Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

Logistics Related

- Eng-IT is still working on assigning VM clusters
  - Will hopefully be done by the end of the day.
  - Watch for an email from us, and CampusWire post with instructions.
- All registered students have been added to Gradescope.
  - If you have registered late / plan on registering when a slot opens up, you can email Sarthak (sm106) to get added to Gradescope.
    - But please wait a week before doing so.

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'**.

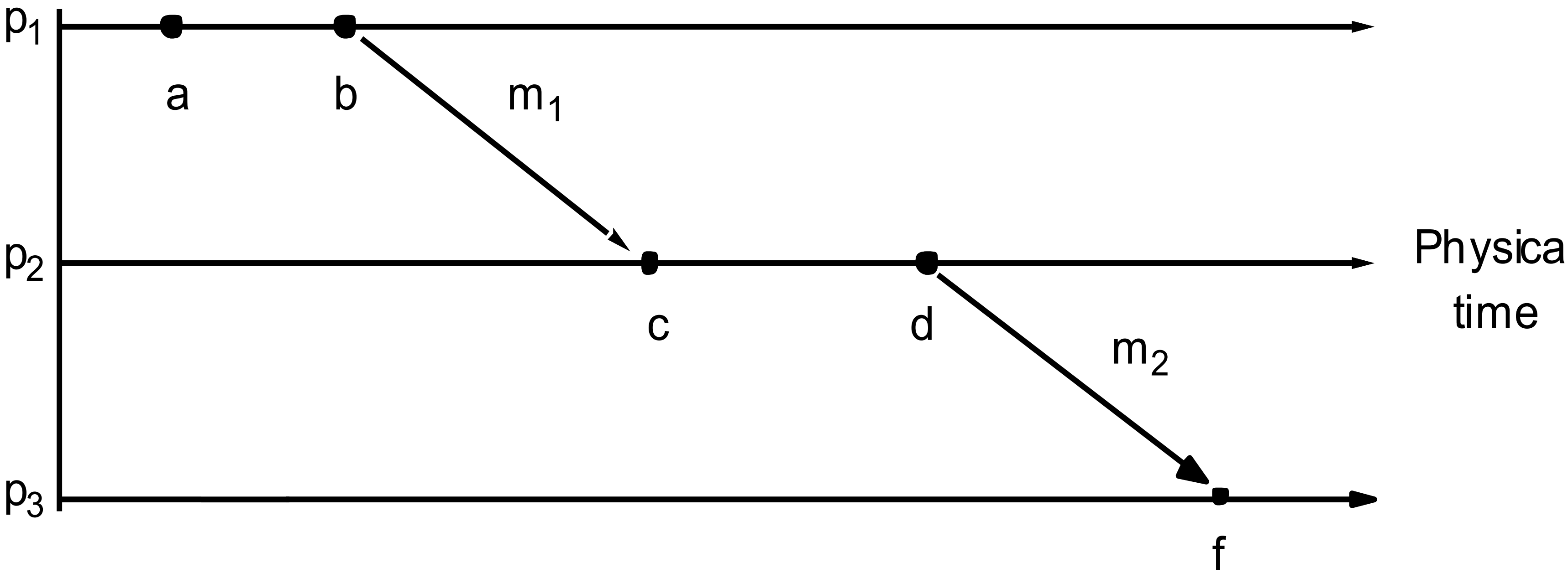
Happened-Before Relationship

- *Happened-before* (HB) relationship denoted by $\rightarrow$.
  - **e** $\rightarrow$ **e'** means **e** *happened before* **e'**.
  - **e** $\rightarrow_i$ **e'** means **e** *happened before* **e'**, as observed by $\mathbf{p_i}$.

- HB rules:
  - If $\exists$ $\mathbf{p_i}$, **e** $\rightarrow_i$ **e'** then **e** $\rightarrow$ **e'**.
  - For any message m, **send(m)** $\rightarrow$ **receive(m)**
  - If **e** $\rightarrow$ **e'** and **e'** $\rightarrow$ **e''** then **e** $\rightarrow$ **e''**

- Also called *"causal" or "potentially causal"* ordering.

Event Ordering: Example

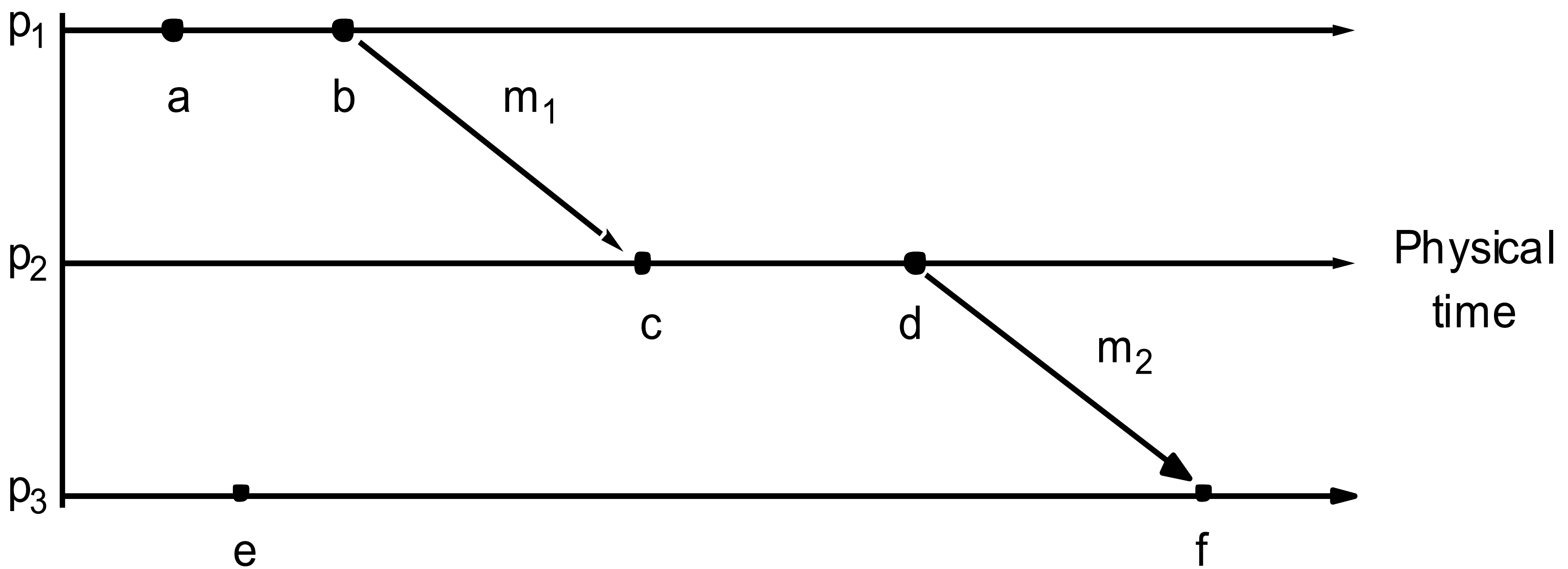


Which event happened first?

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**?

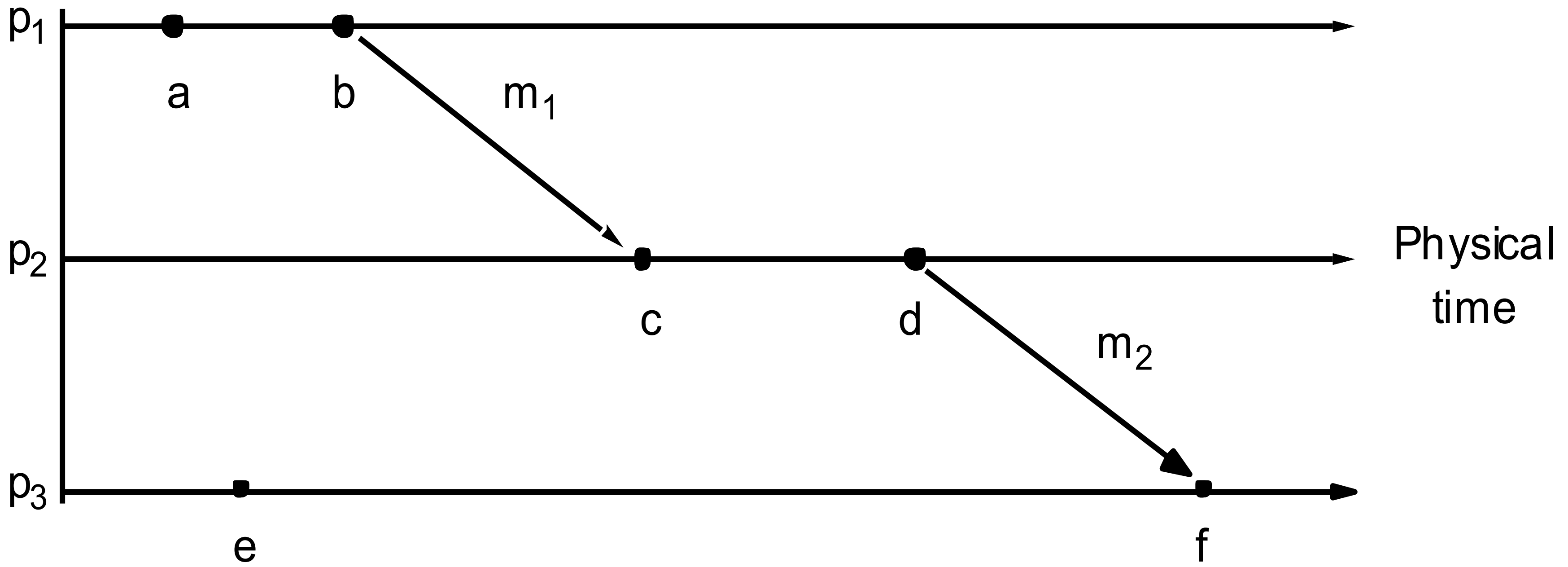
e $\rightarrow$ **f**

a $\not\rightarrow$ **e** and **e** $\not\rightarrow$ **a**

a || **e**

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

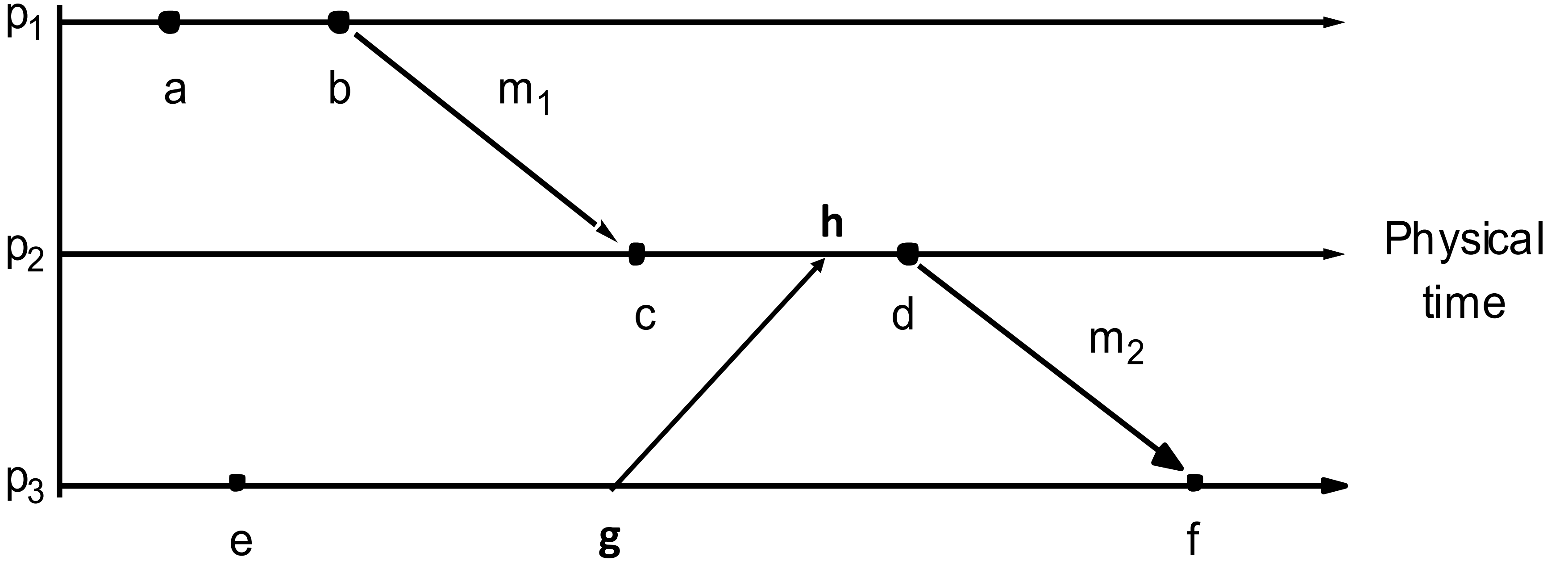
Event Ordering: Example



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

e || d

Logical Timestamps: Example



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

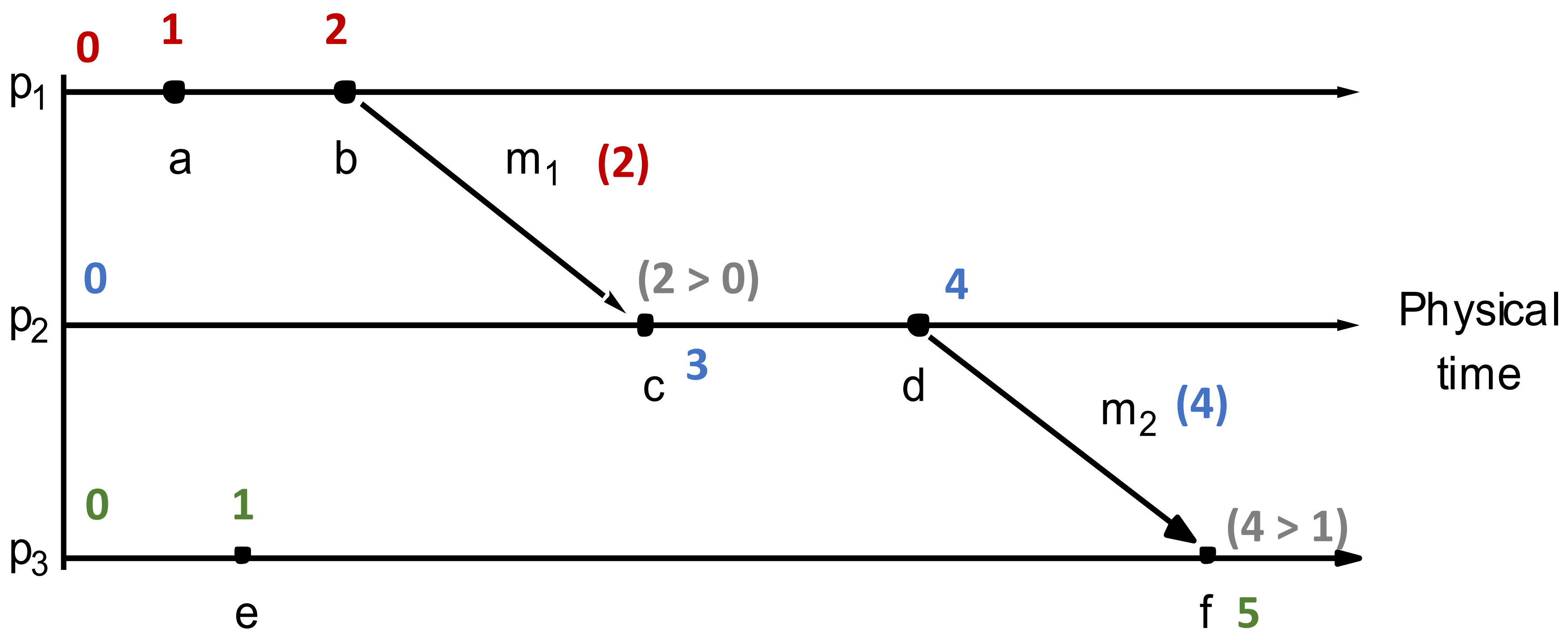
$e \rightarrow d$

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.
  4. upon receiving a message with clock value $\mathbf{t}$
     - 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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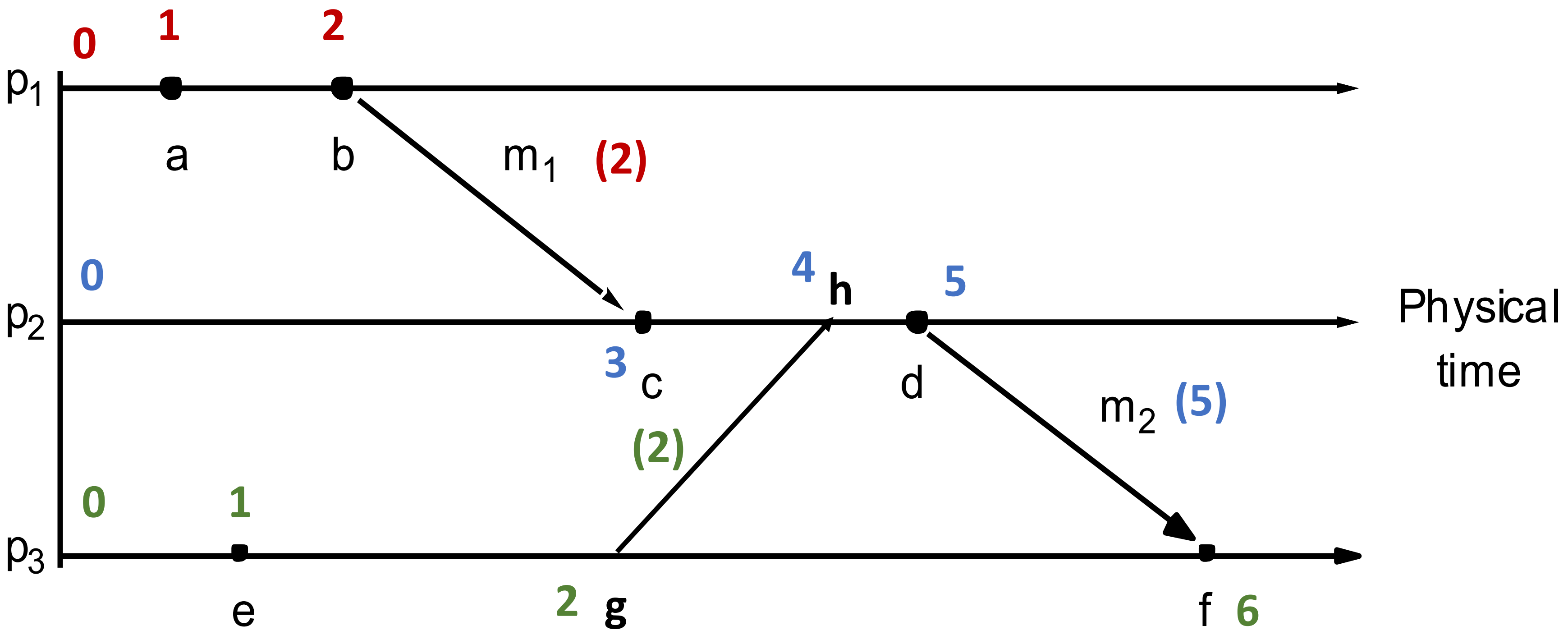


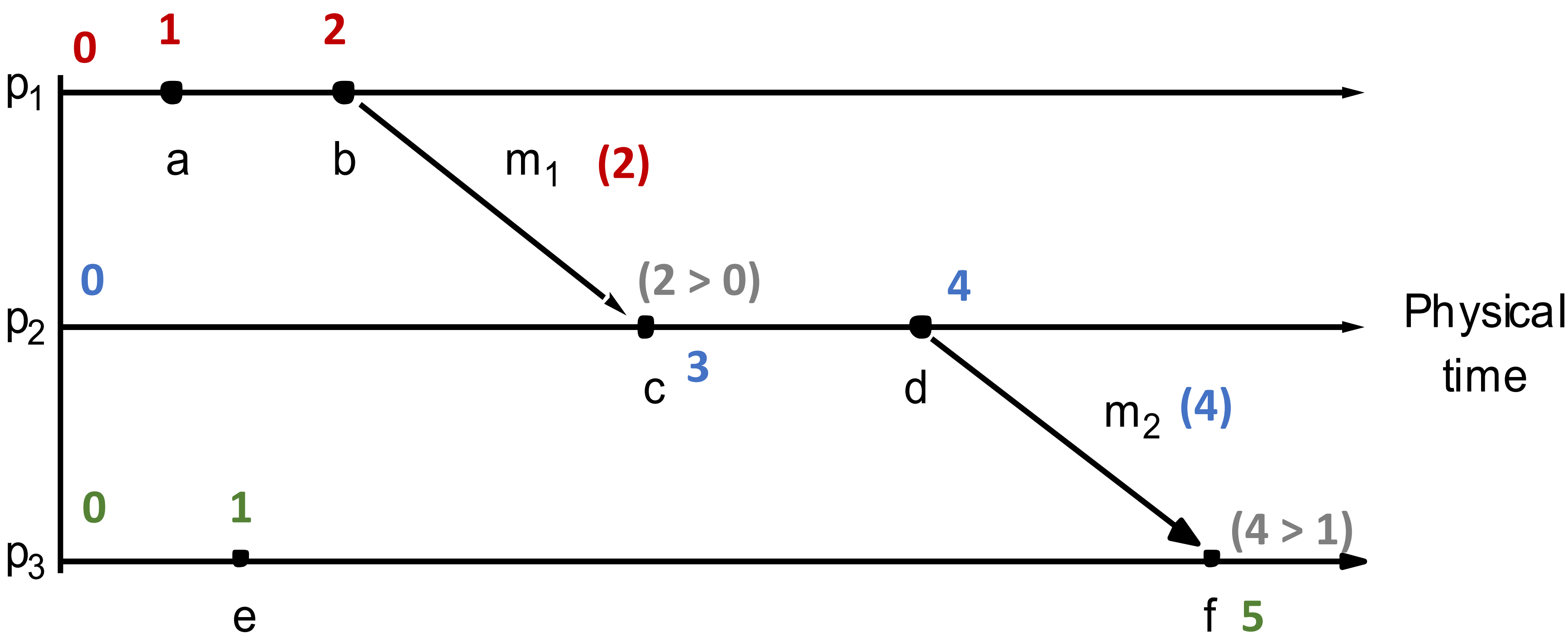
Lamport's Logical Clock

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

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

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

Logical Timestamps: Example



$L(e) < L(d)$, $e \parallel d$ $\qquad$ $L(e) < L(f)$, $e \rightarrow f$

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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  4. upon receiving a message with vector clock value v
     - sets $V_i[j] = \max(V_i[j], v[j])$ for all j=1…n.
     - increments $V_i[i]$ before timestamping receive event (as per step 2).

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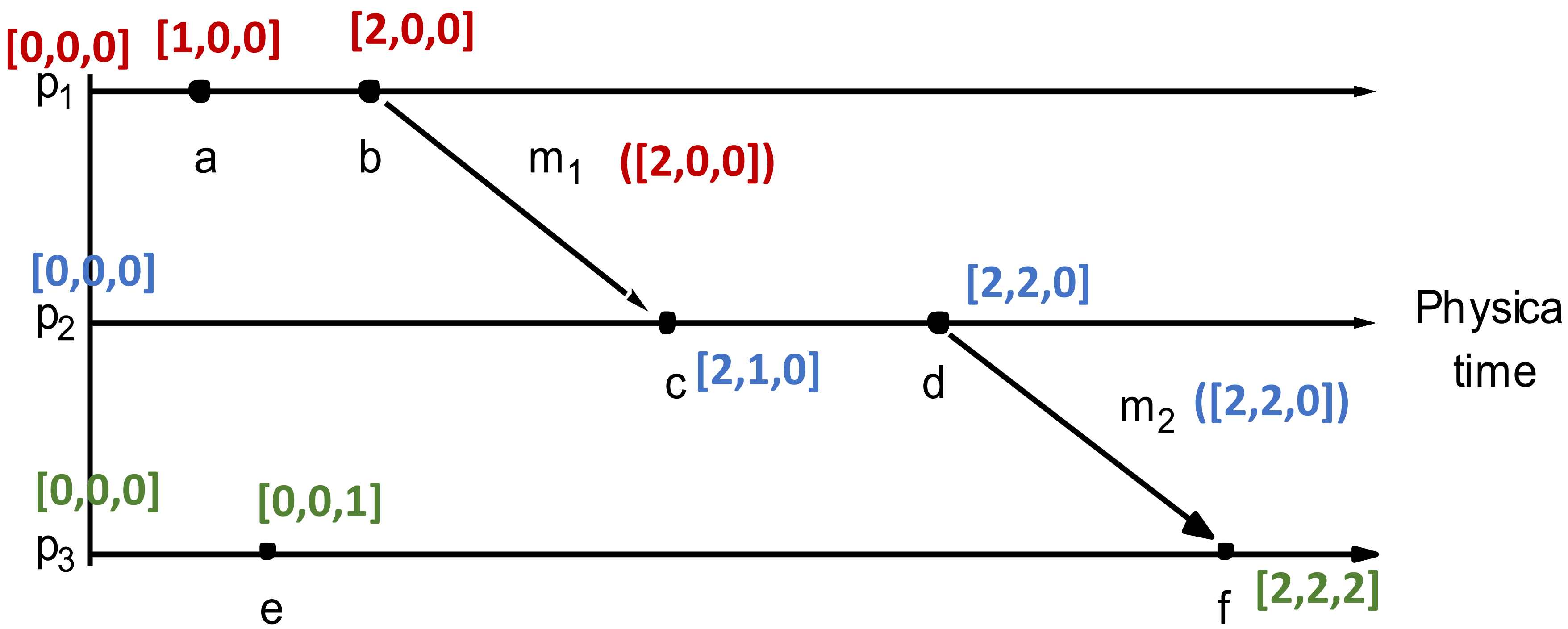

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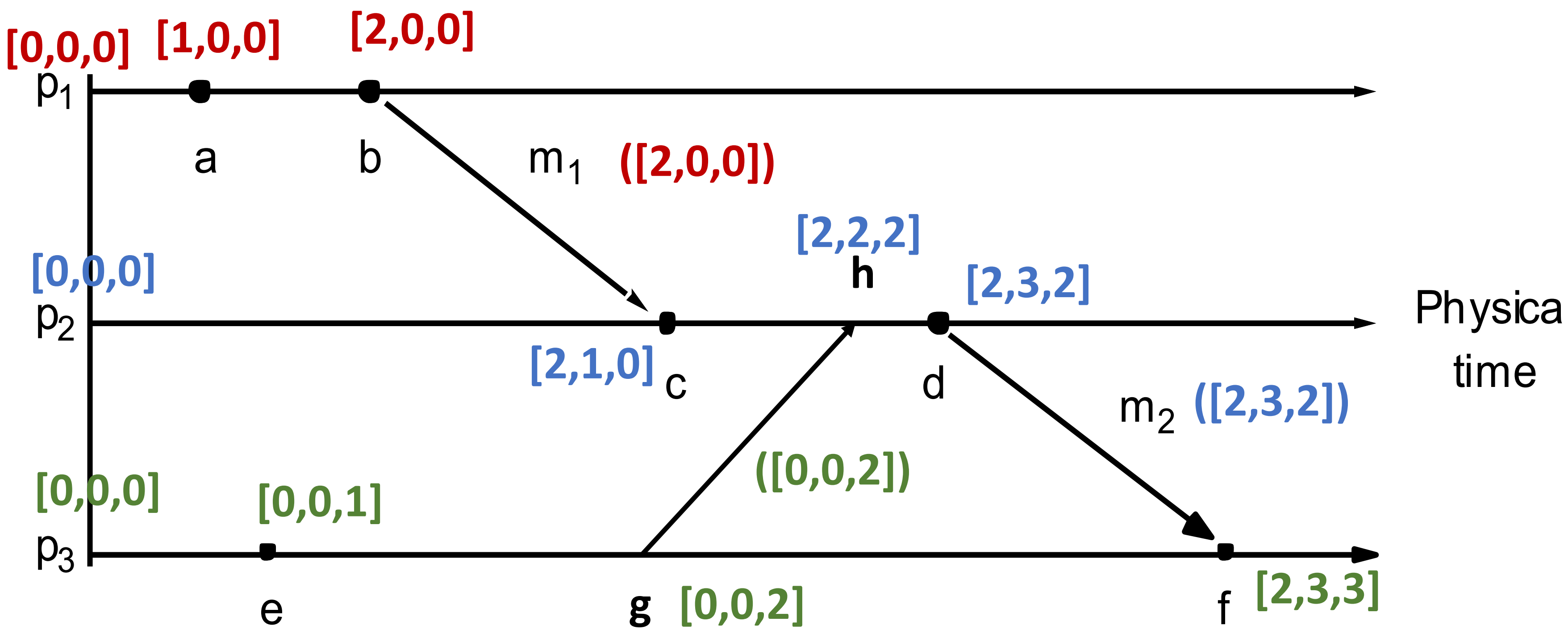


Comparing Vector Timestamps

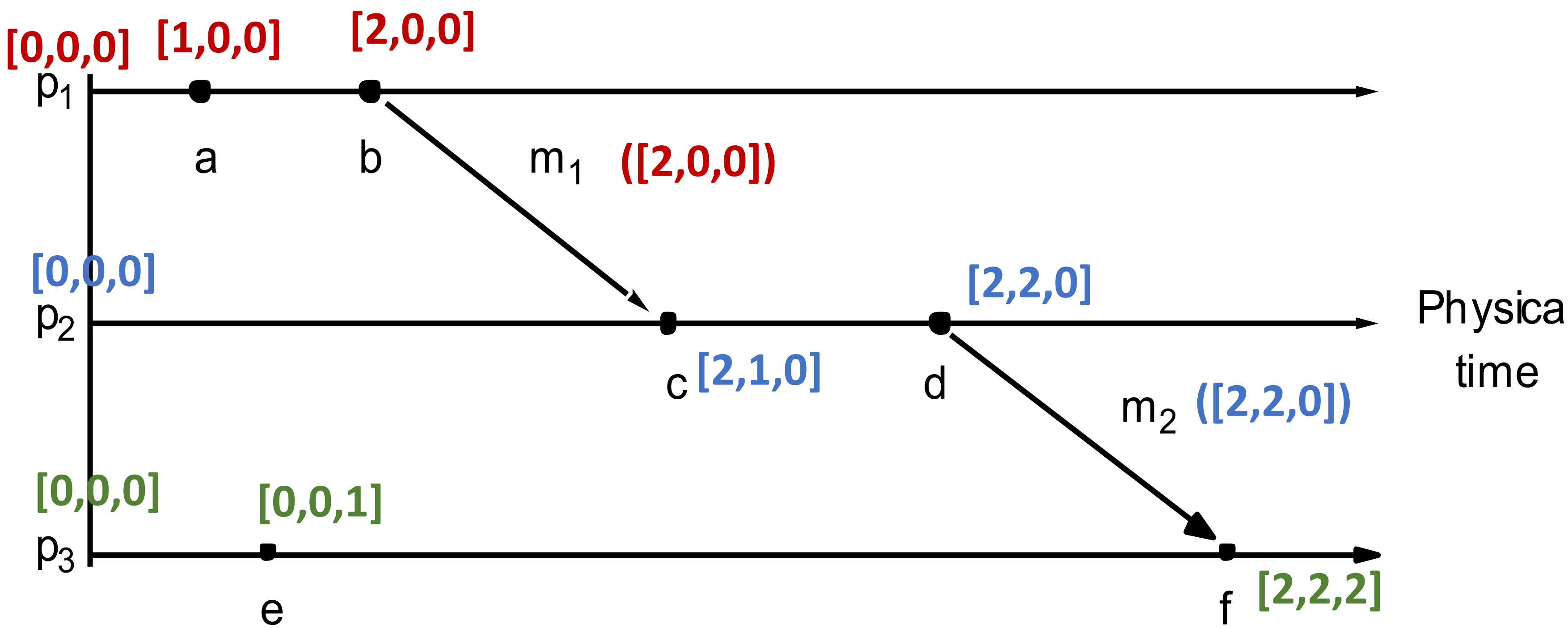
- Let $V(e) = V$ and $V(e') = V'$

- $V = V'$, 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 $(V[j] < V'[j])$

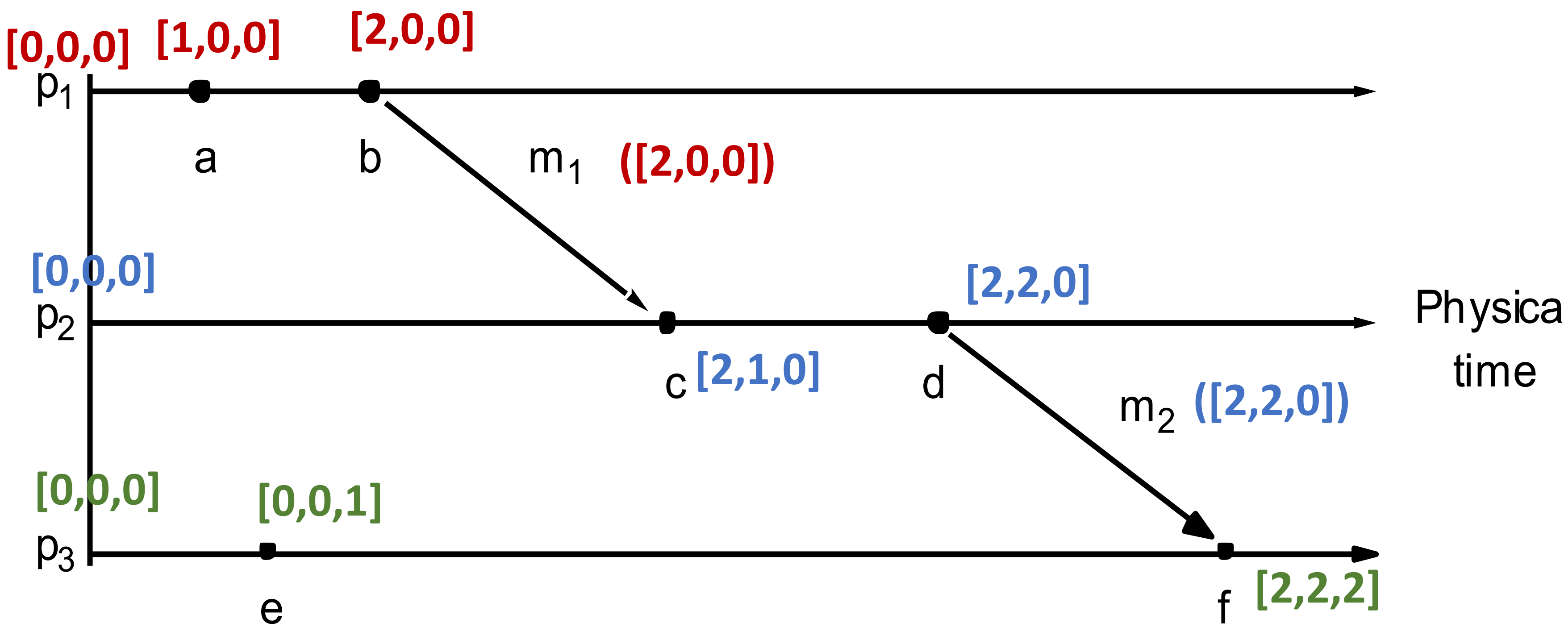
- $e \rightarrow e'$ iff $V < V'$
  - ($V < V'$ implies $e \rightarrow e'$) and ($e \rightarrow e'$ implies $V < V'$)
- $e \mid\mid e'$ iff ($V \not< V'$ and $V' \not< V$)

Vector Timestamps: Example



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

Vector Timestamps: Example



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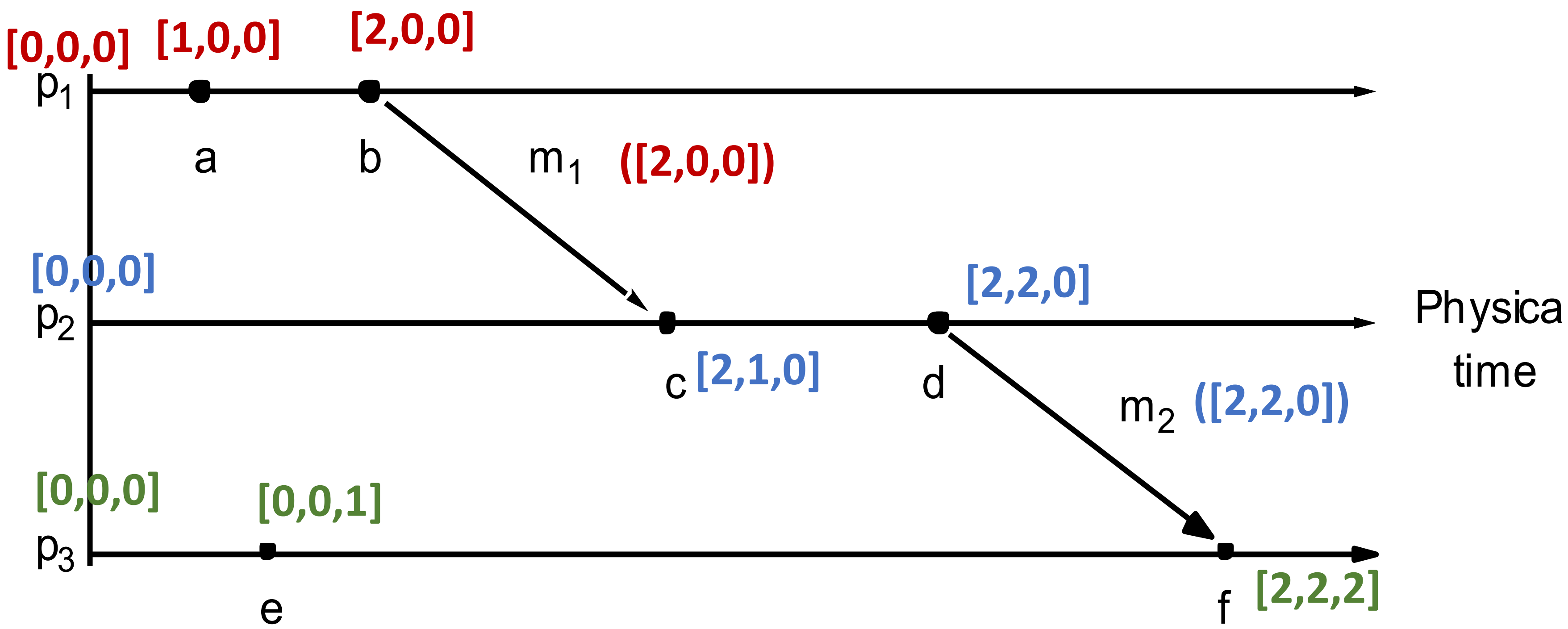

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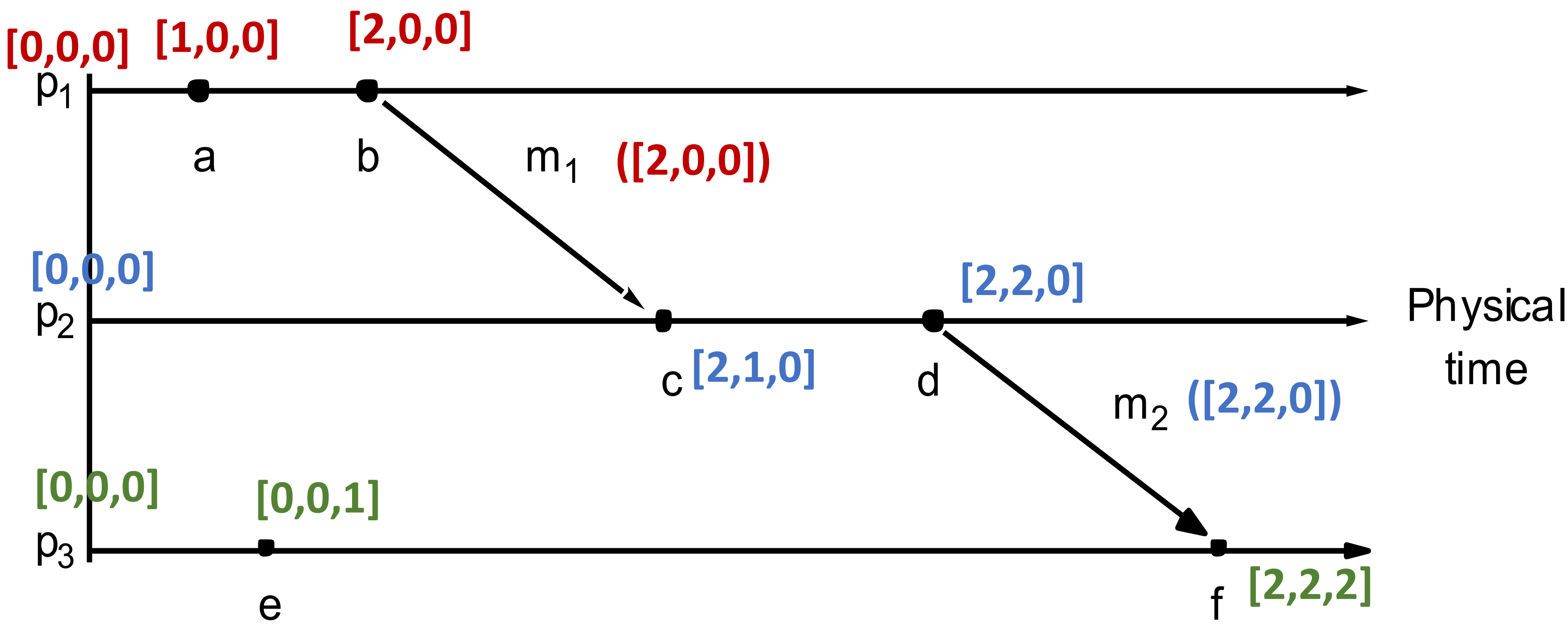
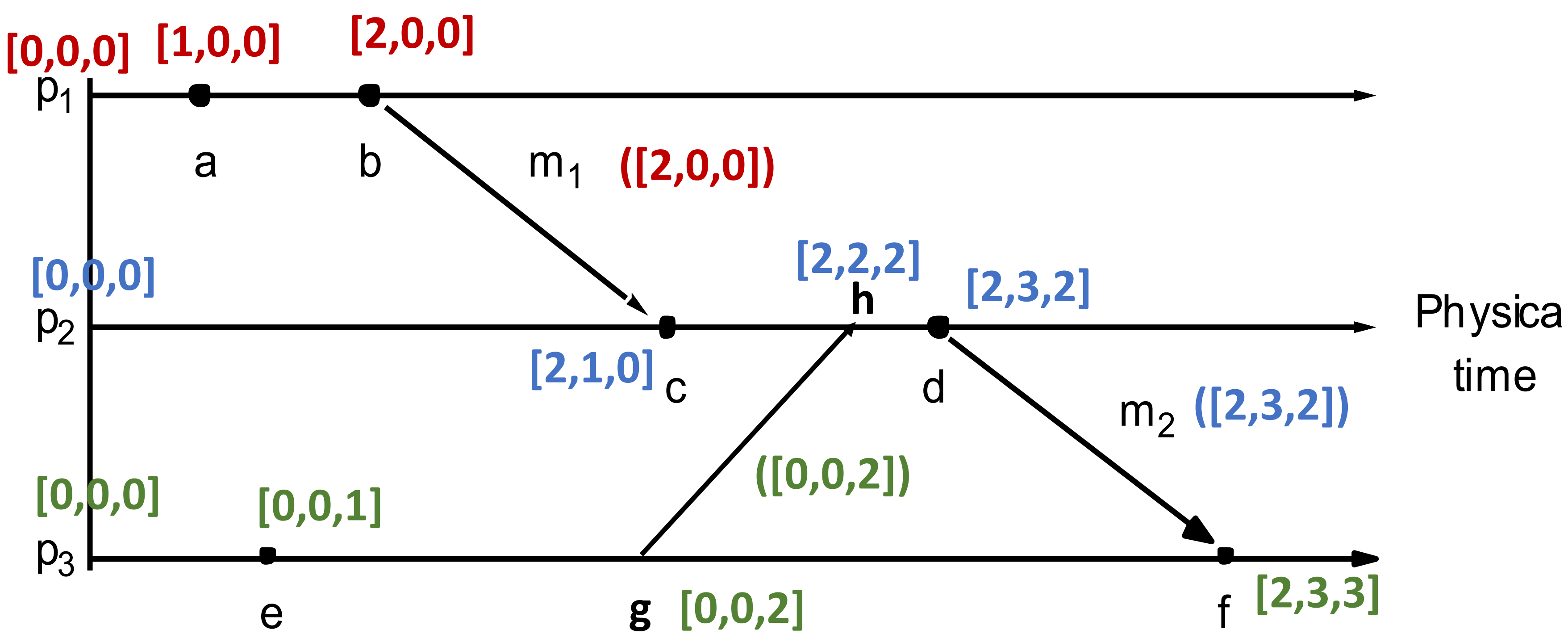


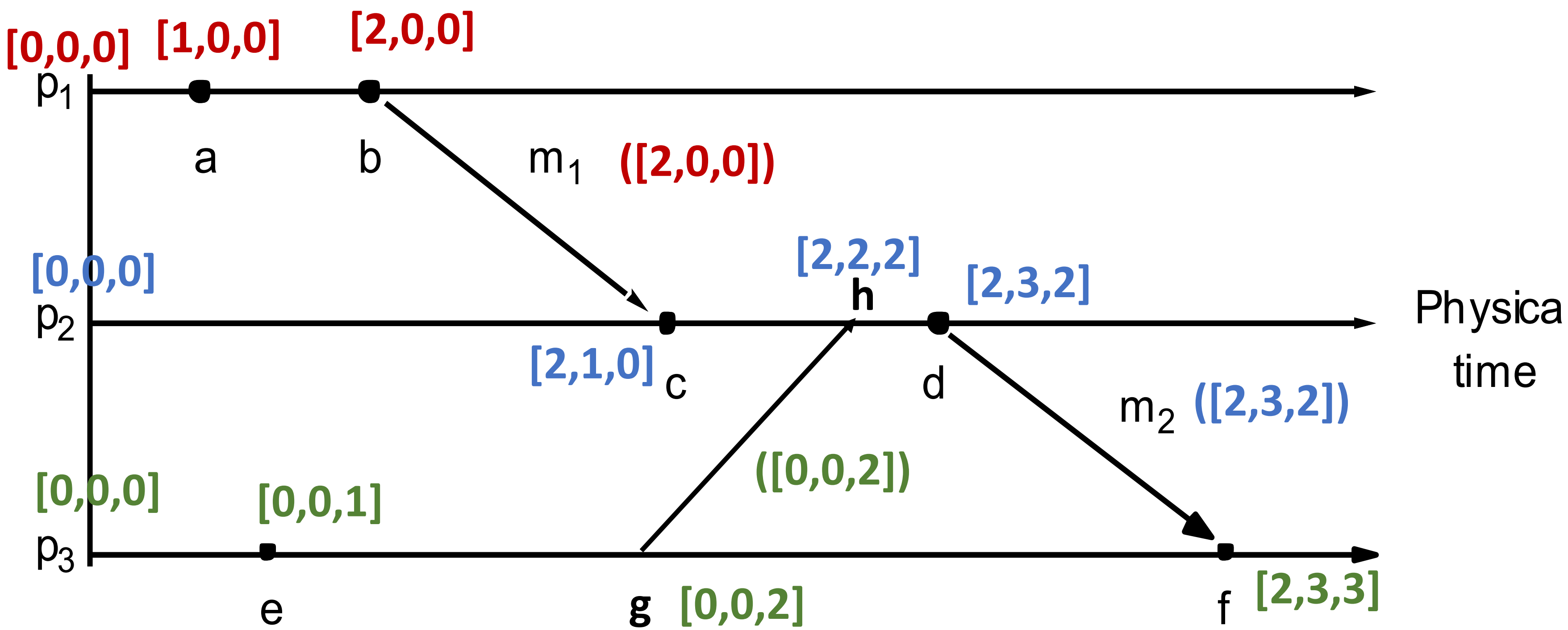
$V(e) \not< V(d)$ and $V(d) \not< V(e)$, $e \parallel d$

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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  - Chapter 14.4
- Global State
  - Chapter 14.5

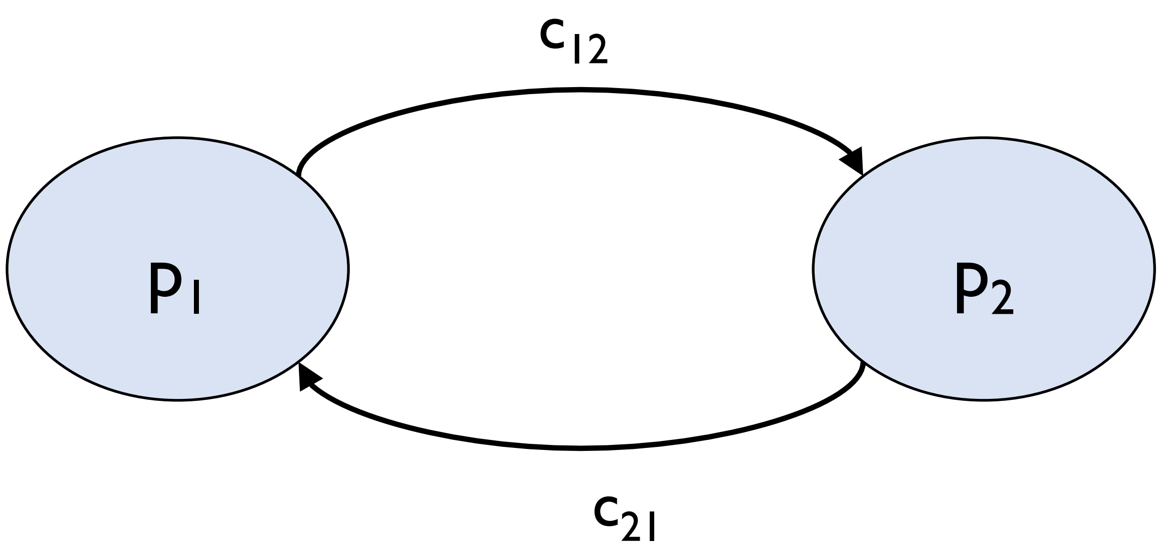
Process, state, events

- 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 p_i sends a message that 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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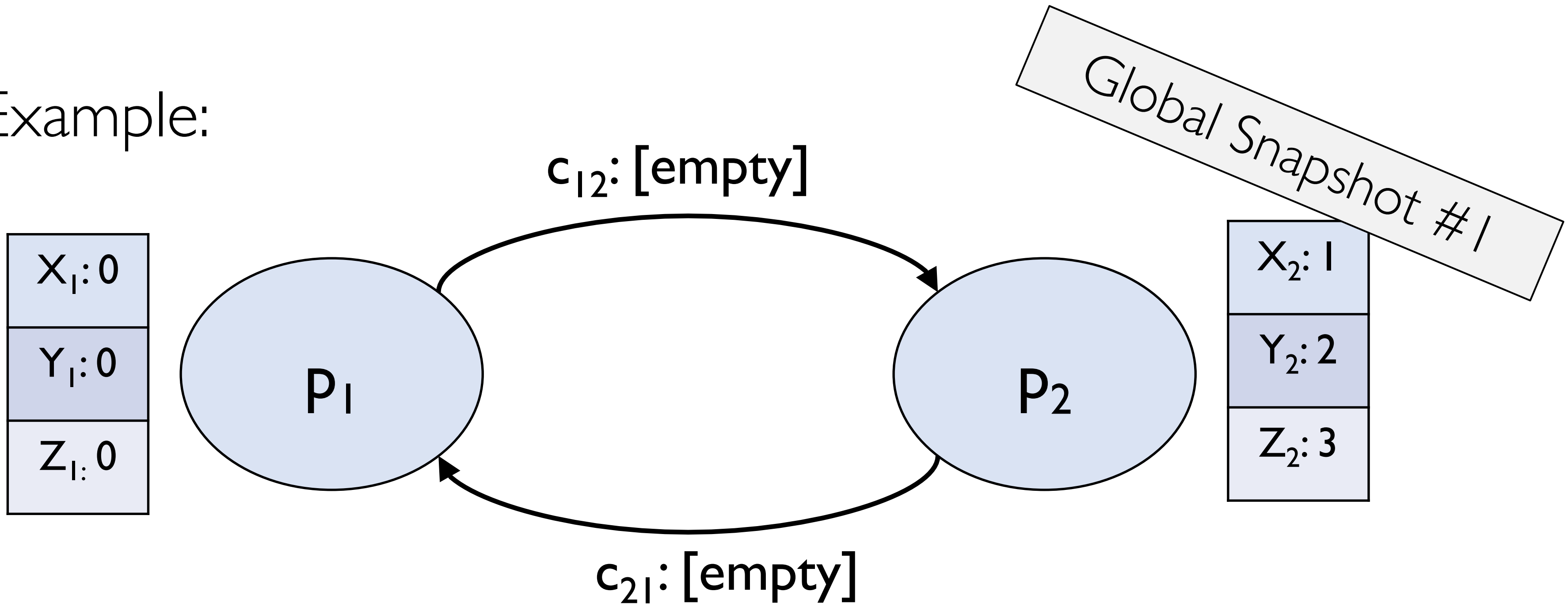

Process state for $\mathbf{p_1}$ and $\mathbf{p_2}$.
No pending messages on the channels.

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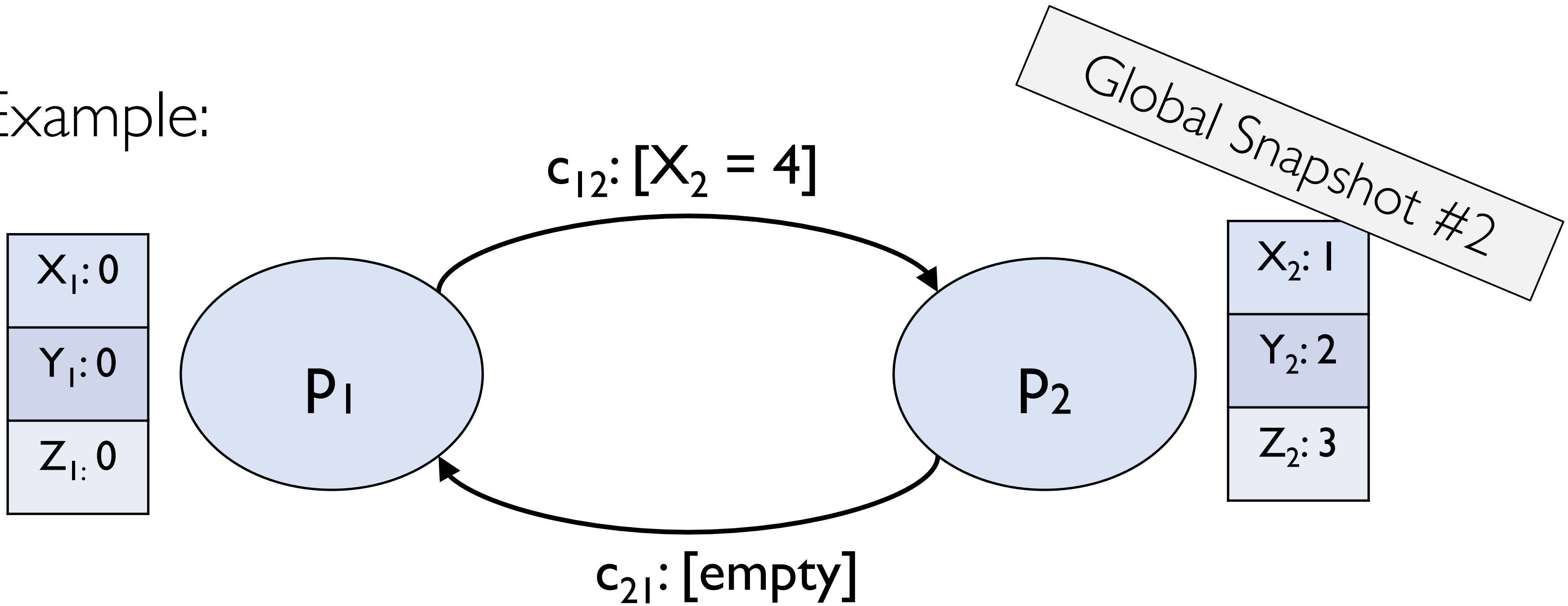

event 1: p_1 sends a message to p_2 asking it to set $X_2 = 4$

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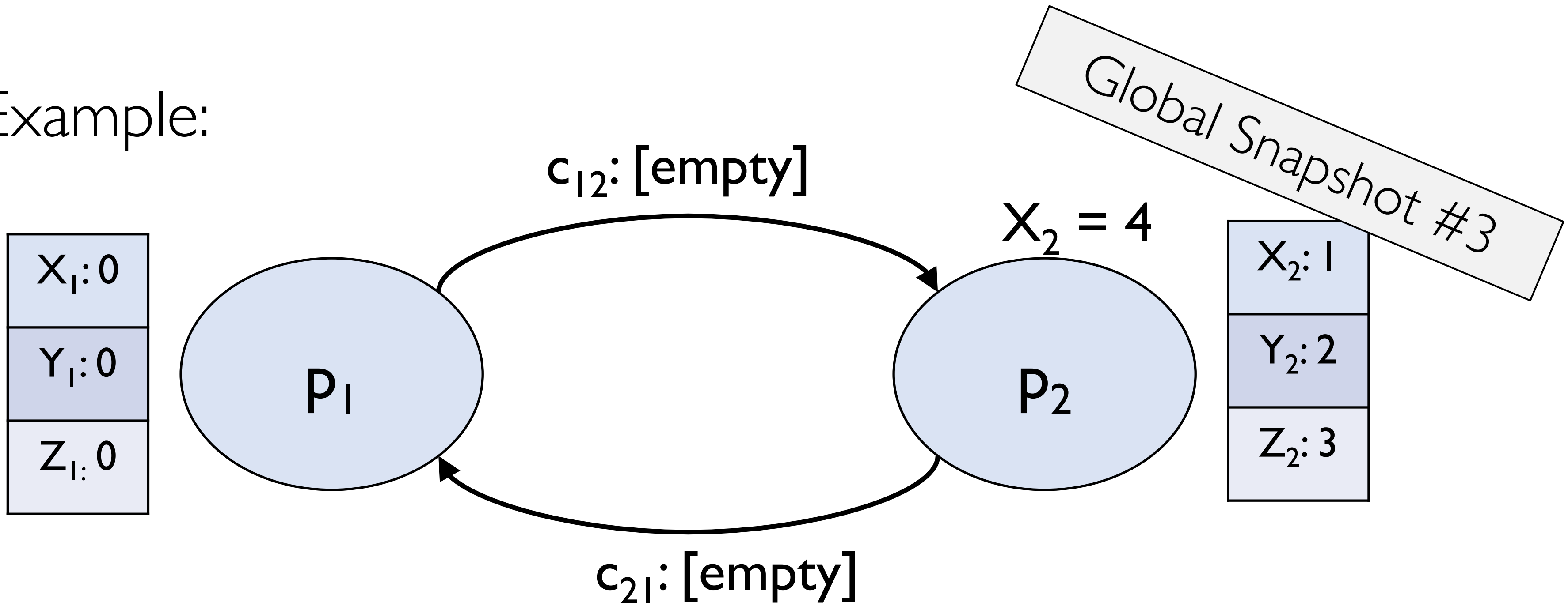

event 2: p_2 receives the message.

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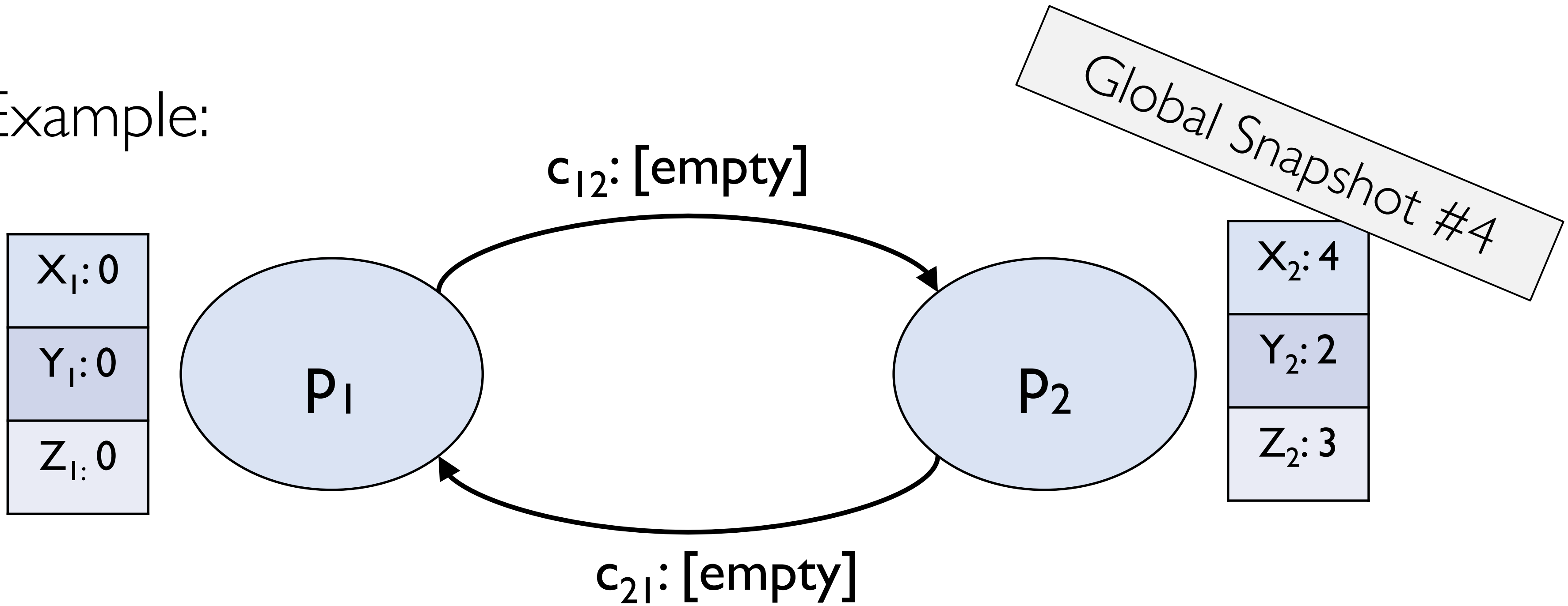

event 3: p_2 changes the value of X_2

Capturing a global snapshot

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

Capturing a global snapshot

- Difficult to capture a global snapshot of the system.
- Global state or global snapshot is state of each process (and each channel) in the system at a given *instant of time*.
- Strawman:
    - Each process records its state at 3:15pm.
    - We get the global state of the system at 3:15pm.
    - *But precise clock synchronization is difficult to achieve.*
- **How do we capture global snapshots without precise time synchronization across processes?**

Some more notations and definitions

- 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.

- $\mathbf{e_i^n}$ is the n^{th} event at $\mathbf{p_i}$.

Some more notations and definitions

- For a process p_i , where events $e_i^0, e_i^1, \ldots$ occur:

  history(p_i) = $h_i = <e_i^0, e_i^1, \ldots>$

  prefix history(p_i^k) = $h_i^k = <e_i^0, e_i^1, \ldots, e_i^k>$

  s_i^k : p_i's state immediately after k^{th} event.

- For a set of processes $<p_1, p_2, p_3, \ldots, p_n>$:

  global history: $H = \cup_i (h_i)$

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  But state at what time instant?

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  global history: $H = \cup_i (h_i)$

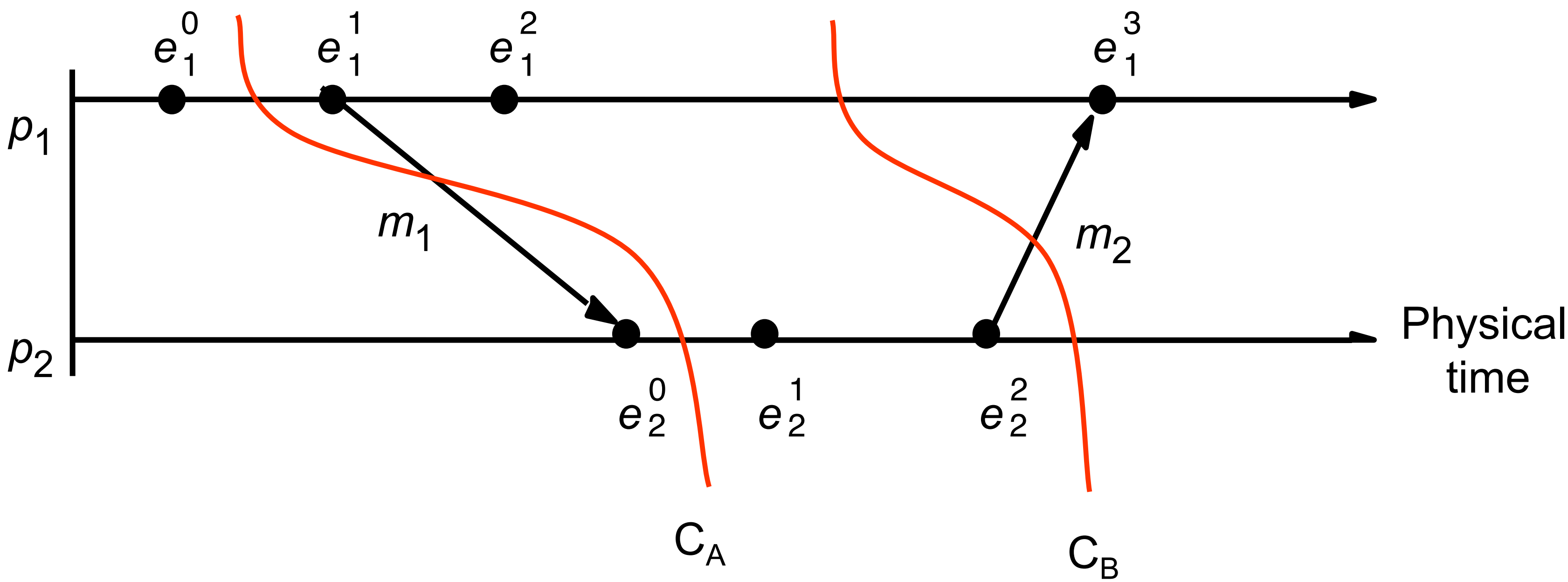
  global state: $S = \cup_i (s_i^{c_i})$

  a cut $C \subseteq H = h_1^{c_1} \cup h_2^{c_2} \cup \ldots \cup h_n^{c_n}$

  the frontier of $C = \{e_i^{c_i}, i = 1,2, \ldots n\}$

  global state S that corresponds to cut $C = \cup_i (s_i^{c_i})$

Example: Cut



C_A: < e_1^0, e_2^0>

Frontier of C_A:

C_B: < e_1^0, e_1^1, e_1^2, e_2^0, e_2^1 e_2^2 >

Frontier of C_B:

Some more notations and definitions

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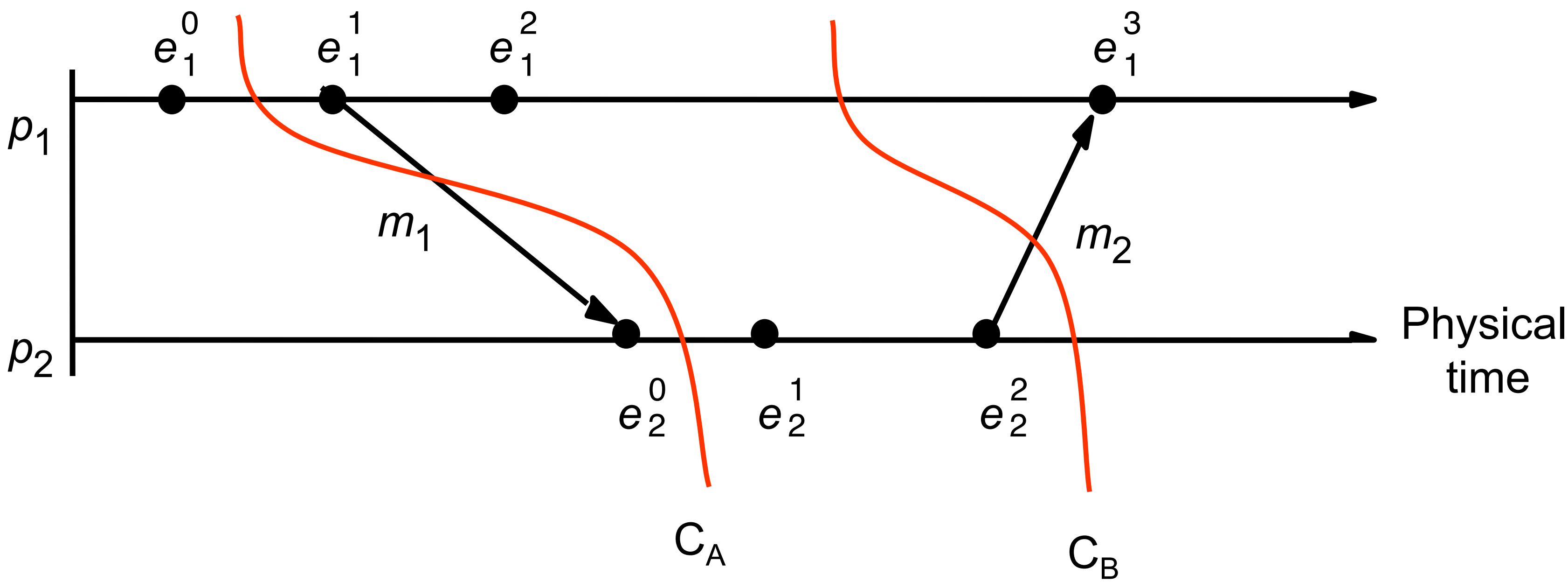
Consistent cuts and snapshots

- A cut **C** is **consistent** if and only if

$$\forall \mathbf{e} \in \mathbf{C} \ (\text{if } \mathbf{f} \rightarrow \mathbf{e} \text{ then } \mathbf{f} \in \mathbf{C})$$

Example: Cut



C_A: < e_1^0, e_2^0>
Frontier of C_A: {e_1^0, e_2^0}
Inconsistent cut.

C_B: < e_1^0, e_1^1, e_1^2, e_2^0, e_2^1 e_2^2 >
Frontier of C_B: {e_1^2, e_2^2}
Consistent cut.

Consistent cuts and snapshots

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- A global state **S** is consistent if and only if it corresponds to a consistent cut.

Consistent cuts and snapshots

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- A global state **S** is consistent if and only if it corresponds to a consistent cut.

How to capture global state?

- State of each process (and each channel) in the system *at a given instant of time.*
  - Difficult to capture -- requires precisely synchronized time.

- Relax the problem: find a consistent global state.
  - For a system with n processes <p_1, p_2, p_3, …., p_n>, capture the state of the system after the c_i th event at process p_i.
    - State corresponding to the cut defined by frontier events $\{e_i^{c_i}$, for $i = 1,2, \ldots n\}$.
  - We want the state to be consistent.
    - Must correspond to a consistent cut.

How to find consistent global state?

Chandy-Lamport Algorithm

- Goal:
  - Record a global snapshot
    - Process state (and channel state) for a set of processes.
  - The recorded global state is consistent.
- Identifies a consistent cut.
- Records corresponding state locally at each process.

Chandy-Lamport Algorithm

- *System model and assumptions:*
  - System of **n** processes: $<p_1, p_2, p_3, \ldots, p_n>$.
  - There are two uni-directional communication channels between each ordered process pair : p_j to p_i and p_i to p_j.
  - Communication channels are FIFO-ordered (first in first out).
  - All messages arrive intact, and are not duplicated.
  - No failures: neither channel nor processes fail.

- *Requirements:*
  - Snapshot should not interfere with normal application actions, and it should not require application to stop sending messages.
  - Any process may initiate algorithm.

Chandy-Lamport Algorithm

- To be continued in next class….