Distributed Systems

06. Logical clocks

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Fall 2017

Logical clocks

Assign sequence numbers to messages

- All cooperating processes can agree on <u>order of events</u>
- vs. *physical clocks*: report time of day

Assume no central time source

- Each system maintains its own local clock
- No total ordering of events
  - No concept of *happened-when*

- Assume multiple actors (processes)
  - Each process has a unique ID
  - Each process has its own incrementing counter

Happened-before

Lamport's "happened-before" notation

a* → *b event ***a*** happened before event ***b***

e.g.: ***a**:* message being sent, ***b***: message receipt

Transitive:

if ***a* → *b*** and ***b* → *c*** then ***a* → *c***

Logical clocks & concurrency

Assign a "clock" value to each event

- if $a \rightarrow b$ then clock(a) < clock(b)
- since time cannot run backwards

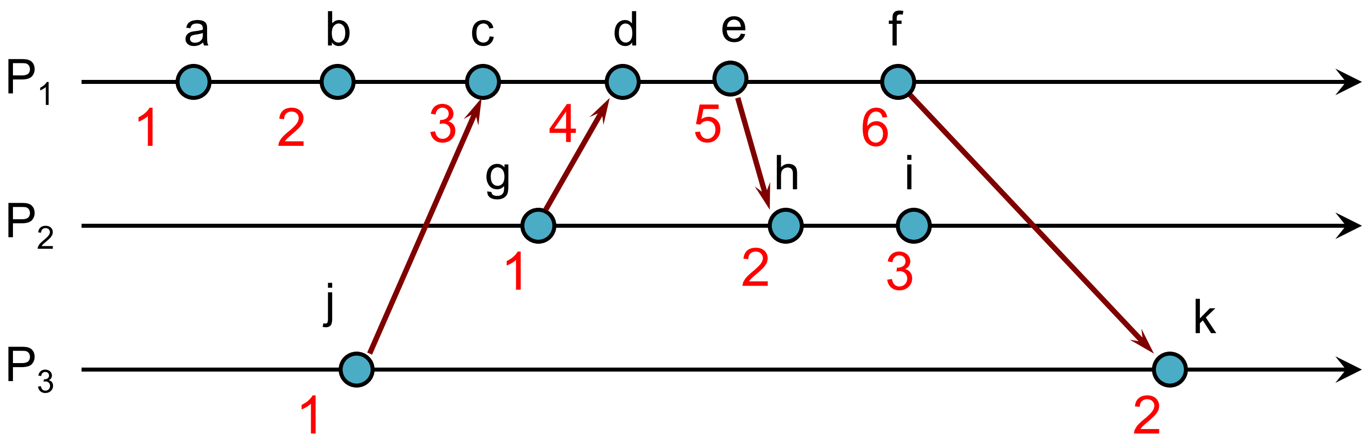
If *a* and *b* occur on different processes that do not exchange messages, then neither $a \rightarrow b$ nor $b \rightarrow a$ are true

- These events are **concurrent**
- Otherwise, they are **causal**

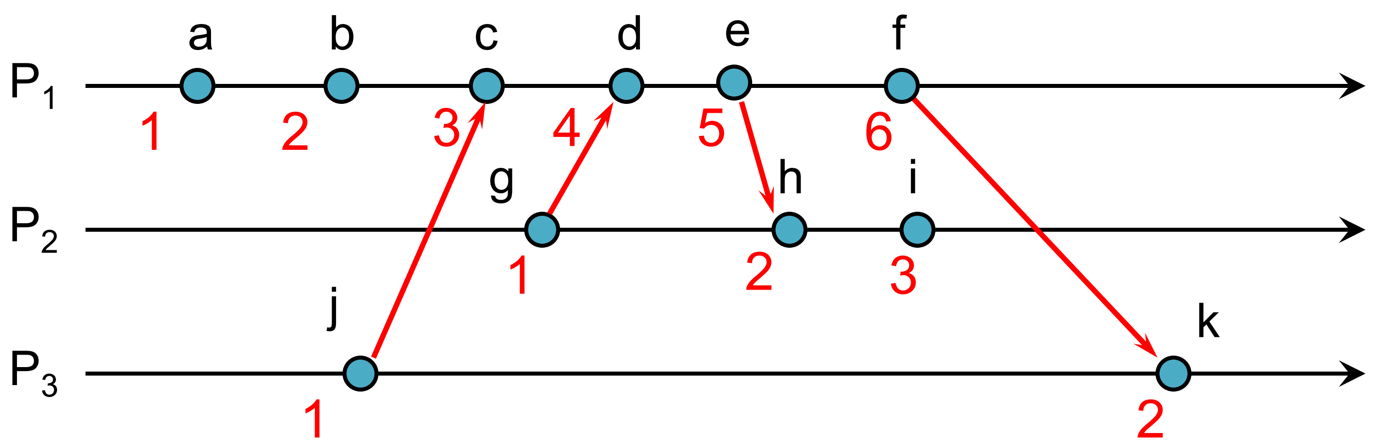
Event counting example

- Three systems: P_0, P_1, P_2
- Events *a*, *b*, *c*, …
- Local event counter on each system
- Systems occasionally communicate

Event counting example



Event counting example



Bad ordering:

e → h but 5 ≥ 2

f → k but 6 ≥ 2

Lamport's algorithm

- Each message carries a timestamp of the sender's clock

- When a message arrives:

  if receiver's *clock* < *message_timestamp*
     set system clock to *(message_timestamp + 1)*

  else do nothing

- Clock must be advanced between any two events in the same process

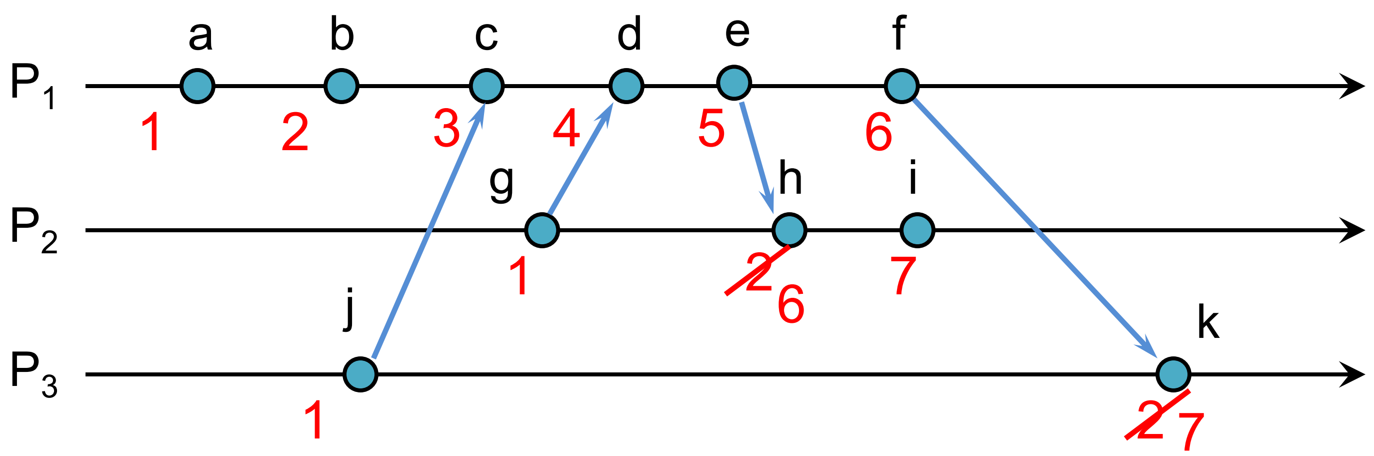
Lamport's algorithm

Algorithm allows us to maintain time ordering among related events

- **Partial ordering**

Event counting example

Applying Lamport's algorithm



We have good ordering where we used to have bad ordering:

e → h and 5 < 6

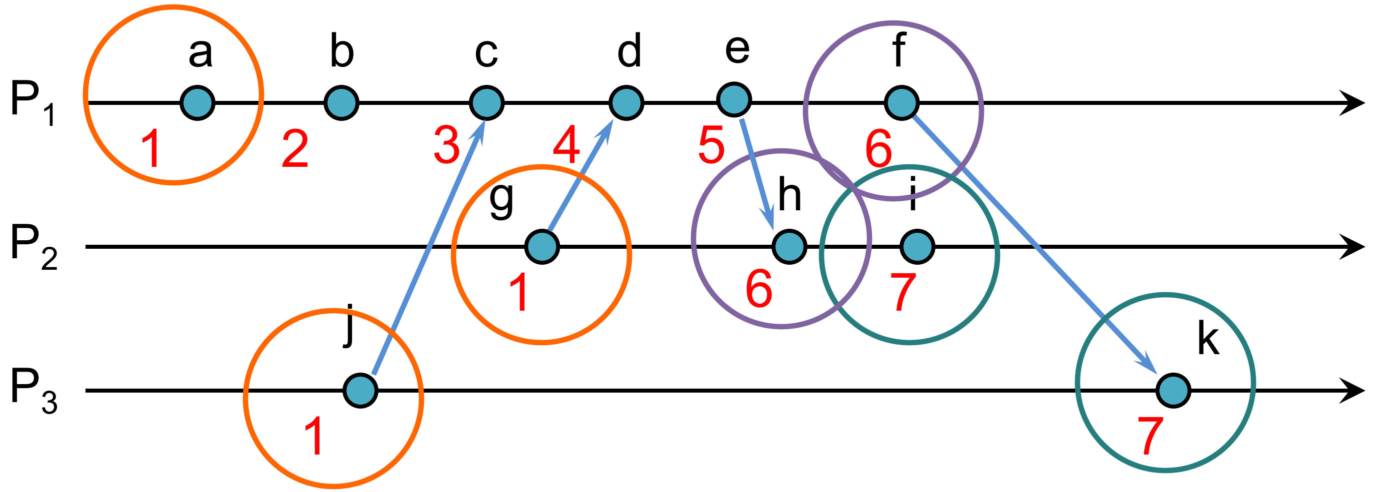
f → k and 6 < 7

Summary

- Algorithm needs monotonically increasing software counter
- Incremented at least when events that need to be timestamped occur
- Each event has a Lamport timestamp attached to it
- For any two events, where $a \rightarrow b$:

  $L(a) < L(b)$

Problem: Identical timestamps



a→*b*, *b*→*c*, … : local events sequenced

i→*c*, *f*→*d* , *d*→*g*, … : Lamport imposes a *send*→*receive* relationship

Concurrent events (e.g., *b* & *g*; *i* & *k*) *may* have the same timestamp … or not

Unique timestamps (total ordering)

We can force each timestamp to be unique

- Define <u>global logical timestamp</u> *(T_i, i)*
  - T_i represents local Lamport timestamp
  - i represents process number (globally unique)
    - e.g., (host address, process ID)
- Compare timestamps:

  $(T_i, i) < (T_j, j)$

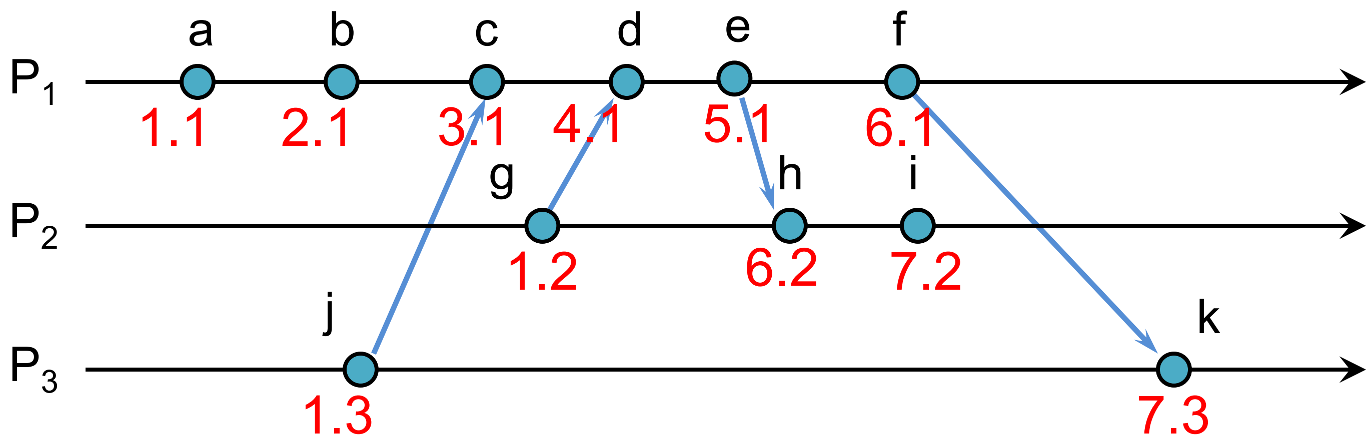
  if and only if

  $T_i < T_j$ or

  $T_i = T_j$ and $i < j$

Does not necessarily relate to actual event ordering

Unique (totally ordered) timestamps



Problem: Detecting causal relations

If $L(e) < L(e')$

– We cannot conclude that $e \rightarrow e'$

By looking at Lamport timestamps

– We cannot conclude which events are causally related

Solution: use a vector clock

Vector clocks are a way to prove the sequence of events bt keeping version history based on each process that made changes to an object

Example

- Group of processes: *Alice, Bob, Cindy, David*
- They concurrently modify one object: *"what should we eat?"*
- Each process keeps a <u>local</u> counter

Alice writes the value & sends to group

Alice: 1

Pizza

To Bob

To Cindy

To David

Bob reads ("Pizza", <alice:1>), modifies the value & sends to group

Alice: 1, Bob: 1

Chinese

To Alice

To Cindy

To David

<u>Receiver</u>
<alice: 1, bob:1> is causal to & follows **<alice: 1>**

Bob's version updates Alice's

Alice reads ("Chinese", <alice:1, bob:1>), modifies the value & sends to group

Alice: 2, Bob: 1

Moroccan

To Bob

To Cindy

To David

<u>Receiver</u>
<alice: 2, bob:1> is causal to & follows **<alice: 1, bob:1>**

Alice makes changes over Bob's

Example

Cindy modifies & sends to group

Alice: 2, Bob: 1, Cindy: 1

Thai

To Alice

To Bob

To David

Bob *concurrently* modifies & sends to group

Alice: 2, Bob: 2

Chinese

To Alice

To Cindy

To David

Cindy & Bob's changes are concurrent – members must resolve conflict

Receiver

<alice: 2, bob:1, cindy:1> is *concurrent* with **<alice: 1, bob:2>**

Vector clocks

Rules:

1. Vector initialized to 0 at each process

   $V_i [j] = 0$ for $i, j = 1, \ldots, N$

2. Process increments its element of the vector in local vector before timestamping event:

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

3. Message is sent from process P_i with V_i attached to it

4. When P_j receives message, compares vectors element by element and sets local vector to higher of two values

   $V_j [i] = max(V_i [i], V_j [i])$ for $I = 1, \ldots, N$

   For example,

   received: *[0, 5, 12, 1]*, have: *[2, 8, 10, 1]*

   new timestamp: *[2, 8, 12, 1]*

Comparing vector timestamps

<u>Define</u>

$V = V'$ iff $V[i] = V'[i]$ for $i = 1 \ldots N$
$V \leq V'$ iff $V[i] \leq V'[i]$ for $i = 1 \ldots N$

For any two events e, e'

if $e \rightarrow e'$ then $V(e) < V(e')$

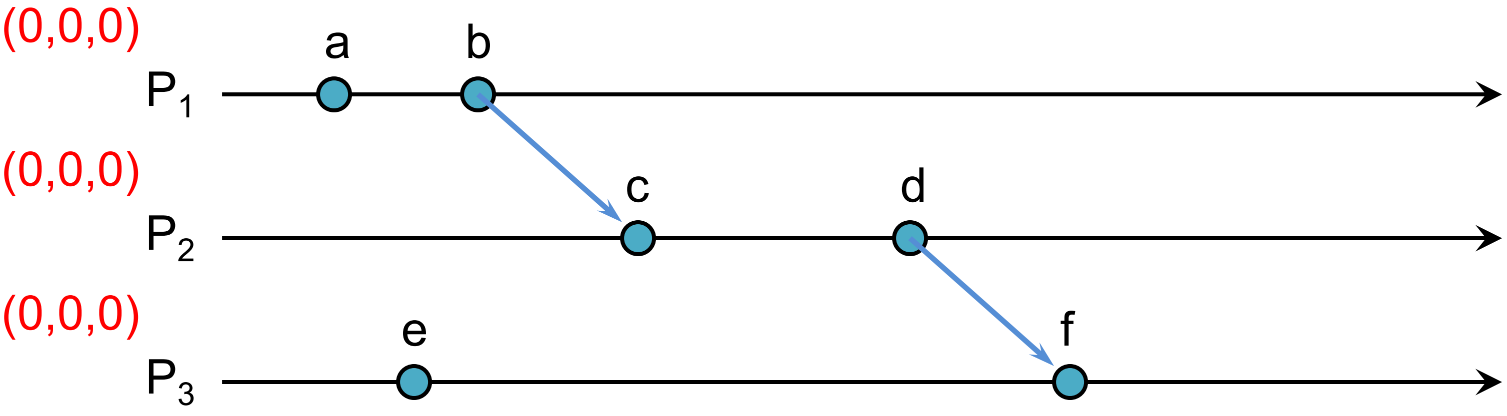
… just like Lamport's algorithm

if $V(e) < V(e')$ then $e \rightarrow e'$

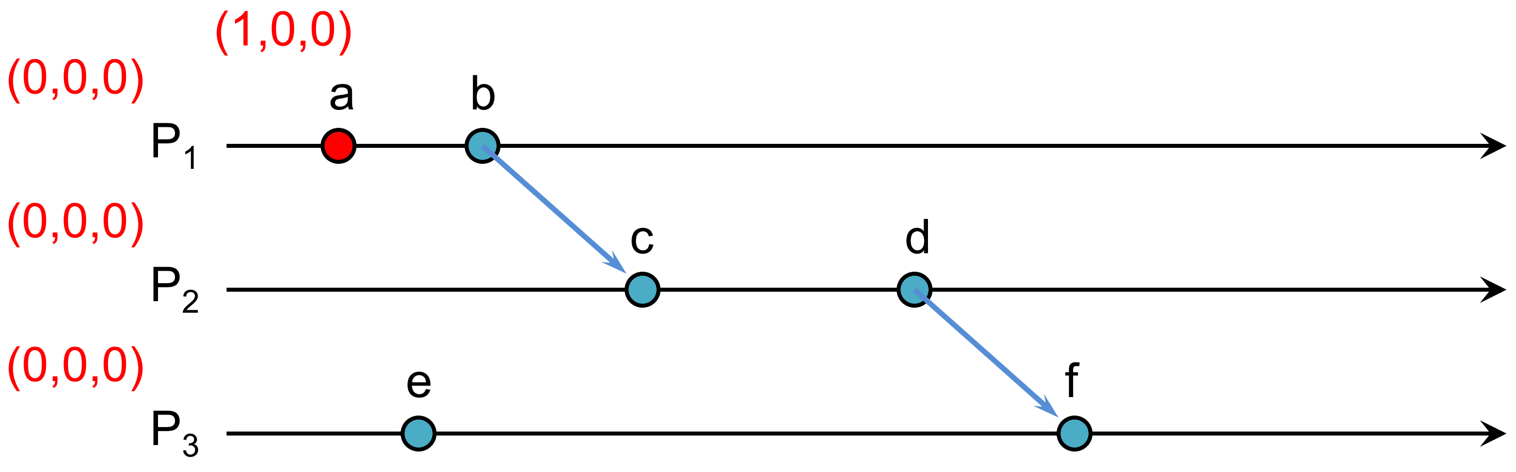
Two events are **concurrent** if **neither**

$V(e) \leq V(e')$ nor $V(e') \leq V(e)$

Vector timestamps

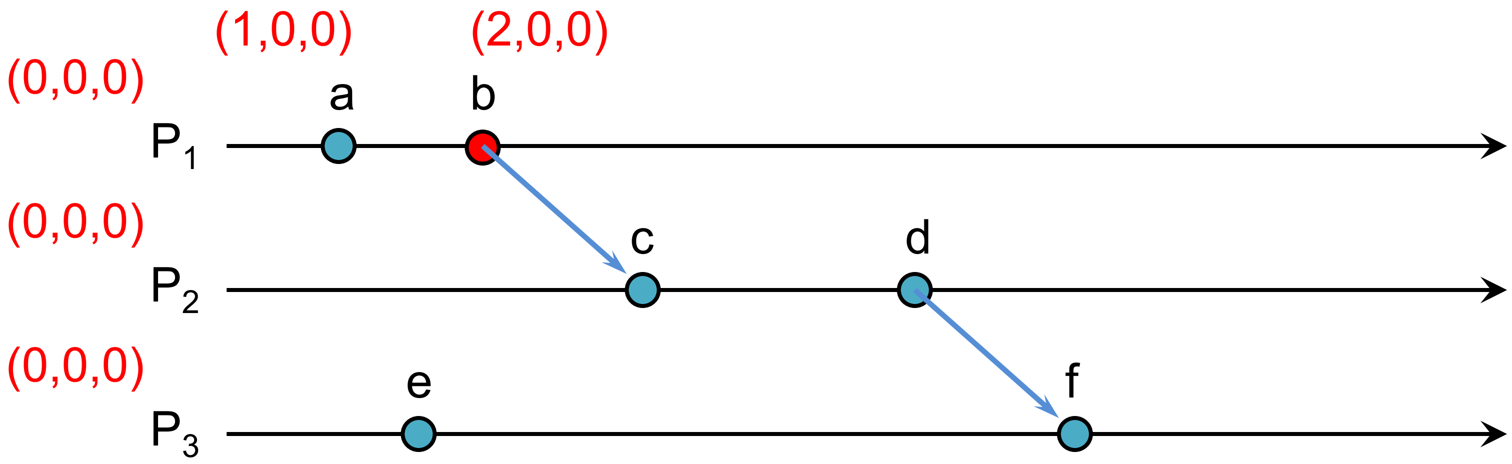


Vector timestamps



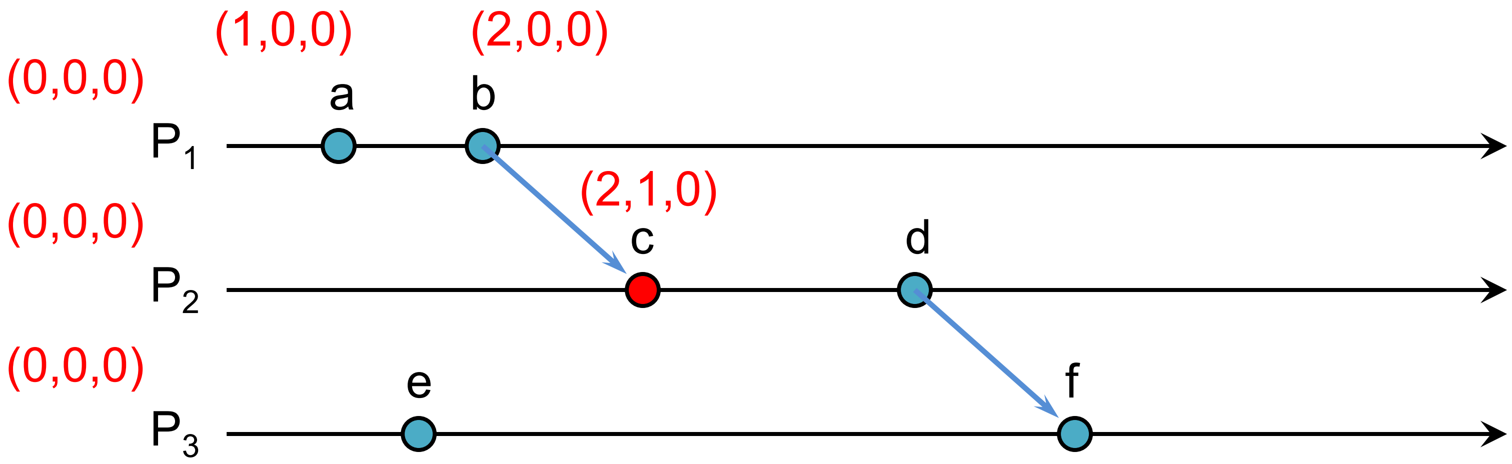
Event	timestamp
a	(1,0,0)

Vector timestamps



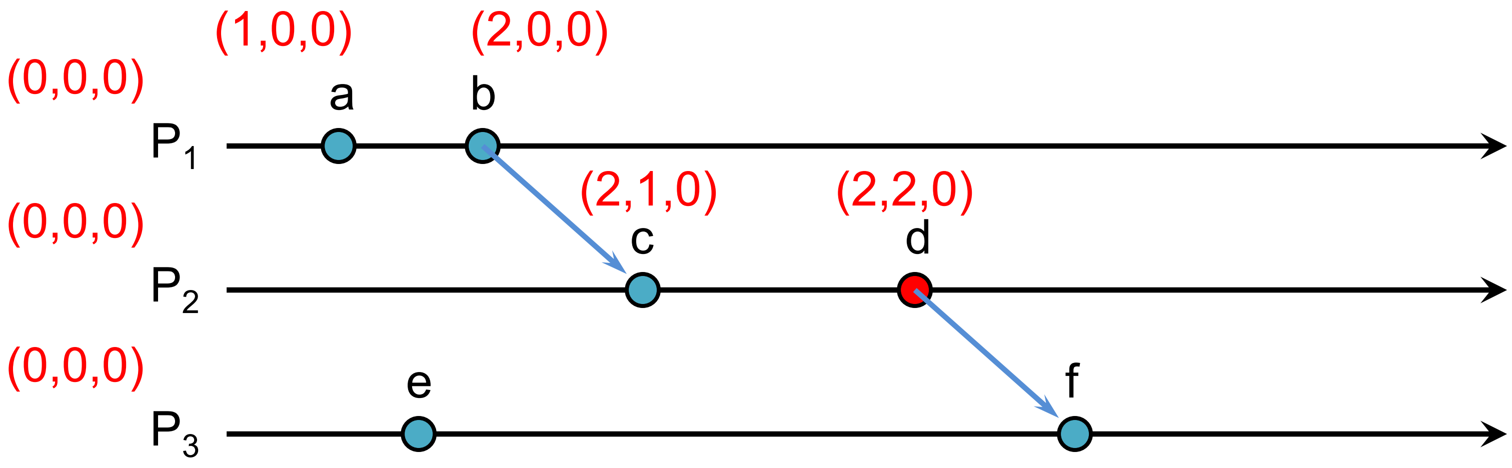
Event	timestamp
a	(1,0,0)
b	(2,0,0)

Vector timestamps



Event	timestamp
a	(1,0,0)
b	(2,0,0)
c	(2,1,0)

Vector timestamps



Event	timestamp
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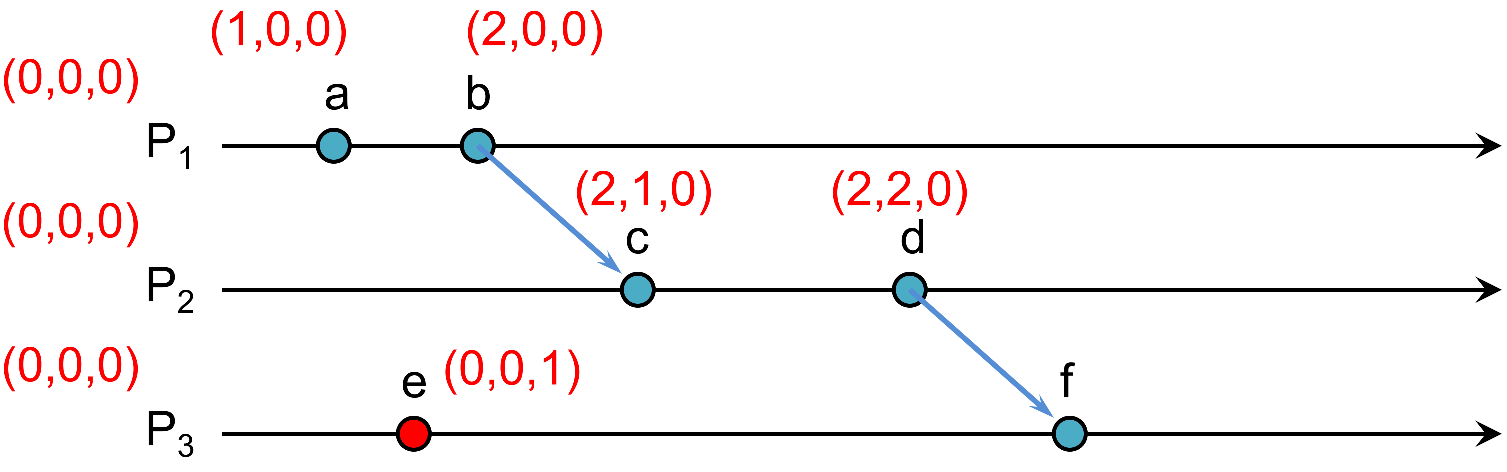
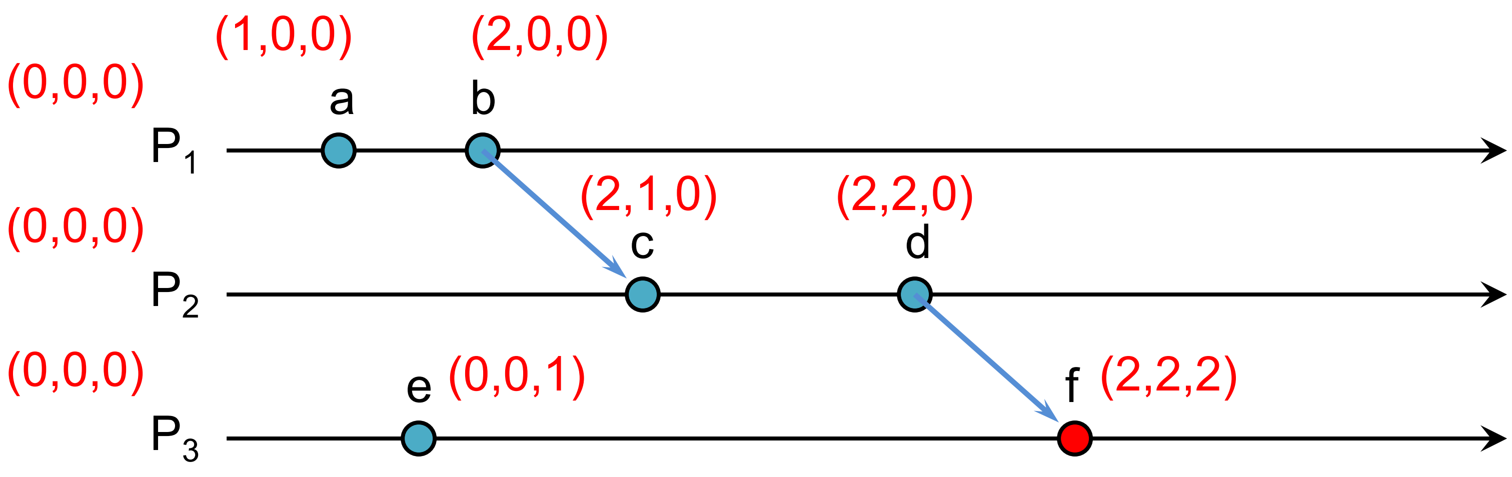
d	(2,2,0)

Vector timestamps



Event	timestamp
a	(1,0,0)
b	(2,0,0)
c	(2,1,0)
d	(2,2,0)
e	(0,0,1)

Vector timestamps



Event	timestamp
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b	(2,0,0)
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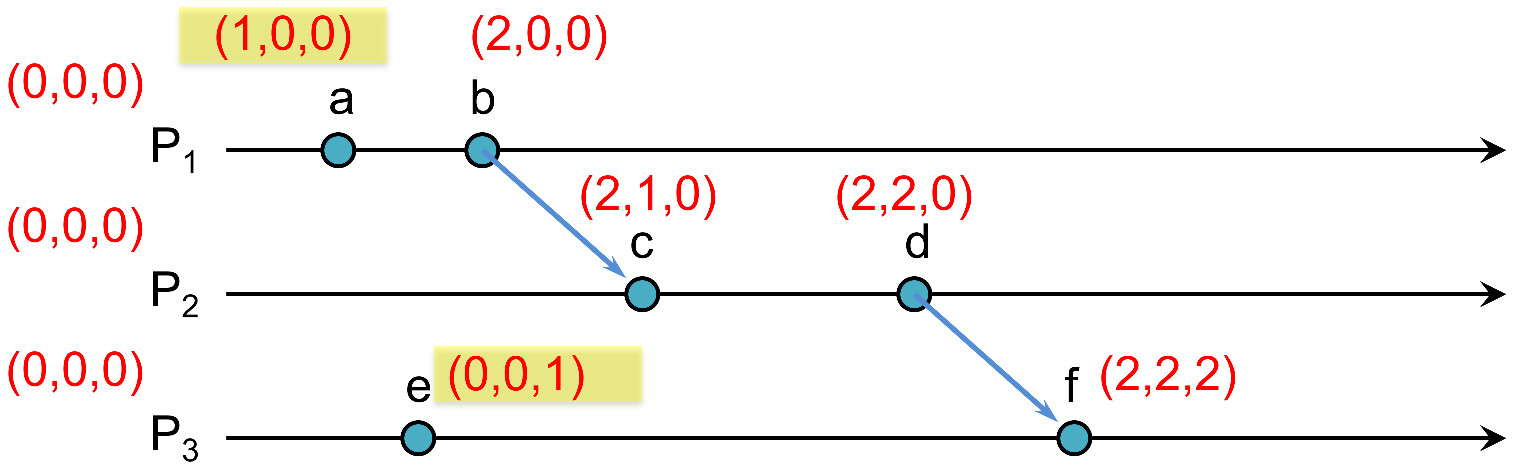
Vector timestamps



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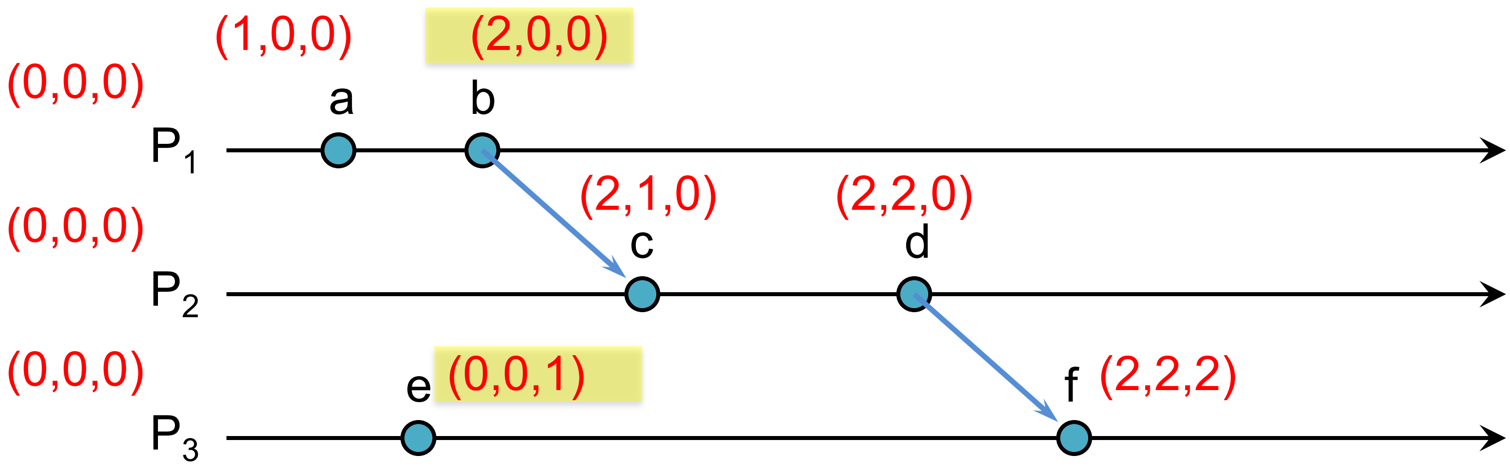
concurrent events

Vector timestamps



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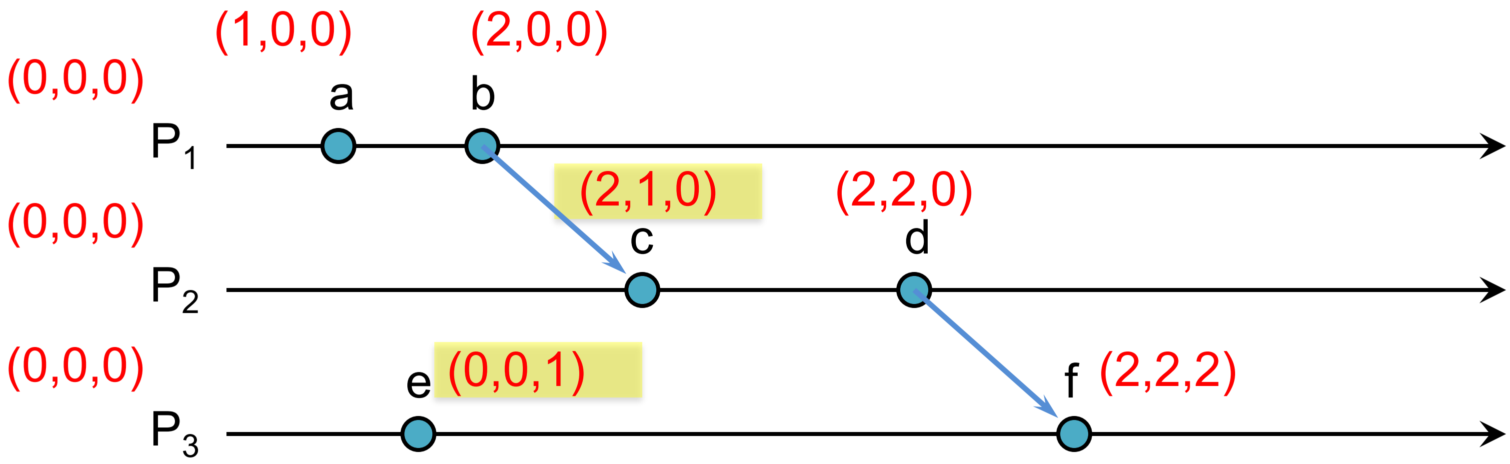
concurrent events

Vector timestamps



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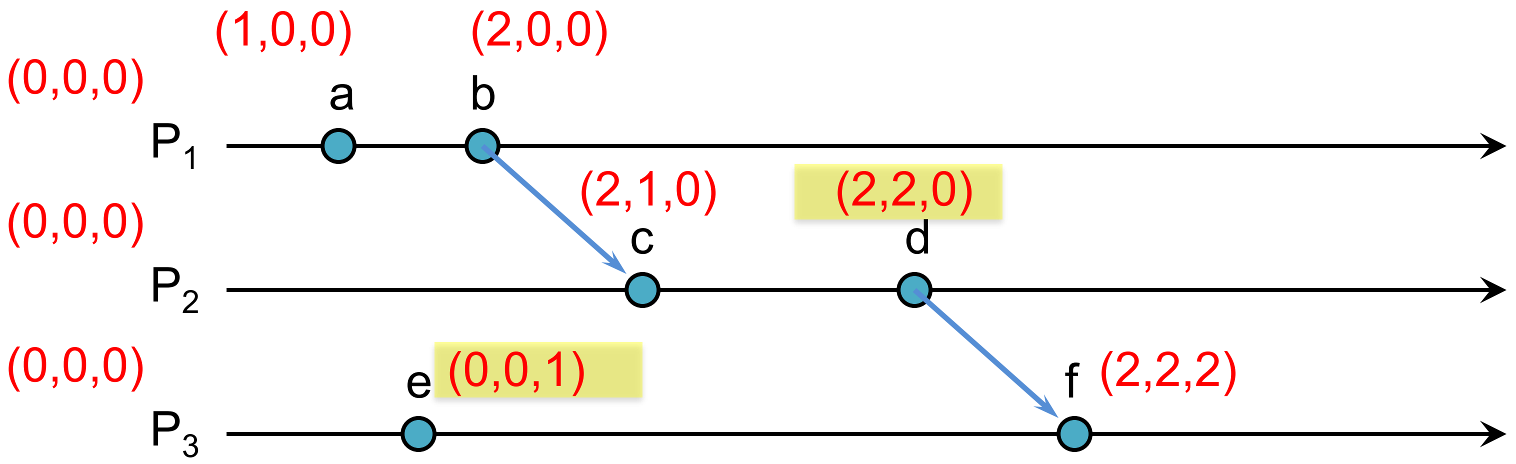
concurrent events

Vector timestamps



Event	timestamp
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c	(2,1,0)
d	(2,2,0)
e	(0,0,1)
f	(2,2,2)

concurrent events

Generalizing Vector Timestamps

- A “vector” can be a list of tuples:
  - For processes P_1, P_2, P_3, …
  - Each process has a globally unique Process ID, P_i (e.g., *MAC_address:PID*)
  - Each process maintains its own timestamp: T_{P1}, T_{P2}, …
  - Vector: { $<P_1, T_{P1}>$, $<P_2, T_{P2}>$, $<P_3, T_{P3}>$, … }

- Any one process may have only partial knowledge of others
  - New timestamp for a received message:
    - Compare all matching sets of process IDs: set to highest of values
    - Any non-matched $<P, T>$ sets get added to the timestamp
  - For a happened-before relation:
    - At least one set of process IDs must be common to both timestamps
    - Match all corresponding $<P, T>$ sets: A:$<P_i, T_a>$, B:$<P_i, T_b>$
    - If $T_a \leq T_b$ for all common processes *P*, then $A \rightarrow B$

Vector Clocks Summary

- Vector clocks give us a way of identifying which events are causally related
- We are guaranteed to get the sequencing correct
- But
  - The size of the vector increases with more actors
    … and the entire vector must be stored with the data.
  - Comparison takes more time than comparing two numbers
  - What if messages are concurrent?
    - App will have to decide how to handle conflicts

Summary: Logical Clocks & Partial Ordering

- Causality
  - If $a \rightarrow b$ then event *a* can affect event *b*
- Concurrency
  - If neither $a \rightarrow b$ nor $b \rightarrow a$ then one event cannot affect the other
- Partial Ordering
  - Causal events are sequenced
- Total Ordering
  - All events are sequenced

The end