**CMPSCI 677 Operating Systems** **Spring 2023**

# Lecture 20: April 24

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## Lecture Overview

- Previous lecture continued, Recovering from a crash and Three phase commit
- Part 1: Consensus
- Part 2: PAXOS
- Part 3 : RAFT

**Recovering from a crash** : When a process recovers from a crash, it may be in one of the following states:

- INIT: If the process recovers and is in INIT state, then abort locally and inform coordinator. This is safe to do since this process had not voted yet and hence coordinator would be waiting for its vote anyway.
- ABORT: The process being in ABORT state means that coordinator would have issued a global-abort based on the abort vote of this process, hence the process can safely stay in the state it is or move to INIT state.
- COMMIT: The process being in COMMIT state means the coordinator already had issued global commit and this process now can safely stay in this state or move to INIT state.
- READY: The process in this state may be due to a variety of possibilities hence as soon as any process recovers and finds itself in a READY state, it checks other processes for their state to get hint of the group status.
  The table describes the actions of recovered process P on seeing the state of a process Q and the reason for such action.

| State of Q | Action by P | Reason |
|---|---|---|
| COMMIT | Make transition to COMMIT | Any process can be in commit only if coordinator issued a global-commit |
| ABORT | Make transition to ABORT | 2 scenarios:<br>• If process Q has aborted itself. Then coordinator would issue a global-abort. Hence, P can abort.<br>• If process Q aborted because of a global-abort. P can abort in this case too.<br>. |
| INIT | Make transition to ABORT | If process Q is in INIT means it has not voted yet. Thus, voting phase is still going on. Process P can abort safely. |
| READY | Contact another participant | Since, based on process Q's READY state, process P can't infer much. Hence, P should ask another process. |

**If process Q is in READY** : Process Q being in READY state requires a further analysis of action:

- Keep asking other processes about their state
- If at least one of them is not in the READY state then choose an appropriate action from the table above.
- If all of them are in the READY state and are waiting to hear from the coordinator, process P can't make a decision yet. All other processes can't make any decision either.
  **The reason:** Coordinator itself is a participant in the vote, hence, based on the action it takes after recovering, the option decided by the processes as a group may be wrong. That is:
  - All processes can't just commit because coordinator may recover and want to abort.
  - All processes can't just abort because coordinator may recover and see that every process had voted commit and want to commit and issue a global-commit. Other processes in abort state would lead to inconsistent state.

**Problem of 2PC** If the coordinator crashes without delivering the results of a vote, all processes will be deadlocked. This is called **blocking property of 2 phase commit**.

**Question**: If the co ordinator has send messages to some processes and not all and then it crashes then what happens ?

**Answer**: Two properties need to be discussed to **Answer** this, safety and livenss. Safety: Nothing bad happens, the protocol does not reach an incorrect decision. Liveness: There is progress, the protocol reaches a decision. The 2pc guarantees safety and not liveness.

**Question**: what happens if a node crashes after it works to commit? *Answer*: Process upon restarting/re-initialisation needs to check it's last state and make a decision.E.g: If it's in init state, that means that it did not vote for the operation otherwise it would have been in the ready state, in this case, it's best to abort and inform coordinator about the decision so it can make progress.

If the process was re-initialised with a "ready" last state, then it means that it voted before crashing but doesn't know the result, so it needs to check other process queues for that operation and figure out the decision.

### 20.0.1 Three phase commit

Three phase commit is a variant of two phase commit which takes care of the liveness property that the 2pc could not guarantee in case of coordinator crash.

**How does the $3^{rd}$ phase PRECOMMIT help?**
Recollecting, blocking problem of 2-phase commit scenario. If a process recovers from a crash and finds itself to be in a READY state, it asks another process about its state. To this the reply is READY state. The processes are still to hear from the coordinator. If every process is in the ready state and the coordinator crashed and can't tell what the outcome of the vote is. A decision can't be made in case of 2PC. However, even in such a scenario a decision can be made safely in case of 3PC. Assuming the coordinator had gone into a PRECOMMIT state and crashed. The processes can decide among themselves and ABORT.

- If the co-ordinator recovers and finds itself in the PRECOMMIT state, it could ABORT the transaction.
- In 2 phase this could not have been possible because the co-ordinator would have gone into COMMIT phase and rest of the processes would have ABORTed leading to an inconsistent state.

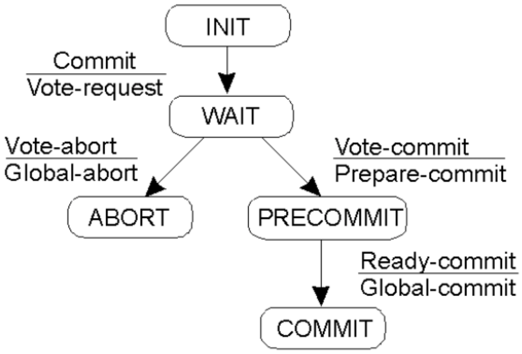


Figure 20.1: **3PC: Coordinator's state transition.** From INIT state, the coordinator asks all processes to vote and goes into WAIT If any process votes abort, the coordinator goes in ABORT and issues global-abort. If all processes vote commit, inform processes to prepare for commit. Go in the PRECOMMIT state. Once all the processes have moved to PRECOMMIT, then issue a global-commit and go into COMMIT state.

**Question** What happens if co-ordinator crashes after everyone is in pre-commit?
**Ans.** If every process is in PRECOMMIT and not in READY state, they can go ahead and COMMIT. This is because, once co-ordinator recovers, it may ask other processes for the state to which the reply would be COMMIT. This way co-ordinator can go in a COMMIT state as well.

## 20.1 Consensus

Definition: get a group of processes to agree on something such as database replication etc. Consensus also means getting the set of processes to agree when some of the processes fail via atomic. More formally, we want to achieve reliability in presence of faulty processes:

- Requires processes to agree on data value needed for computation.
- **Examples**: The operation could be anything - whether to commit a transaction, agree on identity of a leader, atomic multicasts, atomic broadcasts, distributed locks.

The failures are in context of crash faults or Fail-stop failures i.e., a process produces correct output while it is running, but the process can hang/go-down and hence will not produce any results. **Note**: When there are no failures, there are protocols like 2 Phase commits that we discussed, to come to an agreement. For instance, committing a transaction.

**Byzantine Consensus vs Consensus** Byzantine consensus is when we need to come to an agreement in case of processes that are byzantine-faulty i.e., faulty processes continue to run and produce malicious outputs and prevent agreement. Whereas consensus is a benign scenario where some processes fail to respond.

**Q: How to decide what consensus protocol to use?** Depends on what we're trying to achieve. PAXOS, RAFT can be used for crash faults, for implementing a basic fault tolerance mechanism. Byzantine is more elaborate and used in case where we do not want malicious actors to cause confusion as in case of crypto-currency.

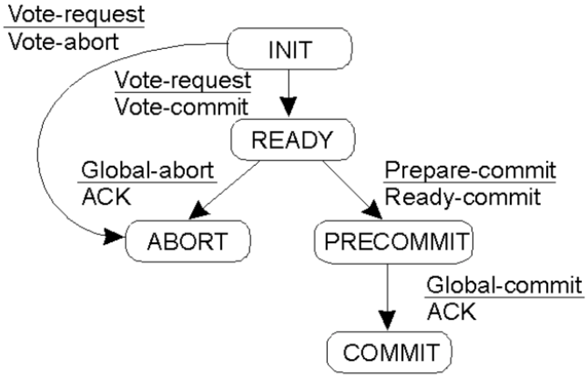


Figure 20.2: **3PC: Subordinate process's state transition.** A process may vote commit and go into READY state. It may vote abort and go directly into ABORT state. This is because this single abort would lead to global-abort. On being READY and receiving an abort, the process goes into ABORT state. On being READY and receiving a prepare-commit, the process goes into PRCOMMIT state. Once in PRECOMMIT, the processes move to COMMIT state on receiving global-commit.

### 20.1.1 Properties of a Consensus Protocol

- **Agreement**: Every correct process *agrees* on the same value.
- **Termination**: Every correct process *decides* on some value.
- **Validity**: If all processes *propose* a value(v), all correct processes must *decide* on that value, v.
- **Integrity**:
  - Every correct process *decides* at most one value.
  - If a correct process *decides* on a value, a process must have *proposed* that value.

**Q: What does 'all' in validity mean?** We will have failures, if any process or say the co-ordinator crashes during agreement, we will not have consensus. But the protocols define that, if we have a majority(and not all) of the nodes up and running and they agree on a value, we have consensus.

### 20.1.2 2PC/3PC Problems

Both two phase commits and three phase commits experience problems in the presence of different types of failures. While the **safety** property can be ensured, the **liveness** properties cannot always be guaranteed due to node failures and network failurs: the system will never perform an operation that leads to an inconsistent state (satisfying the safety property) but can still be deadlocked (violating the liveness property). We describe a few caveats associated with each type of commit below.

**Two Phase Commit**

- It must wait for the coordinator and the subordinates to be running.
- It requires all nodes to vote.
- It requires the coordinator to always be running.

**Three Phase Commit**

- It can handle coordinator failures.
- But network failures are still a problem.

There has been an implicit assumption that there could only be node failures instead of network failures during a two or three phase commit. While a node could crash in the network, the network would never experience any issues. Suppose, however, that the network was partitioned into two partitions due to some problem. Although both partitions will continue to function correctly, each partition cannot communicate with each other. **By definition, if the network is partitioned due to some problem, a two or three phase commit cannot work because every node is required to vote on the answer.**

In order to eliminate such an assumption, we have to revisit the definition of *agreement.* Rather than requiring the vote of every node, we can just require the vote of the majority of nodes. Therefore, if the network were to be separated into two partitions, the partition with the majority of nodes can still continue to function properly. This idea forms the basis of **Paxos**, a consensus protocol. **Instead of requiring every node to vote, Paxos only requires the majority of nodes to vote.**

## 20.2 Paxos: Fault-tolerant agreement

Paxos lets nodes agree on the same value despite node failures, network failures and network delays. **Use-cases include:**

- Nodes agree X is primary (or leader)
- Nodes agree Y is last operation (order operations)

The protocol is widely used in real systems such as Zookeeper, Chubby and Spanner. ***Leader*** is a process that tries to get other processes to agree on a value. For instance, a process says, I propose that the value after computation is X and gets other process to agree that the output after computation is X. Therefore, leader is essentially a proposer. If majority of the processes agree then, the value is agreed upon. If not, then either the leader tries again or some other process becomes a leader and attempts consensus. **Note:** There can be multiple leaders and can attempt to get others to agree on a value.

**Question**: what method would you want to use this as opposed to other approaches (2PC/3PC) ? *Answer*: This can be used in case of failures in the node as well as multiple leader failures. Since it is a quoram based protocol, it allows leader election even if some processes fail as long as majority of them are up.

### 20.2.1 Paxos Requirements

Paxos satisfies the following properties:

- Safety (*Correctness*)
  - All nodes must agree on the same value.
  - The agreed upon value must be computed by some node.
  - **Note:** We do not want just trivial consistency i.e.; everyone agrees value is zero or null. Therefore, the value that is agreed upon must be computed by some node.

- Liveness (*Fault Tolerance*)
  - If less than $\frac{n}{2}$ nodes fail, the remaining nodes will eventually reach agreement. This allows the system to make progress in the presence of failures.
  - Note that that liveness is not guaranteed if there is a steady stream of failures as the protocol determines what to do. If a node fails in the middle of the protocol, it must be restarted.
- **Why is agreement hard?** Because even in the face of failures, we still need to reach agreement.
  - The network might be partitioned.
  - The leader may crash during solicitation or before announcing the outcome of voting. While the current round will not produce any results, a new leader will be elected through leader election. All nodes will then vote again.
  - A new leader may propose different values from the value that had been agreed upon originally.
  - Several nodes may become a leader at the same time. This is possible when the network is partitioned due to a network failure. The left half will elect a new leader while the right half will have the old leader, and they will still continue to function properly. Both sides of the partition may agree on different things unfortunately.

### 20.2.2 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
  - *Learners* do not play an active role, but agree on proposed value.
- Proposals are ordered by unique proposal numbers.
  - Node can choose any high number to try and get proposal accepted
  - An acceptor can accept multiple proposals.
    - If a proposal with value v is chosen, all higher proposals have value v.
- Each node maintains:
  - **n_a, v_a:** The highest proposal number and accepted value during that proposal.
  - **n_h:** The highest proposal number seen so far
  - **my_n:** the current proposal number that is in progress.

### 20.2.3 Paxos Operation : 3 Phase protocol

**Phase 1: Prepare Phase** Leader understands what other processes have seen or accepted before.

- A node decides to be leader and proposes a value
- Leader chooses my_n >n_h
- Leader sends **<prepare, my_n>** to all nodes. **Note that,** during this, the value proposed is not sent, it's just the prepare message with proposal number.

- Upon receiving **<prepare, n>** at acceptor:
  - If n <n_h: Reply with <**prepare-reject**. (Since, already seen a higher # proposal.)
  - Else:
    - n_h = n (Protocol will not accept proposal lower than n)
    - Reply **<prepare-ok, n_a, v_a >.** (Send back the most recently accepted proposal # and value)
    - Reply can be null, if you haven't seen any proposals yet and this is the first proposal.

**Phase 2: Accept Phase**

- If leader gets **<prepare-ok>** from majority *(Actions taken by leader)*
  - V = non empty value from the highest n_a received from prepare phase.
  - 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>*(Actions taken by acceptor)*:
  - If n <n_h : Reply with **<accept-reject >**
  - Else : n_a = n; v_a = V, n_h = h; reply **<accept-ok >**

**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.

**Question**: Are we assuming the number of nodes is fixed? Can new nodes join? *Answer*: It is not sure new nodes can join since we are assuming because as mentioned previously here that if you have a steady stream of failures and recovery liveness is not guaranteed so we can have failures but then if new nodes are joining and they suddenly start saying something that they're in participant participate that's a problem then that round will fail the nodes can join but that round will failure to return. It may also cause problems in majority voting.

**Q: Can Proposals go on indefinitely?** At the beginning, no one has agreed to anything, leader gets null and chooses a value V. Another proposer suggests a value and it gets accepted and so on. Essentially the value will not change and this is similar to electing the same leader over and over again. While anyone can start a proposal at any time, the agreed value will not get affected. However, the phase 3 or decide phase cannot happen if a new proposal with higher proposal number has started making rounds. Nodes may decide to reject the proposal and accept a new one. And this is possible since we can have multiple leaders. Therefore, there must be a gap between decide phase and new proposals for decide phase to happen. To re-iterate, this doesn't change the value however.

**Q: What if you have same proposal numbers?** Proposal numbers are unique, Paxos will not work if two proposals have same number. We can append PID (process id) to make it unique. This is similar to Lamport's clock ordering to convert partially ordered to fully-ordered events where we append process id.

**Properties**

- Property 1: any proposal number is unique.
- Property 2: two sets of acceptors have at least one node in common
- Property 3: value sent in phase 2 is value of the highest numbered proposal received in responses in phase 1.

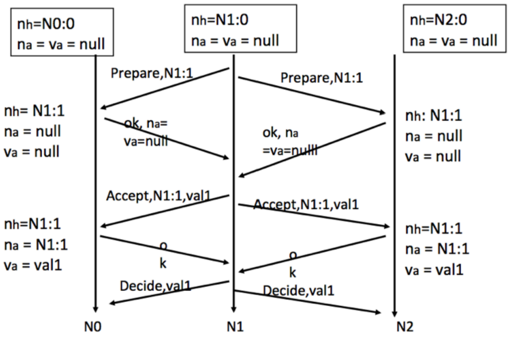


Figure 20.3: Example of Paxos with 3 servers

**An example with three nodes namely N0, N1, N2 where N1 is the proposer:**

- Prepare Phase:
  - N1 sends prepare messages to N0 and N2 i.e. <prepare, N1:1>where 1 is the proposal number and not the value we are trying to get consensus on.
  - N0 and N2 haven't seen any proposals before so send <prepareok, n_a = null, v_a = null>to N1.
- Accept Phase:
  - Values received at N1 after prepare phase are null, so N1 decides on val1 as accepted value and sends accept messages to N0 and N2 as <accept, N1:1, val1>
  - N0 and N2 send <accept-ok>to N1.
  - Decide Phase:
    - N1 sends <decide, val1>to N0, N2.

When we have one leader, the protocol converges easily. But say N0 decides to become a leader while N1 is trying to get consensus as the proposer, the proposal from N0 will get discarded as a new proposal with higher proposal number is now available. Learners/Acceptors can choose to agree to the new proposal.

**Issues :**

- Network Partitions: For a network that has an odd-partition, if there is majority on one side, nodes can come to an agreement whereas they cannot if network is evenly partitioned.
- Timeout:

  - A node has max timeout for each message
  - Upon timeout, it declares itself as leader and restart Paxos

- Two Leaders:
  - Either a leader was not able to execute decide phase (due to lack of majority accept-oks as nodes encountered a higher proposal from other leader) OR,
  - One leader causes the other leader to use its value.

- Leader Failures: This case is same as two leaders or a timeout where a node will decide to become the leader and restart Paxos.

## 20.3 RAFT Consensus Protocol : understandable consensus protocol

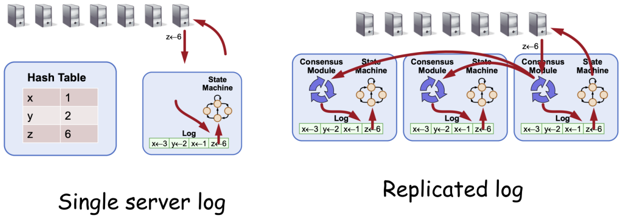
The RAFT protocol is based on how a part-time parliament functions. A parliament is able to pass laws despite some members being out of attendance, or members showing up to the parliament at different times. It reaches consensus despite attendance (read failures, in case of processes).

Raft uses replicated logs or State Machine Replication (SMR) to implement the protocol. Assume we have n servers and each server stores a replica of log of commands and executes them in that order.

**How do we replicate logs in multiple places while keeping the order consistent?** Raft implements a leader election protocol. All incoming requests then go to the leader and it decides the order of execution and informs everyone, as opposed to sending each request to everyone and then deciding on an order. Therefore, we need to elect a responsible leader. And if leader fails, we elect a new one and clean the logs to ensure consistency. We must note that if we have majority i.e. N/2 +1 nodes, consensus can be reached, otherwise it cannot. Also, if an entry is committed, all entries preceding it are committed.

Note : All the metadata such as who was the leader node, term number etc along with the log vaule needs to match for a logs between process and majority to be considered equivalent.

**Log Replication Example:** In case of three servers, the request z = 6 goes to the presumed leader. Leader writes it in log file and sends prompt to other nodes to append it to their logs. The consensus module ensures that the order is maintained. Every committed request is executed. The value needs to first be appended and then committed to the logs.



Single server log

Replicated log

Fig courtesy: D. Ongaro

Figure 20.4: Example of Log replication

**Consensus approaches:**

- Leaderless/Symmetric: Client can send the request to any server and that server decides the order of execution.
- Leader-based/ Asymmetric: One server becomes leader and tells followers what to do.

**Overview of RAFT operations**

- Leader election: Nodes must select one server to serve as RAFT Leader. There must be provision to detect leader crash and provision to elect a new leader in case of a crash.
- Normal operation: This involves performing log replication, leader receiving client commands, appending incoming requests to log. Leader then replicates log to followers. We must ensure safety i.e., committed logs must not get impacted by leader crash and there must be at most one leader at a time.

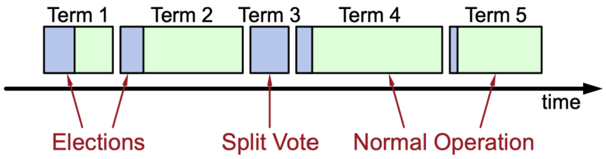


Figure 20.5: Terms

**Terms:**

- Time is divided into terms, a period when a certain node acts as the leader. Term does not change unless the leader crashes/fails.
- Each term has a blue followed by a green part. Blue parts represent leader election, green represents normal operation. If a term has only blue (a failed term), it represents a split vote or no majority to elect a node as the leader.
- All servers maintain the current term value.
- At any time, each server can be either of the three:
  - Leader: receives all client requests and does log replication
  - Follower: passively follows leader
  - Candidate: a node that participates in leader election

**RAFT Election :**

- Election timeout: Communication is over RPCs and if no RPCs are received for a while from the leader, then increment current term and become a candidate.
- Elections are selfish. On an election timeout, candidate node votes for self to become a leader and sends an election message (RequestVote RPC) to followers.

- – If the node receives vote from majority, it becomes the leader and sends heartbeat message (AppendEntries RPC) to inform other nodes.
  - – Failed election: If no majority votes are received within election timeout, the term gets incremented and a new election starts.

- Safety in election: In any election, at most one server wins since you can only cast your vote once per term. Also, there is random back-off in case of a failed election i.e. each node backs off for different amount of time. This ensures that some node starts the leader election and wins majority, while other candidates are in timeout.
- Liveness: One of the nodes will win the leader election.

### Normal RAFT Operation

- Leader receives client commands and appends them to log.
- Each log entry has 3 things: Index (item no. in the log), term (current term value), command.
- Leader sends AppendEntry RPC to all followers.
- Once an entry is safely committed to log (i.e. leader got a majority vote for AppendEntry RPCs sent), the command is then executed and results are sent to the client.
- Committed entries are notified to followers in subsequent RPCs therefore the followers catch up in background. The followers apply the committed commands to their state machines.

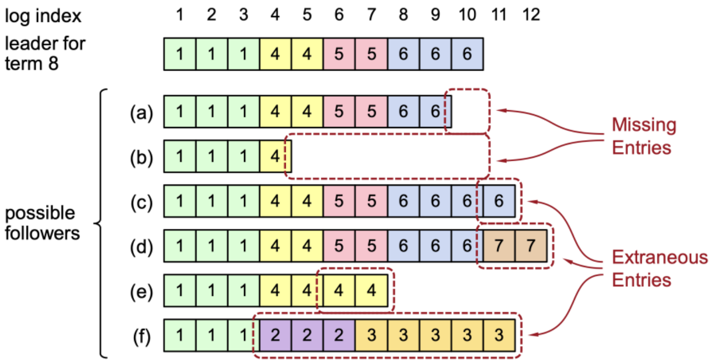


Figure 20.6: Inconsistencies in Logs Example

**Log Consistency** To verify if logs are consistent, leader informs the followers what the previous entry (index, term) in the log was. If the previous entry at the follower and the one sent by the leader do not match, then we know there is inconsistency. Log entries can become inconsistent due to leader failure.

- There can be missing entries as in the case of (a) and (b) followers. Possible causes can be a network partition or failure of those follower nodes when the entries came in.
- There can be extraneous entries as in the case of followers c, d, e and f. This can be because of leader partition, and some other nodes got new requests that haven't yet been committed.

The leader must synchronize the logs to ensure consistency by adding required entries to the missing ones and scrubbing extraneous entries by using pre-fix match. **Note:** These are all entries that have been appended to logs but not committed.

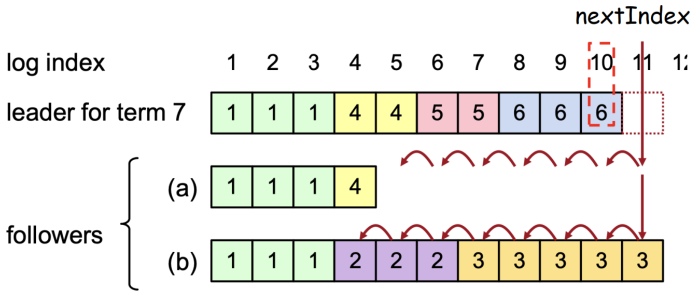


Figure 20.7: Log Repair Example

**Log Repair** The leader tracks nextIndex for each follower. It asks the follower if it has the entry at an index (index of last entry in leader's log) in its log. If the follower doesn't, the nextIndex decrements until a matching entry is found. All missing entries from this point onwards are sent to follower to catch up. In case of extraneous, the subsequent entries from index where we found the match at are deleted and leader replays the rest of the logs for follower to catch up on.

**Leader crashed and some other node becomes the leader, how do we ensure consistency in this scenario?** We check the committed entries until the time of crash and use that to ensure ordering.

**When is consensus achieved in RAFT?** Consensus is achieved when majority of the nodes have appended and committed the entries. To have consensus means we have agreed to commit to an order.

**When does the commit actually happen?** In Normal Operation, if majority of followers agree to append, then you commit the log.

**During election, who ensures log is collected?** The clients cannot send requests during election since there is no leader. Requests can be sent only after a leader is elected.

**If the leader crashes while committing logs, what happens?** RAFT has a way to handle this, TBA on piazza.

**Question**: Why do we have these extraneous entries at all ?

*Answer*: Assume there was a green leader at some point in time it produced three entries and then maybe there was a network partition , so that green leader and some nodes got disconnected from the majority and before we could realize that maybe that green leader sent an extra entry to this follower but it can't send it to the remaining majority but they are already in an unreachable so they will then what they will do is they will elect their own new leader which in this case was yellow and blue and so on so in the network rejoins you will see that some bad things may happen to the minority because before they realize that something had gone wrong they had already written some entries to their law okay and you've got to repair them.

**Question**: What if the step that is extraneous was a really important operation and we deleted them how is whoever made that request is going to figure this out?

*Answer*: In this case, because the leader got disconnected, it couldn't gather the majority vote and hence it never replied to client with a success response. So the client so the request will simply timeout or fail.

## 20.4 Recovery :

We have discussed techniques thus far that allow for failure handling, but how recovery dictates how those failed nodes come back up and recover to the correct state. The techniques include periodic checkpointing of states and roll-back to a previous checkpoint with a consistent state in case of a crash.

- Independent Checkpointing
  - Each process periodically checkpoints independently of other processes.
  - Upon failure, work backwards to locate a consistent cut, last checkpoint.
- Logging
  - Is a common approach to handle failures in databases, file-systems.
  - Done by logging and re-playing logs.

**Trade-offs between checkpointing and logging:** *Checkpointing* doesn't need logs, it saves system state that can be used as last consistent state. This is expensive since we are writing entire system state to disk. But recovery is quick in case of checkpointing, since we are loading the system values from a file essentially. Whereas in *logging*, the logs have to be replayed/executed again from the point of failure. Adding logs to a file is cheap, but it is expensive in terms of recovery as in the case of processes being behind by a lot and all the missed logs have to be executed again. We can combine the two as well.

- Take infrequent checkpoints
- Log all messages between checkpoints to local stable storage.
- To recover: replay messages from previous checkpoint. This avoids re-computations from previous checkpoint.