Distributed Systems: Consensus

Lecture 12b

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http://www.cs.rutgers.edu/~sn624/553-S25

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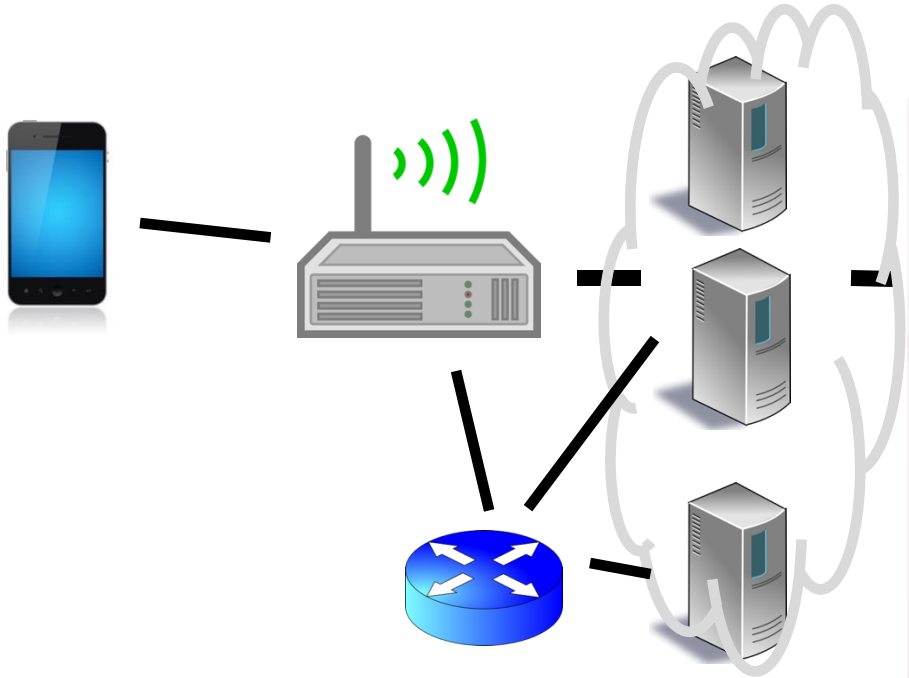
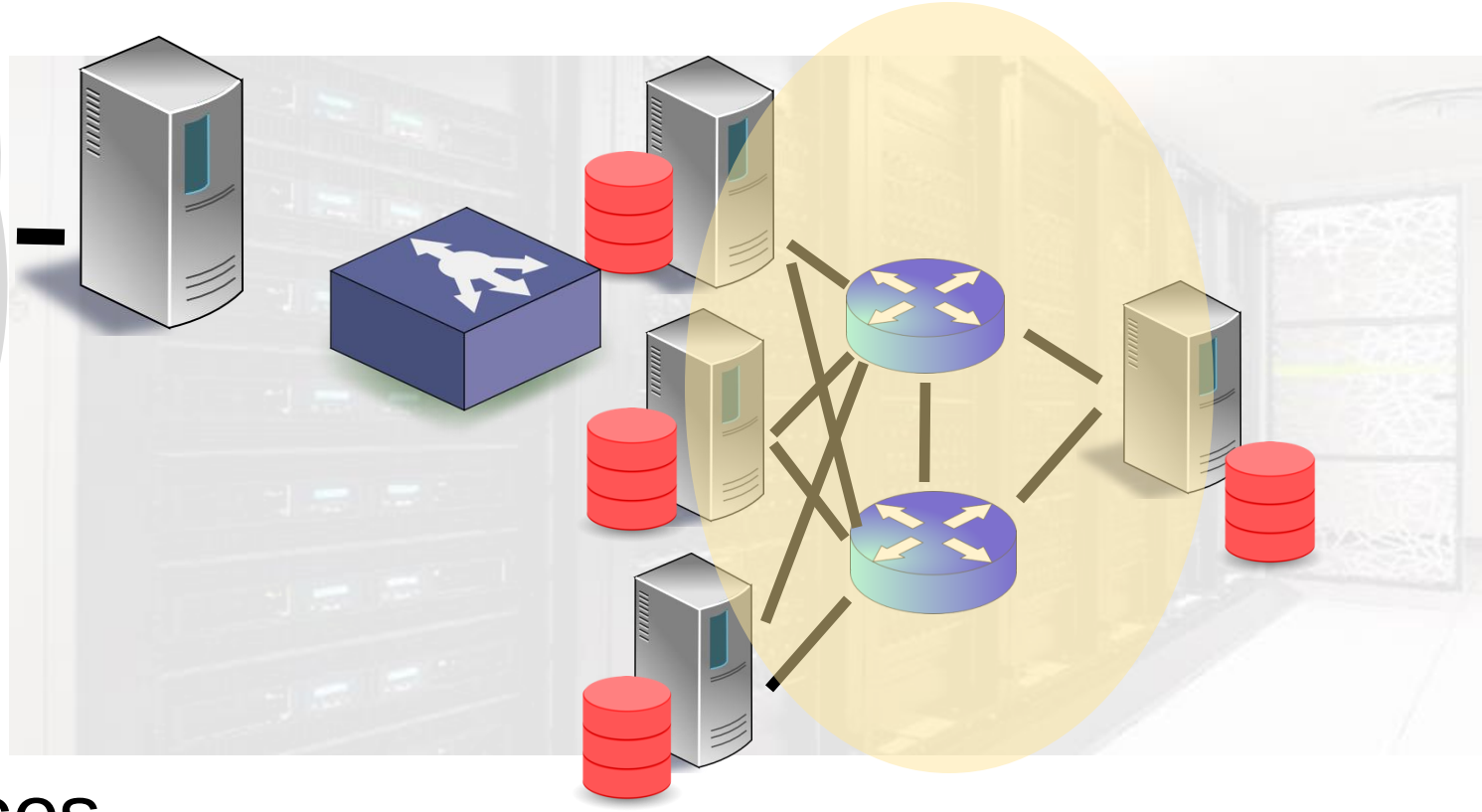
Distributed Systems in Internet Services





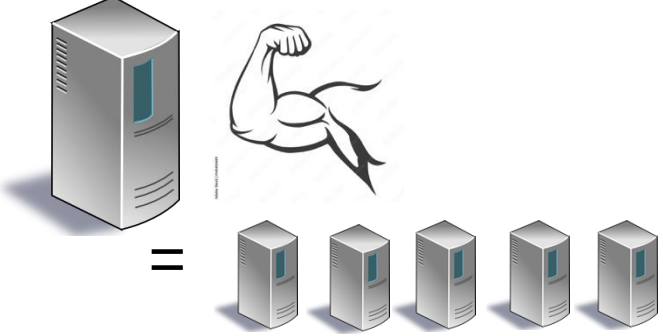
Coordination services

Distributed consensus

Distributed storage

Load management

Distribution & its consequences

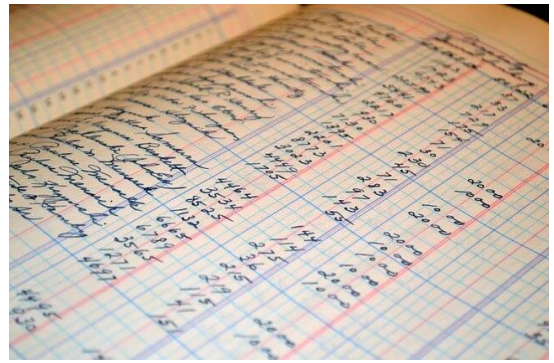


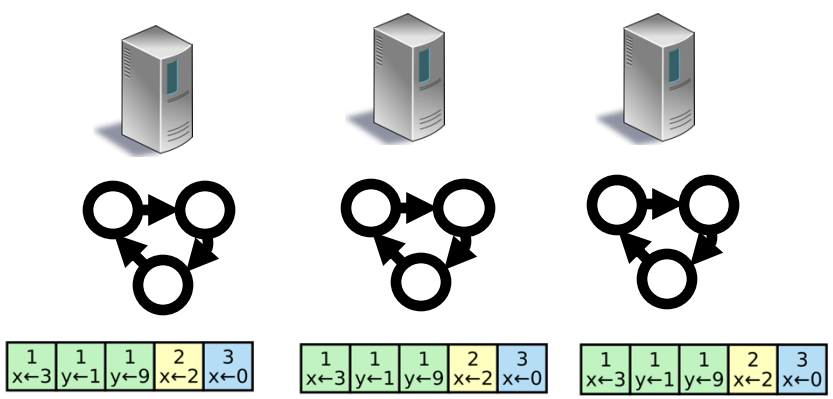
- Need replication to tackle machine failures and unavailability
- Q: How to make data consistent across replicas?
- Strong consistency: all reads (e.g., clients) return the same value
- Why not weaker consistency models? e.g., eventually consistent
  - Complex mental models: e.g., read, write, read
  - Some data is too critical to be out of sync, e.g., Kubernetes cluster state
  - Don’t sacrifice correctness at any point, e.g., financial systems
- CAP theorem:
  - (strong) consistency, availability, partition tolerance: pick 2
  - You really can’t choose CA in a practical system. Network partitions will happen; you must design systems to tolerate them
  - Result: give up either strong consistency or availability

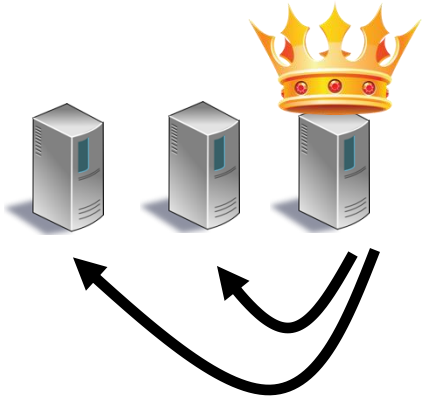
Agreement on (meta)data that is distributed: Consensus

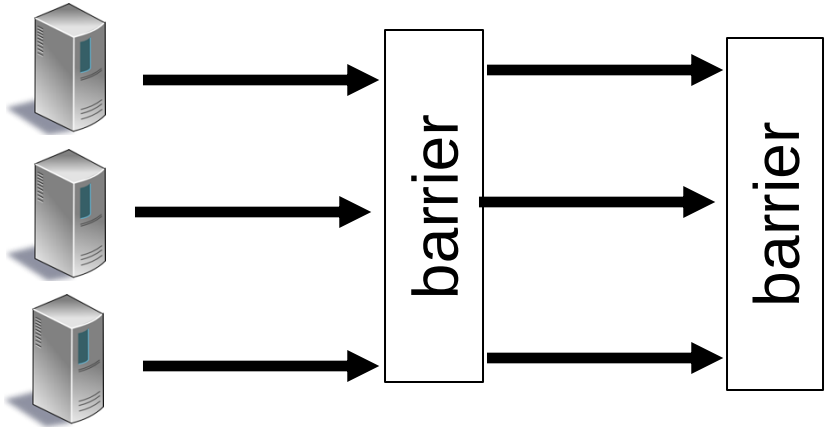
Primitives to build Distributed Systems

- Clients may contact any replica or a distinguished replica
- Replicated state machines
  - Replicated configuration and data stores (e.g., etcd)
- Leader election
- Distributed coordination & locking
  - e.g., barriers between different computation phases (workflow)
- Reliable distributed queueing and messaging



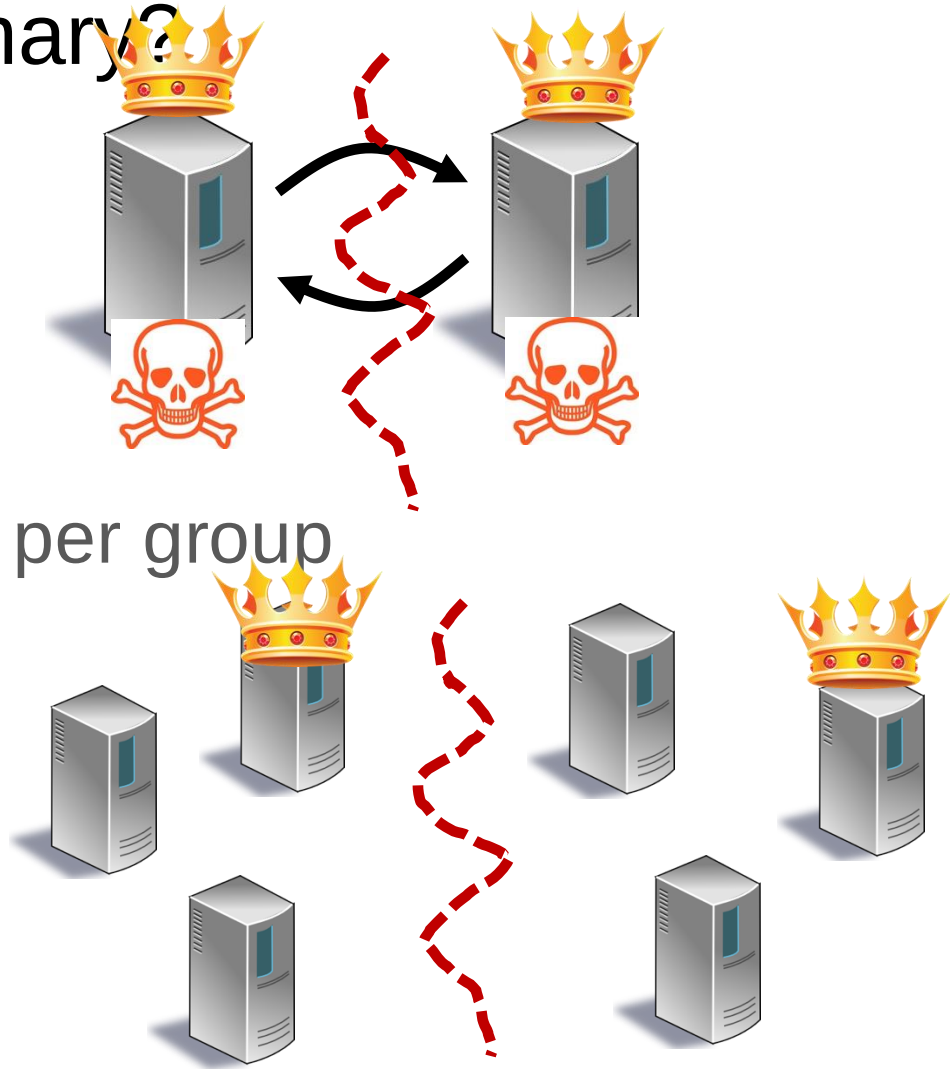






Simple solutions distributed consensus?

- Simple timeouts to determine a primary?
  - “Split brain” problem: data corruption
  - Data unavailable if conservative
- Problem amplified in clusters
  - Disagreement in group membership
  - Data corruption with separate leaders per group
- Network unavailability is common
  - Slow network
  - Some messages being dropped
  - Messages throttled in one direction

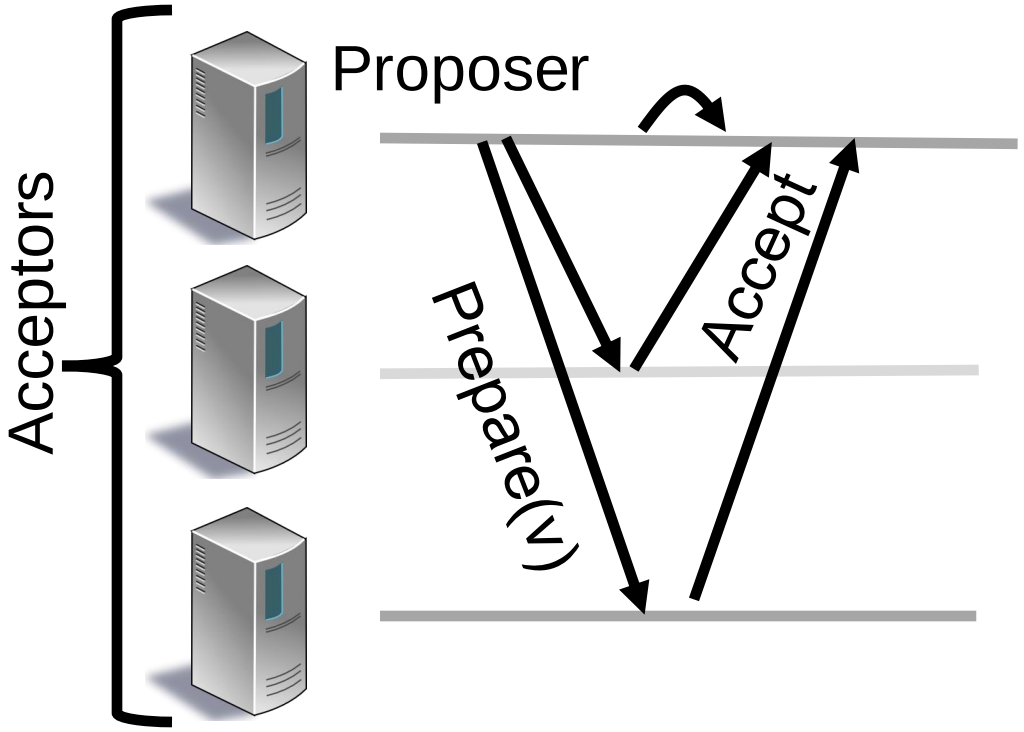


Setup: Agree on one value forever

- Suppose we have N = 2f + 1 nodes
- Want to agree on one value across the distributed system
- Assume no clock synchronization (clocks can drift)
- Asynchronous: the network can delay or drop messages
- Crash recovery
- Nodes execute correctly (not Byzantine)
- Assume a majority of the nodes can reach each other (quorum)
  - Agree on the same value even as nodes crash and recover
- `N = 2f + 1`
  - With f failures (unavailable), the rest is consistent and available

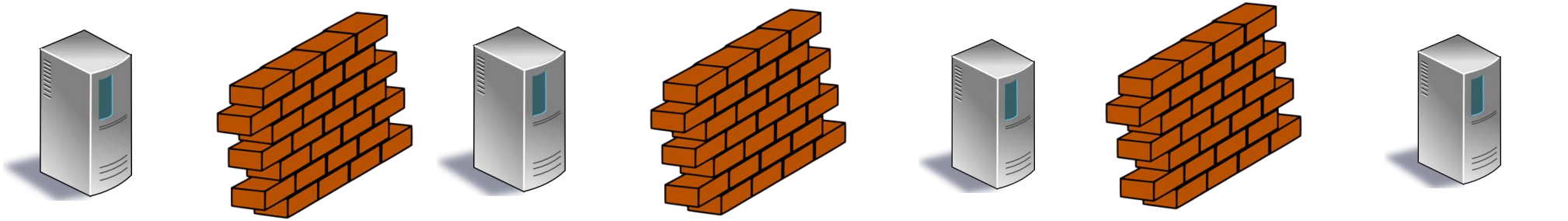
Simple Agreement: Prepare and Accept

- Single designated acceptor?
  - That acceptor node can fail
- Multiple acceptors?
  - If a majority accept, agreement!
- Problems?



Some problems

- Multiple proposers
  - Each proposer may propose different values
  - Each acceptor may hear multiple proposals
- Acceptors may disagree
  - Acceptors don’t know if other acceptors agreeing to the same proposal
- Acceptor may hear a different proposal after it accepted one
  - Should it keep its acceptance or change its mind?

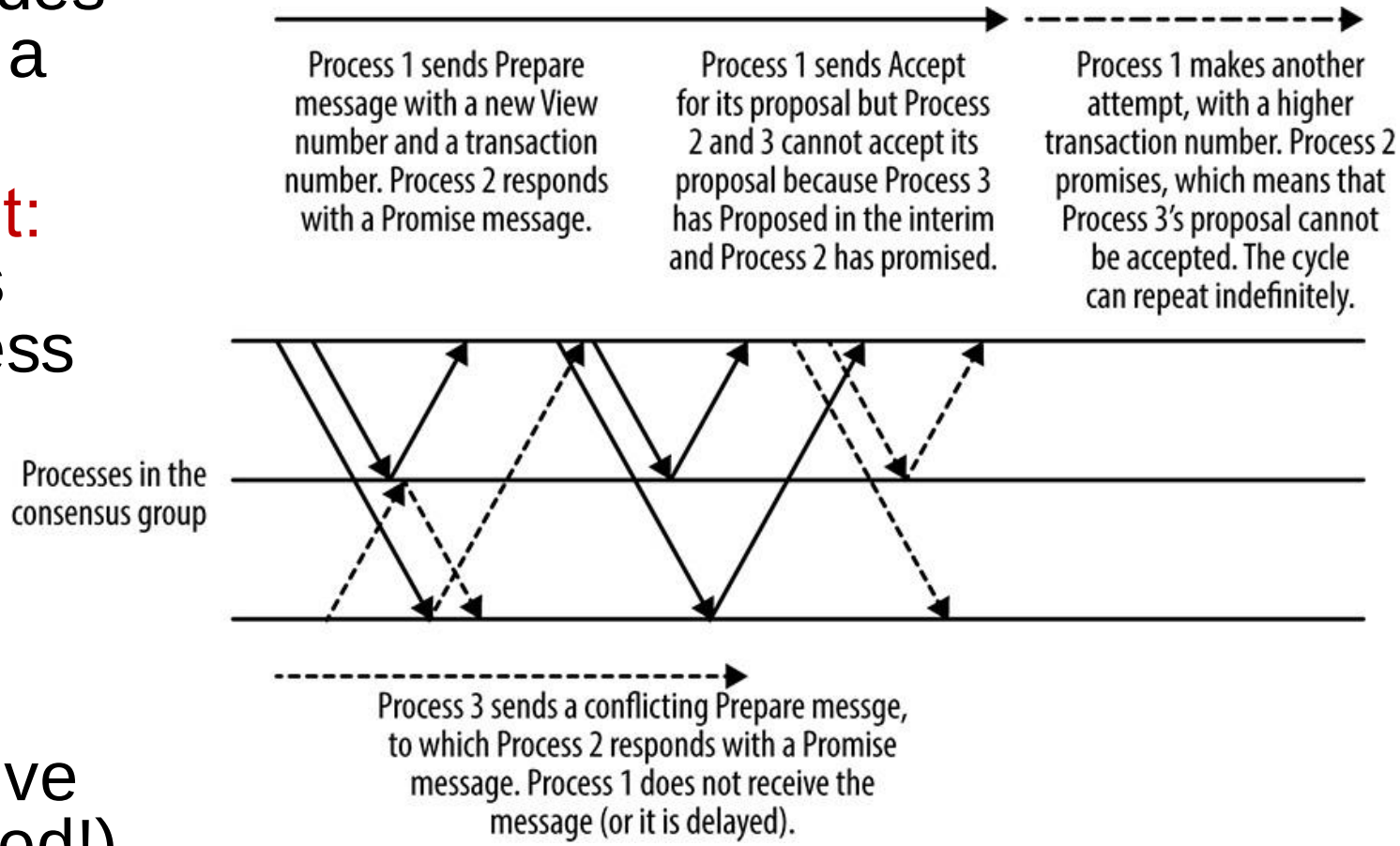


Properties we want: Safety

- If a majority of nodes have agreed on one value, that value cannot change in the future
- e.g., using a different majority or the same majority
- We call this value the chosen value

Properties we want: Liveness

- Liveness: majority of nodes must eventually choose a value
- FLP's impossibility result: Deterministic algorithms cannot guarantee liveness under arbitrary network asynchrony (delay and loss)
- Good news: Realistic networks are not that adversarial (practically live protocols can be designed!)



Basic Paxos (1/3)

- Simple operation: a single proposer and (pure) acceptors
- P1: If only one value were proposed, it must be chosen
  - An acceptor must accept the first proposal it receives
- If an acceptor fails, and two proposals were each accepted by roughly half the acceptors, the cluster cannot determine the chosen value
- Hence, want acceptors to be able to accept multiple proposals
  - Proposals include transaction numbers (n); assume unique & increasing
- P2: If a proposal with value v is chosen, every other chosen proposal must have the same value v
  - “Agree on **some** value, not necessarily **my** value”. P2 guarantees safety

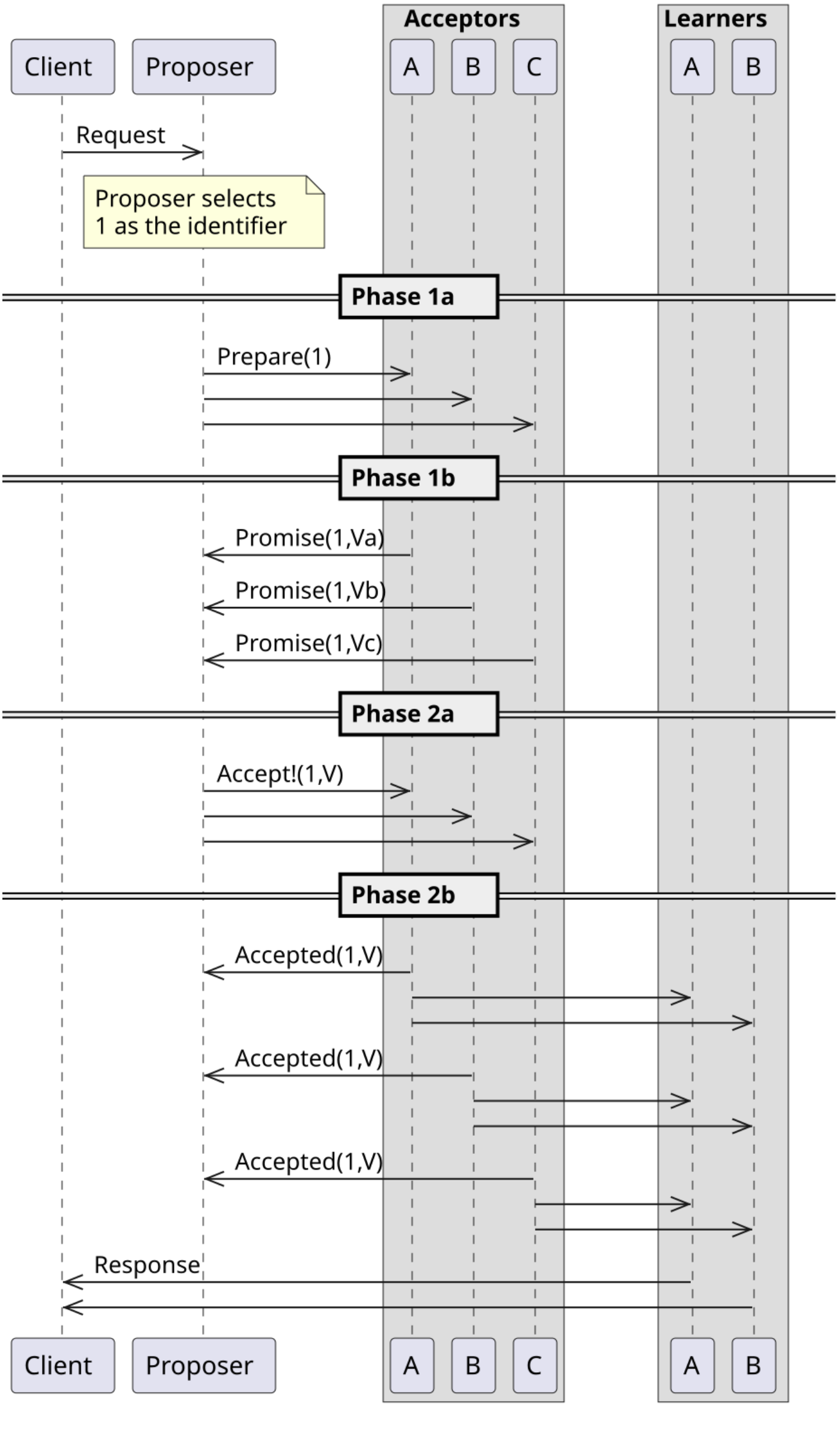
Basic Paxos (2/3)

- P2a: One way to satisfy P2 is for acceptors to only accept proposals with the same value v once v is chosen
- P2b: One way to satisfy P2a for proposers to only propose proposals with the same value v that was chosen earlier
- P2c: One way to satisfy P2b is for any proposer to ask a set of acceptors (at least a majority responding) which proposal # and values accepted so far
  - These are called promises

Basic Paxos (3/3)

- Acceptor agrees not to accept any proposal < n
- Proposer must use the value from the highest-numbered proposal accepted from the responses, or use its own value if no existing proposals were accepted
- Acceptor can only accept if not promised any proposal > n
- If a majority of acceptors promise, at least one acceptor must have responded with the chosen value and chosen proposal # (inductive argument)

- Subtle: Write information that must not be reneged into persistent storage (disk) for use after crash recovery


Acceptors
Learners
Client
Proposer
A
B
C
A
B
Request
Proposer selects
1 as the identifier
Phase 1a
Prepare(1)
Phase 1b
Promise(1,Va)
Promise(1,Vb)
Promise(1,Vc)
Phase 2a
Accept!(1,V)
Phase 2b
Accepted(1,V)
Accepted(1,V)
Accepted(1,V)
Response
Client
Proposer
A
B
C
A
B

Phase 1. (a) A proposer selects a proposal number n and sends a *prepare* request with number n to a majority of acceptors.

(b) If an acceptor receives a *prepare* request with number n greater than that of any *prepare* request to which it has already responded, then it responds to the request with a promise not to accept any more proposals numbered less than n and with the highest-numbered proposal (if any) that it has accepted.

Phase 2. (a) If the proposer receives a response to its *prepare* requests (numbered n) from a majority of acceptors, then it sends an *accept* request to each of those acceptors for a proposal numbered n with a value v, where v is the value of the highest-numbered proposal among the responses, or is any value if the responses reported no proposals.

(b) 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.

Learning the chosen value

- Read-only consensus: A majority of nodes must respond with a specific accepted value
  - e.g., a client sends a message to all nodes
- Read from a replica guaranteed to be up to date, e.g., leader
- Quorum leases: a set of nodes hold a time-bound lease on a value. Updates must be acknowledged by all of these machines (reduced write performance)

Implementing primitives atop Paxos

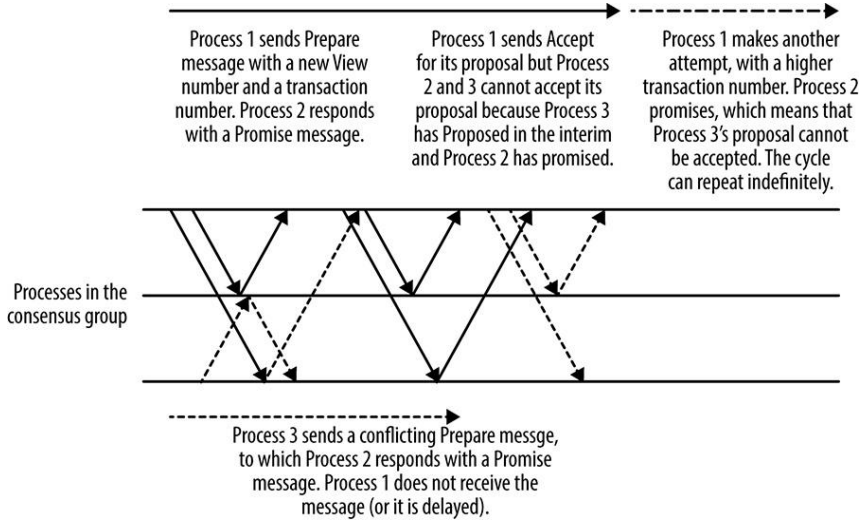
- Leader election: The chosen value is the leader

- Replicated State Machines:
  - Agree on each command through Paxos: one Paxos instance for each ”slot” in the ordered log of commands
  - Once all slots up to slot j chosen, can compute state up to log slot j
  - Locking, configuration store, etc. can be similarly implemented

Paxos does not guarantee liveness

- One solution: pre-determine or elect a distinguished leader

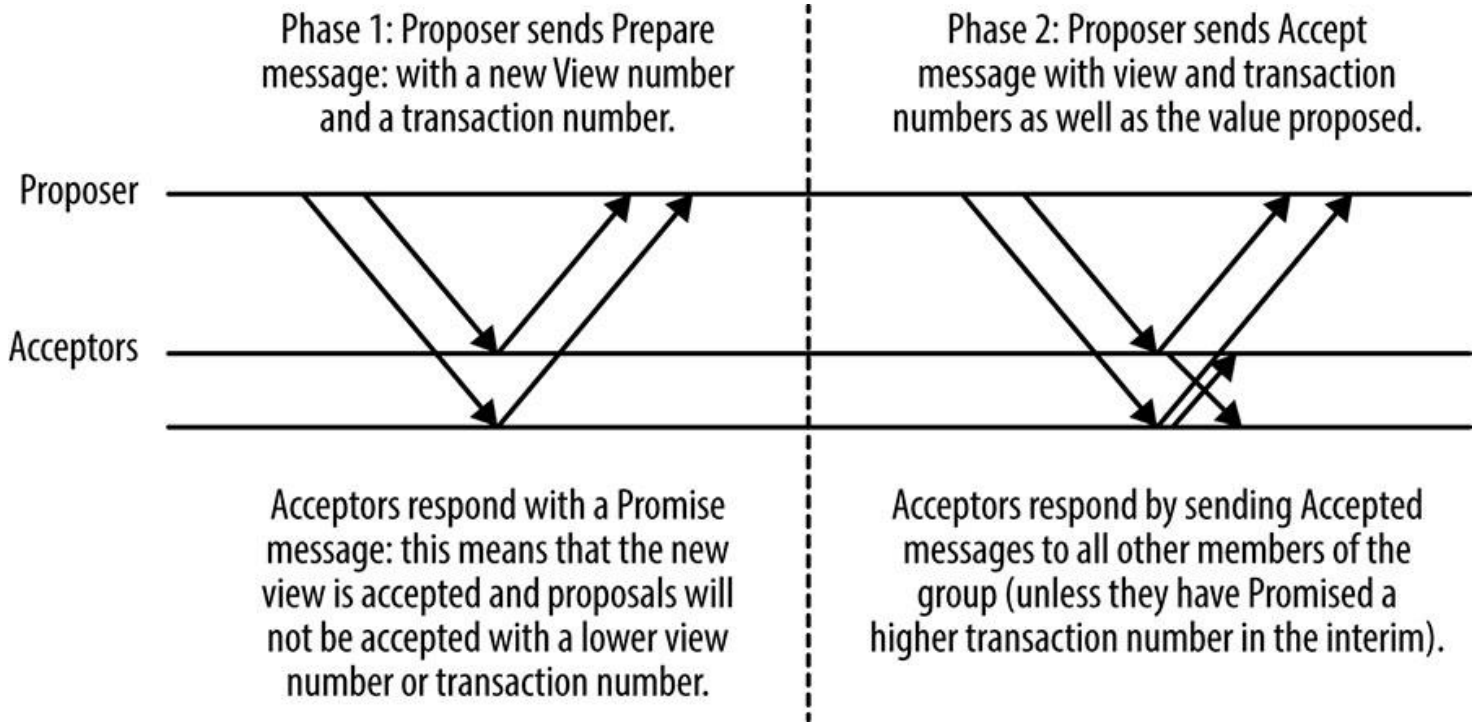
It's easy to construct a scenario in which two proposers each keep issuing a sequence of proposals with increasing numbers, none of which are ever chosen. Proposer p completes phase 1 for a proposal number n_1. Another proposer q then completes phase 1 for a proposal number $n_2 > n_1$. Proposer p's phase 2 *accept* requests for a proposal numbered n_1 are ignored because the acceptors have all promised not to accept any new proposal numbered less than n_2. So, proposer p then begins and completes phase 1 for a new proposal number $n_3 > n_2$, causing the second phase 2 *accept* requests of proposer q to be ignored. And so on.



Improvements and Considerations

- Agreeing on multiple values and ordering
- e.g., multi-paxos: Elect a distinguished node (leader)
- only execute phase 2 afterwards until failure

- Other protocols
  - Epaxos, Mencius, RAFT



Improvements and Considerations

- Disk latency vs. Network latency

- Uneven network latencies and choosing leaders