

CS 425 / ECE 428
Distributed Systems
Fall 2020

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Lecture 12: Time and Ordering

Jokes for this Topic

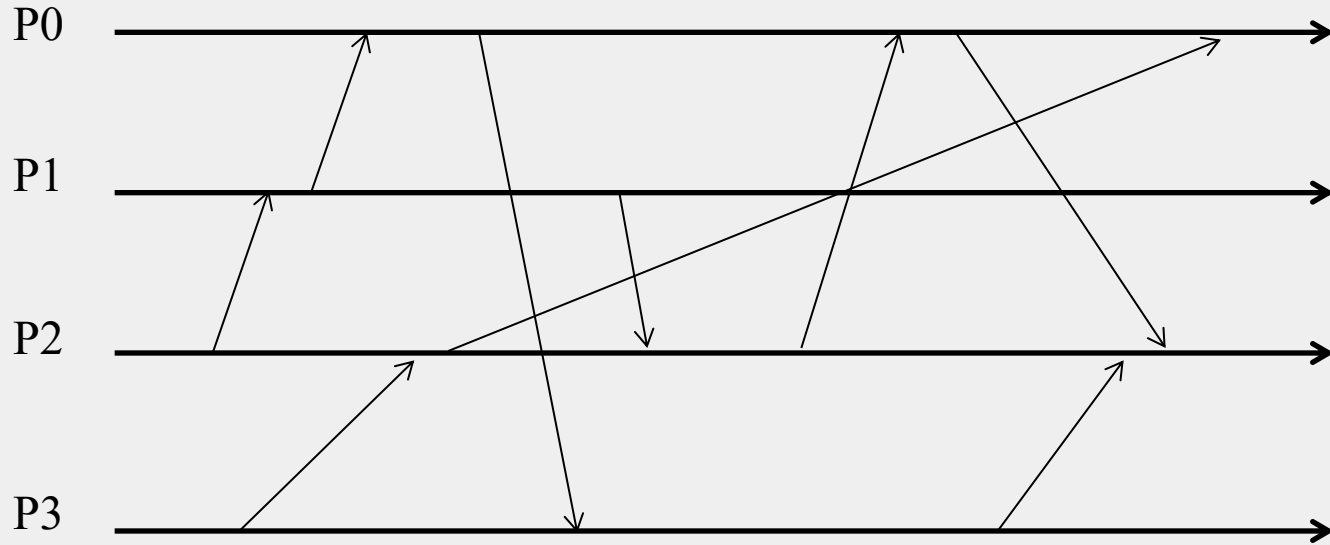
- (You will get these jokes as you start understanding the topic)
- **What's common between a carrier pigeon and a Lamport timestamp? Both like to travel with messages.**
- **Why did the chicken cross the road?**
 - Because Lamport asked it to carry a timestamp.
 - Because it was carrying a Lamport timestamp.
- **What did the chicken carry across the road? A Lamport timestamp.**
- **What's the difference between a blind date and a second date? The first is casual, the second is causal. (this joke is really important)**

(All jokes © unless otherwise mentioned. Apologies for bad jokes!).

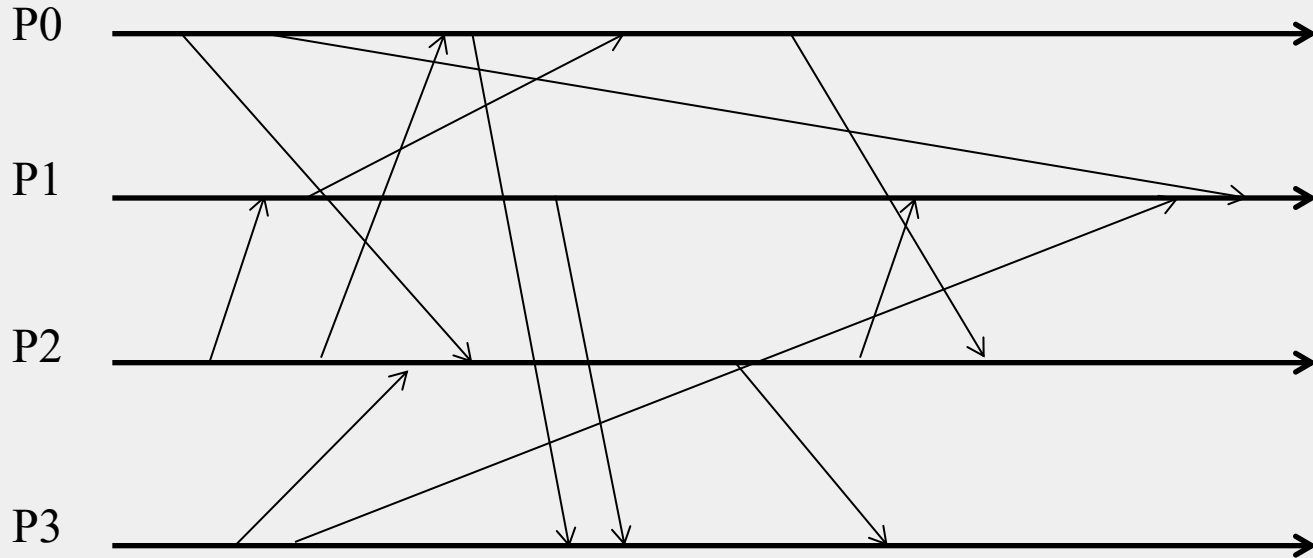
Exercises

1. Cristian's algorithm vs. NTP algorithm: which has a better error bound? (and why?)
2. Why do many distributed systems work correctly without time synchronization?
3. Two events e_1 and e_2 are such that $e_1 \rightarrow e_2$. What does that tell you about their Lamport timestamps? a) $\text{LamportTS}(e_1) < \text{LamportTS}(e_2)$, b) $\text{LamportTS}(e_2) < \text{LamportTS}(e_1)$, c) $\text{LamportTS}(e_1) == \text{LamportTS}(e_2)$, d) Can't tell
4. Two events e_1 and e_2 are such that $\text{LamportTS}(e_1) < \text{LamportTS}(e_2)$. Then which of the following is FALSE: a) e_1 happens before e_2 , b) e_2 happens before e_1 , c) e_1 and e_2 are concurrent, d) Can't tell
5. Two events e_1 and e_2 are such that $\text{VectorTimestamp}(e_1) < \text{VectorTimestamp}(e_2)$. Then which of the following is TRUE: a) e_1 happens before e_2 , b) e_2 happens before e_1 , c) e_1 and e_2 are concurrent, d) Can't tell
6. Prove that $\text{VT}(e_1) < \text{VT}(e_2)$ iff $e_1 \rightarrow e_2$

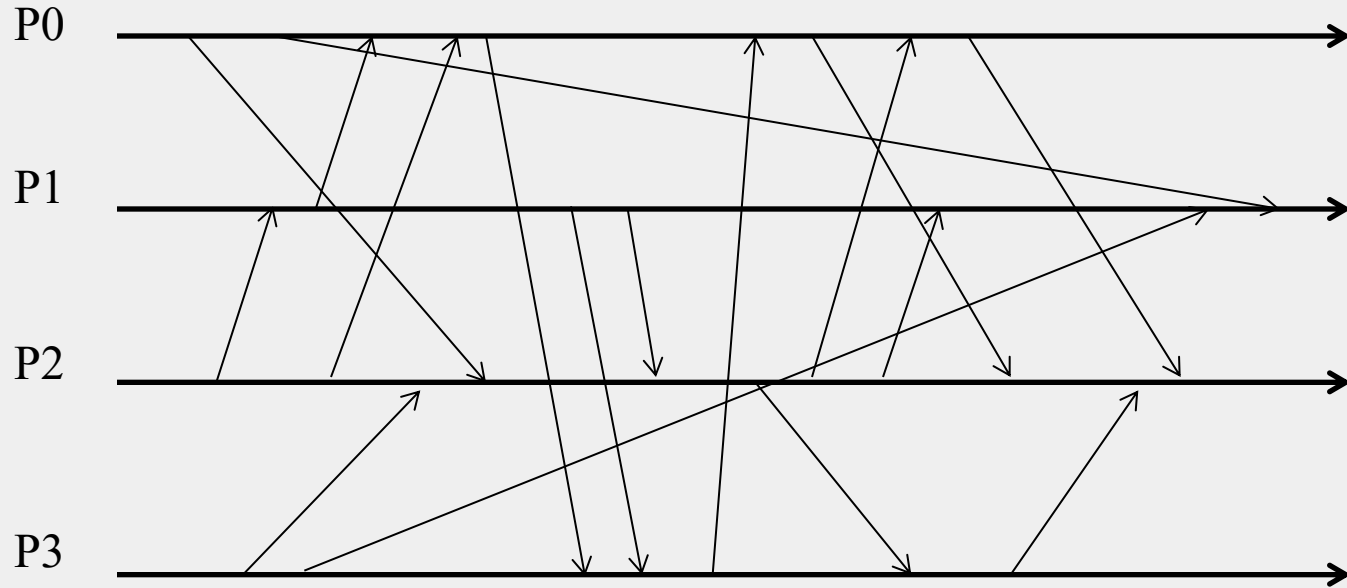
Mark Lamport Timestamps



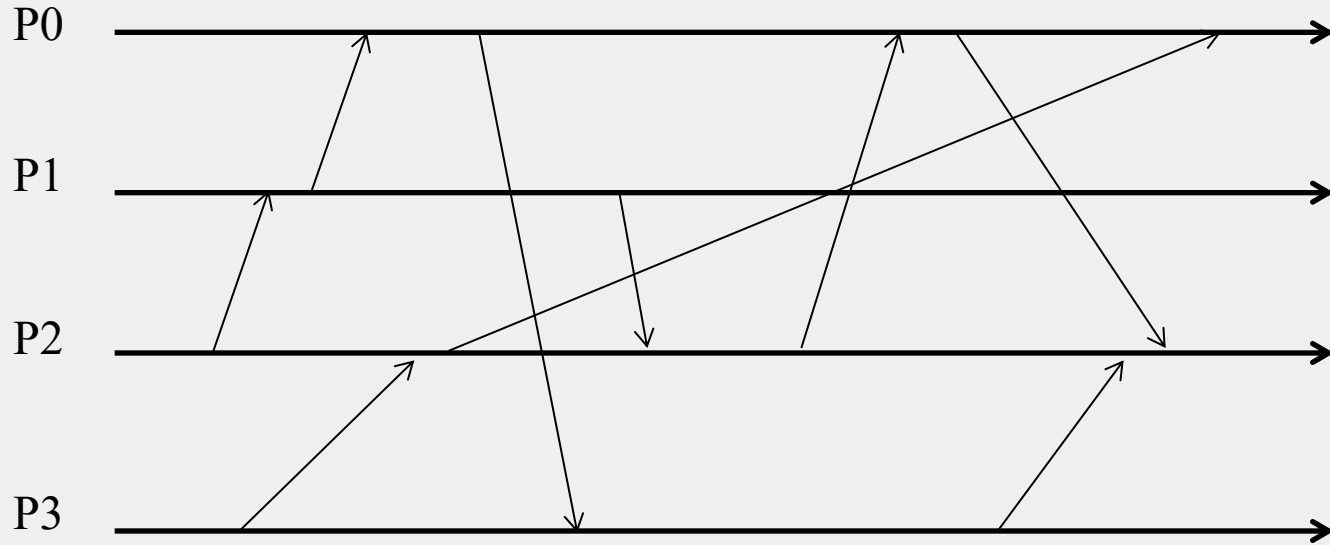
Mark Lamport Timestamps



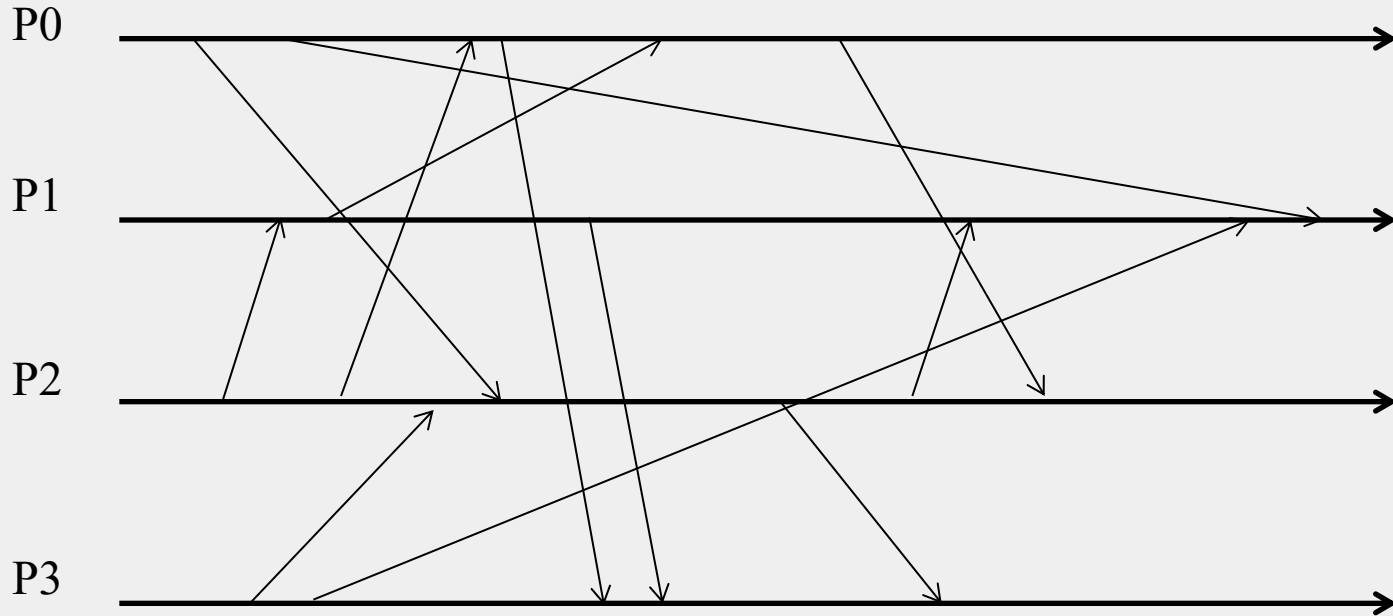
Mark Lamport Timestamps



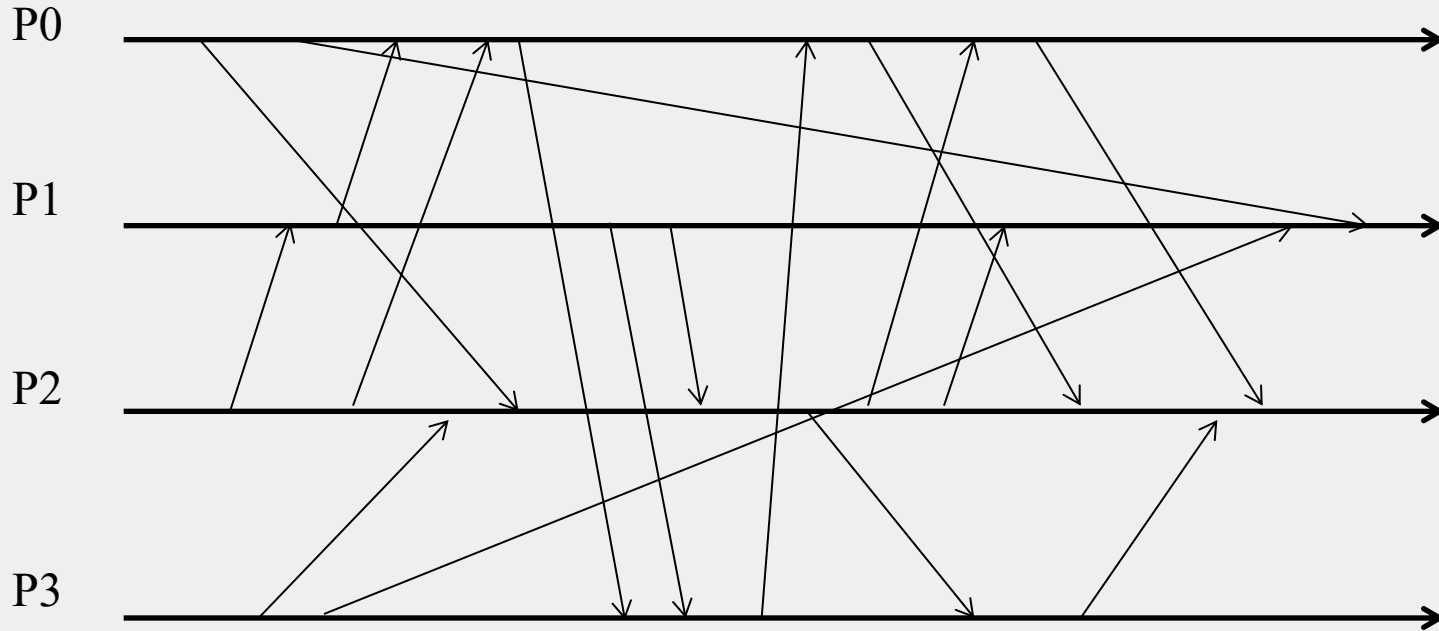
Mark Vector Timestamps



Mark Vector Timestamps



Mark Vector Timestamps



Why Synchronization?

- **You want to catch a bus at 6.05 pm, but your watch is off by 15 minutes**
 - What if your watch is Late by 15 minutes?
 - You'll miss the bus!
 - What if your watch is Fast by 15 minutes?
 - You'll end up unfairly waiting for a longer time than you intended
- **Time synchronization is required for both**
 - Correctness
 - Fairness

Synchronization In The Cloud

- Cloud airline reservation system
- Server A receives a client request to purchase last ticket on flight ABC 123.
- Server A timestamps purchase using local clock **9h:15m:32.45s**, and logs it. Replies ok to client.
- That was the last seat. Server A sends message to Server B saying “flight full.”
- B enters “Flight ABC 123 full” + its own local clock value (which reads **9h:10m:10.11s**) into its log.
- Server C queries A’s and B’s logs. Is confused that a client purchased a ticket at A after the flight became full at B.
- **This may lead to further incorrect actions by C**

Why is it Challenging?

- **End hosts in Internet-based systems (like clouds)**
 - Each have their own clocks
 - Unlike processors (CPUs) within one server or workstation which share a system clock
- **Processes in Internet-based systems follow an *asynchronous* system model**
 - No bounds on
 - Message delays
 - Processing delays
 - Unlike multi-processor (or parallel) systems which follow a *synchronous* system model

Some Definitions

- An Asynchronous Distributed System consists of a number of **processes**
- Each process has a **state** (values of variables).
- Each process takes **actions** to change its state, which may be an **instruction** or a communication action (**send**, **receive**).
- An **event** is the occurrence of an action.
- Each process has a local clock – events *within* a process can be assigned **timestamps**, and thus ordered linearly.
- But – in a distributed system, we also need to know the time order of events *across* different processes.

Clock Skew vs. Clock Drift

- **Each process (running at some end host) has its own clock.**
- **When comparing two clocks at two processes:**
 - Clock **Skew** = **Relative Difference in clock *values* of two processes**
 - Like distance between two vehicles on a road
 - Clock **Drift** = **Relative Difference in clock *frequencies (rates)* of two processes**
 - Like difference in speeds of two vehicles on the road
- **A non-zero clock skew implies clocks are not synchronized.**
- **A non-zero clock drift causes skew to increase (eventually).**
 - If faster vehicle is ahead, it will drift away
 - If faster vehicle is behind, it will catch up and then drift away

How often to Synchronize?

- Maximum Drift Rate (**MDR**) of a clock
- Absolute MDR is defined relative to Coordinated Universal Time (UTC). UTC is the “correct” time at any point of time.
 - MDR of a process depends on the environment.
- Max drift rate between two clocks with similar MDR is $2 * \text{MDR}$
- Given a maximum acceptable skew M between any pair of clocks, need to synchronize at least once every: $M / (2 * \text{MDR})$ time units
 - Since time = distance/speed

External vs Internal Synchronization

- **Consider a group of processes**
- **External Synchronization**
 - Each process $C(i)$'s clock is within a bound D of a well-known clock S external to the group
 - $|C(i) - S| < D$ at all times
 - External clock may be connected to UTC (Universal Coordinated Time) or an atomic clock
 - E.g., Cristian's algorithm, NTP
- **Internal Synchronization**
 - Every pair of processes in group have clocks within bound D
 - $|C(i) - C(j)| < D$ at all times and for all processes i, j
 - E.g., Berkeley algorithm

External vs Internal Synchronization (2)

- **External Synchronization with $D \Rightarrow$ Internal Synchronization with $2 \cdot D$**
- **Internal Synchronization does not imply External Synchronization**
 - In fact, the entire system may drift away from the external clock S !

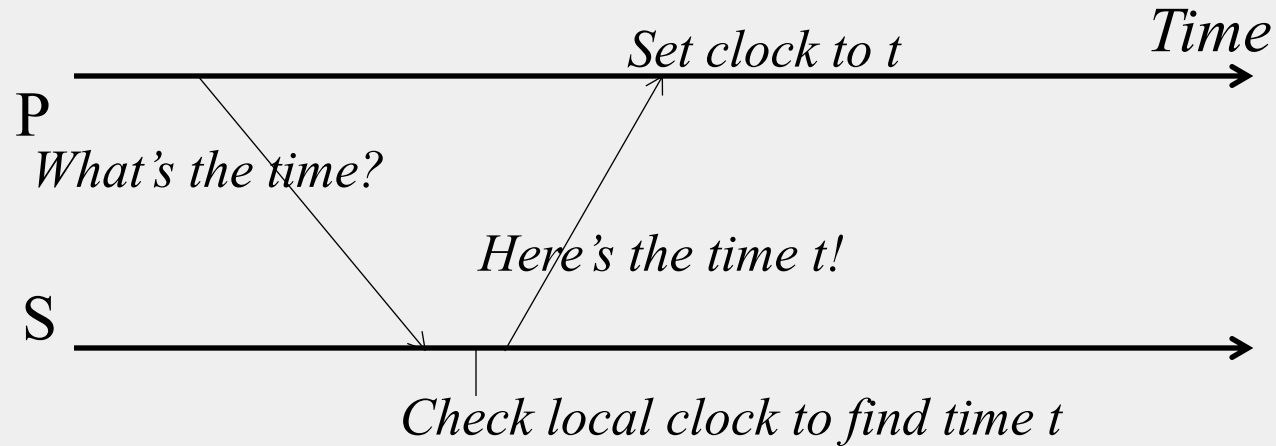
Next

- Algorithms for Clock Synchronization

Cristian's Algorithm

Basics

- **External time synchronization**
- **All processes P synchronize with a time server S**

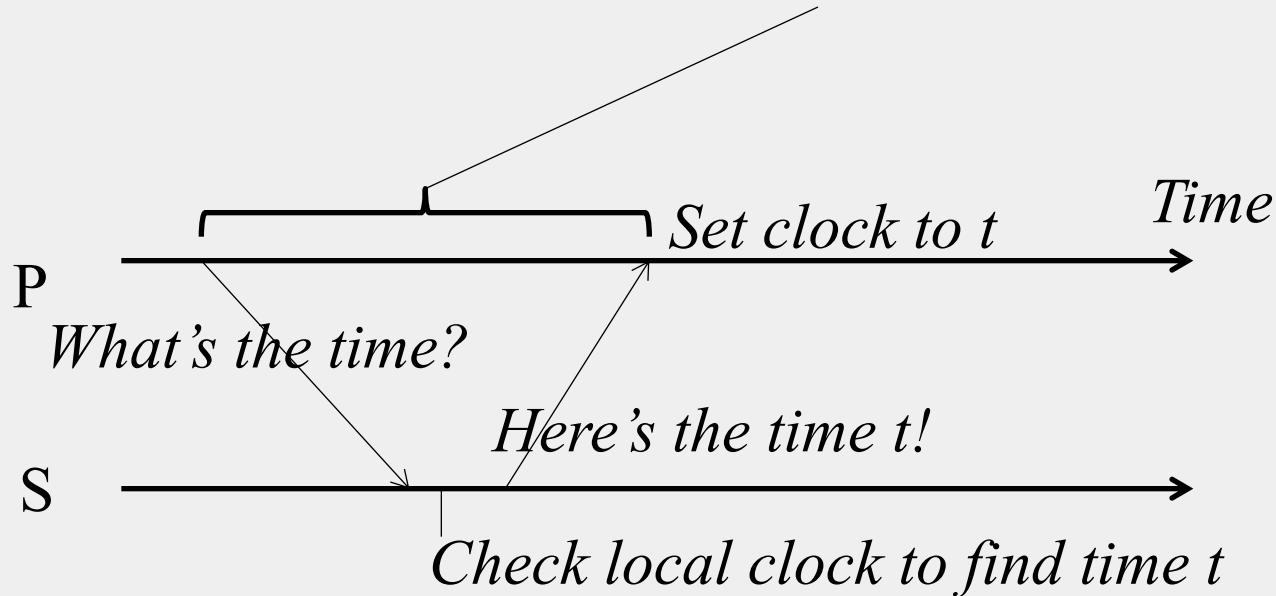


What's Wrong

- By the time response message is received at P, time has moved on
- P's time set to t is inaccurate!
- Inaccuracy a function of message latencies
- Since latencies unbounded in an asynchronous system, the inaccuracy cannot be bounded

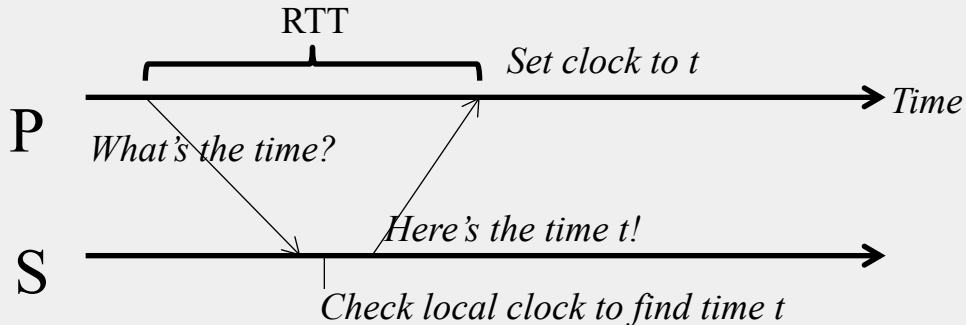
Cristian's Algorithm

- P measures the round-trip-time RTT of message exchange



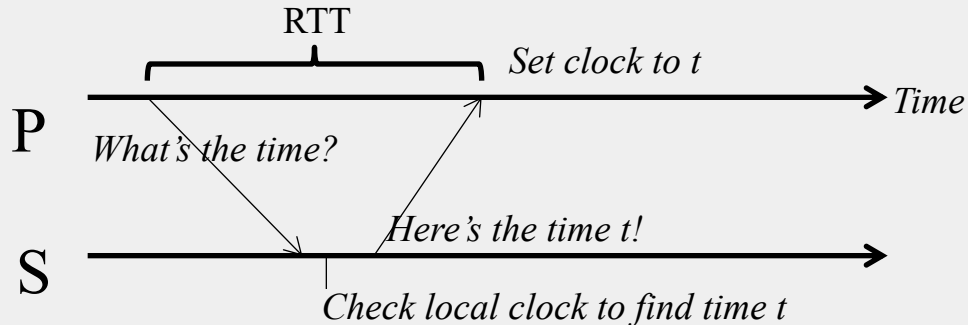
Cristian's Algorithm (2)

- **P** measures the round-trip-time RTT of message exchange
- Suppose we know the minimum $P \rightarrow S$ latency min1
- And the minimum $S \rightarrow P$ latency min2
 - min1 and min2 depend on Operating system overhead to buffer messages, TCP time to queue messages, etc.



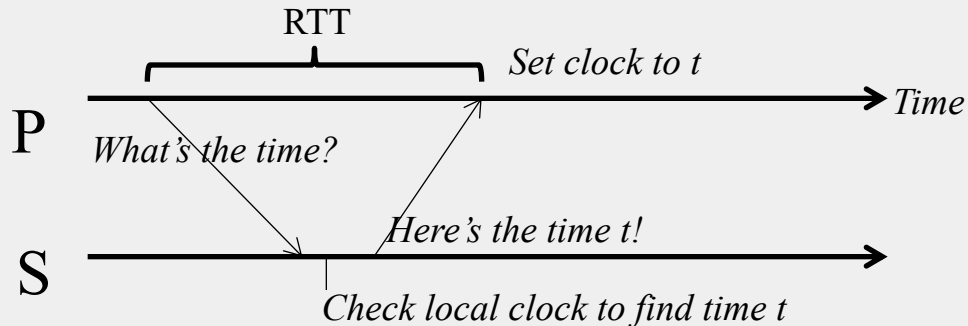
Cristian's Algorithm (3)

- P measures the round-trip-time RTT of message exchange
- Suppose we know the minimum $P \rightarrow S$ latency min1
- And the minimum $S \rightarrow P$ latency min2
 - min1 and min2 depend on Operating system overhead to buffer messages, TCP time to queue messages, etc.
- The actual time at P when it receives response is between $[t+\text{min2}, t+\text{RTT}-\text{min1}]$



Cristian's Algorithm (4)

- The actual time at P when it receives response is between $[t+\min_2, t+\text{RTT}-\min_1]$
- P sets its time to halfway through this interval
 - To: $t + (\text{RTT}+\min_2-\min_1)/2$
- Error is at most $(\text{RTT}-\min_2-\min_1)/2$
 - Bounded!

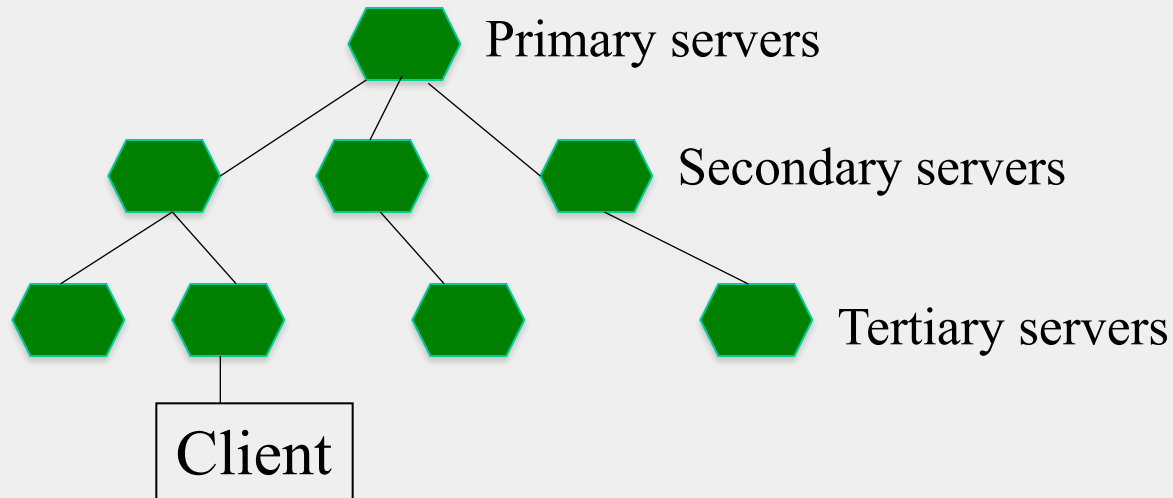


Gotchas

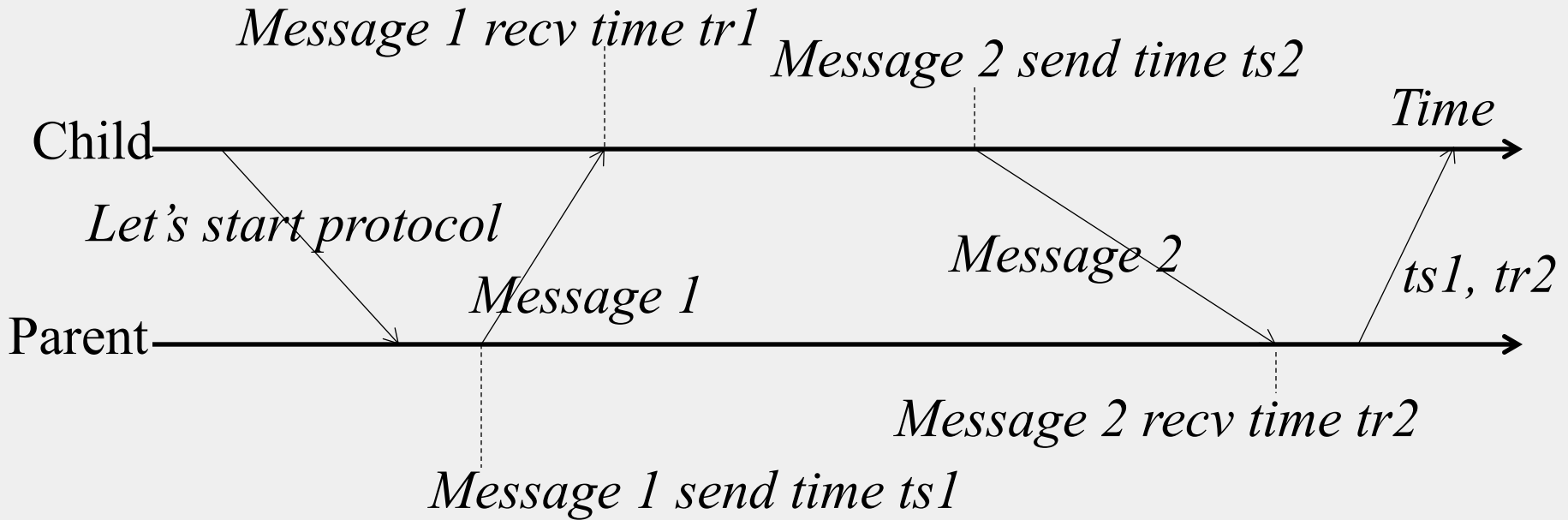
- **Allowed to increase clock value but should never decrease clock value**
 - May violate ordering of events within the same process
- **Allowed to increase or decrease speed of clock**
- **If error is too high, take multiple readings and average them**

NTP = Network Time Protocol

- NTP Servers organized in a tree
- Each Client = a leaf of tree
- Each node synchronizes with its tree parent



NTP Protocol



What the Child Does

- Child calculates *offset* between its clock and parent's clock
- Uses *ts1*, *tr1*, *ts2*, *tr2*
- Offset is calculated as

$$o = (tr1 - tr2 + ts2 - ts1)/2$$

Why $o = (tr1 - tr2 + ts2 - ts1)/2$?

- **Offset $o = (tr1 - tr2 + ts2 - ts1)/2$**
- **Let's calculate the error**
- **Suppose real offset is $oreal$**
 - Child is ahead of parent by $oreal$
 - Parent is ahead of child by $-oreal$
- **Suppose one-way latency of Message 1 is $L1$ ($L2$ for Message 2)**
- **No one knows $L1$ or $L2$!**
- **Then**

$$tr1 = ts1 + L1 + oreal$$

$$tr2 = ts2 + L2 - oreal$$

Why $o = (tr1 - tr2 + ts2 - ts1)/2$? (2)

- **Then**

$$tr1 = ts1 + L1 + o_{real}$$

$$tr2 = ts2 + L2 - o_{real}$$

- **Subtracting second equation from the first**

$$o_{real} = (tr1 - tr2 + ts2 - ts1)/2 + (L2 - L1)/2$$

$$\Rightarrow o_{real} = o + (L2 - L1)/2$$

$$\Rightarrow |o_{real} - o| < |(L2 - L1)/2| < |(L2 + L1)/2|$$

– Thus, the error is bounded by the round-trip-time

And yet...

- **We still have a non-zero error!**
- **We just can't seem to get rid of error**
 - Can't, as long as message latencies are non-zero
- **Can we avoid synchronizing clocks altogether, and still be able to order events?**

Lamport Timestamps

Ordering Events in a Distributed System

- **To order events across processes, trying to sync clocks is one approach**
- **What if we instead assigned timestamps to events that were not *absolute* time?**
- **As long as these timestamps obey *causality*, that would work**

If an event A causally happens before another event B, then $\text{timestamp}(A) < \text{timestamp}(B)$

Humans use causality all the time

E.g., I enter a house only after I unlock it

E.g., You receive a letter only after I send it

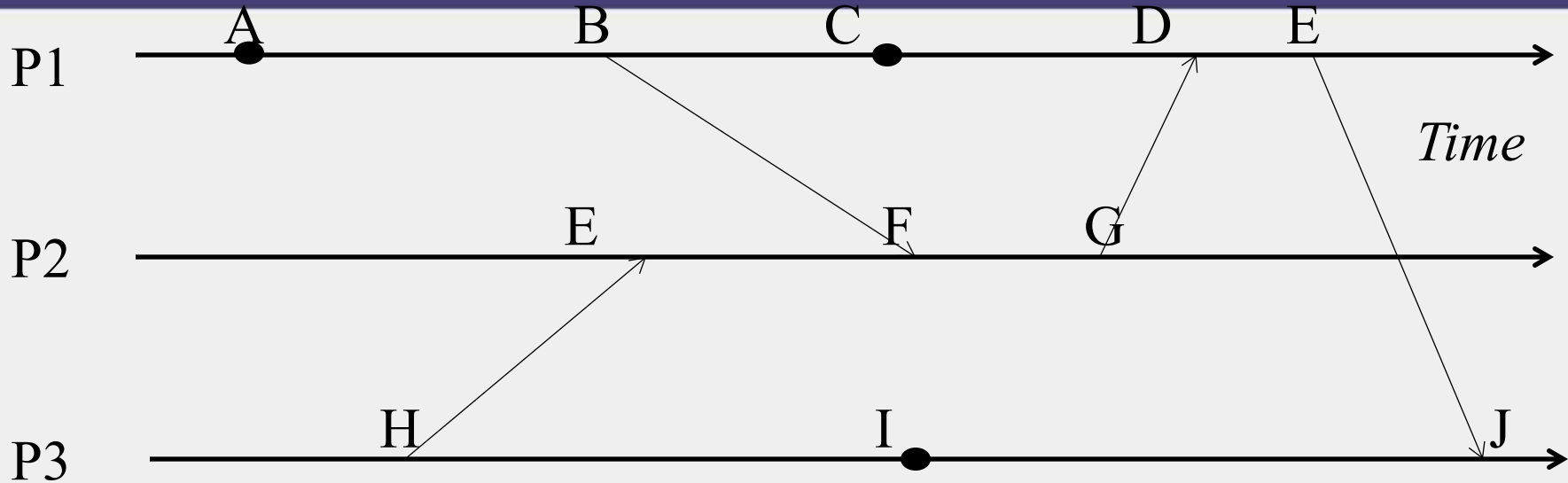
Logical (or Lamport) Ordering

- Proposed by Leslie Lamport in the 1970s
- Used in almost all distributed systems since then
- Almost all cloud computing systems use some form of logical ordering of events

Logical (or Lamport) Ordering(2)

- Define a logical relation *Happens-Before* among pairs of events
- *Happens-Before* denoted as \rightarrow
- Three rules
 1. On the same process: $a \rightarrow b$, if $time(a) < time(b)$ (using the local clock)
 2. If p1 sends m to p2: $send(m) \rightarrow receive(m)$
 3. (Transitivity) If $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$
- Creates a *partial order* among events
 - Not all events related to each other via \rightarrow

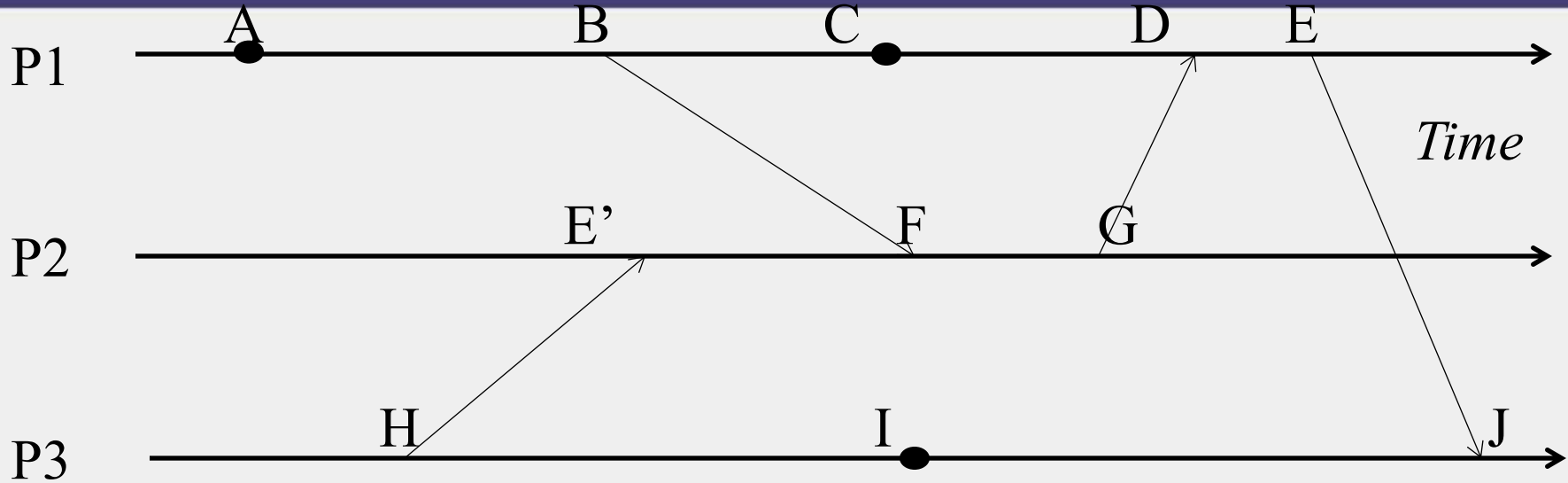
Example



While P1 and P3 each have an event labeled E, these are different events as they occur at different processes.



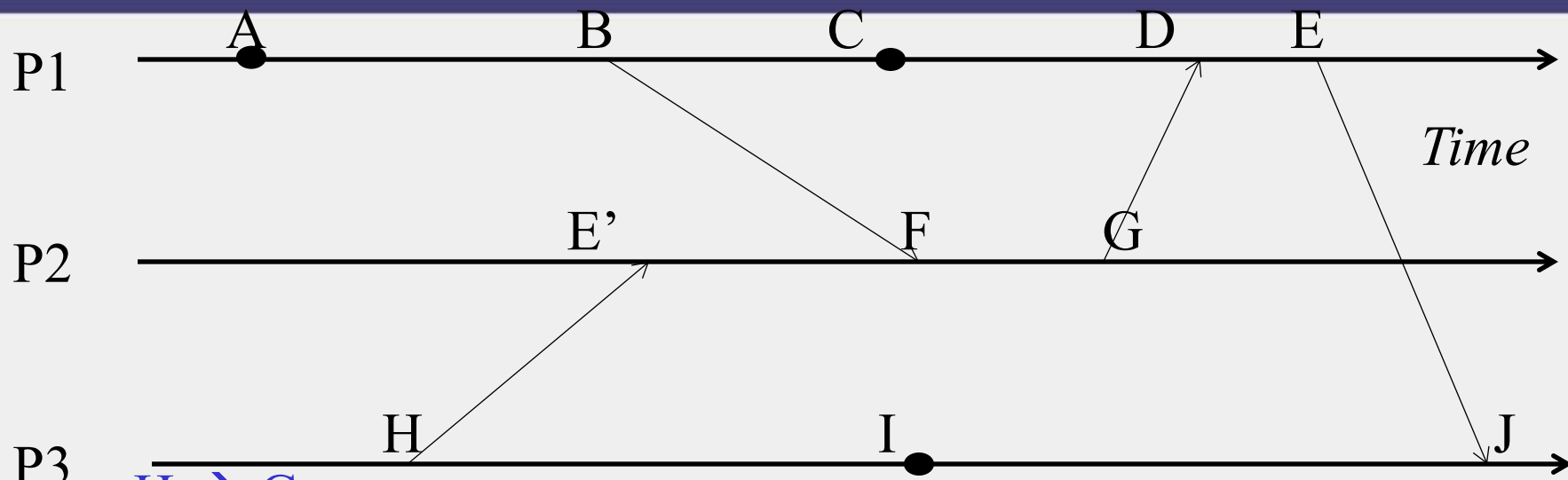
Happens-Before



- $A \rightarrow B$
- $B \rightarrow F$
- $A \rightarrow F$



Happens-Before (2)

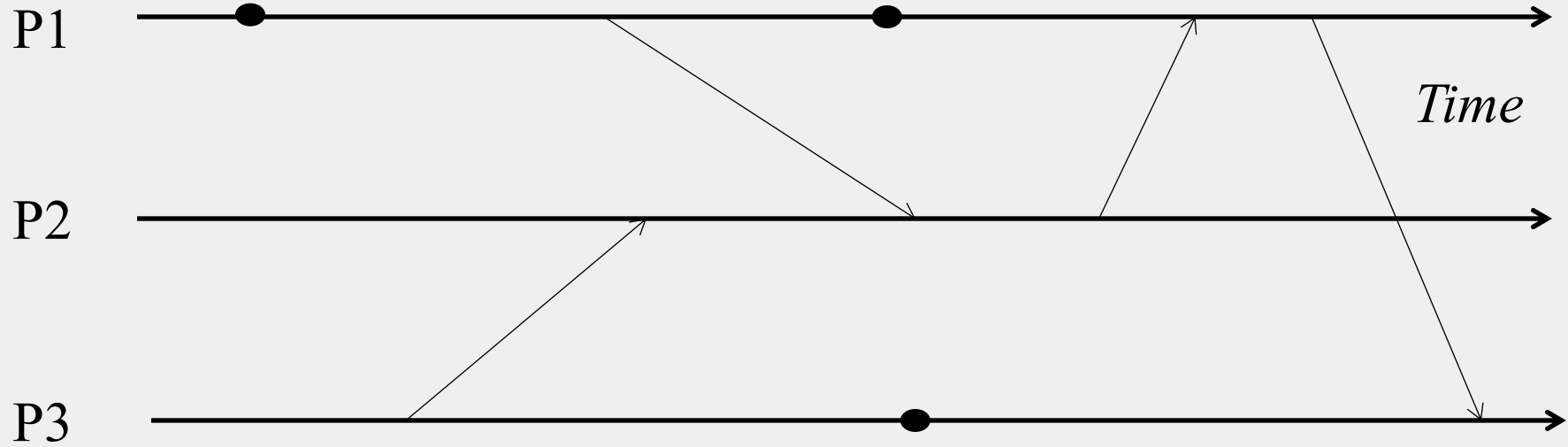


- $H \rightarrow G$
- $F \rightarrow J$
- $H \rightarrow J$
- $C \rightarrow J$

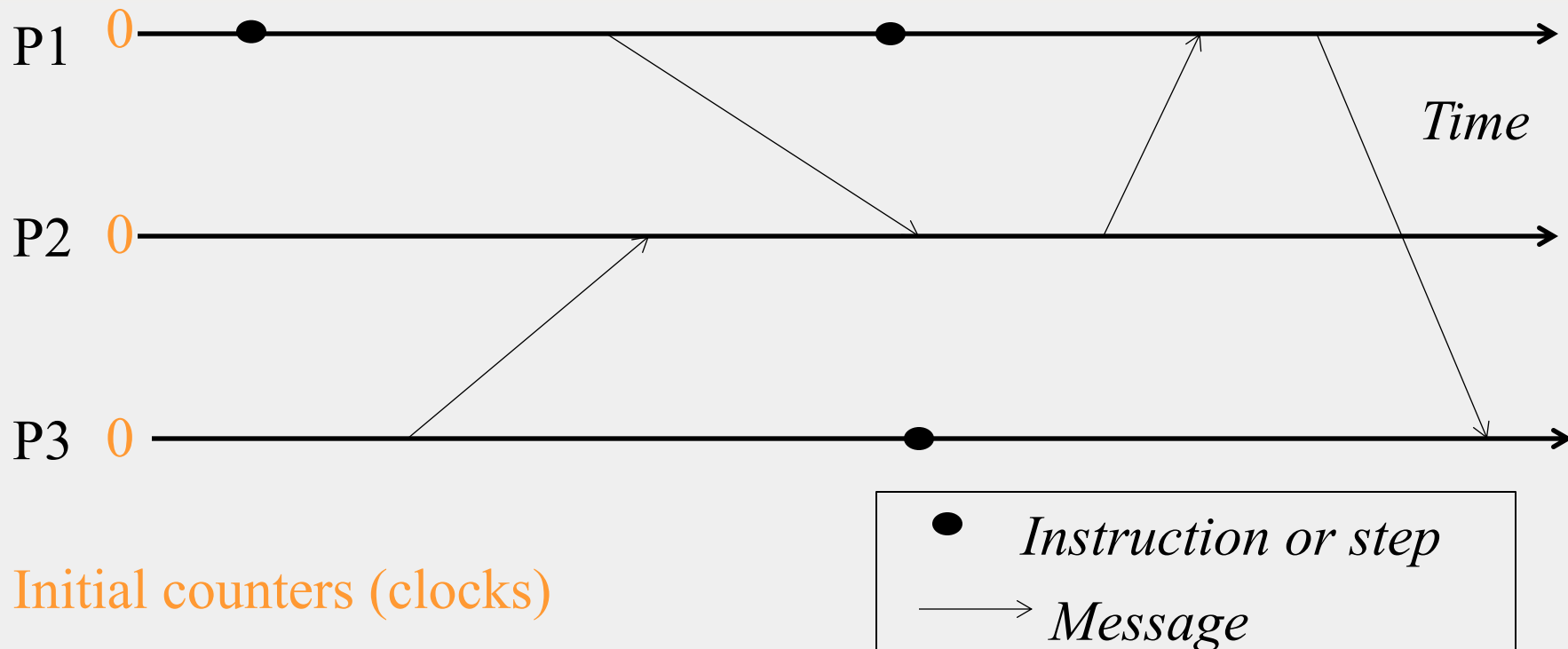
In practice: Lamport timestamps

- **Goal: Assign logical (Lamport) timestamp to each event**
- **Timestamps obey causality**
- **Rules**
 - Each process uses a local counter (clock) which is an integer
 - initial value of counter is zero
 - A process increments its counter when a **send** or an **instruction** happens at it. The counter is assigned to the event as its timestamp.
 - **A send (message)** event carries its timestamp
 - For a **receive (message)** event the counter is updated by
$$\max(\text{local clock, message timestamp}) + 1$$

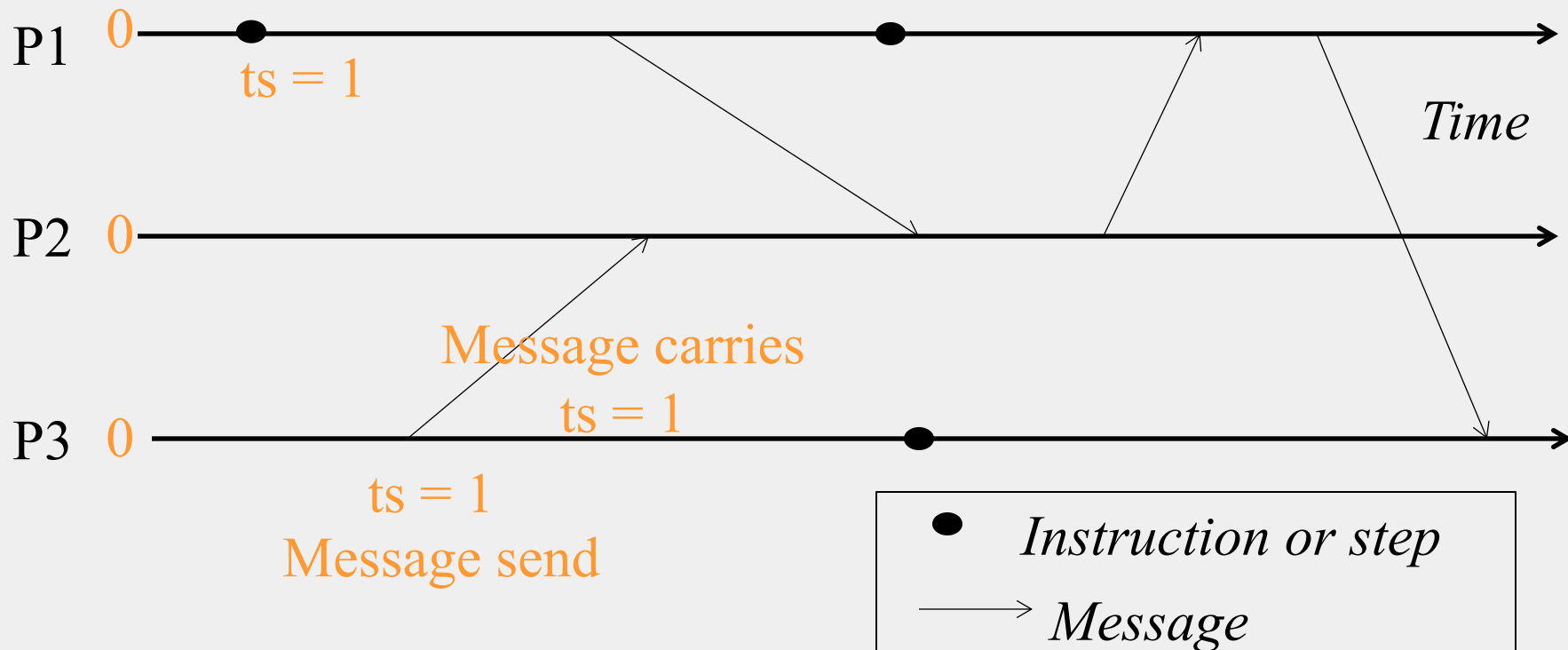
Example



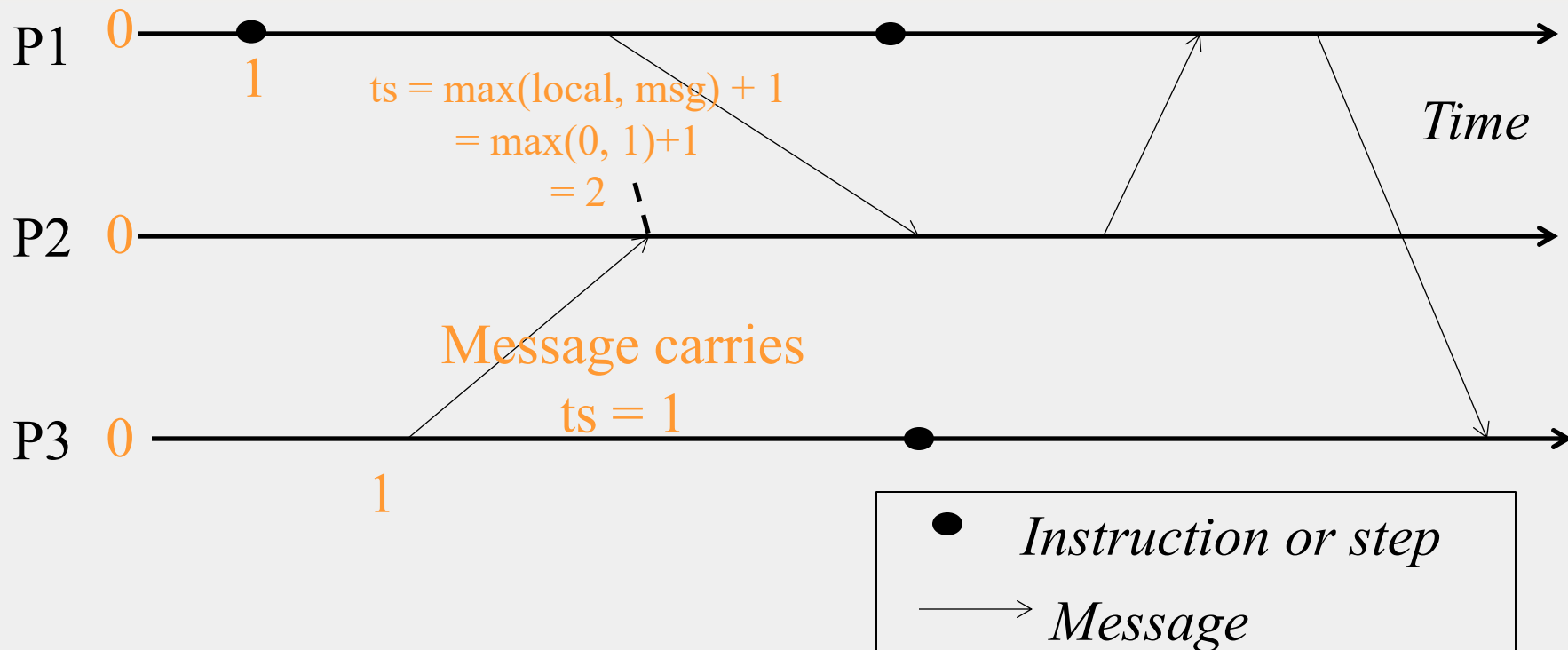
Lamport Timestamps



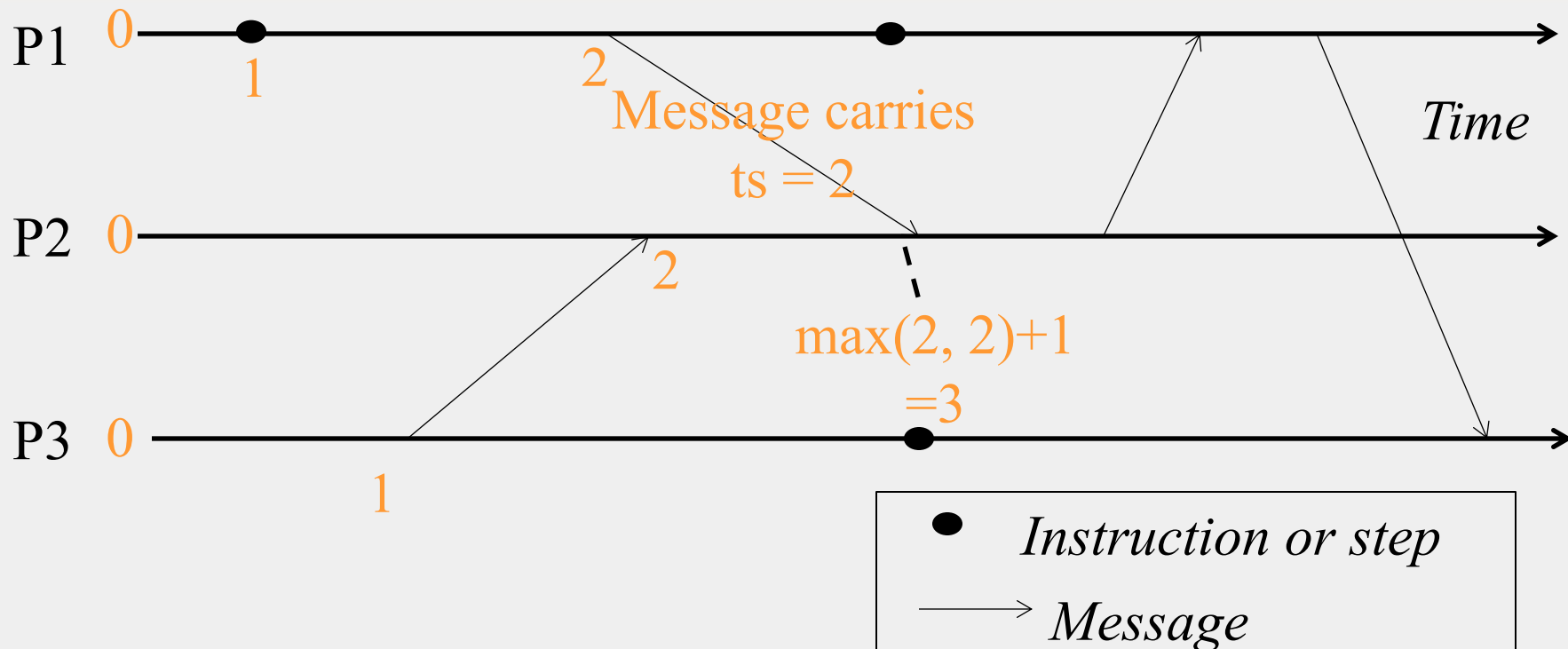
Lamport Timestamps



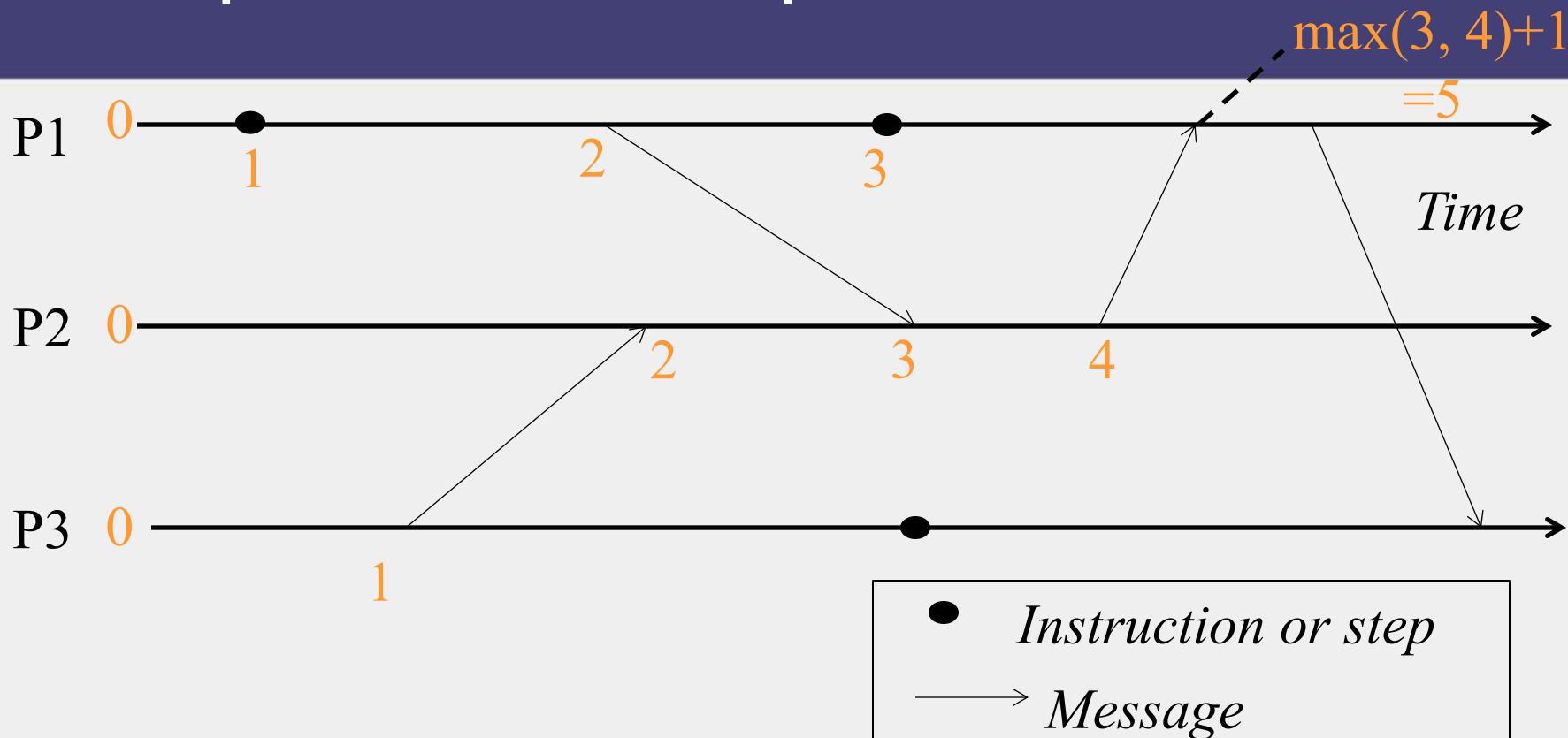
Lamport Timestamps



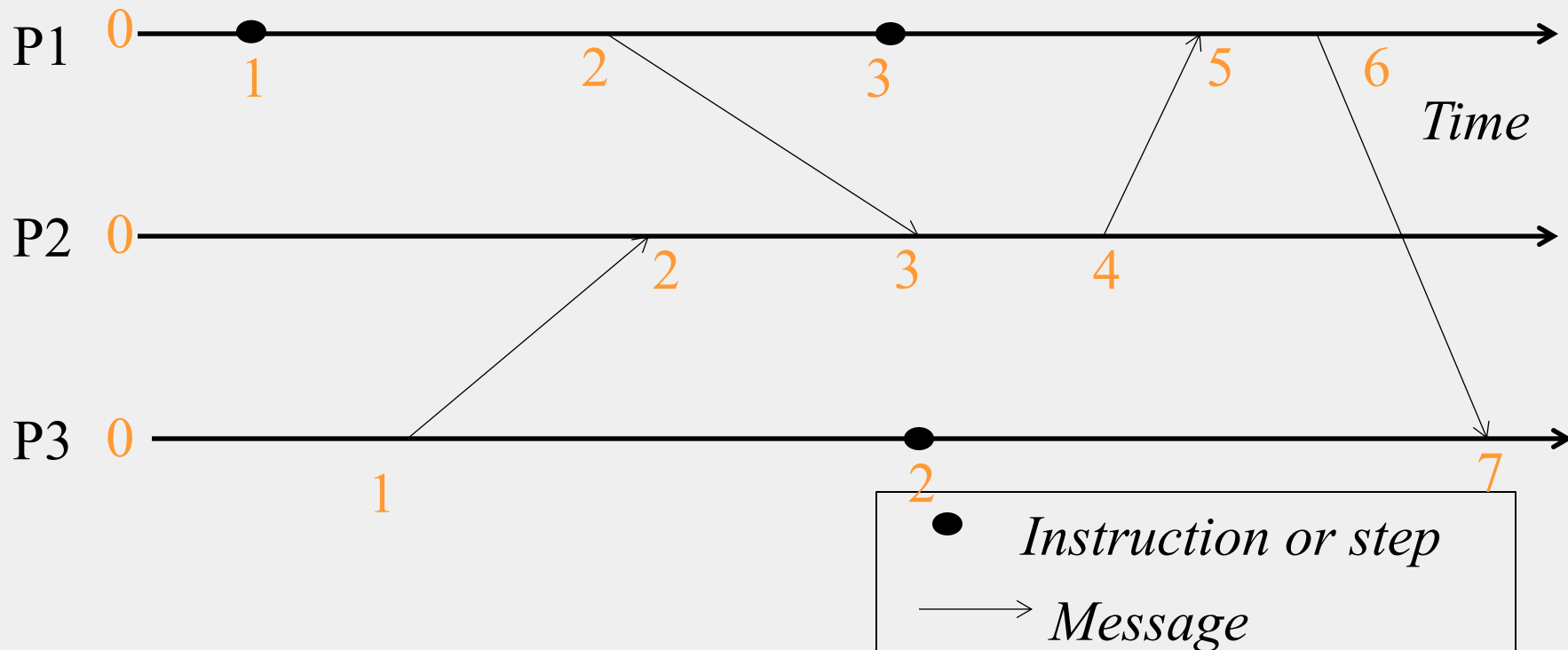
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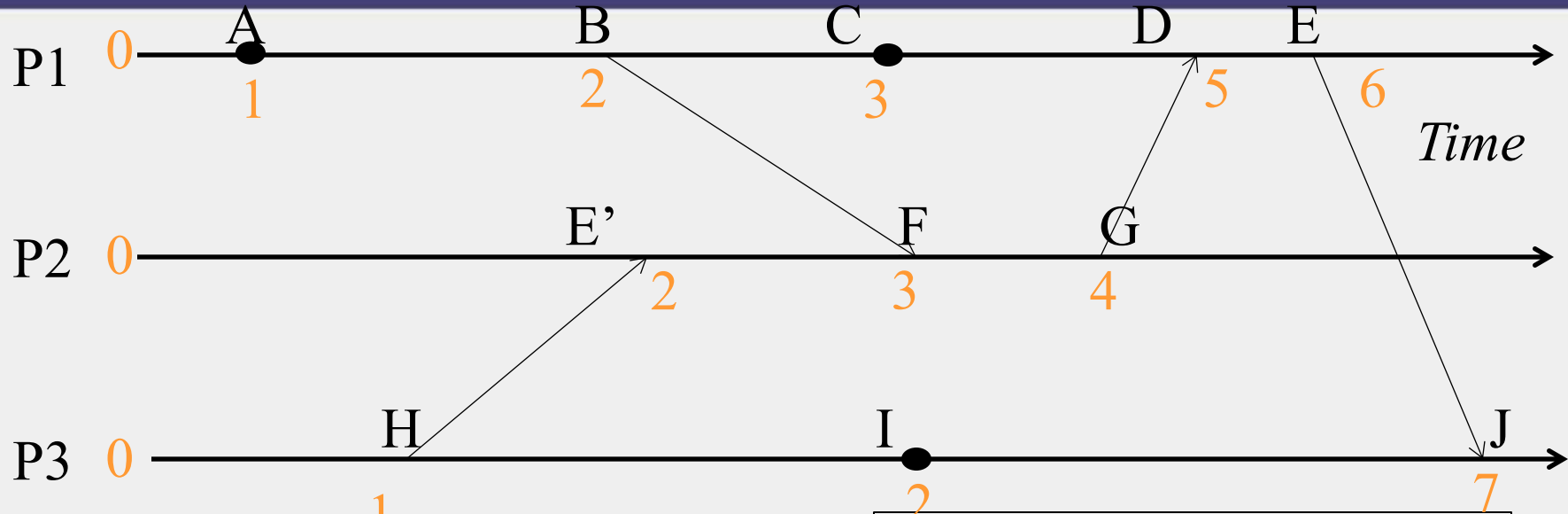
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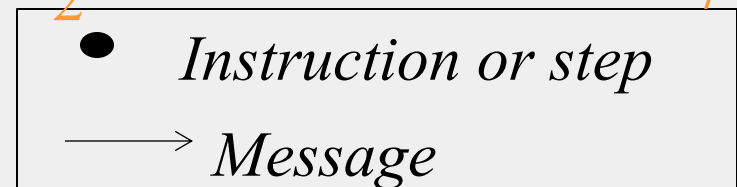
Lamport Timestamps



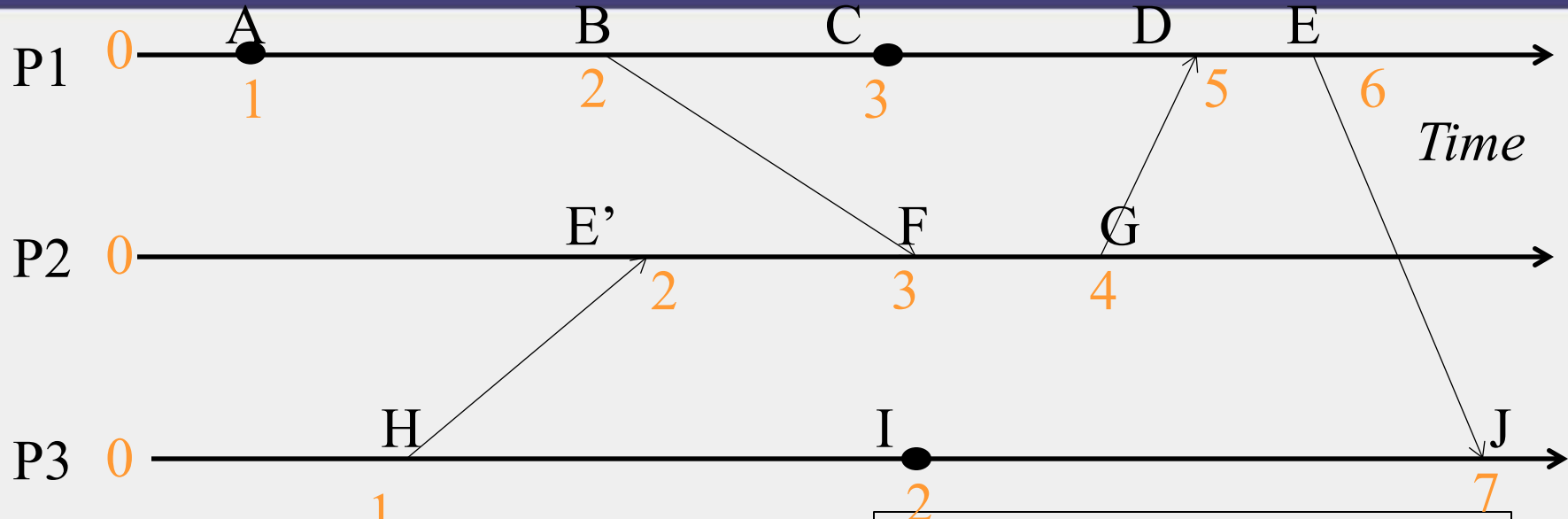
Obeying Causality



- $A \rightarrow B :: 1 < 2$
- $B \rightarrow F :: 2 < 3$
- $A \rightarrow F :: 1 < 3$

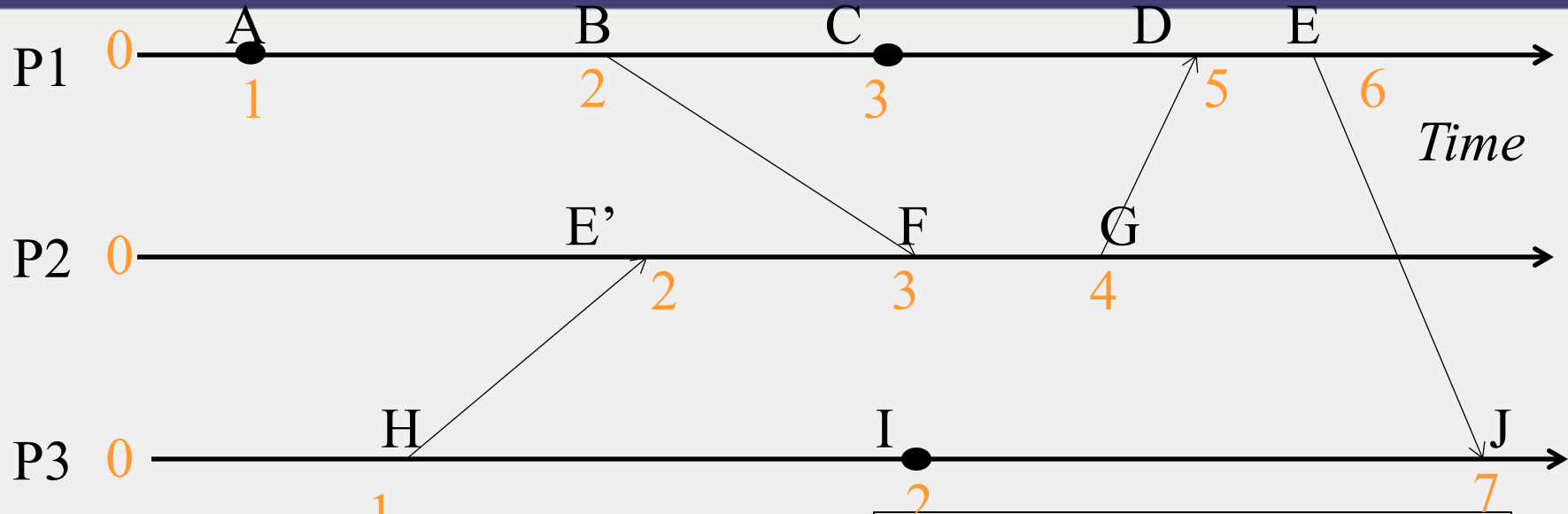


Obeying Causality (2)

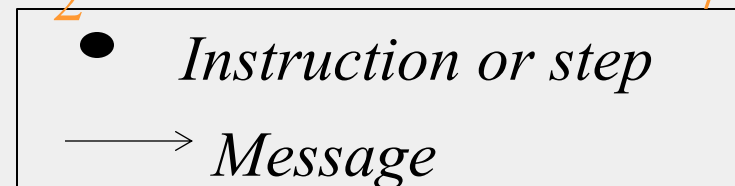


- $H \rightarrow G :: 1 < 4$
- $F \rightarrow J :: 3 < 7$
- $H \rightarrow J :: 1 < 7$
- $C \rightarrow J :: 3 < 7$

Not always implying Causality



- ? $C \rightarrow F$? :: $3 = 3$
- ? $H \rightarrow C$? :: $1 < 3$
- (C, F) and (H, C) are pairs of concurrent events



Concurrent Events

- **A pair of concurrent events doesn't have a causal path from one event to another (either way, in the pair)**
- **Lamport timestamps not guaranteed to be ordered or unequal for concurrent events**
- **Ok, since concurrent events are not causality related!**
- **Remember**

$E1 \rightarrow E2 \Rightarrow \text{timestamp}(E1) < \text{timestamp}(E2)$, **BUT**

$\text{timestamp}(E1) < \text{timestamp}(E2) \Rightarrow$

$\{E1 \rightarrow E2\}$ OR $\{E1 \text{ and } E2 \text{ concurrent}\}$

Next

- Can we have causal or logical timestamps from which we can tell if two events are concurrent or causally related?

Vector Timestamps

- Used in key-value stores like Riak
- Each process uses a vector of integer clocks
- Suppose there are N processes in the group $1 \dots N$
- Each vector has N elements
- Process i maintains vector $V_i[1 \dots N]$
- j th element of vector clock at process i , $V_i[j]$, is i 's knowledge of latest events at process j

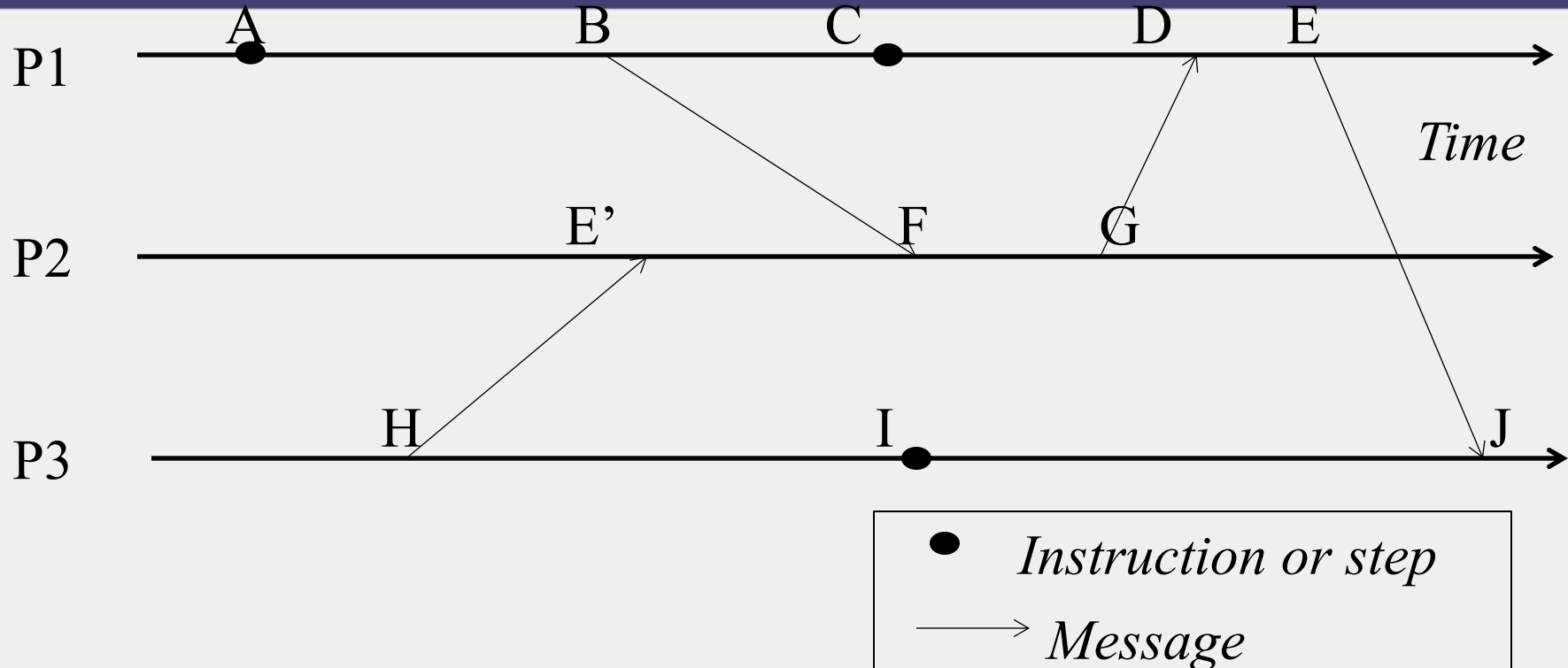
Assigning Vector Timestamps

- Incrementing vector clocks
 1. On an instruction or send event at process i , it increments only its i th element of its vector clock
 2. Each message carries the send-event's vector timestamp $V_{\text{message}}[1 \dots N]$
 3. On receiving a message at process i :

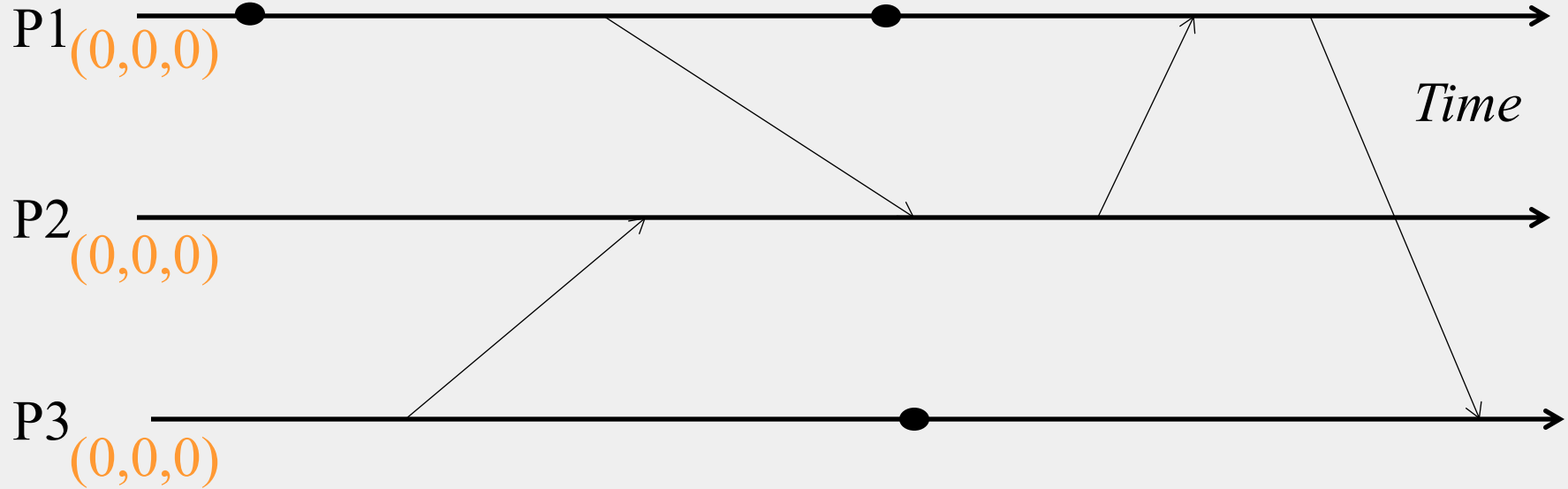
$$V_i[i] = V_i[i] + 1$$

$$V_i[j] = \max(V_{\text{message}}[j], V_i[j]) \text{ for } j \neq i$$

Example

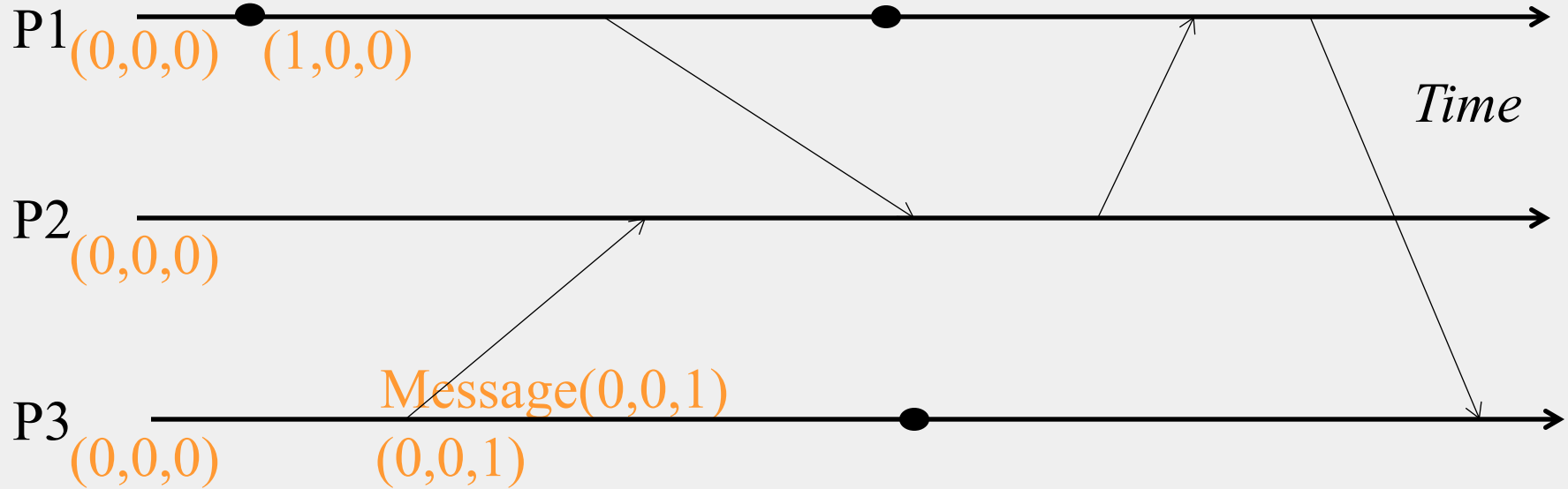


Vector Timestamps

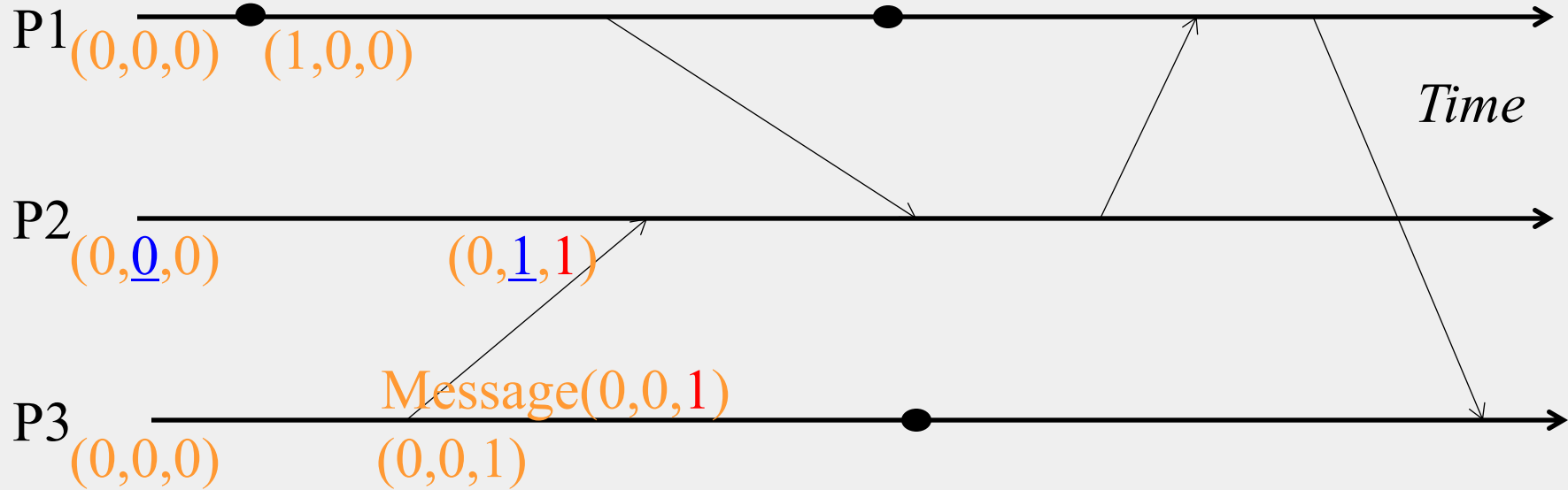


Initial counters (clocks)

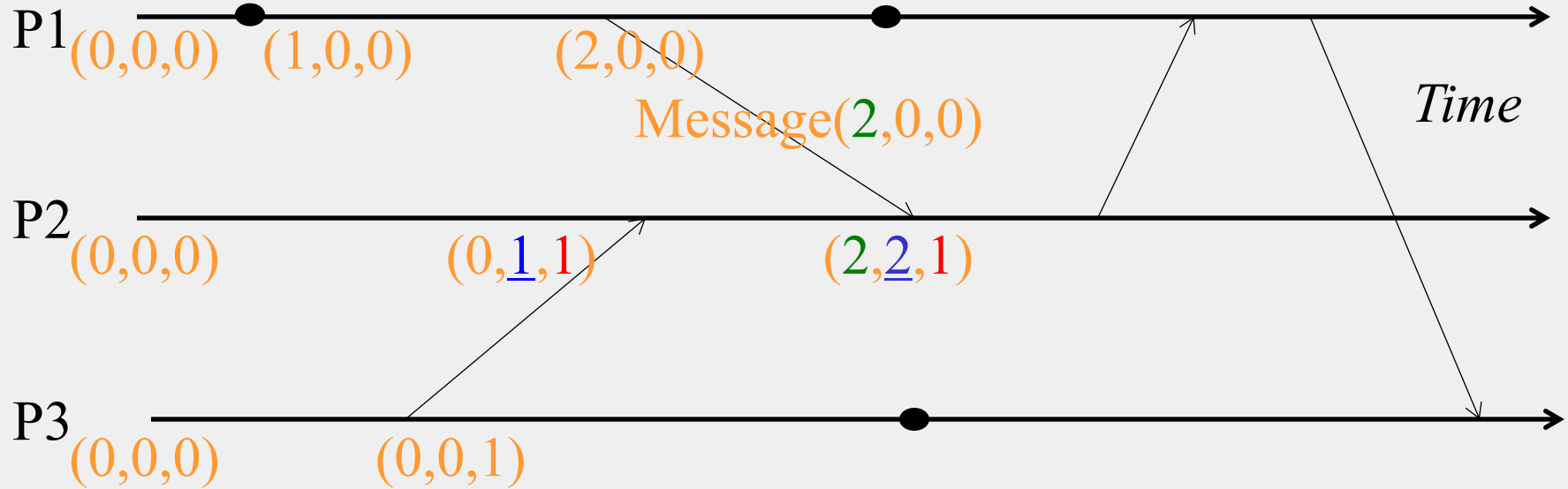
Vector Timestamps



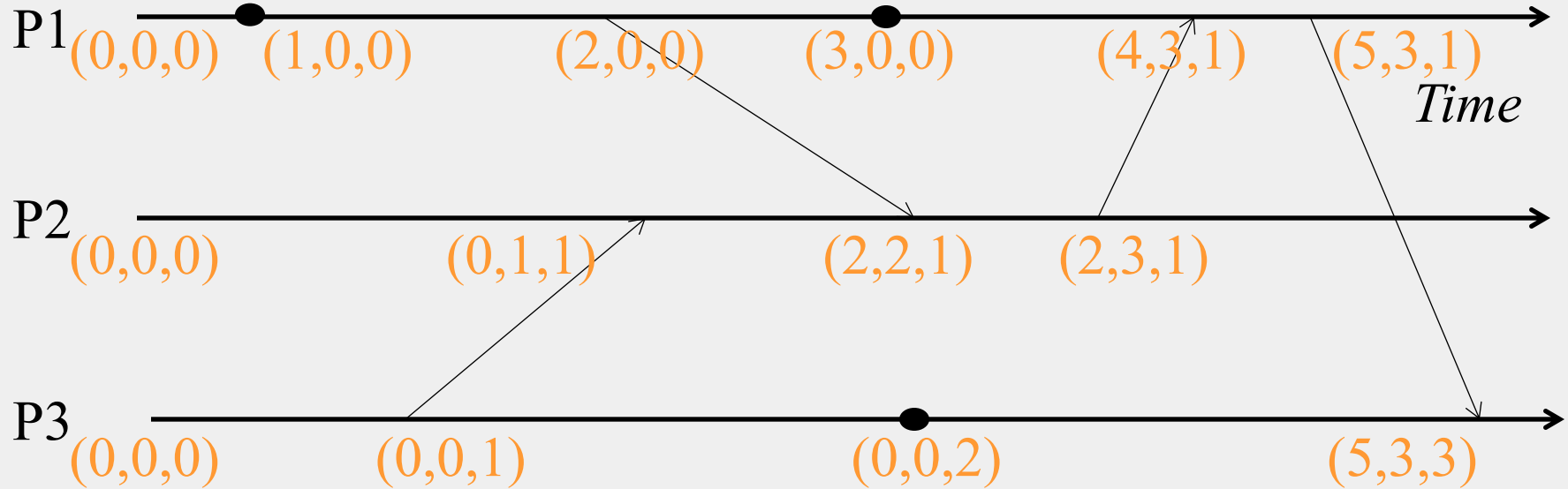
Vector Timestamps



Vector Timestamps



Vector Timestamps



Causally-Related ...

- $VT_1 = VT_2$,
iff (if and only if)
 $VT_1[i] = VT_2[i]$, for all $i = 1, \dots, N$
- $VT_1 \leq VT_2$,
iff $VT_1[i] \leq VT_2[i]$, for all $i = 1, \dots, N$
- Two events are **causally related** *iff*
 $VT_1 < VT_2$, i.e.,
iff $VT_1 \leq VT_2$ &
there exists j such that
 $1 \leq j \leq N$ & $VT_1[j] < VT_2[j]$

... or Not Causally-Related

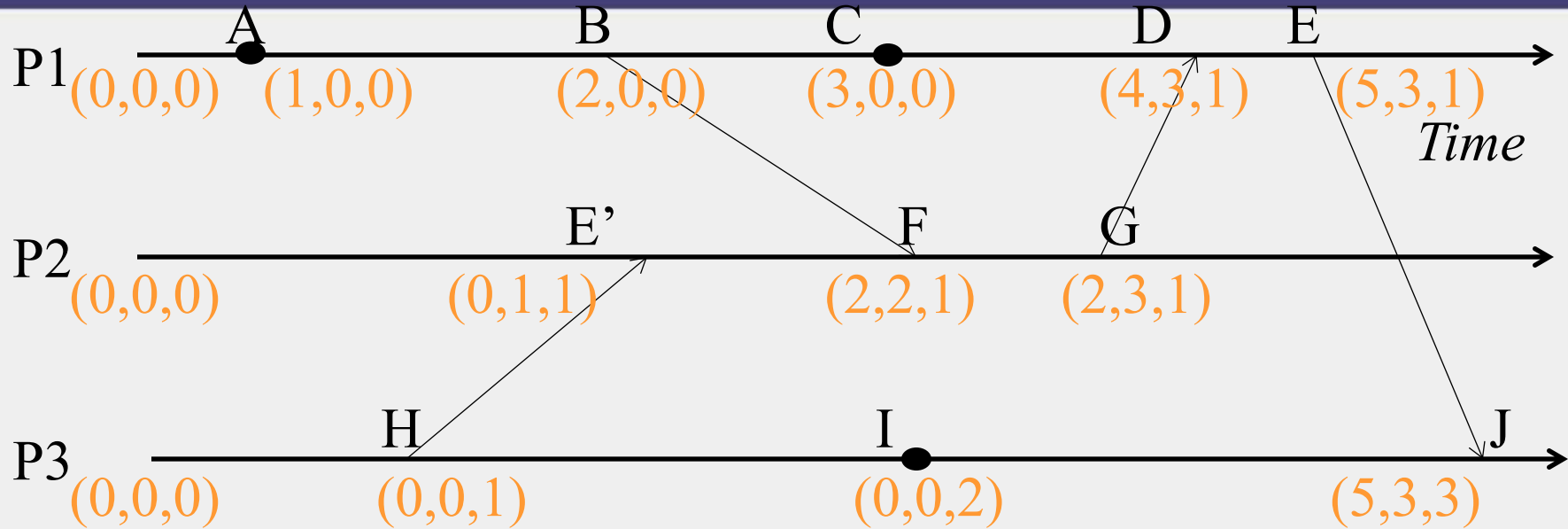
- Two events VT_1 and VT_2 are **concurrent**

iff

NOT ($VT_1 \leq VT_2$) AND NOT ($VT_2 \leq VT_1$)

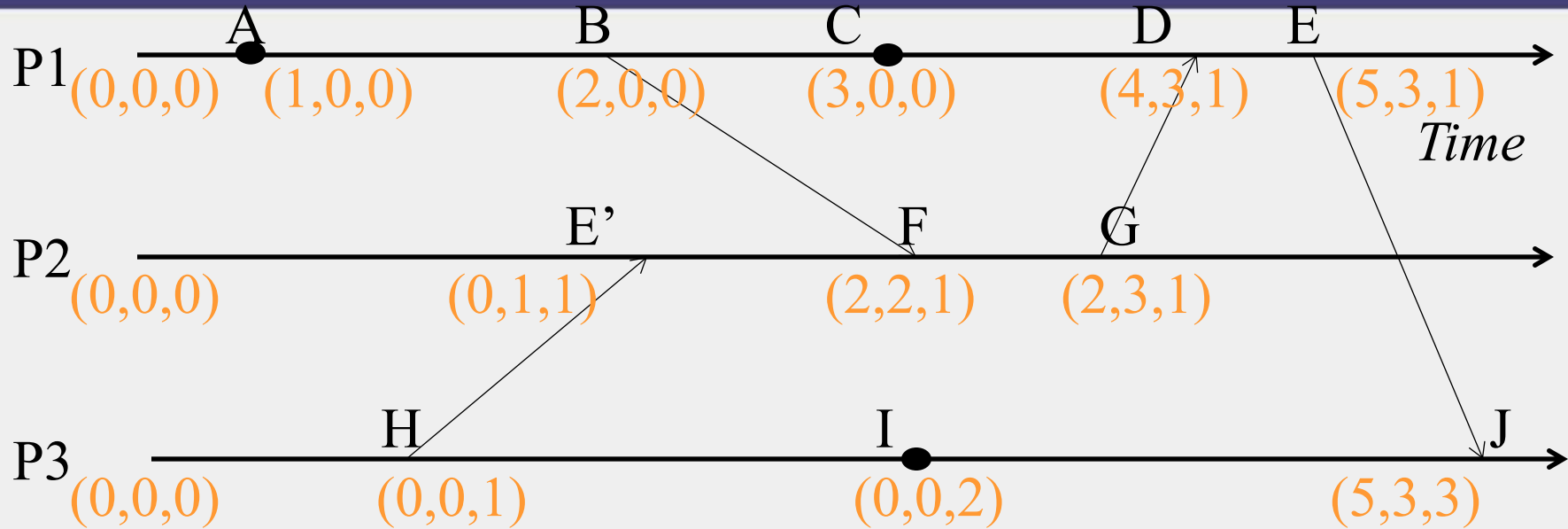
We'll denote this as $VT_2 \parallel VT_1$

Obeying Causality



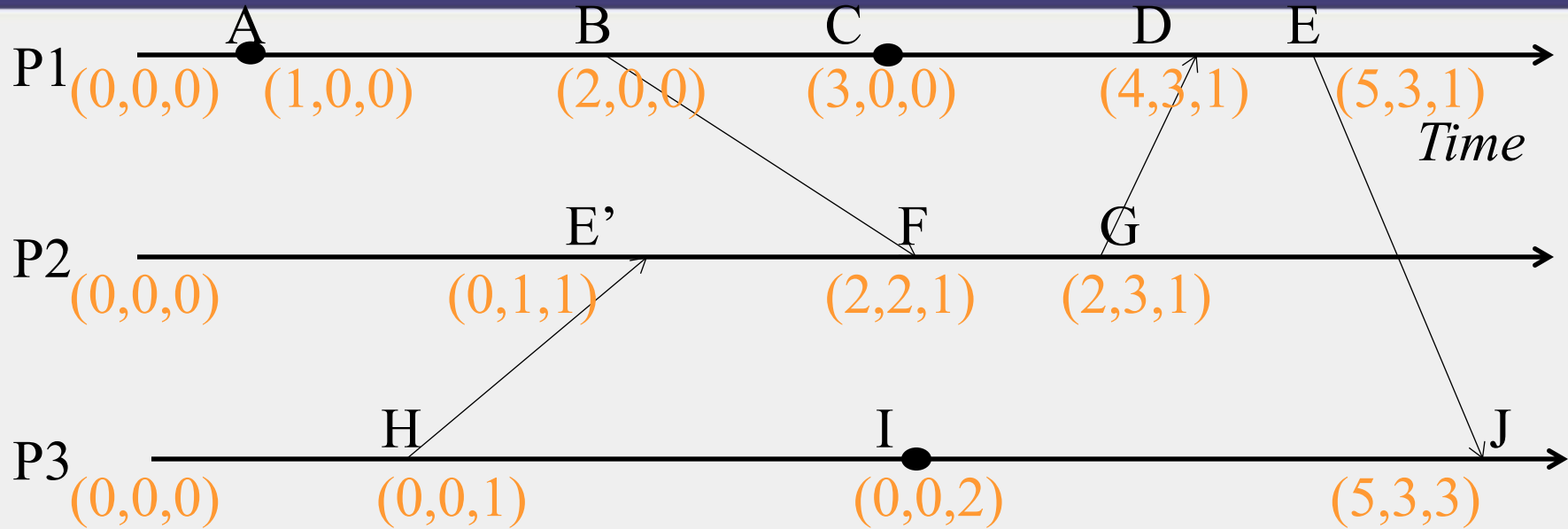
- $A \rightarrow B :: (1,0,0) < (2,0,0)$
- $B \rightarrow F :: (2,0,0) < (2,2,1)$
- $A \rightarrow F :: (1,0,0) < (2,2,1)$

Obeying Causality (2)



- $H \rightarrow G :: (0,0,1) < (2,3,1)$
- $F \rightarrow J :: (2,2,1) < (5,3,3)$
- $H \rightarrow J :: (0,0,1) < (5,3,3)$
- $C \rightarrow J :: (3,0,0) < (5,3,3)$

Identifying Concurrent Events



- C & F :: $(\underline{3},0,0) \parallel (2,2,\underline{1})$
- H & C :: $(0,0,\underline{1}) \parallel (\underline{3},0,0)$
- (C, F) and (H, C) are pairs of concurrent events

Logical Timestamps: Summary

- **Lamport timestamps**
 - Integer clocks assigned to events
 - Obeys causality
 - Cannot distinguish concurrent events
- **Vector timestamps**
 - Obey causality
 - By using more space, can also identify concurrent events

Time and Ordering: Summary

- **Clocks are unsynchronized in an asynchronous distributed system**
- **But need to order events, across processes!**
- **Time synchronization**
 - Cristian's algorithm
 - NTP
 - Berkeley algorithm
 - But error a function of round-trip-time
- **Can avoid time sync altogether by instead assigning logical timestamps to events**

Announcements

- Midterm
- Regrade requests : submit within 1 week of receiving back graded HW/exam/MP report