Distributed Systems

ECE428

Lecture 4

Adopted from Spring 2021

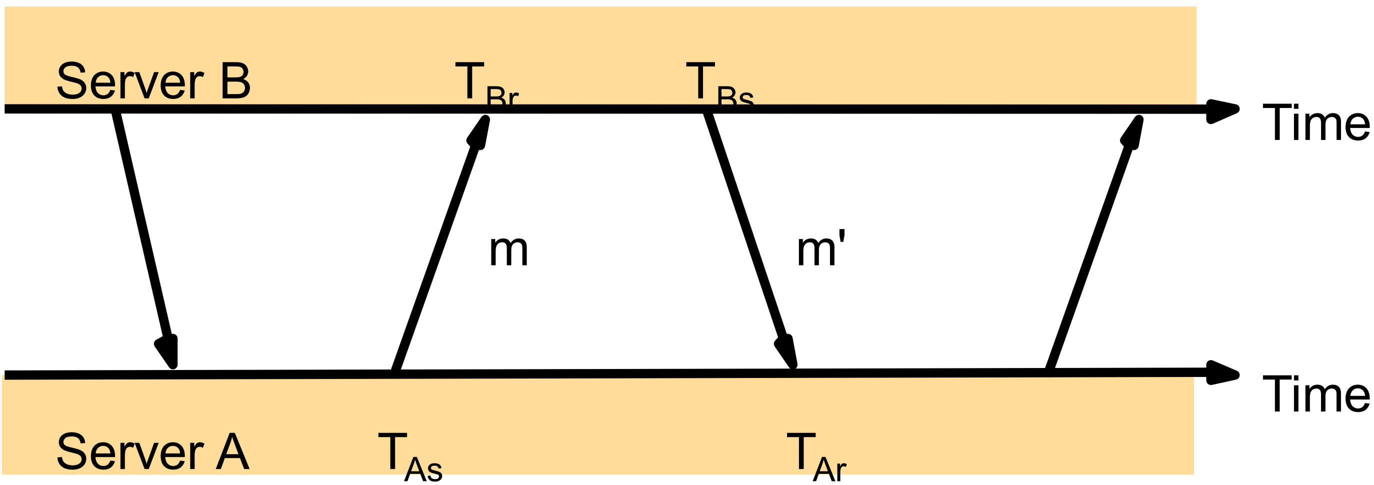
Something to think while we wait…

- What are the practical use-cases of clocks and timestamps?
- Do we necessarily need synchronization to reason about ordering of events across processes?

Quick Recap: Clock Synchronization

- Synchronization in synchronous systems:
  - Synchronization bound = *(max – min)/2*
- Synchronization in asynchronous systems:
  - Cristian Algorithm: Synchronization between a client and a server.
    - Synchronization bound = $(T_{round} / 2) - min \leq T_{round} / 2$
  - Berkeley Algorithm: internal synchronization between clocks.
    - A central server picks the average time and disseminates offsets.
  - Network Time Protocol: Hierarchical time synchronization over the Internet.
    - Symmetric mode synchronization between lower strata servers for greater accuracy.

NTP Symmetric Mode



- t and t': actual transmission times for m and m'(unknown)
- o: true offset of clock at B relative to clock at A (unknown)
- o_i: estimate of actual offset between the two clocks
- d_i: estimate of accuracy of o_i ; $d_i = t + t'$
- skew estimate = $d_i/2$

$$T_{Br} = T_{As} + t + o$$

$$T_{Ar} = T_{Bs} + t' - o$$

$$o = ((T_{Br} - T_{As}) - (T_{Ar} - T_{Bs}) + (t' - t))/2$$

$$o_i = ((T_{Br} - T_{As}) - (T_{Ar} - T_{Bs}))/2$$

$$o = o_i + (t' - t)/2$$

$$d_i = t + t' = (T_{Br} - T_{As}) + (T_{Ar} - T_{Bs})$$

$$(o_i - d_i / 2) \leq o \leq (o_i + d_i / 2) \text{ given } t, t' \geq 0$$

Today's agenda

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

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- Logical Clocks and Timestamps
  - Chapter 14.4
- Global State
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Event Ordering

- A use-case of synchronized clocks:
  - Reasoning about order of events.
- 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 p_i is described by its *state* s_i that gets transformed over time.
  - State includes values of all local variables, affected files, etc.
- 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 p_i, based on their time of occurrence.

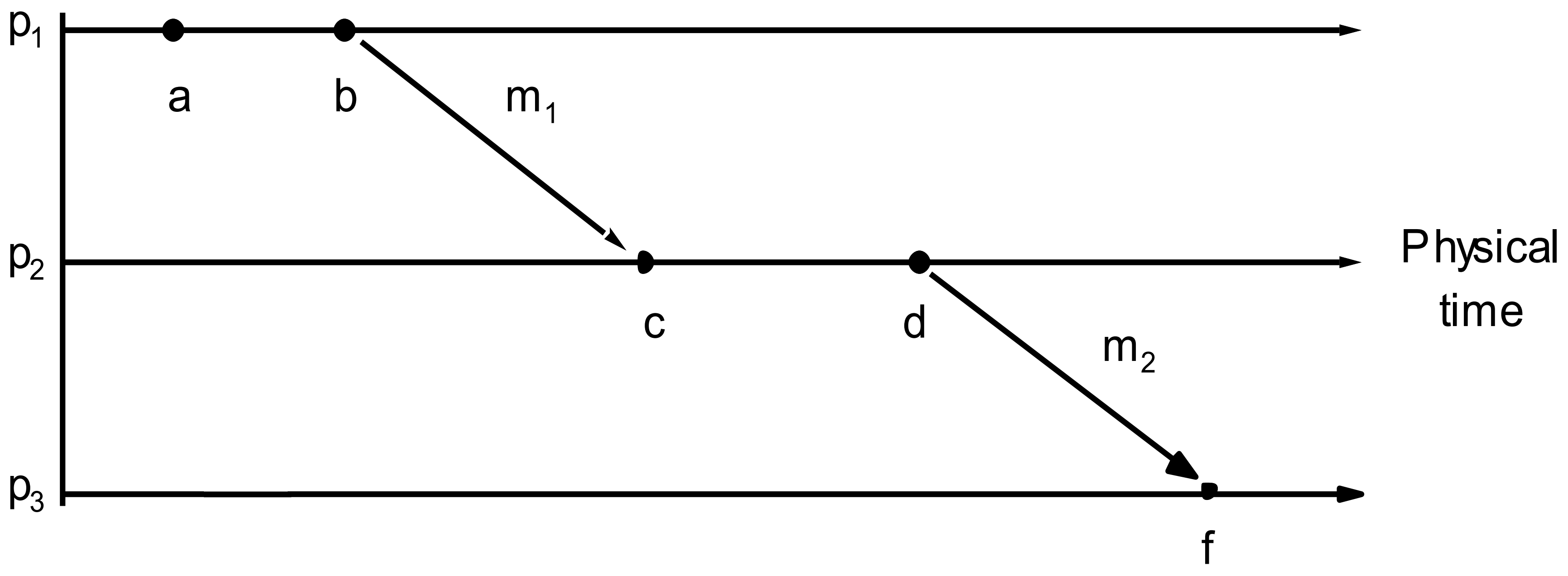
- How do we reason about events across processes?
  - A message must be *sent* before it gets *received* at another process.

- These two notions help define *happened-before* (HB) relationship denoted by $\rightarrow$.
  - $e \rightarrow e'$ 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 p_i.
- HB rules:
  - If $\exists\, p_i$, $e \rightarrow_i e'$ 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

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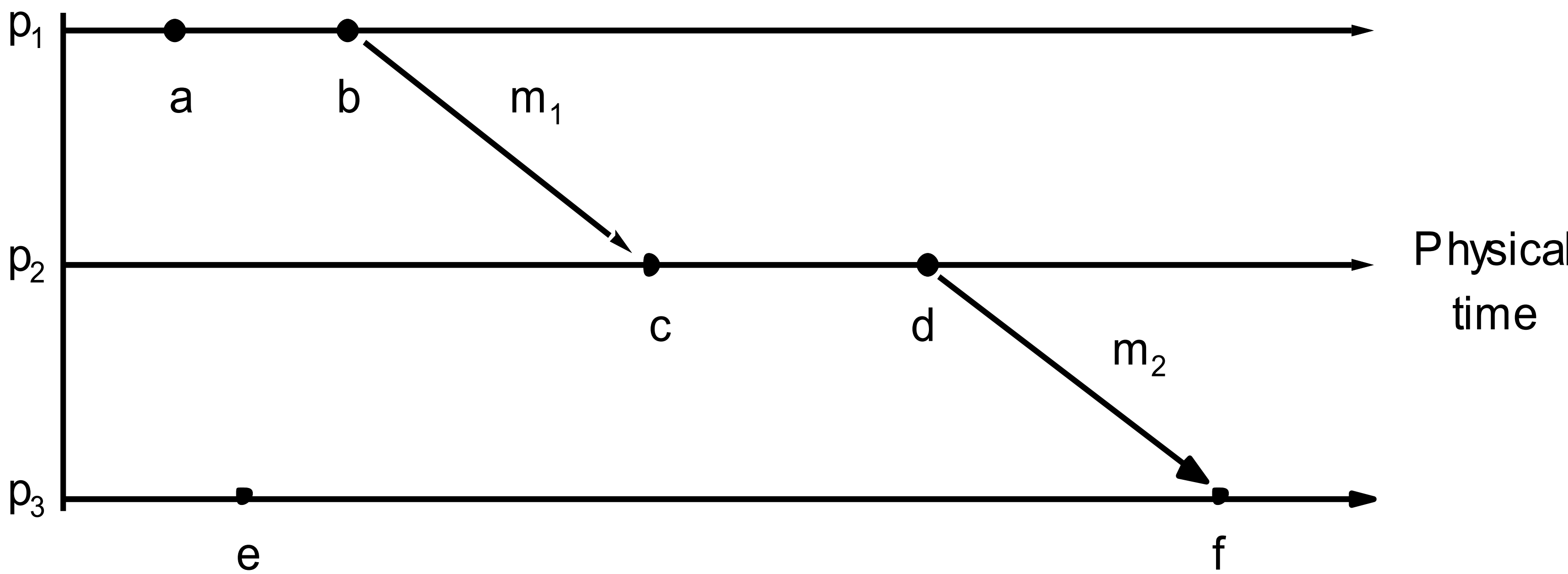
Event Ordering: Example



What can we say about e?

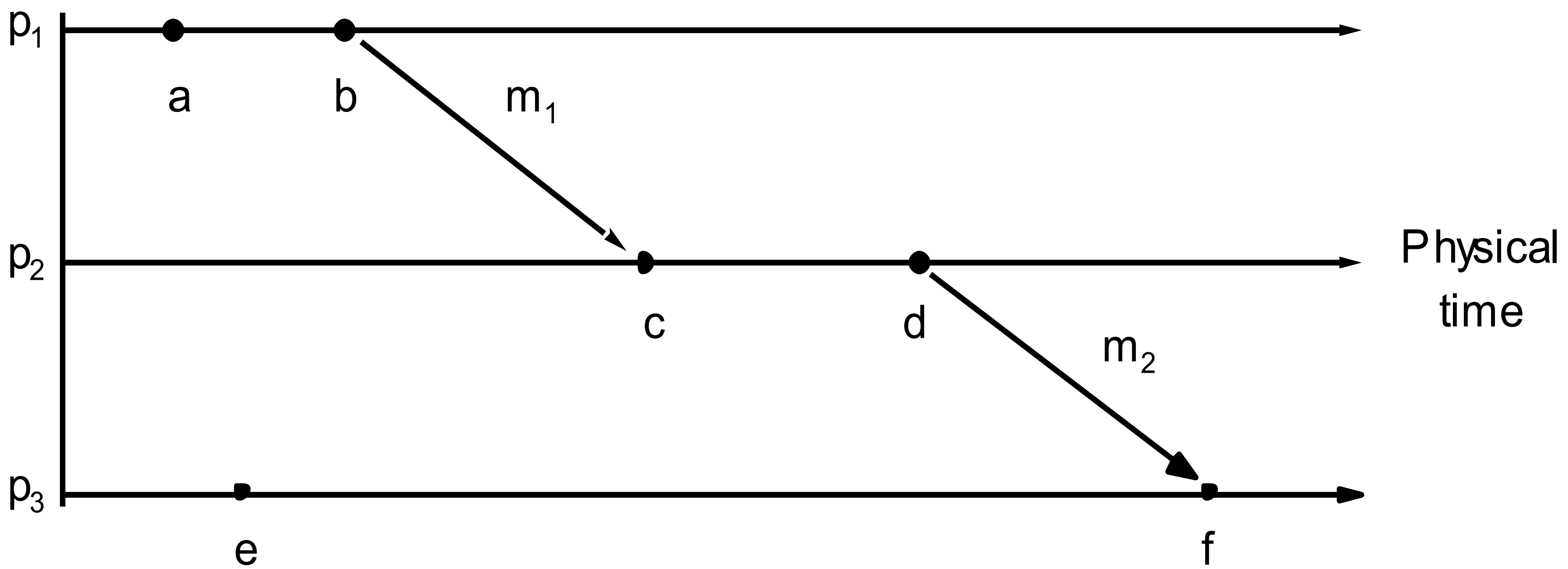
$e \rightarrow f$

$a \nrightarrow e$ and $e \nrightarrow a$

$a \parallel e$

a and e are *concurrent*.

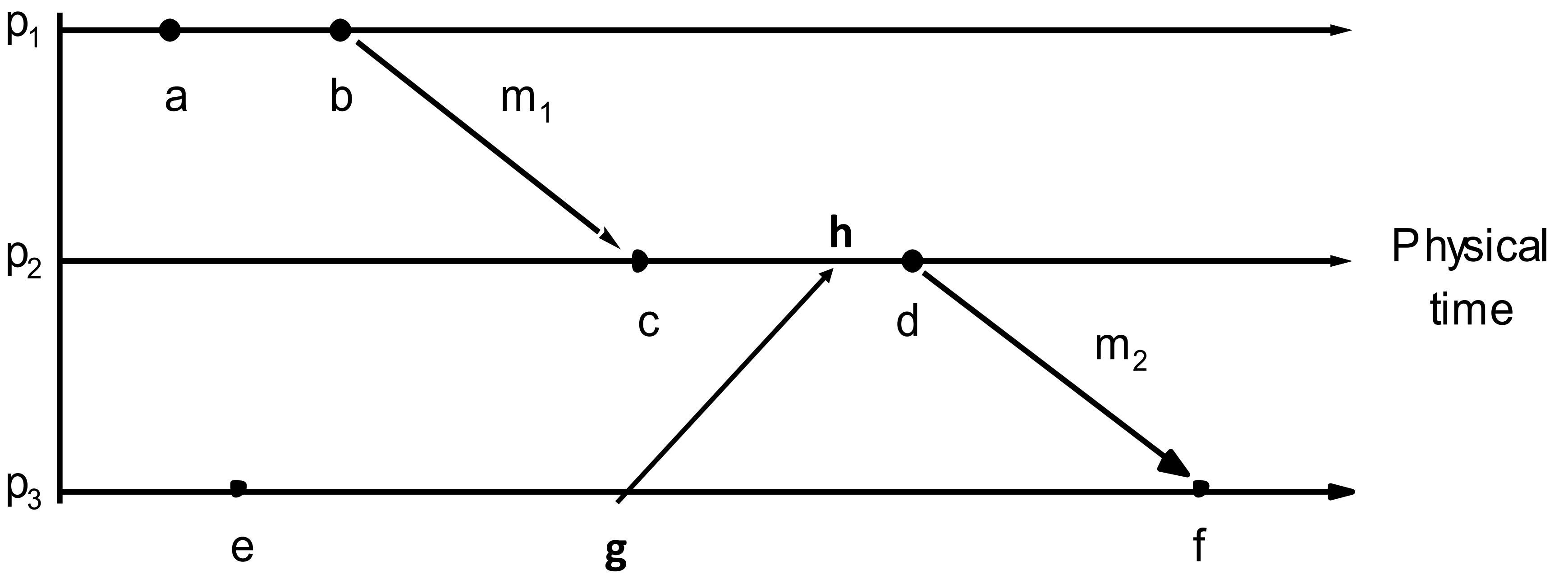
Event Ordering: Example



What can we say about e and d?

e || d

Logical Timestamps: Example



What can we say about e and d?

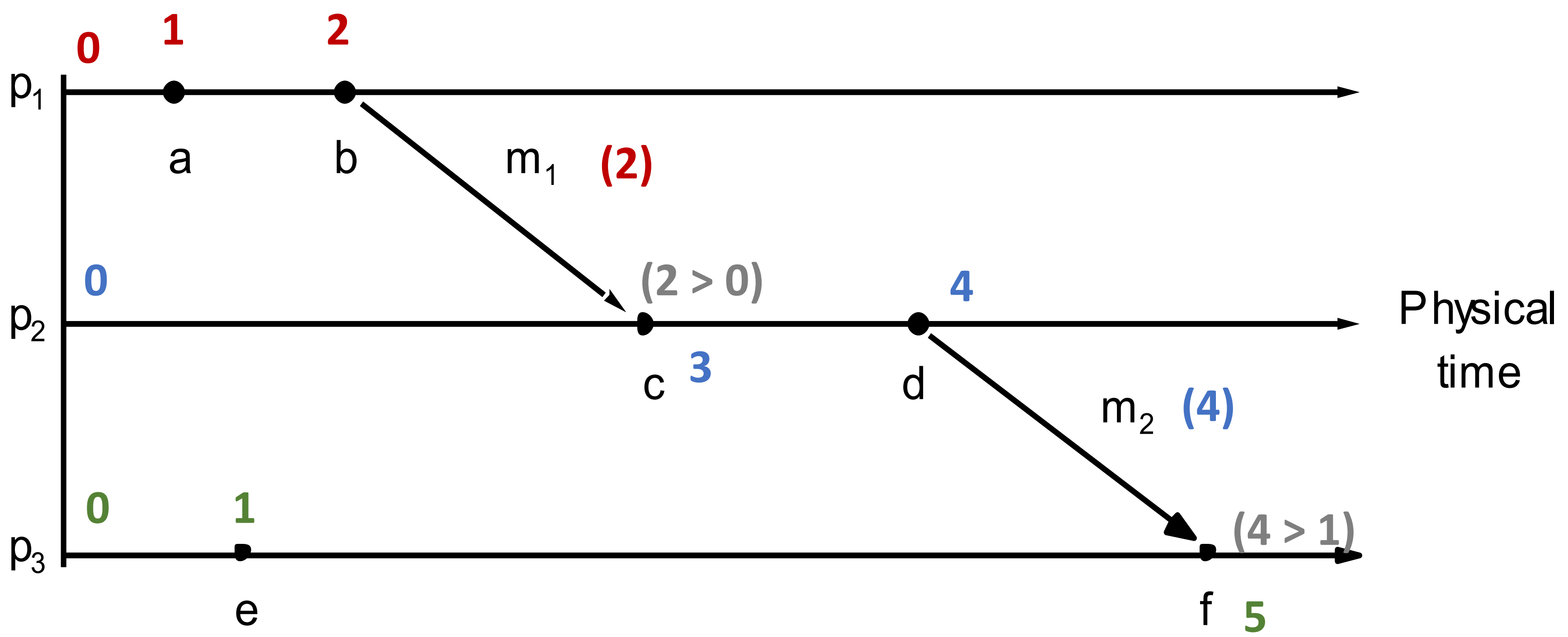
$e \rightarrow d$

Lamport's Logical Clock

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

- *Algorithm:* Each process p_i
  1. initializes local clock L_i = 0.
  2. increments L_i before timestamping each event.
  3. piggybacks L_i when sending a message.
  4. upon receiving a message with clock value t
     - sets $L_i = \max(t, L_i)$
     - increments L_i before timestamping the receive event (as per step 2).

Logical Timestamps: Example



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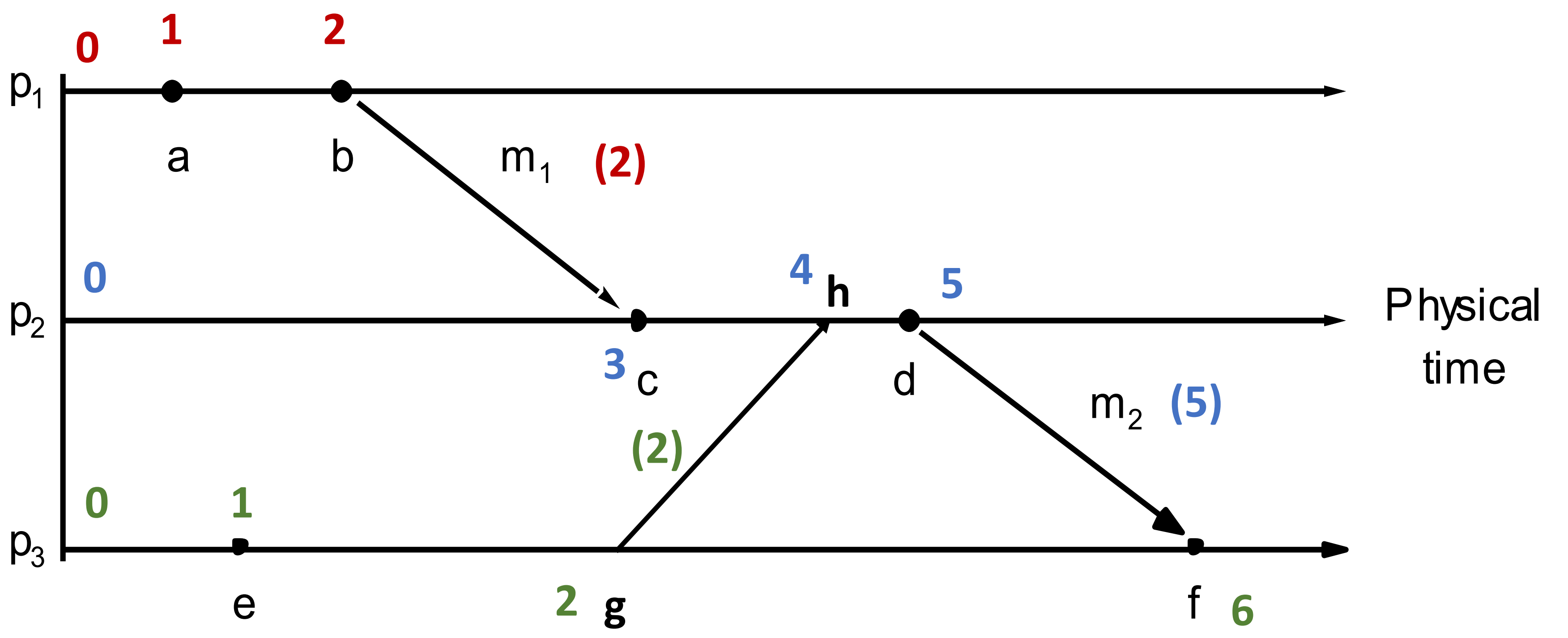
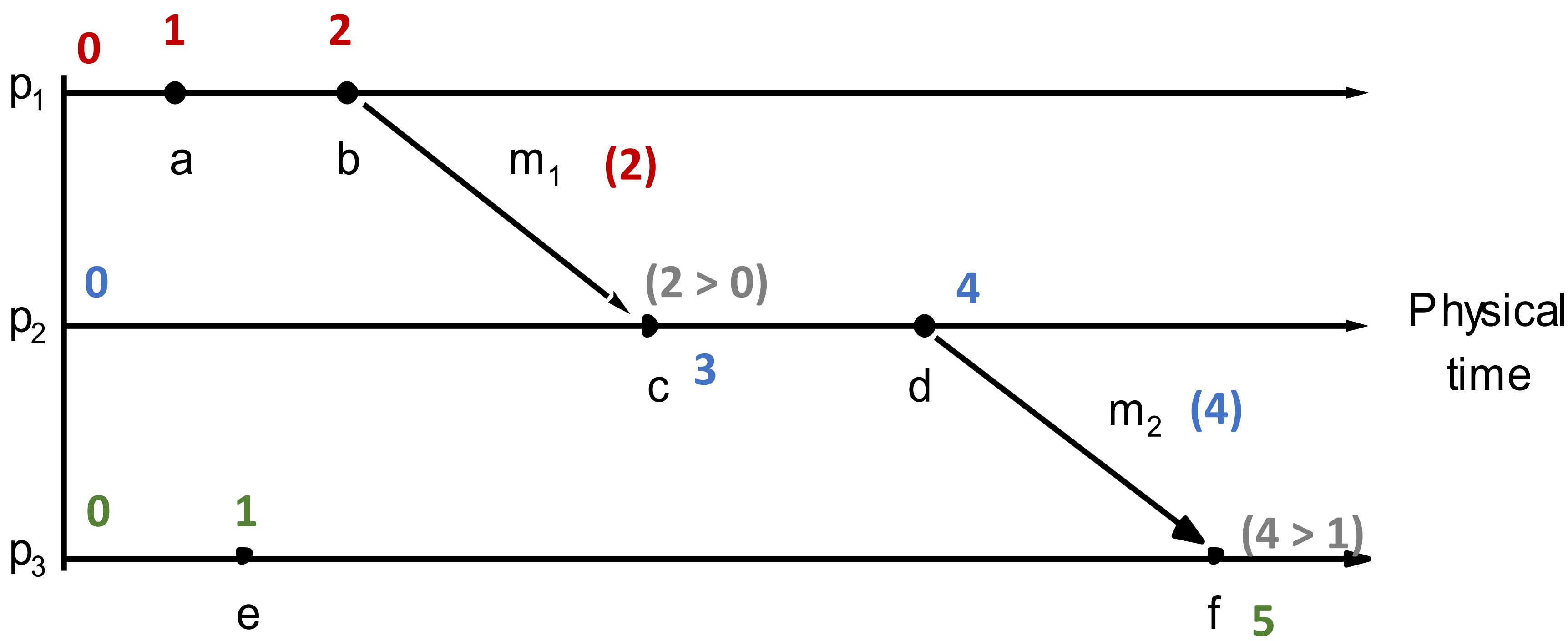


Lamport's Logical Clock

- Logical timestamp for each event that captures the *happened-before* relationship.
- If $e \rightarrow e'$ then $L(e) < L(e')$
- What if $L(e) < L(e')$?
  - We cannot say that $e \rightarrow e'$
  - We can say: $e' \nrightarrow e$
  - Either $e \rightarrow e'$ or $e \parallel e'$

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
- Algorithm: each process p_i:
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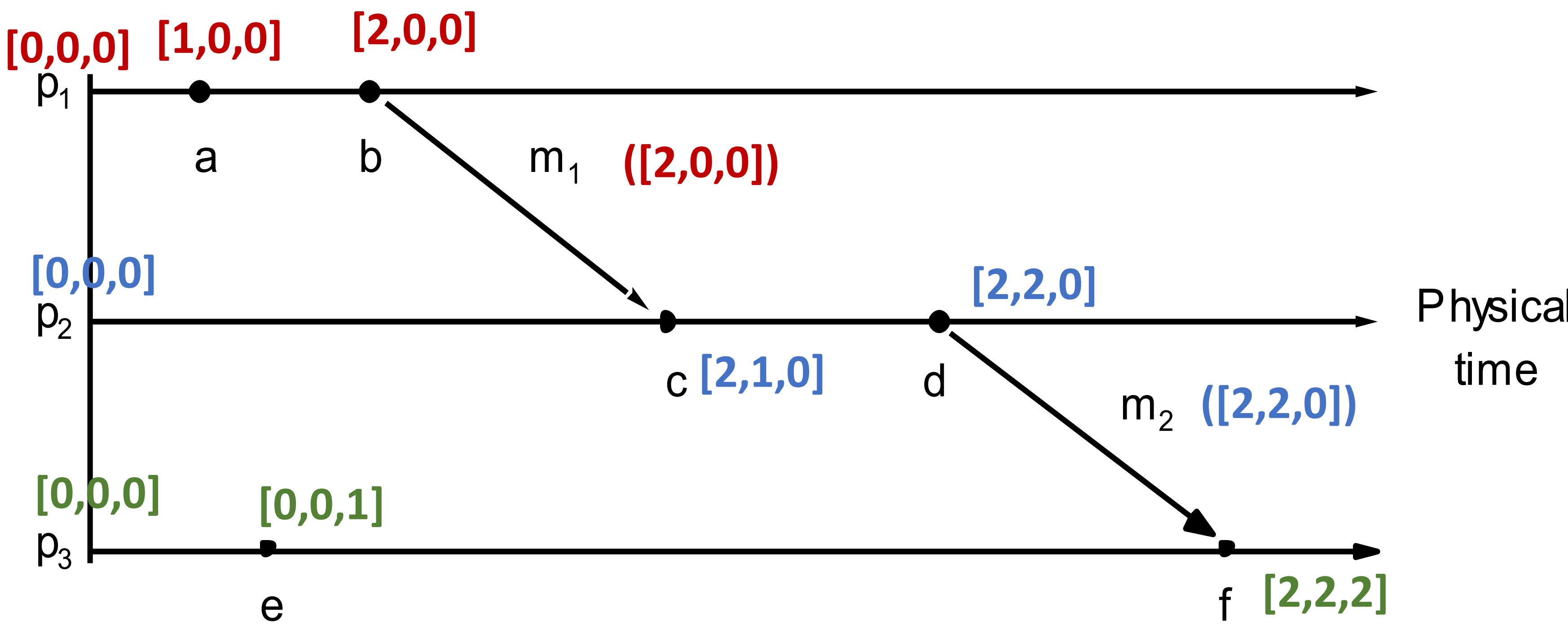
  2. increments $V_i[i]$ before timestamping each event.
  3. piggybacks V_i when sending a message.
  4. upon receiving a message with vector clock value v
     - sets $V_i[j] = \max(V_i[j], v[j])$ for all $j=1\ldots n$.
     - increments $V_i[i]$ before timestamping receive event (as per step 2).

Vector Timestamps: Example



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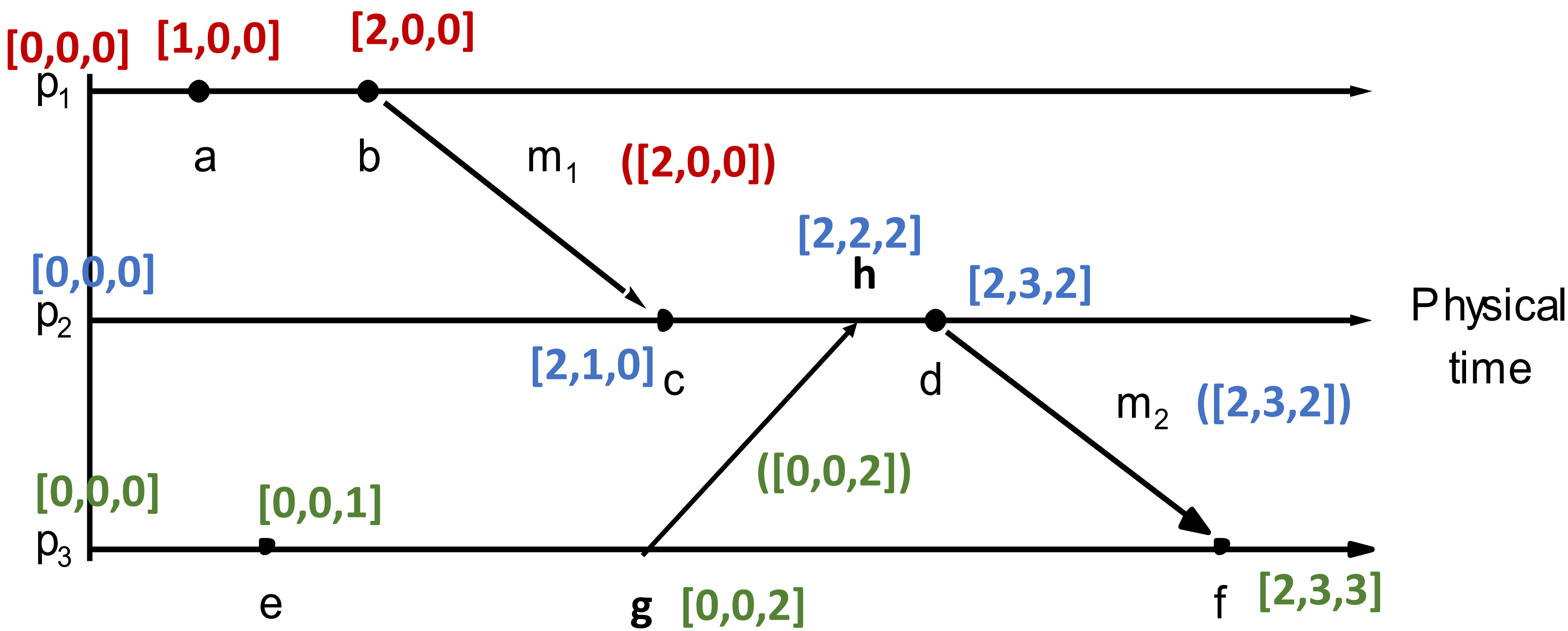


Comparing Vector Timestamps

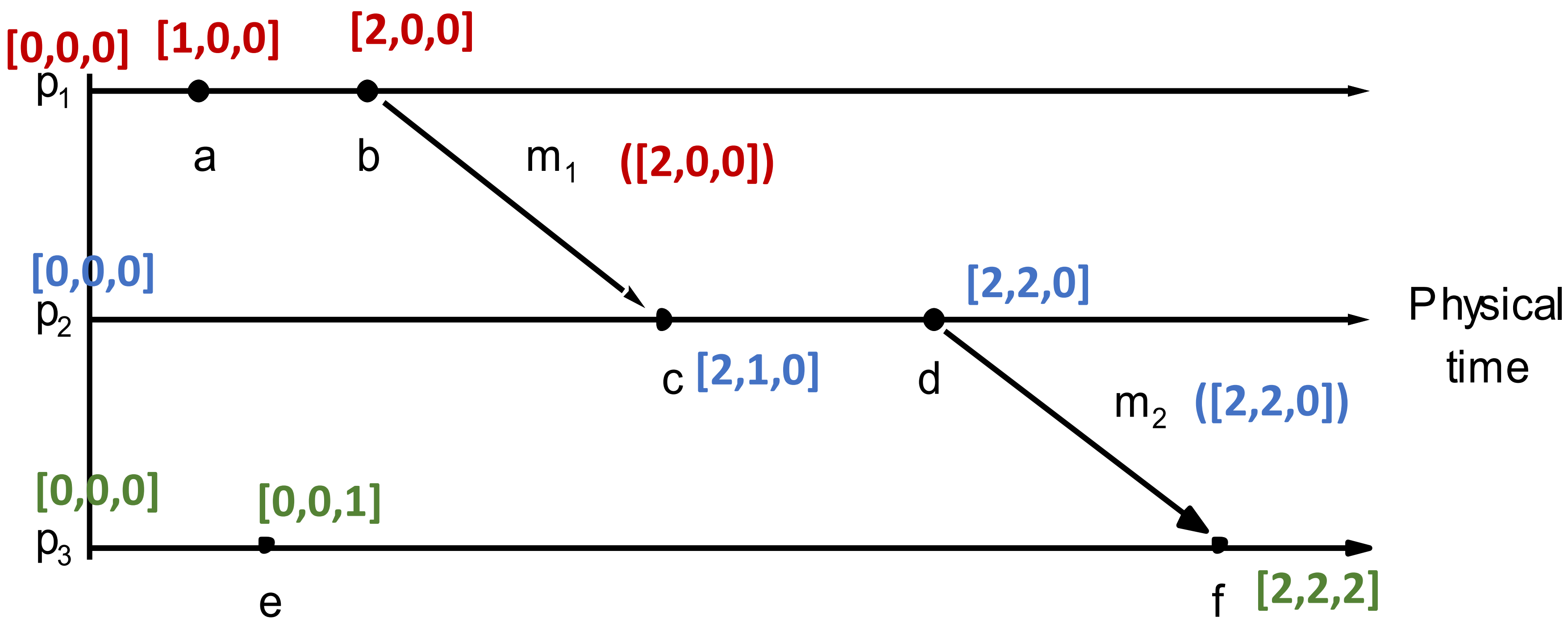
- Let $V(e) = V$ and $V(e') = V'$

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

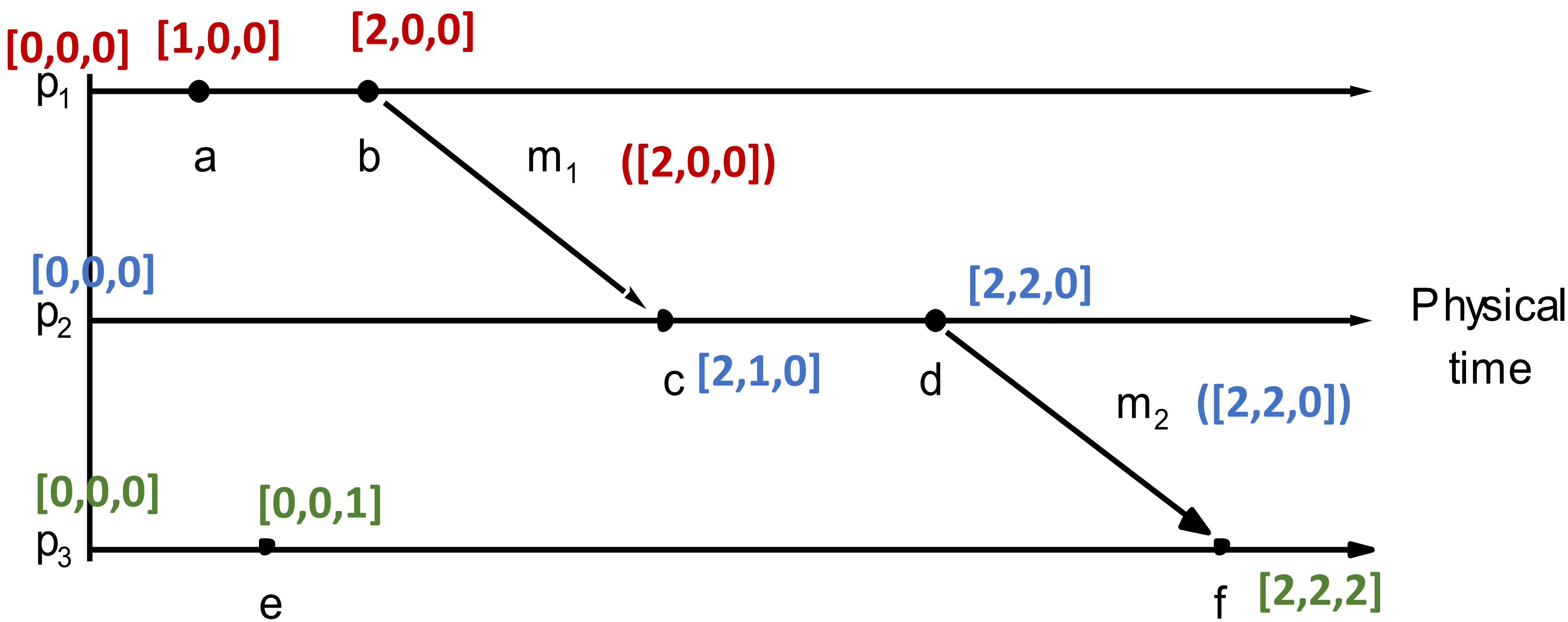
- $e \rightarrow e'$ iff $V < V'$
  - ($V < V'$ implies $e \rightarrow e'$) and ($e \rightarrow e'$ implies $V < V'$)
- $e \parallel e'$ iff ($V \nless V'$ and $V' \nless V$)

Vector Timestamps: Example



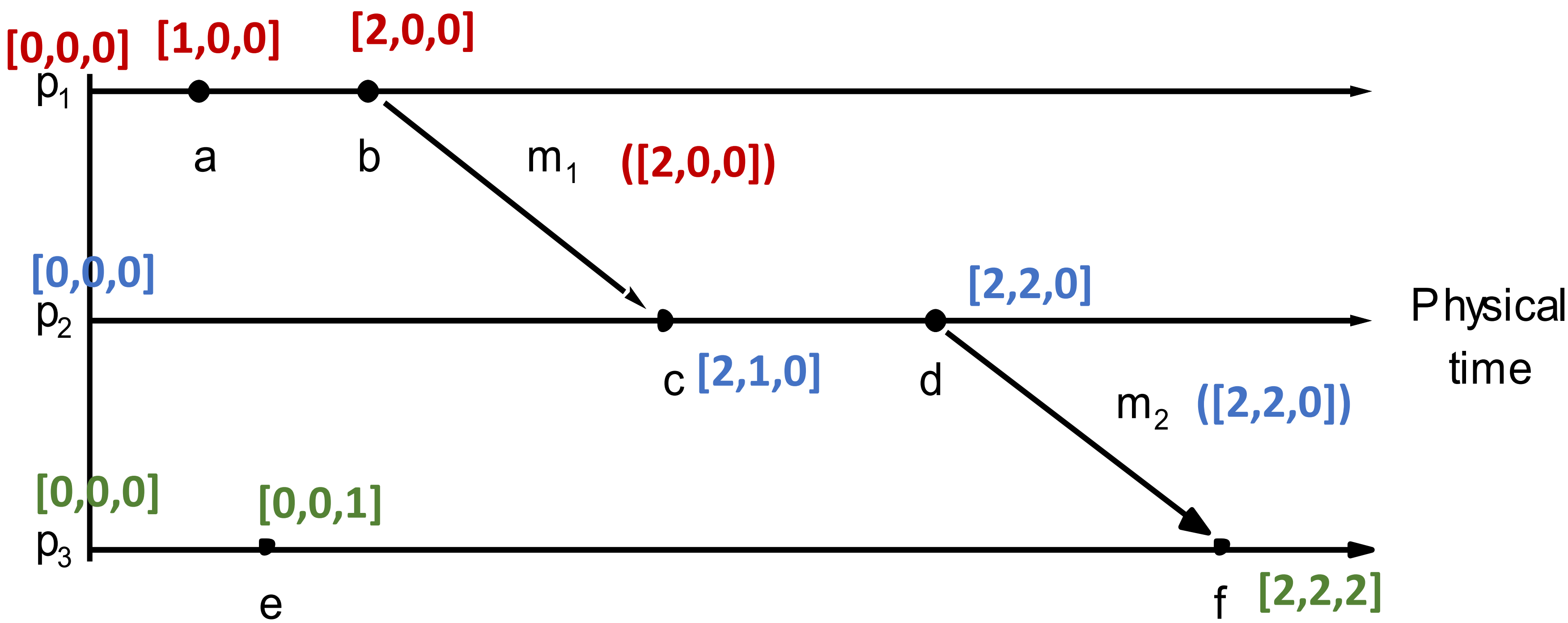
What can we say about e & f based on their vector timestamps?

Vector Timestamps: Example



V(e) < V(f), e → f

Vector Timestamps: Example



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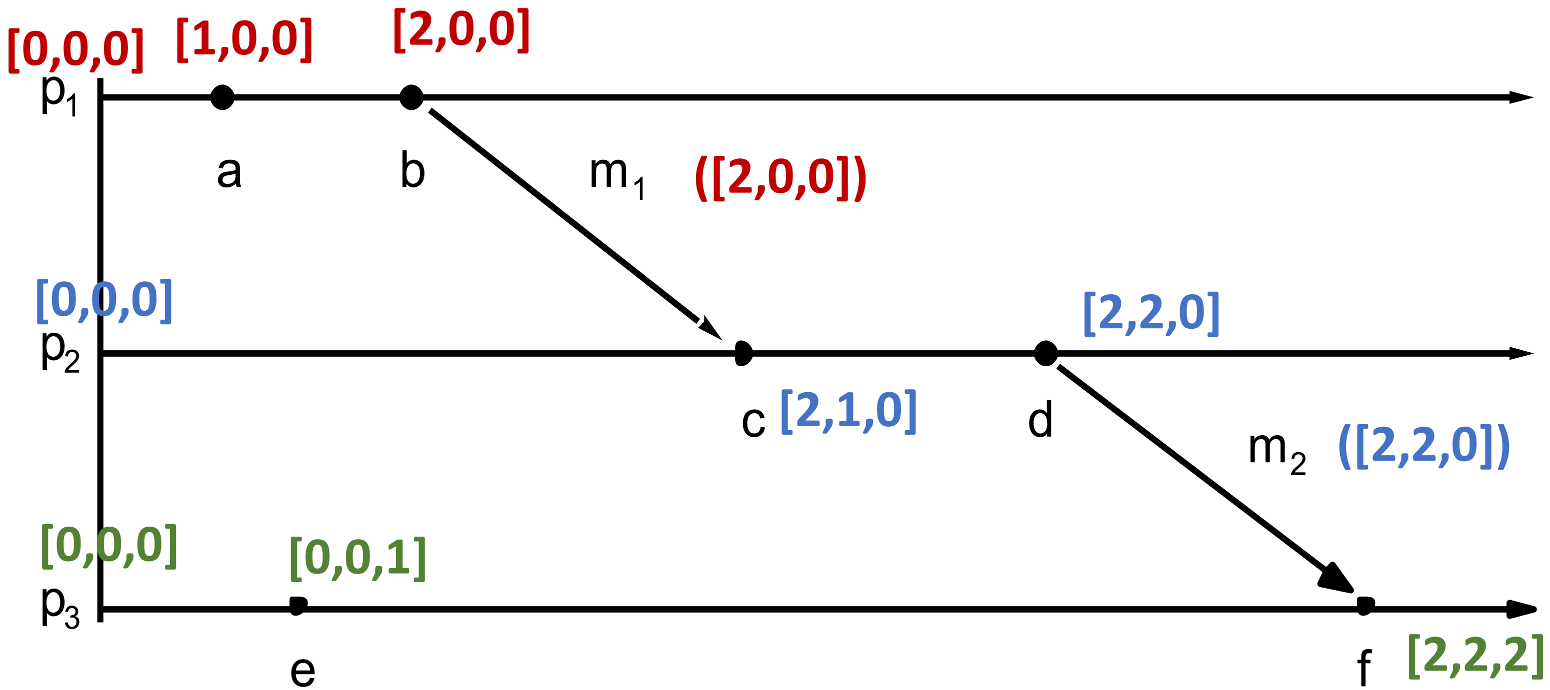
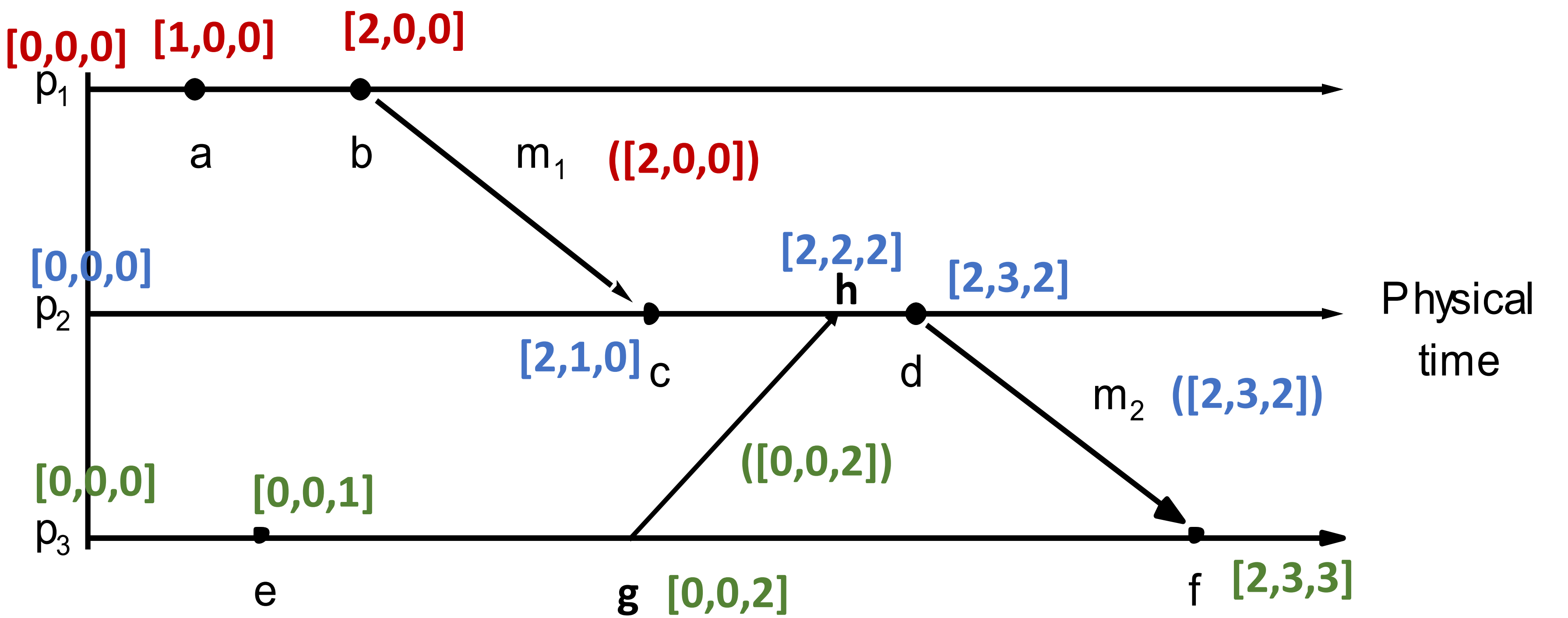


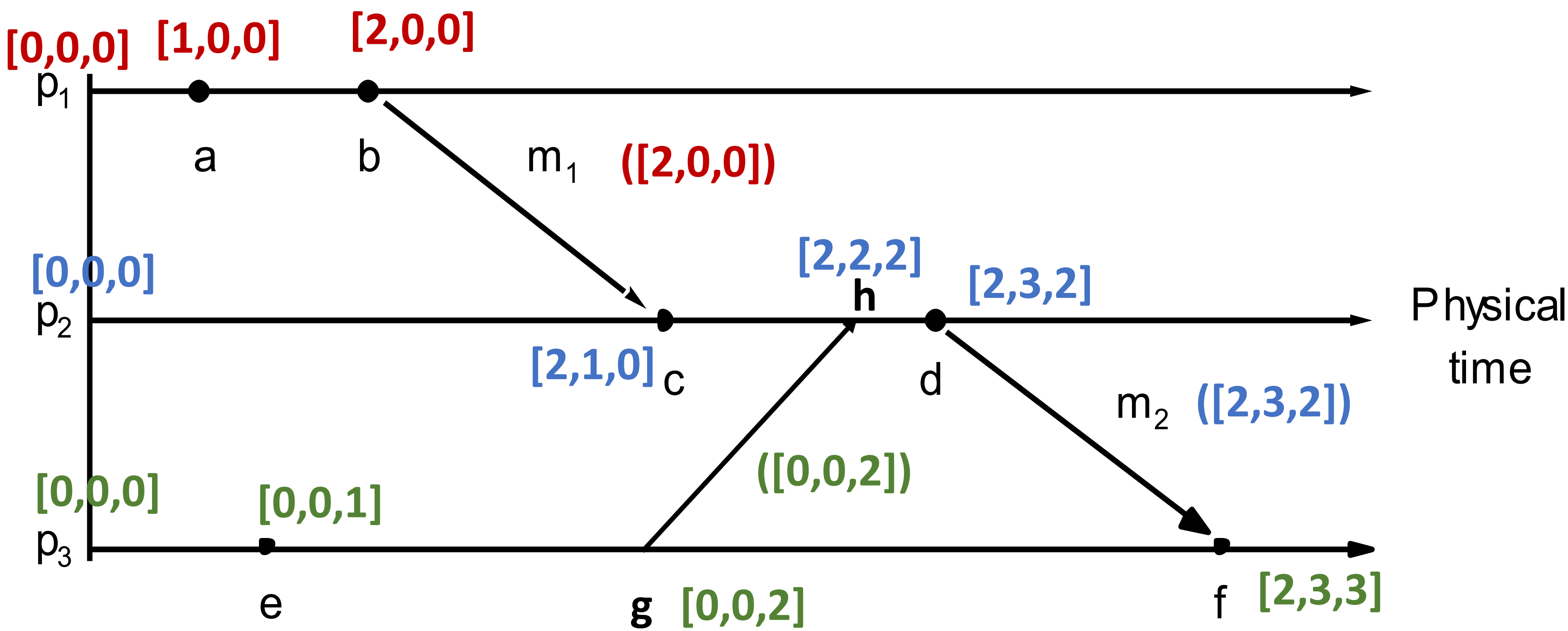
$V(e) \nless V(d)$ and $V(d) \nless V(e)$, $e \parallel d$

Vector Timestamps: Example



How about now?

Vector Timestamps: Example



V(e) < V(f), e → f

V(e) < V(d), e → d

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.