Distributed Systems

The second half of *Concurrent and Distributed Systems*

https://www.cl.cam.ac.uk/teaching/current/ConcDisSys

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Computer Science Tripos, Part IB

Lecture 6

Consensus

Fault-tolerant total order broadcast

Total order broadcast is very useful for state machine replication.

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  Unplanned outage? Humans are slow, may take a long time until system recovers...
- Can we **automatically choose a new leader**?

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Common consensus algorithms:

- **Paxos**: single-value consensus
  Multi-Paxos: generalisation to total order broadcast
- **Raft**, **Viewstamped Replication**, **Zab**:
  FIFO-total order broadcast by default

Consensus system models

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There are also consensus algorithms for a partially synchronous **Byzantine** system model (used in blockchains)

Leader election

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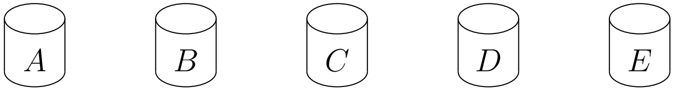
- Require a **quorum** of nodes to elect a leader in a term



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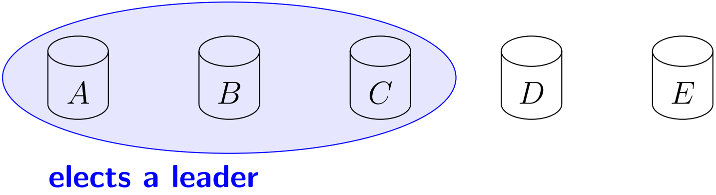

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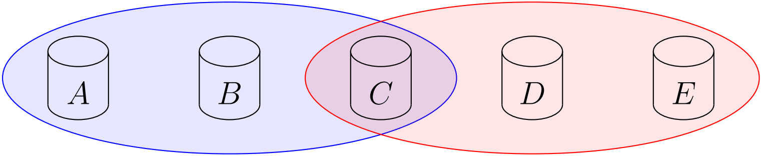

elects a leader

cannot elect a different leader
because C already voted

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Can guarantee unique leader **per term**.

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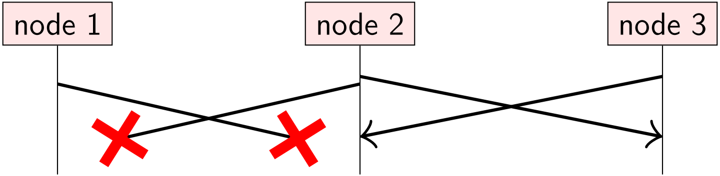
Example: node 1 is leader in term t, but due to a network partition it can no longer communicate with nodes 2 and 3:



Nodes 2 and 3 may elect a new leader in term $t + 1$.

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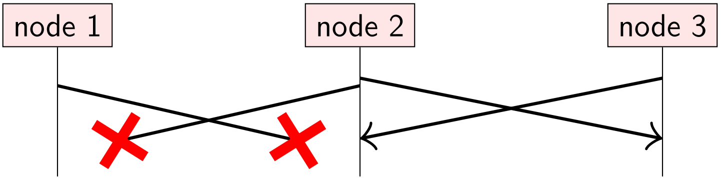
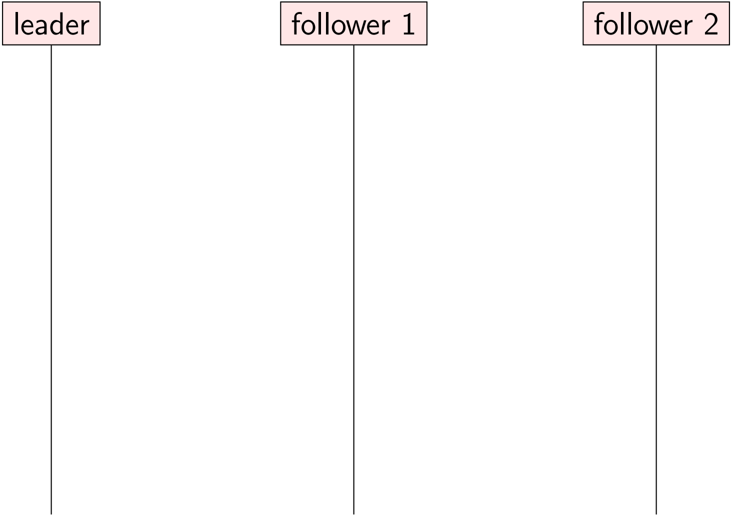


Nodes 2 and 3 may elect a new leader in term $t + 1$.

Node 1 may not even know that a new leader has been elected!

Checking if a leader has been voted out

For every decision (message to deliver), the leader must first get acknowledgements from a quorum.



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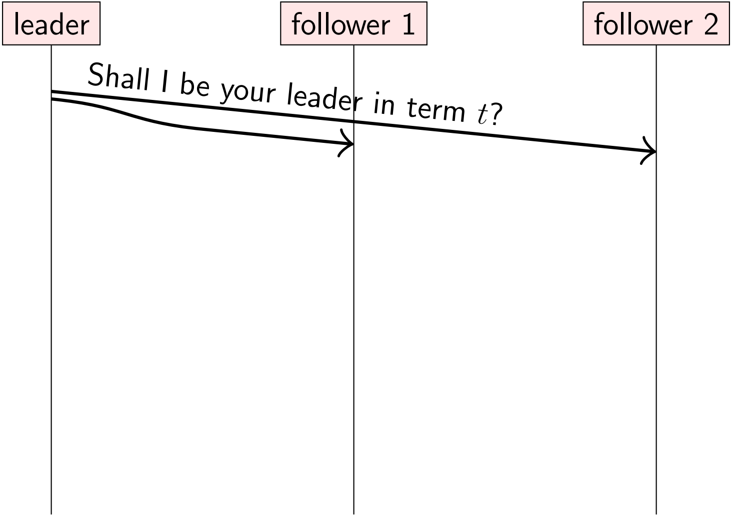

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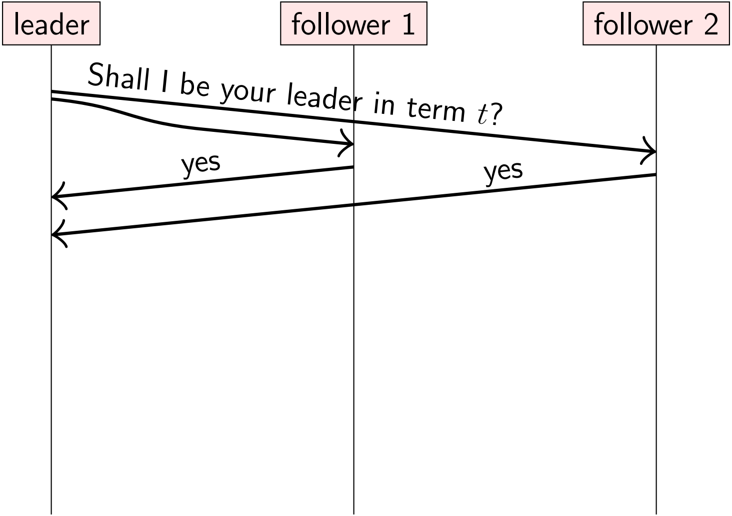

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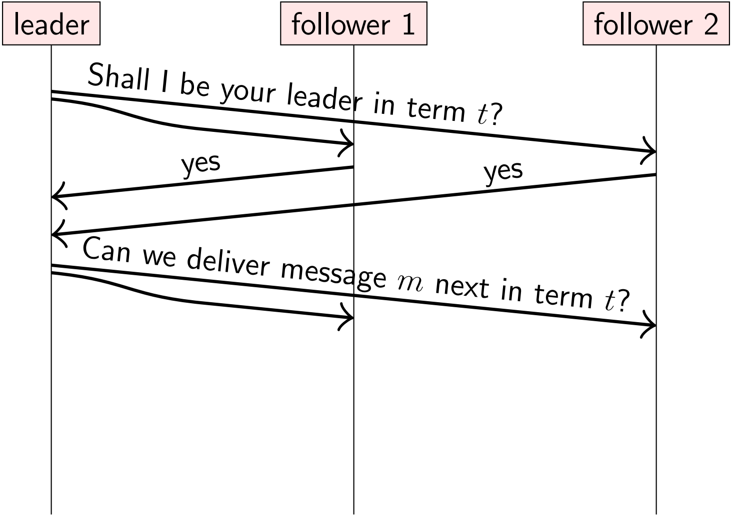

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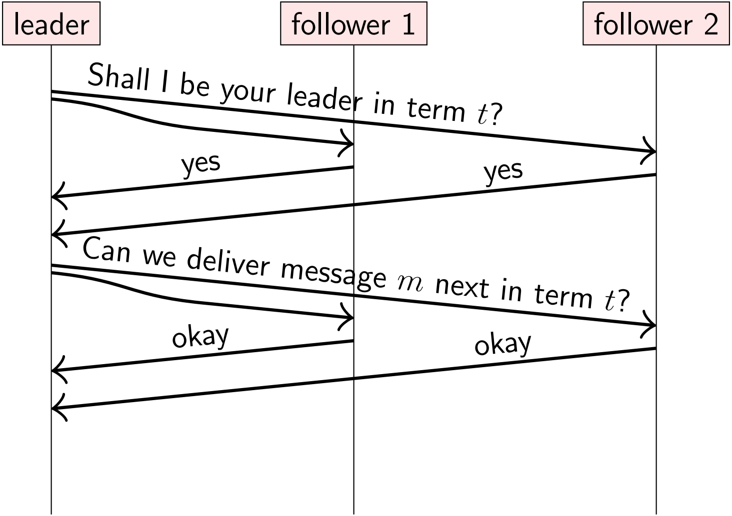

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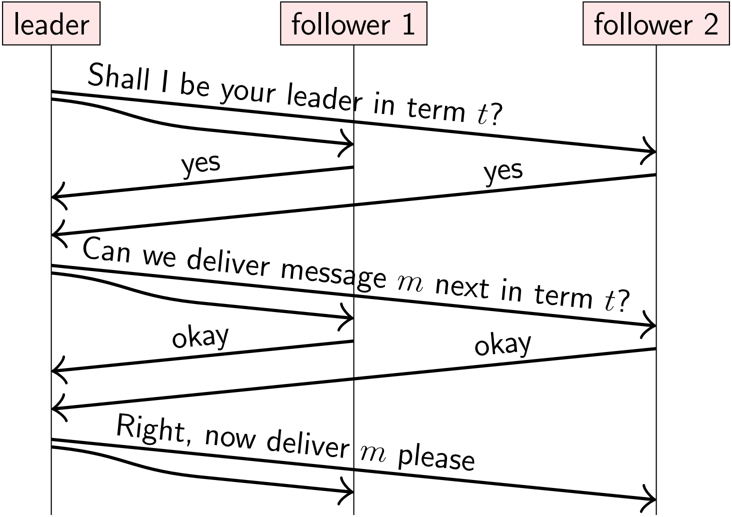
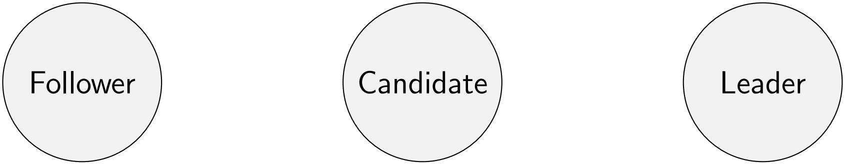


Node state transitions in Raft



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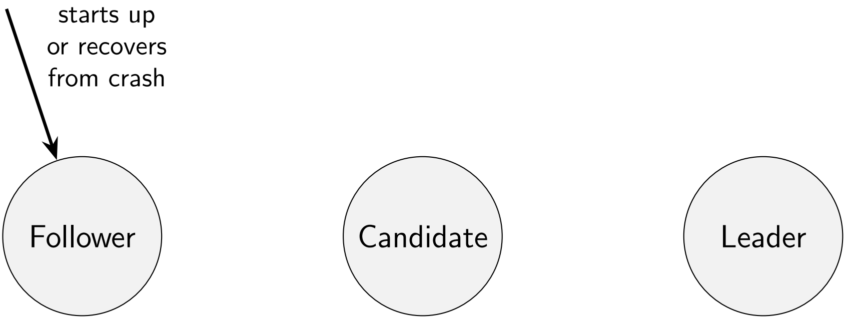

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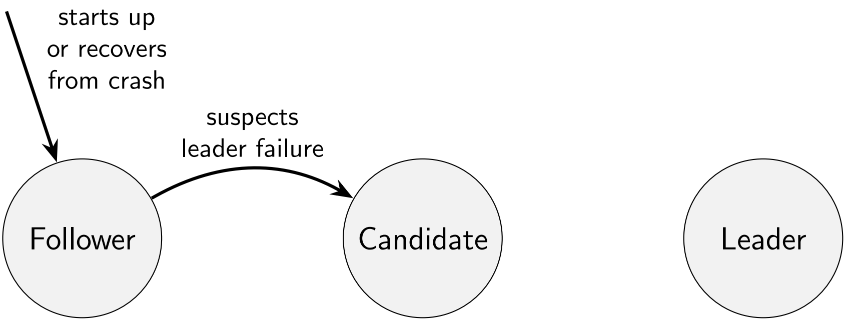

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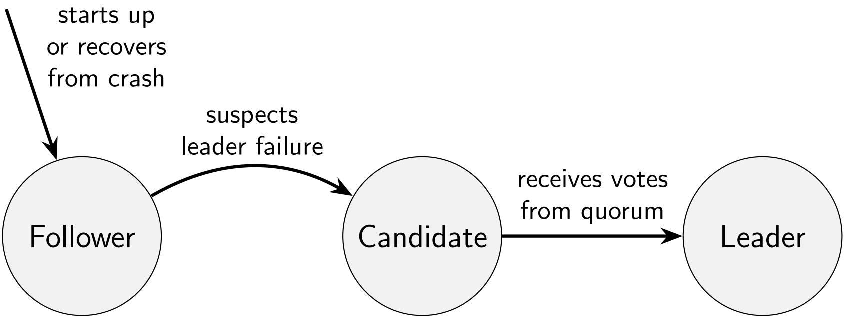

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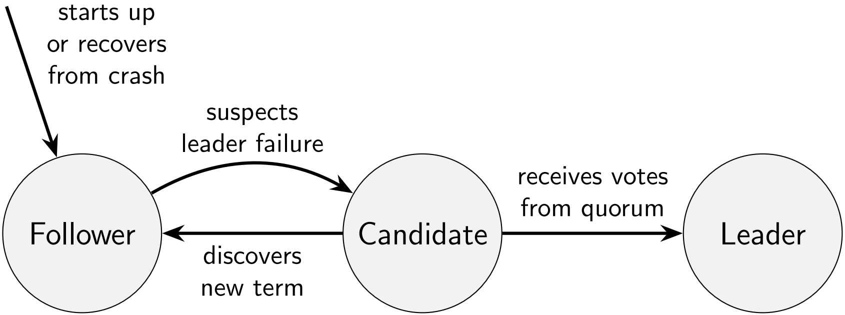

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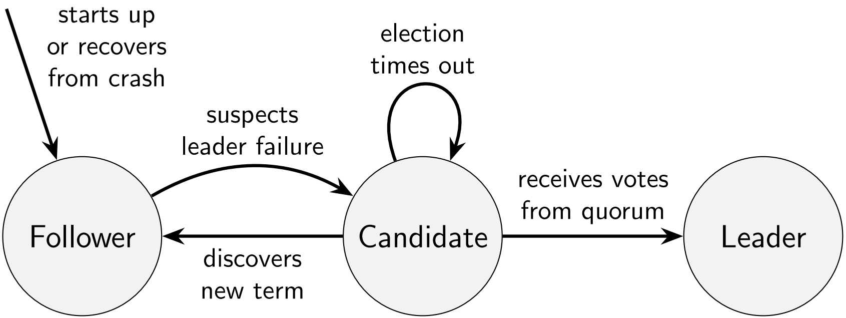

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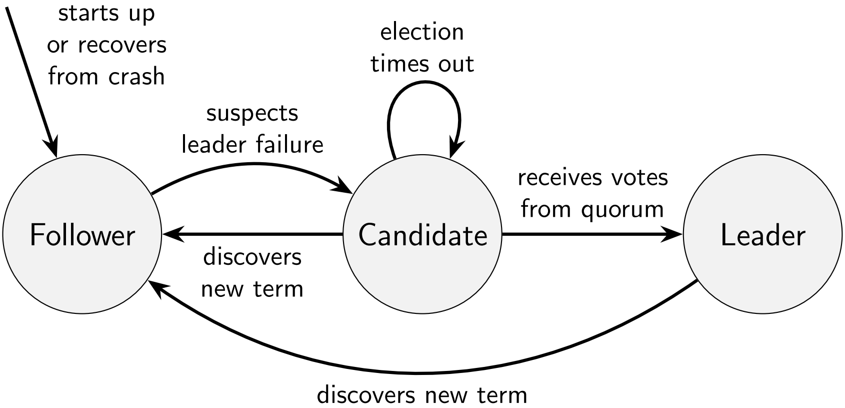

Raft (1/9): initialisation

on initialisation **do**
  $currentTerm := 0$; $votedFor :=$ null
  $log := \langle\rangle$; $commitLength := 0$
  $currentRole :=$ follower; $currentLeader :=$ null
  $votesReceived := \{\}$; $sentLength := \langle\rangle$; $ackedLength := \langle\rangle$
end on

on recovery from crash **do**
  $currentRole :=$ follower; $currentLeader :=$ null
  $votesReceived := \{\}$; $sentLength := \langle\rangle$; $ackedLength := \langle\rangle$
end on

on node $nodeId$ suspects leader has failed, or on election timeout **do**
  $currentTerm := currentTerm + 1$; $currentRole :=$ candidate
  $votedFor := nodeId$; $votesReceived := \{nodeId\}$; $lastTerm := 0$
  if $log.\text{length} > 0$ **then** $lastTerm := log[log.\text{length} - 1].\text{term}$; **end if**
  $msg := (\text{VoteRequest}, nodeId, currentTerm, log.\text{length}, lastTerm)$
  for each $node \in nodes$: **send** msg to $node$
  start election timer
end on

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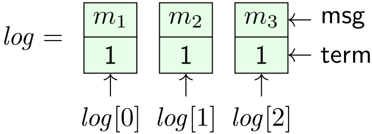

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on recovery from crash **do**
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    $currentTerm := currentTerm + 1$; $currentRole :=$ candidate
    $votedFor := nodeId$; $votesReceived := \{nodeId\}$; $lastTerm := 0$
    if log.length > 0 **then** $lastTerm := log[log$.length $- 1]$.term; **end if**
    $msg :=$ (VoteRequest, $nodeId$, $currentTerm$, log.length, $lastTerm$)
    for each $node \in nodes$: **send** msg to $node$
    start election timer
end on

Raft (2/9): voting on a new leader

on receiving $(\text{VoteRequest}, cId, cTerm, cLogLength, cLogTerm)$
at node $nodeId$ **do**

$myLogTerm := log[log.\text{length} - 1].\text{term}$
$logOk := (cLogTerm > myLogTerm) \lor$
$(cLogTerm = myLogTerm \land cLogLength \geq log.\text{length})$

$termOk := (cTerm > currentTerm) \lor$
$(cTerm = currentTerm \land votedFor \in \{cId, \text{null}\})$

if $logOk \land termOk$ **then**
$currentTerm := cTerm$
$currentRole := \text{follower}$
$votedFor := cId$
send $(\text{VoteResponse}, nodeId, currentTerm, \text{true})$ to node cId
else
send $(\text{VoteResponse}, nodeId, currentTerm, \text{false})$ to node cId
end if
end on

Raft (2/9): voting on a new leader

c for candidate

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    at node $nodeId$ **do**
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  $termOk := (cTerm > currentTerm) \lor$
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  if $logOk \land termOk$ **then**
    $currentTerm := cTerm$
    $currentRole :=$ follower
    $votedFor := cId$
    send (VoteResponse, $nodeId$, $currentTerm$, true) to node cId
  else
    send (VoteResponse, $nodeId$, $currentTerm$, false) to node cId
  end if
end on

Raft (3/9): collecting votes

on receiving (VoteResponse, $voterId, term, granted$) at $nodeId$ **do**
    if $currentRole = \text{candidate} \wedge term = currentTerm \wedge granted$ **then**
        $votesReceived := votesReceived \cup \{voterId\}$
        if $|votesReceived| \geq \lceil (|nodes| + 1)/2 \rceil$ **then**
            $currentRole := \text{leader};\ currentLeader := nodeId$
            cancel election timer
            for each $follower \in nodes \setminus \{nodeId\}$ **do**
                $sentLength[follower] := log.\text{length}$
                $ackedLength[follower] := 0$
                $\textsc{ReplicateLog}(nodeId, follower)$
            end for
        end if
    else if $term > currentTerm$ **then**
        $currentTerm := term$
        $currentRole := \text{follower}$
        $votedFor := \text{null}$
        cancel election timer
    end if
end on

Raft (4/9): broadcasting messages

on request to broadcast msg at node $nodeId$ **do**
  if $currentRole$ = leader **then**
    append the record (msg : msg, term : $currentTerm$) to log
    $ackedLength[nodeId]$:= log.length
    for each $follower \in nodes \setminus \{nodeId\}$ **do**
      $\textsc{ReplicateLog}(nodeId, follower)$
    end for
  else
    forward the request to $currentLeader$ via a FIFO link
  end if
end on

periodically at node $nodeId$ **do**
  if $currentRole$ = leader **then**
    for each $follower \in nodes \setminus \{nodeId\}$ **do**
      $\textsc{ReplicateLog}(nodeId, follower)$
    end for
  end if
end do

Raft (5/9): replicating from leader to followers

Called on the leader whenever there is a new message in the log, and also periodically. If there are no new messages, $entries$ is the empty list. LogRequest messages with $entries = \langle\rangle$ serve as heartbeats, letting followers know that the leader is still alive.

function $\textsc{ReplicateLog}(leaderId, followerId)$
  $i := sentLength[followerId]$
  $entries := \langle log[i],\ log[i+1],\ \ldots,\ log[log.\text{length} - 1]\rangle$
  $prevLogTerm := 0$
  if $i > 0$ **then**
    $prevLogTerm := log[i-1].\text{term}$
  end if
  send $(\text{LogRequest}, leaderId, currentTerm, i, prevLogTerm,$
      $commitLength, entries)$ to $followerId$
end function

Raft (6/9): followers receiving messages

$$
\begin{array}{l}
\textbf{on } \text{receiving } (\text{LogRequest}, \mathit{leaderId}, \mathit{term}, \mathit{logLength}, \mathit{logTerm}, \\
\qquad\qquad \mathit{leaderCommit}, \mathit{entries}) \text{ at node } \mathit{nodeId} \textbf{ do} \\
\quad \textbf{if } \mathit{term} > \mathit{currentTerm} \textbf{ then} \\
\qquad \mathit{currentTerm} := \mathit{term};\ \mathit{votedFor} := \text{null} \\
\quad \textbf{end if} \\
\quad \mathit{logOk} := (\mathit{log}.\text{length} \geq \mathit{logLength}) \\
\quad \textbf{if } \mathit{logOk} \wedge (\mathit{logLength} > 0) \textbf{ then} \\
\qquad \mathit{logOk} := (\mathit{logTerm} = \mathit{log}[\mathit{logLength} - 1].\text{term}) \\
\quad \textbf{end if} \\
\\
\quad \textbf{if } \mathit{term} = \mathit{currentTerm} \wedge \mathit{logOk} \textbf{ then} \\
\qquad \mathit{currentRole} := \text{follower};\ \mathit{currentLeader} := \mathit{leaderId} \\
\qquad \textsc{AppendEntries}(\mathit{logLength}, \mathit{leaderCommit}, \mathit{entries}) \\
\qquad \mathit{ack} := \mathit{logLength} + \mathit{entries}.\text{length} \\
\qquad \textbf{send } (\text{LogResponse}, \mathit{nodeId}, \mathit{currentTerm}, \mathit{ack}, \text{true}) \text{ to } \mathit{leaderId} \\
\quad \textbf{else} \\
\qquad \textbf{send } (\text{LogResponse}, \mathit{nodeId}, \mathit{currentTerm}, 0, \text{false}) \text{ to } \mathit{leaderId} \\
\quad \textbf{end if} \\
\textbf{end on}
\end{array}
$$

Raft (7/9): updating followers' logs

function $\textsc{AppendEntries}(logLength, leaderCommit, entries)$
    if $entries$.length $> 0 \ \wedge \ log$.length $> logLength$ **then**
        if $log[logLength]$.term $\neq entries[0]$.term **then**
            $log := \langle log[0], \ log[1], \ \ldots, \ log[logLength - 1]\rangle$
        end if
    end if
    if $logLength + entries$.length $> log$.length **then**
        for $i := log$.length $- \ logLength$ **to** $entries$.length $- 1$ **do**
            append $entries[i]$ to log
        end for
    end if
    if $leaderCommit > commitLength$ **then**
        for $i := commitLength$ **to** $leaderCommit - 1$ **do**
            deliver $log[i]$.msg to the application
        end for
        $commitLength := leaderCommit$
    end if
end function

Raft (8/9): leader receiving log acknowledgements

```
on receiving (LogResponse, follower, term, ack, success) at nodeId do
    if term = currentTerm ∧ currentRole = leader then
        if success = true ∧ ack ≥ ackedLength[follower] then
            sentLength[follower] := ack
            ackedLength[follower] := ack
            CommitLogEntries()
        else if sentLength[follower] > 0 then
            sentLength[follower] := sentLength[follower] − 1
            ReplicateLog(nodeId, follower)
        end if
    else if term > currentTerm then
        currentTerm := term
        currentRole := follower
        votedFor := null
    end if
end on
```

Raft (9/9): leader committing log entries

Any log entries that have been acknowledged by a quorum of nodes are ready to be committed by the leader. When a log entry is committed, its message is delivered to the application.

define $\mathrm{acks}(\mathit{length}) = |\{n \in \mathit{nodes} \mid \mathit{ackedLength}[n] \geq \mathit{length}\}|$

function $\textsc{CommitLogEntries}$
    $\mathit{minAcks} := \lceil (|\mathit{nodes}| + 1)/2 \rceil$
    $\mathit{ready} := \{\mathit{len} \in \{1, \dots, \mathit{log}.\mathsf{length}\} \mid \mathrm{acks}(\mathit{len}) \geq \mathit{minAcks}\}$
    if $\mathit{ready} \neq \{\} \ \wedge\ \max(\mathit{ready}) > \mathit{commitLength}\ \wedge$
            $\mathit{log}[\max(\mathit{ready}) - 1].\mathsf{term} = \mathit{currentTerm}$ **then**
        for $i := \mathit{commitLength}$ **to** $\max(\mathit{ready}) - 1$ **do**
            deliver $\mathit{log}[i]$.msg to the application
        end for
        $\mathit{commitLength} := \max(\mathit{ready})$
    end if
end function