protocol
  - Two aspects: leader changes and normal operation

RAFT Overview

- Leader election
  - Select one server to serve as a RAFT leader
  - detect leader crash, elect new leader
- Normal operation
  - Perform log replication
  - Leader receives client commands, append to log
  - Leader then replicates log to followers
    - Detect and overwrite consistencies in log
- Safety
  - Committed log entires are not impacted by leader crash
  - Almost one leader

Terms

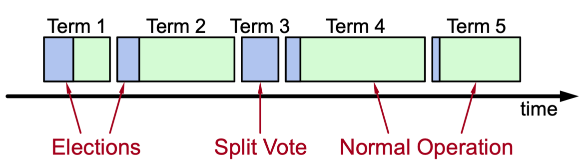


Fig courtesy: D. Ongaro

- Time is divided into terms
  - Election
  - Normal operation with elected leader
  - New term starts upon leader failure
- At most one leader per term
  - Some terms may have no leader (failed term)
- All servers maintain current term value
- At any time, each server is either:
  - **leader**: receives all client requests and log replication
  - **follower**: passively follows leader
  - **candidate**: participates in leader election

RAFT Election

- Election timeout: no RPCs received for a while ~100-500ms
- Increment current term and become candidate
- Vote for self (!)
- Send election (RequestVote RPC) message to followers
  - Receive vote from majority: become leader
    - send heartbeat message (AppendEntries RPC)
  - Receive RPC from leader: become follower again
  - Failed election: no majority votes within election timeout
    - Increment term, start new election
- **Safety**: at most one server wins; servers vote once per term
- **Liveness**: someone eventually wins
  - choose random election timeouts; one server times out/wins

Normal RAFT Operation

- Leader receives client commands and appends to log
- Send AppendEntry RPC to all followers
- Once entry safely committed to log
  - execute command and return result to client
- Followers catch up in background
  - Notify followers of committees entries in subsequent RPCs
  - Followers apply committed commands to their state m/c
- Log entry: index, term, command (stored on disk)

index ->	1	2	3	4	5	6	7	8
term	1	1	1	2	3	3	3	3
command	x←3	y←2	x←1	z←6	z←0	y←9	y←1	x←4

Fig courtesy: D. Ongaro

Log consistency

- Consistency check: include index, term of prev entry
  - follower must contain matching entry: reject otherwise

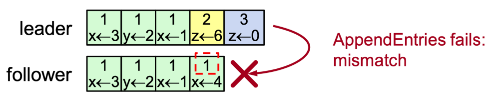


Fig courtesy: D. Ongaro

- Log entries can become inconsistent due to leader failure

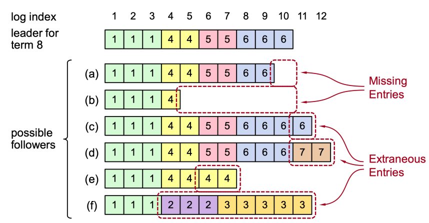


Fig courtesy: D. Ongaro

Log Repair

- Leader tracks nextIndex for each follower
- If AppendEntry check fails, decrement and try again
  - rewind to find match; follower deletes all subsequent entries

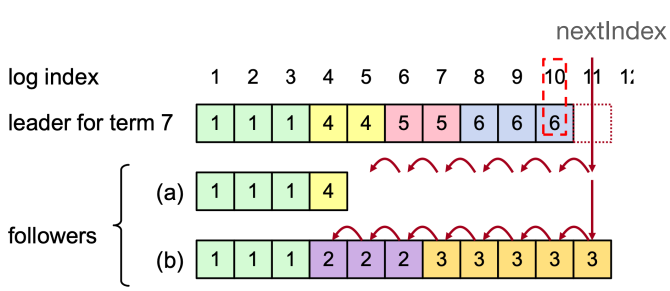
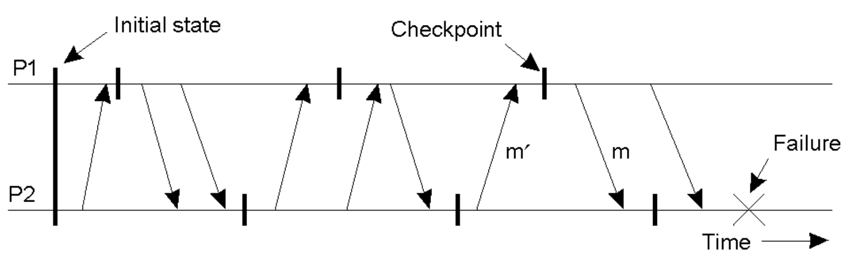


Fig courtesy: D. Ongaro

Recovery

- Techniques thus far allow failure handling
- Recovery: operations that must be performed after a failure to recover to a correct state
- Techniques:
  - Checkpointing:
    - Periodically checkpoint state
    - Upon a crash roll back to a previous checkpoint with a *consistent state*

Independent Checkpointing



- Each processes periodically checkpoints independently of other processes
- Upon a failure, work backwards to locate a consistent cut
- Problem: if most recent checkpoints form inconsistent cut, will need to keep rolling back until a consistent cut is found
- Cascading rollbacks can lead to a domino effect.

Coordinated Checkpointing

- Take a distributed snapshot [discussed in Lec 13]

- Upon a failure, roll back to the latest snapshot
  - All process restart from the latest snapshot

Logging

- Logging : a common approach to handle failures
  - Log requests / responses received by system on separate storage device / file (stable storage)
    - Used in databases, filesystems, ...
- Failure of a node
  - Some requests may be lost
  - Replay log to “roll forward” system state

Message Logging

- Checkpointing is expensive
  - All processes restart from previous consistent cut
  - Taking a snapshot is expensive
  - Infrequent snapshots => all computations after previous snapshot will need to be redone [wasteful]
- Combine checkpointing (expensive) with message logging (cheap)
  - Take infrequent checkpoints
  - Log all messages between checkpoints to local stable storage
  - To recover: simply replay messages from previous checkpoint
    - Avoids recomputations from previous checkpoint