

# Distributed Synchronization



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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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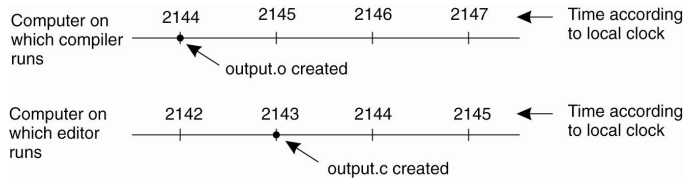
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- ▶ The time is stored on a battery-backed CMOS RAM. At every clock tick, the interrupt service procedure adds one to the stored time.
- ▶ With one computer even if the time is off it is usually not a problem. With  $n$  computers, all  $n$  crystals 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**.



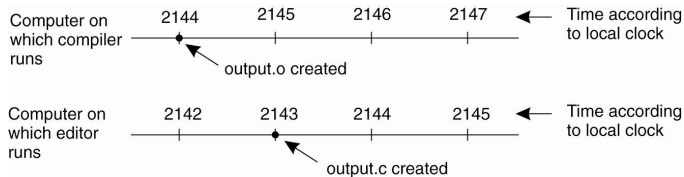
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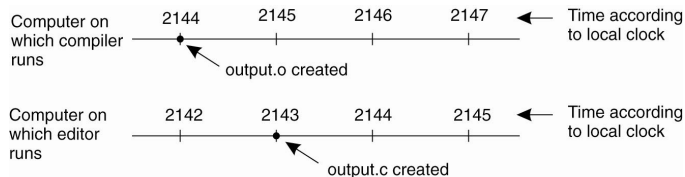
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- ▶ When each machine has its own clock, an event that occurred after another event may nevertheless be assigned an earlier time.
- ▶ **In-class Exercise:** Come up with an example where clock skew causes a build system to compile a file unnecessarily.



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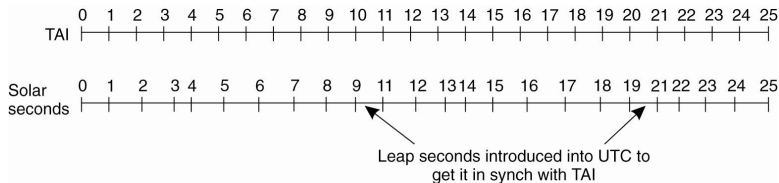
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- ▶ UTC is broadcast over short-wave by NIST on station WWV (and from satellites). See <http://www.nist.gov>.



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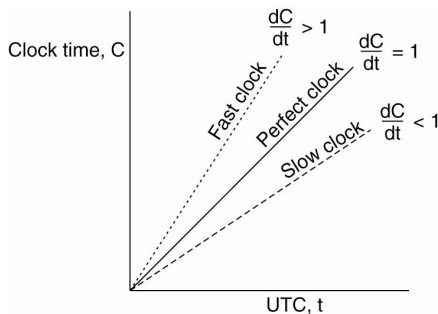
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- ▶ Typical accuracy is 1-5m but can be as good as less than one foot

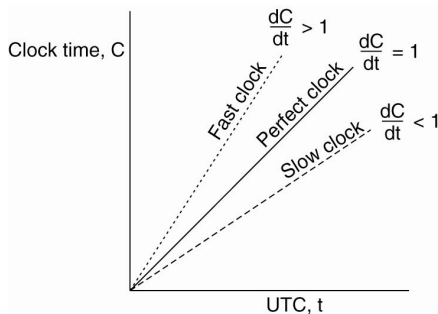
GPS Animation

# Clock Synchronization Algorithms



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- ▶ Let maximum drift rate be  $\rho$ . 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  $\delta$ , the clocks must be synchronized at least every  $\delta/2\rho$  seconds.



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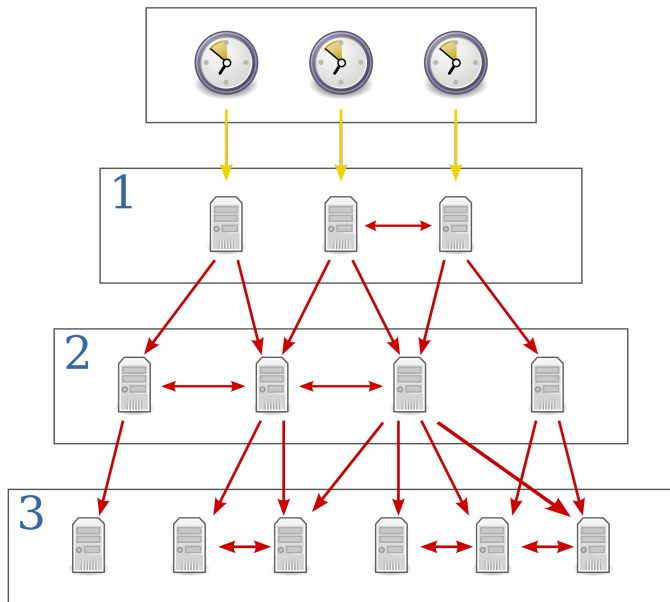
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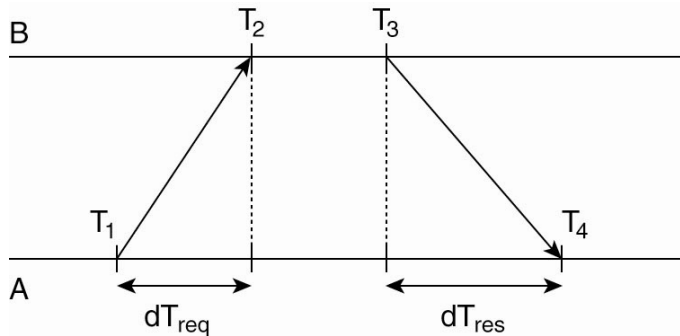
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- ▶ Clients need to slow down or speed up local clocks to sync up gradually with a server.

# Network Time Protocol (2)



## Network Time Protocol (3)



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

## Network Time Protocol (4)

- ▶ NTP can be setup pair-wise between servers. Both servers ask each other for time and calculate the  $\theta$  and  $\delta$ , where

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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 adjust 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.

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- ▶ Try `pdsh -w node[01-63] date -rfc-3339=ns | sort` to see time in nanoseconds resolution.

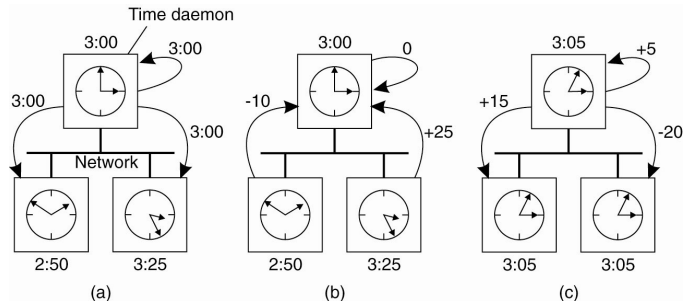
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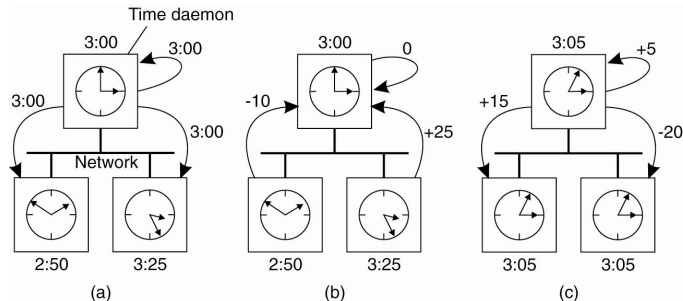
- ▶ Try `pdsh -w node[01-63] date -rfc-3339=ns | sort` to see time in nanoseconds resolution.
- ▶ The cluster uses **NTP** (Network Time Protocol) daemons on each node to keep the machines synchronized.

# Berkeley Time Algorithm



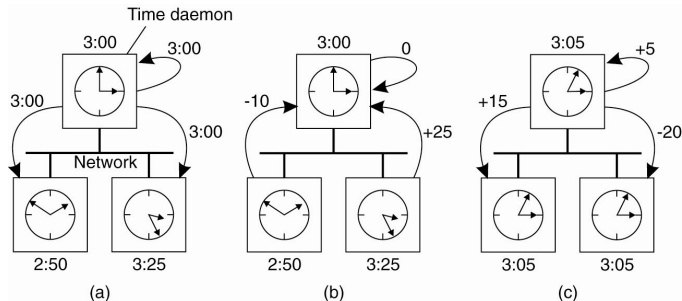
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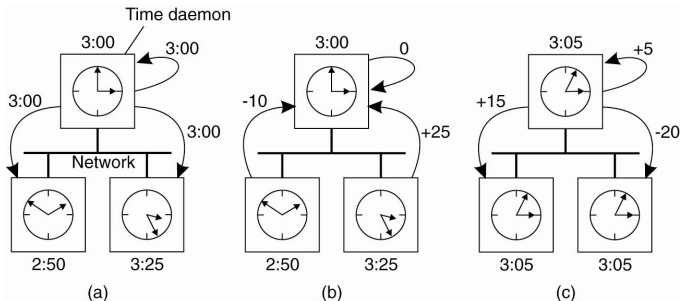
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- ▶ **In-class Exercise.** How would you implement the Berkeley Time Algorithm?

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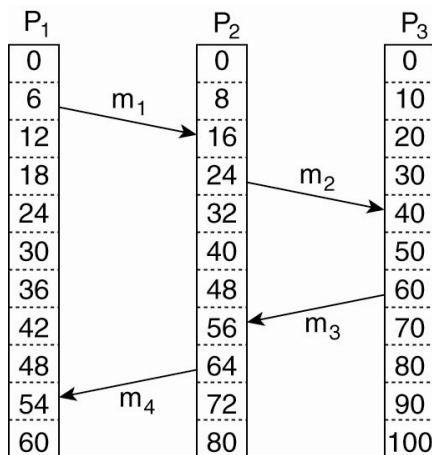
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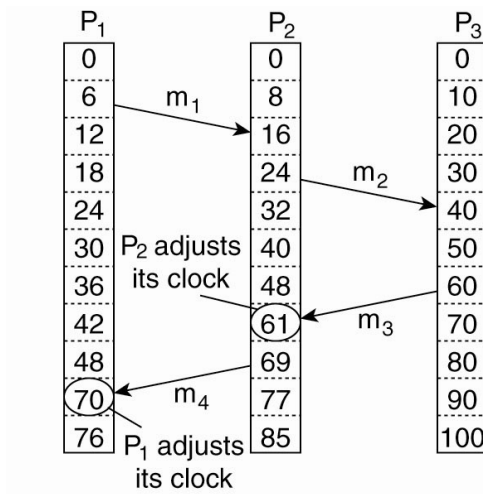
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- ▶ Some noteworthy logical clock algorithms:
  - ▶ **Lamport timestamps**, which are monotonically increasing software counters.
  - ▶ **Vector clocks**, that allow for partial ordering of events in a distributed system.
  - ▶ **Version vectors**, 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)



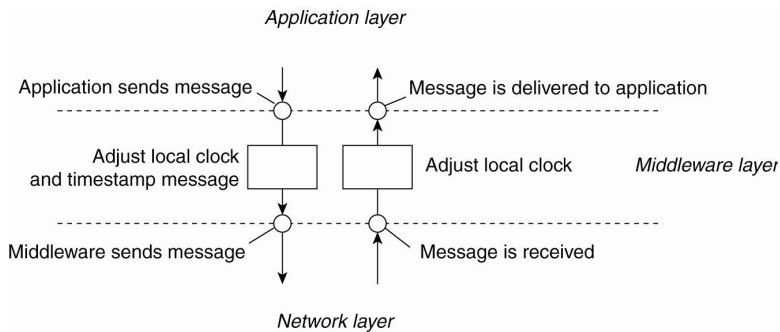
- ▶ Three processes, each with its own clock.

## 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.



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- ▶ In addition, between every two events the clock must tick at least once.
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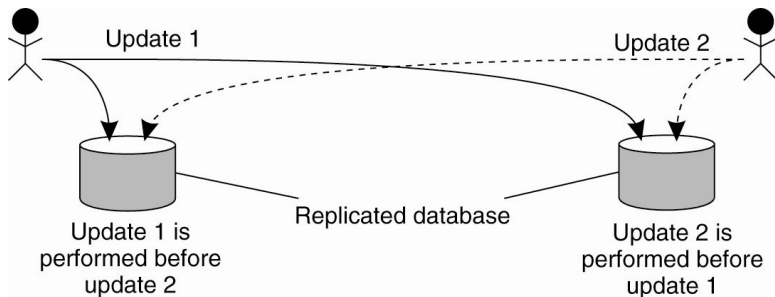
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Step 3. Upon the receipt of a message  $m$ , process  $P_j$  adjusts its own local counter as

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

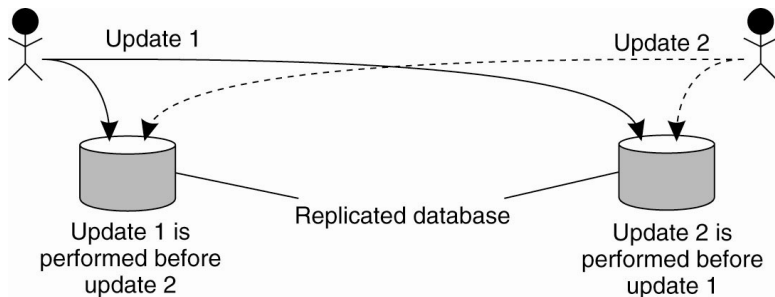
after which it then executes the first step and delivers the message to the application.

## Example: Totally Ordered Multicasting (1)



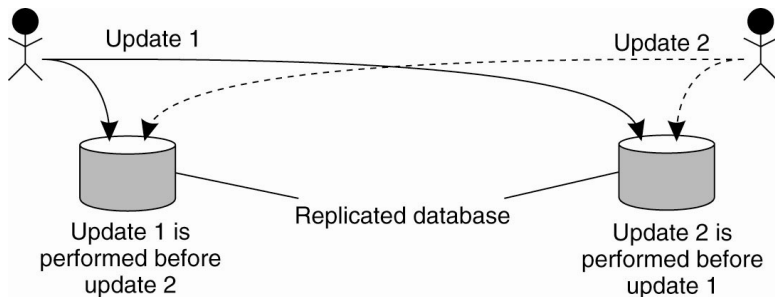
- Updating a database and leaving it in an inconsistent state.

## 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.
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- ▶ Lamport timestamps can be used to fix this problem.

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- ▶ 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.

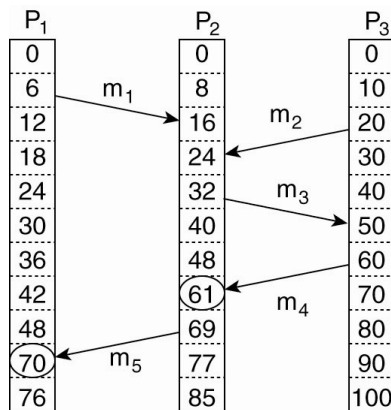
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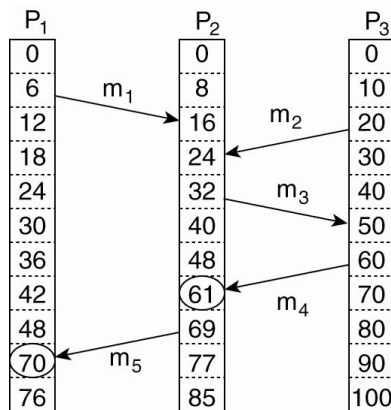
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- ▶ Lamport clocks do not capture **causality**. We need *vector clocks* to capture causality.

## Vector Clocks (2)

- ▶ **Vector clock:** A vector clock  $VC(a)$  assigned to an event  $a$  has the property that if  $VC(a) < VC(b)$  for some event  $b$ , then event  $a$  is known to causally precede event  $b$ .



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

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

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

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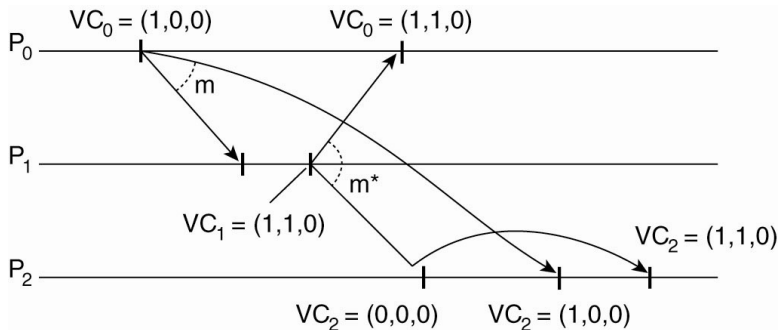
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$$ts(m)[k] \leq VC_j[k], \forall k \neq i$$

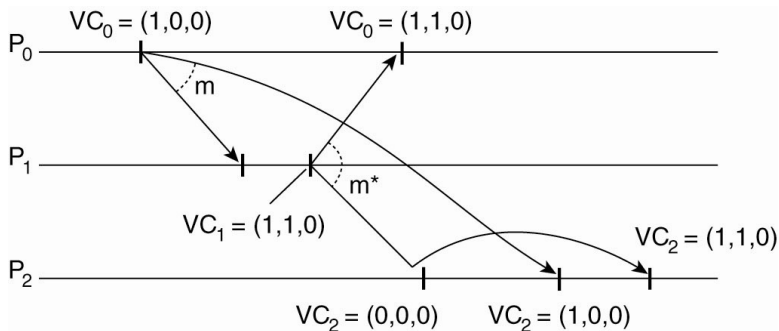
( $P_j$  has seen all the messages that have been seen by  $P_i$  when it sent message  $m$ )

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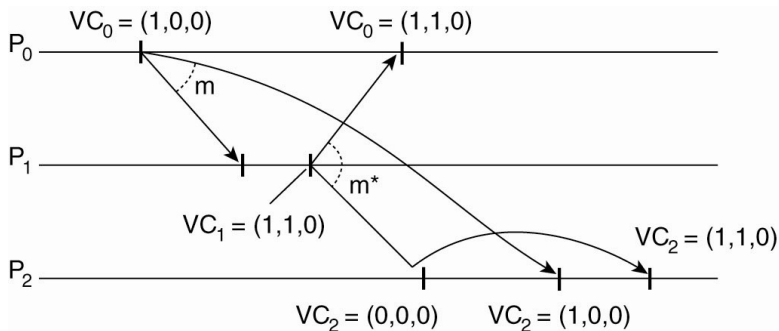
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  - ▶ Two messages sent by the same process are always marked as causally related.
- ▶ Middleware cannot be aware of external communication.  
Ordering issues can be adequately solved by looking at the application for which the communication is taking place. This is known as the **end-to-end argument**.

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- ▶ *Goal:* When an election starts, it ends with all processes agreeing on who the coordinator is.



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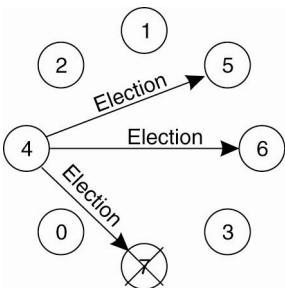
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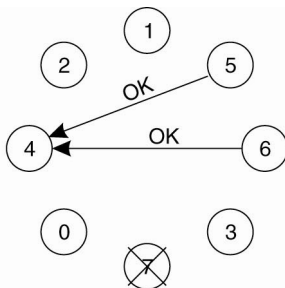
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- ▶ The new coordinator sends a message to all processes announcing that is is the new coordinator.
- ▶ Several elections can be running simultaneously. If a process that was down previously comes back up, it immediately runs an election. The "biggest" process in town always wins, hence the name "**bully algorithm**."

## Bully Algorithm (2)

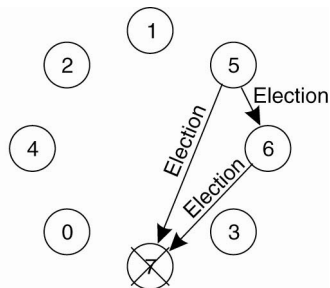


(a)



Previous coordinator  
has crashed

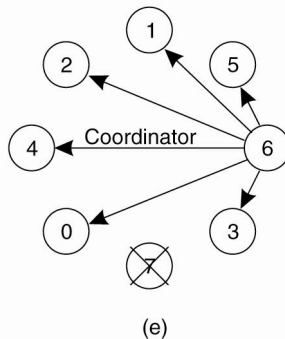
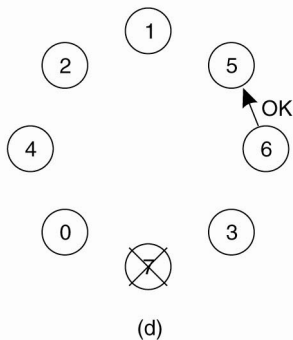
(b)



(c)

- (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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- ▶ 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

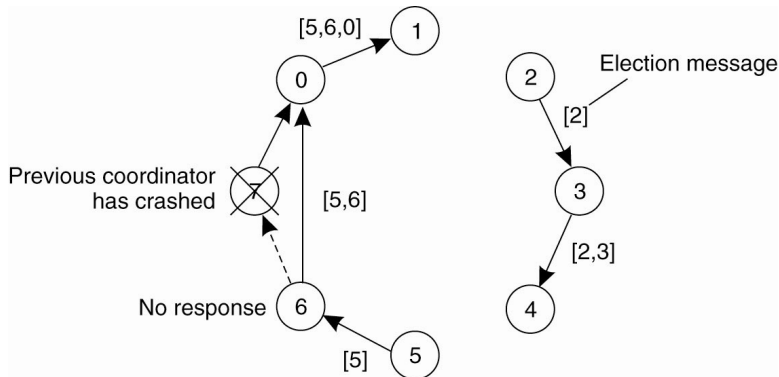
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- ▶ Then the message type is changed to **COORDINATOR** and the message circulates once again so everyone knows the new coordinator and the new ring configuration.

## Ring Algorithm (2)



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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]