Time and Ordering

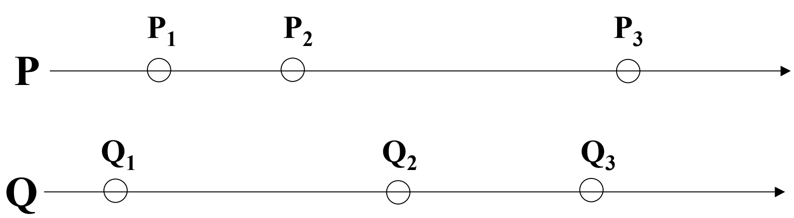
The two critical differences between centralized and distributed systems are:

- absence of shared memory
- absence of a global clock

We will study:

- how programming mechanisms change as a result of these differences
- algorithms that operate in the absence of a global clock
- algorithms that create a sense of a shared, global time
- algorithms that capture a consistent state of a system in the absence of shared memory

Event Ordering



How can the events on P be related to the events on Q?

Which events of P "happened before" which events of Q?

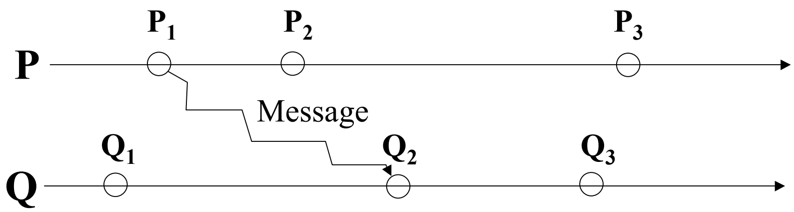
Partial answer: events on P and Q are strictly ordered. So:

$P_1 \dashrightarrow P_2 \dashrightarrow P_3$

and

$Q_1 \dashrightarrow Q_2 \dashrightarrow Q_3$

Event Ordering

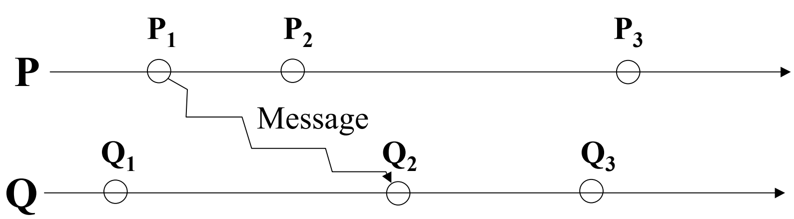


Realization: events only events on P that can causally affect events on Q are those that involve communication between P and Q.

If P_1 is a send event and Q_2 is the corresponding receive event then it must be the case that:

P_1 --> Q_2

Event Ordering



"Happened Before" relation:

If E_i and E_j are two events of the same process, then

E_i --> E_j

if $i < j$.

If E_i and E_j are two events of different processes, then

E_i --> E_j

if E_i is a message send event and E_j is the corresponding message receive event.

The relation is transitive.

Lamport's Algorithm

Lamport's algorithm is based on two implementation rules that define how each process's local clock is incremented.

Notation:

- the processes are named P_i ,
- each process has a local clock, C_i
- the clock time for an event a on process P_i is denoted by C_i (a).

Rule 1:

If a and b are two successive events in P_i and a `-->` b
then $C_i (b) = C_i (a) + d$ where $d > 0$.

Rule 2:

If a is a message send event on P_i and b is the message receive event on P_j then:

- the message is assigned the timestamp $t_m = C_i (a)$
- $C_j (b) = \max (C_j , t_m + d)$

Limitation of Lamport's Algorithm

In Lamport's algorithm two events that are causally related will be related through their clock times. That is:

If a `-->` b then C(a) < C(b)

However, the clock times alone do not reveal which events are causally related. That is, if C(a) < C(b) then it is not known if a `-->` b or not. All that is known is:

if C(a) < C(b) then b `-/->` a

It would be useful to have a stronger property - one that guarantees that

a `-->` b iff C(a) < C(b)

This property is guaranteed by Vector Clocks.

Vector Clock Rules

Each process P_i is equipped with a clock C_i which is an integer vector of length n.

$C_i(a)$ is referred to as the timestamp event a at P_i

$C_i[i]$, the ith entry of C_i corresponds to P_i's on logical time.

$C_i[j], j \neq i$ is P_i's best guess of the logical time at P_j

Implementation rules for vector clocks:

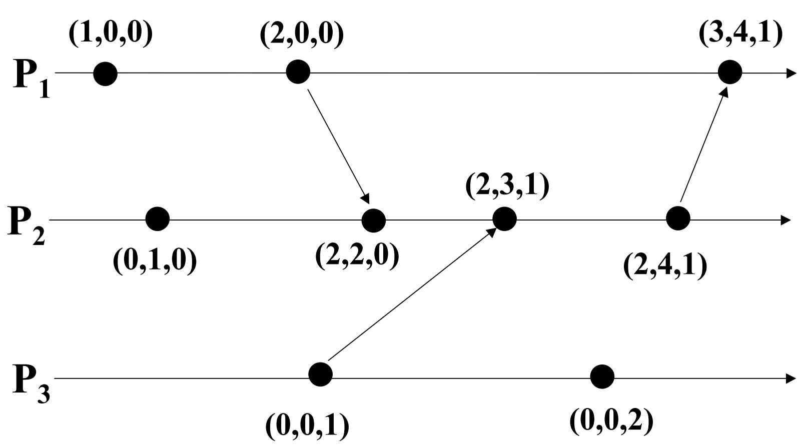
[IR1] Clock C_i is incremented between any two successive events in process P_i

$$C_i[i] := C_i[i] + d \qquad (d > 0)$$

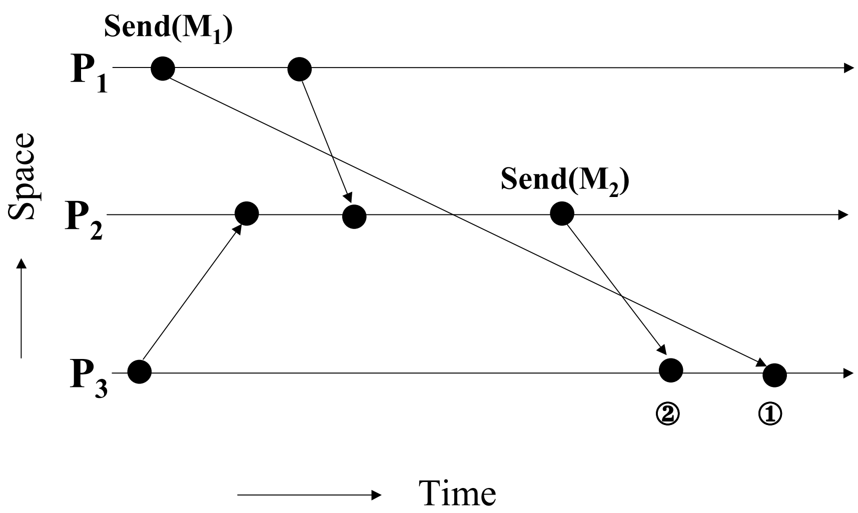
[IR2] If event a is the sending of the message m by process P_i, then message m is assigned a vector timestamp $t_m = C_i(a)$; on receiving the same message m by process P_j, C_j is updated as follows:

$$\forall k,\ C_j[k] := \max(C_j[k],\ t_m[k])$$

Vector Clocks



Causal Ordering of Messages



Birman-Schiper-Stephenson Protocol

1. Before broadcasting a message *m*, a process P_i increments the vector time $VT_{Pi}[i]$ and timestamps *m*. Note that $(VT_{Pi}[i] - 1)$ indicates how many messages from P_i precede *m*.

2. A process $P_j \neq P_i$, upon receiving message *m* timestamped VT_m from P_i, delays its delivery until both the following conditions are satisfied.

   a. $VT_{Pj}[i] = VT_m[i] - 1$

   b. $VT_{Pj}[k] \geq VT_m[k] \ \forall k \in \{1,2,\ldots,n\} - \{i\}$

   where *n* is the total number of processes.

   Delayed messages are queued at each process in a queue that is sorted by vector time of the messages. Concurrent messages are ordered by the time of their receipt.

3. When a message is delivered at a process P_j, VT_{Pj} is updated according to the vector clocks rule [IR2]