Implementing Replicated Logs with Paxos

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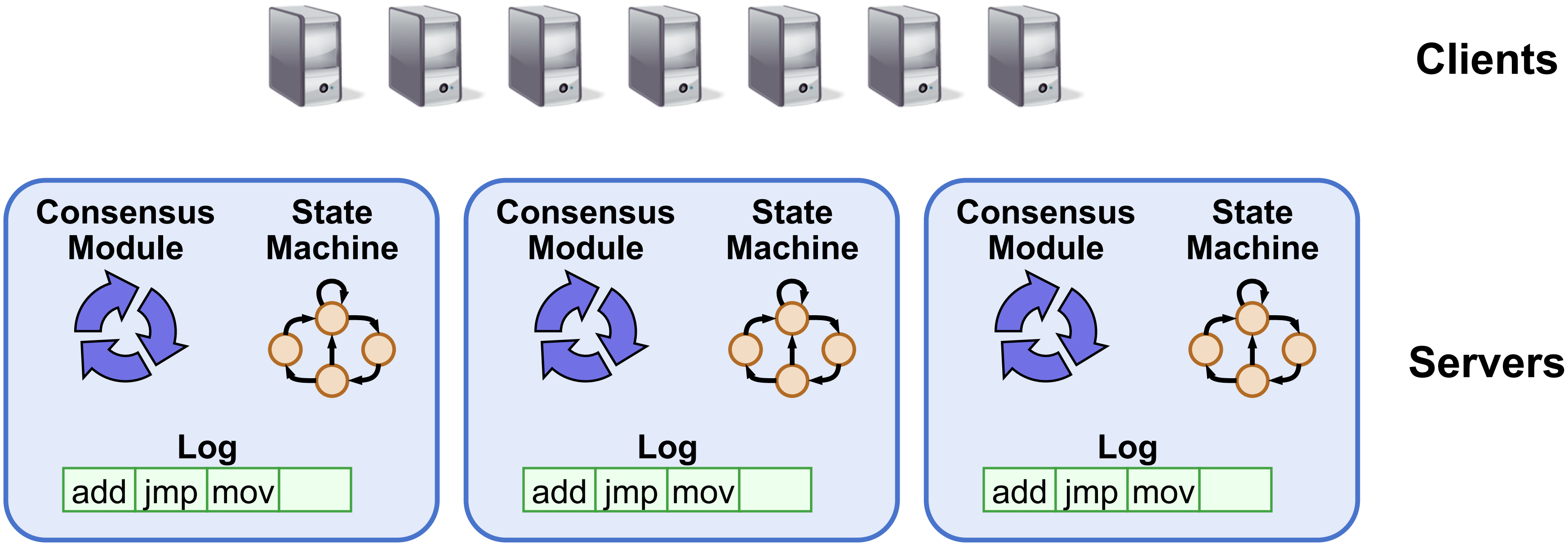
Note: this material borrows heavily from slides by Lorenzo Alvisi, Ali Ghodsi, and David Mazières

Goal: Replicated Log



Clients

Servers

Consensus Module

State Machine

Log

add | jmp | mov

Consensus Module

State Machine

Log

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Consensus Module

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add | jmp | mov

- **Replicated log => replicated state machine**
  - All servers execute same commands in same order
- **Consensus module ensures proper log replication**
- **System makes progress as long as any majority of servers are up**
- **Failure model: fail-stop (not Byzantine), delayed/lost messages**

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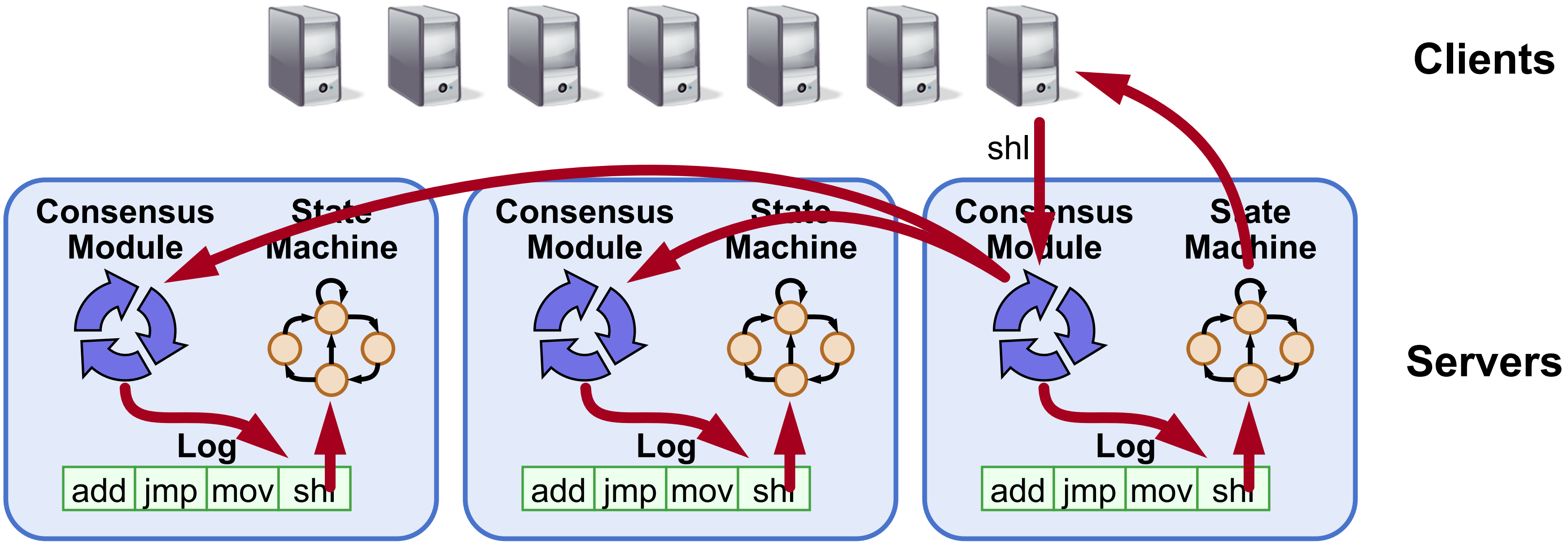

- **Replicated log => replicated state machine**
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The Paxos Approach

Decompose the problem:

- **Basic Paxos (“single decree”):**
  - One or more servers propose values
  - System must agree on a single value as chosen
  - Only one value is ever chosen
- **Multi-Paxos:**
  - Combine several instances of Basic Paxos to agree on a series of values forming the log

Requirements for Basic Paxos

- **Safety:**
  - Only a single value may be chosen
  - A server never learns that a value has been chosen unless it really has been
- **Liveness (as long as majority of servers up and communicating with reasonable timeliness):**
  - Some proposed value is eventually chosen
  - If a value is chosen, servers eventually learn about it

The term "consensus problem" typically refers to this single-value formulation

Paxos Components

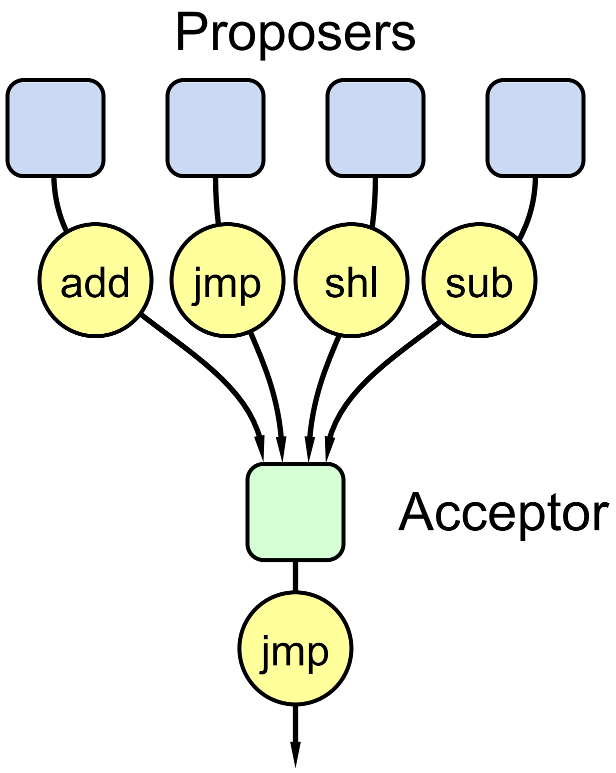
- **Proposers:**
  - Active: put forth particular values to be chosen
  - Handle client requests
- **Acceptors:**
  - Passive: respond to messages from proposers
  - Responses represent votes that form consensus
  - Store chosen value, state of the decision process
  - Want to know which value was chosen

For this presentation:

- Each Paxos server contains both components

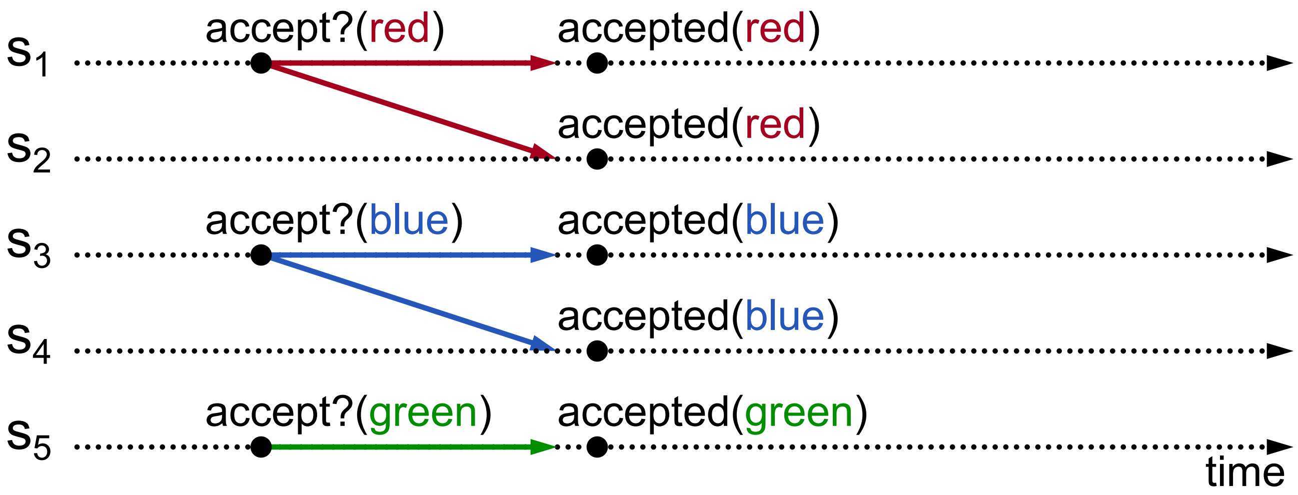
Strawman: Single Acceptor

- **Simple (incorrect) approach: a single acceptor chooses value**
- **What if acceptor crashes after choosing?**
- **Solution: quorum**
  - Multiple acceptors (3, 5, ...)
  - Value v is chosen if accepted by majority of acceptors
  - If one acceptor crashes, chosen value still available



Problem: Split Votes

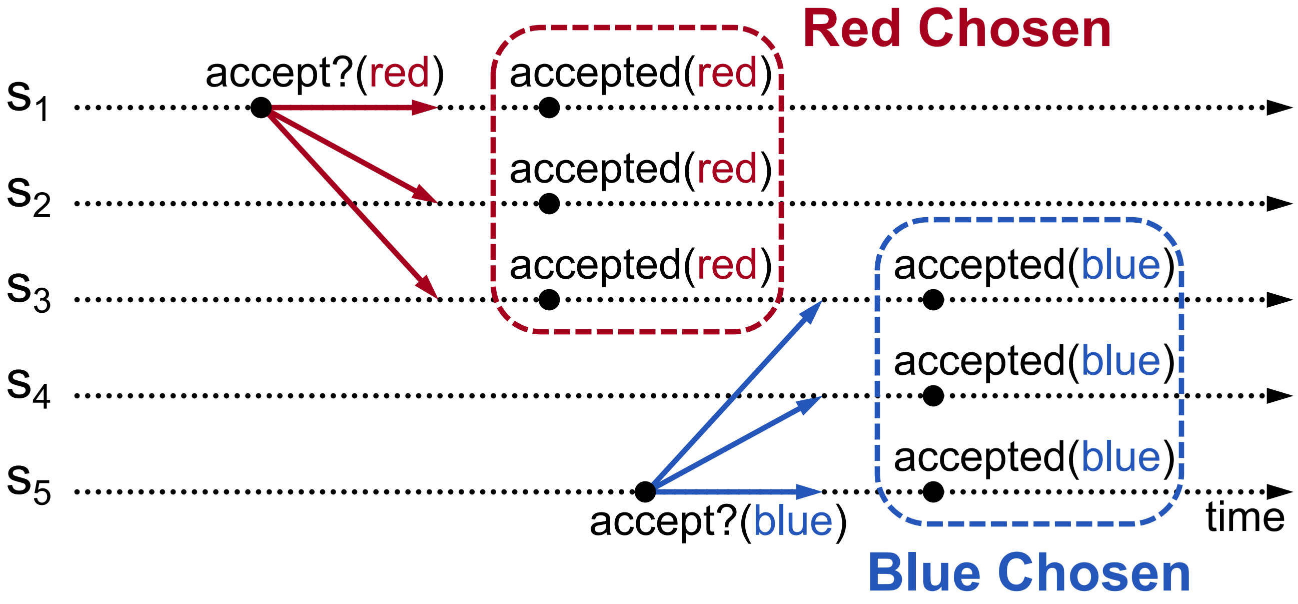
- Acceptor accepts only first value it receives?
- If simultaneous proposals, no value might be chosen



Acceptors must sometimes accept multiple (different) values

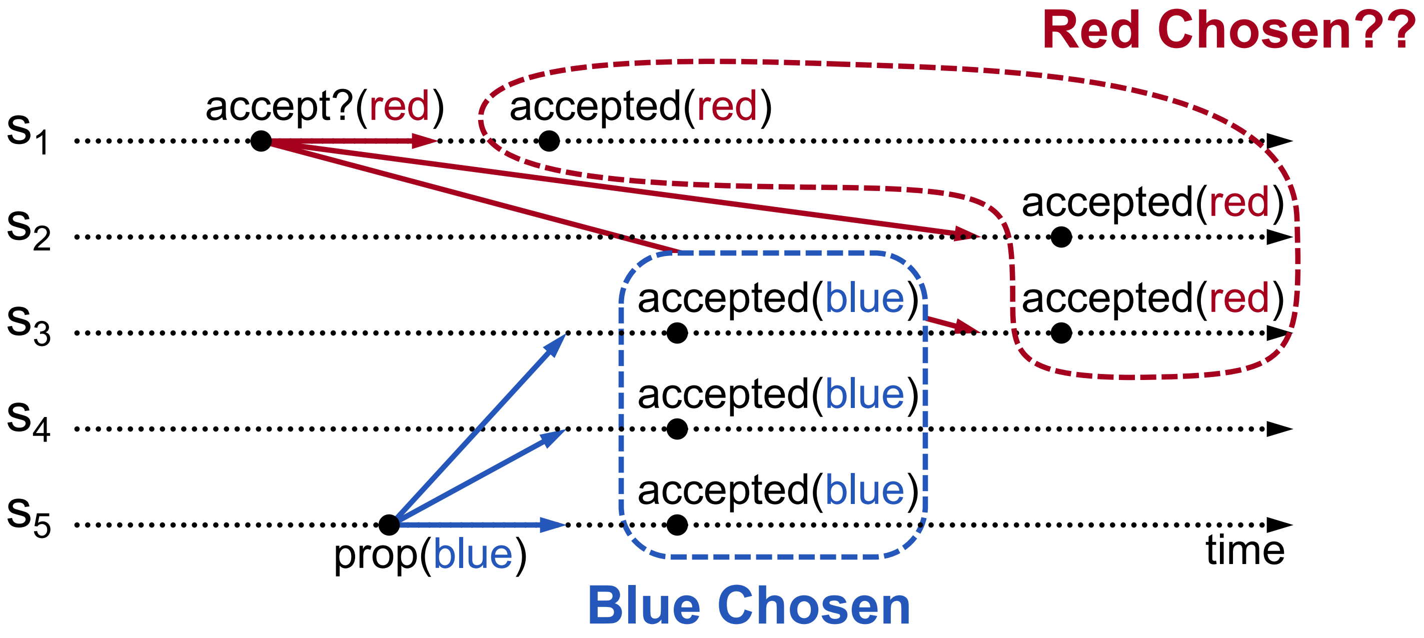
Problem: Conflicting Choices

- Acceptor accepts every value it receives?
- Could choose multiple values



Once a value has been chosen, future proposals must propose/choose that same value (2-phase protocol)

Conflicting Choices, cont’d

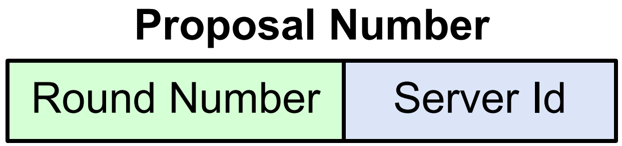


- s_5 needn’t propose red (it hasn’t been chosen yet)
- s_1’s proposal must be aborted (s_3 must reject it)

Must order proposals, reject old ones

Proposal Numbers

- **Each proposal has a unique number**
  - Higher numbers take priority over lower numbers
  - It must be possible for a proposer to choose a new proposal number higher than anything it has seen/used before
- **One simple approach:**



Proposal Number

Round Number | Server Id

  - Each server stores maxRound: the largest Round Number it has seen so far
  - To generate a new proposal number:
    - Increment maxRound
    - Concatenate with Server Id
  - Proposers must persist maxRound on disk: must not reuse proposal numbers after crash/restart

Basic Paxos

Two-phase approach:

- **Phase 1: broadcast Prepare RPCs**
  - Find out about any chosen values
  - Block older proposals that have not yet completed
- **Phase 2: broadcast Accept RPCs**
  - Ask acceptors to accept a specific value

Basic Paxos

Proposers | **Acceptors**

1) Choose new proposal number n

2) Broadcast Prepare(n) to all servers

3) Respond to Prepare(n):
   - If n > minProposal then minProposal = n
   - Return(acceptedProposal, acceptedValue)

4) When responses received from majority:
   - If any acceptedValues returned, replace value with acceptedValue for highest acceptedProposal

5) Broadcast Accept(n, value) to all servers

6) Respond to Accept(n, value):
   - If n ≥ minProposal then
     acceptedProposal = minProposal = n
     acceptedValue = value
   - Return(minProposal)

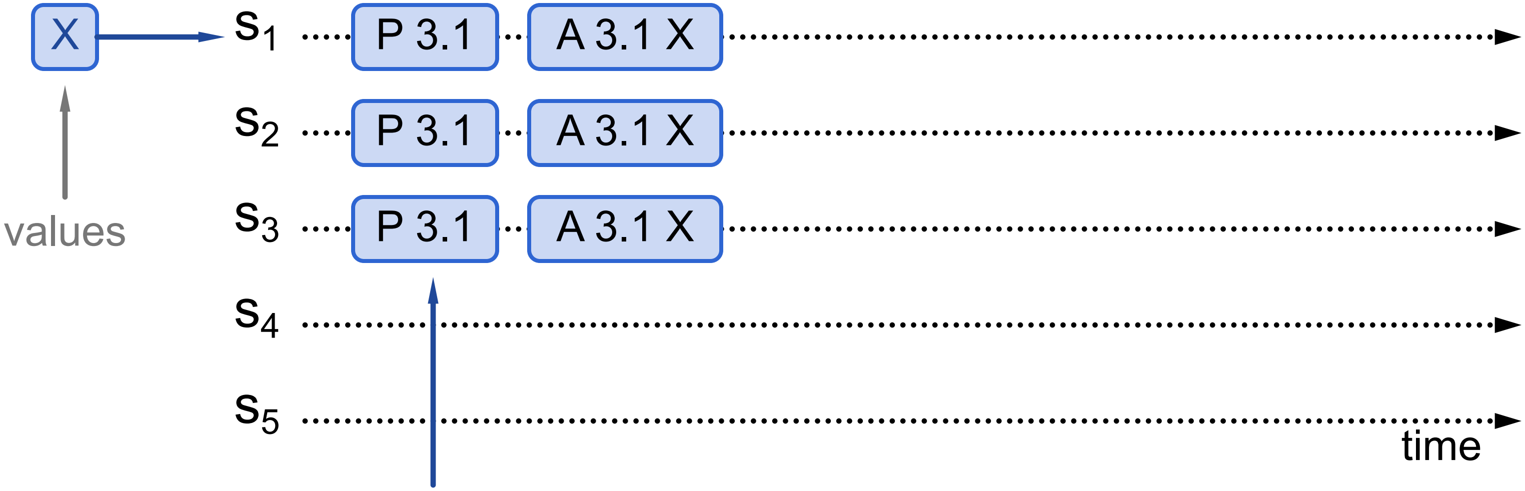
6) When responses received from majority:
   - Any rejections (result > n)? goto (1)
   - Otherwise, **value is chosen**

Acceptors must record minProposal, acceptedProposal, and acceptedValue on stable storage (disk)

Basic Paxos Examples

Three possibilities when later proposal prepares:

1. **Previous value already chosen:**
   - New proposer will find it and use it



“Prepare proposal 3.1 (from s_1)”

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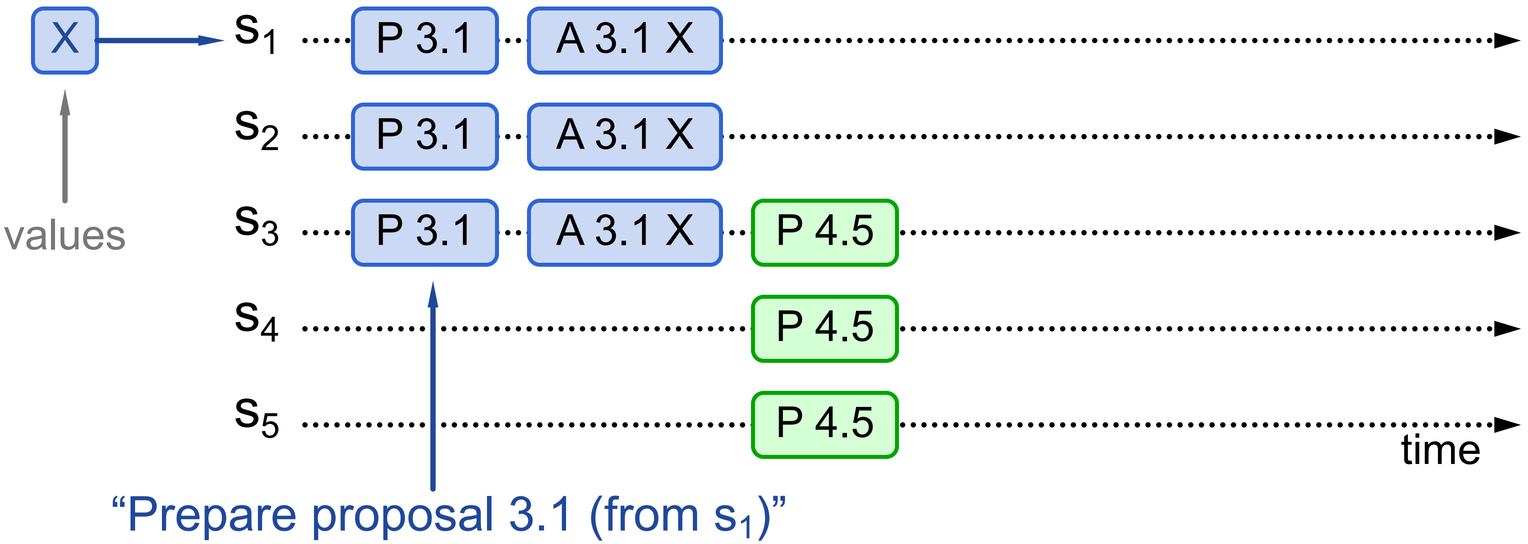

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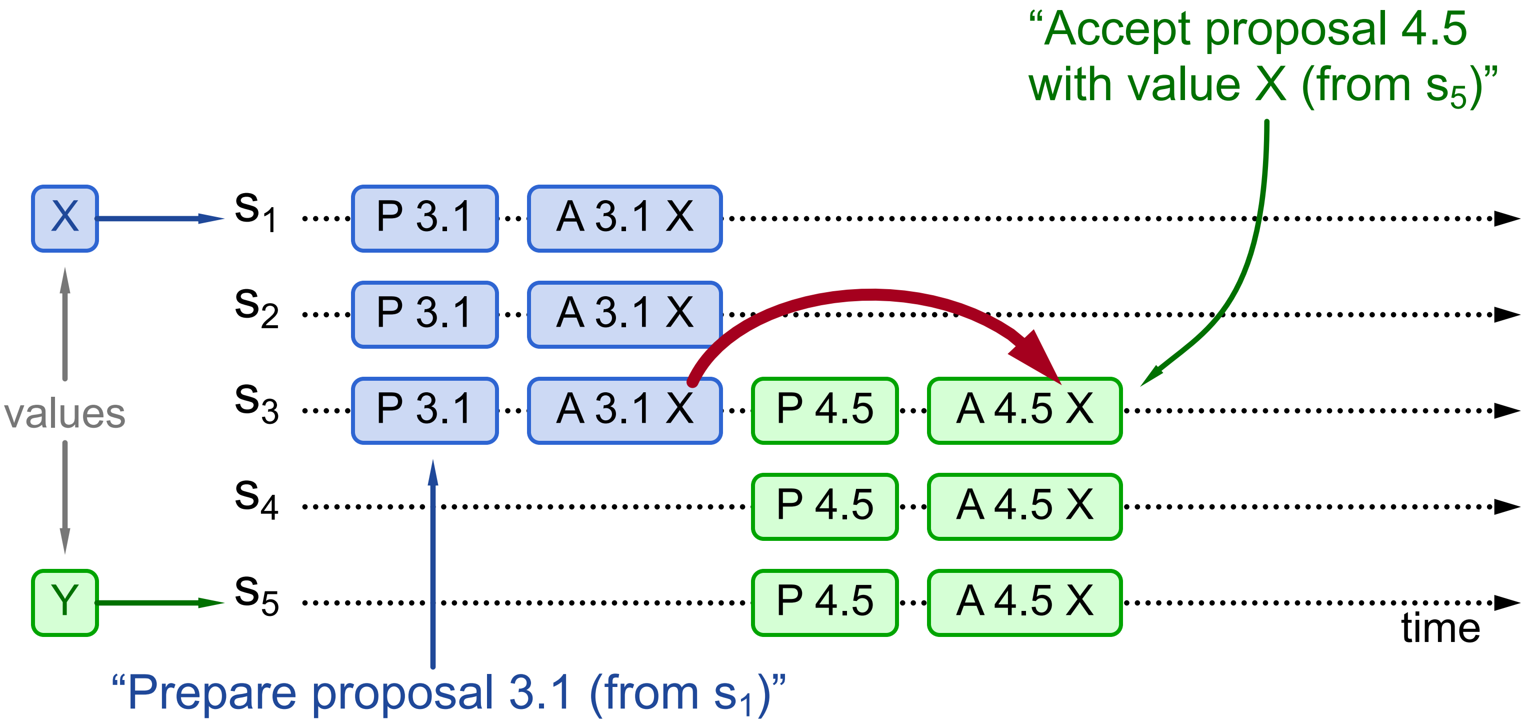
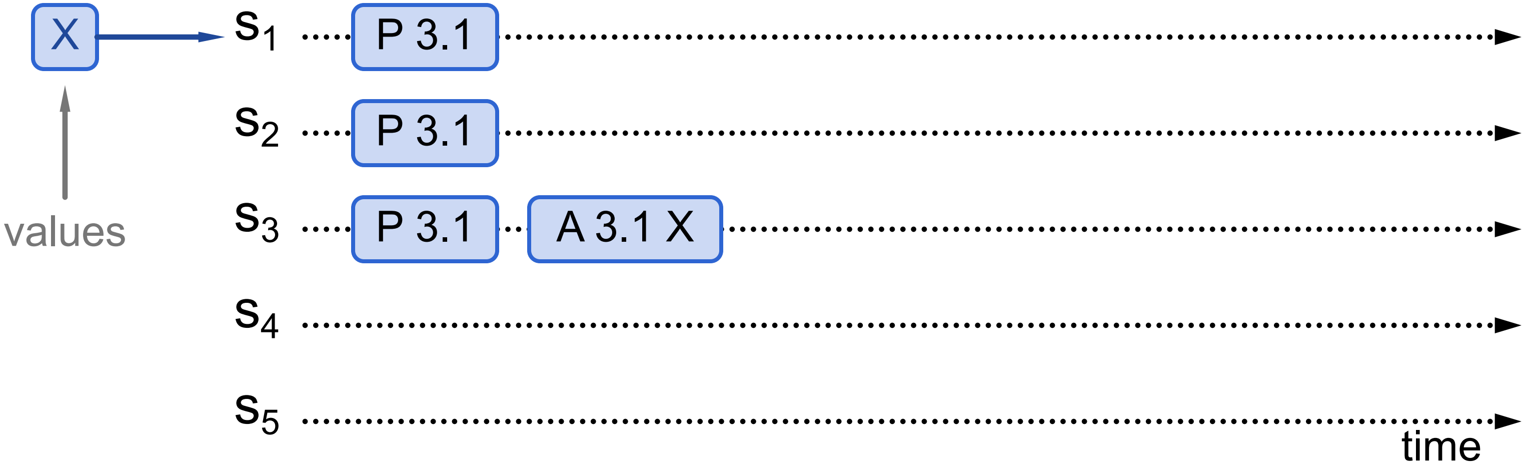


Basic Paxos Examples, cont'd

Three possibilities when later proposal prepares:

2. **Previous value not chosen, but new proposer sees it:**
   - New proposer will use existing value
   - Both proposers can succeed



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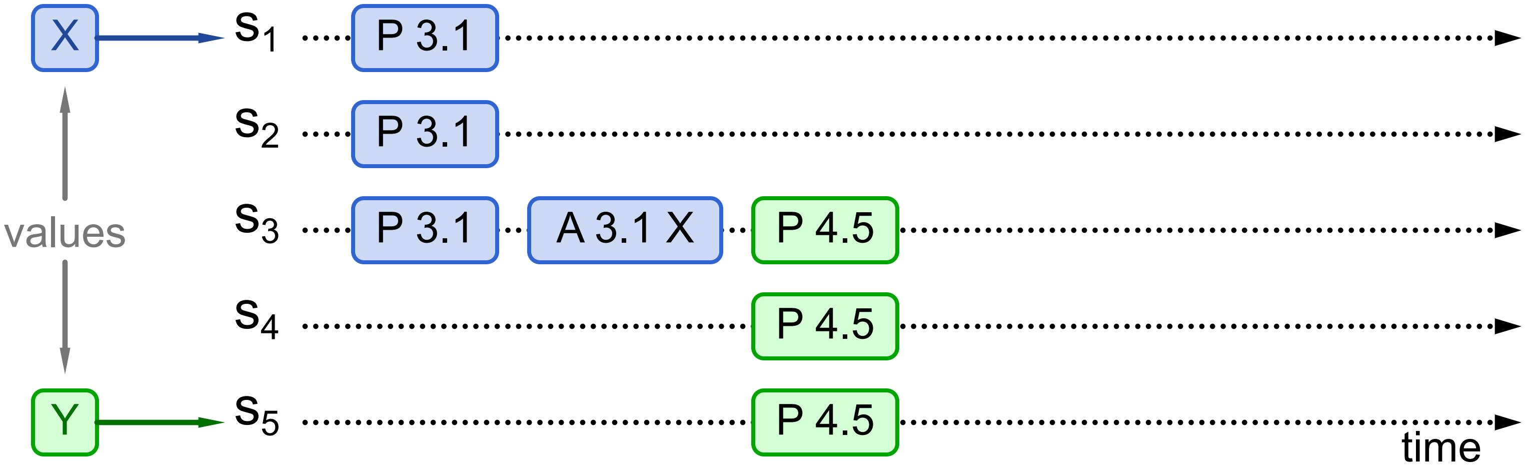

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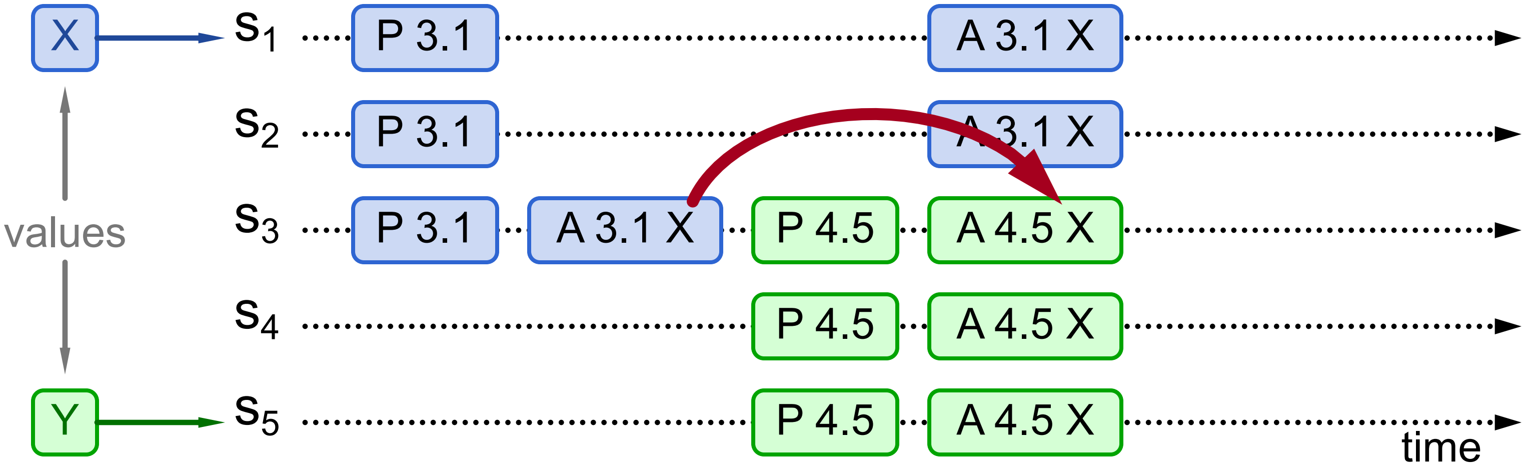
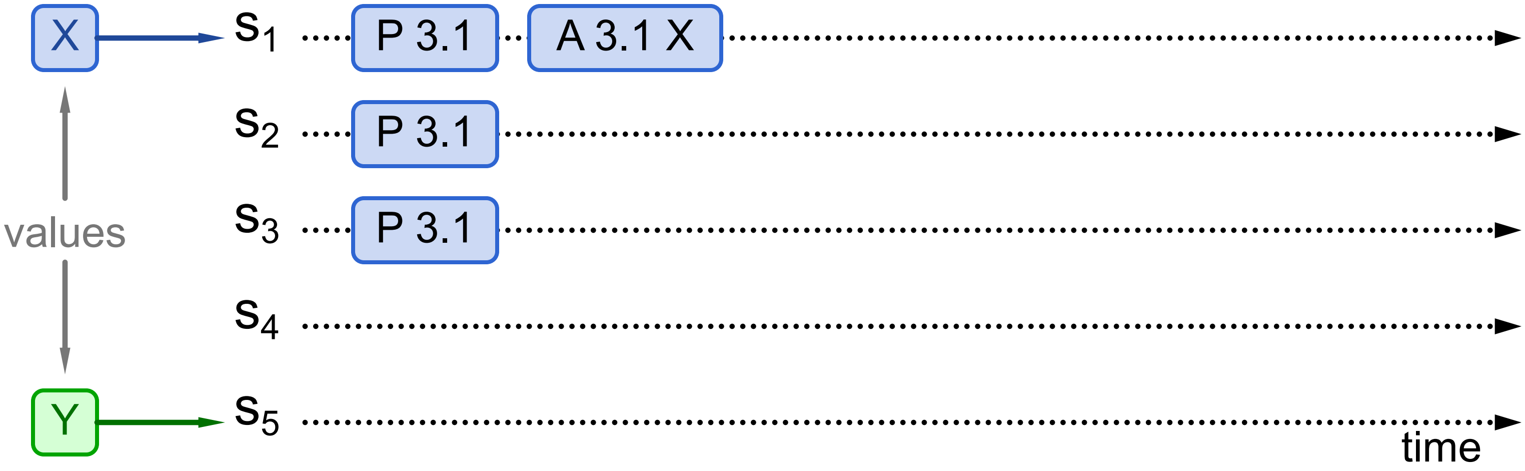


Basic Paxos Examples, cont’d

Three possibilities when later proposal prepares:

3. **Previous value not chosen, new proposer doesn’t see it:**
   - New proposer chooses its own value
   - Older proposal blocked



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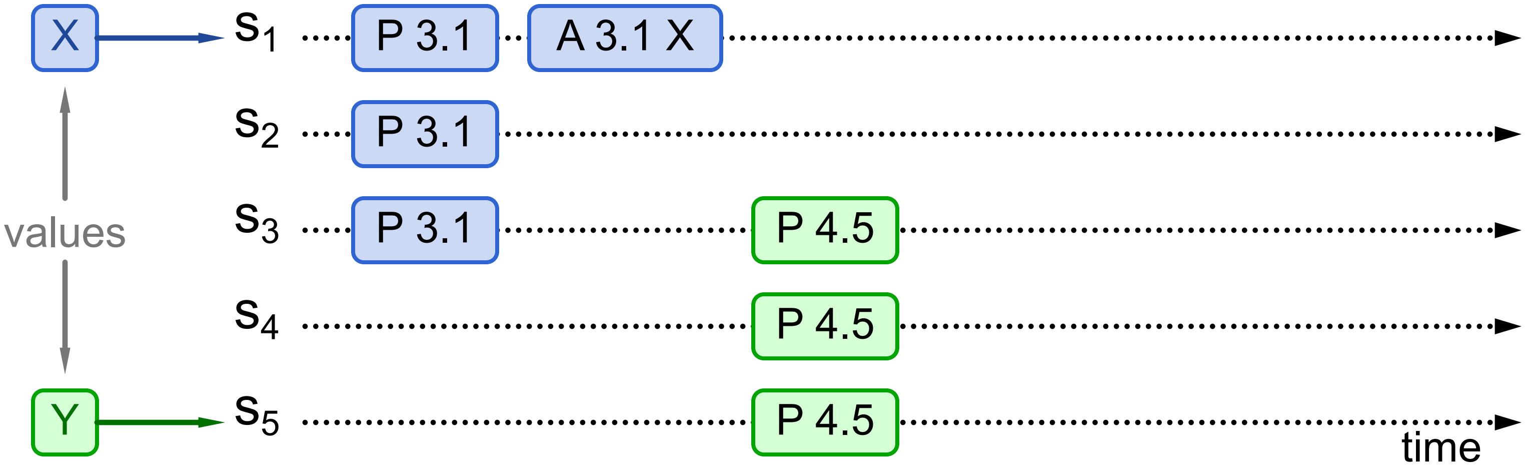

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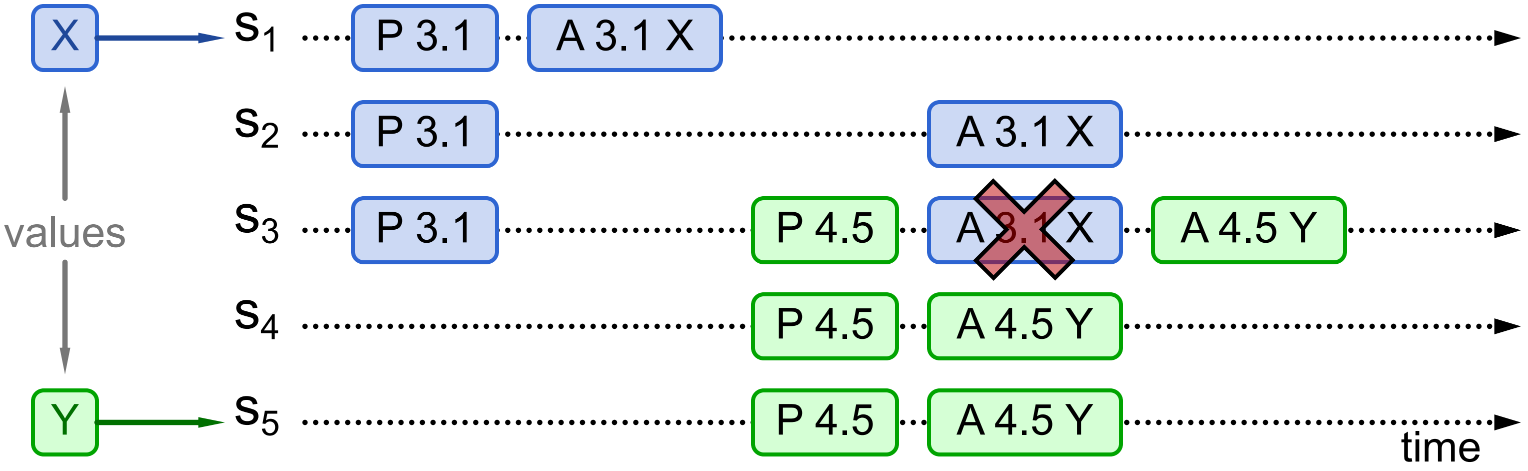

Liveness

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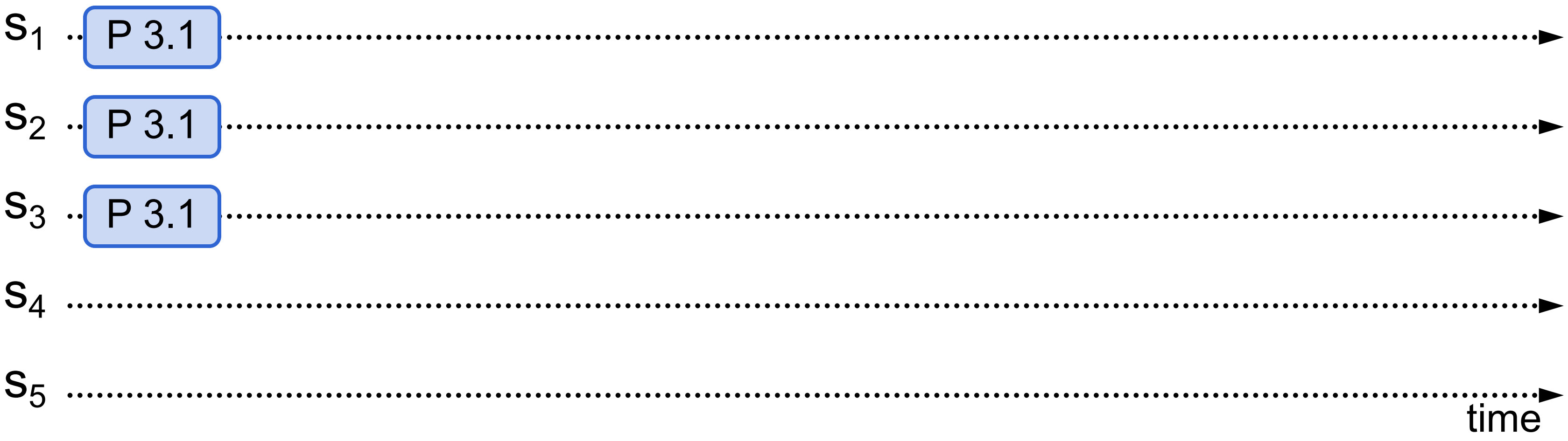

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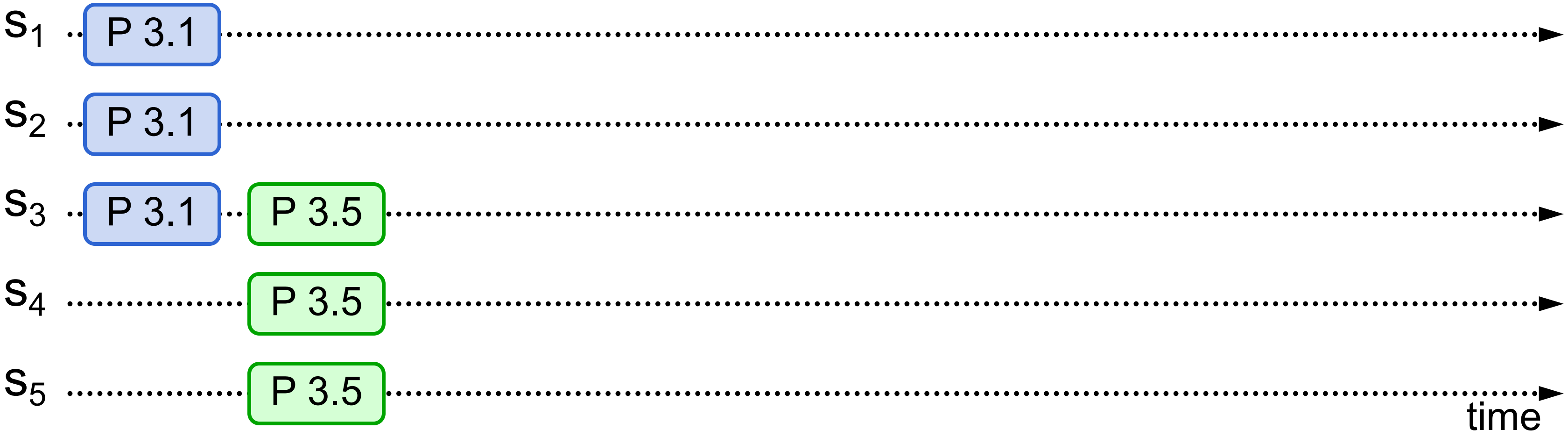

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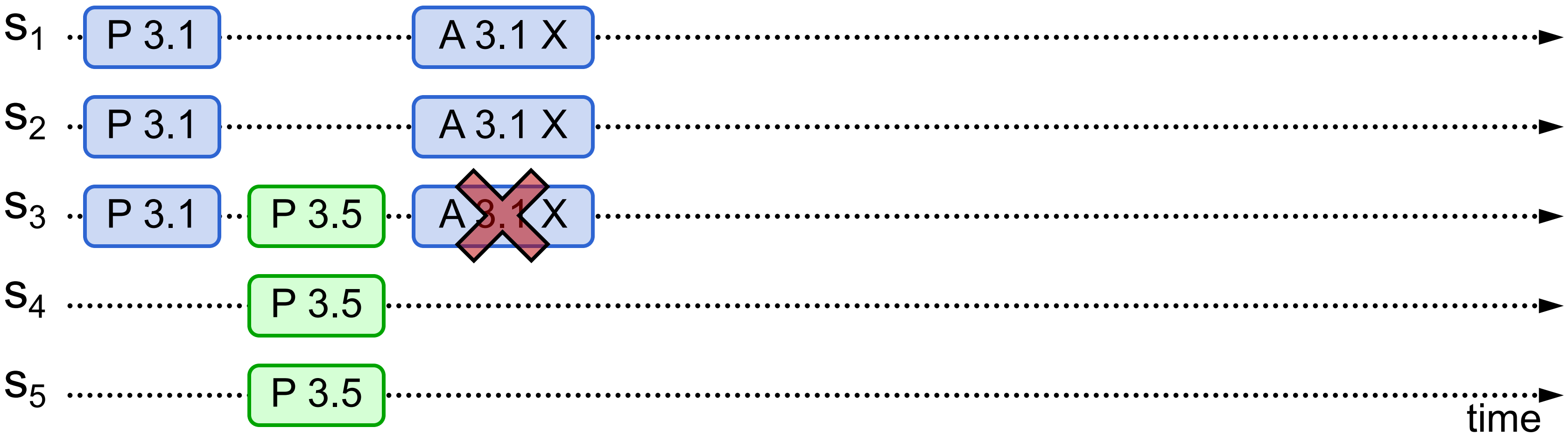

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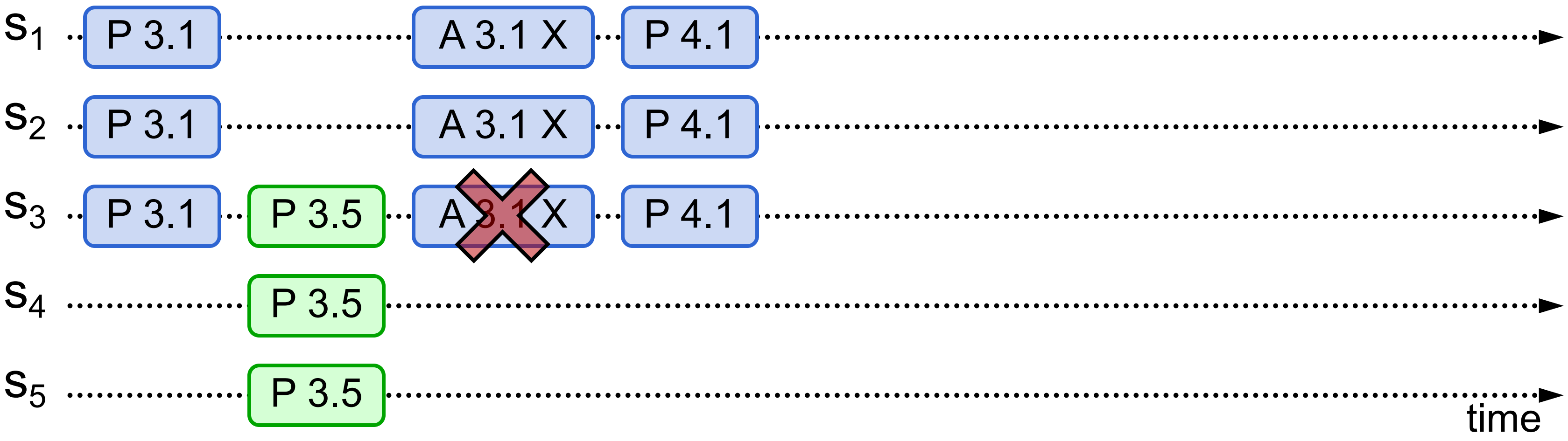

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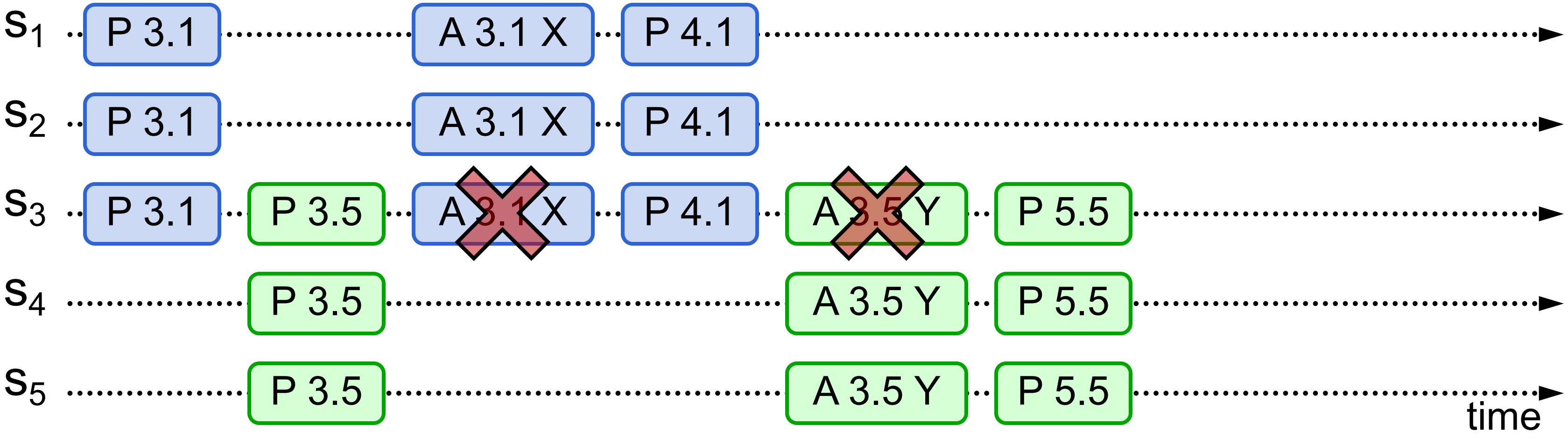

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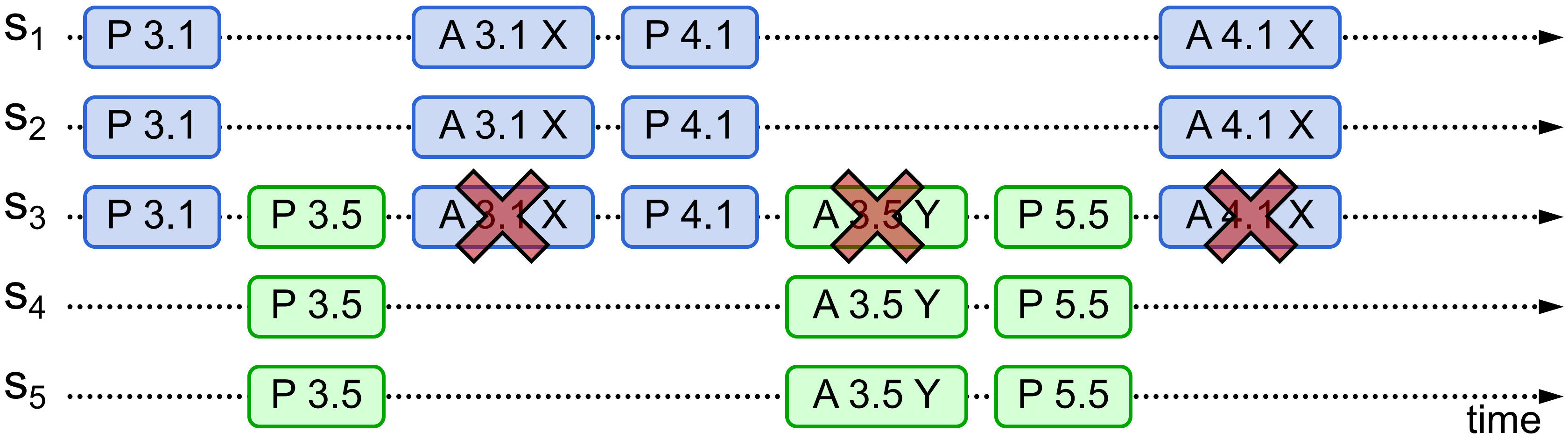
s_1 P 3.1 A 3.1 X P 4.1 A 4.1 X
s_2 P 3.1 A 3.1 X P 4.1 A 4.1 X
s_3 P 3.1 P 3.5 A 3.1 X P 4.1 A 3.5 Y P 5.5 A 4.1 X
s_4 P 3.5 A 3.5 Y P 5.5
s_5 P 3.5 A 3.5 Y P 5.5
time

Liveness

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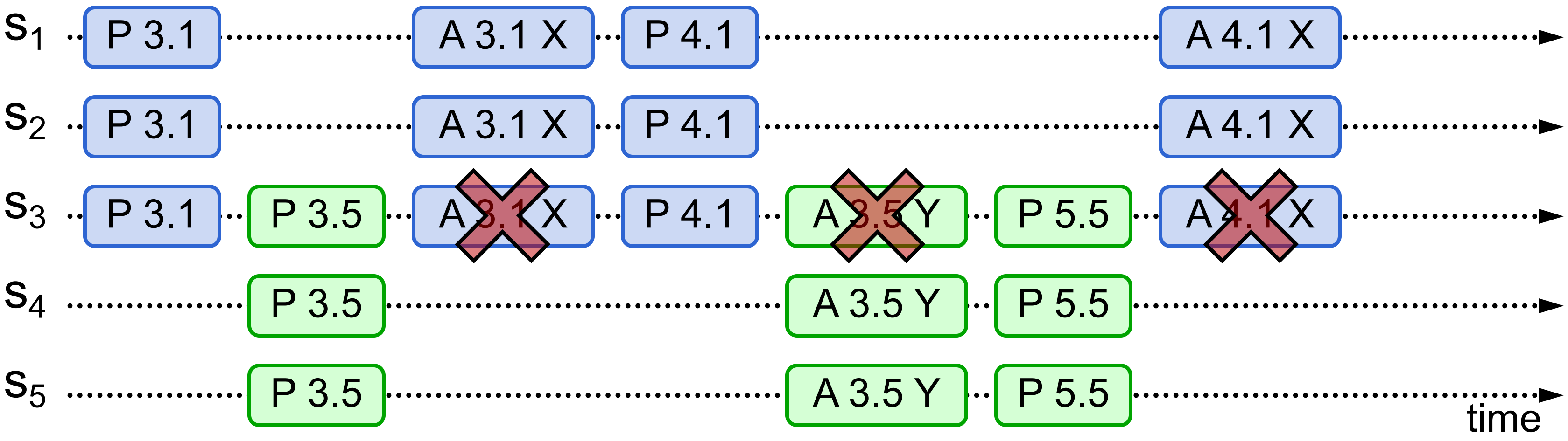


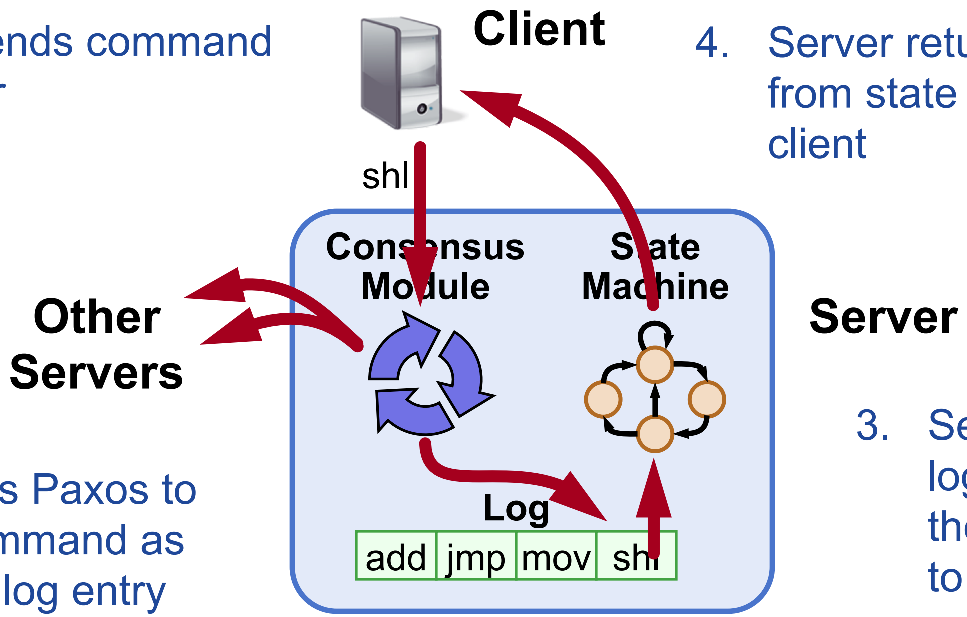
- **One solution: randomized delay before restarting**
  - Give other proposers a chance to finish choosing
- **Multi-Paxos will use leader election instead**

Other Notes

- Only proposer knows which value has been chosen
- If other servers want to know, must execute Paxos with their own proposal

Multi-Paxos

- **Separate instance of Basic Paxos for each entry in the log:**
  - Add index argument to Prepare and Accept (selects entry in log)



Client

shl

Other Servers

Consensus Module

State Machine

Log

add	jmp	mov	shl

Server

1. Client sends command to server
2. Server uses Paxos to choose command as value for a log entry
3. Server waits for previous log entries to be applied, then applies new command to state machine
4. Server returns result from state machine to client

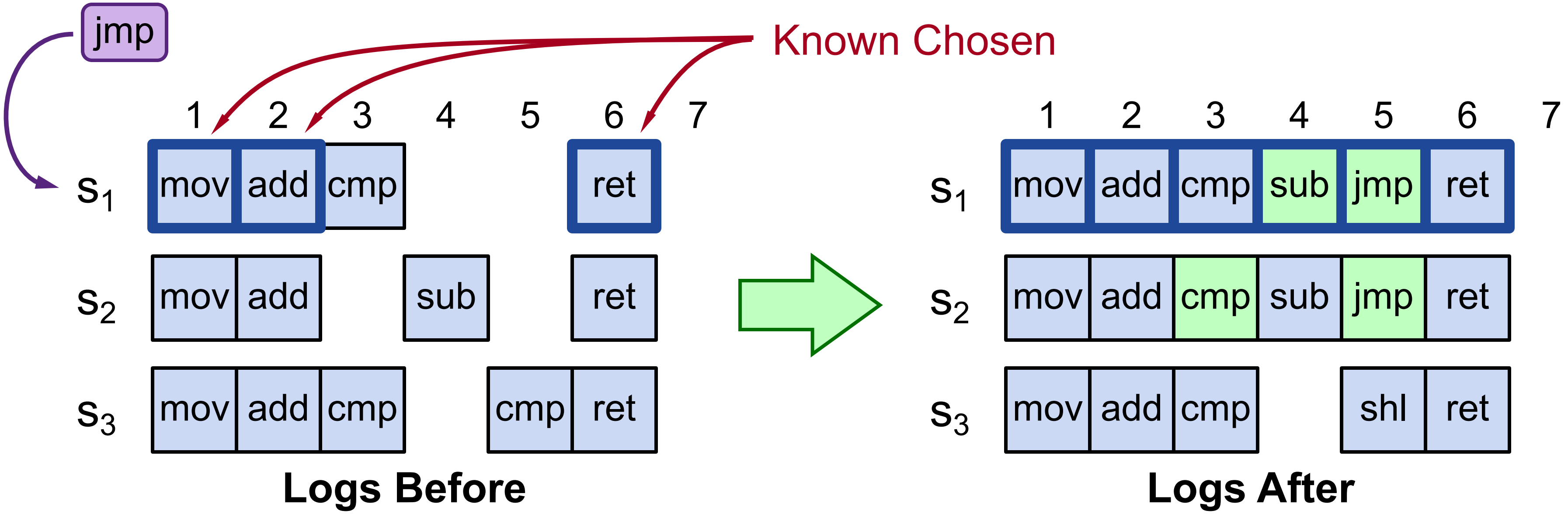
Multi-Paxos Issues

- **Which log entry to use for a given client request?**
- **Performance optimizations:**
  - Use leader to reduce proposer conflicts
  - Eliminate most Prepare requests
- **Ensuring full replication**
- **Client protocol**
- **Configuration changes**

Note: Multi-Paxos not specified precisely in literature

Selecting Log Entries

- **When request arrives from client:**
  - Find first log entry not known to be chosen
  - Run Basic Paxos to propose client's command for this index
  - Prepare returns acceptedValue?
    - Yes: finish choosing acceptedValue, start again
    - No: choose client's command



Selecting Log Entries, cont’d

- **Servers can handle multiple client requests concurrently:**
  - Select different log entries for each
- **Must apply commands to state machine in log order**