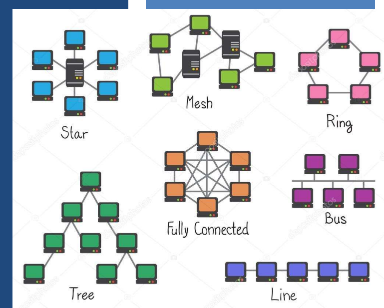
# TCSS 558: APPLIED DISTRIBUTED COMPUTING




## Coordination

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# OBJECTIVES

- Assignment #2 Questions
- Feedback from 11/16

- Ch. 6 – Coordination
  - Clock synchronization
  - Logical clocks, Lamport clocks
  - Vector clocks
  - Distributed mutual exclusion

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# FEEDBACK FROM 11/16

- When using "Gossip" message flooding, is there a possibility that a node is sent a message multiple times?
  - YES
- Is this redundant and possibly inefficient
  - YES
- How does NTP work in an **ad-hoc system?** (unstructured peer-to-peer?)
  We might have some nodes to be synced with atomic clocks (or lower levels), but how can we make sure ALL nodes in the system have access to the "synchronized" nodes
- NTP is UDP (time changes too quick to resend failed msgs)
- NTP typically operates in client/server mode (msgs sent to specific IPs)
- Other modes include broadcast and multicast



# FEEDBACK - 2

- What is the purpose of random graphs?
  - Seem circular?
  - Higher edge probability means more edges per node
  - More edges per node means higher probability
  - Does the number of rounds required for anti-entropy depend on edge probability?
    - YES, the probability graph depicts differences between push, pull, push/pull
- How is gossiping different from flooding?
  - Very similar, gossiping is a way of "thinking about" message interaction and developing the algorithsm
- What if you want to reintroduce an item that was previously removed that has a death certificate?
  - The death certificate would need to be deleted…

# FEEDBACK - 3

- Why are the clocks not synchronized on campus?



# 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. 6.1: CLOCK SYNCHRONIZATION

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# COMPUTING: CLOCK CHALLENGES

- How do we synchronize computer clocks with real-world clocks?
- How do we synchronize computer clocks with each other?

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# CLOCK SYNCHRONIZATION

- **UTC services**: use radio and satellite signals to provide time accuracy to 50ns
- **Time servers**: Server computers with UTC receivers that provide accurate time
- **Precision** ($\pi$): how close together a set of clocks may be
- **Accuracy**: how correct to actual time clocks may be
- **Internal synchronization**: Sync local computer clocks
- **External synchronization**: Sync to UTC clocks
- **Clock drift**: clocks on different machines gradually become out of sync due to crystal imperfections, temperature differences, etc.
- **Clock drift rate**: typical is 31.5s per year
- **Maximum clock drift rate** ($\rho$): clock specifications include one

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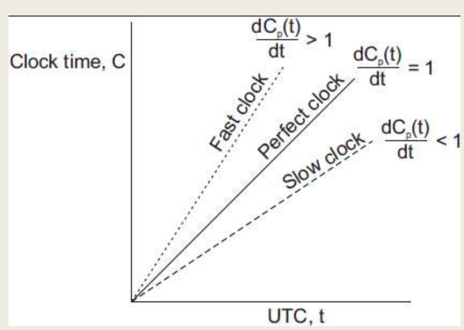
# CLOCK SYNCHRONIZATION - 2

- If two clocks drift from UTC in opposite directions, after time $\Delta t$ after synchronization, they may be $2\rho$ apart.
- Clocks must be resynchronized every $\pi/2\rho$ seconds
- **Network time protocol**
- Provide coordination of time for servers
- Leverage distributed network of time servers

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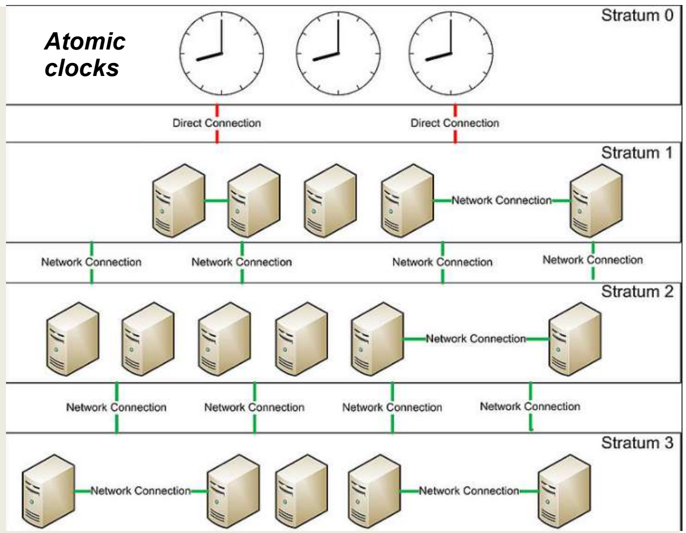
# NETWORK TIME PROTOCOL

- Servers organized into stratums
- Stratum-1 servers have UTC receivers and are sync'd with atomic clocks
- Servers connect with closest NTP server for time synchronization
- Servers assume role as NTP server at stratum+1



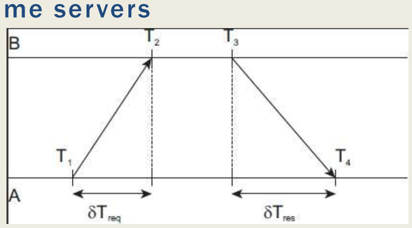



# NTP - 2

- Must estimate network delays when synchronizing with remote UTC receiver clocks / time servers

Time server B

Client A




1. A sends message to B, with timestamp T1
2. B records time of receipt T2 (from local clock)
3. B returns response with send time T3, and receipt time T2
4. A records arrival of T4

- Assuming propagation delay of A→B→A is the same
- Estimate propagation delay: $\theta = T_3 + \frac{(T_2 - T_1) + (T_4 - T_3)}{2} - T_4 = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$
- Add delay to time

## NTP - 3

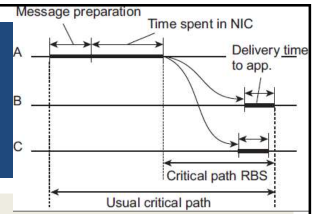
- Cannot set clocks backwards (recall "make" file example)
- Instead, temporarily slow the progress of time to allow fast clock to align with actual time
- Change rate of clock interrupt routine
- Slow progress of time until synchronized
- NTP accuracy is within 1-50ms
- In Ubuntu Linux, to quickly synchronize time:
  `$apt install ntp ntpdate`
- Specify local timeservers in /etc/ntp.conf
  `server time.u.washington.edu iburst`
  `server bigben.cac.washington.edu iburst`
- Shutdown service (sudo service ntp stop)
- Run ntpdate: (sudo ntpdate time.u.washington.edu)
- Startup service (sudo service ntp start)



## BERKELEY ALGORITHM

- Berkeley time daemon server actively polls network to determine average time across servers
- Suitable when no machine has a UTC receiver
- Time daemon instructs servers how much to adjust clocks to achieve precision
- Accuracy can not be guaranteed
- Berkeley is an internal clock synchronization algorithm

# CLOCK SYNCHRONIZATION IN WIRELESS NETWORKS




- Sensor networks bring unique challenges for clock synchronization
  - ***Address resource constraints***: limited power, multihop routing slow
- Reference broadcast synchronization (RBS)
- Provides precision of time, not accuracy as in Berkeley
- No UTC clock available
- RBS sender broadcasts a reference message to allow receivers to adjust clocks
- No multi-hop routing
- Time to propagate a signal to nodes is roughly constant
- Message propagation time does not consider time spent waiting in NIC for message to send
  - Wireless network resource contention may force wait before message even ***can*** be sent



# REFERENCE BROADCAST SYNCHRONIZATION (RBS)

- Node broadcasts reference message m
- Each node p records time Tp,m when m is received
- Tp,m is read from node p's clock
- Two nodes p and q can exchange delivery times to estimate mutual relative offset
- Then calculate relative average offset for the network:

$$Offset[p,q] = \frac{\sum_{k=1}^{M}(T_{p,k} - T_{q,k})}{M}$$

- Where M is the total number of reference messages sent
- Nodes can simply store offsets instead of frequently synchronizing clocks to save energy

# REFERENCE BROADCAST SYNCHRONIZATION (RBS) - 2

- Cloud skew: over time clocks drift apart
- Averages become less precise
- Elson et al. propose using standard linear regression to predict offsets, rather than calculating them
- IDEA: Use node's history of message times in a simple linear regression to continuously refine a formula with coefficients to predict time offsets:

$$Offset[p,q](t) = \alpha t + \beta$$

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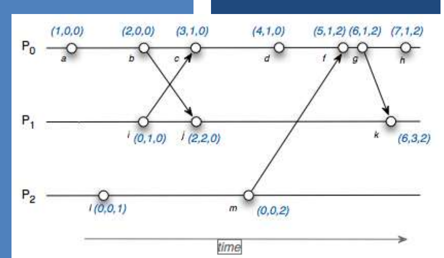


# CH. 6.2: LOGICAL CLOCKS

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# LOGICAL CLOCKS

- In distributed systems, synchronizing to actual time may not be required…
- It may be sufficient for every node to simply agree on a current time (e.g. logical)
- ***Logical clocks*** provide a mechanism for capturing chronological and ***causal*** relationships in a distributed system
- Think ***counters . . .***
- Leslie Lamport [1978] seminal paper showed that absolute clock synchronization often is not required
- Processes simply need to agree on the order in which events occur



# LOGICAL CLOCKS - 2

- **Happens-before relation**
- A→B: **Event A**, happens before **event B…**
- All processes must agree that **event A** occurs first
- Then afterward, **event B**
- Actual time not important. . .
- If **event A** is the event of proc P1 sending a msg to a proc P2, and **event B** is the event of proc P2 receiving the msg, then A→B is also true. . .
- The assumption here is that message delivery takes time
- Happens before is a transitive relation:
- A→B, B→C, therefore A→C

# LOGICAL CLOCKS – 3

- If two events, say event X and event Y do not exchange messages, not even via third parties, then X→Y and Y→X <u>**can not be determined**</u>
- Within the system, these events appear <u>**concurrent**</u>
- <u>**Concurrent:**</u> nothing can be said about when the events happened, or which event occurred first
- Clock time, C, must always go forward (increasing), never backward (decreasing)
- Corrections to time can be made by adding a positive value, but never by subtracting one

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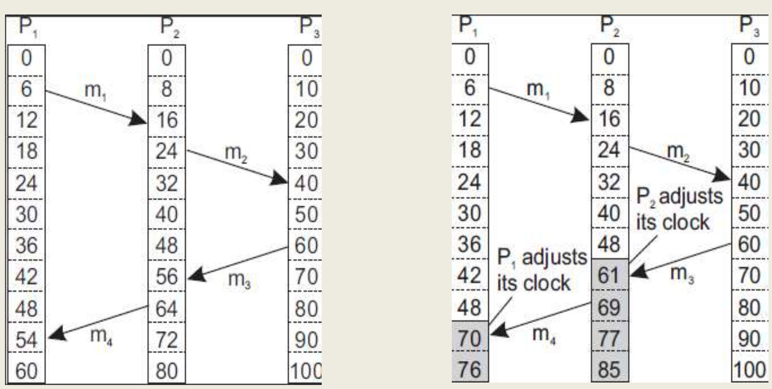
# LOGICAL CLOCKS - 4

- Three processes each with local clocks
- <u>***Lamport's algorithm***</u> corrects their values

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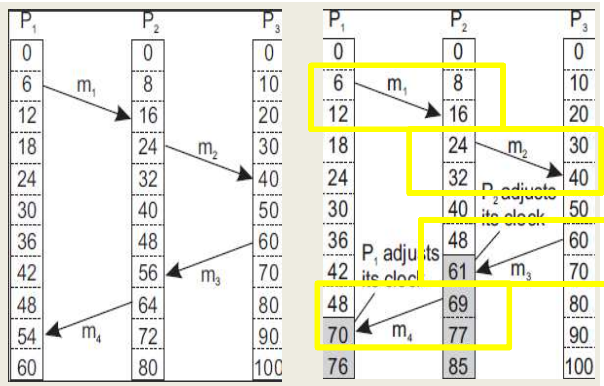
# LOGICAL CLOCKS

- **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
64: 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, ts(m)}
4. Ties broken by considering Proc ID: i<j;  <40,i>  <  <40,j>

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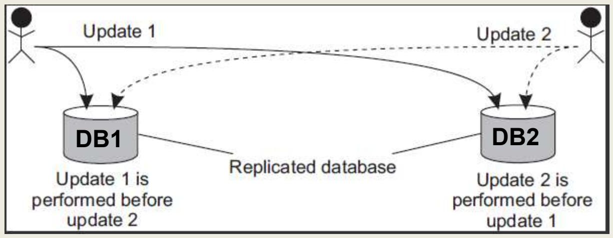
# TOTAL-ORDERED MULTICASTING

- 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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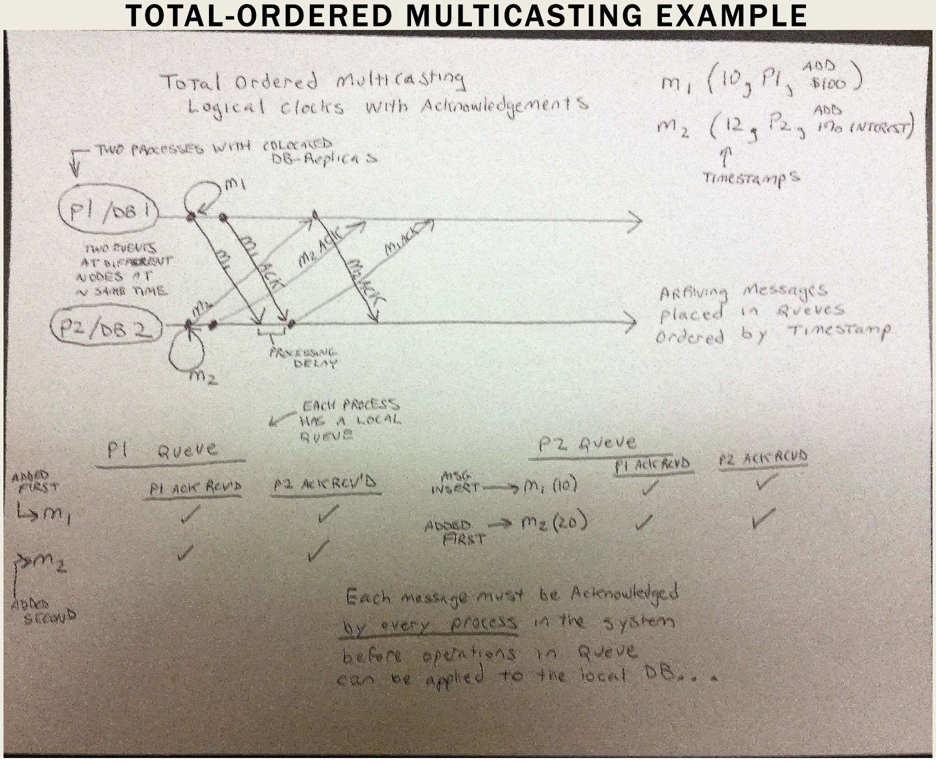
# TOTAL-ORDERED MULTICASTING EXAMPLE

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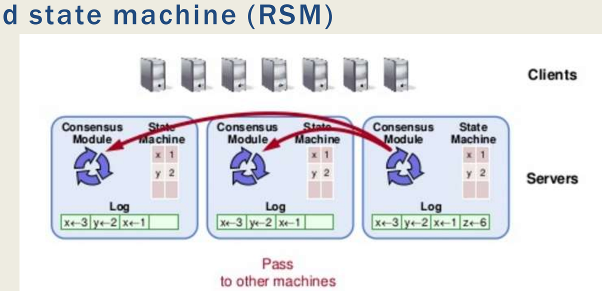
# TOTAL-ORDERED MULTICASTING - 2

- Each message timestamped with local logical clock of sender
- Multicast message is conceptually sent to the sender
- 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
- Process delivers messages to application only when message at the head of the queue has been acknowledged by every process in the system



# TOTAL-ORDERED MULTICASTING - 3

- Can be used to provide 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)



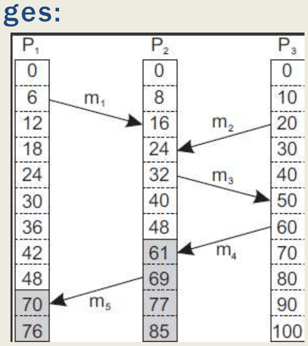
# VECTOR CLOCKS

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



# WHAT IS CAUSALITY?

- 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?***

# VECTOR CLOCKS

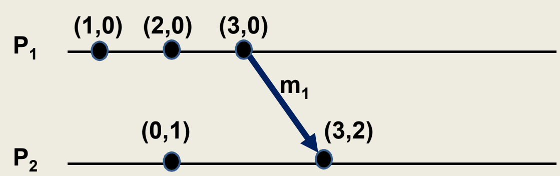
- Vector clocks keep track of <u>causal history</u>
- If two local events happened at process P, then the causal history H(p2) of event p2 is {p1,p2}

- 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 <u>max</u> of: the message timestamp –or- the local vector clock ($VC_j$)

# 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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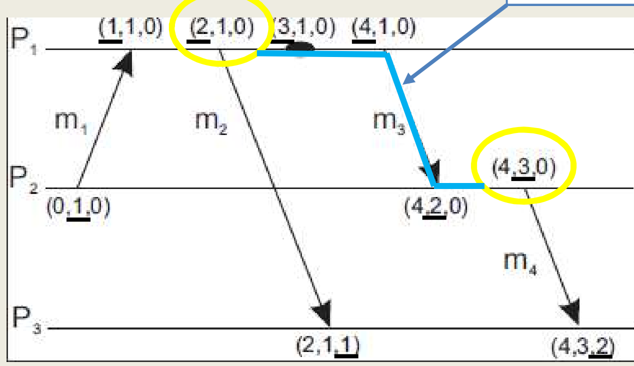
# VECTOR CLOCKS EXAMPLE

- Local clock is underlined

CAUSALITY




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

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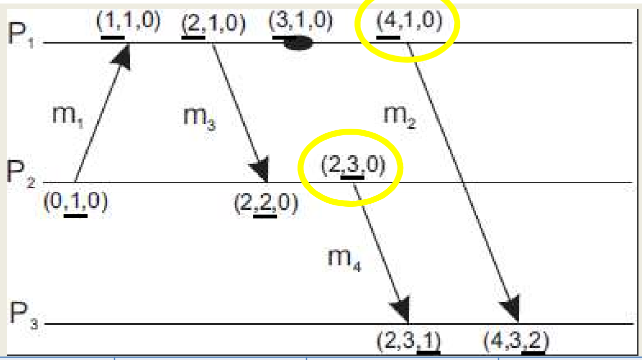
# VECTOR CLOCKS EXAMPLE - 2




| ts ($m_2$) | ts($m_4$) | ts($m_2$)<ts($m_4$) | ts($m_2$)>ts($m_4$) | 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 ?



# QUESTIONS

# EXTRA SLIDES

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