Distributed Systems

Synchronization

Outline

- Clock Synchronization
  - Physical clocks
  - Logical clocks
- Mutual exclusion

Clock Synchronization

- Time in a centralized system
- Lack of global time agreement in a distributed system
  - Implications?
- Physical clocks
- Logical clocks

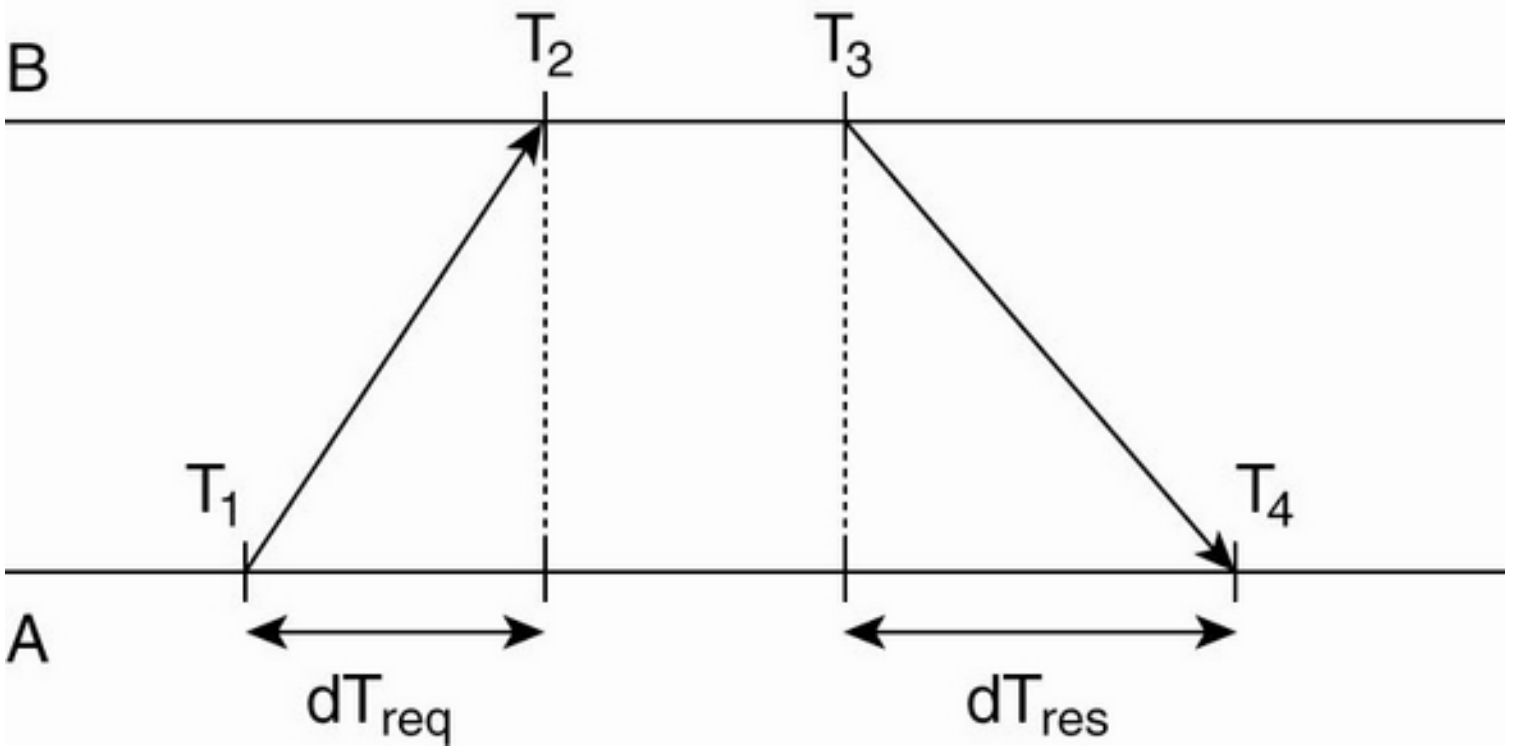
Physical clocks 1/2

- Timer (counter and holding register)
- Clock tick
- Date and time entered after booting converted to the number of ticks after some known starting date and stored in memory
  - Battery-backed up CMOS RAM
  - With every clock tick → ISR (interrupt service routine) adds 1 to time stored in memory
- Multiple CPUs → clock skew

Physical clocks 2/2

- Astronomers (Transit of the sun and mean solar second because days are getting longer)
- Physicists
  - Atomic clock in 1948 → transitions of the cesium 133 atom
  - Atomic second = mean solar second
    - Time it takes cesium 133 atom to make 9,192,631,770 transitions
  - International Atomic Time (TAI)
    - Mean number of ticks of cesium 133 clocks since midnight on Jan, 1, 1958 divided by 9,192,631,770
    - 86,400 TAI seconds is now about 3 msec less than a mean solar day
    - Introduce *leap seconds* whenever discrepancy between TAI and solar time grows to 800 msec
  - Universal coordinated time (UTC)

Getting Time from a Time Server



A's offset relative to B = θ

$$\theta = T_3 - \frac{(T_2 - T_1) + (T_4 - T_3)}{2}$$

NTP buffers eight pairs of (θ,delay) selecting minimal delay

Lamport's Logical Clocks 1/5

- To synchronize logical clocks (need to agree on order of events, but not exact time)
- The "happens-before" relation → can be observed directly in two situations:
  - If *a* and *b* are events in the same process, and *a* occurs before *b*, then $a \rightarrow b$ is true.
  - 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 $a \rightarrow b$
- If $a \rightarrow b$, then $C(a) < C(b)$ where C(i) is a time value

Lamport's Logical Clocks 2/5

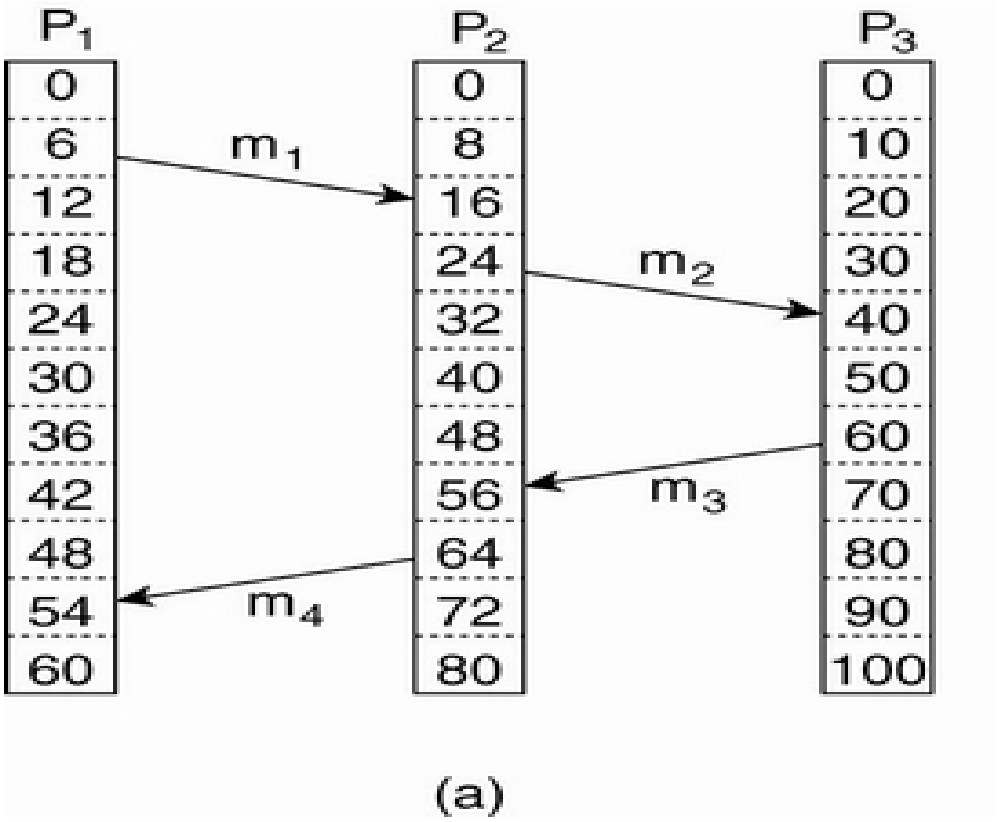


Figure 5-7. (a) Three processes, each with its own clock. The clocks run at different rates.

Lamport's Logical Clocks 3/5

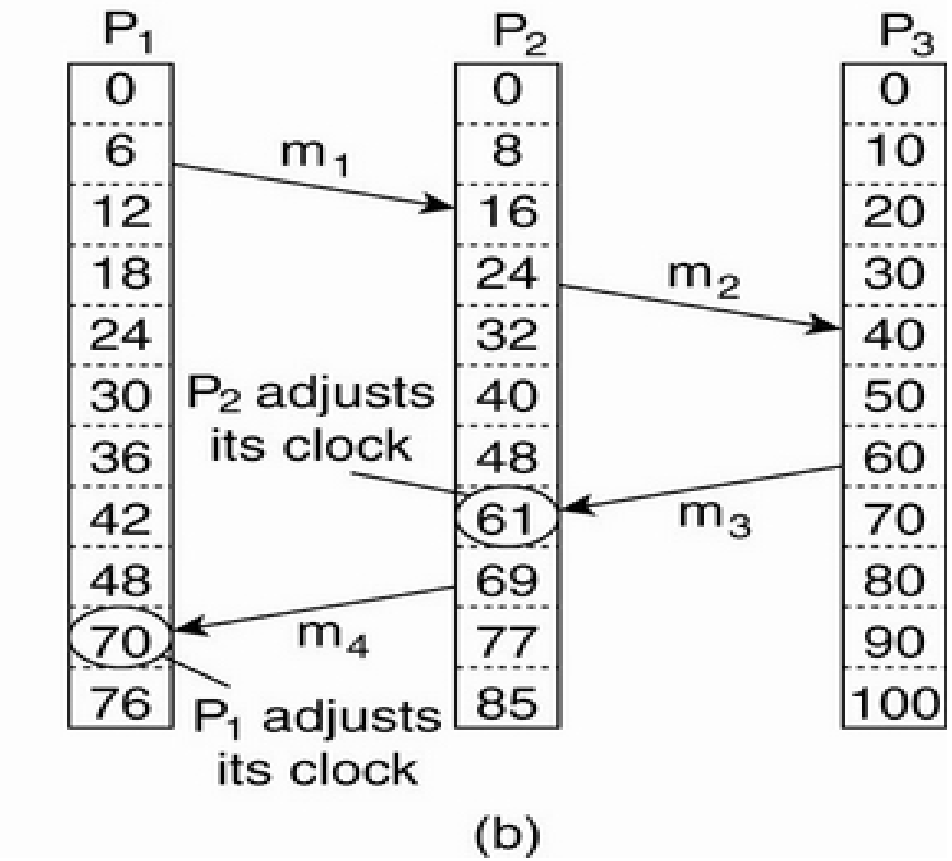
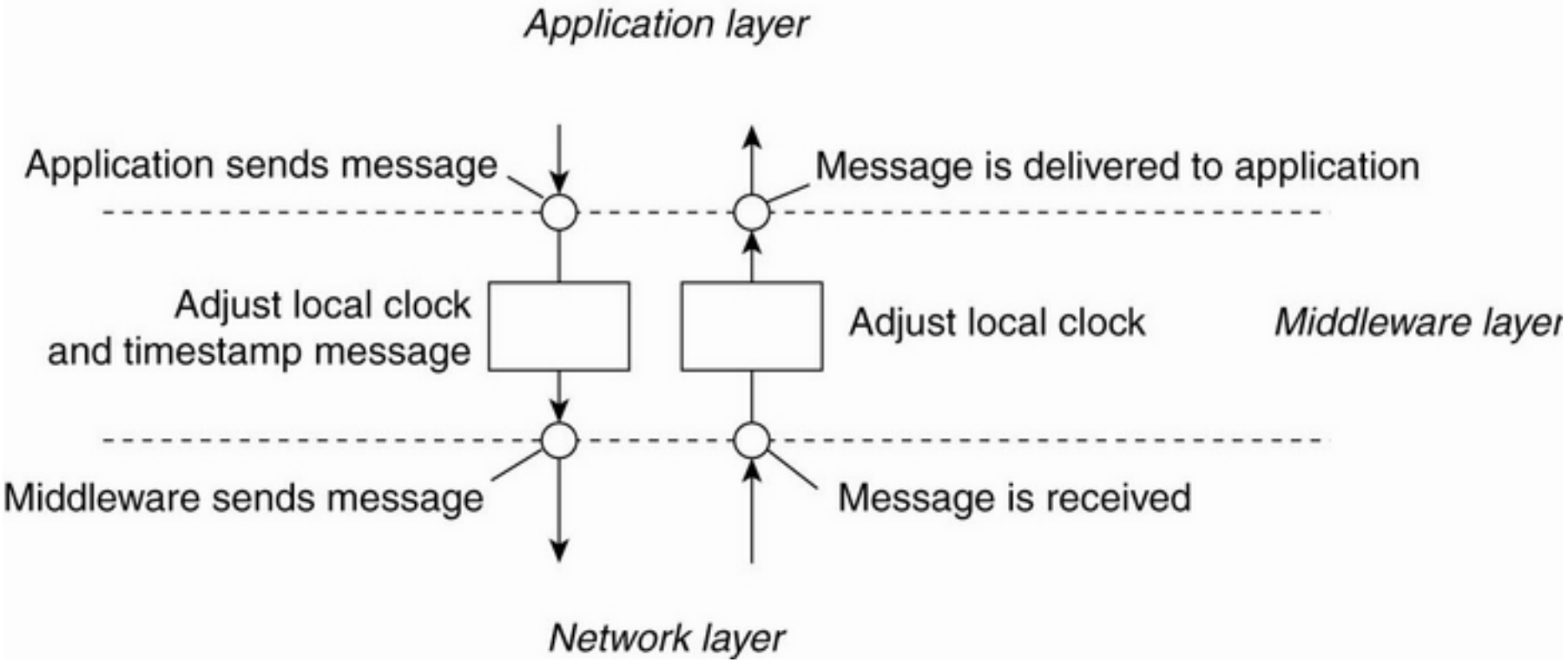


Figure 5-7. (b) Lamport's algorithm corrects the clocks.

Lamport's Logical Clocks 4/5



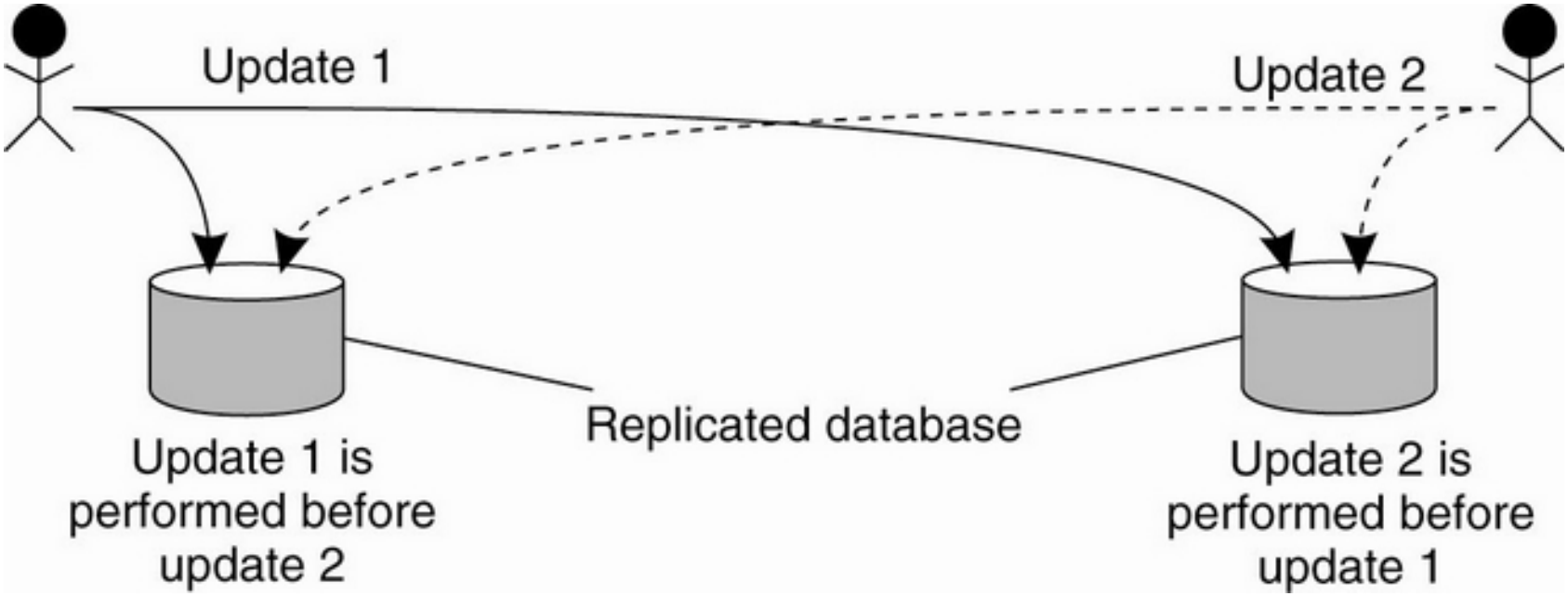
The positioning of Lamport's logical clocks in distributed systems.

Lamport's Logical Clocks 5/5

- Updating counter C_i for process P_i

1. Before executing an event, P_i executes
   $C_i \leftarrow C_i + 1$.
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.
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.

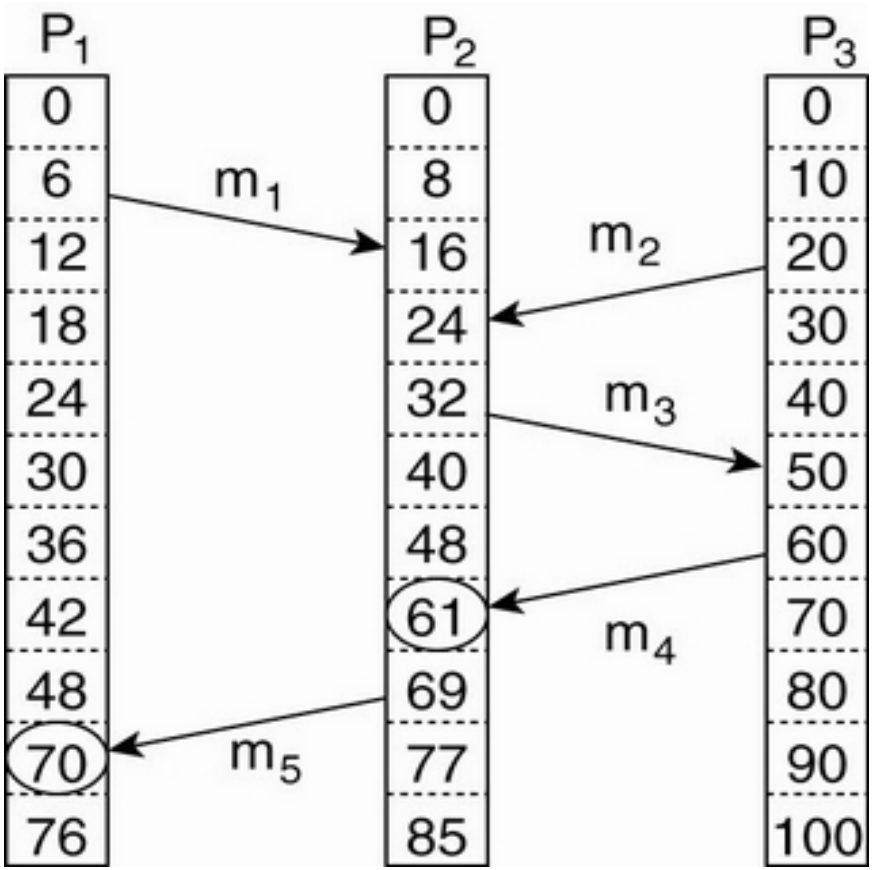
Example: Totally Ordered Multicasting



- Message timestamped with current logical time of sender
- Receiver multicasts an ACK to other processes
- Deliver message when at head of queue and *has been ACKed by each other process*

Vector Clocks 1/3

- If C(a) < C(b) does not imply that *a* happened before *b*?
- $T_{rcv}(m_1) < T_{snd}(m_2)$
- Sending m_2 has nothing to do with receipt of m_1
- *Lamport* clocks do not capture causality
- Need for vector clocks



Concurrent message transmission using logical clocks.

Vector Clocks 2/3

- Vector clocks are constructed by letting each process P_i maintain a vector VC_i with the following two properties:

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 .
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 3/3

Steps carried out to accomplish property 2 of previous slide:

1. Before executing an event P_i executes
   $VC_i[i] \leftarrow VC_i[i] + 1$.
2. When process P_i sends a message m to P_j, it sets m's (vector) timestamp $ts(m)$ equal to VC_i after having executed the previous step.
3. Upon the receipt of a message m, process P_j adjusts its own vector by setting
   $VC_j[k] \leftarrow \max\{VC_j[k], ts(m)[k]\}$ for each k, after which it executes the first step and delivers the message to the application.

Enforcing Causal Communication

- Causally-ordered communication → weaker than totally-ordered communication
- P_j receives a message *m* from P_i with vector timestamp *ts(m)*
- Delivery of message to application layer delayed until 2 conditions met
  - *ts(m)*[i]=VC_j[i]+1
    - m is next message P_j expects from P_i
  - *ts(m)*[k]<= VC_j[k] for all k != i
    - P_j has seen all the messages that have been seen by P_i when it sent message *m*

Important Points

- Physical Clocks

  Can keep closely synchronized, but never perfect

- Logical Clocks

  Encode causality relationship

  Lamport clocks provide only one-way encoding

  Vector clocks provide exact causality information

Distributed Mutual Exclusion

- Token-based solutions
  - One token
  - Whoever has the token, can access the shared resource
  - When finished, pass token to next resource
  - Avoids starvation and deadlock
  - A problem if token is lost
- Permission-based solutions
  - Ask for permission first

Mutual Exclusion: A Centralized Algorithm 1/3

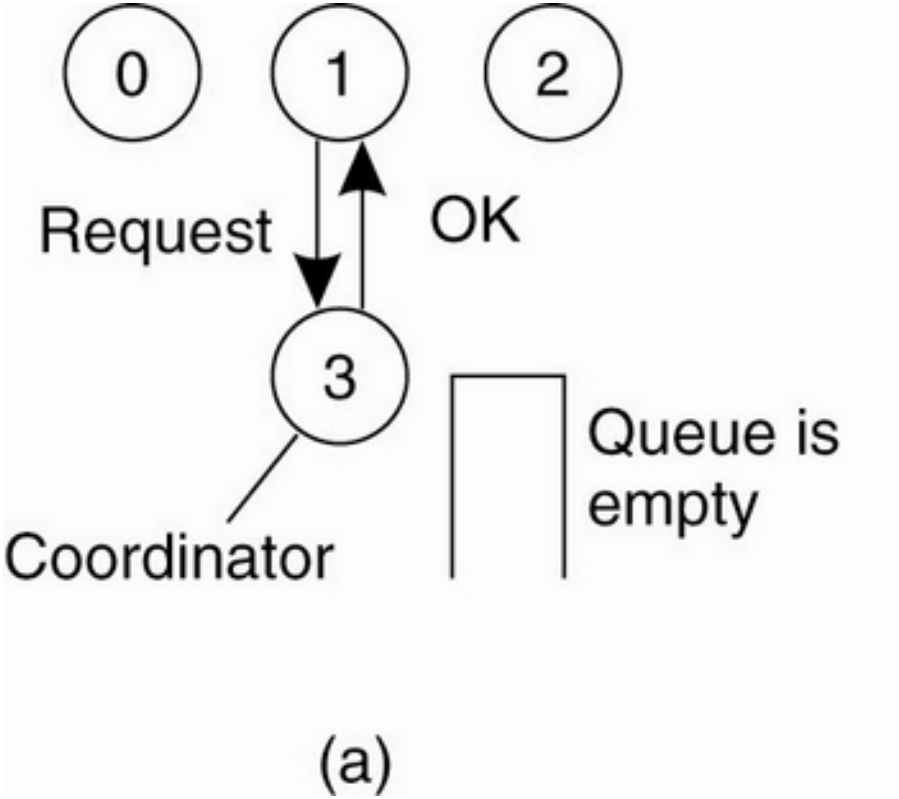


Figure 5-13. (a) Process 1 asks the coordinator for permission to access a shared resource. Permission is granted.

Mutual Exclusion: A Centralized Algorithm 2/3

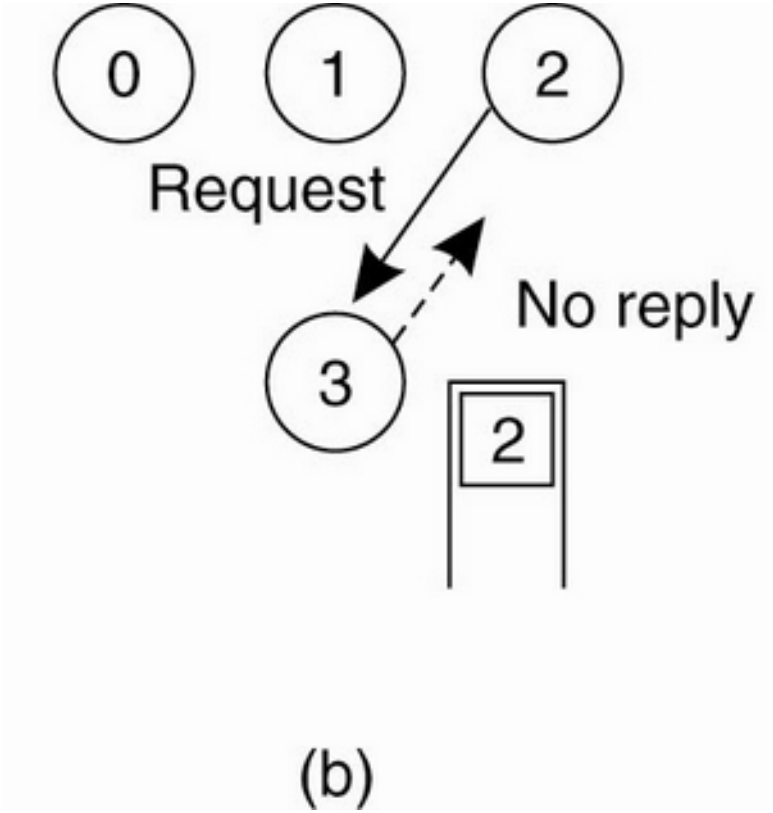


Figure 5-13. (b) Process 2 then asks permission to access the same resource. The coordinator does not reply.

Mutual Exclusion: A Centralized Algorithm 3/3

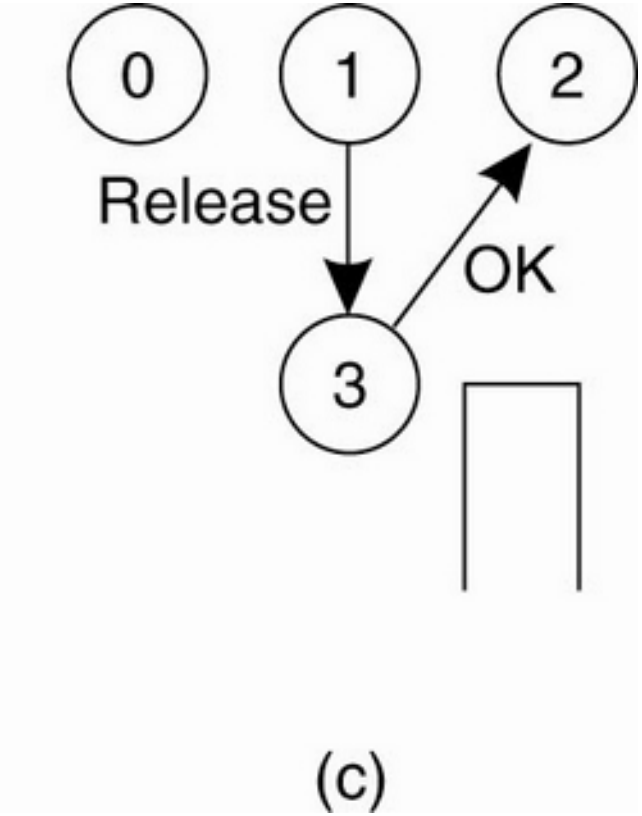


Figure 5-13. (c) When process 1 releases the resource, it tells the coordinator, which then replies to 2.

A Distributed Algorithm 1/6

- Assume total ordering of all events in the system
- When access a shared resource
  - Build a message (resource name, process number, and current logical time)
  - Send message to all other processes, including itself
- When process receives a request
  - Action depends on own state with respect to resource in message
  - 3 different cases

A Distributed Algorithm 2/6

Three different cases:

1. If the receiver is not accessing the resource and does not want to access it, it sends back an OK message to the sender.
2. If the receiver already has access to the resource, it simply does not reply. Instead, it queues the request.
3. 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.

A Distributed Algorithm 3/6

- After sending out asking for permissions
  - Sit back and wait until everyone has given permission
  - After finished
    - send OK to all processes on its queue and delete from queue

A Distributed Algorithm 4/6

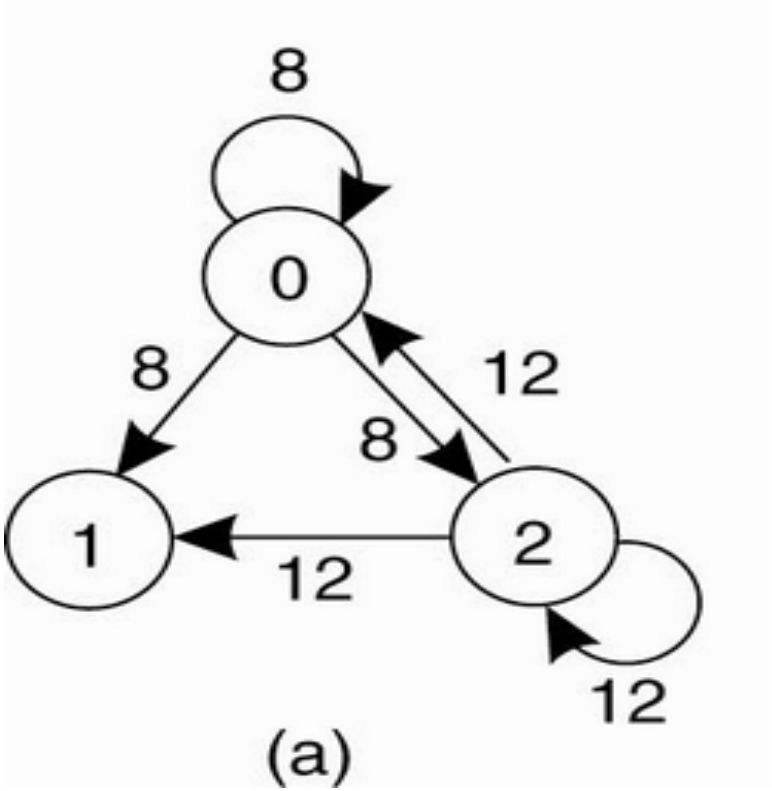


Figure 5-14. (a) Two processes want to access a shared resource at the same moment.

A Distributed Algorithm 5/6

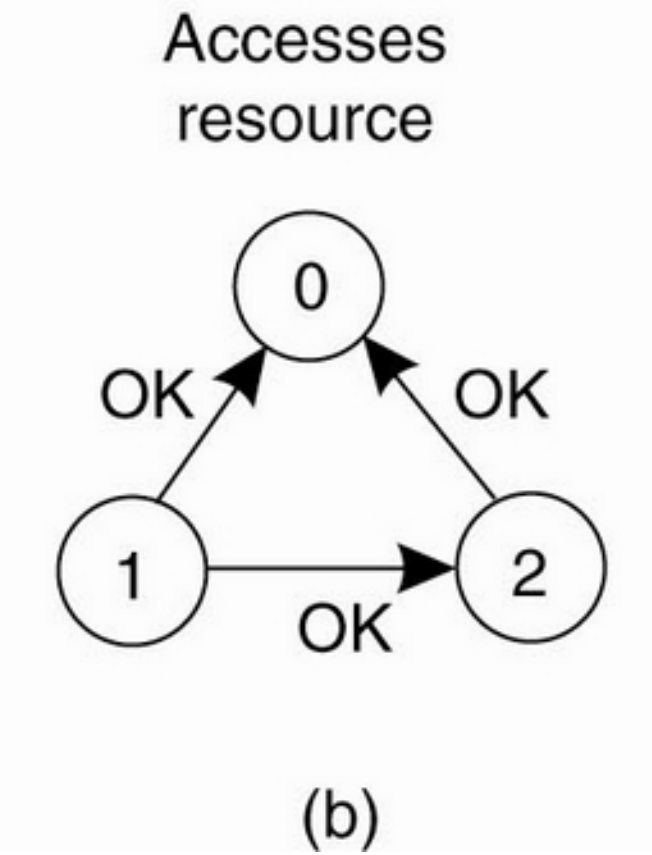


Figure 5-14. (b) Process 0 has the lowest timestamp, so it wins.

A Distributed Algorithm 6/6

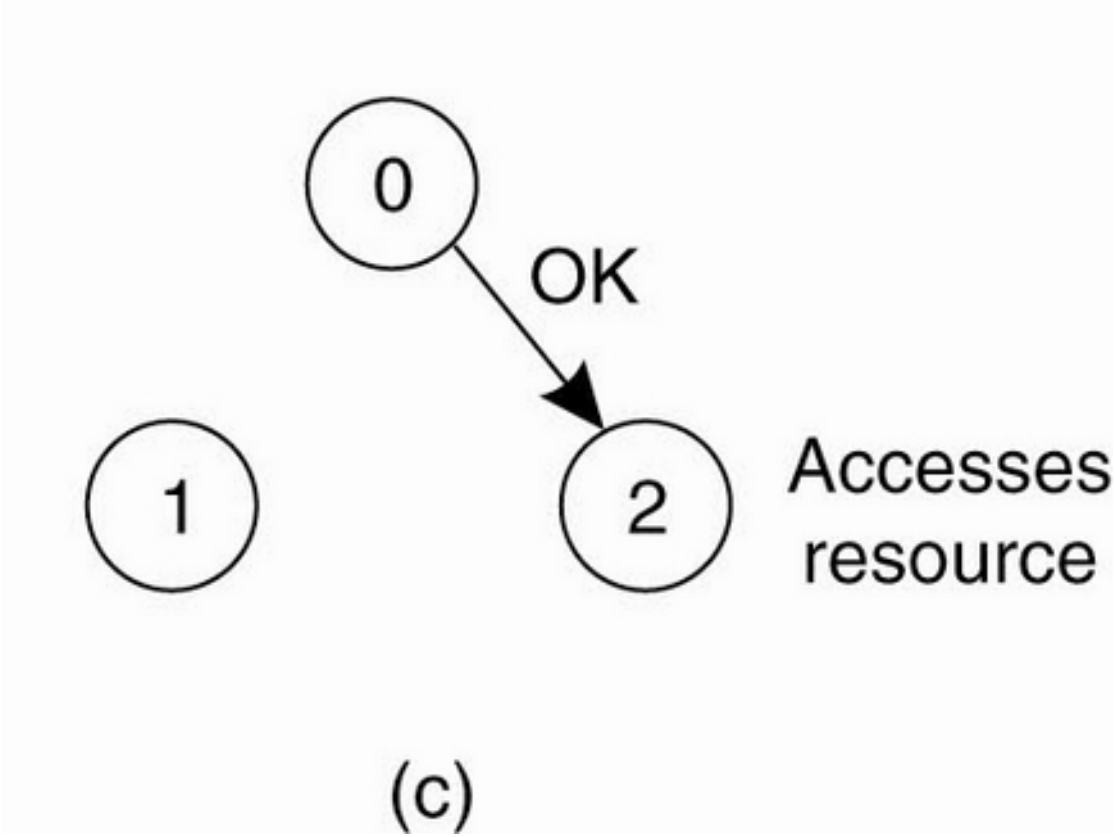


Figure 5-14. (c) When process 0 is done, it sends an OK also, so 2 can now go ahead.

A Token Ring Algorithm

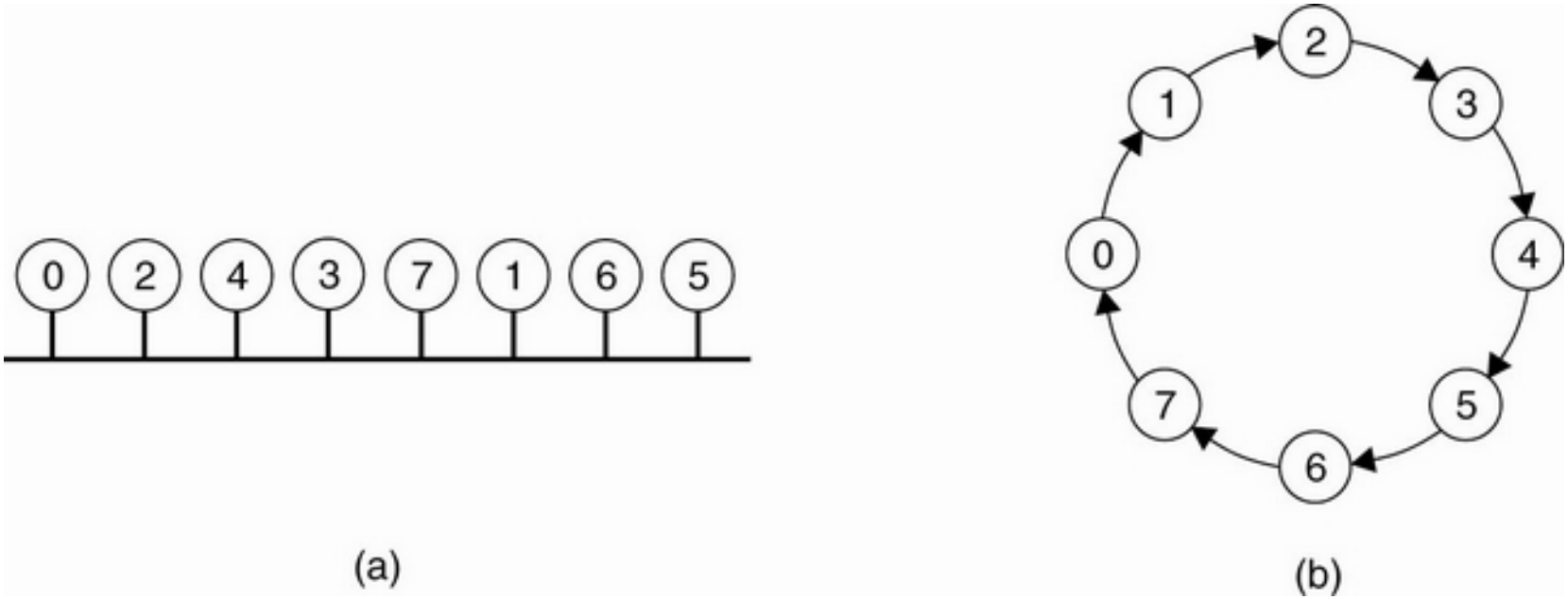


Figure 5-15. (a) An unordered group of processes on a network. (b) A logical ring constructed in software.