ID2203

KTH-2022

Advanced Course

Distributed Systems

Reconfigurable RSMs

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COURSE TOPICS

- Intro to Distributed Systems
- Basic Abstractions and Failure Detectors
- Reliable and Causal Order Broadcast
- Distributed Shared Memory
- Consensus, RSMs (Omni-Paxos, Raft, etc.)
- Dynamic Reconfiguration
- Time Abstractions and Interval Clocks (Spanner etc.)
- Consistent Snapshotting (Stream Data Management)
- Distributed ACID Transactions (Cloud DBs)

RECAP

- From naïve Sequence Paxos to Sequence Paxos
- Ballot Leader Election and partial connectivity:
  - Quorum-connected Leader Election
- Handling crashes and session-drops
  - Get synchronized before handling anything new.
- Today: Reconfiguration
  - How to add/remove processes correctly and efficiently.
- Raft and ZooKeeper

Reconfiguration

MOTIVATION

- A Replicated State Machine (RSM) is running on a set of N processes (typically 3 or 5)
  - Can tolerate up to $\lfloor N/2 \rfloor$ failures.
- Impossible to know if a process is faulty or just slow in Asynchronous model.
  - Need a way to replace any process.
- Scaling *up* (more powerful hardware) or *out* (more processes)

Policy (when) vs Mechanism (how)

- External agent decides when to reconfigure (autonomous or human)

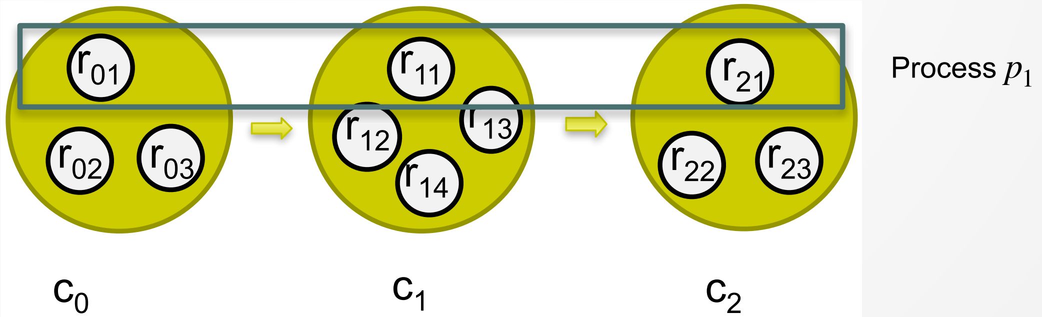
- The agent chooses the new configuration
  - E.g. $c_{old} = \{p_1, p_2, p_3\}$ and $c_{new} = \{p_1, p_2, p_4\}$
  - In general, c_{new} can be a completely new set of processes.

- Only concerned with the mechanism
  - Policy depends on application, deployment settings etc.

CONFIGURATIONS

- Each configuration c_i is conceptually an instance of Sequence Paxos, each with its own BLE instance.
  - Sequence Paxos and BLE instances of different configurations do not communicate!

- A process p that is part of c_i has a *replica instance* $r_{i,p}$
  - A process may have multiple replica instances in different configurations



STOP-SIGN

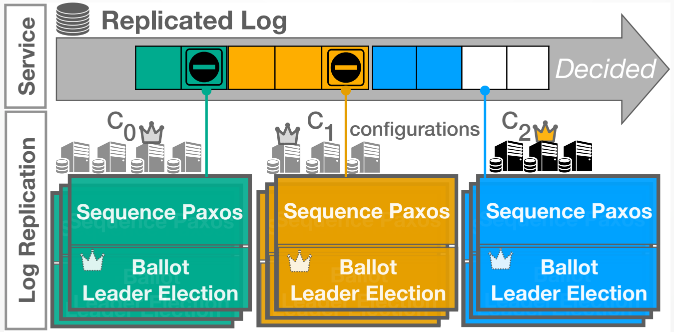
- Must safely stop the current configuration c_i before starting c_{i+1}
- A special **stop-sign (SS)** is proposed. Once it is chosen, the sequence in c_i cannot be extended and c_i is **stopped**. The sequence with SS as last command is the **final sequence** in c_0

Round	Accepted by $r_{0,1}$	Accepted by $r_{0,2}$	Accepted by $r_{0,3}$
…	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$
n=3	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$
n=2		$\langle C_2\rangle$	$\langle C_2\rangle$
n=1	$\langle C_1\rangle$		
n=0	$\langle\rangle$	$\langle\rangle$	$\langle\rangle$

- The final sequence in c_0 is $\sigma_0 = \langle C_2, SS_0\rangle$. Any sequence in round $n > 3$ will be σ_0

Omni-Paxos

- Omni-Paxos executes in one configuration until a reconfiguration occurs, then moves to new configuration.
- Processes transition to the new configuration asynchronously.
- A configuration is **active** once a majority of processes have started in the new configuration.
    - For safety, there can at most be one **running** configuration at all times.



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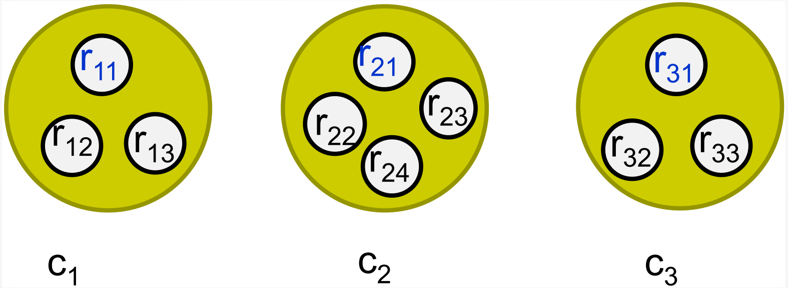
CONFIGURATIONS

- Processes operate at different rates and the leader could fail before everybody have reached the stop-sign.
  - Thus, a process cannot just shut down its replica instance in c_i once it has seen the decided stop-sign.

- As a result, a process p can have multiple replica instances at the same time, each with different state.
  - e.g. p is **stopped** in c_1, **running** in c_2 and **not-started** in c_3



STARTING A NEW CONFIGURATION

- Once SS_i is decided, the new configuration c_{i+1} can start.

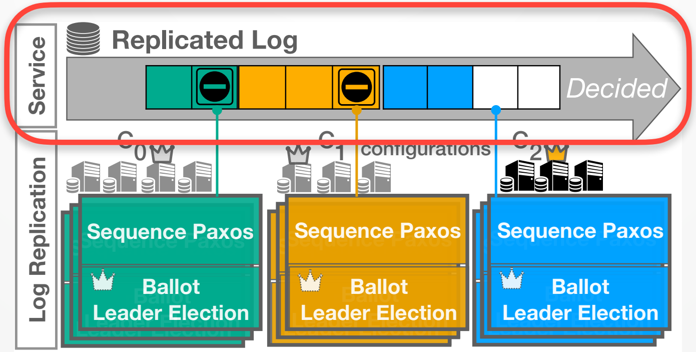
- SS_i contains complete information about c_{i+1}:
  - The set of processes in c_{i+1}
  - The new configuration number: *cid*
  - The identifier for each replica instance in c_{i+1}

- A process that is not part of c_i but added in c_{i+1} must get notified about the reconfiguration.
  - *Log migration:* to have the correct state, it **must** catch up the final sequence σ_i before starting its replica instance in c_{i+1}

- A process p that is part of both c_i and c_{i+1} will eventually see that SS_i is decided in c_i and start its replica instance in c_{i+1}

Service layer

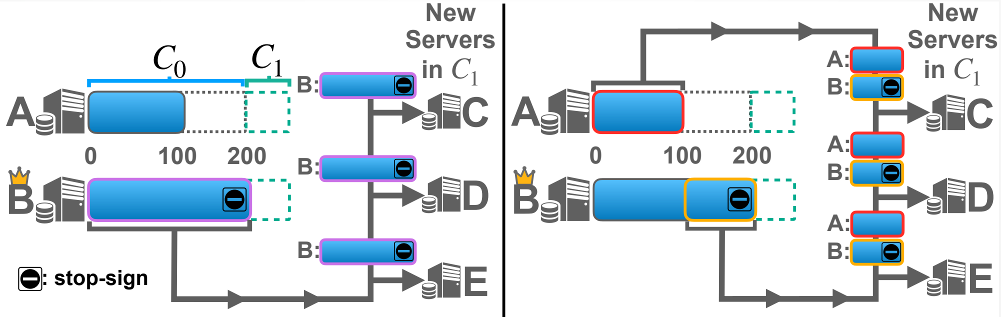
- The notification of reconfiguration and log migration to new processes are performed in the *service layer*.
  - On top of log replication.
- Advantages of having a separated service layer
  - Parallel log migration
  - Flexible transmission scheme
  - Can pull log entries from processes that have not even reached SS_i yet!



EFFICIENT HAND-OVER

- Since we stop and start configurations, there could be periods of down-time e.g. when new servers are still catching up the log and a majority in the new configuration cannot start yet.

- Important with an efficient hand-over procedure.
  - Flexible and parallel log migration
  - Snapshots



a) Leader-Based Log Migration   b) Parallel Log Migration

Correctness

- Must maintain Sequence Consensus invariant across different configurations: *If a proposal with sequence v is chosen, then every higher-numbered proposal that is chosen has v as a prefix.*

- What we have done:
  - Safely stop current configuration c_i before starting c_{i+1}
  - Decide stop-sign as any command using Sequence Paxos. Once chosen, c_i cannot be extended.
  - Require all processes to have the final sequence σ_i before starting in c_{i+1} (log migration)

- Conceptually, we have just **extended the round number** from n to (cid, n) where cid is the configuration number. We made the **round number totally-ordered** across configurations.

ORDERING ROUNDS TOTALLY

Round	Accepted by $r_{c1,1}$	Accepted by $r_{c1,2}$	Accepted by $r_{c1,4}$
…			
$n=(c_1, 3)$	$\langle C_2, SS_0, C_3, C_5\rangle$	$\langle C_2, SS_0, C_3, C_5\rangle$	
$n=(c_1, 2)$			$\langle C_2, SS_0, C_3, C_4\rangle$
$n=(c_1, 1)$	$\langle C_2, SS_0, C_3\rangle$	$\langle C_2, SS_0, C_3\rangle$	$\langle C_2, SS_0, C_3\rangle$
$n=(c_1, 0)$	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$
Round	**Accepted by $r_{c0,1}$**	**Accepted by $r_{c0,2}$**	**Accepted by $r_{c0,3}$**
…	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$
$n=(c_0, 3)$	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$	$\langle C_2, SS_0\rangle$
$n=(c_0, 2)$		$\langle C_2\rangle$	$\langle C_2\rangle$
$n=(c_0, 1)$	$\langle C_1\rangle$		
$n=(c_0, 0)$	$\langle\rangle$	$\langle\rangle$	$\langle\rangle$

SUMMARY

- Reconfiguring an RSM is relatively straight forward.
  - Must avoid "split-brain" problem by first safely stopping the current configuration.
  - Round numbers are totally-ordered across configurations.
- Service layer allows for efficient hand-over with flexible and parallel log migration
- The Omni-Paxos stack is now completed:
  - Service layer for efficient reconfiguration.
  - Sequence Paxos for safely replicating a log.
  - Ballot Leader Election for liveness even in partial connectivity.

Raft

In Search of an Understandable Consensus Algorithm
by Ongaro et al.

TERMINOLOGY

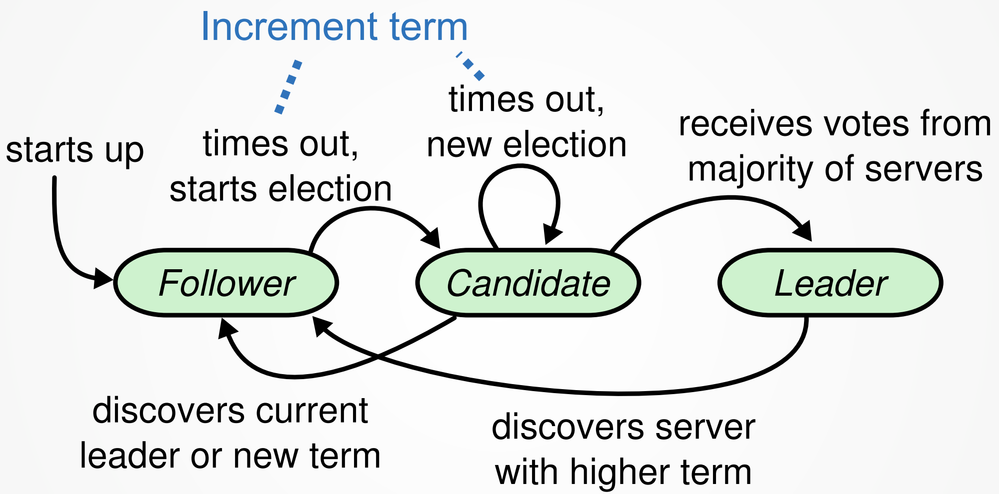
Sequence Paxos	**Raft**
v_a The accepted sequence ⟷	The Log
The Decided sequence ⟷	The committed prefix of Log
Round/ballot number ⟷	Term
Process ⟷	Server
n_{prom} , n_L ⟷	Highest Term
Element in a sequence ⟷	Entry

RAFT DECOMPOSITION

- Leader Election
  - Elect one server as the leader. Detect crashes and choose new leader
  - **Only servers with up-to-date logs can become the leader**
    - The leader election and sequence consensus are fused in one protocol.
    - Incorporates the prepare phase in the leader election algorithm.

- Log replication
  - Leader replicates its log to other servers, overwrites inconsistencies to keep logs consistent
  - Consistent replication is done differently from Sequence Paxos using a *log reconciliation* mechanism.

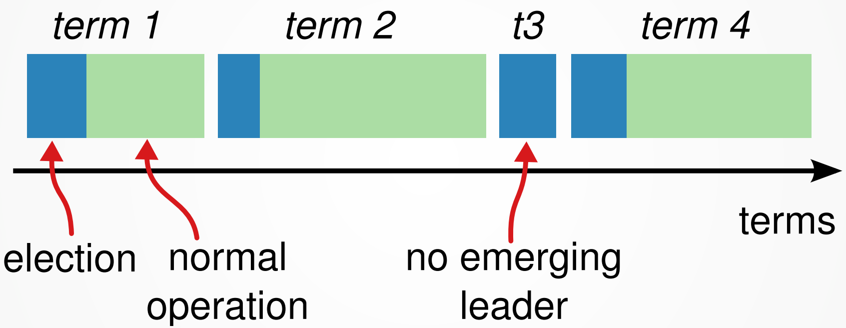
SERVER STATES



LEADER ELECTION

- The servers use remote procedure call (RPC) for communication.
  - RequestVoteRPC
- Each server gives only one vote per term (round)
  - Server *p* votes for server *q* if the latest log entry of *q* has higher term or same term but higher index. In this case, the log of *q* is more ***up-to-date*** than *p*.
- Majority of votes required to win.
- Terms are <u>not unique</u> => could be **split votes** with no winner
  - Retry RequestVoteRPC with higher term after some random time.

EXECUTION

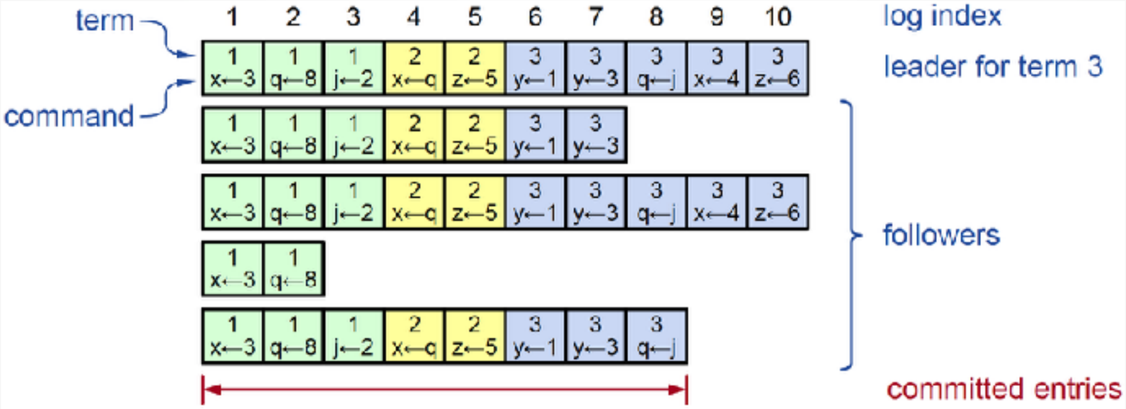


term 1
term 2
t3
term 4
terms
election
normal operation
no emerging leader

LOG REPLICATION

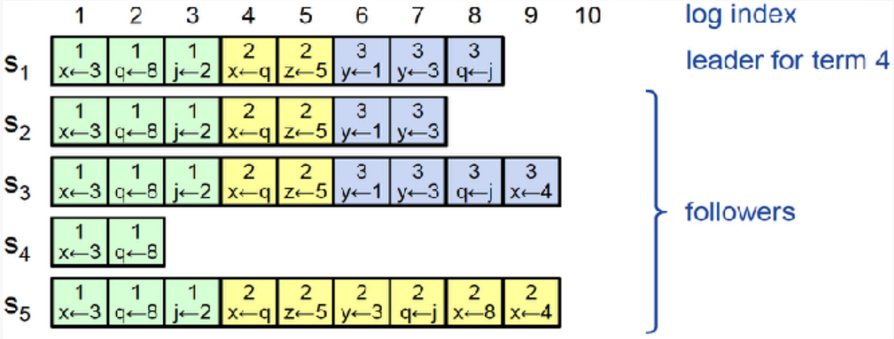
- Client sends commands to leader who appends them to its log.
- Leader sends **AppendEntriesRPC** to all followers (similar to ⟨Accept⟩ in Sequence Paxos)
- Entry is **committed** if AppendEntriesRPC successfully returns from a majority.
- Notify followers of committed index in the next AppendEntriesRPC (similar to ⟨Decide⟩)

LOG STRUCTURE



INCONSISTENCIES

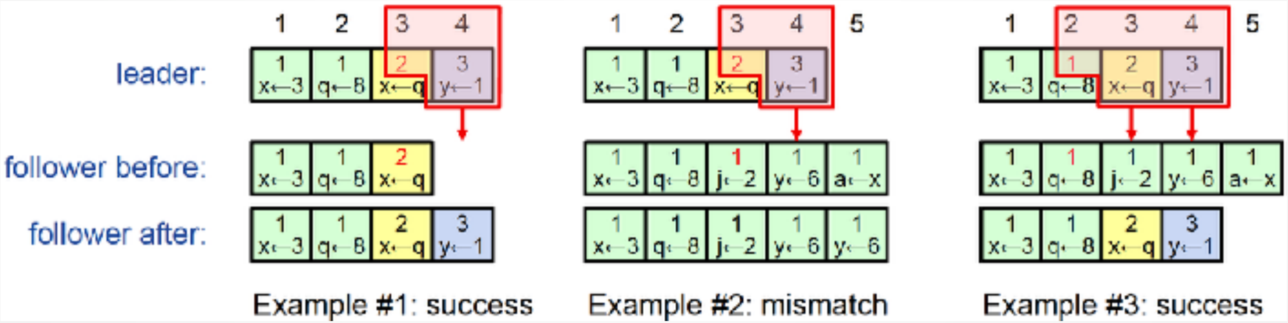
Crashes and network partitions may result in inconsistent logs.



Log Reconciliation

- *Correctness invariant*: Log entries on different servers with same index and term must store the same command, and the logs are identical in all preceding entries.
    - If a given entry is committed, all preceding entries are also committed.

- AppendEntriesRPC include $\langle index, term \rangle$ of entry directly preceding new one(s).
    - Follower must have matching preceding entry; otherwise reject the AppendEntriesRPC and leader retries with lower index.



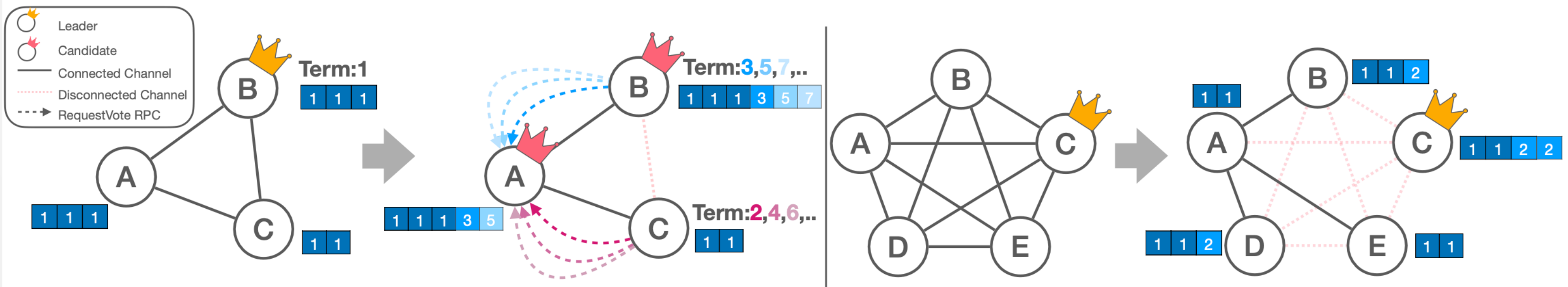
Raft and Sequence Paxos

- Raft and Sequence Paxos are both sequence consensus algorithms.
  - Replicate a growing log.
  - Leader must have highest round or term number.

- Raft differs from Sequence Paxos on:
  - Leader Election: unique ballot numbers in BLE vs. Split votes and randomised retries in Raft.
  - Raft incorporates the prepare phase as part of electing a leader
    - A server must have the most up-to-date log to win election.
    - In Sequence Paxos, any server can become the leader. Will get synchronized in the Prepare phase.
  - Log Reconciliation

CONSEQUENCES

- Cannot handle partial connectivity in Raft.
- Chained scenario: livelock with repeatedly higher term.
  - Term is incremented as soon as a server is not directly connected to leader.
- Only quorum-connected server cannot win election due to its log not being up-to-date.

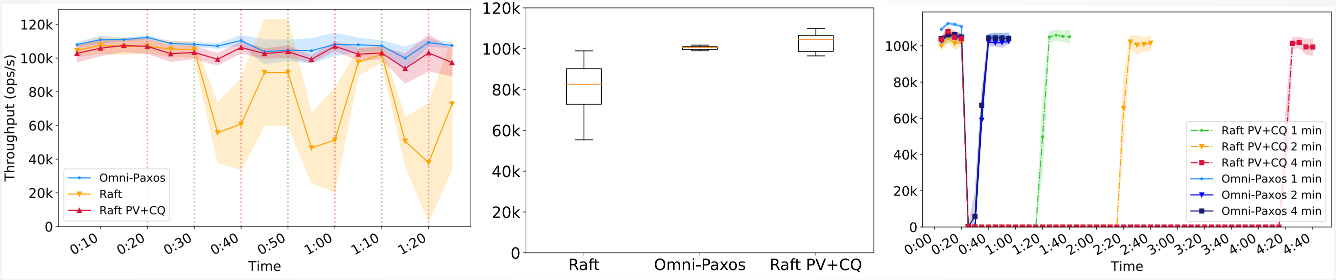


a) **Chained scenario:** Disruptions through repeated elections with higher term caused by C. Resolved if A becomes the leader.

b) **Deadlock scenario:** Despite being majority-connected, server A cannot become the leader due to its lagging log.

Leader Election Experiments

- Chained scenario: Raft recovers when the “central” server is elected. Omni-Paxos changes leader once.
- Deadlock scenario: Raft is deadlocked until partition is recovered. Omni-Paxos recovers in constant time ($2 \times$ leader timeout).



(a) Periodic full partition scenario.   (b) Chained scenario.   (c) Deadlock scenario.

Figure 9: Partial connectivity experiments. The shaded areas in (a) and (c) show the 95% CI using the t-distribution.

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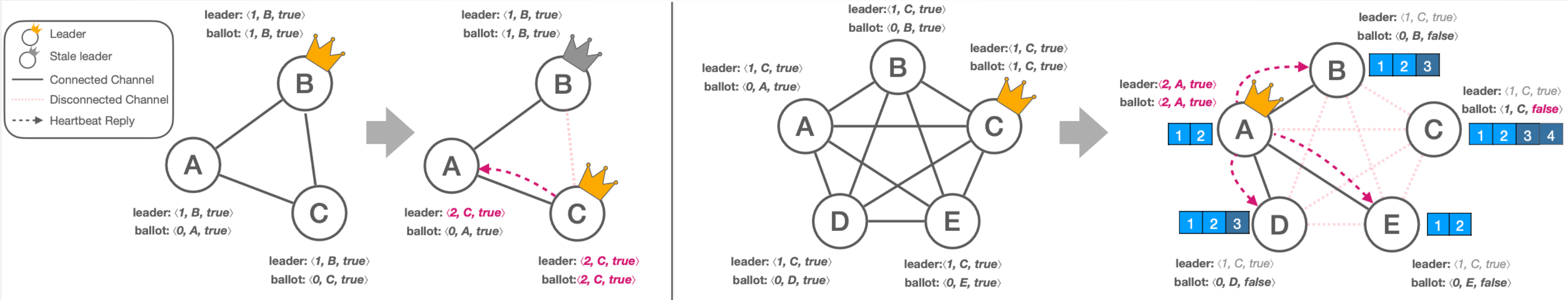
OMNI-PAXOS



a) **Chained scenario:** Server A adopts C as the leader.

b) **Deadlock scenario:** Server A successfully becomes the leader.

Raft Reconfiguration

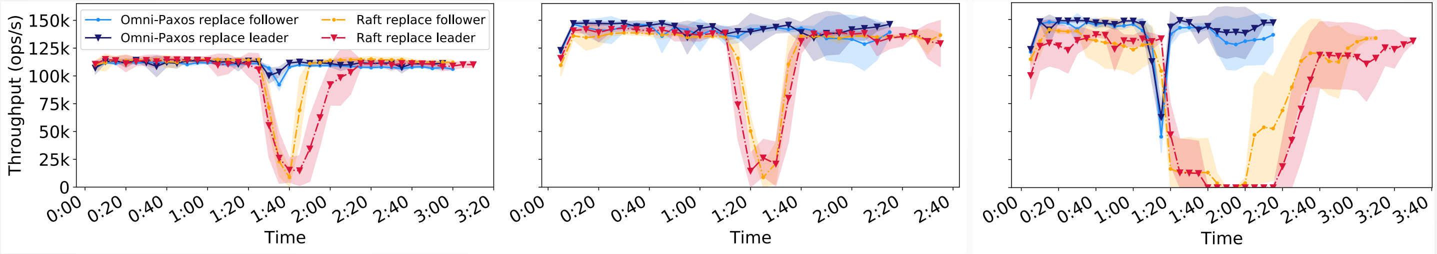
- Omni-Paxos: stop current configuration, then start new one.
  - Log migration to new servers in service layer.

- Raft uses a "joint-consensus" approach.
  - Intermediate configuration with both old and new configuration: $c_{old} \rightarrow c_{old,new} \rightarrow c_{new}$
  - In $c_{old,new}$ commands can continued to be decided, but must get majority from both c_{old} and c_{new}
  - Leader can be any server in c_{old} or c_{new}
  - New servers catch up the log following the normal log replication protocol. When majority in both c_{old} and c_{new} has caught up, only use c_{new}

Reconfiguration experiments

- Raft leader gets overloaded: must migrate log to all new servers.
  - Down-time if leader is replaced.

- Omni-Paxos: parallel log migration in service layer reduces down-time.



(a) Replace single server with $CP = 500$. (b) Replace single server with $CP = 50\text{k}$. (c) Replace majority with $CP = 50\text{k}$.

Figure 11: Reconfiguration experiments. The shaded areas show the 95% CI using the t-distribution.

SUMMARY

- Raft is designed to be understandable.
- Incorporates leader election, log replication and reconfiguration all into a single protocol.
- Log requirement in leader election causes problems with partial connectivity.
- Performing log migration in log replication results in leader-bottleneck.

ZooKeeper

ZooKeeper

- A distributed coordination service.
  - A complete and general-purpose system.
  - File system API: hierarchical structure of nodes
  - Lock service, group membership, leader election, etc.

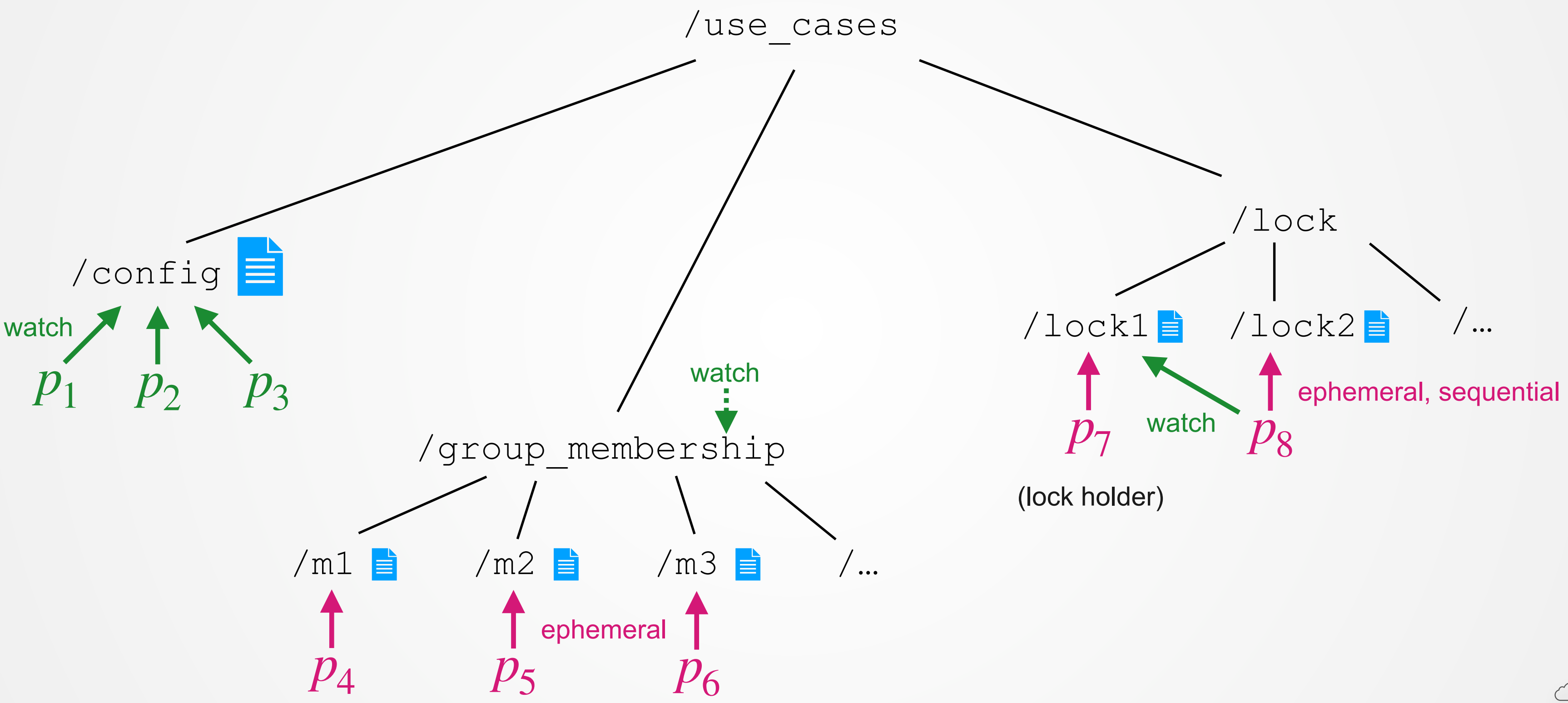
- Widely used: Apache Hadoop, Kafka, Flink, Spark etc.

- Based on ZooKeeper Atomic Broadcast (Zab)
  - Original was similar to Sequence Paxos but later became closer to Raft

Consistency

- Totally-ordered writes.
  - Do not support linearizable reads due to performance.
  - This would require reading via the leader or a majority.
  - Instead, we allow any replica to serve read from its local state.
- FIFO client order:
  - "read-your-writes": read might stall until preceding write is complete.
  - Read after read: must guarantee that the second read is at least as updated as the first. But different replicas could serve these requests and thus might also stall.
- Can use *sync* operation to perform a linearizable read that is decided in the log.

COMMON USE CASES AND PATTERNS



Summary

- Omni-Paxos first stops the current configuration by deciding stop-sign, before starting the new configuration.
  - Parallel log migration in the service layer, decoupled from log replication.
- Raft: designed for understandability
  - Log replication, leader election and reconfiguration - all in a single protocol
  - Cannot handle partial connectivity and leader-bottleneck during reconfiguration.
- ZooKeeper: a general-purpose distributed coordination service
  - File system API: group membership, lock service, etc.
  - Weaker consistencies for performance.