# 416 Distributed Systems

Time Synchronization

(Part 2: Lamport and vector clocks)

Feb 5, 2018

# Important Lessons (last lecture)

- Clocks on different systems will always behave differently
  - Skew and drift between clocks
- Time disagreement between machines can result in undesirable behavior
- Clock synchronization
  - Rely on a time-stamped network messages
  - Estimate delay for message transmission
  - Can synchronize to UTC or to local source
  - Clocks never exactly synchronized
- Often inadequate for distributed systems
  - might need totally-ordered events
  - might need millionth-of-a-second precision

# Today's Lecture

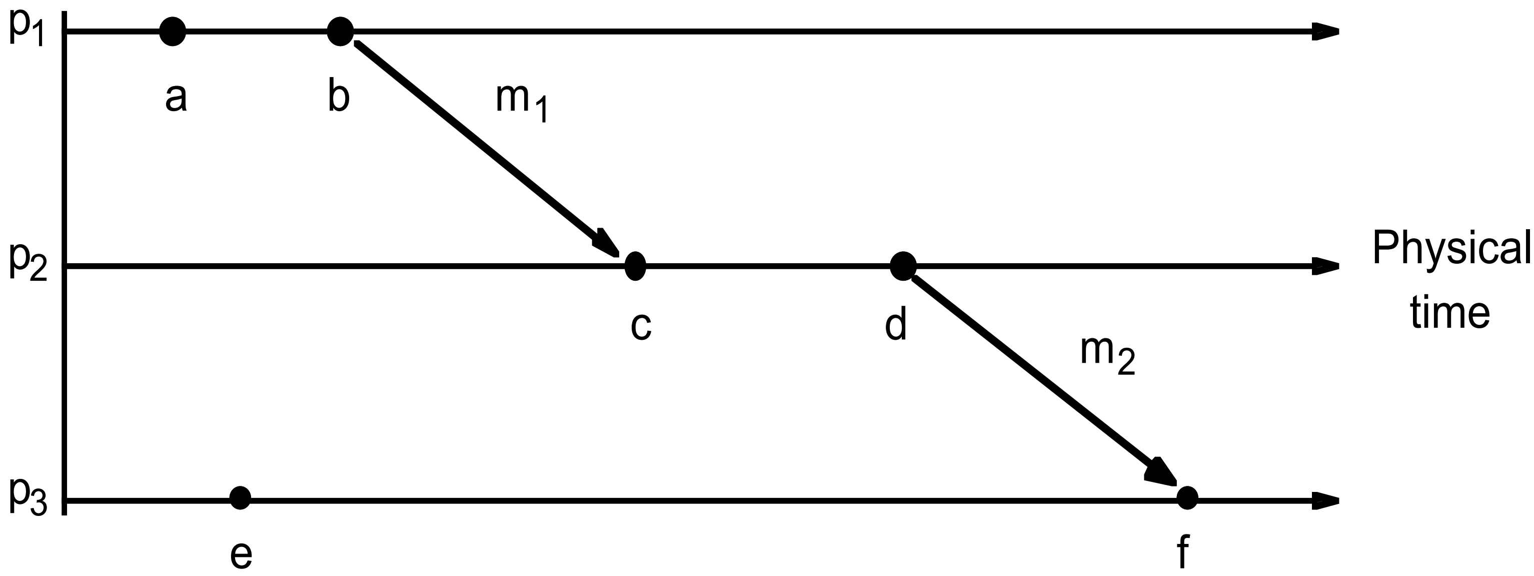
- Need for time synchronization
- Time synchronization techniques
- Lamport Clocks
- Vector Clocks

# Logical time

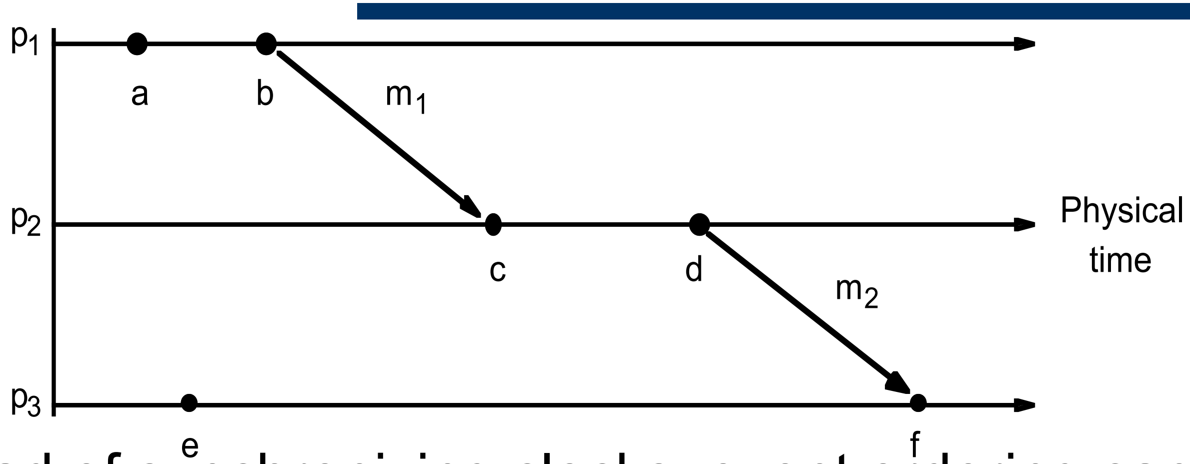
- Capture just the "happens before" relationship between events
  - Discard the infinitesimal granularity of time
  - Corresponds roughly to causality

# Logical time and logical clocks (Lamport 1978)

- Events at three processes



# Logical time and logical clocks (Lamport 1978)

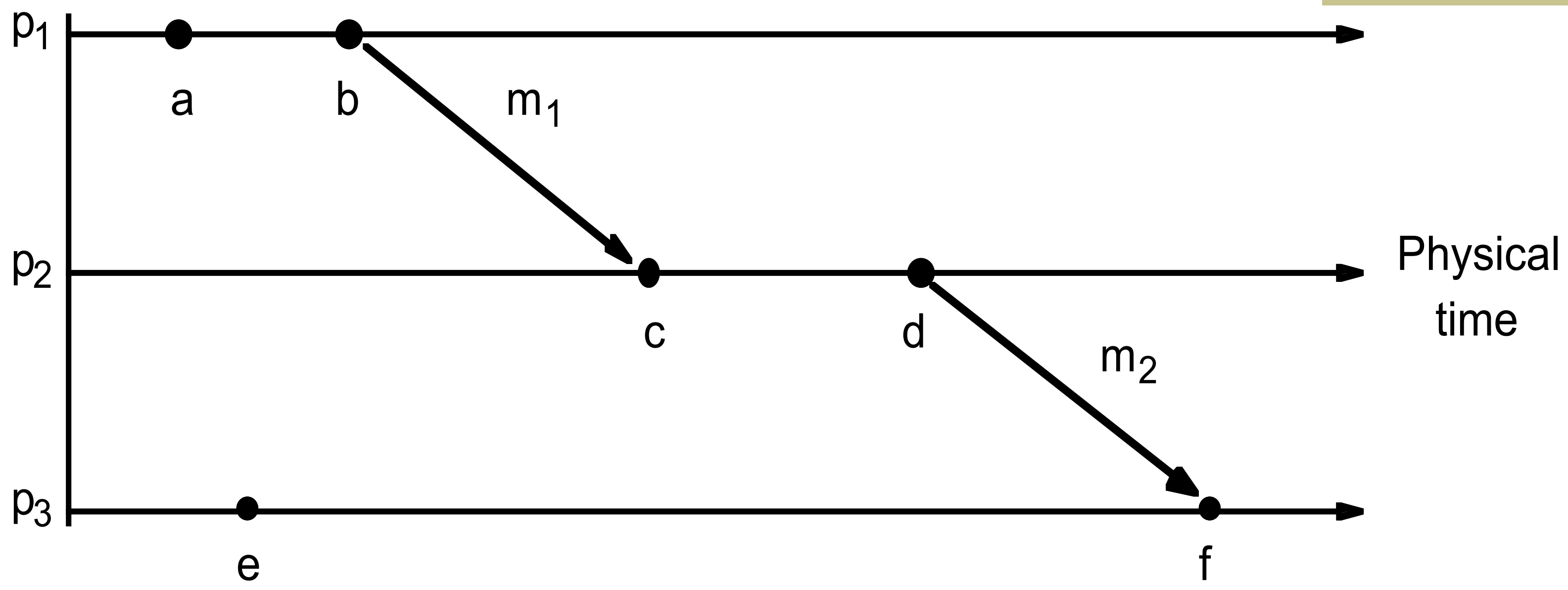



- Instead of synchronizing clocks, event ordering can be used

  1. If two events occurred at the same process $p_i$ ($i = 1, 2, \ldots N$) then they occurred in the order observed by $p_i$, that is the definition of: $\rightarrow_i$
  2. When a message, m is sent between two processes, send(m) 'happens before' receive(m)
  3. The 'happened before' relation is transitive

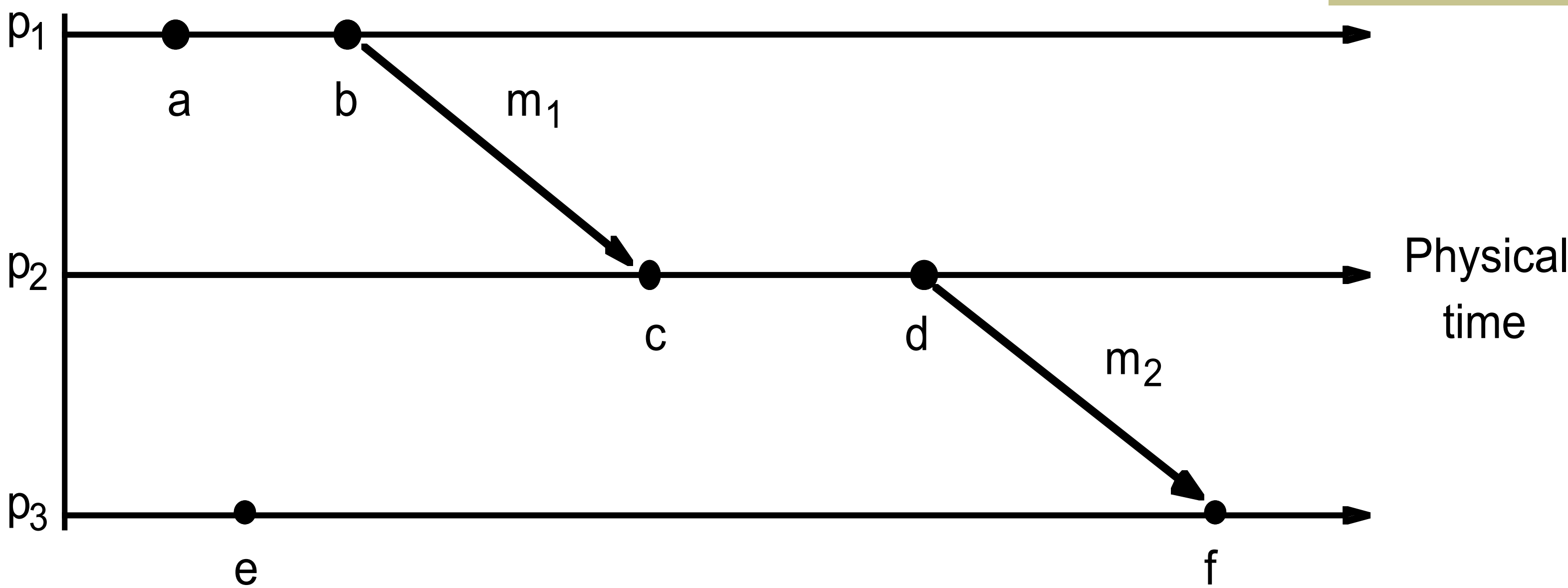
- The happened before relation ($\rightarrow$) is necessary for causal ordering

# Logical time and logical clocks (Lamport 1978)



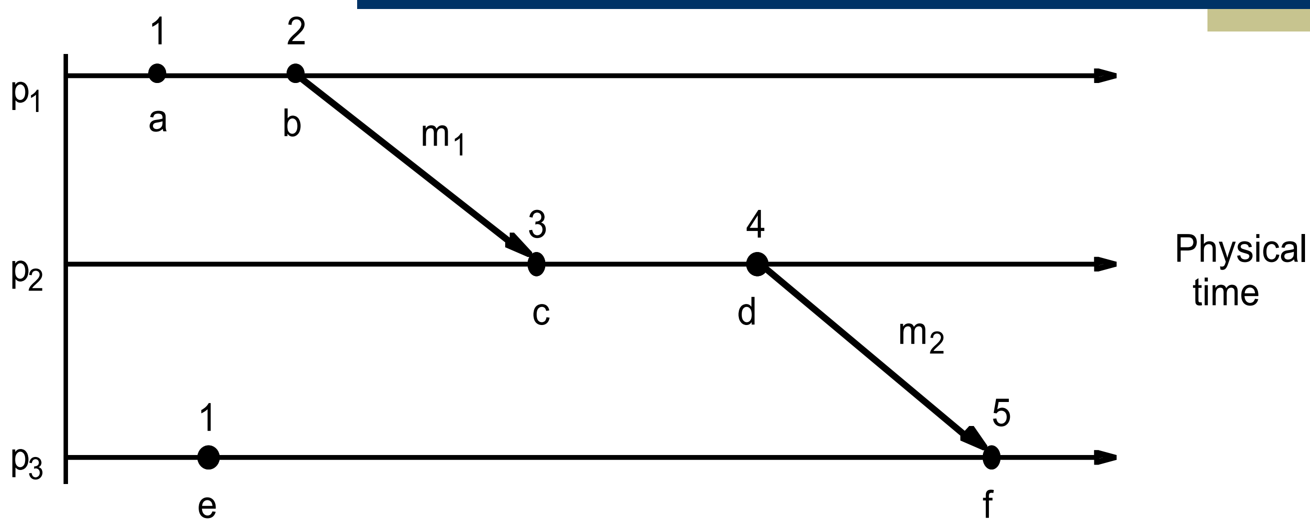

- $a \rightarrow b$ (at $p_1$) $c \rightarrow d$ (at $p_2$)
- $b \rightarrow c$ because of $m_1$
- also $d \rightarrow f$ because of $m_2$

# Logical time and logical clocks (Lamport 1978)



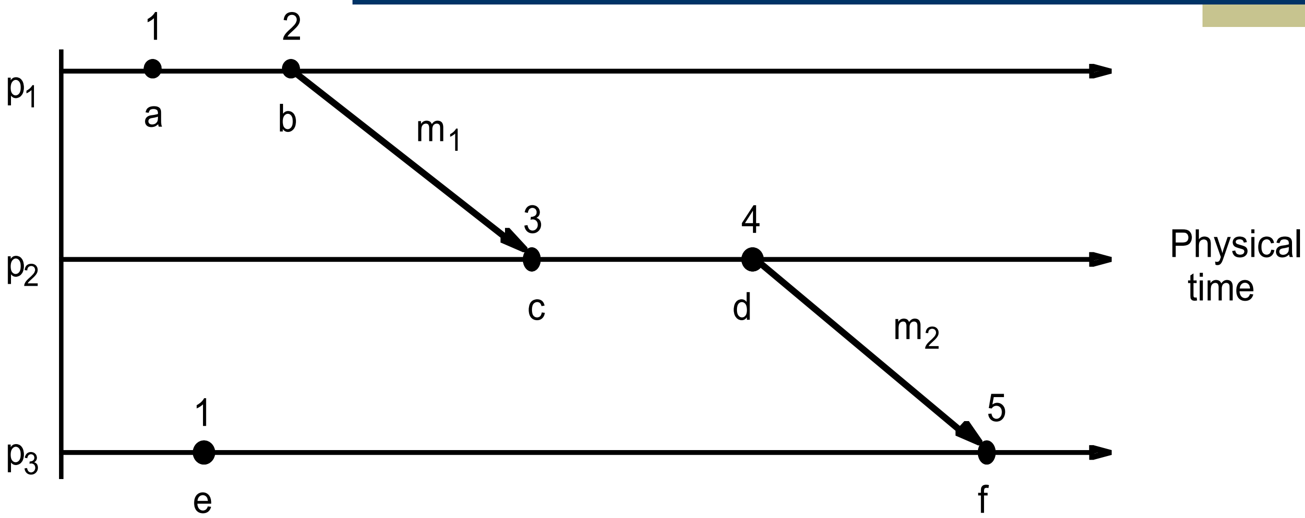

- Not all events are related by $\rightarrow$
- Consider *a* and *e* (different processes and no chain of messages to relate them)
  - they are not related by $\rightarrow$ ; they are said to be concurrent
  - written as *a* || *e*

# Lamport Clock (1)




- A logical clock is a monotonically increasing software counter
  - It need not relate to a physical clock.
- Each process $p_i$ has a logical clock, $L_i$ which can be used to apply logical timestamps to events
  - Rule 0: initially all clocks are set to 0
  - Rule 1: $L_i$ is incremented by 1 before each event at process $p_i$
  - Rule 2:
    - (a) when process $p_i$ sends message *m*, it piggybacks $t = L_i$
    - (b) when $p_j$ receives *(m,t)* it sets $L_j := max(L_j, t)$ and applies rule 1 before timestamping the event *receive* (*m)*

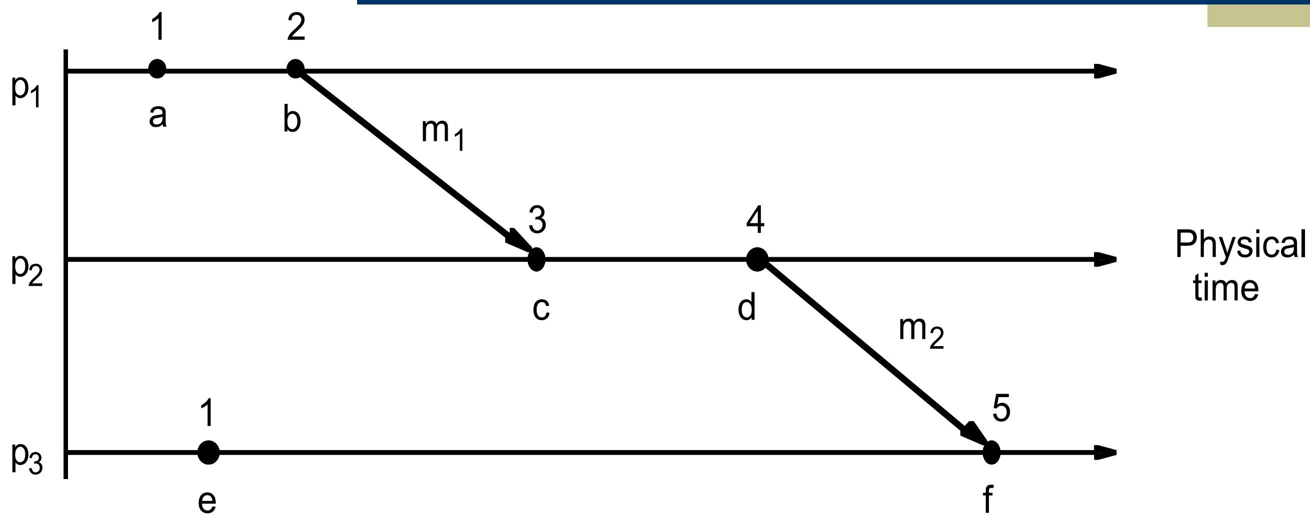
# Lamport Clock (1)




- each of $p_1$, $p_2$, $p_3$ has its logical clock initialised to zero,
- the clock values are those immediately after the event.
- e.g. 1 for a, 2 for b.

- for $m_1$, 2 is piggybacked and c gets max(0,2)+1 = 3

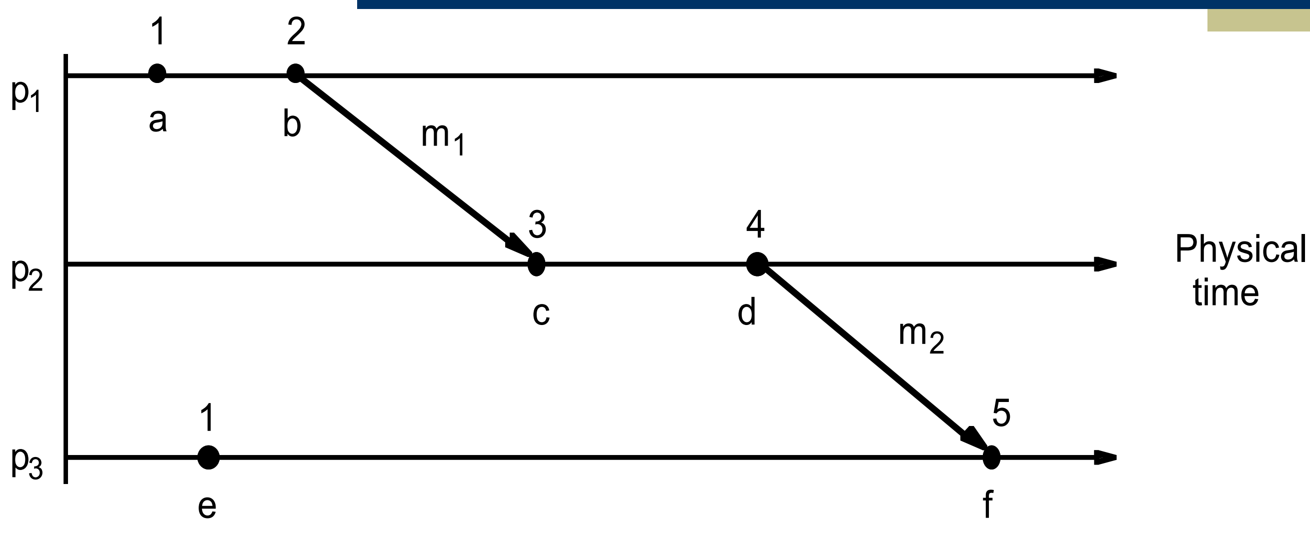
# Lamport Clock (1)




- $e \rightarrow e'$ (e happened before e') implies $L(e)<L(e')$
  (where L(e) is Lamport clock value of event e)

- The converse is not true, that is $L(e)<L(e')$ does not imply $e \rightarrow e'$. What's an example of this above?

# Lamport Clock (1)




- $e \rightarrow e'$ (e happened before e') implies $L(e)<L(e')$
- The converse is not true, that is $L(e)<L(e')$ does not imply $e \rightarrow e'$
  - e.g. $L(b) > L(e)$ but $b \parallel e$

# Lamport logical clocks

- Lamport clock *L* orders events consistent with logical "happens before" ordering
  - If $e \rightarrow e'$, then $L(e) < L(e')$
- But not the converse
  - $L(e) < L(e')$ does not imply $e \rightarrow e'$

- Similar rules for concurrency
  - $L(e) = L(e')$ implies $e \| e'$ (for distinct $e,e'$)
  - $e \| e'$ does not imply $L(e) = L(e')$
  - i.e., Lamport clocks arbitrarily order some concurrent events

# Total-order Lamport clocks

- Many systems require a total-ordering of events, not a partial-ordering
- Use Lamport's algorithm, but break ties using the process ID; one example scheme:
  - $L(e) = M * L_i(e) + i$
    - $M$ = maximum number of processes
    - i = process ID

# Question Break

- Why does Lamport's algorithm not produce a true total ordering?
- Is it true that $L(e) \nless L(e')$ implies $e \nrightarrow e'$?

# Today's Lecture

- Need for time synchronization
- Time synchronization techniques
- Lamport Clocks
- Vector Clocks

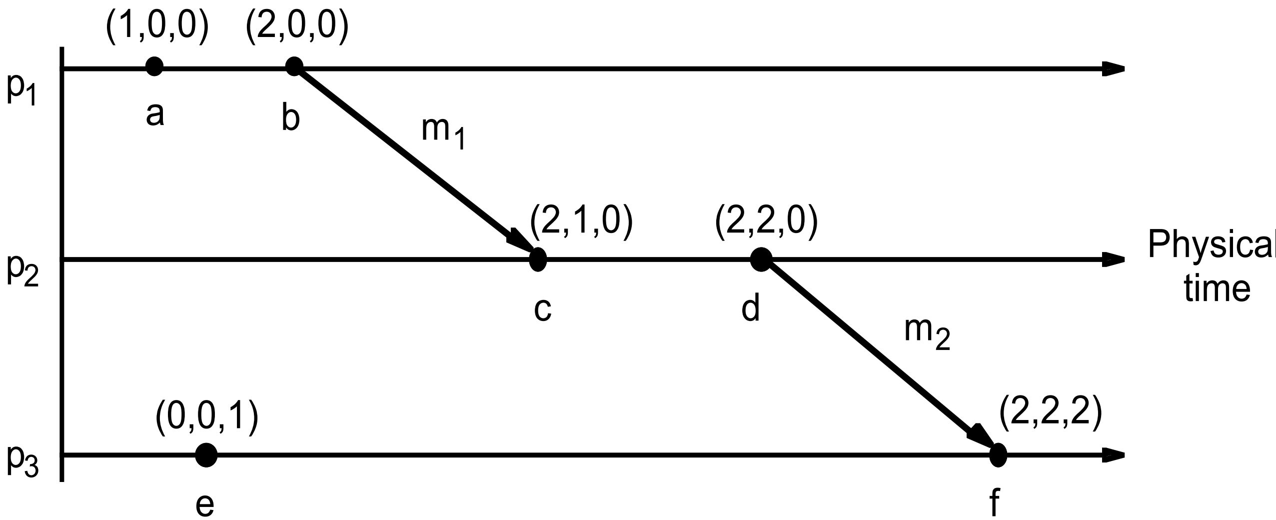
# Vector Clocks

- Vector clocks overcome the shortcoming of Lamport logical clocks
  - $L(e) < L(e')$ does not imply *e* happened before *e*'
- Goal
  - Want ordering that matches happened before
  - $V(e) < V(e')$ if and only if $e \rightarrow e'$
- Method
  - Label each event by vector $V(e)$ $[c_1, c_2 \ldots, c_n]$
    - $c_i$ = # events in process i that precede e

# Vector Clock Algorithm

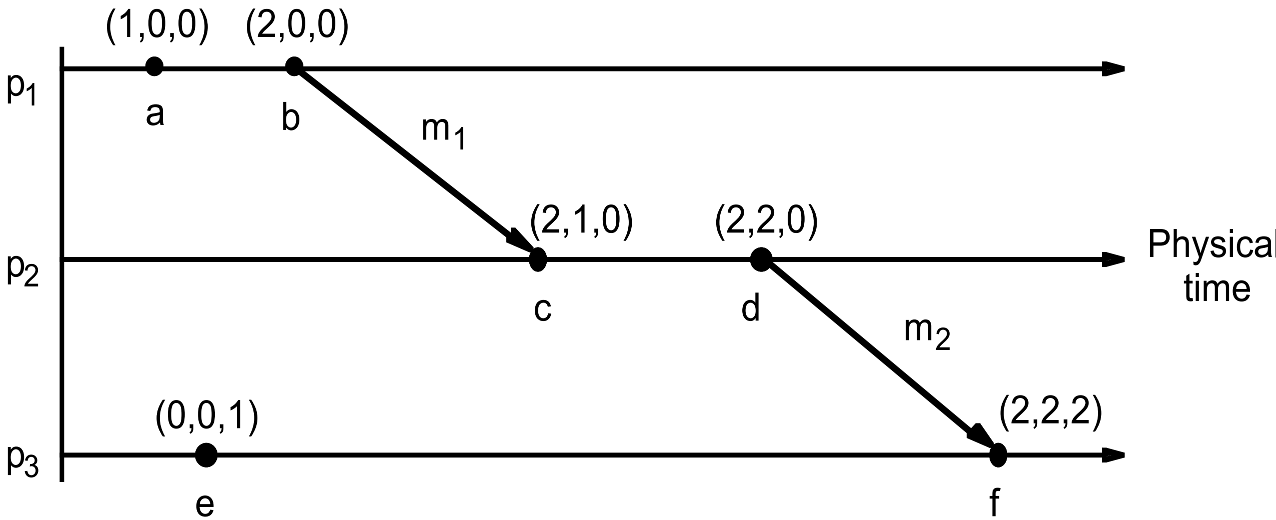
- Initially, all vectors [0,0,…,0]
- For event on process i, increment own $c_i$
- Label message sent with local vector
- When process j receives message with vector $[d_1, d_2, \ldots, d_n]$:
  - Set each local vector entry k to $\max(c_k, d_k)$
  - Increment value of $c_j$

# Vector Clocks



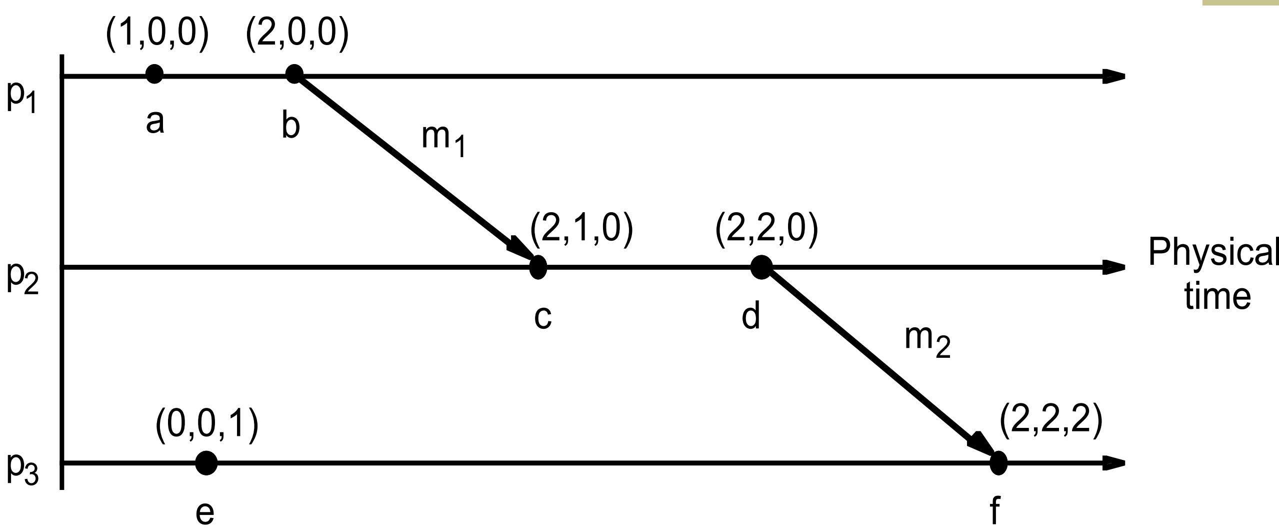

- At $p_1$
  - *a occurs at* (1,0,0); *b* occurs at (2,0,0)
  - piggyback (2,0,0) on $m_1$
- At $p_2$ on receipt of $m_1$ use *max* ((0,0,0), (2,0,0)) = (2, 0, 0) and add 1 to own element = (2,1,0)
- Meaning of =, <=, max etc for vector timestamps
  - compare elements pairwise

# Vector Clocks




- Note that e → e’ implies V(e)<V(e’). The converse is also true
- Can you see a pair of concurrent events; Can you infer they are concurrent from their vectors clocks?

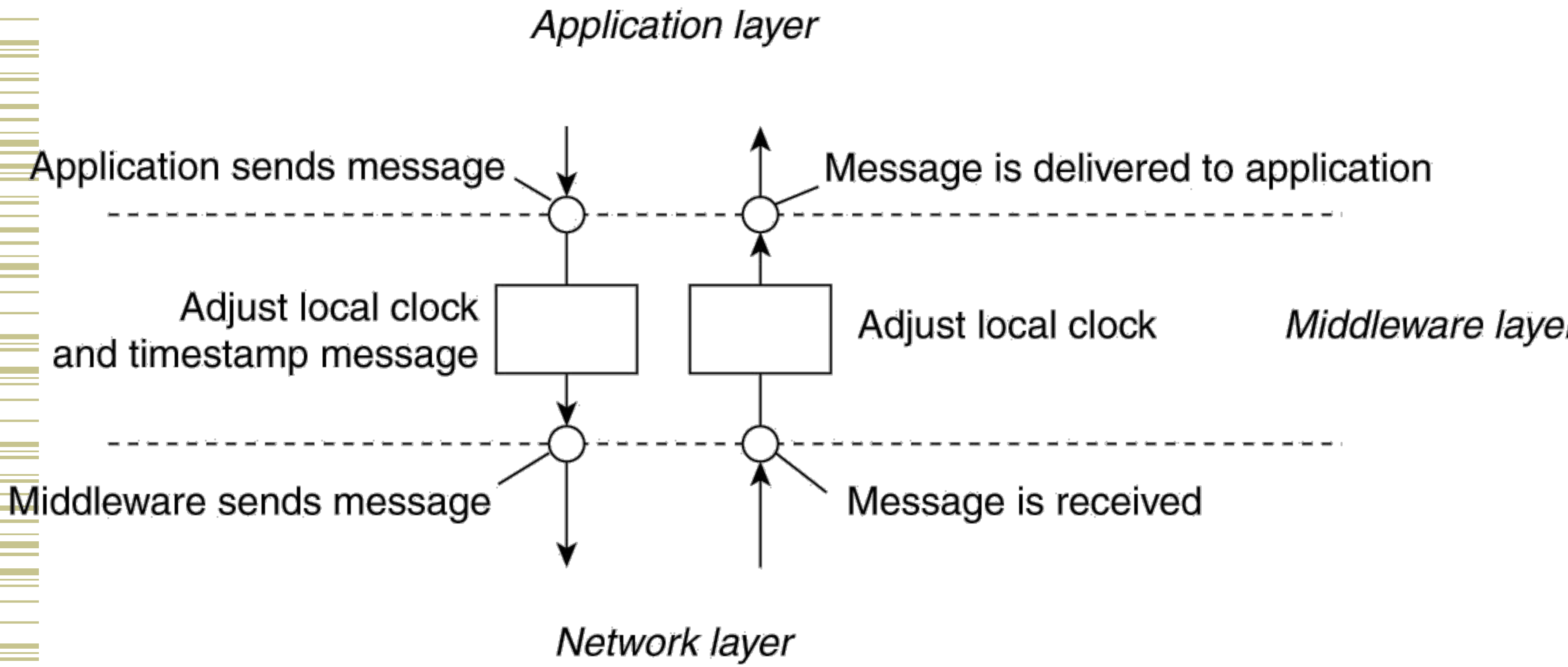
# Vector Clocks




- Note that e → e' implies V(e)<V(e'). The converse is also true
- Can you see a pair of concurrent events?
  - *c* || *e* (concurrent) because neither *V*(c) <= *V*(*e*) nor *V*(*e*) <= *V*(*c*)

# Implementing logical clocks

- Positioning of logical timestamping in distributed systems.



# Distributed time

- Premise
  - The notion of time is well-defined (and measurable) at each single location
  - But the relationship between time at different locations is unclear
    - Can minimize discrepancies, but never eliminate them
- Reality
  - Stationary GPS receivers can get global time with < 1µs error
  - Few systems designed to use this; logical clocks key mechanism for ordering
    - Recent exception: (Spanner system from Google)

# Important Points

- Physical Clocks
  - Can keep closely synchronized, but never perfect
- Logical Clocks
  - Encode happens before relationship (necessary for causality)
  - Lamport clocks provide only one-way encoding
  - Vector clocks precedence necessary for causality (but not sufficient: could have been caused by some event along the path, not all events)