# The Raft Consensus Algorithm

Slides from a talk by Ongaro and Ousterhout, and a talk by Ion Stoica. This version is edited by S. Sudarshan, IIT Bombay, and some further edits by S. Chakraborty, IITKGP

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# RAFT:
# In Search of an Understandable Consensus Algorithm

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# Replicated state machines

Allows a collection of servers to

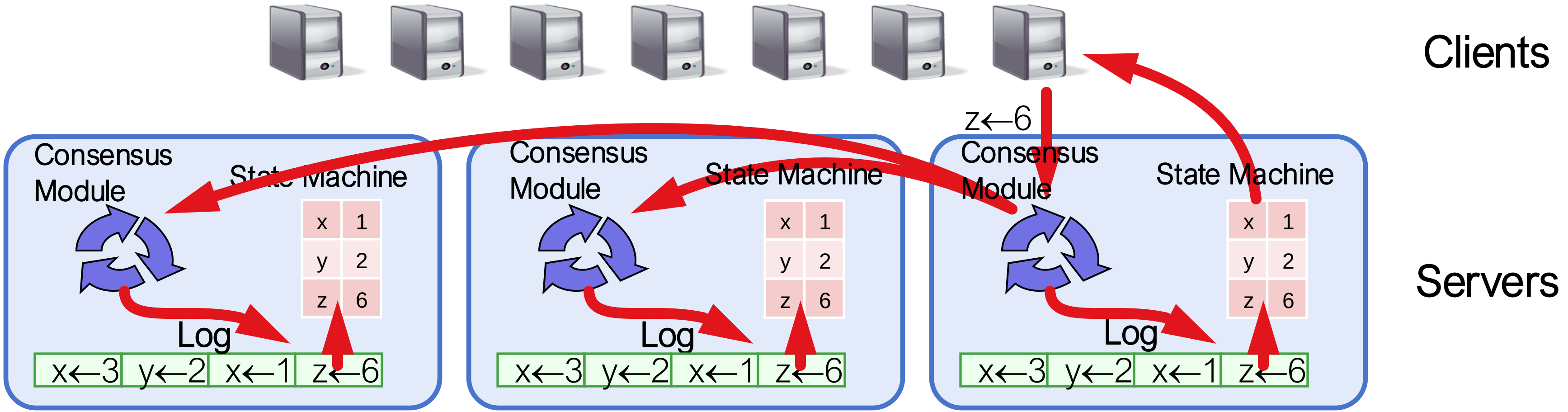
- Maintain identical copies of the same data
- Continue operating when some servers are down
  - A majority of the servers must remain up

Many applications

Typically built around a distributed log

Each server stores a log containing commands

# Replicated State Machines




Replicated log -> replicated state machine

- All servers execute same commands in same order

Consensus module ensures proper log replication

# The distributed log (I)

State machines always execute commands *in the log order*

- They will remain consistent as long as command executions have *deterministic results*

System makes progress as long as any majority of servers are up

Failure model: fail-stop (not Byzantine), delayed/lost messages

# Designing for understandability

Main objective of RAFT

- Whenever possible, select the alternative that is the easiest to understand

Techniques that were used include

- Dividing problems into smaller problems
- Reducing the number of system states to consider

# Raft Overview

1. Leader election
   - Select one of the servers to act as cluster leader
   - Detect crashes, choose new leader

2. Log replication (normal operation)
   - Leader takes commands from clients, appends them to its log
   - Leader replicates its log to other servers (overwriting inconsistencies)

3. Safety
   - Only a server with an up-to-date log can become leader

# Raft basics: the servers

A RAFT cluster consists of several servers

- Typically five

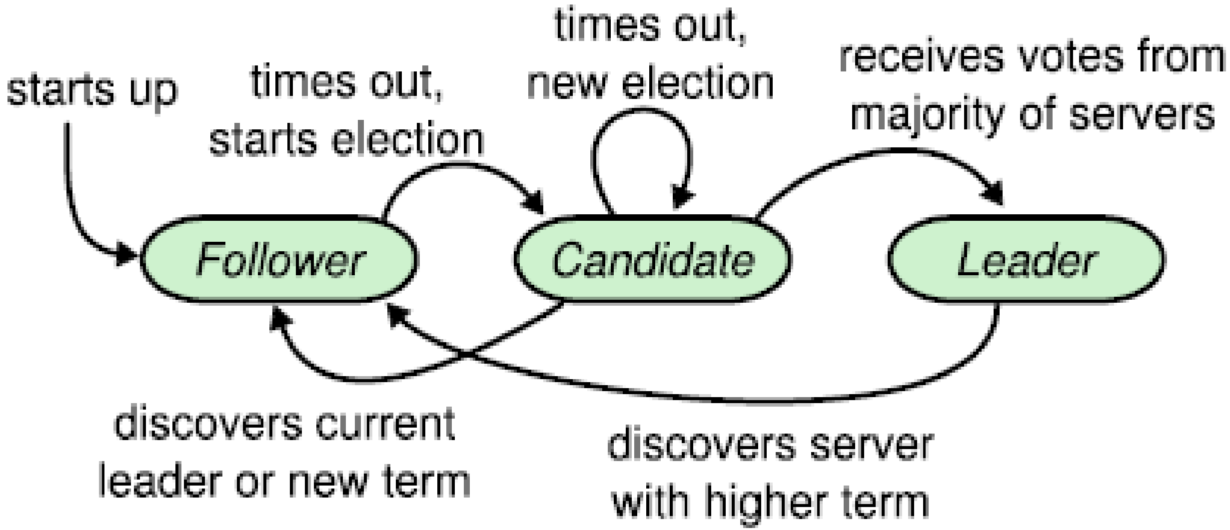
Each server can be in one of three states

- *Leader*
- *Follower*
- *Candidate* (to be the new leader)

Followers are passive:

- Simply reply to requests coming from their leader

# Server states



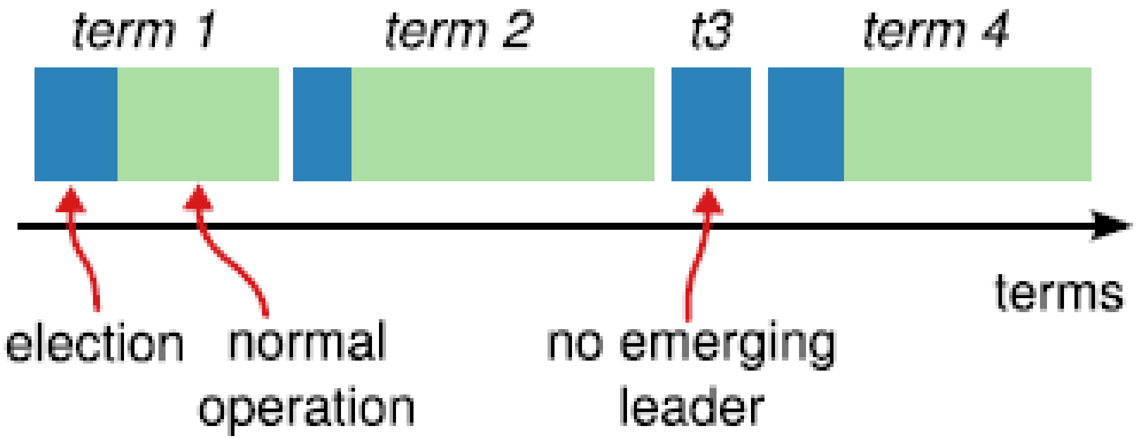
# Raft basics: terms (I)

Epochs of arbitrary length

- Start with the election of a leader
- End when
  - Leader becomes unavailable
  - No leader can be selected (split vote)

Different servers may observe transitions between terms at different times or even miss them

# Raft basics: terms (II)



# Raft basics: RPC

Servers communicate though idempotent RPCs

RequestVote

- Initiated by candidates during elections

AppendEntry: Initiated by leaders to

- Replicate log entries
- Provide a form of heartbeat
  - Empty AppendEntry( ) calls

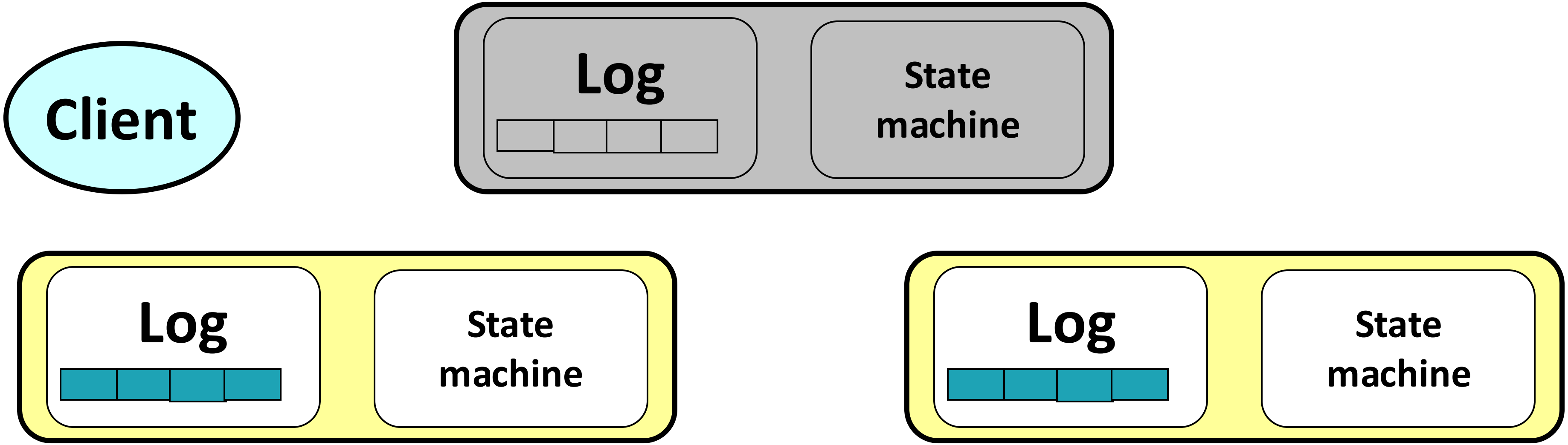
# Leader elections

Servers start being *followers*

Remain followers as long as they receive valid RPCs from a leader or candidate

When a follower receives no communication over a period of time (the *election timeout*), it starts an election to pick a *new leader*

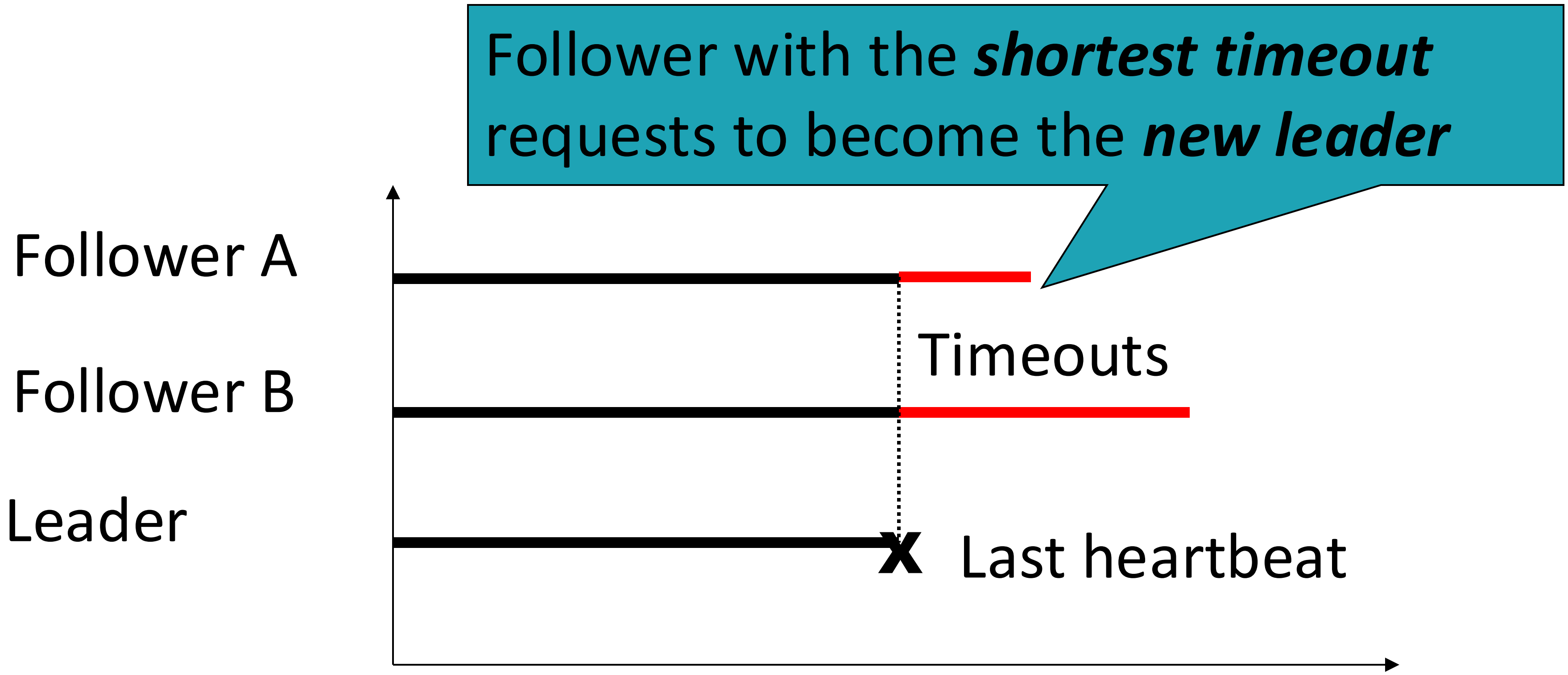
# The leader fails




Followers notice at *different times* the lack of heartbeats

Decide to elect a new leader

# Example


Follower with the ***shortest timeout*** requests to become the ***new leader***
Follower A
Follower B
Leader
Timeouts
Last heartbeat

# Starting an election

When a follower starts an election, it

- Increments its current term
- Transitions to candidate state
- Votes for itself
- Issues *RequestVote* RPCs in parallel to all the other servers in the cluster.

# Acting as a candidate

A candidate remains in that state until

- It wins the election
- Another server becomes the new leader
- A period of time goes by with no winner

# Winning an election

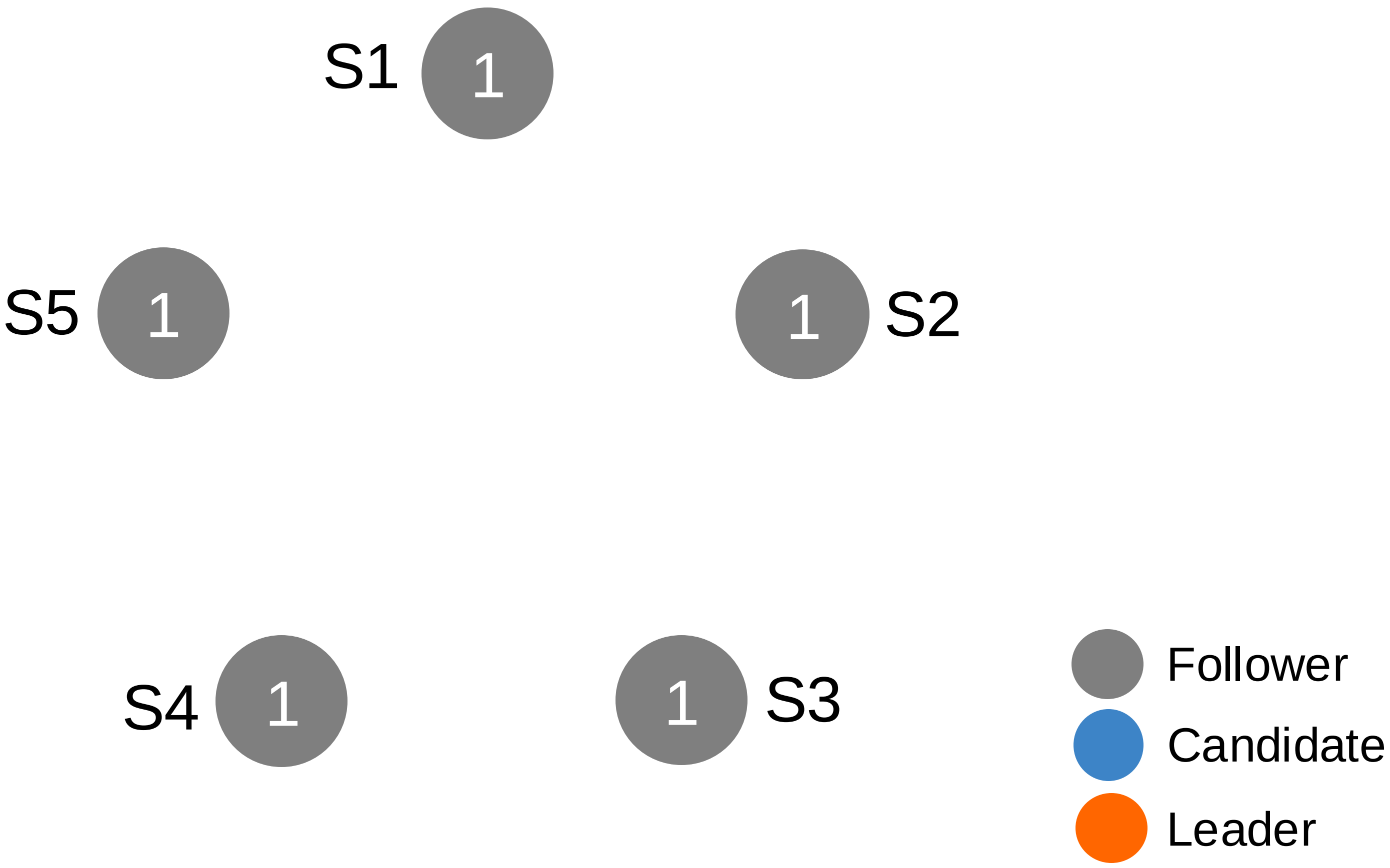
Must receive votes from a majority of the servers in the cluster for the same term

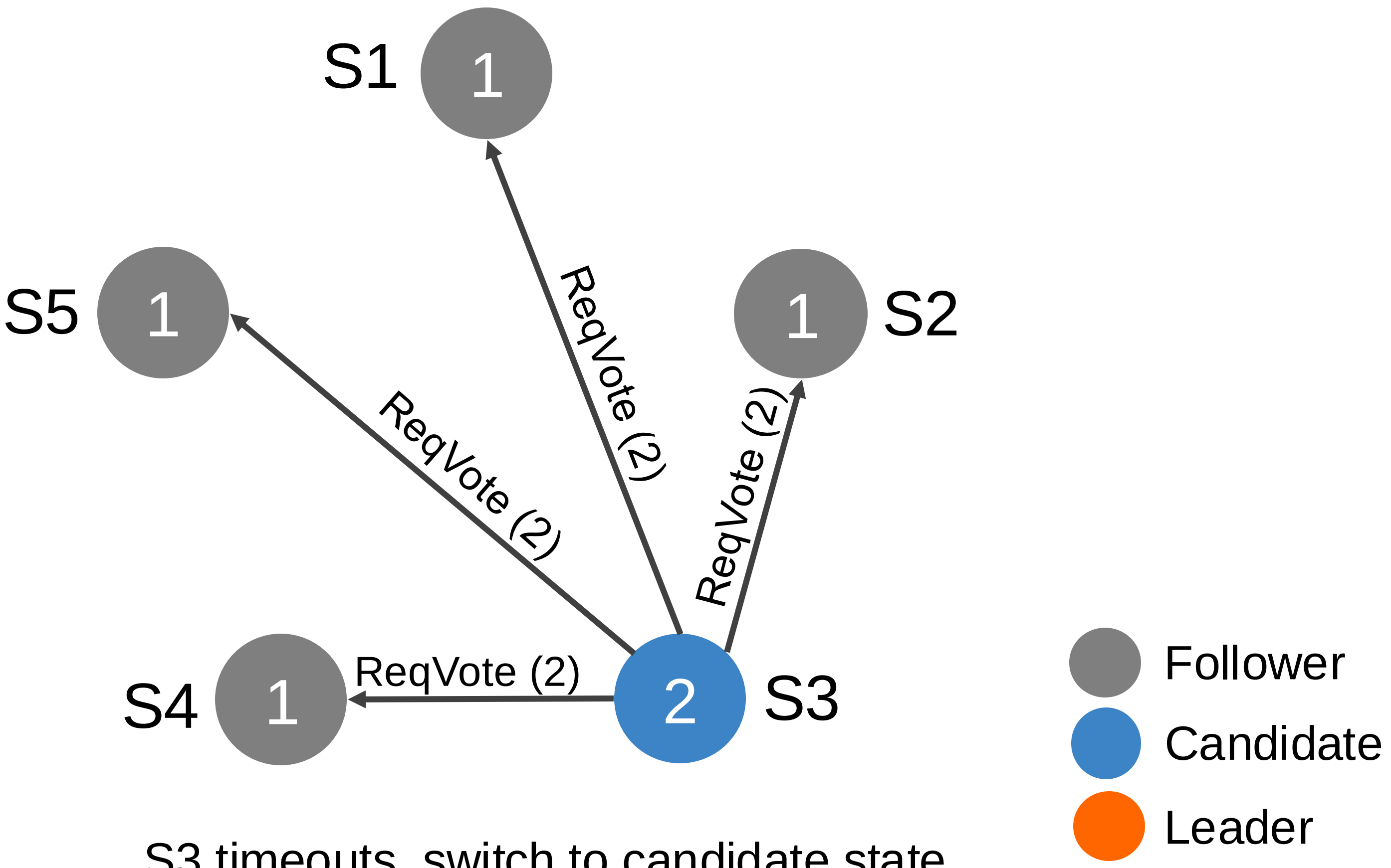
- Each server will vote for at most one candidate in a given term
  - The first one that contacted it

Majority rule ensures that at most one candidate can win the election

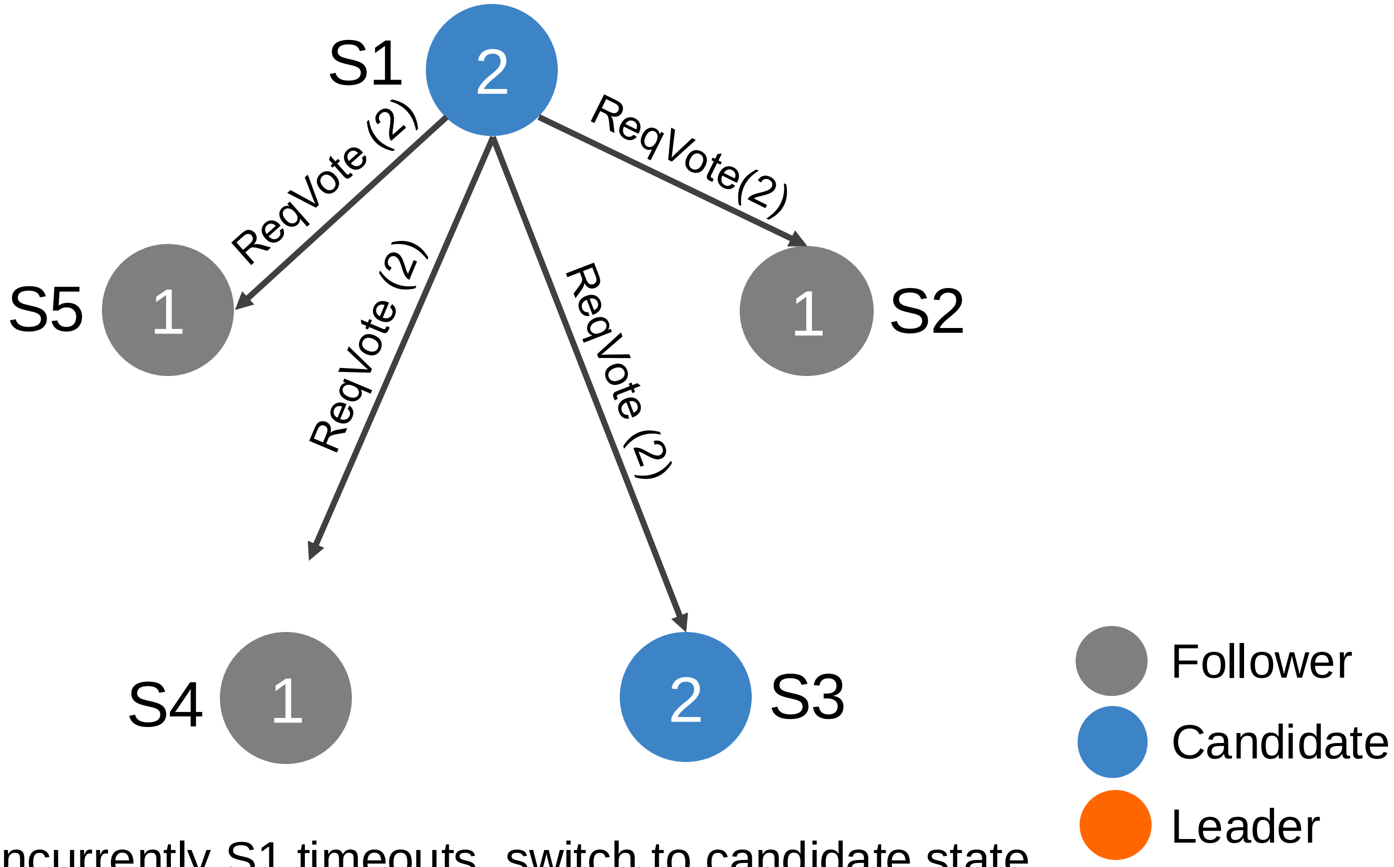
Winner becomes *leader* and sends heartbeat messages to all of the other servers

- To assert its new role

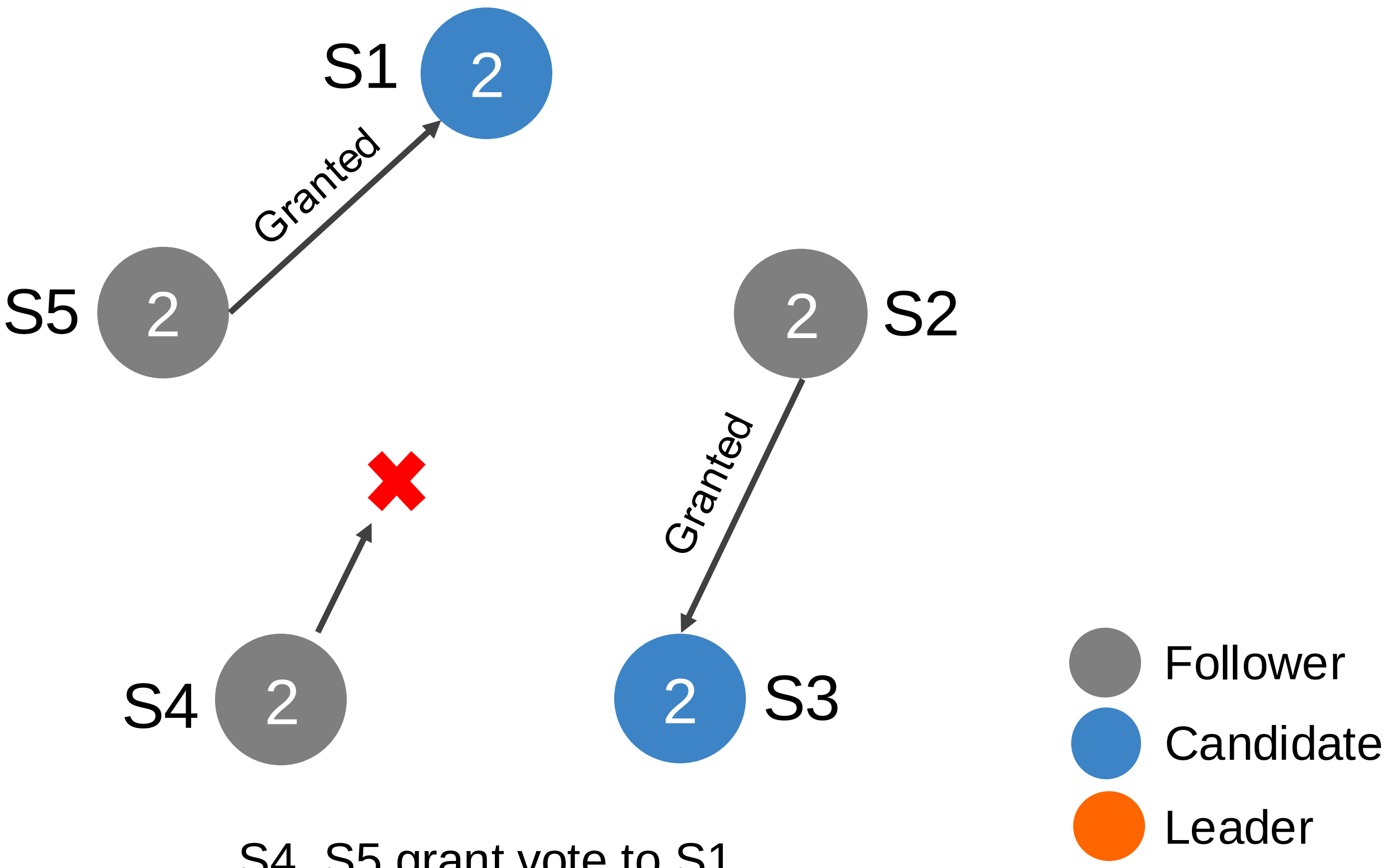

S1
1
S5
1
S2
1
S4
1
S3
1
Follower
Candidate
Leader



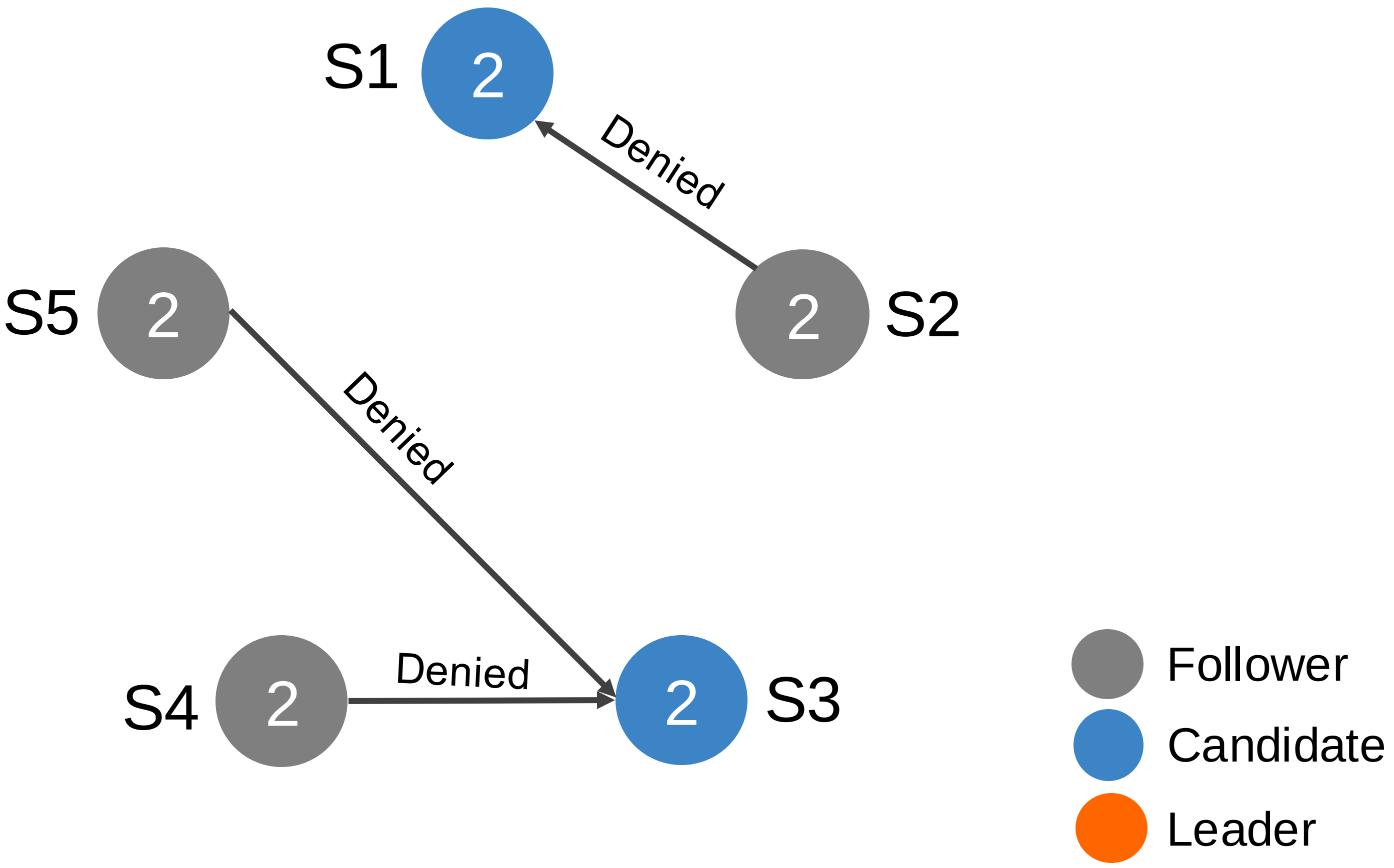

S3 timeouts, switch to candidate state,
increment term, vote itself as a leader and ask everyone else to confirm

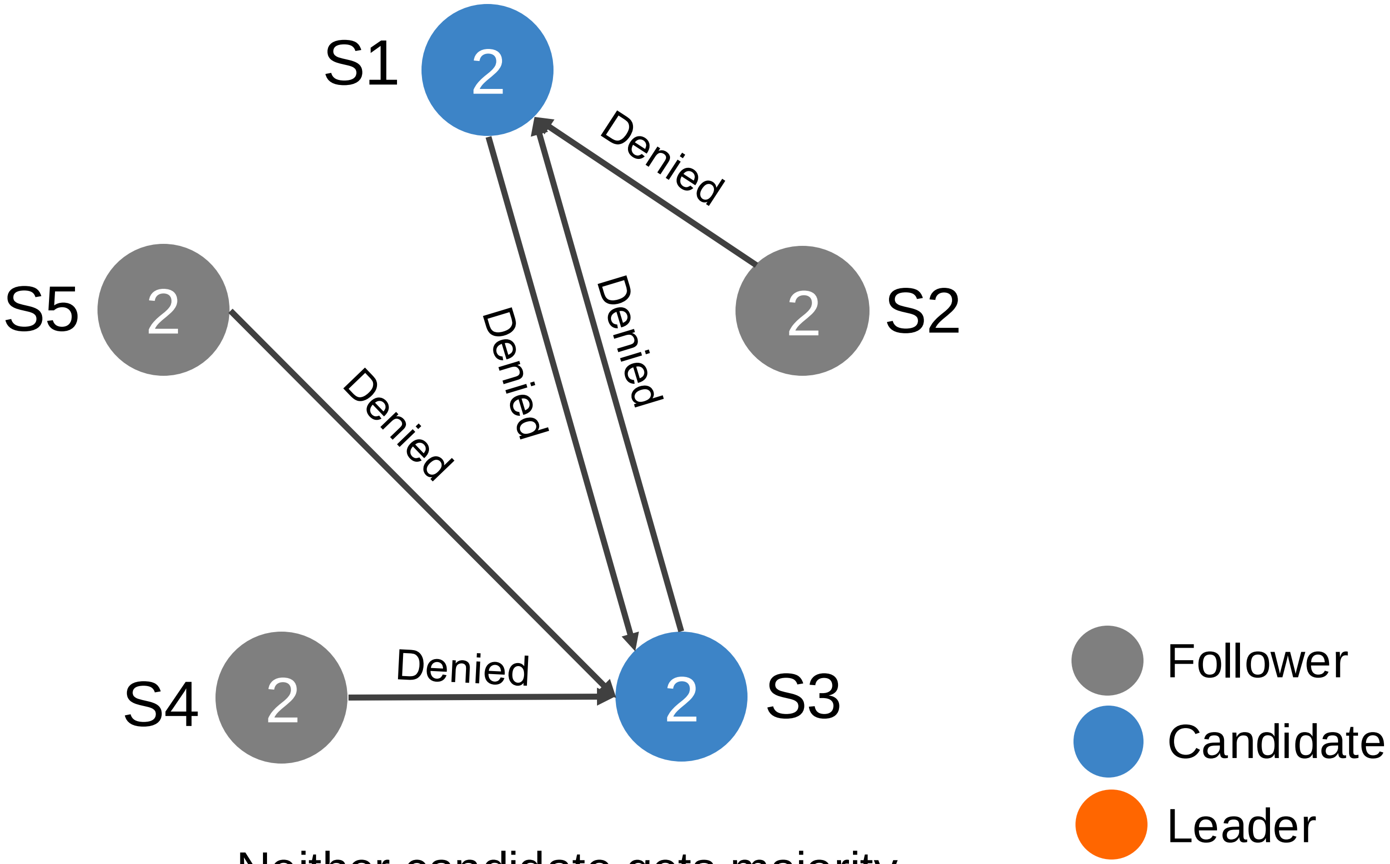



Concurrently S1 timeouts, switch to candidate state,
increment term, vote itself as a leader and ask everyone else to confirm

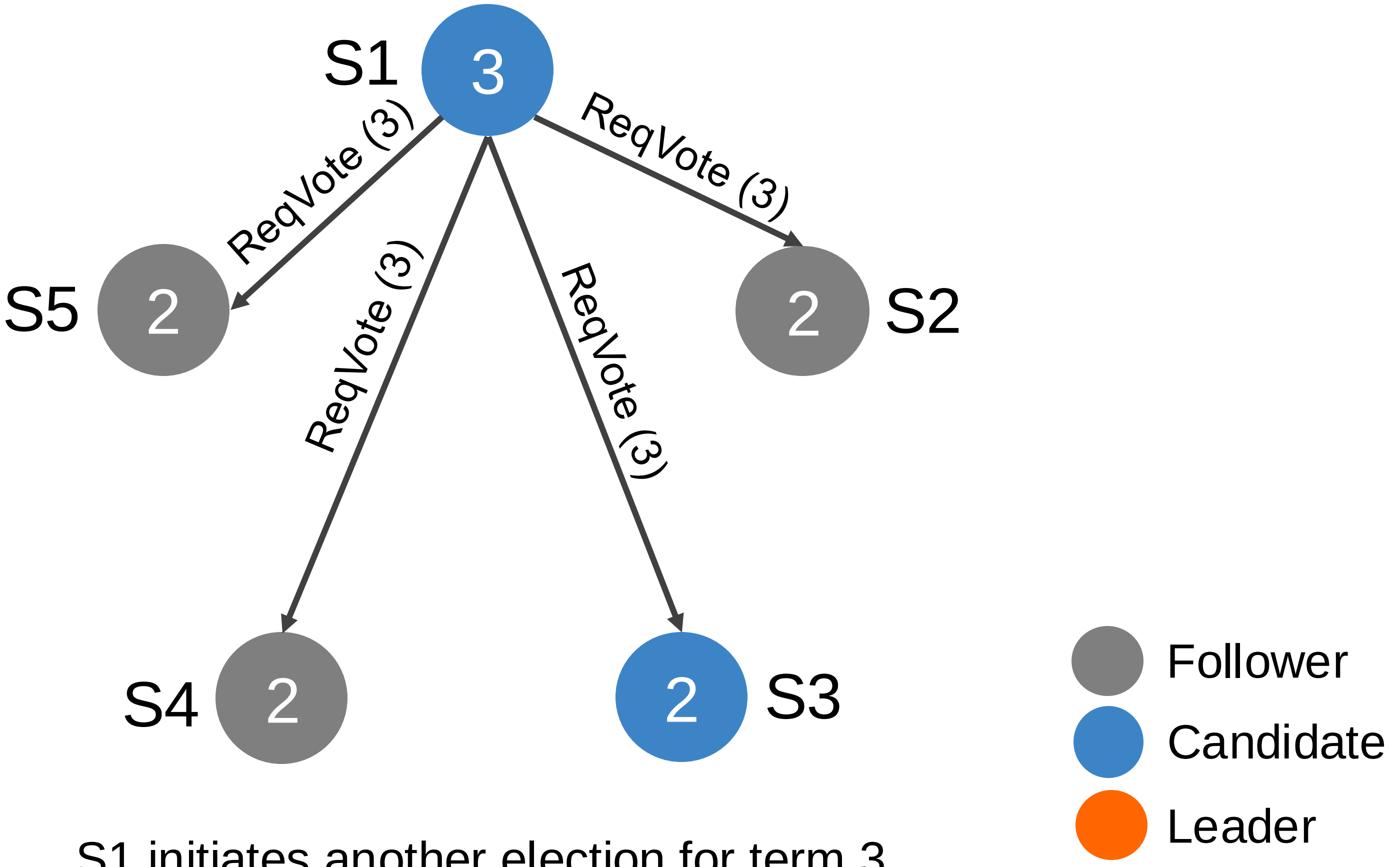



S4, S5 grant vote to S1
S2 grants vote to S3

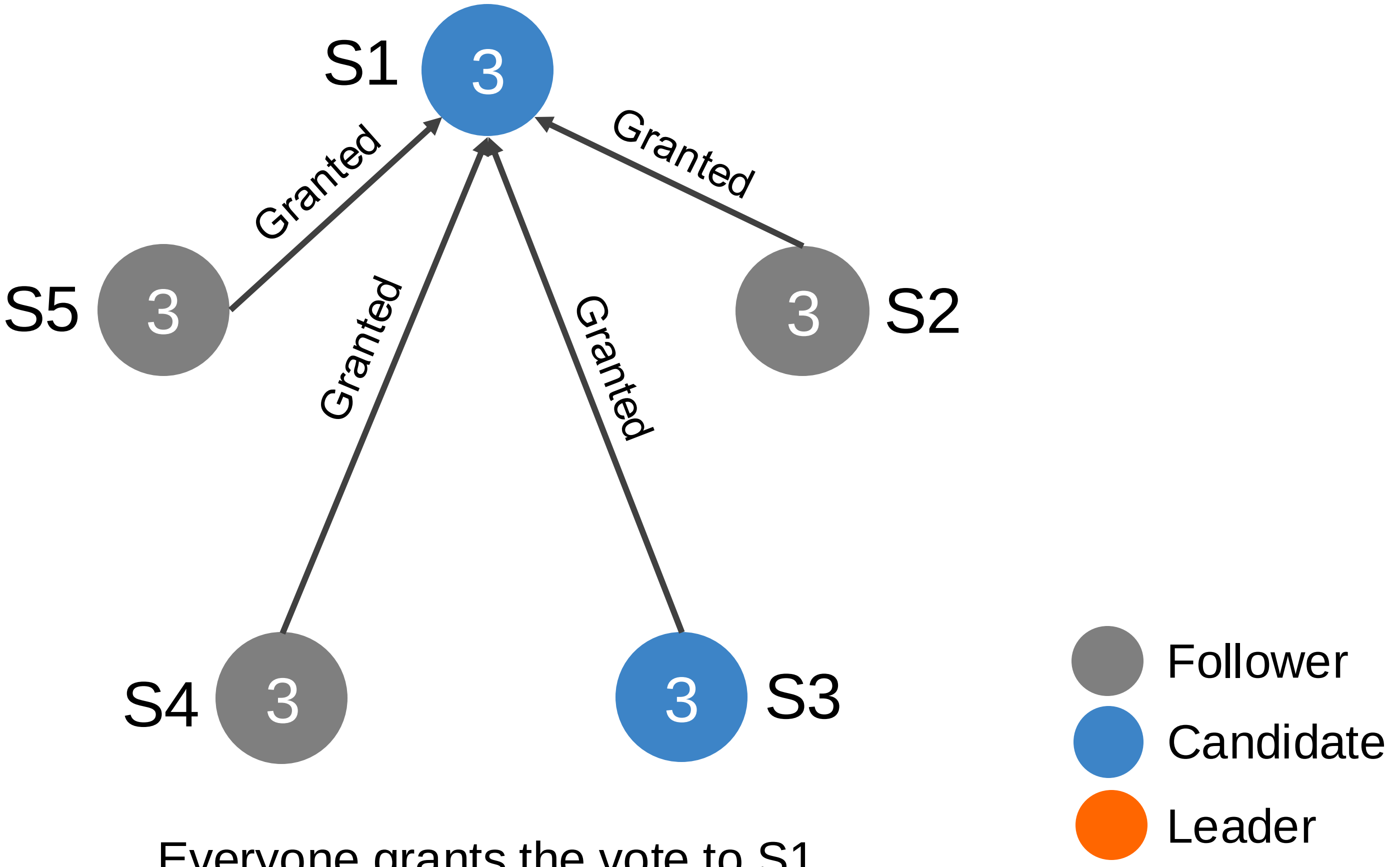

S1
2
Denied
S5
2
2
S2
Denied
S4
2
Denied
2
S3
Follower
Candidate
Leader



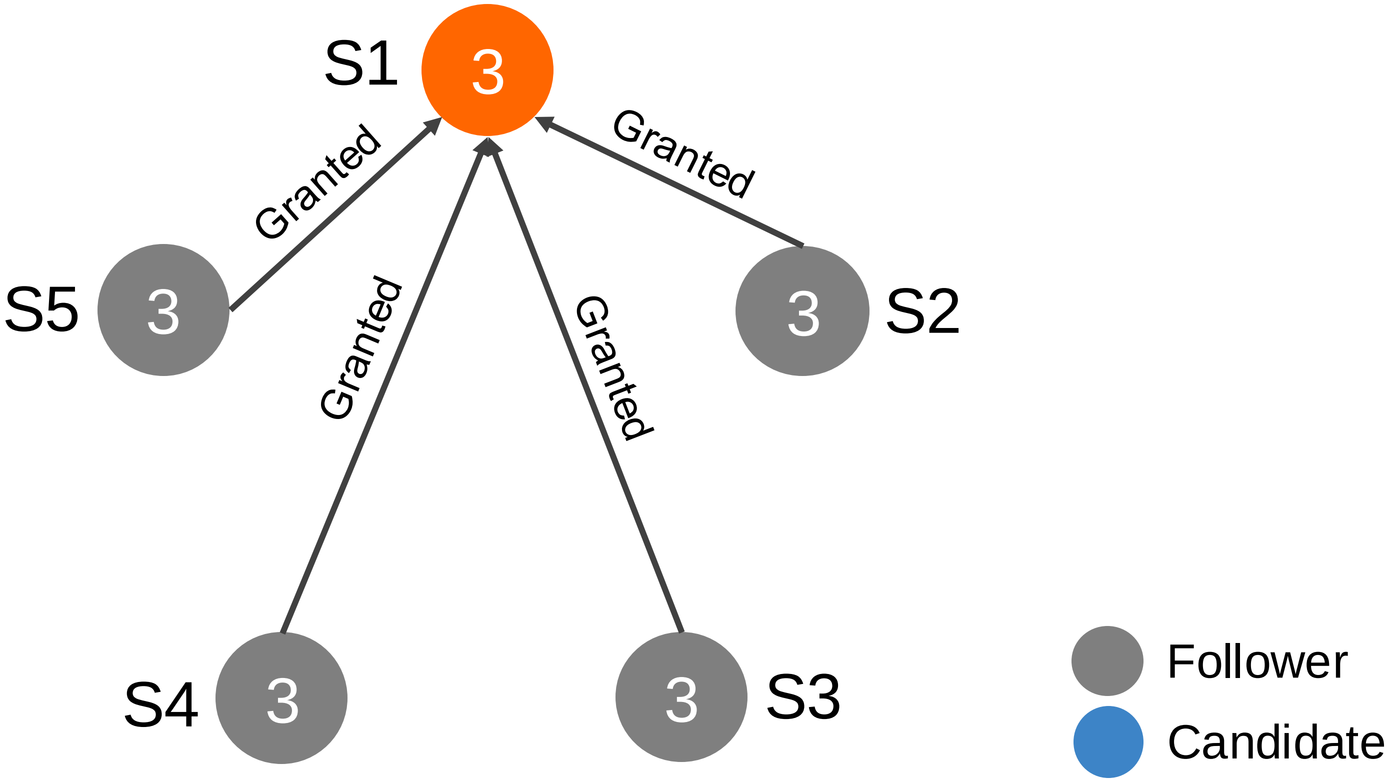

Neither candidate gets majority.
After a random delay between 150-300ms try again.




S1 initiates another election for term 3.




Everyone grants the vote to S1




S1 becomes leader for term 3,
and the others become followers.

# Hearing from other servers

Candidates may receive an *AppendEntries* RPC from another server claiming to be leader

If the leader’s term is at greater than or equal to the candidate’s current term, the candidate recognizes that leader  and returns to follower state

Otherwise the candidate ignores the RPC and remains a candidate

# Split elections

No candidate obtains a majority of the votes in the servers in the cluster

Each candidate will time out and start a new election

- After incrementing its term number

# Avoiding split elections

Raft uses randomized election timeouts

- Chosen randomly from a fixed interval

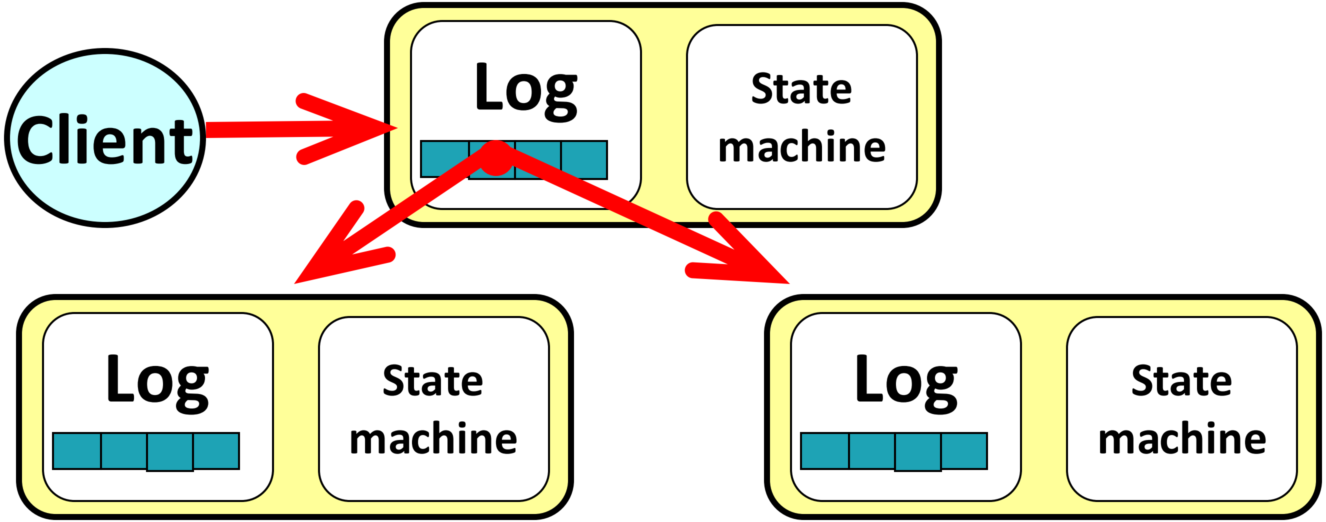
Increases the chances that a single follower will detect the loss of the leader before the others

# Log replication

Leaders

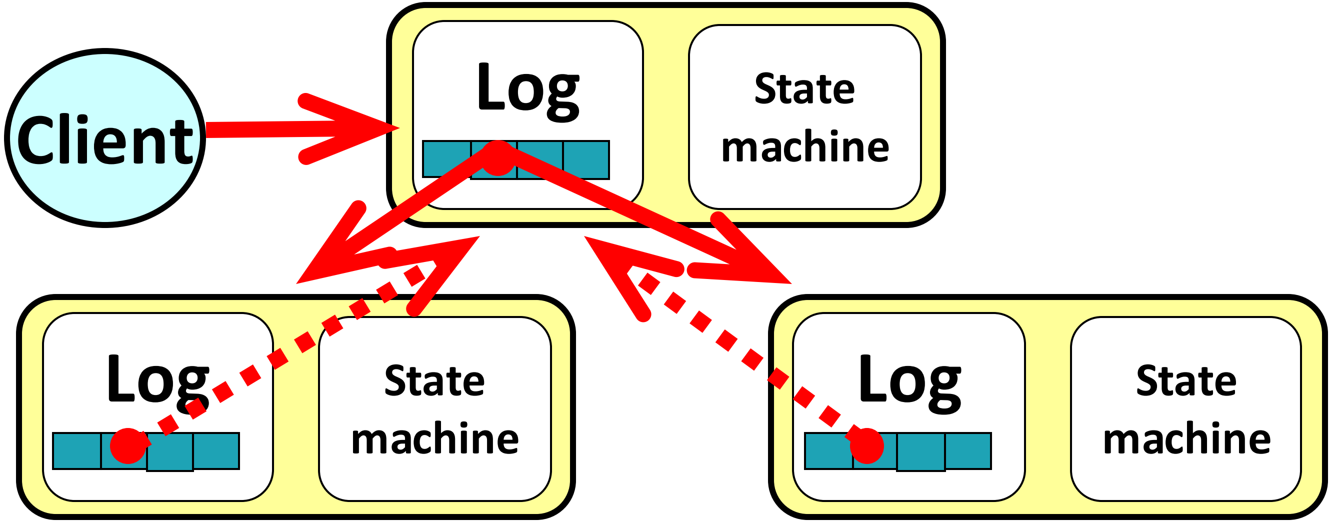
- Accept client commands
- Append them to their log (new entry)
- Issue AppendEntry RPCs in parallel to all followers
- Apply the entry to their state machine once it has been safely replicated
  - Entry is then *committed*

# A client sends a request



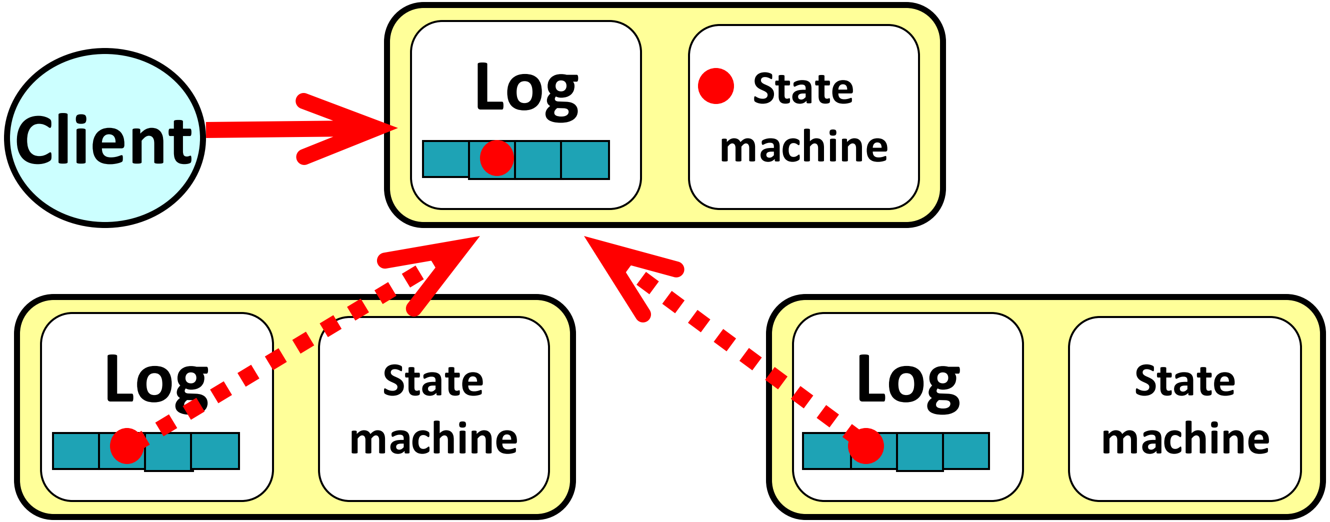

Leader stores request on its log and forwards it to its followers

# The followers receive the request



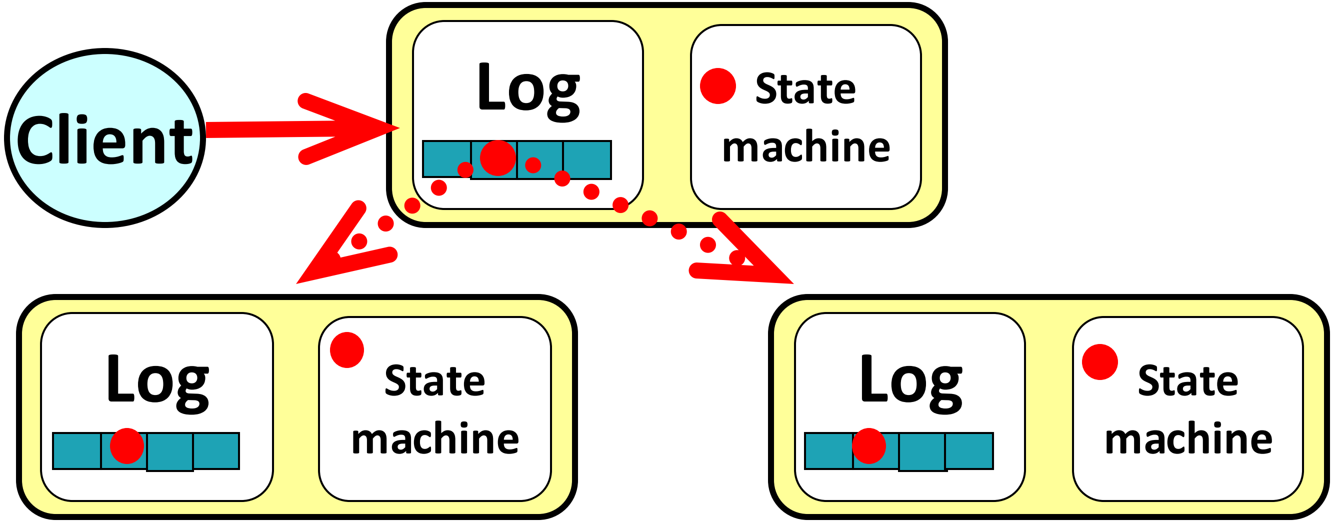

Followers store the request on their logs and acknowledge its receipt

# The leader tallies followers' ACKs



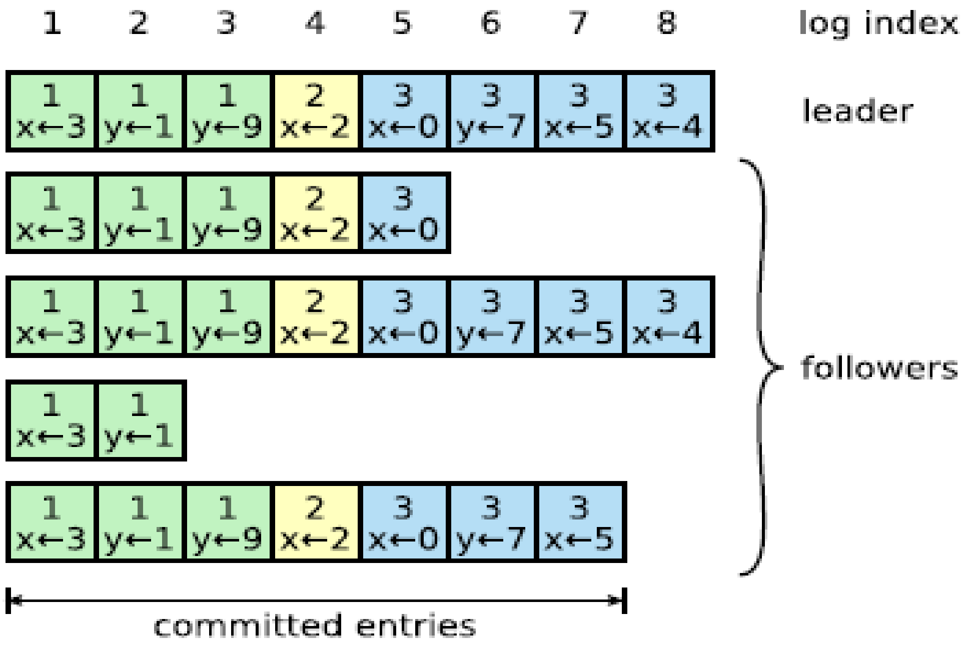

Once it ascertains the request has been processed by a majority of the servers, it updates its state machine

# The leader tallies followers' ACKs




Leader's heartbeats convey the news to its followers: they update their state machines

# Log organization

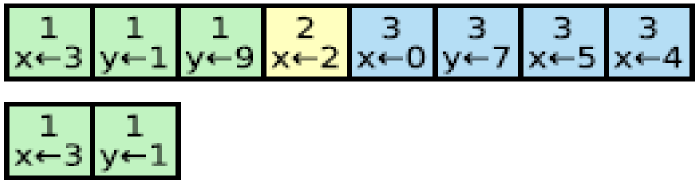



Colors identify terms

# Raft log matching property

If two entries in different logs have the same index and term

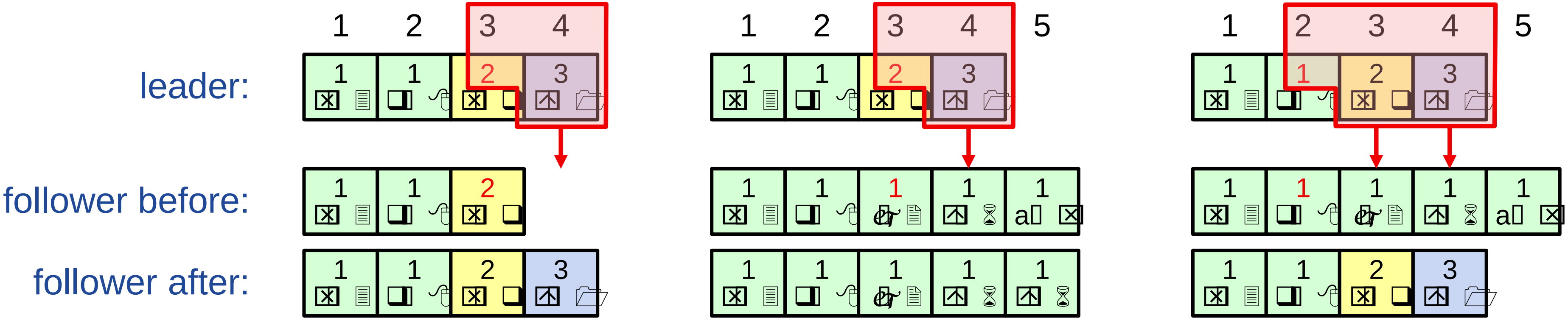
- These entries store the same command
- *All previous entries* in the two logs are *identical*



# AppendEntries Consistency Check

AppendEntries RPCs include <index, term> of entry preceding new one(s)

- Follower must contain matching entry; otherwise it rejects request
    - Leader retries with lower log index
- Implements an induction step, ensures Log Matching Property




Example #1: success Example #2: mismatch Example #3: success

# Why?

Raft commits entries in *strictly sequential order*

- Requires followers to accept log entry appends in the same sequential order
  - *Cannot "skip" entries*

**Greatly simplifies the protocol**

# Handling slow followers ,…

Leader reissues the AppendEntry RPC

- They are idempotent

# Committed entries

Guaranteed to be both

- Durable
- Eventually executed by all the available state machine

Committing an entry also commits all previous entries

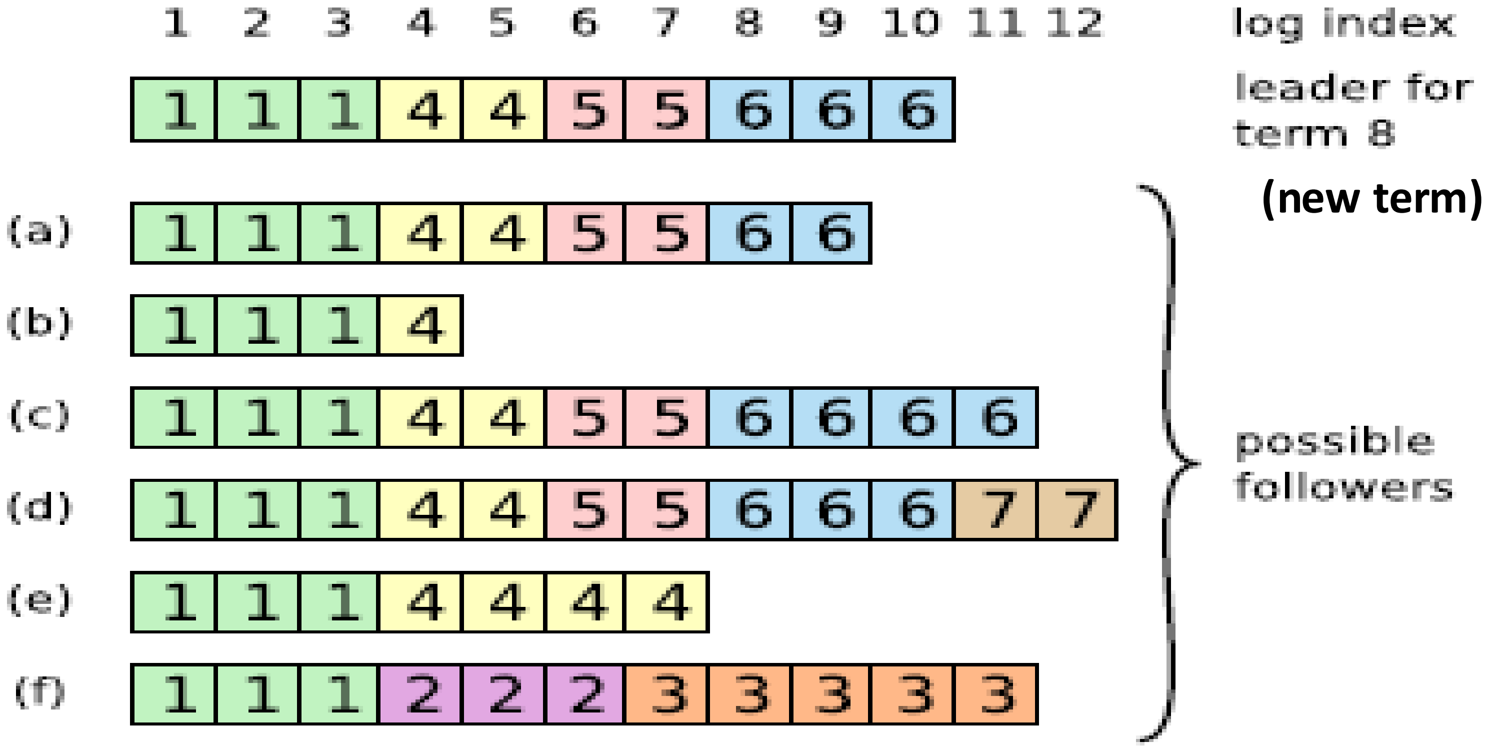
- All AppendEntry RPCs—including heartbeats—include the index of its most recently committed entry

# Handling leader crashes (I)

Can leave the cluster in a inconsistent state if the old leader had not fully replicated a previous entry

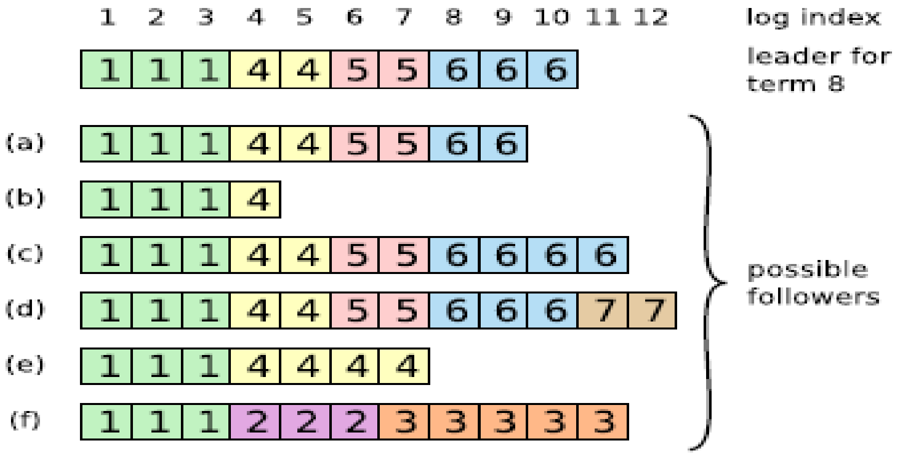
- Some followers may have in their logs entries that the new leader does not have
- Other followers may miss entries that the new leader has

# Handling leader crashes (II)

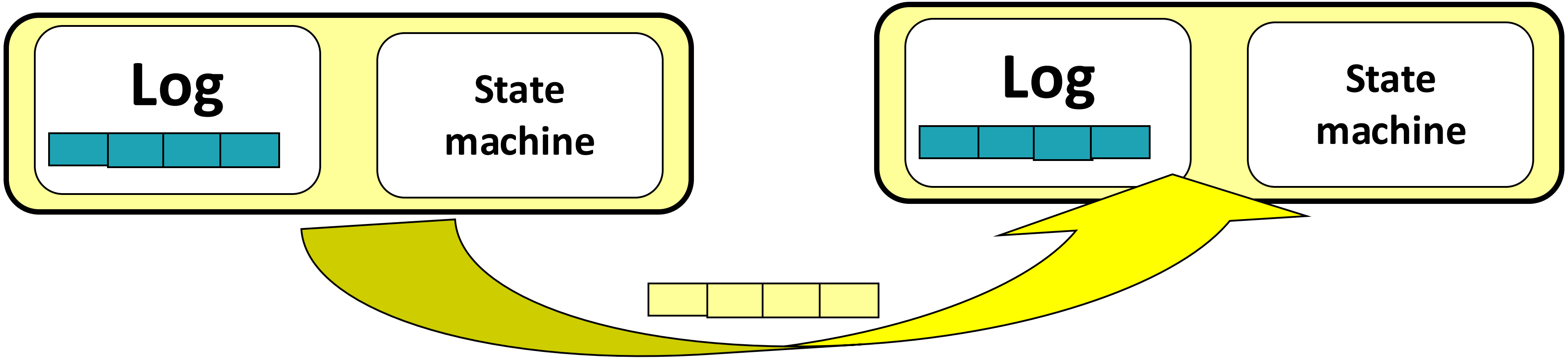


# Log Status After Election

- When the leader at the top comes to power, it is possible that any of scenarios (a–f) could occur in follower logs.
- Each box represents one log entry; the number in the box is its term.
- A follower may be missing entries (a–b),
- May have extra uncommitted entries (c–d), or both (e–f). or several terms.
  - E.g. scenario (f) could occur if that server was the leader for term 2, added several entries to its log, then crashed before committing any of them; it restarted quickly, became leader for term 3, and added a few more entries to its log; before any of the entries in either term 2 or term 3 were committed, the server crashed again and remained down for several terms.



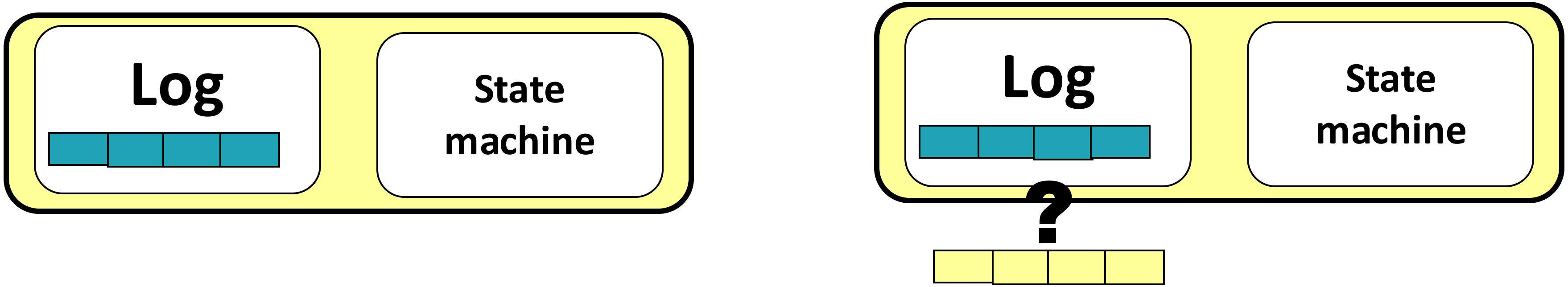
# An election starts




Candidate for leader position requests votes of other former followers

- Includes a summary of the state of its log

# Former followers reply




Former followers compare the state of their logs with credentials of candidate

Vote for candidate unless

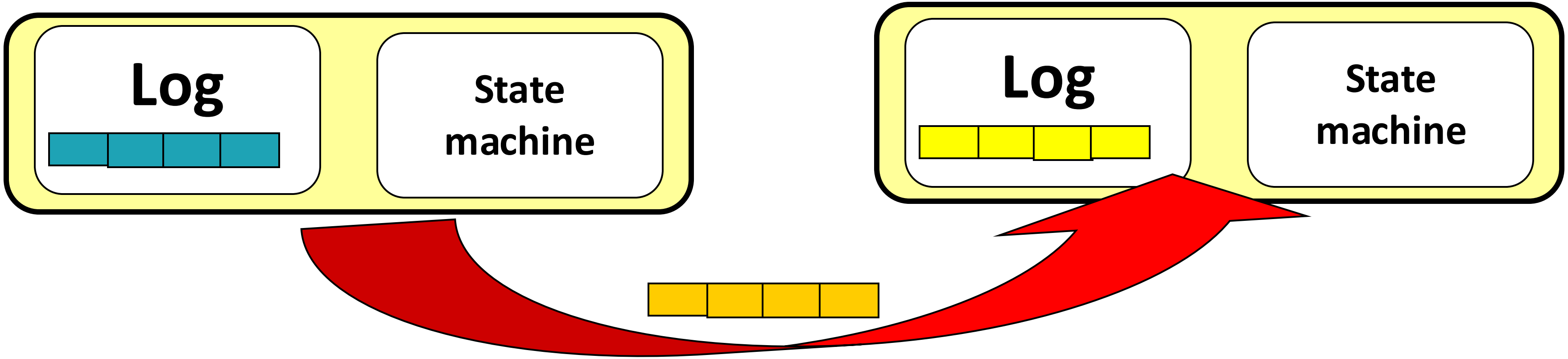
- Their own log is more "up to date"
- They have already voted for another server

# Handling leader crashes (III)

Raft solution is to let the new leader to force followers' log to duplicate its own

- Conflicting entries in followers' logs will be *overwritten*

# The new leader is in charge




Newly elected candidate forces all its followers to duplicate in their logs the contents of its own log

# How? (I)

Leader maintains a *nextIndex* for each follower

- Index of entry it will send to that follower

New leader sets its *nextIndex* to the index *just after its last log entry*

- 11 in the example

Broadcasts it to all its followers

# How? (II)

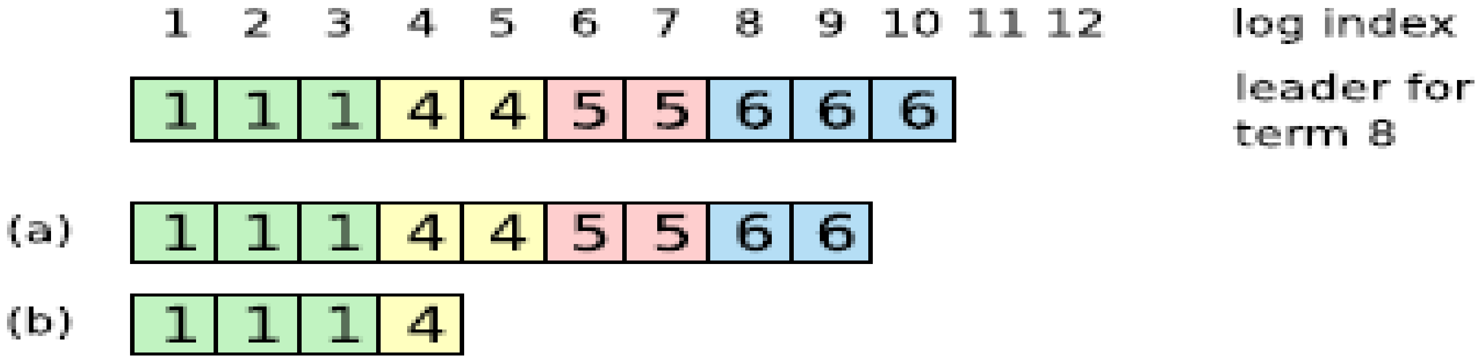
Followers that have missed some  AppendEntry calls will refuse all further AppendEntry calls

Leader will decrement its nextIndex for that follower and redo the previous AppendEntry call

- Process will be repeated until a point where the logs of the leader and the follower **match**

Will then send  to the follower all the log entries it missed

# How? (III)




By successive trials and errors, leader finds out that the first log entry that follower (b) will accept is log entry 5

It then forwards to (b) log entries 5 to 10

# Interesting question

How will the leader know which log entries it can commit

- Cannot always gather a majority since some of the replies were sent to the old leader

Fortunately for us, any follower accepting an AcceptEntry RPC implicitly acknowledges it has processed all previous AcceptEntry RPCs

**Followers' logs cannot skip entries**

# A last observation

Handling log inconsistencies does not require a special sub algorithm

- Rolling back EntryAppend calls is enough

# Safety

Two main questions

1. What if the log of a new leader did not contain all previously committed entries?
   - Must impose conditions on new leaders

2. How to commit entries from a previous term?
   - Must tune the commit mechanism

# Election restriction (I)

The log of any new leader ***must*** contain all previously committed entries

- Candidates include in their *RequestVote* RPCs information about the state of their log
- Before voting for a candidate, servers check that the log of the candidate is at least as up to date as their own log.
  - Majority rule does the rest
- Definition of Up-To-Date: next slide

# Which log is more up to date?

- Raft determines which of two logs is more up-to-date by comparing the index and term of the last entries in the logs.
  - If the logs have last entries with different terms, then the log with the later term is more up-to-date.
  - If the logs end with the same term, then whichever log is longer is more up-to-date.
- A log entry for a term means a leader was elected by a majority, and (inductively) earlier log records are up to date

# New leader will not erase committed entries

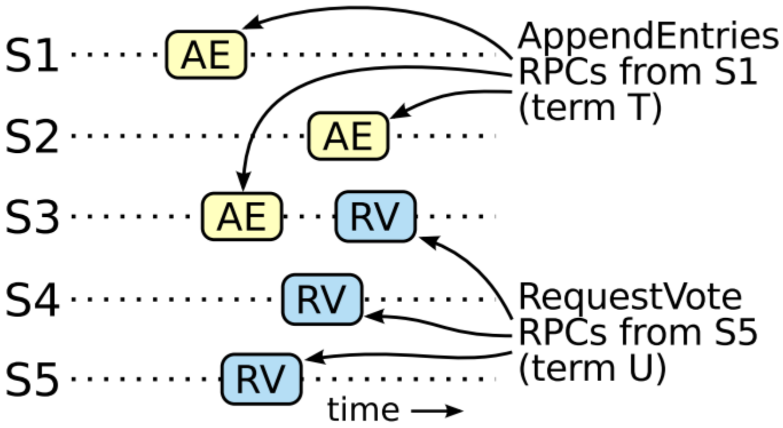
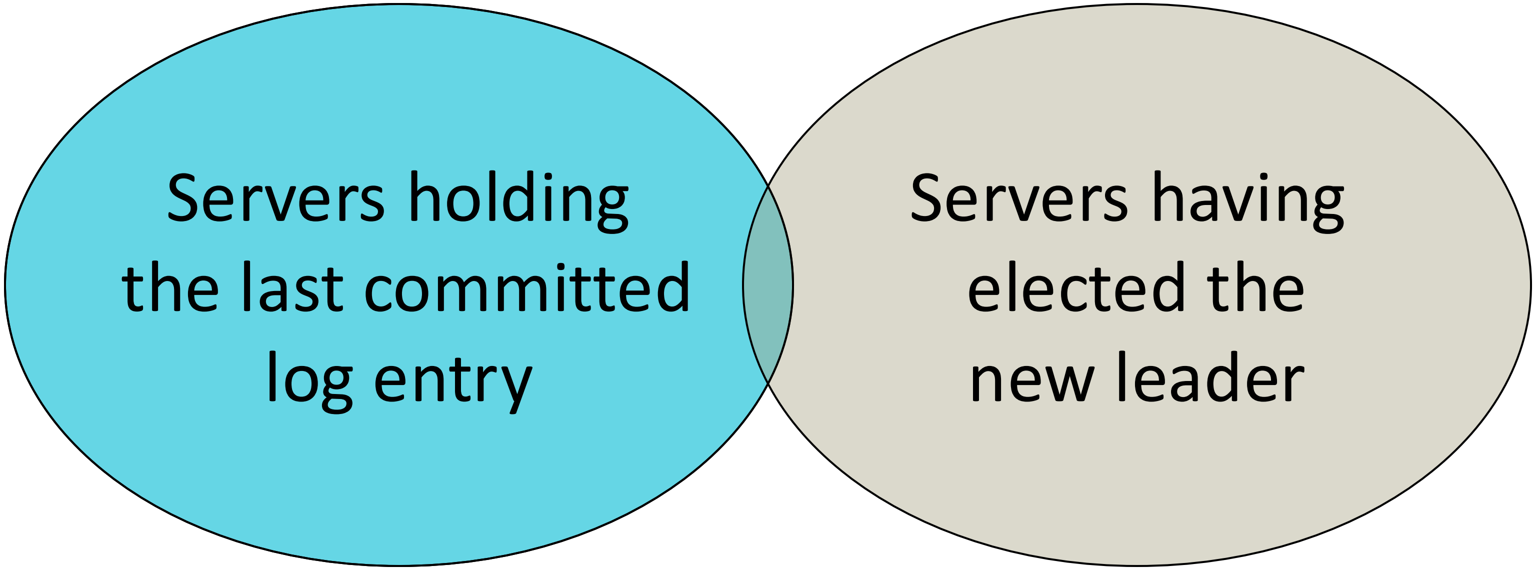



**Figure 9:** If S1 (leader for term T) commits a new log entry from its term, and S5 is elected leader for a later term U, then there must be at least one server (S3) that accepted the log entry and also voted for S5.

# Election restriction (II)




Two majorities of the same cluster ***must*** intersect

# Committing entries from previous term

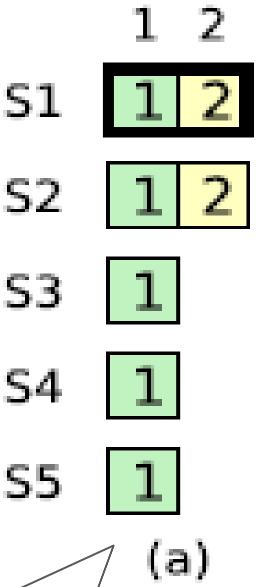
A leader cannot conclude that an entry from a previous term is committed even if stored on a majority of servers.

Leader should never commits log entries from previous terms by counting replicas

Should only do it  for entries from the current term

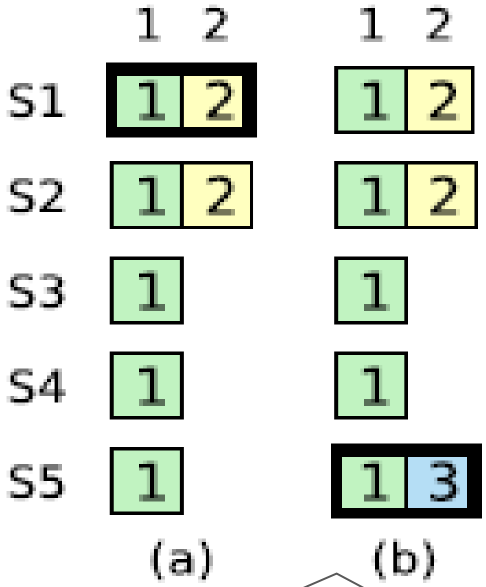
Once it has been able to  do that  for one entry, all prior entries are committed indirectly

# Committing entries from previous term



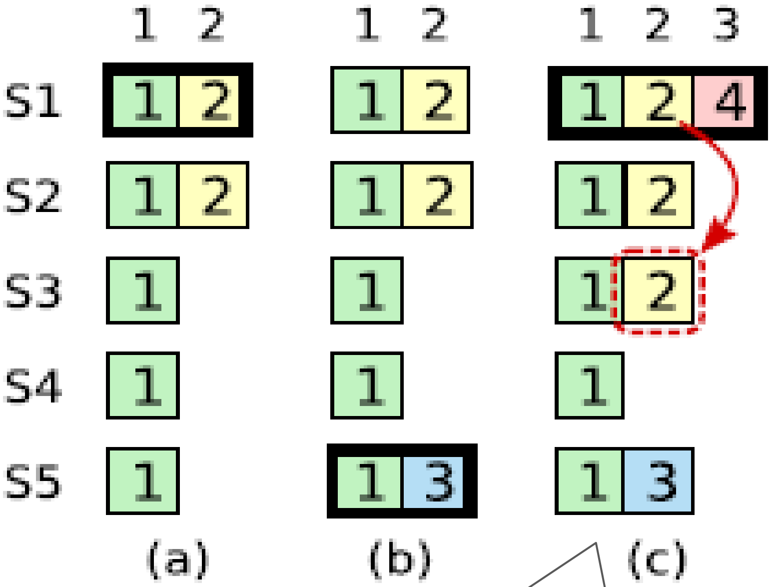

S1 is leader and partially replicates the log entry at index 2.

# Committing entries from previous term



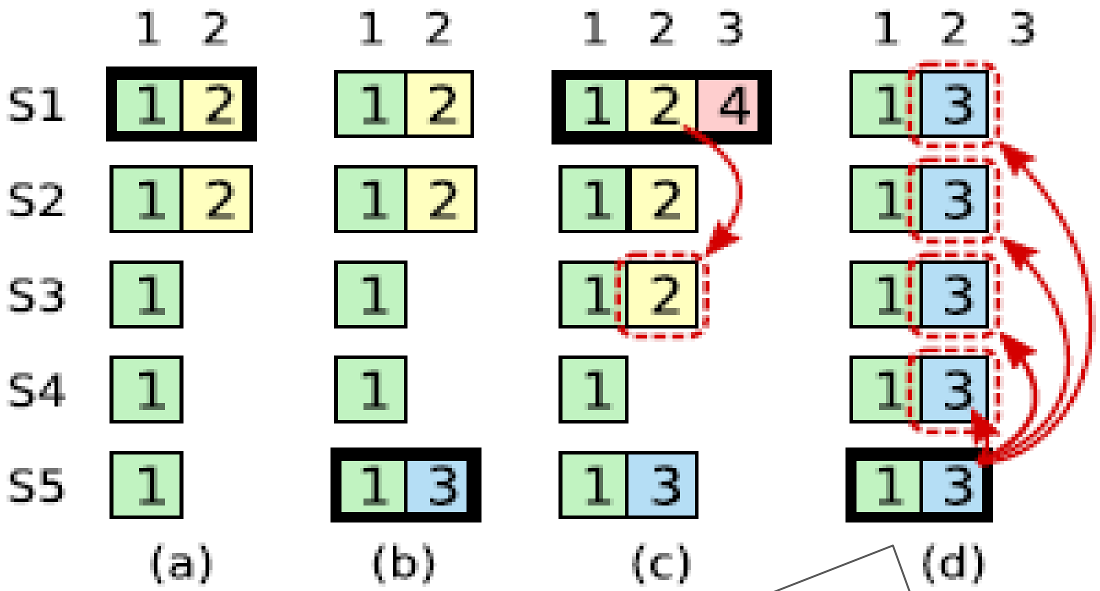

S1 crashes; S5 is elected leader for term 3 with votes from S3, S4, and itself, and accepts a different entry at log index 2.

# Committing entries from previous term



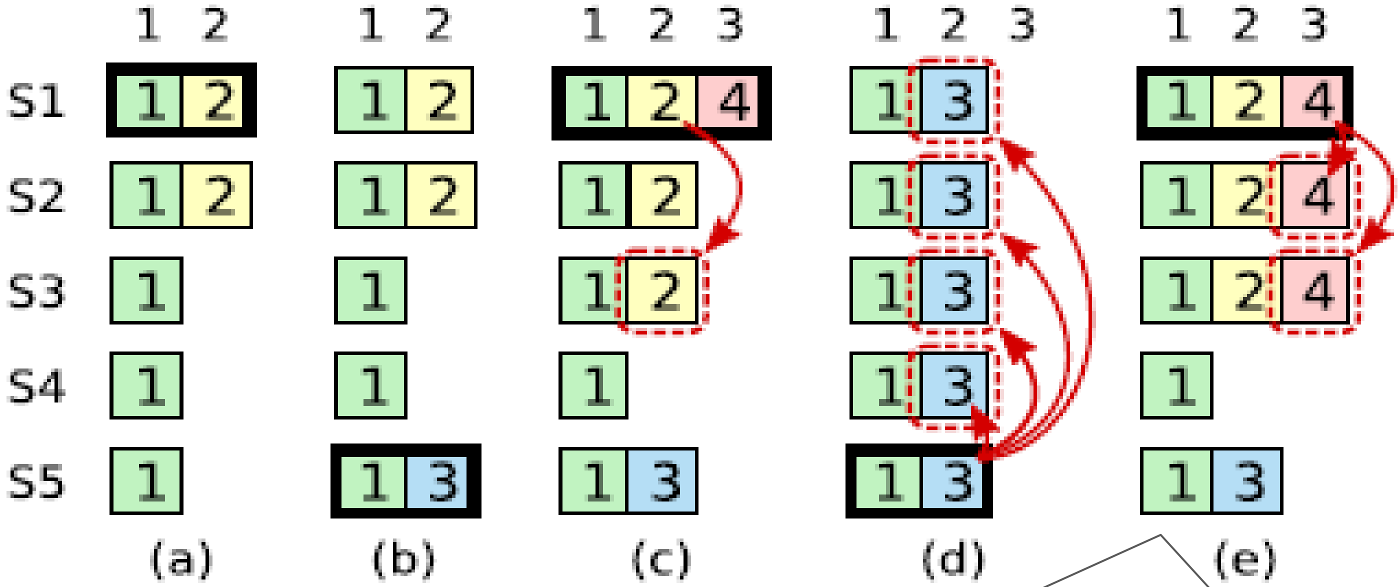

S5 crashes; S1 restarts, is elected leader, and continues replication

# Committing entries from previous term




S1 crashes, S5 is elected leader (with votes from S2, S3, and S4) and overwrites the entry with its own entry from term 3.

# Committing entries from previous term




However, if S1 replicates an entry from its current term on a majority of the servers before crashing, as this entry is committed (S5 cannot win an election).

# Explanations

In (a) S1 is leader and partially replicates the log entry at index 2.

In (b) S1 crashes; S5 is elected leader for term 3 with votes from S3, S4, and itself, and accepts a different entry at log index 2.

In (c) S5 crashes; S1 restarts, is elected leader, and continues replication.

- Log entry from term 2 has been replicated on a majority of the servers, but it is not committed.

# Explanations

If S1 crashes as in (d), S5 could be elected leader (with votes from S2, S3, and S4) and overwrite the entry with its own entry from term 3.

However, if S1 replicates an entry from its current term on a majority of the servers before crashing, as in (e), then this entry is committed (S5 cannot win an election).

At this point all preceding entries in the log are committed as well.

# Cluster membership changes

Not possible to do an atomic switch

- Changing the membership of all servers at one

Will use a two-phase approach:

- Switch first to a transitional *joint consensus* configuration
- Once the joint consensus has been committed, transition to the new configuration

# Summary

Consensus key building block in distributed systems

Raft similar to Paxos

Raft arguably easier to understand than Paxos

- It separates stages which reduces the algorithm state space
- Provides a more detailed implementation

thank you!