Distributed Systems

11. Consensus: Paxos

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Fall 2015

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:
  - Manage group membership
  - Synchronize state to manage replicas: make sure every group member agrees on a (key, value) set
  - Distributed transaction commit
- General consensus problem:
  - *How do we get unanimous agreement on a given value?*

Achieving consensus seems easy!

Designate a system-wide coordinator to determine outcome

BUT … this assumes there are no failures

… or we are willing to wait indefinitely for recovery

Consensus algorithm goal

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

- Goal: agree on one result among a group of participants
  - Processors may fail (some may need stable storage)
  - Messages may be lost, out of order, or duplicated
  - If delivered, messages are not corrupted

Consensus requirements

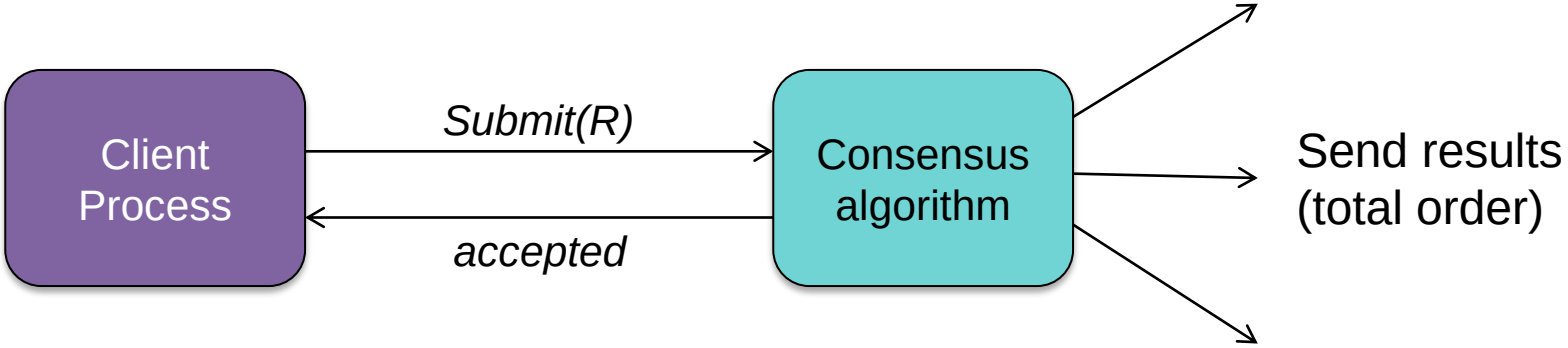
- Validity
  - Only proposed values may be selected
- Uniform agreement
  - No two nodes may select different values
- Integrity
  - A node can select only a single value
- Termination (Progress)
  - Every node will eventually decide on a value

Consensus: Paxos

Paxos

- Fault-tolerant distributed consensus algorithm
  - Does not block if a majority of processes are working
  - The algorithm needs a majority (*2P+1*) of processors survive the simultaneous failure of *P* processors
- Goal: provide a consistent ordering of events from multiple clients
  - All machines running the algorithm **agree on a proposed value** from a client
  - The value will be associated with an event or action
  - Paxos ensures that no other machine associates the value with another event
- **Abortable consensus**
  - A client's request may be rejected
  - It then has to re-issue the request

A Programmer's View



while (submit_request(R) != ACCEPTED) ;

Think of R as a key:value pair in a database

Paxos players

- **Client**: makes a request
- **Proposers**:
  - Get a request from a client and run the protocol
  - Leader: elected coordinator among the proposers
    (not necessary but simplifies message numbering and ensures no contention) – we don't need to rely on the presence of a single leader
- **Acceptors**:
  - Multiple processes that remember the state of the protocol
  - Quorum = any majority of acceptors
- **Learners:**
  - When agreement has been reached by acceptors, a Learner executes the request and/or sends a response back to the client

These different roles are usually part of the same system

What Paxos does

- **Paxos ensures a consistent ordering in a cluster of machines**
  - Events are ordered by sequential event IDs (*N*)
- Client wants to log an event: sends request to a Proposer
  - E.g., *value, v* = "*add $100 to my checking account*"
- **Proposer**
  - Increments the latest event ID it knows about
    - ID = sequence number
  - Asks all the acceptors to reserve that event ID
- **Acceptors**
  - A majority of acceptors have to accept the requested event ID

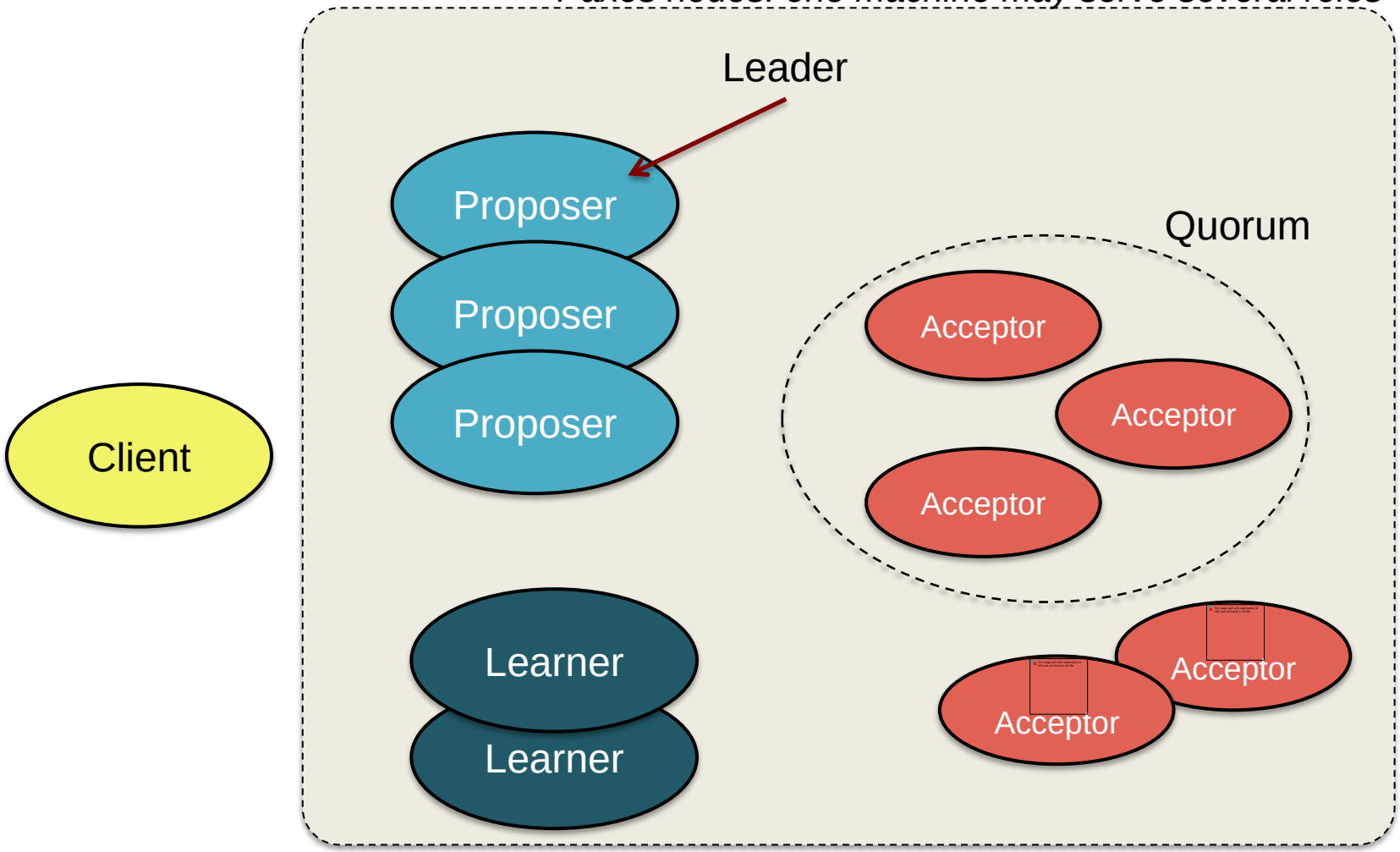
Proposal Numbers

- Each proposal has a number (created by proposer)
  - Must be unique (e.g., <*sequence#*>.<*process_id*>)
- Newer proposals take precedence over older ones
- Each acceptor
  - Keeps track of the largest number it has seen so far
- Lower proposal numbers get rejected
  - Acceptor sends back the {number, value} of the currently accepted proposal
  - Proposer has to “play fair”:
    - It will ask the acceptors to accept the {number, value}
    - Either its own or the one it got from the acceptor

Paxos in action

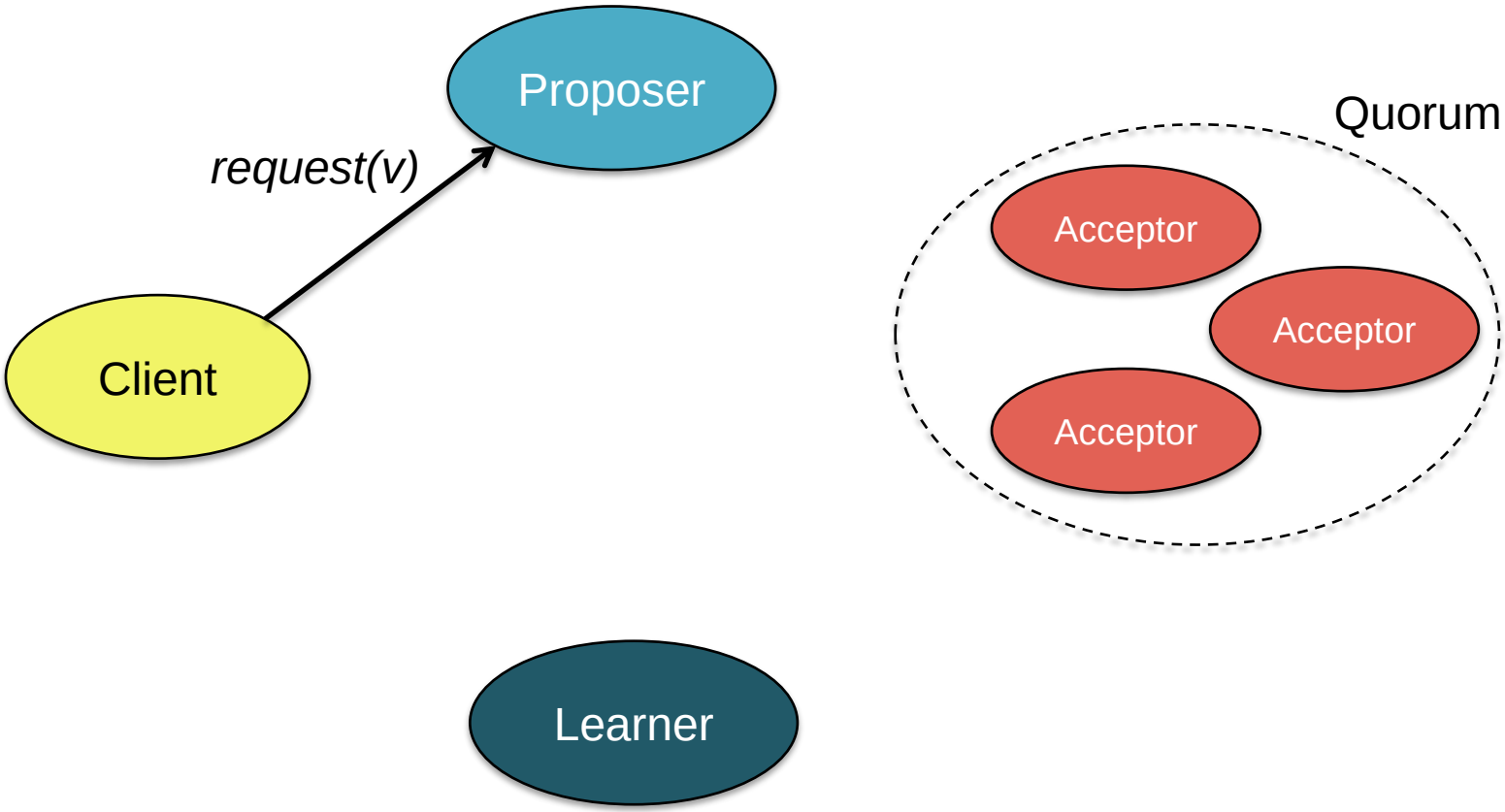
One of the proposers is chosen to be a *leader*: it gets all the requests

Paxos nodes: one machine may serve several roles



Paxos in action: Phase 0

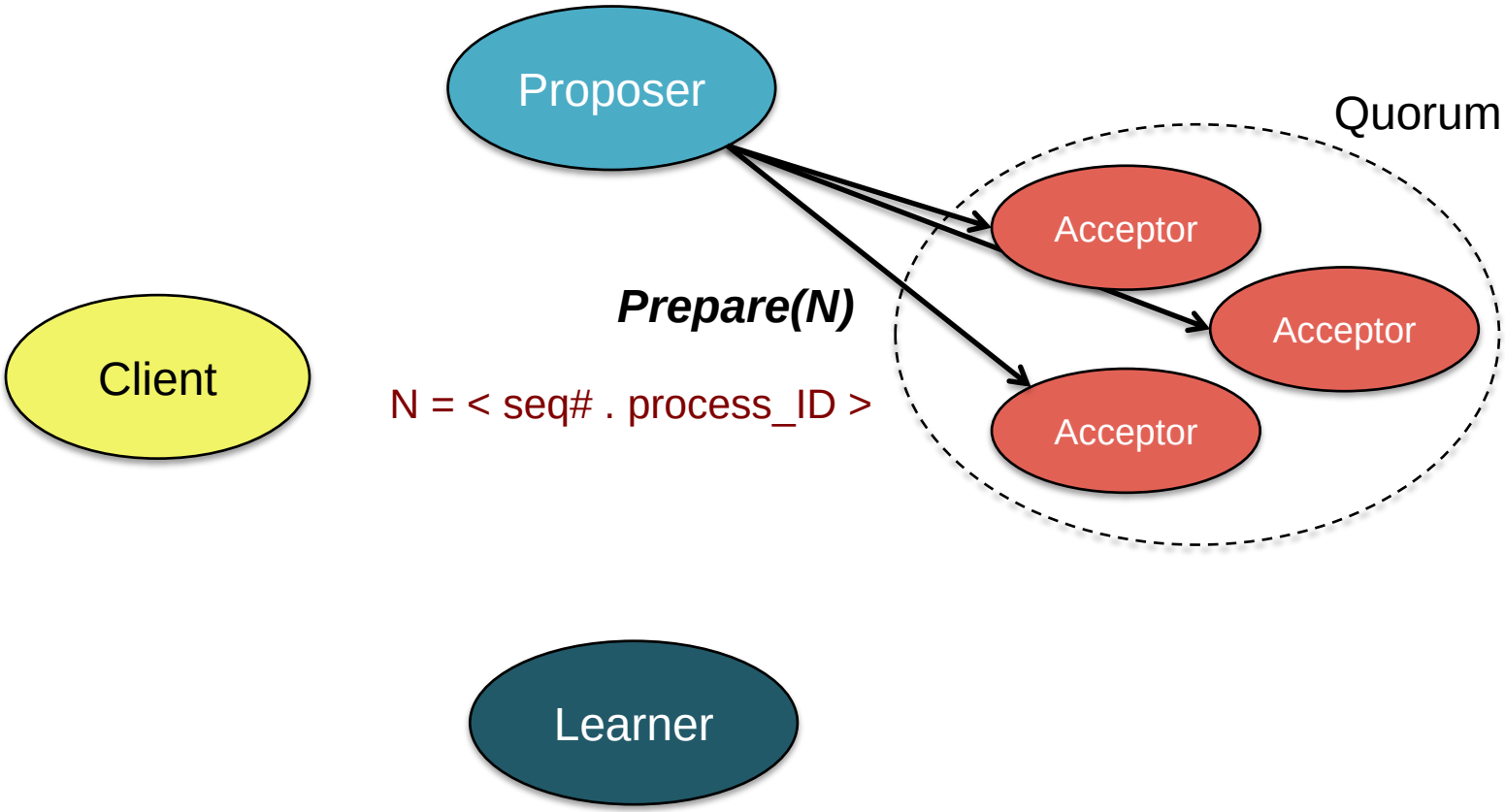
Client sends a request to a proposer



Paxos in action: Phase 1a – *PREPARE*

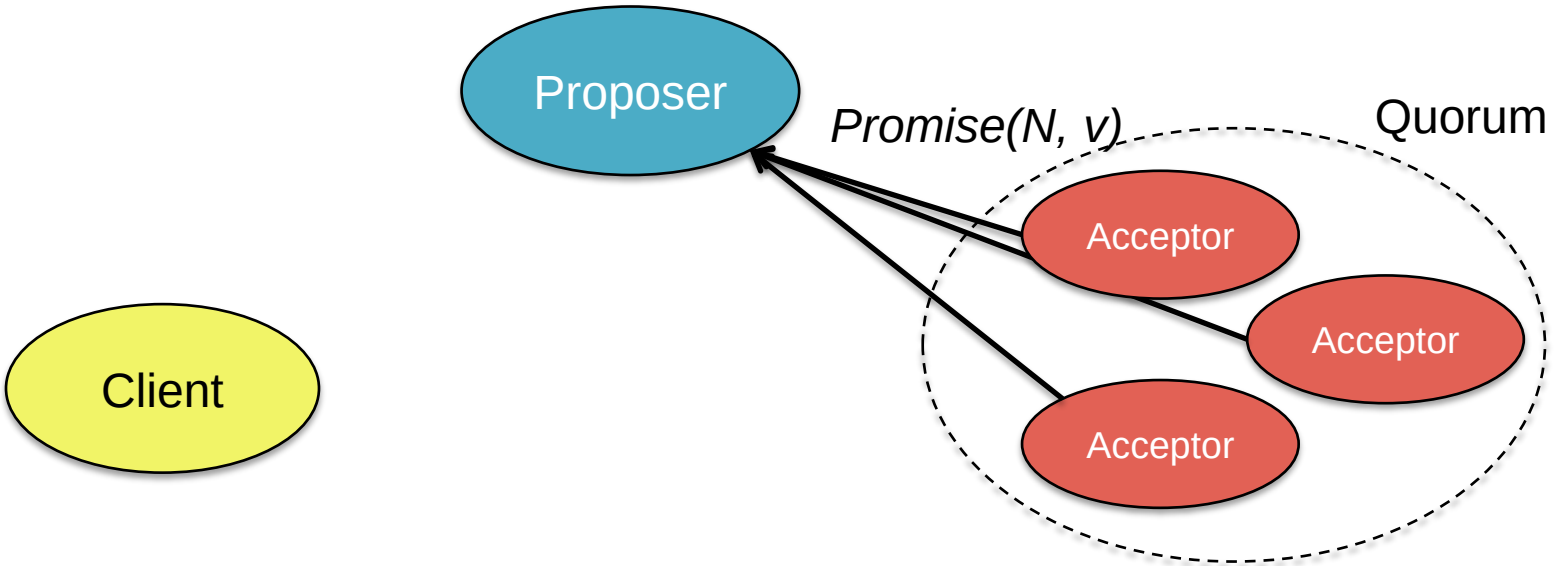
Proposer: creates a *proposal #N (N acts like a Lamport time stamp)*, where *N* is greater than any previous proposal number used by this proposer

Send to Quorum of Acceptors (however many you can reach – but a majority)



Paxos in action: Phase 1b – *PROMISE*

Acceptor: if proposer's ID > any previous proposal
promise to ignore all requests with IDs < N
reply with info about highest accepted proposal, if there is one: { *N, value* }
else *Reject* the proposal



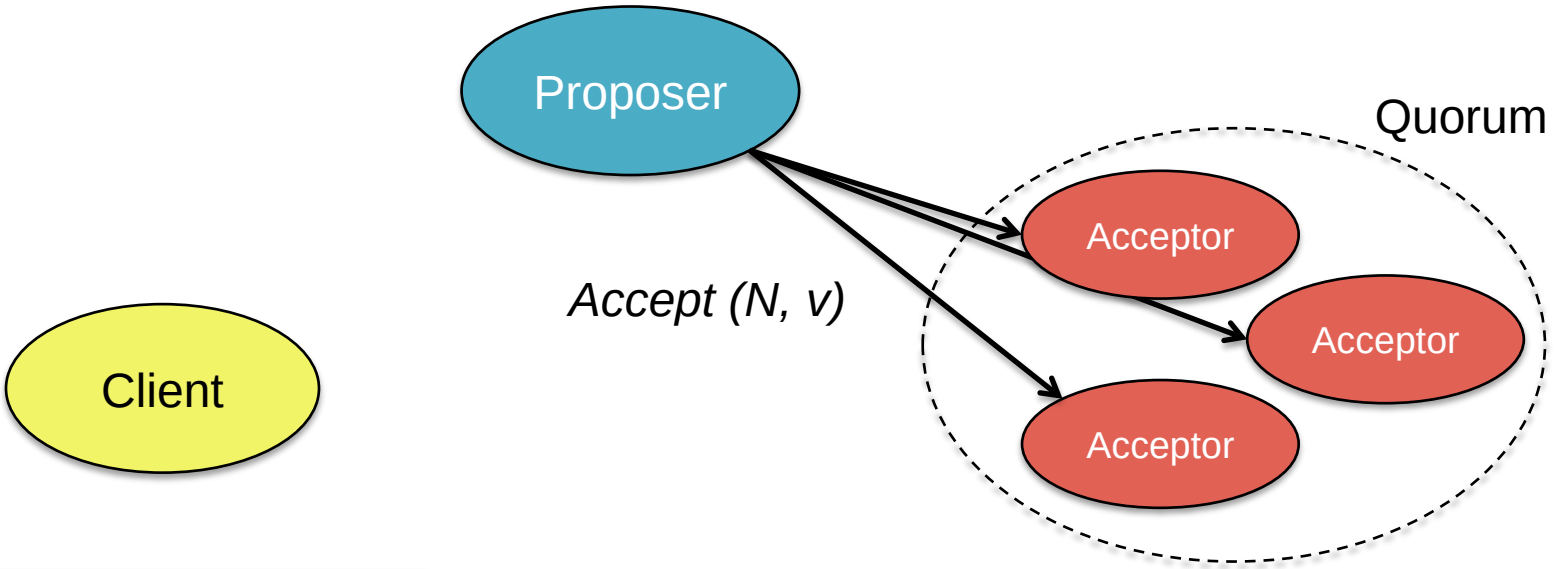
This step:
(a) Tells proposers about any value that has already been accepted.
(b) Rejects older proposals.

Promise to ignore all proposals < *N*

Promise contains the previous *N*

Paxos in action: Phase 2a

Proposer: if proposer receives promises from the quorum (majority):
Attach a value *v* to the proposal (the event).
Send ***Accept*** to quorum with the **chosen** value
If promise was for another {N, v}, proposer MUST accept that instead

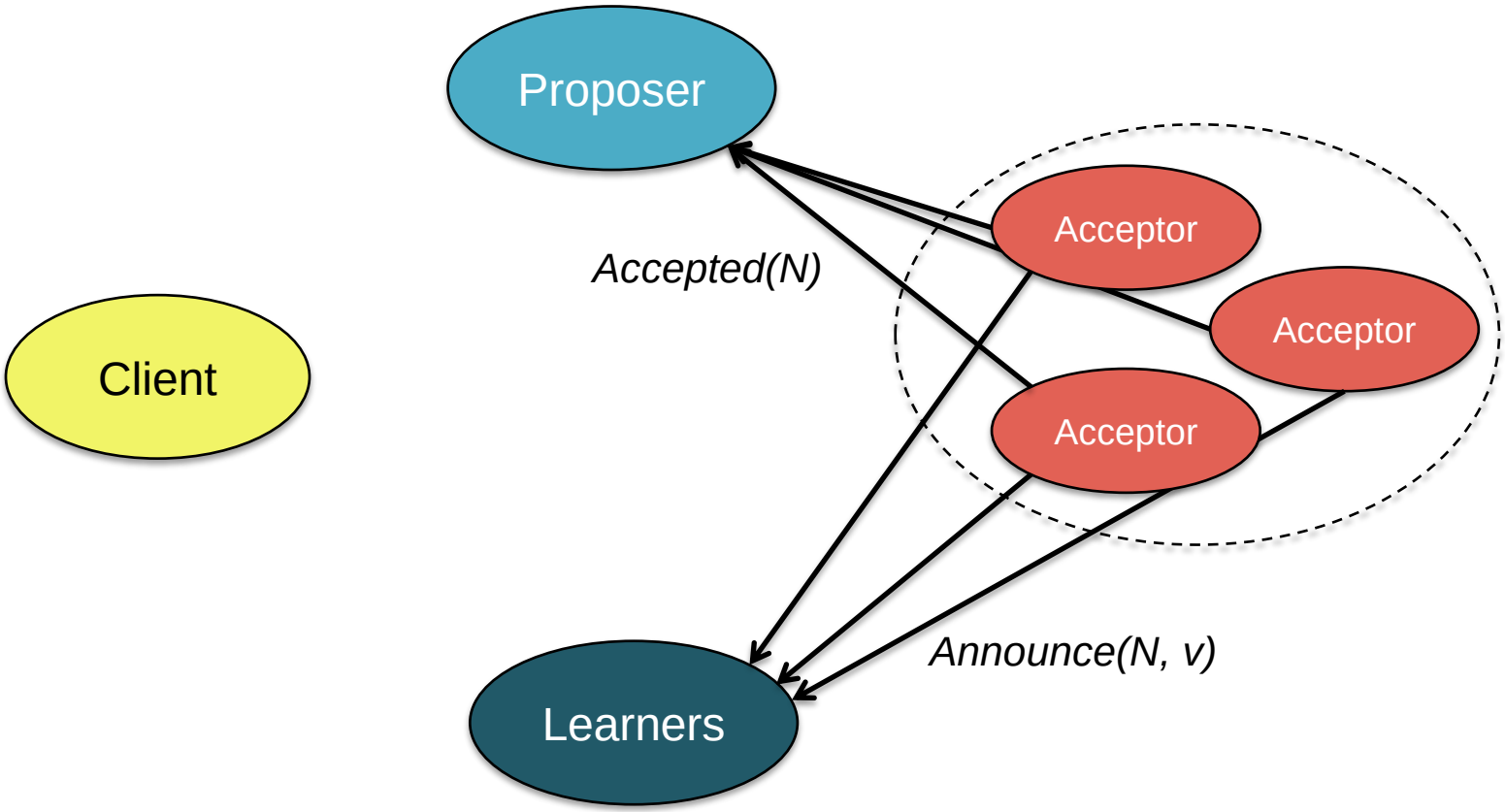


If the acceptor returned any (*N, v*) sets then the proposer must agree to accept one of those values intead of the value it proposed. It picks the *v* for the highest *N.*

Learner

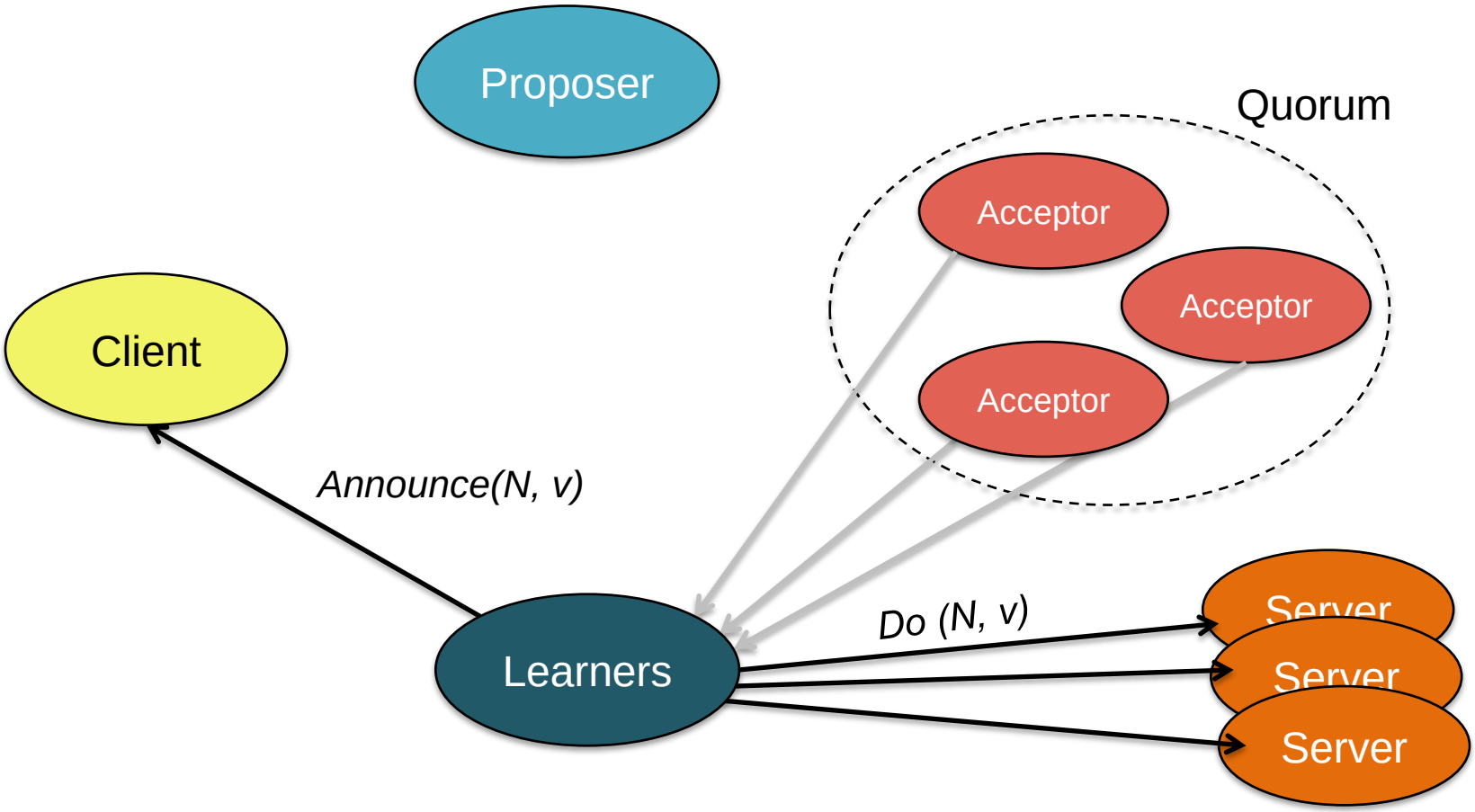
Paxos in action: Phase 2b

Acceptor: if the promise still holds, then announce the value *v*
Send ***Accepted*** message to Proposer and every Learner
else ignore the message (or send *NACK*)



Paxos in action: Phase 3

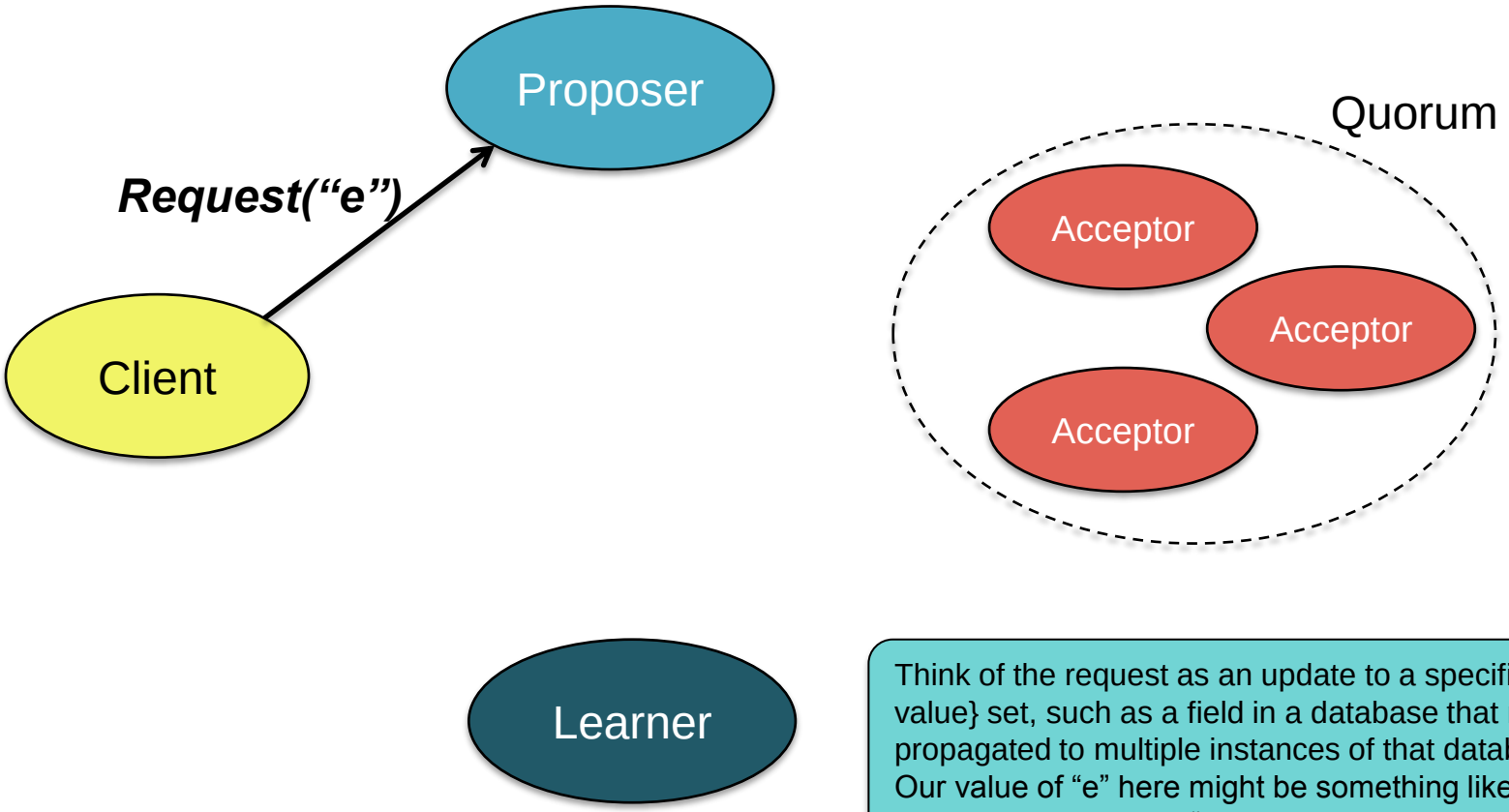
Learner: Respond to client and/or take action on the request



Paxos: A Simple Example – All Good

Paxos in action: Phase 0

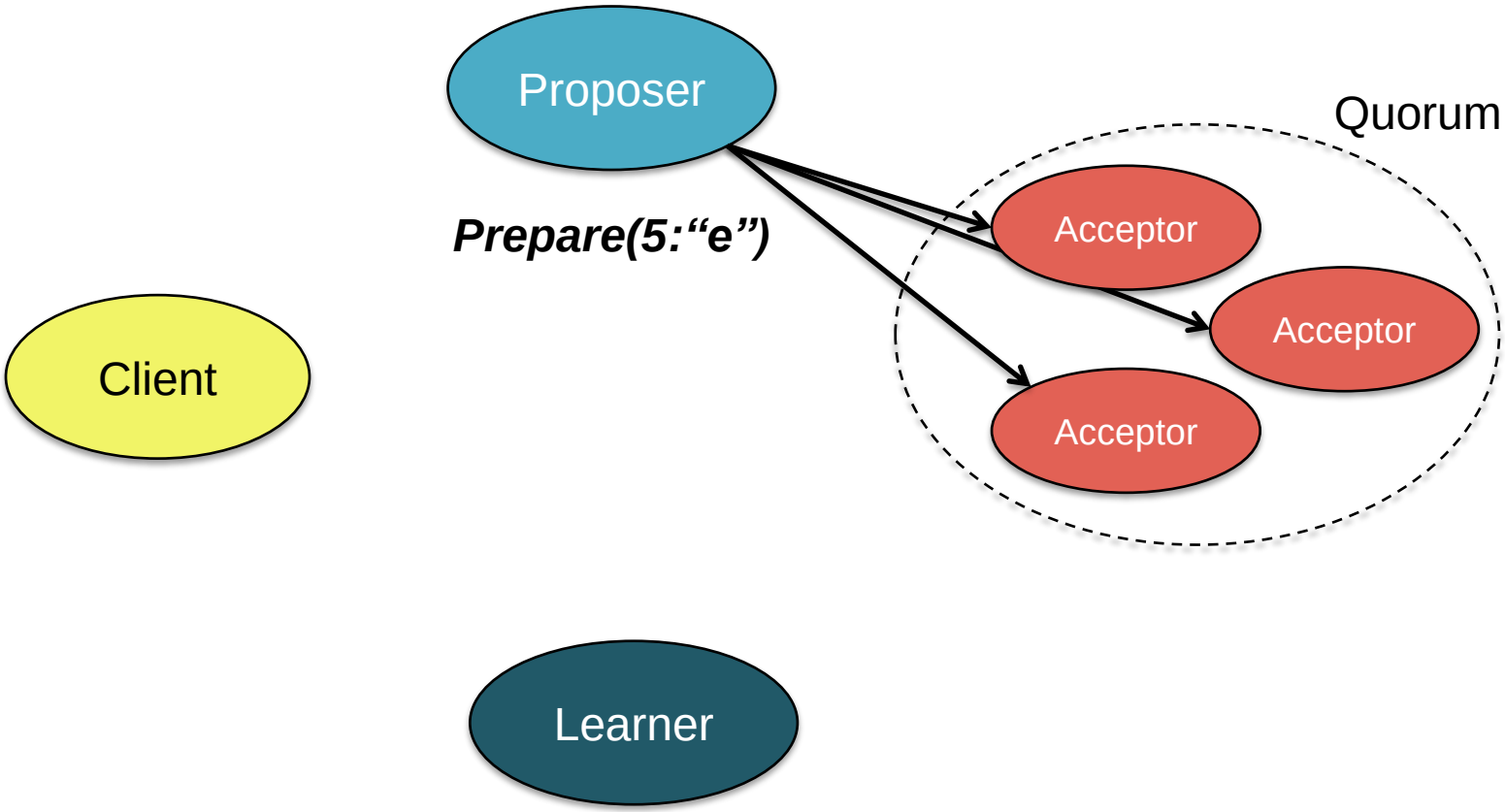
Client sends a request to a proposer



Think of the request as an update to a specific {key, value} set, such as a field in a database that may be propagated to multiple instances of that database. Our value of "e" here might be something like a request to set *name="e"*

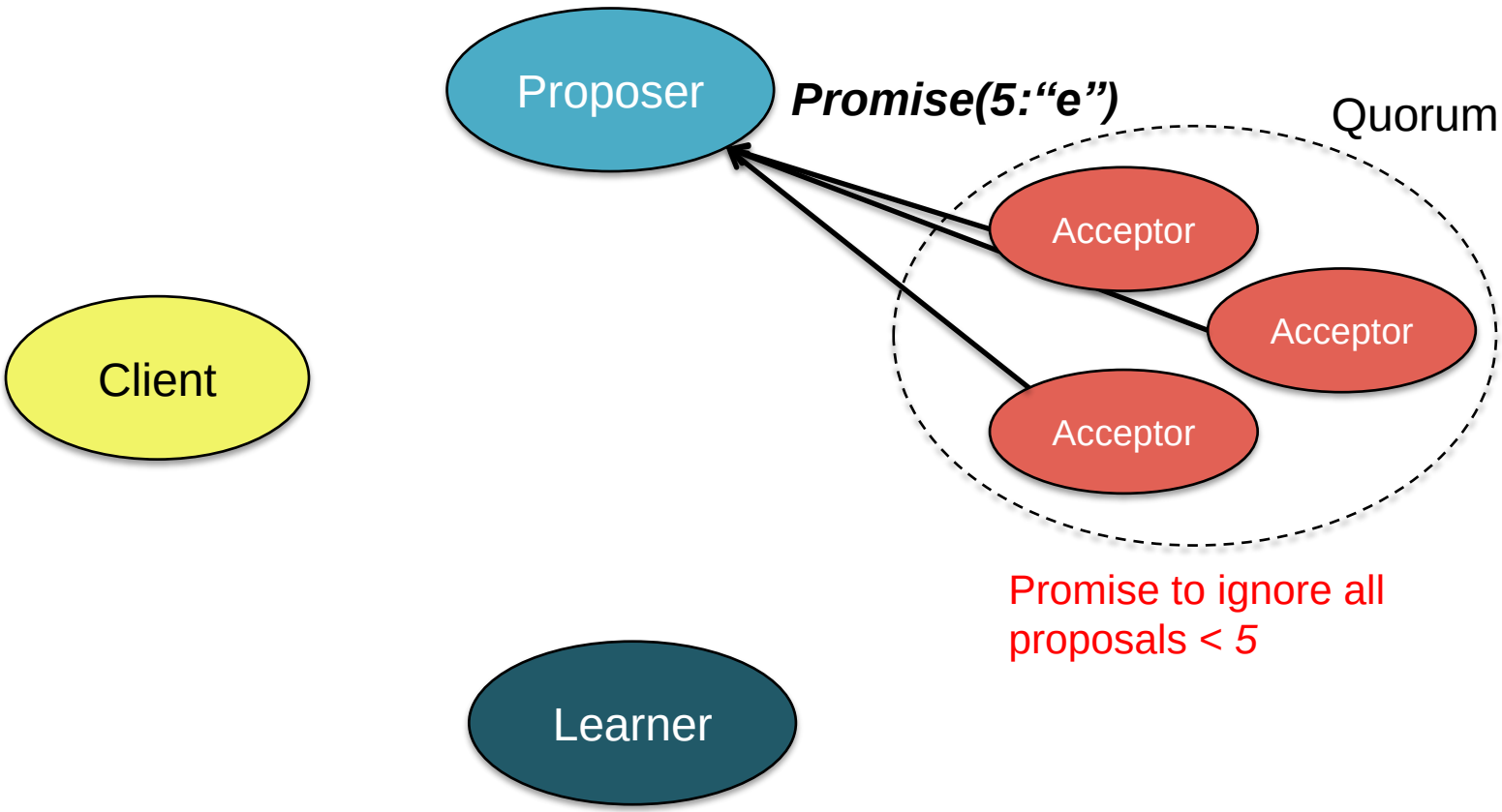
Paxos in action: Phase 1a – *PREPARE*

Proposer: picks a sequence number: 5
Send to Quorum of Acceptors



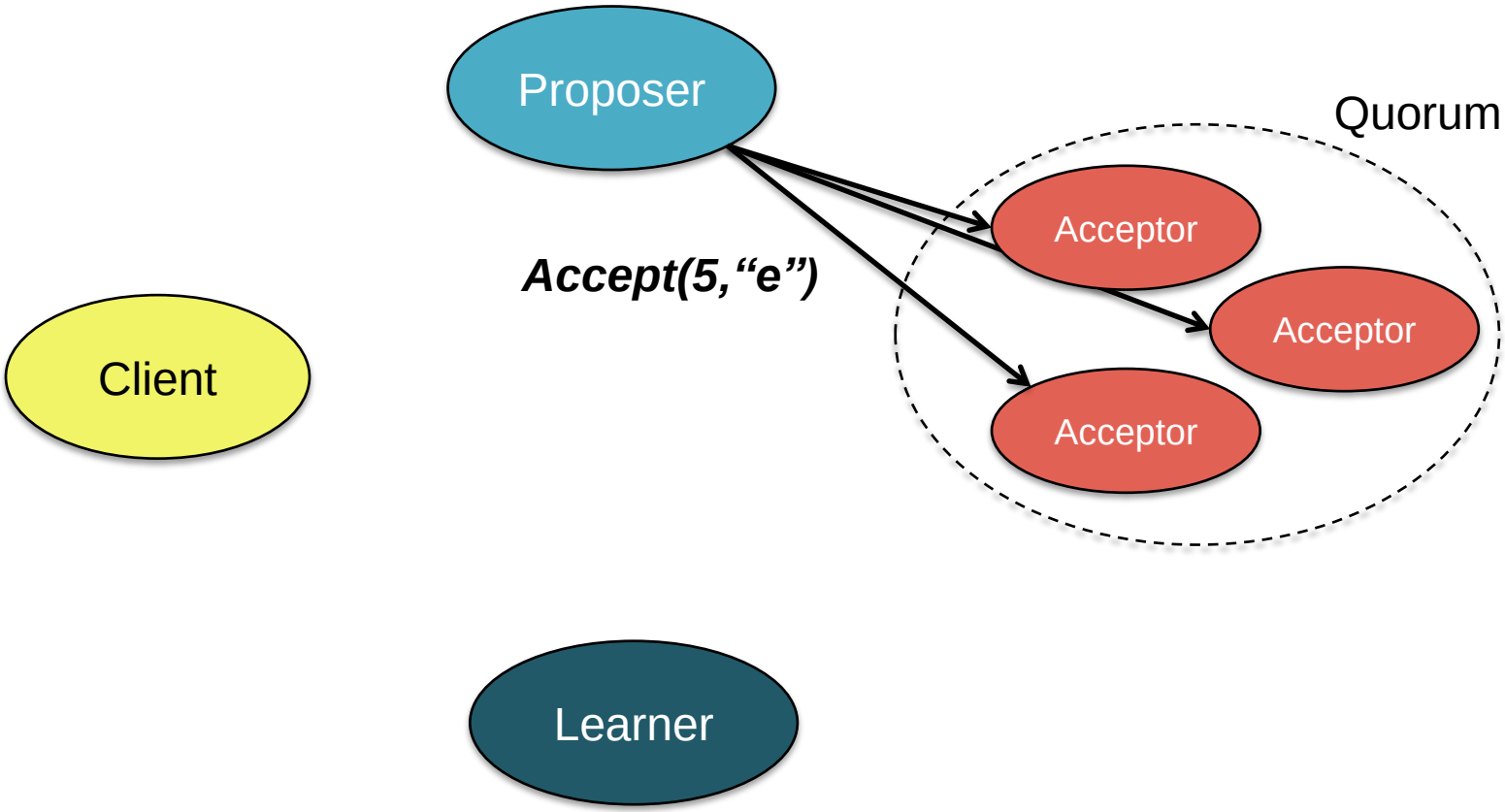
Paxos in action: Phase 1b – *PROMISE*

Acceptor: Suppose 5 is the highest sequence # any acceptor has seen
Each acceptor PROMISES not to accept any lower numbers



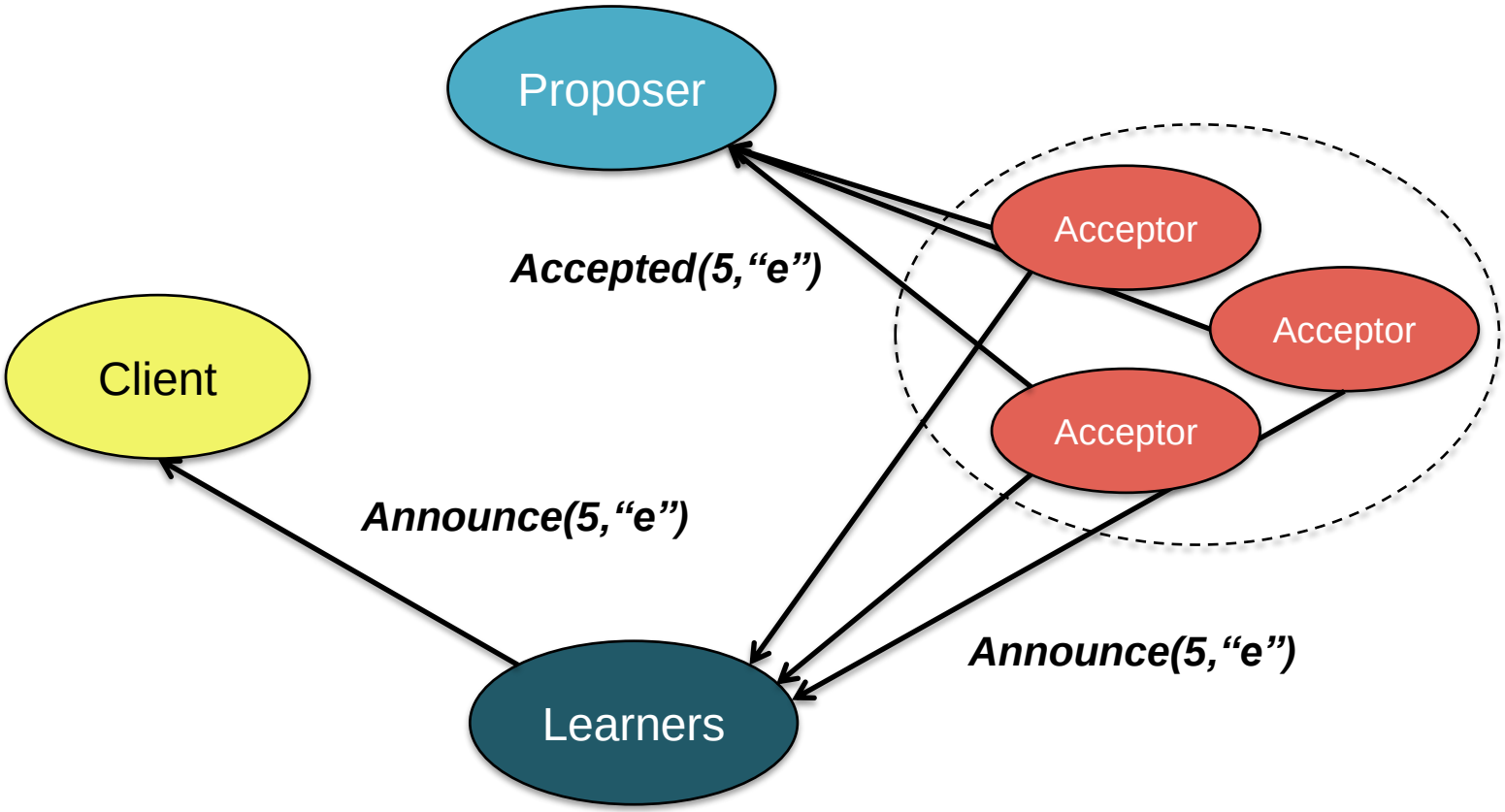
Paxos in action: Phase 2a – *ACCEPT*

Proposer: Proposer receives the promise from a majority of acceptors
Proposer must accept that <seq, value>



Paxos in action: Phase 2b – *ANNOUNCE*

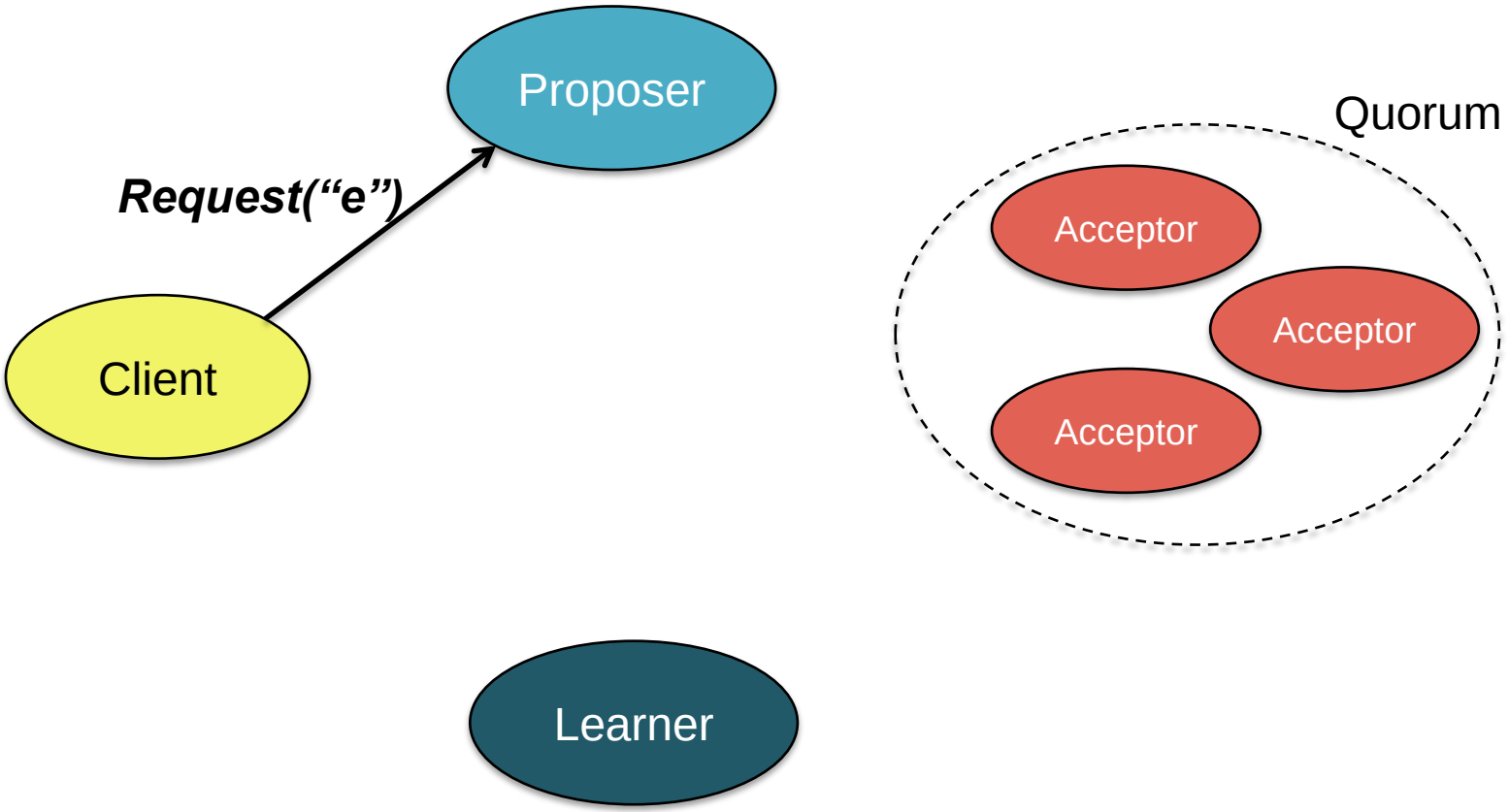
Acceptor: Acceptors state that they accepted the request



Paxos: A Simple Example – Higher Offer

Paxos in action: Phase 0

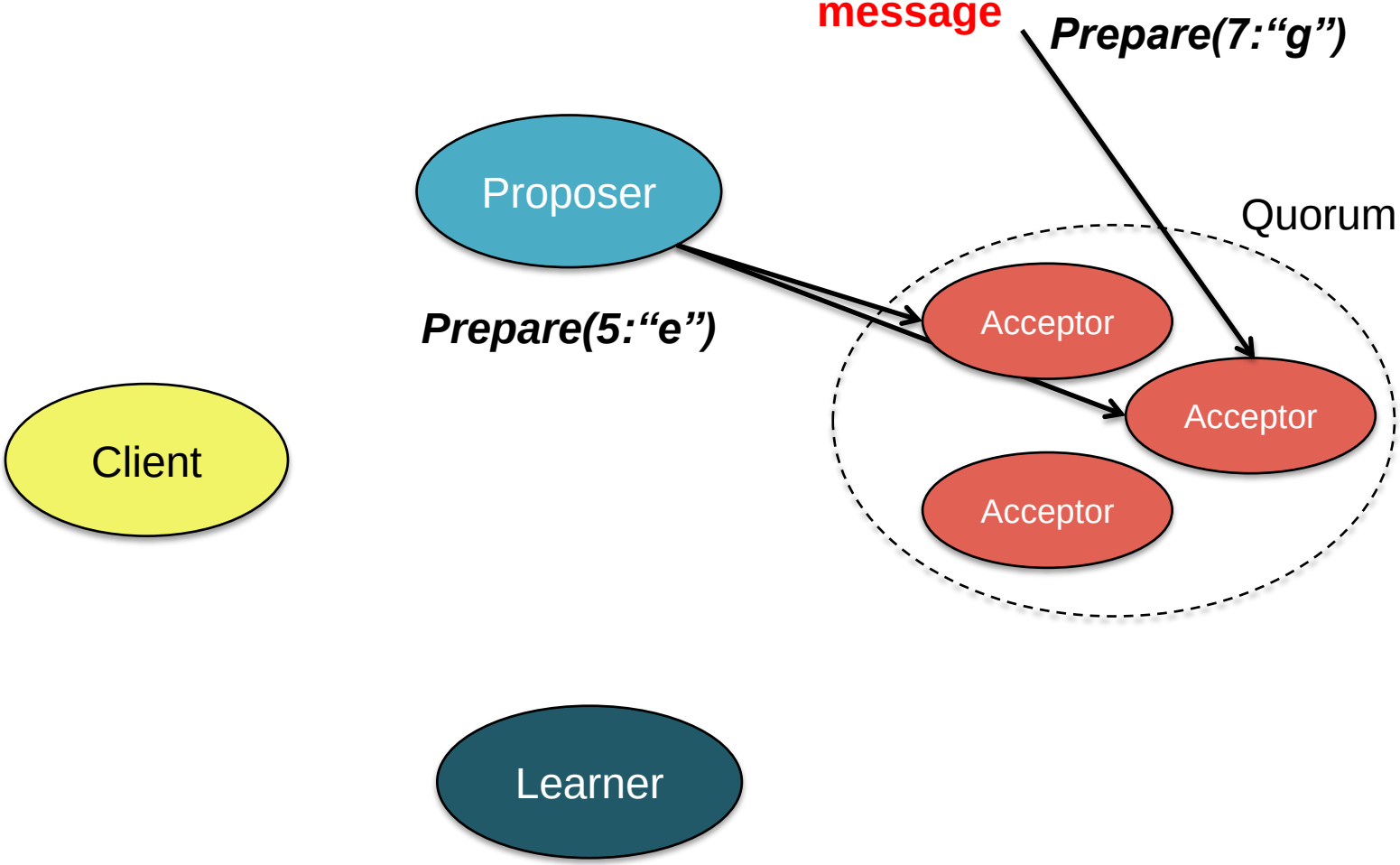
Client sends a request to a proposer



Paxos in action: Phase 1a – *PREPARE*

Proposer: picks a sequence number: 5
Send to Quorum of Acceptors

One acceptor receives a higher offer BEFORE it gets this PREPARE message



Paxos in action: Phase 1b – *PROMISE*

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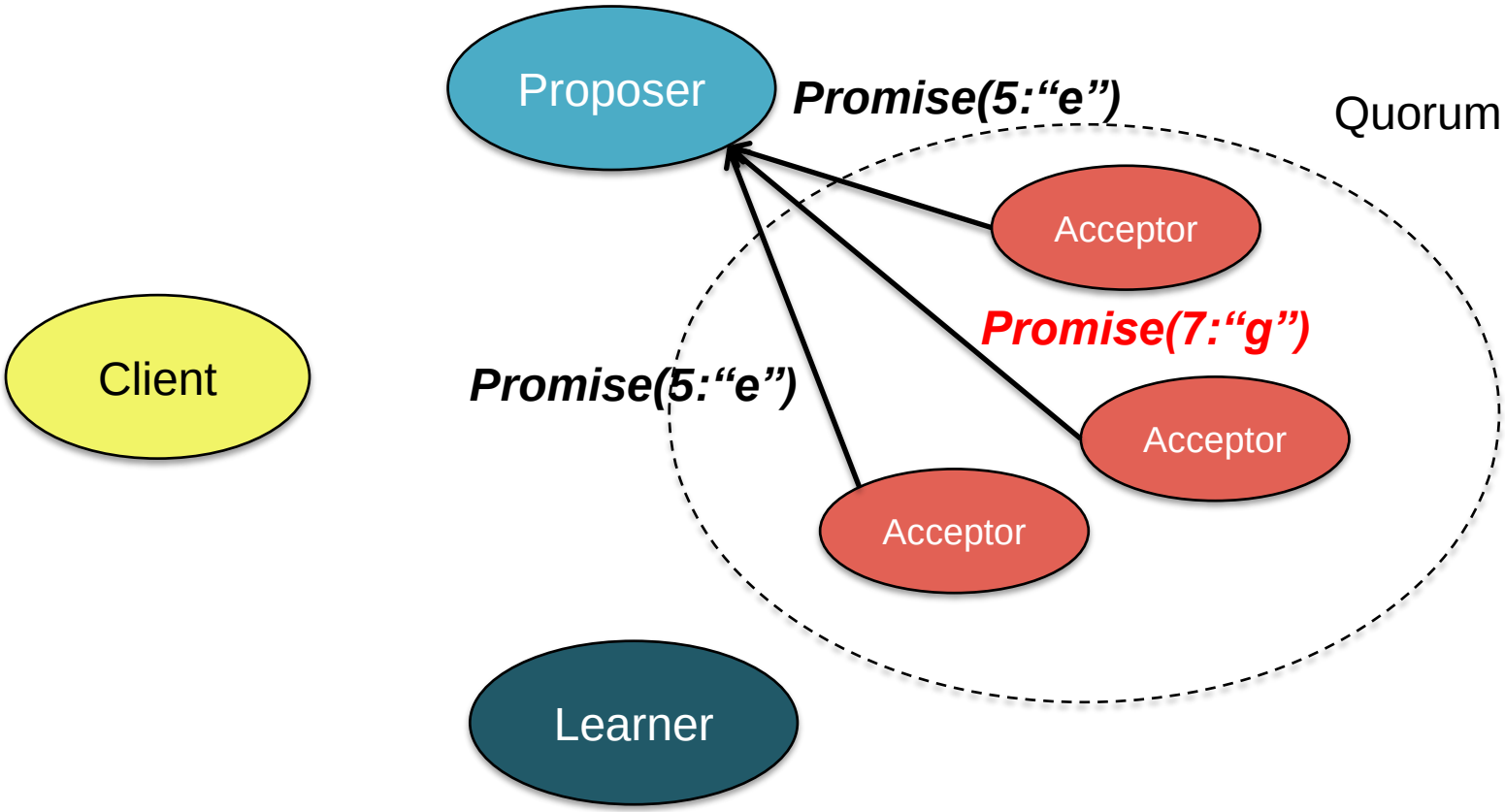
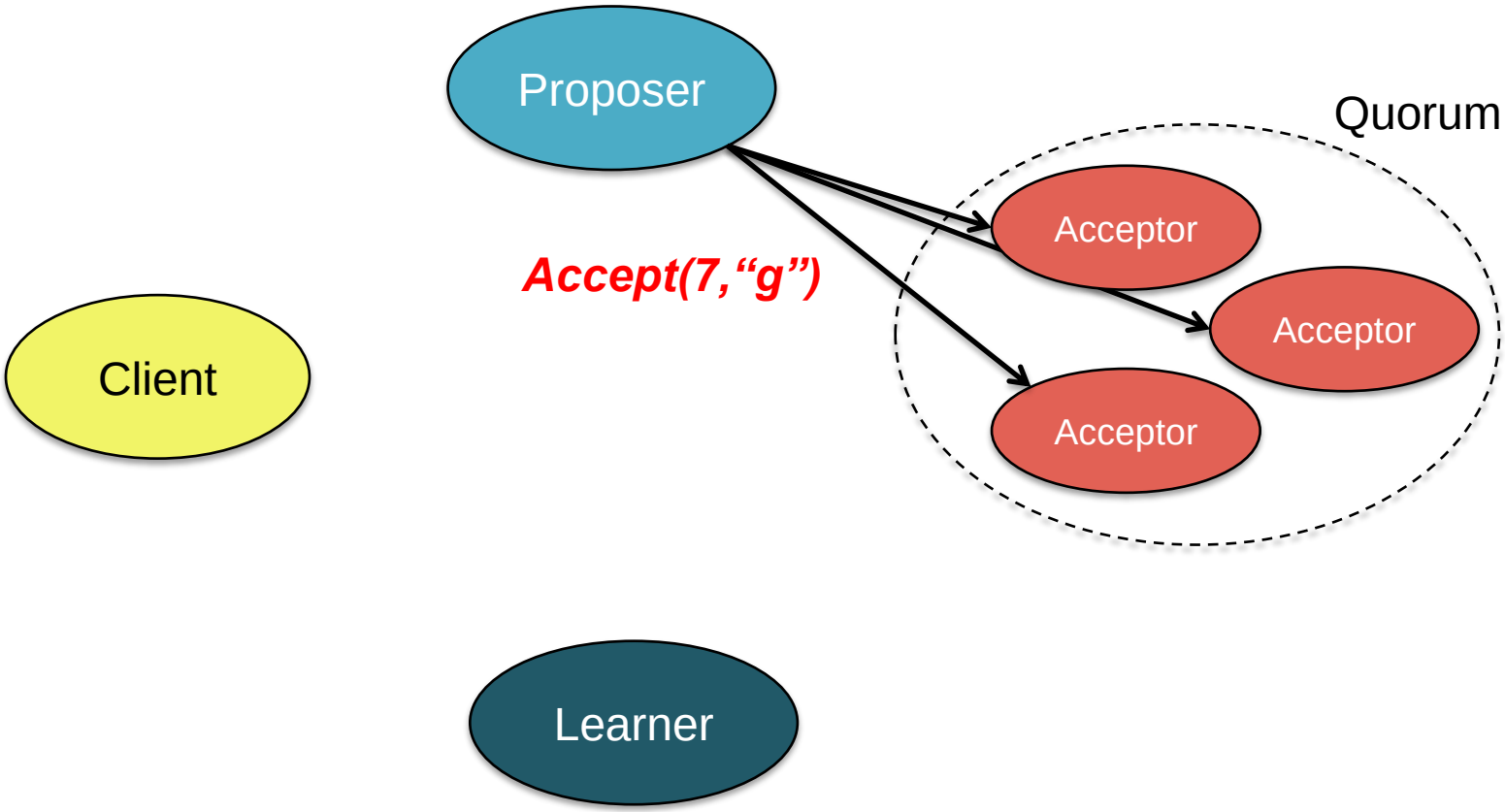
Each acceptor PROMISES not to accept any lower numbers



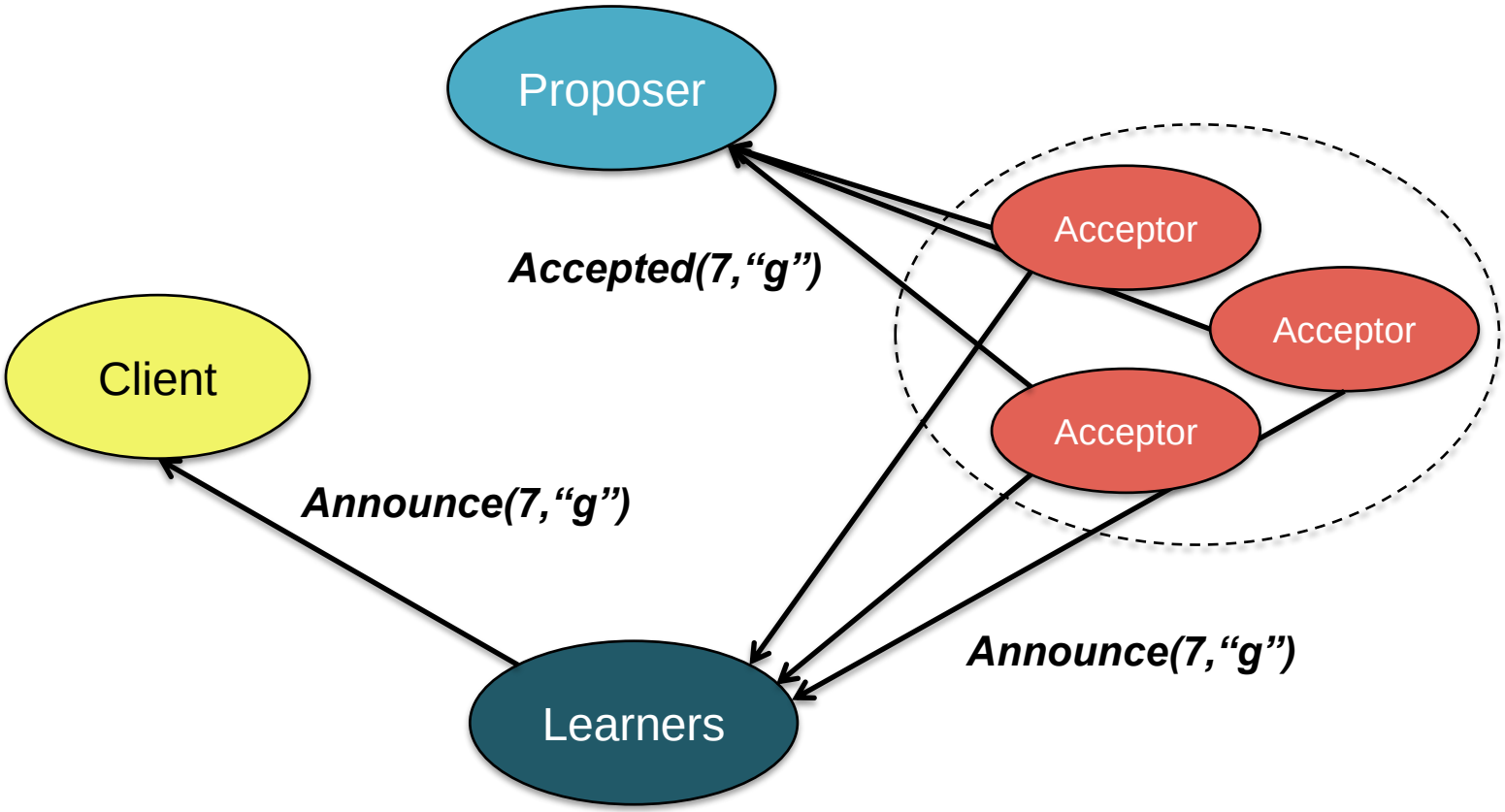
Paxos in action: Phase 2a – *ACCEPT*

Proposer: Proposer receives the higher # offer and **MUST** change its mind and accept the highest offer that it received from any acceptor.



Paxos in action: Phase 2b – *ANNOUNCE*

Acceptor: Acceptors state that they accepted the request. A learner can propagate this information



Paxos: Keep trying if you need to

- A proposal *N* may fail because
  - The acceptor may have made a new promise to ignore all proposals less than some value *M* >*N*
  - A proposer does not receive a quorum of responses: either *promise* (phase 1b) or *accept* (phase 2b)
- Algorithm then has to be restarted with a higher proposal #

Paxos summary

- Paxos allows us to ensure consistent (total) ordering over a set of events in a group of machines
  - Events = commands, actions, state updates
- Each machine will have the latest state or a previous version of the state
- Paxos used in:
  - Cassandra lightweight transactions
  - Google Chubby lock manager / name server
  - Google Spanner, Megastore
  - Microsoft Autopilot cluster management service from Bing
  - Vmware NSX Controller
  - Amazon Web Services

Paxos summary

To make a change to the system:

- Tell the *proposer* (leader) the event/command you want to add
  - Note: these requests may occur concurrently
  - Leader = one elected proposer. Not necessary for Paxos algorithm but an optimization to ensure a single, increasing stream of proposal numbers. Cuts down on rejections and retries.
- The proposer picks its next highest event ID and asks all the acceptors to reserve that event ID
  - If any acceptor sees has seen a higher event ID, it rejects the proposal & returns that higher event ID
  - The proposer will have to try again with another event ID
- When the **majority of acceptors accept the proposal**, accepted events are sent to learners, which can act on them (e.g., update system state)
  - Fault tolerant: need *2k+1* servers for *k* fault tolerance

The End