Time and Ordering

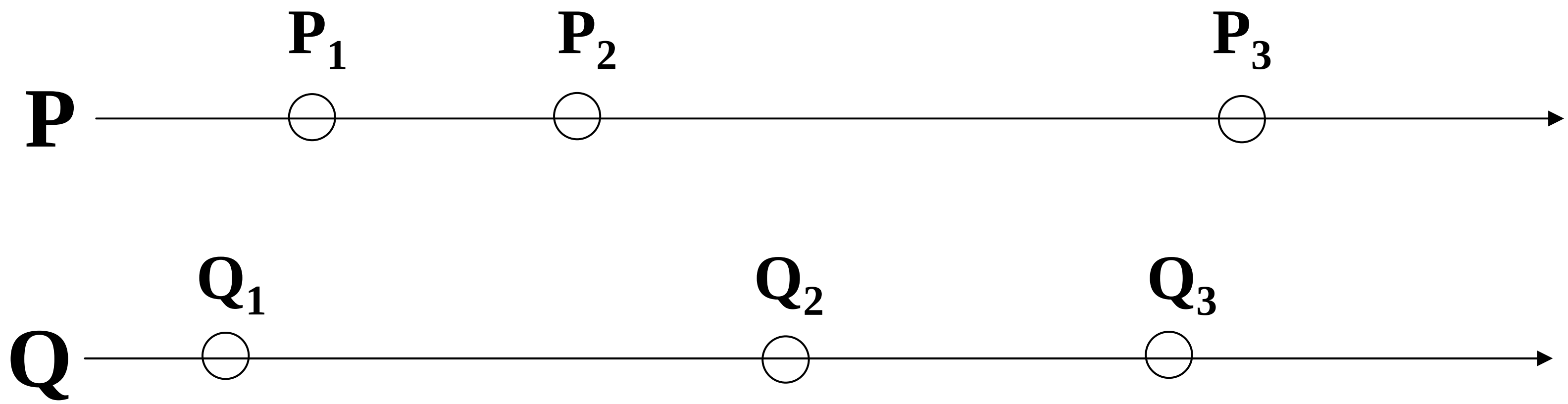
The two critical differences between centralized and distributed systems are:

- 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?

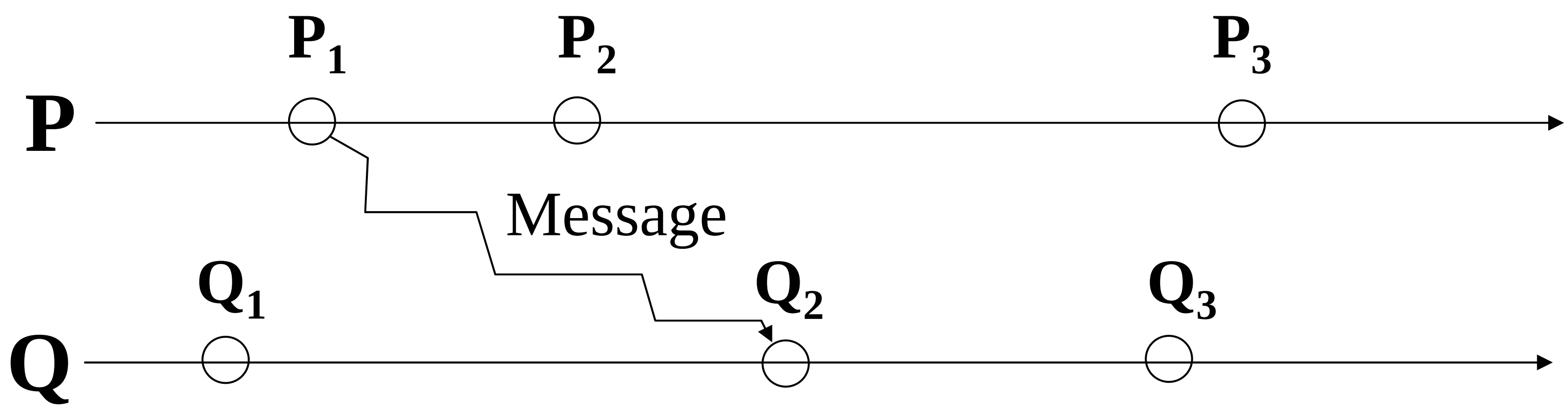
Partial answer: events on P and Q are strictly ordered. So:

P_1 --> P_2 --> P_3

and

Q_1 --> Q_2 --> Q_3

Event Ordering

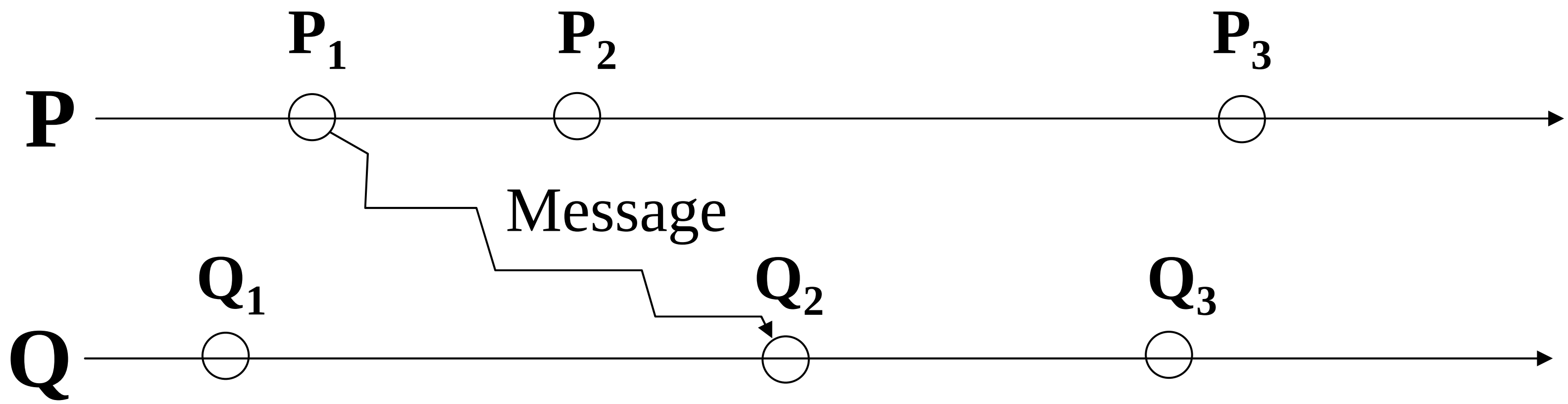


Realization: the only events on P that can causally affect events on Q are those that involve communication between P and Q.

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

$$P_1 \dashrightarrow Q_2$$

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).

<u>Rule 1:</u>

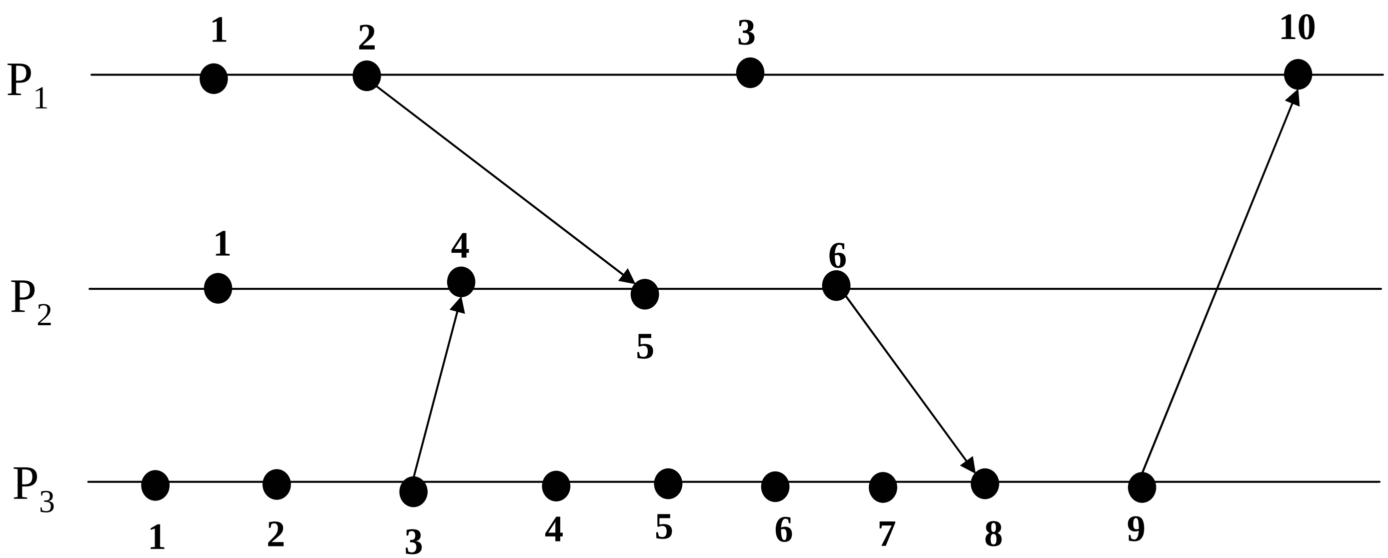
If a and b are two successive events in P_i and a **-->** b
then C_i (b) = C_i (a) + d where d > 0.

<u>Rule 2:</u>

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)

Example of Lamport's Algorithm



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 own 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:

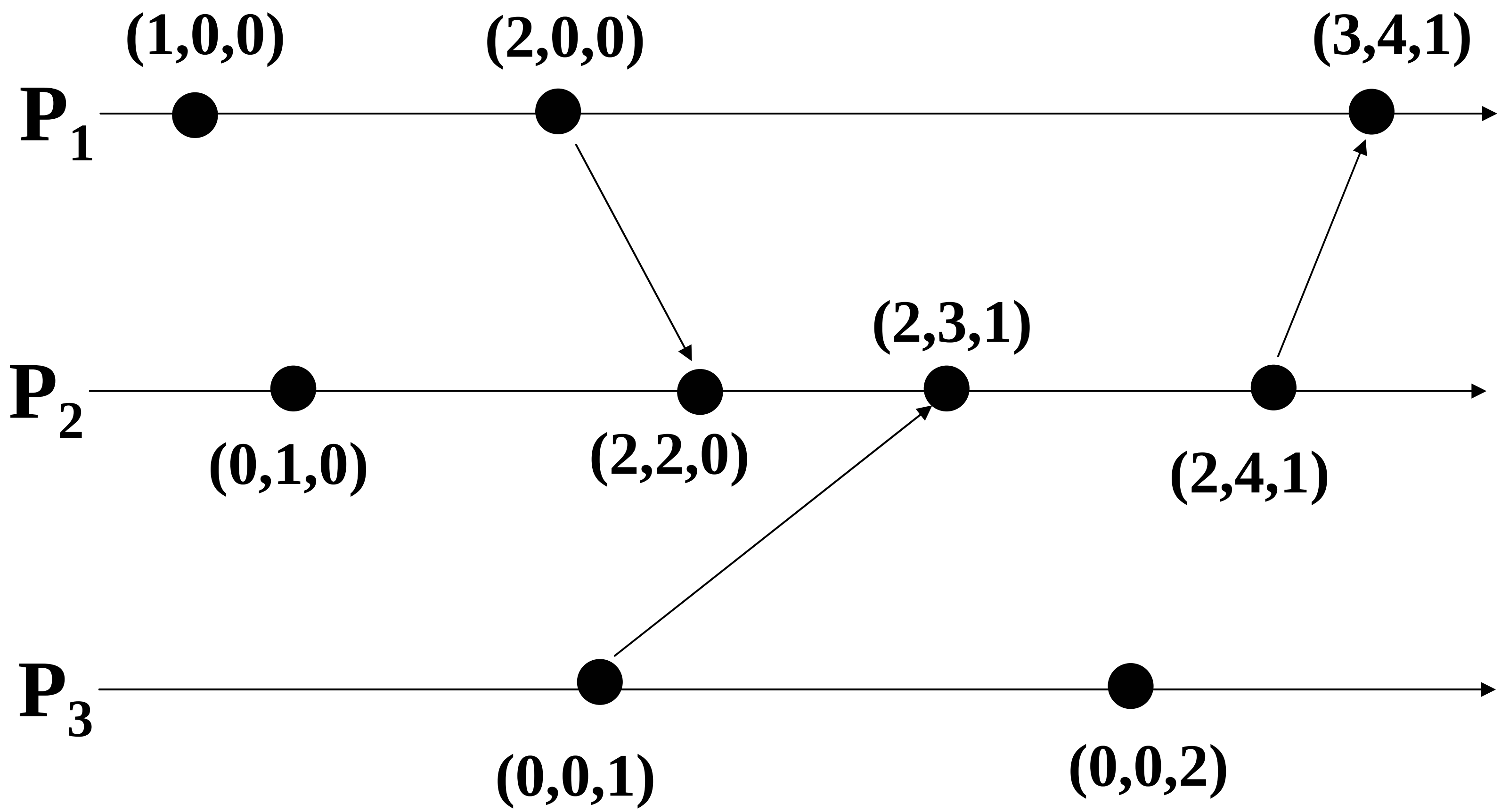
[IR1] Clock C_i is incremented between any two successive events in process P_i

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

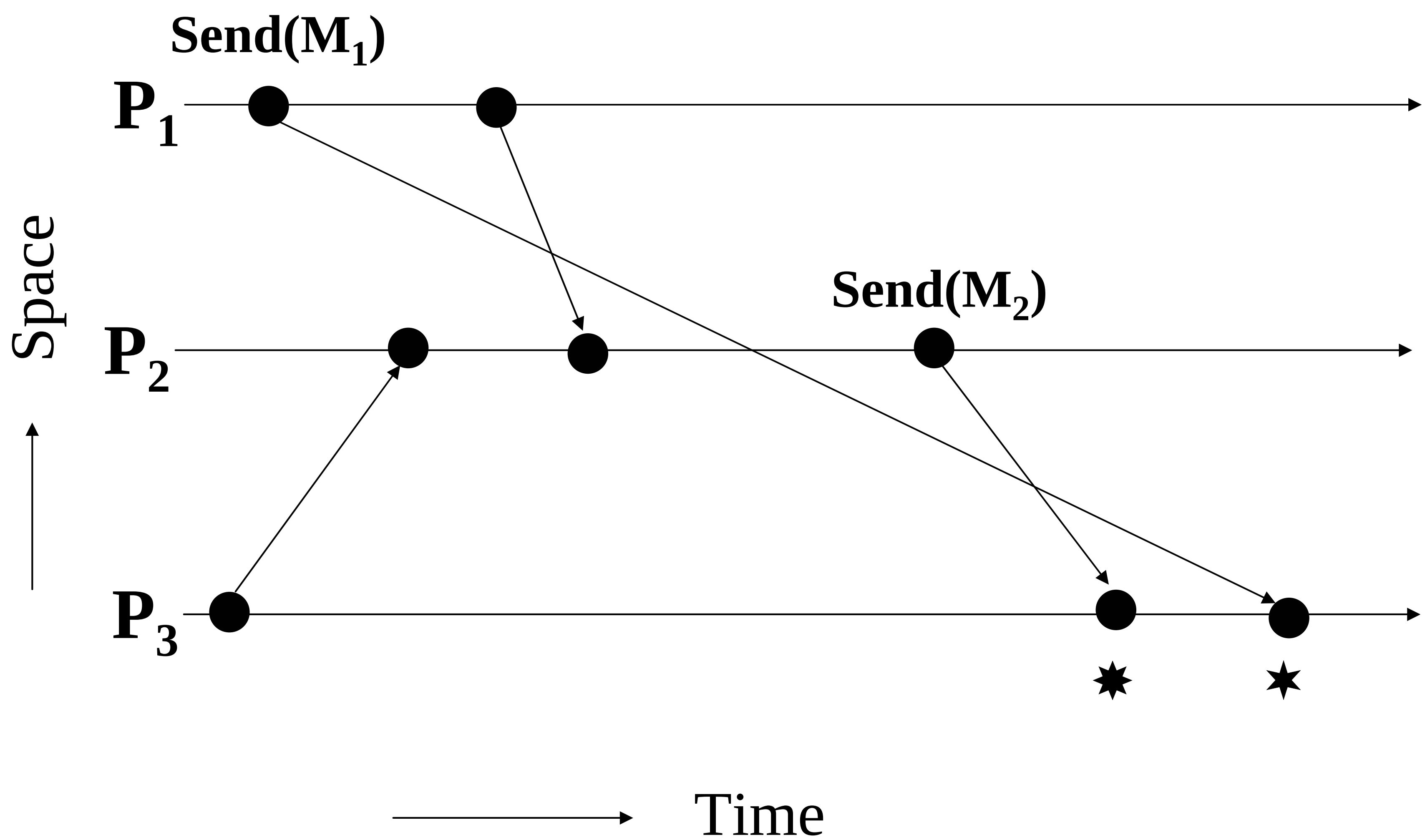
[IR2] If event a is the sending of the message m by process P_i, then message m is assigned a vector timestamp $t_m = C_i(a)$; on receiving the same message m by process P_j, C_j is updated as follows:

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

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]