Distributed Consensus: Paxos

Rong Chen
Institute of Parallel and Distributed Systems
Shanghai Jiao Tong University
http://ipads.se.sjtu.edu.cn/rong_chen

Credits: some slides from Jinyang Li (NYU)

Concurrency so far

Atomicity and Concurrency Control

- All-or-nothing atomicity in transactions
  - **DO-REDO-UNDO** protocol
- Serializability of multiple transactions
  - **Two-phase Locking** (2PL)
  - **Snapshot Isolation** (SI)
- Multiple transactions in distributed systems
  - **Two-phase Commit** (2PC)

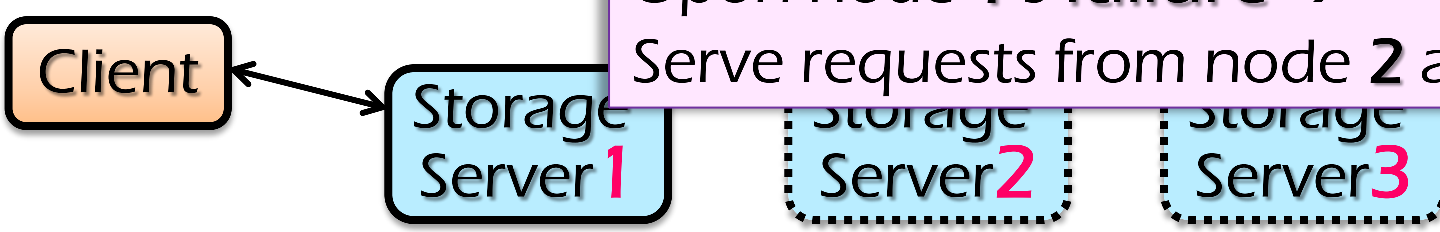
How about fault tolerance
in distributed systems?

Fault Tolerance: Replication

How to **recover** a single node from **failure**?

- Wait for **reboot**
  - Data is **durable**
  - Service is **unavailable** temporarily
- Use **multiple** nodes to provide **equivalent** service

Upon node **1**'s **failure** →
Serve requests from node **2** and **3**

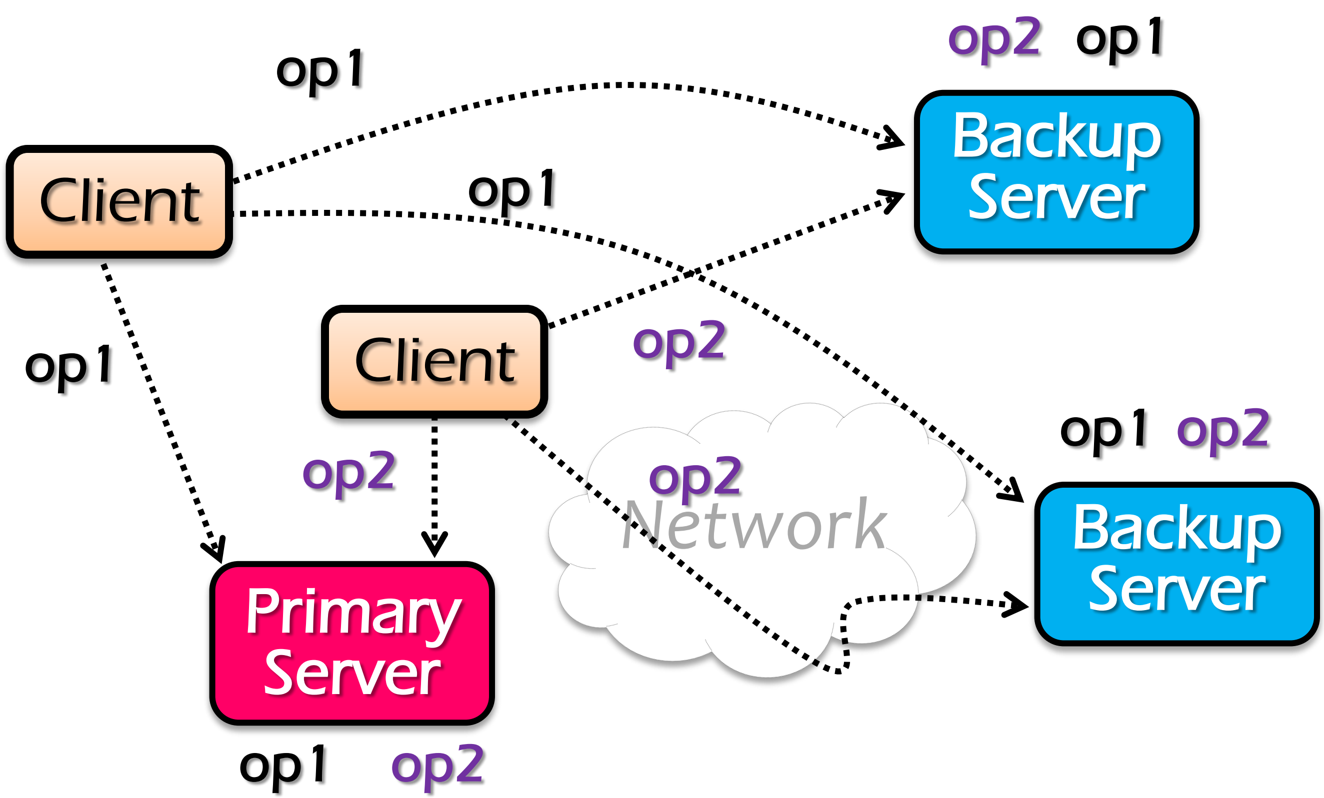


Challenge: ensure sequential consistency across such **reconfiguration**

RSM: Replicated State Machine

- RSM is a general **replication** method
  - e.g., apply RSM to lock service
- RSM rules
  - All replicas **start** in the same **initial** state
  - Each replica apply ops in the same **order**
  - All ops must be **deterministic**
  - All replicas **end** up in the same state

Strawman RSM

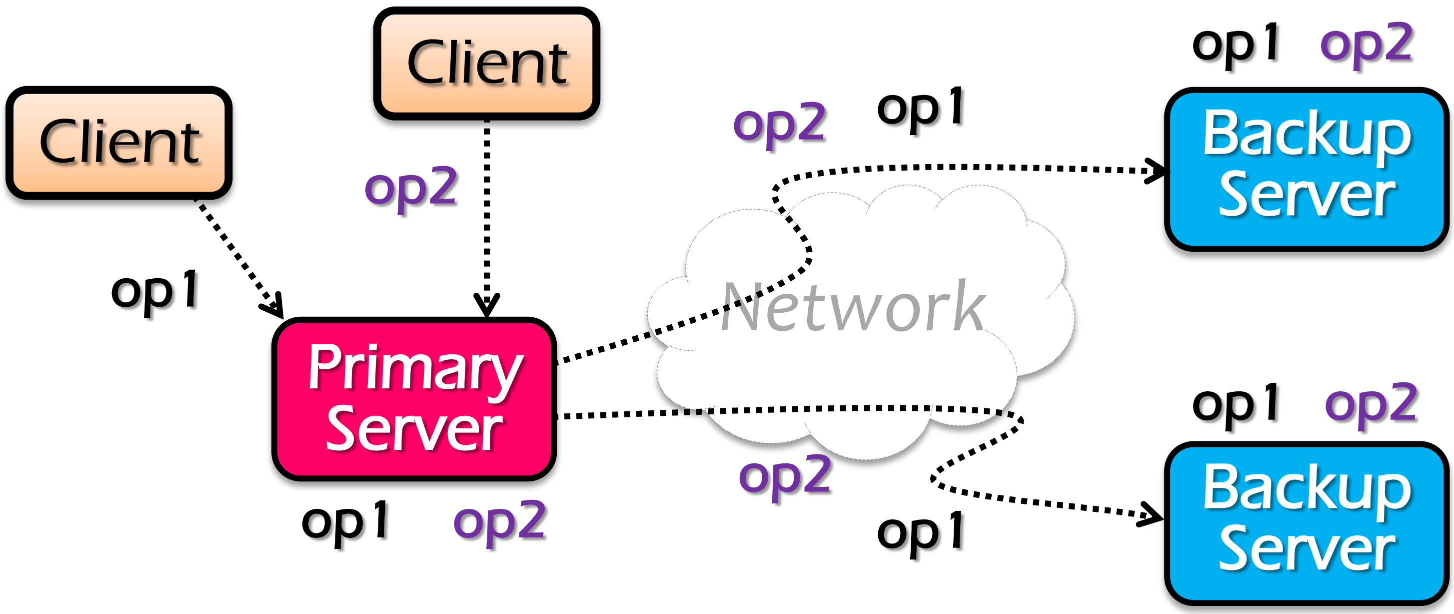


Does it ensure **sequential** consistency?

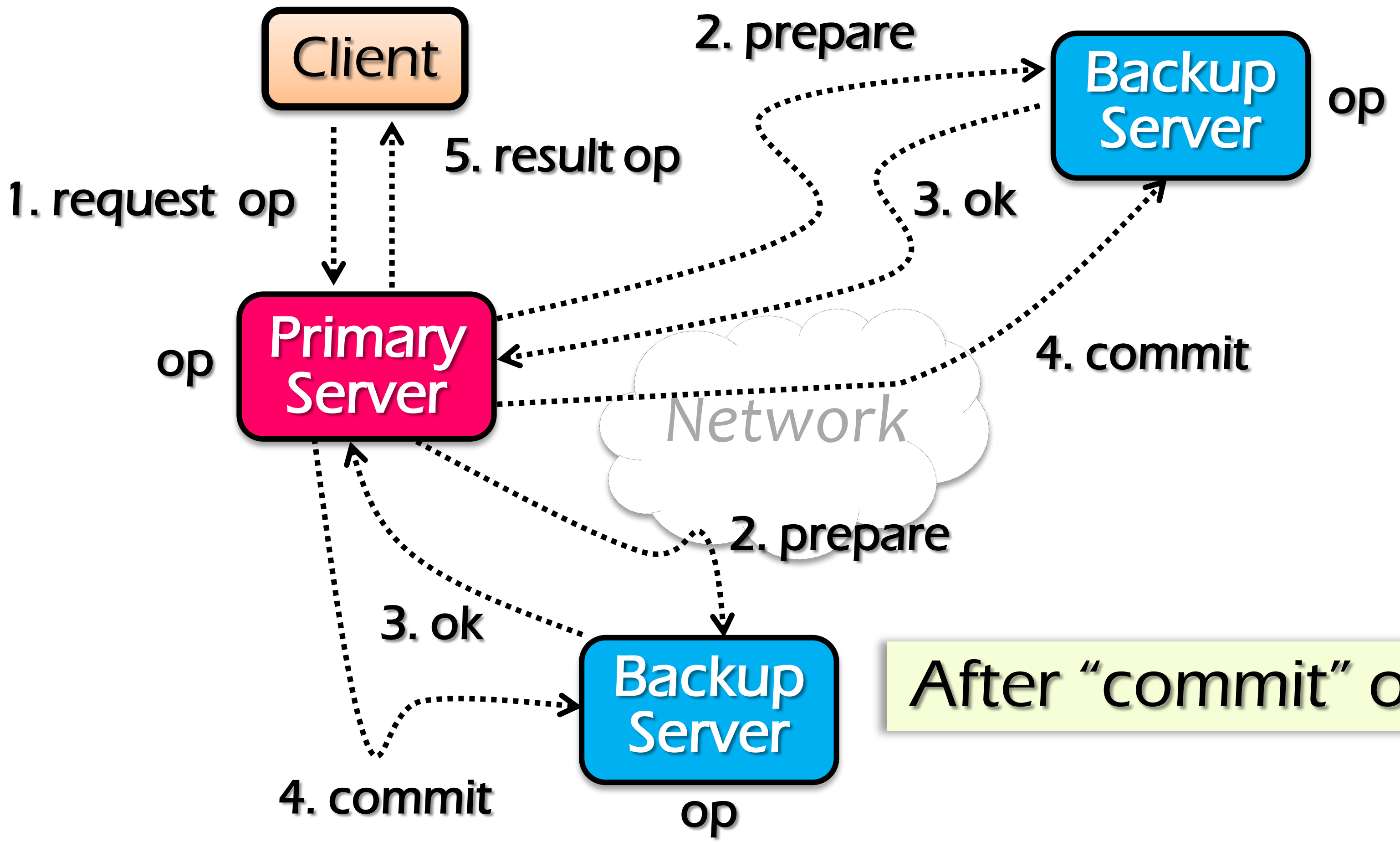
RSM based on Primary/Backup

Primary/Backup ensure a single order of ops

- Primary orders operations
- Backup execute operations in order

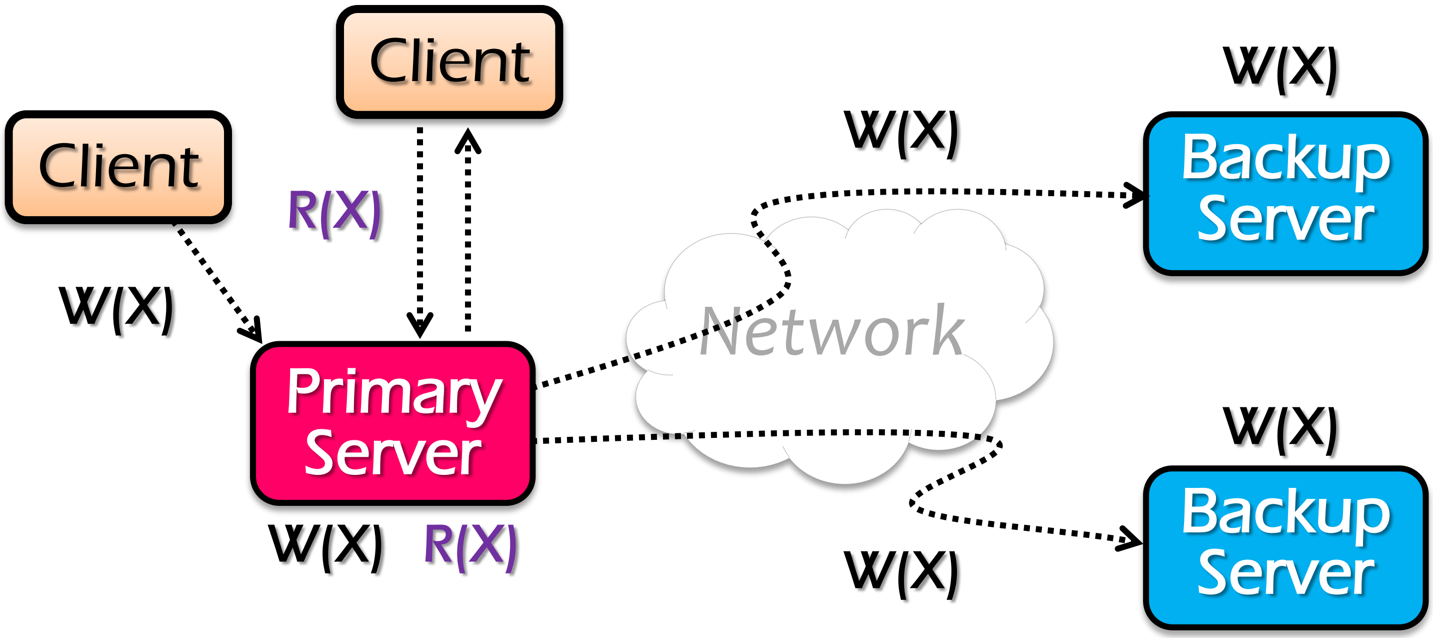


When does Primary Respond?



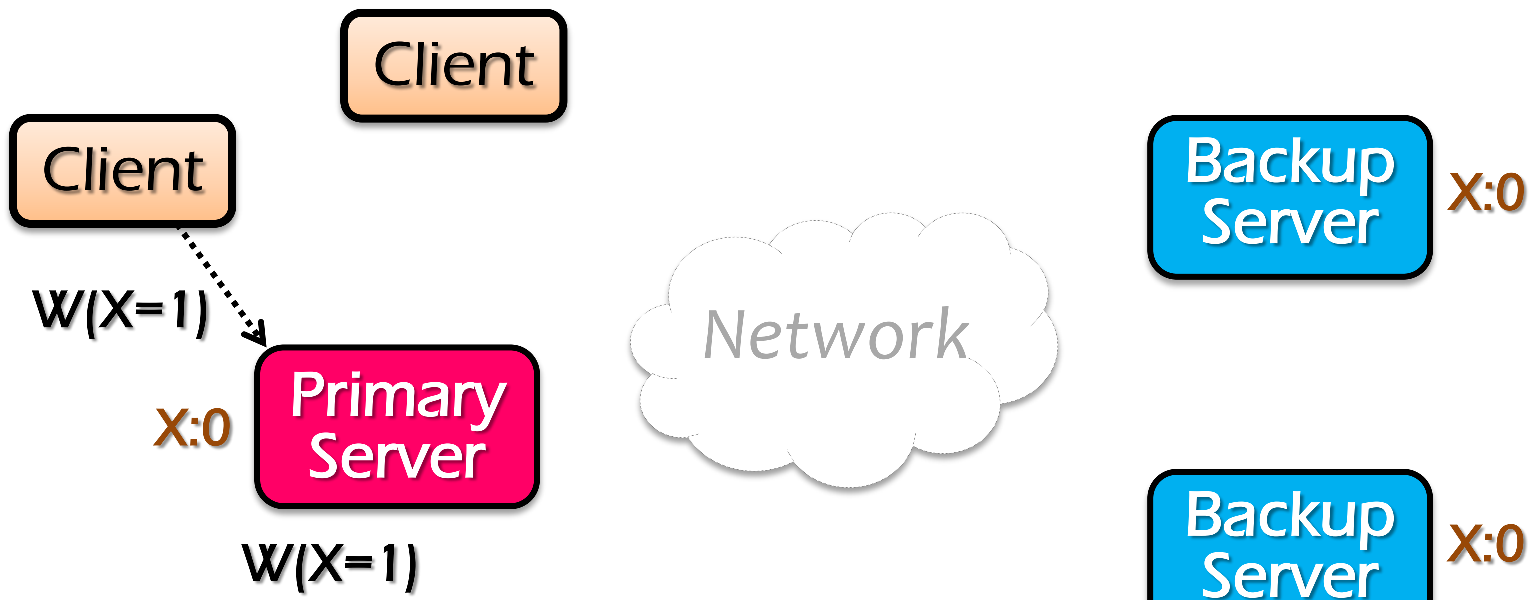
After "commit" of 2PC

RSM: Read-only Operations



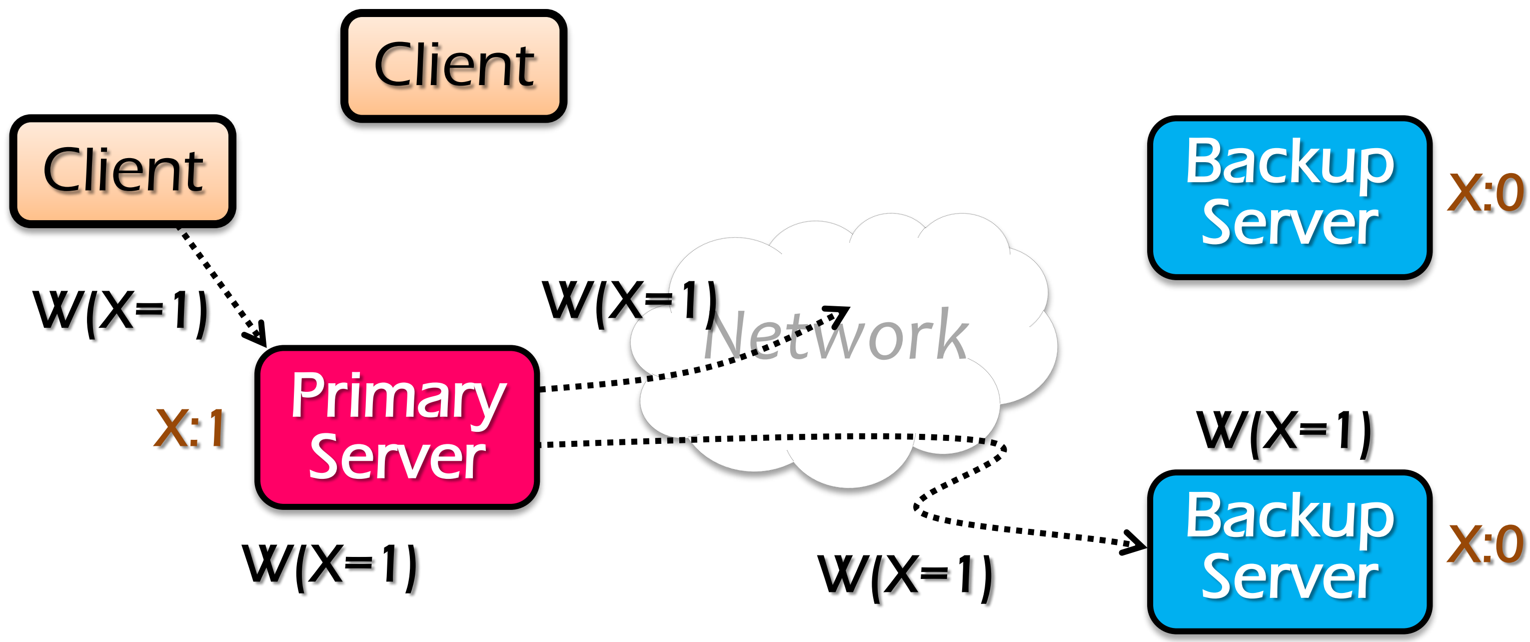
Read-only ops need not be **replicated**

RSM: Read-only Operations



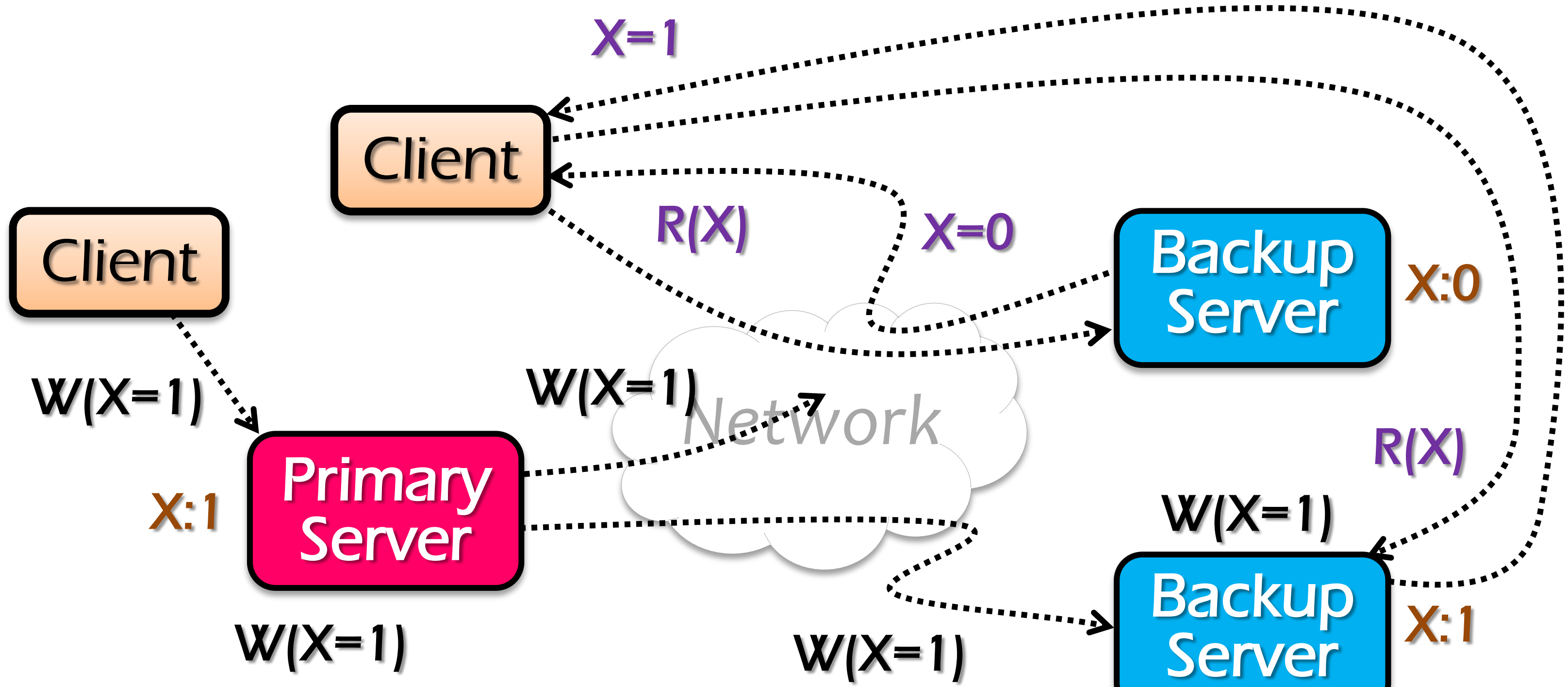
Can client send **read-only** ops to **any** server?

RSM: Read-only Operations



Can client send **read-only** ops to **any** server?

RSM: Read-only Operations



Can client send **read-only** ops to **any** server?

RSM: Failure Handling

If **primary** fails, one **backup** acts as the **new** primary

Challenges

1. How to reliably **detect** primary **failure**?
2. How to ensure no **two** backups simultaneously become new **primary**?
3. How to preserve sequential **consistency** across primary **changes**?

A fault tolerant distributed **consensus** protocol

Consensus

Allow a group of nodes to **agree** on a result

- All nodes must agree on the **same** value
- The value must be one that was **proposed** by **at least** one node (can't just make up a value)

Achieving **consensus** is **easy**!

- A system-wide coordinator determines outcome

BUT ... this ASSUMES there are **no failures**
... or we are willing to wait **indefinitely** for recovery

e.g., two-phase commit protocol → indefinite wait

Consensus Goal

Create an algorithm that does not **block** if a **majority** of processes are working

Goal: agree on **one** result among a group of participants

- Nodes may **fail** (may need stable storage)
- Messages: **lost**, **out of order**, or **duplicated**
- If delivered, messages are not **corrupted**

The algorithm needs (**2P**+**1**) nodes survive the **simultaneous** failures of **P** nodes

Paxos

Paxos: fault-tolerant distributed consensus algorithm (the **only known**)

- All nodes agree on the same value despite node failure, network failure and delays

Extremely useful

- *e.g.*, Nodes agree that X is the primary
- *e.g.*, Nodes agree that OP1 should be the most recent operation executed

Requirements of Consensus

Correctness (safety)

- All nodes agree on the **same** value
- The **agreed** value X has been **proposed** by some node

Fault-tolerance

- If **minority** of nodes **fail**
  → the **rest** should still reach **agreement**

Termination

Impossibility of Consensus

There is no way to check whether a process **failed** or is **alive** but not communicating

It is **impossible** for a set of processors in an **asynchronous** system to agree on a binary value, even if only a **single** processor is subject to an unannounced **failure**.

– Fischer-Lynch-Paterson (FLP'85)

Synchronous vs. **Asynchronous** system

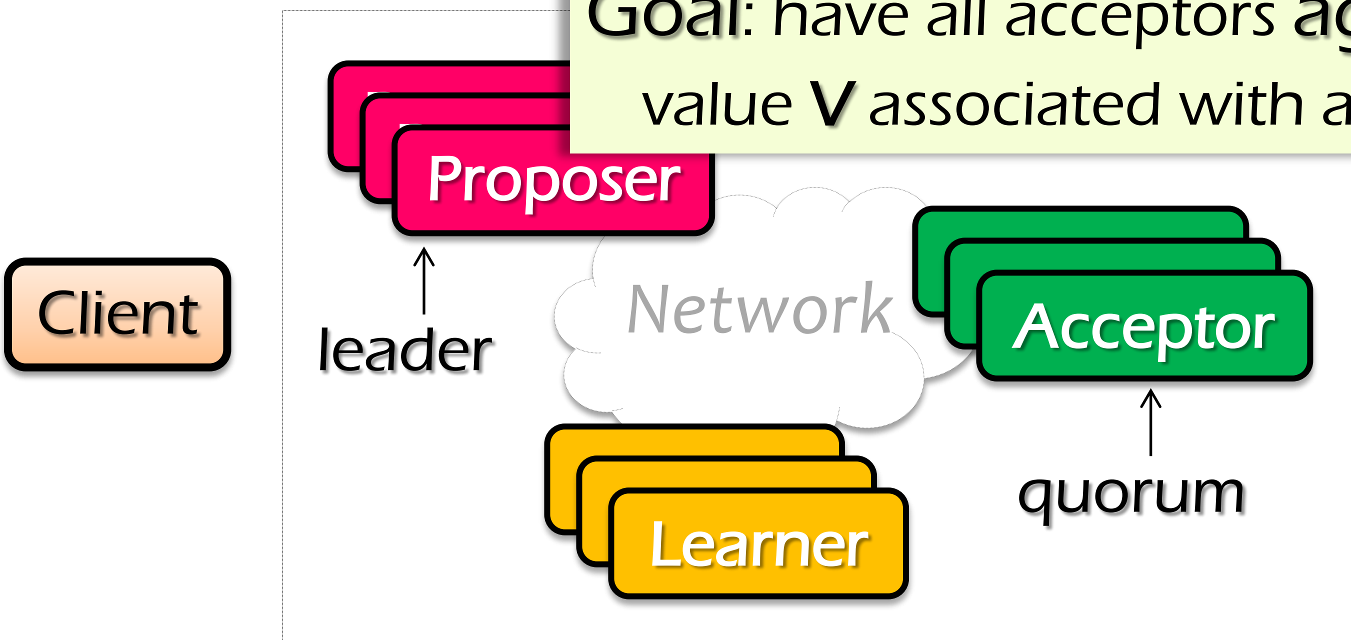
- Sync = responds to a message in a **bounded** time
- *e.g.*, serial port transmission

Paxos

Paxos' properties: correct + fault-tolerance

- *No guaranteed* termination

Goal: have all acceptors **agree** to a value **V** associated with a **proposal**



Paxos: one machine may serve several roles

Paxos Players

Client	makes a request
Proposer	Get a request and run the protocol **Leader** = elected Coordinator
Acceptor	Remember the state of the protocol **Quorum** = any majority of Acceptors
Learner	When agreement has been reached, a Learner executes the request and/or sends a response back to the Client

General Approach

One **proposer** decides to be the **leader**

Leader proposes a value and solicits acceptance from **acceptors** (majority)

Leader announces result or try again

What if >1 **proposers** become **leaders** simultaneously?

What if there is a **network partition**?

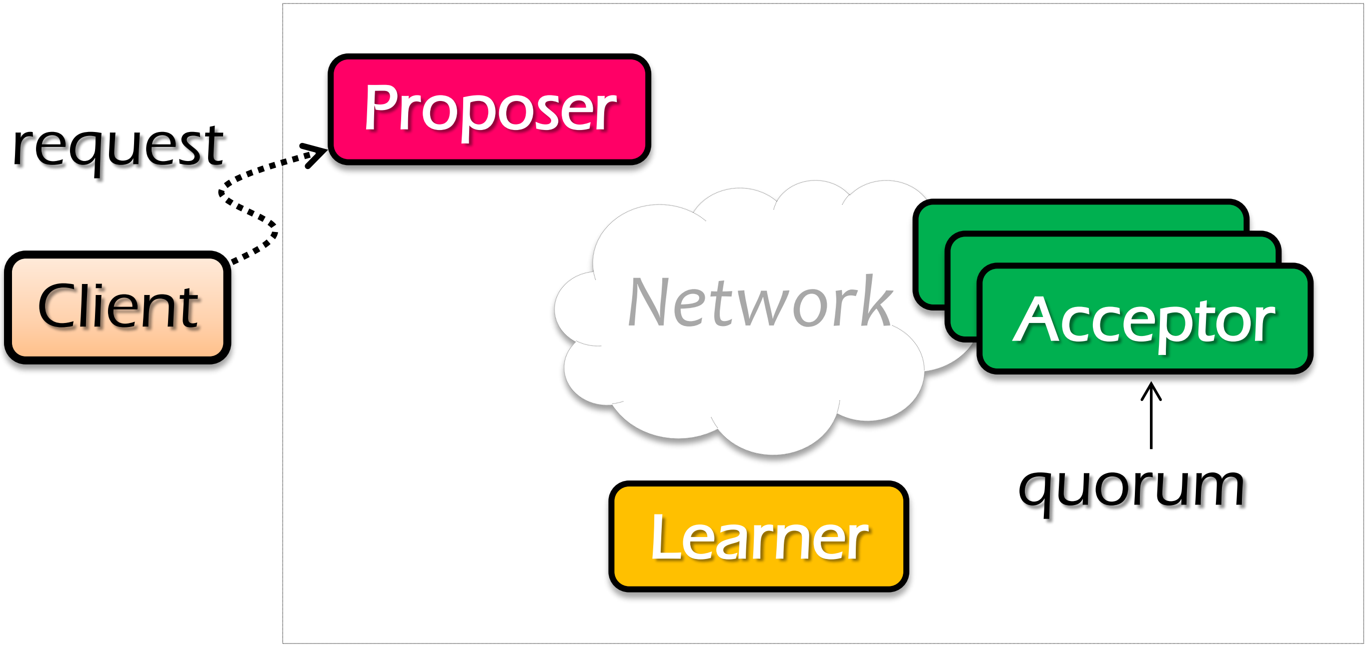
What if a leader **crashes** in the middle of solicitation?

What if a leader **crashes** after **deciding** but before **announcing** results?

. . .

Paxos in Action: Phase 0

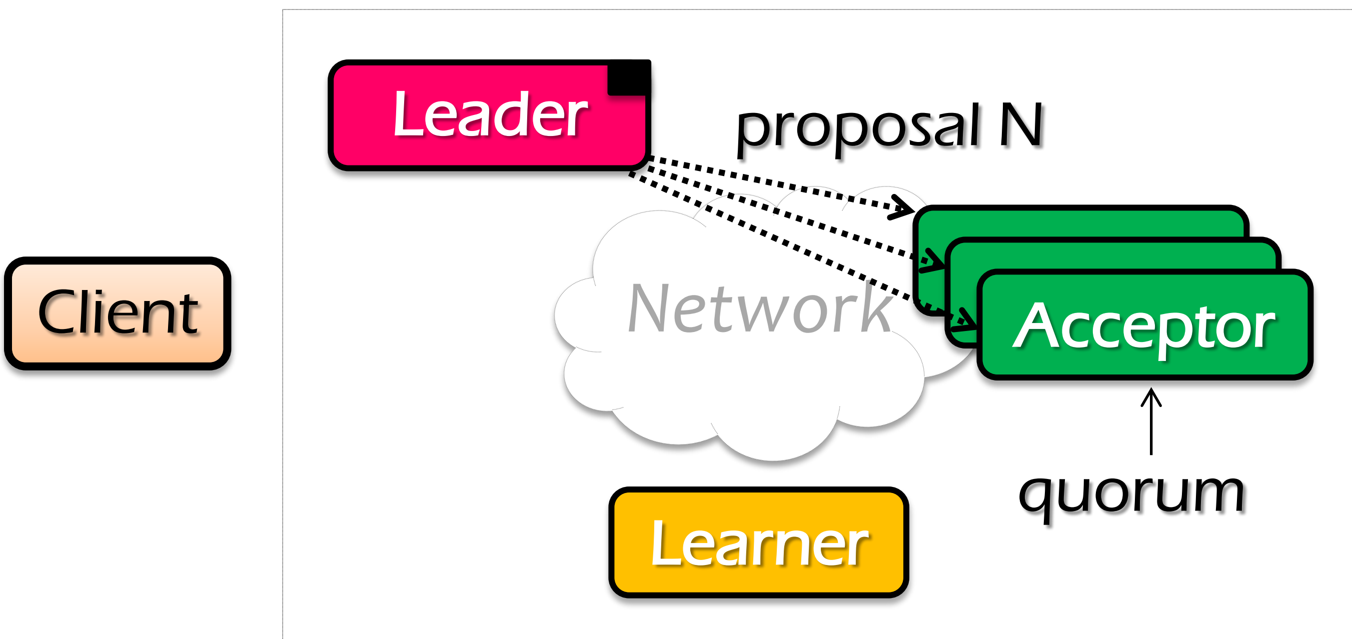
Client sends a request to a proposer



Paxos in Action: Phase 1a

Leader creates a proposal N and send to quorum

N is greater than **any** previous proposal number used by this proposer

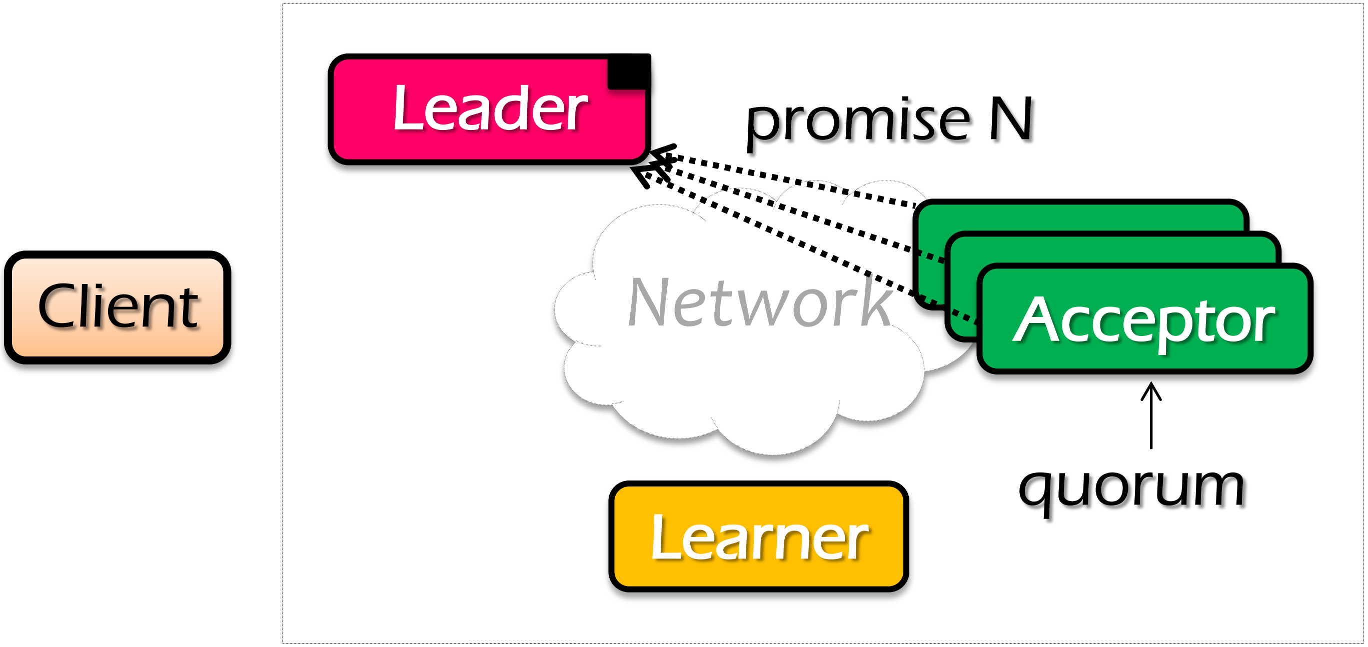


Paxos in Action: Phase 1b

Acceptor: **if** proposal ID > any previous proposal

1. reply with highest past proposal # and value
2. promise to ignore all IDs < N

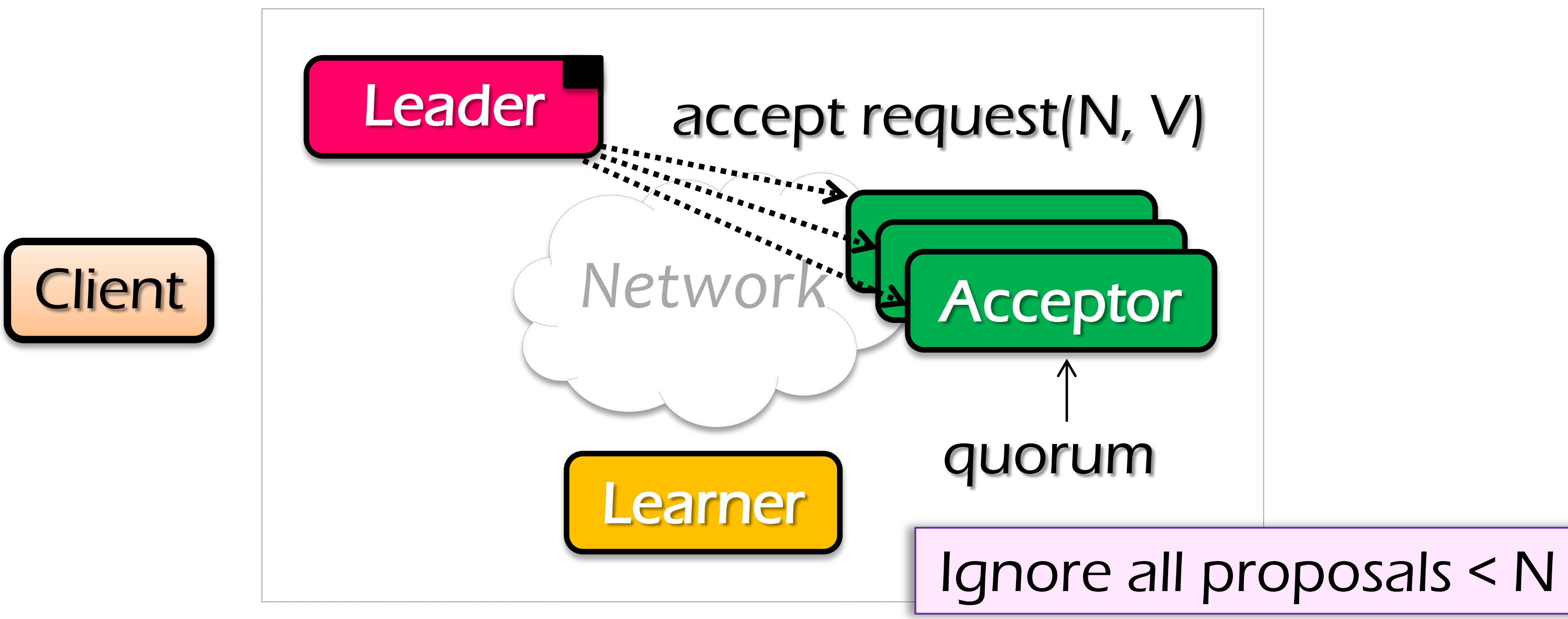
else ignore (proposal is rejected)



Paxos in Action: Phase 2a

Leader: **if** receive enough promise

1. set a value V to the proposal.
   V can be decided value or new value
2. send accept request to quorum with the chosen value V



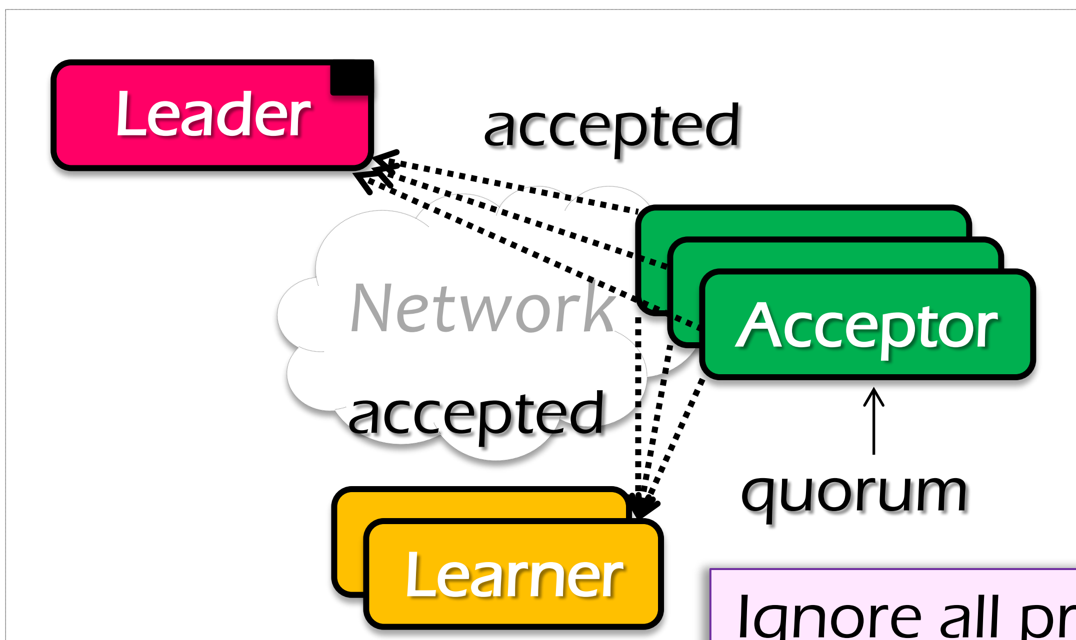
Paxos in Action: Phase 2b

Acceptor: **if** the promise still holds

1. register the value V
2. send accepted message to Proposer/Learners

else ignore the message

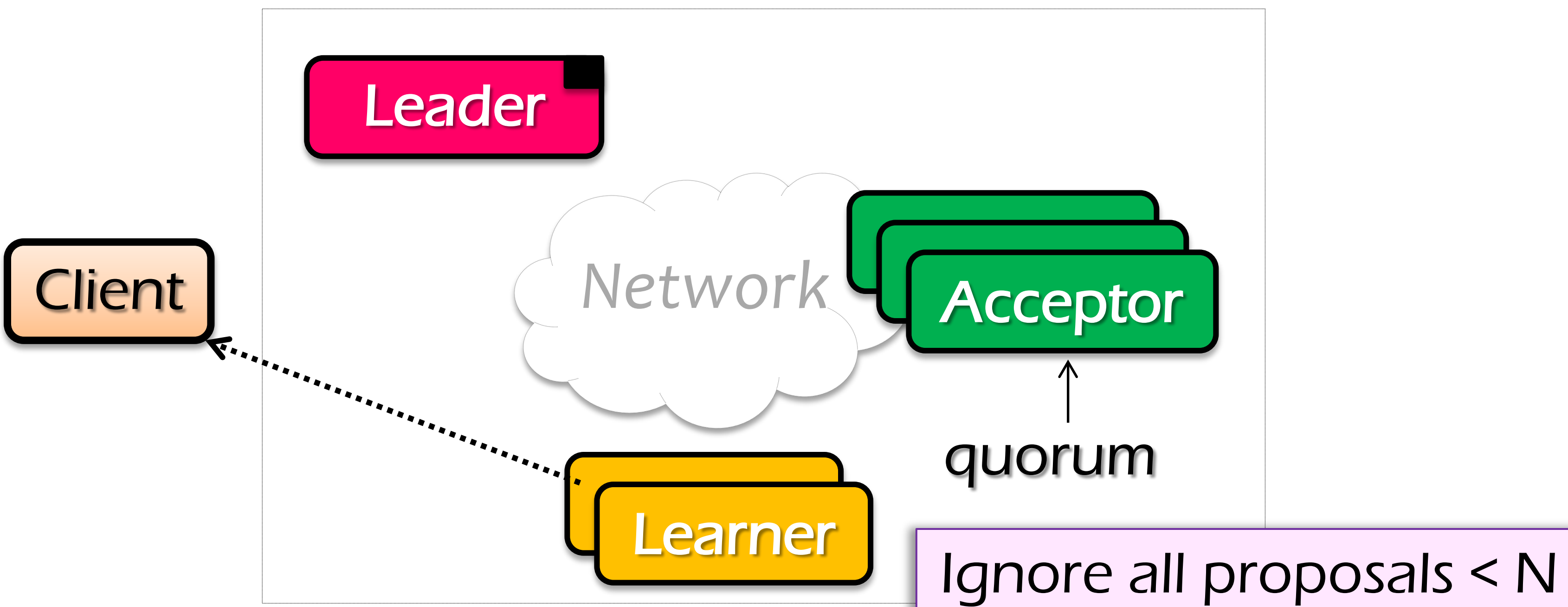
Client



Ignore all proposals < N

Paxos in Action: Phase 3

Learner: responds to Client and/or take action on the request



Paxos Setup

N_a: highest proposal # accepted
V_a: accepted value of **N_a**
N_h: highest proposal # seen
M_n: my proposal #

each round of Paxos, each Node

Paxos Pseudo-code

A node decides to be **Leader**

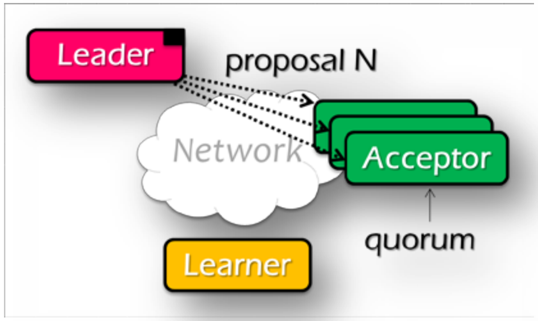
Leader choose $\mathbf{M_n > N_h}$

Leader sends <proposal, $\mathbf{M_n}$> to all nodes

Acceptor receives <proposal, **N**>

if $\mathbf{N < N_h}$
    reply <promise-reject>
else
    $\mathbf{N_h = N}$
    reply <promise-ok, $\mathbf{N_a}$, $\mathbf{V_a}$>

Ignore all proposals $< N_h$



Paxos Pseudo-code

If Leader gets promise-ok from a majority

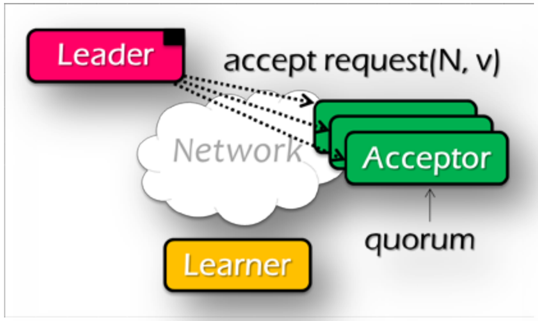
> **V** = non-empty value (highest $\mathbf{N_a}$ received)
> **if V = null**, then Leader can pick any **V**
> send <accept, $\mathbf{M_n}$, **V**> to all nodes

If Leader fails to get majority promise-ok

> delay and restart Paxos

Upon receiving <accept, **N**, **V**>

> **if $\mathbf{N < N_h}$**
> reply <accept-reject>
> **else**
> $\mathbf{N_a = N}$; $\mathbf{V_a = V}$; $\mathbf{N_h = N}$;
> reply <accept-ok>



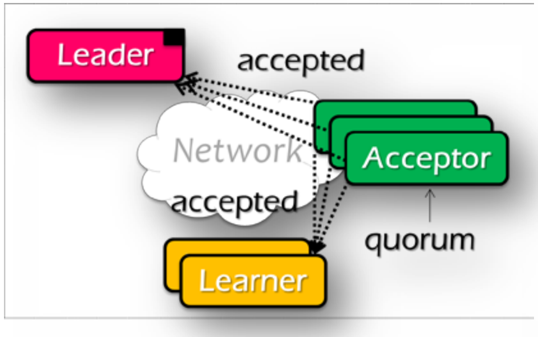
Paxos Pseudo-code

If Leader gets accept-ok from a majority

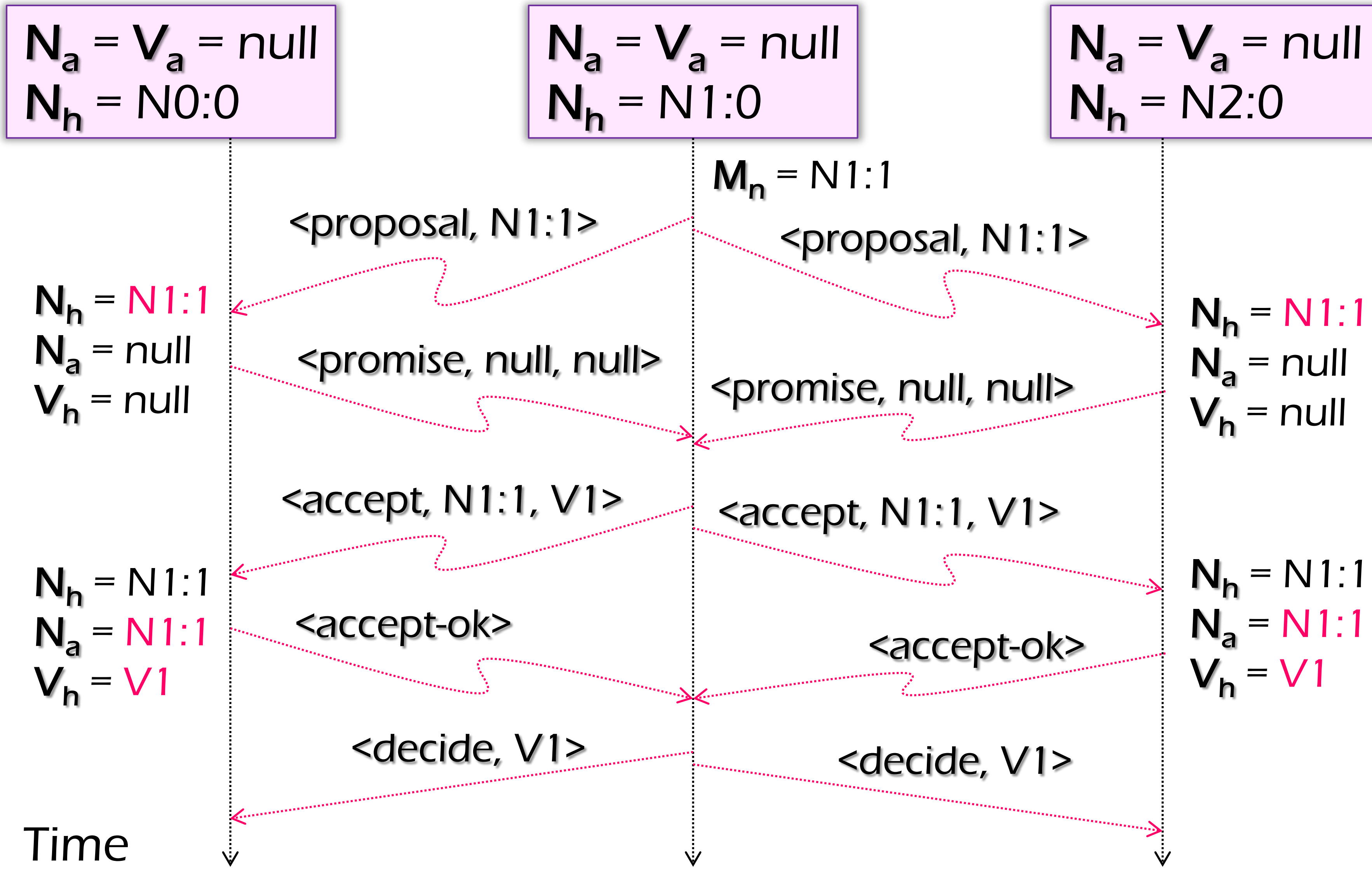
    send <decide, V_a> to all nodes

If Leader fails to get majority accept-ok

    delay and restart Paxos



Paxos Pseudo-code



Inside of Paxos

- Why setups multiple acceptors?
  - Failure of the single acceptor halts decision
- Why not accepts the first proposal and rejects the rest?
  - Multiple leaders result in no majority accepting
  - Leader dies
- What if more than one leader is active?
  - Can both leaders see a majority of promises?
  - Then ... ?

Inside of Paxos

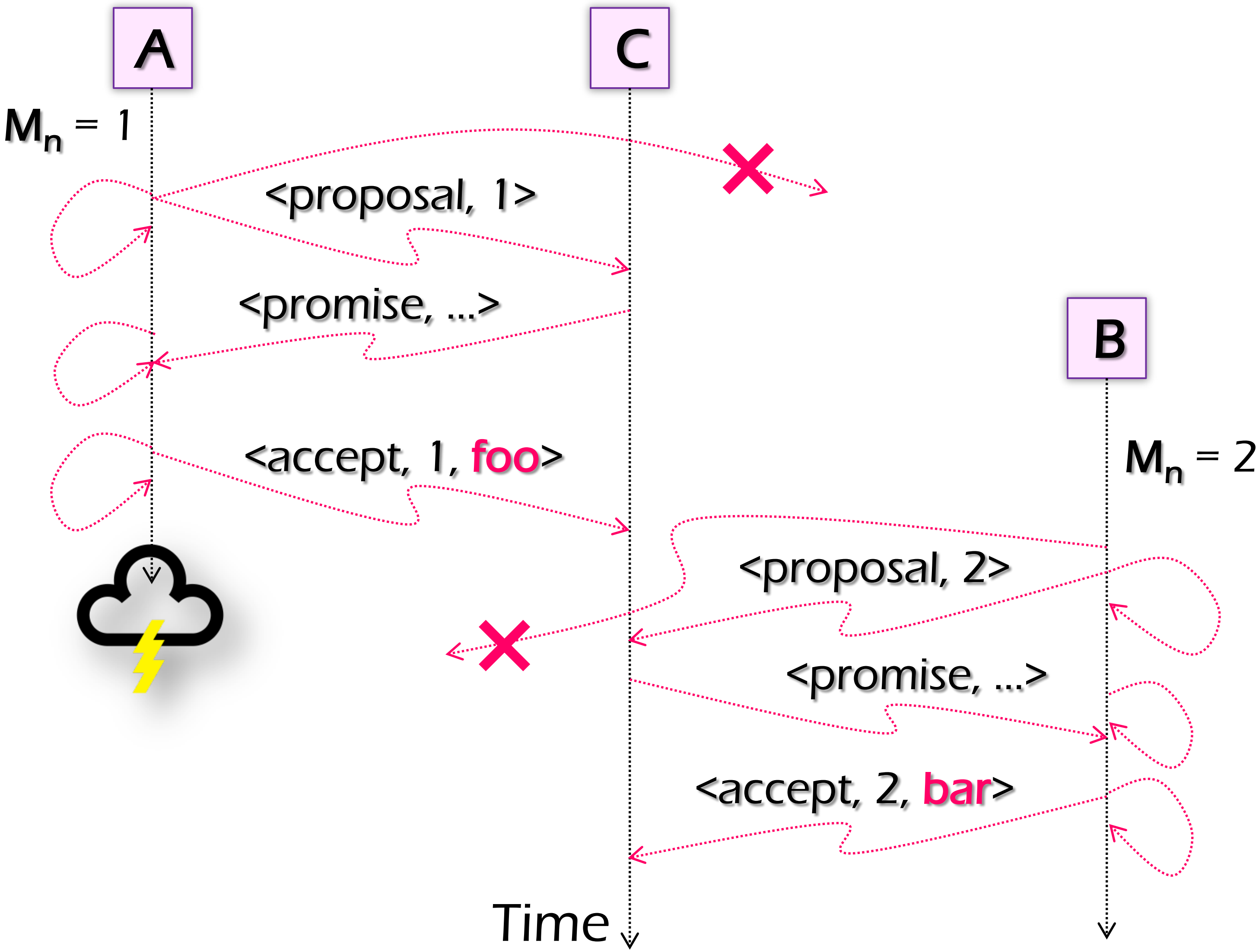
- When is the value V chosen?
  - Leader receives a majority <promise, ...>
  - A majority acceptors receive <accept, N, V>
  - Leader receives a majority <accepted, ...>
- What if acceptor fails after sending promise?
  - Must remember $\mathbf{N_h}$
- What if acceptor fails after receiving accept?
  - Must remember $\mathbf{N_h}$ and $\mathbf{N_a}$ $\mathbf{V_a}$
- What if leader fails while sending accept?
  - Propose $\mathbf{M_n}$ again

Question

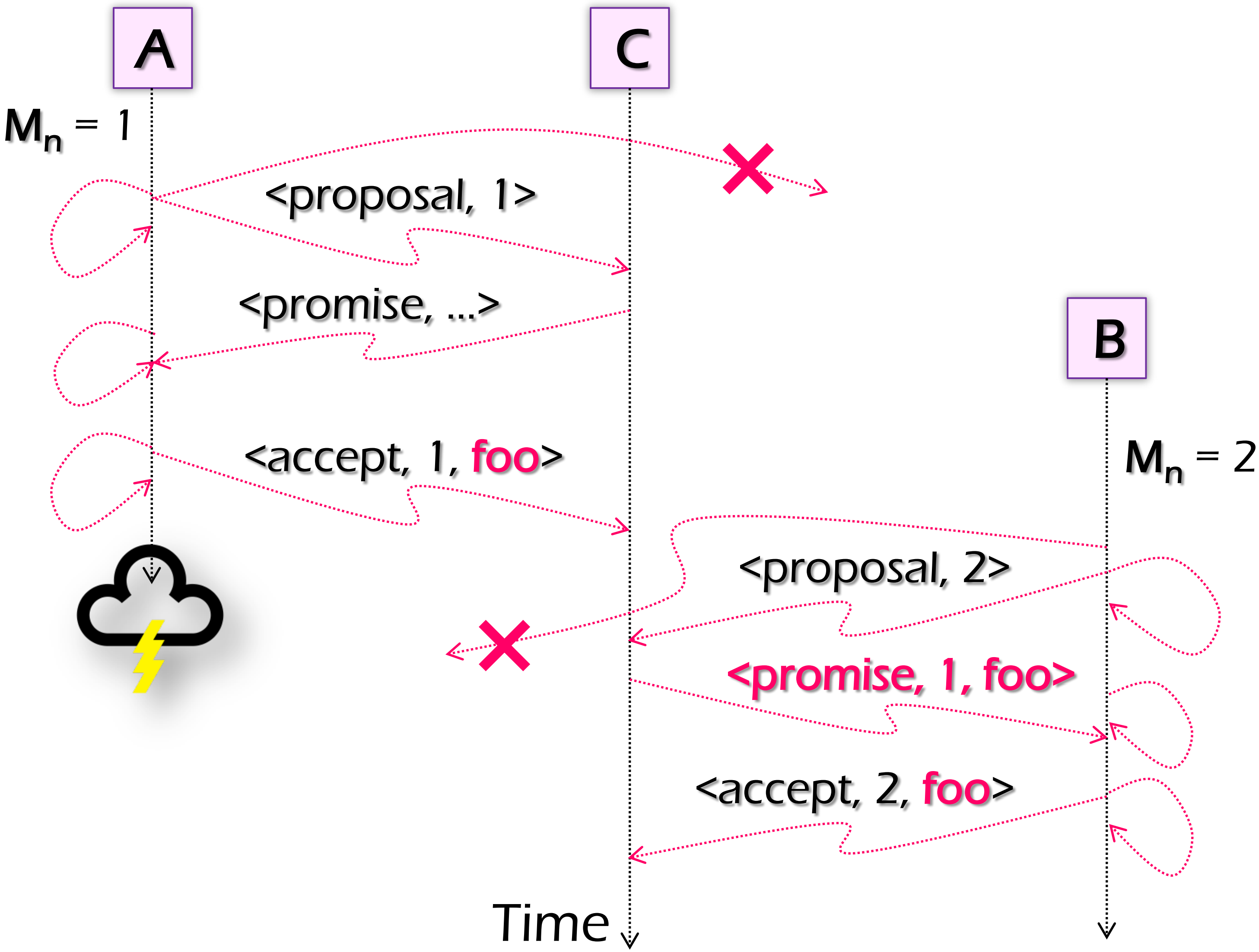
Suppose that the acceptors are A, B, and C. A and B are also proposers. How does Paxos ensure that the following sequence of events can't happen? What actually happens, and which value is ultimately chosen?

- A sends **<prepare, 1>** requests with proposal number **1**, and gets responses from A, B, and C
- A sends **<accept,1, "foo">** to A and C and gets responses from both. Because a majority accepted, A thinks that **"foo"** has been chosen. However, A crashes before sending an **<accept, 1, "foo">** to B
- B sends **<prepare, 2>** messages with proposal number **2**, and gets responses from B and C
- B sends **<accept, 2, "bar">** messages to B and C and gets responses from both, so B thinks that **"bar"** has been chosen

Question


A
C
B
M_n = 1
<proposal, 1>
<promise, ...>
<accept, 1, foo>
M_n = 2
<proposal, 2>
<promise, ...>
<accept, 2, bar>
Time

Question


A
C
B
$M_n = 1$
<proposal, 1>
<promise, ...>
<accept, 1, foo>
$M_n = 2$
<proposal, 2>
<promise, 1, foo>
<accept, 2, foo>
Time

Paxos Summary

Paxos allows us to ensure consistent (total) ordering over a set of events in a group of nodes

- Events = commands / actions / state updates

Each machine will have the latest state or a previous version of the state

Paxos Summary

To make a **change** to the system

1. Tell the **proposer**(**leader**) the event

   (NOTE: these requests may occur **concurrently**)

2. The **leader** picks its next highest ID and asks proposal to all the **acceptors** with that ID

3. When the majority of **acceptors** accept the proposal, accepted event are sent to **learners**

4. The **learners** do event (e.g., update system state)

Paxos for RSM

- **Fault-tolerant** RSM requires **consistent** replica **view**
  - View: <primary, backups> (e.g., <node1, node2>)
- All **active** nodes must agree on the sequence of **view** changes
  - <vid-1, primary, backups>, . . .
- Use **Paxos** to agree on the **<primary, backups>**
  - Each Paxos instance agree to a single **view** (e.g., <2, Node1, Node2>)

Next Lecture

Topic: Complex Data Processing

Paper

Yucheng Low et al, “***Distributed GraphLab: a Framework for Machine Learning and Data Mining in the Cloud***”. Proc. VLDB, 5(8), **2012**

THANKS