Distributed Coordination

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- Topics:
  - Notion of *global time*: absolute time versus relative time
  - *Election algorithms*: for electing a *coordinator* on-the-fly
  - *Distributed mutual exclusion*

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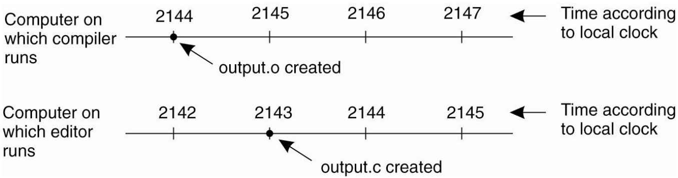
- Each interrupt is called a clock tick (and can be set to interrupt certain number of times per second).
- The time is stored on a battery-backed CMOS RAM. At every clock tick, the interrupt service procedure adds one to the stored time.
- With one computer even if the time is off it is usually not 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:



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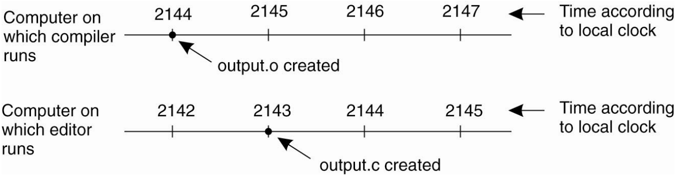

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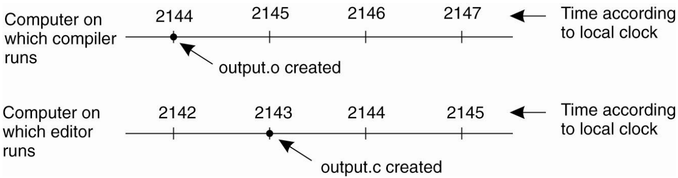

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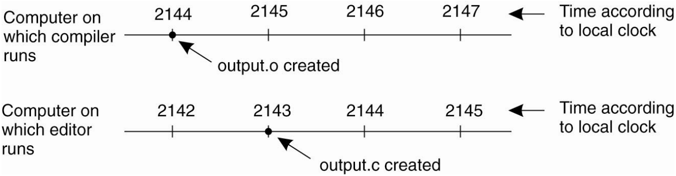

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- **In-class Exercise**: Come up with an example where clock skew causes a build system to compile a file unnecessarily.
- **In-class Exercise**: Come up with another scenario where a build system misses that a file has changed due to clock skew.

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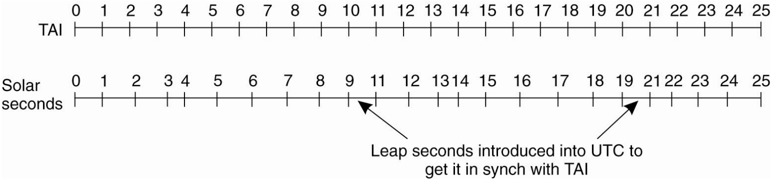
- UTC is broadcast over short-wave by NIST on station WWV (and from satellites). See `http://www.nist.gov`.

Leap Seconds



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

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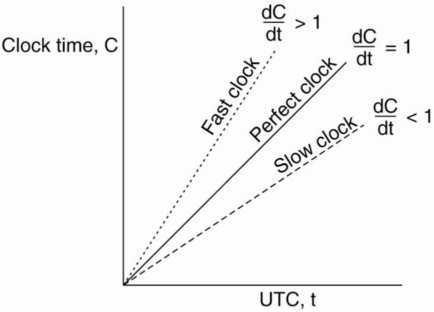
- Typical accuracy is 1-5m but can be as good as less than one foot

GPS Animation

Clock Synchronization Algorithms



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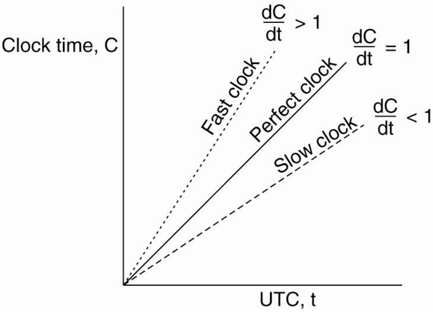

- The relation between clock time and UTC when clocks tick at different rates.
- Let maximum drift rate be ρ. Then $1-\rho \leq dC/dt \leq 1+\rho$ where dC/dt is the rate of drift of the clock relative to UTC. Ideally, we want dC/dt to be 1.To ensure two clocks never differ more than δ, the clocks must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

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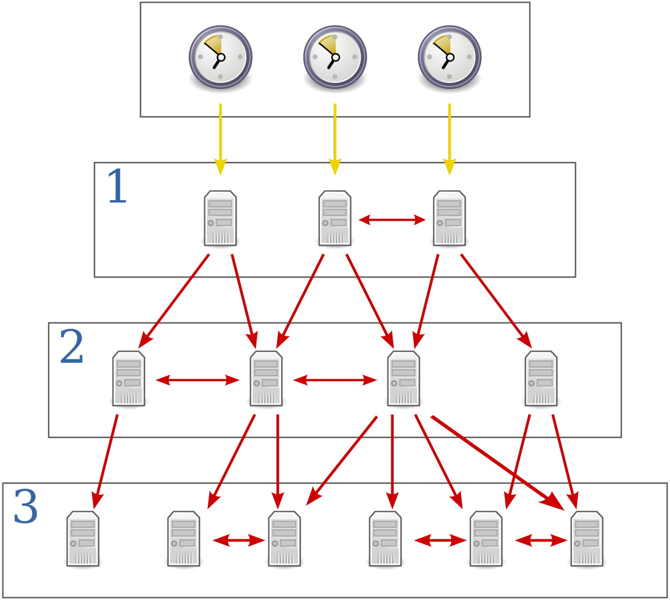
- Clients need to slow down or speed up local clocks to sync up gradually with a server.

Network Time Protocol (2)



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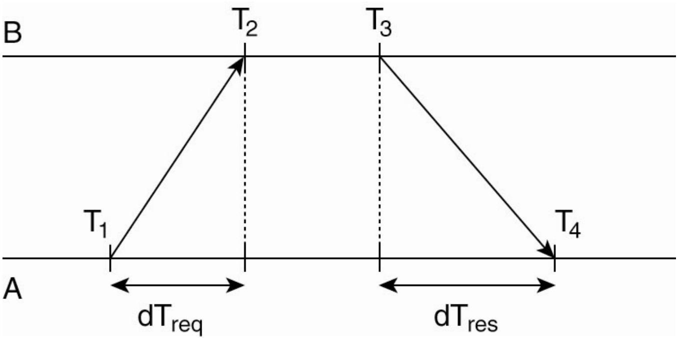

- Getting the current time from a time server. Relative offset $\theta = T3 + ((T2 - T1) + (T4 - T3))/2 - T4$

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- 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 ~]$ pdsh -w onyxnode[01-63] date | sort
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onyxnode02: Wed Mar  9 06:18:26 MST 2020
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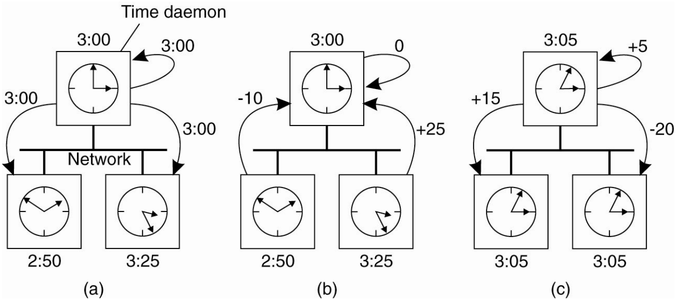
- Try `pdsh -w onyxnode[01-60] date --rfc-3339=ns | sort` to see time in nanoseconds resolution.
- The cluster uses NTP (Network Time Protocol) daemons on each node to keep the machines synchronized. To see the daemon processes, try the command `pdsh -w node[01-60] ps augx | grep ntpd`. On some Linux systems `ntpd` has been replaced by `chronyd`.

Berkeley Time Algorithm



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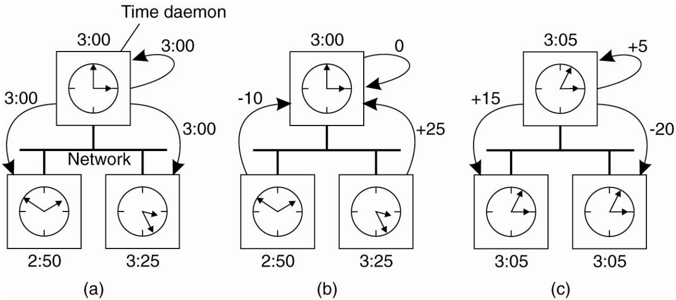

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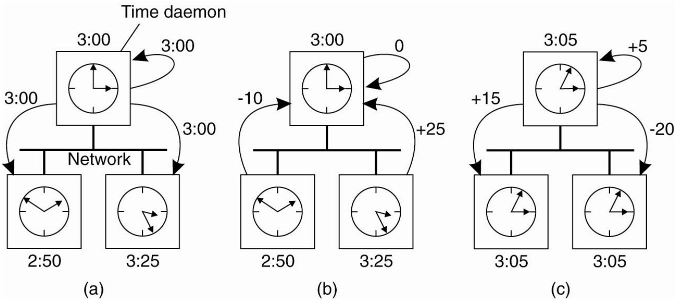

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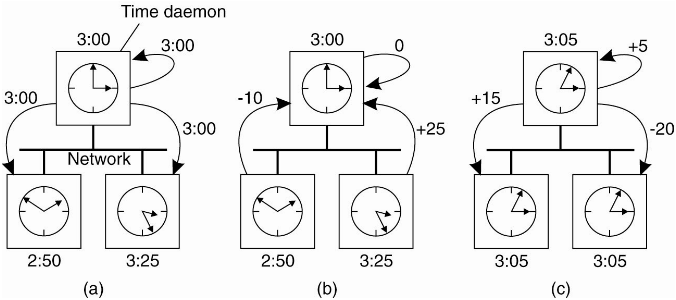

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- **In-class Exercise**. How would you implement the Berkeley Time Algorithm?

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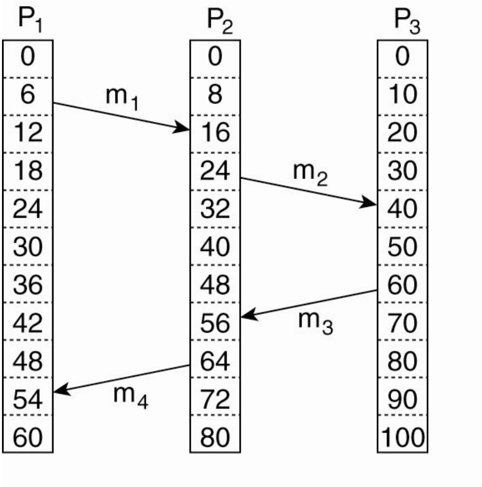
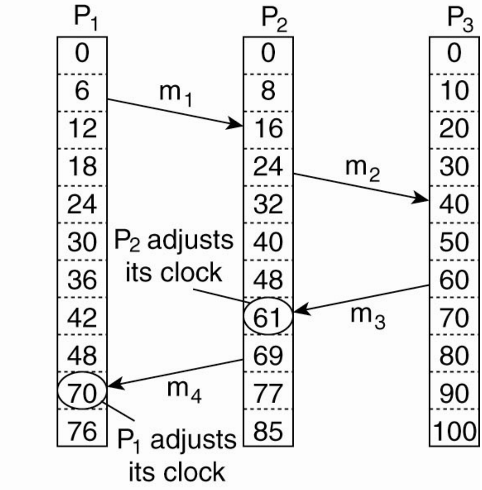
- A logical clock is a mechanism for capturing chronological and causal relationships in a distributed system.
  - The first implementation, the Lamport timestamps, was proposed by Leslie Lamport in 1978 (Turing Award in 2013).
- Some noteworthy logical clock algorithms:
  - Lamport timestamps, which 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.

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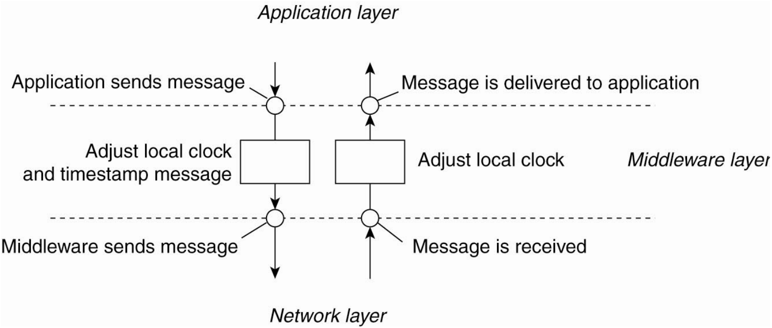

- The positioning of Lamport's logical clocks in a distributed system.

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- 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 are unique.

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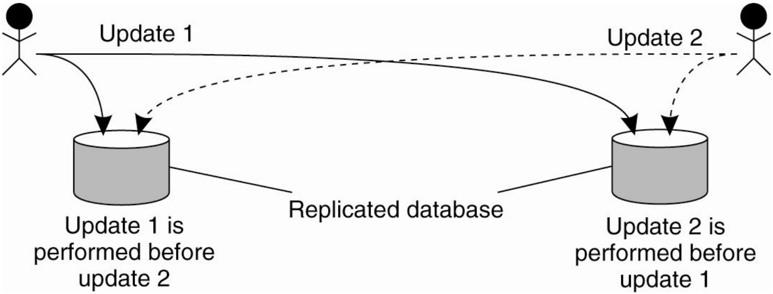
Step 3. Upon the receipt of a message m, process P_j adjusts its own local counter as

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

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

Example: Totally Ordered Multicasting (1)



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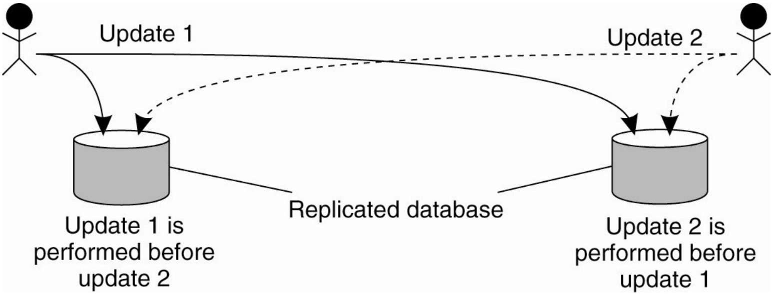

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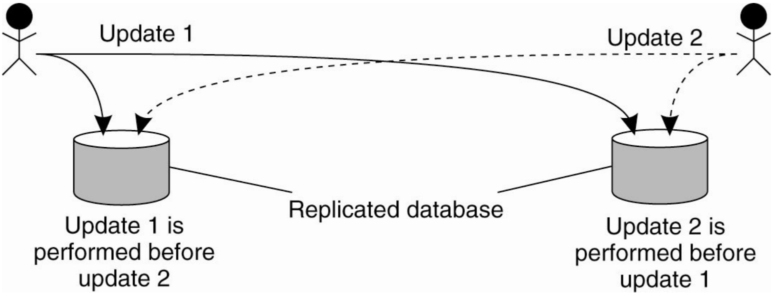

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- Lamport timestamps can be used to fix this problem.

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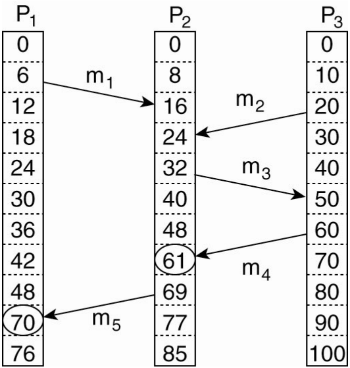
- A process puts received messages into a queue ordered by timestamps. It acknowledges the messages with a multicast to all other processes. Eventually the local queues are the same at all processes.

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.

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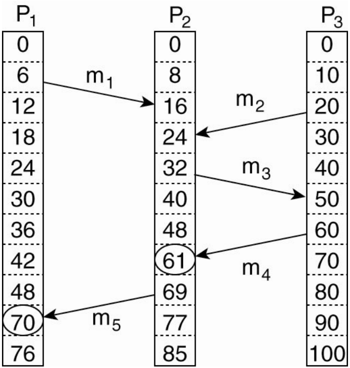

- Concurrent message transmission using Lamport logical clocks. Knowing that m_1 was received before m_2 doesn't tell us if they are connected. Knowing that m_3 was sent after receiving m_1 means that they are likely causally connected.
- Lamport clocks do not capture causality. We need *vector clocks*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

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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

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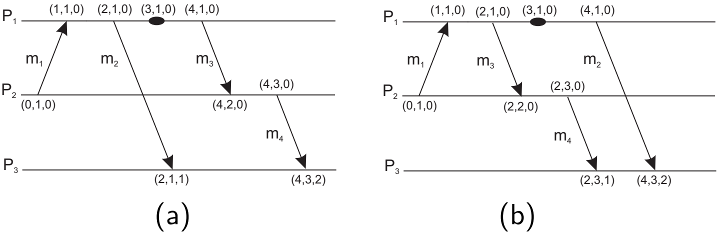
- Upon the receipt of a message m, process P_j adjusts its own vector by setting:

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

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

Vector Clocks (4)



Capturing potential causality when exchanging messages

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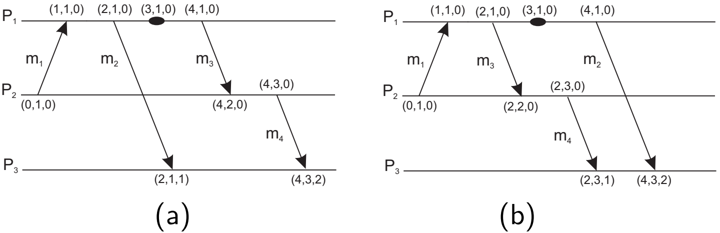

Capturing potential causality when exchanging messages

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 $ts(a)[k'] < ts(b)[k']$

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

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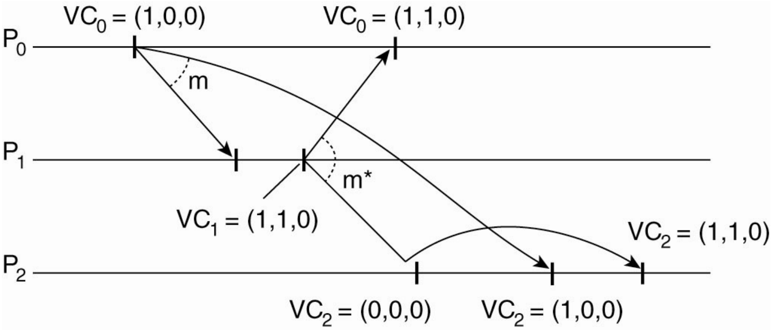

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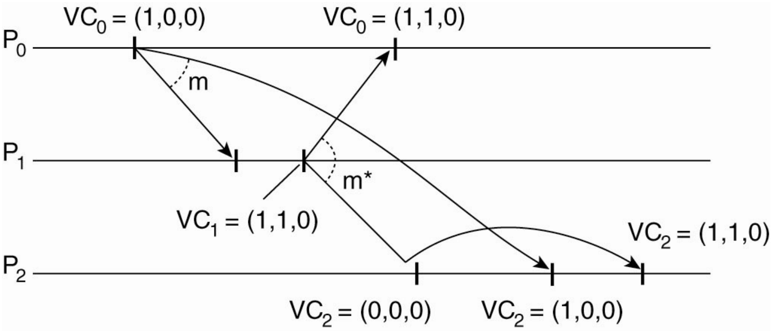

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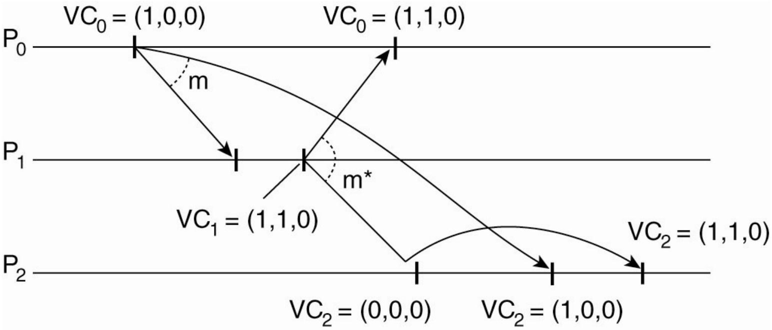

- At time (1,0,0): P_0 sends message m to P_1 and P_2.
- After receipt by P_1, it decides to send m^* to P_2.
- On P_2: The message m^* arrives sooner than m. The delivery of m^* is delayed by P_2 until m has been received and delivered to P_2's application layer.

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- 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.

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  - 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.

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- 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."

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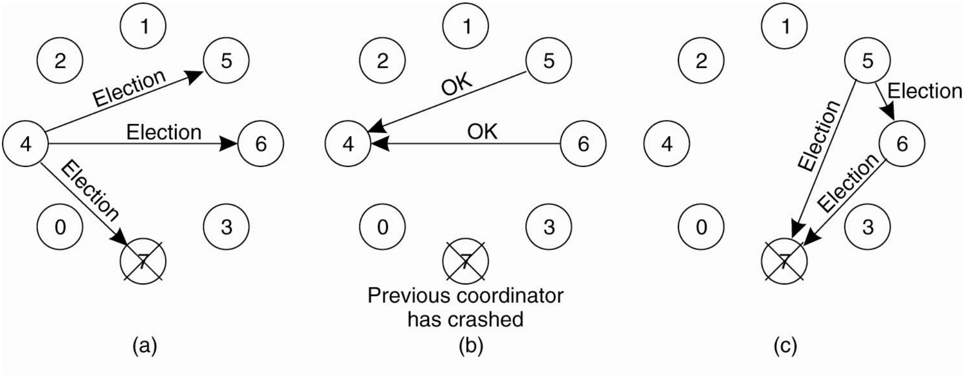
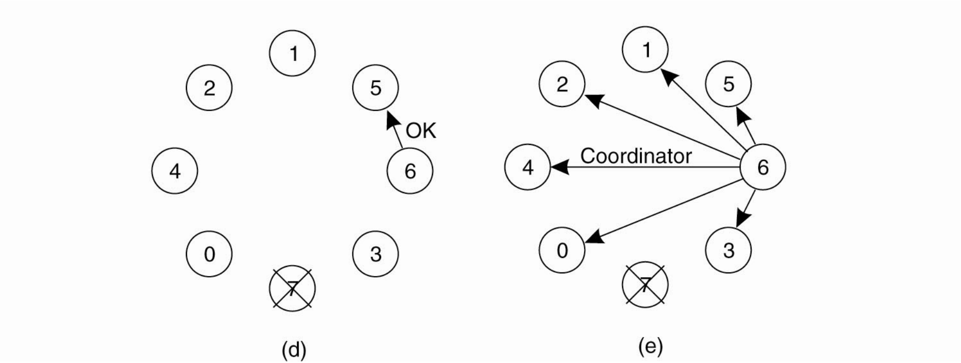


(a) Process 4 holds an election.

(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.

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- 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

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- 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.

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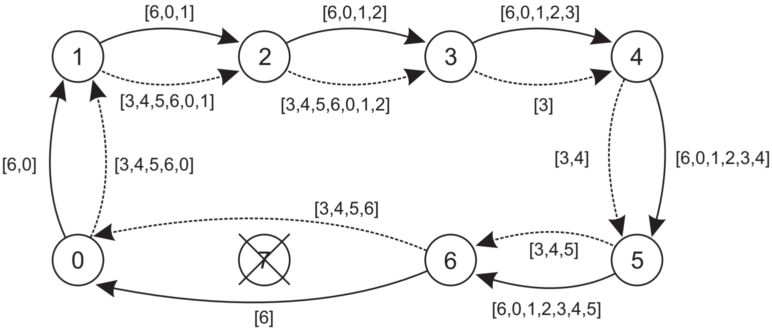

Election algorithm using a ring. Elections were initiated by P_6 and P_3.

Wireless and Large Scale Systems

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  - 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]

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