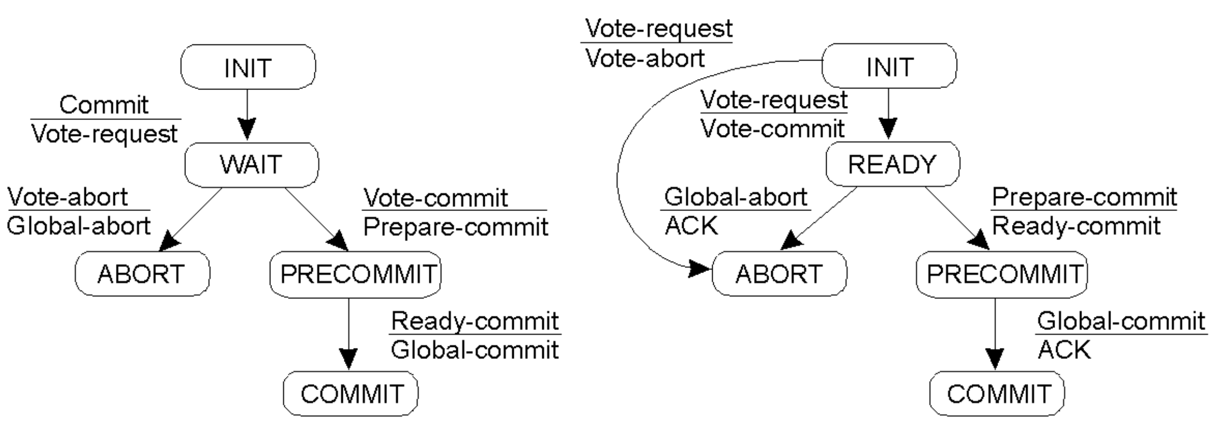
Recovering from a Crash

- If INIT : abort locally and inform coordinator
- If Ready, contact another process Q and examine Q's state

State of Q	Action by P
COMMIT	Make transition to COMMIT
ABORT	Make transition to ABORT
INIT	Make transition to ABORT
READY	Contact another participant

Three-Phase Commit



(a) (b)

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, Agreement

- Consensus protocols
- 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
- 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 particpate

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 in major companies

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 Paxox

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 */

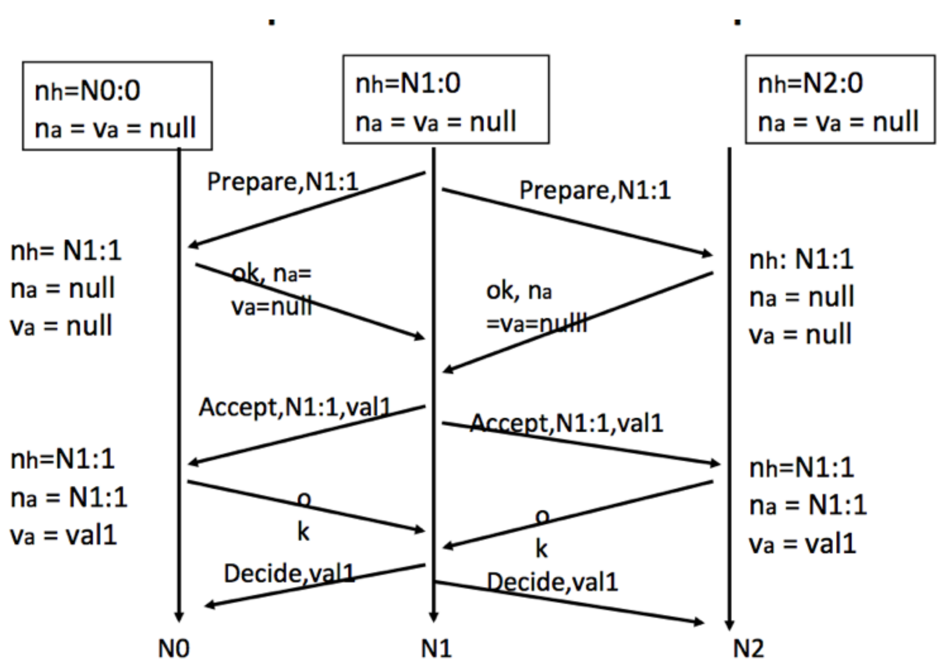
Paxos operation

- **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 Exampe



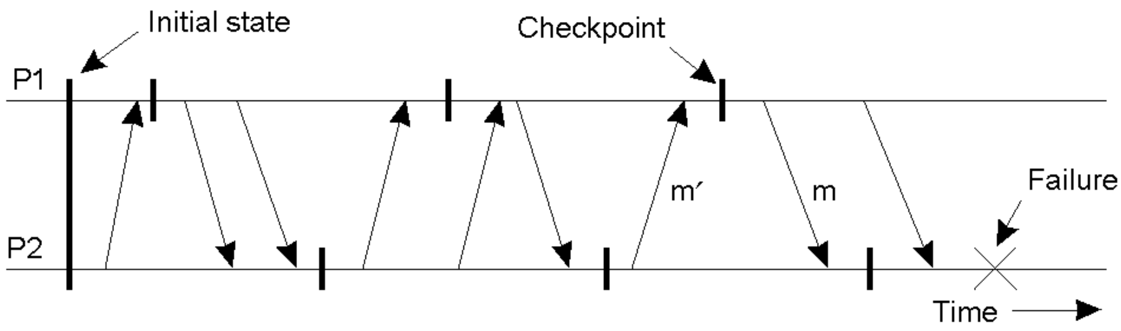
Issues

- 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

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 inconsistenct 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 11]
- 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