Escape to Precaution against Leader Failures

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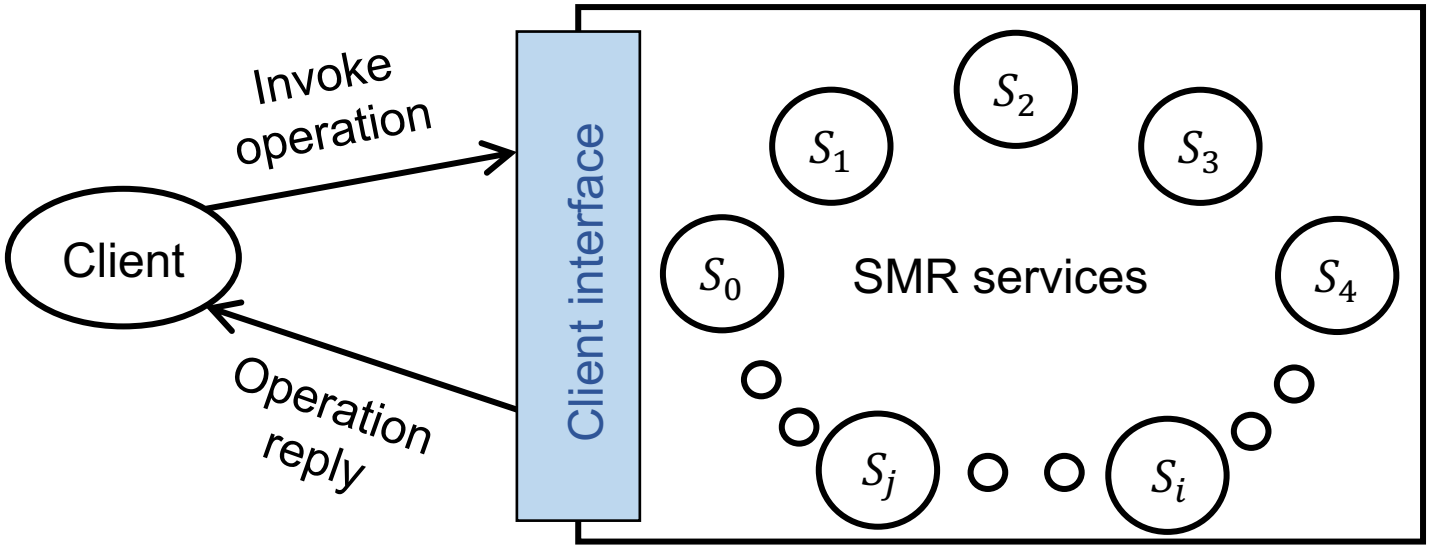
Content

- Consensus and state machine replication
- Leader-based consensus algorithms at a glance
- Problem statements: split votes in leader election
- **The Escape protocol** – avoiding split votes with fast leader election

Consensus and state machine replication

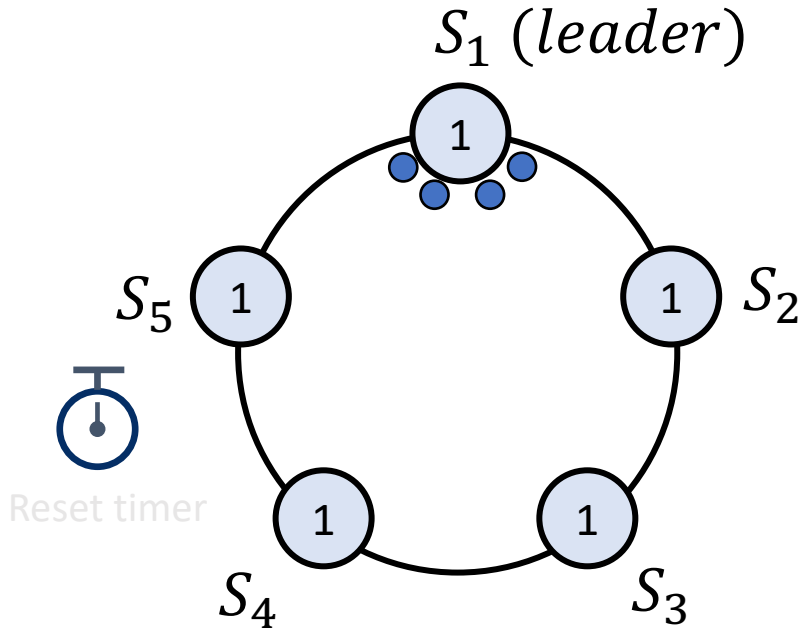
- Consensus algorithms stand at the core of distributed systems
  - Provide state machine replication (SMR) services
  - Coordinate server actions to reach agreement
  - Fault tolerance: Crash and Byzantine fault tolerance (CFT/ BFT)



Safety
All non-faulty replicas agree on a total order for the execution of requests despite failures

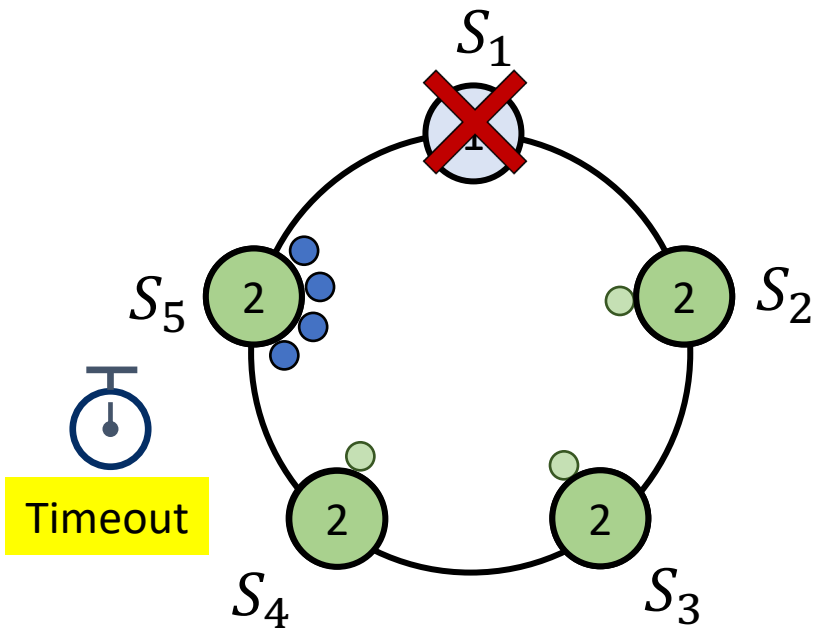
Liveness
Clients eventually receive replies to their requests

Leader, leadership, and Raft



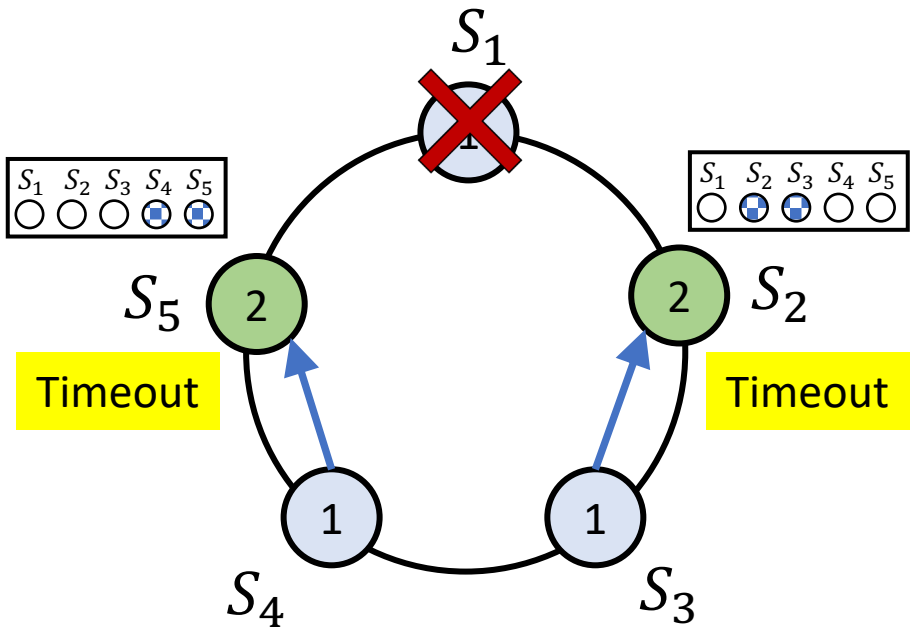
- Leader-based consensus algorithms have been widely developed and deployed
  - Paxos, Viewstamped replication, and **Raft**
- Raft's strong leadership: log entries only flow from the leader to other servers
  - *Heartbeats* – *periodic messaging shuttle*
  - *Terms* – integers representing logical time
  - Three server roles: *leader*, *follower*, and *candidate*
- Raft operates in two phases
  - Log replication when leader is correct
  - Leader election when leader fails

Leader election – when a leader falls



- Candidate starts a new leader election campaign
  - Increments its term
  - Broadcasts a leader election request
  - Votes for itself
  - Needs to collect a majority vote in current term
- A server grants a vote if
  - Candidate's log is at least as up-to-date as its log
  - Candidate's term is not less than its term
  - It has not voted in the current term

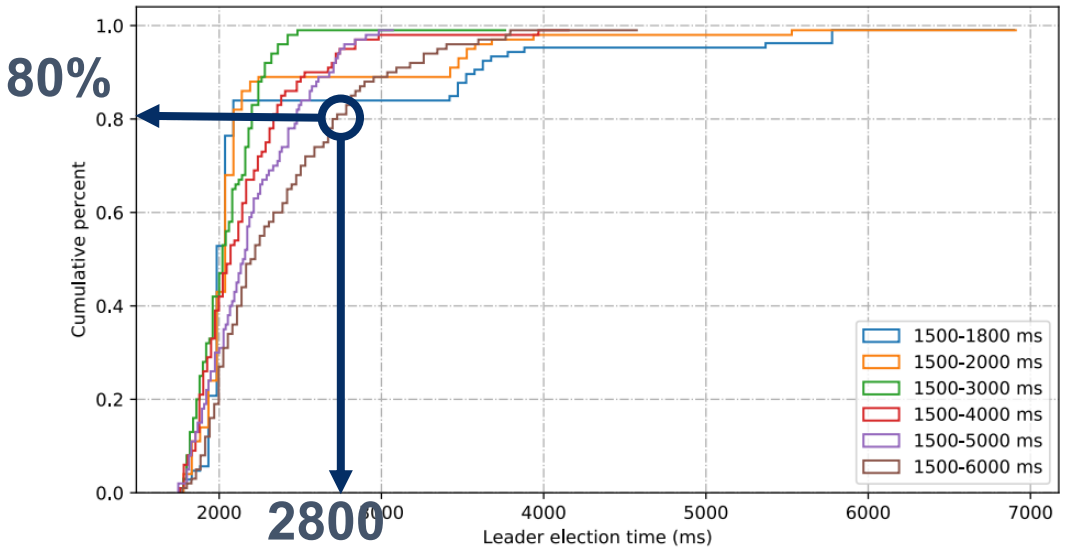
Competition in Raft's leader election



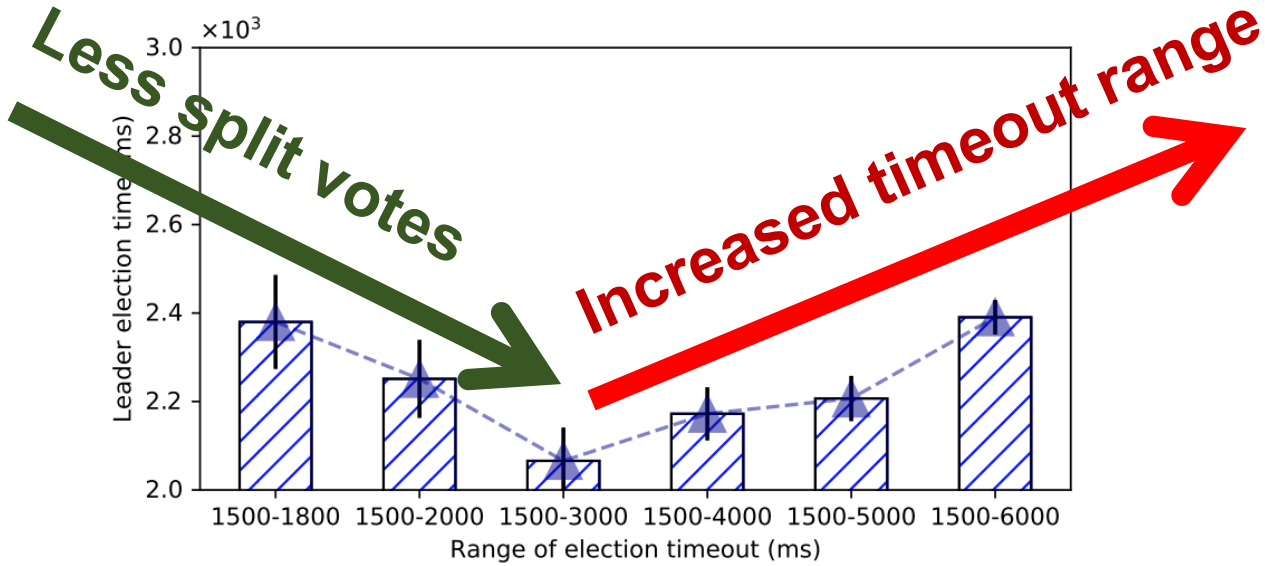
- Split votes: what if no one collects a majority vote?
  - E.g., in a 5-server cluster, the leader is down with 4 servers remaining. Each of the two candidates collects only two votes (one from itself)
- Candidates need to wait for a new timeout
- Split votes significantly increase leader election time (no leader, no service)

Impact of split votes

- Prolonged election time due to split votes



- 1000 runs in a 5-server cluster, 100-200ms network latency
- 80% of evaluation results are less than 2800ms. I.e., 20% of the 1000 runs took more than 2800ms



- Expanding timeout range can mitigate split votes but does not always yield to best configuration
- Best configuration changes adaptively according to network conditions

Escape to precaution against leader failures

- Escape is a leader election protocol that addresses split votes using two key concepts to dynamically prioritize servers
  - Stochastic configurations assignment (SCA)
    - Assigns each server a configuration contains a unique priority and a timeout value
  - Probing patrol function (PPF)
    - Rearranges server priorities based on their log responsiveness
- SCA and PPF work in concert to prepare a pool of candidates as “future leaders” with differently prioritized configurations
- Escape is a general-purpose leader election protocol (not restricted to Raft); it can be adopted by various election algorithms

Stochastic configurations assignment (SCA)

A configuration, $\pi^{\mathcal{P}_i}$, contains:

- Unique priority $(\mathcal{P}_i)$ such that $\mathcal{P}_i = i\ (server\ ID\ of\ S_i)$
- Timeout value $(period_i)$ such that $period_i = baseTime + k(n - \mathcal{P}_i)$

E.g., $baseTime = 100ms, k = 10, n = 10$

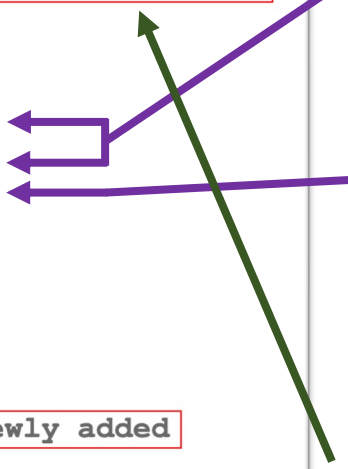
S_1 (1) $\pi^{\mathcal{P}_1} = \begin{cases} \mathcal{P}_1 : 1 \\ period_1 : 190\ ms \end{cases}$ ⇨ (2)

S_{10} (1) $\pi^{\mathcal{P}_{10}} = \begin{cases} \mathcal{P}_{10} : 10 \\ period_{10} : 100\ ms \end{cases}$ ⇨ (11)

- Priority determines term growth
- Timeout impacts speed for leader failure detection

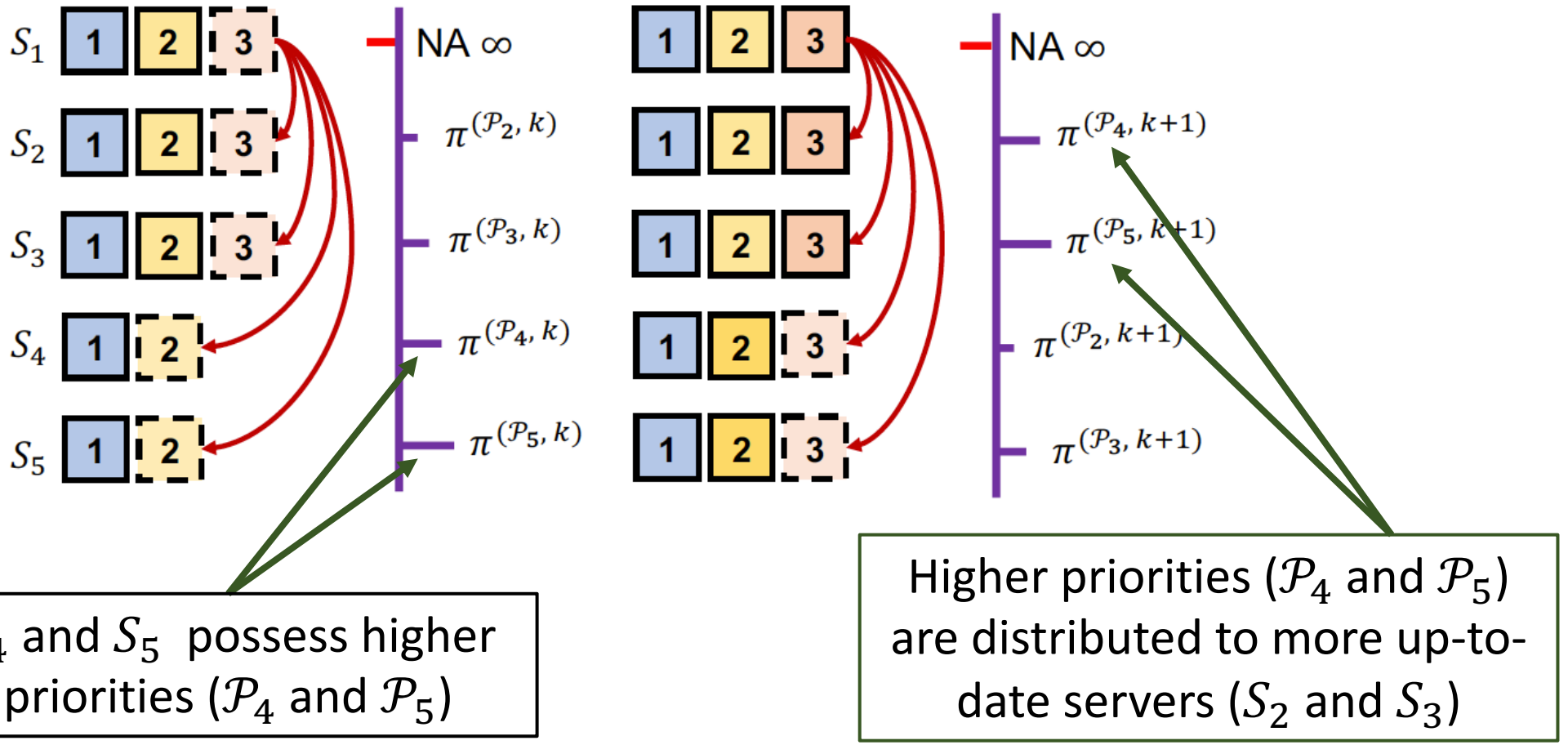
Probing patrol function (PPF)

```
//the parameters of AppendEntries RPCs
type AppendEntriesArgs struct{
    term          int64
    leaderId      string
    prevLogIndex  int64
    prevLogTerm   int64
    entries[]     Entries
    leaderCommit  int64
    newConfig     Configurations //newly added
}

type Configurations struct{
    timerPeriod time.Duration
    priority    int64
    confClock   int64
}

//the reply messages
type AEReplyArgs struct{
    term       int64
    success    bool
    status     configStatus //newly added
}

type configStatus struct{
    LogIndex     int64
    timerPeriod time.Duration
}
```

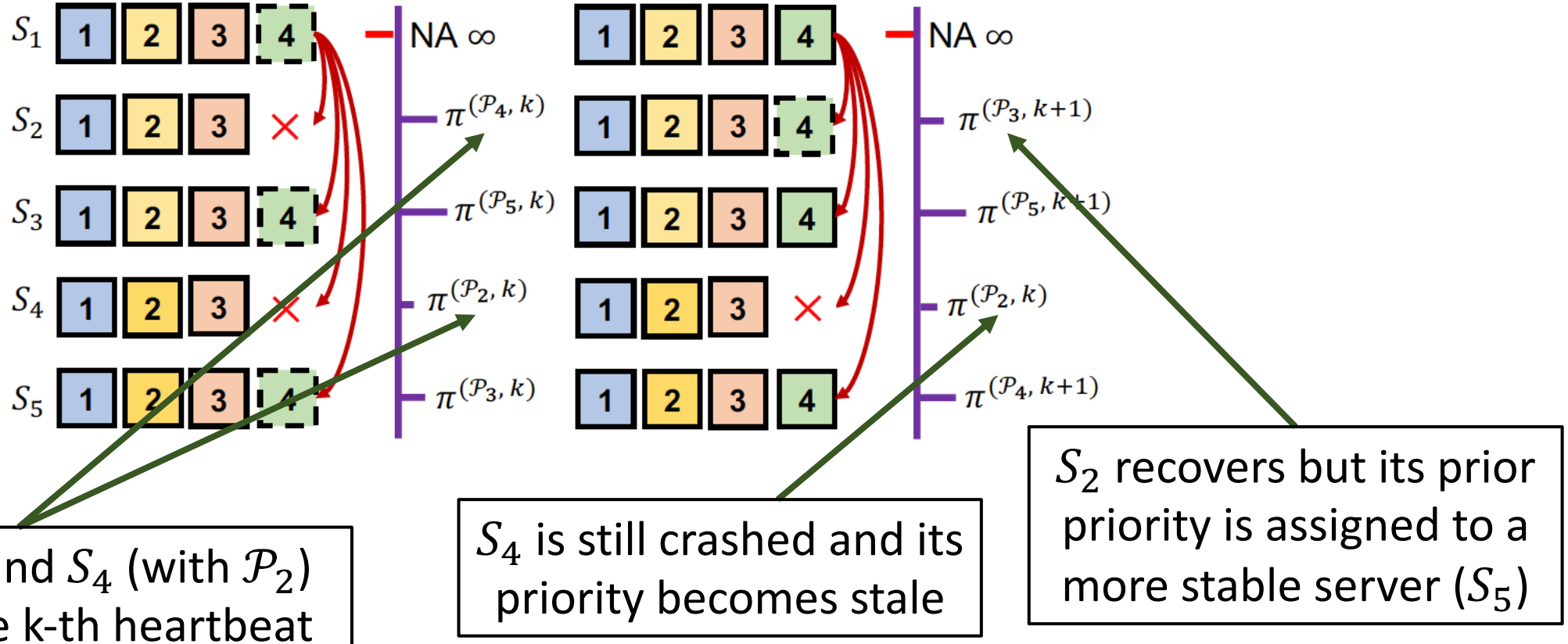


- In each heartbeat, a leader arranges configurations
  - Collects old configurations and rearranges new configurations based on server log responsiveness
  - Assigns logical clocks to new configurations, indicating the freshness of configurations
  - Distributes a new configuration to other servers
- PPF can be decoupled from regular heartbeats
  - E.g., less frequent rearrangement if network is more synchronous

Examples – higher log responsiveness, higher priorities



Examples – stale configurations of crashed servers



S_2 (with $\mathcal{P}_4$) and S_4 (with $\mathcal{P}_2$) crashed in the k-th heartbeat

S_4 is still crashed and its priority becomes stale

S_2 recovers but its prior priority is assigned to a more stable server (S_5)

Design philosophy of leader election protocols

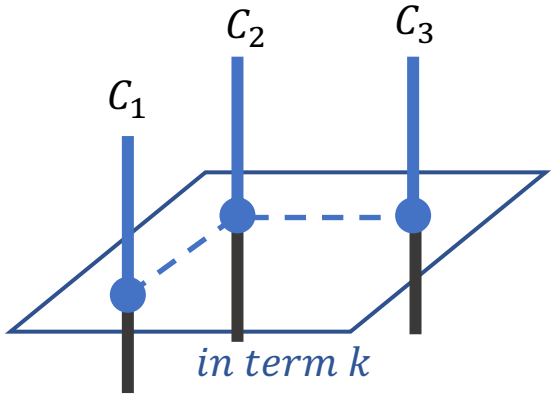
Raft

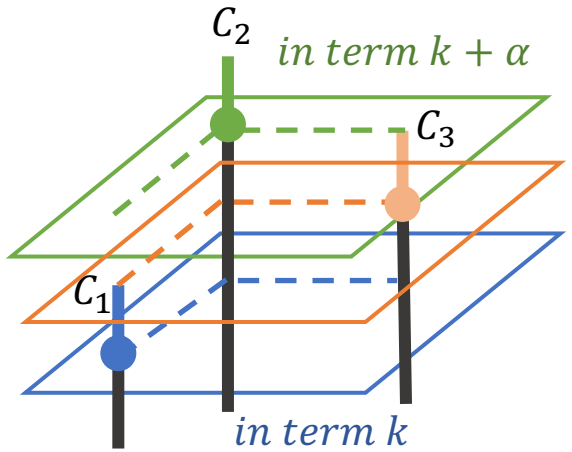
- All servers are created equal
  - Every server has an equal chance to be the next leader
  - The candidate who collects votes faster (a majority vote) is more likely to be elected
- Leadership competition may take place when a leader fails

Escape

- Servers are born with priorities
  - A higher-priority candidate is more likely to defeat its counterparts and win an election campaign
- A queue of future leaders is maintained; leadership competition is resolved before a leader fails

Escape to leadership competition

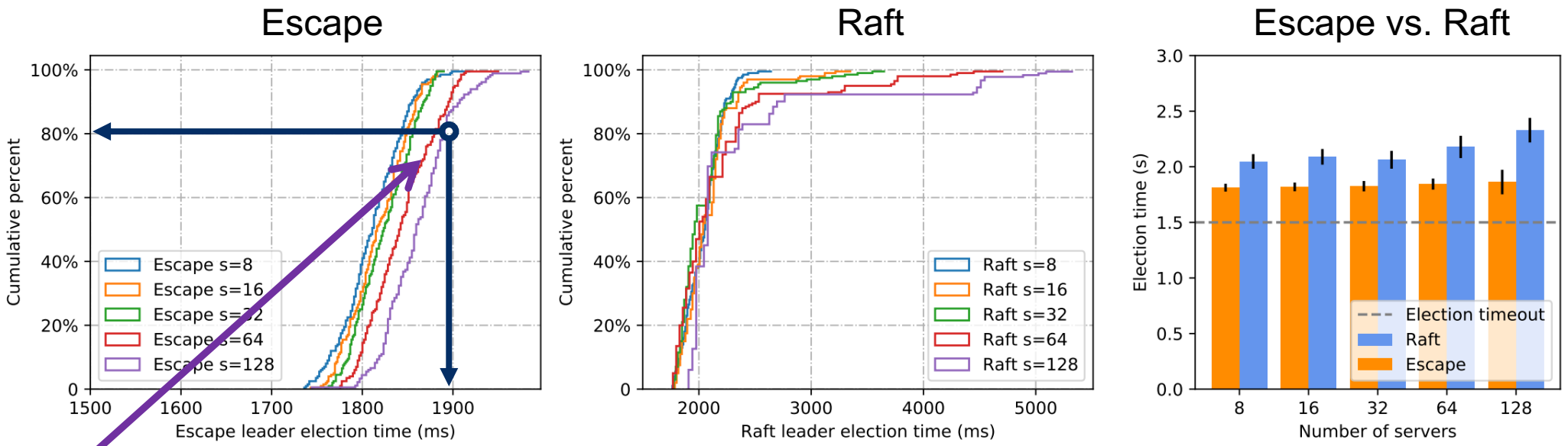




Raft intends to rank competing candidates whose campaigns are in the same term

ESCAPE uses priority-based configuration assignments to distribute concurrent campaigns into different terms

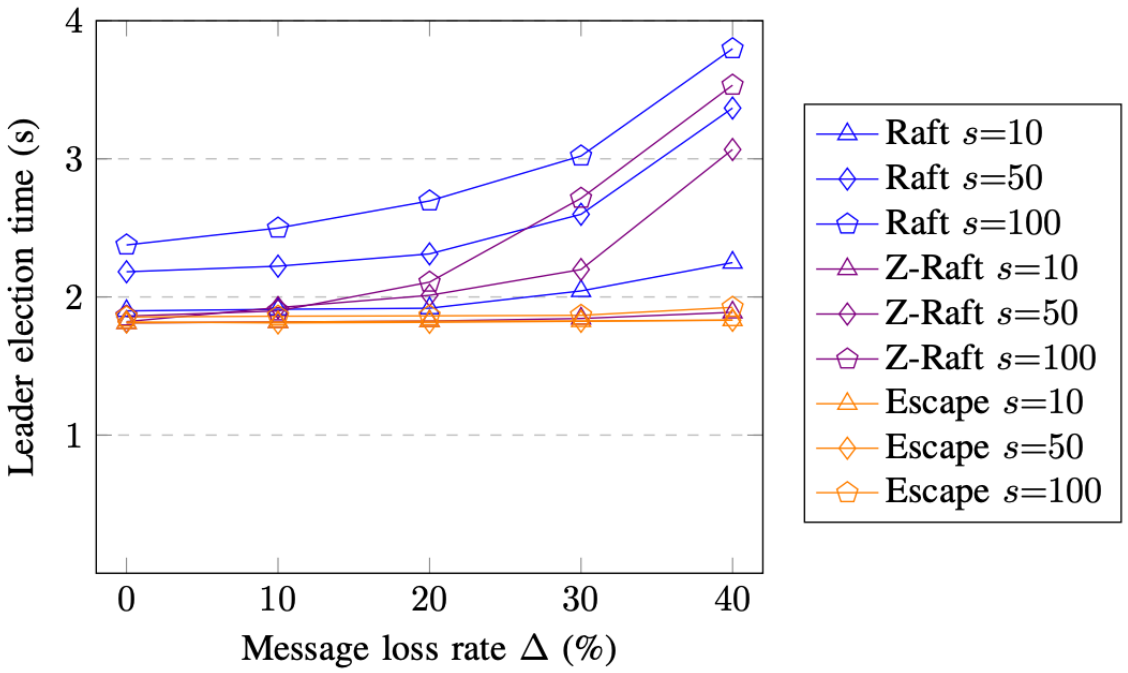
Evaluation – election time under leader failures



80% of the 1000 runs are less than 1900ms. I.e., 20% of runs took more than 1900ms

- Prototypes deployed on 4, 8, 16, 32, 64 and 128 VMs
  - Timeouts set to 1500-2000ms; network latency varies from 100-200ms
  - Each curve shows the cumulative percentage of 1000 runs;
- Escape converges leader election faster at all scales
  - Compared with Raft, Escape shortens leader election time by 11.6% and 21.3% at sizes of 8 and 128 servers, respectively

Evaluation – election time under message loss



- Z-Raft (Zookeeper variant)
  - No rearrangement of configurations

- Under higher message loss rates, configuration rearrangements become more effective as no stale candidate can possess high priorities
- In 10-server cluster, compared with Raft, Escape reduces election time by 9.6% and 19% under Δ=10% and Δ=40%, respectively
- In cluster of 100 servers, Escape reduces the leader election time by 21.4% and 49.3% when Δ=10% and Δ=40%, respectively

Conclusions

- Escape fundamentally resolves split votes by dynamically prioritizing servers according to their log responsiveness
  - A more up-to-date server receives a better configuration that leads it to run an undefeated leader election campaign
  - A pool of differently prioritized candidates is prepared before a future leader election takes place
- Escape progressively reduces leader election time when the cluster scales up, and the improvement becomes more significant under message loss

Thank you for listening!

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More on https://gengruizhang.github.io/