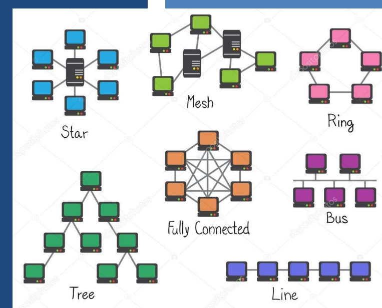
# TCSS 558: APPLIED DISTRIBUTED COMPUTING

## Chapter 6 - Coordination

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## OBJECTIVES

- Assignment 2 - questions
- Feedback from 3/3
- Chapter 6.2: Vector Clocks
- Chapter 6.3: Distributed Mutual Exclusion
- Class Activity – Causality and Vector Clocks
- Chapter 6.4: Election Algorithms

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# MATERIAL / PACE

- Please classify your perspective on material covered in today's class:
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 7.6 (-)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 6.2 (↑)**

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# FEEDBACK FROM 3/3

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## SHORT-HAND-CODES FOR MEMBERSHIP TRACKING APPROACHES

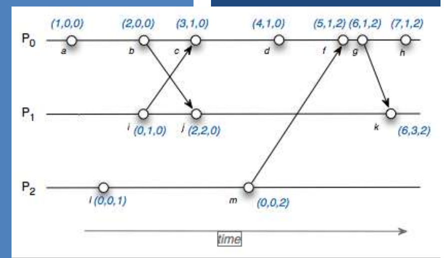
- Include readme.txt or doc file with instructions in submission
- Must document membership tracking method
- S-1: Static file membership tracking only = 0 pts
- T-1: TCP membership tracking only = +5 pts (*should be dynamic once servers point to membership server*)
- U-1: UDP membership tracking only = +10 pts (*automatically discovers nodes with no configuration*)
- S+T-2: Static file + TCP membership tracking = +15 pts (*Static file is not reread to refresh membership during operation*)
- S+U-2: Static file + UDP membership tracking = +15 pts (*Static file is not reread to refresh membership during operation*)
- SD+U-2: Static file + UDP membership tracking = +20 pts (*Static file is periodically reread to refresh membership during operation*)
- T+U-2: TCP + UDP membership tracking = 20 pts (*both dynamic*)





## CHAPTER 6 - COORDINATION

- 6.1 Clock Synchronization
  - Physical clocks
  - Clock synchronization algorithms
- 6.2 Logical clocks
  - Lamport clocks
  - Vector clocks
- 6.3 Mutual exclusion
- 6.4 Election algorithms
- 6.6 Distributed event matching *(light)*
- 6.7 Gossip-based coordination *(light)*




# CH. 6.2: LOGICAL CLOCKS

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# VECTOR CLOCKS

- Lamport clocks don't help to determine causal ordering of messages
- Vector clocks capture causal histories and can be used as an alternative
- But what is causality? …

| | | |
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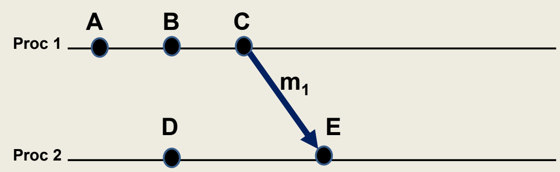
# WHAT IS CAUSALITY?




- Having a causal relationship between two events (A and E) indicates that event E results from the occurrence of event A.
- When one event results from another, there is a causal relationship between the two events.
- This is also referred to as cause and effect.



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# CAUSALITY - 2

- <u>**Disclaimer:**</u>
- Without knowing actual information contained in messages, it is not possible to state with certainty that there is a causal relationship or perhaps a conflict
- Lamport/Vector clocks can help us suggest possible causality
- But we never know for sure…



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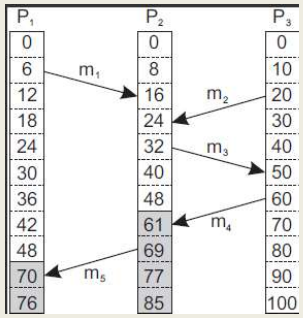
# CAUSALITY - 3

- Consider the messages:




- P2 receives m1, and subsequently sends m3
- <u>**Causality:**</u> Sending m3 ***<u>may</u>*** depend on what's contained in m1
- P2 receives m2, receiving m2 is ***<u>not</u>*** related to receiving m1
- ***<u>Is sending m3 causally dependent on receiving m2?</u>***



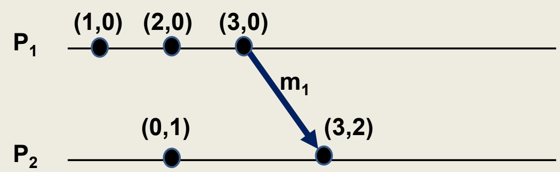
# VECTOR CLOCKS

- Vector clocks help keep track of <u>causal history</u>
- If two local events happened at process P, then the causal history H(p2) of event p2 is {p1,p2}

- P sends messages to Q (*event p3*)
- Q previously performed event q1
- Q records arrival of message as q2
- Causal histories merged at Q H(q2)= {p1,p2,p3,q1,q2}

- Fortunately, can simply store history of last event, as a vector clock → H(q2) = (3,2)
- Each entry corresponds to the last event at the process

# VECTOR CLOCKS - 2




- Each process maintains a vector clock which
  - Captures number of events at the local process (e.g. logical clock)
  - Captures number of events at all other processes
- Causality is captured by:
  - For each event at Pi, the vector clock ($VC_i$) is incremented
  - The msg is timestamped with $VC_i$; and sending the msg is recorded as a new event at $P_i$
  - $P_j$ adjusts its $VC_j$ choosing the **max** of: the message timestamp –or- the local vector clock ($VC_j$)

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# VECTOR CLOCKS - 3

- Pj knows the # of events at Pi based on the timestamps of the received message
- Pj learns how many events have occurred at other processes based on timestamps in the vector
- These events ***"may be causally dependent"***
- **In other words:** they may have been necessary for the message(s) to be sent…

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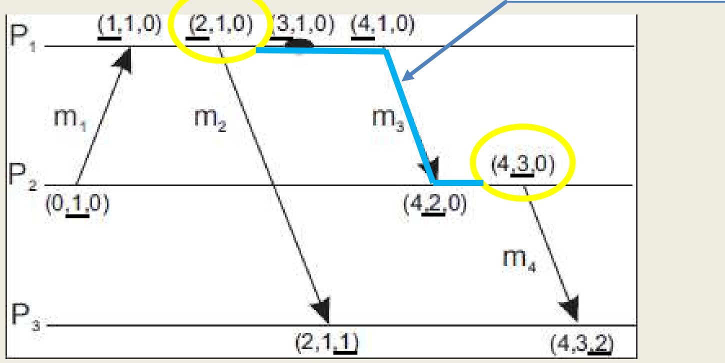
# VECTOR CLOCKS EXAMPLE

- Local clock is underlined

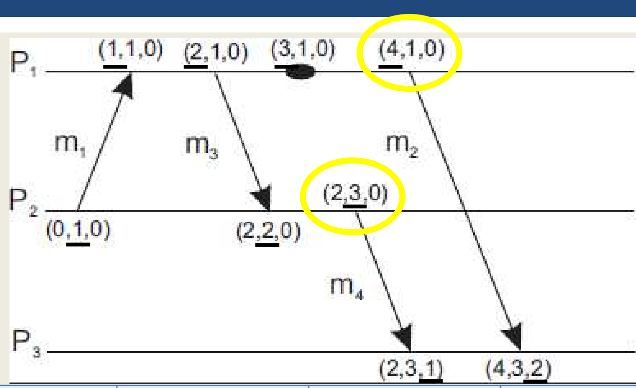
CAUSALITY




| $m_2$ | $m_4$ | $m_2 < m_4$ | $m_2 > m_4$ | Conclusion |
|---|---|---|---|---|
| (2,1,0) | (4,3,0) | Yes | No | m2 may causally precede m4 |



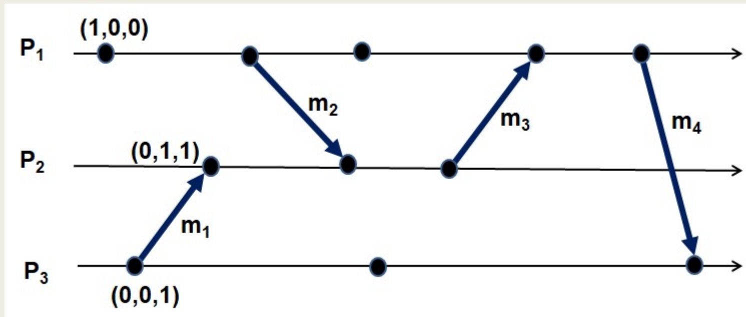
# VECTOR CLOCKS EXAMPLE - 2




| $m_2$ | $m_4$ | $m_2 < m_4$ | $m_2 > m_4$ | Conclusion |
|---|---|---|---|---|
| (4,1,0) | (2,3,0) | No | No | m2 and m4 may conflict |

- P3 can't determine if m4 may be causally dependent on m2
- Is m4 causally dependent on m3 ?

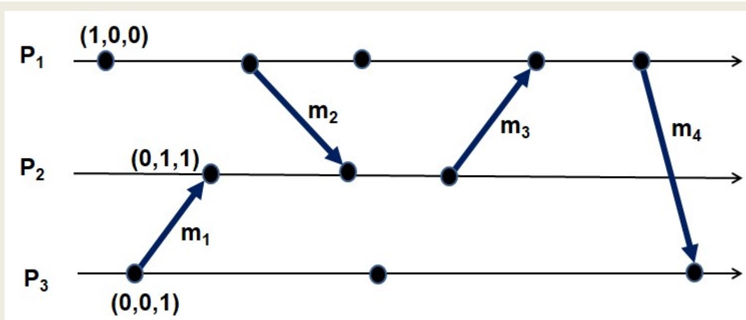
# VECTOR CLOCKS EXAMPLE - 3




- Provide a vector clock label for unlabeled events

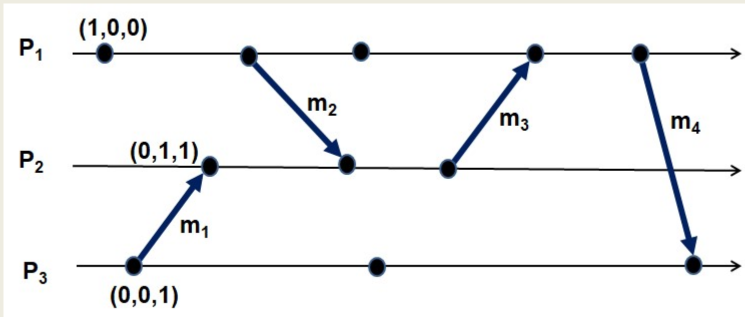


# VECTOR CLOCKS EXAMPLE - 4




- TRUE/FALSE:
- The sending of message $m_3$ is causally dependent on the sending of message $m_1$.
- The sending of message $m_2$ is causally dependent on the sending of message $m_1$.

# VECTOR CLOCKS EXAMPLE - 5




- TRUE/FALSE:
- $P_1$ (1,0,0) and $P_3$ (0,0,1) may be concurrent events.
- $P_2$ (0,1,1) and $P_3$ (0,0,1) may be concurrent events.
- $P_1$ (1,0,0) and $P_2$ (0,1,1) may be concurrent events.

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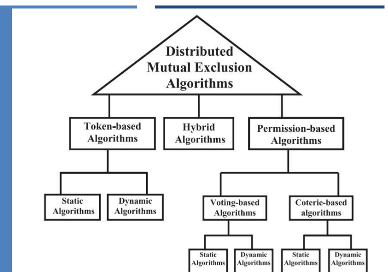


# CH. 6.3: DISTRIBUTED MUTUAL EXCLUSION

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# DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS

- Coordinating access among distributed processes to a shared resource requires **Distributed Mutual Exclusion**
- **Algorithms in 6.3**
- Token-ring algorithm
- ***Permission-based algorithms:***
- Centralized algorithm
- Distributed algorithm (Ricart and Agrawala)
- Decentralized voting algorithm (Lin et al.)

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# TOKEN-BASED ALGORITHMS

- Mutual exclusion by passing a "token" between nodes
- Nodes often organized in ring
- Only one token, holder has access to shared resource
- Avoids starvation: ***everyone gets a chance to obtain lock***
- Avoids deadlock: easy to avoid

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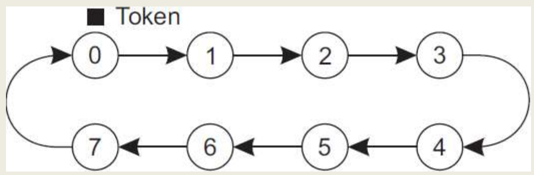
# TOKEN-RING ALGORITHM

- Construct overlay network
- Establish logical ring among nodes




- Single token circulated around the nodes of the network
- Node having token can access shared resource
- If no node accesses resource, token is constantly circulated around ring



# TOKEN-RING CHALLENGES

1. If token is lost, token must be regenerated
   - **Problem**: may accidentally circulate multiple tokens
2. Hard to determine if token is lost
   - What is the difference between token being lost and a node holding the token (***lock***) for a long time?
3. When node crashes, circular network route is broken
   - Dead nodes can be detected by adding a receipt message for when the token passes from node-to-node
   - When no receipt is received, node assumed dead
   - Dead process can be "jumped" in the ring

# DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS - 3

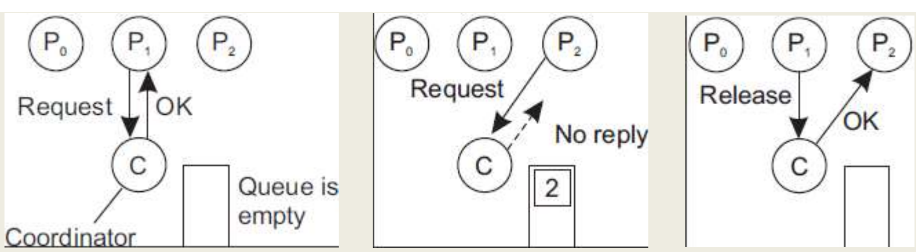
- **Permission-based algorithms**
- Processes must require permission from other processes before first acquiring access to the resource
  - CONTRAST: Token-ring did not ask nodes for permission

- **Centralized algorithm**
- Elect a single leader node to coordinate access to shared resource(s)
- Manage mutual exclusion on a distributed system similar to how it mutual exclusion is managed for a single system
- Nodes must all interact with leader to obtain ***"the lock"***



# CENTRALIZED MUTUAL EXCLUSION

**Permission granted from coordinator ∨ No response from coordinator**




**$P_1$ executes** **$P_2$ blocks** **$P_1$ finishes; $P_2$ executes**

- When resource not available, coordinator can block the requesting process, or respond with a reject message
- P2 must ***poll*** the coordinator if it responds with reject otherwise can wait if simply blocked
- Requests granted permission fairly using FIFO queue
- Just three messages: (request, grant (OK), release)

# CENTRALIZED MUTUAL EXCLUSION - 2

- **Issues**
- Coordinator is a single point of failure
- Processes can't distinguish dead coordinator from ***"blocking"*** when resource is unavailable
  - No difference between CRASH and Block (*for a long time*)
- Large systems, coordinator becomes performance bottleneck
  - Scalability: Performance does not scale

- **Benefits**
- Simplicity:
  Easy to implement compared to distributed alternatives

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# DISTRIBUTED ALGORITHM

- Ricart and Agrawala [1981], use total ordering of all events
  - Leverages Lamport logical clocks

- Package up resource request message (AKA Lock Request)
- Send to all nodes
- Include:
  - Name of resource
  - Process number
  - Current (logical) time

- Assume messages are sent reliably
  - No messages are lost

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# DISTRIBUTED ALGORITHM - 2

- When each node receives a request message they will:

1. Say OK (*if the node doesn't need the resource)*
2. Make **no reply**, queue request (*node is using the resource)*
3. *If node is also waiting to access the resource:* perform a timestamp comparison -
   1. Send OK if requester has lower logical clock value
   2. Make **no reply** if requester has higher logical clock value

- Nodes sit back and wait for all nodes to grant permission
- Requirement: every node must know the entire membership list of the distributed system



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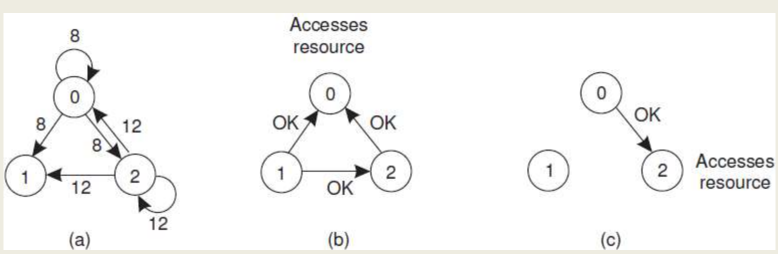
# DISTRIBUTED ALGORITHM - 3

- Node 0 and Node 2 simultaneously request access to **resource**
- Node 0's time stamp is lower (8) than Node 2 (12)
- Node 1 and Node 2 grant Node 0 access
- Node 1 is not interested in the resource, it OKs both requests




- **In case of conflict, lowest timestamp wins!**
  - Node 2 rejects its own request (1@) in favor of node 0 (8)



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## CHALLENGES WITH DISTRIBUTED ALGORITHM

- **Problem:** Algorithm has N points of failure !
- Where N = Number of Nodes in the system

- **No Reply Problem:** When node is accessing the resource, it does not respond
  - Lack of response can be confused with **failure**
  - ***Possible Solution:*** When node receives request for resource it is accessing, always send a reply either granting or denying permission (ACK)
  - Enables requester to determine when nodes have died

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## CHALLENGES WITH DISTRIBUTED ALGORITHM - 2

- **Problem**: Multicast communication required –or- each node must maintain full group membership
  - Track nodes entering, leaving, crashing…
- **Problem**: Every process is involved in reaching an agreement to grant access to a shared resource
  - This approach ***may not scale*** on resource-constrained systems
- **Solution**: Can relax total agreement requirement and proceed when a **simple majority** of nodes grant permission
  - *Presumably any one node locking the resource prevents agreement*
  - *If one node gets majority of acknowledges no other can*
  - *Requires every node to know size of system (# of nodes)*
- Distributed algorithm for mutual exclusion works best for:
  - Small groups of processes
  - When memberships rarely change

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# DECENTRALIZED ALGORITHM

- Lin et al. [2004], decentralized voting algorithm
- Resource is replicated N times
- Each replica has its own coordinator …(N coordinators)
- Accessing resource requires majority vote: total votes (m) > N/2 coordinators
- **Assumption #1:** When coordinator does not give permission to access a resource (because it is busy) it will inform the requester



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# DECENTRALIZED ALGORITHM - 2

- **Assumption #2:** When a coordinator crashes, it recovers quickly, but will have forgotten votes before the crash.
- Approach assumes coordinators reset **arbitrarily** at any time
- **Risk**: on crash, coordinator forgets it previously granted permission to the shared resource, and on recovery it errantly grants permission again
- **The Hope**: if coordinator crashes, *upon recovery*, ***the node granted access to the resource has already finished before the restored coordinator grants access again . . .***



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# DECENTRALIZED ALGORITHM - 3

- With 99.167% coordinator availability (30 sec downtime/hour) chance of violating correctness **<u>is so low</u>** it can be neglected in comparison to other types of failure
- Leverages fact that a new node must obtain a majority vote to access resource, ***which requires time***

| N | m | p | Violation |
|---|---|---|---|
| 8 | 5 | 3 sec/hour | $< 10^{-15}$ |
| 8 | 6 | 3 sec/hour | $< 10^{-18}$ |
| 16 | 9 | 3 sec/hour | $< 10^{-27}$ |
| 16 | 12 | 3 sec/hour | $< 10^{-36}$ |
| 32 | 17 | 3 sec/hour | $< 10^{-52}$ |
| 32 | 24 | 3 sec/hour | $< 10^{-73}$ |

| N | m | p | Violation |
|---|---|---|---|
| 8 | 5 | 30 sec/hour | $< 10^{-10}$ |
| 8 | 6 | 30 sec/hour | $< 10^{-11}$ |
| 16 | 9 | 30 sec/hour | $< 10^{-18}$ |
| 16 | 12 | 30 sec/hour | $< 10^{-24}$ |
| 32 | 17 | 30 sec/hour | $< 10^{-35}$ |
| 32 | 24 | 30 sec/hour | $< 10^{-49}$ |

N = number of resource replicas, m = required "majority" vote
p=seconds per hour coordinator is offline



# DECENTRALIZED ALGORITHM - 4

- **<u>Back-off Polling Approach for *permission-denied:*</u>**
- If permission to access a resource is denied via majority vote, process can poll to gain access again with a ***<u>random</u>*** delay (***known as back-off***)
- Node waits for a random amount, retries…
- If too many nodes compete to gain access to a resource, majority vote can lead to low resource utilization
  - ***No one can achieve majority vote to obtain access to the shared resource***
  - *Mimics elections where with too many candidates, where no one candidate can get >50% of the total vote*
- Problem Solution detailed in [Lin et al. 2014]

# DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS REVIEW

- Which algorithm offers the best scalability to support distributed mutual exclusion in a large distributed system?
- (A) Token-ring algorithm
- (B) Centralized algorithm
- (C) Distributed algorithm
- (D) Decentralized voting algorithm



# DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS REVIEW - 2

- Which algorithm(s) involve blocking when a resource is not available?
- (A) Token-ring algorithm
- (B) Centralized algorithm
- (C) Distributed algorithm
- (D) Decentralized voting algorithm

# DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS REVIEW - 3

- Which algorithm(s) involve arriving at a consensus to determine whether a node should be granted access to a resource?
- (A) Token-ring algorithm
- (B) Centralized algorithm
- (C) Distributed algorithm
- (D) Decentralized voting algorithm

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# DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS REVIEW - 4

- Which algorithm(s) have N points of failure, where N = Number of Nodes in the system?
- (A) Token-ring algorithm
- (B) Centralized algorithm
- (C) Distributed algorithm
- (D) Decentralized voting algorithm

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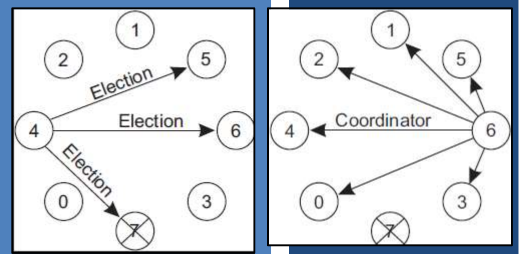


# CH. 6.4: ELECTION ALGORITHMS

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## ELECTION ALGORITHMS

- Many distributed systems require one process to act as a coordinator, initiator, or provide some special role
- Generally any node (or process) can take on the role
  - In some situations there are special requirements
  - Resource requirements: compute power, network capacity
  - Data: access to certain data/information
- Assumption:
  - Every node has access to a "node directory"
  - Process/node ID, IP address, port, etc.
  - Node directory may not know "current" node availability
- Goal of election: at conclusion all nodes agree on a coordinator

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# ELECTION ALGORITHMS

- Consider a distributed system with N processes (*or nodes*)
- Every process has an identifier id(P)
- Election algorithms attempt to locate the highest numbered process to designate as coordinator

- **Algorithms:**
- Bully algorithm
- Ring algorithm
- Elections in wireless environments
- Elections in large-scale systems

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# BULLY ALGORITHM

- When ***any*** process notices the coordinator is no longer responding to requests, it initiates an election
- Process $P_k$ initiates an election as follows:
  1. $P_k$ sends an ELECTION message to all processes with higher process IDs ($P_{k+1}$, $P_{k+2}$, … $P_{N-1}$)
  2. If no one responds, $P_k$ wins the election and becomes coordinator
  3. If a "higher-up" process answers ($P_{k+n}$), it will take over and run the election. $P_k$ will quit sending ELECTION messages.
- When the higher numbered process receives an ELECTION message from a lower-numbered colleague, it responds with "OK", indicating it's alive, and it takes over the election.

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# BULLY ALGORITHM - 2

- The higher numbered process then holds an election with ***only*** higher numbered processes (nodes).
- Eventually ***all*** processes give up except one, and the remaining process becomes the new coordinator.
- The coordinator announces victory by sending all processes a message stating it is starting as the coordinator.
- If a higher numbered node that was previously down comes back up, it holds an election, and ultimately takes over the coordinator role.
- The process with the *"biggest"* ID in town always wins.
- Hence the name, **bully algorithm**

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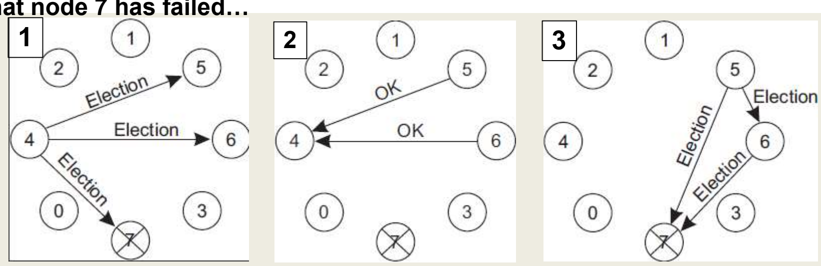
# BULLY ALGORITHM - 3

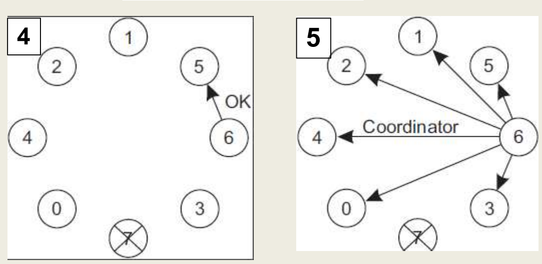
**Note that node 7 has failed…**




**[1]** Process 4 starts an election

**[2]** Process 5 and 6 respond

**[3]** Process 5 and 6 each hold an election




**[4]** Process 6 tells Process 5 to stop

**[5]** Process 6 wins and tells everyone

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# BULLY ALGORITHM - 4

- Every node knows who is participating in the distributed system
  - Each node has a group membership directory
- First process to notice the leader is offline launches a new election
- GOAL: Find the highest number node that is running
  - Loop over the nodes until the highest numbered node is found
  - May require multiple election rounds
- Highest numbered node is always the ***"BULLY"***

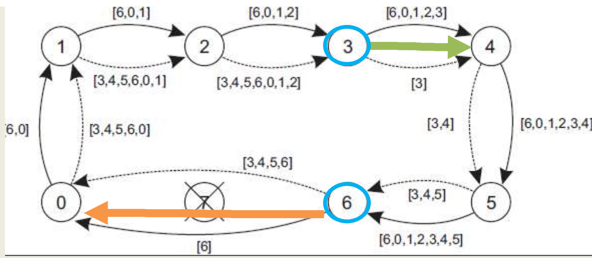


# RING ALGORITHM

- Election algorithm based on a network of nodes in logical ring
- *Does not use a token*
- Any process ($P_k$) starts the election by noticing the coordinator is not functioning

1. $P_k$ builds an **election message**, and sends to its successor in the ring
   - If successor is down, successor is skipped
   - Skips continue until a running process is found
2. When the **election message** is passed around, each node adds its ID to a *separate* **active node list**
3. When **election message** returns to $P_k$, $P_k$ recognizes its own identifier in the **active node list**. Message is changed to COORDINATOR and "**elected($P_k$)**" message is circulated.
   - Second message announces $P_k$ is the NEW coordinator

# RING: MULTIPLE ELECTION EXAMPLE




- **PROBLEM:** Two nodes start election at the same time: **$P_3$** and **$P_6$**
- $P_3$ sends **ELECT($P_3$)** message, $P_6$ sends **ELECT($P_6$)** message
  - $P_3$ and $P_6$ both circulate **ELECTION** messages at the same time
- Also circulated with ELECT message is an **active node list**
- Each node adds itself to the **active node list**
- Each node votes for the highest numbered candidate
- $P_6$ wins the election because it's the candidate with the **highest ID**



# ELECTIONS WITH WIRELESS NETWORKS

- Assumptions made by traditional election algorithms not realistic for wireless environments:
  - >>> Message passing is reliable
  - >>> Topology of the network does not change
- A few protocols have been developed for elections in ad hoc wireless networks
- Vasudevan et al. [2004] solution handles failing nodes and partitioning networks.
  - Best leader can be elected, rather than just a random one

# VASUDEVAN ET AL. WIRELESS ELECTION

1. Any node (***source***) (P) starts the **election** by sending an ELECTION message to immediate neighbors (any nodes in range)
2. Receiving node (Q) designates sender (P) as parent
3. (Q) Spreads election message to neighbors, ***but not to parent***
4. Node (R), receives message, designates (Q) as parent, and spreads ELECTION message to neighbors, ***but not to parent***
5. Neighbors that have already selected a parent immediately respond to R.
   - If ***all*** neighbors already have a parent, R is a leaf-node and will report back to Q quickly.
   - When reporting back to Q, R includes metadata regarding battery life and resource capacity
6. Q eventually acknowledges the ELECTION message sent by P, and also indicates the most eligible node (based on battery & resource capacity)



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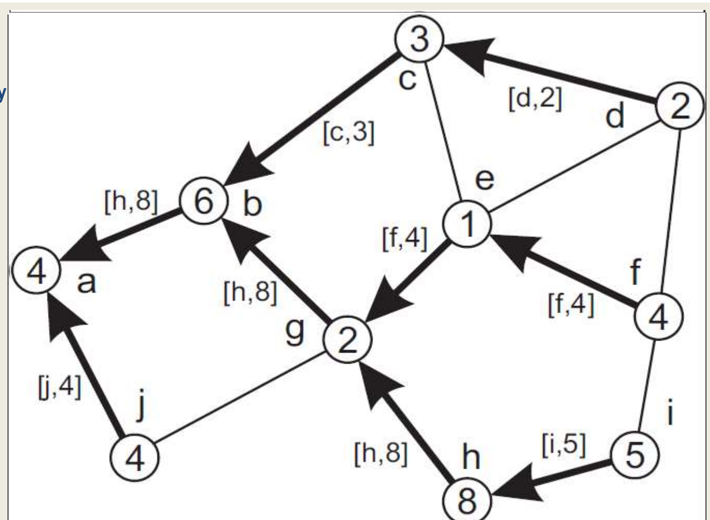
# WIRELESS ELECTION - 2
# SOURCE NODE: [A]

Node [A] initiates election:
find the highest capacity

Election messages propagated to all nodes

Each node reports to its parent node with best capacity

Node A then facilitates Node H becoming leader



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# WIRELESS ELECTION - 3

- When multiple elections are initiated, nodes only join one
- Source node tags its ELECTION message with unique identifier, to uniquely identify the election.
- With minor adjustments protocol can operate when the network partitions, and when nodes join and leave



# ELECTIONS FOR LARGE-SCALE SYSTEMS

- Large systems often require several nodes to serve as coordinators/leaders
- These nodes are considered ***"super peers"***
- ***Super peers*** must meet operational requirements:

1. Network latency from normal nodes to ***super peers*** must be low
2. ***Super peers*** should be evenly distributed across the overlay network (ensures proper load balancing, availability)
3. Must maintain set ratio of ***super peers*** to normal nodes
4. ***Super peers*** must not serve ***too many*** *normal nodes*

# ELECTIONS FOR DHT BASED SYSTEMS

- DHT-based systems use a bit-string to identify nodes
- **Basic Idea**: Reserve fraction of ID space for super peers
- Reserve first $log_2(N)$ bits for super-peer IDs
- m=number of bits of the identifier
- k=# of nodes each node is responsible for (Chord system)
- **Example:**
- For a system with m=8 bit identifier, and k=3 keys per node
- Required number of super peers is $2^{(k-m)} \cdot N$, where N is the number of nodes
  - In this case N=32
  - **Only 1 super peer is required for every 32 nodes**

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# SUPER PEERS IN AN M-DIMENSIONAL SPACE

- Given an overlay network, the idea is to position superpeers throughout the network so they are evenly disbursed
- **Use tokens:**
- Give N tokens to N randomly chosen nodes
- No node can hold more than (1) token
- Tokens are “repelling force”. Other tokens move away
- All tokens exert the same repelling force
- This automates token distribution across an overlay network

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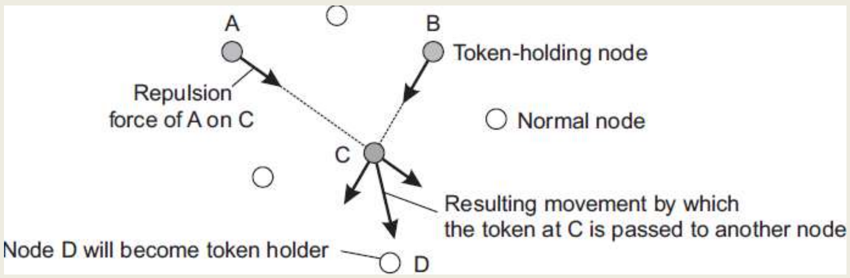
# OVERLAY TOKEN DISTRIBUTION

- Gossping protocol is used to disseminate token location and force information across the network
- If forces acting on a node with a token exceed a **threshold**, token is moved away
- Once nodes hold token for awhile they become superpeers

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# QUESTIONS

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