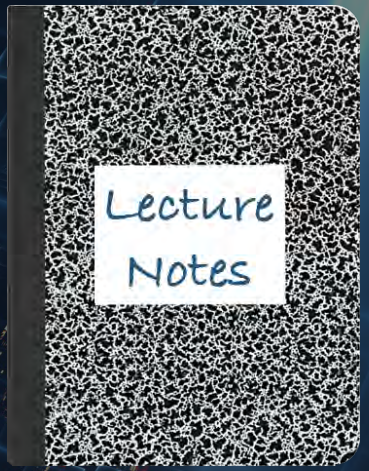
CS 417 – DISTRIBUTED SYSTEMS



Week 5: Part 3

Quorum-Based Consensus: Raft

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Consensus Goal

Allow a group of processes to agree on a result

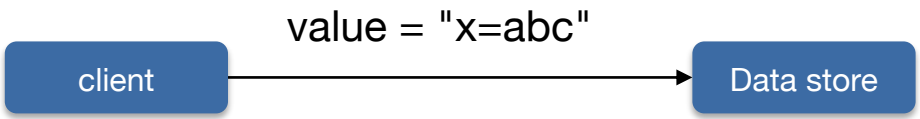
- All processes must agree on the same value
- The value must be one that was submitted by at least one process (the consensus algorithm cannot just make up a value)

We saw versions of this

- Mutual exclusion
  - Agree on who gets a resource or who becomes a coordinator
- Election algorithms
  - Agree on who is in charge
- Other uses of consensus:
  - Synchronize state to manage replicas: make sure every group member agrees on the message ordering of events
  - Manage group membership
  - Agree on distributed transaction commit
- General consensus problem:
  - *How do we get unanimous agreement on a given value?*

    value = sequence number of a message, key=value, operation, whatever…

Achieving consensus seems easy!



- One request at a time
- Server that never dies

Dealing with failure

- **FLP Impossibility result**
  - *Impossibility of distributed consensus with one faulty process*
    by Fischer, Lynch and Patterson
  - Consensus protocols with asynchronous communication & faulty processes

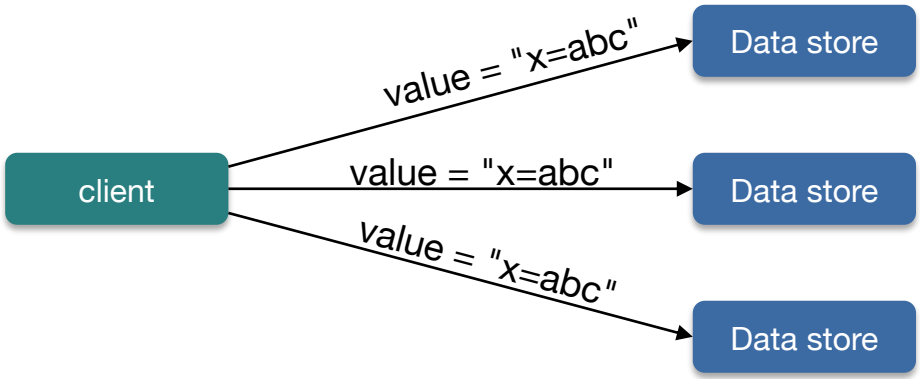
  "every protocol for this problem has the possibility of nontermination, even with only one faulty process"

- It really means *we cannot achieve consensus in bounded time*
  - We can with partially synchronous networks
  - Either wait long enough for messaging traffic so the protocol can complete or terminate

References:

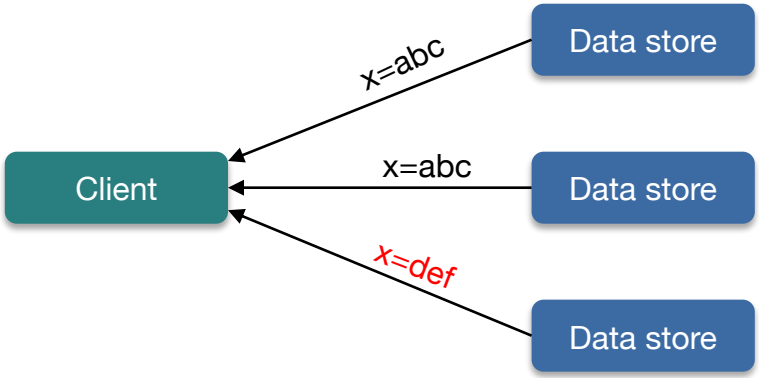
the-paper-trail: https://www.the-paper-trail.org/post/2008-08-13-a-brief-tour-of-flp-impossibility/
original paper: https://dl.acm.org/doi/10.1145/3149.214121

Servers might die – let's add replicas



One request at a time

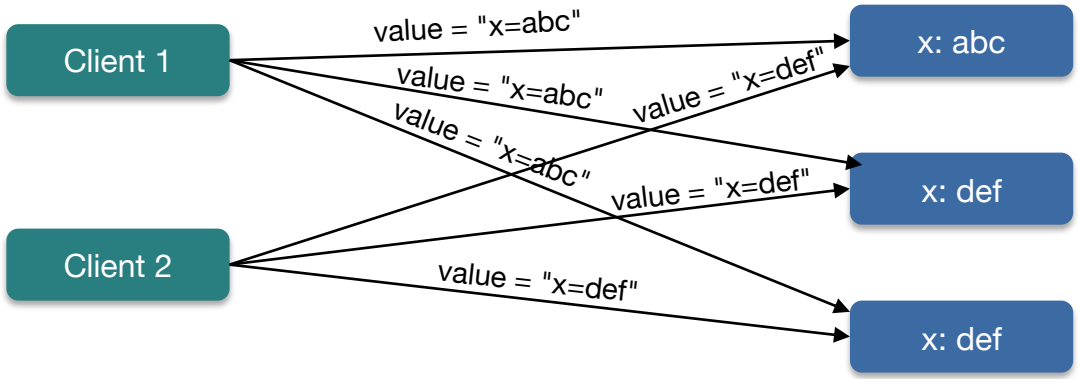
Reading from replicas is easy



We rely on a **quorum** (majority) to read successfully

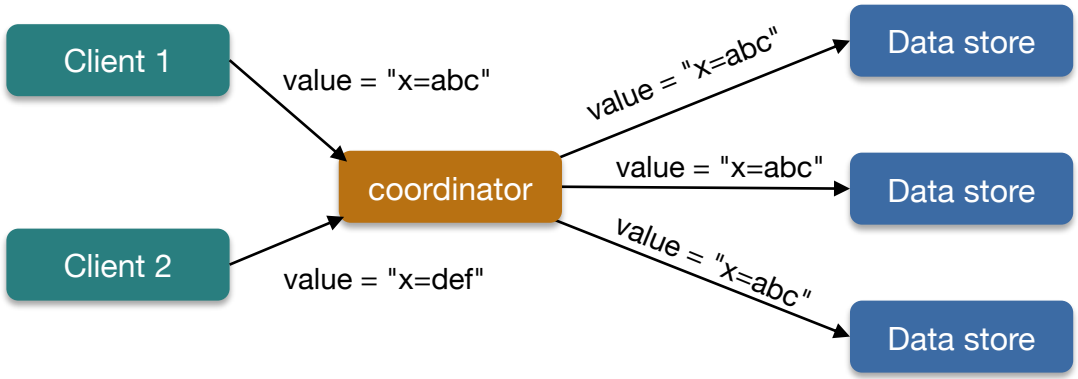
No quorum = failed read!

What about **concurrent updates**?



We risk inconsistent updates

What about **concurrent updates**?



- Coordinator (or sequence # generator) processes requests one at a time
- But now we have a **single point of failure**!
- We need something safer

Consensus algorithm goal

Goal: agree on one result among a group of participants

Create a fault-tolerant consensus algorithm that does not block if a *majority of processes* are working

- Processors may fail (some may need stable storage)
- Messages may be lost, out of order, or duplicated
- If delivered, messages are not corrupted

Quorum: majority (>50%) agreement is the key part: If a majority of coins show heads, there is no way that a majority will show tails at the same time.

If members die and others come up, **there will be one member in common** with the old group that still holds the information.

Consensus requirements

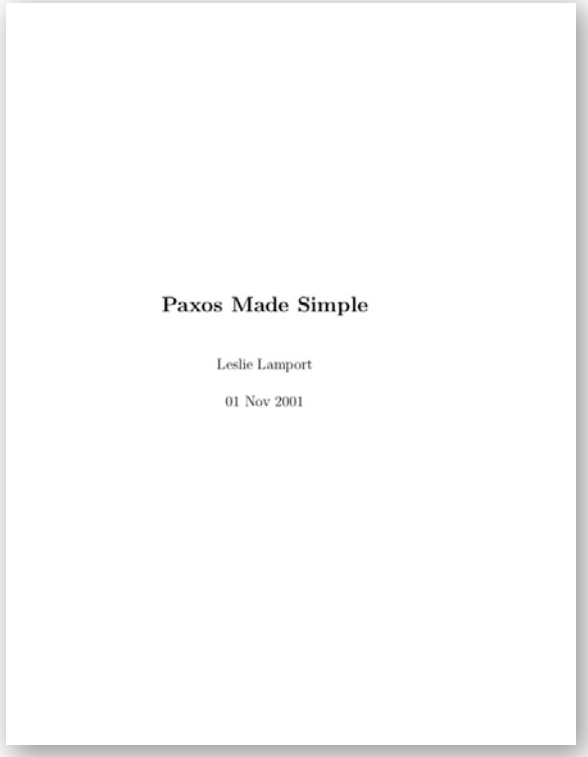
- Validity
  - Only proposed values may be selected
- Uniform agreement
  - No two nodes may select different values
- Integrity
  - A node can select only a single value
- Termination (Progress)
  - Every node will eventually decide on a value

Distributed Consensus Protocols: Paxos

The Part-Time Parliament

LESLIE LAMPORT

Digital Equipment Corporation



Paxos Made Simple

Leslie Lamport

01 Nov 2001

Paxos Made Practical

Daniel Mazières

1 Introduction

Raft Distributed Consensus

Goal: replicated state machines

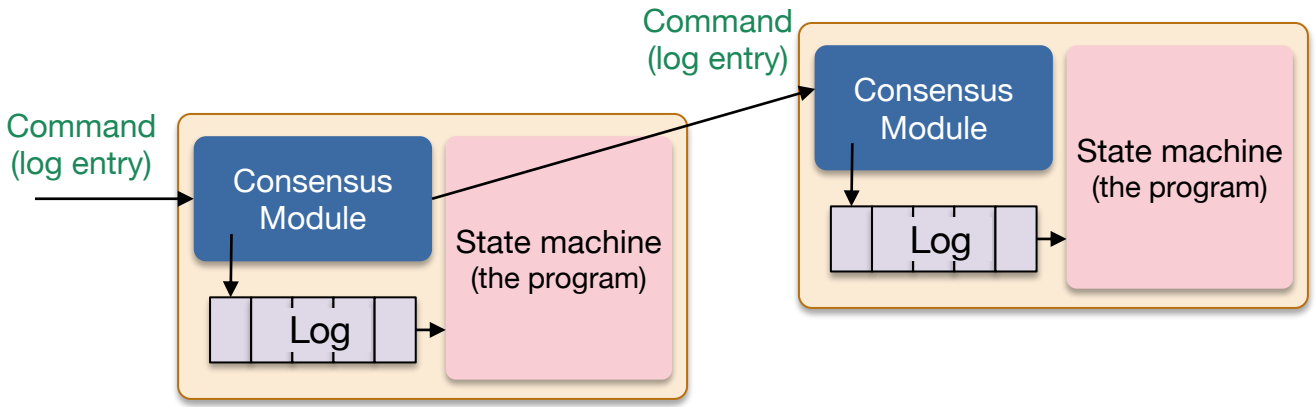
Allow a collection of systems to stay in sync and withstand the failure of some members

- Systems are deterministic – if they receive the same input then they produce the same results
- Required for any system that has a single coordinator
  - Examples: Google Chubby, Apache Zookeeper, Google File System, Hadoop Distributed File System, Google Pregel, Apache Spark, …
- Implement as a **replicated log**
  - Log = list of commands processed by each server in sequence

Consensus algorithm goal

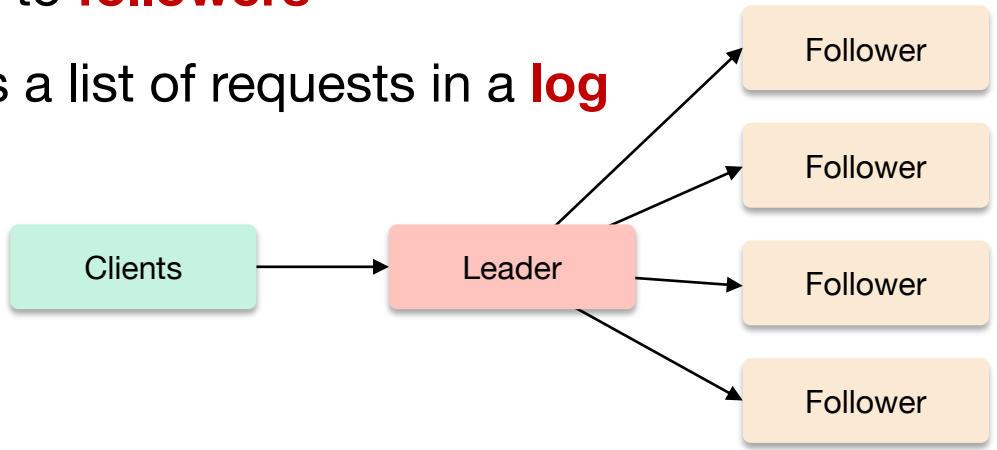
Keep the replicated log consistent

- A consensus module on a server receives commands from clients
- It propagates the commands to consensus modules on other systems to get everyone to agree on the the next log entry
- The entry is added to the log (queue) and a state machine on each server can then process the log data



Raft environment

- Server group = set of replicas (replicated state machine)
  - Typically a small odd number (5, 7)
- Clients send data to a **leader**
- The leader forwards the data to **followers**
- Each leader & follower stores a list of requests in a **log**
- Raft has two phases
  1. Leader election
  2. Log propagation



Participant states

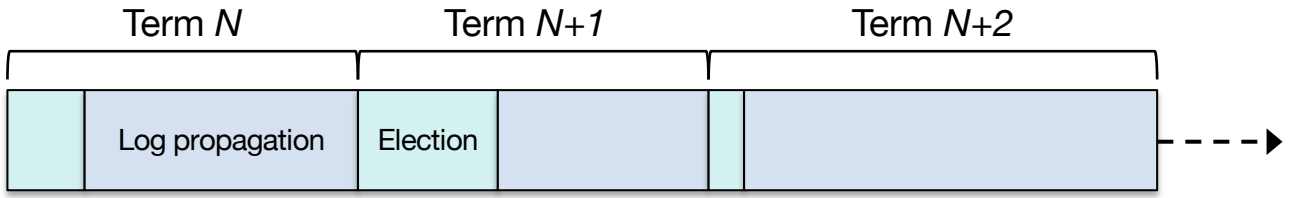
- **Leader**: handles all client requests
  - There is only one leader at a time
- **Candidate**: used during leader election
  - One leader will be selected from one or more candidates
- **Follower**: doesn't talk to clients
  - Responds to requests from leaders and candidates

Raft RPCs

- The Raft protocol uses two RPCs
- **RequestVotes**
  - Used during elections
- **AppendEntries**
  - Used by leaders to
    - Propagate log entries to replicas (followers)
    - Send commit messages (inform that a majority of followers received the entry)
    - Send heartbeat messages – a message with no log entry

Terms

- Each **term** begins with an election
- Any requests from smaller term numbers are rejected
- If a participant discovers its term is smaller than another's
  - It updates its term number
  - If the participant was a **leader** or **candidate** then it reverts to a **follower** state



Leader Election

Everyone starts off as a *follower* and waits for messages from the *leader*

Leaders periodically send *AppendEntries* messages

- A *leader* must send a message to all followers at least every ***heartbeat*** interval
- These might contain no entries but act as a heartbeat

If a *follower* times out waiting for a heartbeat from a *leader*, it starts an election

- Follower changes its state to ***candidate***
- Increments its term number
- Set a random election timeout
- Votes for itself
- Sends **RequestVote** RPC messages to all other members
  - Any receiving process will vote for this candidate if it has not voted yet in this term

Leader Election: Outcomes

Possible outcomes

1. Candidate receives votes from a majority of servers

- It becomes a leader and starts to send *AppendEntries* messages to others

2. Candidate receives an *AppendEntries* RPC

- That means someone else thinks they're the leader – check the *term* # in the message
- If term # in message > candidate's term #
  It accepts the server as the leader and becomes a follower
- If term # in message < candidate's term #
  It rejects the RPC and remains a candidate

3. Election timeout is reached with no majority response

- Split vote: if more than one server becomes a candidate at the same time, there is a chance the vote may be split with no majority

Leader Election: Randomized timeouts

If more than one server becomes a candidate at the same time, there is a chance the vote may be split with no majority

- We want to avoid this situation
- Raft uses **randomized timeouts** to ensure concurrent elections and split votes are rare
- Election timeouts chosen randomly (e.g., in the range 150-300ms)
- Usually, only one server will time out –
  - winning the election and then sending heartbeats before others time out
- If multiple servers hold concurrent elections and we have a split vote
  - They simply restart their elections: it's highly unlikely that both will choose the same random *election timeout*

Log replication: *leader* to *followers*

- Commands from clients are sent only to the current leader
  - Leader appends the request to its own log
    - Log entry has a term # and an index # associated with it
  - Sends an ***AppendEntries*** RPC to all the followers
    - Retry until all followers acknowledge it
- Each ***AppendEntries*** RPC request contains:
  - Command to be run by each server
  - Index to identify the position of the entry in the log (first is 1)
  - Term number - identifies when the entry was added to the leader's log
  - Index and term # of previous log entry

Log replication: *followers*

A follower receives an ***AppendEntries*** message

- If leader's term < follower's term
  - Reject the message
- If the log does not contain an entry at the previous (index, term)
  - Reject the message
- If the the log contains a conflicting entry (same index, different term)
  - Delete that entry and all following entries from the log
- Add the data in the message to the log

Log replication: execution

- When a log entry is accepted by the ***majority*** of servers, it is considered **committed**
- The leader can then execute the log entry & send a result to the client
- Each ***AppendEntries*** RPC request also contains a *commit index*
  - Index of highest committed log entry
- When followers are told the entry is committed, they apply the log entry to their state machine

Forcing consistency

- Leaders & followers may crash
  - Causes logs (& knowledge of current term) to become inconsistent
- Leader tries to find the last index where its log matches that of the follower
  - Leader tracks `nextIndex` for ***each*** follower
    (index of next log entry that will be sent to that follower)
  - If ***AppendEntries*** returns a rejection
    - Leader decrements `nextIndex` for that follower
    - Sends an ***AppendEntries*** RPC with the previous entry
  - Eventually the leader will find an index entry that matches the follower's

This technique means no special actions need to be taken to restore logs when a system restarts

The End