Implementing Replicated Logs with Paxos

John Ousterhout and Diego Ongaro

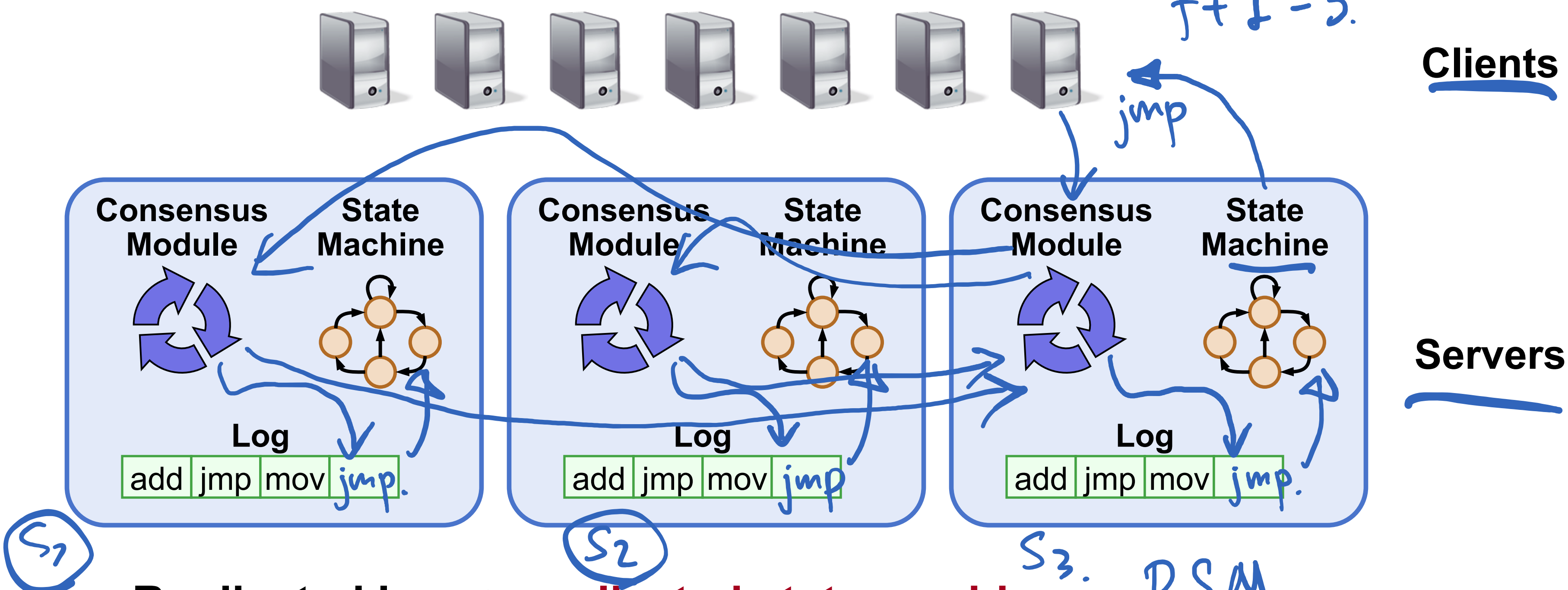
Stanford University

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

$f=1$
$f+1=2.$

Goal: Replicated Log

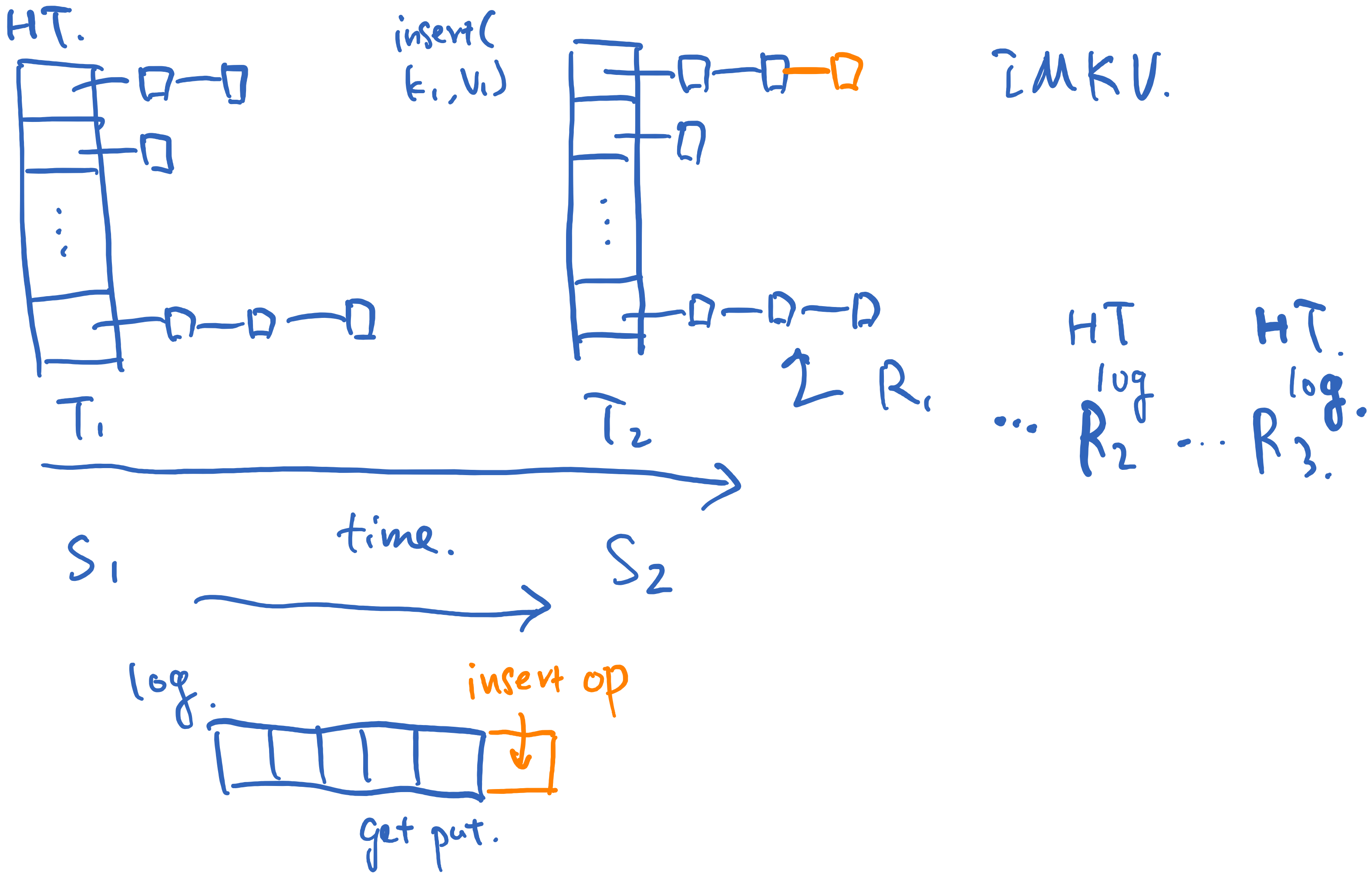
$2f+1=N.$ 3
$f=2.$ 5.
$f+1=3.$



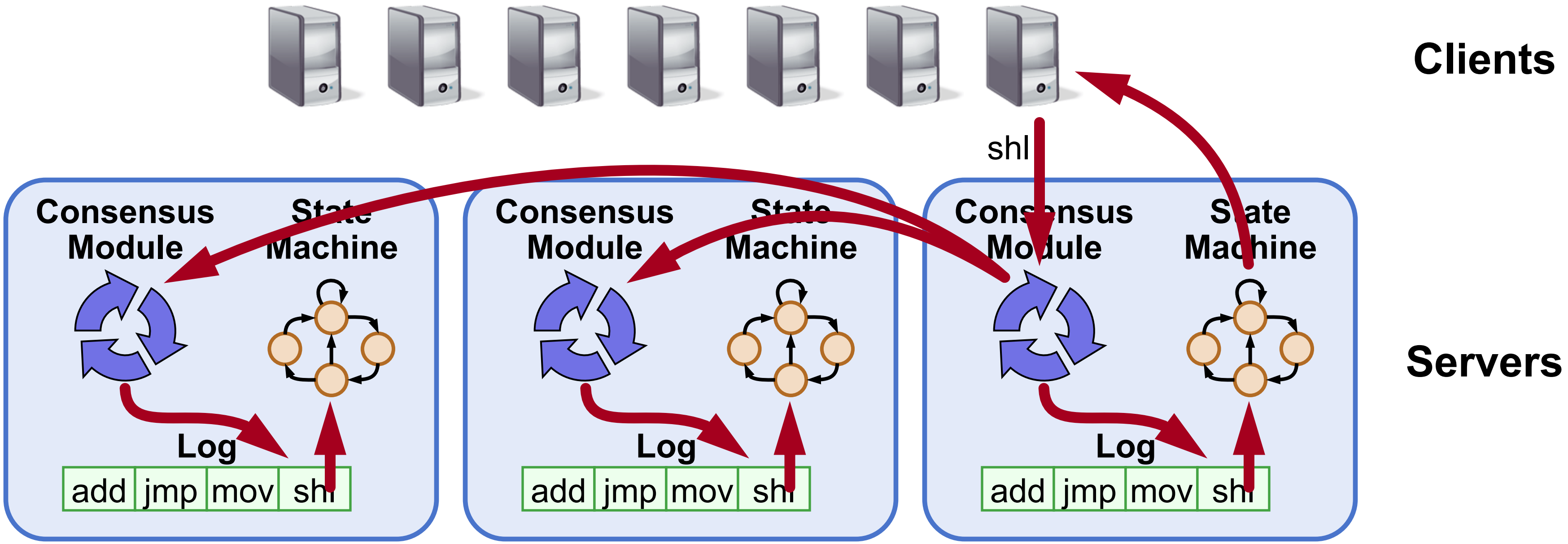
RSM.

3 5 7 9.

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


HT.
insert(
(k1, v1)
IMKV.
T1
T2
R1
... R2
log
HT
... R3.
HT.
log.
S1
time.
S2
log.
insert op
get put.

Goal: Replicated Log



- **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**

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

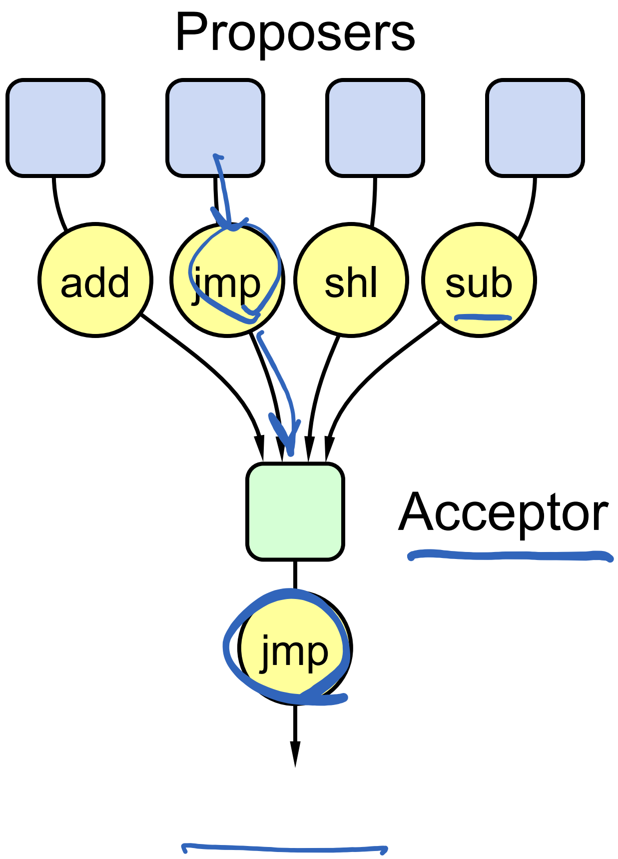
- **Proposers:**
  - Active: put forth particular values to be chosen
  - Handle client requests
- **Acceptors:**
  - Passive: respond to messages from proposers
  - Responses represent votes that form consensus
  - Store chosen value, state of the decision process
  - Want to know which value was chosen

For this presentation:

- Each Paxos server contains both components

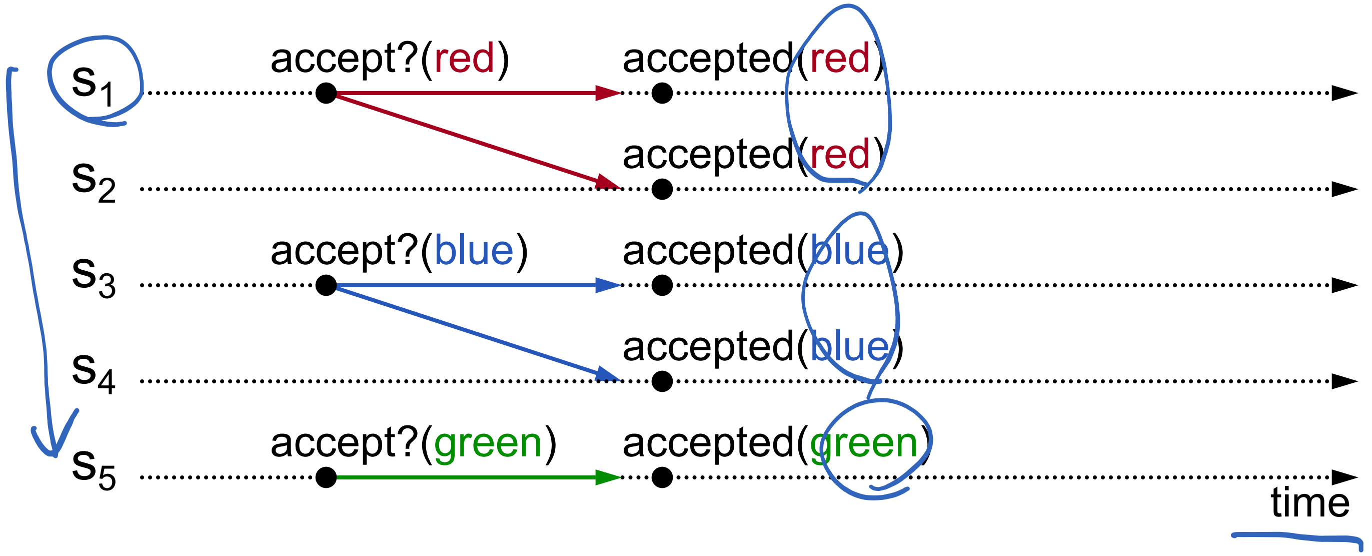
Strawman: Single Acceptor

- **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

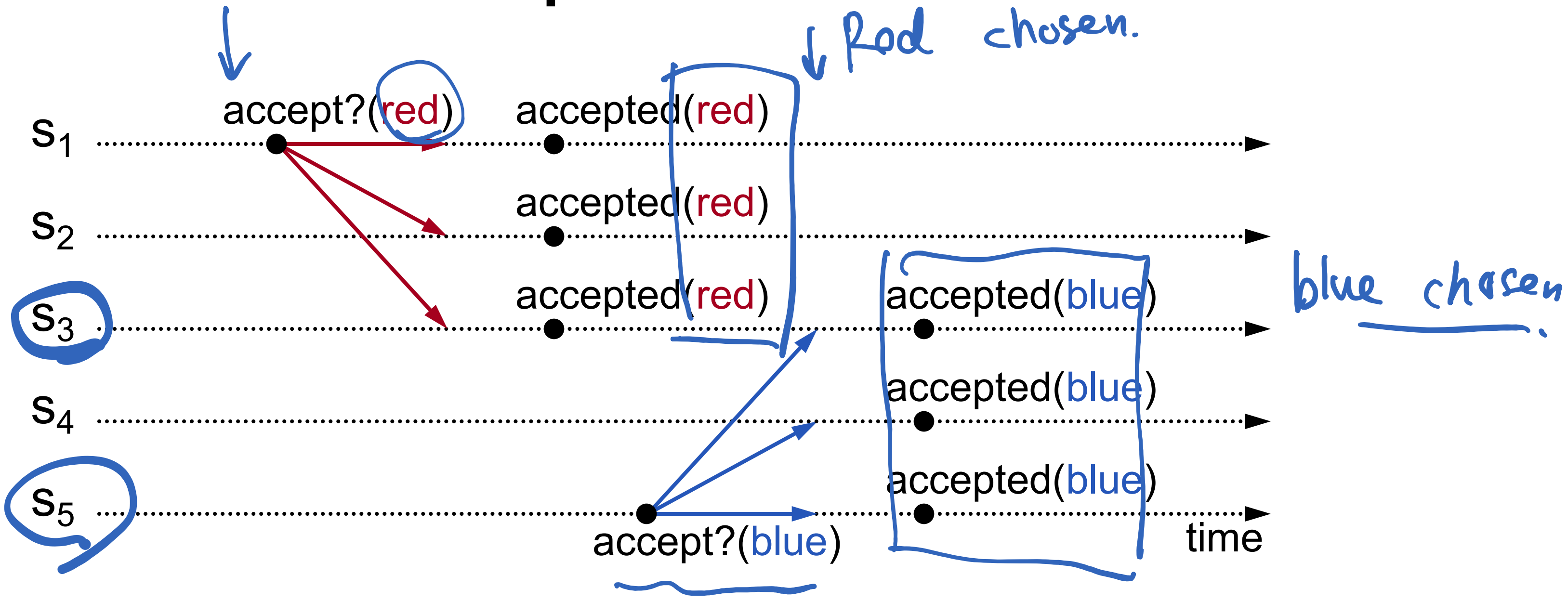
- Acceptor accepts only first value it receives?
- If simultaneous proposals, no value might be chosen



Acceptors must sometimes accept multiple (different) values

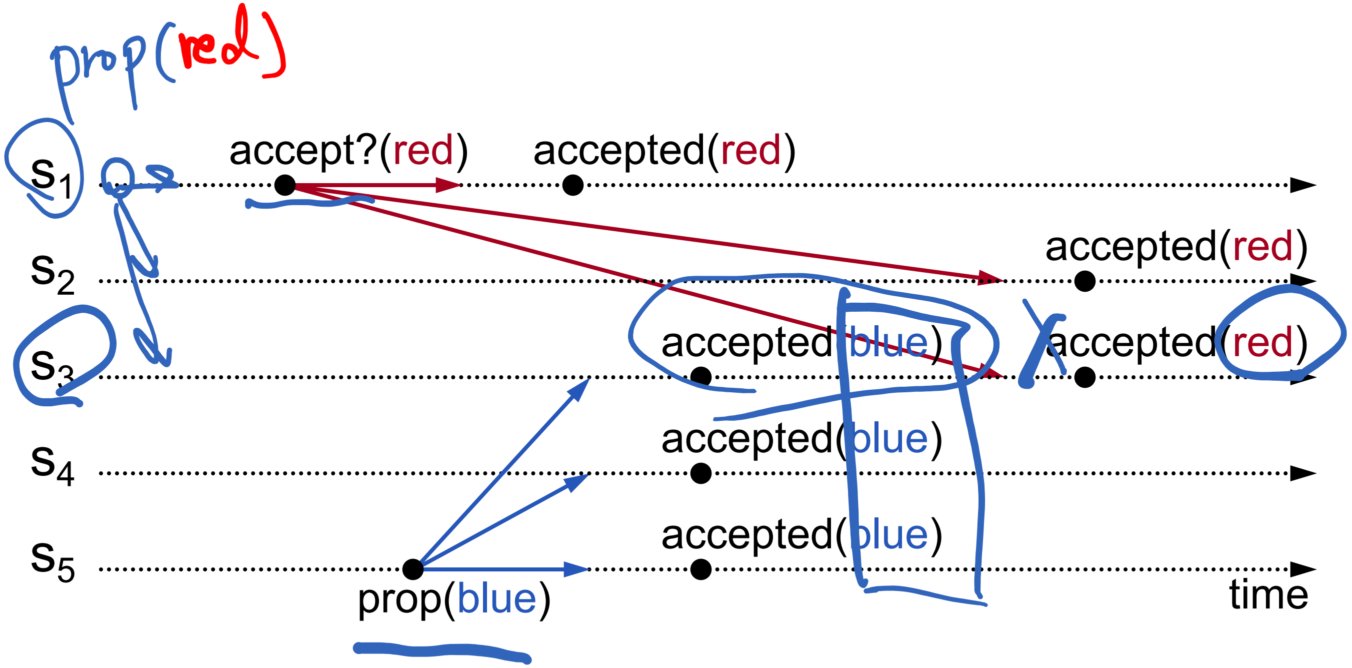
Problem: Conflicting Choices

- 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

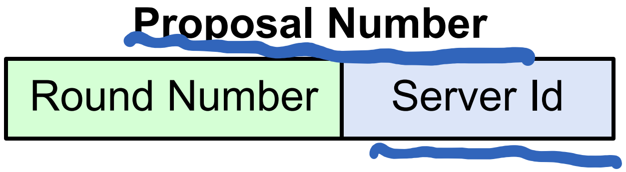


- s_5 needn't propose red (it hasn't been chosen yet)
- s_1's proposal must be aborted (s_3 must reject it)

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:**



  - 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

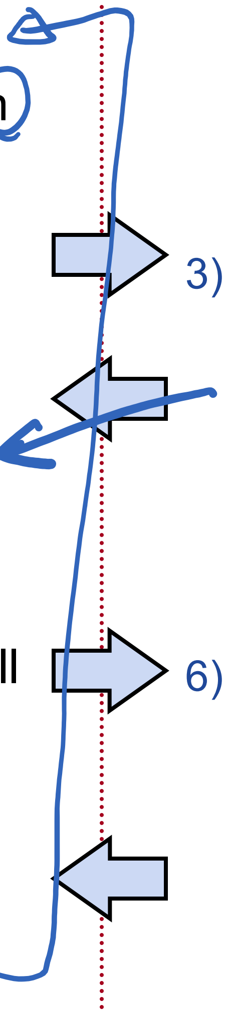
Basic Building Blocks.

1. Logical Clock. → (Proposal #).

2. RPC.

3. 2P protocol.

Basic Paxos



Proposers

Acceptors

P1

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

P2

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:

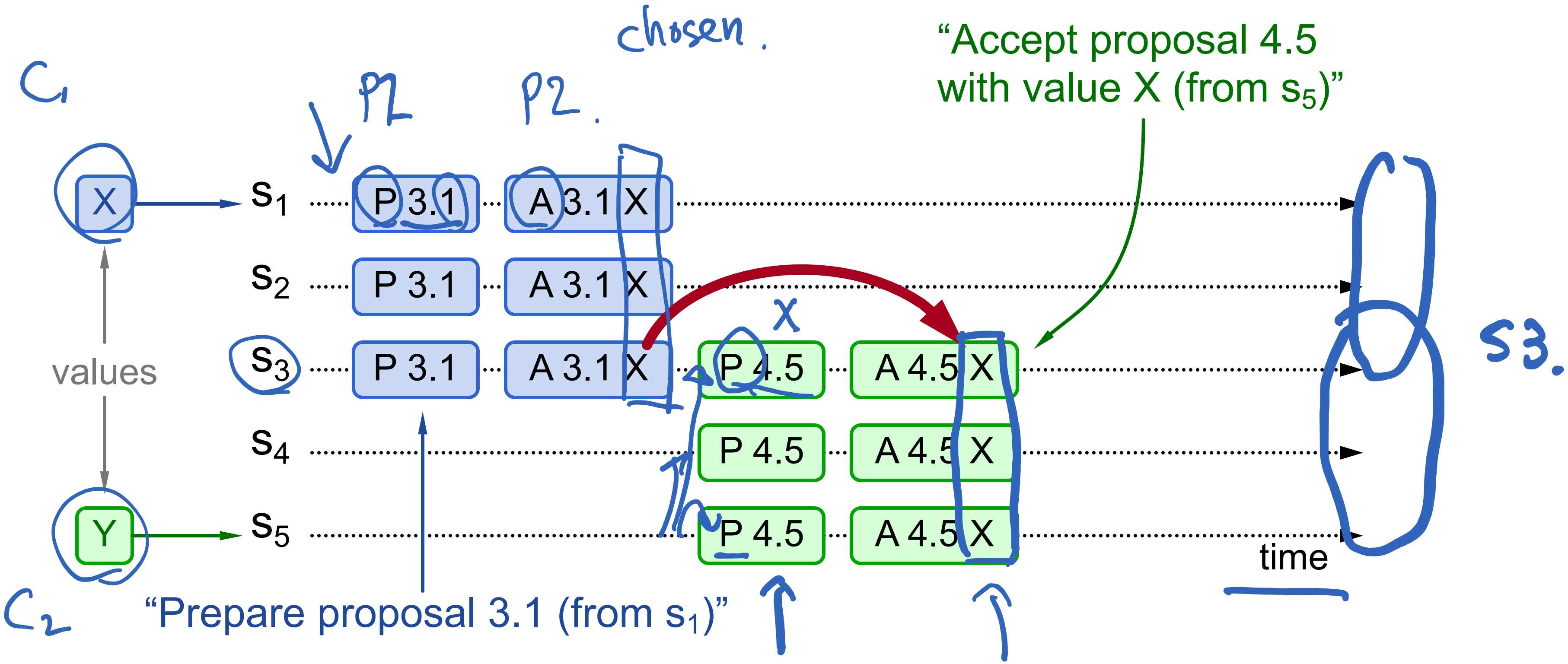
- Any rejections (result > n)? goto (1)
- Otherwise, **value is chosen**

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



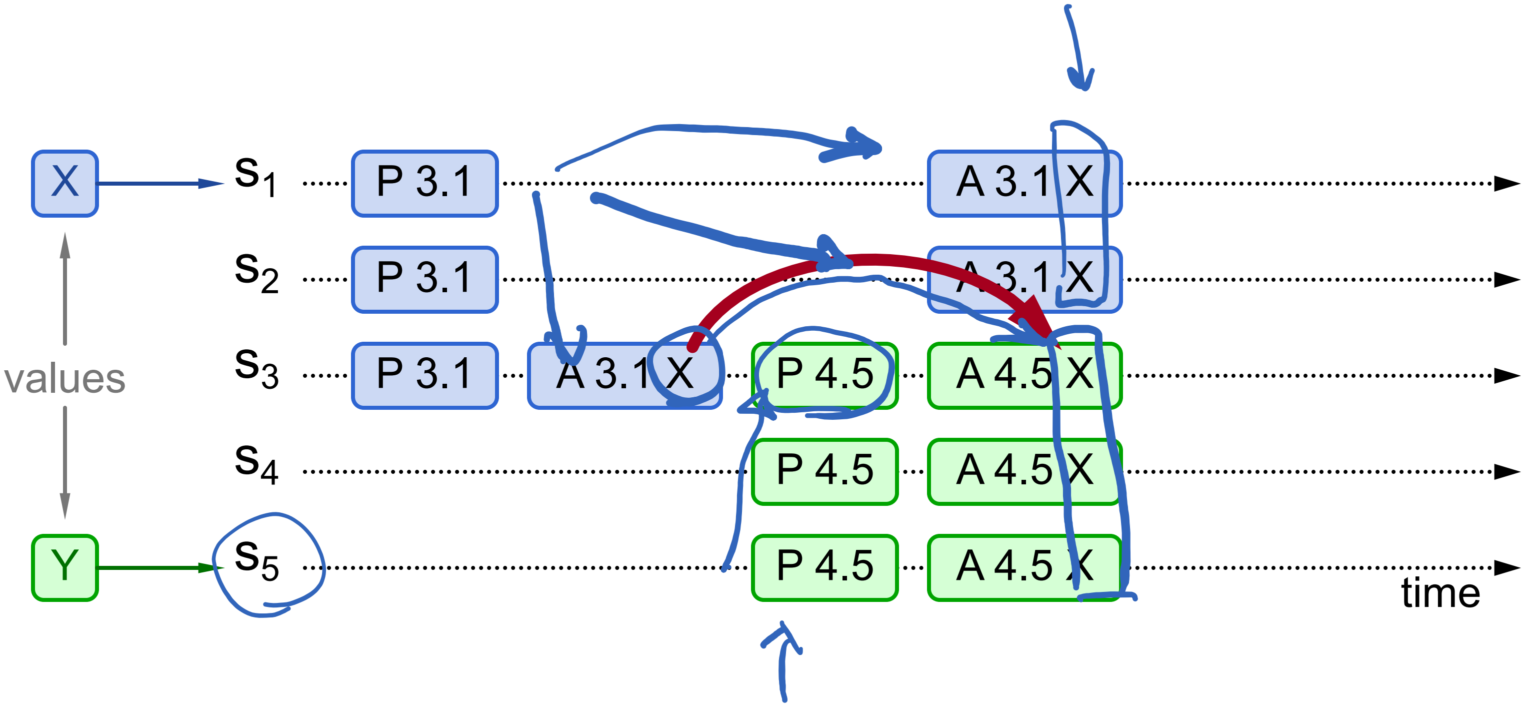
"Accept proposal 4.5 with value X (from s_5)"

"Prepare proposal 3.1 (from s_1)"

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



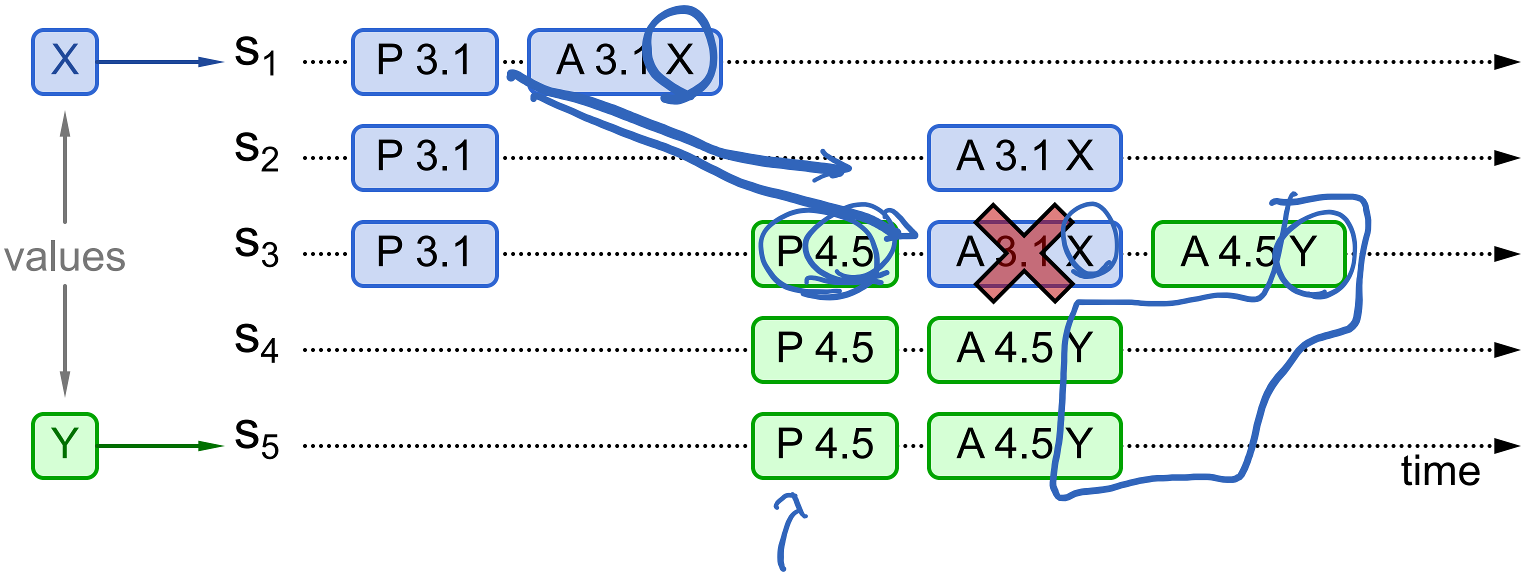
Basic Paxos Examples, cont’d

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

min Proposal

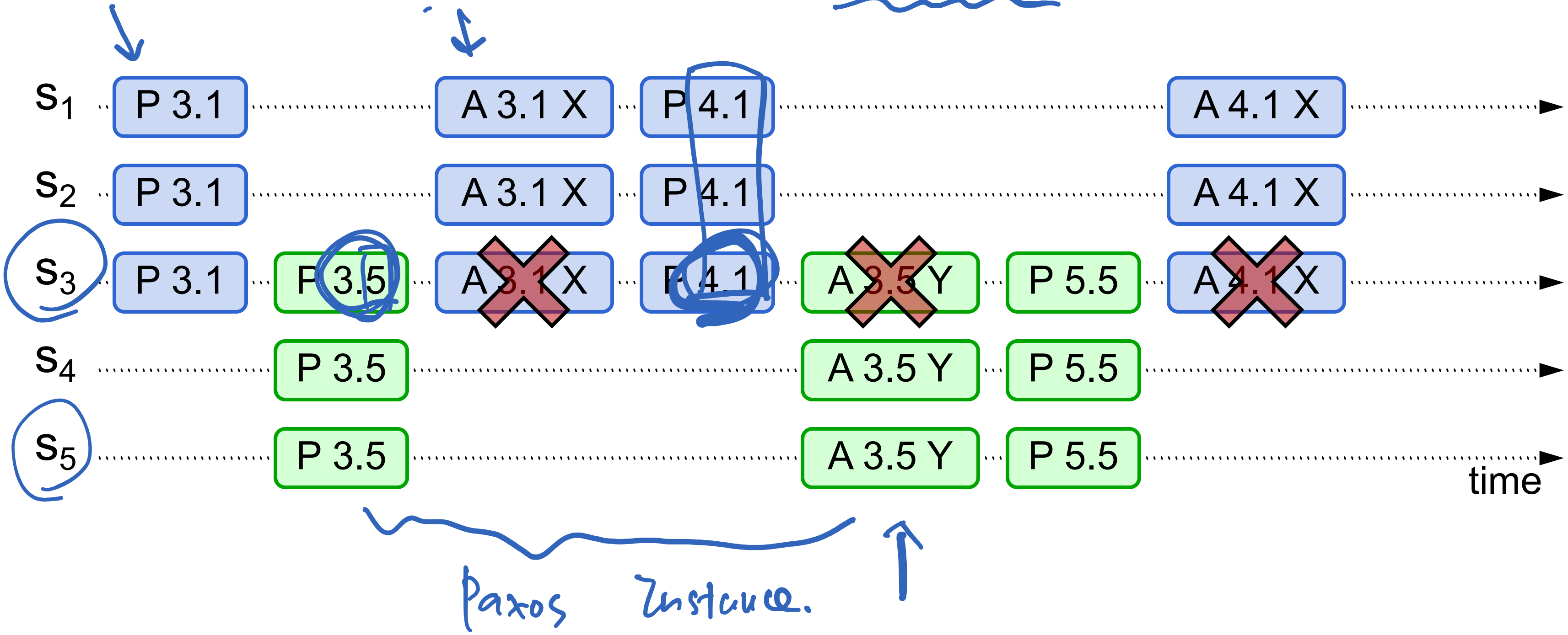
4.5 > 3.1 ← n (s1)



Paxos Instance

Liveness

- **Competing proposers can livelock:**



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	

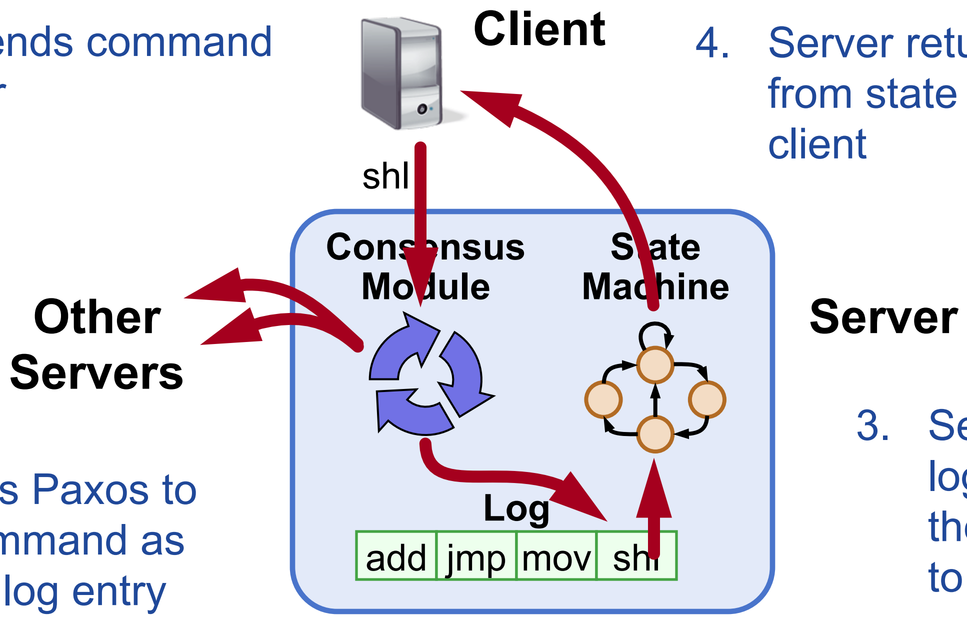
- **One solution: randomized delay before restarting**
  - Give other proposers a chance to finish choosing
- **Multi-Paxos will use leader election instead**

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)



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

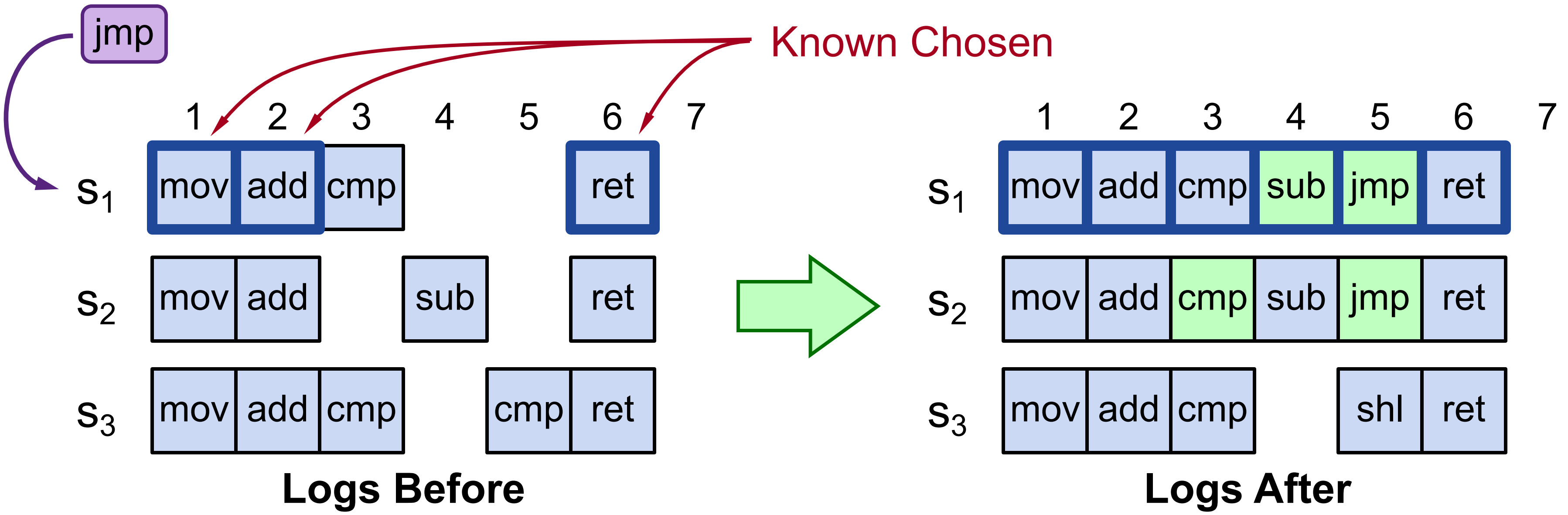
Multi-Paxos Issues

- **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



Logs Before

	1	2	3	4	5	6	7
s_1	mov	add	cmp			ret	
s_2	mov	add		sub		ret	
s_3	mov	add	cmp		cmp	ret	

Logs After

	1	2	3	4	5	6	7
s_1	mov	add	cmp	sub	jmp	ret	
s_2	mov	add	cmp	sub	jmp	ret	
s_3	mov	add	cmp		shl	ret	

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**

Improving Efficiency

- **Using Basic Paxos is inefficient:**
  - With multiple concurrent proposers, conflicts and restarts are likely (higher load → more conflicts)
  - 2 rounds of RPCs for each value chosen (Prepare, Accept)

Solution:

1. **Pick a leader**
   - At any given time, only one server acts as Proposer
2. **Eliminate most Prepare RPCs**
   - Prepare once for the entire log (not once per entry)
   - Most log entries can be chosen in a single round of RPCs

Leader Election

One simple approach from Lamport:

- **Let the server with highest ID act as leader**
- **Each server sends a heartbeat message to every other server every T ms**
- **If a server hasn't received heartbeat from server with higher ID in last 2T ms, it acts as leader:**
  - Accepts requests from clients
  - Acts as proposer and acceptor
- **If server not leader:**
  - Rejects client requests (redirect to leader)
  - Acts only as acceptor

Eliminating Prepares

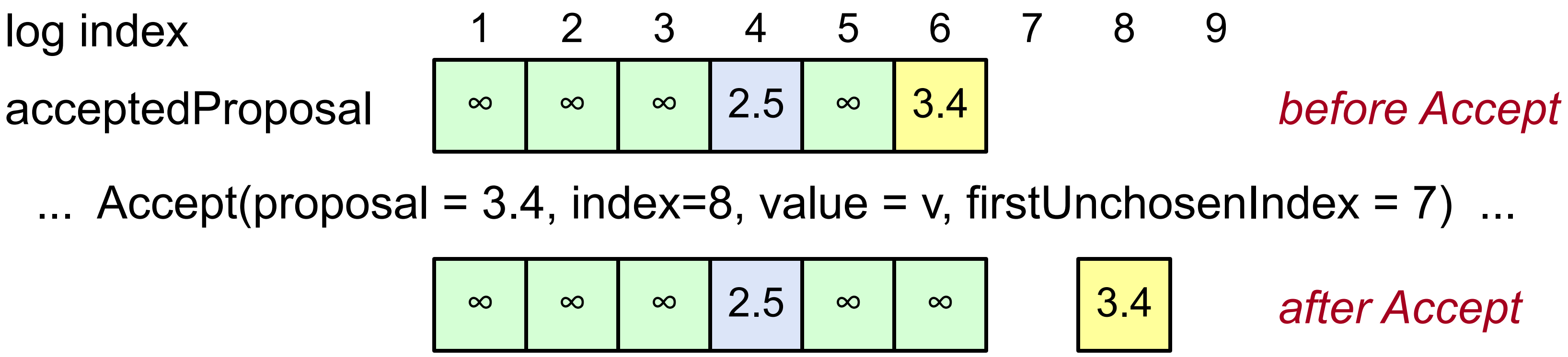
- **Why is Prepare needed?**
  - Block old proposals
    - Make proposal numbers refer to the entire log, not just one entry
  - Find out about (possibly) chosen values
    - Return highest proposal accepted for current entry
    - Also return noMoreAccepted: no proposals accepted for any log entry beyond current one
- **If acceptor responds to Prepare with noMoreAccepted, skip future Prepares with that acceptor (until Accept rejected)**
- **Once leader receives noMoreAccepted from majority of acceptors, no need for Prepare RPCs**
  - Only 1 round of RPCs needed per log entry (Accepts)

Full Disclosure

- **So far, information flow is incomplete:**
  - Log entries not fully replicated (majority only)
    Goal: full replication
  - Only proposer knows when entry is chosen
    Goal: all servers know about chosen entries
- **Solution part 1/4: keep retrying Accept RPCs until all acceptors respond (in background)**
  - Fully replicates most entries
- **Solution part 2/4: track chosen entries**
  - Mark entries that are known to be chosen:
    acceptedProposal[i] = ∞
  - Each server maintains firstUnchosenIndex: index of earliest log entry not marked as chosen

Full Disclosure, cont’d

- **Solution part 3/4: proposer tells acceptors about chosen entries**
  - Proposer includes its firstUnchosenIndex in Accept RPCs.
  - Acceptor marks all entries i chosen if:
    - i < request.firstUnchosenIndex
    - acceptedProposal[i] == request.proposal
  - Result: acceptors know about *most* chosen entries



log index	1	2	3	4	5	6	7	8	9	
acceptedProposal	∞	∞	∞	2.5	∞	3.4				*before Accept*

... Accept(proposal = 3.4, index=8, value = v, firstUnchosenIndex = 7) ...

	∞	∞	∞	2.5	∞	∞		3.4		*after Accept*

Still don’t have complete information

Full Disclosure, cont'd

- **Solution part 4/4: entries from old leaders**
  - Acceptor returns its firstUnchosenIndex in Accept replies
  - If proposer's firstUnchosenIndex > firstUnchosenIndex from response, then proposer sends Success RPC (in background)
- **Success(index, v): notifies acceptor of chosen entry:**
  - acceptedValue[index] = v
  - acceptedProposal[index] = ∞
  - return firstUnchosenIndex
  - Proposer sends additional Success RPCs, if needed

Client Protocol

- **Send commands to leader**
  - If leader unknown, contact any server
  - If contacted server not leader, it will redirect to leader
- **Leader does not respond until command has been chosen for log entry and executed by leader's state machine**
- **If request times out (e.g., leader crash):**
  - Client reissues command to some other server
  - Eventually redirected to new leader
  - Retry request with new leader

Client Protocol, cont'd

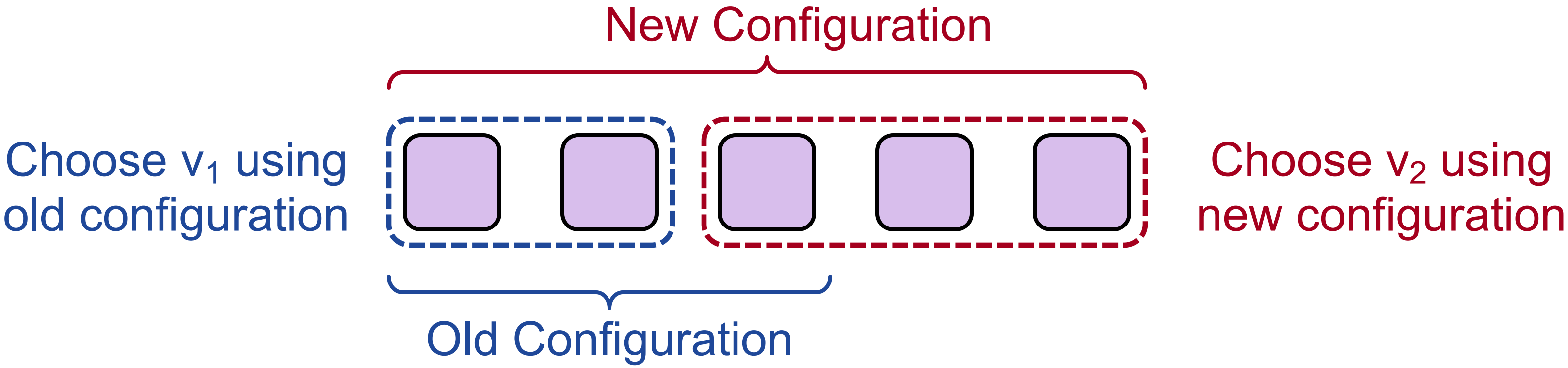
- **What if leader crashes after executing command but before responding?**
  - Must not execute command twice
- **Solution: client embeds a unique id in each command**
  - Server includes id in log entry
  - State machine records most recent command executed for each client
  - Before executing command, state machine checks to see if command already executed, if so:
    - Ignore new command
    - Return response from old command
- **Result: exactly-once semantics as long as client doesn't crash**

Configuration Changes

- **System configuration:**
    - ID, address for each server
    - Determines what constitutes a majority
- **Consensus mechanism must support changes in the configuration:**
    - Replace failed machine
    - Change degree of replication

Configuration Changes, cont'd

- **Safety requirement:**
    - During configuration changes, it must not be possible for different majorities to choose different values for the same log entry:



New Configuration

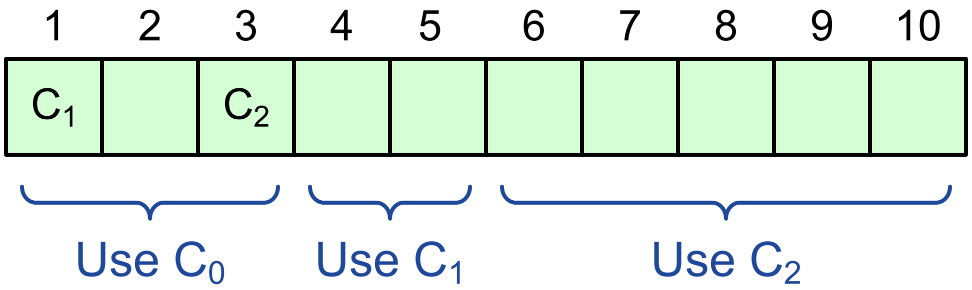
Choose v_1 using old configuration

Choose v_2 using new configuration

Old Configuration

Configuration Changes, cont'd

- **Paxos solution: use the log to manage configuration changes:**
  - Configuration is stored as a log entry
  - Replicated just like any other log entry
  - Configuration for choosing entry i determined by entry i-α. Suppose α = 3:



1 2 3 4 5 6 7 8 9 10

C_1 C_2

Use C_0 Use C_1 Use C_2

- **Notes:**
  - α limits concurrency: can't choose entry i+α until entry i chosen
  - Issue no-op commands if needed to complete change quickly

Paxos Summary

- **Basic Paxos:**
  - Prepare phase
  - Accept phase
- **Multi-Paxos:**
  - Choosing log entries
  - Leader election
  - Eliminating most Prepare requests
  - Full information propagation
- **Client protocol**
- **Configuration changes**