TCSS 558: APPLIED DISTRIBUTED COMPUTING

Chapter 4 – Communication
Chapter 6 - Coordination

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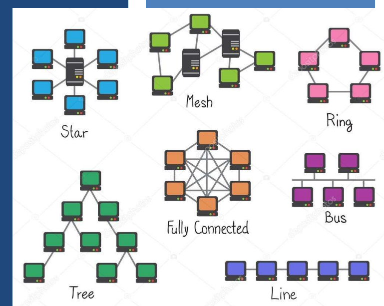


OBJECTIVES

- Homework 2
- Active Reading Quiz

- Chapter 4 Communication
- 4.4 Multicast communication

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

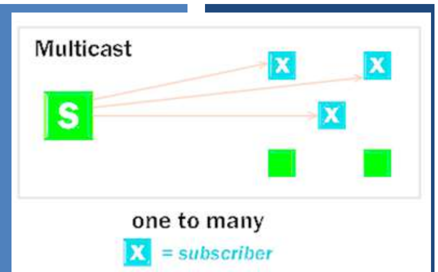
FEEDBACK – 3/4

- **How do you give MPI failure transparency?**
- Failure transparency involves hiding from the user, the fact that the system (or some aspect of it) has failed
- Providing failure transparency requires a system to implement fault tolerance
- Here is an FAQ on fault tolerance in OpenMPI:
- https://www.open-mpi.org/faq/?category=ft
- A number of techniques for fault tolerance have been employed previously in OpenMPI, but are not deprecated
- OpenMPI is said to mimic the fault tolerance provided by the FT-MPI framework

FEEDBACK - 2

- **What types of messages are usually sent with gossip spreading?**

- Gossip, in the context of Ch. 4.4, refers to multicast communication (one to many) across unstructured peer-to-peer network
- These are ad hoc connections where the structure of the network is unknown
- Multicast messages could be anything
- Multicast often concerns data dissemination – spreading data to many peer nodes as quickly and efficiently as possible



Apache ActiveMQ

CH. 4.4: MULTICAST COMMUNICATION

L14.5

MULTICAST COMMUNICATION

- Sending data to multiple receivers
- Many ***failed*** proposals for network-level / transport-level protocols to support multicast communication
- **Problem:** How to set up communication paths for information dissemination?
- **Solutions:** require huge management effort, human intervention

- Focus shifted more recently to **peer-to-peer** networks
  - Structured overlay networks can be setup easily and provide efficient communication paths
  - Application-level multicasting techniques more successful
  - Gossip-based dissemination: unstructured p2p networks

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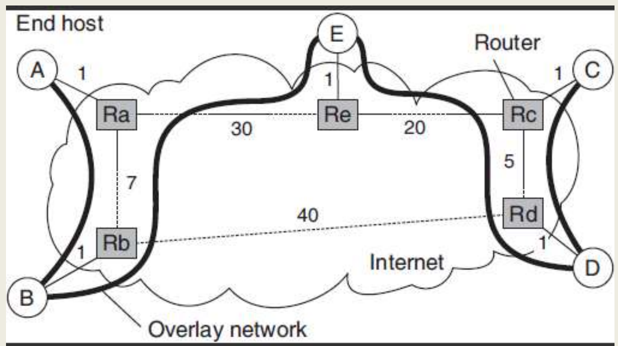
NETWORK STRUCTURE

- **Overlay network**
  - Virtual network implemented on top of an actual physical network
- **Underlying network**
  - The actual physical network that implements the overlay



FLOOD-BASED MULTICASTING

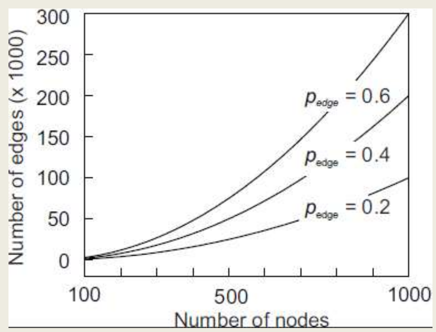
- Broadcasting: every node in overlay receives message
- Key design issue: minimize the use of intermediate nodes for which the message is not intended
- Tree: if only the leaf nodes are to receive the multicast message, many intermediate nodes are involved
- Solution: construct an overlay network for each multicast group
- **Flooding**: each node simply forwards a message to each of its neighbors, except to the message originator

RANDOM GRAPHS

- When no information on the structure of the overlay network
- Assume network can be represented as a <u>Random graph</u>
- Probability P_{edge} that two nodes are joined
- Overlay network will have: 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, concept is to enforce a probability of message spread (p_{flood})
- Throttles message flooding based on a probability
- Implementation needs to consider # of neighbors to achieve various p_{flood} scores
- With lower p_{flood} messages may not reach all nodes
- <u>**USEFULNESS:**</u> 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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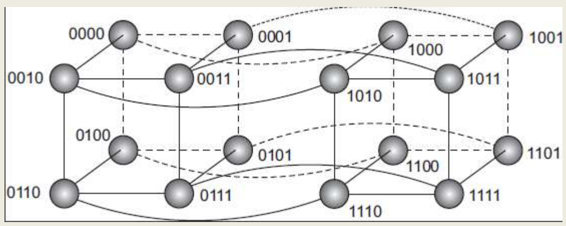
MESSAGE FLOODING

- For deterministic topologies (such as hypercube), design of efficient flooding scheme is much simpler
- If the overlay network is structured, this gives us a deterministic topology
- Schlosser et al [2002] – offer simple and efficient ***broadcasting scheme*** that relies on keeping track of neighbors per dimension



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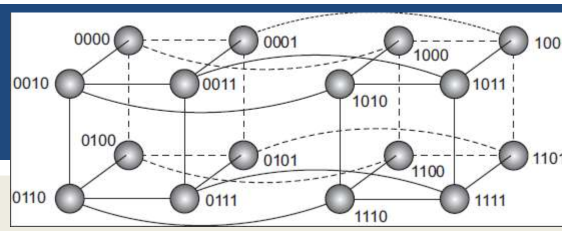
MESSAGE FLOODING - 2



- **Hypercube Broadcast**
- N(1001) starts the network broadcast
- N(1001) neighbors {0001,1000,1011,1101}
- N(1001) Sends message to all neighbors
- **Edge Labels *(which bit is changed, 1st, 2nd, 3rd, 4th…)***
- Edge to 0001 – labeled 1 – change the 1st bit
- Edge to 1000 – labeled 4 – change the 4th bit
- Edge to 1011 – labeled 3 – change the 3rd bit
- Edge to 1101 – labeled 2 – change the 2nd bit
- **RULE: nodes only forward along edges with a higher dimension**
- Node 1101 receives message on edge labeled 2
- Broadcast msg is only forwarded on higher dimension edges

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MESSAGE FLOODING - 3

- Hypercube: forward msg along edges with higher dimension
- Node(1101)–neighbors {0101,1100,1001,1111}
- Node (1101) - incoming broadcast edge = 2
- Label Edges:
- Edge to 0101 – labeled 1 – change the 1st bit
- Edge to 1100 – labeled 4 – change the 4th bit *<FORWARD>*
- Edge to 1001 – labeled 2 – change the 2nd bit
- Edge to 1111 – labeled 3 – change the 3rd 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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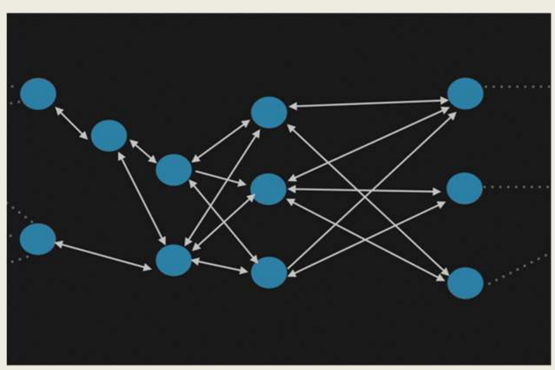
GOSSIP BASED DATA DISSEMINATION

- When structured peer-to-peer topologies are not available
- Gossip based approaches support multicast communication over unstructured peer-to-peer networks
- General approach is to leverage how gossip spreads across a group
- This is also called "epidemic behavior"…
- Data updates for a specific item begin at a specific node



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INFORMATION DISSEMINATION

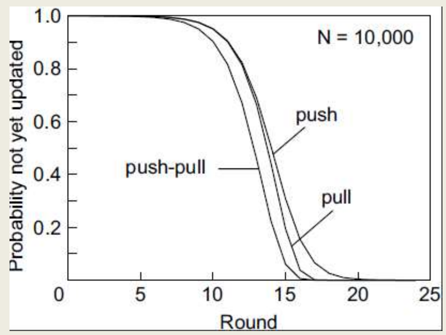
- **Epidemic algorithms**: algorithms for large-scale distributed systems that spread information
- Goal: "infect" all nodes with new information as fast as possible
- **Infected**: node with data that can spread to other nodes
- **Susceptible**: node without data
- **Removed**: node with data that is unable to spread data

ANTI ENTROPY DISSEMINATION MODEL

- **Anti-entropy:** Propagation model where node P picks node Q at random and exchanges message updates
- Akin to random walk
- **PUSH:** P only **pushes** its own updates to Q
- **PULL:** P only **pulls** in new updates from Q
- **TWO-WAY:** P and Q send updates to each other (i.e. a push-pull approach)
- Push only: hard to propagate updates to last few hidden susceptible nodes
- Pull: better because susceptible nodes can pull updates from infected nodes
- Push-pull is better still

ANTI ENTROPY EFFECTIVENESS

- **Round**: span of time during which every node takes initiative to exchange updates with a randomly chosen node
- The number of rounds to propagate a single update to all nodes requires O(log(N)), where N=number of nodes
- Let p_i denote probability that node P has not received msg m after the i^{th} round.
- For pull, push, and push-pull based approaches:



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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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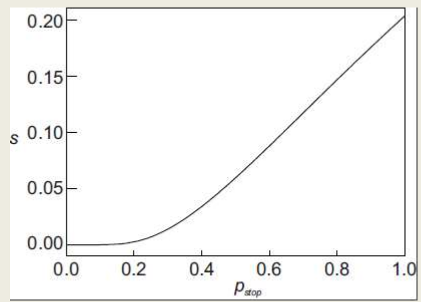
RUMOR SPREADING - 2

- Does not guarantee all nodes will be updated
- The 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 →



DIRECTIONAL GOSSIPING

- Taking network topology into account can help
- When gossiping, nodes connected to only a few other nodes are more likely to be contacted
- <u>Epidemic protocols assume:</u>
- For gossiping, nodes are randomly selected
- One node, can randomly select any other node in the network
- Complete set of nodes is known to each member

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

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**

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)*

CHAPTER 6 - COORDINATION

- How can processes synchronize and coordinate data?
- Process synchronization
  - Coordinate cooperation to grant individual processes temporary access to shared resources (e.g. a file)
- Data synchronization
  - Ensure two sets of data are the same (data replication)
- Coordination
  - Goal is to manage interactions and dependencies between activities in the distributed system
  - Encapsulates synchronization

COORDINATION - 2

- Synchronization challenges begin with <u>time</u>:
  - How can we synchronize computers, so they all agree on the time?
  - How do we measure and coordinate when things happen?
- Fortunately, for synchronization in distributed systems, it is often sufficient to only agree on a relative ordering of events
  - E.g. not actual time

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COORDINATION - 3

- Groups of processes often appoint a <u>coordinator</u>
- <u>Election algorithms</u> can help elect a leader
- Synchronizing access to a shared resource is achieved with <u>distributed mutual exclusion</u> algorithms
- Also in chapter 6:
  - Matching subscriptions to publications in publish-subscribe systems
  - Gossip-based coordinate problems:
    - Aggregation
    - Peer sampling
    - Overlay construction

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CH. 6.1: CLOCK SYNCHRONIZATION

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CLOCK SYNCHORNIZATION

- 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 that 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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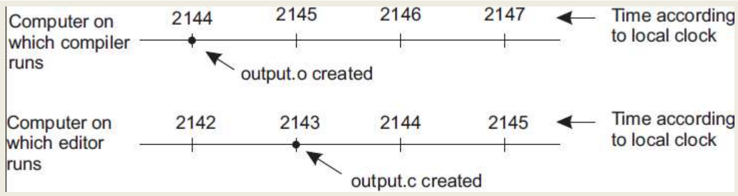
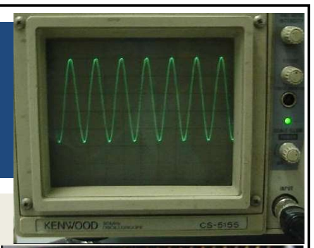
TIME SYNCHRONIZATION PROBLEM FOR DISTRIBUTED SYSTEMS



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

PHYSICAL CLOCKS

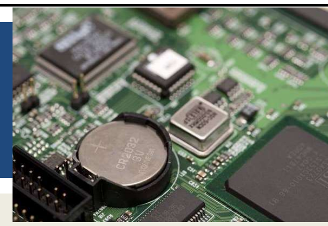


- <u>**Computer timers:**</u> precisely machined quartz crystals
- When under tension, they oscillate at a well defined frequency
- In analog electronics/communications crystals once used to set the frequency of two-way radio transceivers for
- Today, crystals are associated with a counter and holding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

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

UNIVERSAL COORDINATED TIME

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

- Universal Coordinated Time (UTC)
  - 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

COMPUTING: CLOCK CHALLENGES

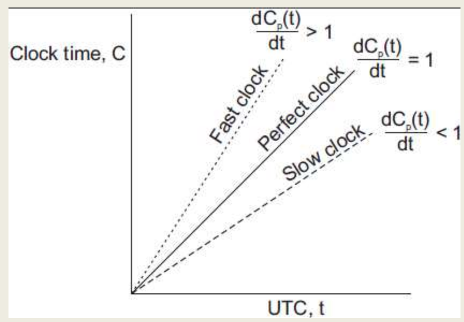
- How do we synchronize computer clocks with real-world clocks?
- How do we synchronize computer clocks with each other?

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

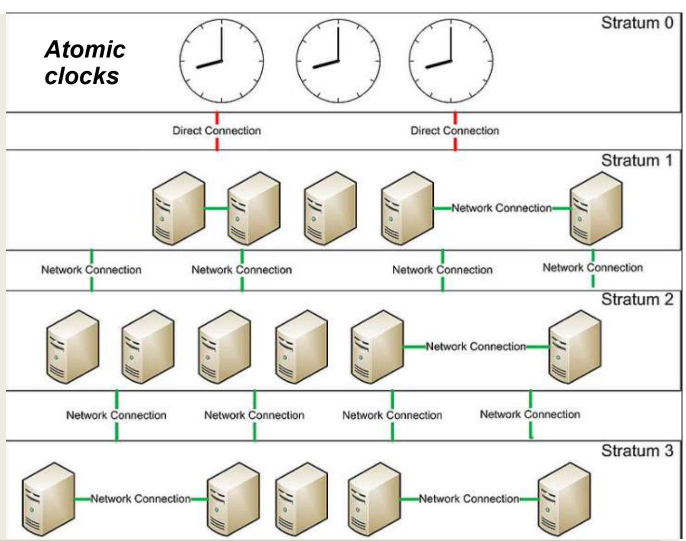
CLOCK SYNCHRONIZATION - 2

- If two clocks drift from UTC in opposite directions, after time Δt after synchronization, they may be 2ρ 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



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

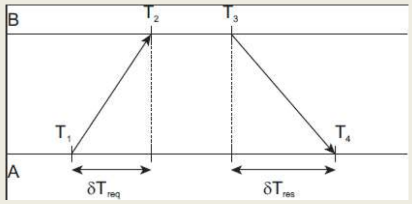


NTP - 2

- 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

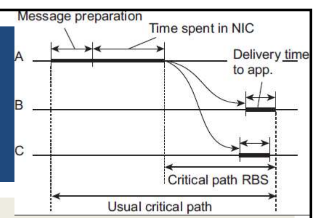
- Cannot set clocks backwards (recall “make” file example)
- Instead, temporarily slow the progress of time to allow fast clock to align with actual time
- Change rate of clock interrupt routine
- Slow progress of time until synchronized
- NTP accuracy is within 1-50ms

- 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:

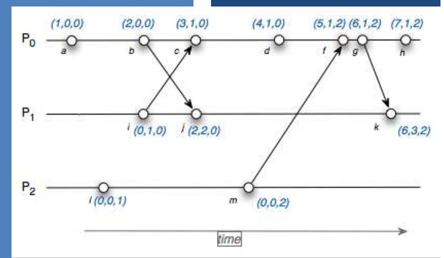
$$Offset[p,q] = \frac{\sum_{k=1}^{M}(T_{p,k} - T_{q,k})}{M}$$

- 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:

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



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

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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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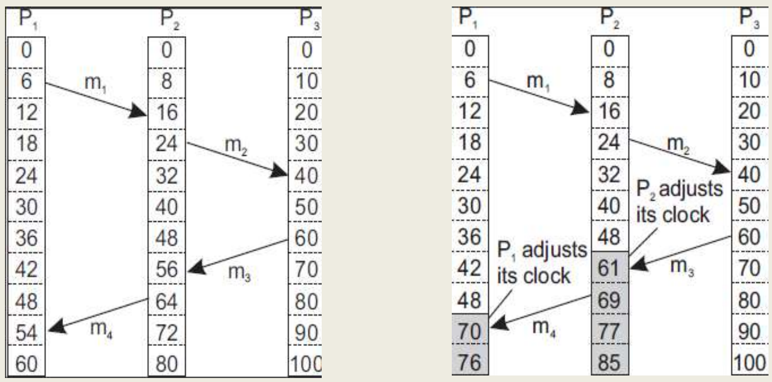
LOGICAL CLOCKS - 4

- Three processes each with local clocks
- ***Lamport's algorithm*** corrects their values



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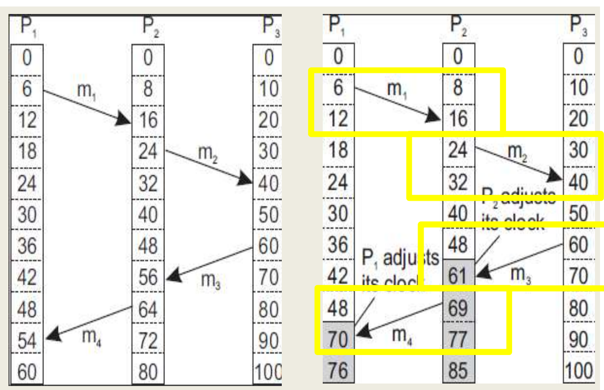
LOGICAL CLOCKS

- **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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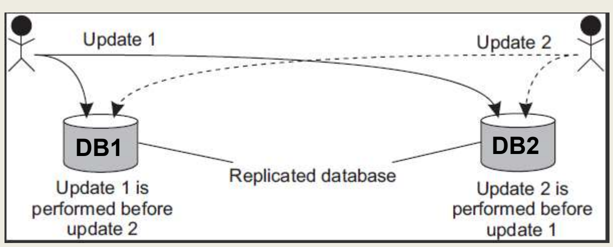
LAMPORT LOGICAL CLOCKS - IMPLEMENTATION

- 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>

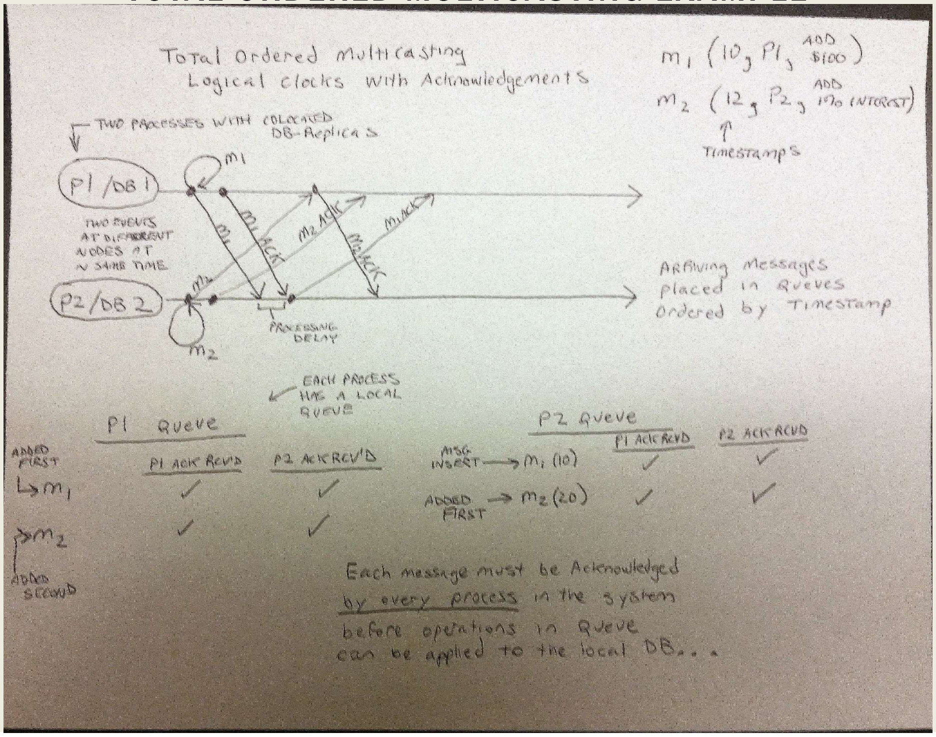
TOTAL-ORDERED MULTICASTING

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



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

TOTAL-ORDERED MULTICASTING EXAMPLE

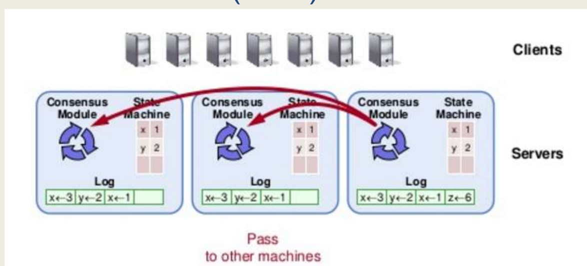


TOTAL-ORDERED MULTICASTING - 2

- 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)

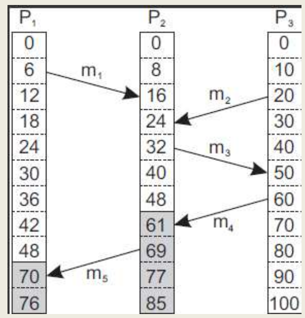


VECTOR CLOCKS

- 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?***

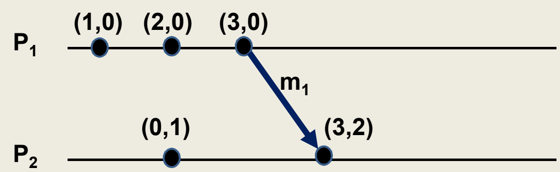
VECTOR CLOCKS

- Vector clocks keep track of **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



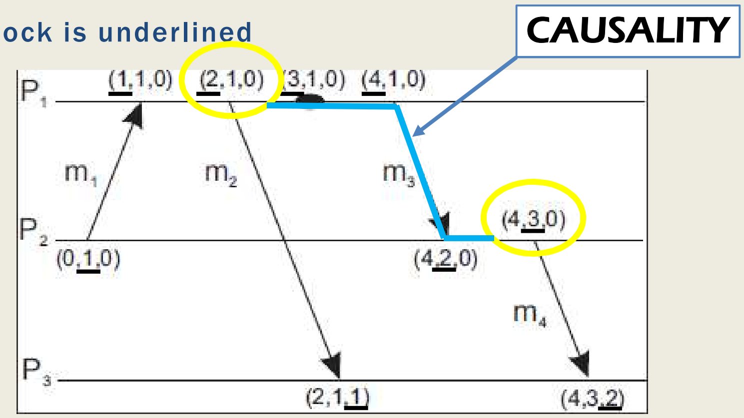
- Each process maintains a vector clock which
  - Captures number of events at the local process (e.g. logical clock)
  - Captures number of events at all other processes
- Causality is captured by:
  - For each event at Pi, the vector clock (VC_i) is incremented
  - The msg is timestamped with VC_i; 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…

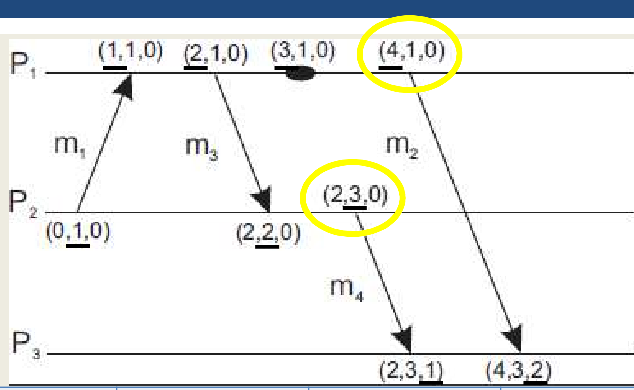
VECTOR CLOCKS EXAMPLE

- Local clock is underlined



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

VECTOR CLOCKS EXAMPLE - 2



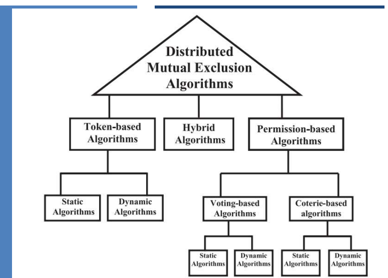
ts (m_2)	ts(m_4)	ts(m_2)<ts(m_4)	ts(m_2)>ts(m_4)	Conclusion
(4,1,0)	(2,3,0)	No	No	m2 and m4 may conflict

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

VECTOR CLOCKS - 4

- **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

- Vector clocks can help us suggest possible causality
- We never know for sure…



CH. 6.3: DISTRIBUTED MUTUAL EXCLUSION

DISTRIBUTED MUTUAL EXCLUSION

- Coordinating access among distributed processes to a shared resource requires **Distributed Mutual Exclusion**
- 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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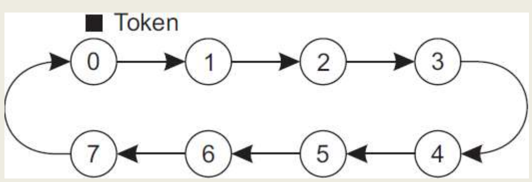
TOKEN-RING ALGORITHM

- 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 for a long time?
3. When node crashes, circular network route is broken
   - Dead nodes can be detected by adding a receipt message for when the token passes from node-to-node
   - When no receipt is received, node assumed dead
   - Dead process can be "jumped" in the ring

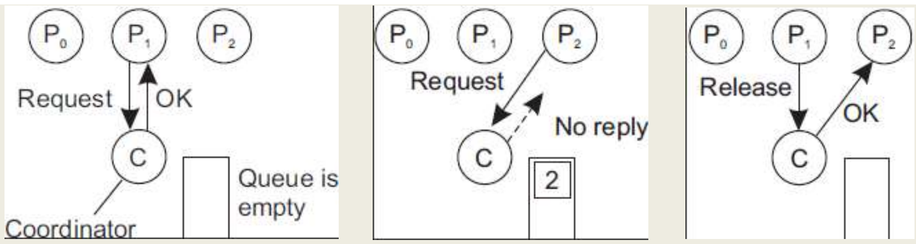
DISTRIBUTED MUTUAL EXCLUSION - 2

- **Permission-based algorithms**
- Processes must require permission from other processes before first acquiring access to the resource

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

CENTRALIZED MUTUAL EXCLUSION

Permission granted from coordinator \/ No response from coordinator



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

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

CENTRALIZED MUTUAL EXCLUSION - 2

- **Issues**
- Coordinator is a single point of failure
- Processes can't distinguish dead coordinator from "permission denied"
  - 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

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

DISTRIBUTED ALGORITHM - 2

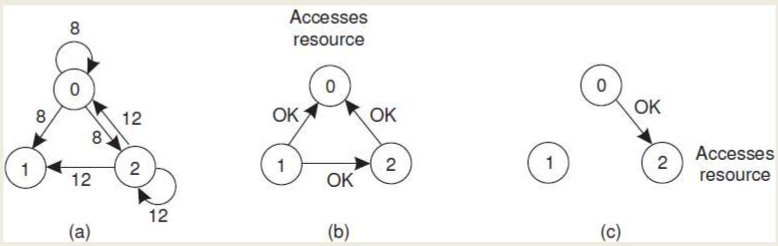
- When each node receives a request message they will:

1. Say OK (*if the node doesn't need the resource*)
2. Make no reply, queue request (*node is using the resource)*
3. Perform a timestamp comparison (*if node is waiting to access the resource*), then:
   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

DISTRIBUTED ALGORITHM - 3

- If Node 0 and Node 2 simultaneously request access
- Node 0's time stamp is lower (8) than Node 2 (12)
- Node 1 and Node 2 grant Node 0 access
- Notice that Node 1 also grants Node 2 permission



- **In case of conflict, lowest timestamp wins!**

CHALLENGES WITH DISTRIBUTED ALGORITHM

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

- **Problem:** When node is accessing the resource, it does not respond
  - Lack of response can be confused with **failure**
  - 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

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*
- Distributed algorithm for mutual exclusion works best for:
  - Small groups of processes
  - When memberships rarely change

QUESTIONS

EXTRA SLIDES

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