TDDE35: Distributed Systems

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Notes derived from "Distributed Systems: Principles and Paradigms", by Andrew S. Tanenbaum and Maarten Van Steen, Pearson Int. Ed.

The slides are adapted and modified based on slides used by other instructors, including slides used in previous years by Juha Takkinen, as well as slides used by various colleagues from the distributed systems and networks research community.

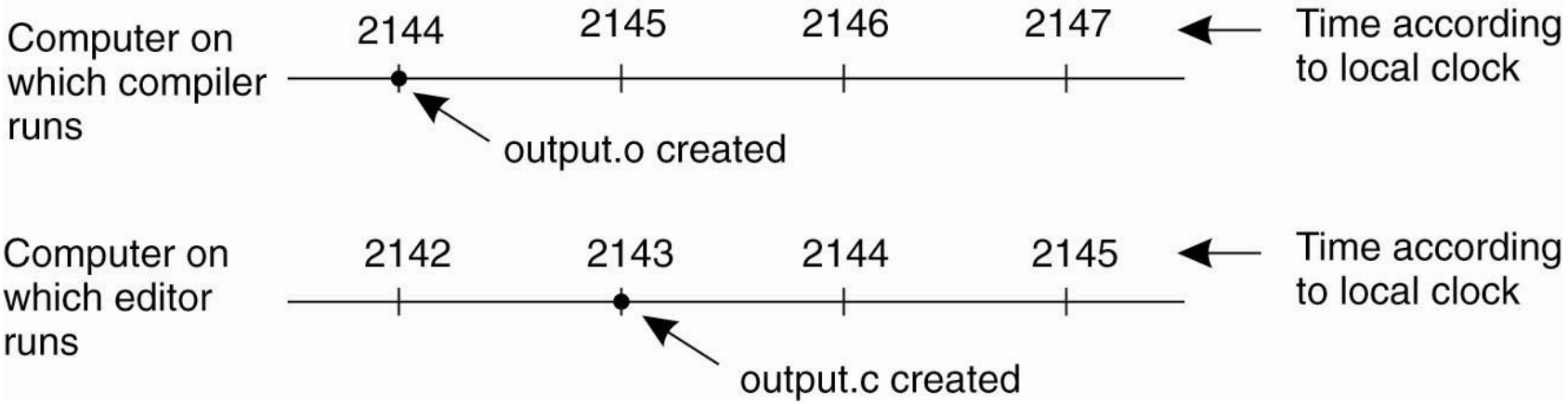
Synchronization

- Agreement over global state among distributed servers/processes

Time synchronization

- Uniprocessors
  - Single clock
  - All processes see the same time
- Distributed systems
  - Different clocks
  - Each machine sees different times

Clock synchronization



When each machine has its own clock, an event that occurred after another event may nevertheless be assigned an earlier time.

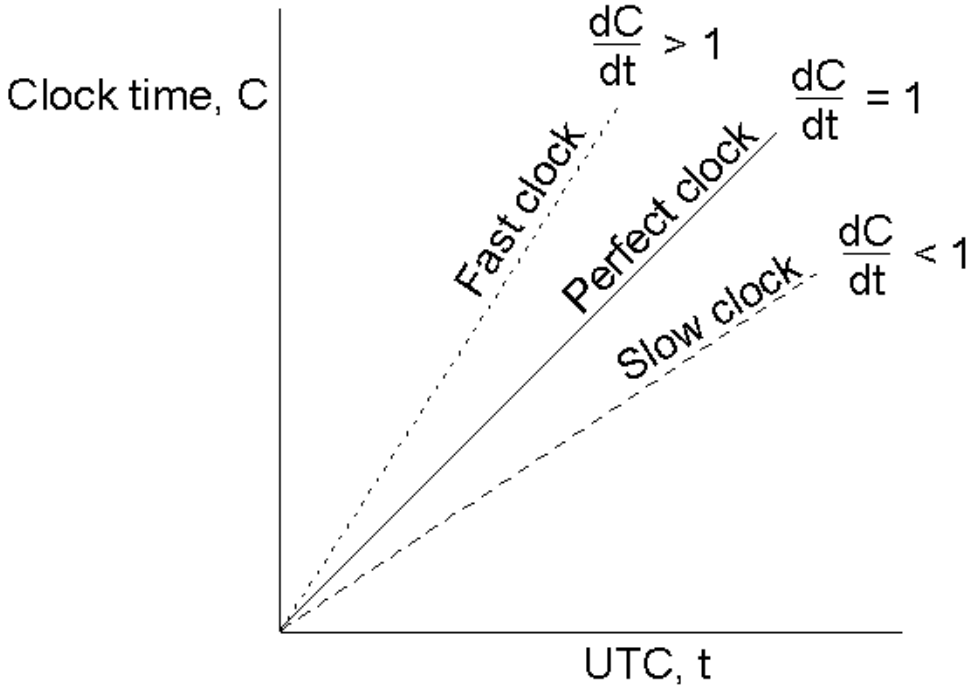
Synchronization

- Time synchronization
  - Physical clocks
- Event ordering
  - Logical clocks

Clocks and clock drifts

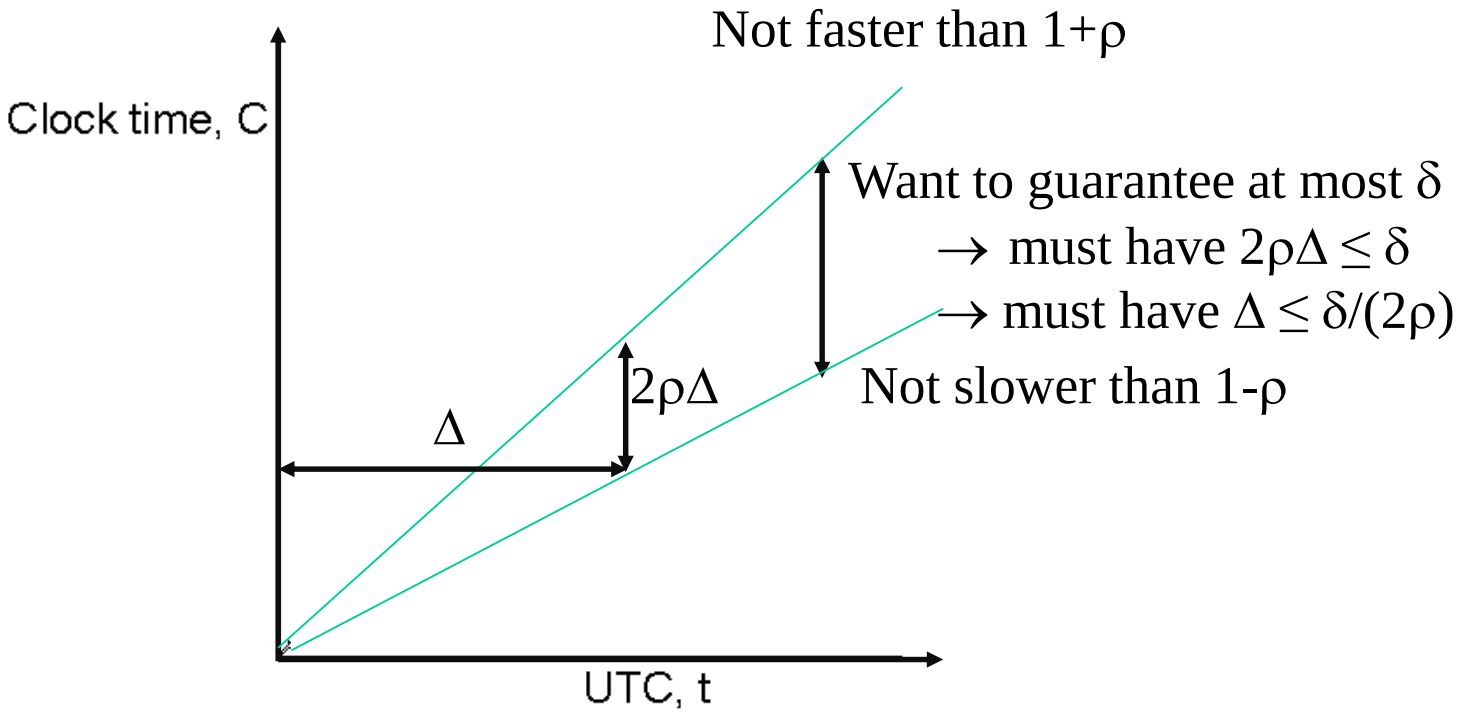
- Clocks are oscillators
  - Drift caused by differences in oscillator frequencies
- Coordinated universal time (UTC)
  - International standard based on atomic time
  - Broadcast via radio, satellites

Clock synchronization



- Each clock has a maximum drift rate ρ
  - $1-\rho \leq dC/dt \leq 1+\rho$

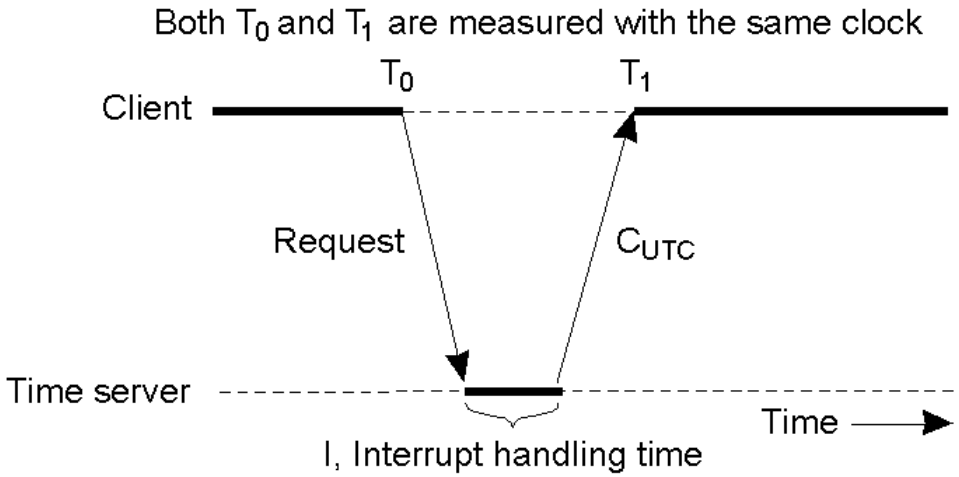
Clock synchronization



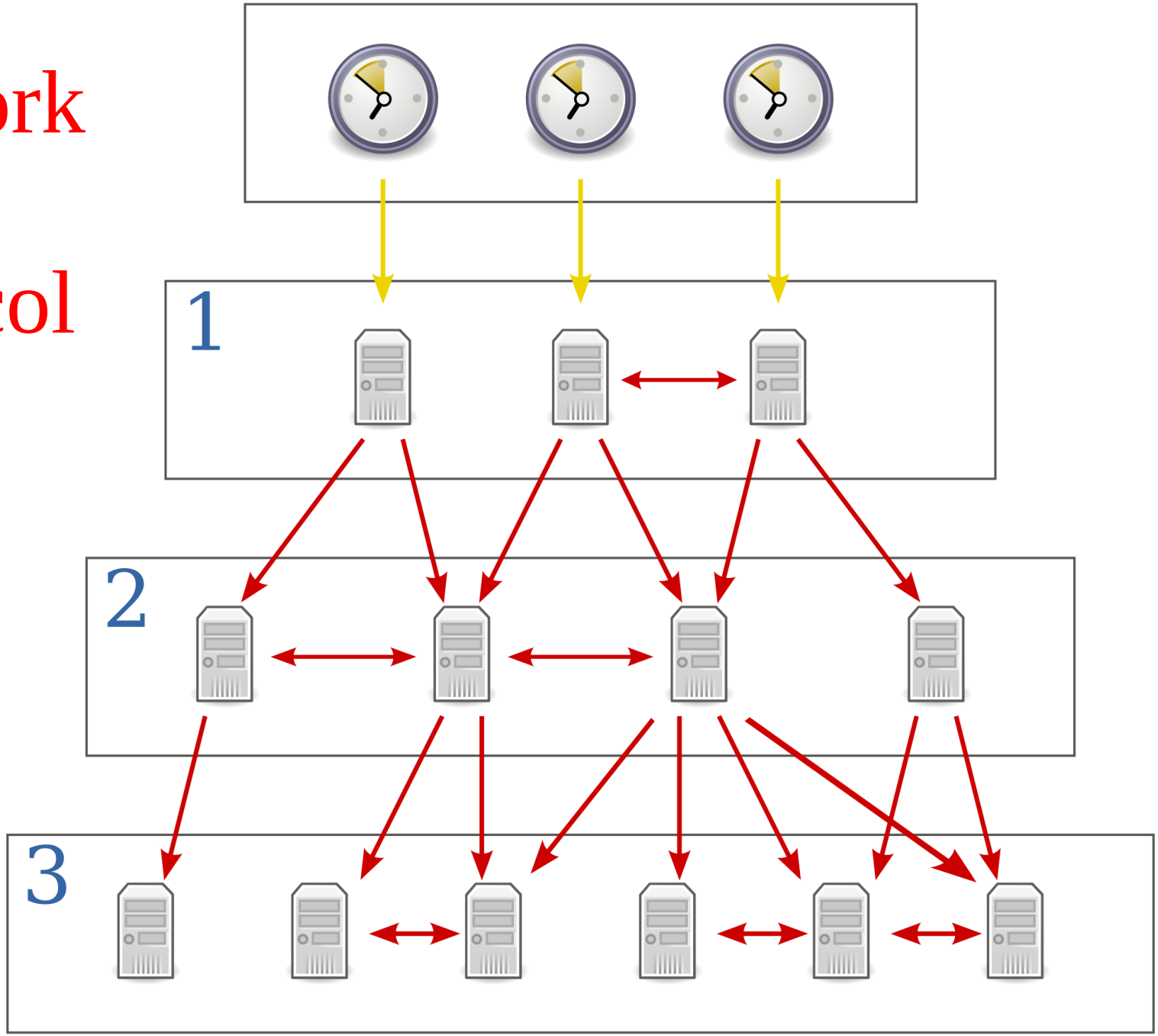
- Each clock has a maximum drift rate ρ
  - $1-\rho \leq dC/dt \leq 1+\rho$
  - Two clocks may drift by $2\rho\Delta$ in time Δ
  - To limit drift to δ, we must therefore resynchronize every $\delta/2\rho$ seconds

Physical Clock Synchronization

- Cristian's Algorithm and NTP – periodically get information from a time server (assumed to be accurate).



Network Time Protocol



Source: Wikipedia

Physical Clock Synchronization

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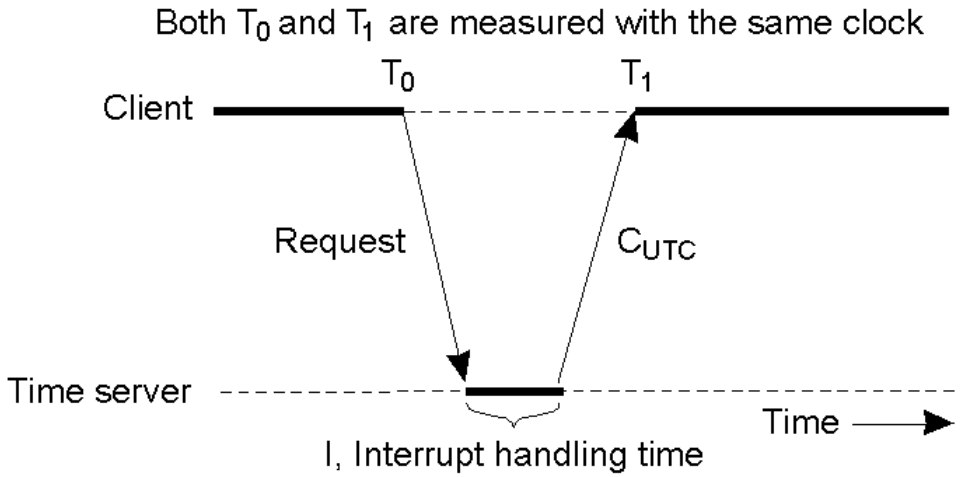
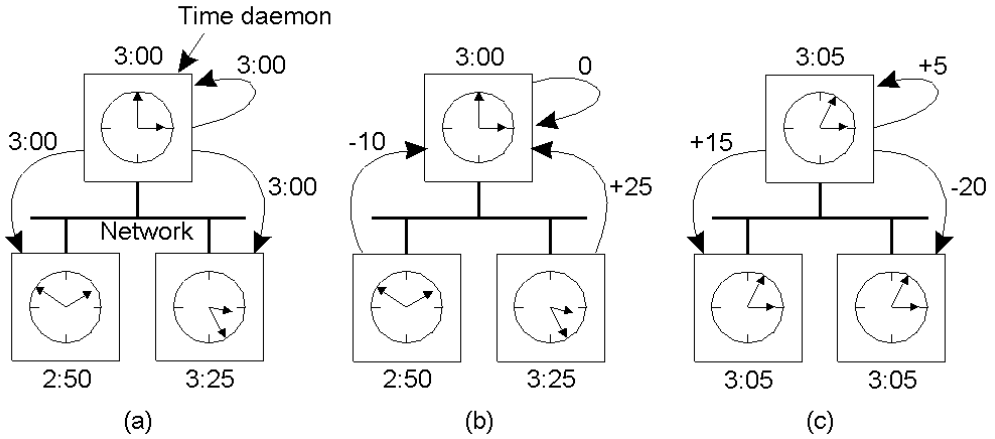


- Berkeley – active time server uses polling to compute average time. Note that the goal is the have correct "relative" time



Logical clocks

Observation: It may be sufficient that every node agrees on a current time – that time need not be ‘real’ time.

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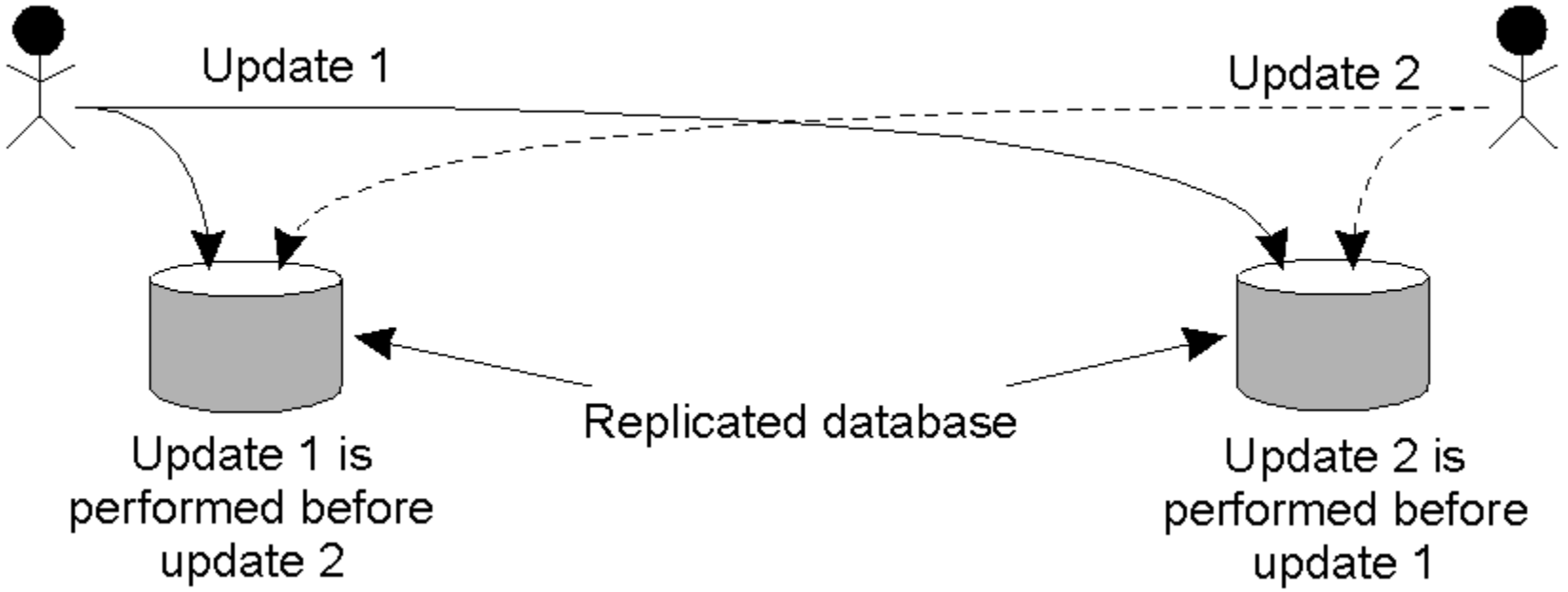
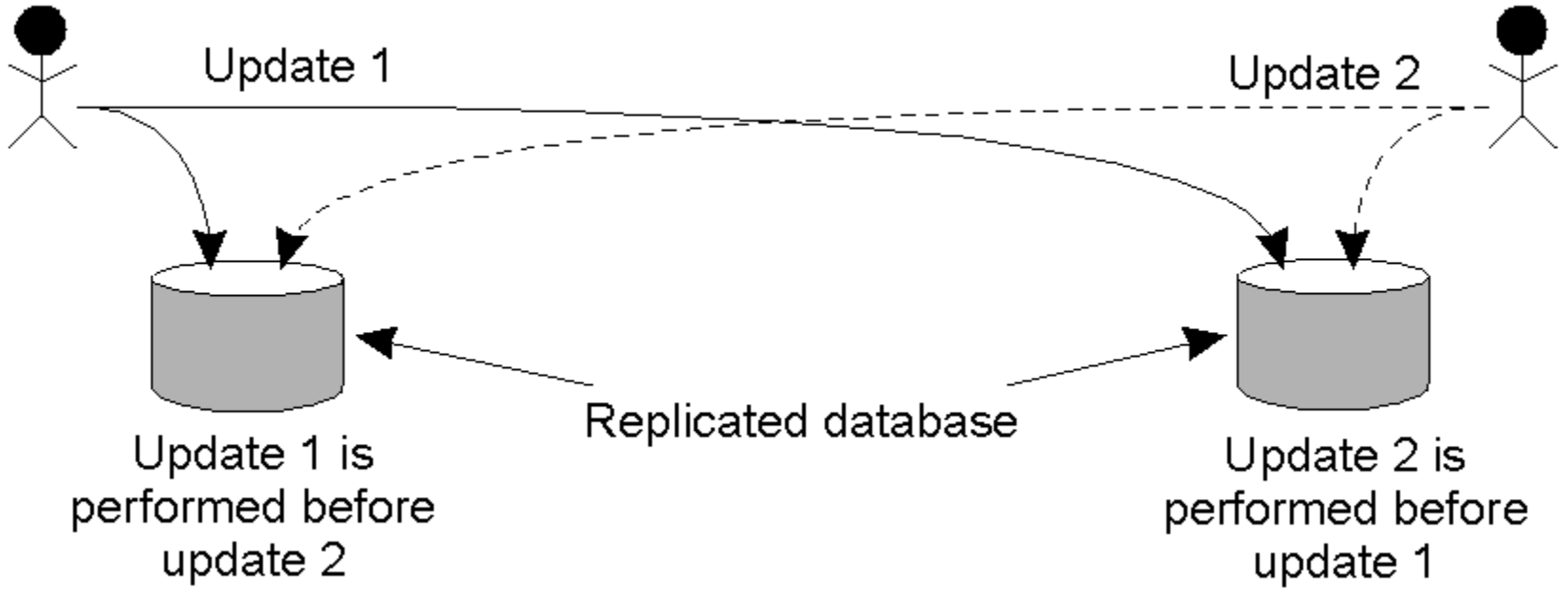


Logical clocks

Observation: It may be sufficient that every node agrees on a current time – that time need not be ‘real’ time.

Taking this one step further, in some cases, it is adequate that two systems simply agree on the order in which system events occurred.



Event ordering

- Multiple communicating processes running on different machines
- Events taking place on each process
  - Computation
  - Data read/write
  - Sending/receiving of messages
- In what order are these events happening?
- Can we use clock times of machines?

Logical clocks

- Maintain ordering of distributed events in a consistent manner
- Main Ideas:
  - Idea 1: Non-communicating processes do not need to be synchronized
  - Idea 2: Agreement on ordering is more important than actual time
  - Idea 3: Ordering can be determined by sending and receiving of messages

Event ordering

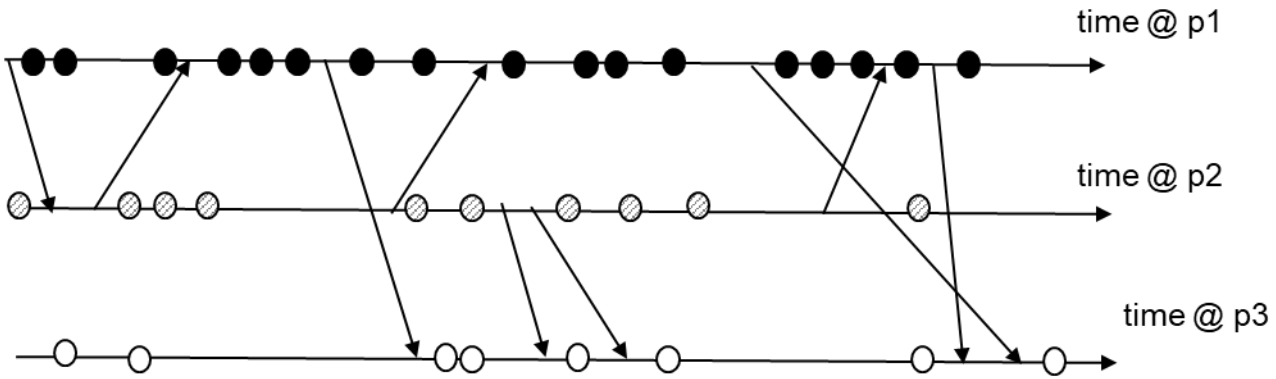
The "happens-before" relation $\rightarrow$ can be observed directly in two situations:

- **Rule 1:** If *a* and *b* are events in the same process, and *a* occurs before *b*, then $a \rightarrow b$ is true.
- **Rule 2:** If *a* is the event of a message being sent by one process, and *b* is the event of the message being received by another process, then $a \rightarrow b$

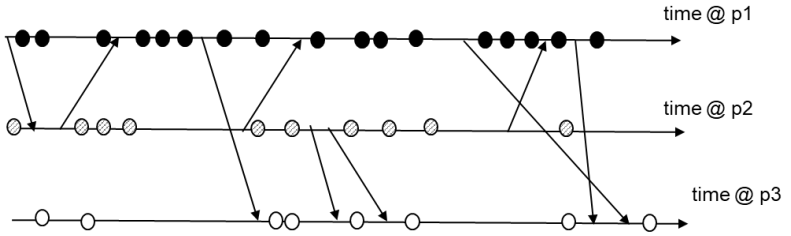
Transitivity: $A \rightarrow B$ and $B \rightarrow C$ => $A \rightarrow C$

Partial ordering

- "Happens-before" operator creates a partial ordering of all events
- If events *A* and *B* are connected through other events
  - Always a well-defined ordering
- If no connection between *A* and *B*
  - *A* and *B* are considered concurrent



Lamport timestamps



- Timestamps should follow the partial event ordering
  - $A \rightarrow B \Rightarrow C(A) < C(B)$
  - Timestamps always increase
- Lamport's Algorithm:
  - Each processor i maintains a logical clock C_i
  - Whenever an event occurs locally, $C_i = C_i + 1$
  - When i sends message to j, piggyback C_i
  - When j receives message from i
    - $C_j = \max(C_i, C_j) + 1$

Lamport's logical clocks (with)

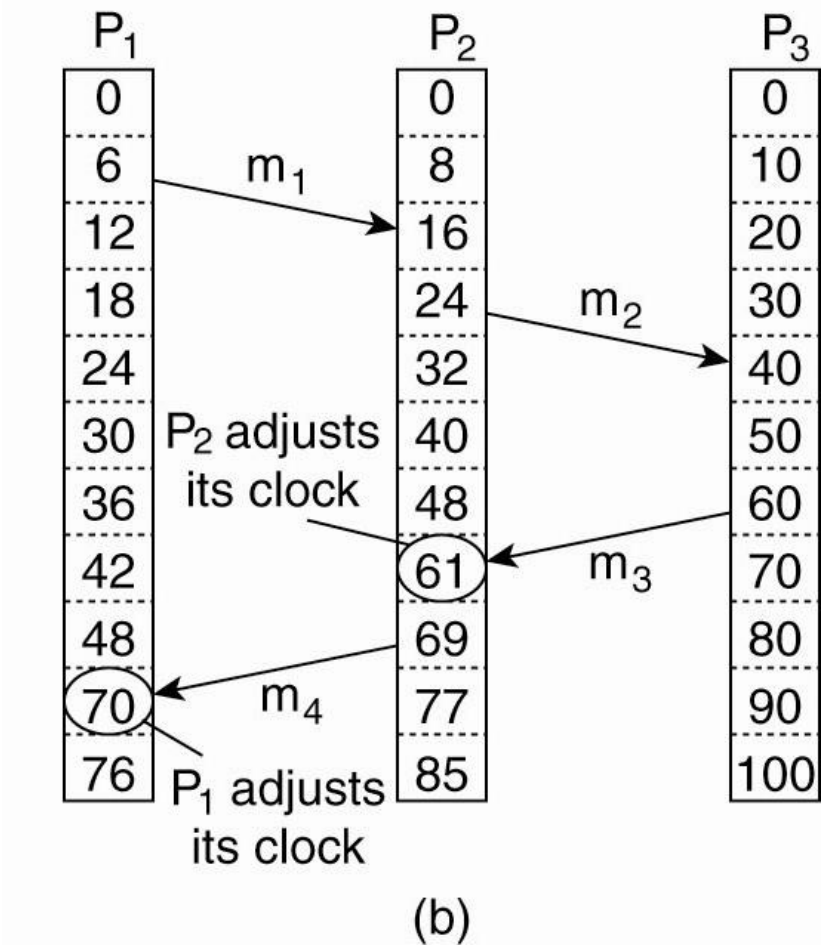


Figure 6-9. (b) Lamport's algorithm corrects the clocks.

Lamport's logical clocks

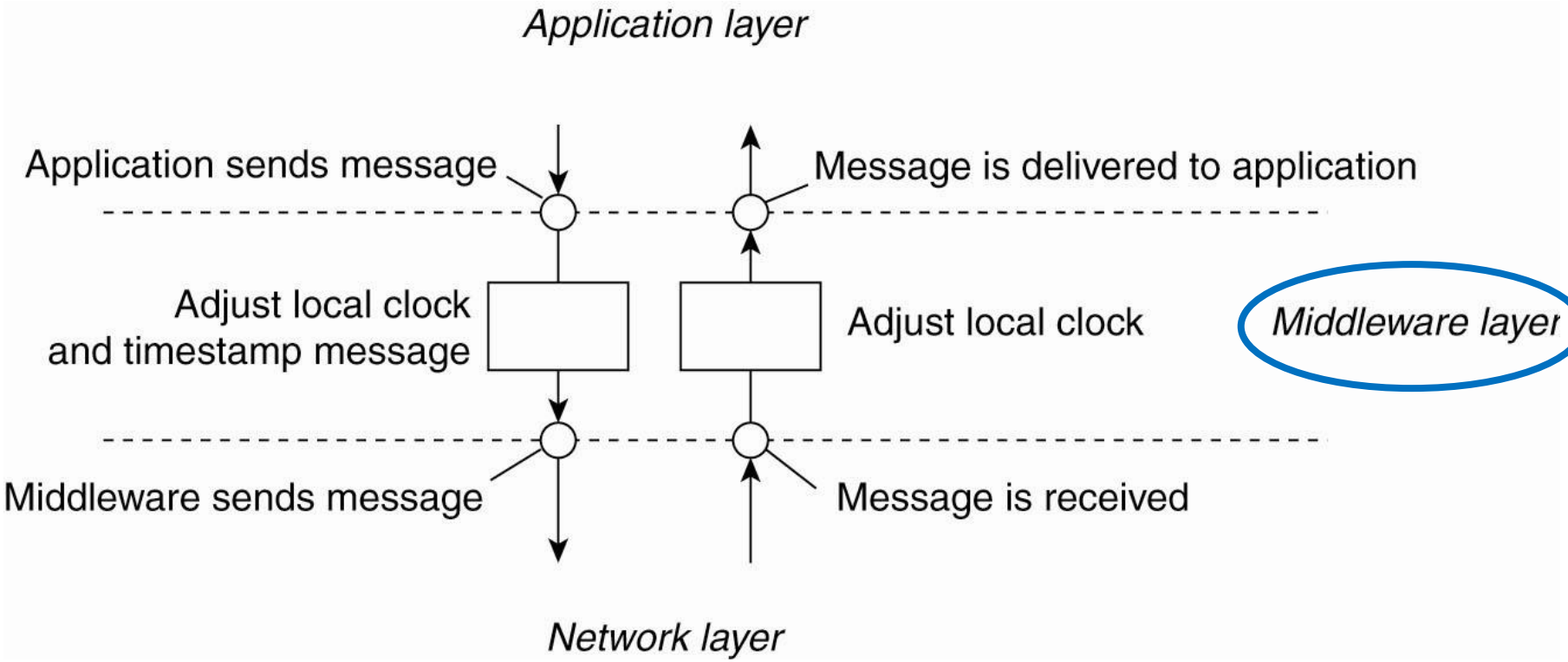
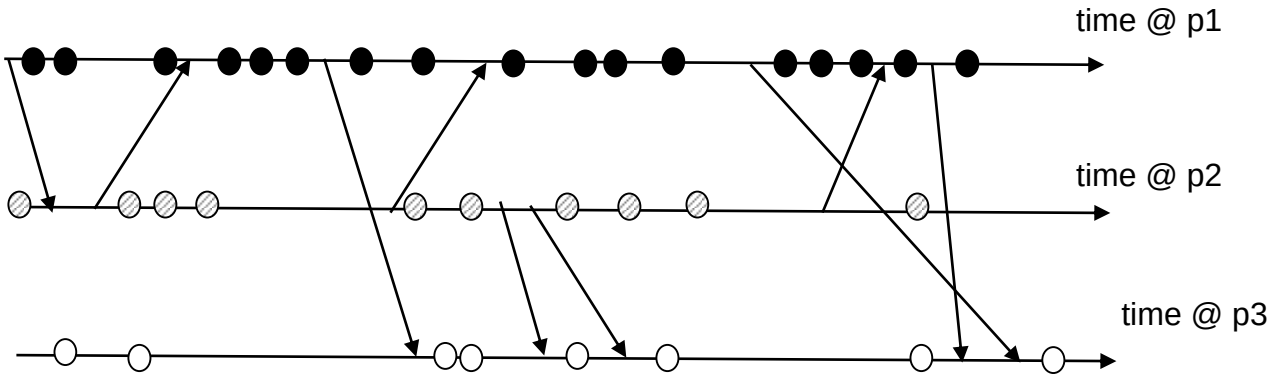


Figure 6-10. The positioning of Lamport's logical clocks in distributed systems.

Example …

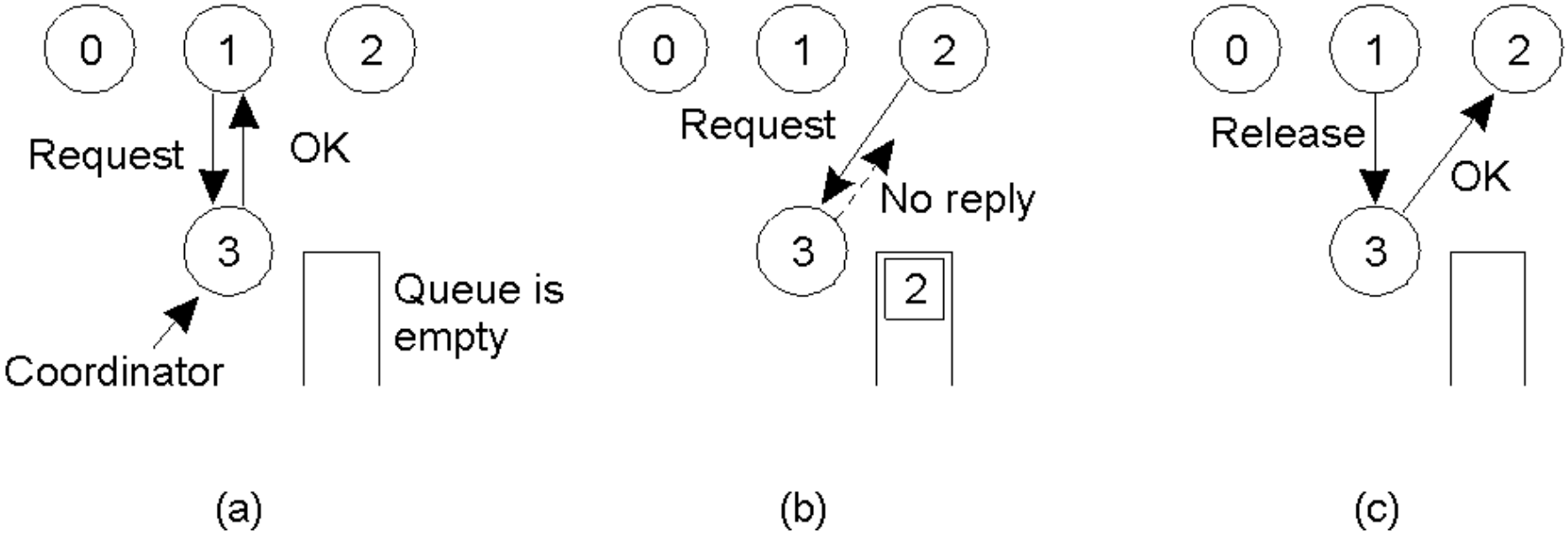


Shared resources

Distributed mutual exclusion

- Multiple processes on different machines may need to access a critical section
- Shared-memory systems:
  - Typically implemented in shared memory
  - Processes share same blocking queues
- How to implement mutual exclusion in distributed systems?

Mutual Exclusion: A Centralized Algorithm



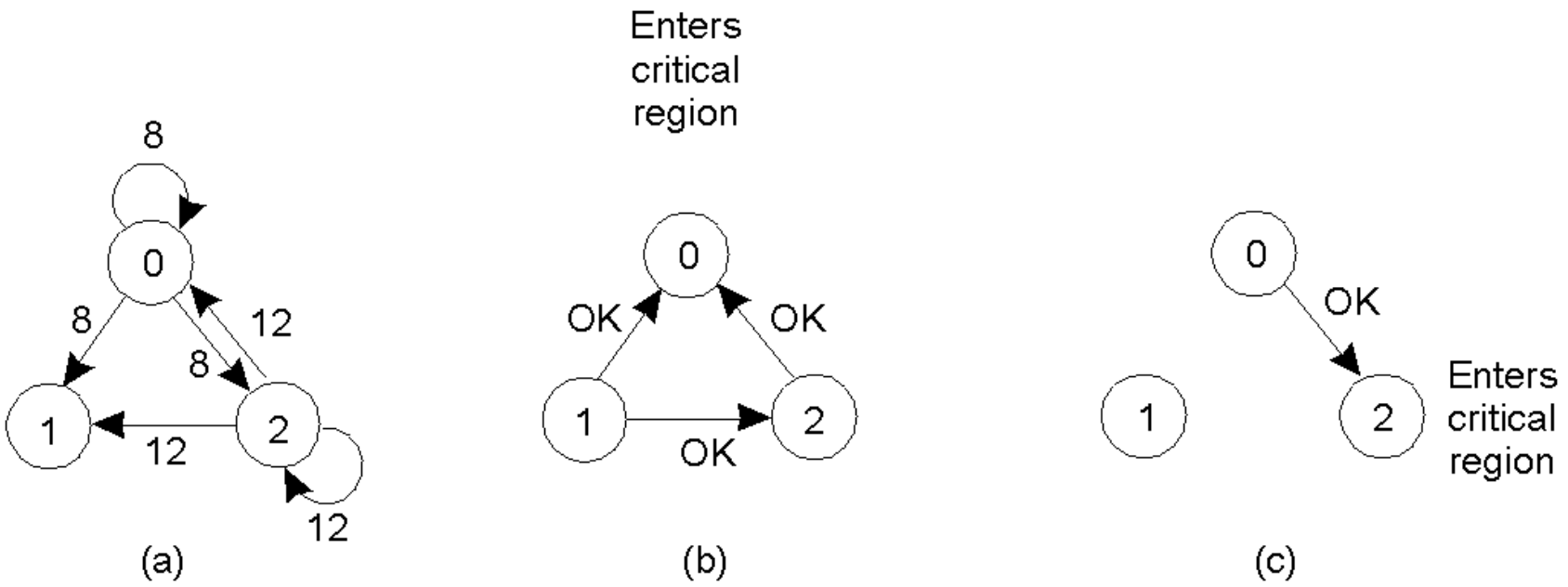
Permission is granted

b) Process 2 then asks permission to enter the same critical region. The coordinator does not reply.

c) When process 1 exits the critical region, it tells the coordinator, when then replies to 2

Algorithm	Messages per entry/exit	Delay before entry (in message times)	Problems
Centralized	3	2	Coordinator crash

Distributed Mutual Exclusion: Ricart/Agrawala



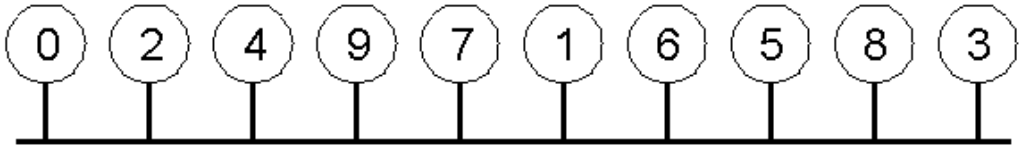
a) Two processes want to enter the same critical region at the same moment.

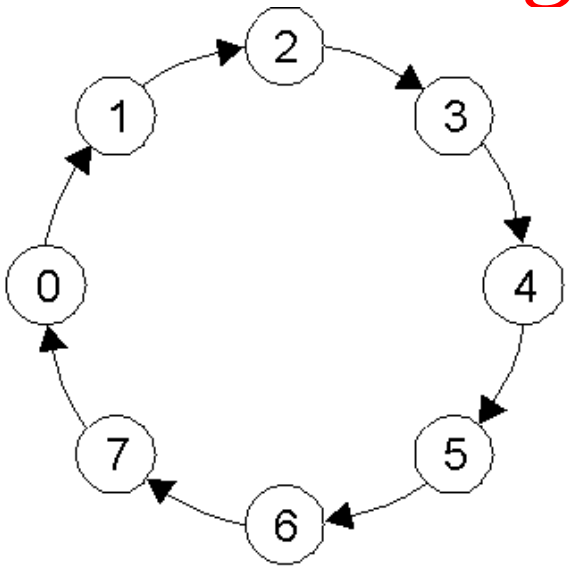
b) Process 0 has the lowest timestamp, so it wins.

c) When process 0 is done, it sends an OK also, so 2 can now enter the critical region.

Algorithm	Messages per entry/exit	Delay before entry (in message times)	Problems
Distributed (Ricart/Agrawala)	2 (n – 1)	2 (n – 1)	Crash of any process

Distributed Mutual Exclusion: Token Rings





a) An unordered group of processes on a network.

b) A logical ring constructed in software.

Algorithm works by passing a token around the ring. When a process holds the token, it decides if it needs to access the resource at this time. If so, it holds the token while it does so, passing the token on once done.

Problems if the token is ever 'lost' – token loss may also be difficult to detect.

Algorithm	Messages per entry/exit	Delay before entry (in message times)	Problems
Token ring	1 to ∞	0 to n – 1	Lost token, process crash

Comparison

Algorithm	Messages per entry/exit	Delay before entry (in message times)	Problems
Centralized	3	2	Coordinator crash
Distributed (Ricart/Agrawala)	2 (n – 1)	2 (n – 1)	Crash of any process
Token ring	1 to ∞	0 to n – 1	Lost token, process crash

A comparison of three mutual exclusion algorithms.

Election Algorithms

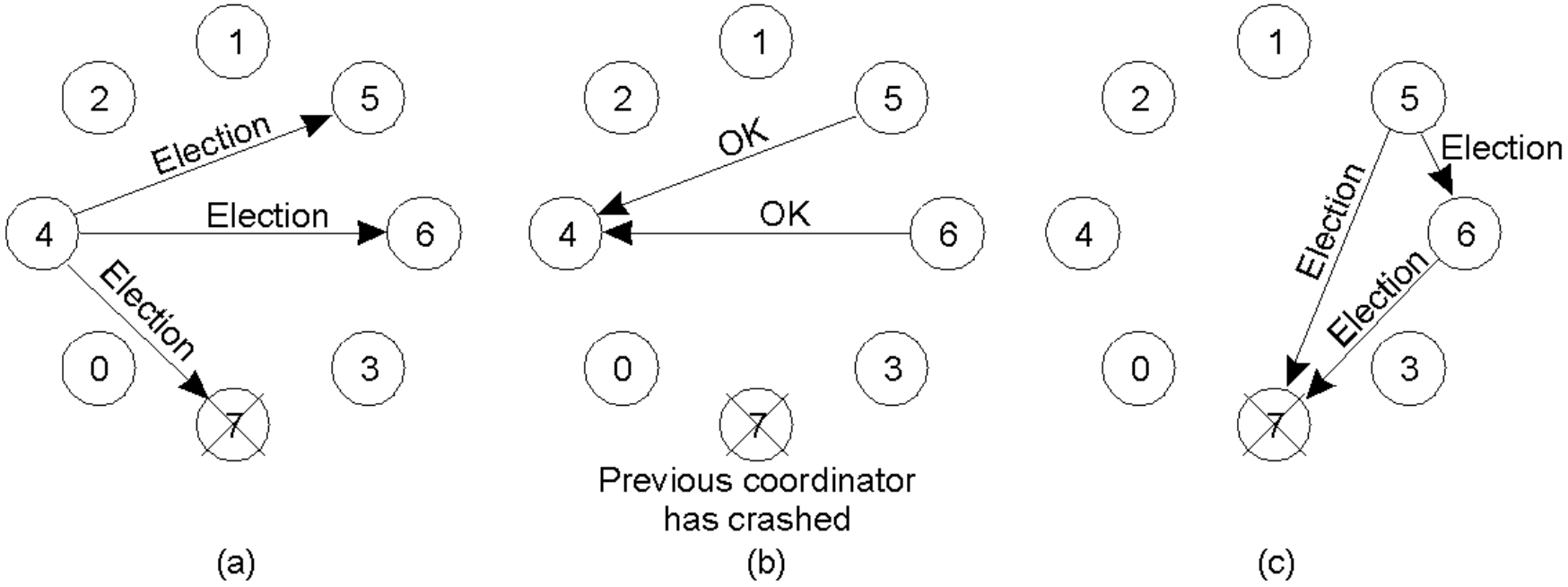
Some algorithms require some participating process to act as coordinator.

Assuming

- all processes are the same except for a unique number
- the highest numbered process gets to be coordinator
- processes can fail and restart

Election algorithms are a method of finding this highest numbered process and making it known to all processes as the coordinator.

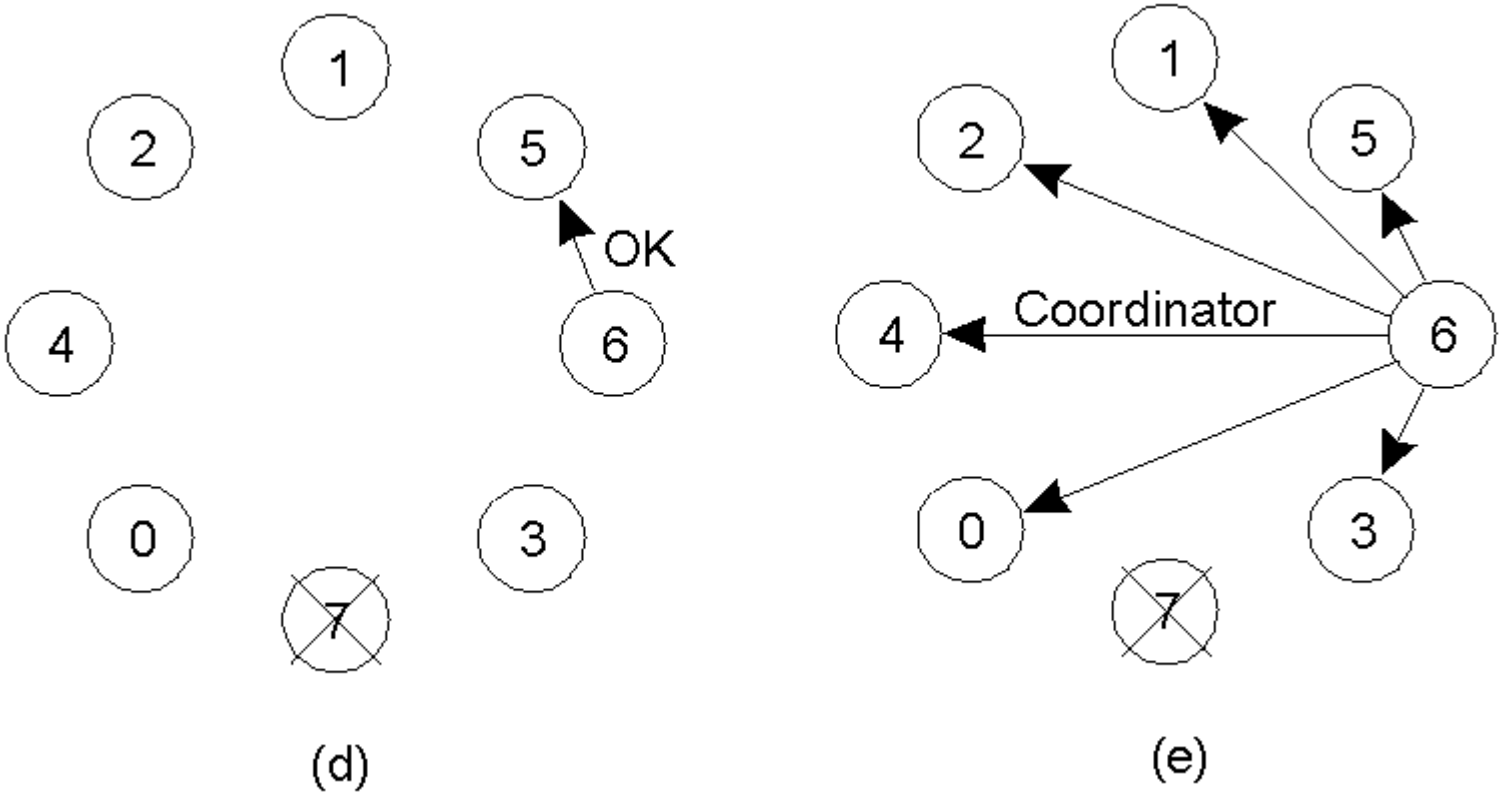
The Bully Algorithm (2)



The bully election algorithm

- Process 4 notices that 7 is no longer available and holds an election by sending messages to 5 and 6
- Process 5 and 6 respond, telling 4 to stop
- 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

f) if process 7 ever restarts, it will notify everyone that it is the coordinator

Reasons for Replication

- Data are replicated to increase the reliability and performance of a system.
- Replication for performance
  - Scaling in numbers
  - Scaling in geographical area
  - Nearby replicas + load distribution
- Caveat
  - Gain in performance
  - Cost/complexity of maintaining replication

Content Replication and Placement

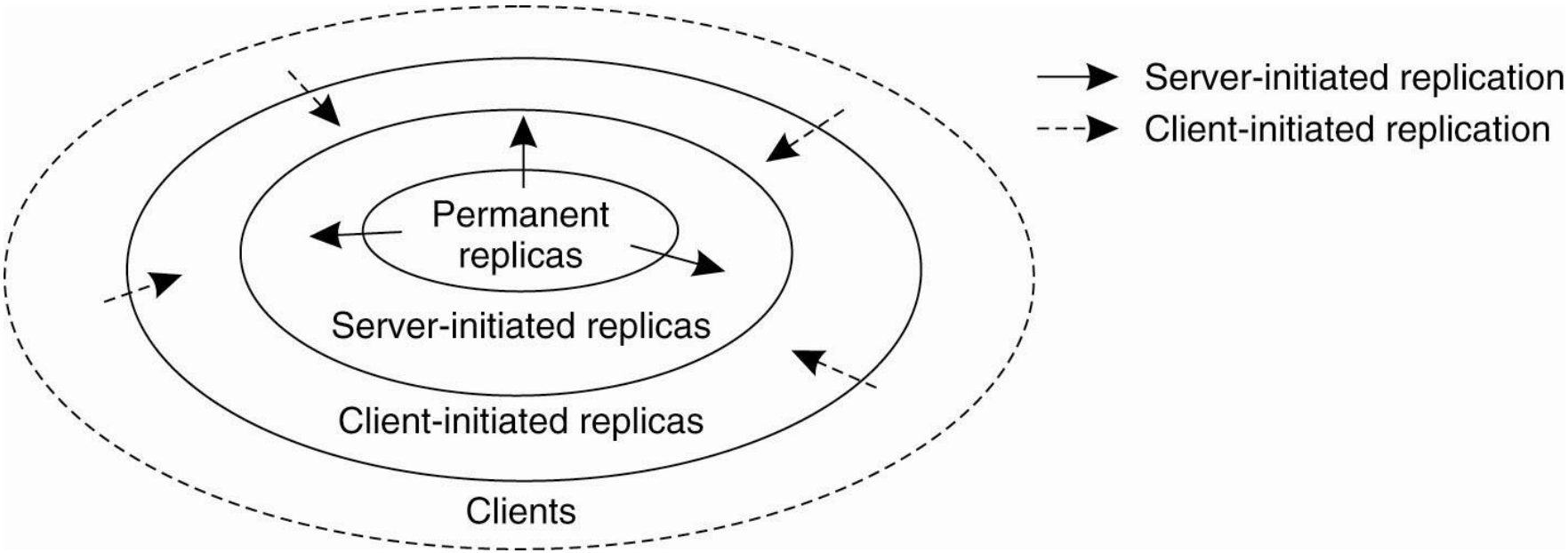


Figure 7-17. The logical organization of different kinds of copies of a data store into three concentric rings.

Dan and Carlsson, Dynamic Content Allocation for Cloud-assisted Service of Periodic Workloads, Proc. INFOCOM 2014.

Fixed vs elastic

Cloud-based delivery

- Flexible computation, storage, and bandwidth
- Pay per volume and access

Dedicated infrastructure

- Limited storage
- Capped unmetered bandwidth
- Potentially closer to the user

Cloud bandwidth elastic; however, flexible comes at premium …