# Distributed Systems

## CS425/ECE428

March 17 2021

*Instructor: Radhika Mittal*

# Logistics

- MP1 is due today.
- MP2 was released today. Due on Friday, April 9th, 11:59pm.
- HW3 deadline extended to Friday, March 19th, 11:59pm.
- HW4 will be released on Friday.
- Midterm 1 grades and solutions will be released early next week.

# Agenda for today

- **Consensus**
  - Consensus in synchronous systems
    - *Chapter 15.4*
  - Impossibility of consensus in asynchronous systems
    - *We will not cover the proof in details*
  - Good enough consensus algorithm for asynchronous systems:
    - *Paxos made simple, Leslie Lamport, 2001*
  - Other forms of consensus algorithm
    - Raft (log-based consensus)
    - Block-chains (distributed consensus)

# Recap

- Consensus is a fundamental problem in distributed systems.
- Possible to solve consensus in synchronous systems.
    - Algorithm based on time-synchronized rounds.
    - Need at least (f+1) rounds to handle up to f failures.
- Impossible to solve consensus is asynchronous systems.
    - Cannot distinguish between a timeout and a very very slow process.
    - Paxos algorithm:
        - Guarantees safety but not liveness.
        - Hopes to terminate if under good enough conditions.

# Paxos Algorithm

- Three types of roles:
  - **Proposers:** propose values to *acceptors*.
    - All or subset of processes.
    - Having a *single proposer* (leader) may allow faster termination.
  - **Acceptors:** accept proposed values (under certain conditions).
    - All or subset of processes.
  - **Learners:** learns the value that has been accepted by *majority* of acceptors.
    - All processes.

# Paxos Algorithm

- Key condition:
  - When majority of acceptors accept a single proposal with a value v, then that value v becomes the decided value.
    - This is an implicit decision. Learners may not know about it right-away.
  - Any higher-numbered proposal that gets accepted by majority of acceptors after the implicit decision must propose the same decided value.

# Paxos Algorithm: Two phases

- **Phase 1:**
  - A proposer selects a proposal number (*n*) and sends a prepare request with *n* to majority of acceptors, requesting:
    - Promise me you will not reply to any other proposal with a lower number.
    - Promise me you will not accept any other proposal with a lower number.
  - If an acceptor receives a prepare request for proposal #*n*, and it has not responded to a prepare request with a higher number, it replies back saying:
    - OK! I will make that promise for any request I receive in the future.
    - (If applicable) I have already accepted a value *v* from a proposal with lower number m < n. This proposal has the highest number among the ones I accepted so far.

# Paxos Algorithm: Two phases

- **Phase 2:**
  - If a proposer receives an OK response for its prepare request #n from a *majority* of acceptors, then it sends an accept request with a proposed value. What is the proposed value?
    - The value v of the *highest numbered proposal* among the received responses.
    - Any value if no previously accepted value in the received responses.
  - If an acceptor receives an accept request for proposal #*n*, and it has not responded a prepare request with a higher number, it accepts the proposal.

- *What if the proposer does not hear from majority of acceptors?*
  - Wait for some time, and then issue a new request with higher number.

# Paxos Algorithm

- When majority of acceptors accept a single proposal with a value *v*, then that value v becomes the *decided* value.
  - Suppose this proposal has a number *m*.
  - By design of the algorithm: *any subsequent proposal with a number n higher than m will propose a value v.*
  - Proof by induction:
    - Induction hypothesis: every proposal with number in [m,…..n-1] proposes value *v*.
    - Consider a set C with majority of acceptors that have accepted m's proposal (and value *v*).
    - Every acceptor in C has accepted a proposal with number in [m,…..n-1] .
      - Every acceptor in C has accepted a proposal with value *v*.
    - Any set consisting of a majority of acceptors has at least one member in C.
      - Proposal #n's prepare request will receive an OK reply with value v.

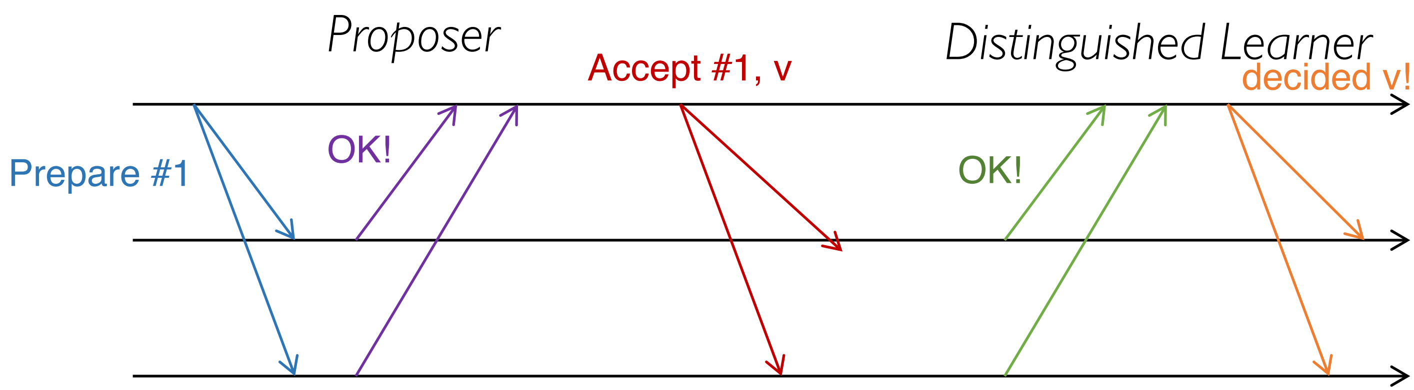
# Paxos Algorithm

- When majority of acceptors accept a single proposal with a value *v*, then that value v becomes the *decided* value.

- How do learners learn about it?
  - Every time an acceptor accepts a value, send the value and proposal # to a *distinguished learner.*
  - This *distinguished learner* will check if a decision has been reached and will inform other learners.
    - When it receives the same value and proposal # from a majority of acceptors.
  - Use a set of distinguished learners to better handle failures.
  - What happens if a message is lost or all distinguished learners fail?
    - May not know that a decision has been reached.
    - A proposer will issue a new request (and will propose the same value). Acceptors will accept the same value and will notify the learner again.

# Paxos Algorithm

- Best strategy: elect a single leader who proposes values.
- Assume this leader is also the distinguished learner.




- What if we have multiple proposers? (leader election is not perfect is asynchronous systems)
  - May have a livelock! Two proposers may keep pre-empting each-other's requests by constantly sending new proposals with higher numbers.
  - Safety is still guaranteed!

# Paxos Algorithm

- What if majority of acceptors fail before a value is decided?
  - Algorithm does not terminate.
  - Safety is still guaranteed!

- What if a process fails and recover again?
  - If it is an acceptor, it must remember highest number proposal it has accepted.
    - Acceptors log accepted proposal on the disk.
  - As long as this state can be retrieved after failure and recovery, algorithm works fine and safety is still guaranteed.

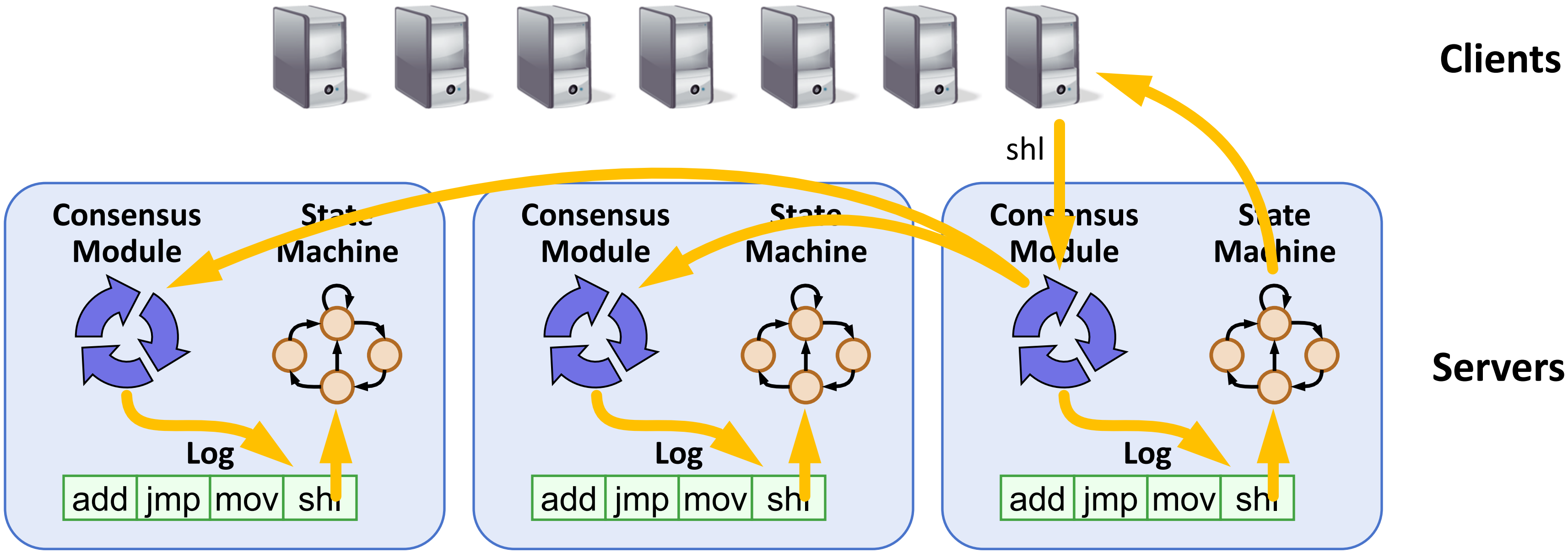
- *Exercise: think about what else can go wrong and how would Paxos handle that situation?*

# Log Consensus

- Paxos algorithm (discussed so far) is used for deciding on a single value.

- Many practical systems need to decide on a sequence of values (log).

# Replicated Log




- Replicated log => replicated state machine
  - All servers execute same commands in same order
- Consensus module ensures proper log replication

# Log Consensus

- Paxos algorithm (discussed so far) is used for deciding on a single value.

- Many practical systems need to decide on a sequence of values (log).

- **Multi-Paxos:** run Paxos repeatedly for each log entry.
    - Quickly becomes very complex.
    - Performance optimizations further increase the complexity.

# Paxos is difficult to understand

*"The dirty little secret of the NSDI* community is that at most five people really, truly understand every part of Paxos ;-)."*
– Anonymous NSDI reviewer

*The USENIX Symposium on Networked Systems Design and Implementation

# Paxos is difficult to implement

> “*There are significant gaps between the description of the Paxos algorithm and the needs of a real-world system…the final system will be based on an unproven protocol.*”
>
> – Chubby authors

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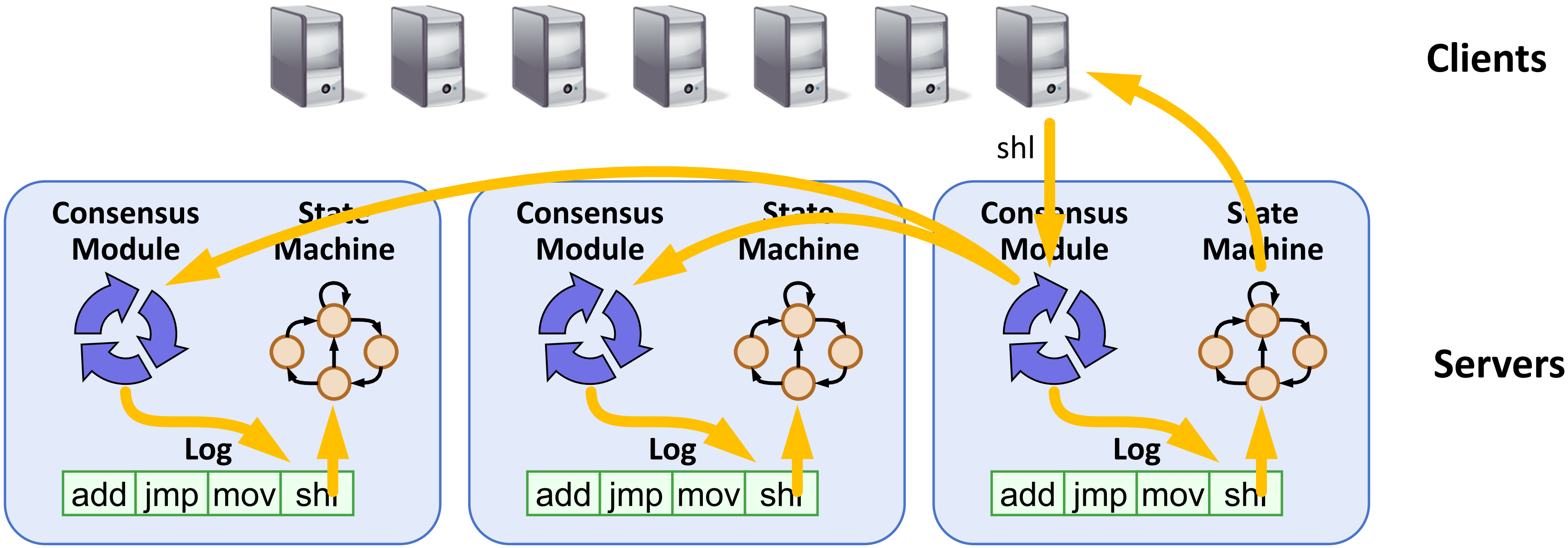
  - Other forms of consensus algorithm
    - **Raft (log-based consensus)**
    - Block-chains (distributed consensus)

# Raft: A Consensus Algorithm for Replicated Logs

Slides from Diego Ongaro and John Ousterhout, Stanford University

# 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**

# Goal: Design for understandability

- Main objective of Raft's design
  - 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.

# Approaches to Consensus

Two general approaches to consensus:

- Symmetric, leader-less:
  - All servers have equal roles
  - Clients can contact any server
- Asymmetric, leader-based:
  - At any given time, one server is in charge, others accept its decisions
  - Clients communicate with the leader
- **Raft uses a leader:**
  - Decomposes the problem (normal operation, leader changes)
  - Simplifies normal operation (no conflicts)
  - More efficient than leader-less approaches

# Raft Overview

1. Leader election:
   - Select one of the servers to act as leader
   - Detect crashes, choose new leader
2. Normal operation (basic log replication)
3. Safety and consistency after leader changes
4. Neutralizing old leaders

# Raft Overview

1. Leader election:
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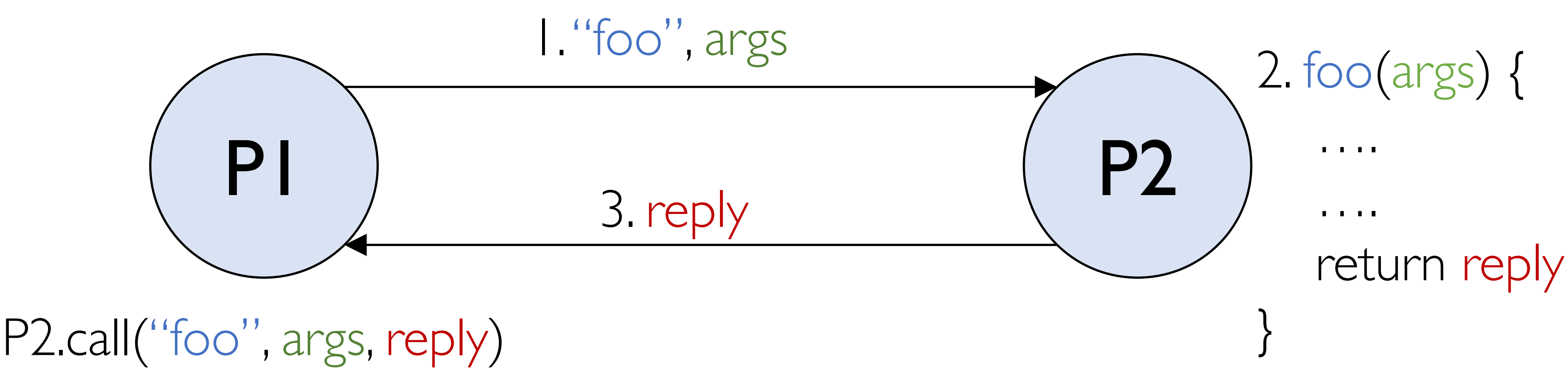
4. Neutralizing old leaders

# Server States

- At any given time, each server is either:
  - Leader: handles all client interactions, log replication
    - At most 1 viable leader at a time
  - Follower: completely passive: issues no RPCs (requests), responds to incoming RPCs
  - Candidate: used to elect a new leader
- Normal operation: 1 leader, N-1 followers

# Quick Detour: RPCs

- Raft servers communicate via RPCs.
- What are RPCs?
  - Remote Procedure Calls: *procedure call between functions on different processes*
  - *Convenient programming abstraction.*



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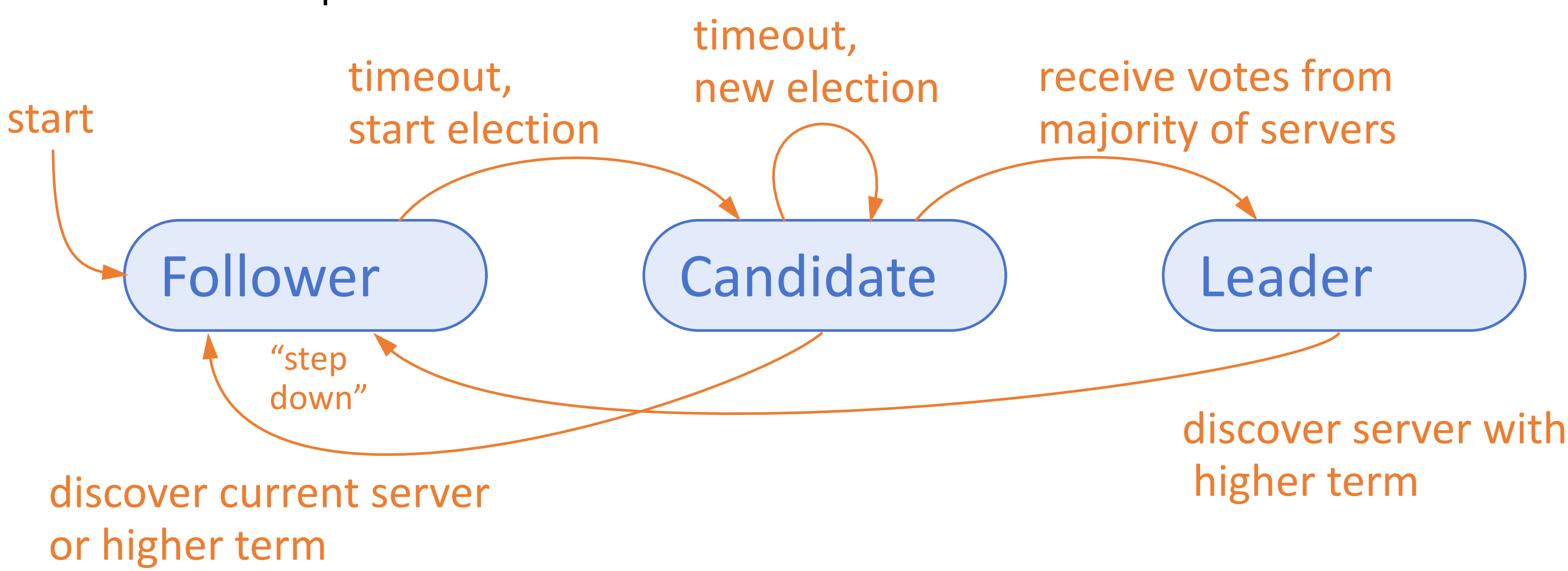
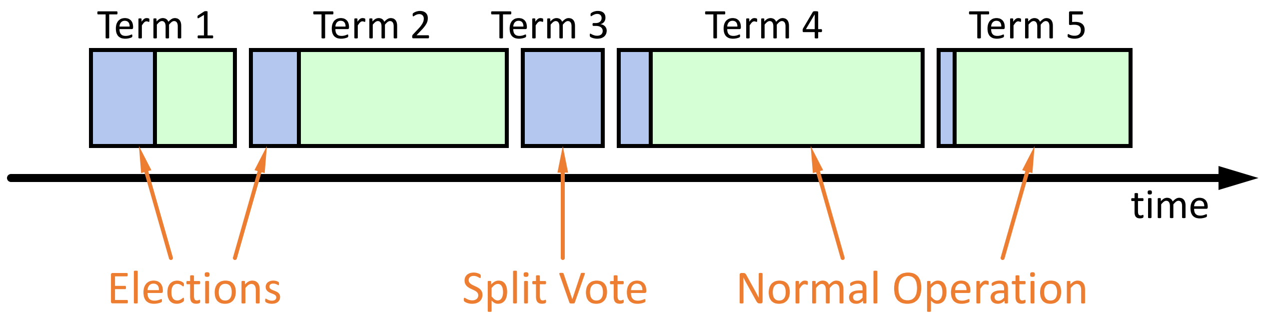


# Terms




- Time divided into terms:
  - Election
  - Normal operation under a single leader
- At most 1 leader per term
- Some terms have no leader (failed election)
- Each server maintains current term value
- Key role of terms: identify obsolete information

# Heartbeats and Timeouts

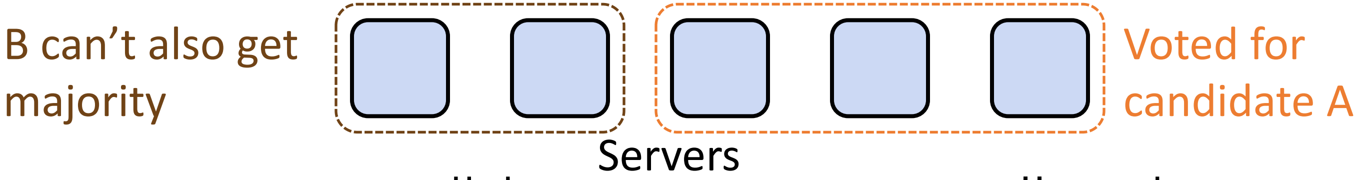
- Servers start up as followers
- Followers expect to receive RPCs from leaders or candidates
- Leaders must send heartbeats (empty AppendEntries RPCs) to maintain authority
- If electionTimeout elapses with no RPCs:
  - Follower assumes leader has crashed
  - Follower starts new election
  - Timeouts typically 100-500ms

# Election Basics

- On timeout:
  - Increment current term
  - Change to Candidate state
  - Vote for self
  - Send RequestVote RPCs to all other servers:
    1. Receive votes from majority of servers:
       - Become leader
       - Send AppendEntries heartbeats (RPCs) to all other servers
    2. Receive RPC from valid leader:
       - Return to follower state
    3. No-one wins election (election timeout elapses):
       - Increment term, start new election

# Elections, cont'd

- Safety: allow at most one winner per term
  - Each server gives out only one vote per term (persist on disk)
  - Two different candidates can't accumulate majorities *in same term*




- Liveness: some candidate must eventually win

- *Safety is guaranteed. Liveness is not.*
  - *Election may result in a split vote – no candidate gets majority.*

# Elections, cont'd

- Safety: allow at most one winner per term
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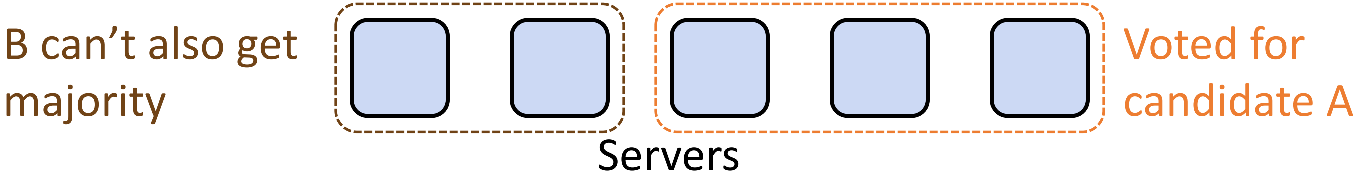


- Liveness: some candidate must eventually win
  - Choose election timeouts randomly in [T, 2T]
  - One server usually times out and wins election before others wake up
  - Works well if T >> broadcast time
- *Safety is guaranteed. Liveness is not.*
  - *Election may result in a split vote – no candidate gets majority.*

# Next Class

- Visualizations to better leader election with Raft.
- Raft's log replication algorithm.

# MP2: Raft Leader Election and Log Consensus

- https://courses.grainger.illinois.edu/cs425/sp2021/mps/mp2.html

- Objective:
  - Implement a leader-based consensus protocol for replicated state machine, that maintains log consensus even when nodes crash or get temporarily disconnected.

- Task:
  - Beef up a skeleton code provided to you to implement Raft leader election and log consensus.
  - We provide an emulation framework and a test suite.
  - Strive to pass all the test cases provided in our test suite.

# MP2: Logistics

- Due on Friday, April 9th.
  - Allowed to submit up to 50 hours late, but with 2% penalty for every late hour (rounded up).
- Must be implemented in Go.
  - The framework we provide is in Go.
- Read the specification and the comments in the provided code carefully.
- **Start early!!**
  - MP2 is harder than MP1.