Paxos, Agreement, Consensus

Notes from reviews

- PtP:
  - How bring nodes up to date?
  - Wait through a whole round of voting?
  - How are decrees propagated to legislators?
  - Can ask for piggy-back up past decrees
  - How select quorum for a ballot?
  - Tend to use all alive nodes
  - Why wait three decrees for changing membership
    - Cannot be immediate (would affect that ballot)
    - Could be next one, but could be outstanding proposals using old membership
    - Gives time to finish ballot before starting next.

Questions

- PmS
  - Will elections terminate
    - PBFT is byzantine paxos, provide time guarantees on state transitions assuming limited number of failures
    - Generally, unsolvable in the presence of slow machines and failures to guarantee termination
- Unique proposal numbers?
  - Local number + node ID is unique

Core problem

- Want multiple nodes to agree on something
  - example: change the primary site for replication to a new node
- Challenge:
  - Make it fault tolerant
- Approaches
  - 2-phase commit
  - (3-phase commit)
  - Paxos

2 phase commit

- Developed for distributed databases
- Model:
  - Resource managers (RM) manage individual resources on different nodes
  - Transaction coordinator (TC) centrally coordinates operations that span multiple nodes
  - Operations (replicated or different) are sent to nodes in a transaction
    - would like to have atomicity: either everybody commits transaction, or nobody

2PC diagram
2PC Protocol: Phase 1

- TC sends out “prepare” message to all RMs
- RMs save enough state that they are guaranteed to be able to prepare if necessary
  - Any transient changes must be written to stable storage
  - Often done with a log
- RMs must still be able to abort
  - Don’t erase old data yet
  - Don’t know whether all other RMs will vote to commit

2PC protocol: phase 1.5

- RMs log the prepare message and the vote
- RMs send back a vote
  - “Commit” – RM is prepared to commit
  - “Abort” – RM is not able to commit and wants everyone else to abort
- Phase 2: TC sends out “Commit” or “abort”
  - Log result first at TC
  - RMs do the appropriate thing

Failure in 2PC

- RM failure
  - It it fails before/during prepare, TX is aborted (need unanimity)
  - If it fails after prepare, wakes up knowing it was prepared and can ask TC for outcome
- TC failure:
  - Before logging outcome, abort
  - TC aborts TX in prepared stage, resends outcome for Commit/abort
  - THIS BLOCKS
    - RMs don’t communicate, so cannot ask each other what happened

2PC vs. Replication

- 2PC works well if different nodes play different roles (e.g., Bank A, Bank B)
- 2PC isn’t perfect
  - Must wait for all sites and TC to be up
  - Must know if each site voted yes or no
  - TC must be up to decide
  - Doesn’t tolerate faults well; must wait for repair
- Can clients make progress when some nodes unreachable?
  - Yes! When data replicated.

Can we fix 2PC

- Yes: 3-phase commit
  - Add another stage (pre-prepare)
  - Allow electing a new coordinator if it fails
- No: 3pc protocols don’t handle partition
  - two coordinators may be elected on different sides of the network
- No
  - Known 3pc protocols have flaws

Paxos

- Developed independently by Leslie Lamport and Barbara Liskov (View Stamped Replication)
  - Widely seen as the only solution to this problem
  - Widely used in real systems – Google, Microsoft
- Written in 1990, but lost & not published until 1998
- Solves consensus in asynchronous system
  - Never makes the wrong choice, but may not make progress (consistency not availability)
**Problem**

- How to reach consensus/data consistency in distributed system that can tolerate non-malicious failures?

**Paxos: fault tolerant agreement**

- Paxos lets all nodes agree on the same value despite node failures, network failures and delays
- Extremely useful:
  - e.g. Nodes agree that X is the primary
  - e.g. Nodes agree that Y is the last operation executed

**Paxos: general approach**

- One (or more) node decides to be the leader
- Leader proposes a value and solicits acceptance from others
- Leader announces result or try again

**Paxos requirement**

- Correctness (safety):
  - All nodes agree on the same value
  - The agreed value X has been proposed by some node
  - **NOTE:** Like BGP
- Fault-tolerance:
  - If less than N/2 nodes fail, the remaining nodes should reach agreement eventually w.h.p
  - Liveness is not guaranteed if there are a steady stream of failures

**Why is agreement hard?**

- What if >1 nodes become leaders simultaneously?
- What if there is a network partition?
- What if a leader crashes in the middle of solicitation?
- What if a leader crashes after deciding but before announcing results?
- What if the new leader proposes different values than already decided value?

**Paxos setup**

- Each node runs as a *proposer, acceptor and learner*
- Proposer (leader) proposes a value and solicits acceptance from acceptors
- Leader announces the chosen value to learners
  - Roles are transient (can be reassigned or float around), just someone has to do it in the protocol
  - *Acceptor* generally is the set of nodes that want to agree
Strawman 1: single acceptor

- Designate a single node X as acceptor (e.g., one with smallest id)
  - Each proposer sends its value to X
  - X decides on one of the values
  - X announces its decision to all learners
- **Problem**?
  - Failure of the single acceptor halts decision
  - Need multiple acceptors!

Strawman 2: multiple acceptors

- Each proposer (leader) propose to all acceptors
- Each acceptor accepts the first proposal it receives and rejects the rest
- If the leader receives positive replies from a majority of acceptors, it chooses its own value
  - There is at most 1 majority, hence only a single value is chosen
- Leader sends chosen value to all learners
- **Problem**: What if multiple leaders propose simultaneously so there is no majority accepting? (not live?)

Paxos solution

- Proposals are ordered by proposal #
  - A node can choose an arbitrarily high number to try to have their proposal accepted...
- Each acceptor may accept multiple proposals
  - If a proposal with value $v$ is chosen, all higher proposals have value $v$

  - Ensures that proposed values converge

Paxos operation: node state

- Each node maintains:
  - $n_a, v_a$: highest proposal # and its corresponding accepted value
  - $n_h$: highest proposal # seen
  - $m_k$: my proposal # in current Paxos

Paxos algorithm

- Phase 1 (prepare):
  - A proposer selects a proposal number $n$ and sends a prepare request with number $n$ to majority of acceptors.
  - If an acceptor receives a prepare request with number $n$ greater than that of any prepare request it saw, it responds YES to that request with a promise not to accept any more proposals numbered less than $n$ and include the highest-numbered proposal (if any) that it has accepted.

Paxos operation: 3P protocol

- Phase 1 (Prepare)
  - A node decides to be leader (and propose)
    - Leader choose $m_k > m$.
    - Leader sends $\langle$prepare, $m_k\rangle$ to all nodes
    - Upon receiving $\langle$prepare, $n\rangle$
      - If $n < m_k$
        - reply $\langle$prepare-reject$\rangle$
      - Else
        - $m = n$
        - reply $\langle$prepare-ok, $n_a,v_a\rangle$

    - Send back previous number, value

    - Already seen a higher-numbered proposal

    - This node will not accept any proposal lower than $n$
Paxos algorithm

• Phase 2 (accept):
  – If the proposer receives a response YES to its prepare requests from a majority of acceptors, then it sends an accept request to each of those acceptors for a proposal numbered \( n \) with a values \( v \) which is the value of the highest-numbered proposal among the responses.
  – If an acceptor receives an accept request for a proposal numbered \( n \), it accepts the proposal unless it has already responded to a prepare request having a number greater than \( n \).

Paxos’s properties

• P1: Any proposal number is unique.
• P2: Any two set of acceptors have at least one acceptor in common.
• P3: the value sent out in phase 2 is the value of the highest-numbered proposal of all the responses in phase 1.

Learning a chosen value

• There are some options:
  – Ask a single acceptor
    • May not know all outcomes or result of a vote
  – Each acceptor, whenever it accepts a proposal, informs all the learners.
  – Acceptors informs a distinguished learner (usually the proposer) and let the distinguished learner broadcast the result.
    • Partition results between multiple learners
    • Use timeouts to fail over between learners
Reading the result of an agreement

- Without designated learners/decide message:
  - Must run Paxos to learn what all nodes agreed
  - Otherwise cannot learn that a majority agreed
- With designated learner:
  - It gets notified of every decision
- Leases: allow fault-tolerant learners
  - Promise a single learner for a while (with timeout),
    must be renewed or else a new learner will be found
  - Avoids paxos for learning

Paxos properties

- When is the value V chosen?
  1. When leader receives a majority prepare-ok and proposes V
  2. When a majority nodes except V
  3. When the leader receives a majority accept-ok for value V

Definition of chosen

- A value is chosen at proposal number n iff
  majority of acceptor accept that value in
  phase 2 (accept message) of the proposal number.
- Note: this is a stable property
  - Once majority accepts, all future majorities will

What About Omissions?

- Does not block in case of a lost message
  - Phase I can start with new proposal even if
    previous attempts never ended

Understanding Paxos

- What happens if the network is partitioned?
  - With one partition, will have a majority on one side, can come to agreement (if nobody else fails)

Paxos: Timeouts

- All nodes wait a maximum period (timeout) for messages they expect
- Upon timeout, a node declares itself a leader and initiates a new Phase 1 of algorithm
Paxos: Ensuring Agreement

- When would non-agreement occur?
  - When nodes with different $v_a$ receive Decide

- Safety goal:
  - If Accept could have been sent, future Decide’s guaranteed to reach nodes with same $v_a$

Risk: More Than One Leader

- Can occur after timeout during Paxos algorithm, partition, lost packets
- Two leaders must use different $n$ in their Prepare(), by construction of $n$
- Suppose two leaders proposed $n = 10$ and $n = 11$

More Than One Leader (2)

- Case 1: proposer of 10 didn’t receive Accept-ok()s from majority of participants
  - Proposer never will receive accept-ok()s from majority, as no node will send accept-ok() for prepare(10,...) after seeing prepare(11,...)
  - Or proposer of 10 may be in network partition with minority of nodes

  Result: 10’s proposed not decided!

More than One Leader (3)

- Case 2: proposer of 10 (10) did receive accept-ok()s from majority of participants
  - Thus, 10’s originator may have sent decide()!
  - But 10’s majority must have seen 10’s accept() before 11’s prepare()
    - Otherwise, would have ignored 10’s accept, and no majority could have resulted
  - Thus, 11 must receive prepare from at least one node that saw 10’s accept
  - Thus, 11 must be aware of 10’s value
  - Thus, 11 would have used 10’s value, rather than creating one!

  Result: agreement on 10’s proposed value!

Risk: Leader Fails Before Sending accept()s

- Some node will time out and become a leader
- Old leader didn’t send any decide()s, so no risk of non-agreement caused by old leader
- Good, but not required, that new leader chooses higher $n$ for proposal
  - Otherwise, timeout, some other leader will try
  - Eventually, will find leader who knew old $n$ and will use higher $n$

Risks: Leader Failures

- Suppose leader fails after sending minority of accept()s
  - Same as two leaders!
- Suppose leader fails after sending majority of accept()s
  - i.e., potentially after reaching agreement!
  - Also same as two leaders!
Risk: Node Fails After Receiving accept(), and After Sending accept-ok()

- If node doesn’t restart, possible timeout in Phase 3, new leader
- If node does restart, it must remember \( v_a \) and \( n_a \) on disk!
  - Leader might have failed after sending a few \( Q3() \)s
  - New leader must choose same value
  - This failed node may be only node in intersection of two majorities!

Paxos and BFT

- The BFT protocol really is a byzantine version of Paxos
  - Signed messages
  - \( 2F+1 \) responses needed to make progress rather than a simple majority

Variants

- Multi-paxos
  - Once a leader has an established ballot number, it can pass multiple steps without sending out a new prepare
    - It already has a good idea what the other nodes ballot/proposal numbers are and what they will accept
    - Just send “accept” and “decide” (like two-phase commit) with the correct numbers
- Change memberships
  - Pass it in one ballot and use it later

Checkpoint+log recovery

- How does a dead node come up to speed?
  - Copy state from another node + replay log
  - Need to snapshot state periodically
- Complication: must synchronize snapshot (slow operation) with log, so set is consistent
  - Think copy-on-write

Real-world problems

- Disk corruption on failure recovery
  - Must checksum log
- Simplifying reads: master leases
  - Ensure no one else will try to propose
  - Replicas refuse prepare messages from anyone but master
  - Flip-flop from repeated master failover
  - Upgrades between protocol versions

Other problems

- Changing membership
  - Need a quorum to change membership with Paxos
  - Catastrophic failure may prevent this
- Otherwise:
  - Pass a decree with new membership for future ballots