TCSS 558: APPLIED DISTRIBUTED COMPUTING

Chapter 6 – Coordination - II

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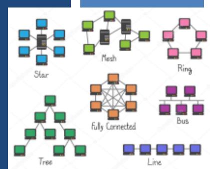

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OBJECTIVES – 2/29

- Questions from 2/27
- Assignment 3: Replicated Key Value Store
- Chapter 6: Coordination
  - Chapter 6.2: Logical Clocks
    Vector Clocks
- Class Activity 4 – Total Ordered Multicasting
- Chapter 6: Coordination
  - Chapter 6.3: Distributed Mutual Exclusion

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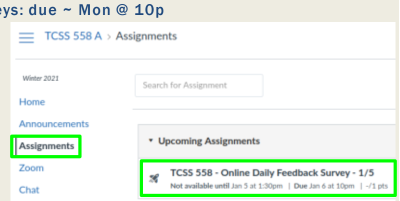
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 10p
- Thursday surveys: due ~ Mon @ 10p



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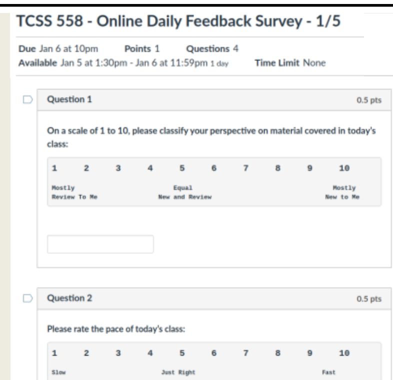

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (21 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.67** (↑ - *previous 6.09*)

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.52** (↑ - *previous 5.36*)

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FEEDBACK FROM 2/27

- ***Can you please explain again the graph mentioned in Rumor Spreading which is plotted between P_stop and s ?***

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RUMOR SPREADING

- Variant of epidemic protocols
- Provides an approach to **"stop"** message spreading
- Mimics "gossiping" in real life

- **Rumor spreading:**
- **Node P** receives new data **item X**
- Contacts an arbitrary **node Q** to push update
- **Node Q** reports already receiving **item X** from another node
- **Node P** may loose interest in spreading the rumor with probability = p_{stop}, let's say 20% . . . (or 0.20)

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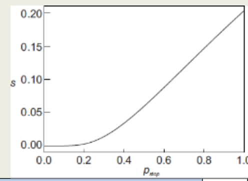
RUMOR SPREADING - 2

- p_{stop}, is the probability node will stop spreading once contacting a node that already has the message
- Rumor spreading does not guarantee all nodes will be updated
- Fraction of nodes s, that remain susceptible grows relative to the probability that node P stops propagating when finding a node already having the message
- Fraction of nodes not updated remains < 20% with high p_{stop}
- Susceptible nodes (s) vs. probability of stopping →



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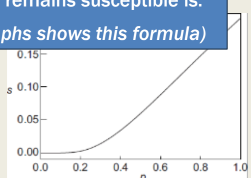
- Once P finds a node Q that already has the message X, P begins evaluating whether it should stop spreading message X
- P decides randomly when to stop spreading the message X
- With p_{stop},=.20, the odds are 1 in 5 that P will stop
- *On average*, after 5 attempts, P will stop trying to spread the message X
- The number of nodes that remains susceptible is: $s=e^{1(\frac{1}{pstop}+1)(1-s)}$ *(this graphs shows this formula)*

message

- Fraction of nodes not updated remains < 20% with high p_{stop}
- Susceptible nodes (s) vs. probability of stopping →



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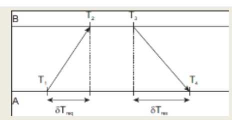
REVIEW: NTP EXAMPLE

- Time server B



θ = clock offset
δ = propagation delay

Client A

- Assume: δT_{req}= δT_{res} *(request latency equals response latency)*
- T_1=50, T_2(@A)=100, T_2=200, T_3=300, T_3(@A)=200, T_4=250
- Calculate clock offset (θ) between A and B
- $\theta = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$ $\delta = \frac{(T_4 - T_1) - (T_3 - T_2)}{2}$
- **What is the propagation delay between A and B?**
- **What is the clock offset between A and B?**

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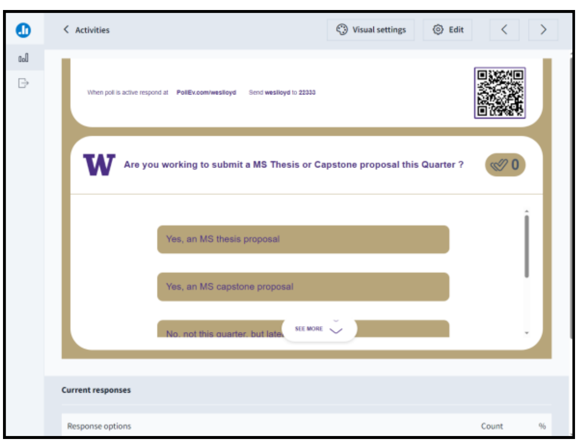

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OBJECTIVES – 2/29

- Questions from 2/27
- **Assignment 3: Replicated Key Value Store**
- Chapter 6: Coordination
  - Chapter 6.2: Logical Clocks
    Vector Clocks
- Class Activity 4 – Total Ordered Multicasting
- Chapter 6: Coordination
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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

>> please indicate which types to test <<

ID	Description
F	Static file membership tracking – file is not reread
FD	Static file membership tracking DYNAMIC - file is periodically reread to refresh membership list
T	TCP membership tracking – servers are configured to refer to central membership server
U	UDP membership tracking - automatically discovers nodes with no configuration

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ASSIGNMENT 3

- **Sunday March 10th**
- Goal: Replicated Key Value Store
- Team signup to be posted on Canvas under 'People'
- Build off of Assignment 2 GenericNode
- Focus on TCP client/server w/ replication
- How to track membership for data replication?
  - Can implement multiple types of membership tracking for extra credit
- REQUIREMENT: 'store' command needs to output 1 key-value pair per line using ASCII text (no binary)

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  - **Chapter 6.2: Logical Clocks**
    Vector Clocks
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- Chapter 6: Coordination
  - Chapter 6.3: Distributed Mutual Exclusion

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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)*

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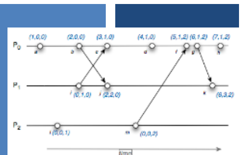

CH. 6.2: LOGICAL CLOCKS

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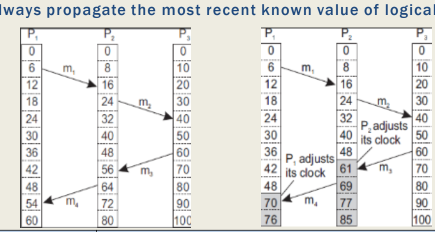
LOGICAL CLOCKS - 4

- Three processes each with local clocks
- ***Lamport's algorithm*** corrects process clock values
- Always propagate the most recent known value of logical time



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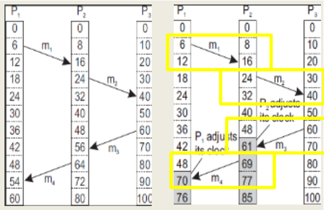
LOGICAL CLOCKS

- **Events**:

6: P1 send m1 to P2
16: P2 receives m1
24: P2 sends m2 to P3
40: P3 receives m2
60: P3 sends m3 to P2
56: P2 receives m3
56: P2 clock reset=61
69: P2 sends m4 to P1
54: P1 receives m4
70: P1 clock reset=70



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LAMPORT LOGICAL CLOCKS - IMPLEMENTATION

- Negative values not possible
- When a message is received, and the local clock is before the timestamp when then message was sent, the local clock is updated to message_sent_time + 1

1. Clock is incremented before an event: (*sending-a-message, receiving-a-message, some-other-internal-event*)
   Pi increments Ci: Ci ← Ci + 1
2. When Pi send msg m to Pj, m's timestamp is set to Ci
3. When Pj receives msg m, Pj adjusts its local clock
   Cj ← max{Cj, timestamp(m)}
4. Ties broken by considering Proc ID: i<j; <40,i> < <40,j>
   Both Lamport clocks are = 40
   The winner has a higher alphanumeric Process ID
   J (winner) is greater than i, alphabetically

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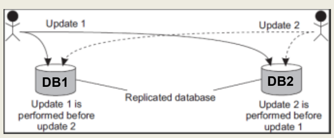
TOTAL-ORDERED MULTICASTING

- Consider concurrent updates to a replicated database
- Communication latency between DB1 and DB2 is 250ms



- **Initial Account balance**: $1,000
- **Update #1**: Deposit $100
- **Update #2**: Add 1% Interest
- Total Ordered Multicasting needed

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TOTAL-ORDERED MULTICASTING EXAMPLE

- Two messages (m_1, m_2) must be distributed, to two processes (p_1, p_2)
- We assume messages have correct lamport clock timestamps
- m_1(10, p_1, add $100)
- m_2(12, p_2, add 1% interest)

- Each process maintains a queue of messages
- Arriving messages are placed into queues ordered by the Lamport clock timestamp

- In each queue, each message must be acknowledged by every process in the system before operations can be applied to the local database

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TOTAL-ORDERED MULTICASTING EXAMPLE

- Two messages (m_1, m_2) must be distributed, to two processes (p_1, p_2)
- We assume messages have correct lamport clock timestamps
- m_1(10, p_1, add $100)

Key point:

Multicast messages are also received by the sender (*itself*)

- Arriving messages are placed into queues ordered by the Lamport clock timestamp

- In each queue, each message must be acknowledged by every process in the system before operations can be applied to the local database

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TOTAL-ORDERED MULTICASTING EXAMPLE

Total Ordered Multicasting
Logical Clocks with Acknowledgements

messages:
m_1 (10, P_1, add $100)
m_2 (12, P_2, add 1% interest)
↑
timestamps

Two processes with collocated DB replicas:

P_1/DB_1 →

P_2/DB_2 →

arriving messages are placed in queues ordered by timestamp

P_1 queue — each process has a local queue — **P_2 queue**

P_1 ack rcv'd | P_2 ack rcv'd | P_1 ack rcv'd | P_2 ack rcv'd

Each message must be acknowledged by every process in the system before operations in queue can be applied to the local DB…

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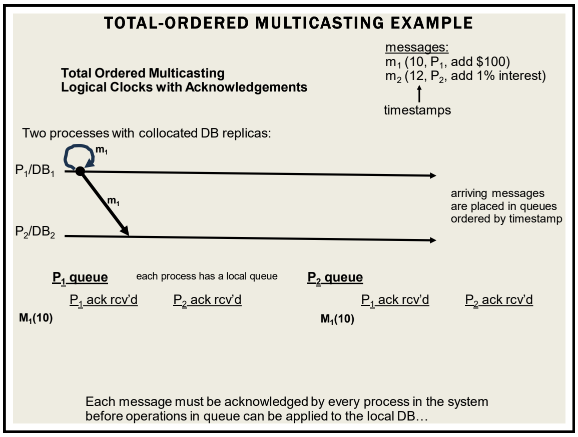

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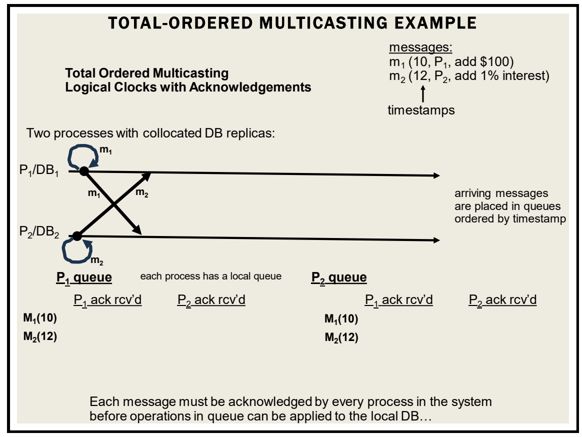

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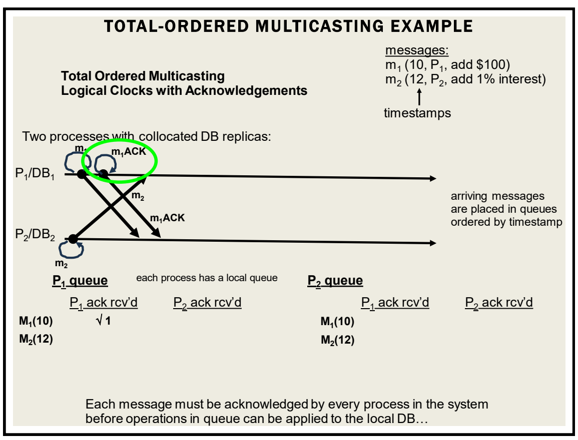

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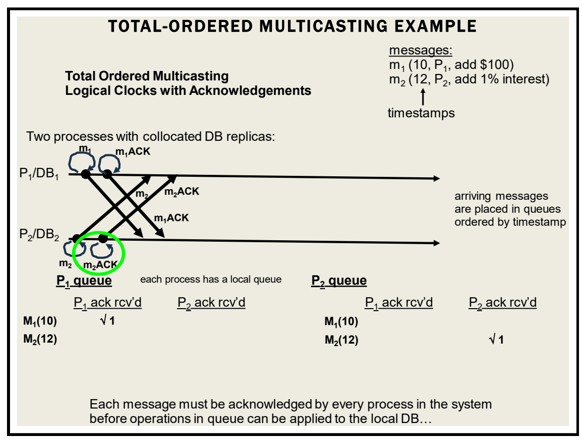

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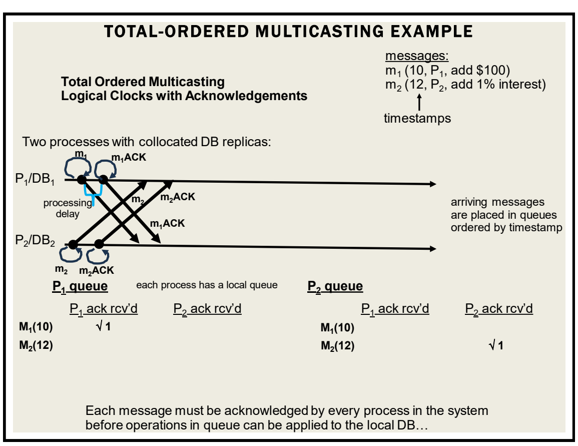

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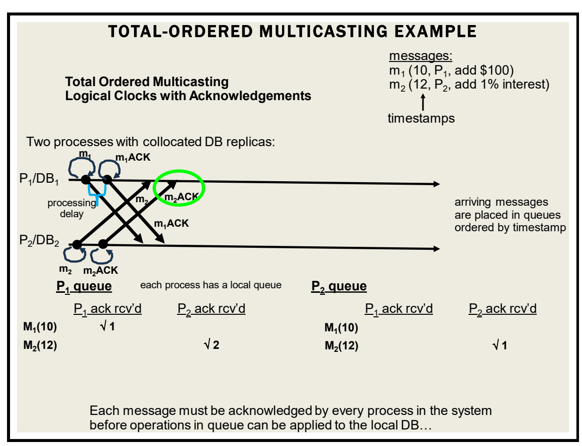

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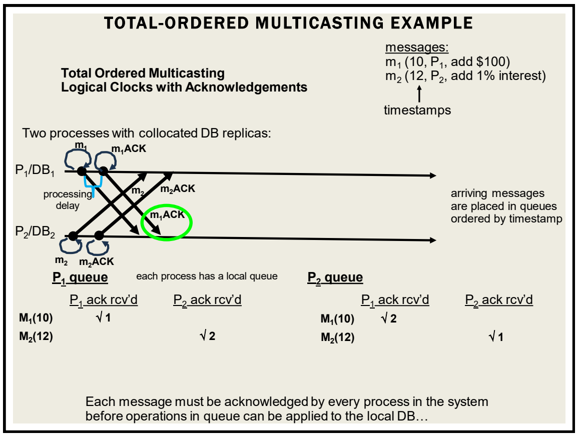

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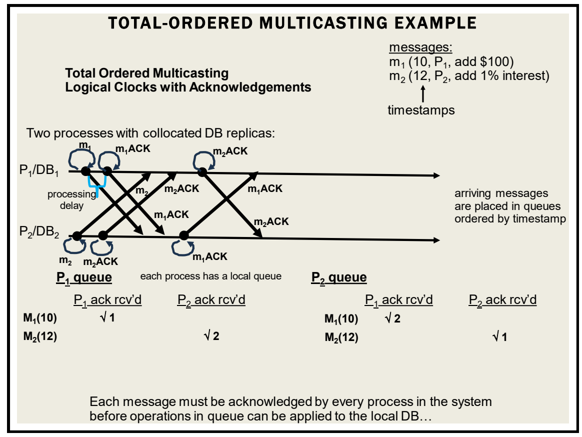

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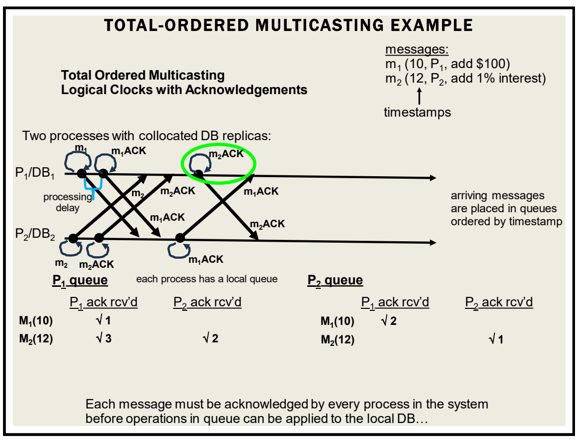

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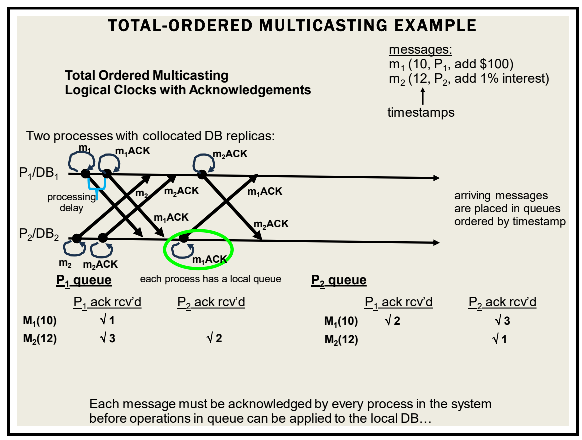

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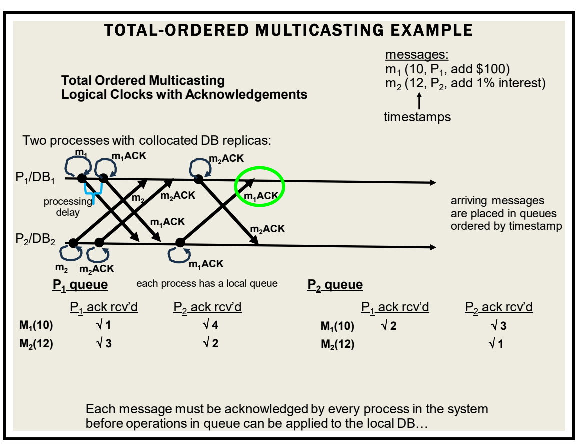

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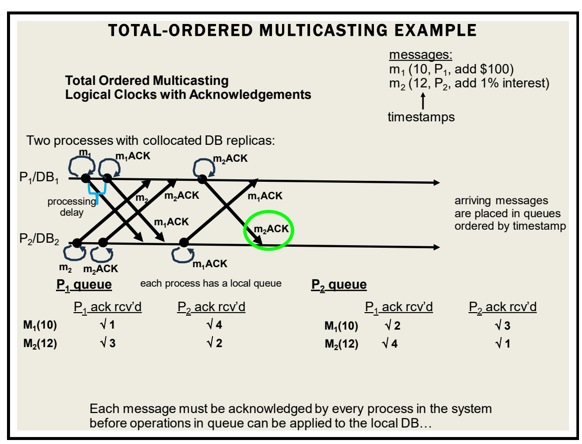

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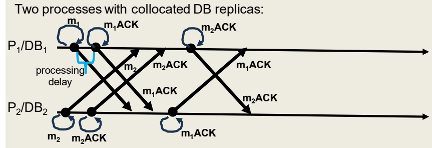
TOTAL-ORDERED MULTICASTING EXAMPLE

Total Ordered Multicasting
Logical Clocks with Acknowledgements

messages:
m_1 (10, P_1, add $100)
m_2 (12, P_2, add 1% interest)
↑
timestamps

Two processes with collocated DB replicas:



arriving messages are placed in queues ordered by timestamp

P_1 queue — each process has a local queue — **P_2 queue**

	P_1 ack rcv'd	P_2 ack rcv'd
M_1(10)	√1	√4
M_2(12)	√3	√2

	P_1 ack rcv'd	P_2 ack rcv'd
M_1(10)	√2	√3
M_2(12)	√4	√1

What is the final account balance?

Each message must be acknowledged by every process in the system before operations in queue can be applied to the local DB…

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TOTAL-ORDERED MULTICASTING EXAMPLE

Total Ordered Multicasting
Logical Clocks with Acknowledgements

messages:
m_1 (10, P_1, add $100)
m_2 (12, P_2, add 1% interest)
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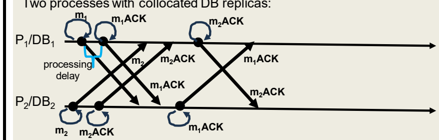
timestamps

Two processes with collocated DB replicas:



arriving messages are placed in queues ordered by timestamp

P_1 queue — each process has a local queue — **P_2 queue**

	P_1 ack rcv'd	P_2 ack rcv'd
M_1(10)	√1	√4
M_2(12)	√3	√2

$1,000 + $100 = $1,100
$1,100 * 1% = $1,111

	P_1 ack rcv'd	P_2 ack rcv'd
M_1(10)	√2	√3
M_2(12)	√4	√1

$1,000 + $100 = $1,100
$1,100 * 1% = $1,111

Messages are processed in timestamp order
Messages aren't processed until all acknowledgements are received

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TOTAL-ORDERED MULTICASTING - 2

- Each message timestamped with local logical clock of sender
- **Multicast messages are also received by the sender (*itself*)**
- Assumptions:
  - Messages from same sender received in order they were sent
  - No messages are lost
- When messages arrive they are placed in local queue ordered by timestamp
- Receiver ***multicasts*** acknowledgement of message receipt to other processes
  - Time stamp of message receipt is lower the acknowledgement
- This process ***replicates*** queues across sites
- Messages delivered to application (database) only when message at the head of the queue has been acknowledged by ***every*** process in the system

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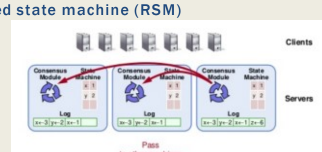
TOTAL-ORDERED MULTICASTING - 3

- Can be used to implement replicated state machines (RSMs)
- Concept is to replicate event queues at each node
- (1) ***Using logical clocks*** and (2) ***exchanging acknowledgement messages***, allows for events to be ***"totally"*** ordered in replicated event queues
- Events can be applied **"in order"** to each (distributed) replicated state machine (RSM)



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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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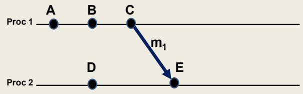
WHAT IS CAUSALITY?



- 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

- **Disclaimer:**
- 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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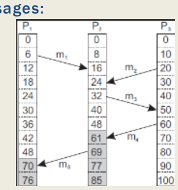
CAUSALITY - 3

- Consider the messages:



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

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VECTOR CLOCKS

- Vector clocks help keep track of **causal history**
- 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

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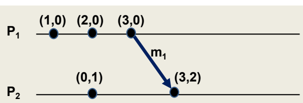
VECTOR CLOCKS - 2



- 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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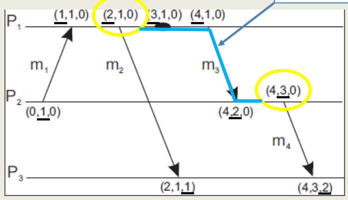
VECTOR CLOCKS EXAMPLE

- 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

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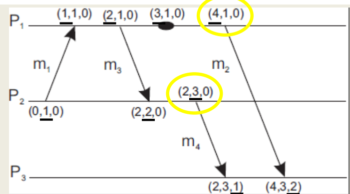
VECTOR CLOCKS EXAMPLE - 2



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 ?**

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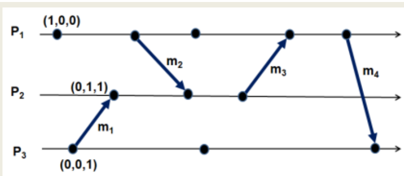
VECTOR CLOCKS EXAMPLE - 3



- Provide a vector clock label for unlabeled events

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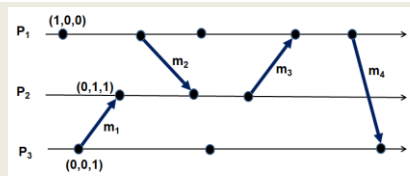
VECTOR CLOCKS EXAMPLE - 4



- 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.

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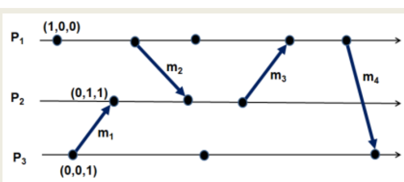
VECTOR CLOCKS EXAMPLE - 5



- 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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WE WILL RETURN AT 2:40 PM

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OBJECTIVES – 2/29

- Questions from 2/27
- Assignment 3: Replicated Key Value Store
- Chapter 6: Coordination
  - Chapter 6.2: Logical Clocks
    Vector Clocks
- **Class Activity 4 – Total Ordered Multicasting**
- Chapter 6: Coordination
  - Chapter 6.3: Distributed Mutual Exclusion

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OBJECTIVES – 2/29

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- Chapter 6: Coordination
  - **Chapter 6.3: Distributed Mutual Exclusion**

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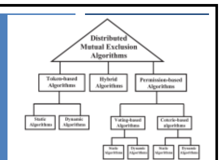

CH. 6.3: DISTRIBUTED MUTUAL EXCLUSION

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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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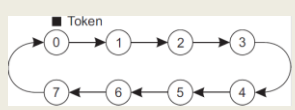
TOKEN-RING ALGORITHM

- 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

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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

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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 mutual exclusion is managed for a single system
- Nodes must all interact with leader to obtain ***"the lock"***

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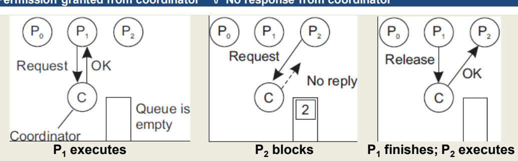
CENTRALIZED MUTUAL EXCLUSION

Permission granted from coordinator ∨ No response from coordinator



- 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 are granted permission fairly using FIFO queue
- Just three messages: (request, grant (OK), release)

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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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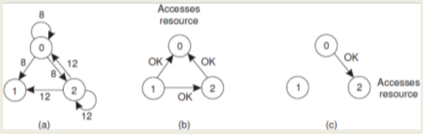
DISTRIBUTED ALGORITHM - 3

- 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 (12) 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 (>50%)
  - *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)*
- **Problem:** 2 concurrent transactions get 50% permission → deadlock?
- 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 **is so low** 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

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DECENTRALIZED ALGORITHM - 4

- **Back-off Polling Approach for *permission-denied*:**
- If permission to access a resource is denied via majority vote, process can poll to gain access again with a ***random*** 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]

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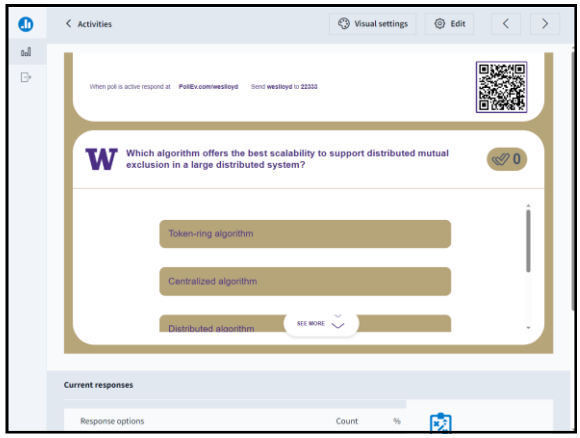

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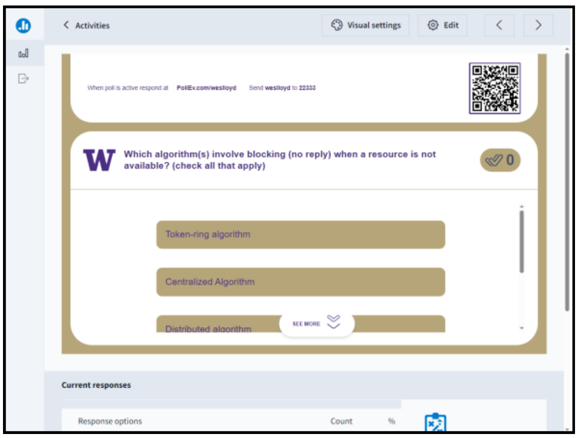

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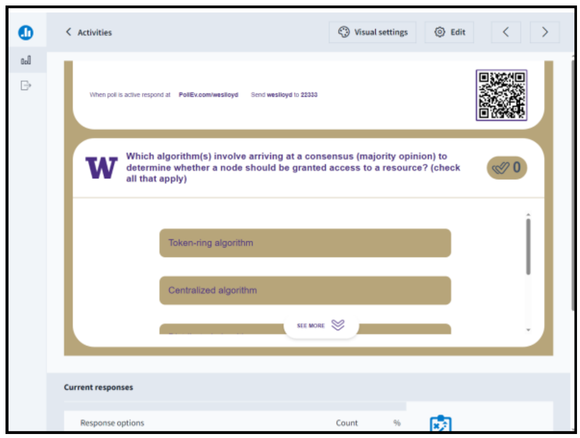

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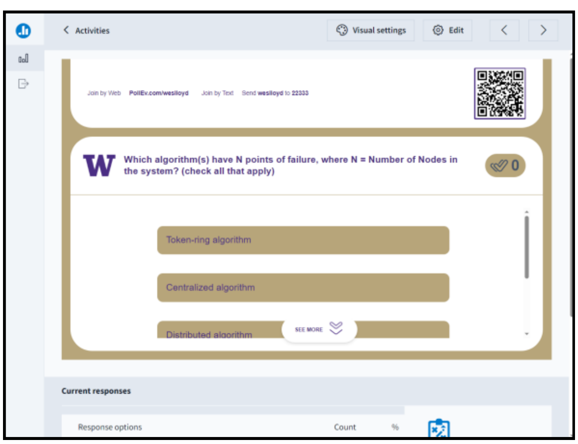

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DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS REVIEW

- 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

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DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS REVIEW - 2

- Which algorithm(s) involve blocking (no reply) when a resource is not available?
- (A) Token-ring algorithm
- (B) Centralized algorithm
- (C) Distributed algorithm
- (D) Decentralized voting algorithm

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DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS REVIEW - 3

- Which algorithm(s) involve arriving at a consensus (majority opinion) 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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QUESTIONS

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