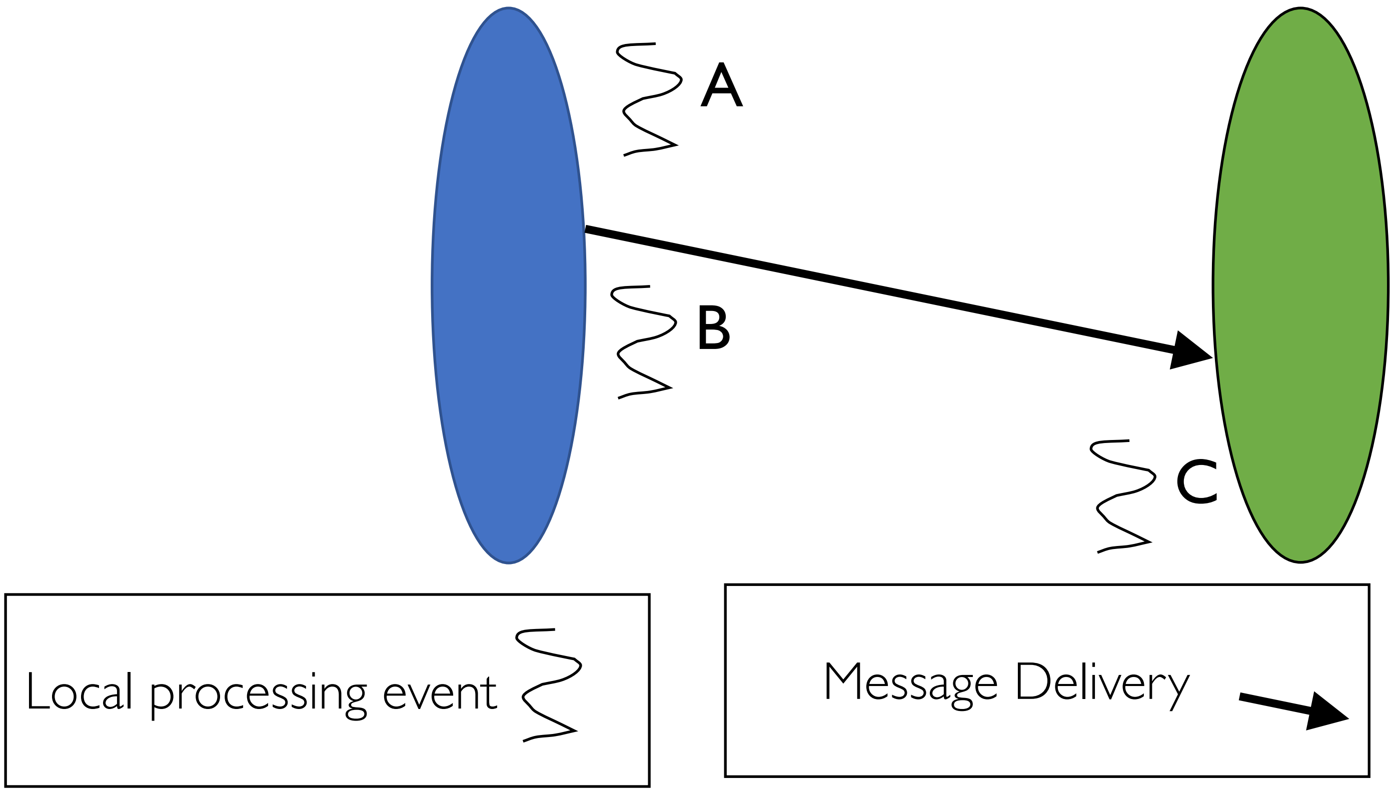
Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

While we wait…



- Can we conclude that event A occurred before event C?
- Can we conclude that event B occurred before event C?

The clocks of blue and green processes cannot be perfectly synchronized. Can we simply compare timestamps of these events?

Logistics Related

- VM clusters have been assigned!
- Newly registered students:
    - Please make sure you have access to Campuswire and Gradescope
    - If you are in 4 credits, make sure you have been allocated a VM cluster for the MPs.
    - Email Neel (netid: neeld2) to get the required access.
- *Can you please say your name before speaking up in class?*

Today's agenda

- Logical Clocks and Timestamps
  - Chapter 14.4
- Global State (if time)
  - Chapter 14.5

Event Ordering

- A usecase of synchronized clocks:
  - Reasoning about order of events.
- Why is it useful?
  - Debugging distributed applications
  - Reconciling updates made to an object in a distributed datastore.
  - Rollback recovery during failures:
    1. *Checkpoint state of the system; 2. Log events (with timestamps); 3. Rollback to checkpoint and replay events in order if system crashes.*
  - ….
- Can we reason about order of events without synchronized clocks?

Process, state, events

- Consider a system with **n** processes: $<p_1, p_2, p_3, \ldots., p_n>$
- Each process $\mathbf{p_i}$ is described by its *state* $\mathbf{s_i}$ that gets transformed over time.
  - State includes values of all local variables, affected files, etc.
- $\mathbf{s_i}$ gets transformed when an *event* occurs.
- Three types of events:
  - Local computation.
  - Sending a message.
  - Receiving a message.

Event Ordering

- Easy to order events within a single process $\mathbf{p_i}$, based on their time of occurrence.

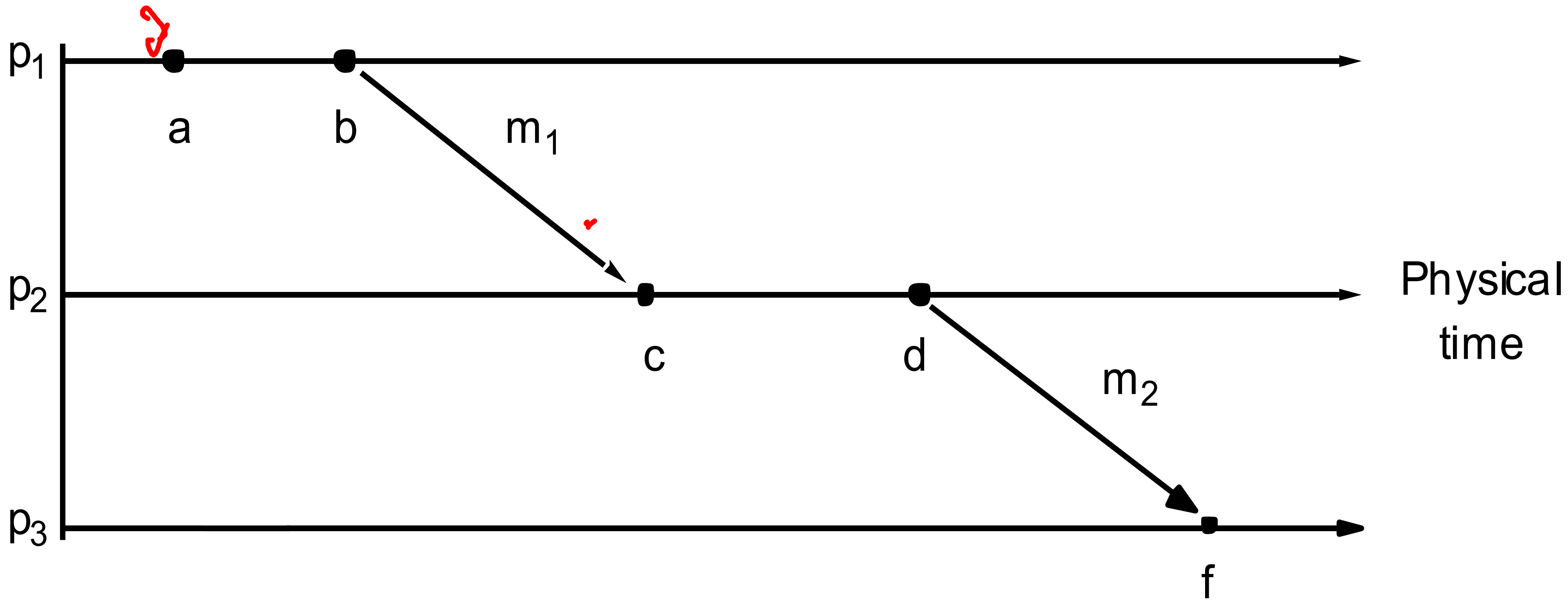
- How do we reason about events across processes?
  - A message must be *sent* before it gets *received* at another process.

- These two notions help define *happened-before* (HB) relationship denoted by $\rightarrow$.
  - $\mathbf{e} \rightarrow \mathbf{e'}$ means **e** *happened before* **e'**.

Happened-Before Relationship

- *Happened-before* (HB) relationship denoted by →.
  - **e** → **e'** means **e** *happened before* **e'**.
  - **e** $\rightarrow_i$ **e'** means **e** *happened before* **e'**, as observed by $\mathbf{p_i}$.
- HB rules:
  - If ∃ $\mathbf{p_i}$, **e** $\rightarrow_i$ **e'** then **e** → **e'**.
  - For any message m, **send(m)** → **receive(m)**
  - If **e** → **e'** and **e'** → **e''** then **e** → **e''**
- Also called *"causal" or "potentially causal"* ordering.

Event Ordering: Example

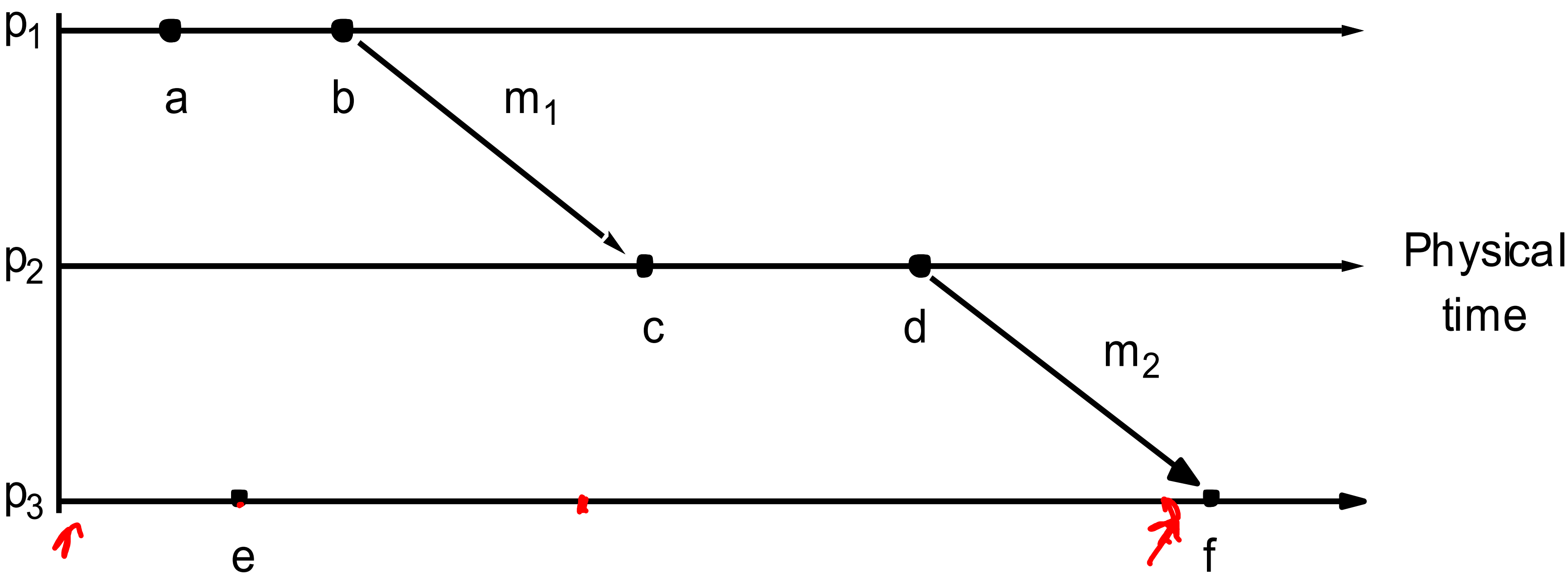


Which event happened first?

a → b and b → c and c → d and d → f

a → b and a → c and a → d and a → f

Event Ordering: Example



What can we say about **e**?

e → **f**

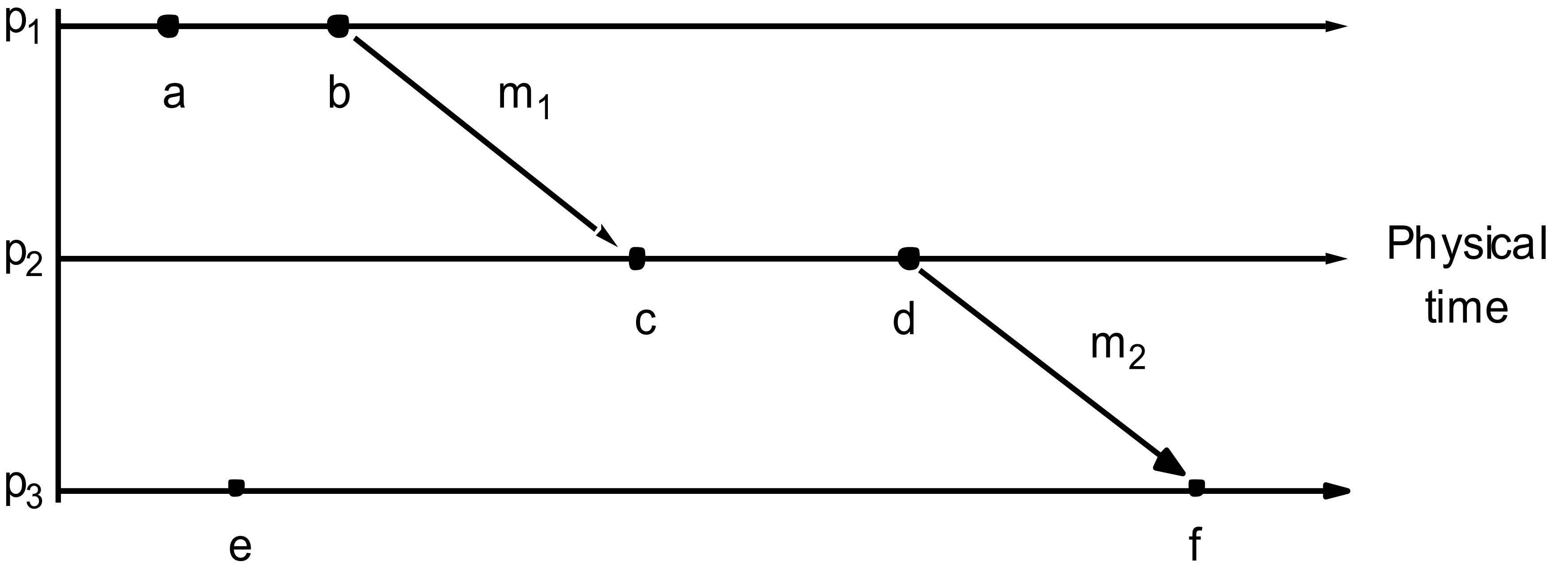
e||b, e||c, e||d

a ↛ **e** and **e** ↛ **a**

a || **e**

a and **e** are *concurrent*.

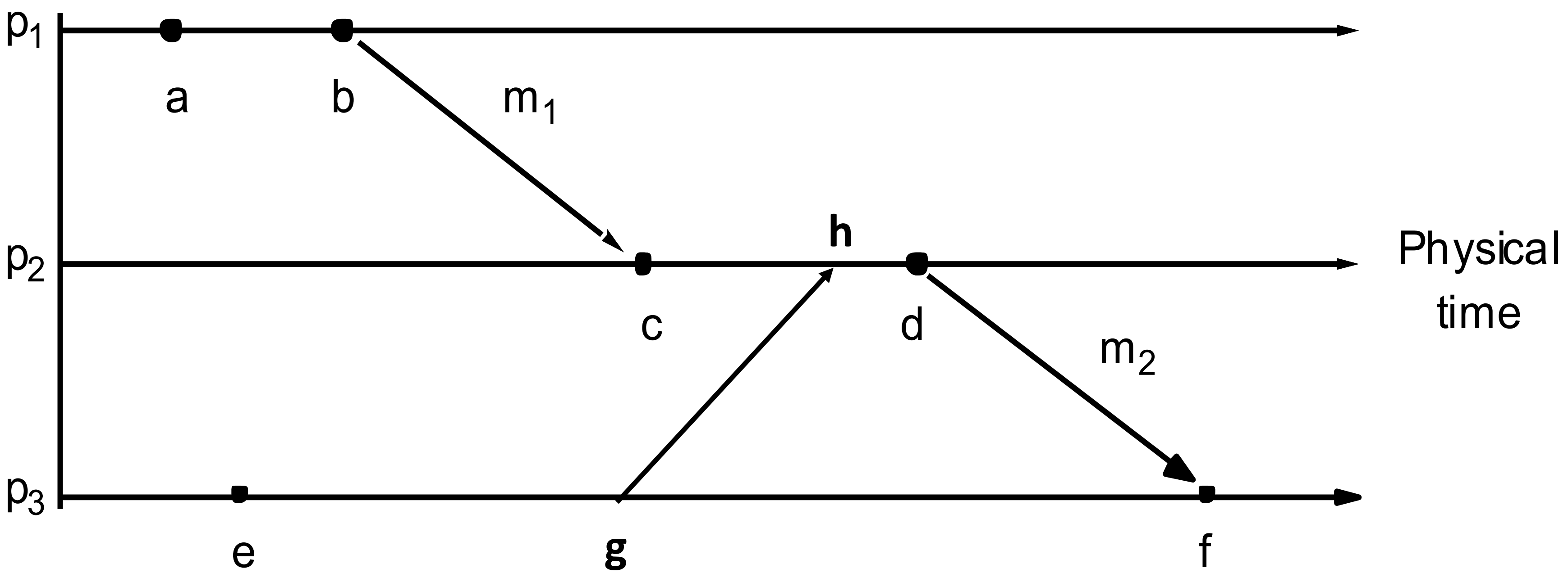
Event Ordering: Example



What can we say about **e** and **d**?

e || d

Logical Timestamps: Example



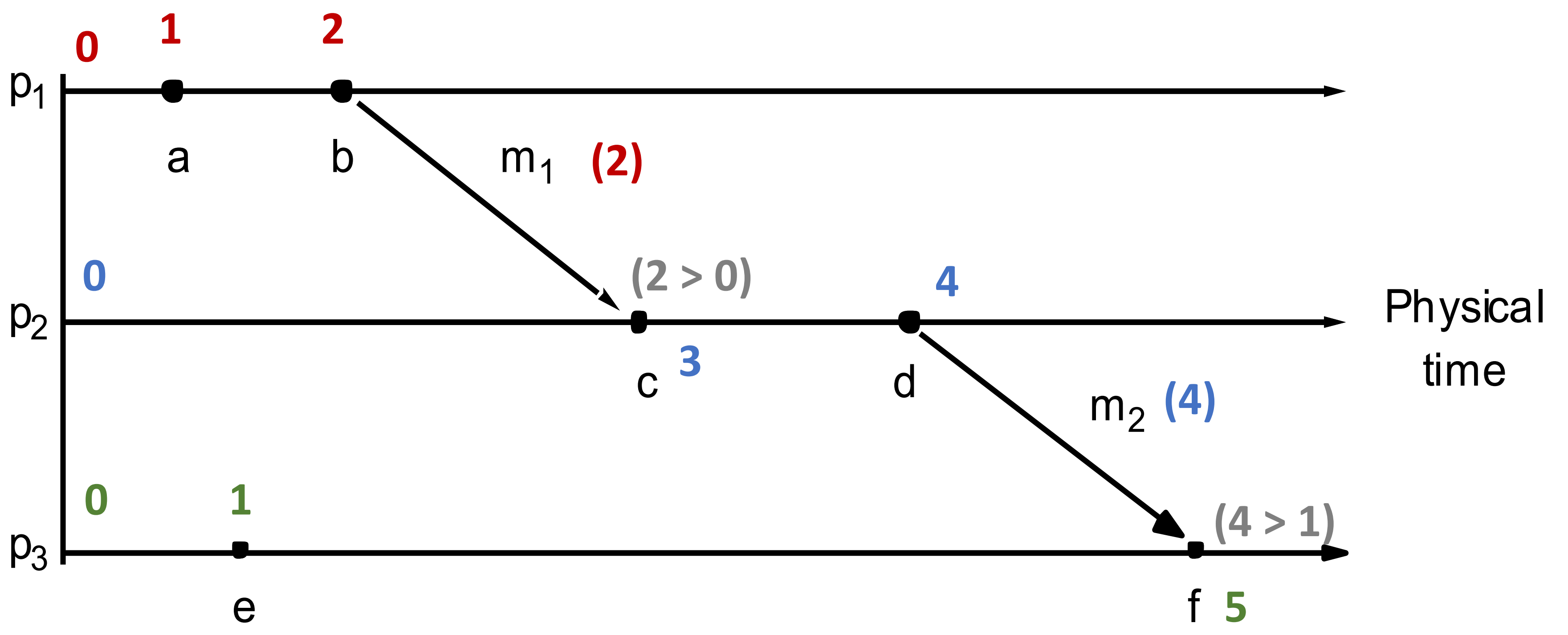
What can we say about **e** and **d**?

e → d

Lamport's Logical Clock

- Logical timestamp for each event that captures the *happened-before* relationship.
- *Algorithm:* Each process $\mathbf{p_i}$
  1. initializes local clock $\mathbf{L_i = 0}$.
  2. increments $\mathbf{L_i}$ before timestamping each event.
  3. piggybacks $\mathbf{L_i}$ when sending a message.
     - (i.e. sends $\mathbf{L_i}$ along with the message)
  4. upon receiving a message with clock value **t**
     - sets $\mathbf{L_i = max(t, L_i)}$
     - increments $\mathbf{L_i}$ before timestamping the receive event (as per step 2).

Logical Timestamps: Example



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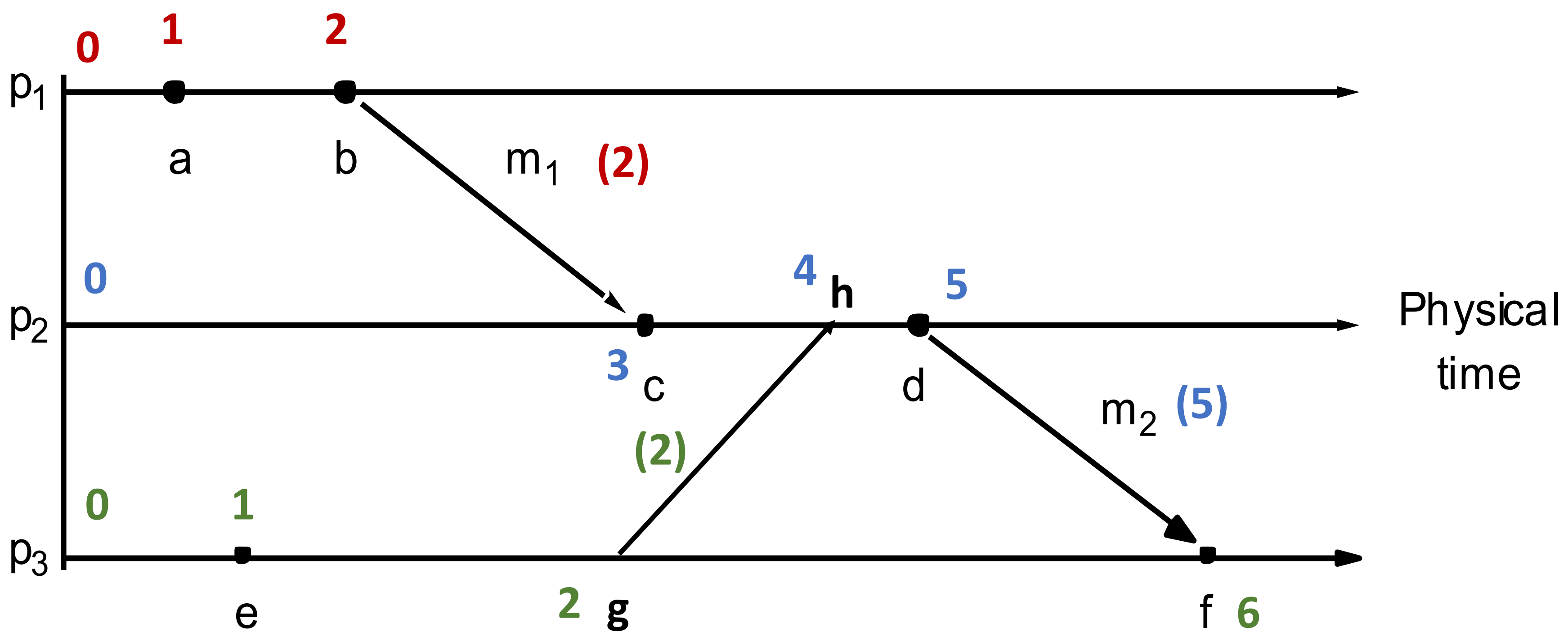


Lamport's Logical Clock

- Logical timestamp for each event that captures the *happened-before* relationship.

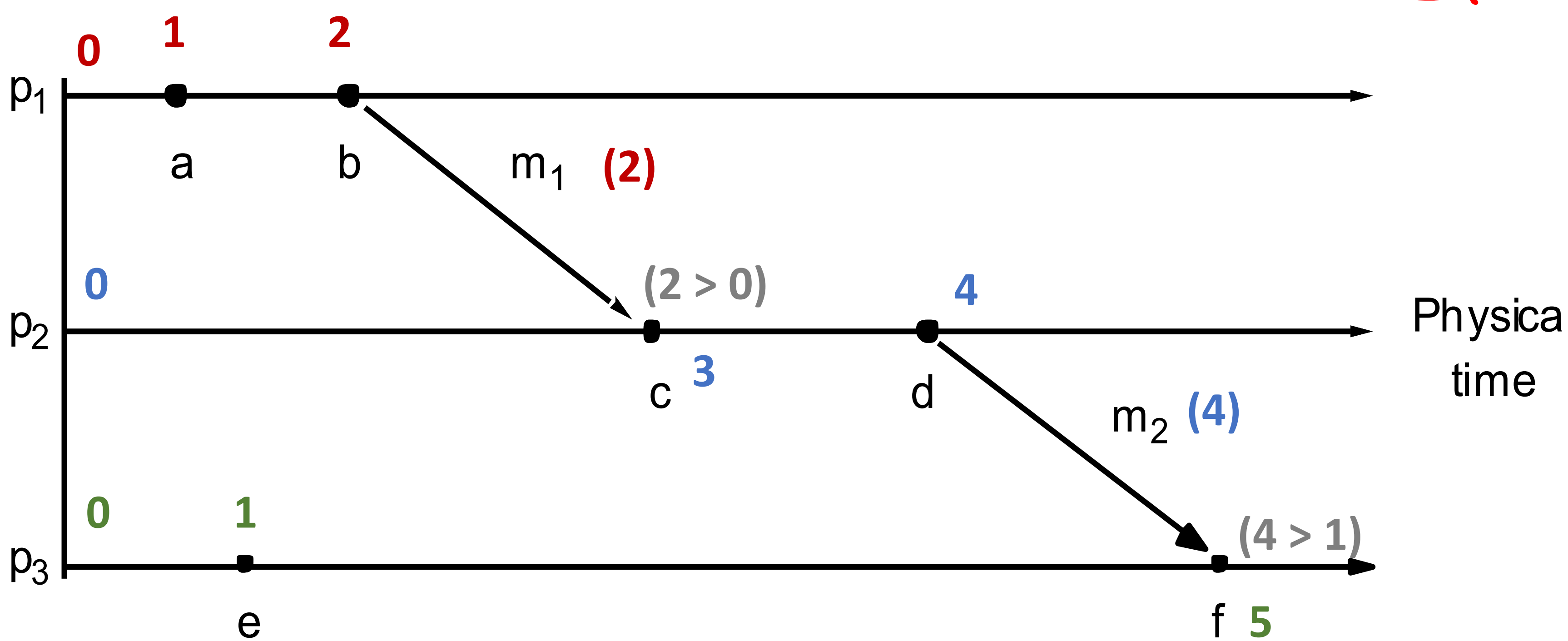
- If **e** → **e'** then
  - **L(e) < L(e')**

- What can we conclude if **L(e) < L(e')**?
  - We cannot say that **e** → **e'**
  - We can say: **e'** ↛ **e**
  - Either **e** → **e'** or **e** || **e'**

$e \to e'$ $L(e) < L(e')$

$L(e) = L(e')$
$L(e) \not< L(e')$
$e \not\to e'$
$e' \not\to e$
$e \| e'$

Logical Timestamps: Example



L(e) < L(d), e || d

L(e) < L(f), e → f

Vector Clocks

- Each event associated with a vector timestamp.
- Each process p_i maintains vector of clocks V_i
- The size of this vector is the same as the no. of processes.
  - $V_i[j]$ is the clock for process p_j as maintained by p_i
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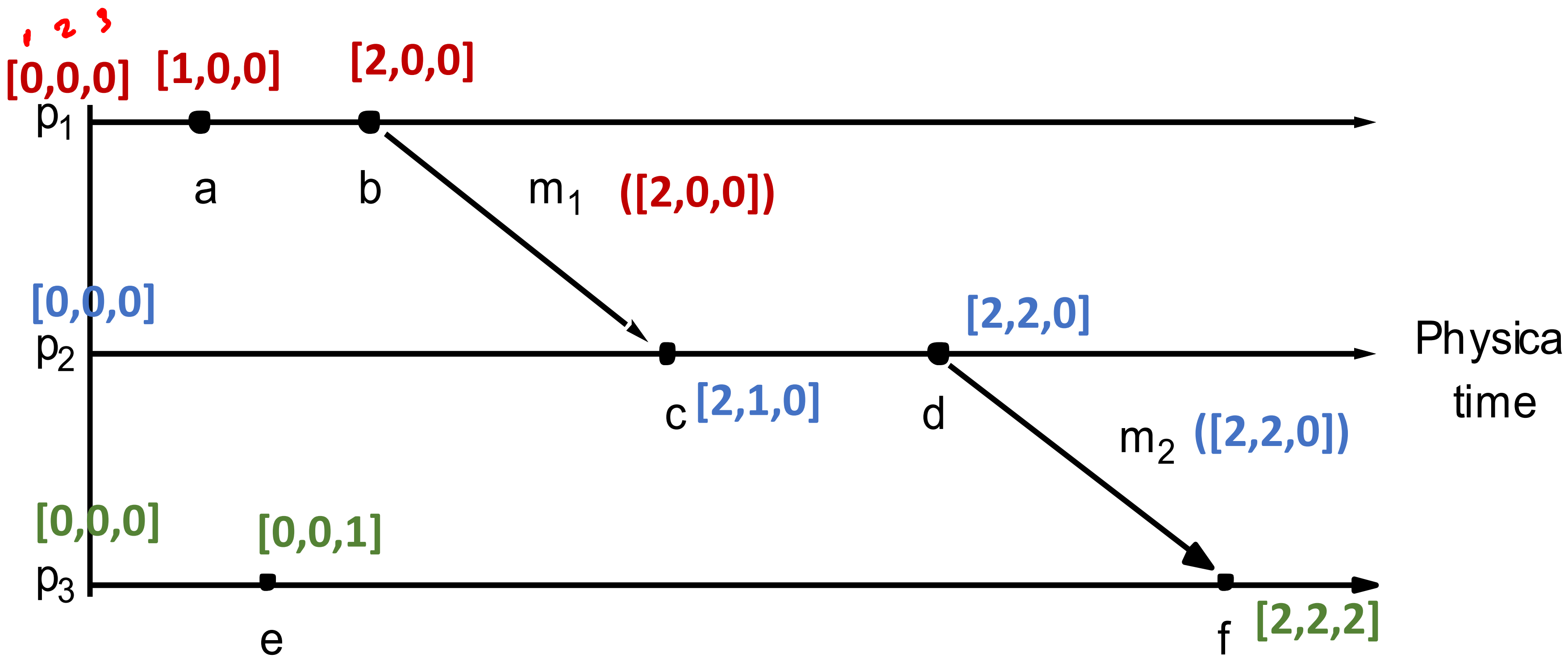
- Algorithm: each process $\mathbf{p_i}$:
  1. initializes local clock $\mathbf{V_i[j] = 0}$
  2. increments $\mathbf{V_i[i]}$ before timestamping each event.
  3. piggybacks $\mathbf{V_i}$ when sending a message.
  4. upon receiving a message with vector clock value $\mathbf{v}$
     - sets $\mathbf{V_i[j] = max(V_i[j], v[j])}$ for all j=1…n.
     - increments $\mathbf{V_i[i]}$ before timestamping receive event (as per step 2).

Vector Timestamps: Example



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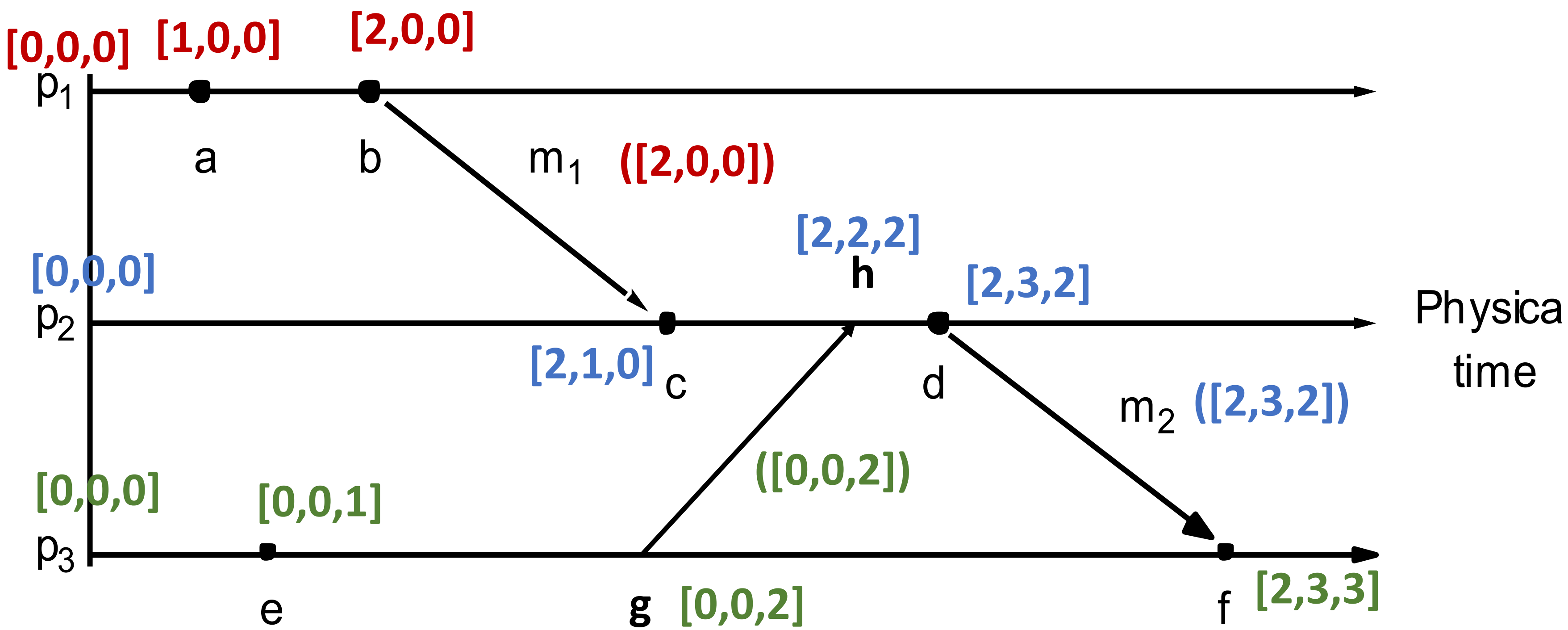


Comparing Vector Timestamps

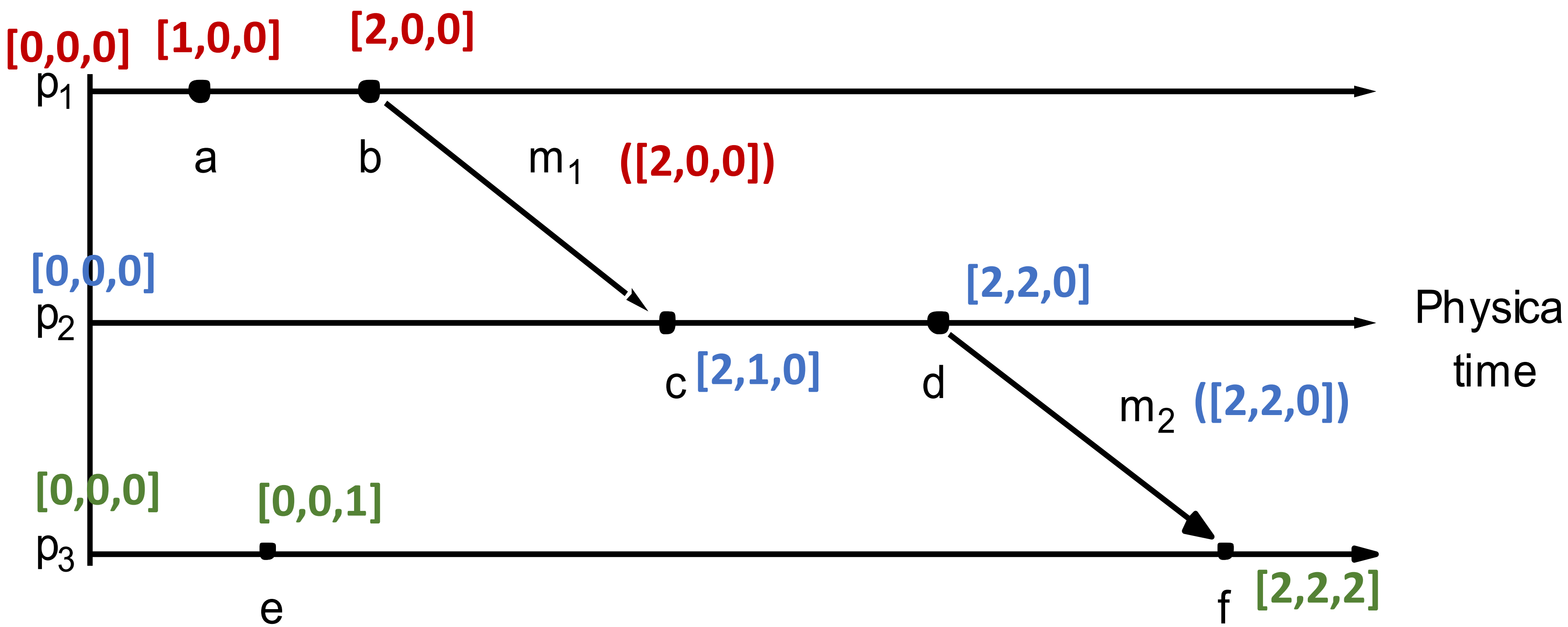
- Let $V(e) = V$ and $V(e') = V'$

- $V = V'$, iff $V[i] = V'[i]$, for all $i = 1, \ldots, n$
- $V \leq V'$, iff $V[i] \leq V'[i]$, for all $i = 1, \ldots, n$
- $V < V'$, iff $V \leq V'$ & $V \neq V'$

  iff $V \leq V'$ & $\exists$ j such that $(V[j] < V'[j])$

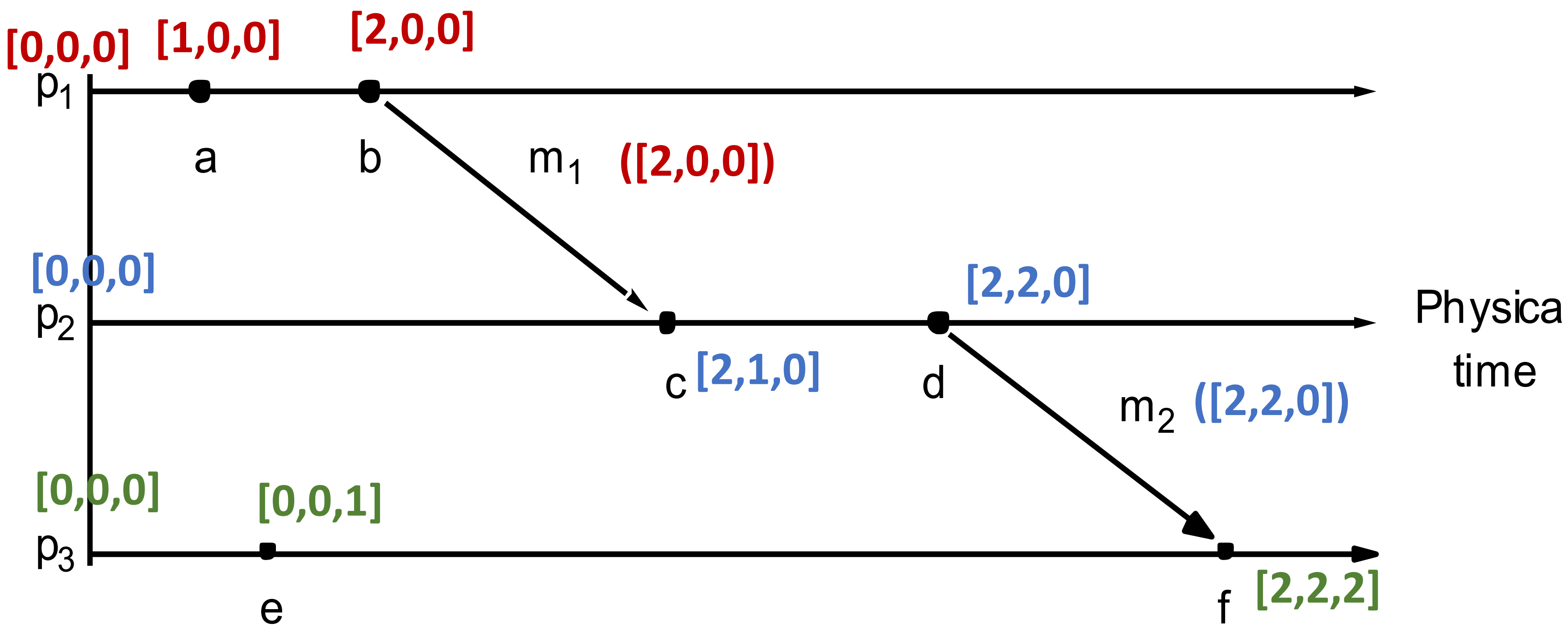
- $e \rightarrow e'$ iff $V < V'$
  - ($V < V'$ implies $e \rightarrow e'$) and ($e \rightarrow e'$ implies $V < V'$)
- $e \parallel e'$ iff ($V \nless V'$ and $V' \nless V$)

Vector Timestamps: Example



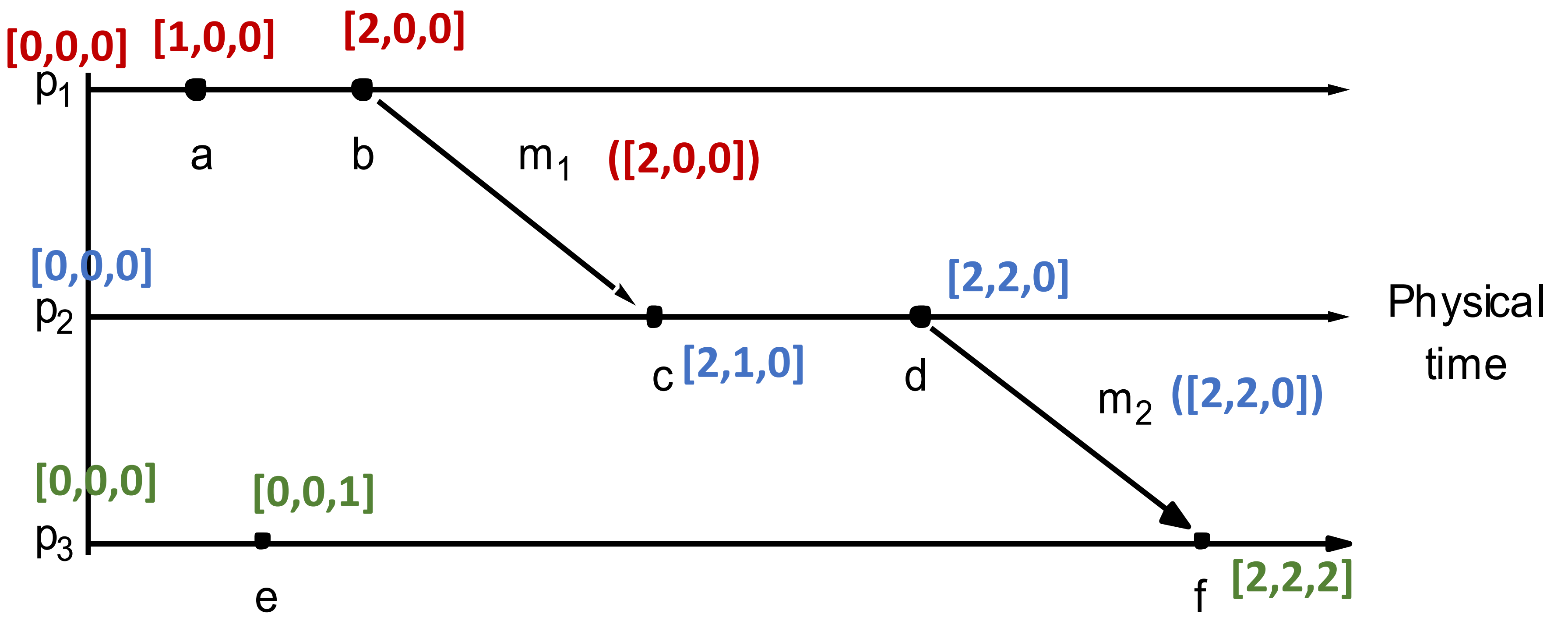
What can we say about e & f based on their vector timestamps?

Vector Timestamps: Example



V(e) < V(f), e → f

Vector Timestamps: Example



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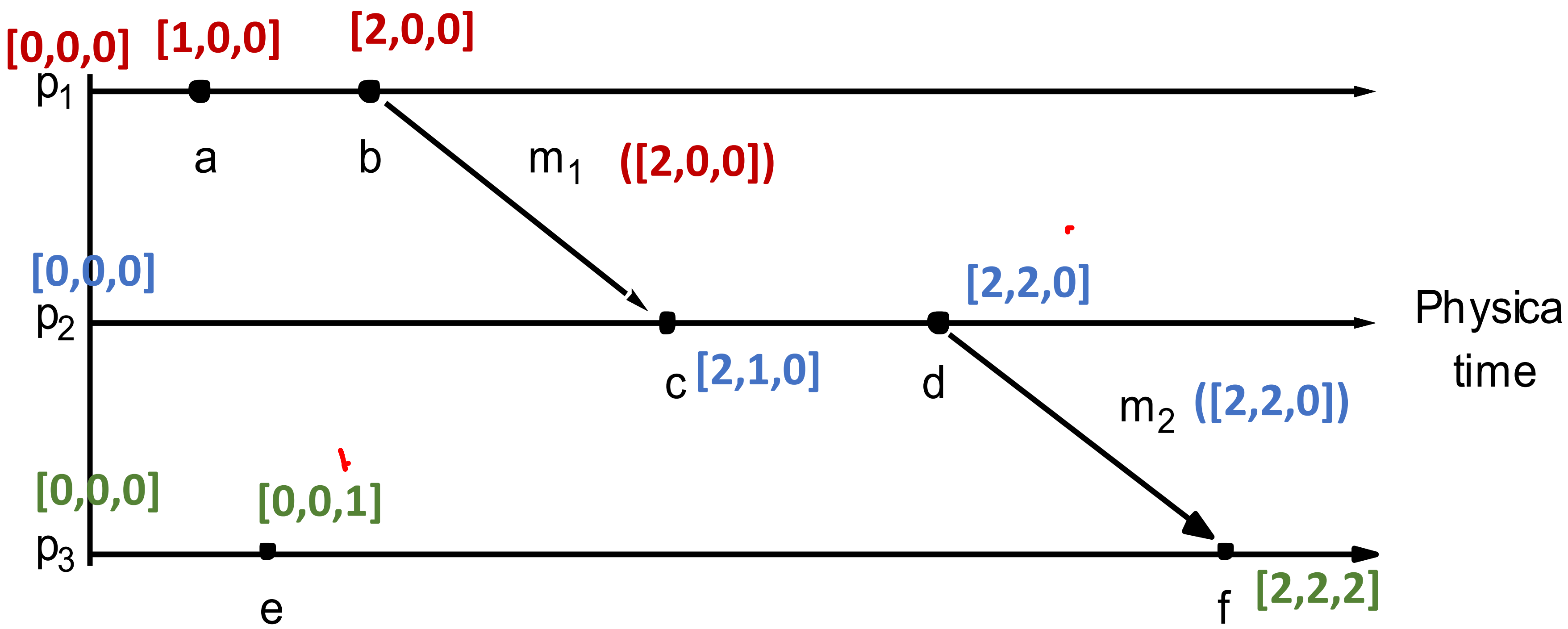
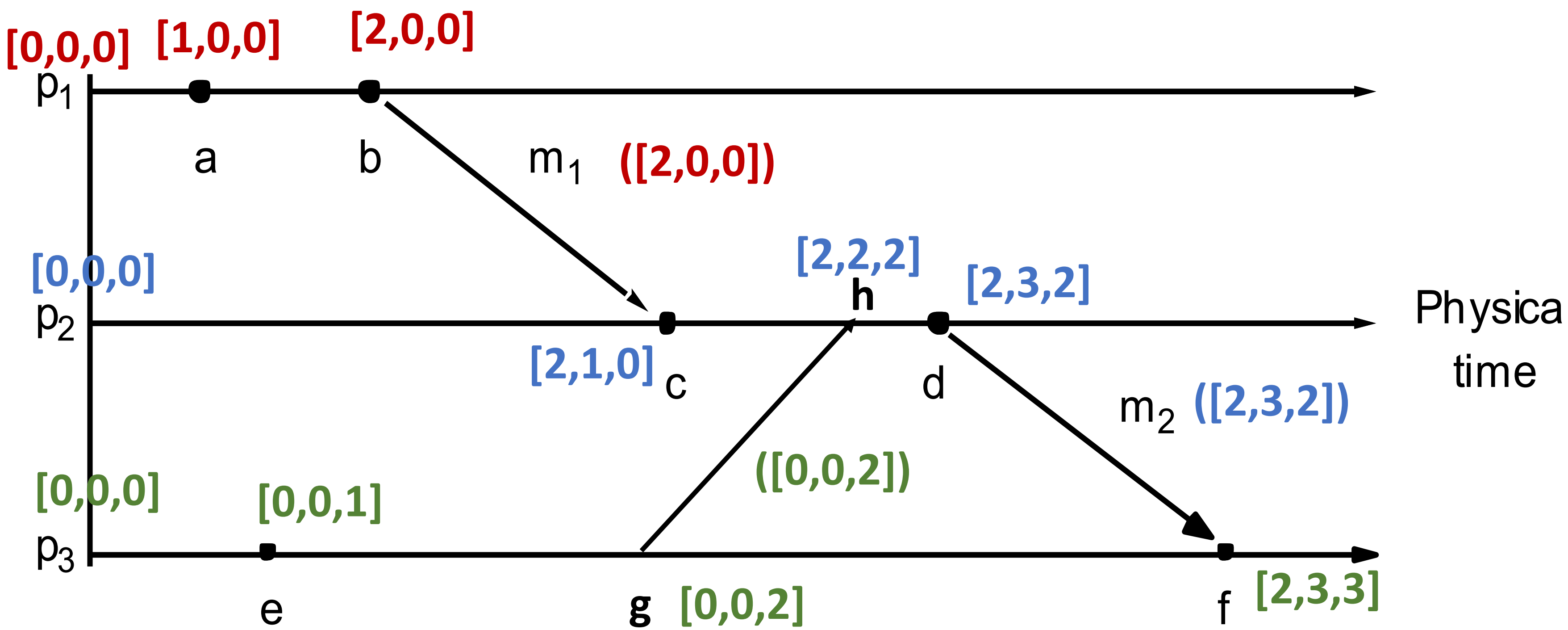


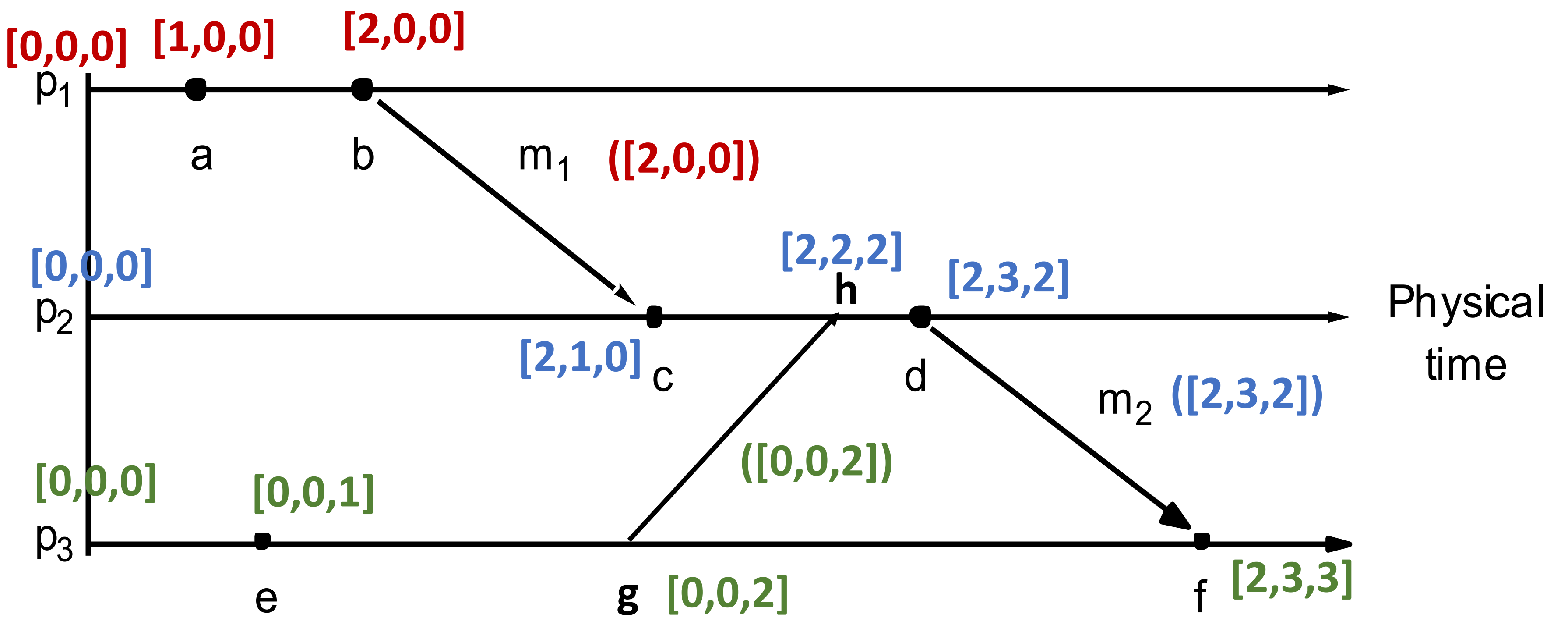
$V(e) \nless V(d)$ and $V(d) \nless V(e)$, e || d

Vector Timestamps: Example



How about now?

Vector Timestamps: Example



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Timestamps Summary

- **Comparing timestamps across events is useful.**
  - Reconciling updates made to an object in a distributed datastore.
  - Rollback recovery during failures:

    1. Checkpoint state of the system; 2. Log events (with timestamps);
    3. Rollback to checkpoint and replay events in order if system crashes.

- **How to compare timestamps across different processes?**
  - **Physical timestamp:** requires clock synchronization.
    - Google's Spanner Distributed Database uses "TrueTime".
  - **Lamport's timestamps:** cannot fully differentiate between causal and concurrent ordering of events.
    - Oracle uses "System Change Numbers" based on Lamport's clock.
  - **Vector timestamps:** larger message sizes.
    - Amazon's DynamoDB uses vector clocks.

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Today's agenda

- Logical Clocks and Timestamps
  - Chapter 14.4
- Global State
  - Chapter 14.5

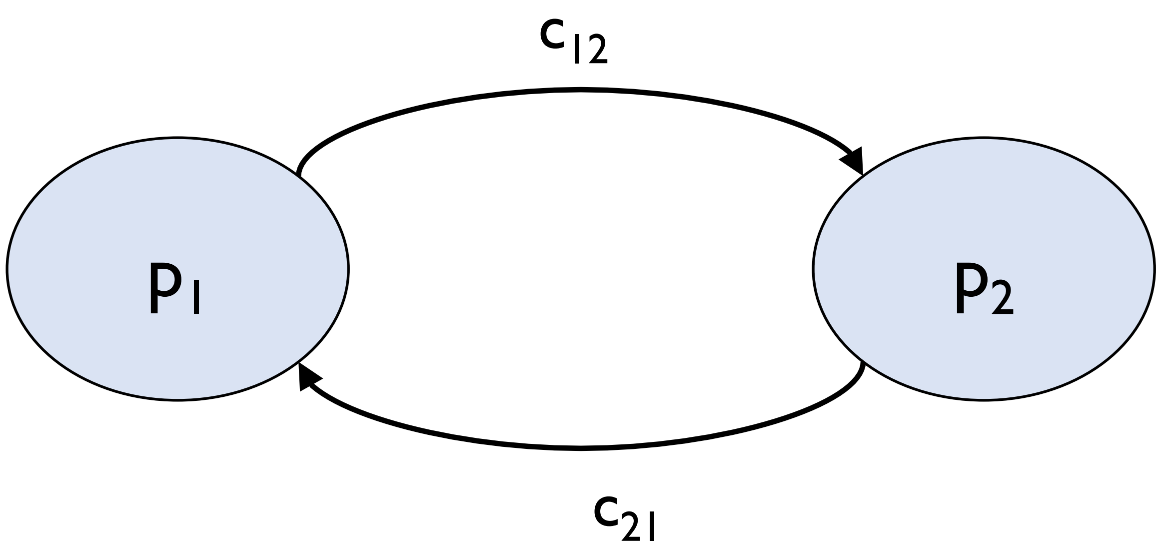
Process, state, events

- Consider a system with **n** processes: <$p_1, p_2, p_3, \ldots, p_n$>.
- Each process p_i is associated with *state* $\mathbf{s_i}$.
  - State includes values of all local variables, affected files, etc.
- Each channel can also be associated with a state.
  - Which messages are currently *pending* on the channel.
  - Can be computed from process' state:
    - Record when a process sends and receives messages.
    - if $\mathbf{p_i}$ sends a message that $\mathbf{p_j}$ has not yet received, it is pending on the channel.
- State of a process (or a channel) gets transformed when an *event* occurs. 3 types of events:
  - local computation, sending a message, receiving a message.

Global State (or Global Snapshot)

- State of each process (and each channel) in the system at a given instant of time.

- Example:



Two processes: $\mathbf{p_1}$ and $\mathbf{p_2}$.

$\mathbf{c_{12}}$: channel from $\mathbf{p_1}$ to $\mathbf{p_2}$. $\mathbf{c_{21}}$: channel from $\mathbf{p_2}$ to $\mathbf{p_1}$.

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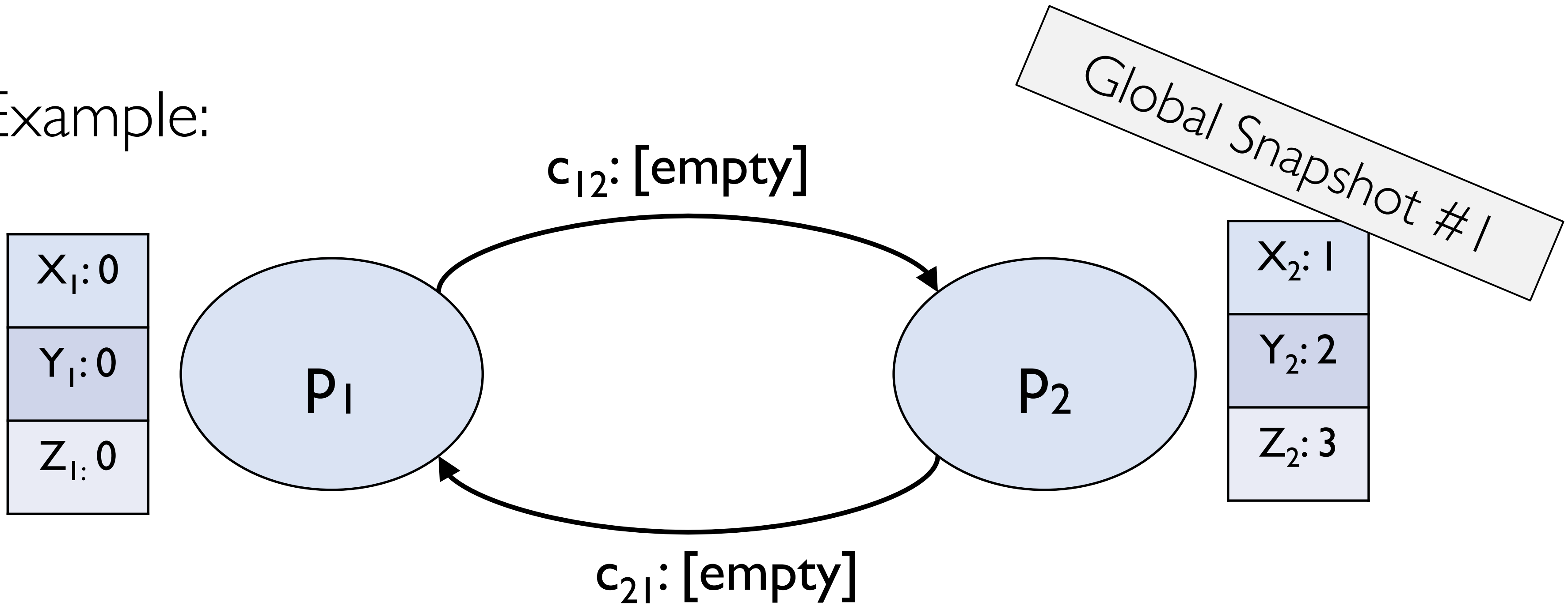

Process state for p_1 and p_2.
No pending messages on the channels.

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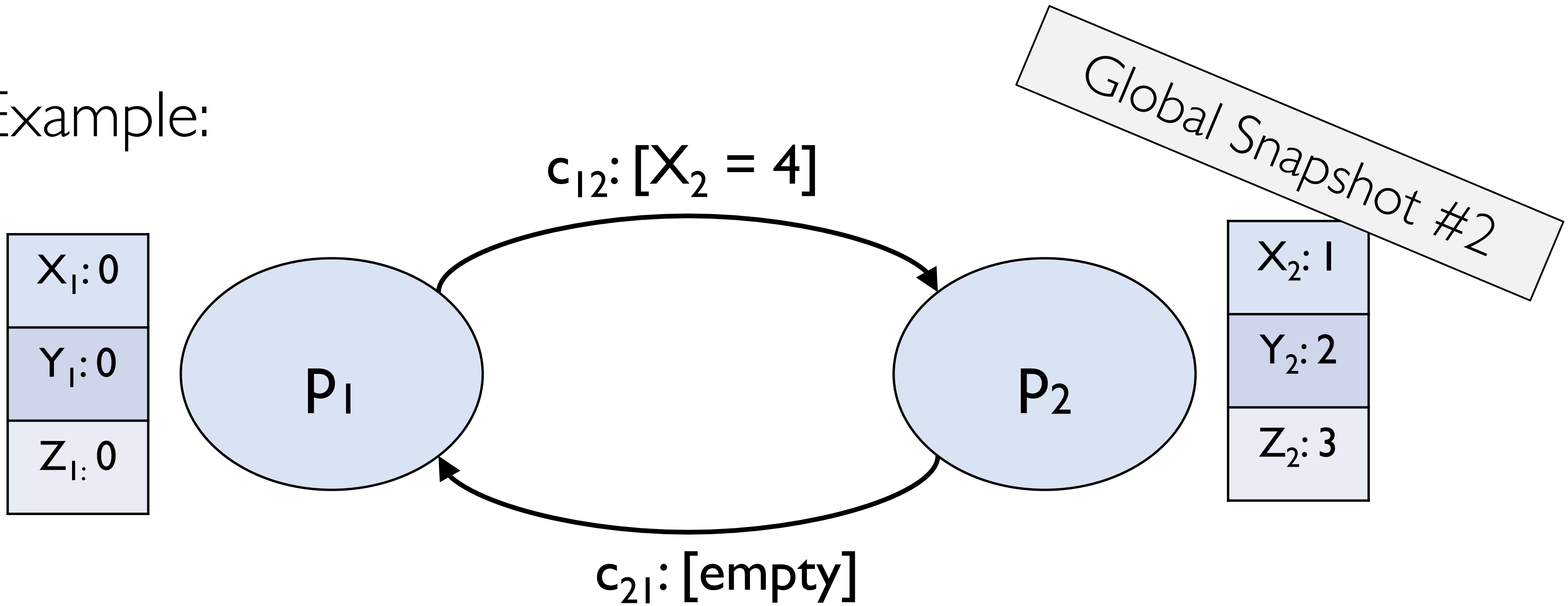

event 1: p_1 sends a message to p_2 asking it to set $X_2 = 4$

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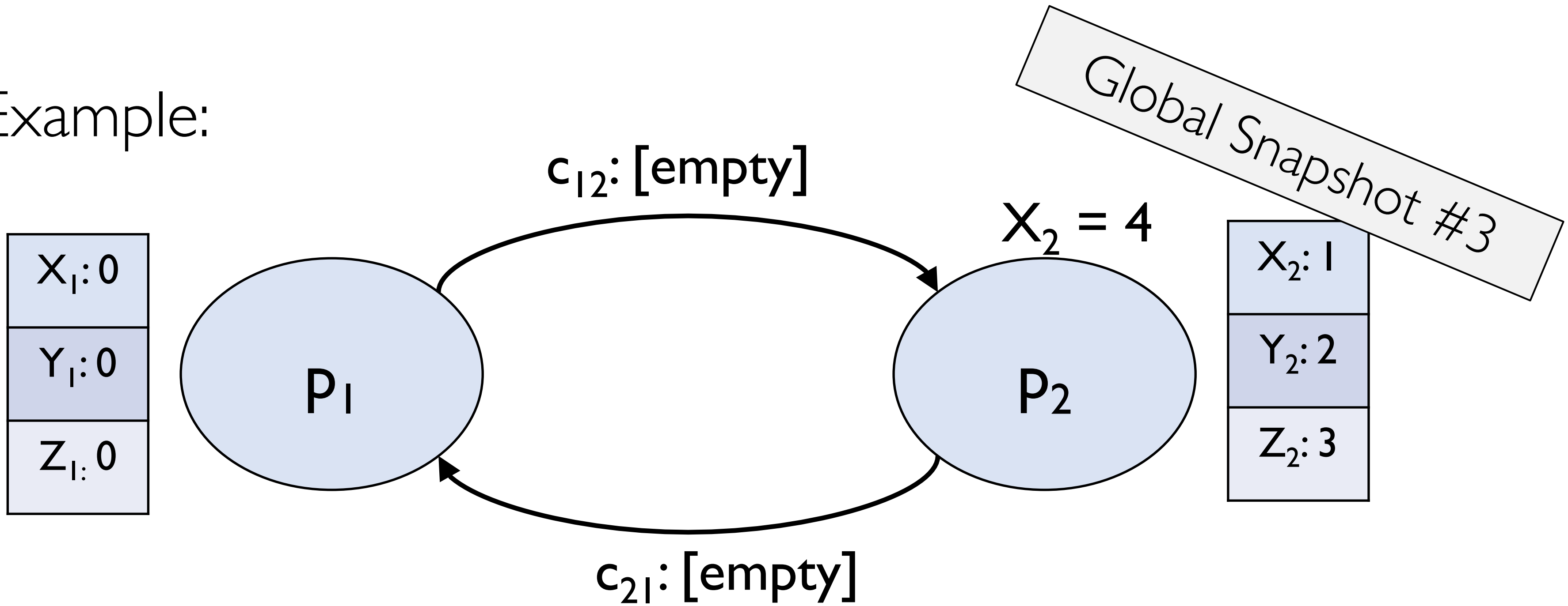

event 2: p_2 receives the message.

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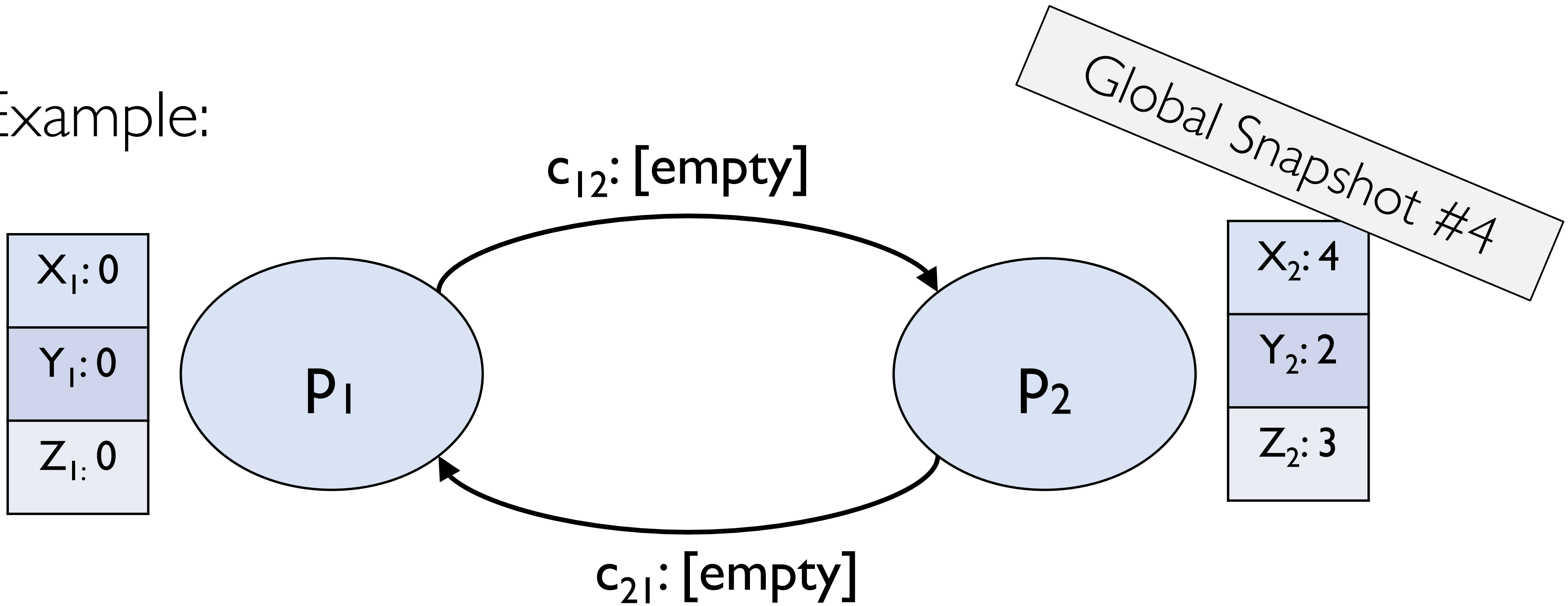

event 3: p_2 changes the value of X_2

Capturing a global snapshot

- Useful to capture a global snapshot of the system:
  - *Checkpointing* the system state.
  - Reasoning about unreferenced objects (for garbage collection).
  - Deadlock detection.
  - Distributed debugging.

To be continued in next class….