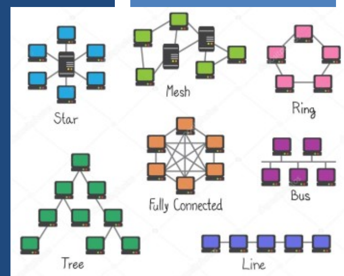
TCSS 558:
APPLIED DISTRIBUTED COMPUTING



Chapter 6 – Coordination - II

Wes J. Lloyd
School of Engineering
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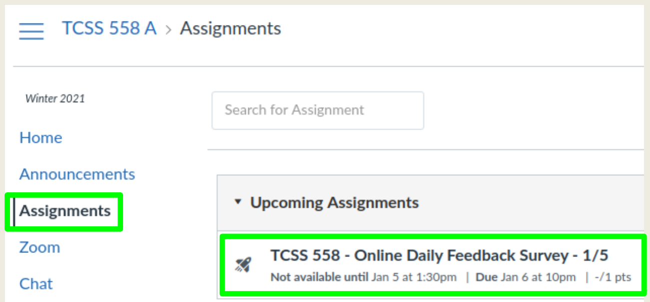
OBJECTIVES – 2/28

- **Questions from 2/23**
- Assignment 2: Replicated Key Value Store
- Chapter 4.4 - Review / Finish
- Chapter 6: Coordination
  - Chapter 6.1: Clock Synchronization
  - Chapter 6.2: Logical Clocks
    Vector Clocks
- Class Activity – Total Ordered Multicasting (Thursday)
  - Chapter 6.3: Distributed Mutual Exclusion

2

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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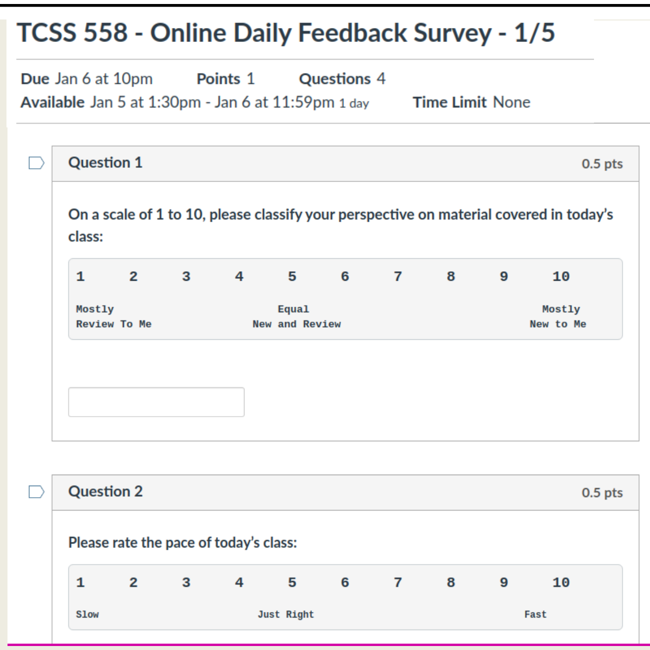

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (31 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.57 (↑ - *previous 6.42*)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.94 (↑ - *previous 5.81*)**

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TENURE TRACK FACULTY CANDIDATE RESEARCH SEMINARS – EXTRA CREDIT

- Wednesday March 1 – 12:30pm – Cherry Parkes room 106
  - Dr. Jiaxuan You CS PhD Stanford University
    Talk title: Learning from the Interconnected World with Graphs
- Friday March 3 – 12:30pm – Cherry Parkes room 106
  - Dr. Dongfang Zhao CS PhD Illinois Institute of Technology
    Talk title: High-Performance Data-Intensive Computing Systems
- Earn up to 2.5% extra credit added to the overall course grade
- Scored out of 5 total points
- First seminar – earn 2 points
- 2nd, 3rd, 4th seminar – earn 1 point each

Add to final course grade:
(Total_seminar_points / 5 points) * 2.5%

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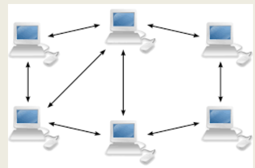
FEEDBACK FROM 2/23

- ***Where are the message queues located in peer-to-peer systems?***



- "**Peer-to-peer**" refers to a network topology, which is how nodes are connected
- A **message queue** is a component of a component-based or n-tier application
- A message queue is an architectural component that facilitates implementation of distributed applications
- *Where could a message queue be located for a distributed system that exists across a group of nodes with a peer-to-peer network topology ?*
  - *Is the message queue replicated?*
  - *If numbering nodes from left-to-right, which is most accessible?*

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FEEDBACK - 2

- ***Is rumor spreading a subset of gossiping spreading, just with the addition of the stopping mechanism?***
- YES
- ***Does rumor spreading also apply the push/pull/push-pull model?***
- Yes, it could
- Push/pull/push-pull refers to how data is spread in the system between nodes

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FEEDBACK - 3

- ***About message flooding on page 59 of slides. What's the meaning of a higher dimension? Why just choose node 1101…?***
- If the message arrives at node 1101 on an edge labeled as level 2
- We then label all outbound edges from 1101, and only forward the message along edges that are a higher order than that of the edge that received the message
- This way we can minimize the number of messages for broadcast of the n-dimensional hypercube
- We will go over this again…

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OBJECTIVES – 2/28

- Questions from 2/23
- **Assignment 2: Replicated Key Value Store**
- Chapter 4.4 - Review / Finish
- Chapter 6: Coordination
  - Chapter 6.1: Clock Synchronization
  - Chapter 6.2: Logical Clocks
    Vector Clocks
- Class Activity – Total Ordered Multicasting (Thursday)
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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 2

- **Sunday March 12th**
- Goal: Replicated Key Value Store
- Team signup posted on Canvas under 'People'
- Build off of Assignment 1 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

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OBJECTIVES – 2/28

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    Vector Clocks
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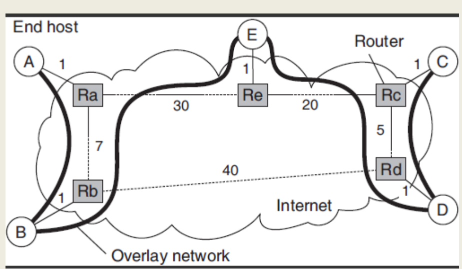
REVIEW

- Consider sending a message from node B to D:
- What is the Link Stress at physical node Re ?
- What is the delay from B to D via the underlying network ?
- What is the delay from B to D via the overlay network ?
- What is the stretch from B to D ?

Numbers represent network delay between nodes



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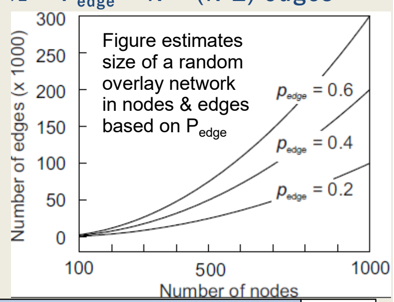
RANDOM GRAPHS

- Used when no information on the structure of the overlay network
- Assume network can be represented as a **Random graph**
- Random graphs are described by a probability distribution:

1. Given a probability P_{edge} that two nodes are joined
2. Size of a random overlay network is: ½ * P_{edge} * N * (N-1) edges

Random graphs allow us to assume some structure (# of nodes, # of edges) regarding the network by scaling the P_{edge} probability

Assumptions may help then to reason or rationalize about the network…



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PROBABILISTIC FLOODING

Washington state in winter?

- When a node is flooding a message m: (p_{flood}) is the probability that the message is spread to a specific neighbor =(p_{flood})
- Throttle message flooding based on a probability
- Implementation needs to considers # of neighbors to achieve various p_{flood} scores
- With lower p_{flood} messages may not reach all nodes

- **Efficiency of probabilistic broadcasting:** For random network with 10,000 nodes
- With p_{edge} = 0.1 and p_{flood} =.01
- Achieves 50-fold reduction in messages vs. full flooding

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PROBABILISTIC FLOODING

Washington state in winter?

- When a node is flooding a message m:
  (p_{flood}) is the probability that the message is spread to a specific neighbor =(p_{flood})
- Thrott
- Imple[…] to achiev
- With l[…]s
- **Efficiency of probabilistic broadcasting:** For random network with 10,000 nodes
- With p_{edge} = 0.1 and p_{flood} =.01
- Achieves 50-fold reduction in messages vs. full flooding

How many edges does network with 10,000 nodes have with p_{edge}=0.1?

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PROBABILISTIC FLOODING

Washington state in winter?

- When a node is flooding a message m:
  (p_{flood}) is the probability that the message is spread to a specific neighbor =(p_{flood})
- Thrott
- Imple[…] to achiev
- With l[…]s
- **Efficie**[…]m netwo
- With p_{edge} = 0.1 and p_{flood} =.01
- Achieves 50-fold reduction in messages vs. full flooding

How many edges does network with 10,000 nodes have with p_{edge}=0.1?

Edges = $\frac{1}{2} * P_{edge} * N * (N-1)$

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PROBABILISTIC FLOODING

Washington state in winter?

- When a node is flooding a message m:
  (p_{flood}) is the probability that the message is spread to a
  speci
- Throt
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- With
- **Effici** ... n
  network with 10,000 nodes
- With p_{edge} = 0.1 and p_{flood} =.01
- Achieves 50-fold reduction in messages vs. full flooding

How many edges does network with 10,000 nodes have with p_{edge}=0.1?

Edges = ½ * P_{edge} * N * (N-1)
½ * (.1) * (10000) * (9999)

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PROBABILISTIC FLOODING

Washington state in winter?

- When a node is flooding a message m:
  (p_{flood}) is the probability that the message is spread to a
  speci
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- **Effici** ... n
  netw
- With p_{edge} = 0.1 and p_{flood} =.01
- Achieves 50-fold reduction in messages vs. full flooding

How many edges does network with 10,000 nodes have with p_{edge}=0.1?

Edges = ½ * P_{edge} * N * (N-1)
½ * (.1) * (10000) * (9999)
4,999,500 edges

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PROBABILISTIC FLOODING

Washington state in winter?

- When a node is flooding a message m:
  (p_{flood}) is the probability that the message is spread to a specific neighbor =(p_{flood})
- Throt
- Imple ... achie
- With
- Effici ... netw
- With p_{edge} = 0.1 and p_{flood} =.01
- Achieves 50-fold reduction in messages vs. full flooding

What does it mean to have p_{flood} =.01?

With lower p_{flood} messages may not reach all nodes

If there are 10,000 nodes and ~5 million edges, how many messages is full flooding?

> every node sends to all neighbors across all edges

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PROBABILISTIC FLOODING

Washington state in winter?

- When a node is flooding a message m:
  (p_{flood}) is the probability that the message is spread to a specific neighbor =(p_{flood})

What does it mean to have p_{flood} =.01?

node Q has n neighbors
Probability that ***all*** neighbors don't forward message to Q is $p=(1-p_{flood})^n$

network with 10,000 nodes
- With p_{edge} = 0.1 and p_{flood} =.01
- Achieves 50-fold reduction in messages vs. full flooding

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PROBABILISTIC FLOODING

Washington state in winter?

What does it mean to have p_{flood} =.01?

node Q has n neighbors

Probability that ***no*** neighbors of Q forward the message to Q:

$p=(1-p_{flood})^n$ ← *probability of Q not getting the message*

10 nodes: if n=10, $p=(1-.01)^{10}=.904$ (small network, few edges, likely Q doesn't get msg)

100 nodes: if n=100, $p=(1-.01)^{100}=.366$ (less likely Q doesn't get msg)

298 nodes: if n=298, $p=(1-.01)^{298}=.05$ (Q probably get msg)

- Achieves 50-fold reduction in messages vs. full flooding

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MESSAGE FLOODING W/ HYPERCUBE

- **Hypercube:** for broadcast send minimum # of messages
  Only forward msg along edges with **higher dimension**
- Node(1101)–neighbors {0101,1100,1001,1111}
- Node (1101) – receives msg on incoming broadcast edge = 2
- Broadcast from 1101 - Label Edges:
- Edge to 0101 – labeled 1 – change the 1^{st} bit
- Edge to 1100 – labeled 4 – change the 4^{th} bit ***<FORWARD>***
- Edge to 1001 – labeled 2 – change the 2^{nd} bit
- Edge to 1111 – labeled 3 – change the 3^{rd} bit ***<FORWARD>***
- N(1101) broadcast – forward only to N(1100) and N(1111)
- (1100) and (1111) are the ***higher dimension edges***
- Broadcast requires just: N-1 messages, where nodes $N=2^n$, n=dimensions of hypercube

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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

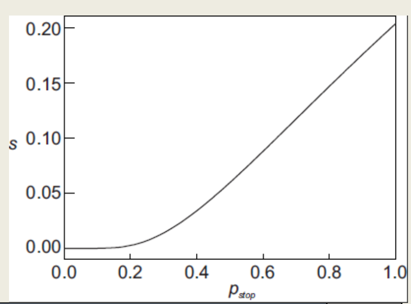
- p_{stop}, is the probability node will stop spreading once contacting a node that already has the message

- 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 < 0.20 with high p_{stop}

- Susceptible nodes (s) vs. probability of stopping →



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REMOVING DATA

- Gossiping is good for spreading data
- **But how can data be removed from the system?**
- Idea is to issue ***"death certificates"***
- Act like data records, which are spread like data
- When death certificate is received, data is deleted
- Certificate is held to prevent data element from reinitializing from gossip from other nodes
- Death certificates time-out after expected time required for data element to clear out of entire system
- A few nodes maintain death certificates forever

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DEATH CERTIFICATE EXAMPLE

- **For example:**
- **Node P** keeps death certificates forever
- **Item X** is removed from the system
- **Node P** receives an update request for **Item X**, but ***also*** holds the death certificate for **Item X**
- **Node P** will recirculate the death certificate across the network for **Item X**

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OBJECTIVES – 2/28

- Questions from 2/23
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    Vector Clocks
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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)*

CH. 6.1: CLOCK SYNCHRONIZATION

L16.31

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CLOCK SYNCHRONIZATION

- Example:
- "make" is used to compile source files into binary object and executable files
- As an optimization, make only compiles files when the "last modified time" of source files is more recent than object and executables
- Consider if files are on a shared disk of a distributed system where there is no agreement on time
- Consider if the program has 1,000 source files

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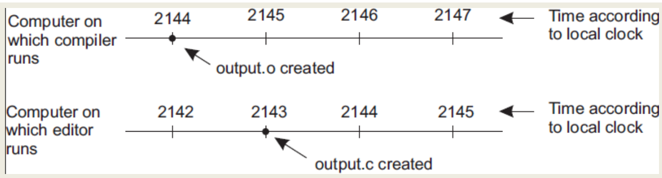
TIME SYNCHRONIZATION PROBLEM FOR DISTRIBUTED SYSTEMS



- Updates from different machines, may have clocks set to different times
- Make becomes confused with which files to recompile

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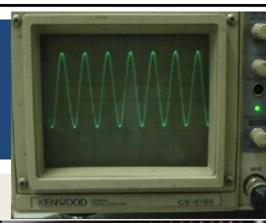
PHYSICAL CLOCKS



- **Computer timers:** precisely machined quartz crystals
- When under tension, they oscillate at a well defined frequency
- In analog electronics/communications crystals once used to set the frequency of two-way radio transceivers for
- Today, crystals are associated with a counter and holding register on a digital computer.

1960s ERA radio crystal →

- Each oscillation decrements a counter by one
- When counter gets to zero, an interrupt fires
- Can program timer to generate interrupt, let's say 60 times a second, or another frequency to track time

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COMPUTER CLOCKS

- Digital clock on computer sets base time
- Crystal clock tracks forward progress of time
  - Translation of wave "ticks" to clock pulses
- CMOS battery on motherboard maintains clock on power loss

- **Clock skew**: physical clock crystals are not exactly the same
- Some run at slightly different rates
- Time differences accumulate as clocks drift forward or backward slightly

- In an automobile, where there is no clock synchronization, clock skew may become noticeable over months, years

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UNIVERSAL COORDINATED TIME

- **Universal Coordinated Time (UTC)**

```
ubuntu@ip-172-31-58-89:~$ date
Thu Nov 16 10:13:39 UTC 2017
```

  - Worldwide standard for time keeping
  - Equivalent to Greenwich Mean Time (United Kingdom)
  - 40 shortwave radio stations around the world broadcast a short pulse at the start of each second (WWV)
  - World wide "atomic" clocks powered by constant transitions of the non-radioactive caesium-133 atom
    - 9,162,631,770 transitions per second

- Computers track time using UTC as a base
  - Avoid thinking in local time, which can lead to coordination issues
  - Operating systems may translate to show local time

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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** (π): 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** (ρ): clock specifications include one

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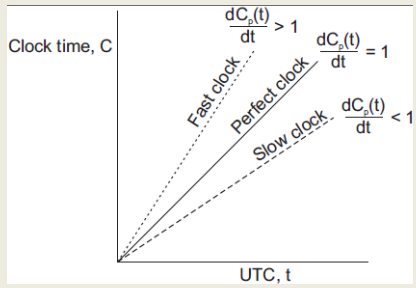
CLOCK SYNCHRONIZATION - 2

- If two clocks drift from UTC in opposite directions, after time Δt after synchronization, they may be 2ρ apart.
  - ρ - clock drift rate, π - clock precision (max 50ns)
- 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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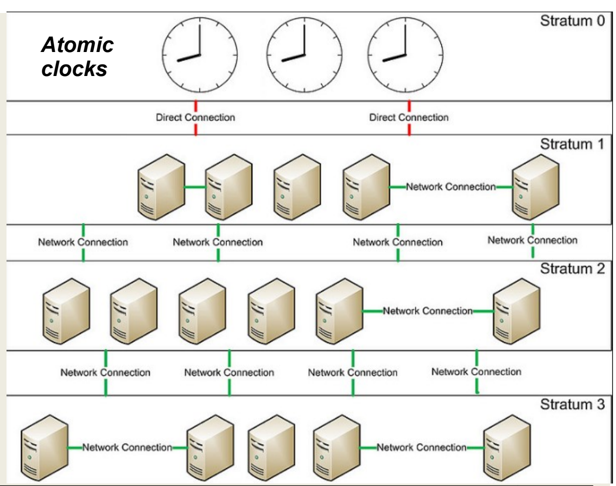
NETWORK TIME PROTOCOL

- 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



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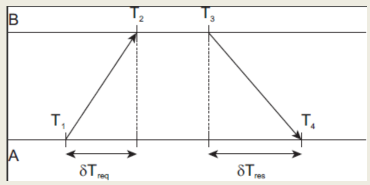
NTP - 2

- 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

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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)

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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

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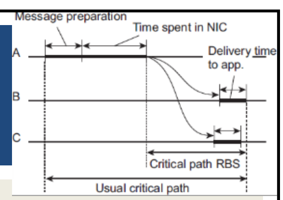
CLOCK SYNCHRONIZATION IN WIRELESS NETWORKS



- Sensor networks bring unique challenges for clock synchronization
  - ***Address resource constraints***: limited power, multihop routing slow
- <u>**Reference broadcast synchronization (RBS)**</u>
- Provides time precision, 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 ***<u>can</u>*** be sent

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REFERENCE BROADCAST SYNCHRONIZATION (RBS)

- Node broadcasts reference message k
- Each node p records time Tp,k when k is received
- Tp,k 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

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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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WE WILL RETURN AT 3:01 PM

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OBJECTIVES – 2/28

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- Assignment 2: Replicated Key Value Store
- Chapter 4.4 - Review / Finish
- Chapter 6: Coordination
  - Chapter 6.1: Clock Synchronization
  - **Chapter 6.2: Logical Clocks**
    Vector Clocks
- Class Activity – Total Ordered Multicasting (Thursday)
  - 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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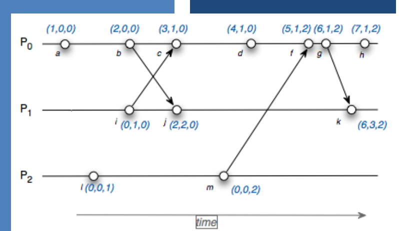

CH. 6.2: LOGICAL CLOCKS

L16.50

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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

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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

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LOGICAL CLOCKS – 3

- If two events, say event X and event Y do not exchange messages, not even via third parties, then the sequence of X→Y vs. Y→X **can not be determined!!**
- Within the system, these events appear **concurrent**
- **Concurrent:** 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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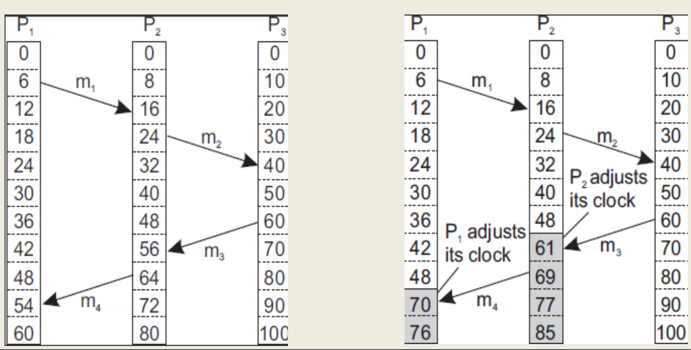
LOGICAL CLOCKS - 4

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



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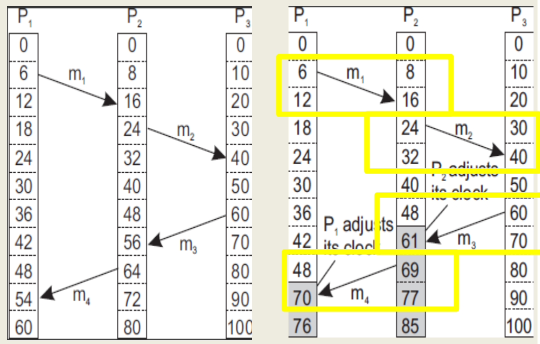
LOGICAL CLOCKS

- **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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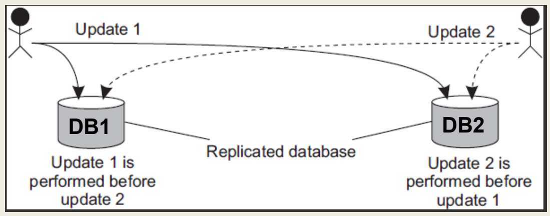
TOTAL-ORDERED MULTICASTING

- 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

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

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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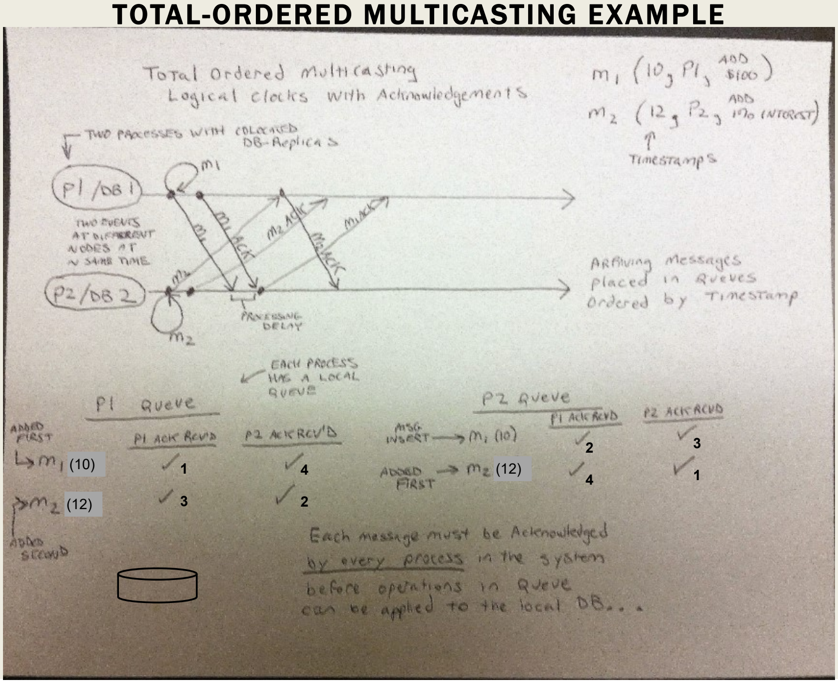
TOTAL-ORDERED MULTICASTING EXAMPLE



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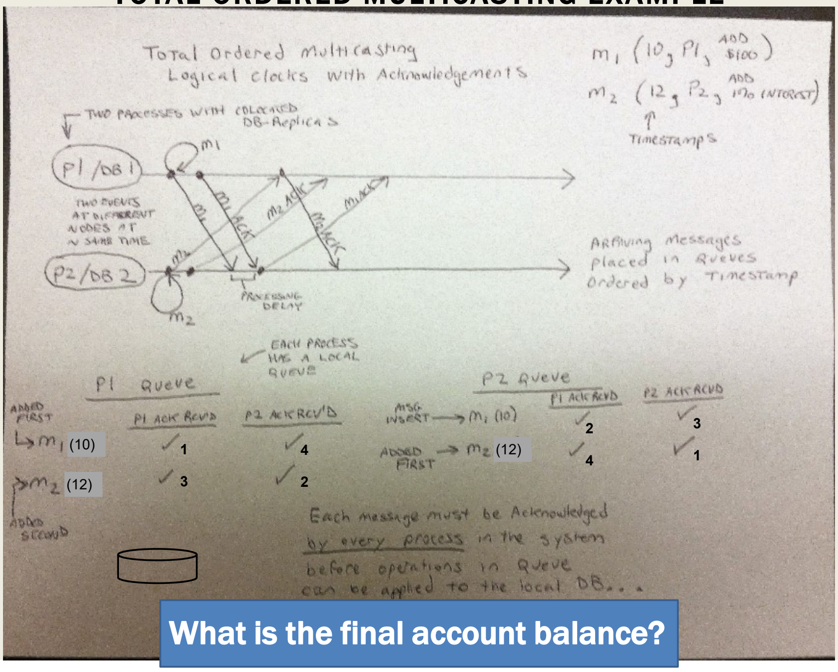
TOTAL-ORDERED MULTICASTING EXAMPLE



What is the final account balance?

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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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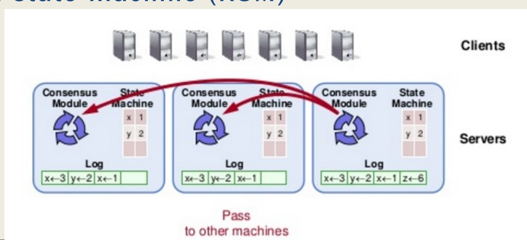
TOTAL-ORDERED MULTICASTING - 3

- 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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OBJECTIVES – 2/28

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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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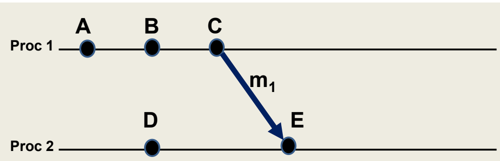
WHAT IS CAUSALITY?



- 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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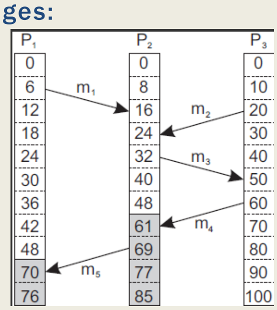
CAUSALITY - 2

- **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…

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?***

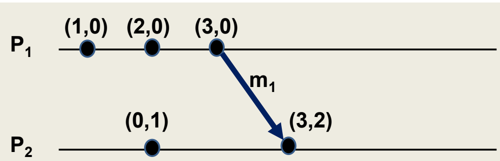
VECTOR CLOCKS

- 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

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)

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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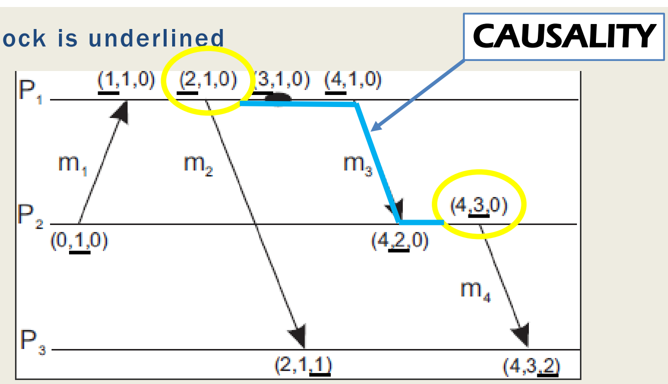
VECTOR CLOCKS EXAMPLE

- Local clock is underlined



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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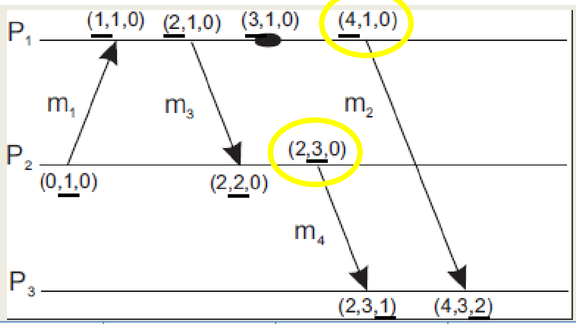
VECTOR CLOCKS EXAMPLE - 2



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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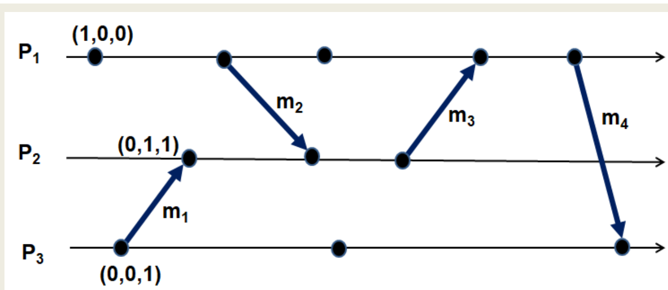
VECTOR CLOCKS EXAMPLE - 3



- Provide a vector clock label for unlabeled events

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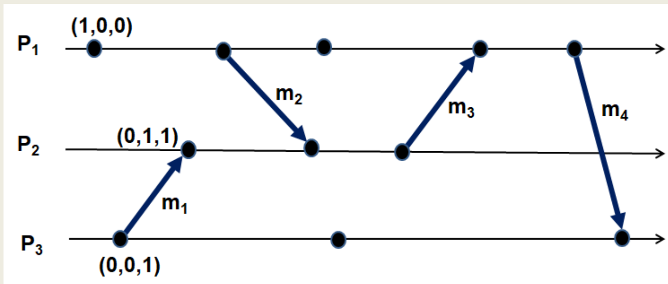
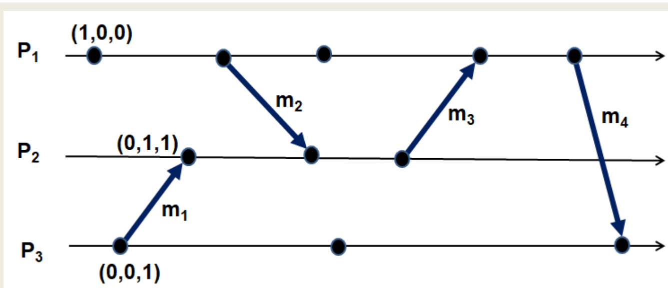
VECTOR CLOCKS EXAMPLE - 4



- 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.

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.

OBJECTIVES – 2/28

- Questions from 2/23
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OBJECTIVES – 2/28

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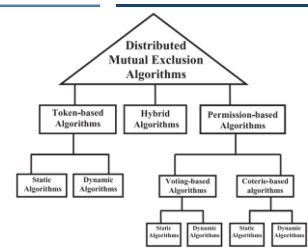

CH. 6.3: DISTRIBUTED MUTUAL EXCLUSION

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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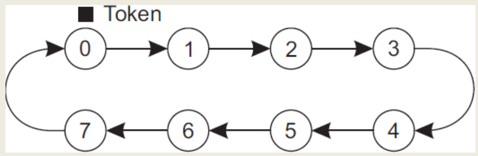
TOKEN-RING ALGORITHM

- 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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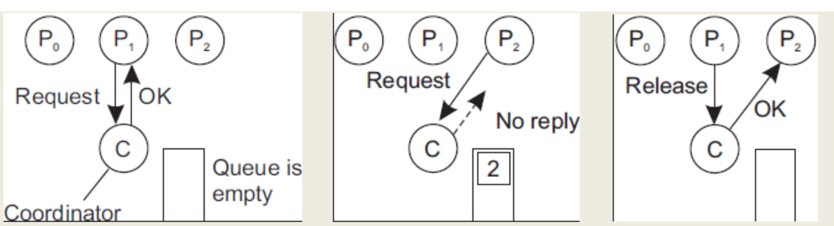
DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS - 3

- **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 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 V 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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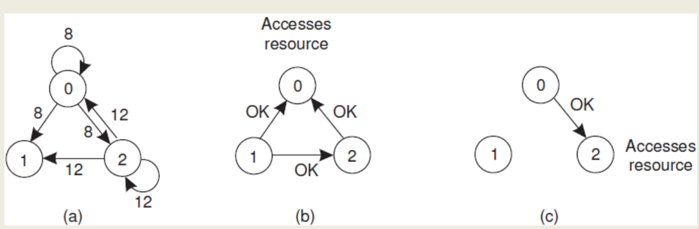
DISTRIBUTED ALGORITHM - 3

- 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 **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

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]

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 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 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

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

QUESTIONS

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