Distributed Coordination

Overview

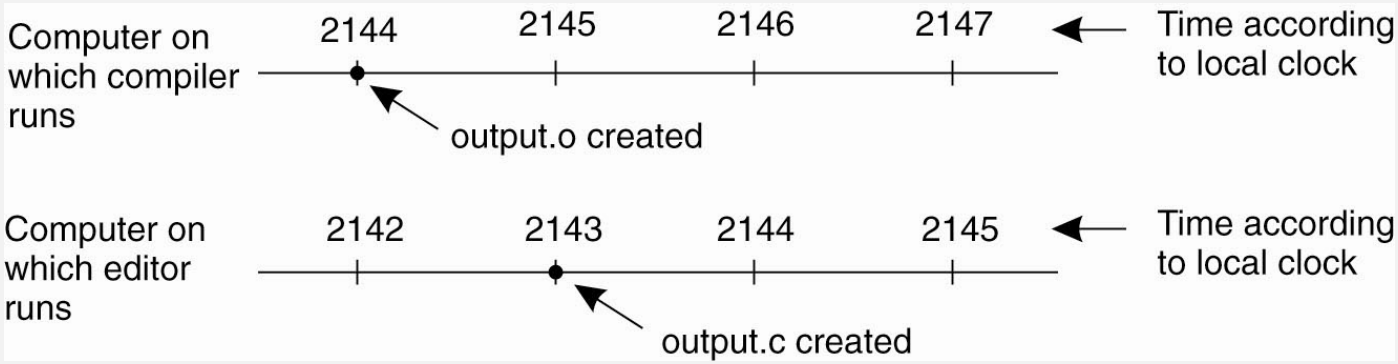
- Synchronization of distributed processes requires new concepts in addition to synchronization of processes in single multi-core systems.
- Topics:
  - Notion of *global time*: absolute time versus relative time
  - *Election algorithms*: for electing a *coordinator* on-the-fly
  - *Distributed mutual exclusion*

Clocks on Computing Devices

- A computer timer is a quartz crystal that oscillates at a well defined frequency.
- Each oscillation decrements a counter by one. When the counter goes down to zero, an interrupt is generated and the counter is reloaded from a holding register.
- Each interrupt is called a clock tick (and can be set to interrupt certain number of times per second).
- The time is stored on a battery-backed CMOS RAM. At every clock tick, the interrupt service procedure adds one to the stored time.
- With one computer even if the time is off it is usually not a problem. With n computers, all n crystals will run at slightly different rates, causing the software clocks to gradually get out of sync. This difference in time values is called clock skew.

Clock Skew

- Clock skew illustrated on a shared file system:

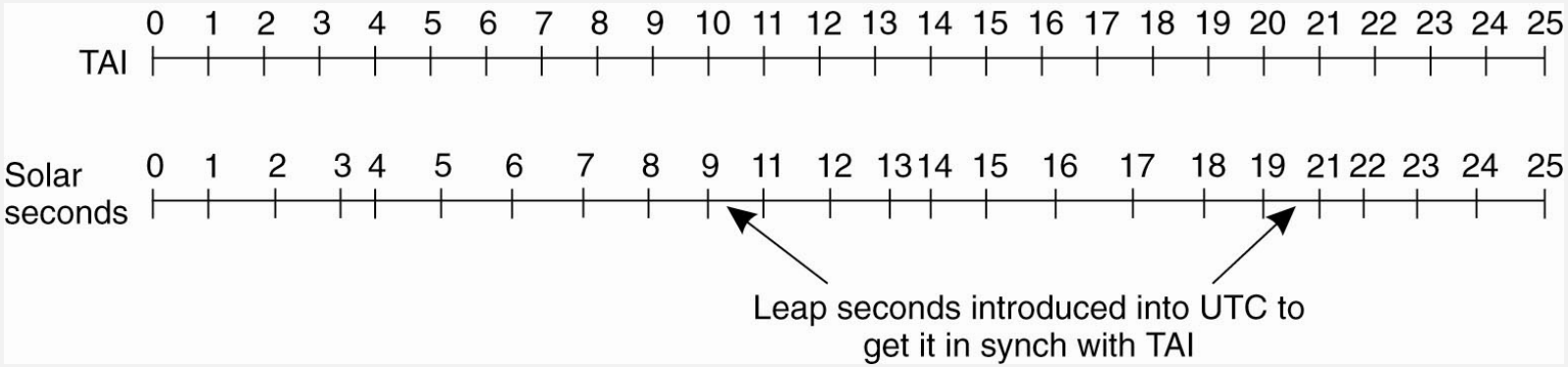


- When each machine has its own clock, an event that occurred after another event may nevertheless be assigned an earlier time.
- **In-class Exercise**: Come up with an example where clock skew causes a build system to compile a file unnecessarily.
- **In-class Exercise**: Come up with another scenario where a build system misses that a file has changed due to clock skew.

How to Measure Real Time?

- Measure a large number of days and average them and then divide by 86400 to obtain mean solar second. However, this value is changing as Earth's rotation is slowing over time.
- Atomic time: one second = time taken for Cesium 133 atom to make 9,192,631,770 transitions. The International Atomic Time (TAI - from the French name Temps Atomique International)) is the average of over 400 Cesium clocks over 50 labs around the world. TAI is the mean number of ticks of the Cesium 133 atom since midnight, 1st Jan, 1958 reported by the *Bureau International de l'Heure* in Paris.
- A leap second is introduced whenever the discrepancy between TAI and solar time grows to 800 msec. About 30 leap seconds have been introduced since 1958. This is known as the Universal Coordinated Time (UTC).
- UTC is broadcast over short-wave by NIST on station WWV (and from satellites). See `http://www.nist.gov`.

Leap Seconds



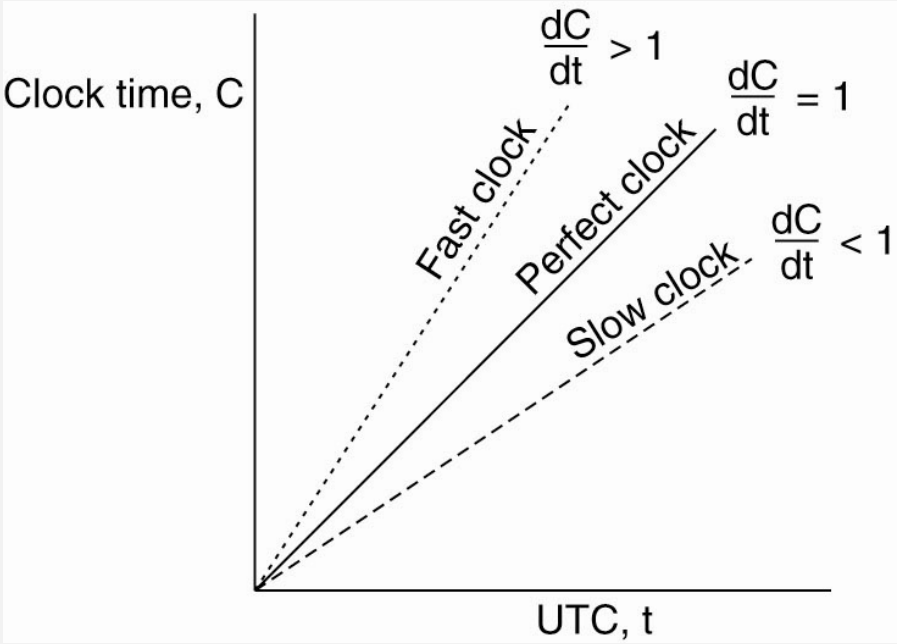
- TAI seconds are of constant length, unlike solar seconds. Leap seconds are introduced when necessary to keep in phase with the sun.

Global Positioning System (GPS)

- GPS is a satellite-based distributed geographical positioning system consisting of 31 satellites at an orbit of around 20,000 km above Earth.
- Each satellite has four atomic clocks, which are regularly calibrated from Earth.
- Each satellite continuously broadcasts its position and timestamps its message with its local time.
- A GPS receiver can compute its own position using three satellites, assuming that the receiver has accurate time. Otherwise it requires four satellites.
- Typical accuracy is 1-5m but can be as good as less than one foot

GPS Animation

Clock Synchronization Algorithms

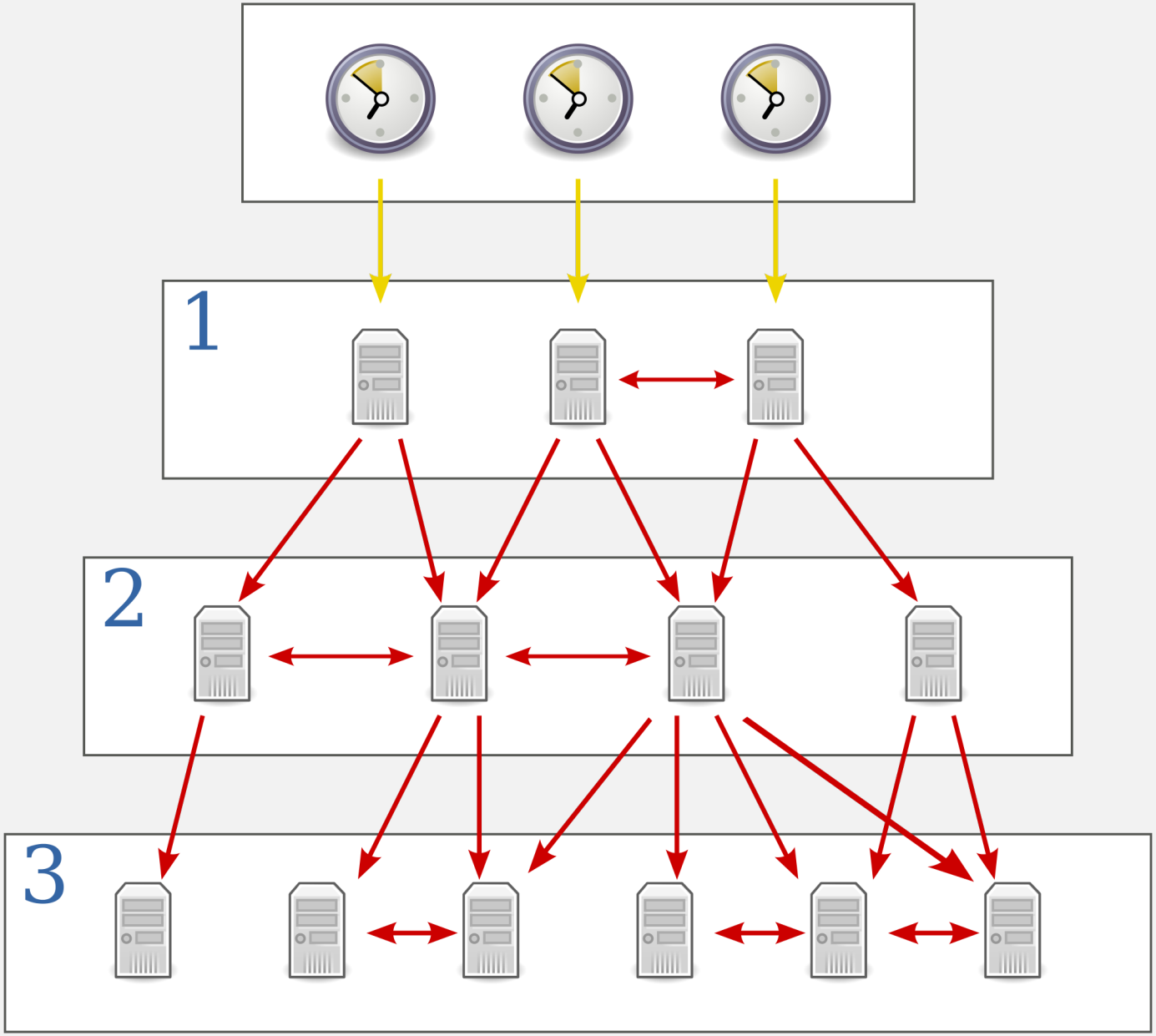


- The relation between clock time and UTC when clocks tick at different rates.
- Let maximum drift rate be ρ. Then $1 - \rho \leq dC/dt \leq 1 + \rho$ where dC/dt is the rate of drift of the clock relative to UTC. Ideally, we want dC/dt to be 1.To ensure two clocks never differ more than δ, the clocks must be synchronized at least every $\delta/2\rho$ seconds.

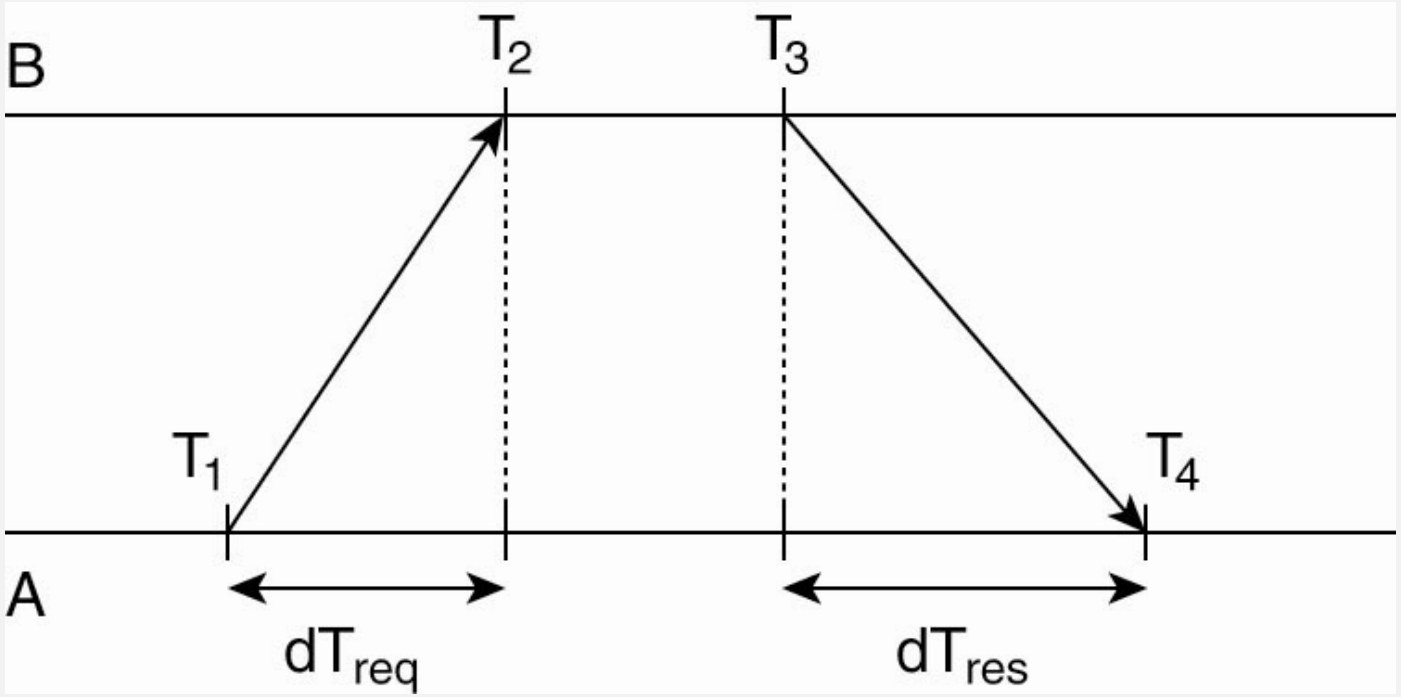
Network Time Protocol (1)

- NTP can achieve worldwide accuracy in the range 1-50 msec. Widely used on the Internet.
- Uses combination of various advanced clock synchronization algorithms (RFC1305).
- Uses a distributed shortest paths algorithm to determine who gets served by whom. Has mechanisms for dealing gracefully with servers being down.
- Clients need to slow down or speed up local clocks to sync up gradually with a server.

Network Time Protocol (2)



Network Time Protocol (3)



- Getting the current time from a time server. Relative offset $\theta = T3 + ((T2 - T1) + (T4 - T3))/2 - T4$

Network Time Protocol (4)

- NTP can be setup pair-wise between servers. Both servers ask each other for time and calculate the θ and δ, where

$$\delta = ((T4 - T1) + (T3 - T2))/2$$

- Eight pairs of θ and δ are buffered and the minimal value is taken as the delay between the servers
- A server with a reference clock such as a WWV receiver or an atomic clock is a stratum-1 server. When A contacts B it will only adjusts its clock if its stratum number is higher than B. Moreover, after the synchronization, A's stratum level becomes one more than B's level

Synchronized Time in the Lab

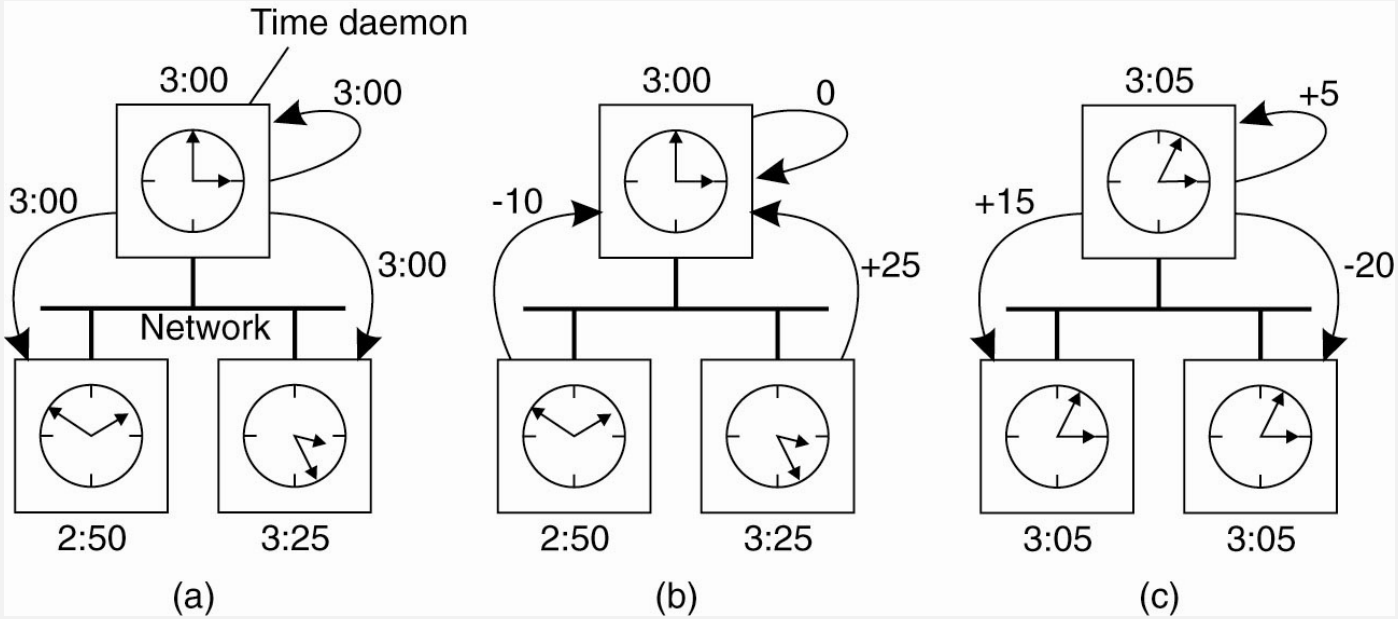
- The command pdsh runs a parallel/distributed shell across the nodes.

```
[amit@onyx ~]$ ssh cscluster00
[amit@cscluster00 ~]$ pdsh -w cscluster[00-08] date

cscluster00: Fri Mar 22 12:01:53 MDT 2024
cscluster02: Fri Mar 22 12:01:54 MDT 2024
cscluster04: Fri Mar 22 12:01:54 MDT 2024
cscluster05: Fri Mar 22 12:01:54 MDT 2024
cscluster06: Fri Mar 22 12:01:54 MDT 2024
cscluster07: Fri Mar 22 12:01:54 MDT 2024
cscluster03: Fri Mar 22 12:01:54 MDT 2024
cscluster08: Fri Mar 22 12:01:54 MDT 2024
cscluster01: Fri Mar 22 12:01:54 MDT 2024
```

- The cluster uses NTP (Network Time Protocol) daemons on each node to keep the machines synchronized. To see the daemon processes, try the command `pdsh -w onyxnode[01-60] ps augx | grep chronyd`.
- **In-class exercise**: Try
  `pdsh -w cscluster[00-08] date --rfc-3339=ns | sort`
  to see time in nanoseconds resolution. What is the biggest clock skew in nanoseconds? Assuming a CPU clock of 1 GHZ – that is roughly 1 billion instructions per second, how many instructions can be executed during that clock skew?

Berkeley Time Algorithm



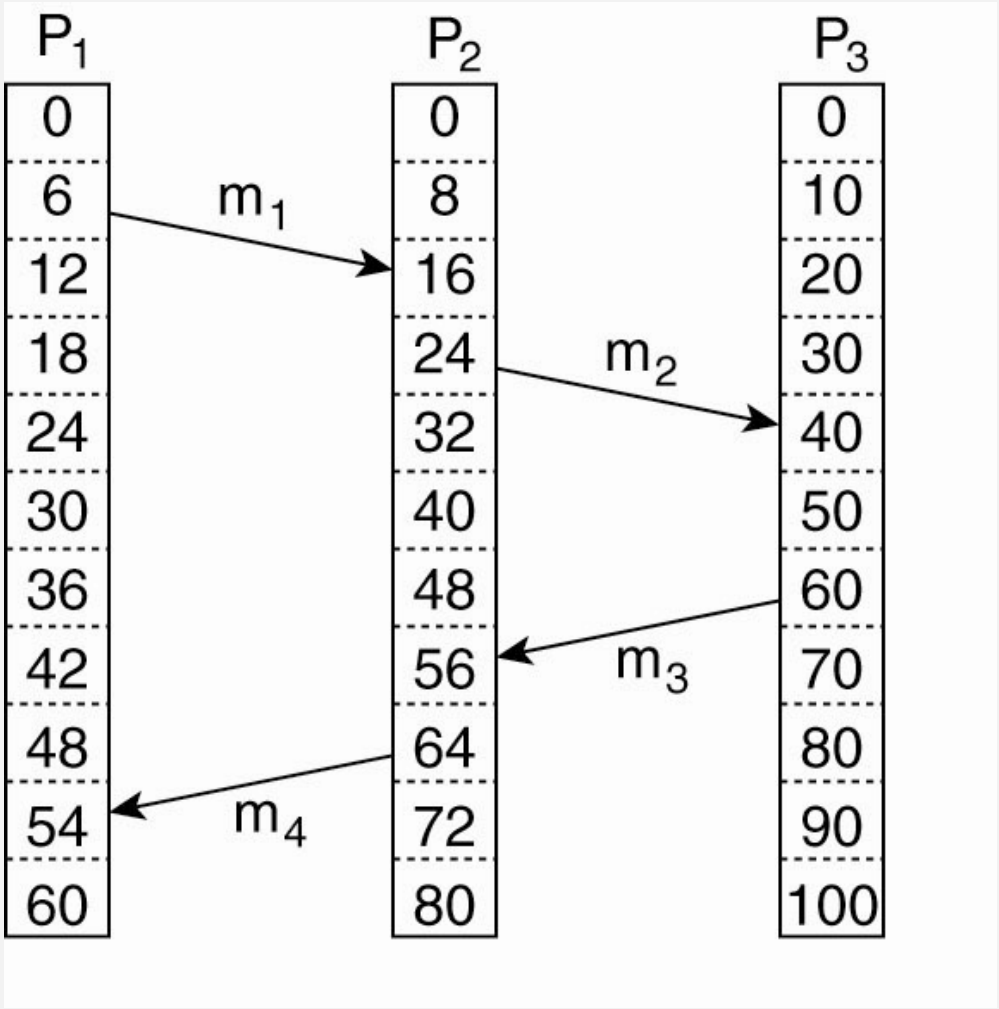
- The time daemon asks all other machines for their clock values.
- The machines answer.
- The time daemon tells everyone how to adjust their clock.
- **In-class Exercise**. How would you implement the Berkeley Time Algorithm?

Logical Clocks

Logical Clocks

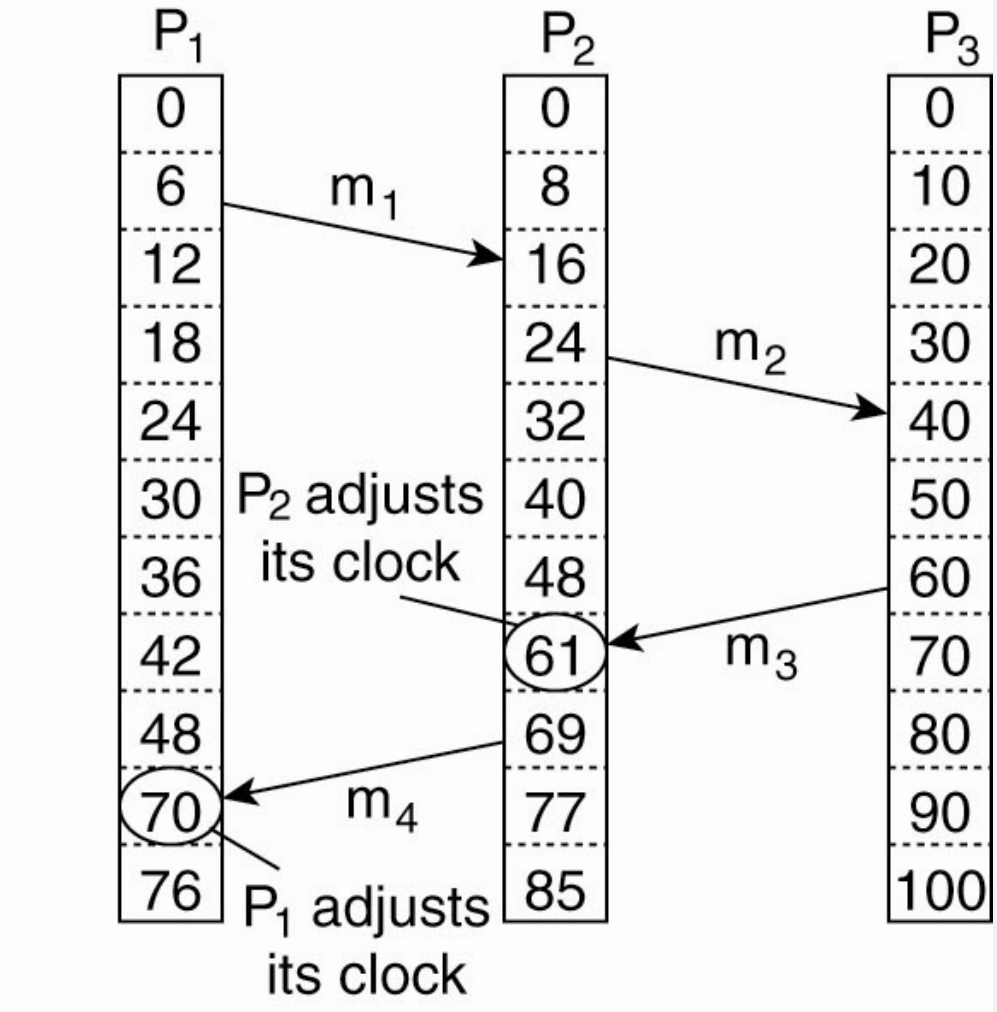
- For many purposes, it is sufficient that machines agree on the same time even though that time may not agree with real world.
- If two process do not interact, it is not necessary that their clocks be synchronized. Furthermore, if all processes agree on the order in which events occur, then they need not agree on the time.
- A logical clock is a mechanism for capturing chronological and causal relationships in a distributed system.
  - The first implementation, the Lamport timestamps, was proposed by Leslie Lamport in 1978 (Turing Award in 2013).
- Some noteworthy logical clock algorithms:
  - Lamport timestamps, which are monotonically increasing software counters.
  - Vector clocks, that allow for partial ordering of events in a distributed system.
  - Version vectors, order replicas, according to updates, in an optimistic replicated system.
  - Matrix clocks, an extension of vector clocks that also contains information about other processes' views of the system.

Lamport's Logical Clocks (1)



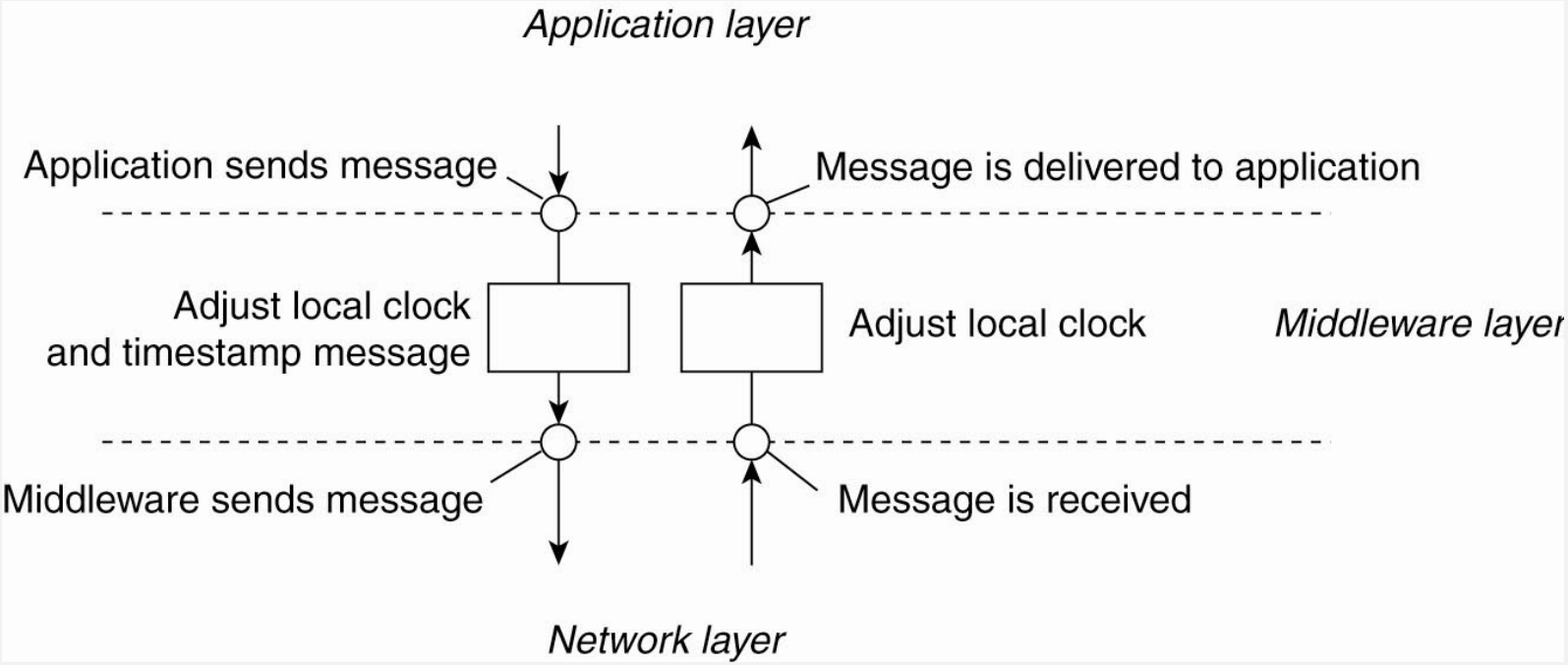
- Three processes, each with its own clock.

Lamport's Logical Clocks (2)



- Lamport's algorithm corrects the clock by adjusting the timestamps.

Lamport's Logical Clocks (3)



- The positioning of Lamport's logical clocks in a distributed system.

Lamport's Logical Clocks (4)

- C is the timestamp function that is defined as follows:
  1. If a happens before b in the same process, $C(\mathtt{a}) < C(\mathtt{b})$
  2. If a represents sending and b receiving of a message, then $C(\mathtt{a}) < C(\mathtt{b})$
  3. For all distinct events a and b, $C(\mathtt{a}) \neq C(\mathtt{b})$
- The time is always adjusted forward. Each message carries the sending time according to the sender's clock. If receiver's time is prior to the sending time, the receiver fast forwards its clock to be 1 more than the sending time.
- In addition, between every two events the clock must tick at least once.
- No two events ever occur at exactly the same time. Tag process ids to low bits of time to make time be unique since process ids can be made unique.

Lamport's Logical Clocks (5)

To implement Lamport's logical clocks, each process P_i maintains a *local counter* C_i that is updated as follows:

Step 1. Before executing an event, P_i executes

$$C_i \leftarrow C_i + 1$$

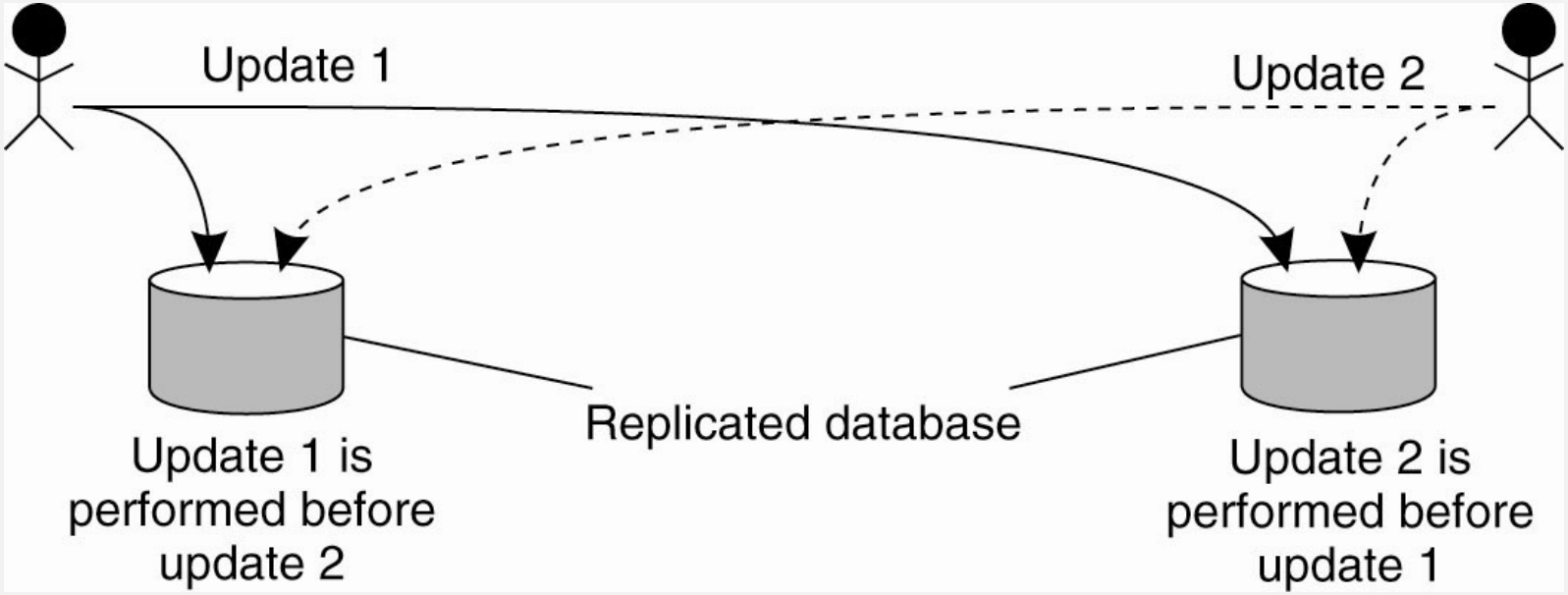
Step 2. When process P_i sends a message m to P_j, it sets m's timestamp $ts(m)$ equal to C_i after having executed the previous step.

Step 3. Upon the receipt of a message m, process P_j adjusts its own local counter as

$$C_j \leftarrow \max\{C_j, ts(m)\}$$

after which it then executes the first step and delivers the message to the application.

Example: Totally Ordered Multicasting (1)

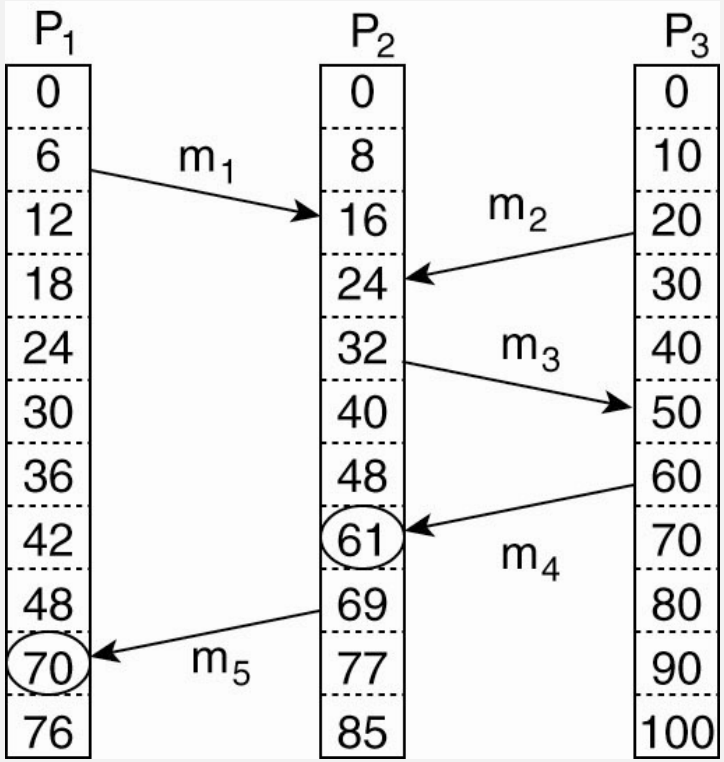


- Updating a database and leaving it in an inconsistent state. Consider two transactions on an account with a balance of \$1,000.
  - *Transaction A*: Customer wants to deposit \$100 to the account in Boise.
  - *Transaction B*: A bank employee in Bilbao initiates a 10% interest payment to the same account.
- Lamport timestamps can be used to fix this problem.

Example: Totally Ordered Multicasting (2)

- Totally Ordered Multicast: A multicast operation by which all messages are delivered in the same order to each receiver.
  - Can be implemented using Lamport's logical clock algorithm.
- Each message is time-stamped with the current (logical) time of the sender.
  - Assumption. Messages from one receiver are ordered and messages aren't lost.
- A process puts received messages into a queue ordered by timestamps. It acknowledges the messages with a multicast to all other processes. Eventually the local queues are the same at all processes.
- A process can deliver a queued message to an application only if it is at the head of queue and has been acknowledged by each other process.

Vector Clocks (1)



- Concurrent message transmission using Lamport logical clocks. Knowing that m_1 was received before m_2 doesn't tell us if they are connected. Knowing that m_3 was sent after receiving m_1 means that they are likely causally connected.
- Lamport clocks do not capture causality. We need *vector clocks* to capture causality.

Vector Clocks (2)

- Vector clock: A vector clock $VC(\mathtt{a})$ assigned to an event a has the property that if $VC(\mathtt{a}) < VC(\mathtt{b})$ for some event b, then event a is known to causally precede event b.
- Vector clocks are constructed by letting each process P_i maintain a vector VC_i with the following two properties:

Step 1. $VC_i[i]$ is the number of events that have occurred so far at P_i. In other words, $VC_i[i]$ is the local logical clock at process P_i.

Step 2. If $VC_i[j] = k$ then P_i knows that k events have occurred at P_j. It is thus P_i's knowledge of the local time at P_j

Vector Clocks (3)

Step 2 is carried out by piggybacking vectors along with messages. The details are shown below:

- Before an event (send/receive or internal event), P_i executes

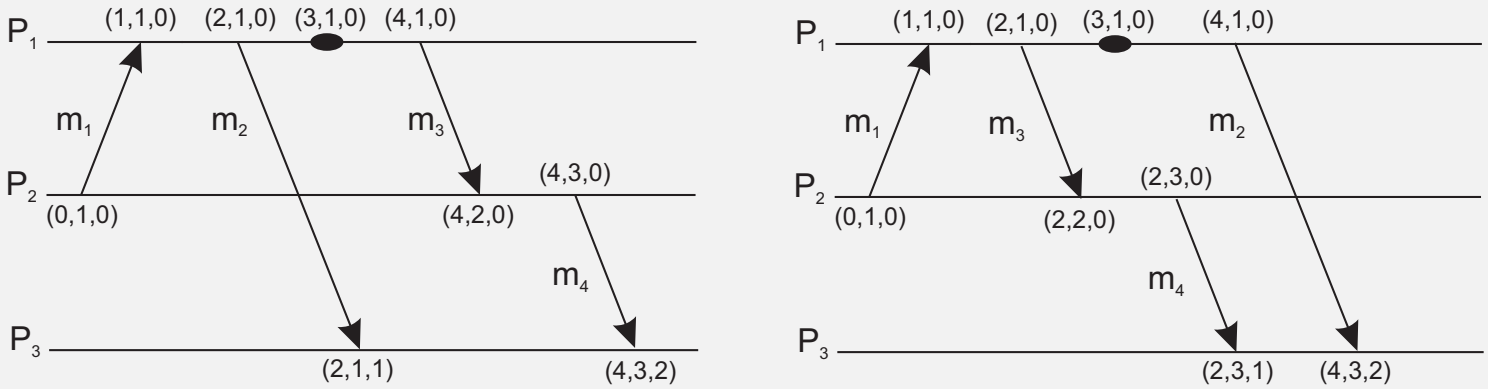
$$VC_i[i] \leftarrow VC_i[i] + 1$$

- When process P_i sends a message m to P_j, it sets m's (vector) timestamp $ts(\mathtt{m})$ equal to VC_i after having executed the previous step.
- Upon the receipt of a message m, process P_j adjusts its own vector by setting:

$$VC_j[k] \leftarrow \max\{VC_j[k], ts(\mathtt{m})[k]\}, \forall k$$

after which it executes the first step and delivers the message to the application.

Vector Clocks (4)



Capturing potential causality when exchanging messages

Situation	$ts(m_2)$	$ts(m_4)$	$ts(m_2) < ts(m_4)$	$ts(m_2) > ts(m_4)$	**Conclusion**
(a)	$(2,1,0)$	$(4,3,0)$	Yes	No	m_2 may causally precede m_4
(b)	$(4,1,0)$	$(2,3,0)$	No	No	m_2 and m_4 may conflict

We say that $ts(a) < ts(b)$, if and only if, $ts(a)[k] \leq ts(b)[k], \forall k$ and there is at least one k' such that $ts(a)[k'] < ts(b)[k']$

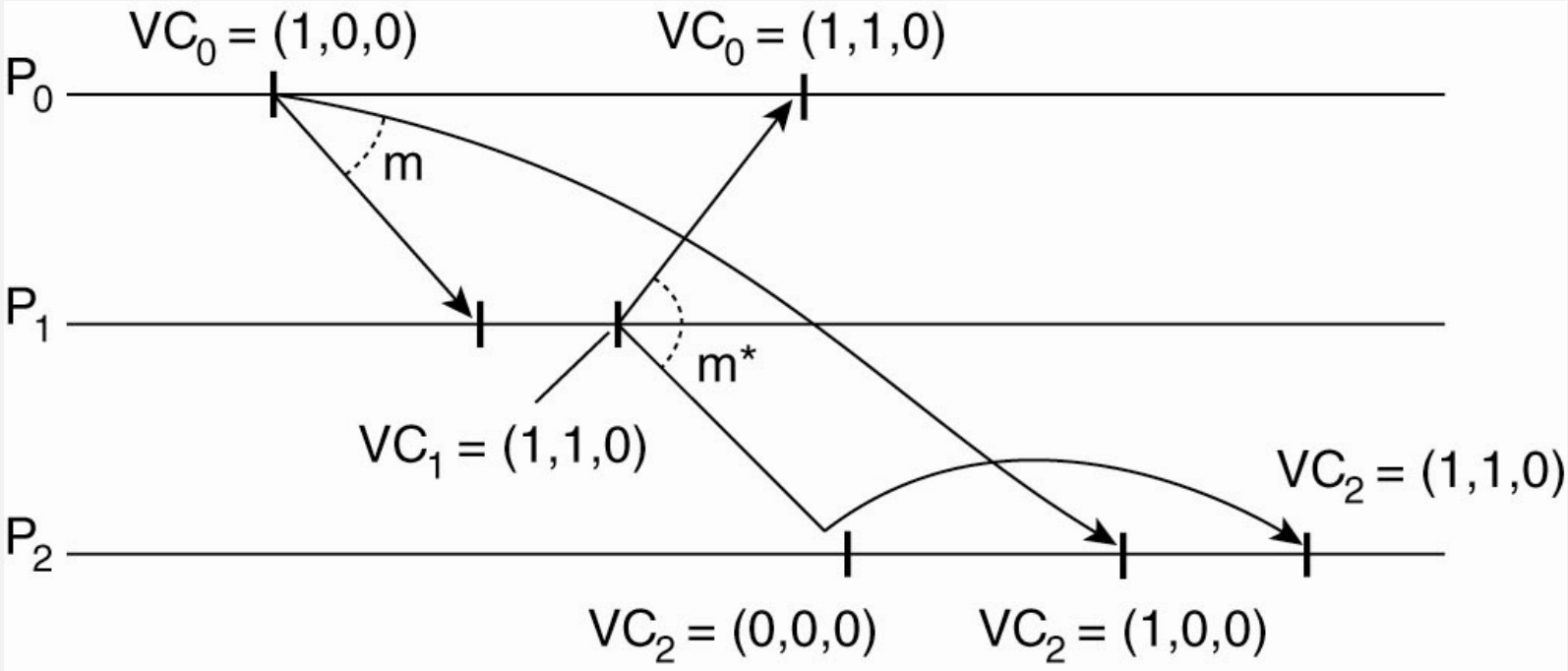
Example: Enforcing Causal Communication (1)

- Causally-ordered multicasting: We want to ensure that a message is delivered only if all messages that causally precede it have been delivered. We assume that the messages are multicast within the group.
- Clocks are adjusted only when sending or delivering a message.
- Then if P_j receives a message m from P_i with vector timestamp $ts(m)$, the delivery is delayed until the following conditions are met:
  - $$ts(m)[i] = VC_j[i] + 1$$

    (m is the next message P_j was expecting from P_i)
  - $$ts(m)[k] \leq VC_j[k], \forall k \neq i$$

    (P_j has seen all the messages that have been seen by P_i when it sent message m)

Example: Enforcing Causal Communication (2)



- At time (1,0,0): P_0 sends message m to P_1 and P_2.
- After receipt by P_1, it decides to send m^* to P_2.
- On P_2: The message m^* arrives sooner than m. The delivery of m^* is delayed by P_2 until m has been received and delivered to P_2's application layer.

Whose problem is it?

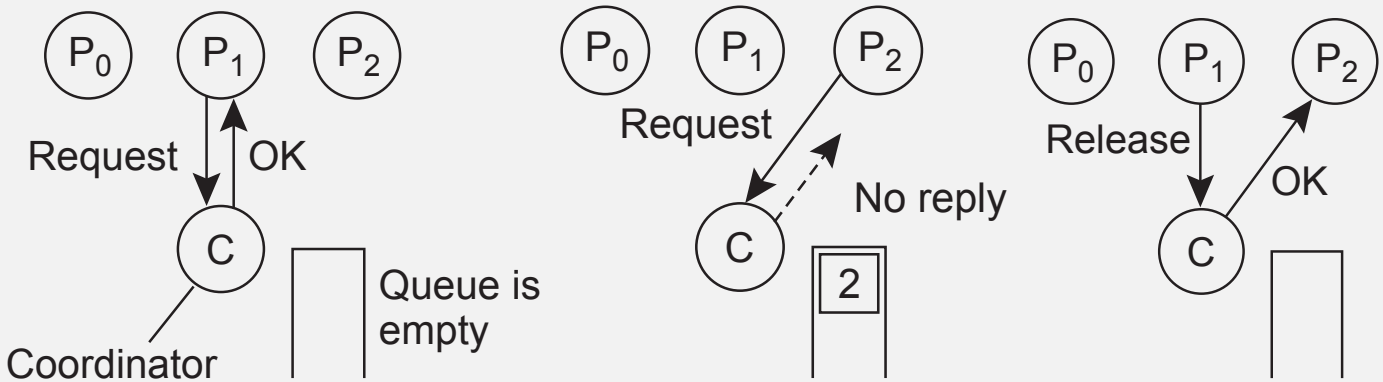
- Middleware deals with message ordering:
  - The middleware cannot tell what the message contains so only potential causality is captured.
  - Two messages sent by the same process are always marked as causally related.
- Middleware cannot be aware of external communication. Ordering issues can only be adequately solved by looking at the application for which the communication is taking place. This is known as the end-to-end argument.

Distributed Mutual Exclusion

- Multiple processes in a distributed systems often need to access shared resources. To prevent corruption of the resources, solutions are need to grant mutually exclusive access by the processes.
- Similar to synchronization problems for multiple threads accessing resources in a single program. However, solutions used in single program (like synchronized keyword in Java) do not work across multiple processes on the same system or on different systems.
- Permissions-based approach versus token-based approach.

Centralized

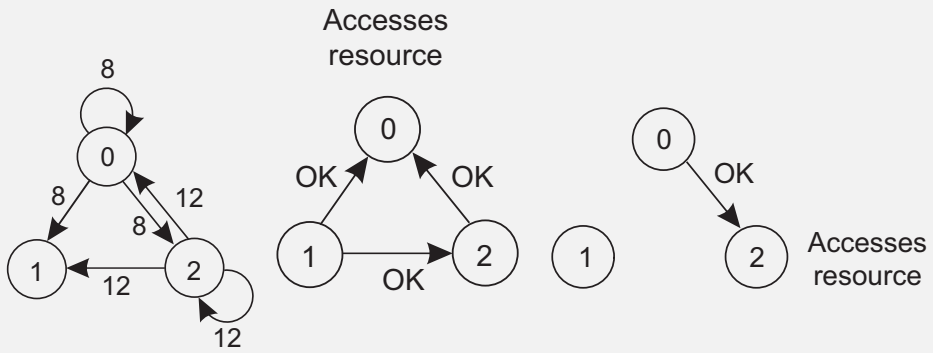
- One process is elected as a coordinator (we will see later how that can be done) and other processes ask it permission to access the mutually exclusive resource.



- The coordinator replies immediately if no other process has access.
- If another process has access, the coordinator notes the new request in a queue and does not reply. (Also, possible to send back a denied message instead).
- When the process that had access releases it by sending a message to the coordinator, then it can reply to the first waiting process in the queue.
- Single point of failure. Performance bottleneck. However, widely used due to its simplicity.

Distributed

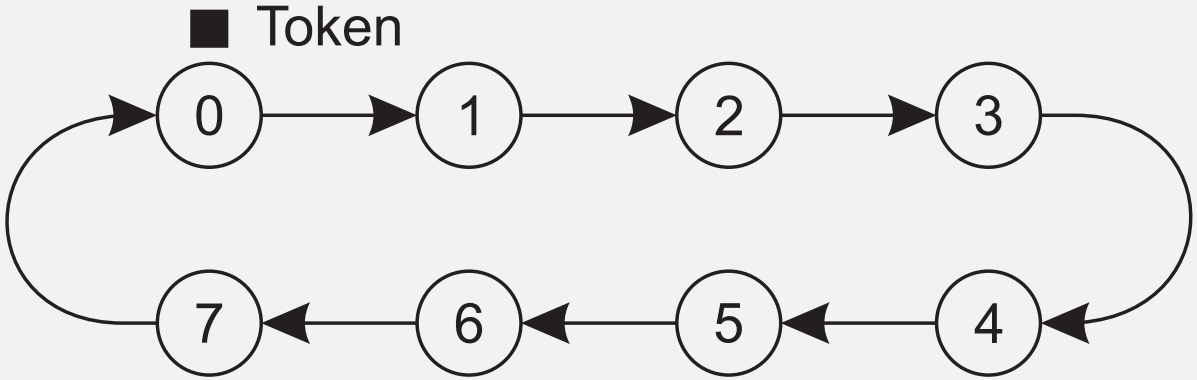
- This solution requires a total ordering of all events in the system (using Lamport's Logical Clock).



- A process wanting access sends a message to all processes containing the name of the resource, its process number, and its logical clock.
- When a process receives a message, it takes one of the following actions:
  - If the receiver is not accessing the resource and does not want to access it, it sends back an OK message to the sender.
  - If the receiver already has access to the resource, it simply does not reply. Instead, it queues the request.
  - If the receiver wants to access the resource as well but has not yet done so, it compares the timestamp of the incoming message with the one contained in the message that it has sent everyone. The lowest one wins. If the incoming message has a lower timestamp, the receiver sends back an OK message. If its own message has a lower timestamp, the receiver queues the incoming request and sends nothing.
- Requires $2 * (N - 1)$ messages for n processes to get mutual exclusion. Has N points of failure! Also, requires true multicast communication or each process has to track who is in the group. Do we really need an OK from all other processes?

Token Ring

- In software, we construct an overlay network in the form of a logical ring in which each process is assigned a position in the ring.
- When the ring is initialized, process P0 is given a token. The token circulates around the ring.



- A process wishing to enter the critical section has wait for the token to come around. Then it has mutual exclusion to complete its work.
- After it has finished, it passes the token along the ring. It is not permitted to enter the resource immediately again using the same token.
- Lost Token. Process Crash.

Case Study: Apache ZooKeeper (1)

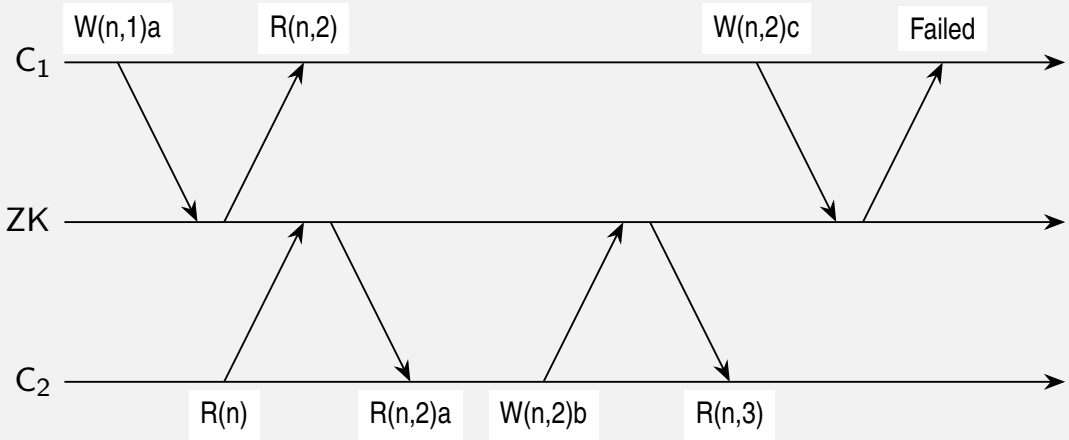
- Apache ZooKeeper is a widely used distributed system with multiple servers that provides locking, naming, election, monitoring, and other services.
- We will illustrate its use as a single server providing locking (mutual exclusion)
- An important design principle is its lack of blocking primitives: clients send messages to the ZooKeeper service and, in principle, are always immediately returned a response
- To facilitate a range of coordination functions, ZooKeeper maintains a namespace, organized as a tree. Operations on the tree are simple: creating and deleting nodes, as well as reading and updating the data contained in a node (if any).

Case Study: Apache ZooKeeper (2)

- To acquire a lock, simply let a process create a special node, say lock, but have that operation fail if the node already exists. Releasing a lock is done by merely deleting the node lock.
- ZooKeeper supports a notification mechanism by which a client can subscribe to a change in a node or a branch in the tree. When a change happens, the client receives a message.
- Suppose a client subscribes to changes at a specific node after having read the state of that node. If the node is updated twice in a row, we want to prevent that the client sees the second update before being notified, as the notification dealt with changes to the previous state, i.e., the state after the first update took place.
- ZooKeeper handles this by using version numbers.

Case Study: Apache ZooKeeper (3)

- We use the notation $W(n, k)a$ to denote the request to write the value a to node n, under the assumption that its current version is k. $R(n, k)$ denotes that the current version of node n is k.
- The operation $R(n)$ tells that a client wants to read the current value of node n, and $R(n, k)a$ means that the value a from node n is returned with its current version n.
- Based on the above, see below for an example where ZooKeeper denies an update because of consistency issues.



- Each client may need to try several times before an update actually takes place. This may not always seem so efficient, yet this approach ensures that data maintained by ZooKeeper is at least consistent with what clients expect it to be.

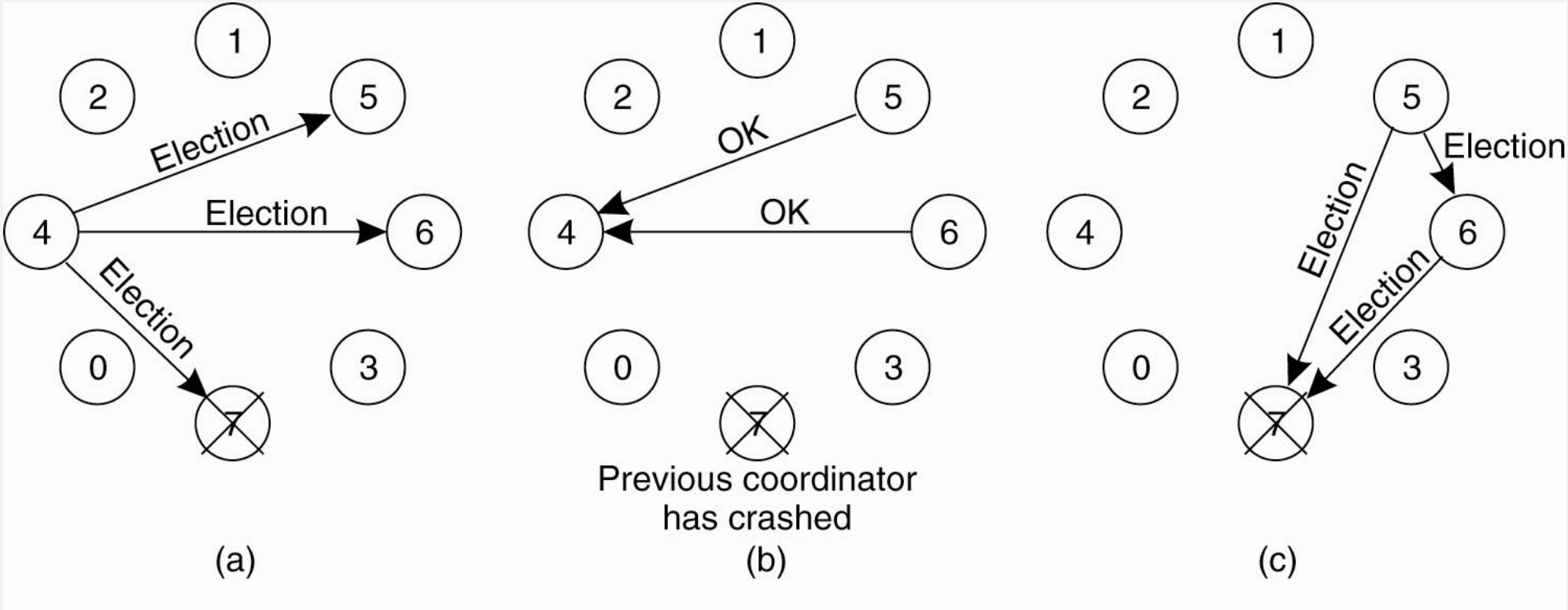
Election Algorithms

- Many distributed systems need one process to act as a coordinator to initiate actions or to resolve conflicts.
- *Assumptions*:
  - We will assume that each process has a unique process number id so we can attempt to locate the highest numbered process to act as the coordinator.
  - Every process knows the id numbers of all other processes.
  - A process doesn't not know which of the other processes is up or down.
- *Goal*: When an election starts, it ends with all processes agreeing on who the coordinator is.

Bully Algorithm (1)

- When a process P notices that the coordinator is no longer responding to requests, it initiates an election as follows:
  1. P sends an `ELECTION` message to all processes with a higher id numbers.
  2. If no one responds, P wins the election and becomes coordinator.
  3. If one of the higher-ups answers, it takes over. P's job is done.
- The new coordinator sends a message to all processes announcing that it is the new coordinator.
- Several elections can be running simultaneously. If a process that was down previously comes back up, it immediately runs an election. The "biggest" process in town always wins, hence the name "bully algorithm."

Bully Algorithm (2)

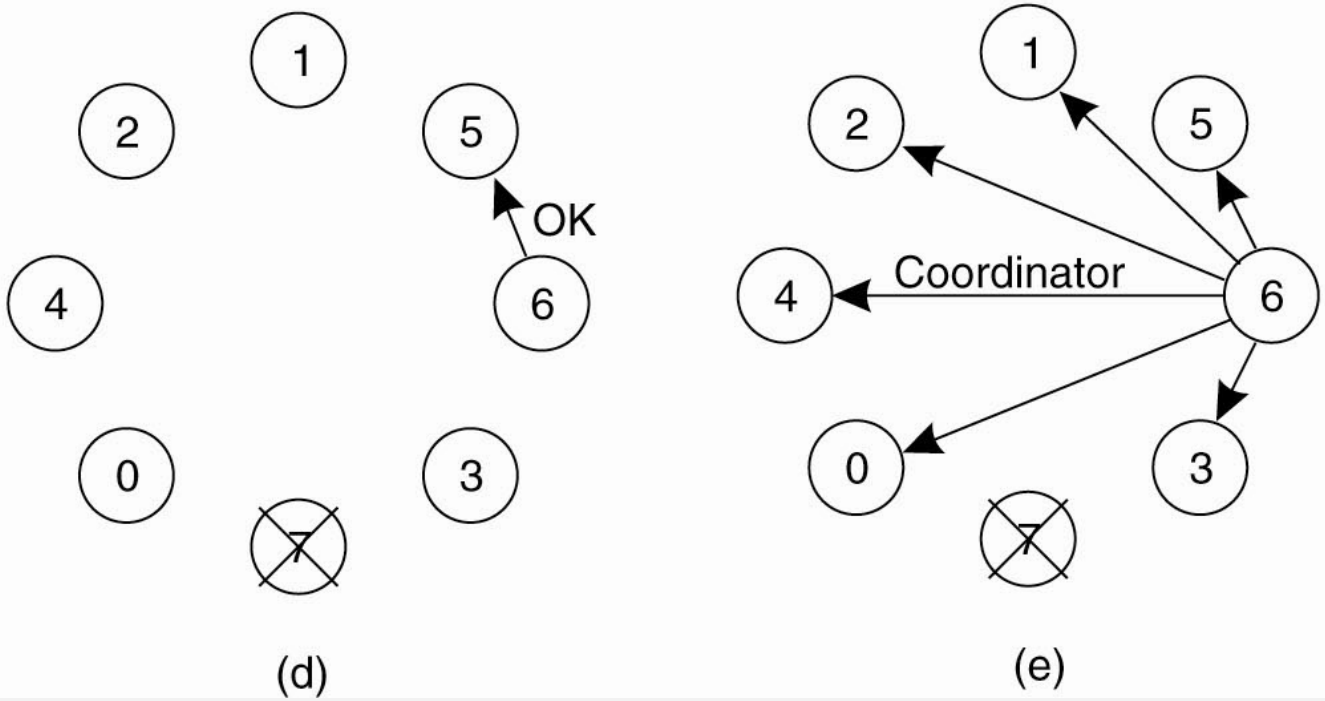


(a) Process 4 holds an election.

(b) Processes 5 and 6 respond, telling 4 to stop.

(c) Now 5 and 6 each hold an election.

Bully Algorithm (3)



(d) Process 6 tells 5 to stop.

(e) Process 6 wins and tells everyone.

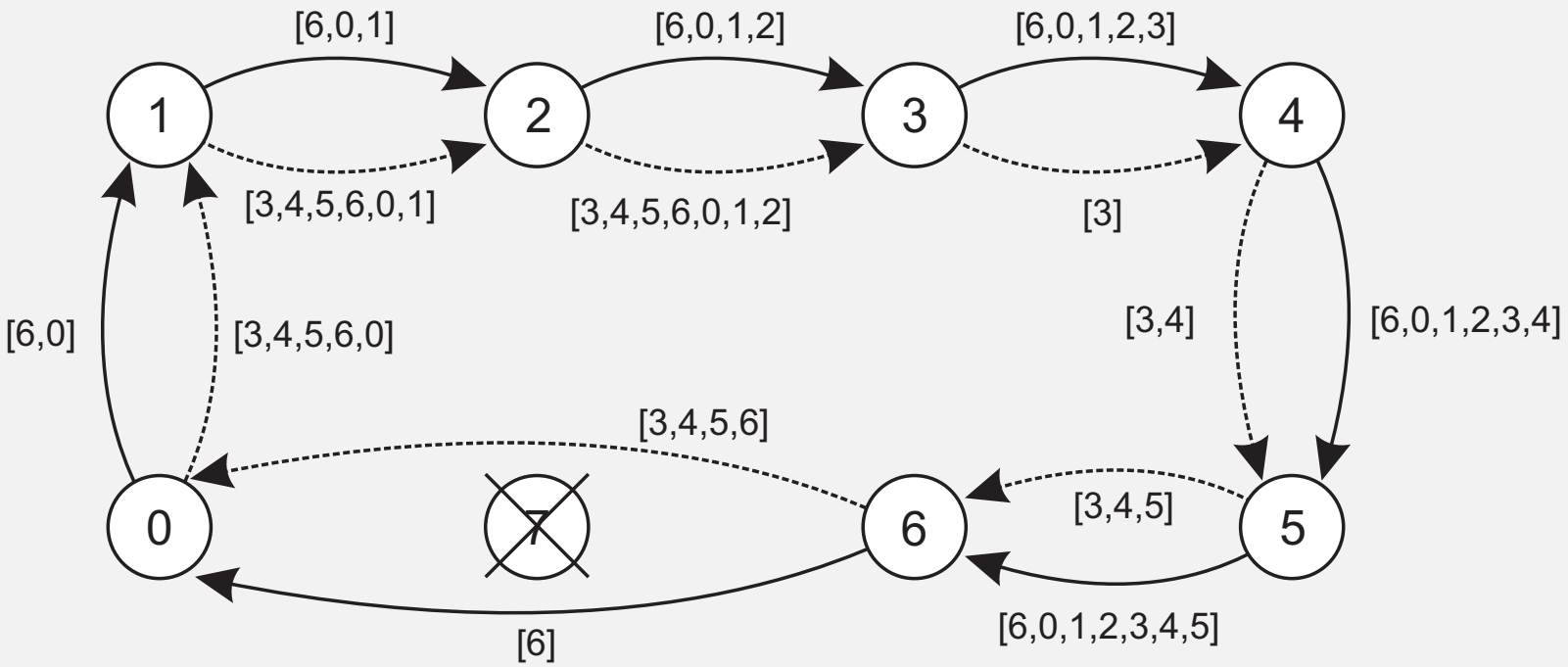
Bully Algorithm (4)

- The new coordinator typically has to pick up the state information left off by the old coordinator before it announces the results of the election.
- If Process 7 comes back up, it just sends a new election message and bullies them into submission.
- We can use `Are You Alive` messages periodically to speed up detection of absconding coordinators

Ring Algorithm (1)

- The processes are logically arranged in a ring. Each process knows its neighbor in the ring as well who all is in the ring.
- When any process notices that the coordinator is not responding, it builds an `ELECTION` message containing its own process number and sends it to its successor
- At each step, the sender adds its own number to the list in the message thus making itself be a candidate. Eventually, the message reaches the process that started it all. Then it looks through the message and decides which process has the highest number and that becomes the coordinator
- Then the message type is changed to `COORDINATOR` and the message circulates once again so everyone knows the new coordinator and the new ring configuration.

Ring Algorithm (2)



Election algorithm using a ring. Elections were initiated by P_6 and P_3.

Wireless and Large Scale Systems

- Elections in Wireless Environments. We often want the best leader (the one with most battery life or other relevant resources in mobile environments).
  - Impose a tree on the network and work our way backwards to determine the best leader.
- Elections in Large Scale Systems. Several superpeer nodes may be selected instead of just one. The superpeers should be evenly distributed across the network. Normal nodes should have low latency access to superpeers. There should be a predefined portion of superpeers and each superpeer should not have to serve more than a fixed number of normal nodes.
  - Solutions use either DHT (Distributed Hash Tables) or randomly unstructured layouts.

References

- Time, clocks, and the ordering of events in a distributed system. Leslie Lamport. *Communications of the ACM* 21 (7): 558–565, 1978.
- Time is an illusion. Lunchtime doubly so. George V. Neville-Neil. *Communications of the ACM*, January 2016, Vol. 59. No. 1, pages 50–55. [Note: this article is only accessible on campus]