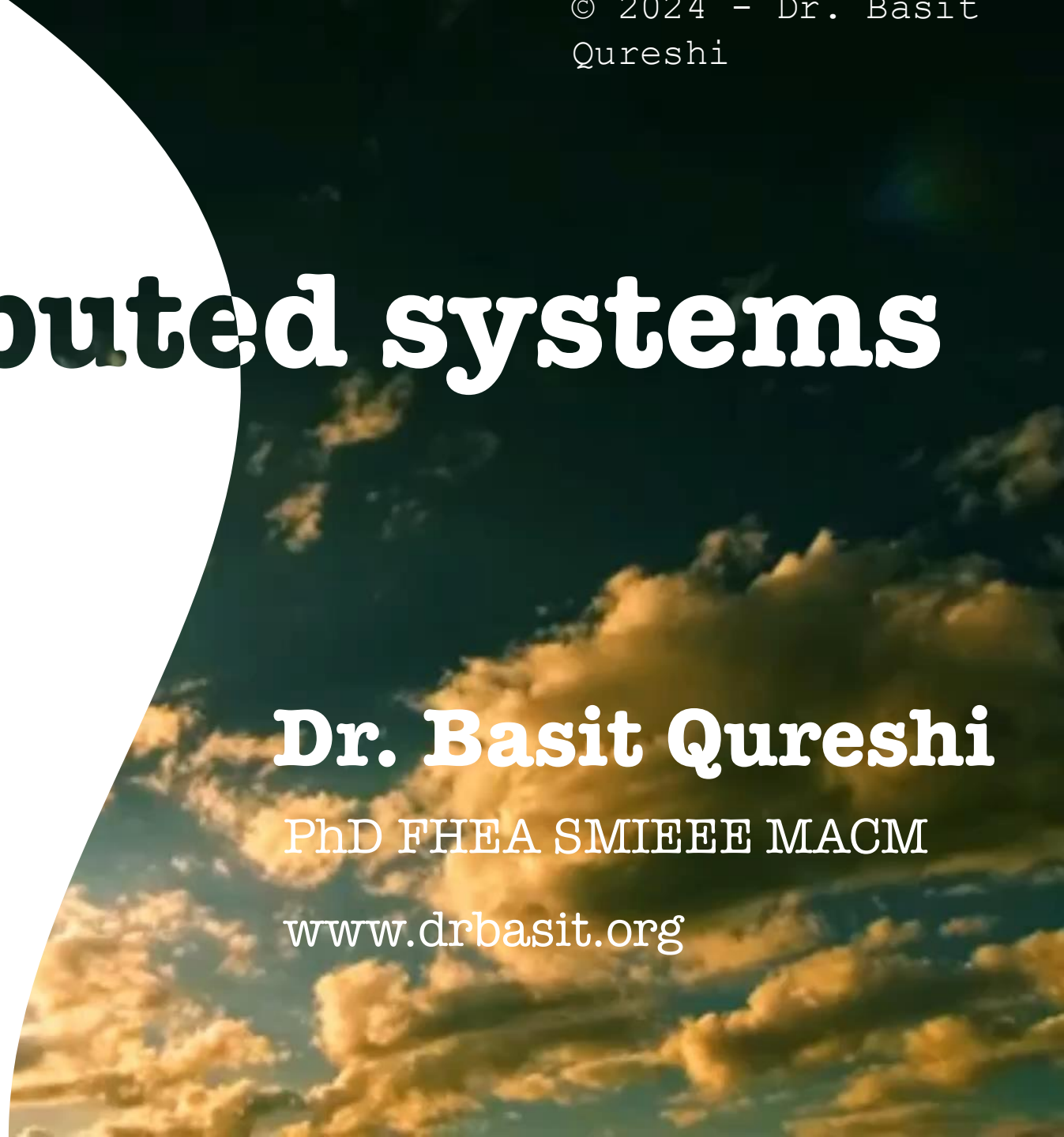
جامعة الأمير سلطان
PRINCE SULTAN UNIVERSITY

CS435 Distributed systems

DISTRIBUTED MUTUAL EXCLUSION



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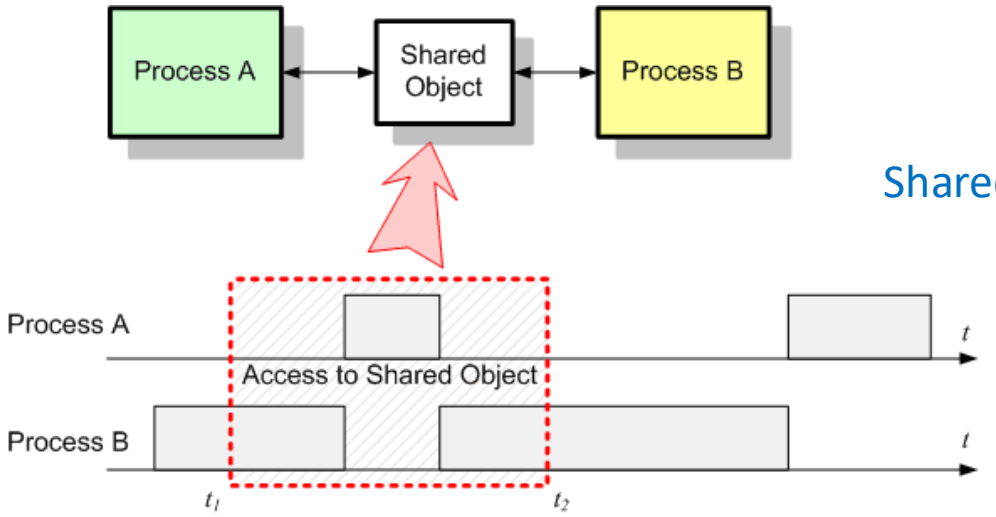
TOPICS

- Dist. Mutual Exclusion
  - Centralized Algorithm
  - Token Ring Algorithm
- Dist. Mutual Exclusion Algorithms
  - Lamport
  - Ricart & Agarwala
  - Other algorithms
- Leader Election Algorithms
  - Bully
  - Ring
- Concensus Algorithms
- Raft

CS330 OPERATING SYSTEMS (RECAP)

- Mutual Exclusion?
  - TO prevent multiple processes from accessing a shared resource or critical section at the same time.
    - **Mutual Exclusion** – Only one process in critical section.
    - **Progress** – If no one is in the critical section, some process should be allowed in.
    - **Bounded Waiting** – A process should not wait forever to enter the critical section.



Shared Object: Processor (CPU)

  - Examples:
    - Dining Philosopher problem (Deadlocks, starvation, locks etc)
  - Solutions?
    - Semaphores, Mutex locks, Monitors

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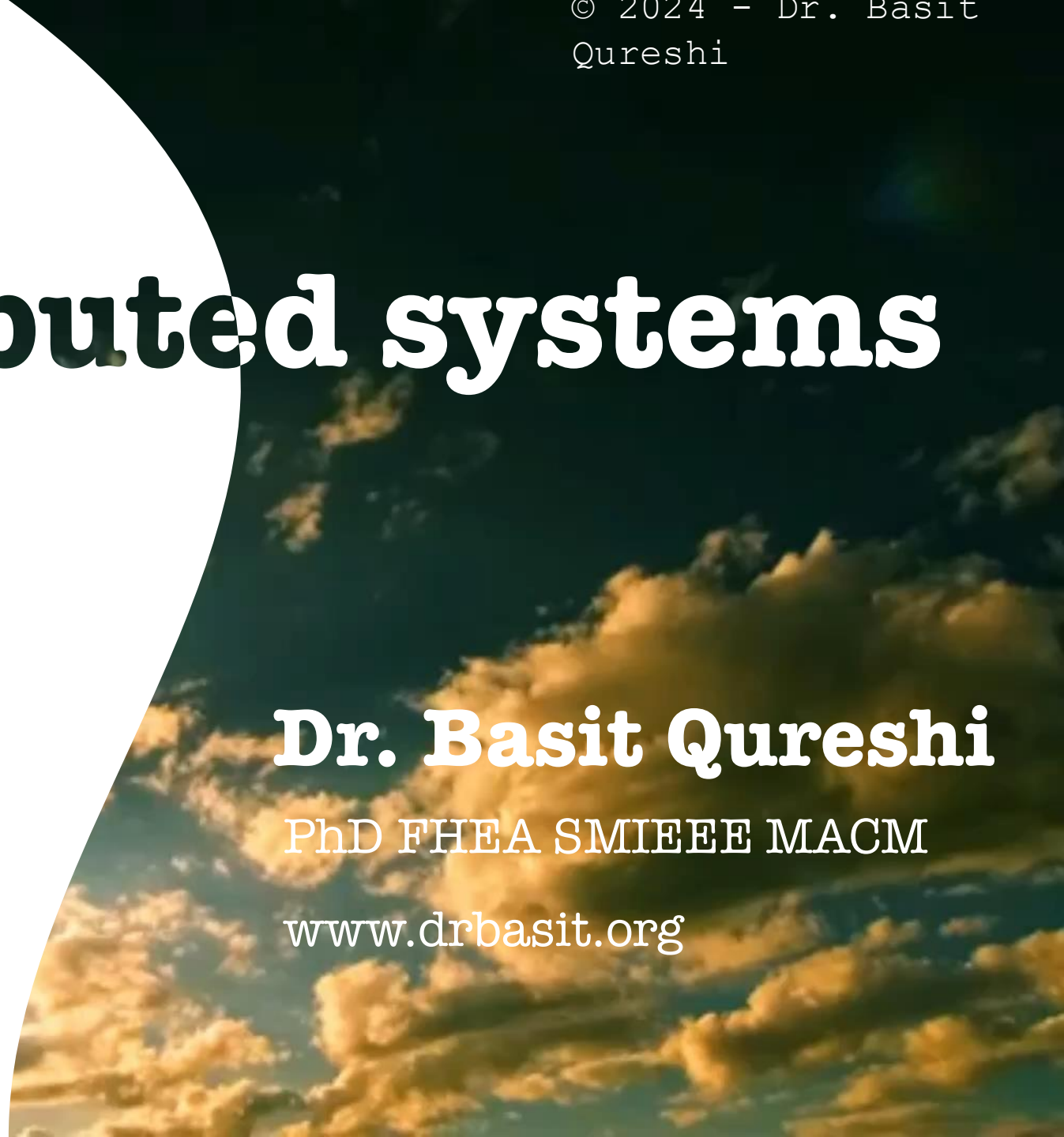

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DIST MUTUAL EXCLUSION

"A distributed system ensures that only **one process or node** can access a **shared resource** or **critical section** at any given time".

- Examples:
  - Modify a shared file
  - Update a database field
  - Modify replication messages
- Easy to handle for **atomic** requests [Covered in CS330]
  - One message, one server
  - One system: Hardware compatibility, Semaphores, Messages, Condition variables
- Challenging if
  - Multiple messages on multiple servers with different hardware capabilities
  - *Need synchronization and coordination*

DIST MUTUAL EXCLUSION

GOAL:

- *Distributed Mutual Exclusion ensures that only **one process is granted permission to access the resource at a time,** while others are **blocked** or **delayed** until the resource becomes available.*

AIM:

- **Safety**: Ensuring that only one process accesses the **Critical Section** at a time
- **Liveness**: Ensuring that processes **eventually gain access** to the critical section, even in the presence of failures, delays, or network partitions.
- **Efficiency**: [Optional] **Minimizing overhead and maximizing resource utilization** while maintaining safety and liveness properties.

APPLICATION (Few Examples): Shared printers, ATM machines, Shared DB tables, Shared files etc.

DIST MUTUAL EXCLUSION

HOW Dist Mutual Exclusion Differs from a Single Processor Mut. Exl.:

NEEDS:

- Process identification: Every process has a **unique** Identifier (e.g., `address.process_id`)
- Reliable communication: Network messages are **reliable**
- Live processes: Ensure system processes are **responsive** & do not die.
- Resource identification: All Agree on resource identification

HOW:

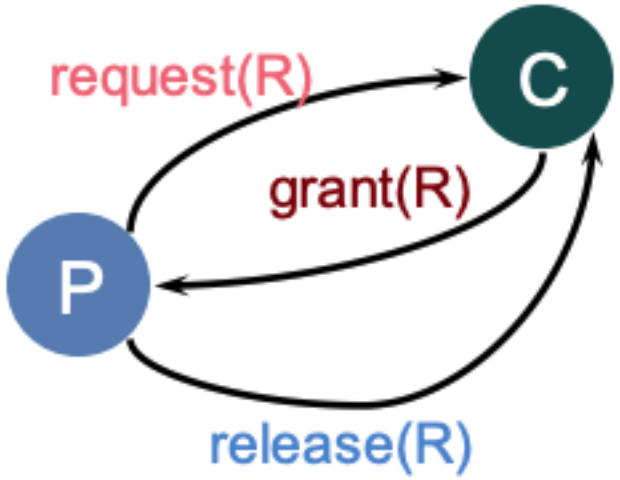
- Pass the identifier with each request
- e.g., `lock("printer"), lock("table:employees"), lock("table:employees;row:15"), lock("shared_file.txt")`
- We'll just use `request(R)` to request exclusive access to resource `R`

DIST MUTUAL EXCLUSION

- Algorithms
  - **Centralized**: A coordinator is responsible for allowing access to a shared resource
  - **Token-based:** Access if a token was granted
  - **Contention-based (Quorum)**: Via Distributed agreement

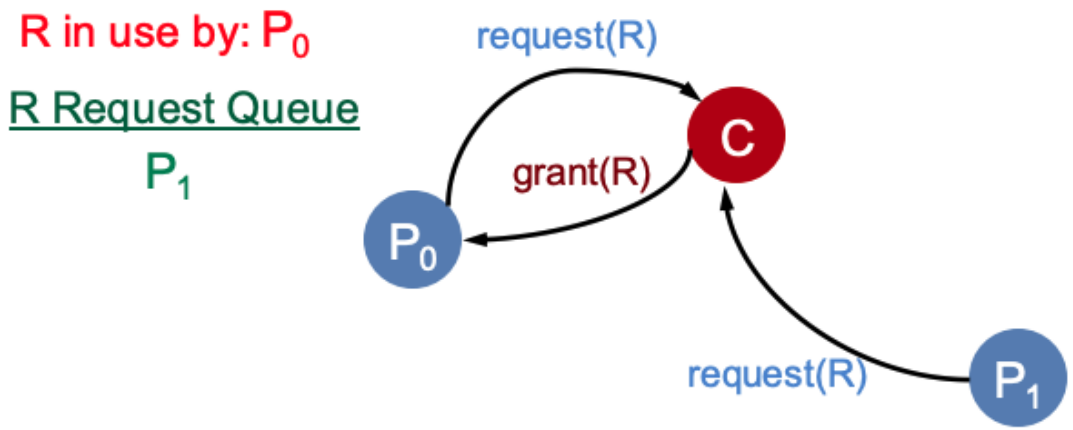
DIST MUTUAL EXCLUSION

- **Centralized Algorithms**: Similar to a single processor system:
  - Process **P** Request(**R**) access to resource **R** from Coordinator **C**
  - Wait for response
  - Receive Access
  - Access resource
  - Release(**R**)



DIST MUTUAL EXCLUSION

- **Centralized Algorithms**: If another Process tries to access:
  - Maintain a FIFO queue at coordinator
  - Coordinator: Donot reply until resource available



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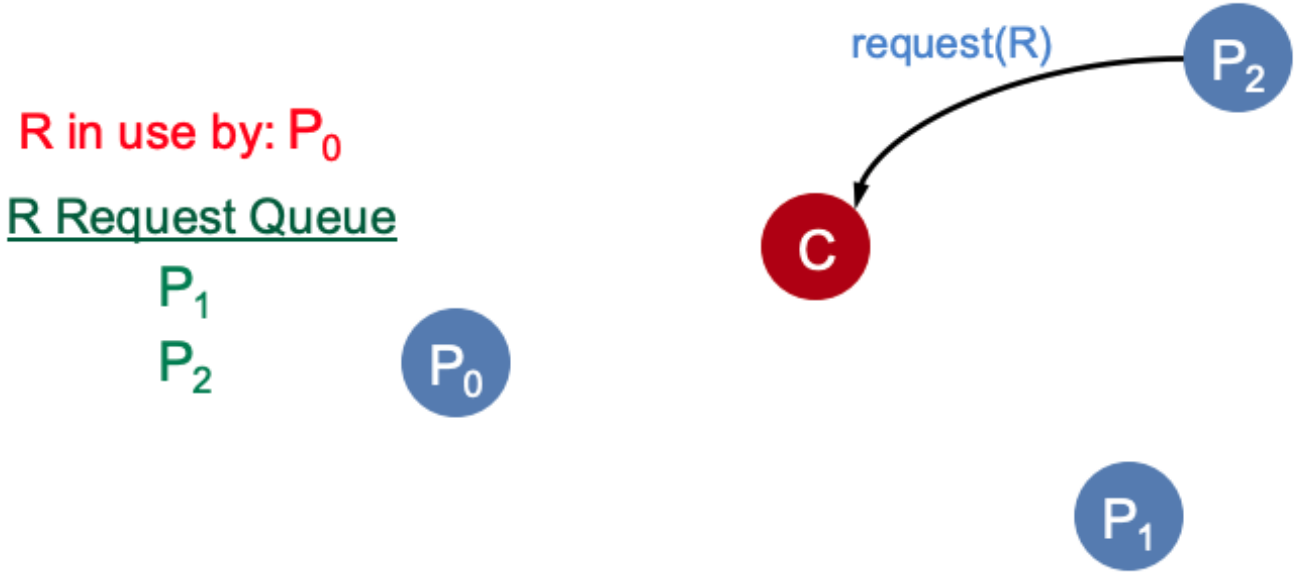

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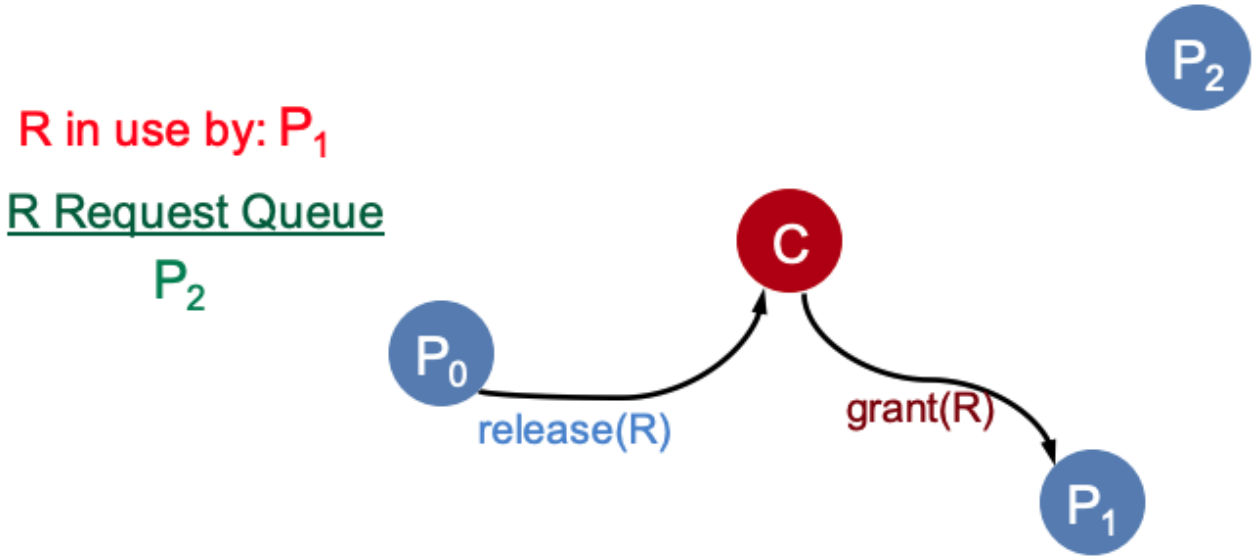

DIST MUTUAL EXCLUSION

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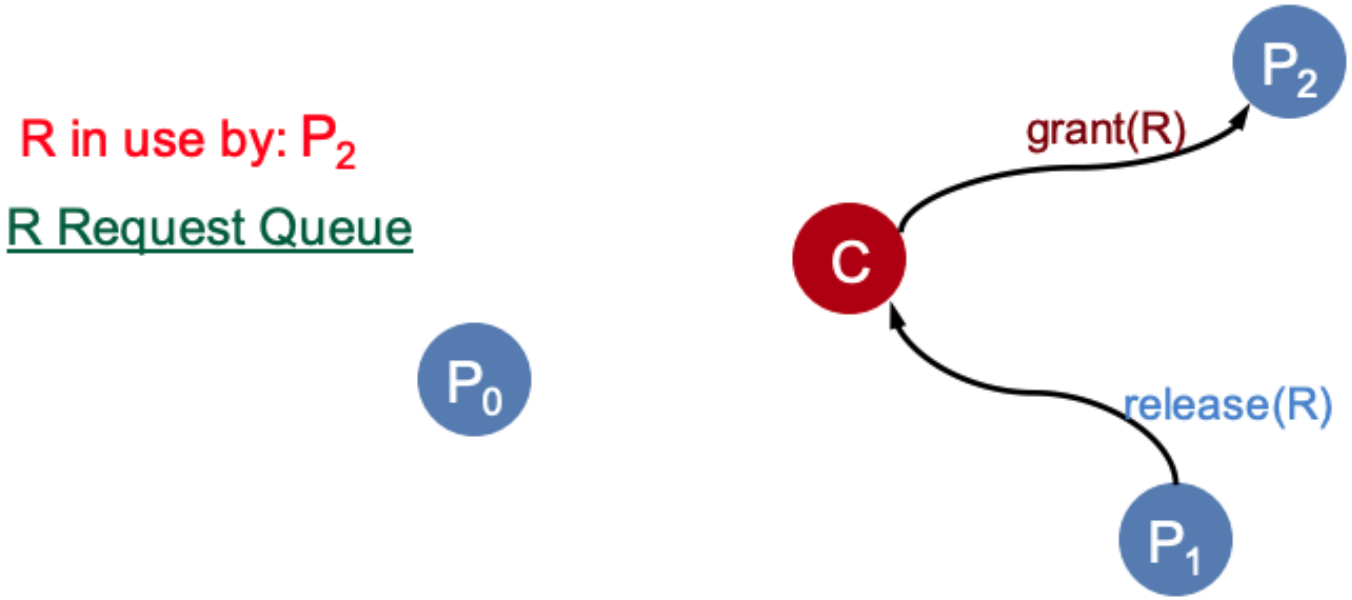
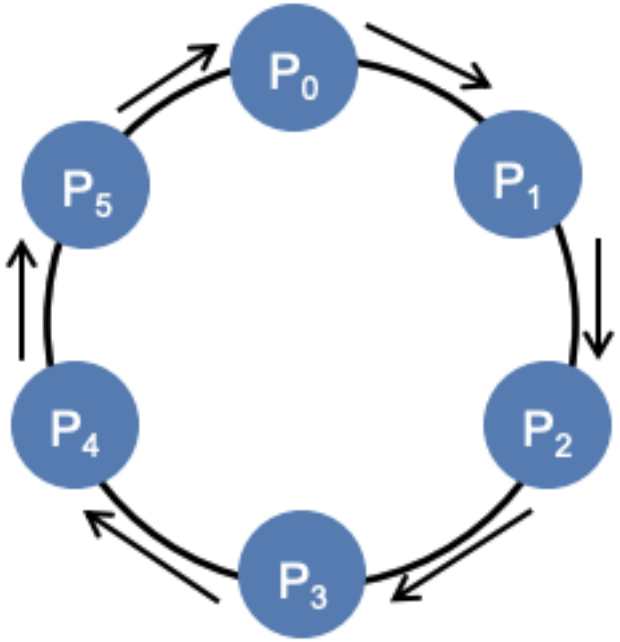


DIST MUTUAL EXCLUSION

- **Centralized Algorithms**:
- The Good
  - Easy to implement
  - FIFO Queue takes order into consideration
  - Processes do not need to communicate to other processes; just the coordinator
  - Efficient: 2 message to enter, 1 message to exit
- The Bad
  - Single point of failure: Coordinator crashes!
  - A crashed coordinator blocks access to resource
  - Coordinator can become a bottleneck!

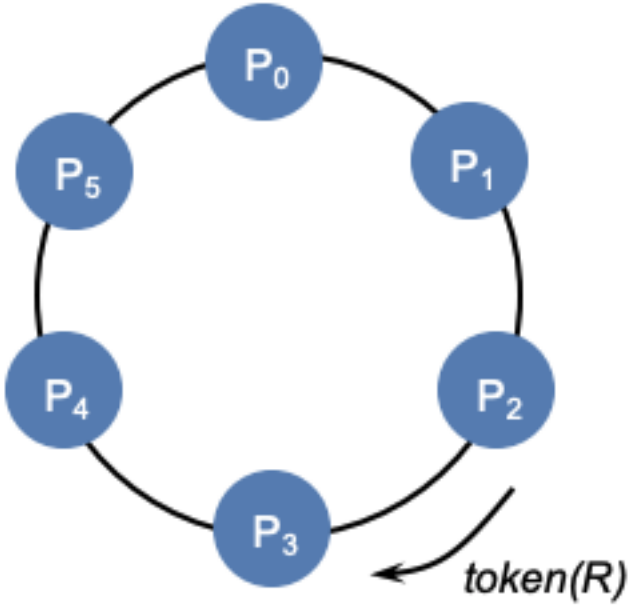
DIST MUTUAL EXCLUSION

- **De-Centralized Algorithms:** Token-Ring Algorithm
- Processes known each other in a group
  - Processes can be assigned a unique process IDs
  - Construct logical ring in software
  - Process communicates with its neighbor and not with the coordinator



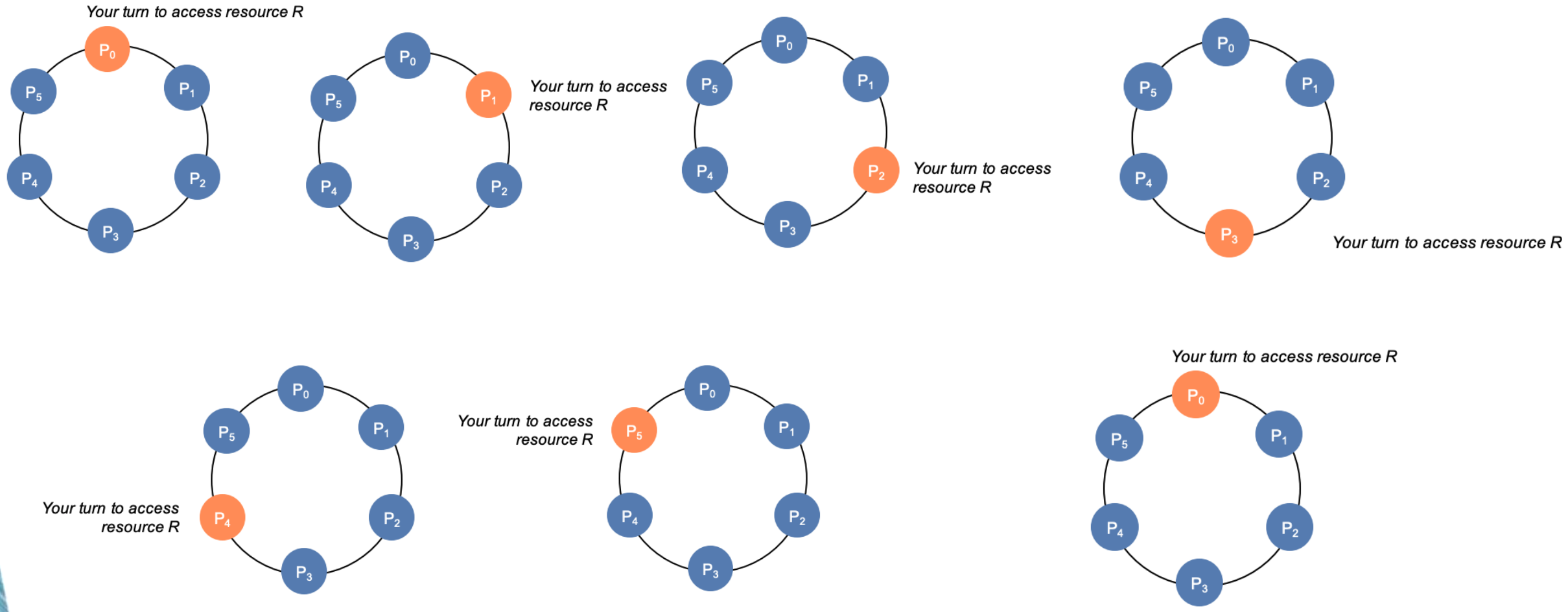
DIST MUTUAL EXCLUSION

- **De-Centralized Algorithms:** Token-Ring Algorithm
- Initialization
  - Process 0 creates a token for resource R
- Token circulates around ring from **P_i to $P_{(i+1)}$mod N**
  - When process acquires token
    - Checks to see if it needs the resource (**the lock**)
    - **No**: send the token to its neighbor
    - **Yes**: access resource & hold token until done



DIST MUTUAL EXCLUSION

- **De-Centralized Algorithms:** Token-Ring Algorithm



DIST MUTUAL EXCLUSION

- **De-Centralized Algorithms:** Token-Ring Algorithm
- The Good
  - **Saftey**: Only One process at a time [**Mutual Exclusion is guaranteed**]
  - **Liveness**: Order is defined, but not always First-Come-First-Serve (FCFS)
  - **Delay**: Request = 0…N-1 messages; Release = 1 message
- The Bad
  - Constant activity
  - Process dies: **Token is lost**! Needs to be re-generated
    - Detecting loss can be challenging (really lost or someone is holding it)
  - Communication error: What if no communication with neighbor

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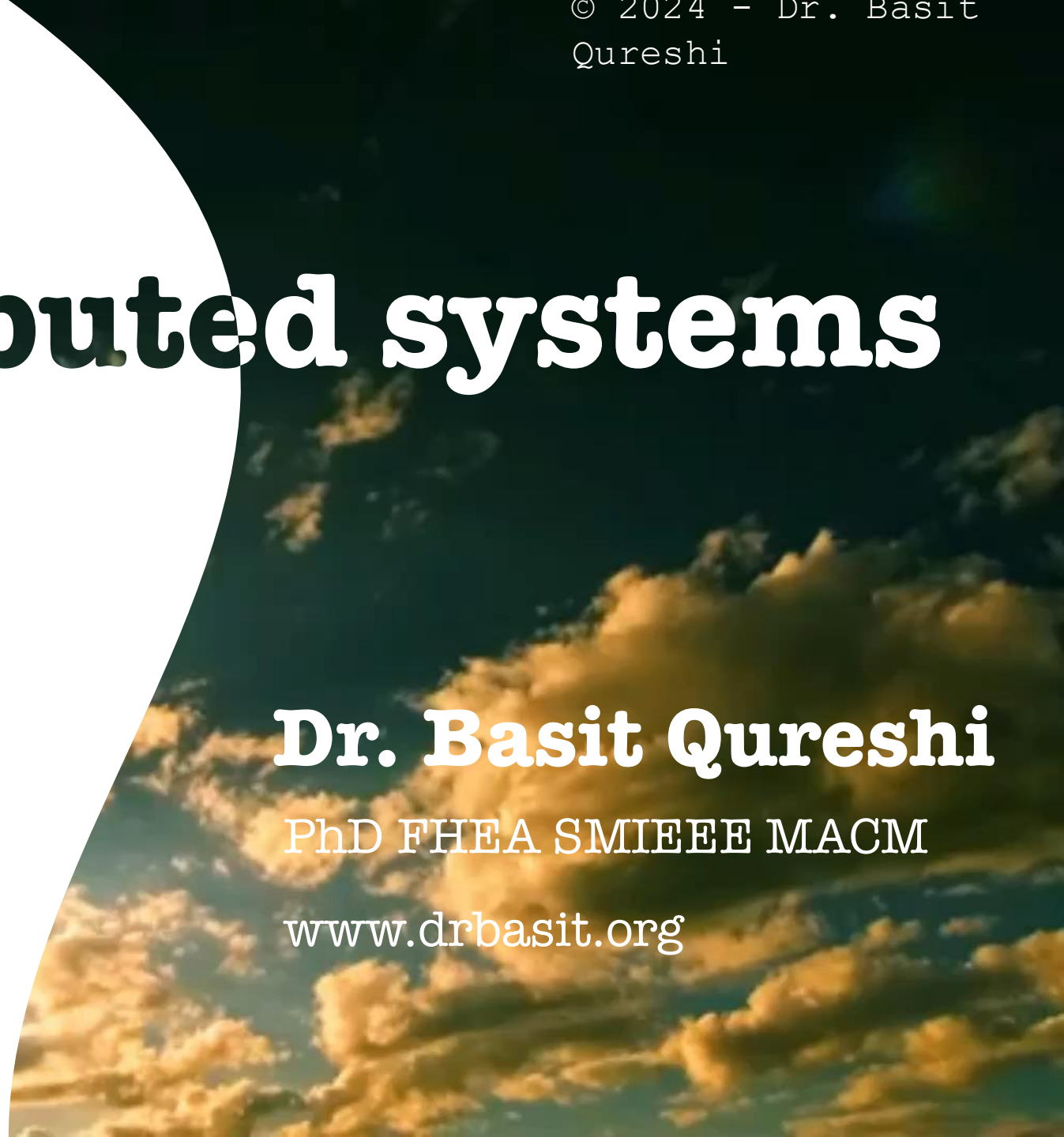
DIST MUTUAL EXCLUSION DE-CENTRALIZED ALGORITHMS



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LAMPORT MUTUAL EXCLUSION

- Uses Lamport's logical clocks and message passing to coordinate access to a shared resource among multiple processes.
- **Messages are sent reliably and in single-source FIFO order**
  - Each message is time stamped with **totally ordered (i.e., unique)** Lamport timestamps
  - Ensures that each timestamp is unique
  - Every node can make the same decision by comparing timestamps
- **Each process maintains a request queue**
  - Queue contains **mutual exclusion requests**
  - Queues are sorted by message timestamps

LAMPORT MUTUAL EXCLUSION

Step 1: Request a resource R:

- Process `Pi` **sends** `Request(R, i, Ti)` to **ALL** nodes
  - It also places the same request onto its own queue
- When a process `Pj` receives a request:
  - Places the request on its request queue
  - It **returns** a timestamped `Reply(Tj)`

- Every process will have an identical queue

Process	Time stamp
P_4	1021
P_8	1022
P_1	3944
P_6	8201
P_{12}	9638

Sample request queue for R
Identical at each process

LAMPORT MUTUAL EXCLUSION

Step 2: Use the resource R:

- `Pi` can access the resource if
  - `Pi` has received `Reply` messages from every process `Pj` where `Tj > Ti`
  - `Pi` request has the earliest timestamp in its queue

Process	Time stamp
P_4	1021
P_8	1022
P_1	3944
P_6	8201
P_{12}	9638

Sample request queue for R
Identical at each process

i.e. If your request is at the head of the queue AND you received Replies for that request
… then you can access the critical section

LAMPORT MUTUAL EXCLUSION

Step 3: Release the resource R:

- Process `Pi` removes its request from its queue
- Sends `Release(Ti)` to all nodes
- Each process now checks if its request is the earliest in its queue
- If so, that process now has the `lock` on the resource

Process	Time stamp
P_4	1021
P_8	1022
P_1	3944
P_6	8201
P_{12}	9638

Sample request queue for R
Identical at each process

LAMPORT MUTUAL EXCLUSION

Assessment

- **Safety**: Replicated queues – same process on top
- **Liveness**: Sorted queue & Lamport timestamps ensure First come first serve
- **Delay/Bandwidth:**
  - *Request* = `2(N-1) messages: (N-1) Request msgs + (N-1) Reply msgs`
  - *Release* = `(N-1) Release msgs`
- **Problems**
  - N points of failure
  - **A lot of messaging traffic**: **Requests & releases are sent to the entire group**

RICART & AGARWALA MUTUAL EXCLUSION

Designed to **reduce message overhead** compared to Lamport's algorithm

Basic Idea:

- Allow processes to grant permission to enter the critical section directly
- No need to consult a central authority

RICART & AGARWALA MUTUAL EXCLUSION

When a process wants to enter critical section:

1. Compose a **`Request(R, i, Ti)`** message containing:
   - **`R`**: Name of resource
   - **`i`**: Process Identifier(machine ID, process ID)
   - **`Ti`**: Timestamp (totally-ordered Lamport)
2. Reliably **`multicast`** request to all processes in group
3. **`Wait`** until everyone gives permission (sends a **`Reply`**)
4. **`Enter`** critical section / use resource

RICART & AGARWALA MUTUAL EXCLUSION

When process receives a request:

- If receiver not interested: send `Reply` to sender
- If receiver is using the resource: **do not reply**; **add request to queue**
- If receiver just sent a request as well: (**potential race condition**)
  - **Compare timestamps** on received & sent messages: earliest timestamp wins
  - If receiver is the **loser**: `send Reply`
  - If receiver is the **winner**: `do not Reply`
  - Queue the request
    - When **done** with resource: `send Reply to all` queued requests

RICART & AGARWALA MUTUAL EXCLUSION

Assessment

- **Safety**: Two competing processes will not send a `Reply` to each other
  - Timestamps in the requests are unique
  - one will be earlier than the other
- **Liveness**: Lamport timestamps ensure First come first serve
- **Delay/Bandwidth:**
  - *Request* = `2(N-1) messages: (N-1) Request msgs + (N-1) Reply msgs`
  - *Release* = `0…(N-1) Reply msgs to queued requests`
- **Problems**
  - N points of failure
  - **A lot of messaging traffic**: Requests & releases are sent to the entire group

LAMPORT VS RICART & AGARWALA MUTUAL EXCLUSION

Lamport

- Everyone replies … always – no hold-back
- **3(N-1) messages Request → Reply → Release**
- Always compares Timestamps: Process is granted the resource if its request is the earliest in its queue

Ricart & Agarwala

- Reply only if you are in the critical section (or won a tie)
  - Don’t respond with a Reply until you are done with the critical section
- **2(N-1) messages**
  - Request → ACK
- Process is granted the resource if it gets ACKs from everyone

COMPARISON

Lamport

- **Traffic**: 3(N-1) messages per Critical Section entry
- **Timestamps**: Always
- **Total ordering**: Uses a centralized timestamp mechanism that requires all messages to be delivered and processed for accurate ordering
- **Less fault tolerant**: failure in message delivery could cause issues with synchronization
- **Application**: Better for applications requiring strict global ordering
- Ensures **fairness** because requests are processed in the order of timestamps

Ricart & Agarwala

- 2(N - 1) messages per critical section entry.
- Only use time stamps to resolve race condition
- Is fully decentralized, with no single point of failure. However, it still requires all processes to respond to each other, meaning that if a node fails, it can block access to the critical section.
- Fault tolerance can be an issue if there is no handling of non-responsive nodes
- Offers more relaxed synchronization, benefiting applications with simpler access needs
- Fairness is more conditional on all processes responding in a timely manner. Delays can cause issues

LAMPORT VS RICART & AGARWALA MUTUAL EXCLUSION

Other algorithms

- Suzuki-Kasami
  - Token-based mutual exclusion algorithm
  - + Efficient in systems with low contention
  - - High message overhead in high-contention situations
- Maekawa
  - Groups nodes in Quorums (a subset of nodes).
  - + Reduces message complexity by limiting the number of nodes
  - - Can cause deadlocks on quorum (subset of nodes).
- Dijkstra's Token Ring Algorithm
  - Only the process holding the token is allowed to enter the critical section
  - + Each process gets a fair turn with minimal communication
  - - High latency in large systems, as the token must travel through each node
- Raynal's Algorithm
  - Similar to Lamport but requires acknowledgements
  - +Reliable and ensures that requests are handled in a well-defined order
  - -Message overhead is relatively high increasing latency

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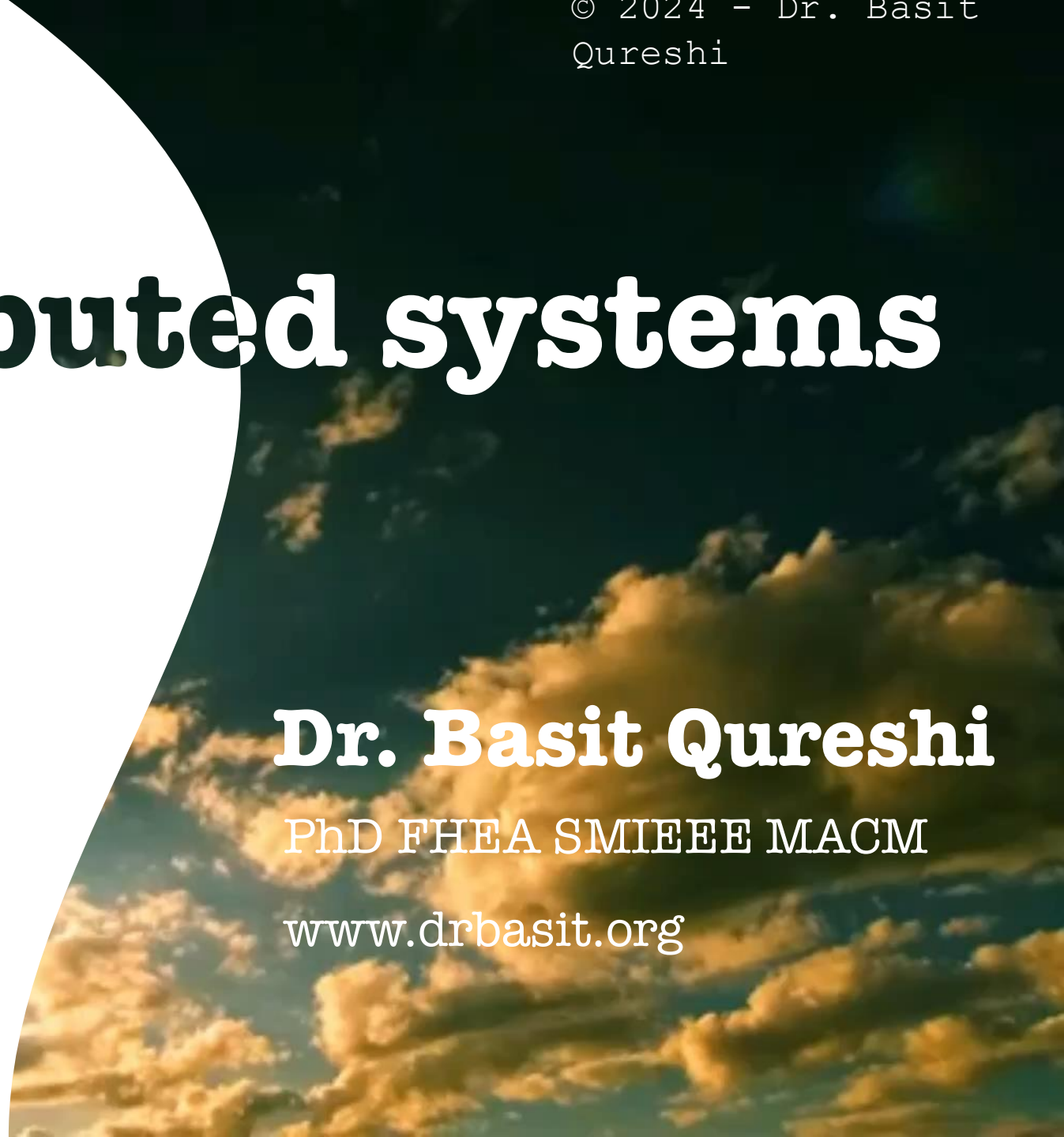
CONTENTION- BASED (QUORUM) / LEADER ELECTION ALGORITHMS



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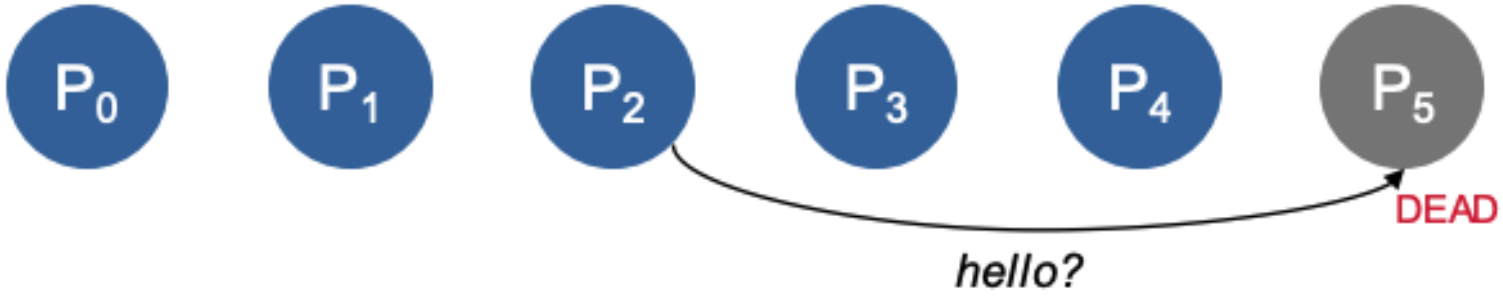
BULLY ALGORITHM

- **Bully Algorithm**
- GOAL: Select the process with the largest ID as a leader
- Holding an election: when process Pi detects a dead leader:
  - Send **election** message to all processes with higher IDs
    - If nobody responds, **Pi wins** and takes over
    - If any process responds, P's job is done
  - Optional: Let all nodes with lower IDs know an election is taking place

- If a process receives an **election** message
  - Send an **OK** message back
  - Hold an election (unless it is already holding one)

BULLY ALGORITHM

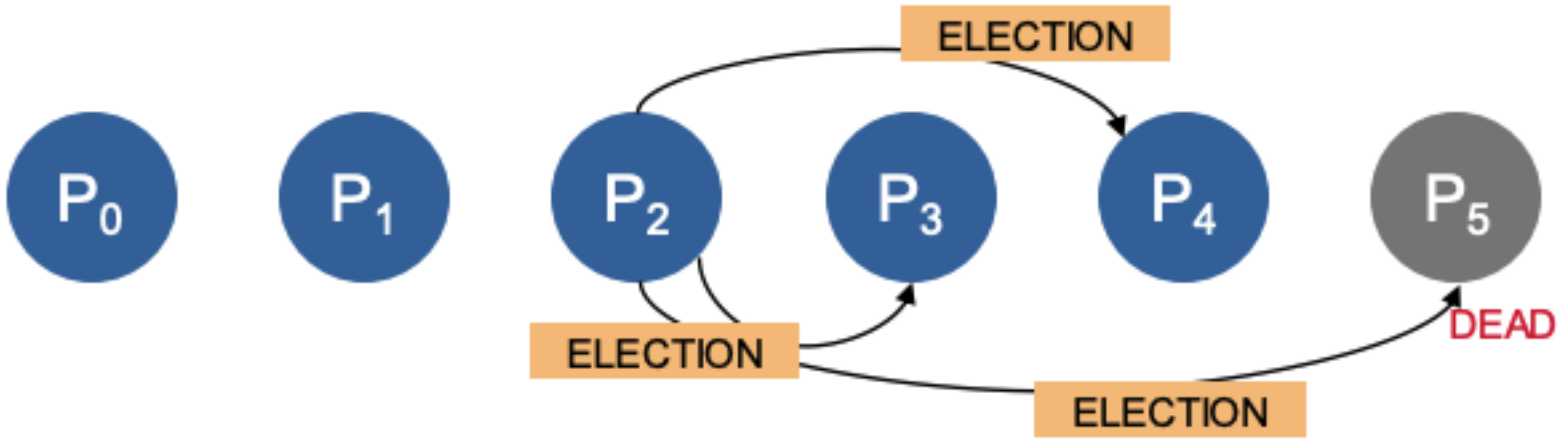


Rule: highest # process is the leader

Suppose P_5 dies

P_2 detects P_5 is not responding

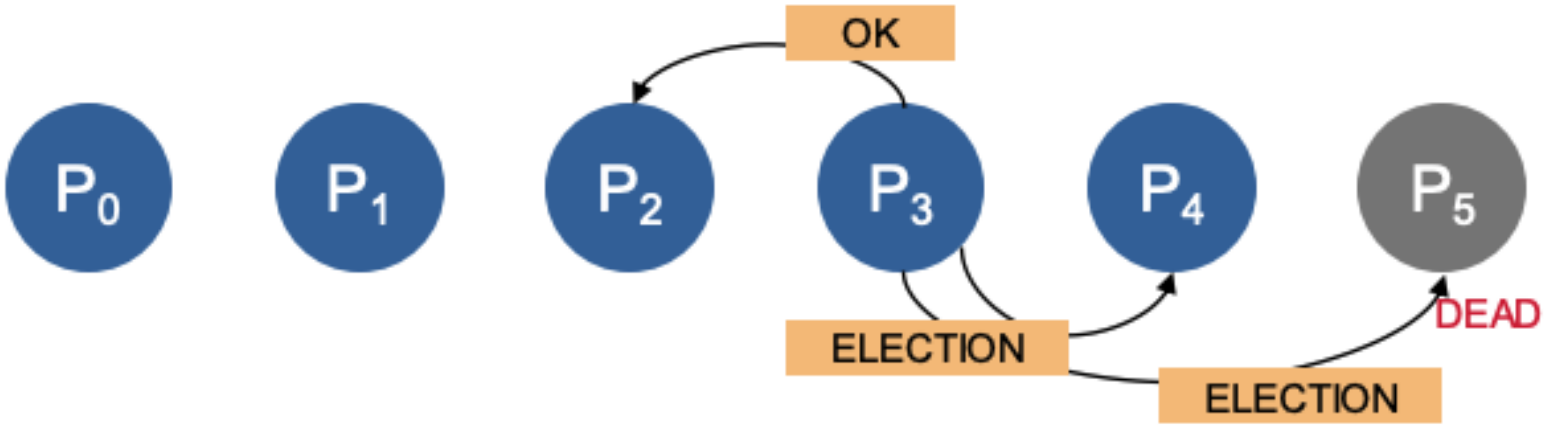
BULLY ALGORITHM



P_2 starts an election

Contacts all higher-numbered systems

BULLY ALGORITHM



Everyone who receives an ***election*** message responds

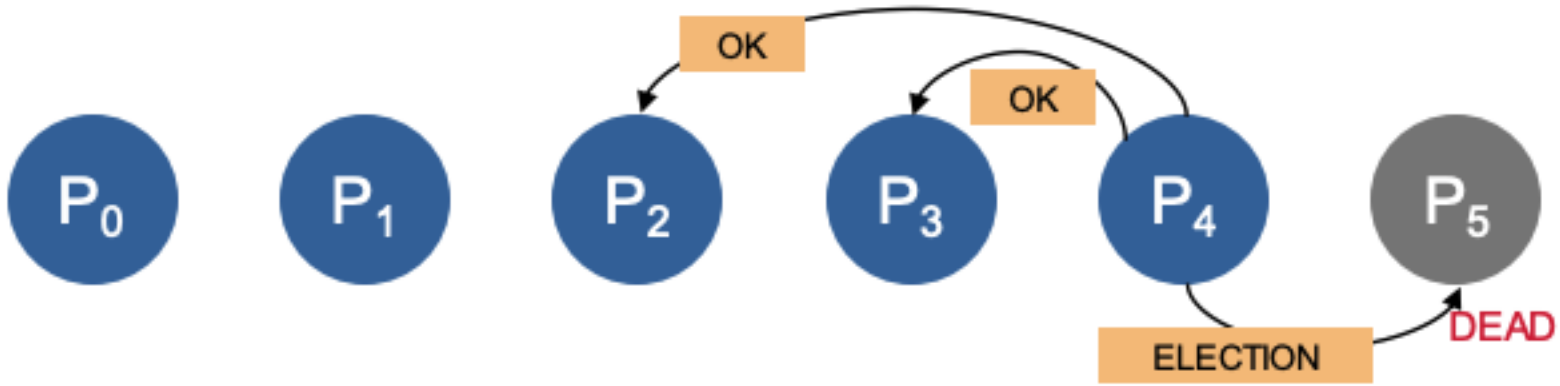
… and holds their own election, contacting higher # processes

Example: P_3 receives the message from P_2

Responds to P_2

Sends ***election*** messages to P_4 and P_5

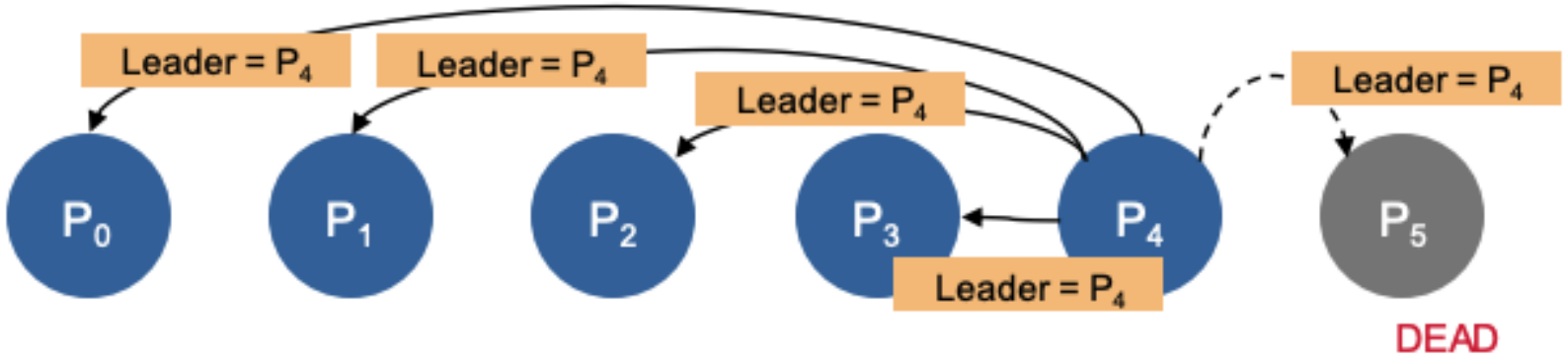
BULLY ALGORITHM



P_4 responds to P_3 and P_2's messages

… and holds an election

BULLY ALGORITHM



Nobody responds to P_4

After a timeout, P_4 declares itself the leader

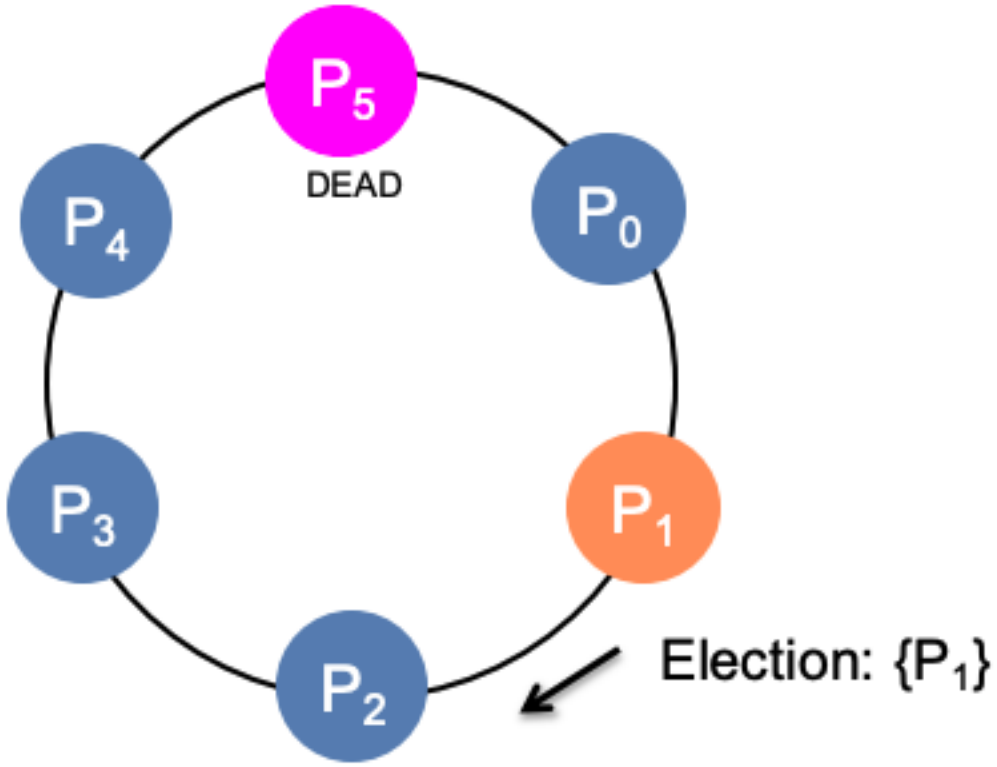
RING ELECTION ALGORITHM

Ring Election Algorithm

- GOAL: Select the process with the largest ID as a leader
- Initiate the election by **sending** an "`election`" message to its neighbor with the next highest priority.
- Upon receiving an election message, compare the priority value in the message with its own.
  - If priority is **higher** than its own, it forwards the message to its neighbor.
  - If priority is **lower or equal**, it discards the message.
- The election message continues around the ring until it reaches the highest priority process.
- The new leader broadcasts a "`leader`" message to inform all other processes of its election.

RING ELECTION ALGORITHM

Ring Election Algorithm



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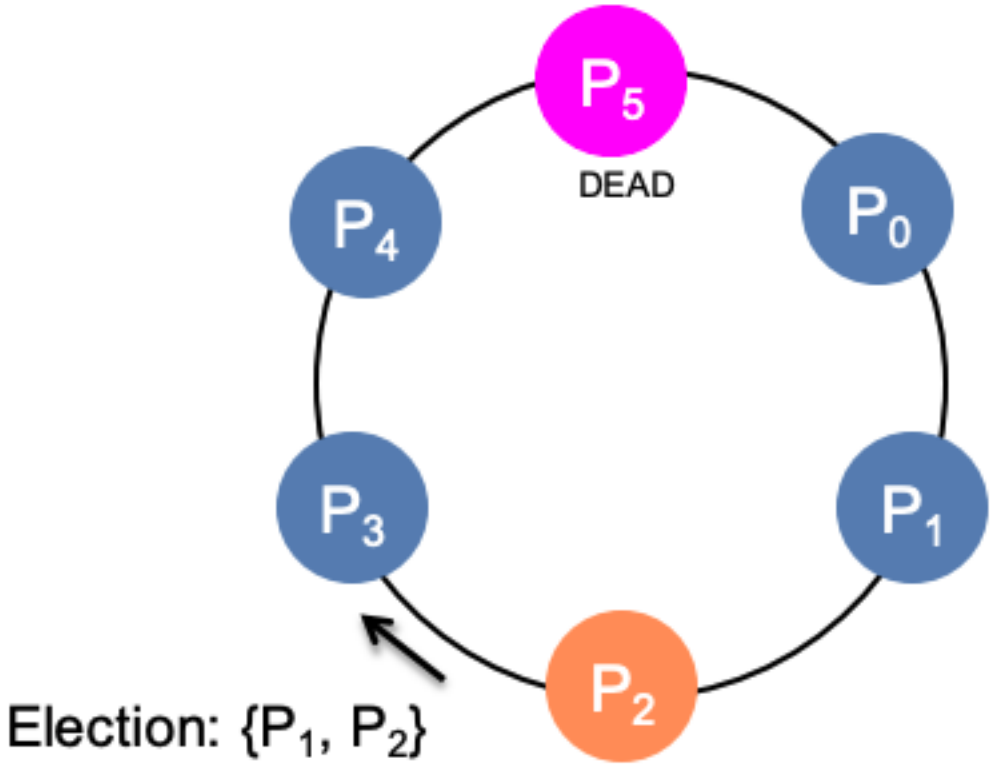

RING ELECTION ALGORITHM

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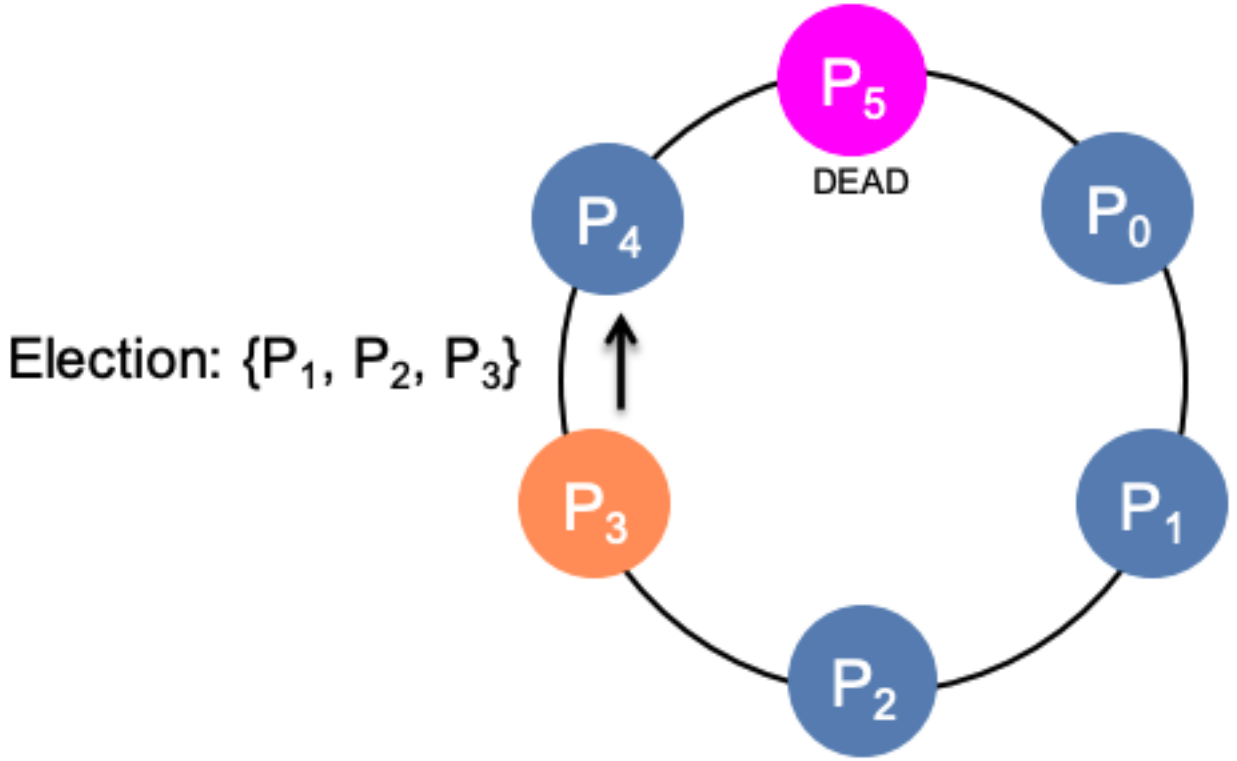
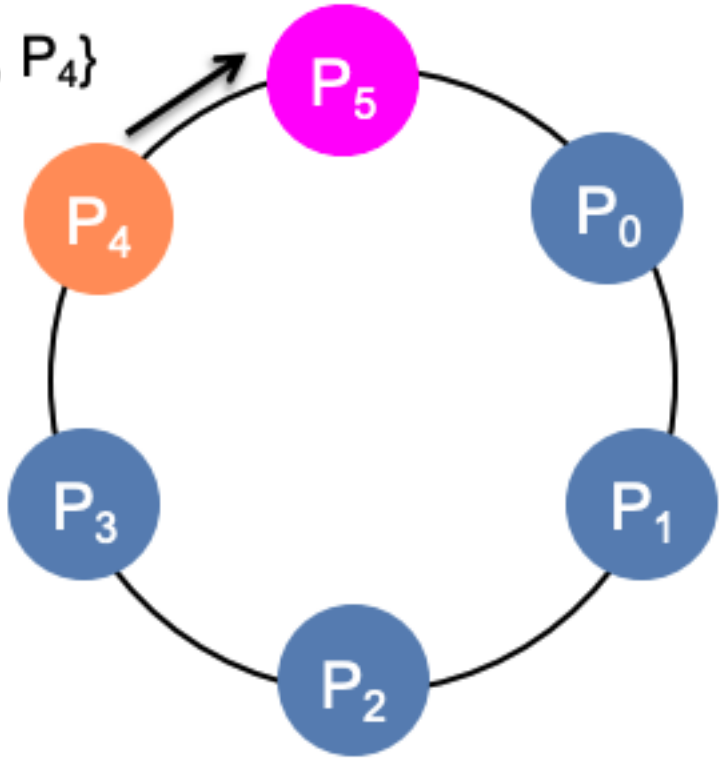


RING ELECTION ALGORITHM

Ring Election Algorithm

Election: {P_1, P_2, P_3, P_4}

Fails: P_5 is dead

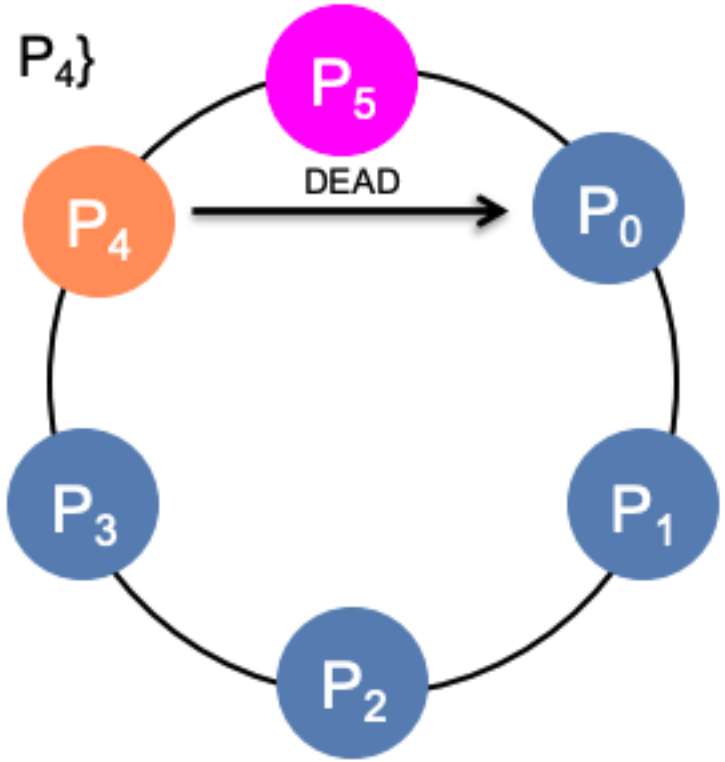


RING ELECTION ALGORITHM

Ring Election Algorithm

Election: {P_1, P_2, P_3, P_4}

Skip to P_0



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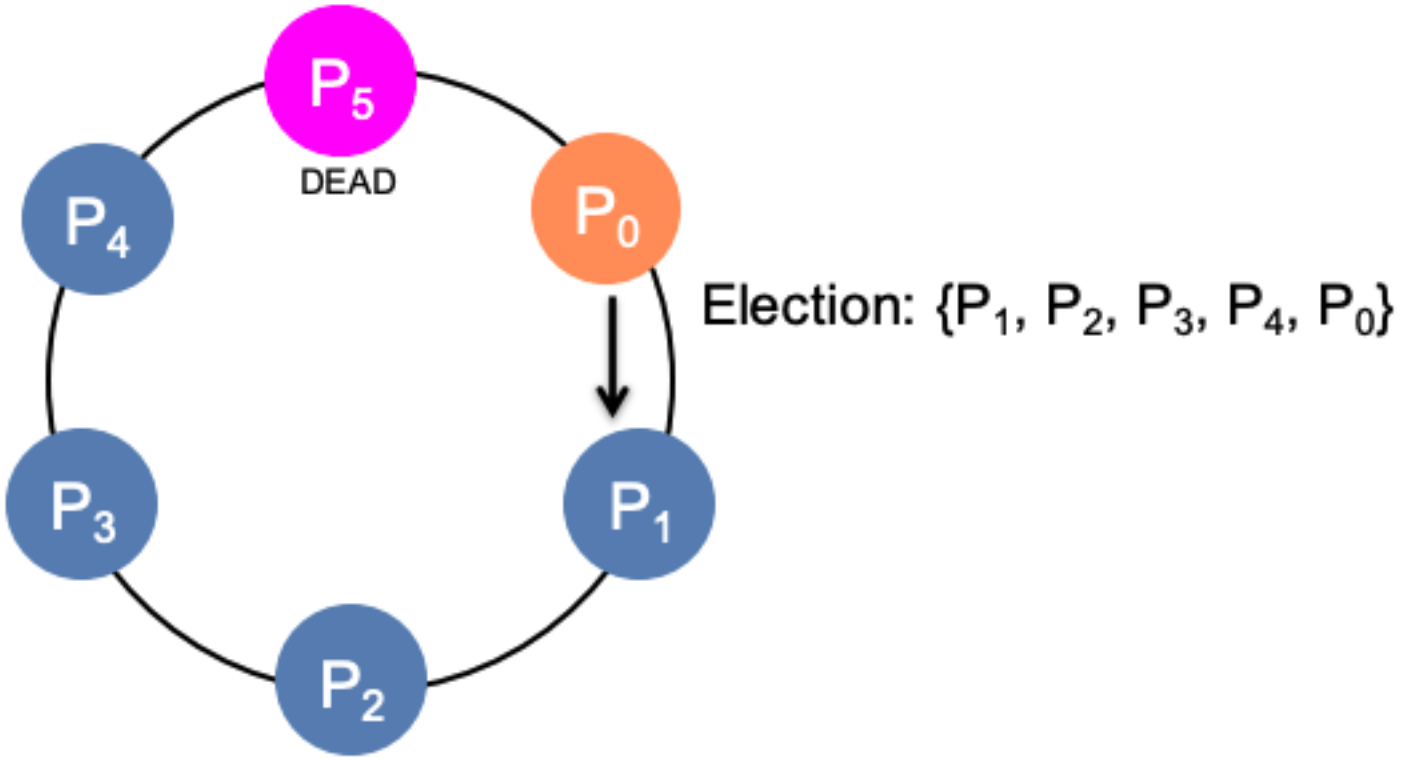
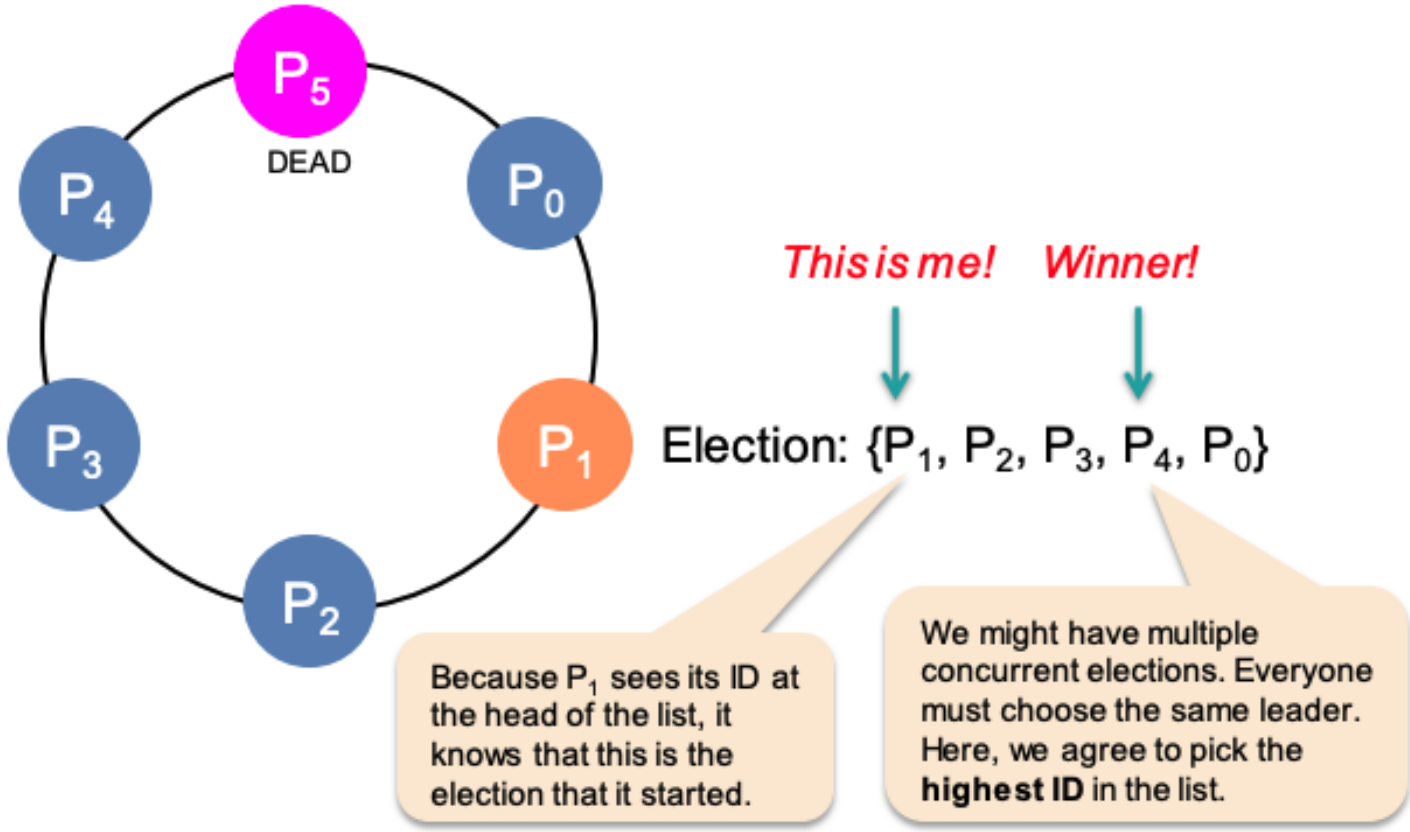


RING ELECTION ALGORITHM

Ring Election Algorithm

P_2 receives the election message that it initiated

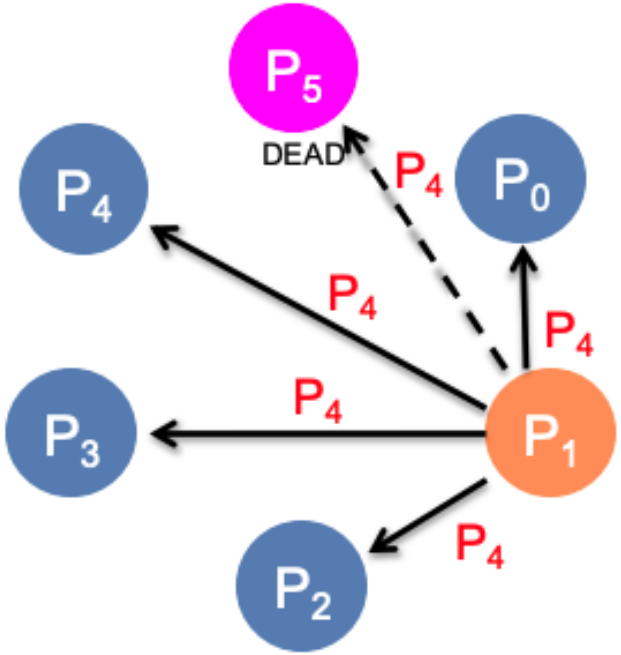
P_2 now picks a leader (e.g., highest ID)



RING ELECTION ALGORITHM

Ring Election Algorithm

P_1 announces that P_4 is the new leader to the group



Many other election algorithms that target other topologies: mesh, torus, hypercube, trees, …

COMPARISON

Bully

Pros:

- **Fast in small systems** – Elects a leader quickly if the initiator has the highest ID.
- **Guaranteed to elect the highest-ID process** as the leader.
- Works **even if multiple processes initiate election** at the same time.

Cons:

- **High message overhead** in large systems – Worst case: $O(n^2)$ messages.
- **Single point of restart** – Only works if higher-ID processes respond correctly.
- More sensitive to **crashes during election**.
- Assumes **synchronous communication** for timeout detection.

Ring Election

Pros:

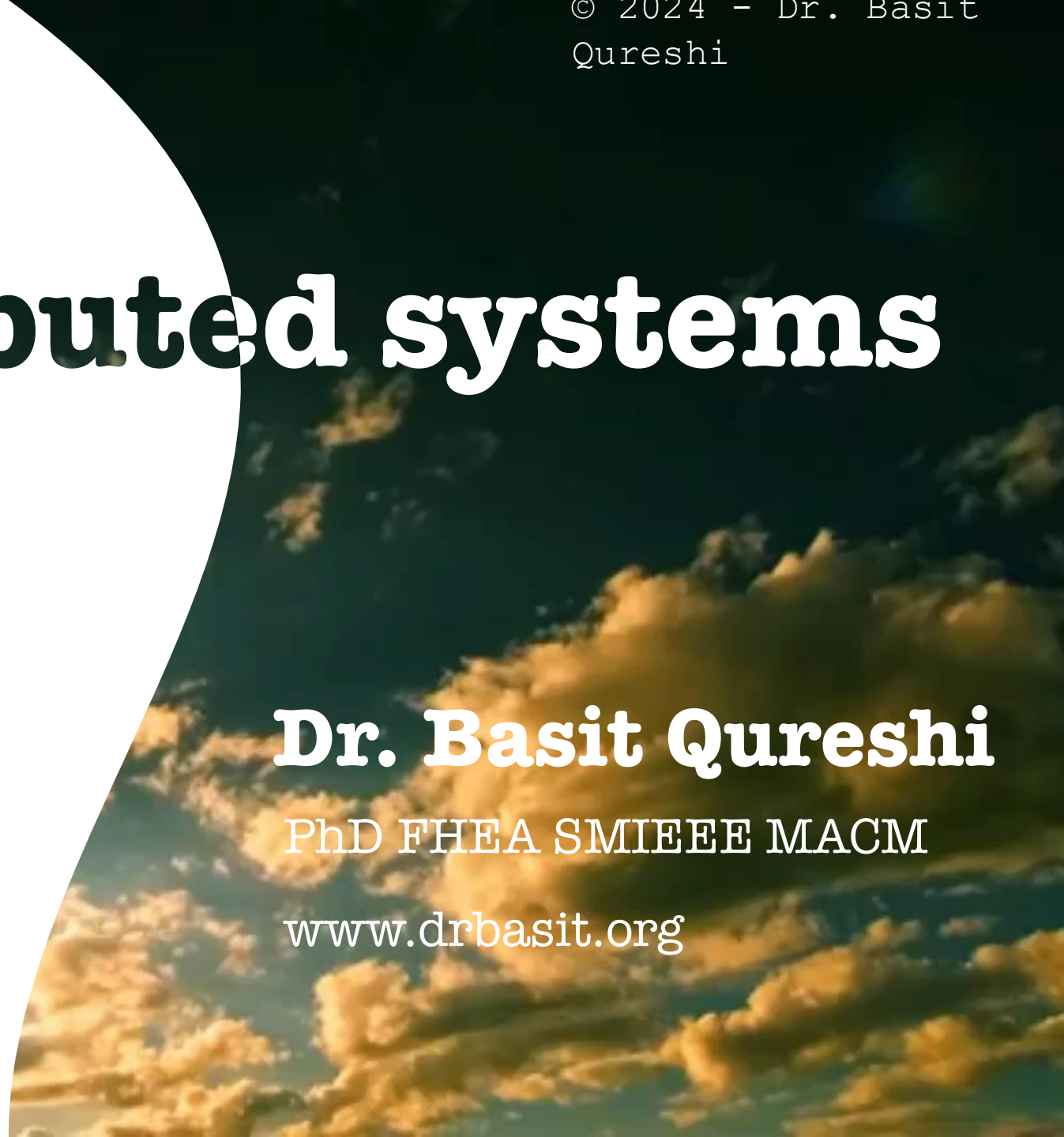
- **Lower message complexity** – Around O(n) messages.
- **Simple and easy to implement** in a ring-structured system.
- Works well in **synchronous and asynchronous systems**.
- No need for global knowledge (like all process IDs).

Cons:

- **Slower in large rings**, since messages travel one-by-one around the ring.
- Vulnerable to **ring breakage** (e.g., if a process in the ring fails and breaks the path).
- Doesn't always elect the highest-ID process unless designed to do so.

CS435 Distributed systems

ADDRESSING NETWORK PARTITIONS IN CONTENTION- BASED (QUORUM) / LEADER ELECTION ALGORITHMS



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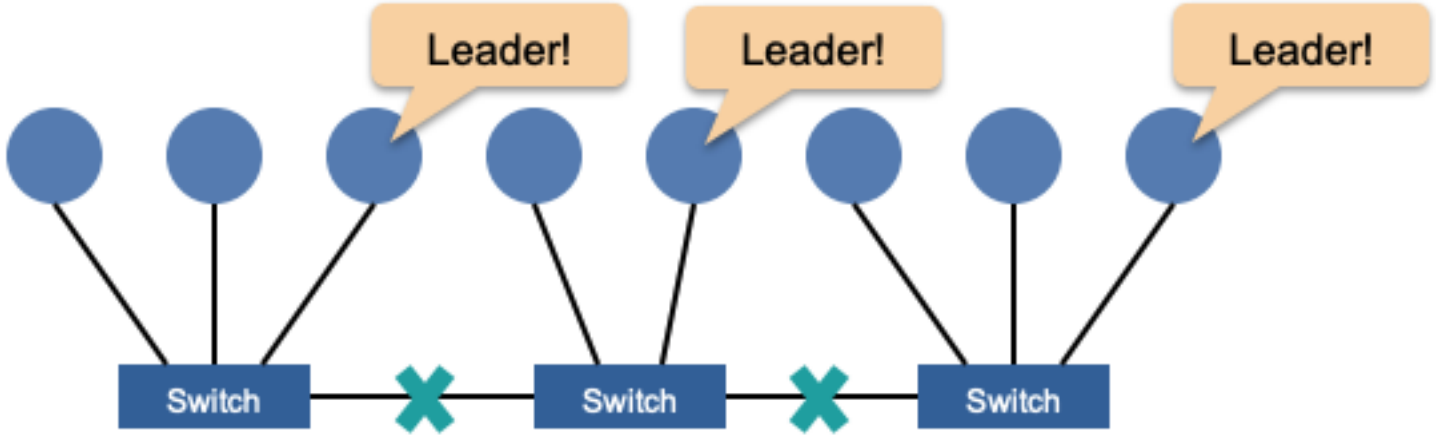
ELECTIONS & NETWORK PARTITIONS

- Network partitions (segmentation)
  - Multiple nodes may decide they're the leader
  - Multiple groups, each with a leader & diverging data among them → **split brain**

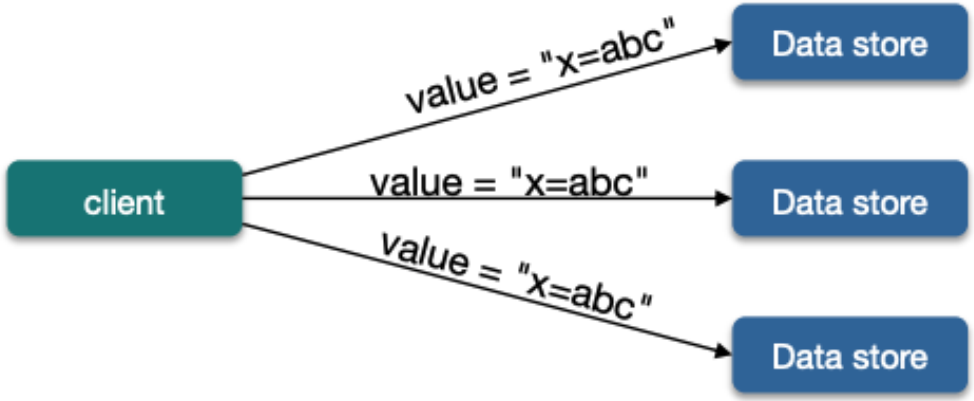


- Insist on a **majority** → if no majority, the system will not function.
- **Quorum** = minimum # of participants required for a system to function.

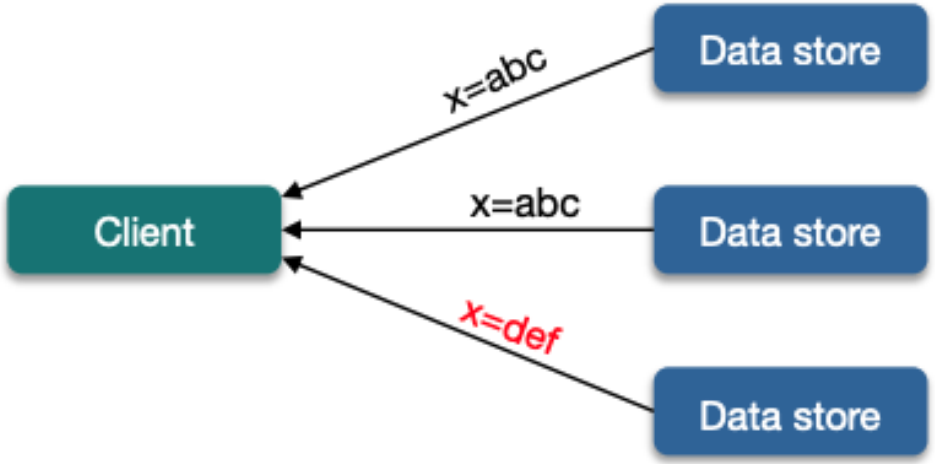
CONSENSUS

Why consensus is needed?

- Single Client



Easy if only one client sends request at a time



We rely on a **quorum** (majority) for reads & writes

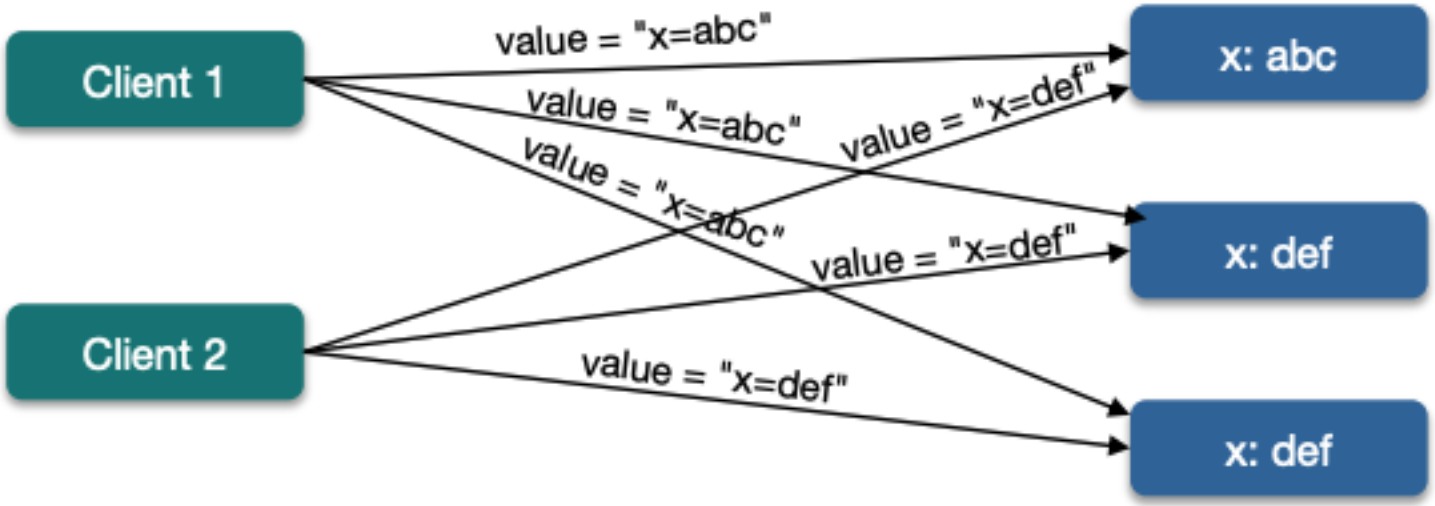
If we have to write to a majority of servers for the write to succeed **and** we have to read from a majority of servers for the read to succeed **then** we can be certain that at least one server has the latest version of data.

No quorum = failed read!

CONSENSUS

Why consensus is needed?

- Multiple clients

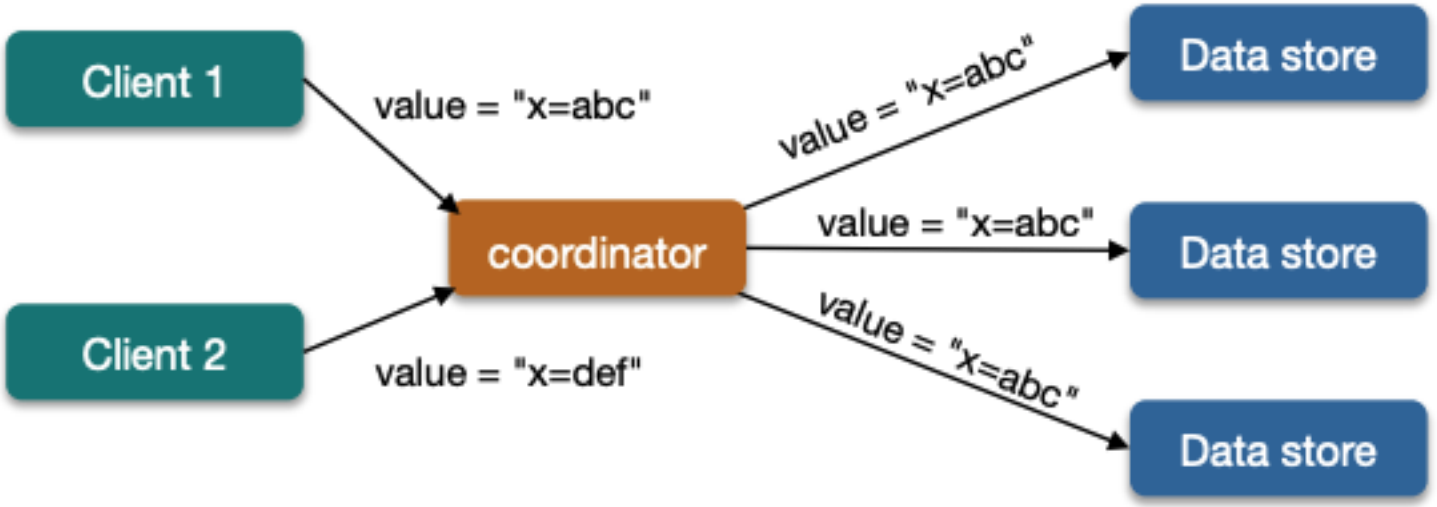


We risk inconsistent updates

CONSENSUS

Why consensus is needed?

- Multiple clients -> use Coordinator?



Coordinator (or sequence # generator) processes requests one at a time

But now we have a single point of failure!

CONSENSUS

Why consensus is needed?

- **Mutual Exclusion**
  - Choose which process can access a resource from all who want it
  - Agree on who gets a resource or who becomes a coordinator
- **Election algorithms**
  - Choose one process from the set of willing processes
- Uses:
  - **Dist Databases:** Google Spanner, Amazon DynamoDB, CockroachDB, TiDB.
  - **Blockchain Technology**: enable nodes to agree on the validity and ordering of transactions.
  - **Cryptocurrencies**: Bitcoin, Ethereum etc, rely on consensus algorithms to validate and confirm transactions, preventing double-spending and ensuring the integrity of the currency.
  - **Internet of Things (IoT)**: reach agreement on the state of sensor data
  - **Dist File Systems**: Google File System (GFS), Amazon S3 and Hadoop File System
  - **Container orchestration**: Kubernetes, Docker swarm.

CONSENSUS

Why consensus is needed?

- Without consensus
  - Processors may fail (some may need stable storage)
  - Messages may be lost, out of order, or duplicated
  - If delivered, messages are not corrupted

Quorum: majority (>50%) agreement is the key part:

It avoids split-brain: you cannot have two majorities doing their own thing

It ensures continuity: if members die and others come up, **there will be one member in common** with the old group that still holds the information.

CONSENSUS

Consensus GOAL

- **AGREE** on one result among a group of participants

Consensus Requirements

- **Validity**: Only proposed values may be selected (you can't make stuff up)
- **Uniform agreement**: No two nodes may select different values (you agree with everyone else)
- **Integrity**: A node can select only a single value (you cannot change your mind)
- **Termination**: Every node will eventually decide on a value (you come to a decision)

CONSENSUS

The Fischer Lynch Patterson (FLP) Impossibility

Consensus protocols with asynchronous communication & faulty processes, "**Every protocol for this problem has the possibility of nontermination, even with only one faulty process**"

- *Impossibility of distributed consensus with one faulty process by Fischer, Lynch and Patterson*

What does it mean?

- We cannot achieve consensus in bounded time, but we can, with partially synchronous networks
  - Partially synchronous = network with a **bounded time** for message delivery but we don't know ahead of time what that bound is
- We can either wait long enough for messaging traffic so the protocol can complete or else terminate

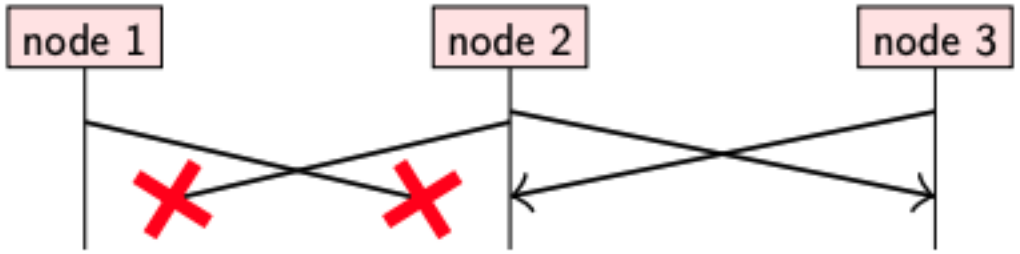
CONSENSUS

Common Consensus Algorithms

- Guarantee a leaders term
- In a partially synchronous system, a timeout-based failure detector may be inaccurate: it may suspect a node has, having crashed, when in fact the node is functioning fine, for example due to a spike in network latency

Cannot prevent having multiple leaders from different terms.

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 $t + 1$.

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

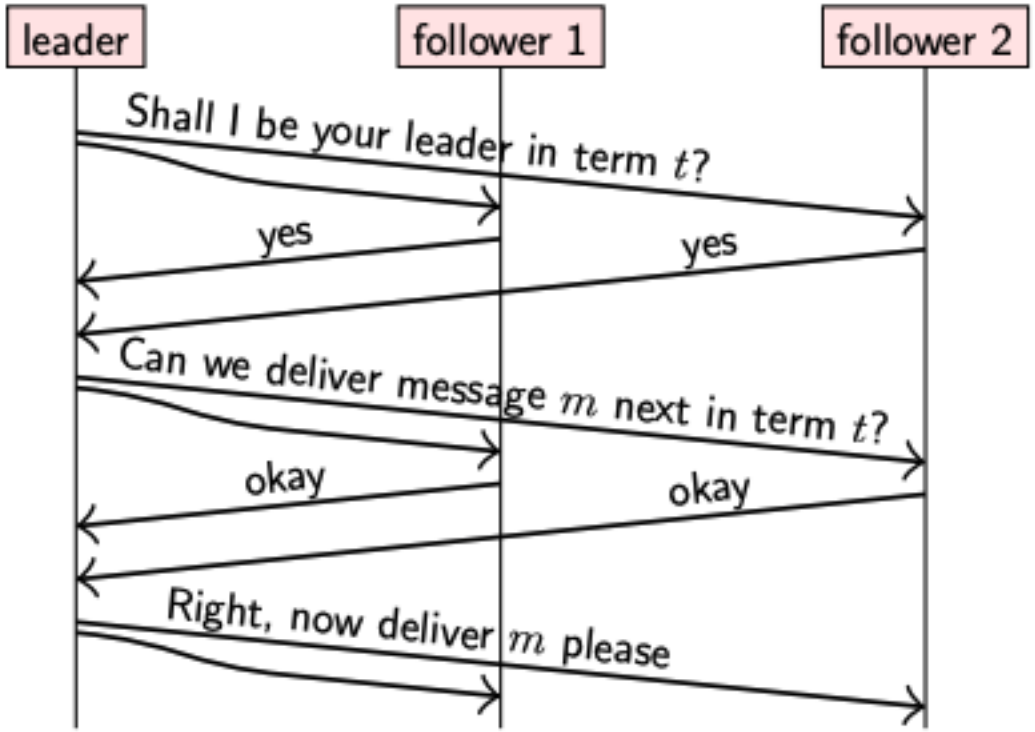
Now we have two leaders !??

CONSENSUS

Common Consensus Algorithms

- Solution?
- Even after a node has been elected leader, it must act carefully

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



CONSENSUS

- In decentralized systems, with no central authority, achieving consensus is crucial for ensuring the integrity and consistency of the shared data

1. If a node hasn't received a message for some time, assume it is **DEAD**
2. When nodes suspect the current leader has failed: **HOLD ELECTION**
3. One or more nodes becomes a **CANDIDATE**
4. Other nodes **VOTE** on whether they accept the candidate as their new leader.
5. Election, the new **LEADER**:
    - If a **quorum** of nodes vote in favor of the candidate, it becomes the new leader.
    - If a majority quorum is used, this vote can succeed as long as a majority of nodes (2 out of 3, or 3 out of 5, etc.) are working and able to communicate.

- Challenge: **How do we get unanimous agreement on a given value**?

CONSENSUS

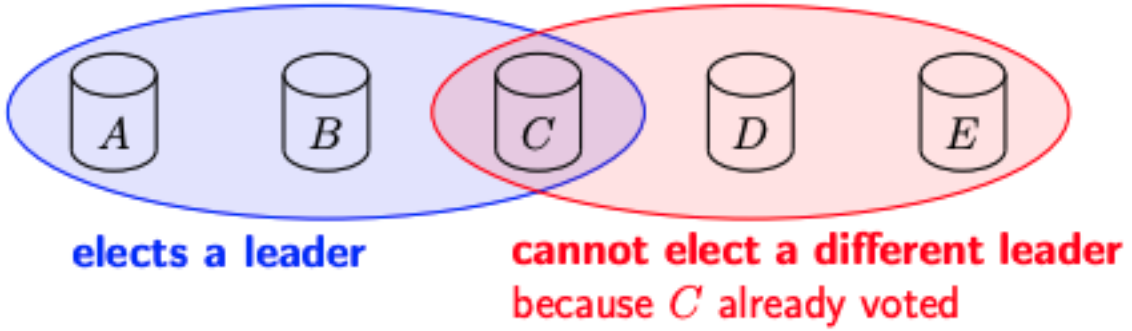
Common Consensus Algorithms

- **Paxos**: Lamport [*ACM Transactions on Computer Systems* - 1998]
- **Multi-Paxos**: Lamport [2000]
- **Fast-Paxos**: Lamport [2005]
- **Raft**: Diego Ongaro and John Ousterhout [*USENIX Annual Technical Conference* (ATC) 2014]
- Use
  - **Google**: Google's *Chubby* lock service, which manages distributed locks and data, is built on Paxos.
  - **Amazon Web Services (AWS)**: AWS uses Paxos within *DynamoDB* for distributed consensus and coordination of replica data storage.
  - **Microsoft**: Paxos is integral to Microsoft's *Cosmos DB*.
  - **Yahoo!**: *Zookeeper, now a Apache project*.
  - **Docker**: Docker's *Swarm* mode uses Raft to manage the state and roles of nodes in a Docker cluster
  - **Kubernetes**: The *Etcd* data store uses Raft to maintain cluster state, including pod configurations, namespaces, and other metadata.

CONSENSUS

Common Consensus Algorithms

- Multi-Paxos, Raft, etc. use a leader to sequence messages.
  - Use a failure detector (timeout) to determine suspected crash or unavailability of leader.
  - On suspected leader crash, elect a new one.
  - Prevent two leaders at the same time (“split-brain”)
- Ensure ≤ 1 leader per term:
  - Term is incremented every time a leader election is started
  - A node can only vote once per term
  - Require a quorum of nodes to elect a leader in a term



CONSENSUS

Common Consensus Algorithms

- Paxos by Lamport (1989)
  - Robust but complex to understand
- Multi-Paxos by Lamport (2001)
  - Extended to work with multiple instances
- Fast-Paxos by Lamport (2005)
  - An optimization of the original Paxos algorithm, aimed at reducing latency and improving efficiency
- Raft (2014)
  - Specifically designed with understandability and ease of implementation in mind
- Paxos vs Raft (2020)
  - Heidi Howard and Richard Mortier

Heidi Howard, Richard Mortier, "Paxos vs Raft: have we reached consensus on distributed consensus?" Proceedings of the 7th Workshop on Principles and Practice of Consistency for Distributed Data, April 2020. https://doi.org/10.1145/3380787.3393681

CS435 Distributed systems

Diego Ongaro and John Ousterhout
Stanford University

RAFT: A CONSENSUS ALGORITHM FOR REPLICATED LOGS

RAFT slides based on those from Diego Ongaro and John Ousterhout.

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Raft Overview

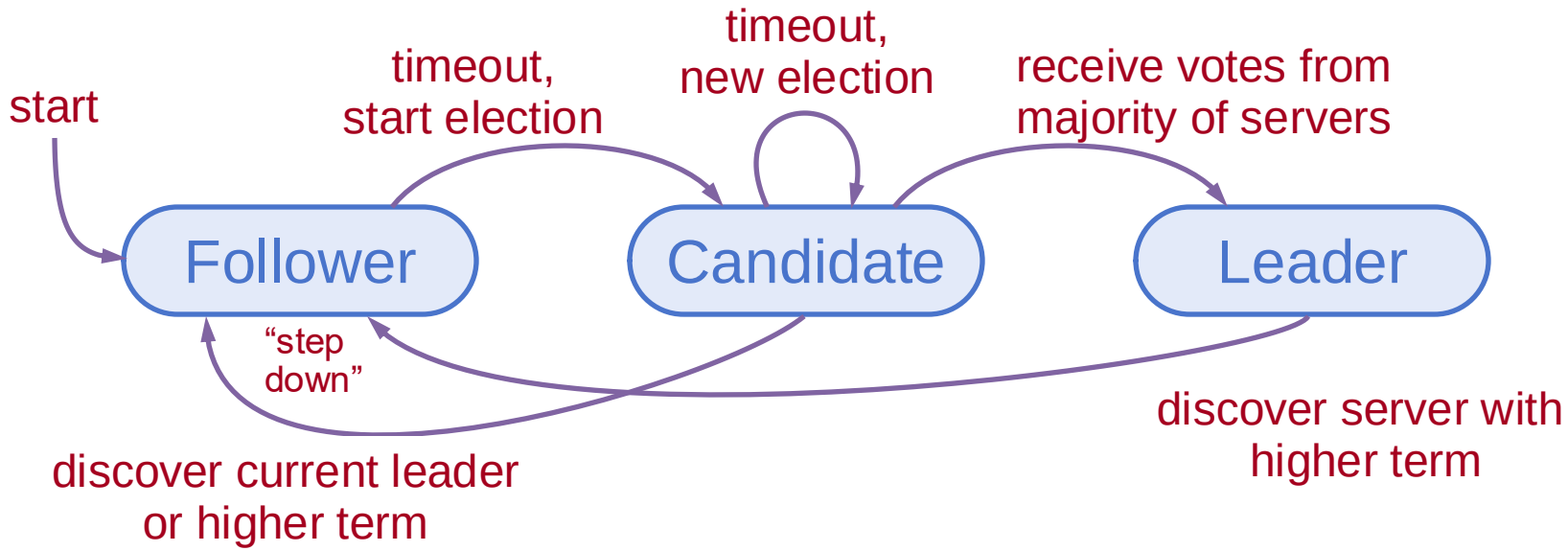
1. Leader election
2. Normal operation (basic log replication)
3. Safety and consistency after leader changes
4. Neutralizing old leaders
5. Client interactions
6. Reconfiguration

Server States

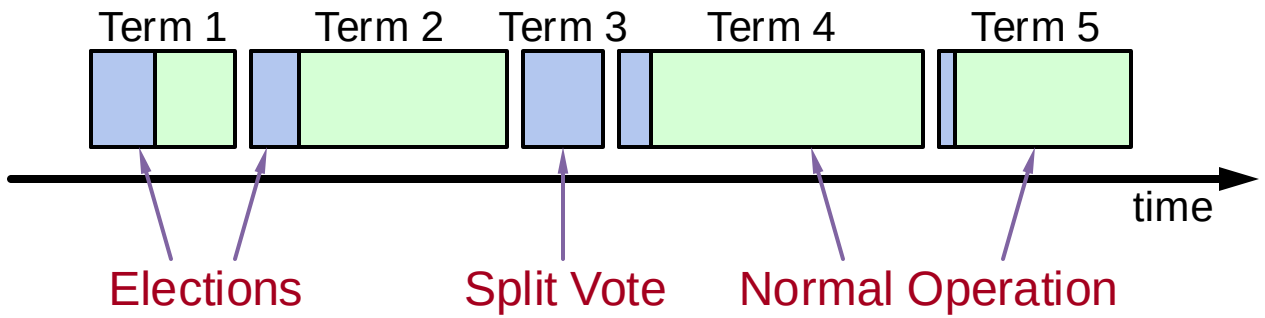
- At any given time, each server is either:
  - Leader: handles all client interactions, log replication
  - Follower: completely passive
  - Candidate: used to elect a new leader
- Normal operation: 1 leader, N-1 followers

Liveness Validation

- Servers start as followers
- Leaders send heartbeats (empty **AppendEntries** RPCs) to maintain authority
- If electionTimeout elapses with no RPCs (100-500ms), follower assumes leader has crashed and starts new election (**RequestVotes** RPC)



Terms (aka epochs)



- Time divided into terms
  - Election (either failed or resulted in 1 leader)
  - Normal operation under a single leader
- Each server maintains current term value
- Key role of terms: identify obsolete information

Elections

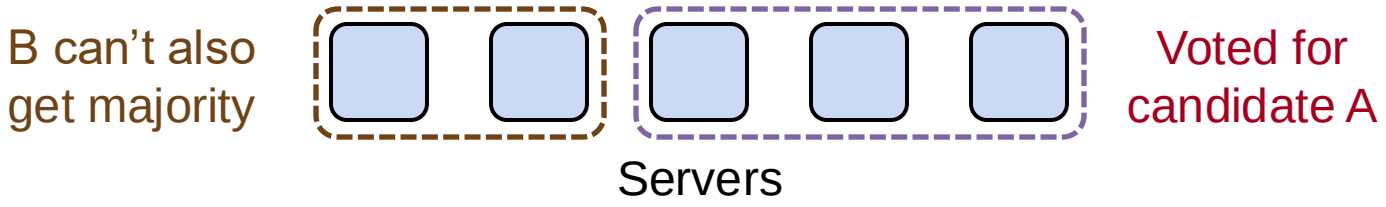
- **Start election:**
  - Increment current term, change to candidate state, vote for self

- **Send RequestVote to all other servers, retry until either:**

  1. Receive votes from majority of servers:
     - Become leader
     - Send **AppendEntries** heartbeats 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

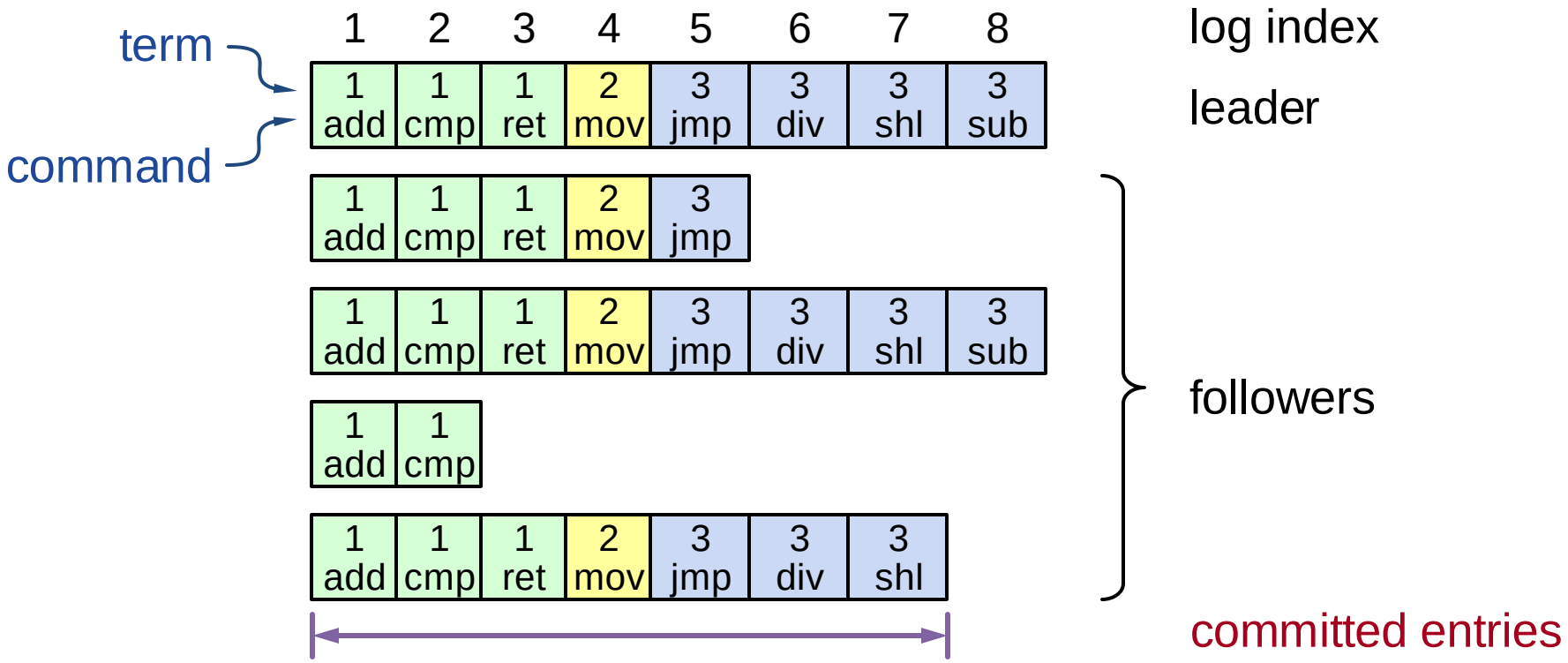
Elections

- **Safety: allow at most one winner per term**
  - Each server votes only once per term (persists on disk)
  - Two different candidates can't get majorities in same term



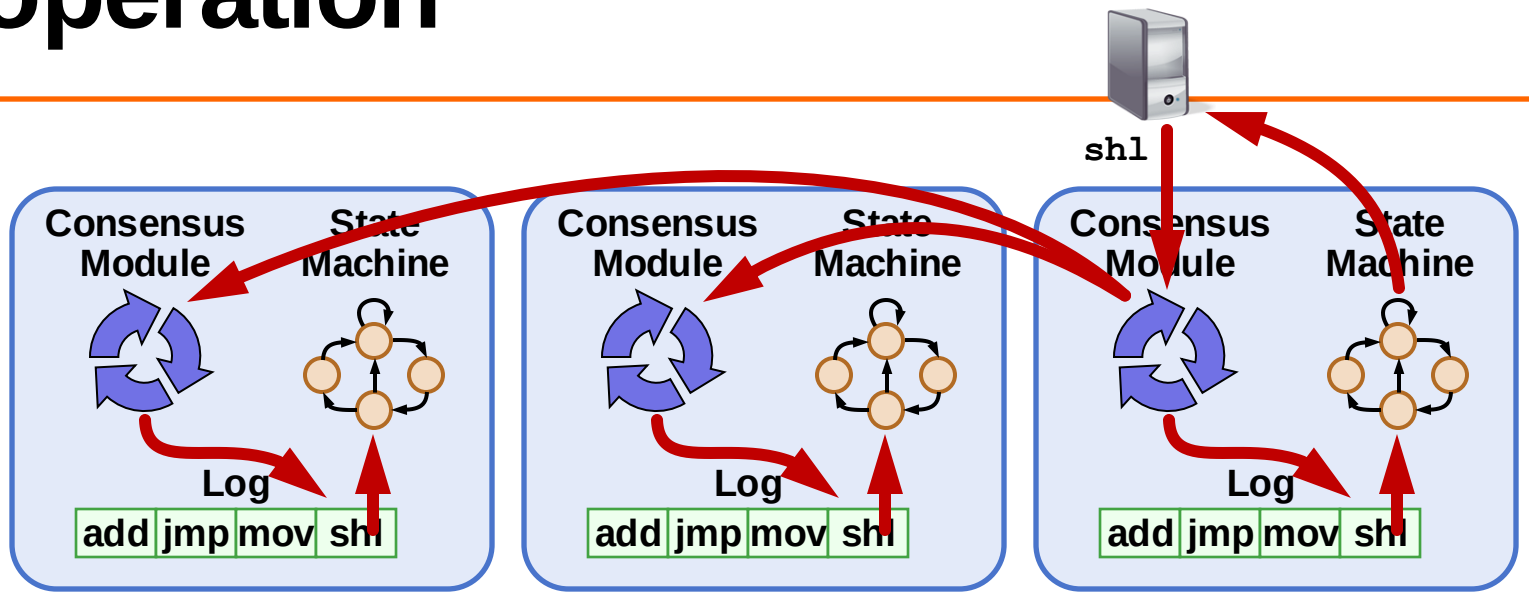
- **Liveness: some candidate must eventually win**
  - Each choose election timeouts randomly in [T, 2T]
  - One usually initiates and wins election before others start
  - Works well if T >> network RTT

Log Structure



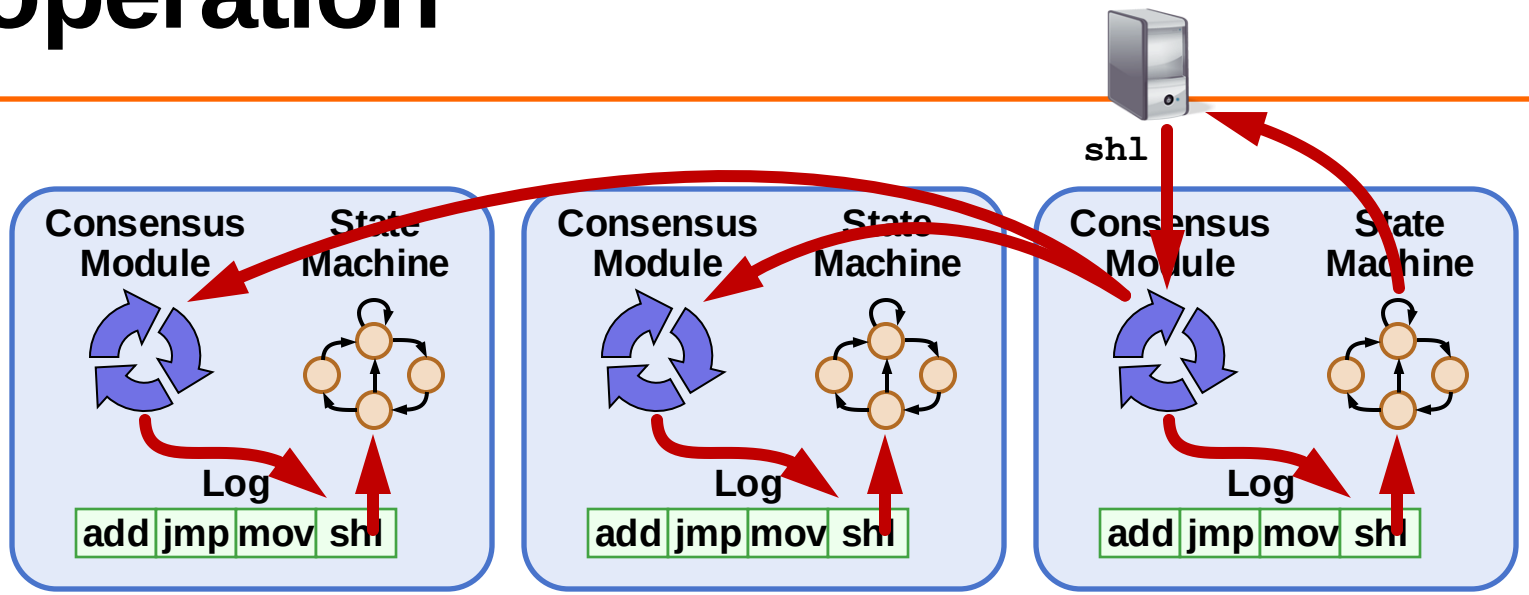
- Log entry = < index, term, command >
- Log stored on stable storage (disk); survives crashes
- Entry committed if known to be stored on majority of servers
  - Durable / stable, will eventually be executed by state machines

Normal operation



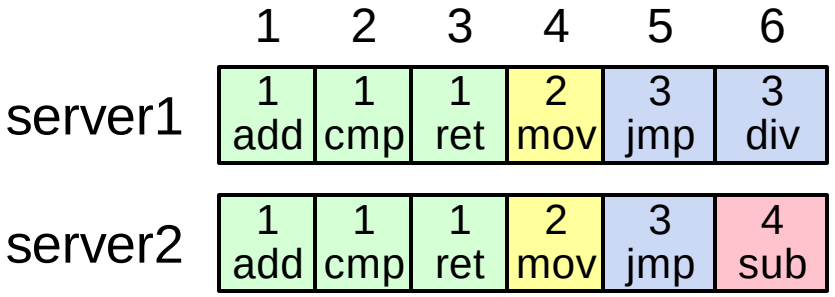
- Client sends command to leader
- Leader appends command to its log
- Leader sends **AppendEntries** RPCs to followers
- Once new entry committed:
  - Leader passes command to its state machine, sends result to client
  - Leader piggybacks commitment to followers in later **AppendEntries**
  - Followers pass committed commands to their state machines

Normal operation



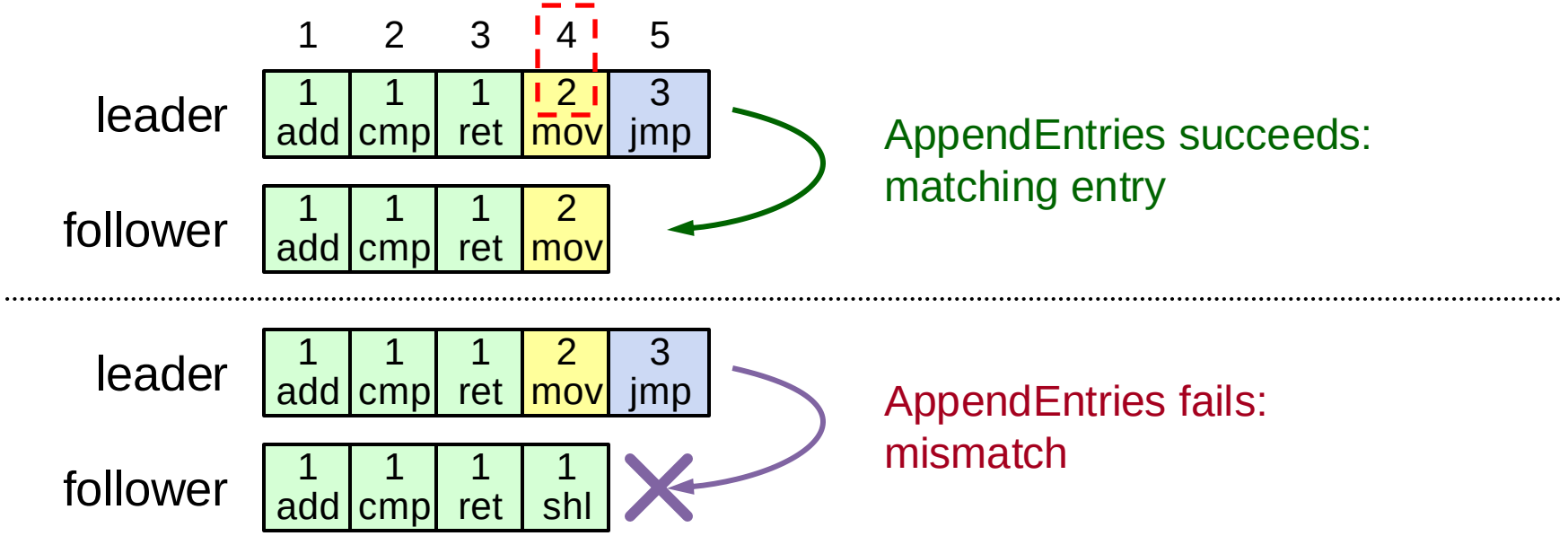
- Crashed / slow followers?
  - Leader retries RPCs until they succeed
- Performance is optimal in common case:
  - One successful RPC to any majority of servers

Log Operation: Highly Coherent



- If log entries on different server have same index and term:
  - Store the same command
  - Logs are identical in all preceding entries
- If given entry is committed, all preceding also committed

Log Operation: Consistency Check

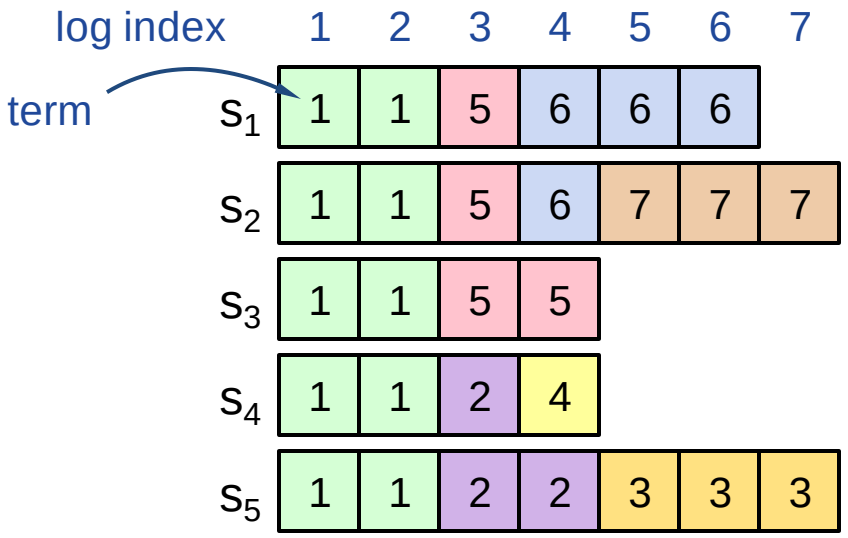


- AppendEntries has <index,term> of entry preceding new ones
- Follower must contain matching entry; otherwise it rejects
- Implements an induction step, ensures coherency

Leader Changes

- New leader's log is truth, no special steps, start normal operation
  - Will eventually make follower's logs identical to leader's
  - Old leader may have left entries partially replicated

- Multiple crashes can leave many extraneous log entries



Safety Requirement

Once log entry applied to a state machine, no other state machine must apply a different value for that log entry

- Raft safety property: If leader has decided log entry is committed, entry will be present in logs of all future leaders

- Why does this guarantee higher-level goal?

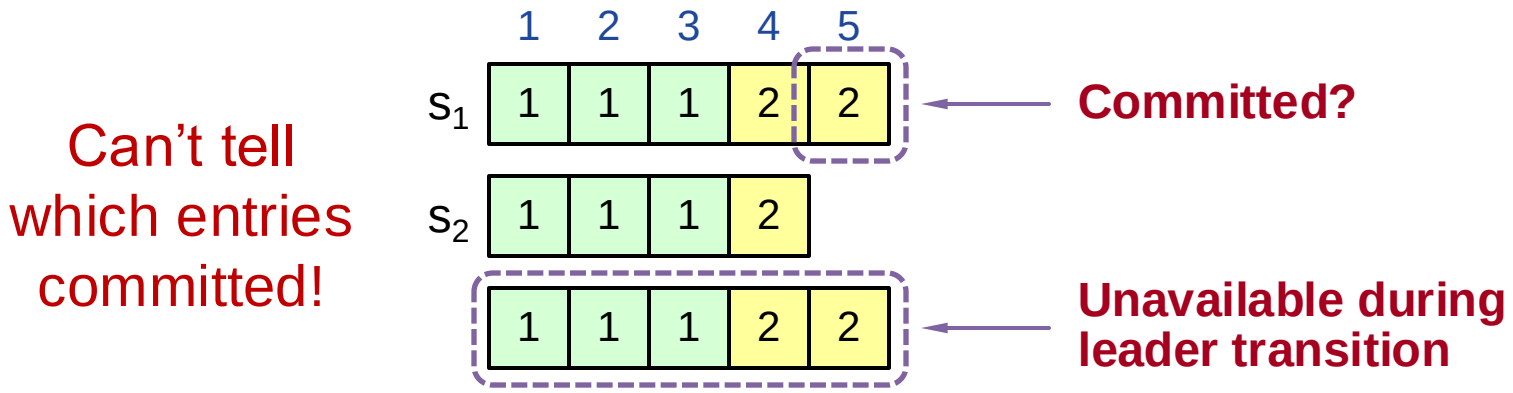
1. Leaders never overwrite entries in their logs
2. Only entries in leader's log can be committed
3. Entries must be committed before applying to state machine

Committed → Present in future leaders' logs

Restrictions on commitment

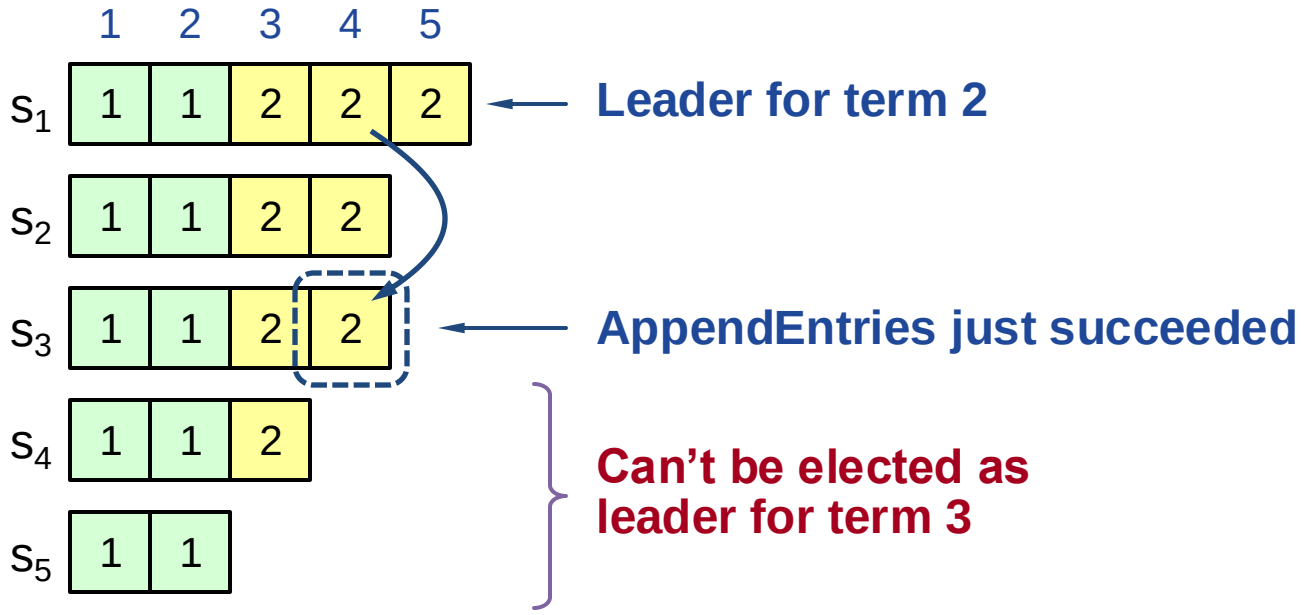
Restrictions on leader election

Picking the Best Leader



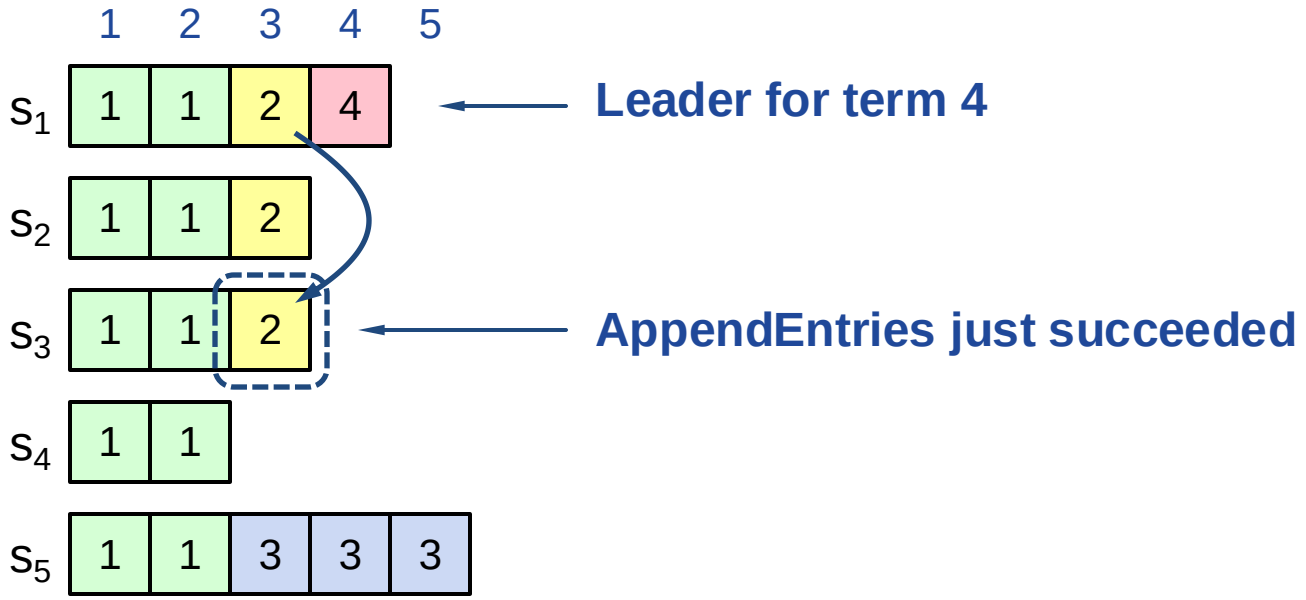
- Elect candidate most likely to contain all committed entries
  - In RequestVote, candidates incl. index + term of last log entry
  - Voter V denies vote if its log is "more complete":
    (newer term) or (entry in higher index of same term)
  - Leader will have "most complete" log among electing majority

Committing Entry from Current Term



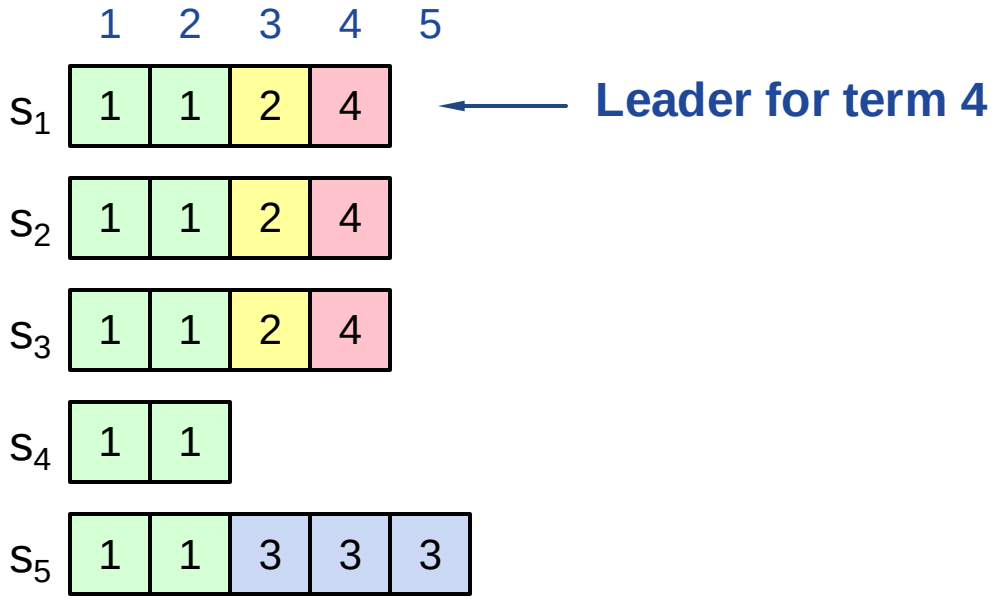
- **Case #1:** Leader decides entry in current term is committed
- Safe: leader for term 3 must contain entry 4

Committing Entry from Earlier Term



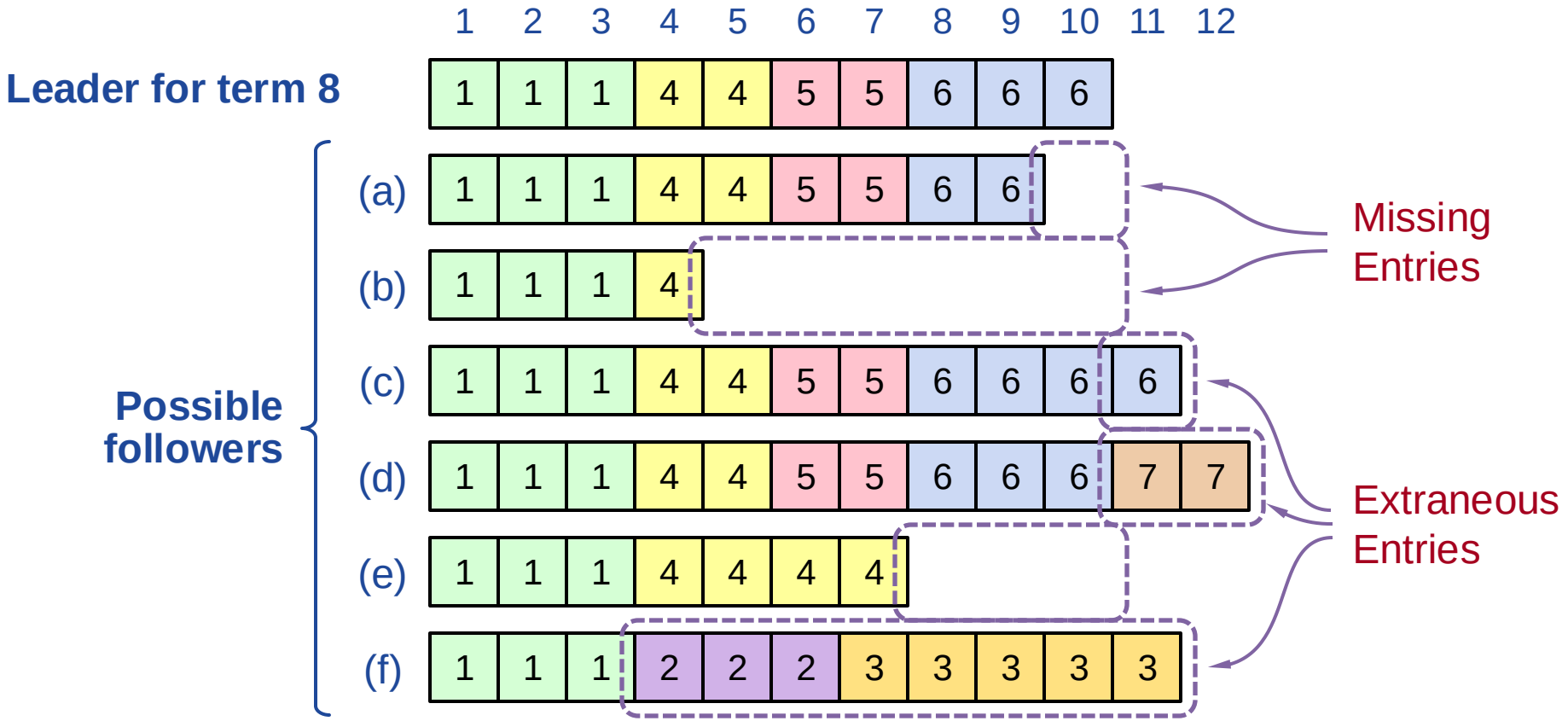
- **Case #2:** Leader trying to finish committing entry from earlier
- Entry 3 not safely committed:
  - s_5 can be elected as leader for term 5 (how?)
  - If elected, it will overwrite entry 3 on s_1, s_2, and s_3

New Commitment Rules



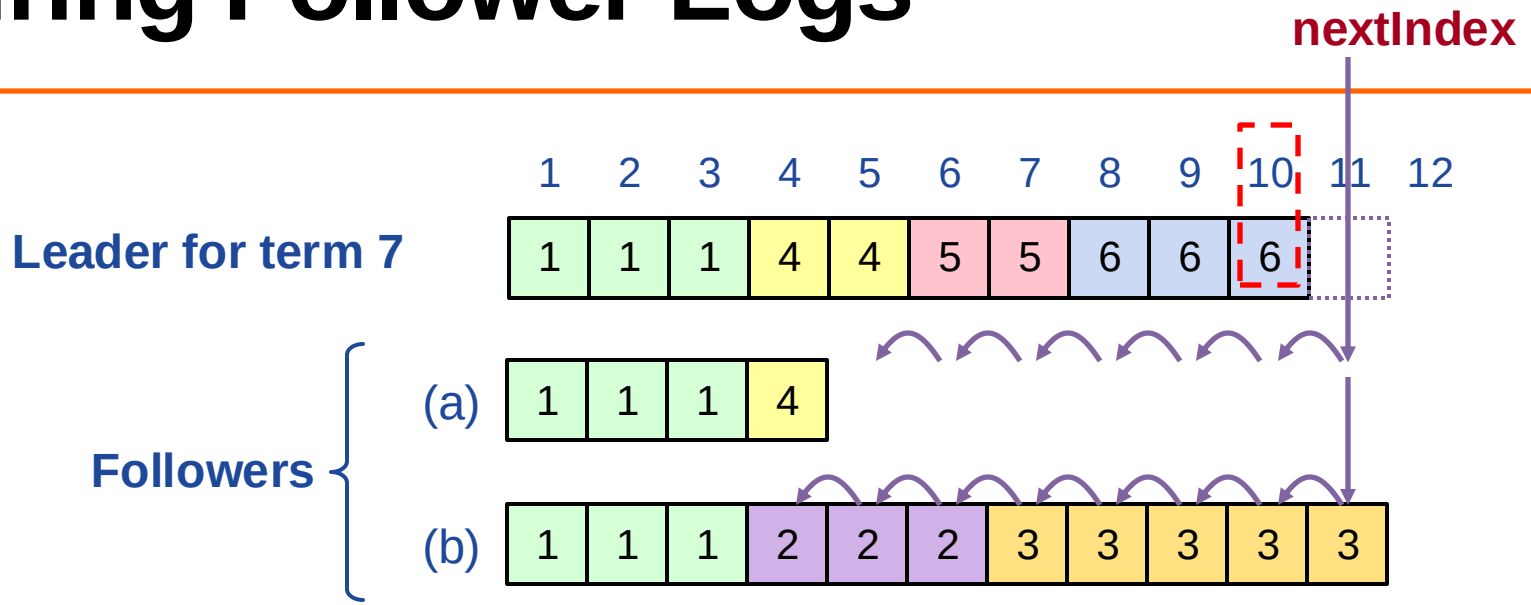
- **For leader to decide entry is committed:**
  1. Entry stored on a majority
  2. ≥ 1 new entry from leader's term also on majority
- Example; Once e4 committed, s_5 cannot be elected leader for term 5, and e3 and e4 both safe

Challenge: Log Inconsistencies



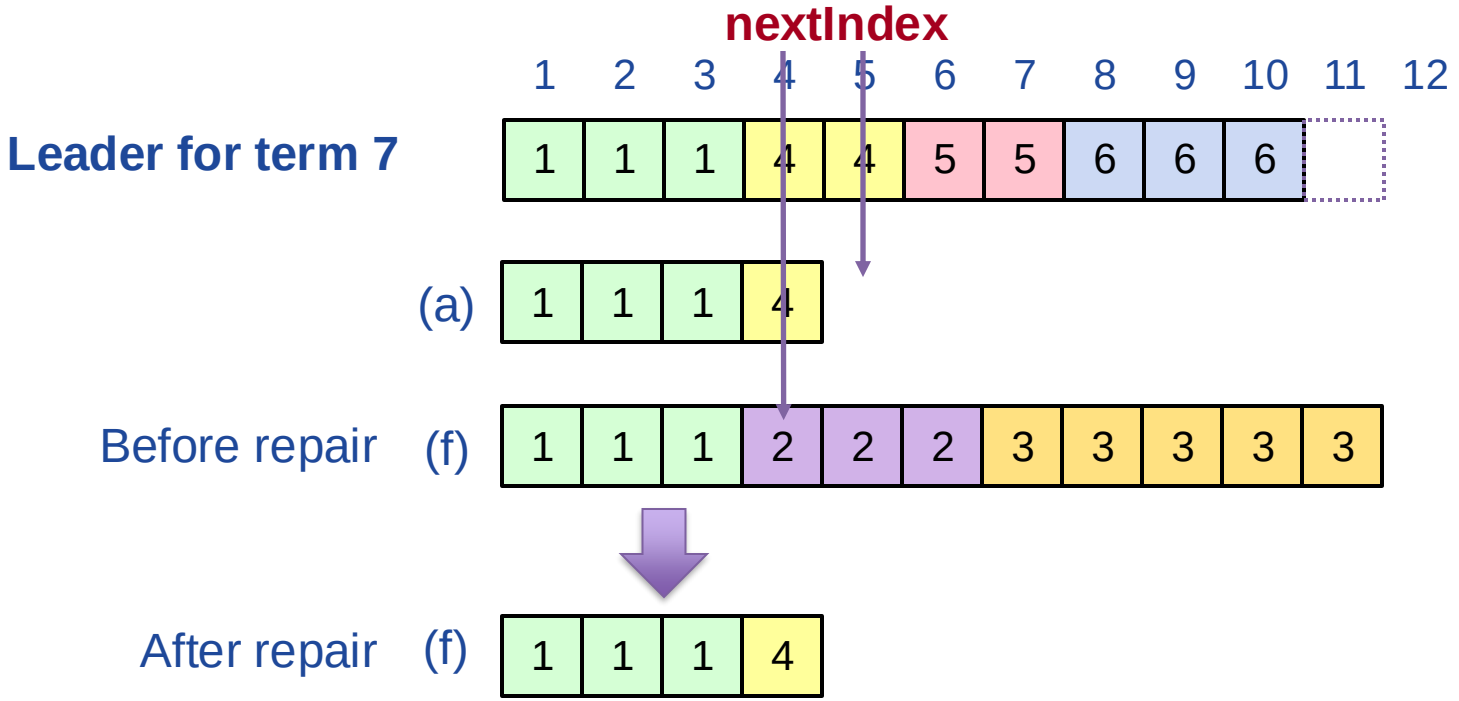
Leader changes can result in log inconsistencies

Repairing Follower Logs



- **New leader must make follower logs consistent with its own**
  - Delete extraneous entries
  - Fill in missing entries
- **Leader keeps nextIndex for each follower:**
  - Index of next log entry to send to that follower
  - Initialized to (1 + leader's last index)
- If AppendEntries consistency check fails, decrement nextIndex, try again

Repairing Follower Logs



Neutralizing Old Leaders

Leader temporarily disconnected

→ other servers elect new leader

→ old leader reconnected

→ old leader attempts to commit log entries

- **Terms used to detect stale leaders (and candidates)**
  - Every RPC contains term of sender
  - Sender's term < receiver:
    - Receiver: Rejects RPC (via ACK which sender processes…)
  - Receiver's term < sender:
    - Receiver reverts to follower, updates term, processes RPC
- **Election updates terms of majority of servers**
  - Deposed server cannot commit new log entries

Client Protocol

- **Send commands to leader**
  - If leader unknown, contact any server, which redirects client to leader
- **Leader only responds after command logged, committed, and executed by leader**
- **If request times out (e.g., leader crashes):**
  - Client reissues command to new leader (after possible redirect)
- **Ensure exactly-once semantics even with leader failures**
  - E.g., Leader can execute command then crash before responding
  - Client should embed unique ID in each command
  - This client ID included in log entry
  - Before accepting request, leader checks log for entry with same id

RAFT

- An excellent visual representation of RAFT
- https://thesecretlivesofdata.com/raft/