IPADS INSTITUTE OF PARALLEL AND DISTRIBUTED SYSTEMS

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

RSM & PAXOS & Raft

Consistency across replicas

IPADS, Shanghai Jiao Tong University

https://www.sjtu.edu.cn

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Pessimistic Replication

Some applications may prefer not to tolerate inconsistency

- E.g., a replicated lock server, or replicated coordinator for 2PC
    - Better not give out the same lock twice
- E.g., Better have a consistent decision about whether transaction commits

Trade-off: stronger consistency with pessimistic replication means:

- Lower availability than what you might get with optimistic replication
- Performance overhead for waiting syncing w/ other replicas

Review: Single-copy Consistency (Linearizability)

Problem of optimistic way: replicas get out of sync

- One replica writes data, another doesn't see the changes
- This behavior was impossible with a single server

Ideal goal: single-copy consistency

- Property of the externally-visible behavior of a replicated system
- Operations appear to execute as if there's only a single copy of the data
    - Internally, there may be failures or disagreement, which we have to mask
- Similar to how we defined serializability goal ("as if executed serially")

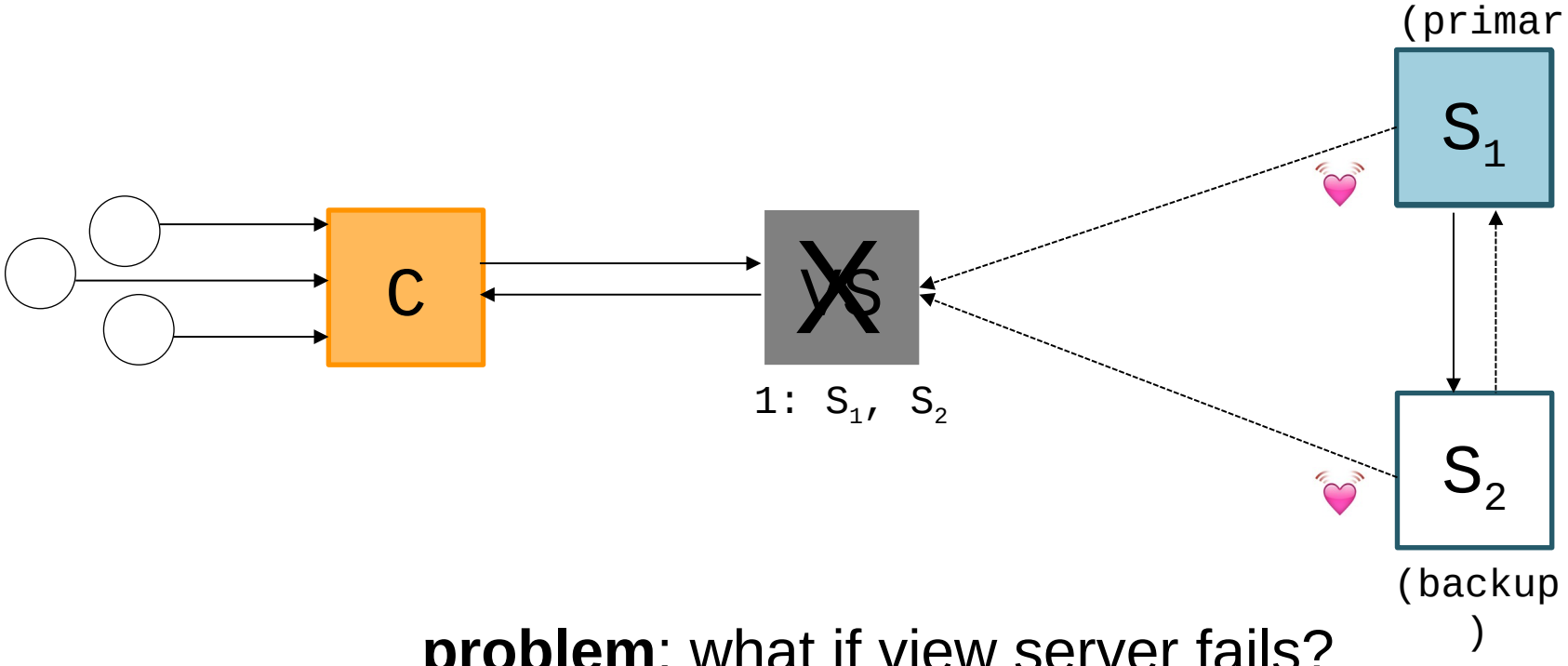
Review: Replicated State Machines

A general approach to making consistent replicas of a server:

- Start with the **same initial state** on each server
- Provide each replica with the **same input** operations, in **same order**
- Ensure all operations are **deterministic**
    - E.g., no randomness, no reading of current time, etc.

These rules ensure each server will end up in the same final state

Review: primary/backup model & view server



problem: what if view server fails?

Now, we need **Paxos**

Quorum

Goal: assume a single write finishes its writes

- A later reader will read its value

Write execution

- The writer sends requests to Nreplicas, return ok if Qw servers ACK the write

Read execution

- The reader sends requests to Nreplicas, return ok if Qr servers ACK the read

Quorum: Qr + Qw > Nreplicas (Can achieve our goal; why?)

- Confirm a write after writing to at least Qw of replicas
- Read at least Qr agree on the data or witness value

Review: Majority in Distributed Systems

Why does the majority rule work?

- Any two majority sets of servers overlap
- Suppose two clients issue operations to a majority of servers
- Must have overlapped in at least one server, will help ensure single-copy

When is it OK to reply to client?

- Must wait for majority of replicas to reply
- Otherwise, if a minority crashes, remaining servers may continue without op

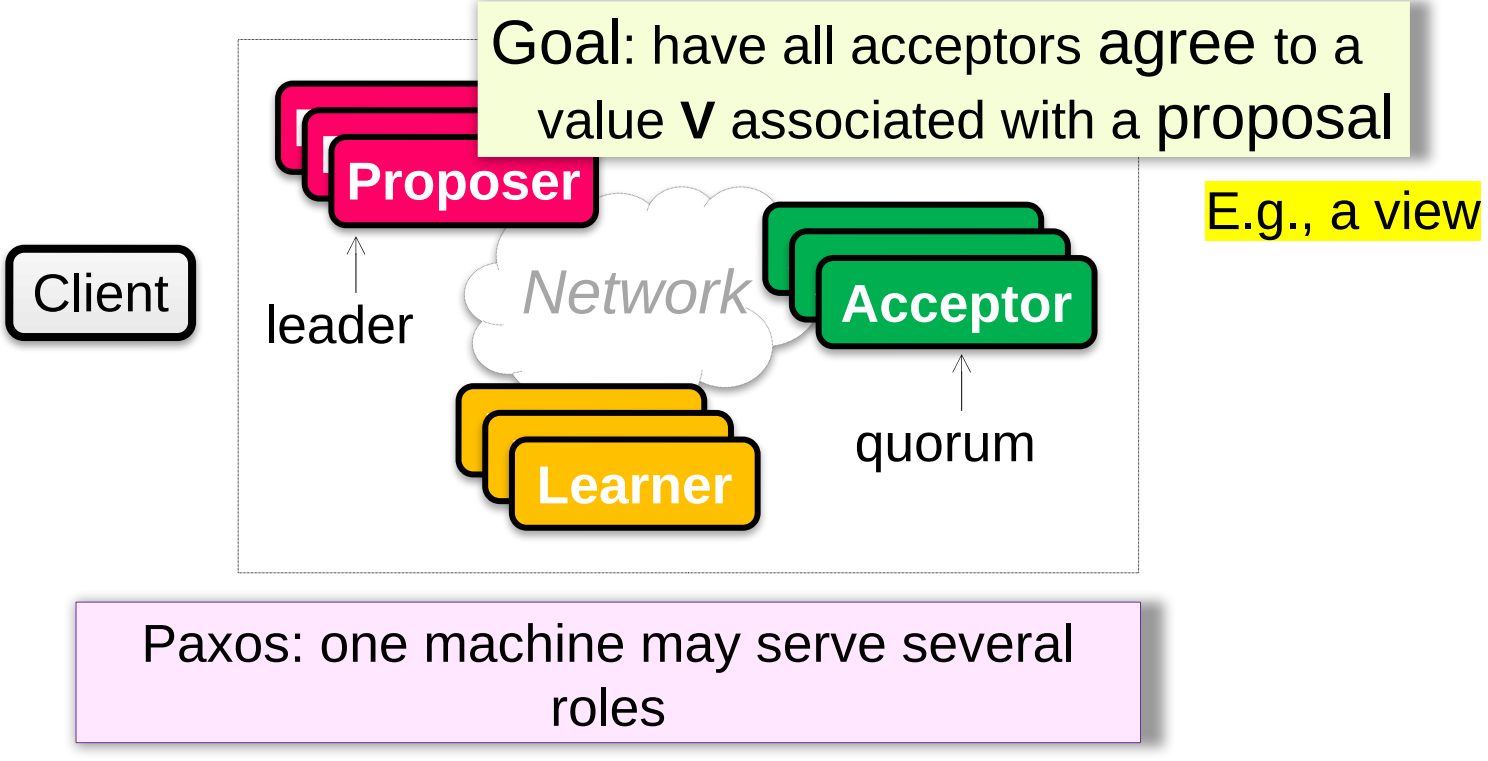
Remaining question: what if multiple writers exist?

Single-decree Paxos

Agree on a single value

Paxos' properties: correct + fault-tolerance

- *No guaranteed* termination (i.e., lack of availability guarantee)



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

Review: Political Science 101 in Paxos

Paxos has rounds; each round has a unique ID (N, i.e., proposal number)

- Goal: “the propose with the highest proposed number win”

Rounds are asynchronous

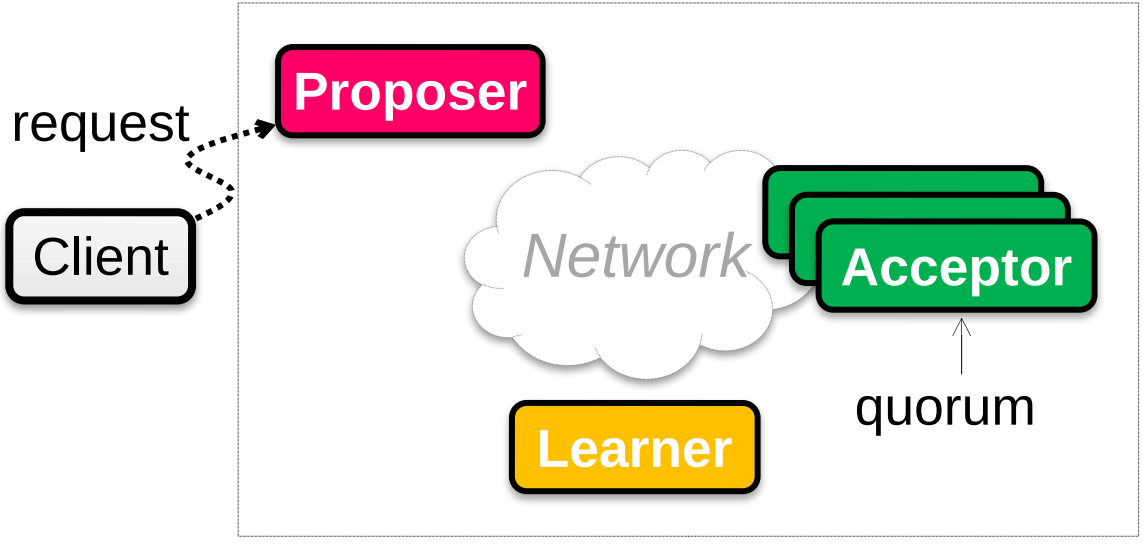
- Time synchronization not required
- If you are in round *j* and hear a message from round *j+1*, abort everything and move over to round *j+1*
- Use timeouts; may be pessimistic

Each round itself broken into phases

- Phases are also asynchronous

Paxos in Action: Phase 0

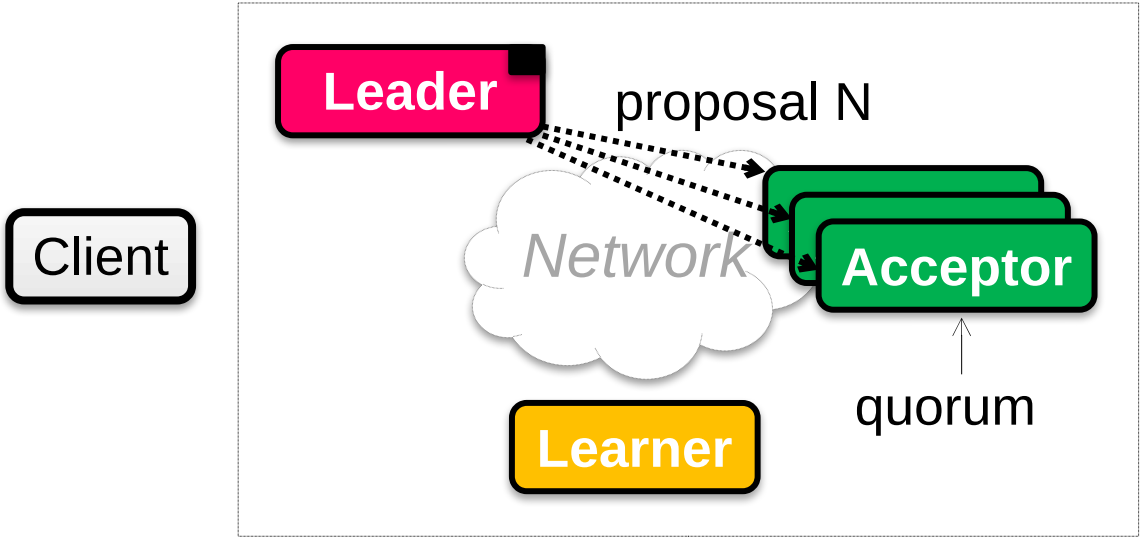
Client sends a request to a proposer



Paxos in Action: Phase 1a (Prepare)

Leader creates a proposal N and send to quorum

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



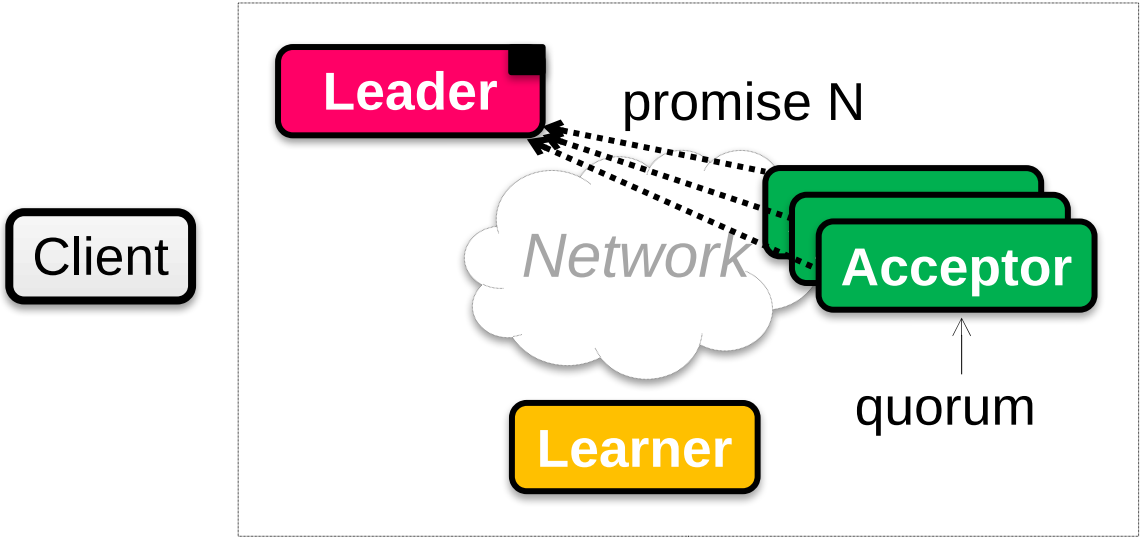
Paxos in Action: Phase 1b (Prepare)

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

1. reply with the highest past proposal number and value

2. promise to ignore all IDs < N

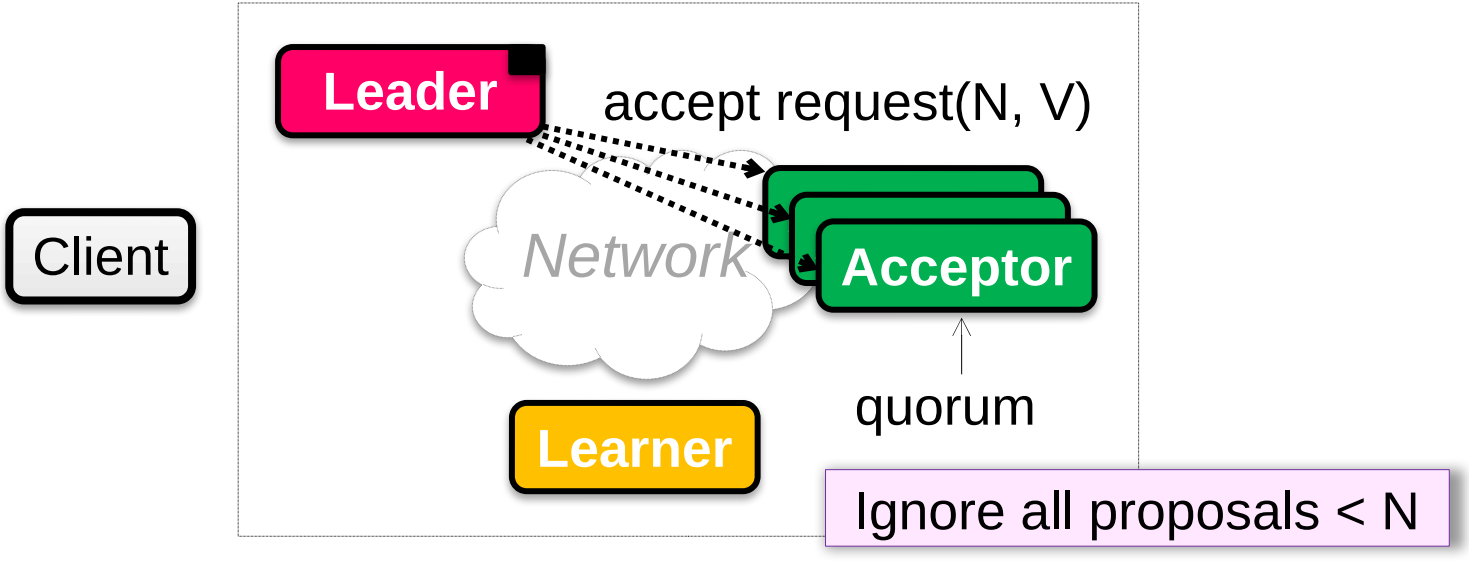
else ignore (proposal is rejected)



Paxos in Action: Phase 2a (Accept)

Leader: if receive enough promise

1. **set a value V to the proposal V, if any accepted value returned, replace V with the returned one**
2. **send accept request to quorum with the chosen value V**



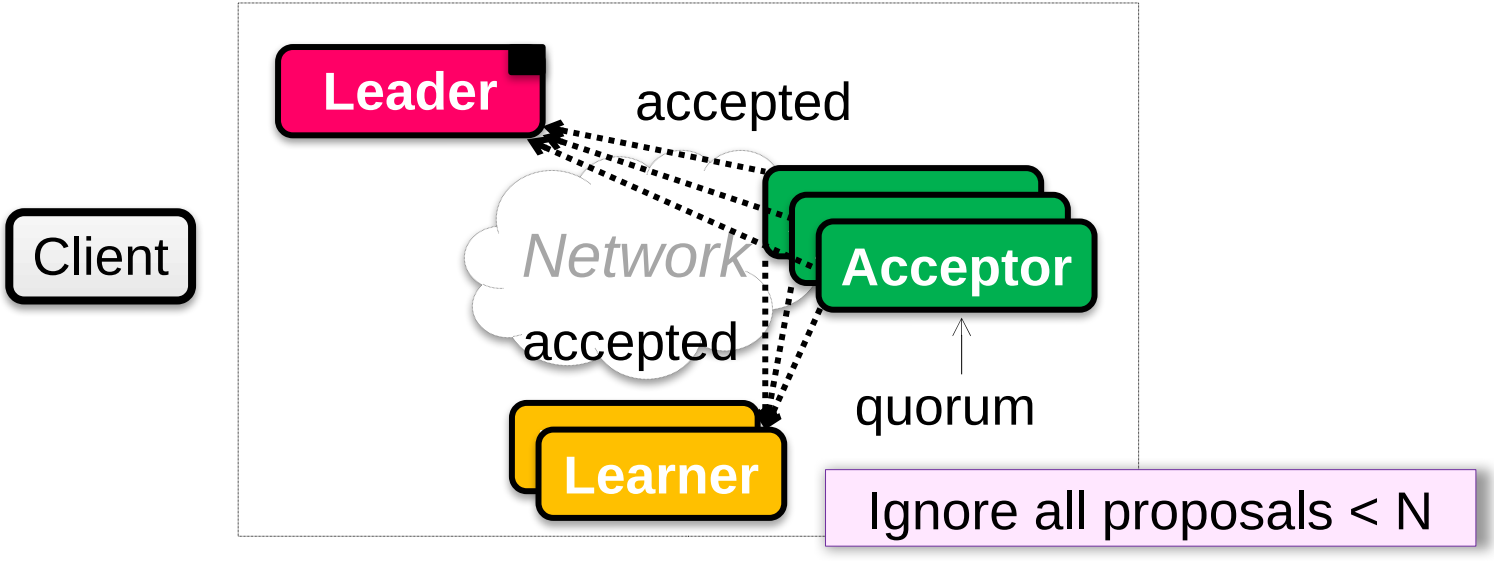
Paxos in Action: Phase 2b (Accept)

Acceptor: if the promise still holds

1. register the value V

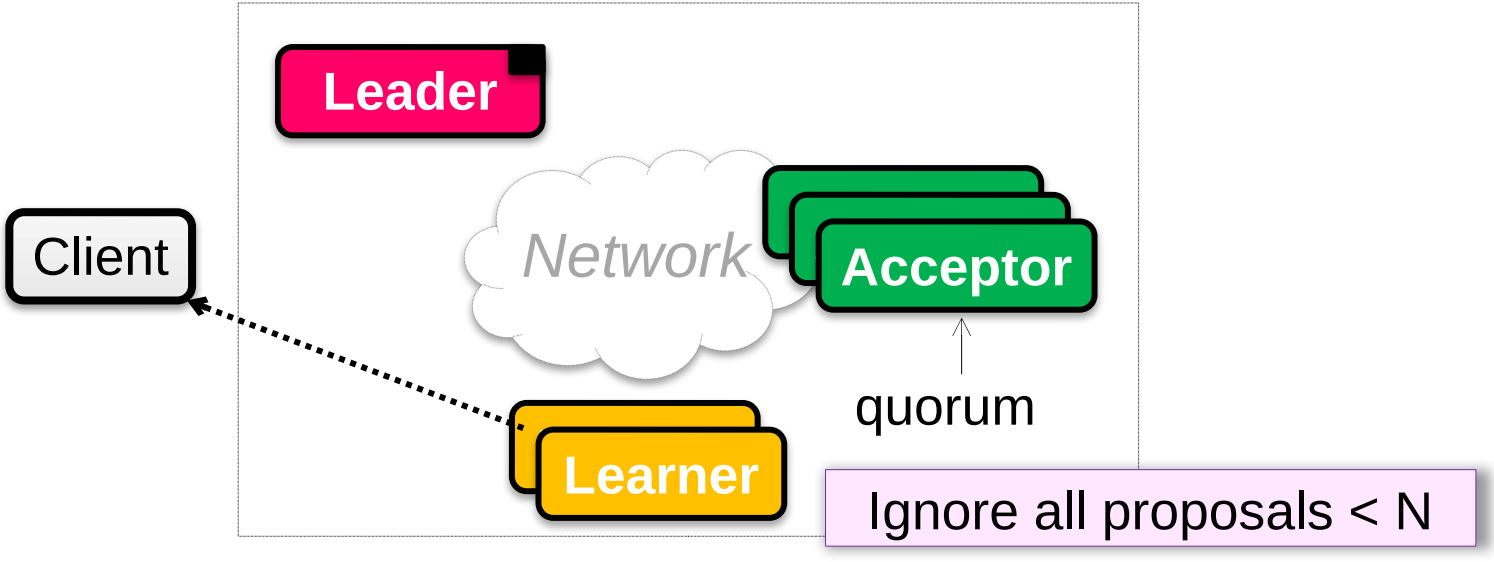
2. send accepted message to Proposer/Learners

else ignore the message

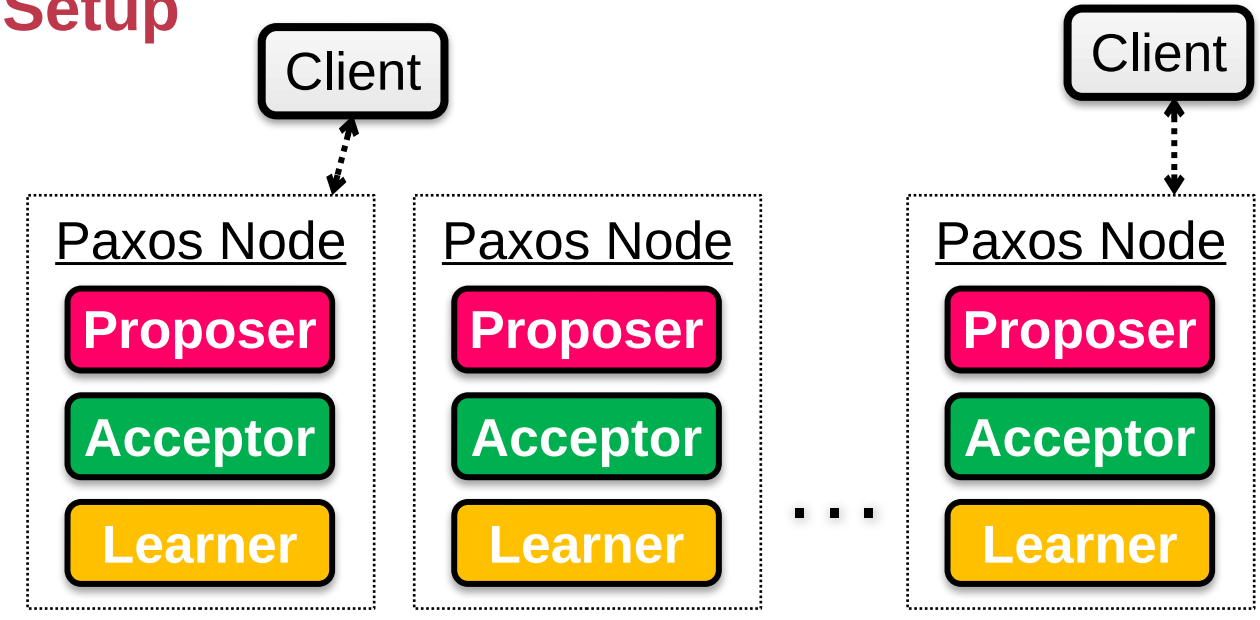


Paxos in Action: Phase 3 (Learn)

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



Paxos Setup



$\mathbf{N_a}$: highest proposal number accepted

$\mathbf{V_a}$: accepted value of $\mathbf{N_a}$

$\mathbf{N_h}$: highest proposal number seen

$\mathbf{M_n}$: my proposal number

each round of Paxos, each Node

Paxos Pseudo-code

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

A node decides to be Leader

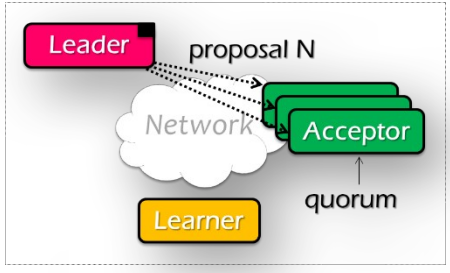
Leader chooses $M_n > N_h$

Leader sends <proposal, M_n> to all nodes

Acceptor receives <proposal, N>

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

Ignore all proposals < N_h



Paxos Pseudo-code

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

If Leader gets promise-ok from a majority

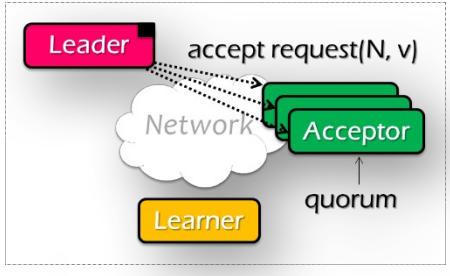
if V != null, V = the value of the highest N_a received
if V = null, then Leader can pick any **V**
send <accept, M_n, **V**> to all nodes

If Leader fails to get majority promise-ok

delay and restart Paxos

Upon receiving <accept, N, V>

if $N < N_h$
    reply <accept-reject>
else
    $N_a = N$; $V_a = V$; $N_h = N$;
    reply <accept-ok>



Paxos Pseudo-code

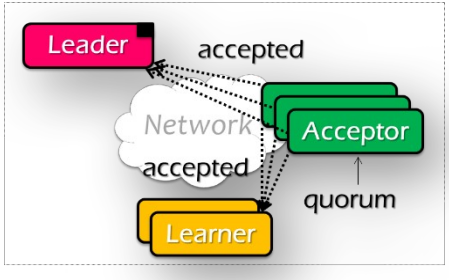
N_a: highest proposal number accepted
V_a: accepted value of N_a
N_h: highest proposal number seen
M_n: my proposal number

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

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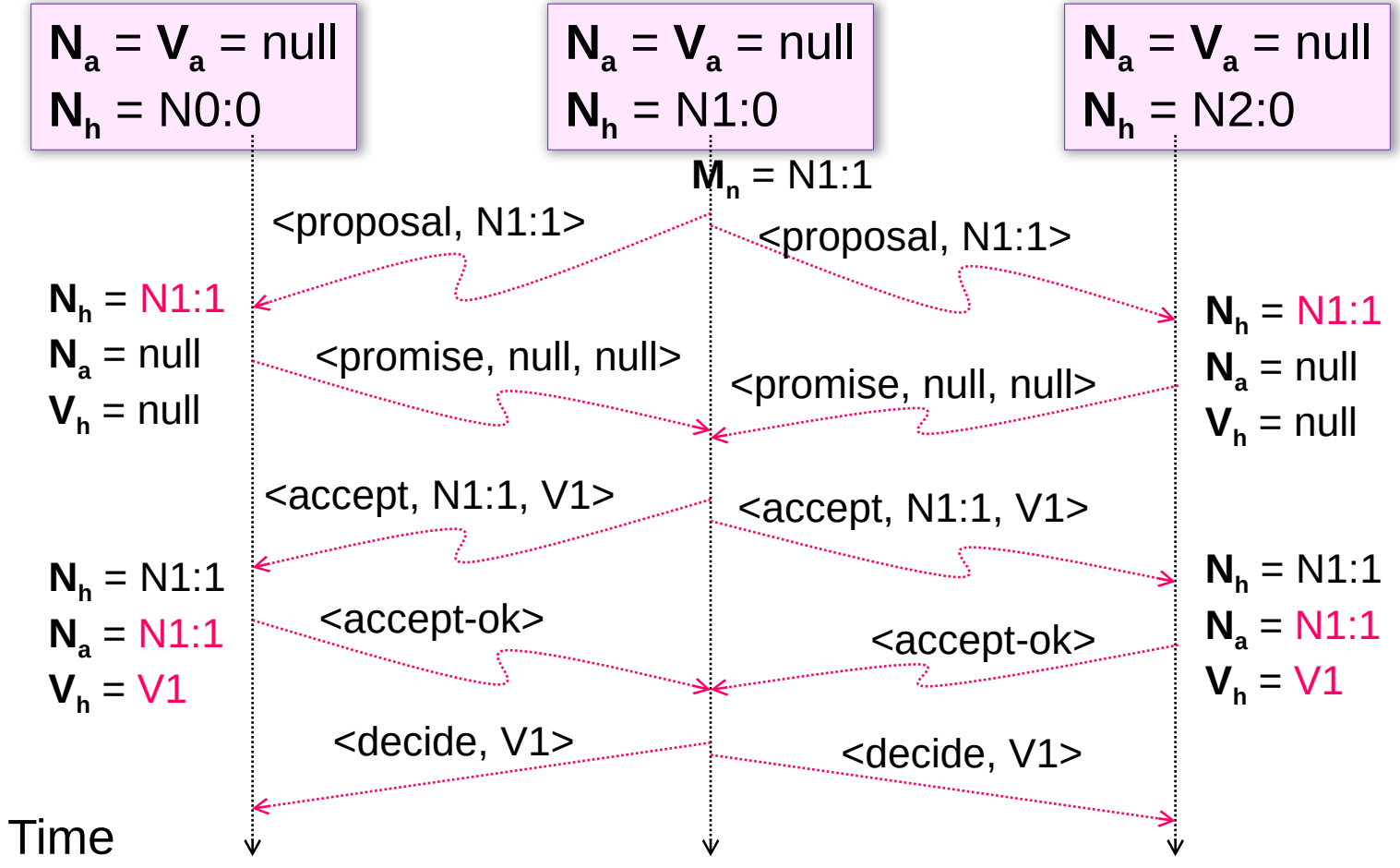


Inside of Paxos

$\mathbf{N_a}$: highest proposal number accepted
$\mathbf{V_a}$: accepted value of $\mathbf{N_a}$
$\mathbf{N_h}$: highest proposal number seen
$\mathbf{M_n}$: my proposal number

Why setups multiple acceptors?

- Failure of the single acceptor halts decision

Why not accepts the first proposal and rejects the rest?

- Leader dies
- Multiple leaders result in no majority accepting

What if more than one leader is active?

- Can both leaders see a majority of promises?

Inside of Paxos

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

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 N_h

What if acceptor fails after receiving accept?

- Must remember N_h and N_a V_a

What if leader fails while sending accept?

- Propose M_n again

Question

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

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, C

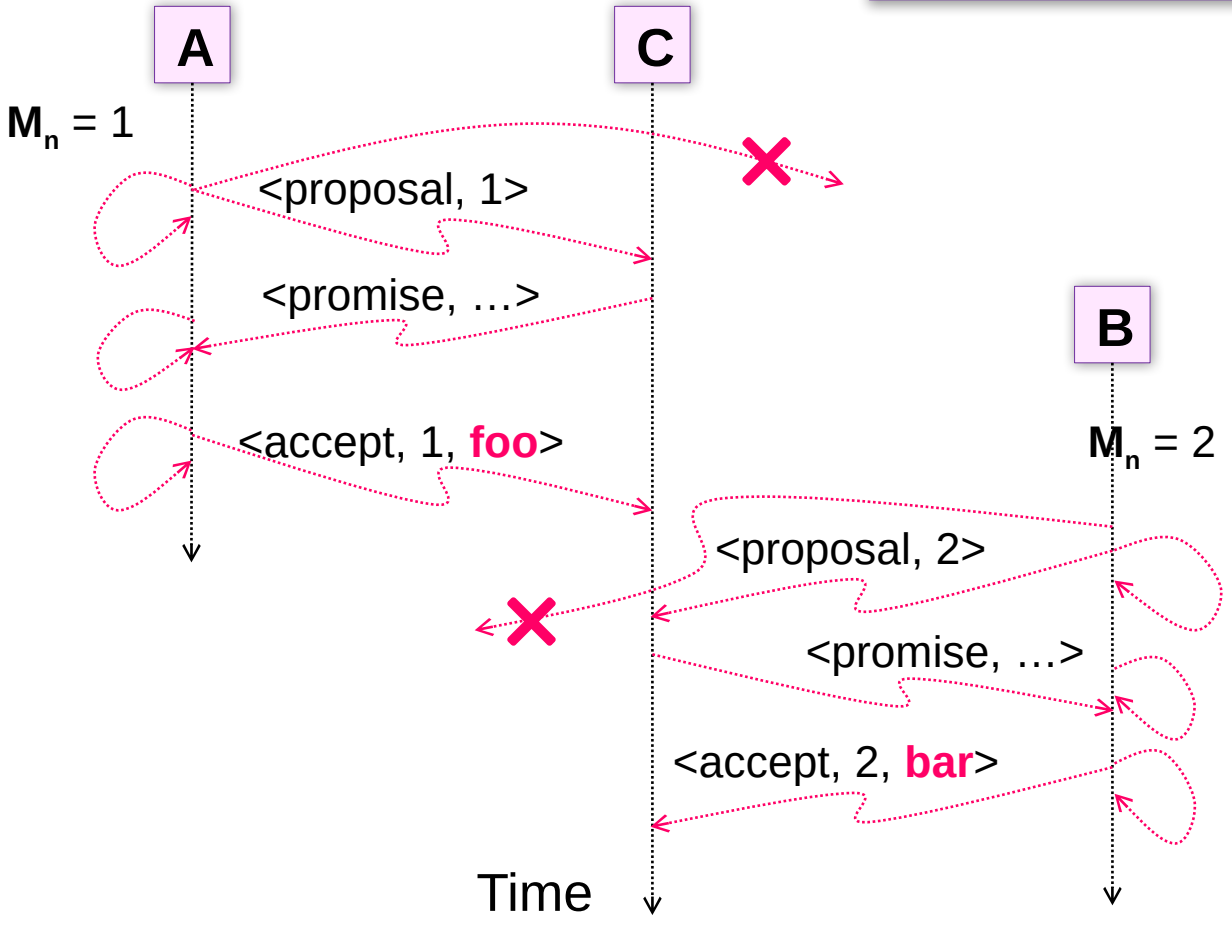
A sends <accept,1, "foo"> to A and C and gets responses from both. Because a majority accepted, A thinks that "foo" has been chosen. However, A crashes before sending an <accept, 1, "foo"> to B

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

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



Question

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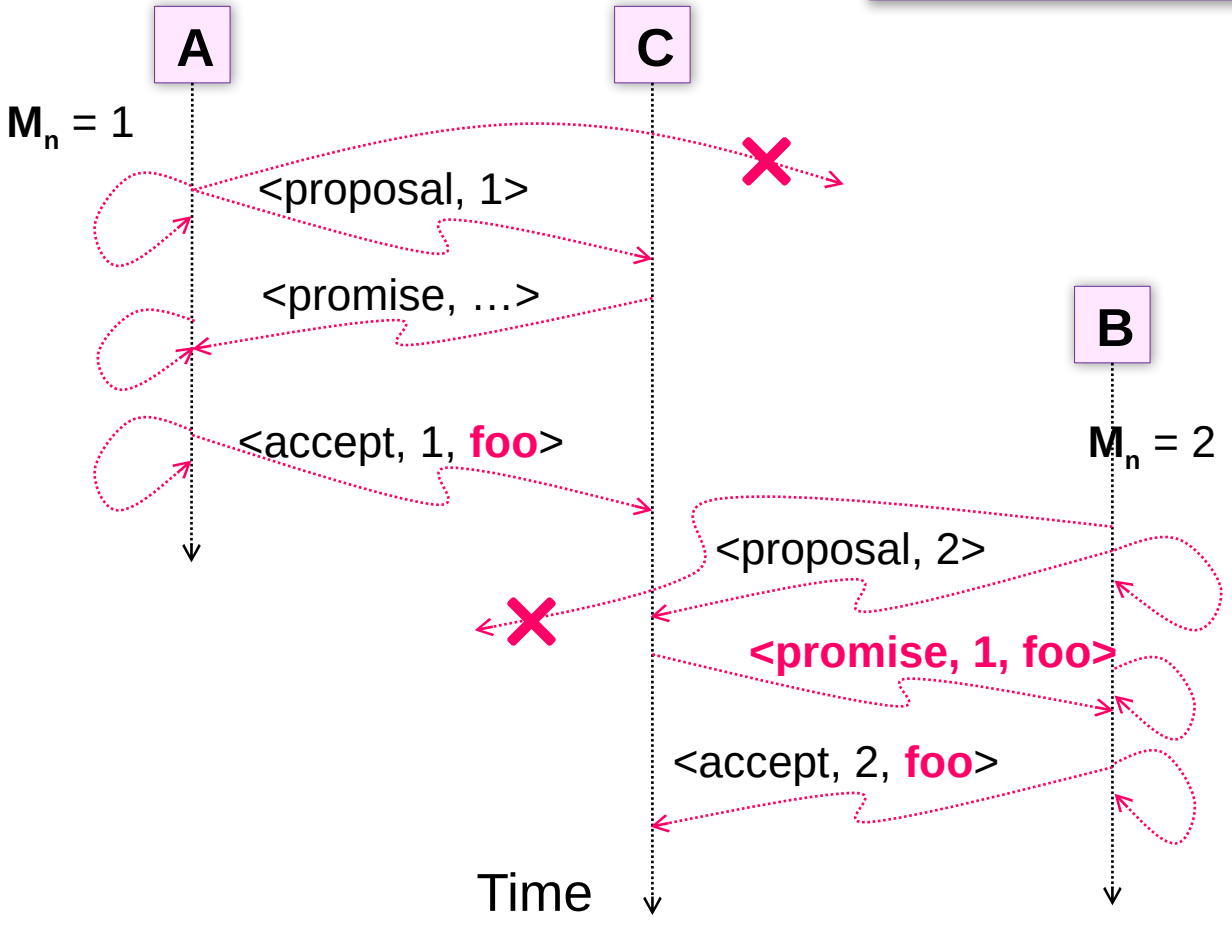
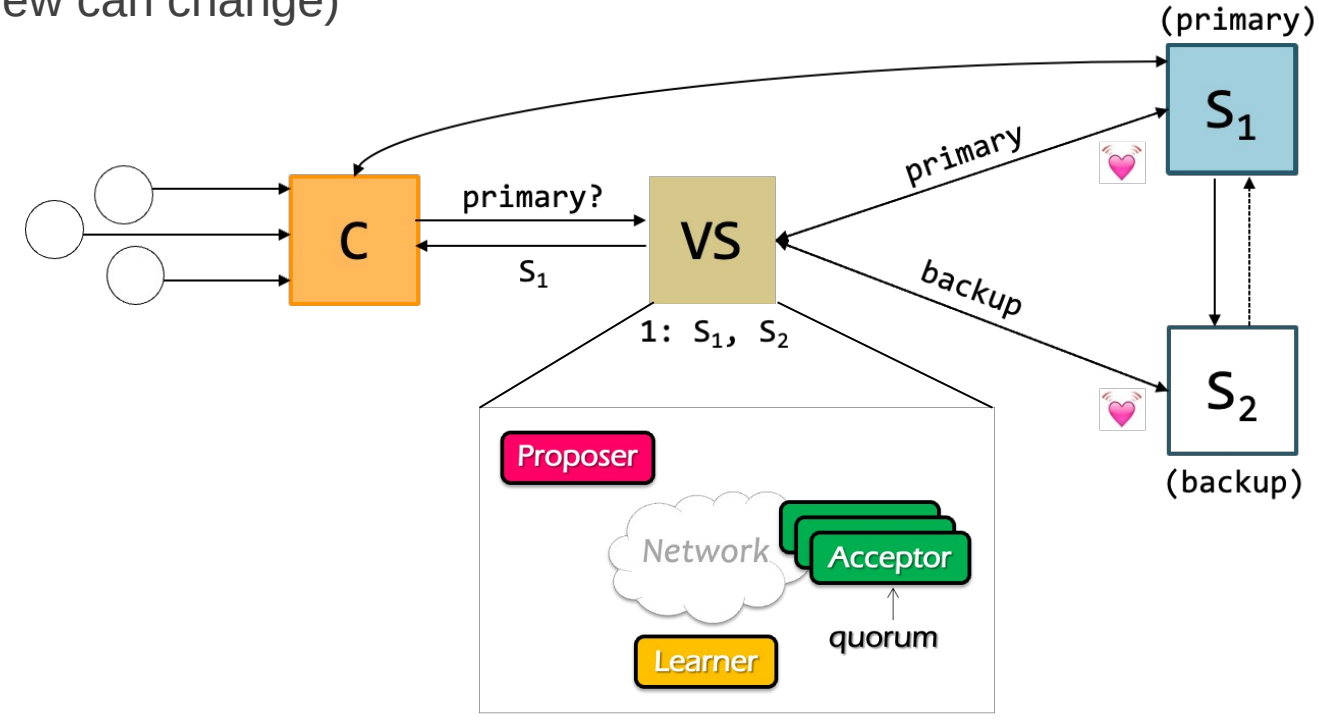


Question

Does single-decree Paxos works fine for our view server example?

– When can it go wrong? Accepting a single value is not enough (because view can change)



Multi-Paxos builds on top of the basic Paxos

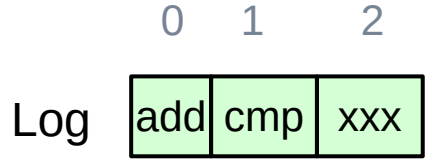
Useful when agreeing on a sequences of values, examples including:

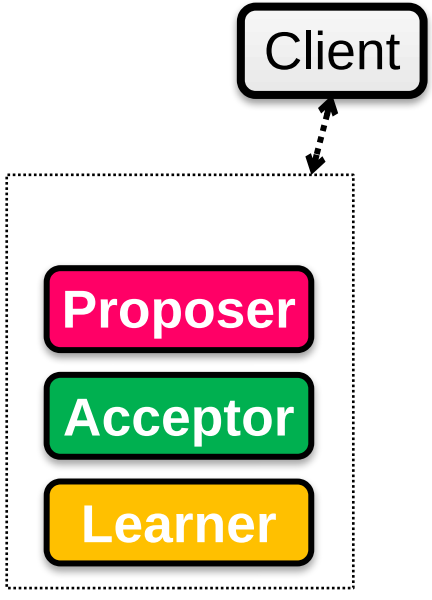
- Views in primary-backup replication
- Logs in a replicated state machine
    - i.e., use Multi-Paxos to implement RSM

The basic approach

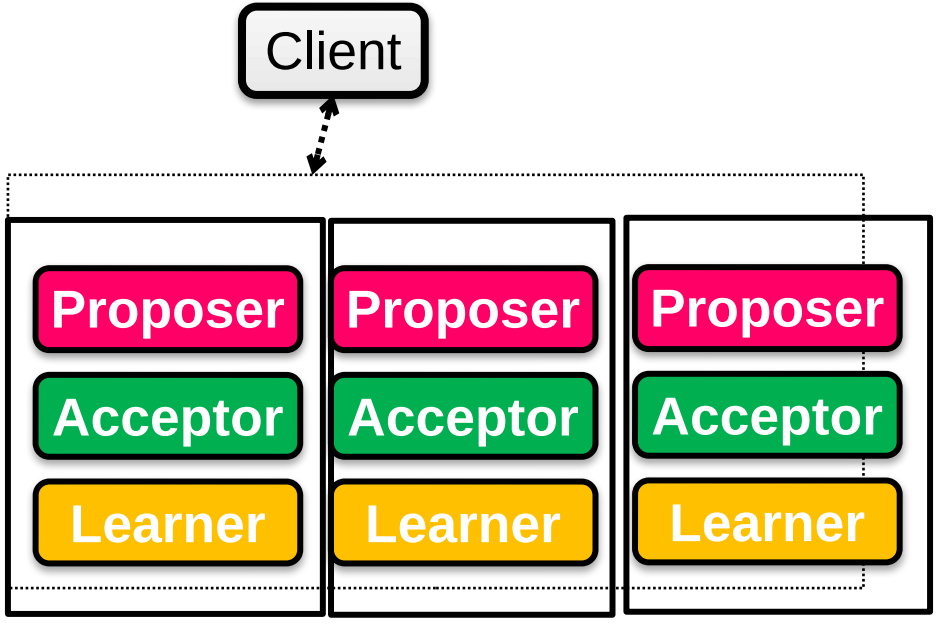
- Run a separate instance of Paxos to agree on the value of each index
- Each instance of Paxos has its own copy of state
    - highest proposal seen
    - accepted proposal number
    - accepted proposal value

Single-decree Paxos vs. Multi-Paxos





Single-decree Paxos



Single-decree instance for 0

Single-decree instance for 1

Single-decree instance for 2

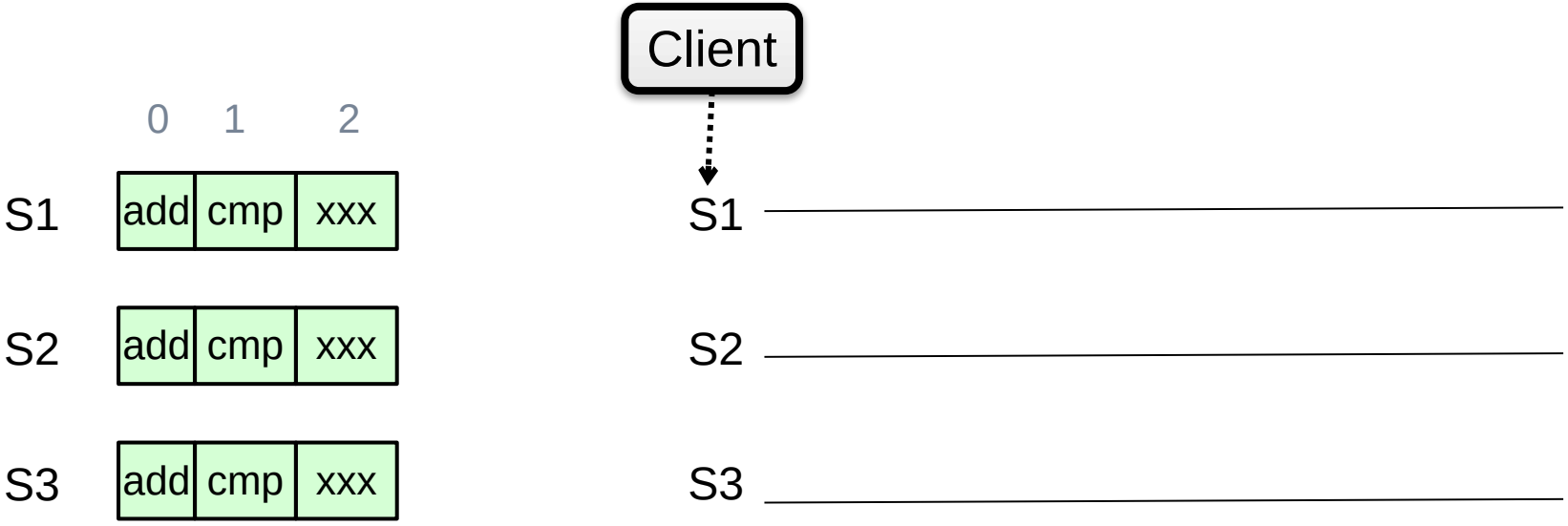
Multi-Paxos

Basic Multi-Paxos

Server simultaneously acts as proposer, acceptor & learner

Example

– Suppose we want to append an entry to the log



Basic Multi-Paxos

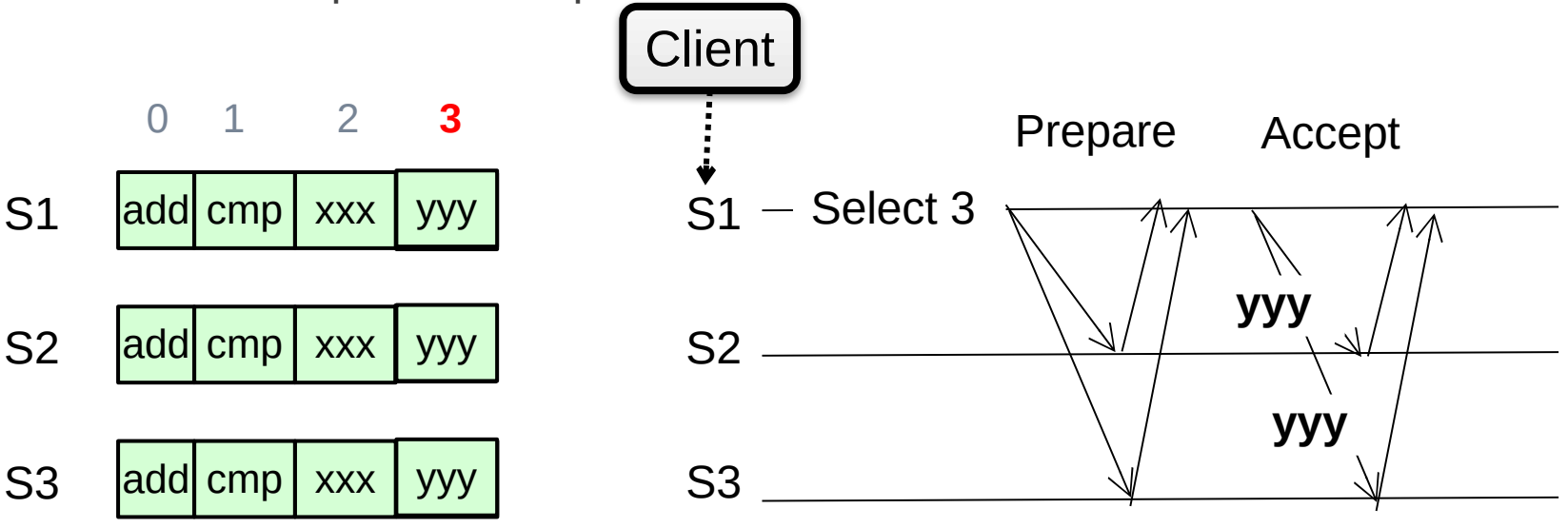
Question: what could happen if instance 3 has already gotten a value?

After receiving the request from a client, the server will

① Decide the number of the instance to append (3 in our example)

② Do the single-decree paxos to append the log entry to the instance 3

① Prepare + Accept

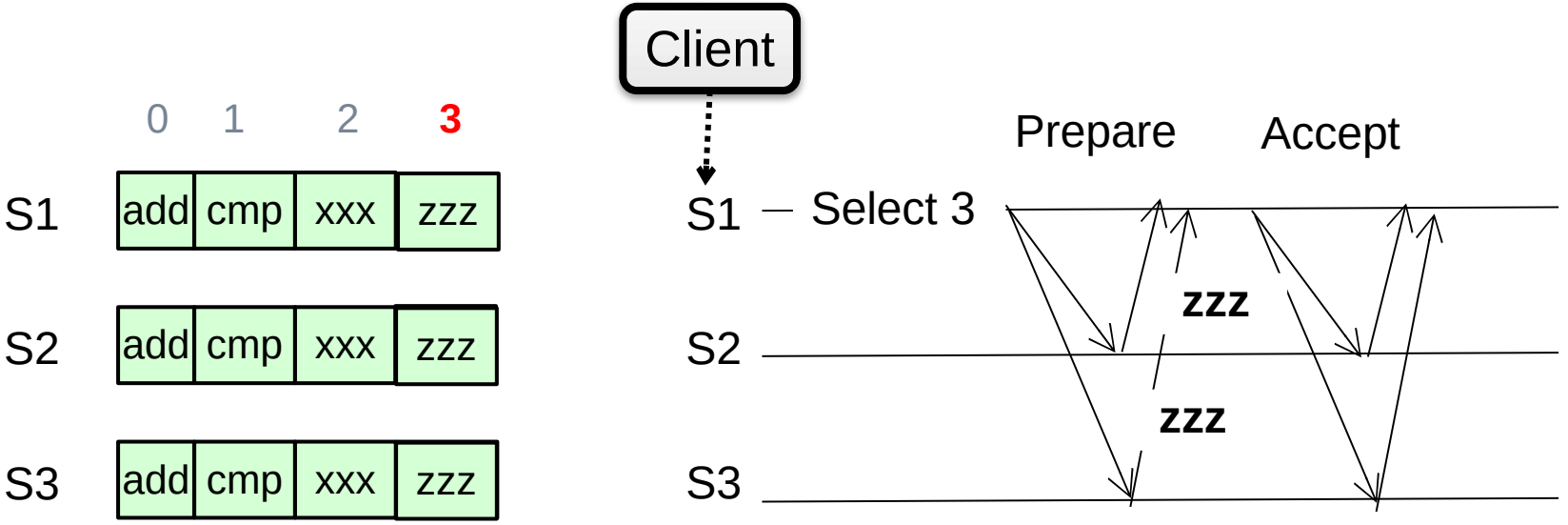


Basic Multi-Paxos

Question: what could happen if instance 3 has already gotten a value?

Example: S1 receives the request, but S2 and S3 has already accepted the value (zzz)

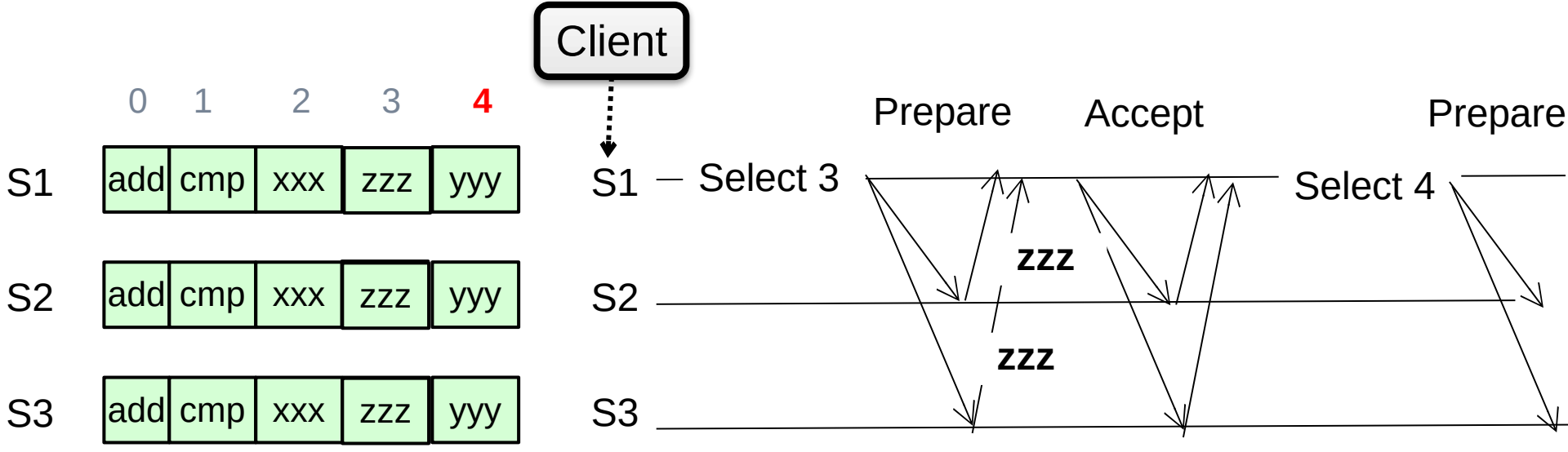
- Our single-decree paxos will not choose the value client sent



Basic Multi-Paxos

In case of conflict, S1 will choose a larger instance (e.g., 4)

- And re-run the instance until find the largest available instance
- May possible try many times until find an available slot



Question

How many RTTs are required for appending a single log entry?

Basic Multi-Paxos is correct but inefficient

2 rounds of RPCs for each value chosen in the optimal case

- Prepare, Accept

With multiple concurrent proposers, conflicts and restarts are likely

- 1. The server may conflict on the position of the new log entry to insert (our previous example)
- 2. Even in the same Paxos instance, different proposer may conflict
    - Only the proposers with the highest number can win

Solution

① Select a leader: most of the time, only one server can propose

② Batch the prepare requests from multiple instances sent from a leader

Multi-paxos uses a distinguished proposer (leader)

Distinguished proposer (aka. leader)

- The only one that issues proposals
    - i.e., no proposer conflicts in the optimal case

Client only sends the commands to the leader

- Decides the value position

Note, single leader is *not* necessary for Multi-paxos

- E.g., if two or more servers act as proposers at the same time, the protocol still works correctly

Not relying a single leader simplifies user implementation

i.e., the user can choose the leader in an arbitrary way

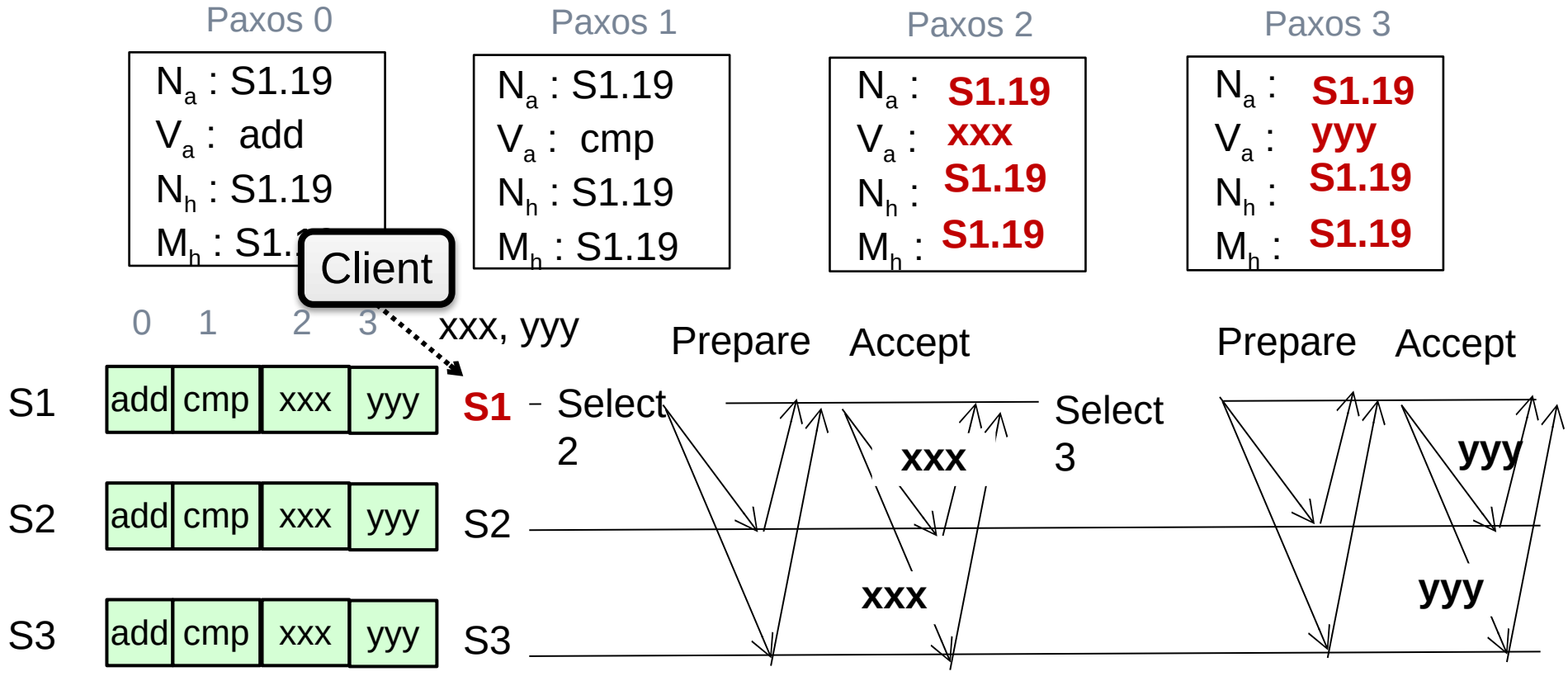
- i.e., all the server don't need to agree on the same leader
- Performance degradations if multiple leaders exist

We can also use multi-paxos for the leader election ⏪

- Similar to implementing a view server

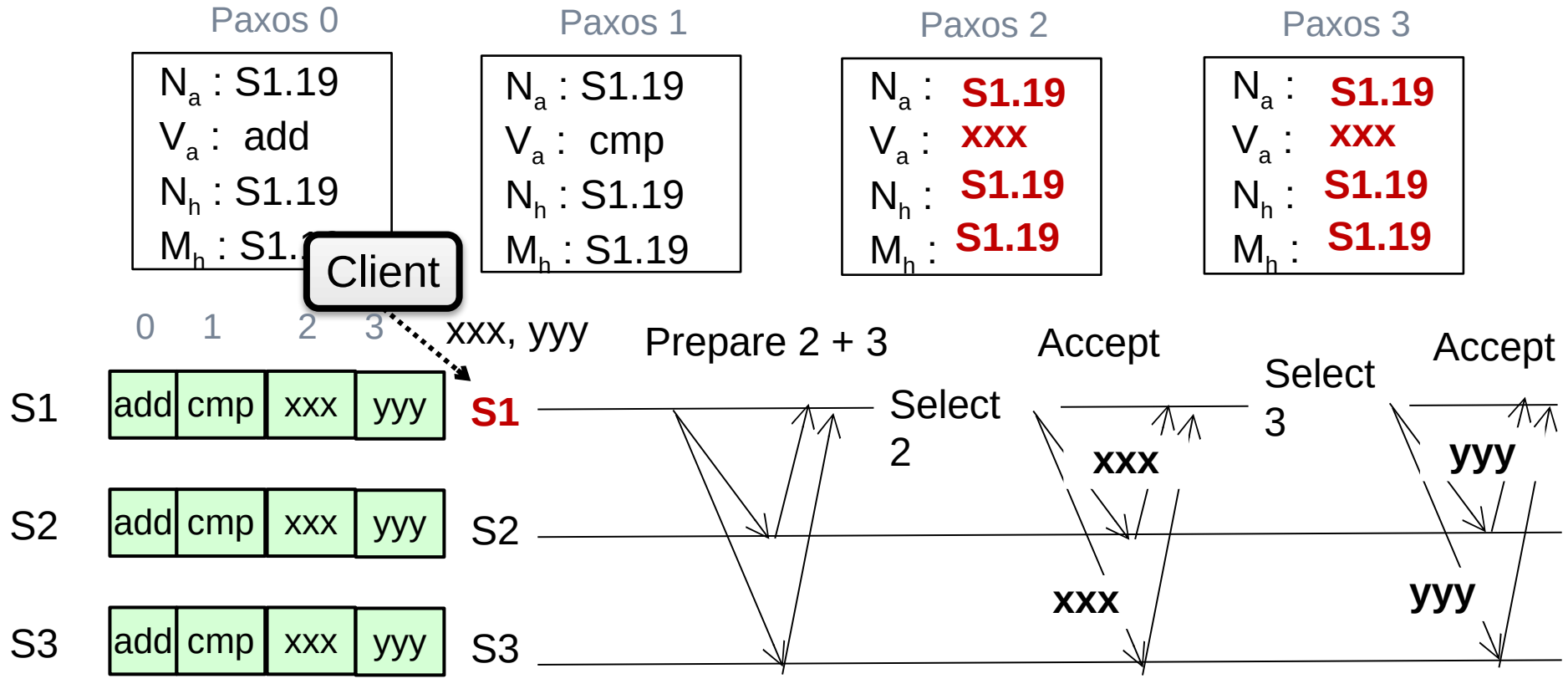
Benefits of leader election: prepare message batching

Suppose S1 is the leader (w/o batching)



Benefits of leader election: prepare message batching

Suppose S1 is the leader (+ batching)

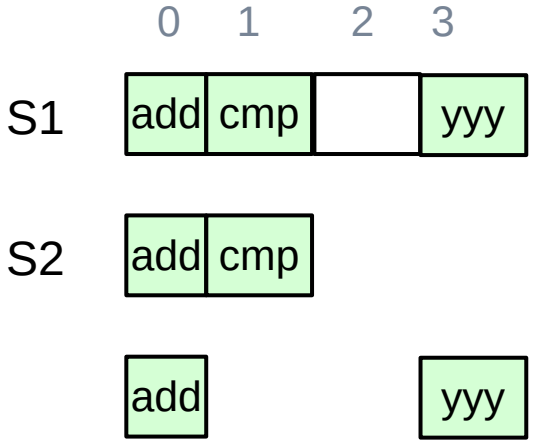


Problem: hole in the log

Suppose S1 is the leader (with batching)

- What happens after S1 crashes w/ unfinished entry?
- Entry 2 will be empty

Application should fill the gap itself, e.g., w/ no-op



Summary of Multi-Paxos

Based on single-decree Paxos, realizing RSM

Needs non-trivial application efforts to make it work

- E.g., should use a leader for better performance
- Should fill the holes of the log entries

More: Raft replicated log

A different approach for consensus

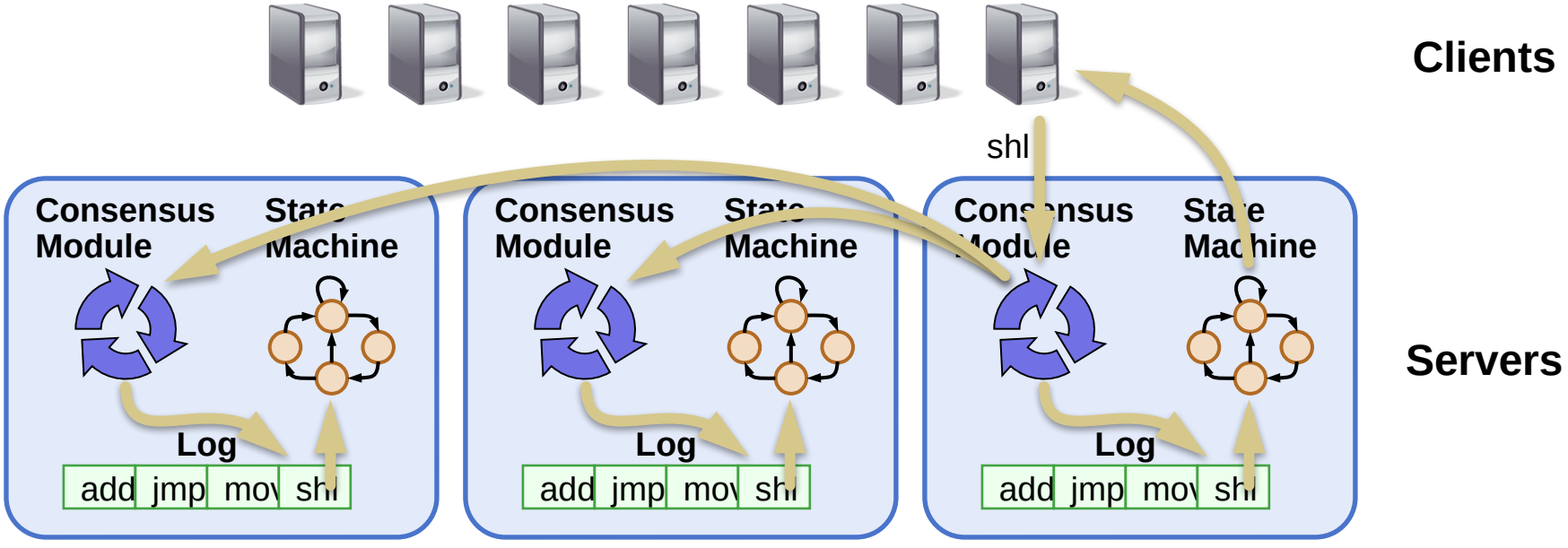
- Paxos's approach (bottom-up)
  - solve single-decree consensus first
  - replicate a sequence of values using single-decree consensus
- Raft's approach (top-down)
  - directly solve log replication without first solving single-decree consensus

Why learn raft?

Raft is described in a concrete form that favors system design & impl.

- Widely implemented and deployed nowadays
- Especially for open-source projects

Abstraction of the operations: replicated log



Replicated log => replicated state machine

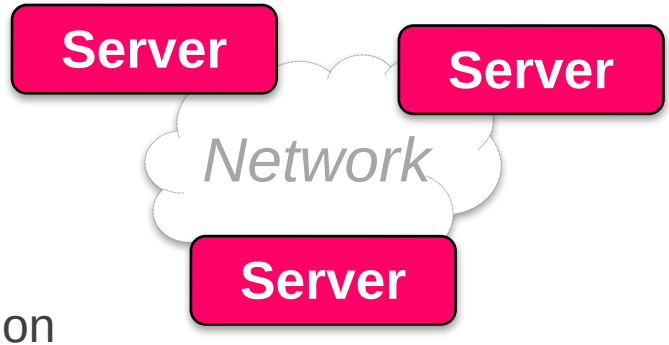
- All servers execute same (deterministic) commands in same order

Consensus module ensures proper logs are the same!

Raft’s high-level approach: problem decomposition

1. **Leader election**
   - Select one server as the leader
   - Detect crashes, choose new leader
2. **Log replication (normal operation)**
   - Leader accepts commands from clients, append to its log
   - Leader replicates its log to other servers (overwrites inconsistencies)
3. **Safety**
   - Keep logs consistent
   - Only servers with up-to-date logs can become the leader

Raft server states



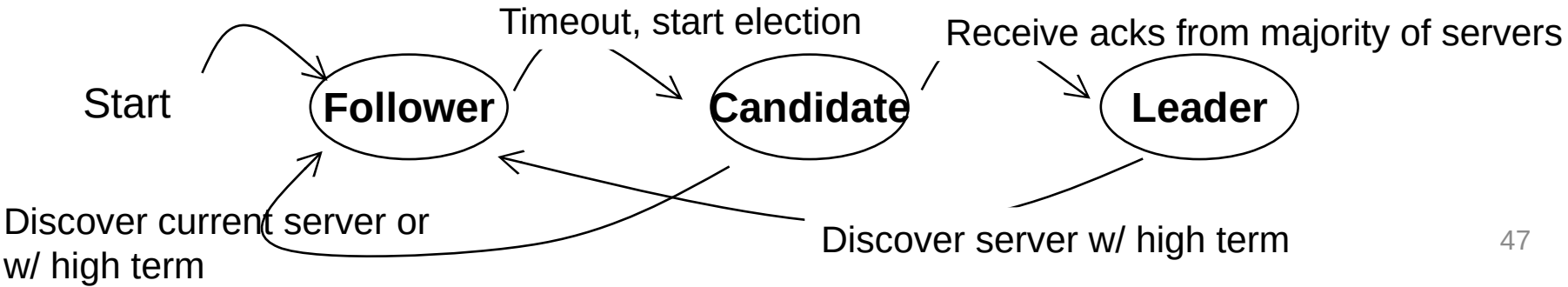
Servers communicates w/ RPCs

At any time, each server is either:

- **Leader**: handles all client interactions, log replication
  - Invariant: At most 1 viable leader at a time
- **Follower**: passive (only responds to incoming RPCs)
- **Candidate**: used to elect a new leader

Normal workloads

- 1 server is the leader, others are the followers



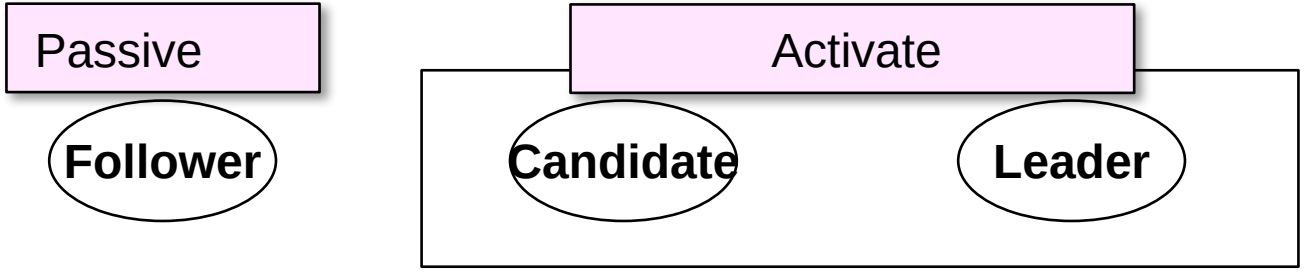
Raft server states

Leader is active

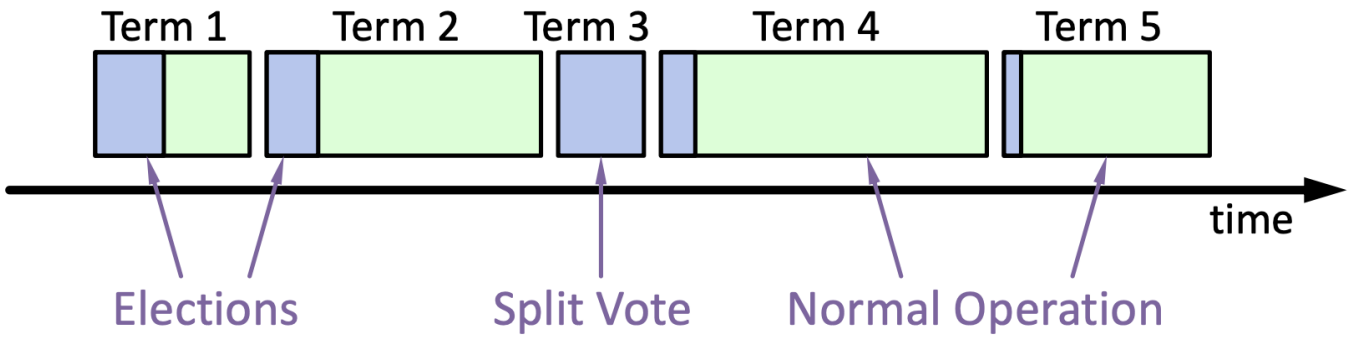
- Receive client requests, replicate logs to the followers

Followers are passive

- Only respond to the requests from leaders or candidates



Raft basics: terms for one leader



Raft divides time into terms (with arbitrary length):

- Each term starts with an election
- Ends with one leader or no leader
- At most one leader per term

Each leader is uniquely associated with a term

- Key role: identify obsolete information

Raft server state switch: Heartbeats & Timeouts

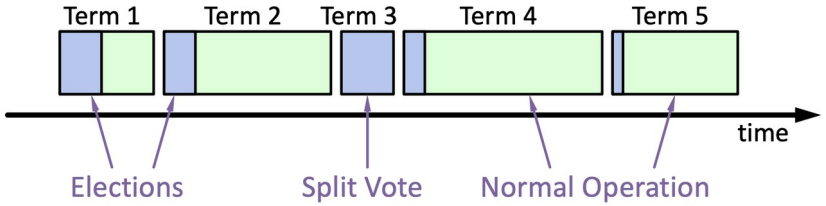
Servers start as followers (except one server is assigned as the leader)

- Followers expect to receive RPCs from leaders or candidates

Leaders must send heartbeats to maintain authority in a term

- If election timeout elapses with no RPCs:
  - Follower assumes leader has crashed
  - Follower starts **new election**
  - Timeouts typically 100-500ms

Election Basics



1. Change its state to the candidate state
2. Increment current term
3. Vote for itself

   Send **`RequestVote RPC`**s to all other servers, retry until either

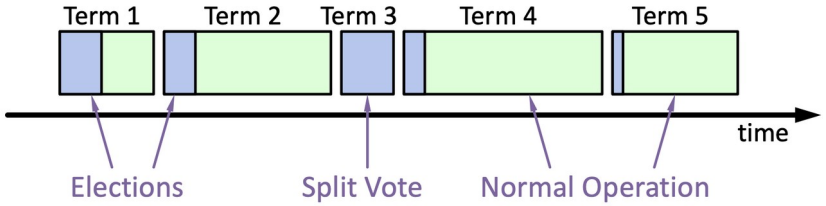
   ① Receive votes from majority of servers ➔ Become the leader!

   ② Receiver RPC from a valid leader ➔ Return to the follower

Question: what is the condition for the follower to vote?

The leader's term >= self's term & never vote before

Election Basics



1. Change its state to the candidate state
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   Send **`RequestVote RPC`**s to all other servers, retry until either

   ① Receive votes from majority of servers ➔ Become the leader!

   ② Receiver RPC from a valid leader ➔ Return to the follower

   ③ No one wins election (timeouts on the election) ➔ Increase the term, start the new election

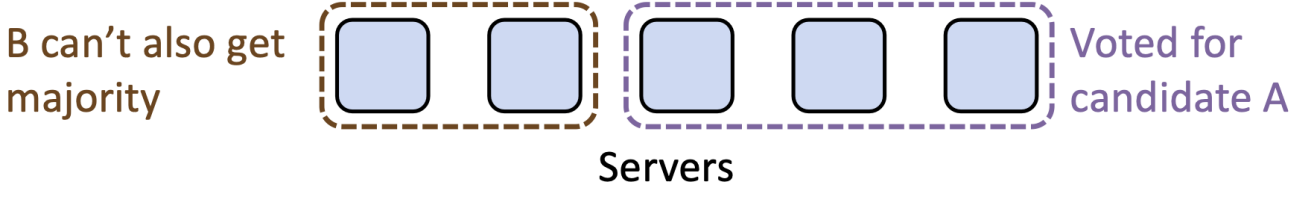
Election requirements: safety

At most one winner per term

- How to achieve so? Each server only gives one vote per term (persist on disk)
- Majority ensures at least one leader (similar to phase #1 of Paxos)

Question

- Can different candidates exist in the same term?
- Yes. Each server should keep a VotedFor variable to ensure it only gives vote to one candidate.



Election requirements: liveness

Some candidate must eventually win

- If multiple candidates started, non will win

Raft's key idea: use random timeout before the retry

- So as to minimize the possibilities that two candidates retry at the same time
- Typically, it randomly selects a time between `[T, 2T]`
    - T is the election timeout

Persistent state of each server so far

currentTerm

Latest term server has seen (initialized to 0 on first boot)

votedFor

Candidate Id that received vote in current term (or null if none)

Basic request vote RPC so far

Invoked by candidates to gather votes.

Arguments:

candidateId candidate requesting vote

term candidate's term

Results:

term currentTerm, for candidate to update itself

voteGranted true means candidate received vote

Implementation:

1.If term > currentTerm, currentTerm ← term
(step down if leader or candidate)

2.If term == currentTerm, votedFor is null or candidateId, grant vote and reset election timeout

Raft's high-level approach: problem decomposition

1. **Leader election**

   Select one server as the leader

   Detect crashes, choose new leader

2. **Log replication (normal operation)**

   Leader accepts commands from clients, append to its log

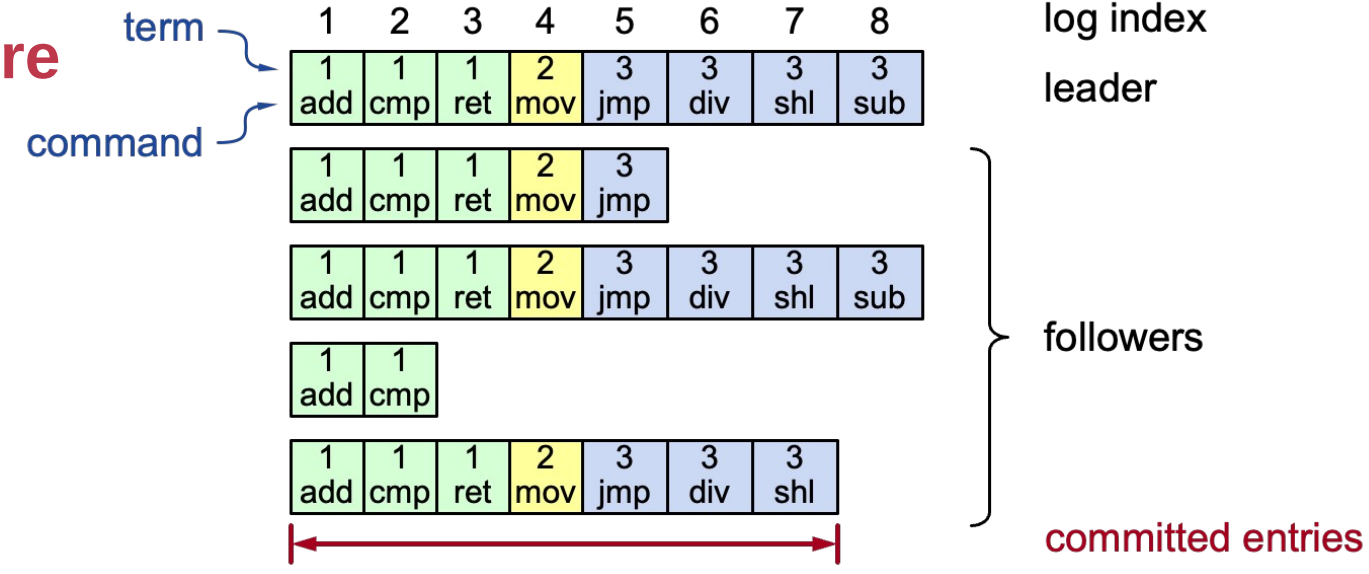
   Leader replicates its log to other servers (overwrites inconsistencies)

3. **Safety**

   Keep logs consistent

   Only servers with up-to-date logs can become the leader

Log structure



Log entry = index, term, command

- Stored on the disk to tolerate failures

A log is committed if it can be safely applied to the state machine

- i.e., eventually stored on all the servers with the same value

Not all entries are committed (will talk about later)

Persistent state of each server + log

currentTerm

Latest term server has seen (initialized to 0 on first boot)

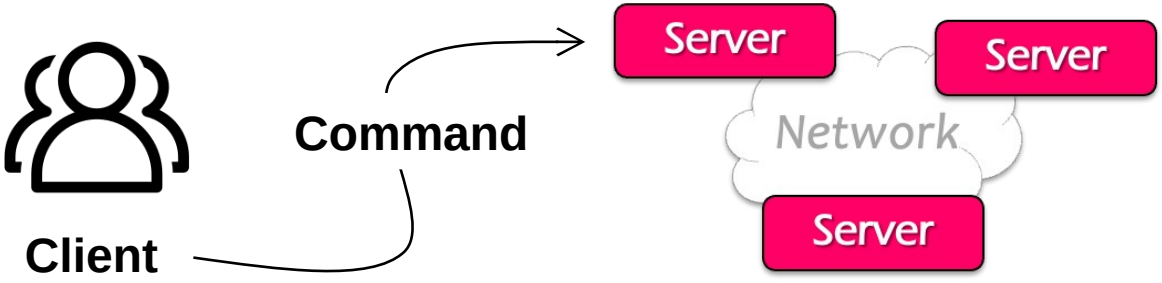
votedFor

Candidate Id that received vote in current term (or null if none)

Log[]

Log entries

Normal operations to update the log



① Send command to the leader

② Leader appends command to its log

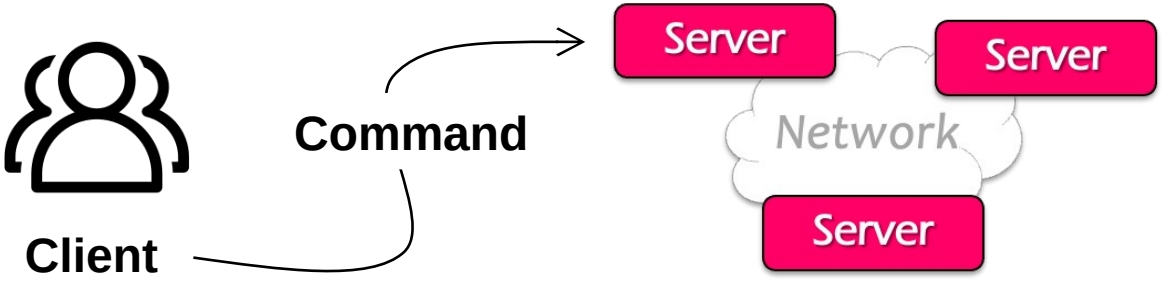
③ Leader sends `AppendEntries` RPCs to followers

④ Once a new entry (of log) **committed**:

Leader passes command to its state machine, returns results to client

Notifies followers of committed entries, Follower pass committed commands to their state machines

Normal operations to update the log



Crashed/slow followers?

- Leader retries RPCs until they succeed (at least once)

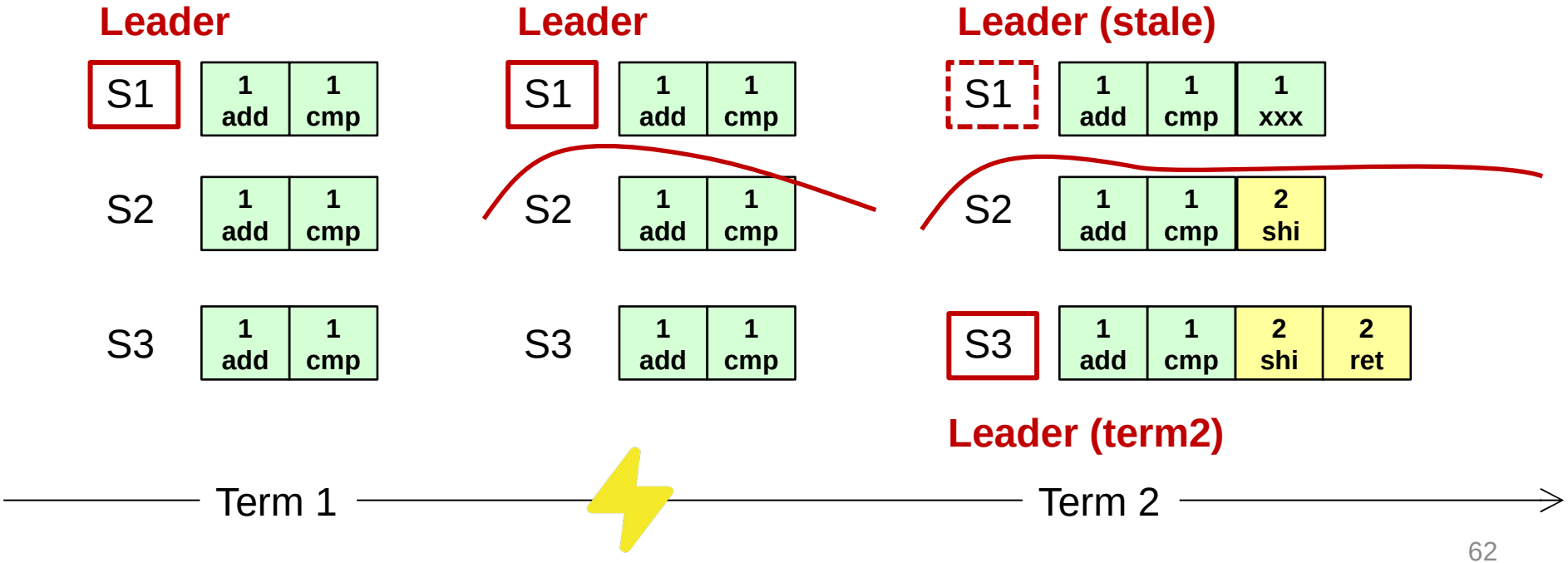
Performance is optimal in the common case

- One successful RPC to any majority of servers

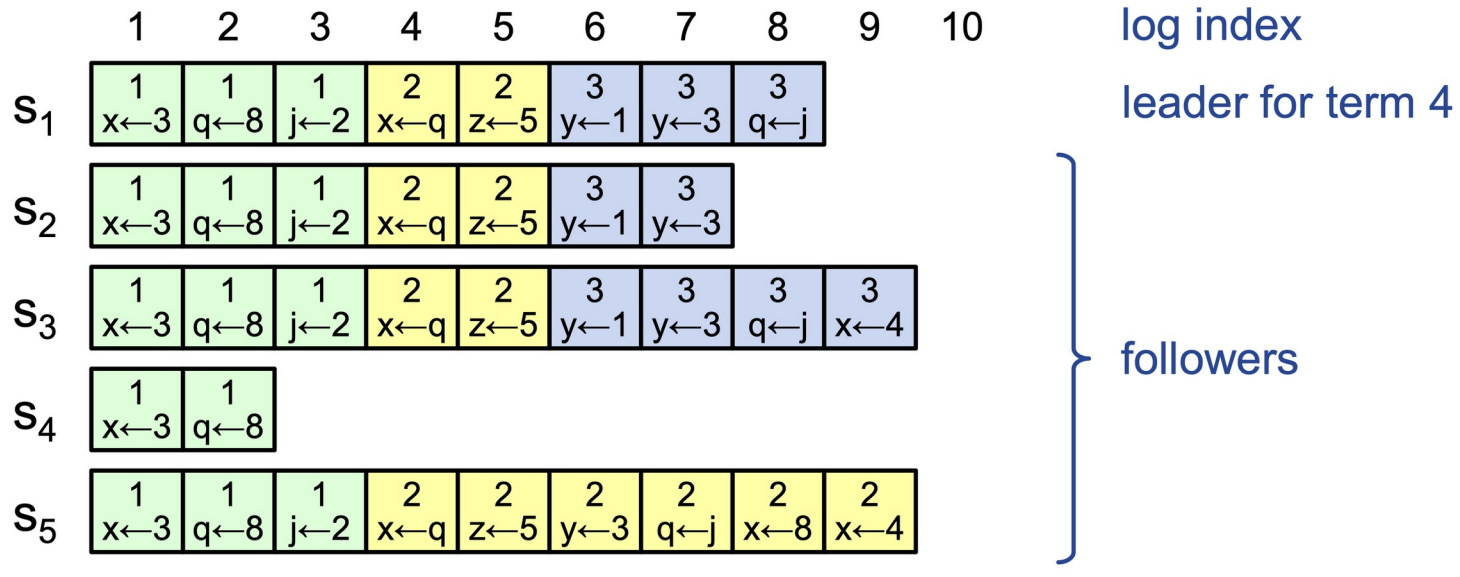
Challenge: crash can cause log to inconsistencies

Case: an old leader is unaware of the new leader due to network partition

- Yet, it can still get commands from the clients



Challenge: crash can cause log to inconsistencies



Raft minimizes special code for repairing inconsistencies

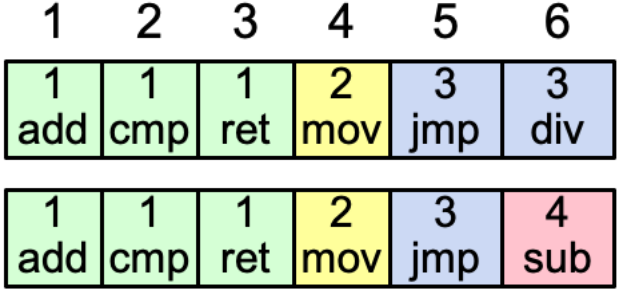
- Leaders assume its log is correct
- Normal operation will repair all inconsistencies

Consistency of the log

Question: how to achieve this property?

High level of coherency between logs maintained by the raft:

- If log entries on different servers have the same index & term
  - They store the same command
  - The logs are identical in all preceding entries



If a given entry is committed, all preceding entries are also committed

- Note that not all log entries are committed

`AppendEntries` consistency checks

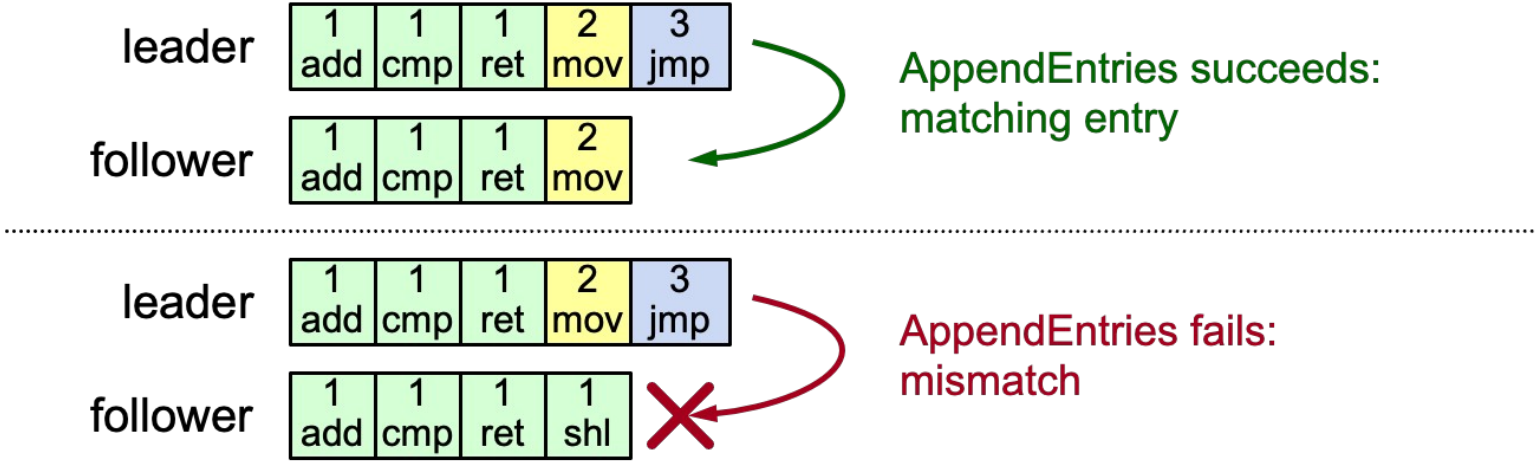
Implements an induction step, ensures coherency

Each RPC argument contains

- Append index, term, **term of entry preceding new ones**

Follower checks whether it has the matching entry

- Otherwise, it rejects the request



Why can rejection happens? Leader changes

At beginning of new leader's term:

- Old leader may have left entries partially replicated

No special steps by new leader: just start normal operation, w/ different position

- Leader's log is "the truth"
- Will eventually make follower's logs identical to leader's (overwrite the divergent log entries with the leader's ones)

The rejected entries will be overwritten by the leader's log entry

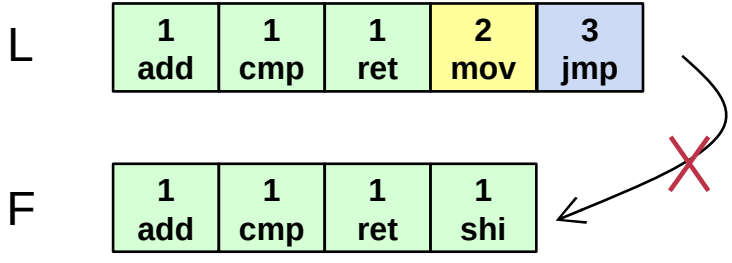
Handle rejections

Implements an induction step, ensures coherency

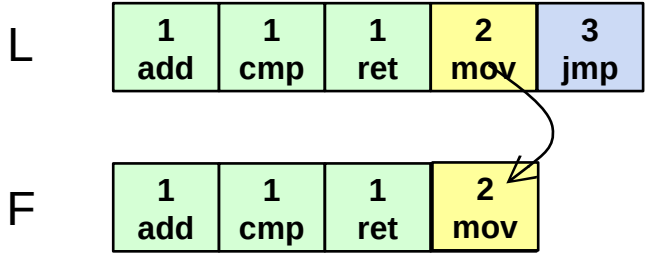
In this example, the leader will

- Overwrite index 4 with [2 mov] with AppendEntries
- Then append entry [3 jmp] to the end of the follower

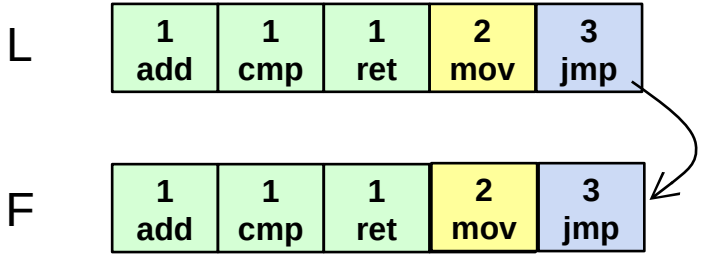
Fail to append case



Overwrite mismatched entry



Append the new entry



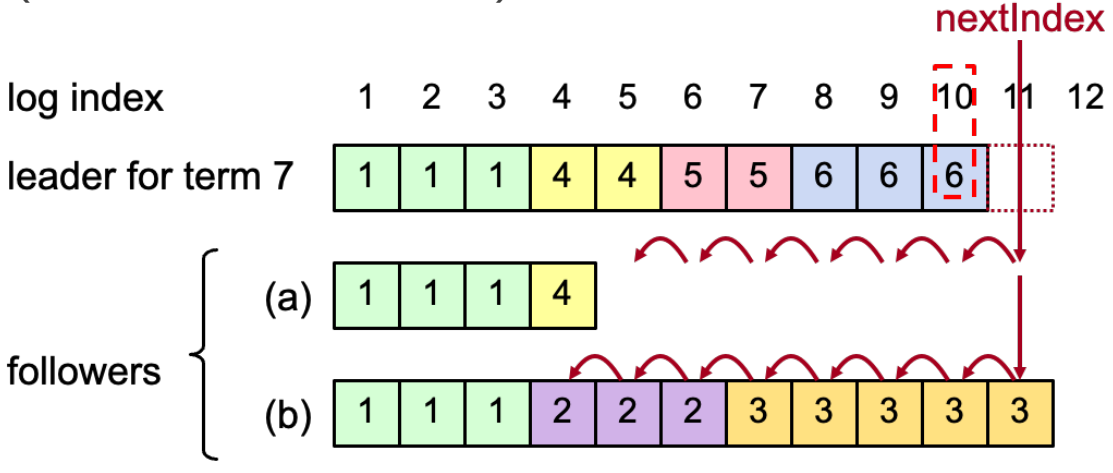
More on Repairing Follower Logs

New leader must make follower logs consistent with its own

- Delete extraneous entries
- Fill in missing entries

Leader keeps `nextIndex` for each follower:

- Index of next log entry to send to that follower
- Initialized to (1 + leader's last index)



AppendEntries RPC (Simplified)

Invoked by leader to replicate log entries and discover inconsistencies

Arguments:

term leader's term

prevLogIndex index of log entry immediately preceding new ones

prevLogTerm term of prevLogIndex entry

entries[] log entries to store (empty for heartbeat)

Results:

success true if follower contained entry matching prevLogIndex and prevLogTerm

AppendEntries RPC (Simplified)

Implementation:

1. Return false if term < currentTerm
2. If term > currentTerm, currentTerm ← term
3. If candidate or leader, step down
4. Reset election timeout
5. Return failure if log doesn't contain an entry at prevLogIndex whose term matches prevLogTerm
6. If existing entries conflict with new entries, delete all existing entries starting with first conflicting entry
7. Append any new entries not already in the log

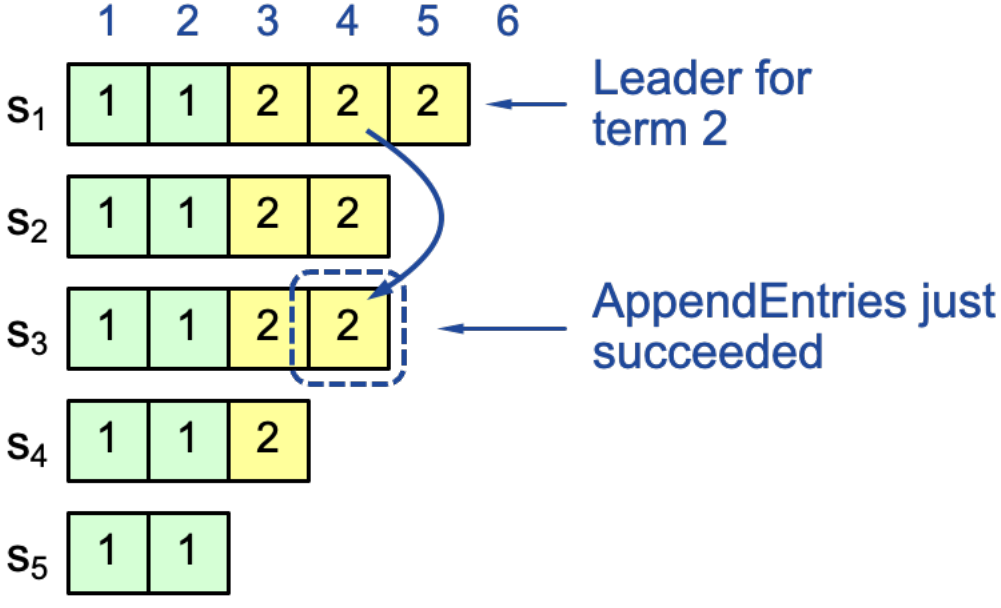
Overwrite makes a subtle issue:
When can we commit a log entry? (Since an appended log entry may be overwritten)

Intuitive result: replicating on a majority

If the log is replicated on a majority of servers, it can be replicated on the state machine

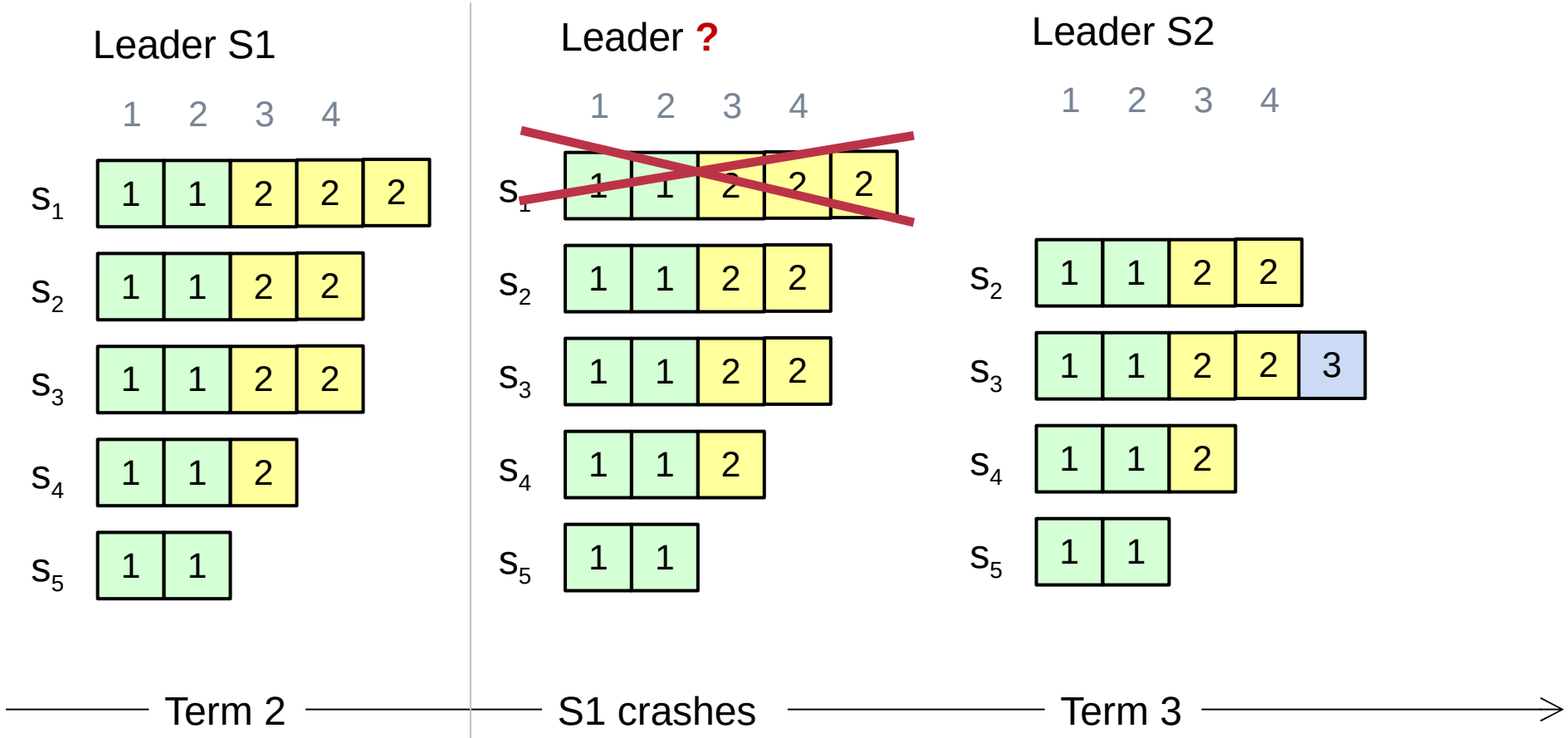
- Not always true on raft so far

Question: can index 4 be overwritten after appending to S3?



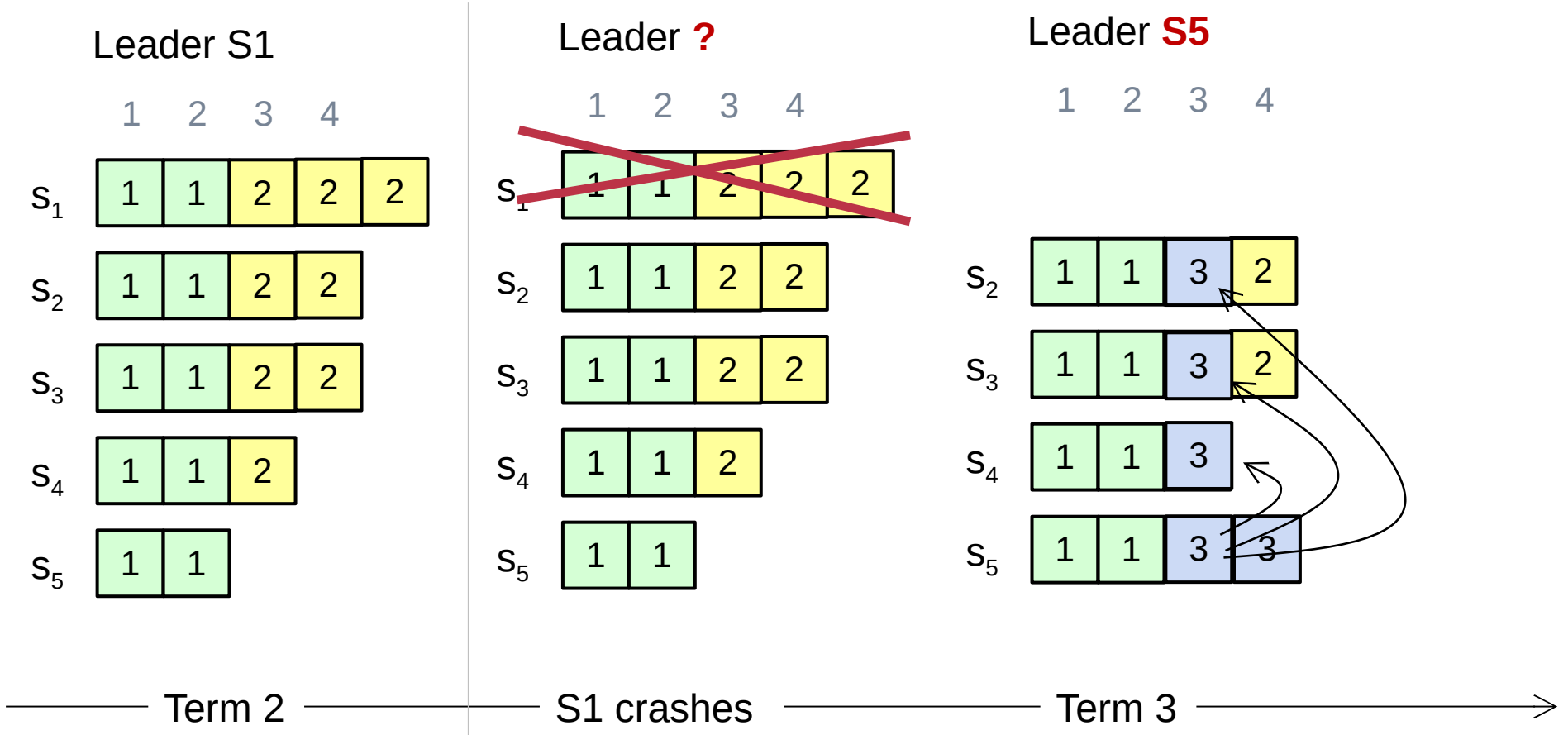
Case study: raft overwriting

Question: can index 4 be overwritten?



Case study: raft overwriting

Question: can index 4 be overwritten?



Safety requirement of the commit entry

Once a log entry has been applied to a state machine, no other state machine must apply a different value for that log entry

Raft safety property:

- If a leader has decided that a log entry is committed, that entry will be present in the logs of all future leaders (no overwritten)

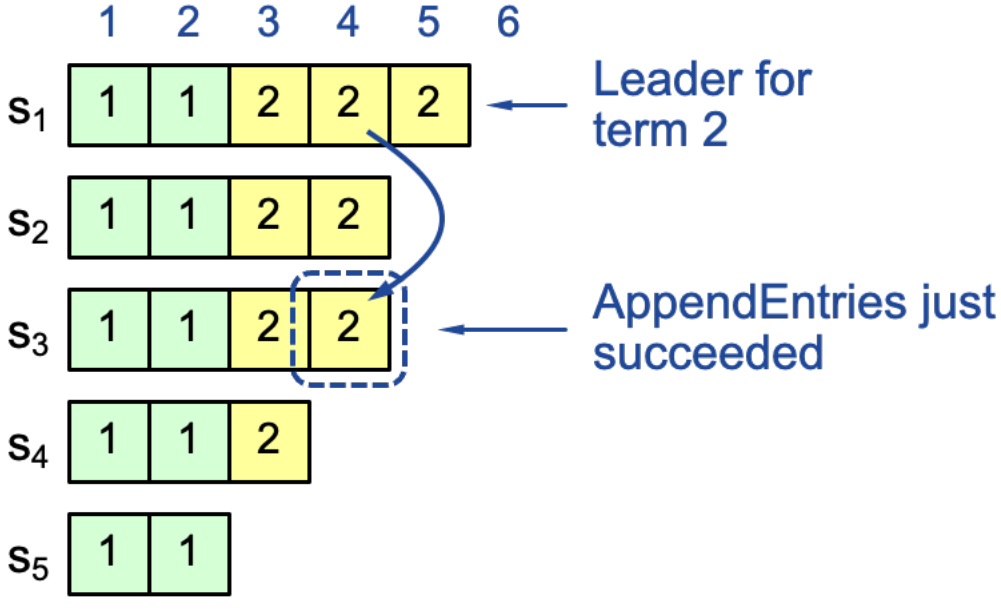
This guarantees the safety requirement

- Leaders never overwrite entries in their logs
- Only entries in the leader's log can be committed
- Entries must be committed before applying to state machine

Goal: if a log entry has been replicated to majority followers, it is likely to commit

Committing Entry from the Current Term

Case #1/2: Leader decides entry in current term is committed



Question: how to prevent index 4 from being overwritten? Prevent S4 or S5 from becoming the leader

Picking the Best Leader

During elections, choose candidate with log most likely to contain all committed entries

- Candidates include log info in RequestVote RPCs
  (index & term of last log entry)
- Voting server V denies vote if its log is “more complete”:

```
(lastTermV > lastTermC) ||
(lastTermV == lastTermC) && (lastIndexV > lastIndexC)
```

- Leader will have “most complete” log among electing majority

Comparing the best leader

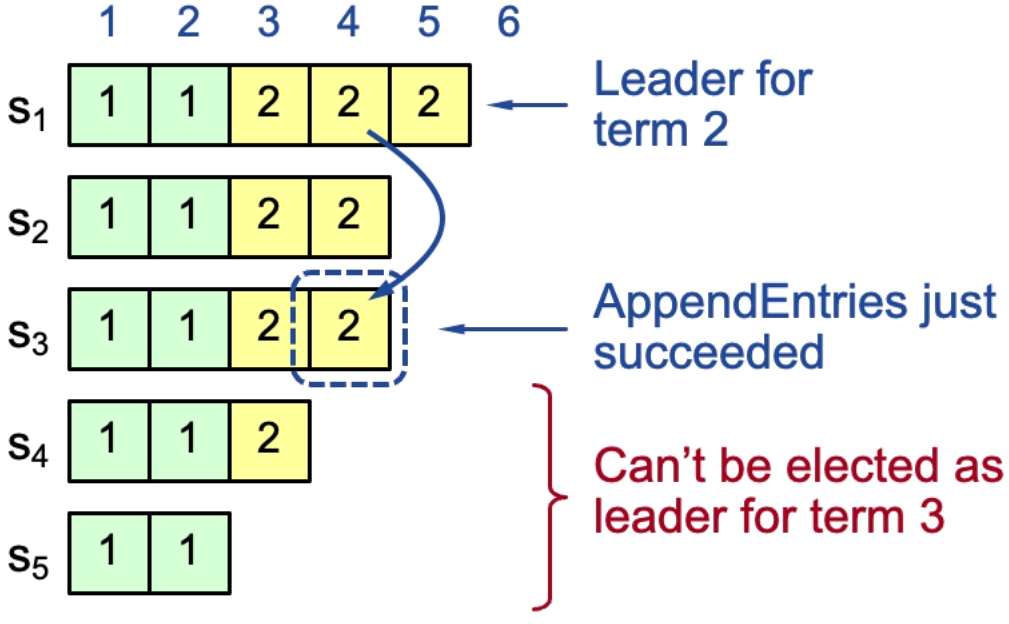
```
(lastTermV > lastTermC) ||
(lastTermV == lastTermC) && (lastIndexV > lastIndexC)
```

Question: which log is longer?

– S1 & S2, respectively

Committing Entry from the Current Term

Leader decides entry in current term is committed



Safe: leader for term 3 must contain entry 4

Complete picture of request vote RPC

Invoked by candidates to gather votes.

Arguments:

candidateId candidate requesting vote

term candidate's term

lastLogIndex index of candidate's last log entry

lastLogTerm term of candidate's last log entry

Results:

term currentTerm, for candidate to update itself

voteGranted true means candidate received vote

Implementation:

1.If term > currentTerm, currentTerm ← term
(step down if leader or candidate)

2.If term == currentTerm, votedFor is null or candidateId, and candidate's log is at least as complete as local log, grant vote and reset election timeout

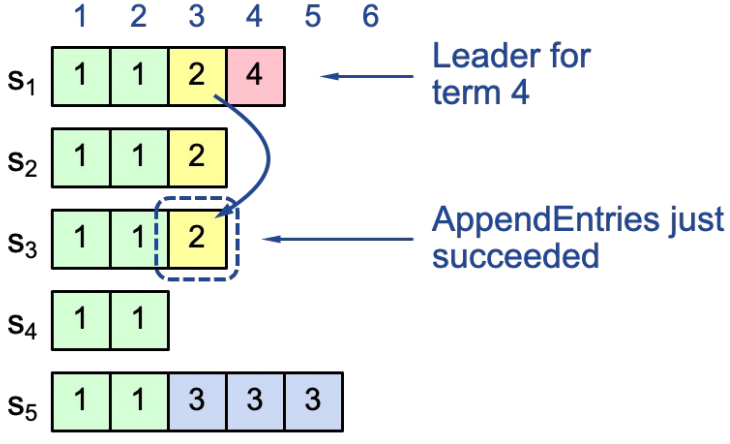
Commit rule for raft so far

If the log entry from the leader term is replicated to a majority of followers

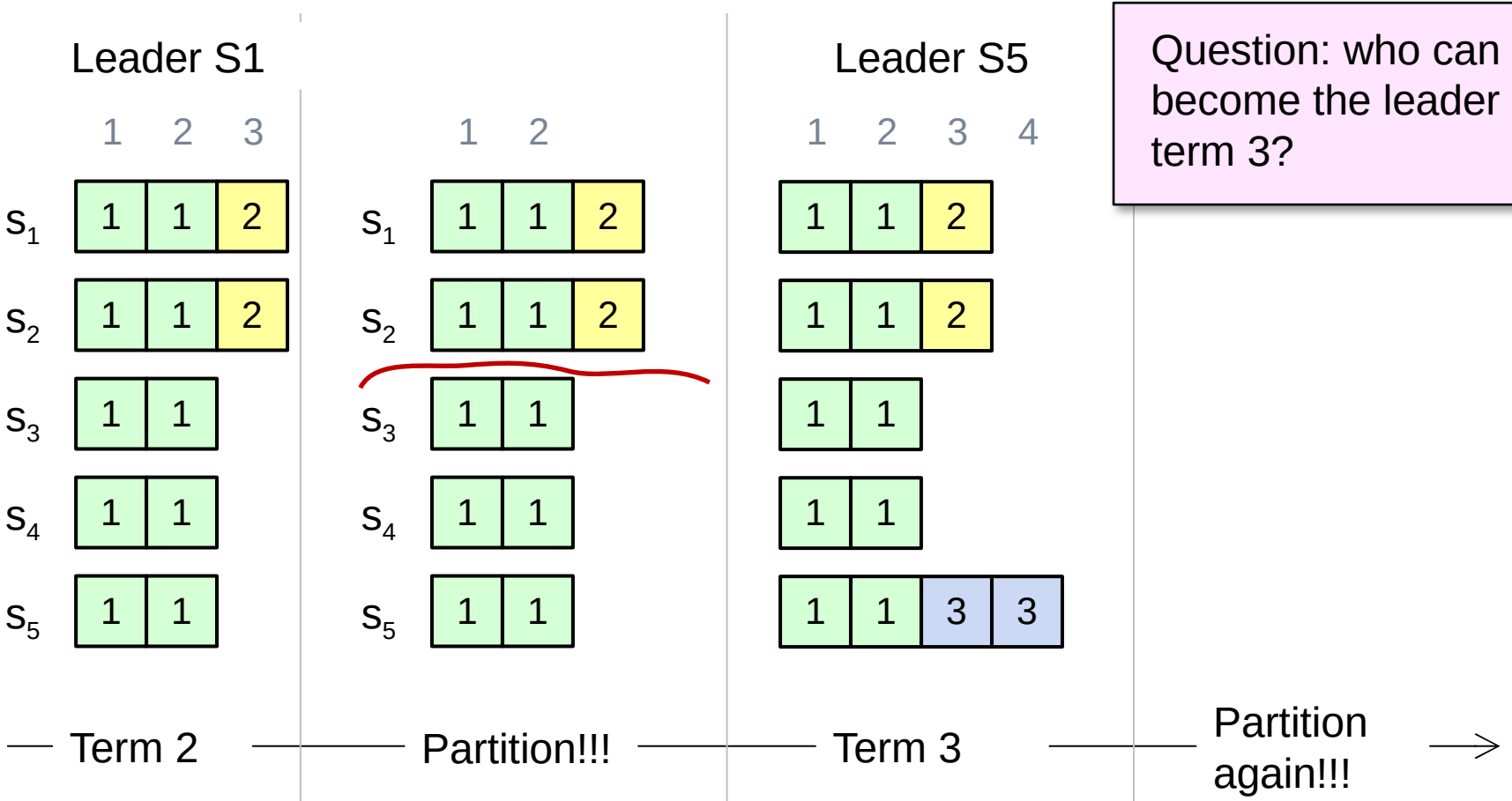
- Then we can treat it as committed
  - The later leader must contain the entry

But, what about replicating log entry from a previous term?

- The previous term's entry may fail to reach a majority

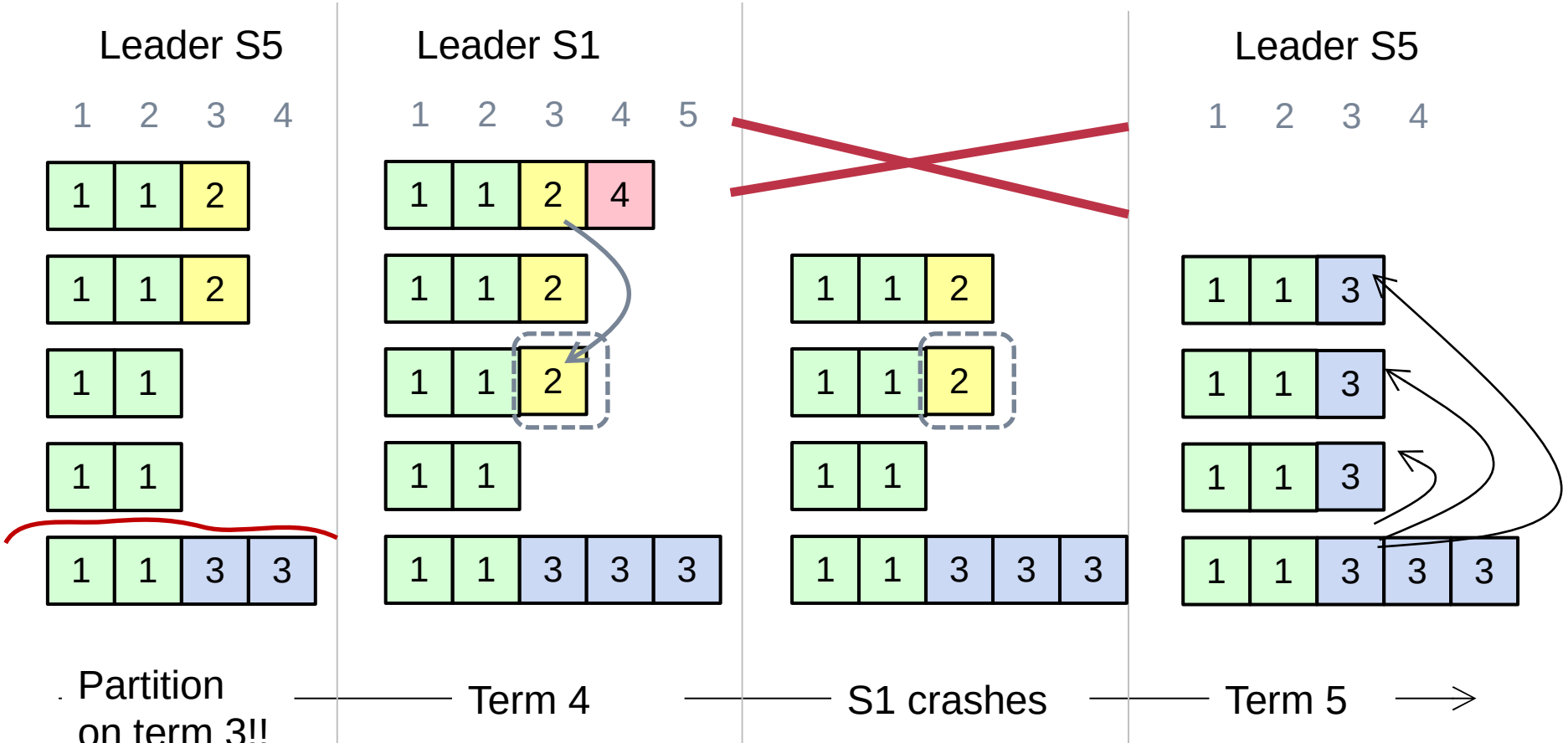


Case study: a majority replicated entry can be overwritten



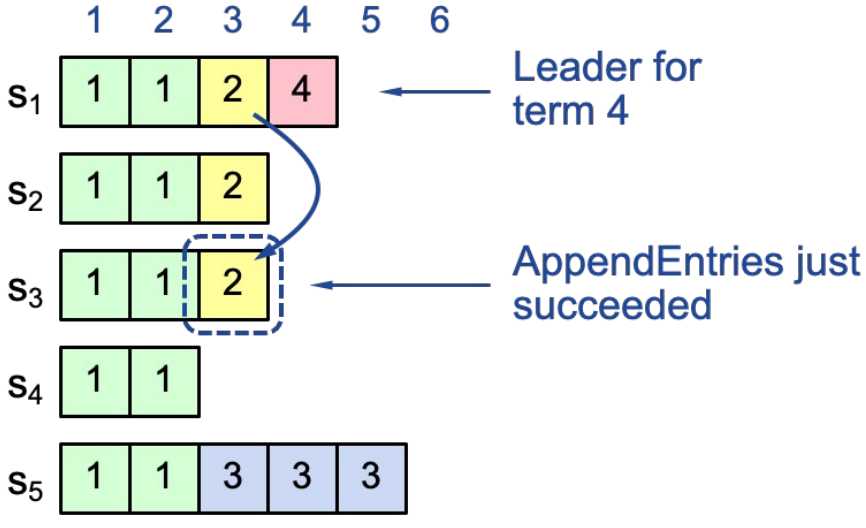
Question: who can become the leader for term 3?

Case study: a majority replicated entry can be overwritten



Committing Entry from Earlier Term

Case #2/2: Leader is trying to finish committing entry from an earlier term



Entry 3 not safely committed:

- S5 can still be elected as leader for term 5
- If elected, it will overwrite entry 3 on S1, S2 and S3 (recall our previous example)

Commit rules

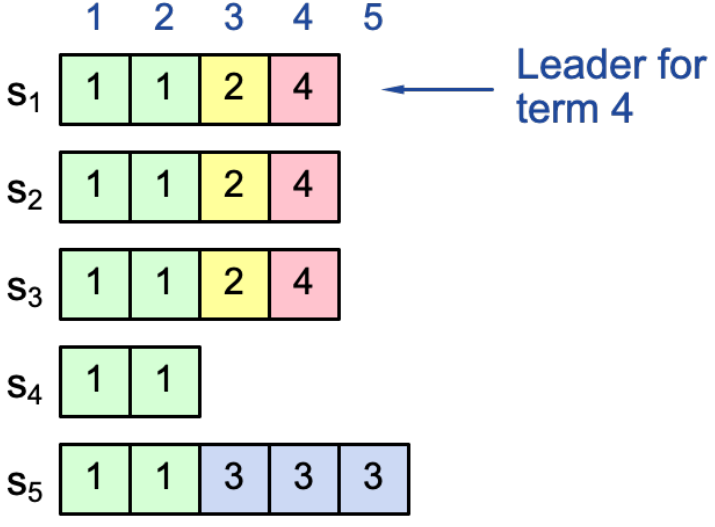
For a leader to decide an (previous) entry is committed:

- Must be stored on a majority of servers
- At least one new entry from leader's term must also be stored on majority of servers

This is because once entry 4 committed:

- s_5 cannot be elected leader for term 5
- Entries 3 and 4 both safe

Combination of election rules & commitment rules makes Raft safe



Neutralizing Old Leaders

Deposed leader may not be dead:

- Temporarily disconnected from network
- Other servers elect a new leader
- Old leader becomes reconnected, attempts to commit log entries

Terms used to detect stale leaders (and candidates)

- Every RPC contains term of the sender
- If sender's term is older, RPC is rejected, sender reverts to follower and updates its term
- If receiver's term is older, it reverts to follower, updates its term, then processes RPC normally