

Times, Clocks, and the Ordering of Events in a Distributed System

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Main objectives and outline

In this paper Lamport:

- ① gives a distributed algorithm for extending the partial ordering defined by the “happened before” relation to a consistent total ordering of all the events,
- ② uses this algorithm to solve a mutual exclusion problem.

Distributed system

Definition (Distributed system)

A *distributed system* consists of a collection of distinct processes which are “spatially separated”, and which communicate with one another by exchanging messages. A system is distributed if the message transmission delay is not negligible compared to the time between events in a single process.

Examples of distributed systems

- A worldwide network of interconnected computers
- A cluster of workstation in a data center
- Processes on a single computer

Review of ordering relations

Definition (Partial order)

A *partial order* \leq_P on a set X is a reflexive, antisymmetric, transitive relation.

Definition (Total order)

A *total order* \leq on a set X is a partial order such that, if $a, b \in X$, then either $a \leq b$ or $b \leq a$.

Definition (Linear extension)

We say that a total order \leq on X *extends* a partial order \leq_P if $\forall a, b \in X$ we have $a \leq_P b \Rightarrow a \leq b$.

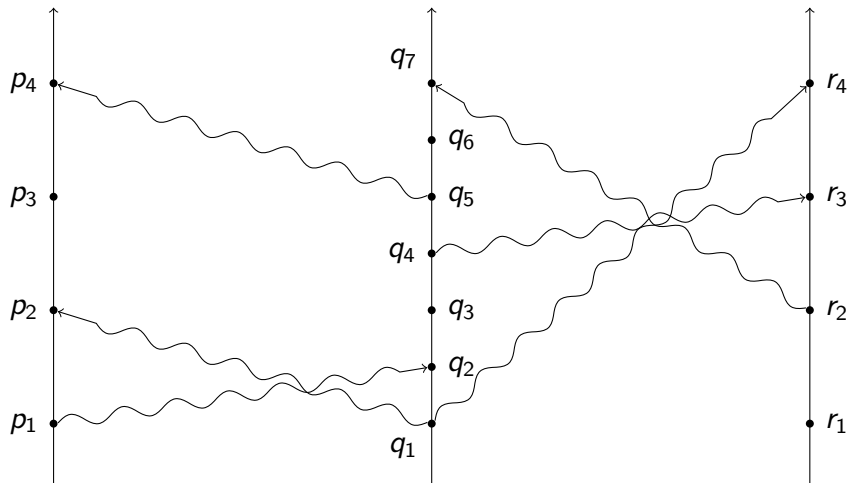
The “ \rightarrow ” relation

Definition (The “ \rightarrow ” relation)

The “ \rightarrow ” relation on the set of events of a system is the smallest relation satisfying the following three conditions:

- 1 If a and b are events in the same process, and a comes before b , then $a \rightarrow b$.
- 2 If a is the sending of a message by one process, and b is the receipt of the same message by another process, then $a \rightarrow b$.
- 3 If $a \rightarrow b$, and $b \rightarrow c$, then $a \rightarrow c$.

The space-time diagram



Definition (Clock)

For each process P_i we define a *clock* C_i to be a function that assigns a number $C_i\langle a \rangle$ to each event a in the process.

Definition (System of clocks)

A *system of clocks* is a function C that assigns to the event b in process P_j the time $C\langle b \rangle = C_j\langle b \rangle$.

The clock condition

Definition (The clock condition)

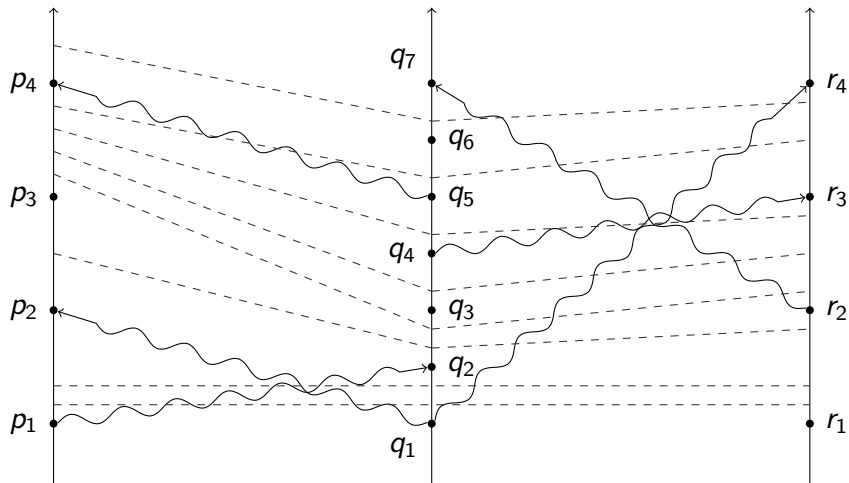
We say that a system of clocks satisfies the *clock condition* if, for any events a and b , we have: if $a \rightarrow b$ then $C\langle a \rangle < C\langle b \rangle$.

Lemma

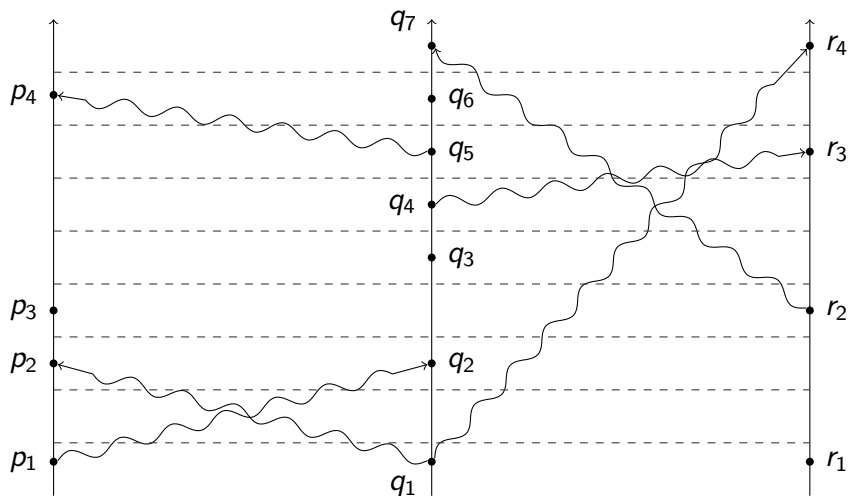
The clock condition is satisfied if the following conditions hold:

- 1 *If a and b are events in process P_i and a comes before b , then $C_i\langle a \rangle < C_i\langle b \rangle$.*
- 2 *If a is the sending of a message by process P_i and b is the receipt of that message by process P_j , then $C_i\langle a \rangle < C_j\langle b \rangle$.*

The space-time diagram, revisited



The space-time diagram, rearranged



Implementation of the clock condition

Lemma

To guarantee that a system of clocks satisfies the clock condition we need to obey the following implementation rules:

- 1 *Each process P_i increments C_i between any two successive events.*
- 2 *If event a is the sending of a message m by process P_i , then the message m contains a timestamp $T_m = C_i\langle a \rangle$.*
- 3 *Upon receiving a message m , process P_j sets C_j greater than or equal to its present value and greater than T_m .*

The “ \Rightarrow ” relation

Definition (The “ \Rightarrow ” relation)

Let \leq be a total ordering on the processes. If a is an event in process P_i and b is an event in process P_j , then $a \Rightarrow b$ if and only if either

- 1 $C_i\langle a \rangle < C_j\langle b \rangle$ or
- 2 $C_i\langle a \rangle = C_j\langle b \rangle$ and $P_i \leq P_j$.

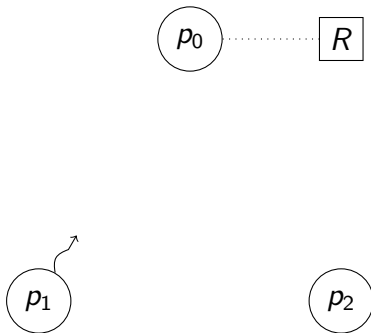
A mutual exclusion problem

A fixed collection of processes share a single resource, which can be used by one process at a time. We want to find an algorithm that satisfies the following conditions:

- 1 A process which has been granted the resource must release it before it can be granted to another process.
- 2 Different requests for the resource must be granted in the order in which they are made.
- 3 If every process which is granted the resource eventually releases it, then every request is eventually granted.

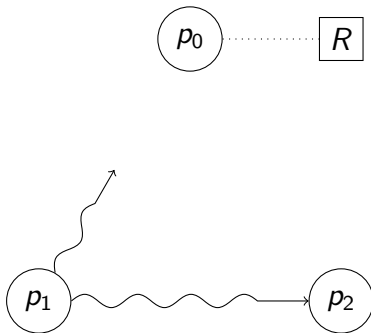
A wrong solution, 1/3

We can't elect a central scheduling process which grants requests in the order they are received. Suppose that p_1 sends a message to p_0 , the scheduler, to request the resource R .



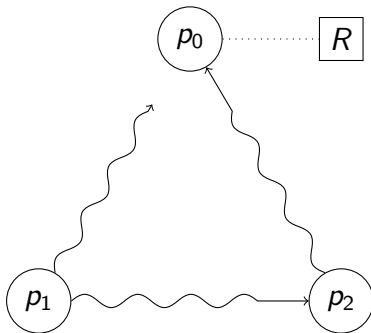
A wrong solution, 2/3

Then p_1 sends a message to p_2 . Suppose that this message is received while the other is still traveling due to network congestion.



A wrong solution, 3/3

Finally, p_2 sends a message to p_0 requesting the resource. p_0 then grants the resource to p_2 , which requested the resource after p_1 .



Some assumptions

To simplify the problem, we make some assumptions.

- ① For any two processes P_i and P_j , the messages sent from P_i to P_j are received in the same order as they are sent.
- ② Every message is eventually received.
- ③ A process can send messages directly to every other process.

The request queue

Let P_0 be the process to which the shared resource is initially allocated. Let T_0 be less than the initial value of any logical clock in the system. Each process maintains a private *request queue*, which initially contains one message: " T_0 : P_0 requests resource".

Resource request and acknowledgment

- 1 Process P_i sends the message " T_m : P_i requests resource" to every other process where T_m is the process clock's value at the time of the request. P_i also puts the request message on its request queue.
- 2 When process P_j receives P_i 's request message, it puts it in its queue and sends an acknowledgment message to P_i .

Resource release and acknowledgement

- ③ Process P_i removes request message " $T_m: P_i$ requests resource" from its queue and sends the release message " P_i releases resource" to every other process.
- ④ Process P_j removes the " $T_m: P_i$ requests resource" from its queue.

Resource allocation

- 5 Process P_i is granted the resource when:
 - There is a “ T_m : P_i requests resource” in P_i 's request queue which is before any other request according to \Rightarrow .
 - P_i has received messages from every other process timestamped later than T_m .

Proof of correctness (sketch)

Theorem

The algorithm described by rules 1 to 5 is a correct solution to the mutual exclusion problem.

Proof (sketch).

The ordering is guaranteed by the fact that relation " \Rightarrow " extends relation " \rightarrow ".

