# CS 425 / ECE 428
# Distributed Systems
# Fall 2018

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*Lecture 12: Time and Ordering*

# 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 * MDR
- Given a maximum acceptable skew M between any pair of clocks, need to synchronize at least once every: M / (2 * 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 => Internal Synchronization with 2*D**

- **Internal Synchronization does not imply External Synchronization**
  - In fact, the entire system may drift away from the external clock S!

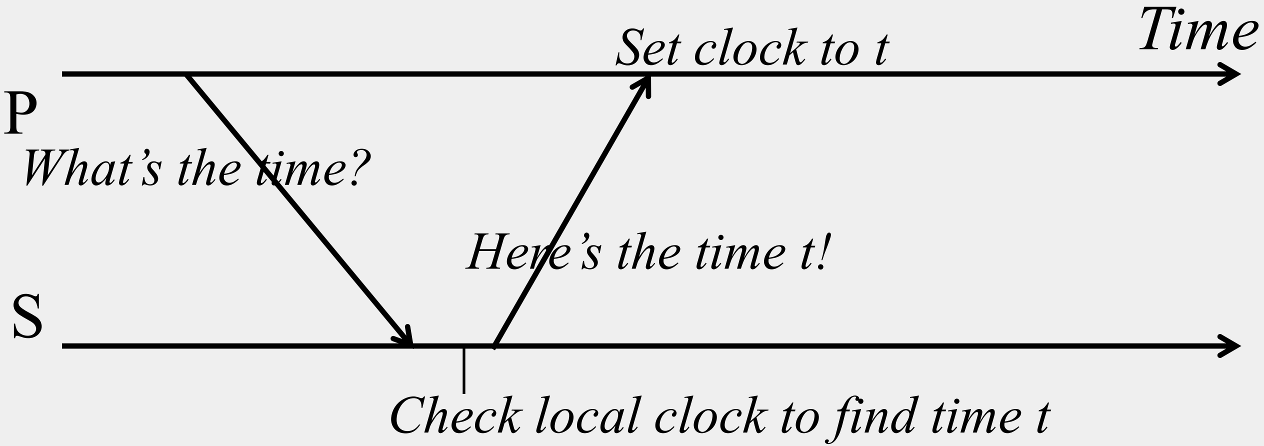
# Next

- Algorithms for Clock Synchronization

# Cristian’s Algorithm

# Basics

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

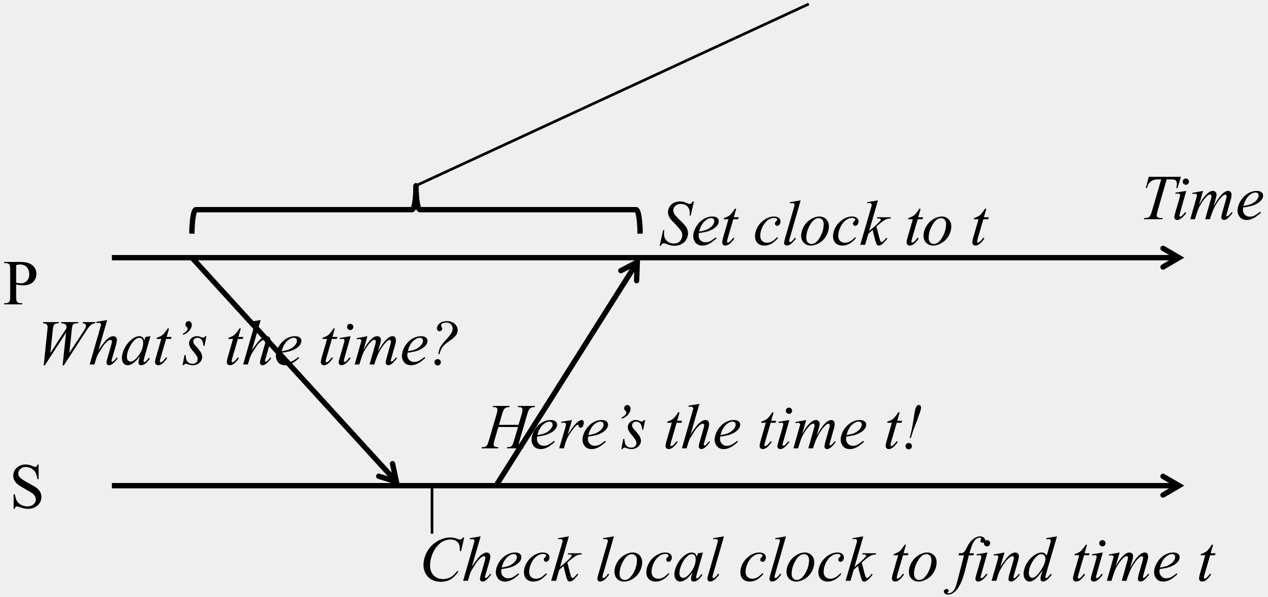


# What’s Wrong

- 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

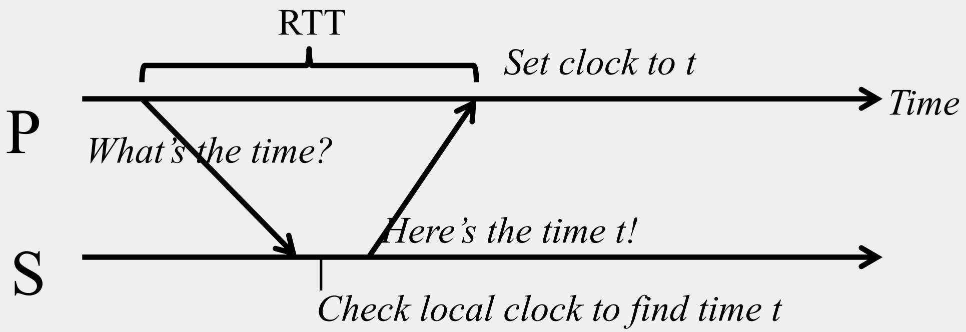
# Cristian's Algorithm

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



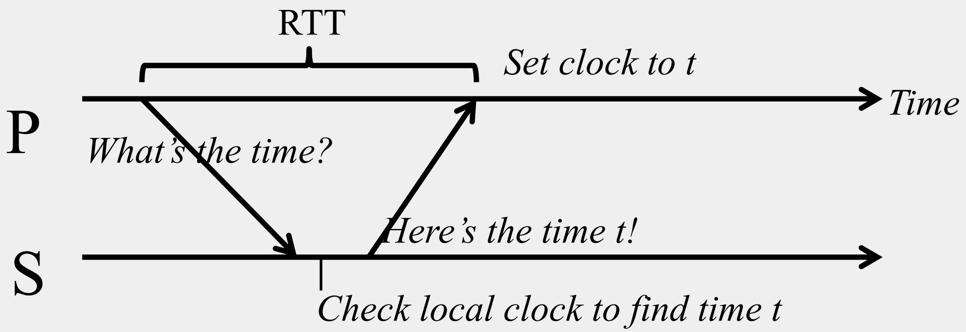
# Cristian's Algorithm (2)

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



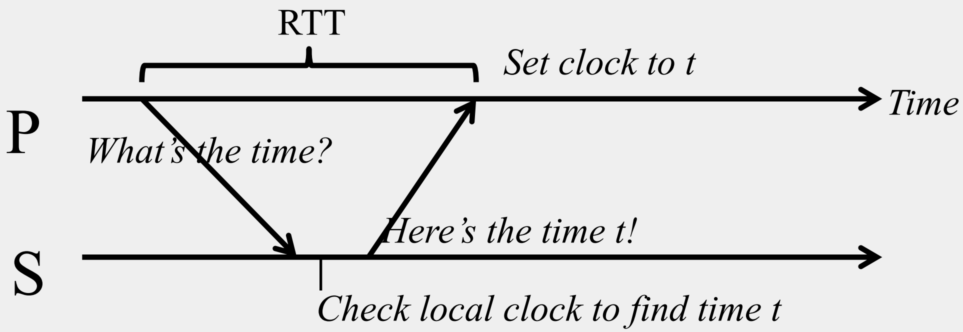
# Cristian's Algorithm (3)

- P measures the round-trip-time RTT of message exchange
- Suppose we know the minimum P → S latency min1
- And the minimum S → 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+min2, t+RTT-min1]



# Cristian's Algorithm (4)

- The actual time at P when it receives response is between [t+min2, t+RTT-min1]
- P sets its time to halfway through this interval
  - To: t + (RTT+min2-min1)/2
- Error is at most (RTT-min2-min1)/2
  - Bounded!



# Gotchas

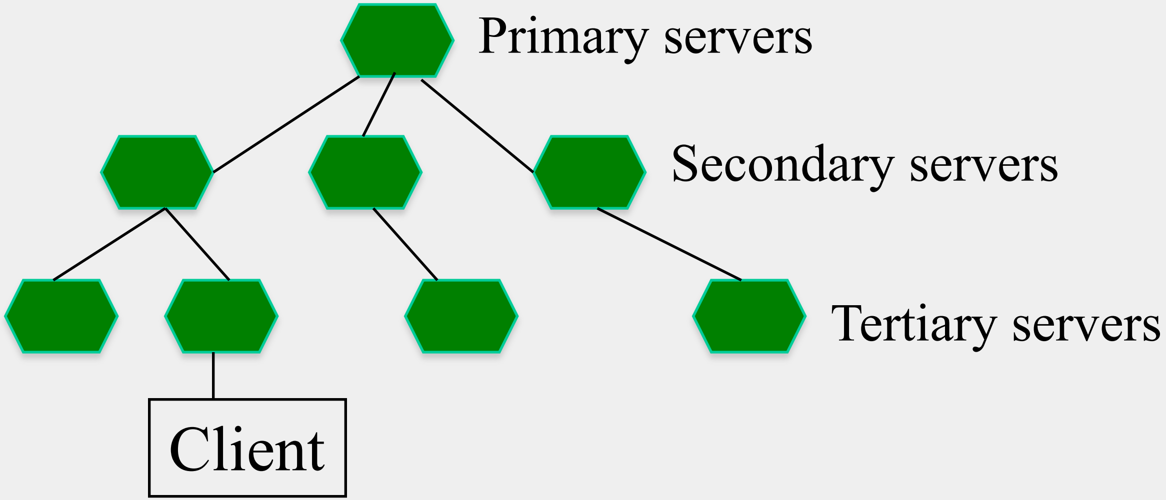
- **Allowed to increase clock value but should never decrease clock value**
  - May violate ordering of events within the same process

- **Allowed to increase or decrease speed of clock**

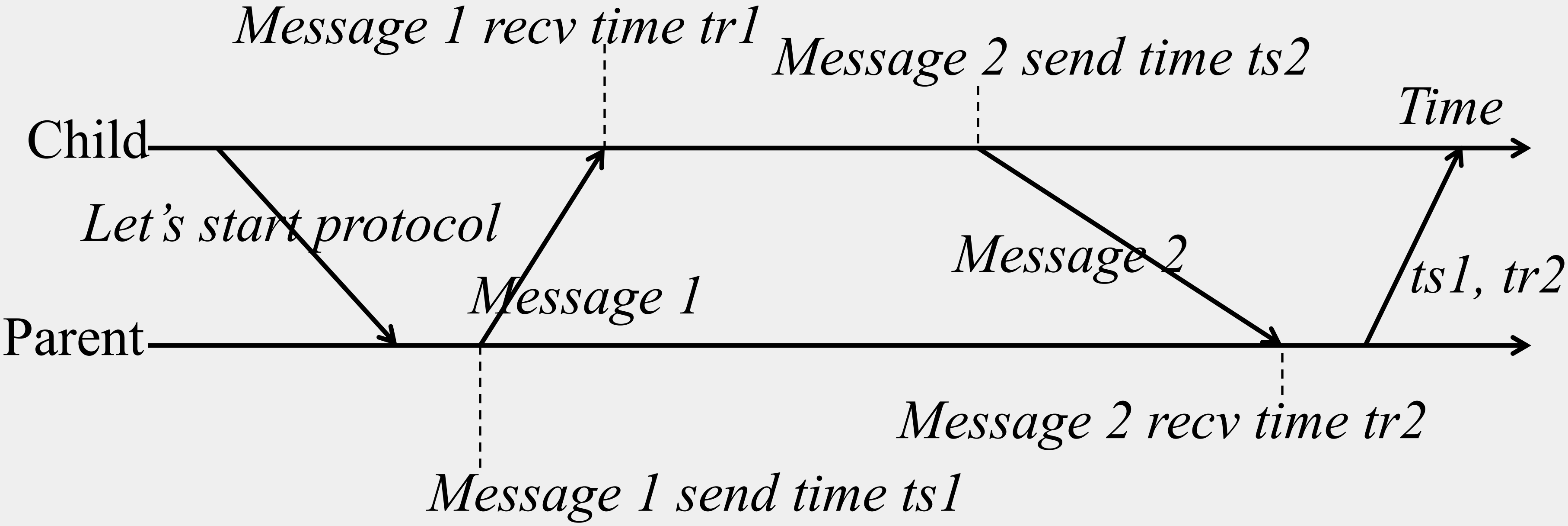
- **If error is too high, take multiple readings and average them**

# 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**

  $tr1 = ts1 + L1 + oreal$

  $tr2 = ts2 + L2 - oreal$

- **Subtracting second equation from the first**

  $oreal = (tr1 - tr2 + ts2 - ts1)/2 + (L2 - L1)/2$

  $\Rightarrow oreal = o + (L2 - L1)/2$

  $\Rightarrow |oreal - o| < |(L2 - L1)/2| < |(L2 + L1)/2|$

  – 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 timestamp(A) < 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

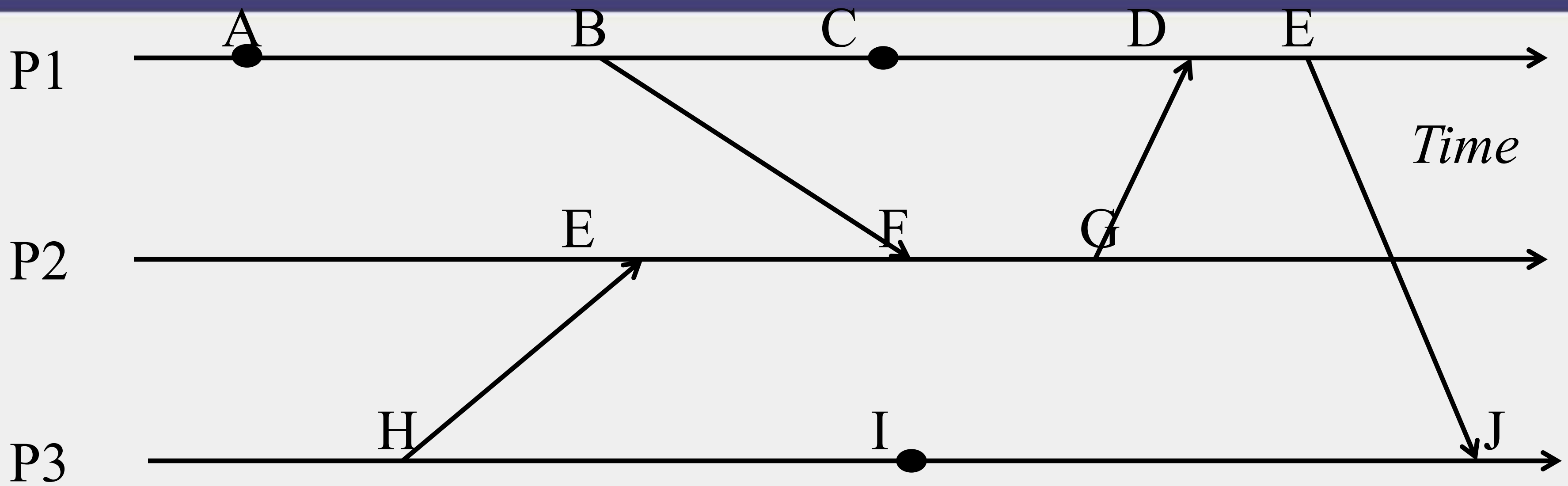
# Logical (or Lamport) Ordering(2)

- 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

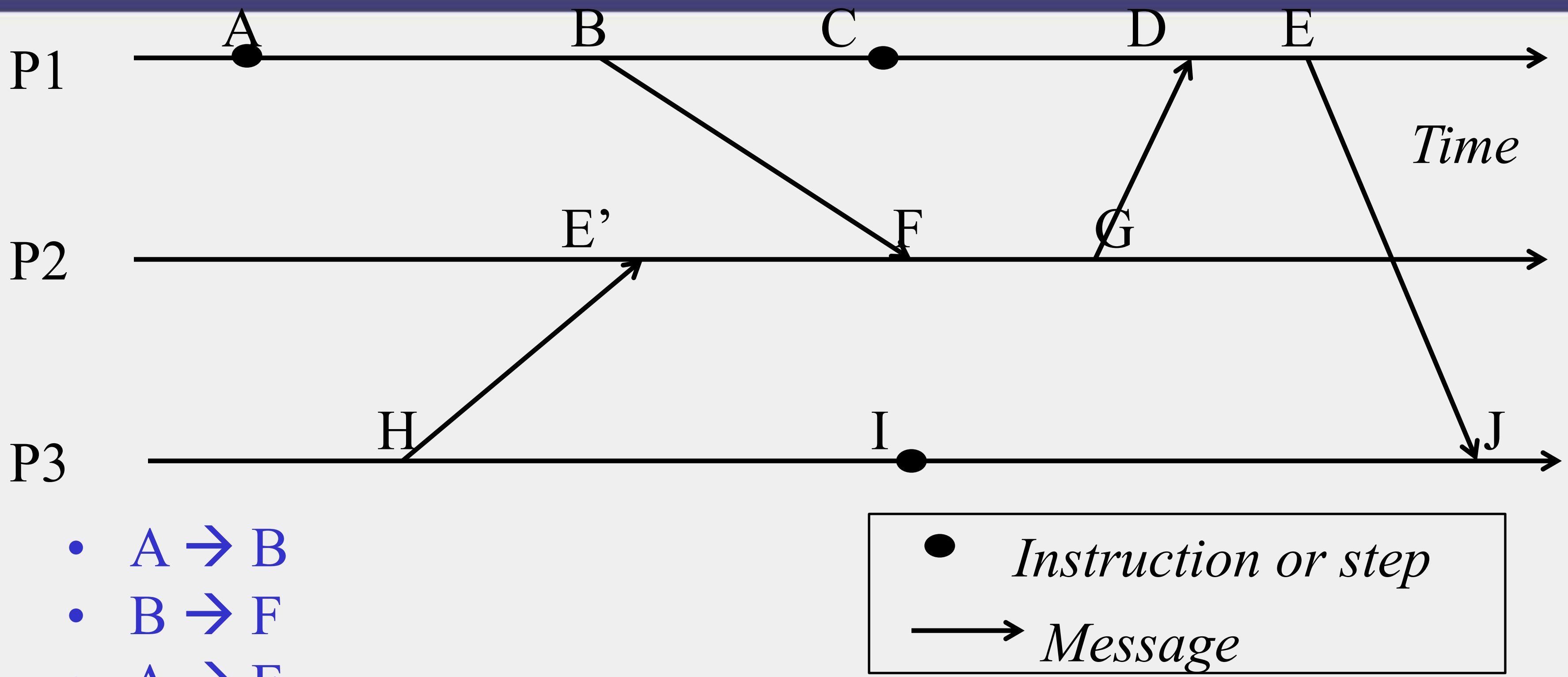



While P1 and P3 each have an event labeled E, these are different events as they occur at different processes.

● *Instruction or step*

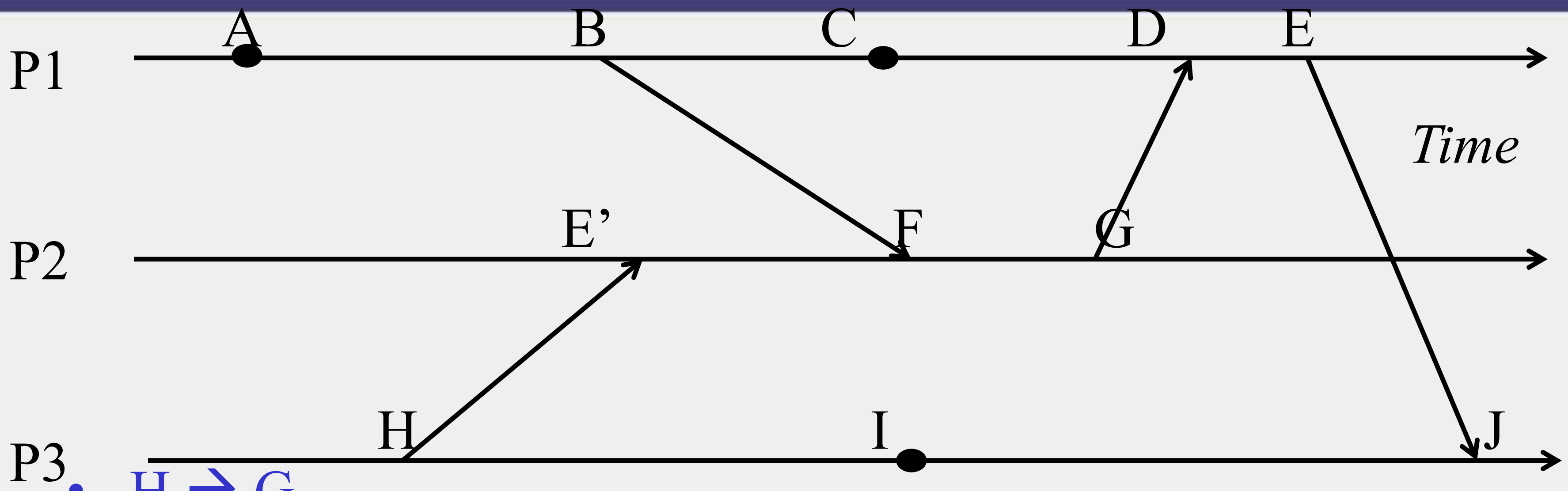
→ *Message*

# Happens-Before

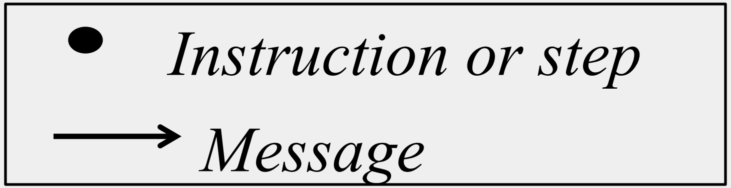



- A → B
- B → F
- A → F

# Happens-Before (2)




- H → G
- F → J
- H → J
- C → J

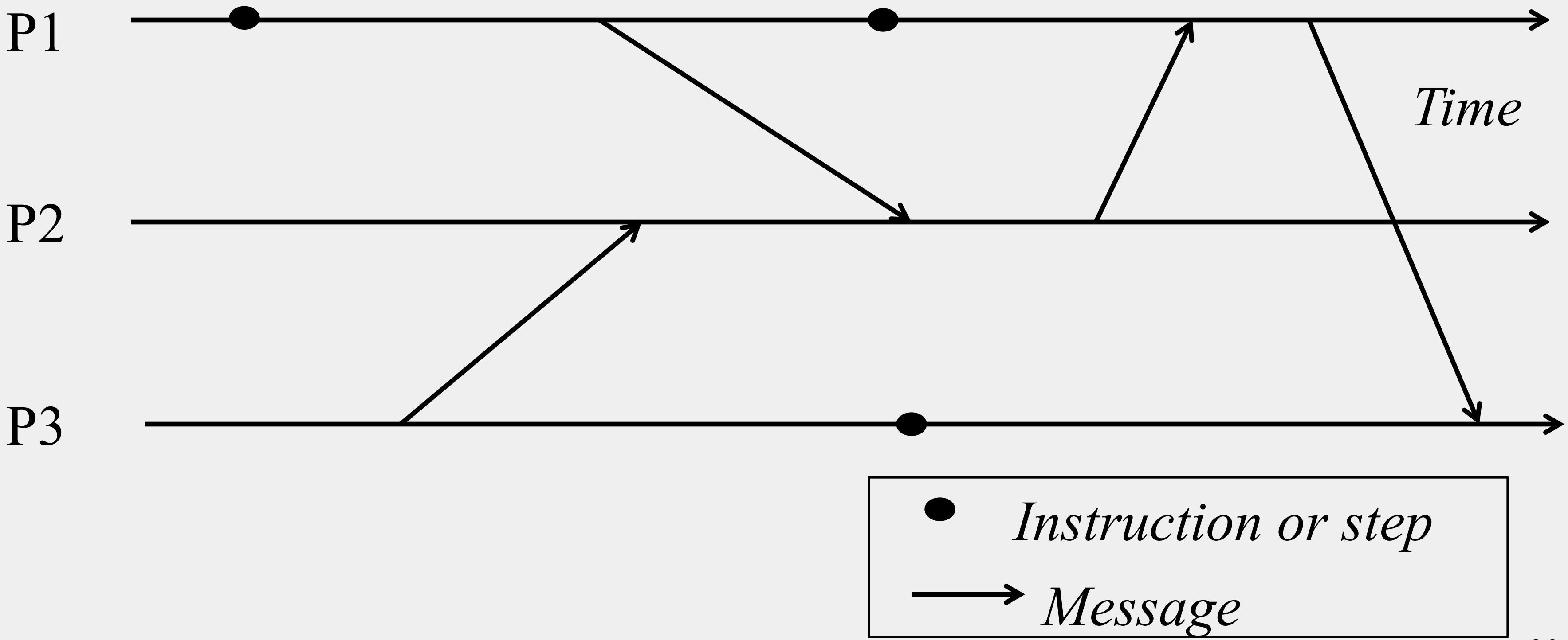


# In practice: Lamport timestamps

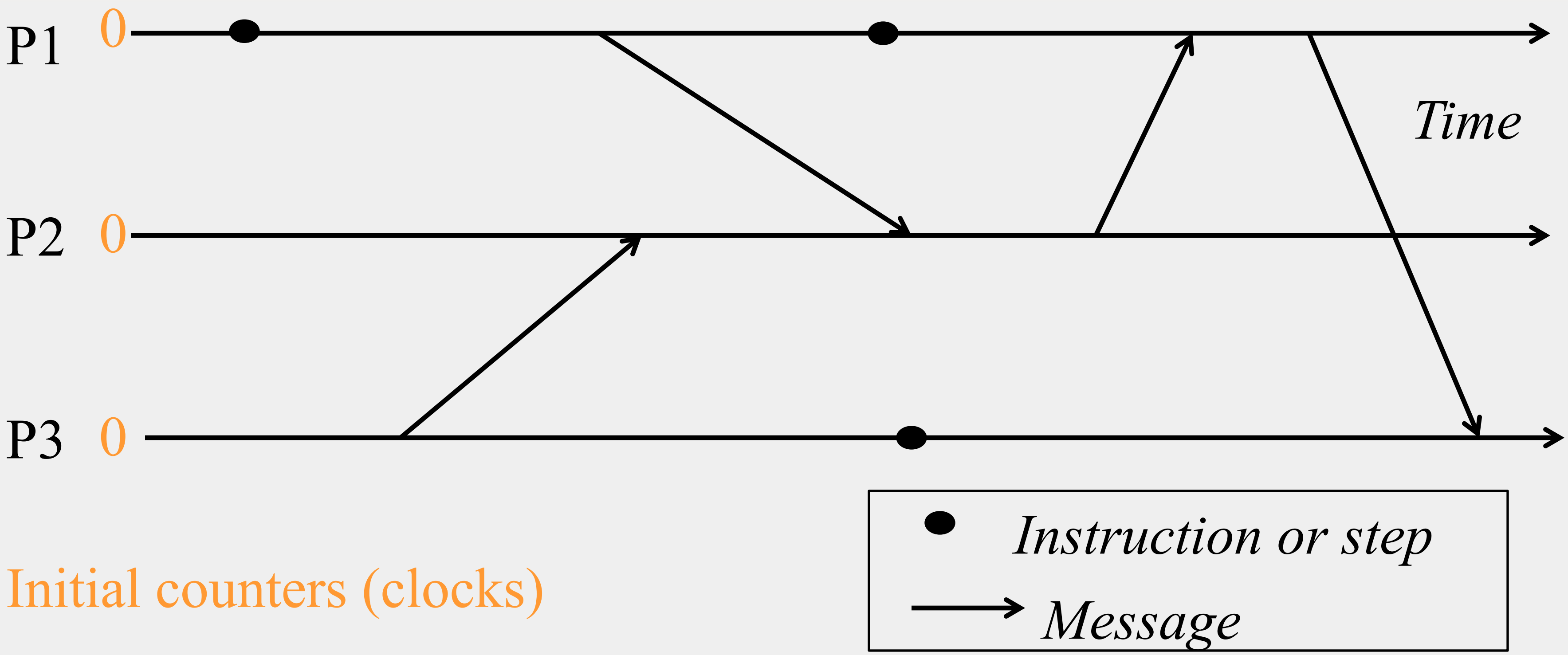
- **Goal: Assign logical (Lamport) timestamp to each event**
- **Timestamps obey causality**
- **Rules**
  - Each process uses a local counter (clock) which is an integer
    - initial value of counter is zero
  - A process increments its counter when a send or an instruction happens at it. The counter 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

$$\max(\text{local clock}, \text{message timestamp}) + 1$$

# Example

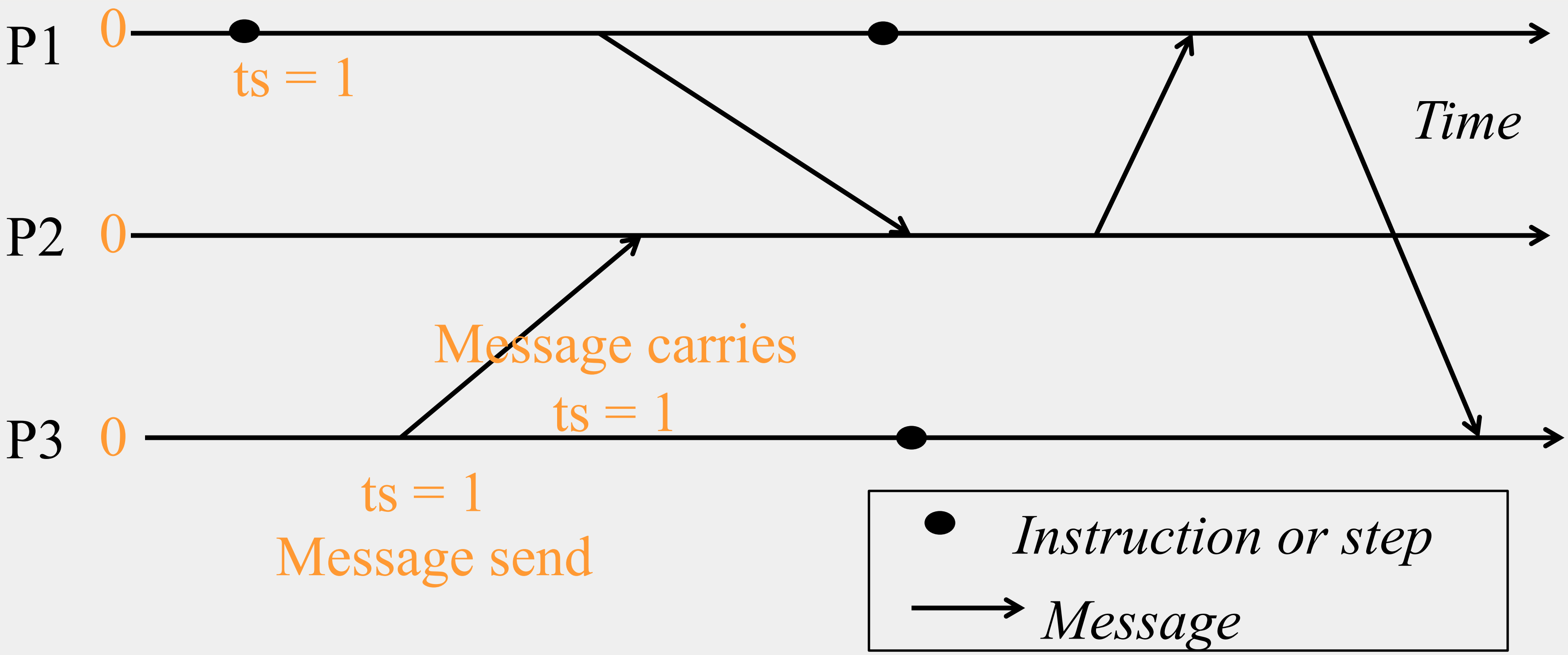


# Lamport Timestamps




Initial counters (clocks)

# Lamport Timestamps



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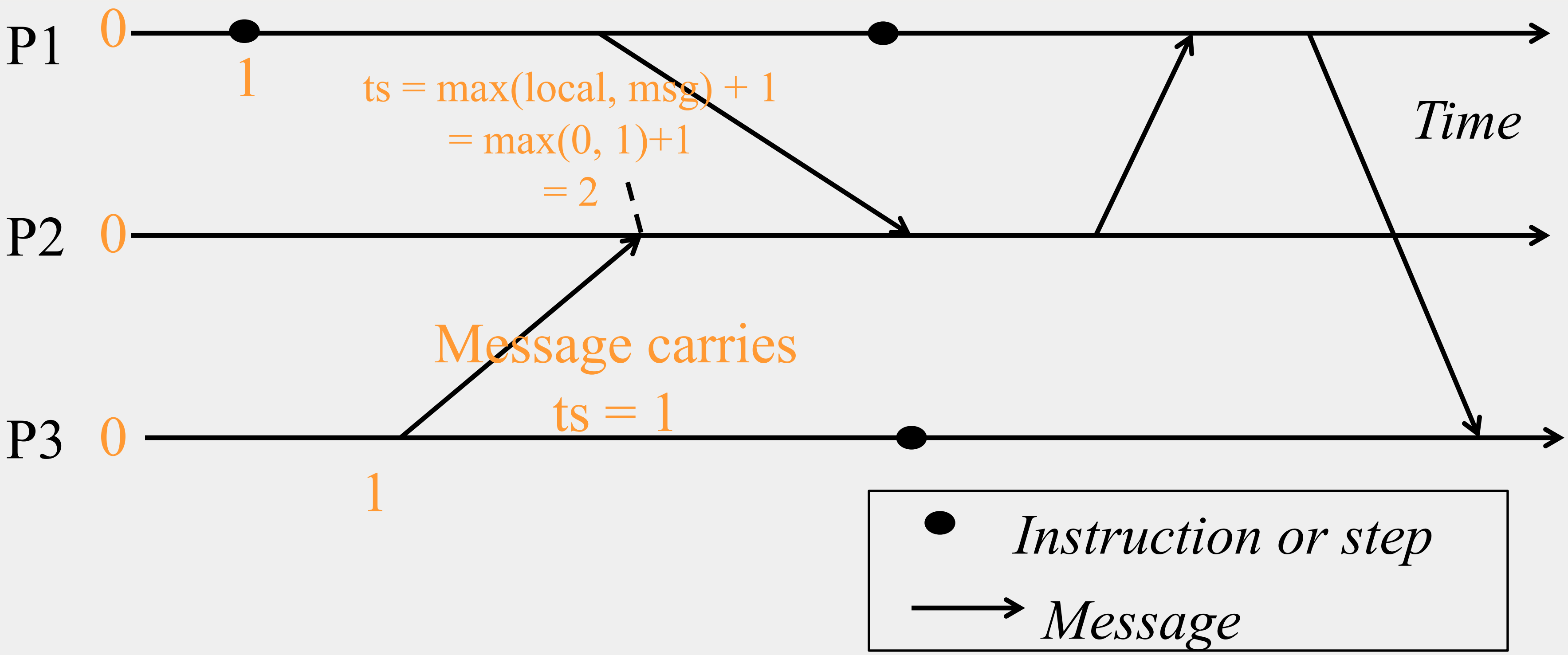

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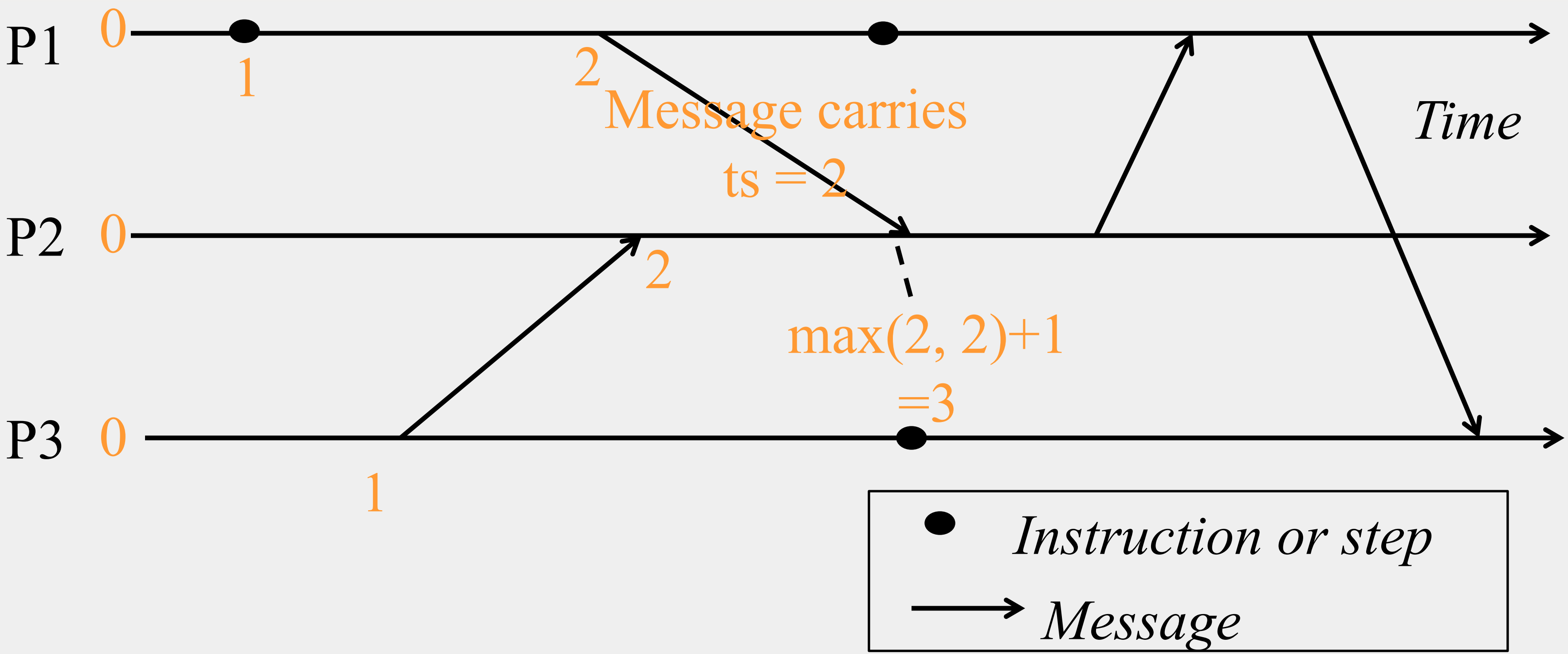

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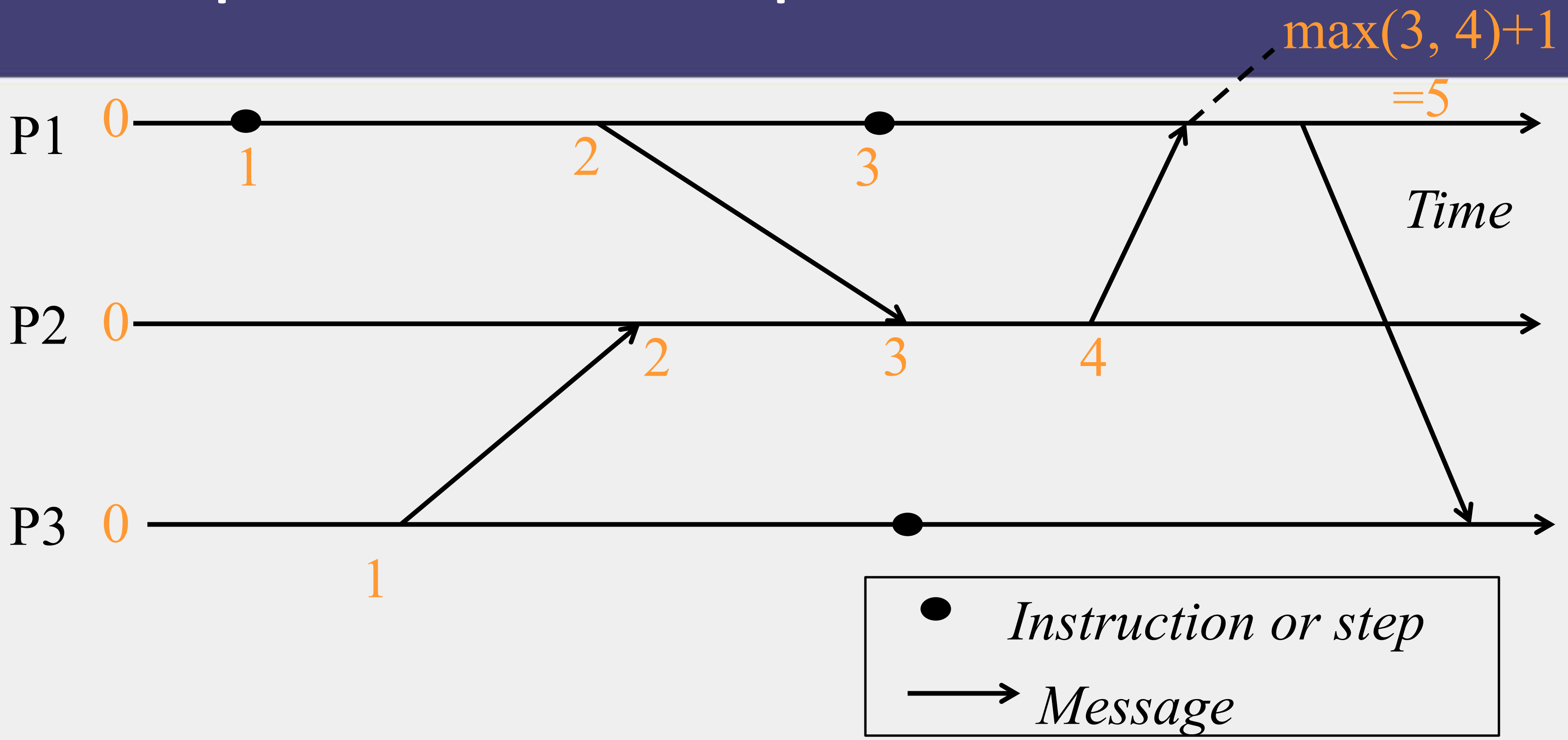

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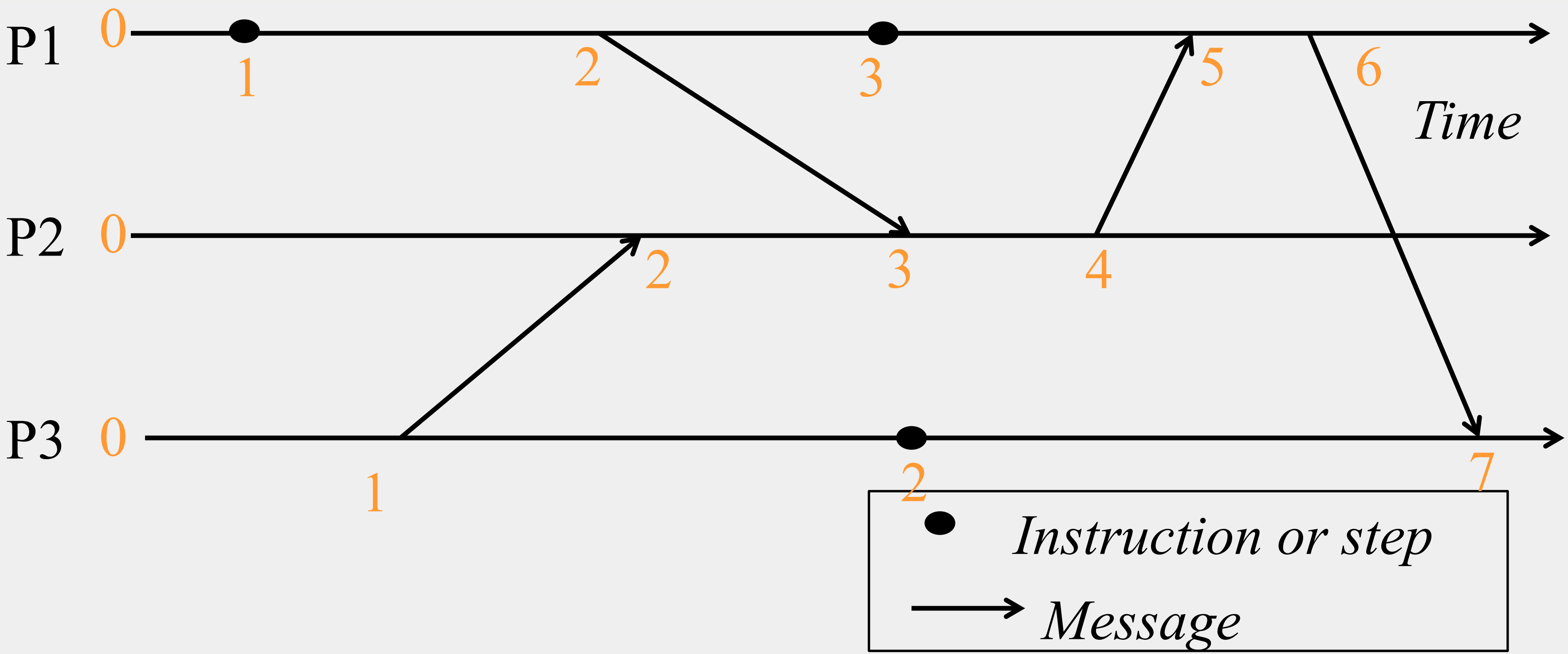
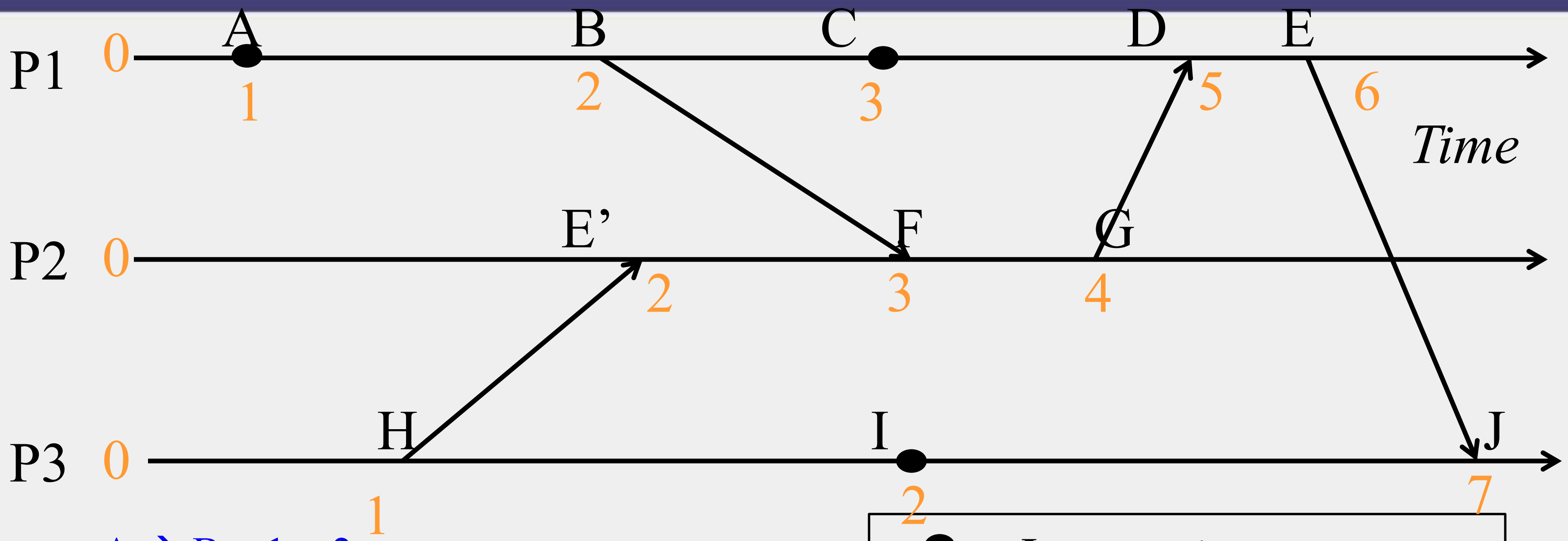
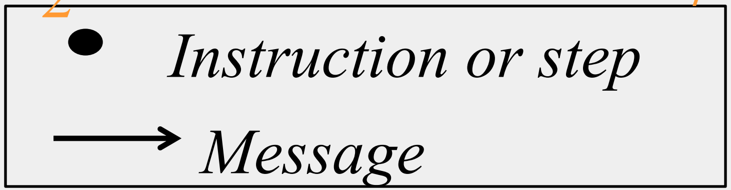


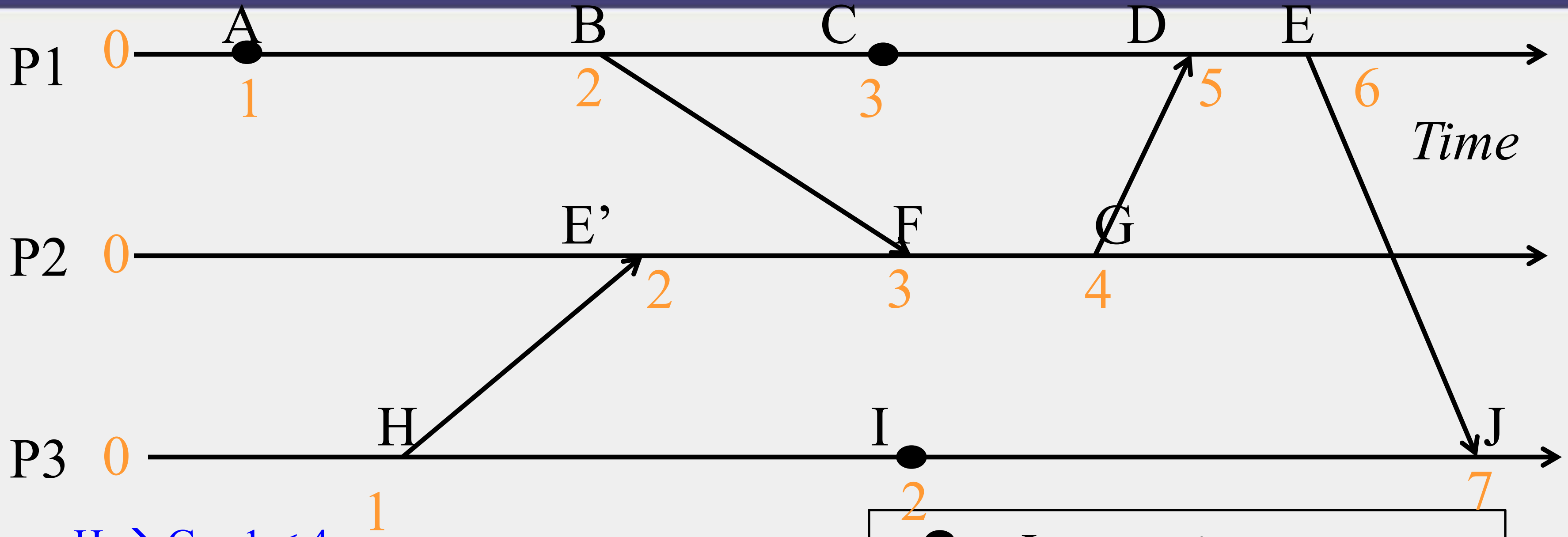
# Obeying Causality

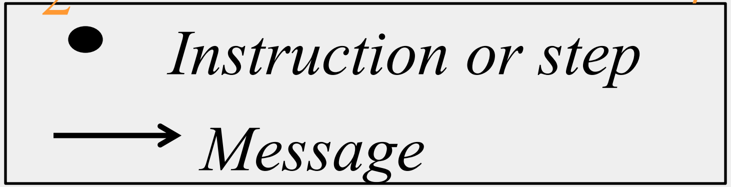



- A → B :: 1 < 2
- B → F :: 2 < 3
- A → F :: 1 < 3



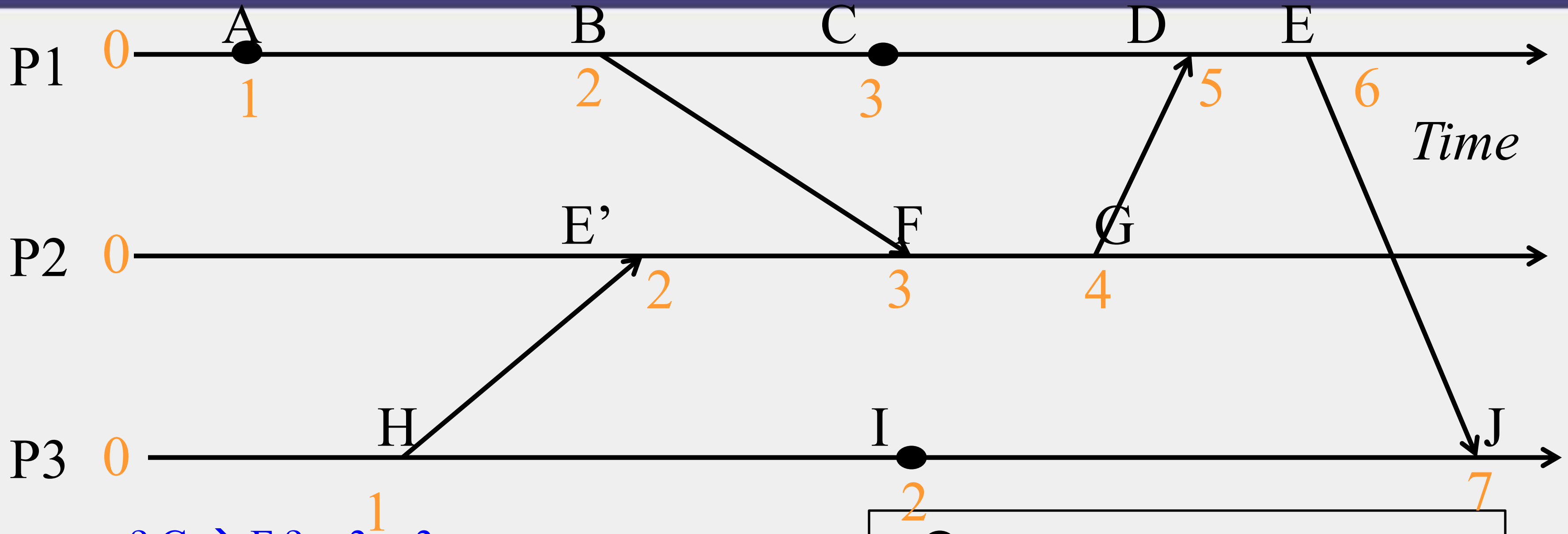
# Obeying Causality (2)

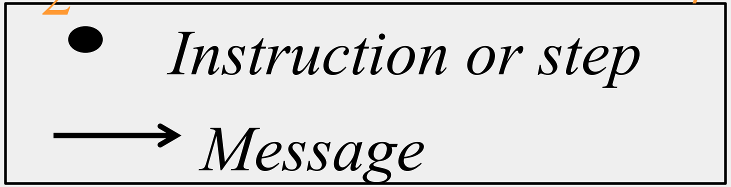



- H → G :: 1 < 4
- F → J :: 3 < 7
- H → J :: 1 < 7
- C → J :: 3 < 7

# Not always *implying* Causality




- ? C → F ? :: 3 = 3
- ? H → 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 → E2 ⇒ timestamp(E1) < timestamp (E2), BUT

timestamp(E1) < timestamp (E2) ⇒

{E1 → E2} OR {E1 and E2 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…N
- Each vector has N elements
- Process *i maintains vector* $\mathbf{V}_i[\mathit{1}\ldots\mathit{N}]$
- *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

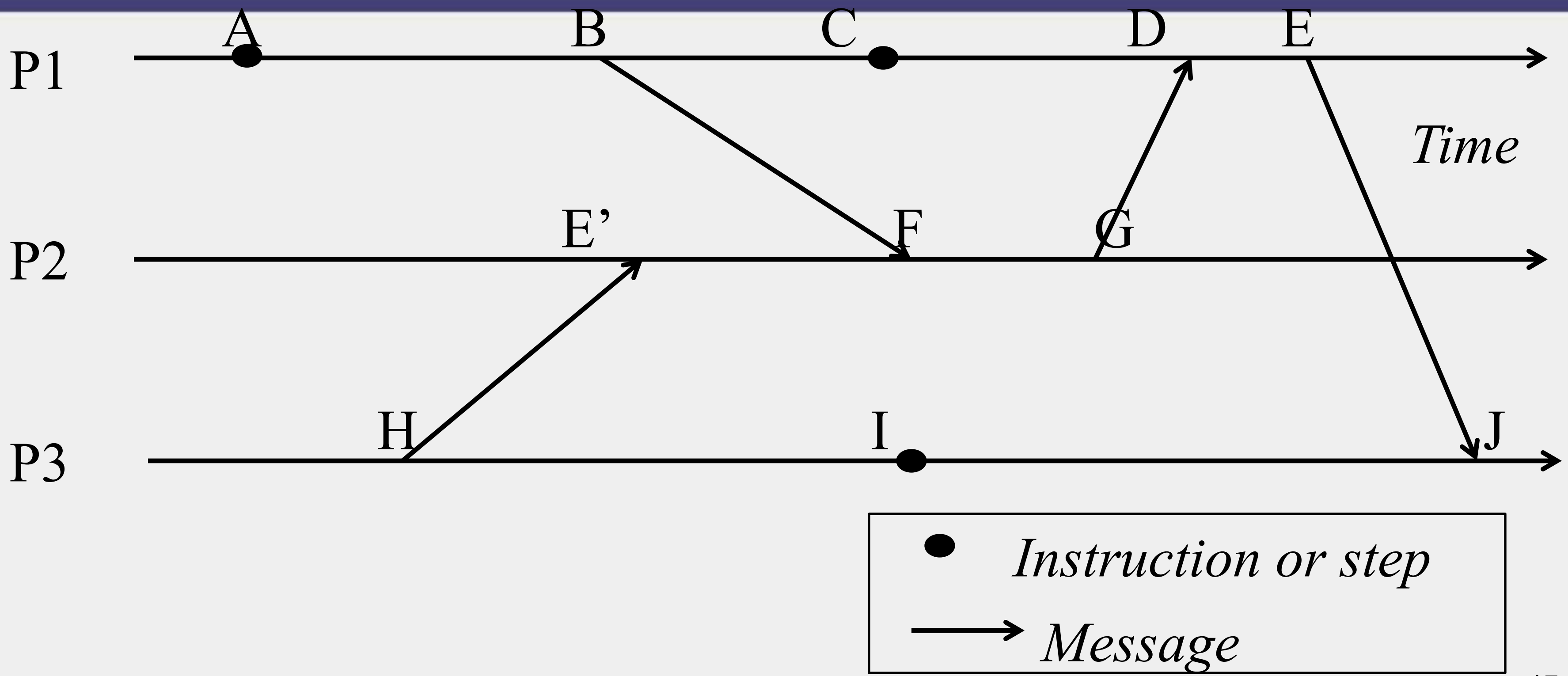
- Incrementing vector clocks

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 $V_{message}[1 \ldots N]$
3. On receiving a message at process *i*:

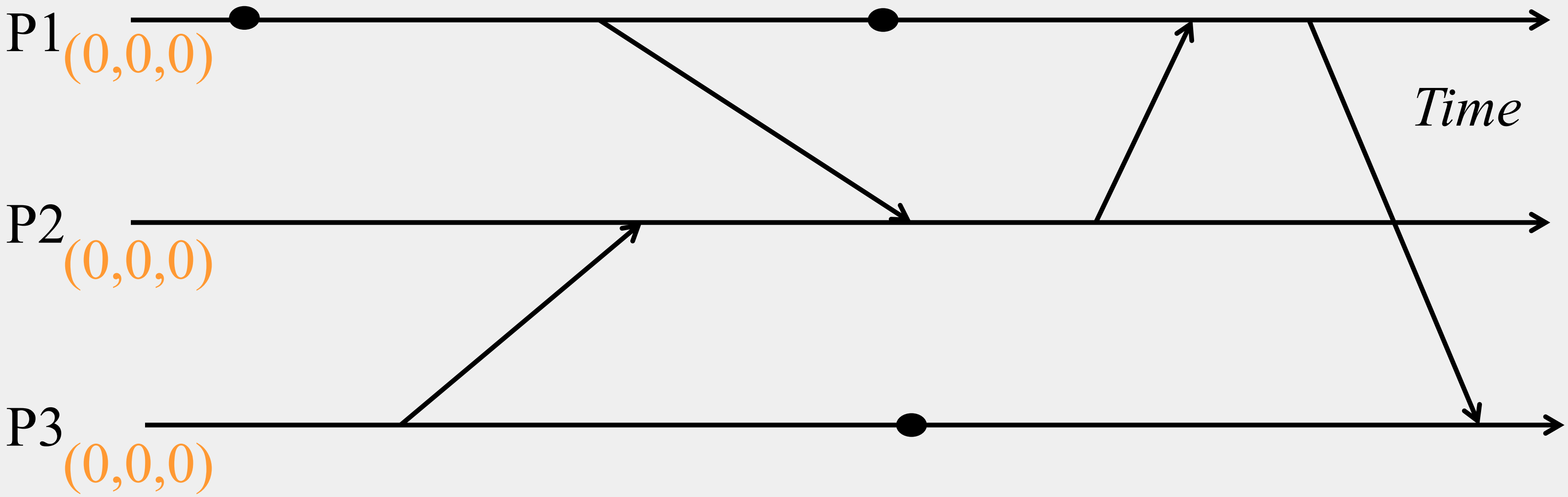
   $$V_i[i] = V_i[i] + 1$$

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

# Example

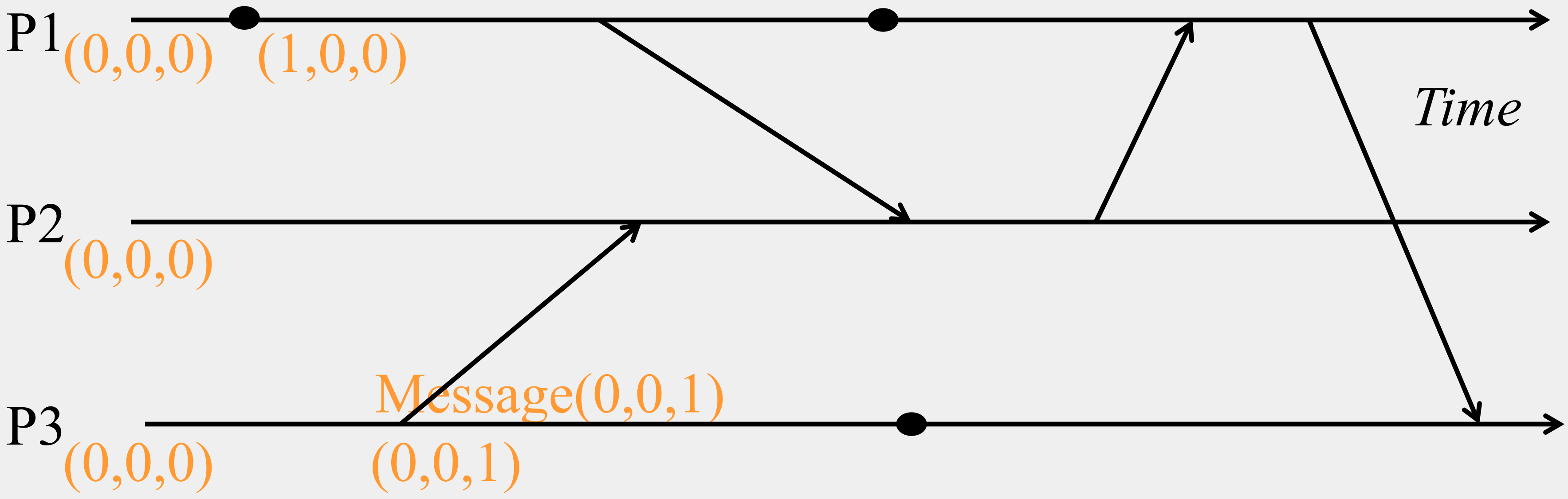


# Vector Timestamps




Initial counters (clocks)

# Vector Timestamps



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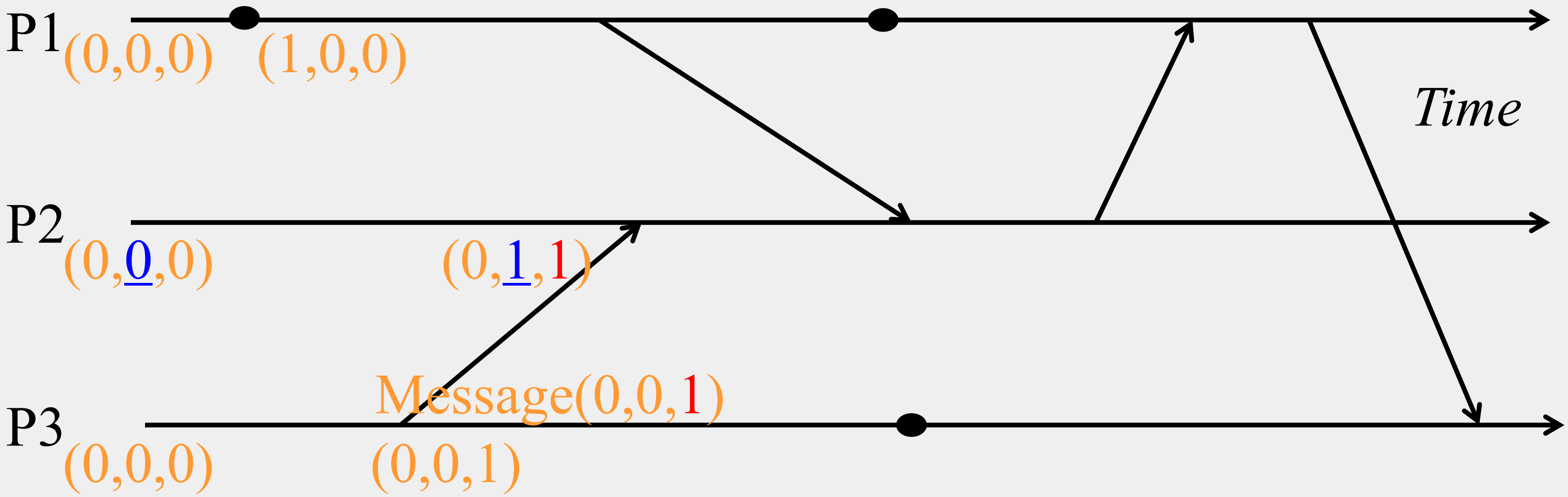

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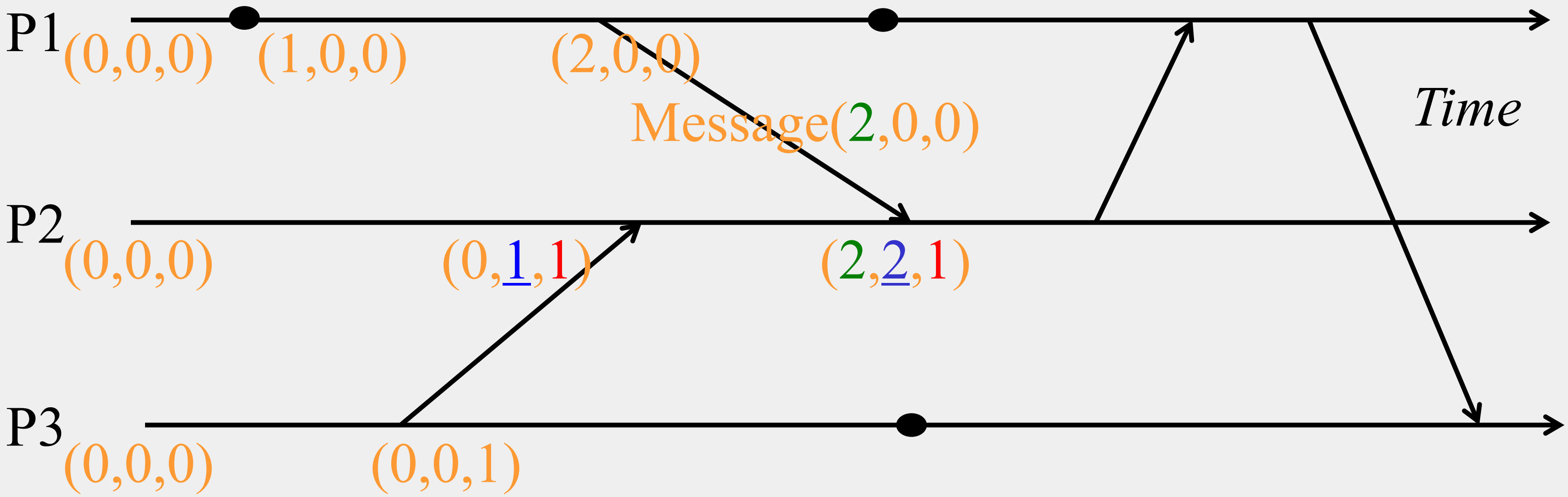

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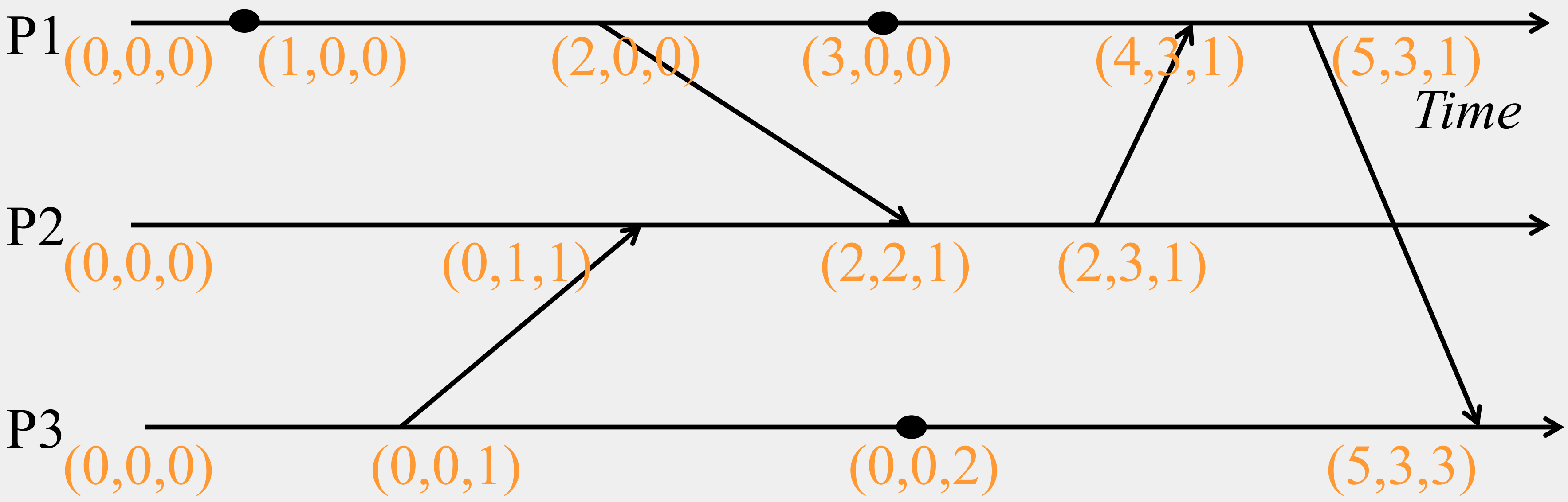


# Causally-Related …

- $VT_1 = VT_2$,

  *iff* (if and only if)

  $VT_1[i] = VT_2[i]$, for all $i = 1, \ldots, N$

- $VT_1 \leq VT_2$,

  *iff* $VT_1[i] \leq VT_2[i]$, for all $i = 1, \ldots, N$

- Two events are causally related *iff*

  $VT_1 < VT_2$, i.e.,

  *iff* $VT_1 \leq VT_2$ &

  there exists $j$ such that

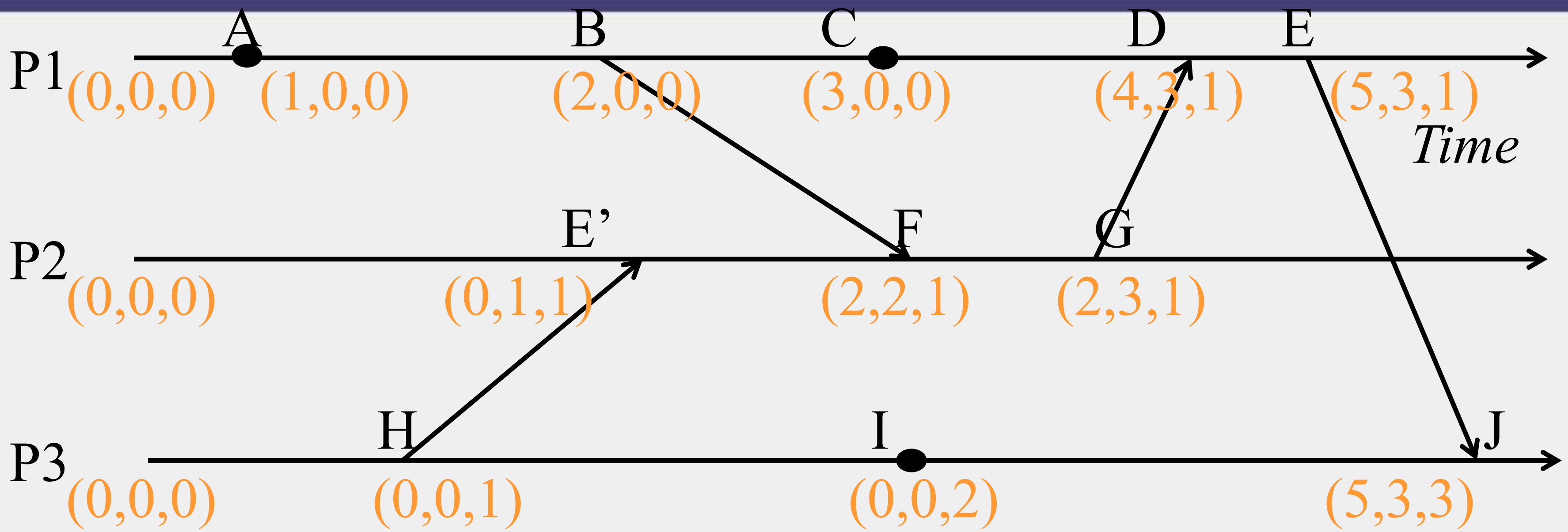
  $1 \leq j \leq N$ & $VT_1[j] < VT_2[j]$

# … or Not Causally-Related

- Two events $VT_1$ and $VT_2$ are concurrent
  *iff*
  NOT ($VT_1 \leq VT_2$) AND NOT ($VT_2 \leq VT_1$)

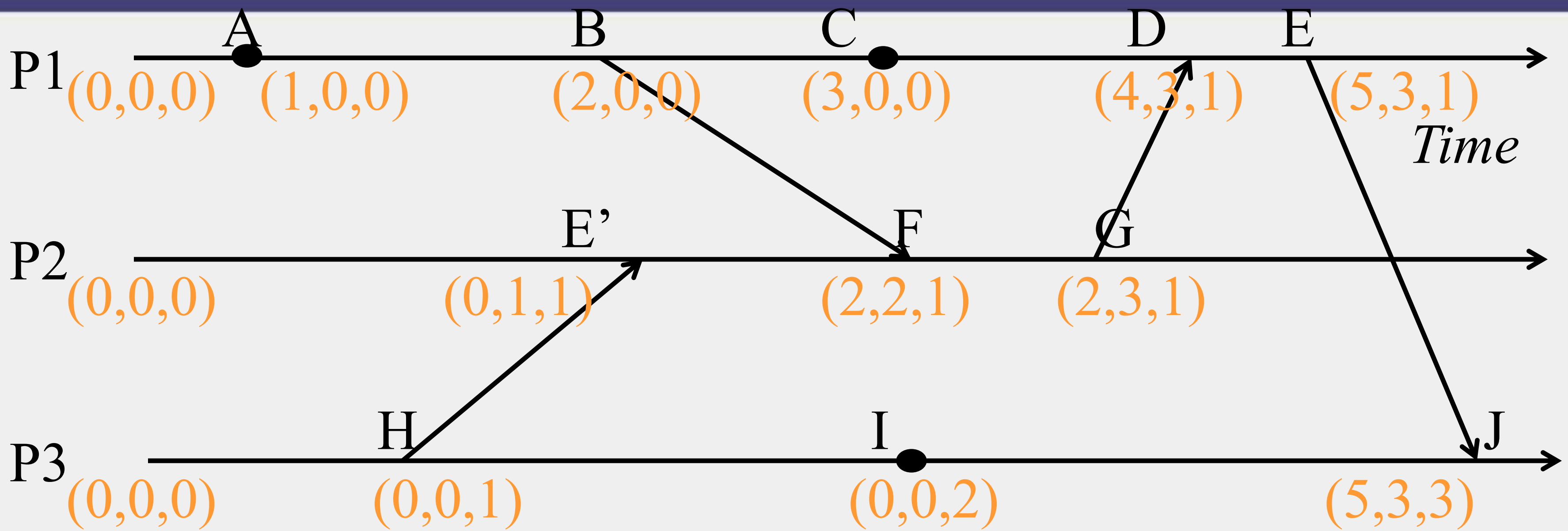
  We'll denote this as $VT_2 \ ||| \ VT_1$

# Obeying Causality



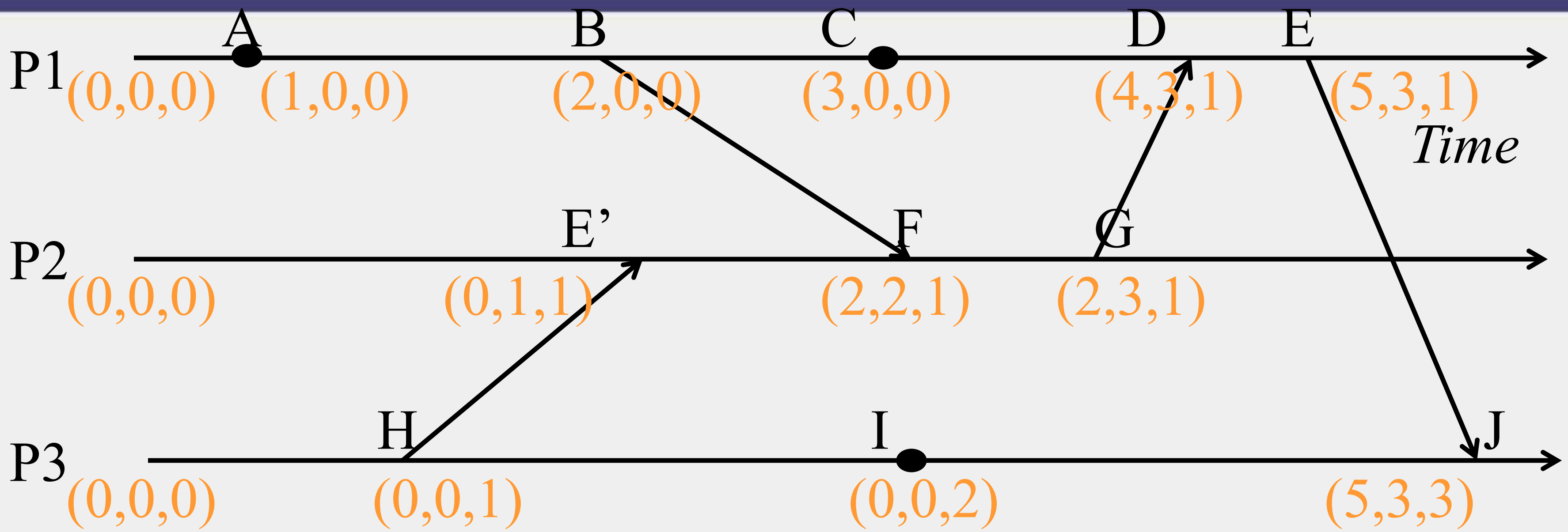

- A → B :: (1,0,0) < (2,0,0)
- B → F :: (2,0,0) < (2,2,1)
- A → F :: (1,0,0) < (2,2,1)

# Obeying Causality (2)




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

# Identifying Concurrent Events




- C & F :: (<u>3</u>,0,0) ||| (2,2,<u>1</u>)
- H & C :: (0,0,<u>1</u>) ||| (<u>3</u>,0,0)
- (C, F) and (H, C) are pairs of <u>*concurrent*</u> 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**

# Reminders

- (4 cr students) MP2 due this Sunday, Demos on Monday
  - Signup sheet (soon) on Piazza
- (All) HW2 due next Tuesday
- Practice Midterm has been released