Optimizing and Implementing Paxos

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Review: Basic Paxos

- **Termination**: Every correct process decides some value when there are no asynchronous events.
- **Validity**: If all processes propose the same value v, then all correct processes decide v.
- **Integrity**: Every correct process decides at most one value, and if it decides some value v, then v must have been proposed by some process.
- **Agreement**: Every correct process must agree on the same value.
- Validity and integrity are trivial in fail-stop model. Let's focus on termination and agreement.

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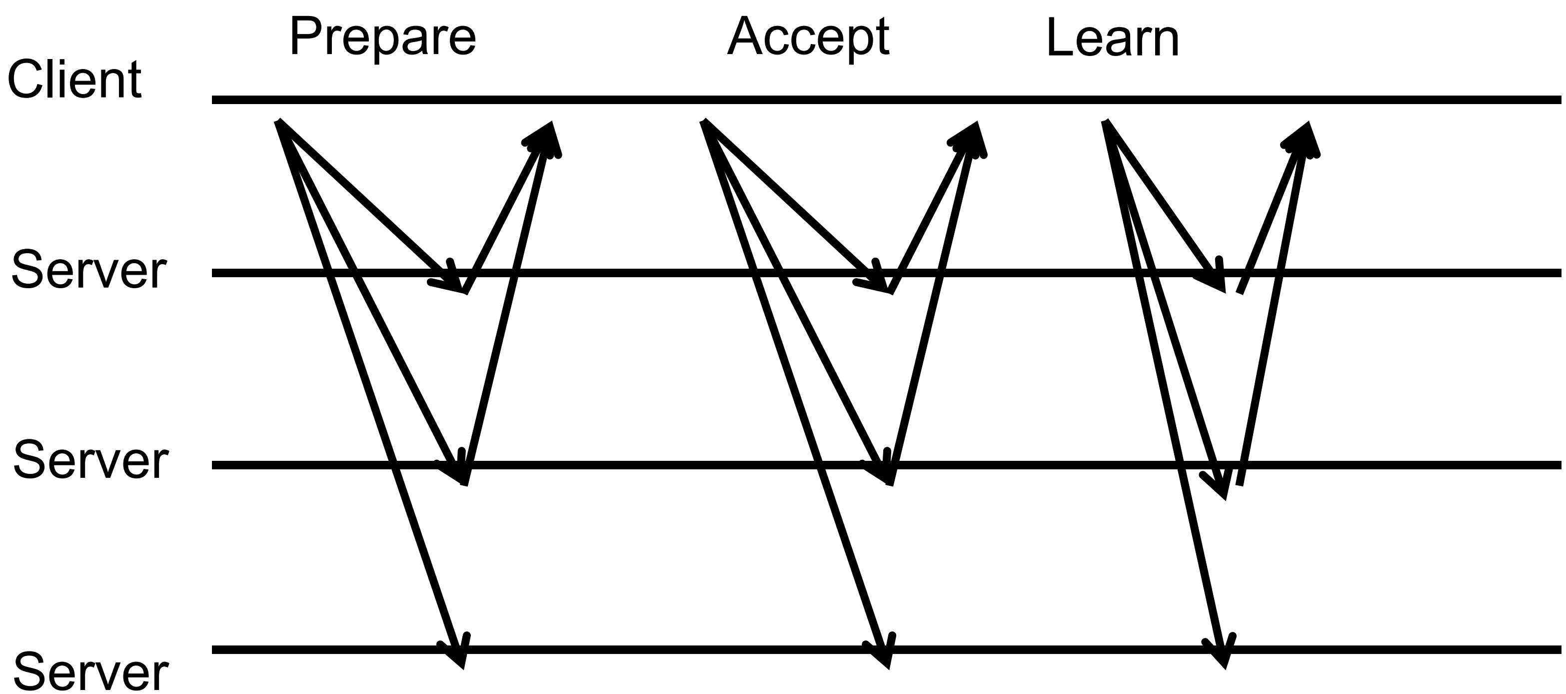

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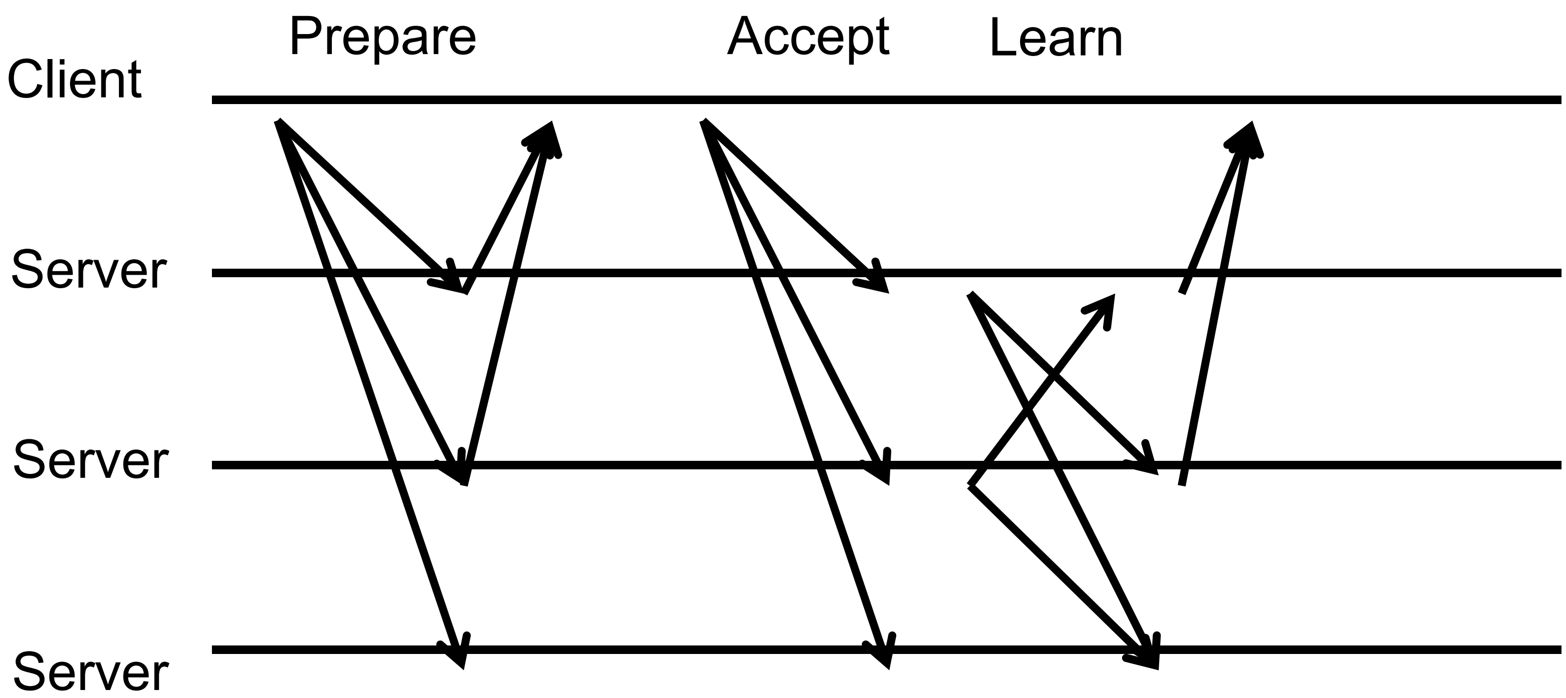

This is equivalent to the previous one with less latency but more messages

Acceptor and learner

- Revise state machine replication
  - Model application as a deterministic state machine --- This part is called a learner in Paxos
  - Run a consensus protocol to decide the next request --- This part is called an acceptor in Paxos
- A replica is logically separated into an acceptor and a learner
  - Many implementations collocate them in a single process

Optimization 1: Elect a leader

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- Optimization: elect one server as the leader and ask all clients to send requests to the leader. Only the leader makes proposals.

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- Wait. How is it different from Primary Backup?

Optimization 1: Elect a leader

- Primary backup: if there are more than one leaders, agreement may be violated
- Paxos: if there are more than one leaders, agreement will not be violated. Termination may be violated when there are asynchronous events.

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- Primary backup: if there are more than one leaders, agreement may be violated
- Paxos: if there are more than one leaders, agreement will not be violated. Termination may be violated when there are asynchronous events.
- Accurate failure detection = ensure there is at most one leader = solve consensus

Optimization 1: Elect a leader

- How to elect the leader?
  - There are multiple solutions.

- Simplest solution: round robin
  - Server 1 is the first leader. If it fails, server 2 becomes the leader, and then server 3, …

Optimization 1: Elect a leader

- When to elect a leader?
  - When the current leader fails, but we don't know.

- Simplest solution: timeout
  - Timeout may be inaccurate, so multiple leaders may be elected, but that is fine.
  - For termination, use a exponentially growing timeout

Optimization 2: Multi Paxos

- So far, we have talked about how to decide the next request
- A real application needs to execute a sequence of requests, instead of just one
- Naive solution: run basic Paxos multiple times
  - Divide execution into multiple slots
  - Use Paxos to decide a request for each slot
  - (Prepare, Accept, Learn) for slot 1, and then for slot 2, …

Optimization 2: Multi Paxos

- Optimization: only need to run “Prepare” once
  - Prepare, Accept for slot 1, Learn for slot 1, Accept for slot 2, Learn for slot 2, …
- Revise what Prepare does:
  - Proposer needs to know what has been agreed.
  - Proposer needs an acceptor to promise not to agree on earlier proposals.

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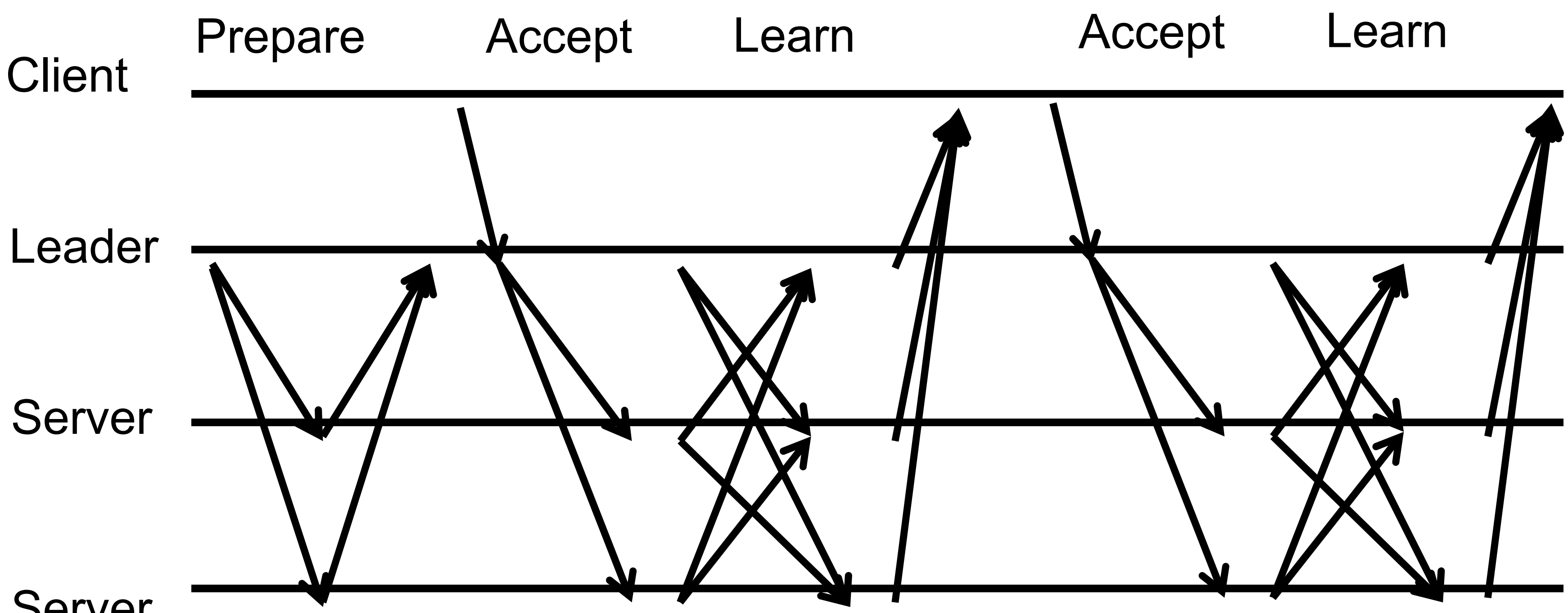
  - Prepare, Accept for slot 1, Learn for slot 1, Accept for slot 2, Learn for slot 2, …
- Revise what Prepare does:
  - Proposer needs to know what has been agreed.
  - Proposer needs an acceptor to promise not to agree on earlier proposals.
- Instead of "prepare" for one request, we can prepare for 100 requests, or more

Multi Paxos

- Each leader is assigned a unique number (epoch number)
  - Simplest approach: round robin
- After a leader is elected, it sends the prepare messages to all acceptors
  - Ask for all requests that have been agreed.
  - Ask acceptors to promise that they will not accept proposals from earlier leaders.

Multi Paxos


Prepare
Accept
Learn
Accept
Learn
Client
Leader
Server
Server

Pipeline execution

- To reduce latency, a leader can propose the next request before the previous one is agreed
- Problem 1: learner must execute requests in order
  - Solution: learner maintains the last slot it has executed.
- Problem 2: after a leader election, during the prepare phase, the new leader may find slot 100 is already agreed while slot 99 is not.
  - Solution: the new leader can propose a special “noop” operation for slot 99

Failure recovery

- If an acceptor or a learner is destroyed, we will need to replace it with a new server
- The server needs to know what requests have been agreed (and record or execute them)
- It can use a protocol similar to Prepare

Garbage collection

- An acceptor needs to remember requests that it has agreed.
  - Otherwise, failures may cause requests to be lost.
  - The log may grow arbitrarily.
- Periodically, the system asks a learner to take a snapshot of its state machine
  - By doing so, the learner promises that it will never need earlier requests.
  - Then the acceptor can delete those requests.

Implementation details

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- Possible reasons:
  - Request to the leader is lost
  - Leader receives the request but it fails before it proposes the request
  - Leader proposes the request but it fails before the proposal is agreed by f+1 replicas
  - The proposal is passed but the message to the learner is lost
  - Learner executes the request but the reply to the client is lost
  - …

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- Solution: the client resends the request
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- Leader:
  - If never proposed the request, propose it
  - If already proposed, but not stable, just wait
  - If already stable, send it to the learner

Implementation details

- What to do if a client does not get the reply in time?

- Solution: the client resends the request
  - A client should remember all outstanding requests

- Learner:
  - If never executed it, execute it (but need to follow order)
  - If has already executed, how? Can it execute the request again?

Implementation details

- What to do if a client does not get the reply in time?
- Solution: the client resends the request
  - A client should remember all outstanding requests
- Learner:
  - If never executed it, execute it (but need to follow order)
  - If has already executed, send the previous reply to clients
    - To doing so, a learner needs to remember replies sent to clients

Implementation details

- Reply cache: Learner should remember replies to clients
- Limit the size of reply cache
  - Solution 1: limit the number of outstanding requests per client (e.g. 100): if learner receives request 101, it knows the client must have received the reply for request 1
  - Solution 2: client piggybacks the received reply ID in its requests, so that learner can know the information
- Reply cache is critical for correctness
  - Snapshot of a learner should include the reply cache