Distributed Systems: Logical Clocks

Dr Soumyabrata DEV
https://soumyabrata.dev/

School of Computer Science and Informatics
University College Dublin
Ireland

These course slides are adapted from the original course slides prepared by Dr Anca Jurcut, University College Dublin.

Logical Clocks

- A second approach to dealing with distributed synchronization is based on the concept of "relative time".

- Based on the notion of event ordering:
  - Temporal Ordering: the time of occurrence in real-time
    - induces a 'happens-before' relation
  - Causal Ordering: cause-effect relationship; implies temporal order

- Note that (with this mechanism) there is no requirement for "relative time" to have any relation to the "real time".

- Such "clocks" are referred to as Logical Clocks.

Lamport's Logical Clocks

- Lamport made two observations about the nature of process interaction:
  - First point: if two processes do not interact, then their clocks do not need to be synchronized – they can operate concurrently without fear of interfering with each other.
  - Second (critical) point: it does not matter that two processes share a common notion of what the "real" current time is. What does matter is that the processes have some agreement on the order in which certain events occur.

- Based upon these observations, he devised the "happens-before" relation (denoted "→").

The “Happens-Before” Relation

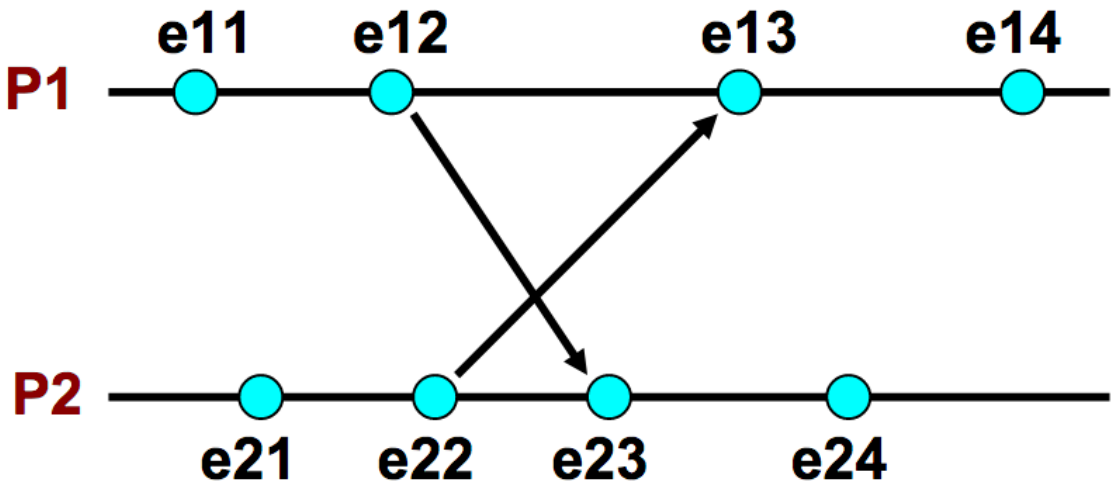
- Properties of “→”:
  - If A and B are events in the same process, and A occurs before B, then we can state that A “ happens-before” B (denoted A → B)
  - If A is the event of sending a message, and B is the event of receiving the same message, then A → B.
  - If A → B and B → C, then A → C (transitivity).
  - If A and B are not related by →, then they occurred at the same time (i.e. they are concurrent events).

- We can make some deductions about the current clock time based on “→”:
  - If C(A) is the time when A occurred, then C(A) < C(B)

Example

Two distinct events a and b are said to be concurrent (denoted by a||b)

$$\text{if } a \not\rightarrow b \text{ and } b \not\rightarrow a$$



A space-time diagram

e11 and e21 are concurrent

e14 and e23 are concurrent

e22 causally affects e14

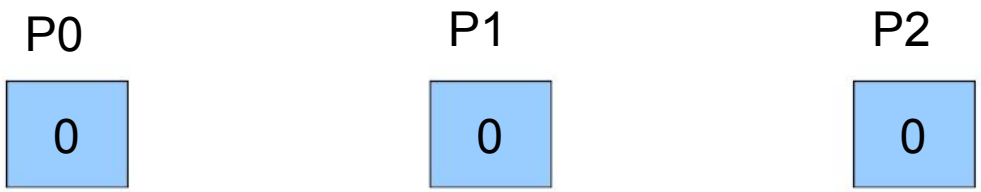
The “Happens-Before” Relation

- Now, assume three processes are in a Distributed System: A, B and C.
  - All have their own physical clocks (which are running at differing rates due to “clock skew”, etc.).
  - A sends a message to B and includes a “timestamp”.
  - If this sending timestamp is less than the time of arrival at B, things are OK, as the “happens-before” relation still holds (i.e. A “happens-before” B is true).
  - However, if the timestamp is more than the time of arrival at B, things are NOT OK (as A “happens-before” B is not true, and this cannot be as the receipt of a message has to occur after it was sent).

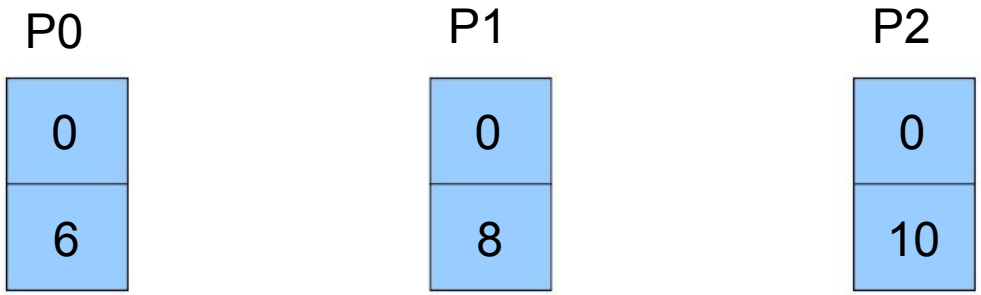
The “Happens-Before” Relation

- The question to ask is:
  - How can some event that “happens-before” some other event possibly have occurred at a later time??
- The answer is: it can’t!
  - So, Lamport’s solution is to have the receiving process adjust its clock forward to one more than the sending timestamp value.
  - This allows the “happens-before” relation to hold, and also keeps all the clocks running in a synchronized state.
  - The clocks are all kept in sync relative to each other.

Example

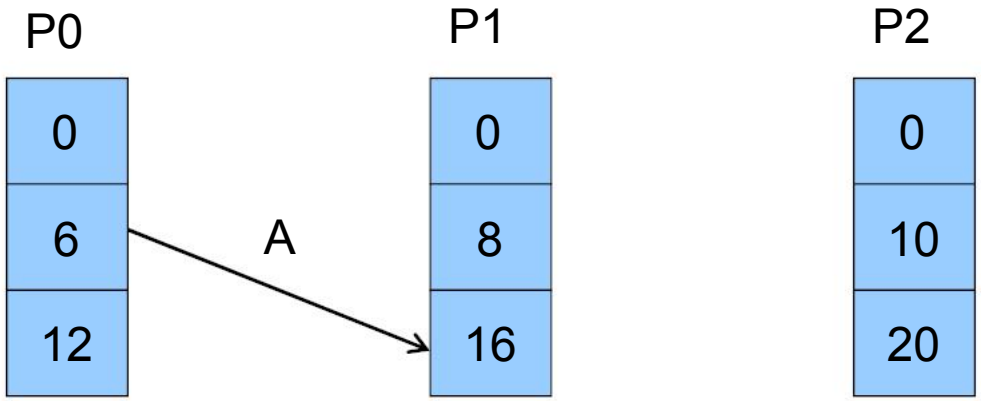


Example



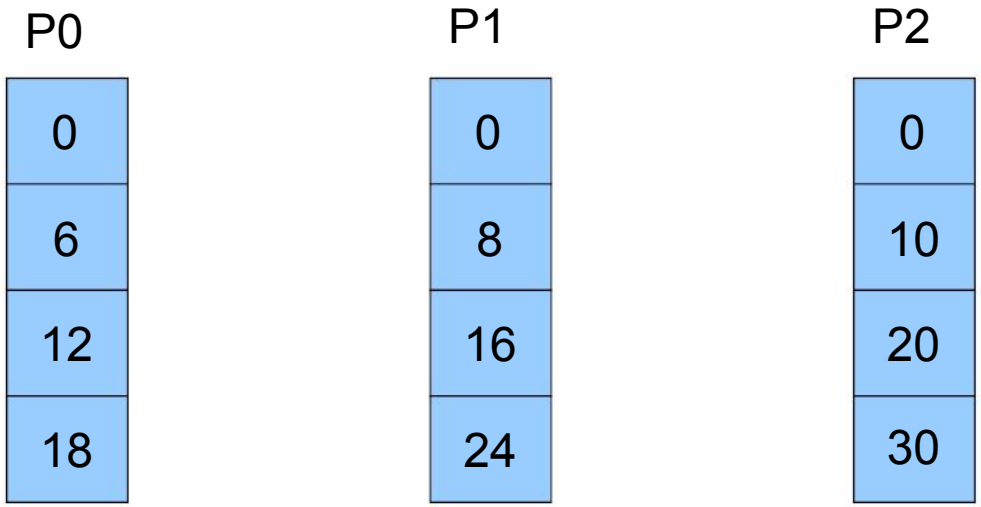
- P0 sends message A to P1

Example



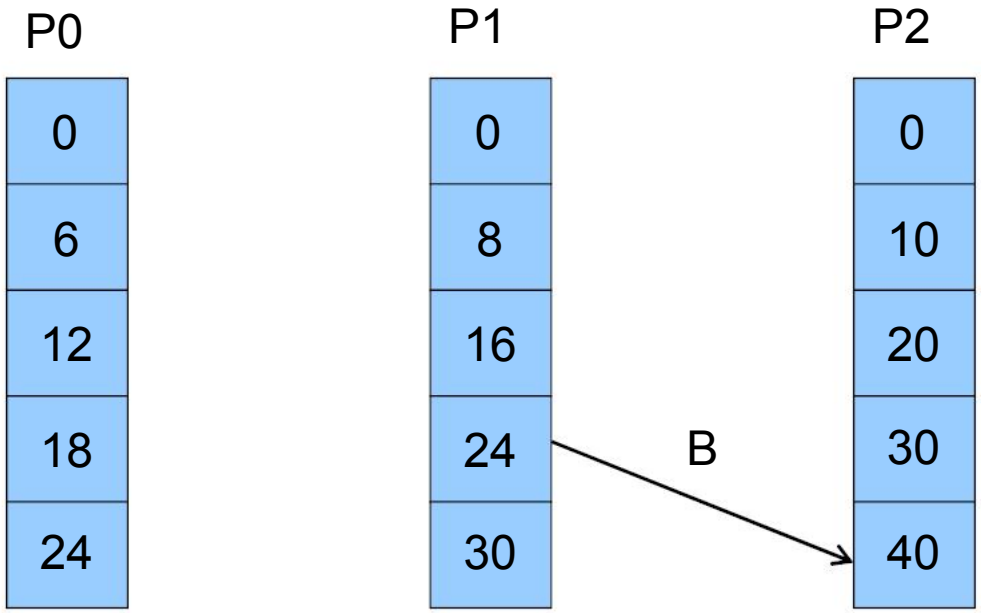
- P1 receives message A (everything is OK since 6 < 16)

Example



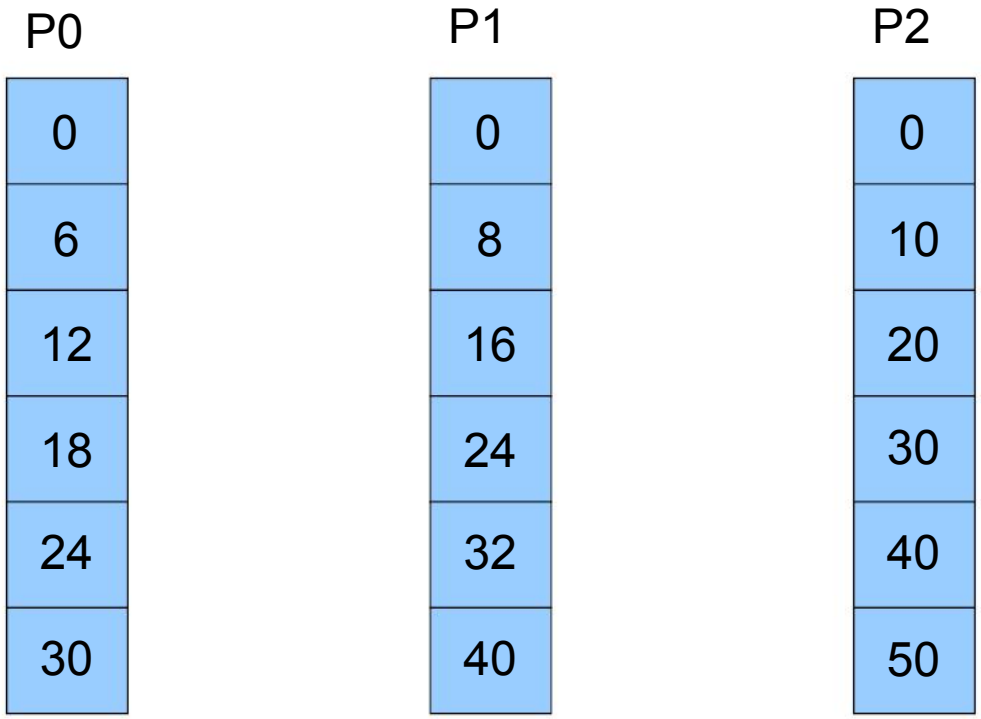
- P1 sends message B to P2

Example

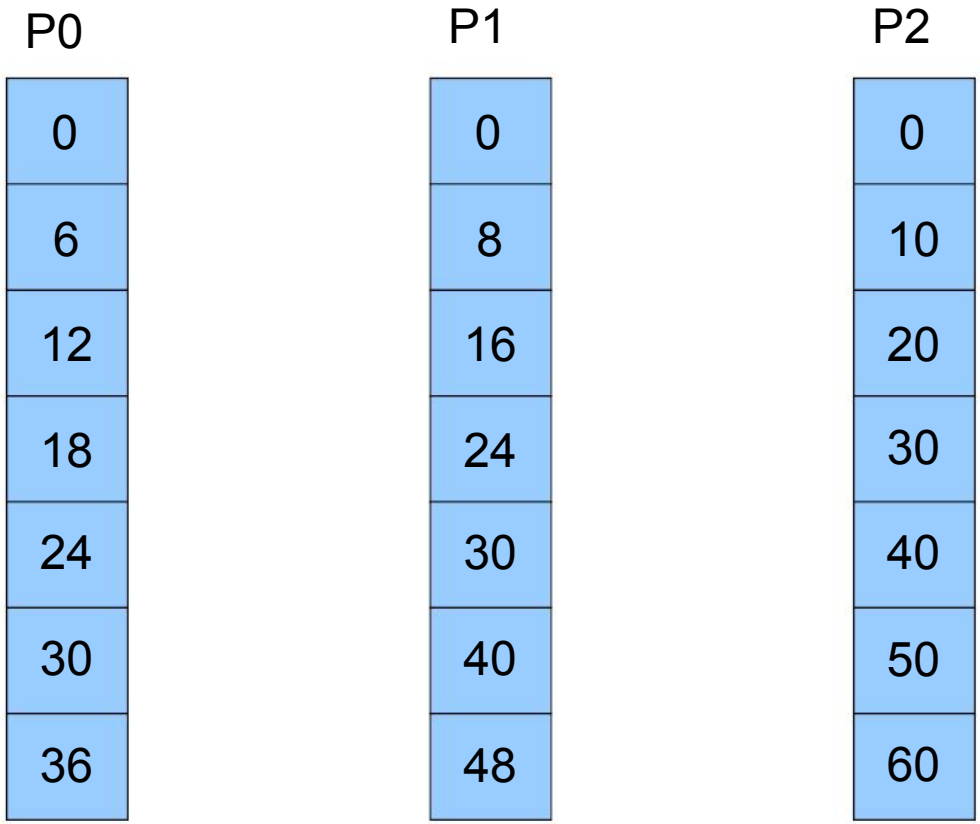


- P2 receives message B (everything is OK since 24 < 40)

Example

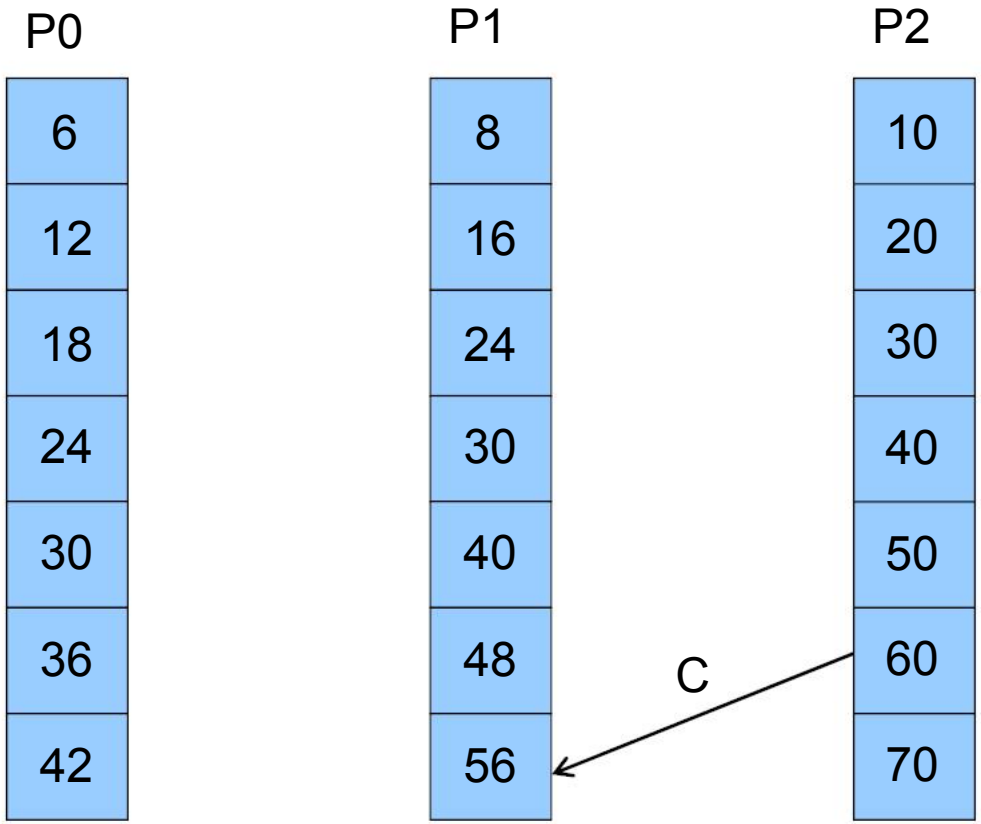


Example



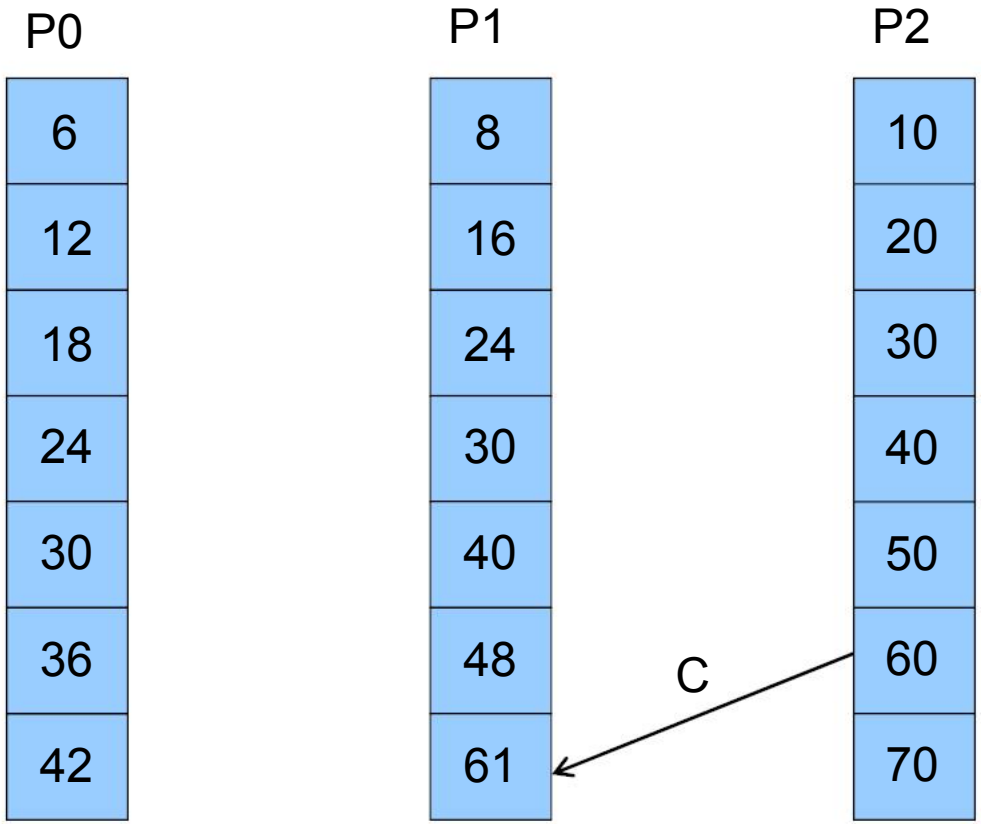
- P2 sends message C to P1

Example



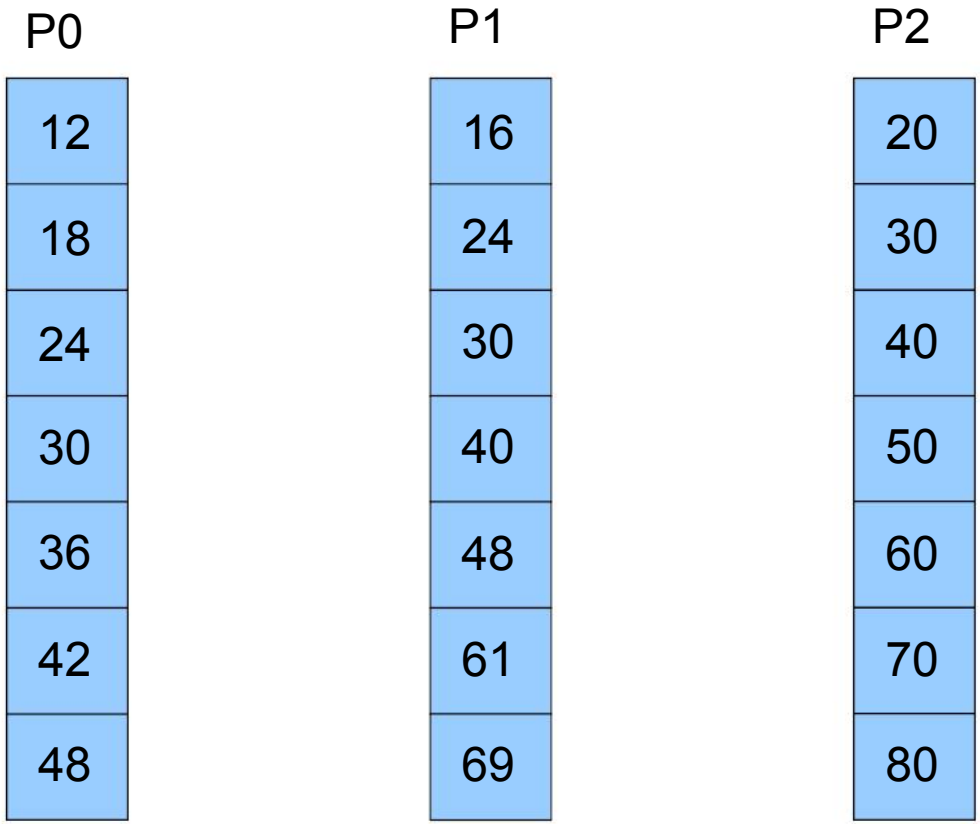
- P1 receives message C (Ouch! The message was sent at time 60 but received at time 56)

Example



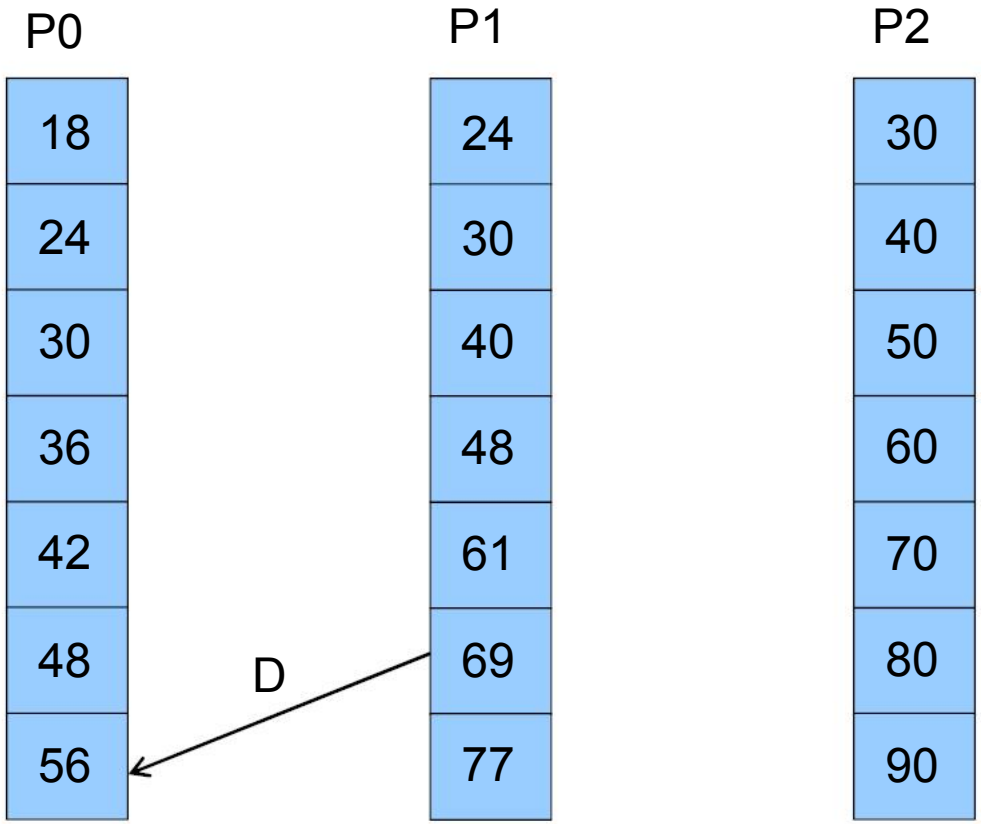
- Logical Time at P1 updated to be 1 greater than the time C was sent at.

Example



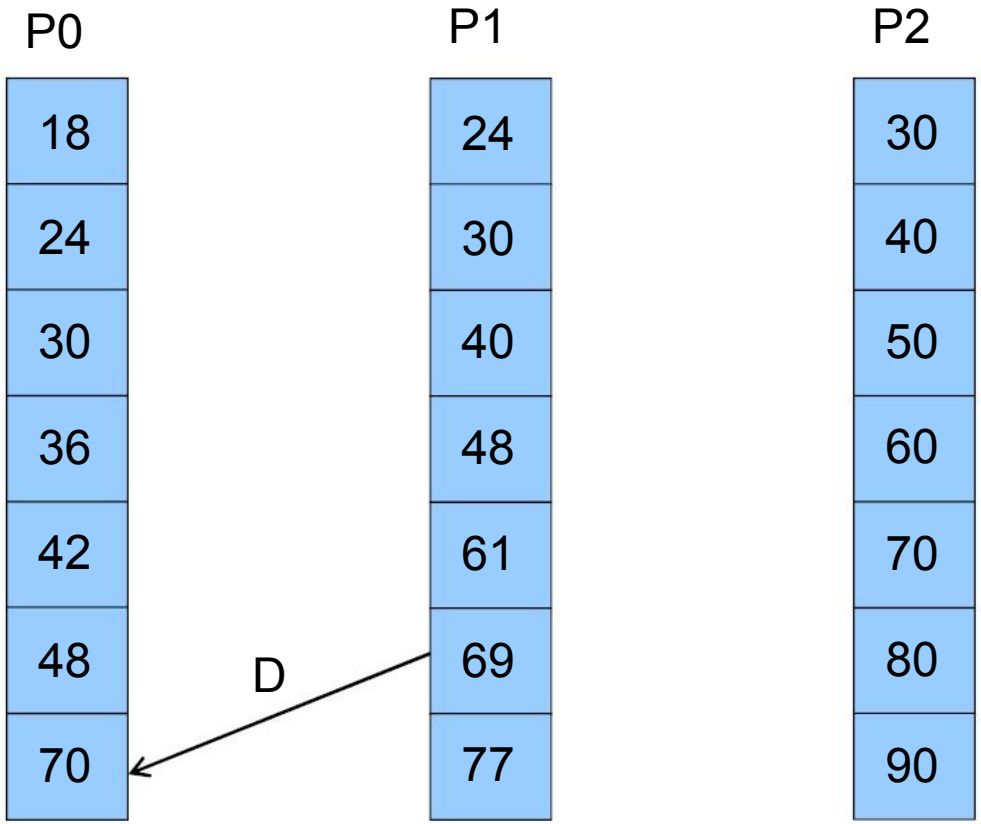
- P1 sends message D to P0

Example



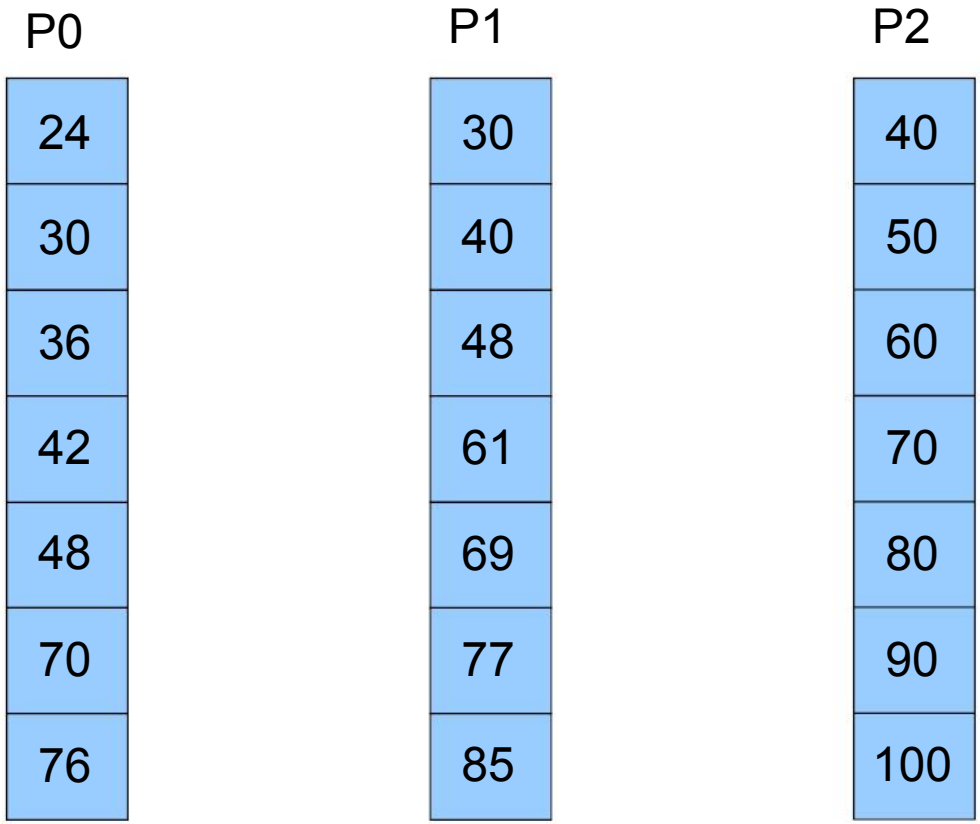
- P0 receives message D (Ouch! 56 < 69)

Example



- Logical Time at P0 updated

Example



- End of Run

Limitation of Lamport's algorithm

- If e1 → e2 then e1.TS < e2.TS (TS = "Time Stamp")
- But it is not necessarily the case that if e1.TS < e2.TS then e1 → e2

e1.TS < e8.TS, but is e1 → e8 true?

Given two events, we cannot say whether they are causally related from their timestamps.

Vector Time

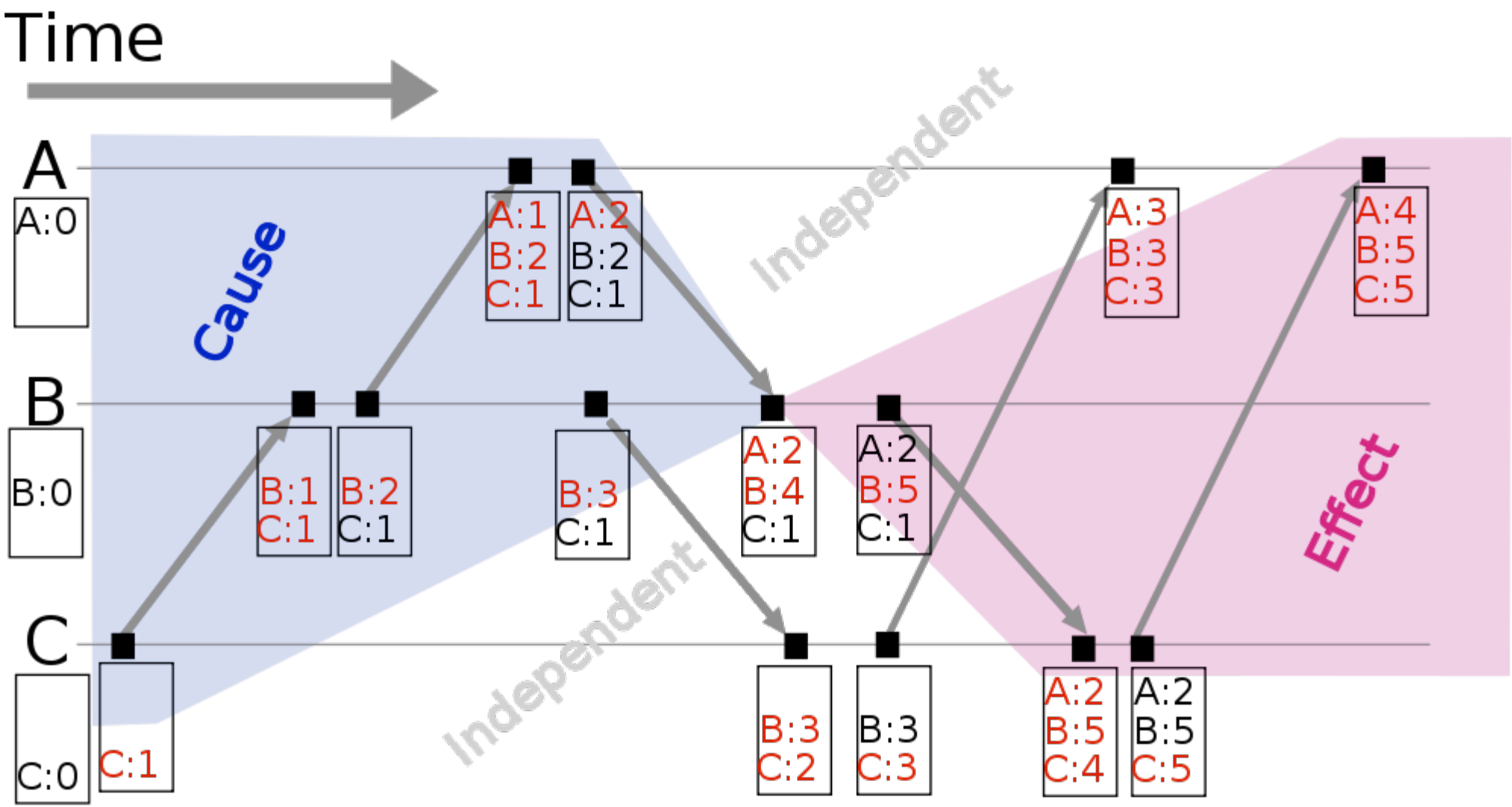
- A vector clock is an algorithm for generating a partial ordering of events in a distributed system and detecting causality violations.

- Just as in Lamport timestamps, interprocess messages contain the state of the sending process's logical clock.

Rules:

- Initially all clocks are zero.
- Each time a process experiences an internal event, it increments its own logical clock in the vector by one.
- Each time a process sends a message, it increments its own logical clock in the vector by one and then sends a copy of its own vector.
- Each time a process receives a message, it increments its own logical clock in the vector by one and updates each element in its vector by taking the maximum of the value in its own vector clock and the value in the vector in the received message (for every element).

Vector Time


Time
A
B
C
A:0
B:0
C:0
C:1
A:1
B:2
C:1
A:2
B:2
C:1
B:1
C:1
B:2
C:1
B:3
C:1
A:2
B:4
C:1
A:2
B:5
C:1
A:3
B:3
C:3
A:4
B:5
C:5
B:3
C:2
B:3
C:3
A:2
B:5
C:4
A:2
B:5
C:5
Cause
Independent
Independent
Effect

Distributed Systems:
Global State

Introduction

- Sometimes we need to capture the global state of a distributed system.
  - E.g. Deadlock Detection, Termination Detection, Distributed Debugging, …
- Capturing the state of the individual processes is relatively easy:
  - We simply write the state of each process to the hard disk.
- How can we synchronise this write activity to capture the state of all the processes simultaneously?

Introduction

- Naïve Approach: We send a global “capture state message”
- Upon receipt of this message, each process writes it state to disk.
- But, in large systems this may take time:
- How can we ensure that the state we capture is consistent?

Cut

- Cut: time frontier at each process and at each channel in the system.
- Events at the process/channel that happen before the cut (or the time point) are "in the cut".
  - And happening after the cut are "out of the cut".

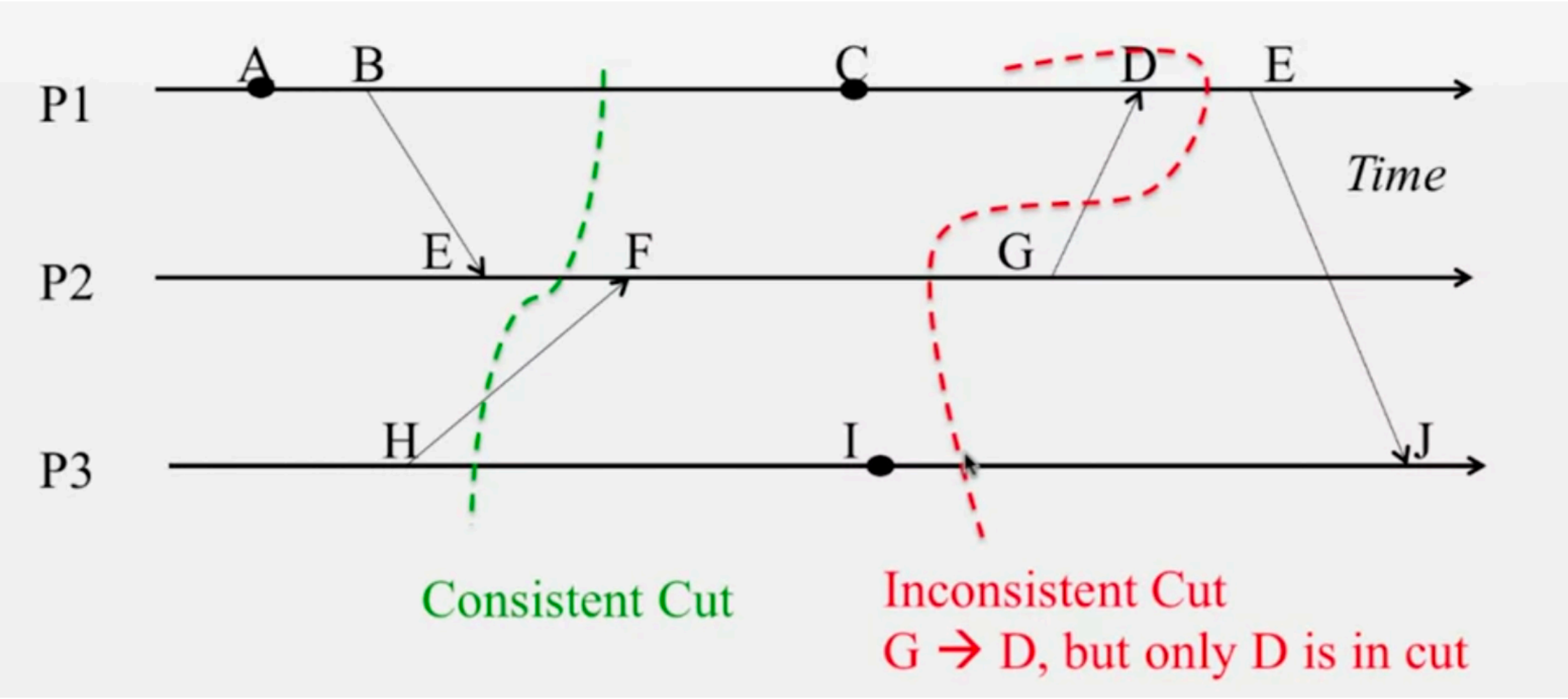
Consistent Cut

Consistent cut: a cut that obeys causality

- A cut C is consistent if and only if:

  for (each pair of events e,f in the system)
  - Such that event e is in the cut C, and if f→e (f happens before e)
  - Then: Event f is also in the cut C

Example


P1
P2
P3
A
B
C
D
E
E
F
G
H
I
J
Time
Consistent Cut
Inconsistent Cut
G → D, but only D is in cut

Snapshot algorithm

- Developed by Chandy and Lamport in 1985

- Assumptions:
  - neither channels nor processes fail and communication is reliable so that every message send is eventually received intact, exactly once
  - channels are unidirectional and provide FIFO-ordered message delivery
  - the graph of processes and channels is strongly connected (there is a path between any two processes)
  - any process may initiate a global snapshot at any time
  - the processes may continue their execution and send and receive normal messages while the snapshot takes place

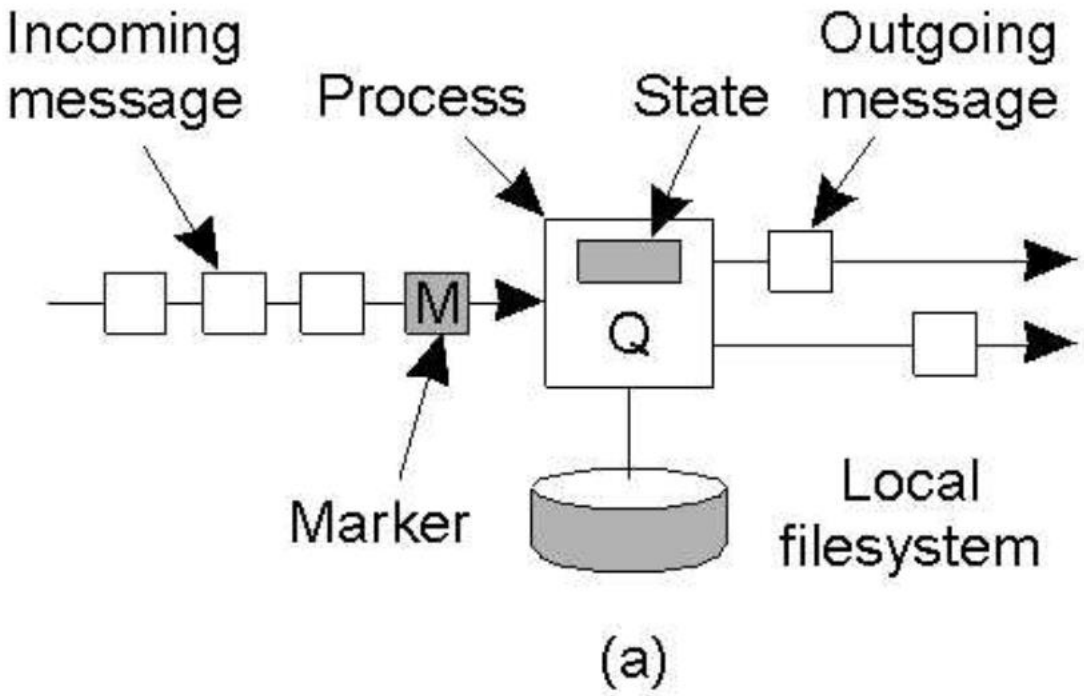
Snapshot algorithm

- Requires the implementation of two “rules” that together ensure a correct snapshot is taken:
- A “Marker” message is sent around the system to instruct processes to take snapshots, and to get them to record the state of communication channels.
- Marker sending rule for process P
- After P has recorded its state, for each outgoing channel, C:
  - P sends one marker message over C (before it sends any other message)

Snapshot algorithm

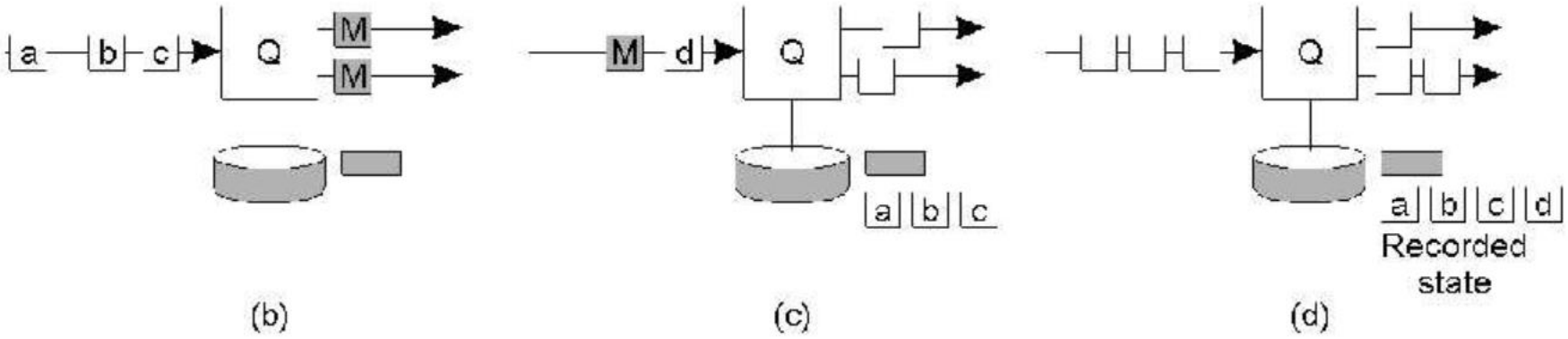
- Requires the implementation of two “rules” that together ensure a correct snapshot is taken:
- Marker-receiving rule for process P
- On P’s receipt of a marker message over channel C
  - If P has not yet recorded its state it:
    - Records its process state now
    - Records the state of C as the empty set
    - Turns on recording of messages that arrive over other incoming channels
  - Else
    - P records the state of C as the set of messages it has received over C since it saved its state
  - Endif

Snapshot algorithm



(a) Process Q receives a marker for the first time and records its local state

Snapshot algorithm



b) Q records its own state and sends a marker down all outgoing communication channels.

c) Q records all incoming messages.

d) Q receives a second marker on an incoming channel and finishes recording the state of that channel.

Termination of Snapshot

- We assume that:
  - a process that has received a marker message records its state within a finite time, and
  - Sends marker messages over each outgoing channel within a finite time.

- If there is a path of communication channels and processes from a process p_i to a process p_j ($j \neq i$), then it is clear the p_j will record its state a finite time after p_i recorded its state.

- Since we are assuming the graph of processes and channels to be strongly connected:
  - It follows that all processes will have recorded their states and the states of incoming channels a finite time after some process initially records its state.

Distributed Systems
Coordination: Mutual Exclusion

Mutual Exclusion

- It is often necessary to protect a shared resource within a Distributed System using “mutual exclusion”
  - For example, it might be necessary to ensure that no other process changes a shared resource while another process is working with it.

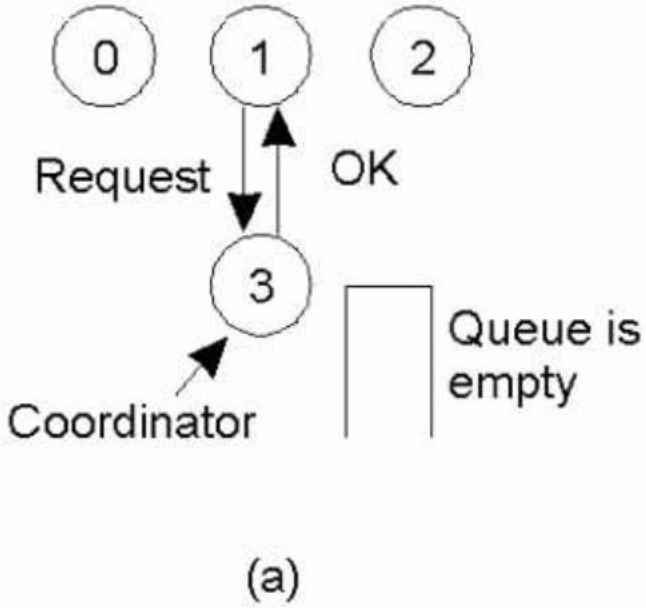
- In non-distributed, uniprocessor systems, we can implement “critical regions” using techniques such as semaphores, monitors and similar constructs – thus achieving mutual exclusion.

- These techniques have been adapted to Distributed Systems …

Mutual Exclusion: Techniques

- In this course we will consider three techniques:
  - Centralized: a single coordinator controls whether a process can enter a critical region.
  - Distributed: the group confers to determine whether or not it is safe for a process to enter a critical region.
  - Token Ring: processes are organised into a logical loop and use a token to determine when to enter a critical region.
- We will look at each technique over the coming slides…

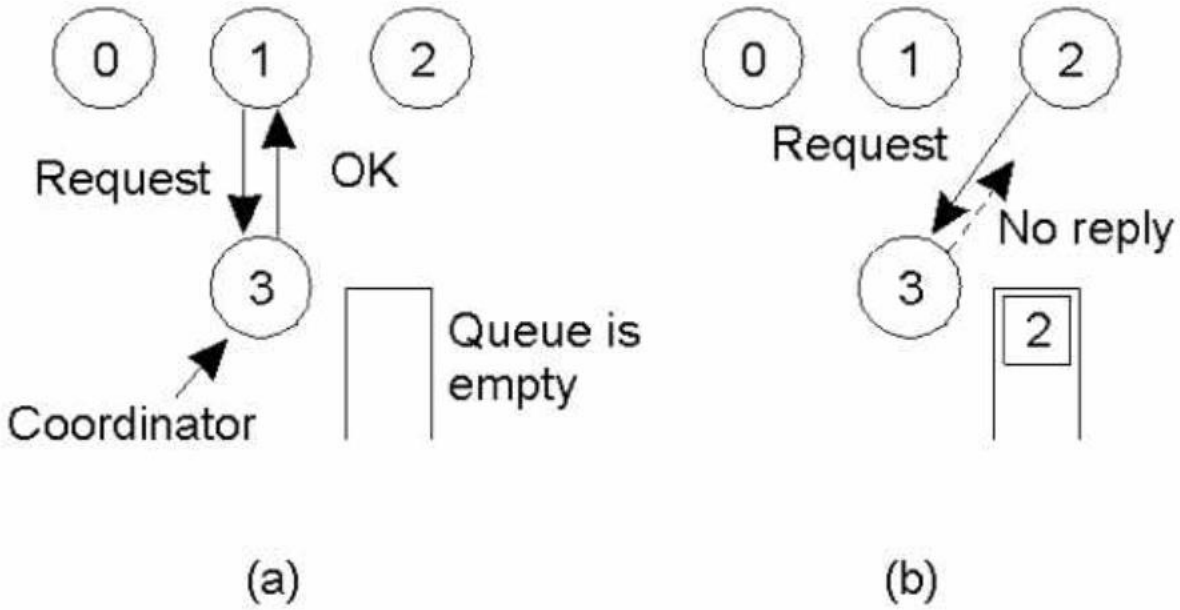
Centralized Algorithm



(a)

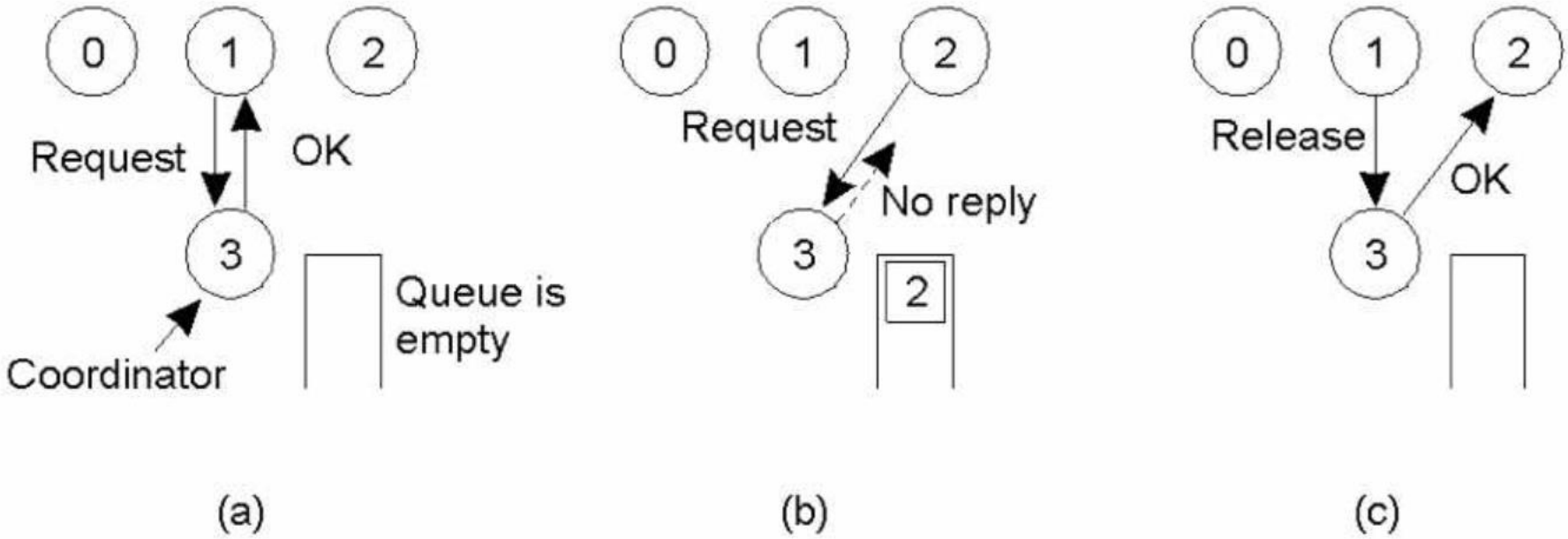
a)Process 1 asks the coordinator for permission to enter a critical region. Permission is granted by an OK message (assuming it is, of course, OK).

Centralized Algorithm



a)Process 2 then asks permission to enter the same critical region. The coordinator does not reply (but adds 2 to a queue of processes waiting to enter the critical region). No reply is interpreted as a “busy state” for the critical region.

Centralized Algorithm



a)When process 1 exits the critical region, it tells the coordinator, which then replies to 2 with an OK message.

The Centralized Algorithm

- Advantages:
  - It works.
  - It is fair.
  - There's no process starvation.
  - Easy to implement.

- Disadvantages:
  - There's a single point of failure!
  - The coordinator is a bottleneck on busy systems.

- Critical Question: When there is no reply, does this mean that the coordinator is "dead" or just busy?

Distributed Mutual Exclusion

- Based on work by Ricart and Agrawala (1981).

- Requirement of their solution: total ordering of all events in the distributed system (which is achievable with Lamport's timestamps).

- Note that messages in their system contain three pieces of information:
  - The critical region ID.
  - The requesting process ID.
  - The current time.

Distributed Algorithm

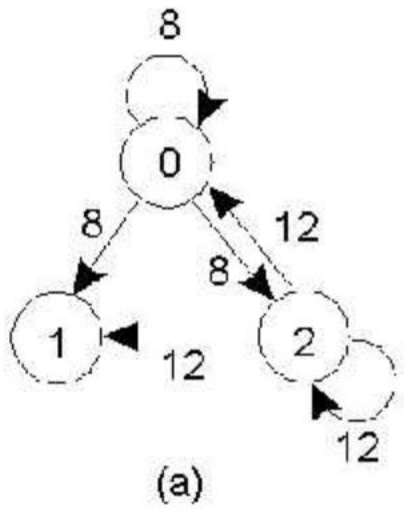
- When a process (the “requesting process”) decides to enter a critical region, a message is sent to all processes in the Distributed System (including itself).

- What happens at each process depends on the “state” of the critical region.
  - If not in the critical region (and not waiting to enter it), a process sends back an OK to the requesting process.
  - If in the critical region, a process will queue the request and send back no reply to the requesting process.

Distributed Algorithm

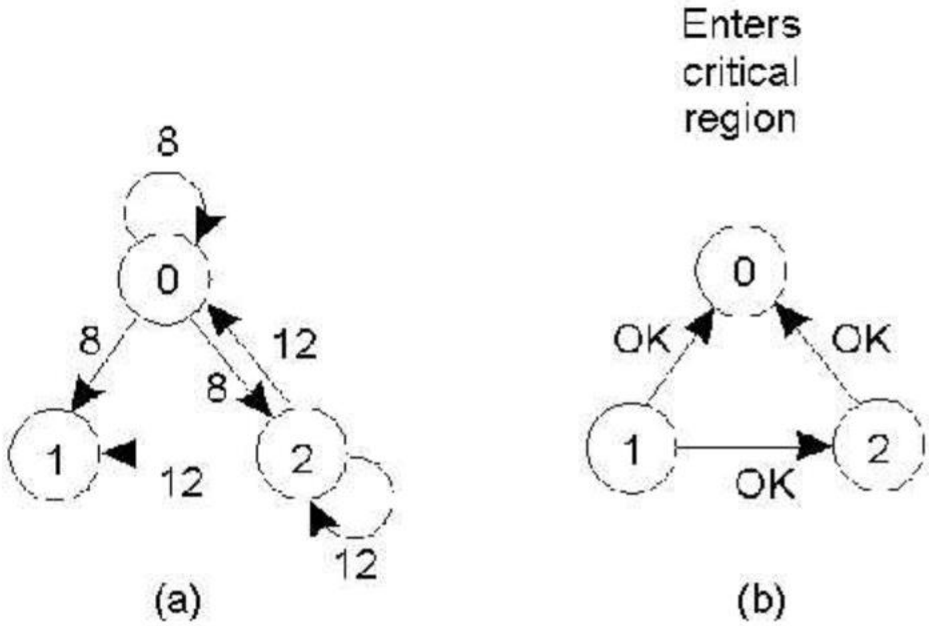
- If waiting to enter the critical region, a process will:
  - Compare the timestamp of the new message with that in its queue (note that the lowest timestamp wins).
  - If the received timestamp wins, an OK is sent back, otherwise the request is queued (and no reply is sent back).
- When all the processes send OK, the requesting process can safely enter the critical region.
- When the requesting process leaves the critical region, it sends an OK to all the process in its queue, then empties its queue.

Distributed Algorithm Example



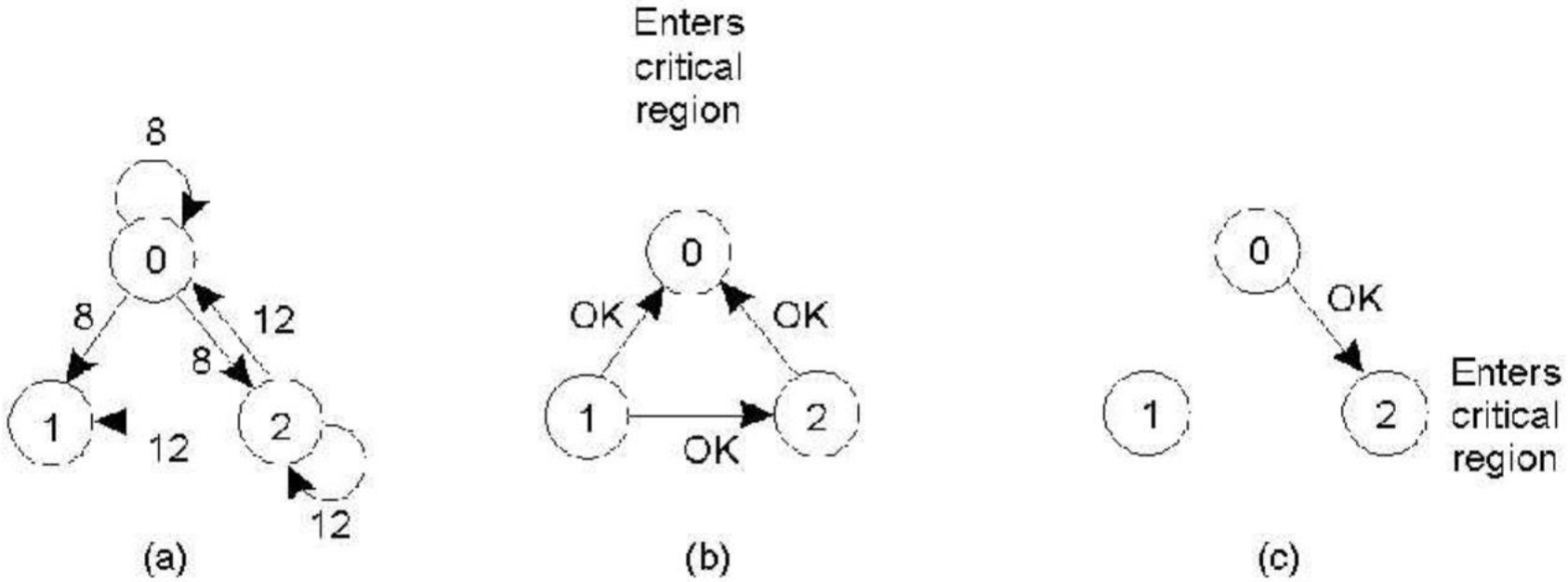
a) Processes 0 and 2 wish to enter the critical region “at the same time”.

Distributed Algorithm Example



b) Process 0 wins as it's timestamp is lower than that of process 2.

Distributed Algorithm Example



c) When process 0 leaves the critical region, it sends an OK to 2.

The Distributed Algorithm

- The algorithm works because in the case of a conflict, the lowest timestamp wins as everyone agrees on the total ordering of the events in the distributed system.

- Advantages:
  - It works.
  - There is no single point of failure

- Disadvantages:
  - We now have multiple points of failure!!!
  - A “crash” is interpreted as a denial of entry to a critical region.
  - (A patch to the algorithm requires all messages to be ACKed).

The Distributed Algorithm

- Worse still - all processes must maintain a list of the current processes in the group (and this can be tricky)

- Worse still is that one overworked process in the system can become a bottleneck to the entire system – so, everyone slows down.

Which Just Goes To Show …

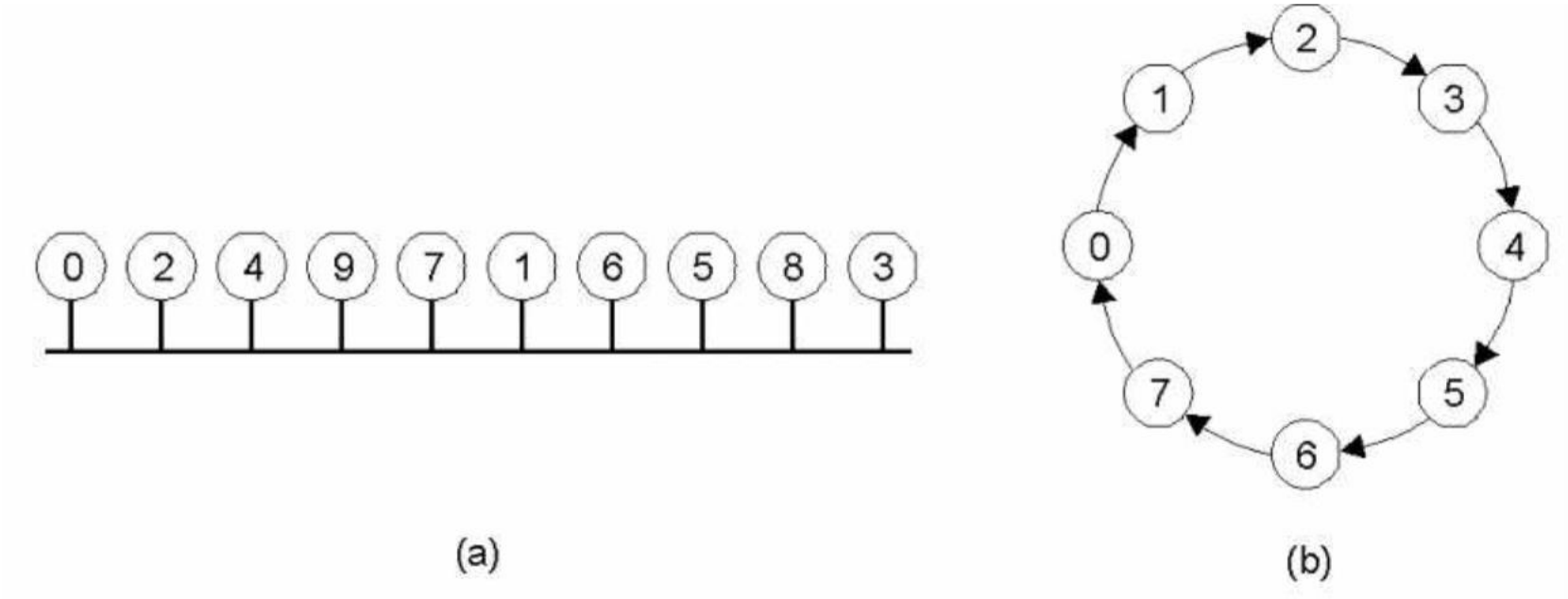
- It isn't always best to implement a distributed algorithm when a reasonably good centralized solution exists.

- Also, what's good in theory (or on paper) may not be so good in practice.

- Finally, think of all the message traffic this distributed algorithm is generating (especially with all those ACKs).

- Remember: every process is involved in the decision to enter the critical region, whether they have an interest in it or not. (Oh dear …!)

Token-Ring Algorithm



a) An unordered group of processes on a network. Note that each process knows the process that is next in order on the ring after itself.

b) A logical ring is constructed in software, around which a token can circulate – a critical region can only be entered when the token in held. When the critical region is exited, the token is released.

Token-Ring Algorithm

- When the ring is initialized, process 0 is given a token.
- The token circulates around the ring.
- It is passed from process k to process k+1.
- When a process acquires the token from its neighbor it checks to see if it is attempting to enter a critical region.
- If so, the process enters the region, does all the work it needs to and leaves the region.
- Token is passed to the next process in the ring.

Token-Ring Algorithm

- Advantages:
  - It works (as there's only one token, so mutual exclusion is guaranteed).
  - It's fair – everyone gets a shot at grabbing the token at some stage.

- Disadvantages:
  - Lost token! How is the loss detected (it is in use or is it lost)? How is the token regenerated?
  - Process failure can cause problems – a broken ring!
  - Every process is required to maintain the current logical ring in memory – not easy.

Comparison: Mutual Exclusion

- The “Centralized” algorithm is simple and efficient, but suffers from a single point-of-failure.

- The “Distributed” algorithm has nothing going for it – it is slow, complicated, inefficient of network bandwidth, and not very robust. It “sucks”!

- The “Token-Ring” algorithm suffers from the fact that it can sometimes take a long time to reenter a critical region having just exited it.

- All perform poorly when a process crashes, and they are all generally poorer technologies than their non-distributed counterparts.
  - Only in situations where crashes are very infrequent should any of these techniques be considered.

Election Algorithms

- Some Distributed Systems requires that one of the processes play a particular role.
  - For example, selecting a process to play the role of “central-server” in a variant of the Centralized Mutual Exclusion algorithm.
- In such situations, we need to employ a mechanism for selecting the “leader” process.
  - This mechanism must allow all relevant processes to participate in the choice.
  - It must also produce a single choice that is accepted by all the processes.
  - Once chosen the “leader” performs the assigned role until either they “retire” or fail.
- We term such a mechanism an Election Algorithm.

Thank you

For general enquries, contact:

Please contact the Head Teaching Assistant: Xingyu Pan (Star), Xingyu.Pan@ucdconnect.ie