Time & Clocks

CS 475: Concurrent & Distributed Systems (Fall 2021)

Lecture 6

Yue Cheng

Some material taken/derived from:

- Princeton COS-418 materials created by Michael Freedman and Wyatt Lloyd.
- MIT 6.824 by Robert Morris, Frans Kaashoek, and Nickolai Zeldovich.

Today's outline

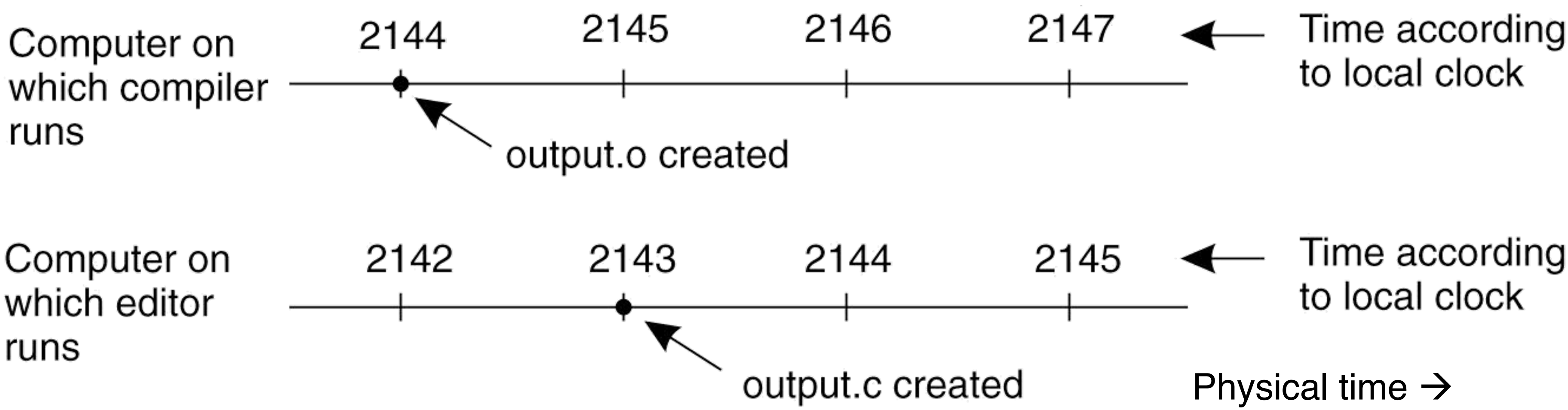
- The need for time synchronization

- "Wall clock time" synchronization

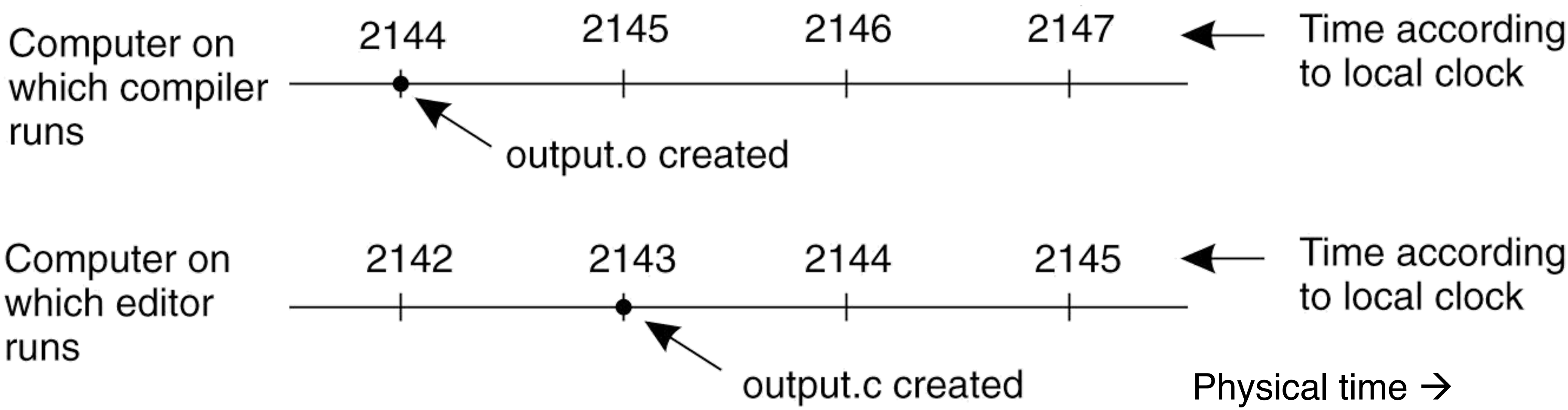
- Logical Time: Lamport Clocks

- Vector clocks

A distributed edit-compile workflow

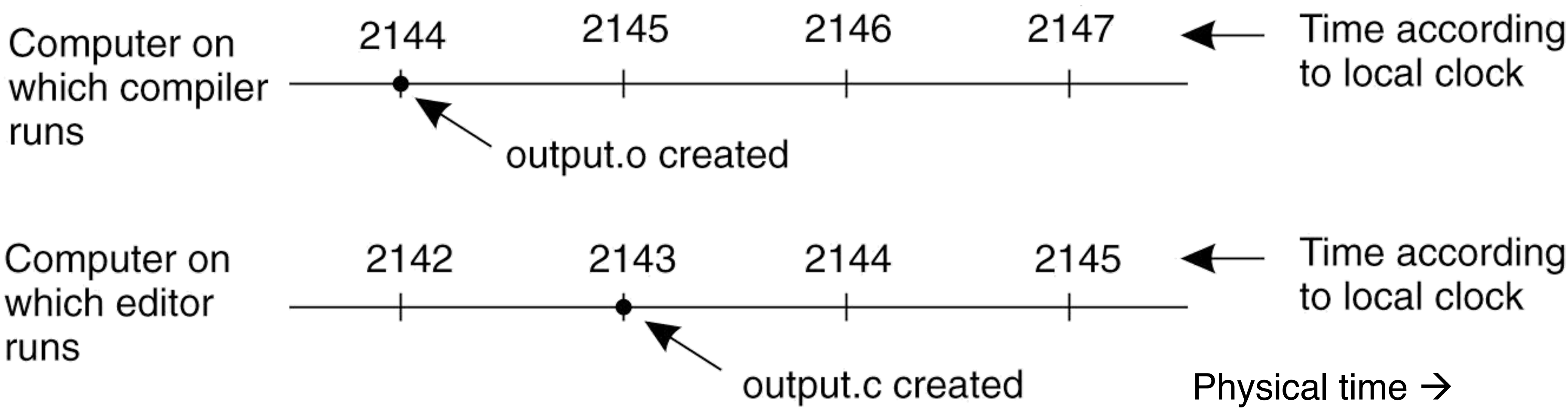


A distributed edit-compile workflow



- 2143 < 2144 ➔ make doesn't call compiler

A distributed edit-compile workflow



- 2143 < 2144 ➔ make doesn't call compiler

Lack of time synchronization result – possible object file mismatch

What makes time synchronization hard?

1. Quartz oscillator sensitive to temperature, age, vibration, radiation
   - Accuracy ~one part per million
     - (one second of clock drift over 12 days)

2. The internet is:
   - **Asynchronous:** arbitrary message delays
   - **Best-effort:** messages don't always arrive

Today's outline

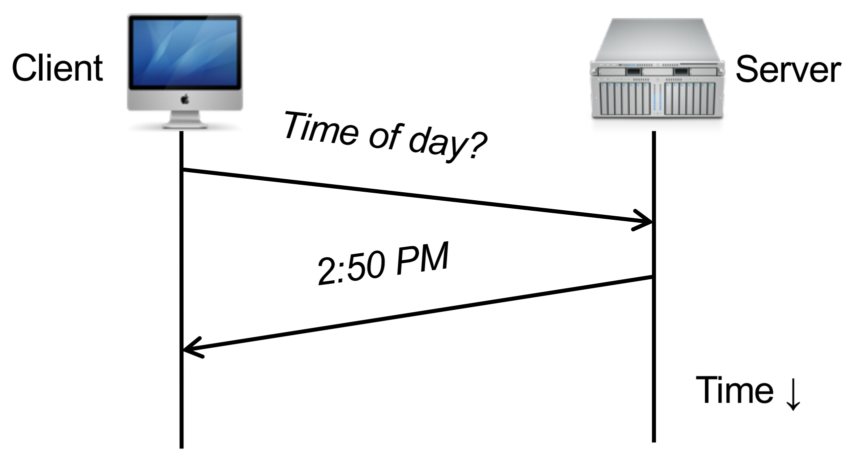
- The need for time synchronization
- "Wall clock time" synchronization
  - Cristian's algorithm
- Logical Time: Lamport Clocks
- Vector clocks

Just use Coordinated Universal Time?

- UTC is broadcast from radio stations on land and satellite (e.g., the Global Positioning System)
  - Computers with receivers can synchronize their clocks with these timing signals
- Signals from land-based stations are accurate to about 0.1–10 milliseconds
- Signals from GPS are accurate to about one microsecond
  - *Why can't we put GPS receivers on all our computers?*

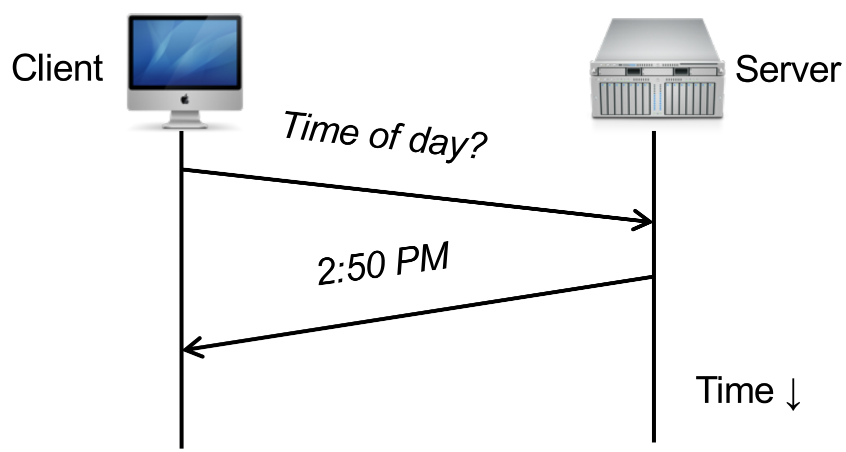
Synchronization to a time server

- Suppose a server with an accurate clock (e.g., GPS-receiver)
  - Could simply issue an RPC to obtain the time:



Synchronization to a time server

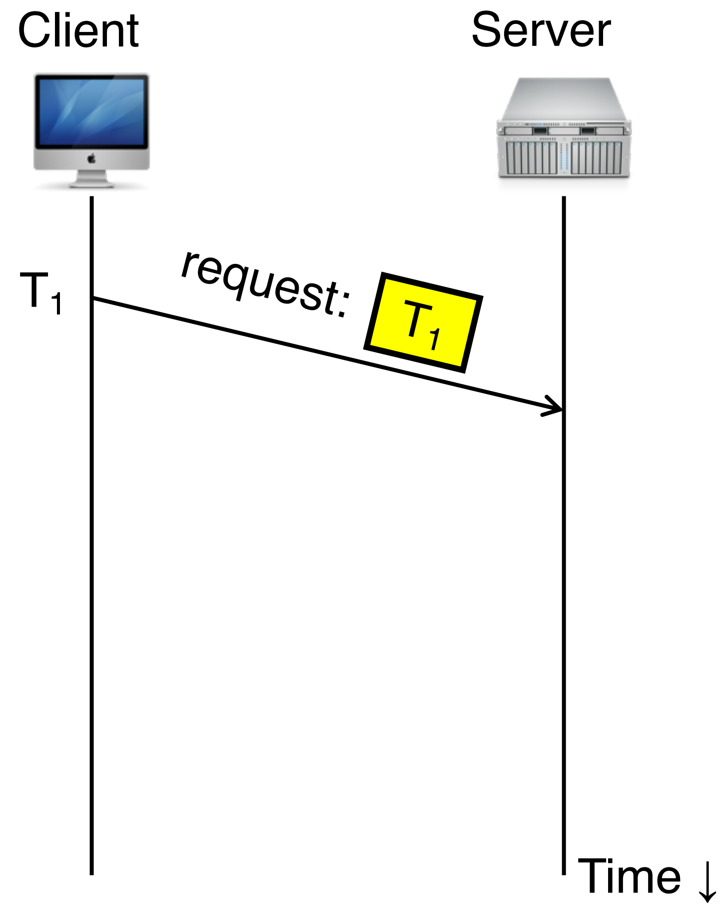
- Suppose a server with an accurate clock (e.g., GPS-receiver)
  - Could simply issue an RPC to obtain the time:



- But this doesn't account for network latency
  - Message delays will have outdated server's answer

Cristian's algorithm: Outline

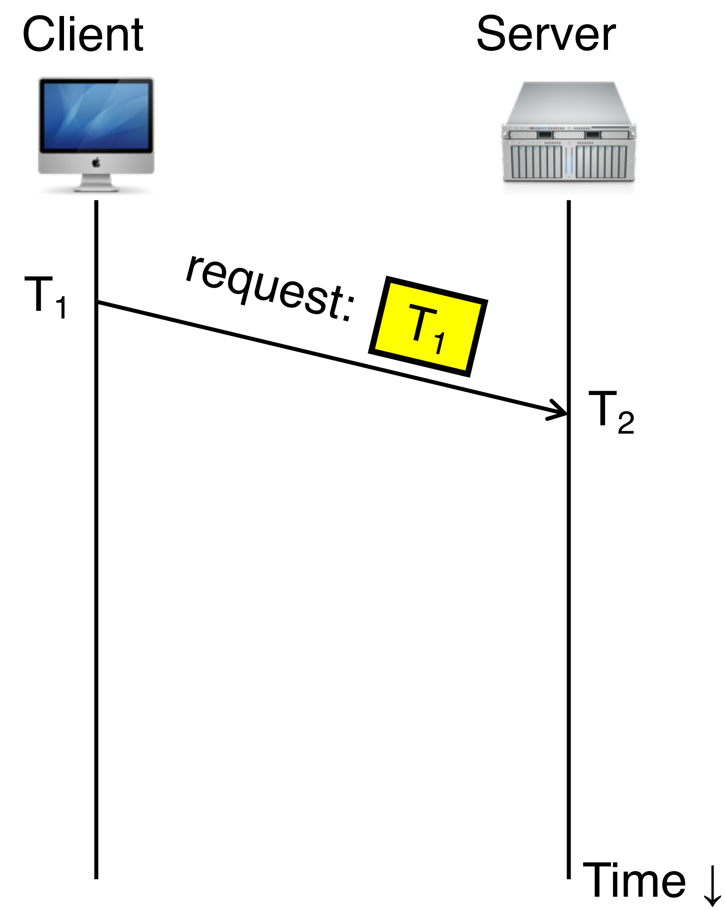
1. Client sends a request packet, timestamped with its local clock T_1



Cristian's algorithm: Outline

1. Client sends a request packet, timestamped with its local clock T_1

2. Server timestamps its receipt of the request T_2 with its local clock

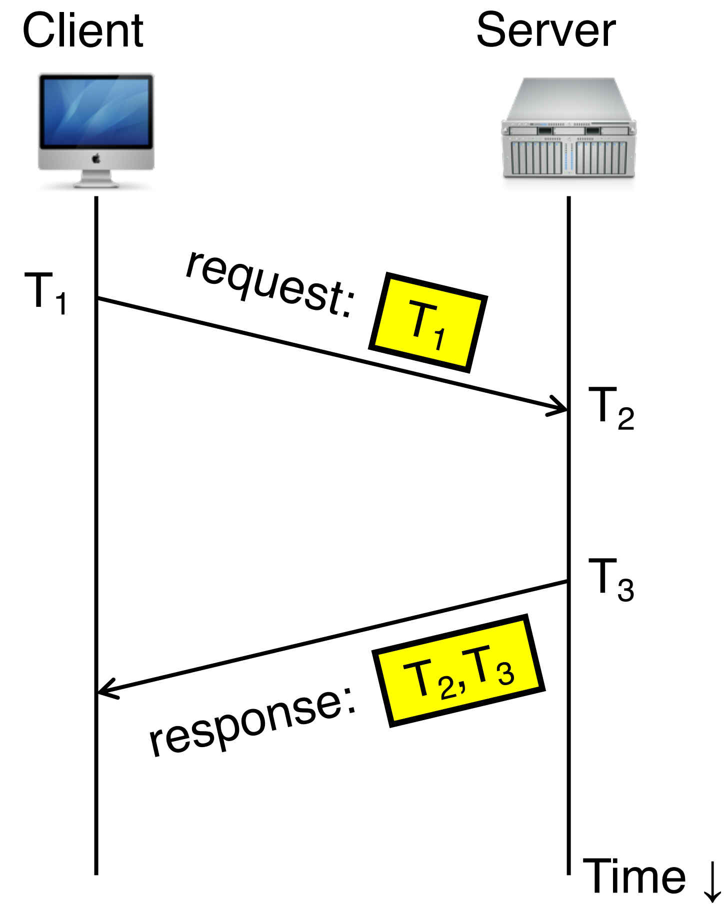


Cristian's algorithm: Outline

1. Client sends a request packet, timestamped with its local clock T_1

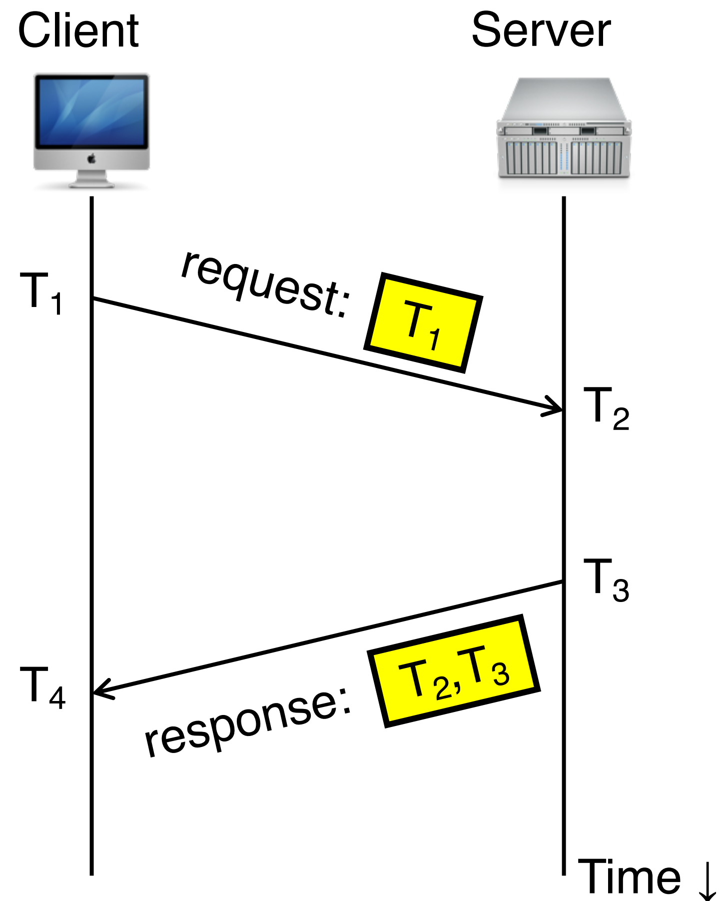
2. Server timestamps its receipt of the request T_2 with its local clock

3. Server sends a response packet with its local clock T_3 and T_2



Cristian's algorithm: Outline

1. Client sends a request packet, timestamped with its local clock T_1
2. Server timestamps its receipt of the request T_2 with its local clock
3. Server sends a response packet with its local clock T_3 and T_2
4. Client locally timestamps its receipt of the server's response T_4



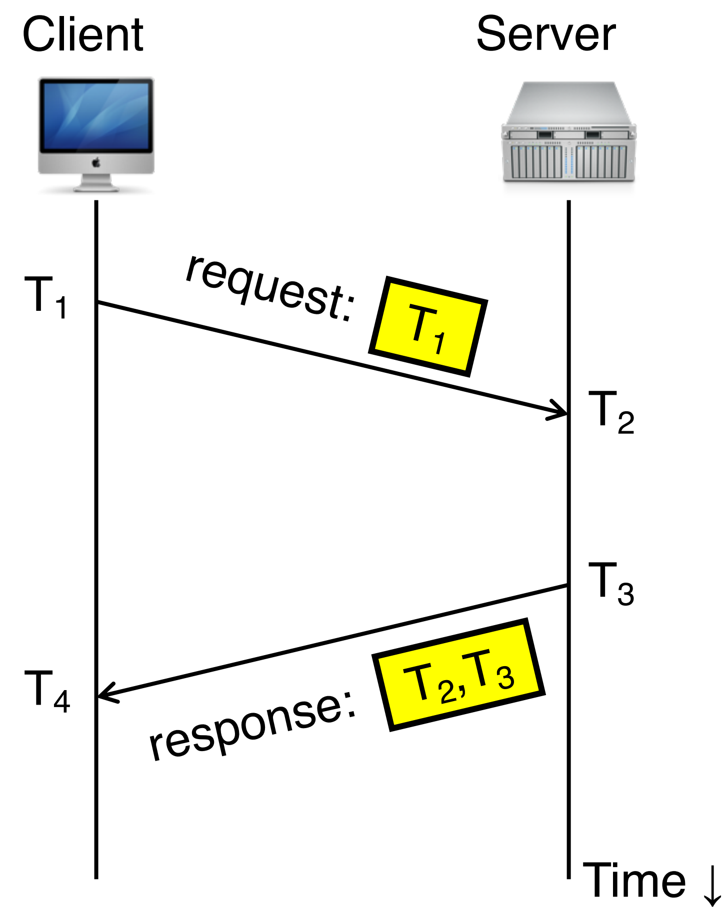
Cristian's algorithm: Outline

1. Client sends a request packet, timestamped with its local clock T_1

2. Server timestamps its receipt of the request T_2 with its local clock

3. Server sends a response packet with its local clock T_3 and T_2

4. Client locally timestamps its receipt of the server's response T_4

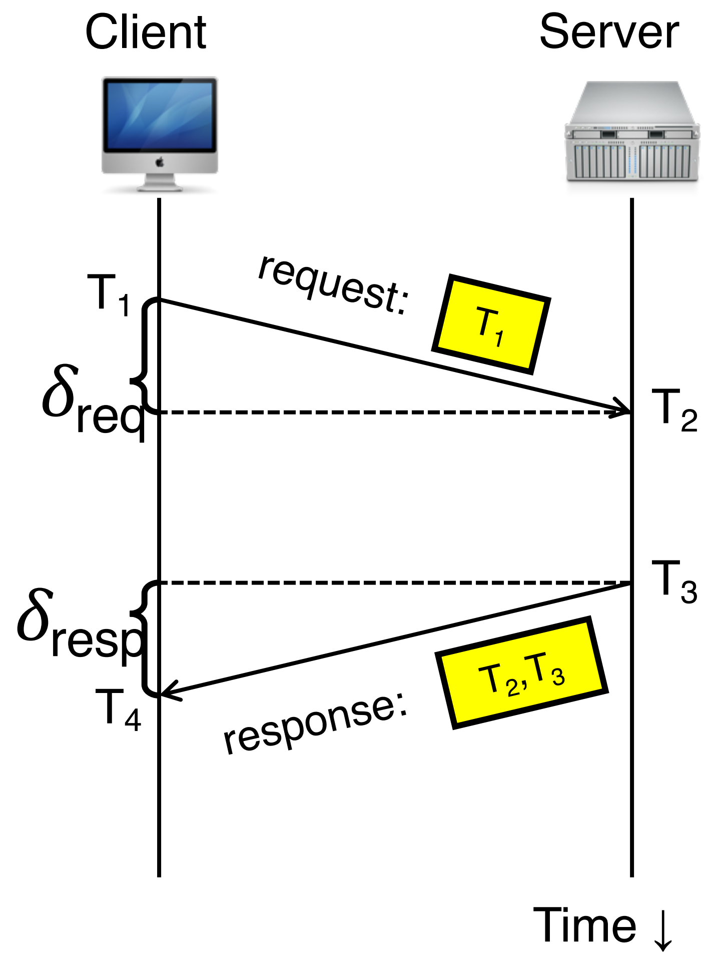


How can the client use these timestamps to synchronize its local clock to the server's local clock?

Cristian's algorithm: Offset sample calculation

Goal: Client sets clock ← $T_3 + \delta_{resp}$

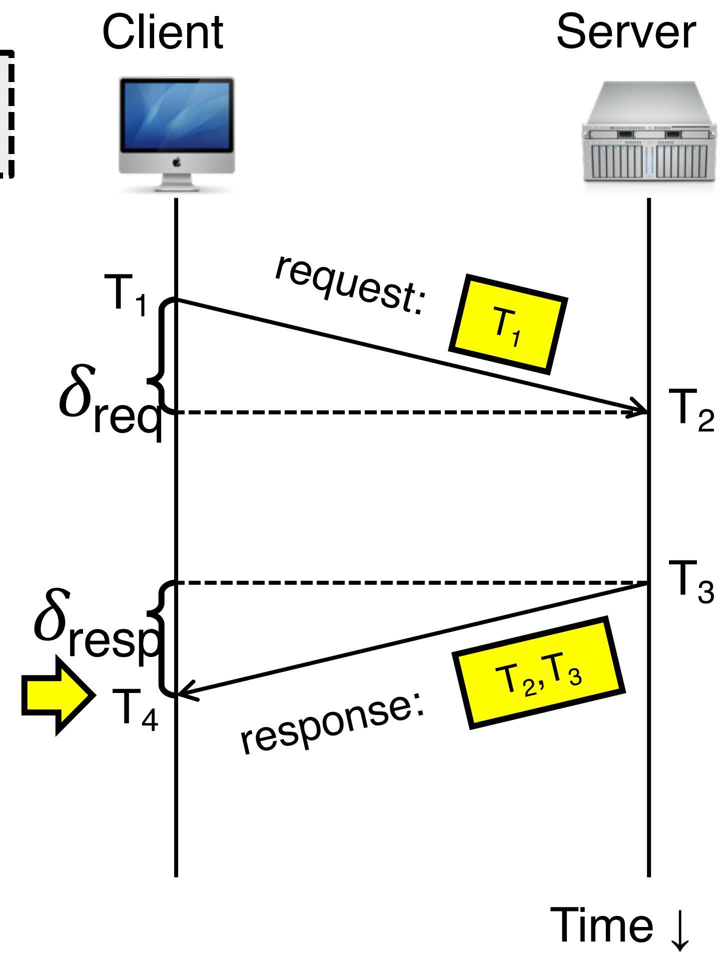
- Client samples round trip time $\delta = \delta_{req} + \delta_{resp} = (T_4 - T_1) - (T_3 - T_2)$



Cristian's algorithm: Offset sample calculation

Goal: Client sets clock ← $T_3 + \delta_{resp}$

- Client samples round trip time $\delta = \delta_{req} + \delta_{resp} = (T_4 - T_1) - (T_3 - T_2)$

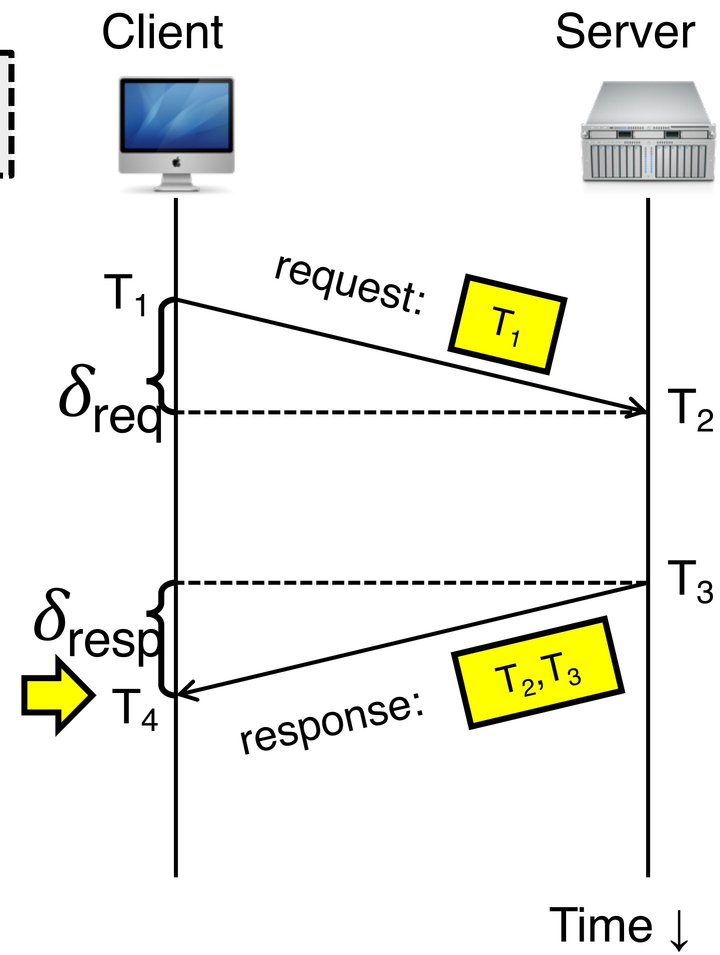


Cristian's algorithm: Offset sample calculation

Goal: Client sets clock ← $T_3 + \delta_{resp}$

- Client samples round trip time δ = $\delta_{req} + \delta_{resp} = (T_4 - T_1) - (T_3 - T_2)$

- But client knows δ, not δ_{resp}

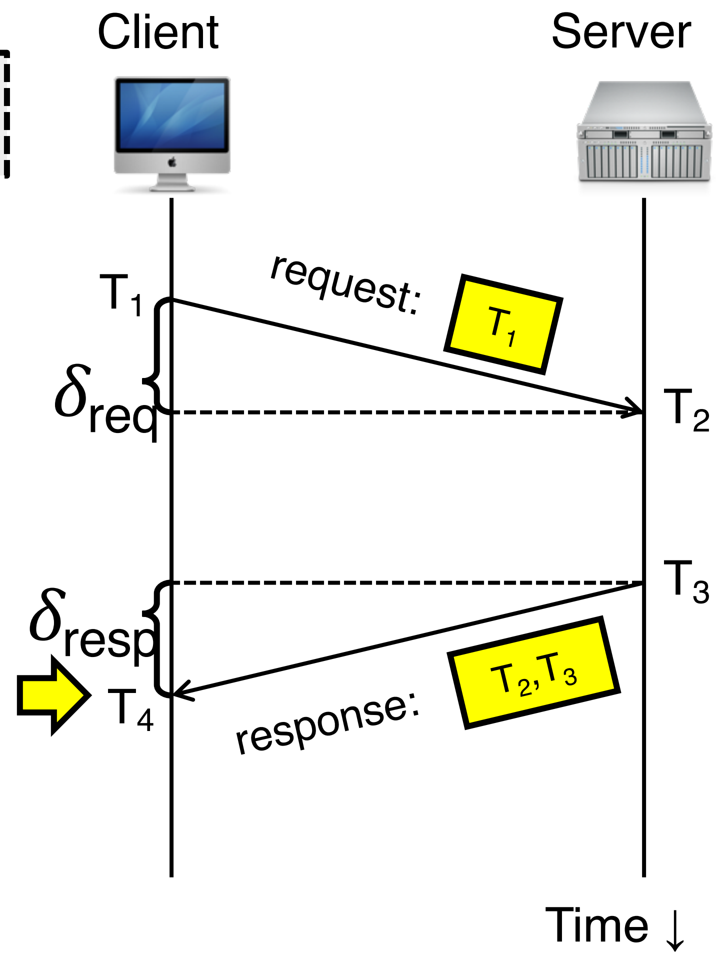


Cristian's algorithm: Offset sample calculation

Goal: Client sets clock ← $T_3 + \delta_{resp}$

- Client samples round trip time δ = $\delta_{req} + \delta_{resp} = (T_4 - T_1) - (T_3 - T_2)$
- But client knows δ, not δ_{resp}

Assume: $\delta_{req} \approx \delta_{resp}$



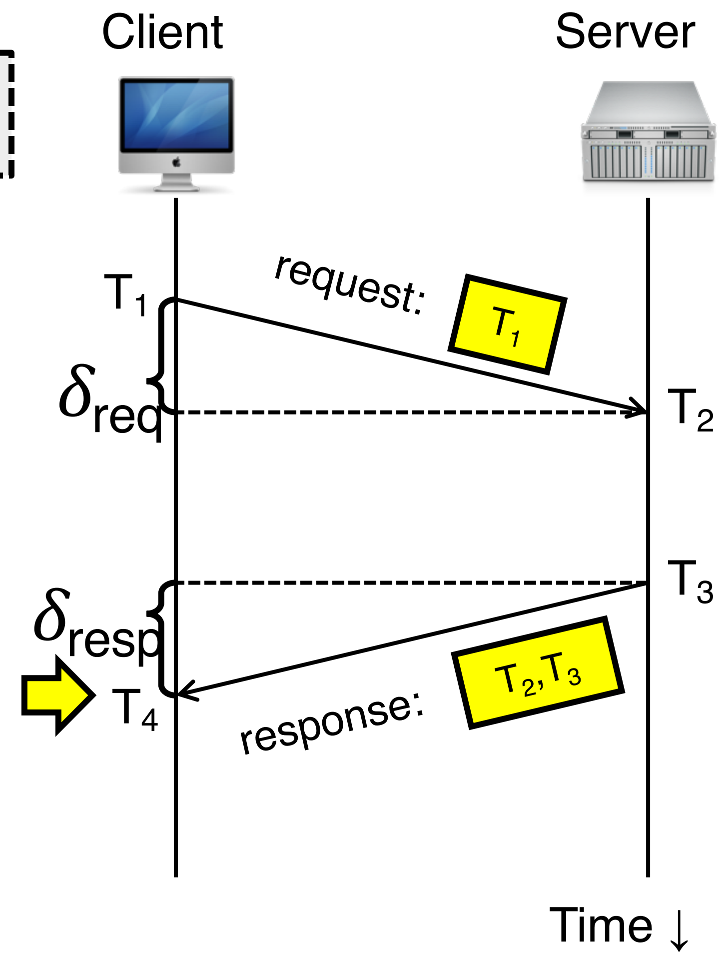
Cristian's algorithm: Offset sample calculation

Goal: Client sets clock ← $T_3 + \delta_{resp}$

- Client samples round trip time $\delta = \delta_{req} + \delta_{resp} = (T_4 - T_1) - (T_3 - T_2)$
- But client knows δ, not δ_{resp}

Assume: $\delta_{req} \approx \delta_{resp}$

Client sets clock ← $T_3 + ½\delta$



Clock synchronization: Takeaway points

- Clocks on different systems will always behave differently
  - Disagreement between machines can result in undesirable behavior

Clock synchronization: Takeaway points

- Clocks on different systems will always behave differently
  - Disagreement between machines can result in undesirable behavior

- Clock synchronization algorithms
  - Rely on timestamps to estimate network delays
  - 100s μs–ms accuracy
  - Clocks never exactly synchronized

Clock synchronization: Takeaway points

- Clocks on different systems will always behave differently
  - Disagreement between machines can result in undesirable behavior

- Clock synchronization algorithms
  - Rely on timestamps to estimate network delays
  - 100s μs–ms accuracy
  - Clocks never exactly synchronized

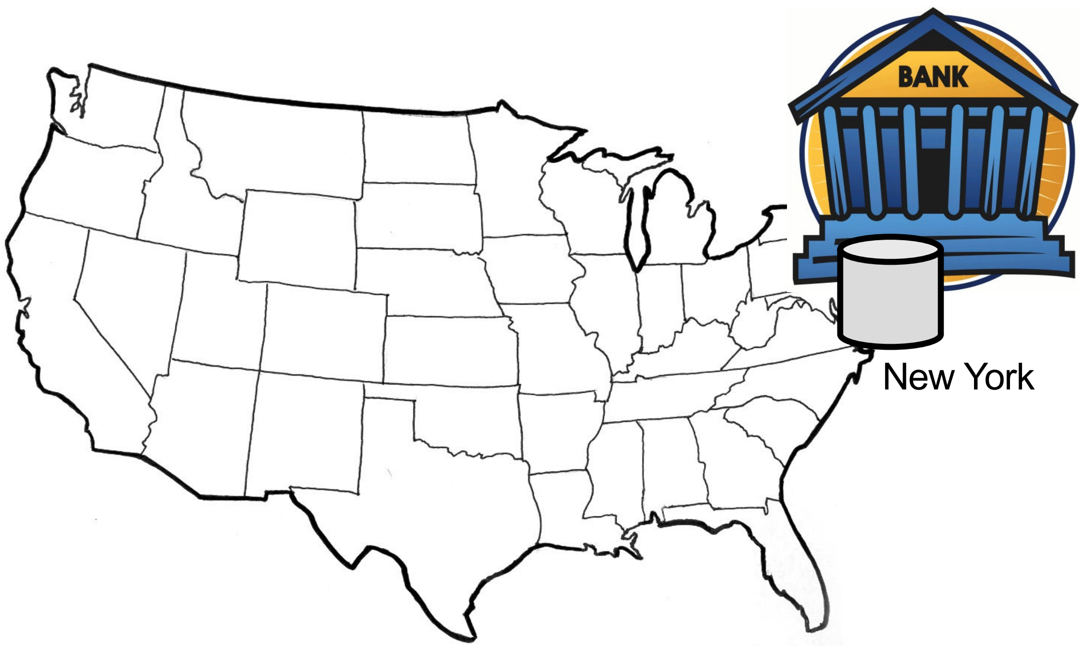
- Often inadequate for distributed systems
  - Often need to reason about the order of events
  - Might need precision on the order of ns

Today's outline

- The need for time synchronization
- "Wall clock time" synchronization
  - Cristian's algorithm
- Logical Time: Lamport Clocks
- Vector clocks

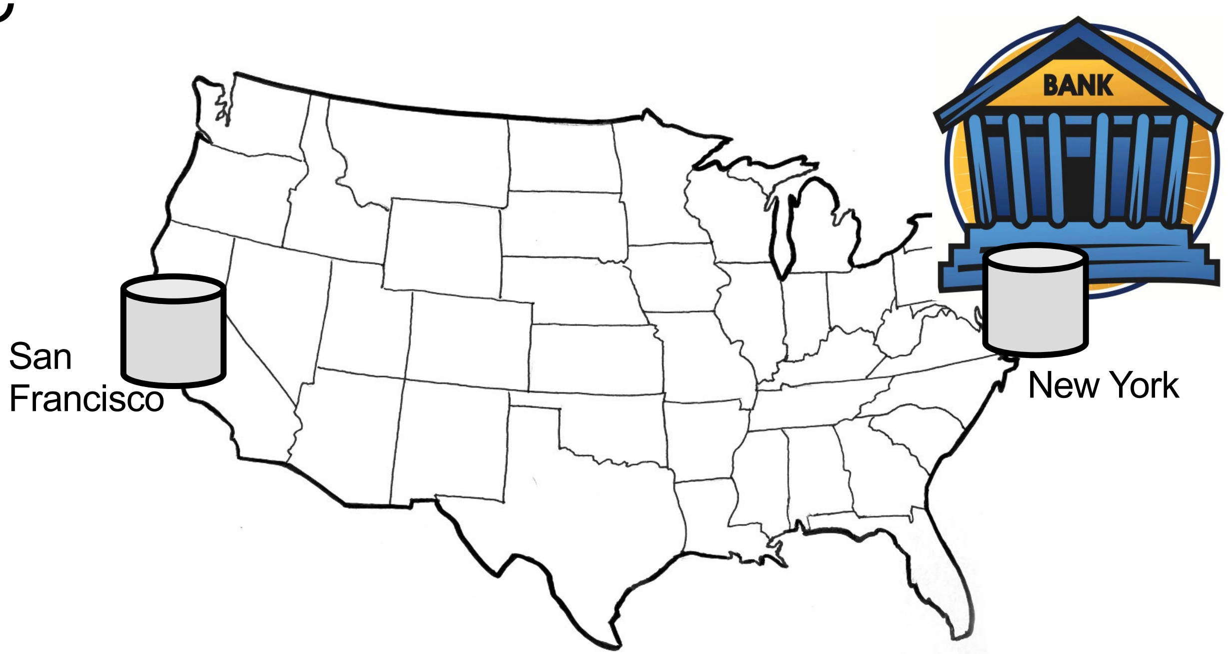
Motivation: Multi-site database replication

- A New York-based bank wants to make its transaction ledger database resilient to whole-site failures



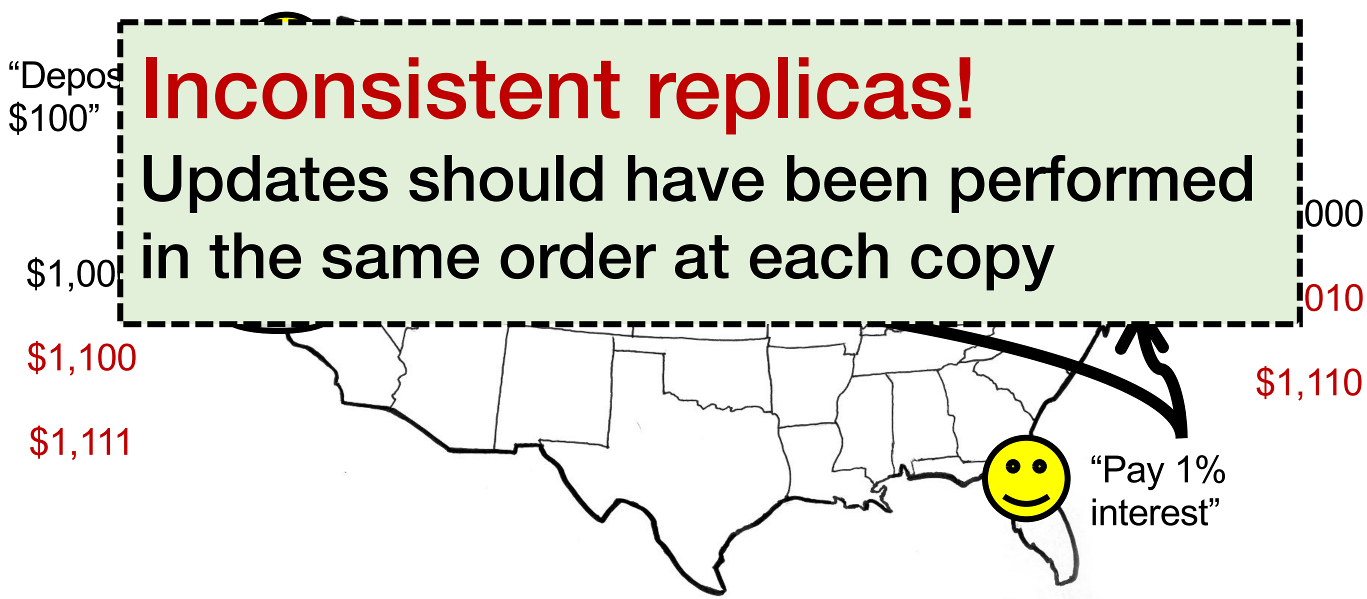
Motivation: Multi-site database replication

- A New York-based bank wants to make its transaction ledger database resilient to whole-site failures
- Replicate the database, keep one copy in **SF**, one in **NYC**



The consequences of concurrent updates

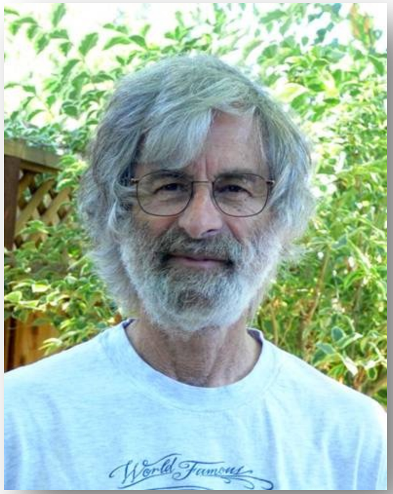
- Replicate the database, keep one copy in **SF**, one in **NYC**
  - Client sends reads to the nearest copy
  - Client sends update to both copies



Inconsistent replicas!

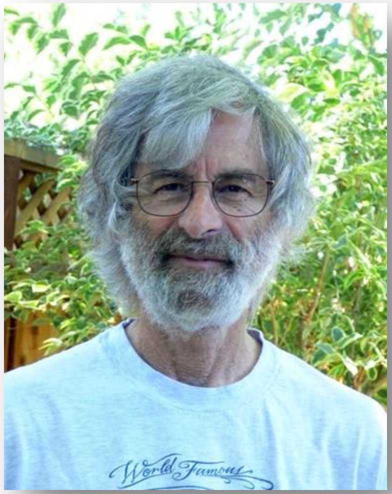
Updates should have been performed in the same order at each copy

Idea: Logical clocks



- Landmark 1978 paper by Leslie Lamport

Idea: Logical clocks



- Landmark 1978 paper by **Leslie Lamport**
- **Insights:** only the events themselves matter

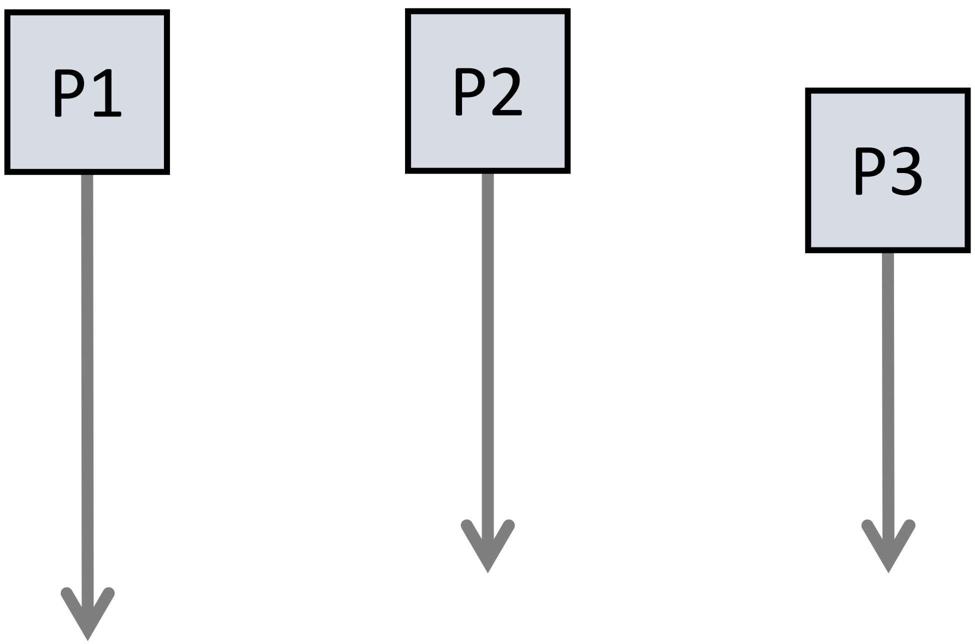
Idea: Disregard the precise clock time

Instead, capture just a "**happens before**" relationship between a pair of events

Defining “happens-before” (→)

- Consider three processes: P1, P2, and P3

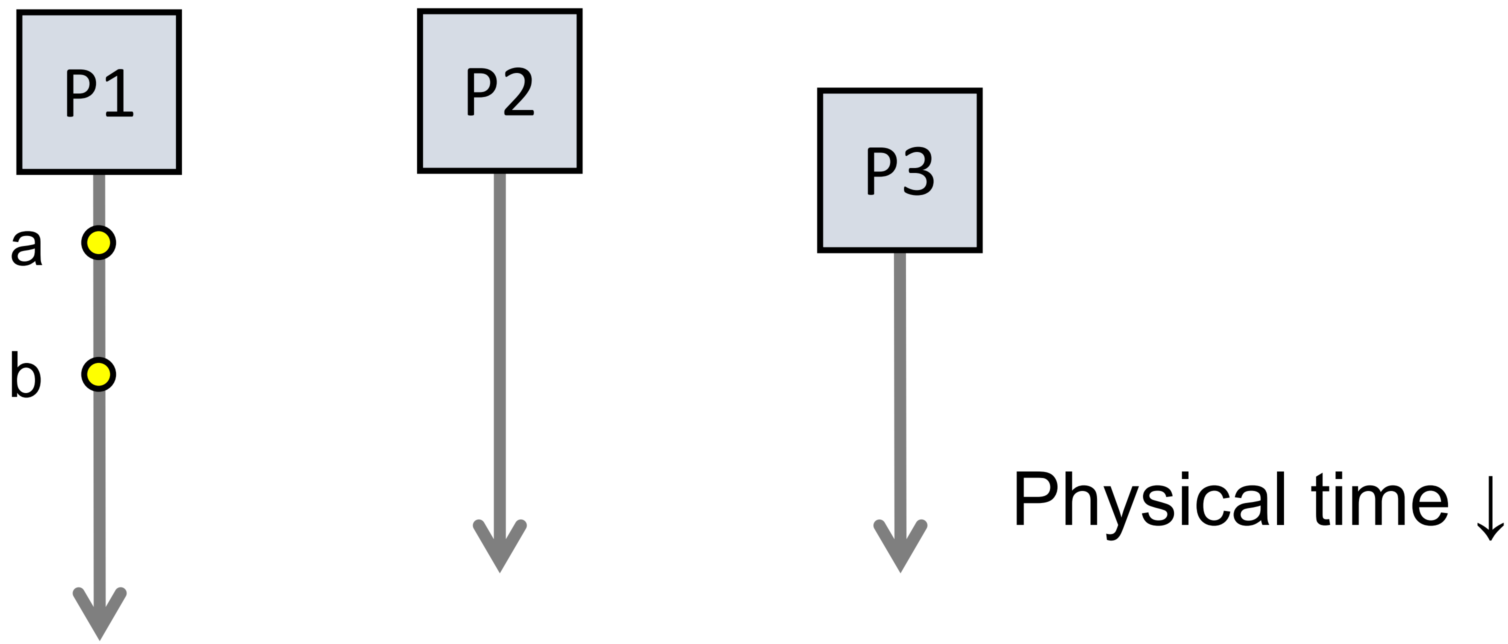
- Notation: Event a happens before event b (a → b)



Physical time ↓

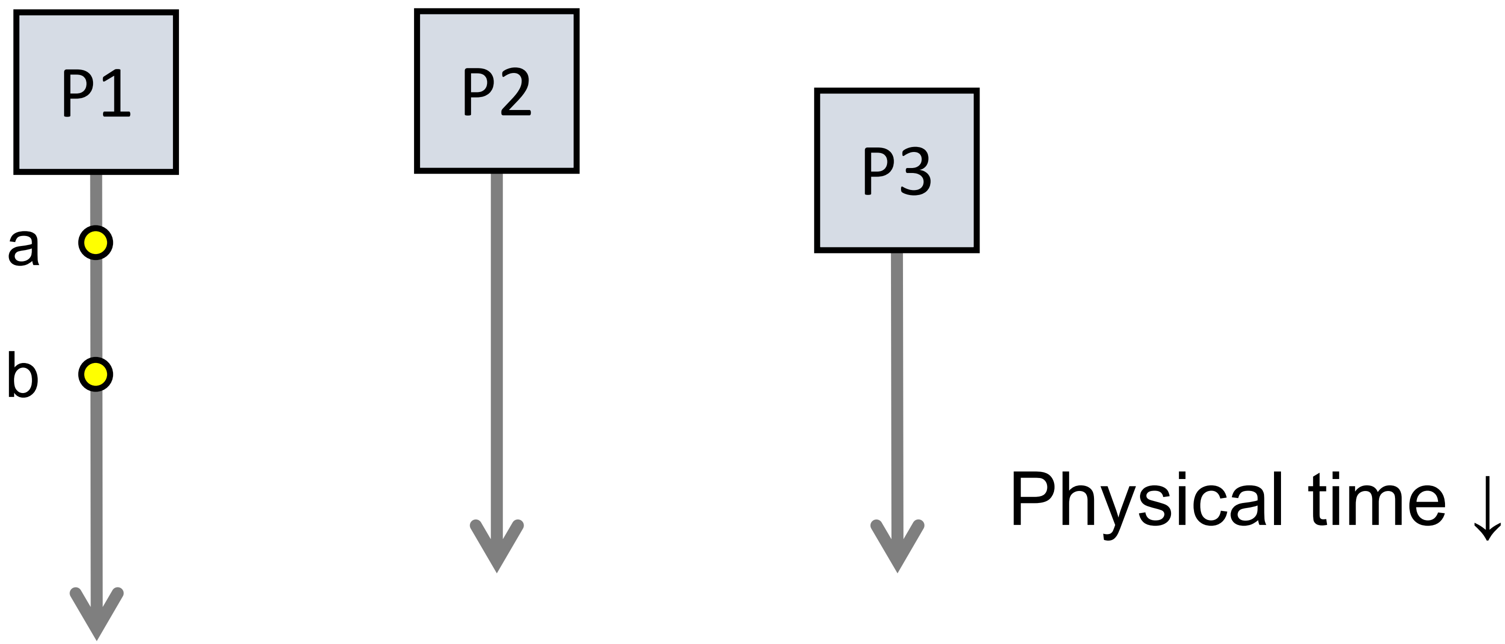
Defining "happens-before" (→)

- Can observe event order at a single process



Defining "happens-before" (→)

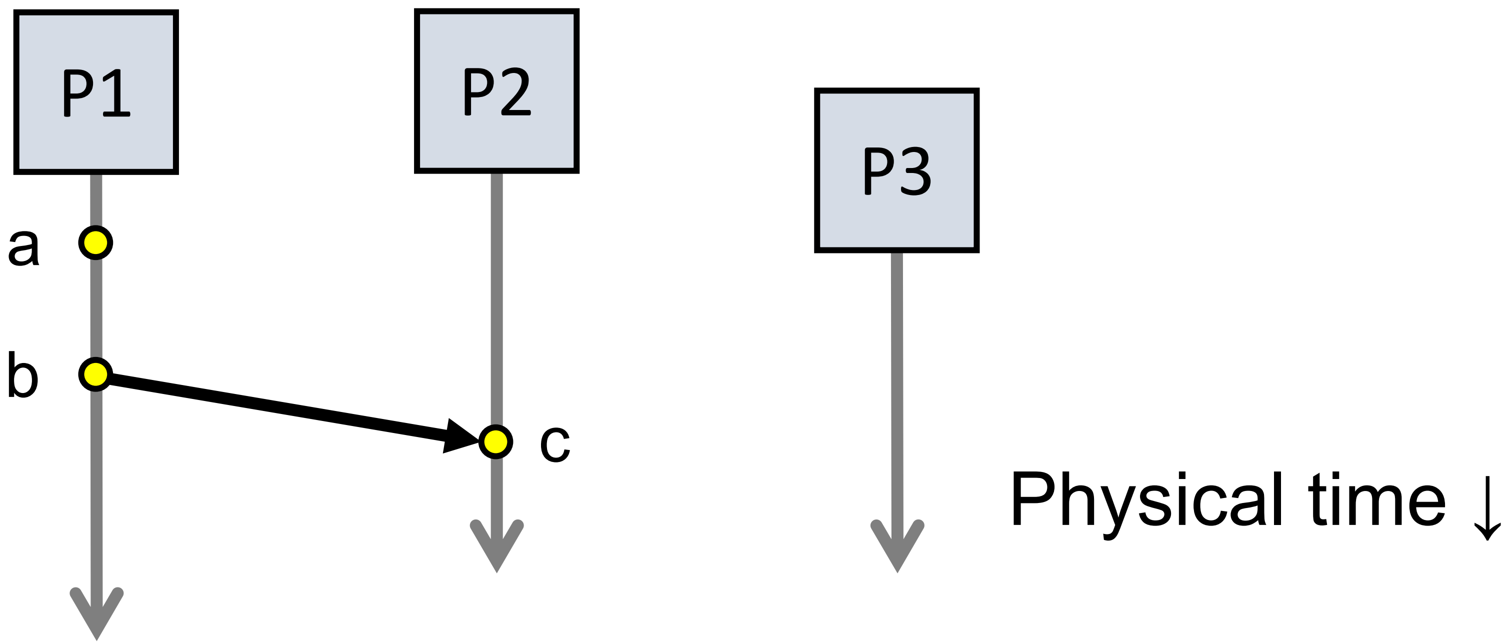
1. If same process and a occurs before b, then a → b



Defining "happens-before" (→)

1. If same process and a occurs before b, then a → b

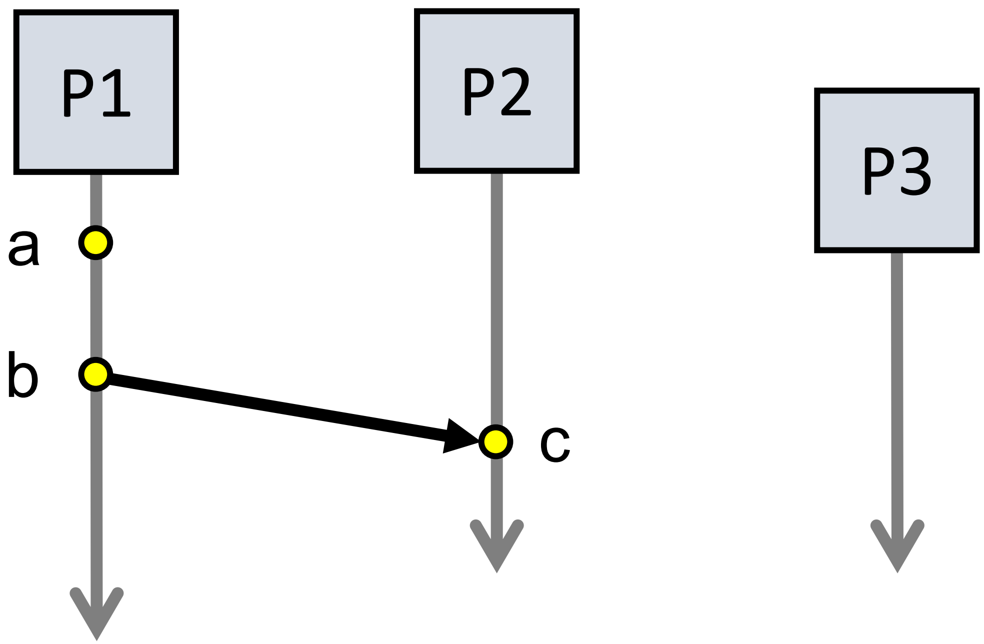
2. Can observe ordering when processes communicate



Defining "happens-before" (→)

1. If same process and a occurs before b, then a → b

2. If c is a message receipt of b, then b → c



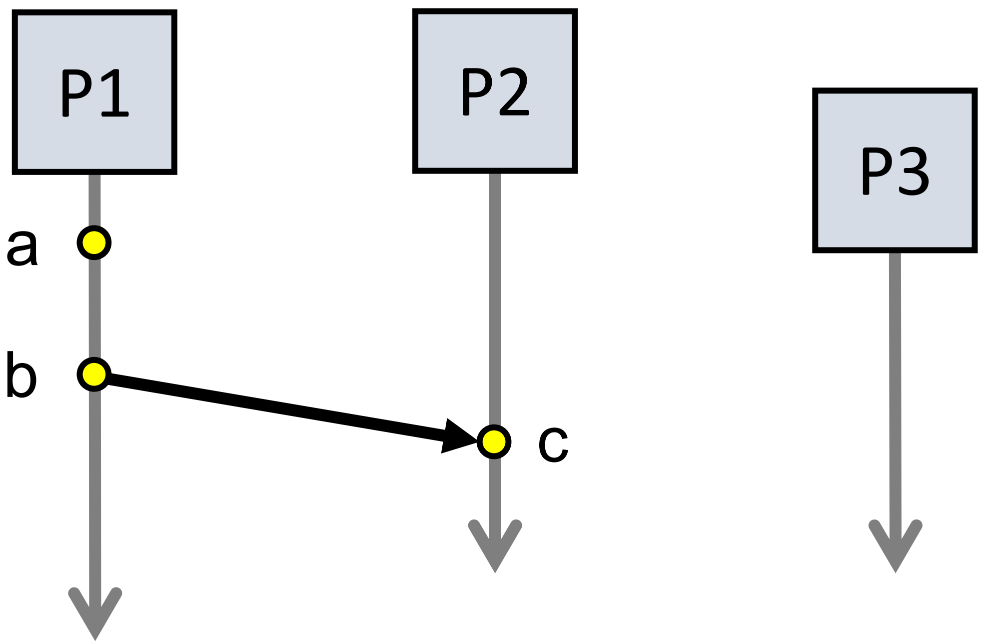
Physical time ↓

Defining "happens-before" (→)

1. If same process and a occurs before b, then a → b

2. If c is a message receipt of b, then b → c

3. Can observe ordering transitively



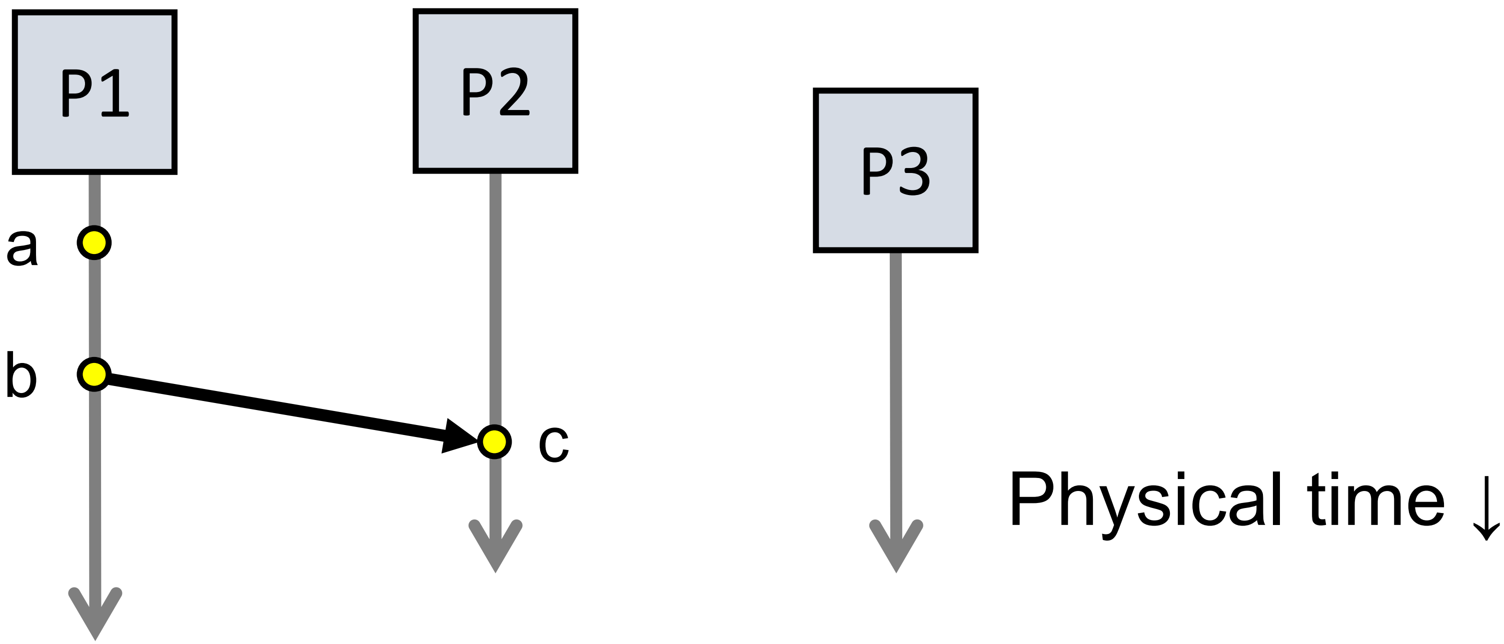
Physical time ↓

Defining "happens-before" (→)

1. If same process and a occurs before b, then a → b

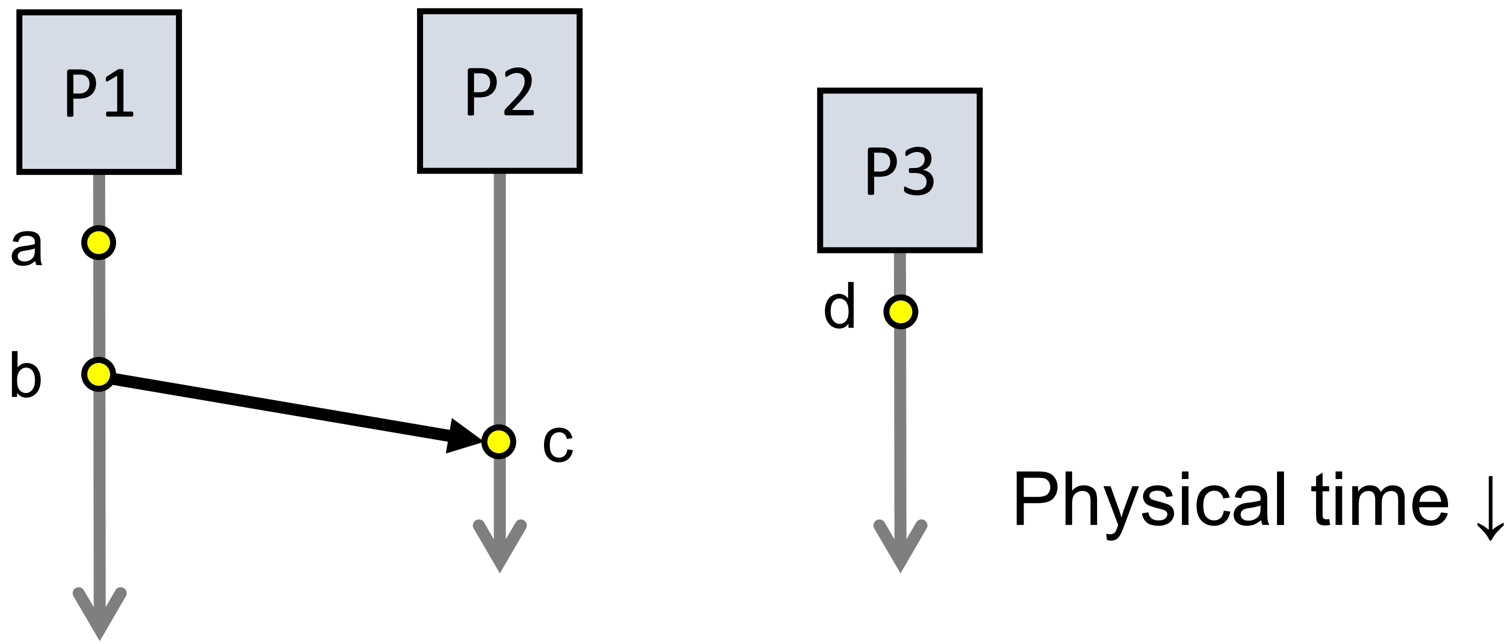
2. If c is a message receipt of b, then b → c

3. If a → b and b → c, then a → c



Defining "happens-before" (→)

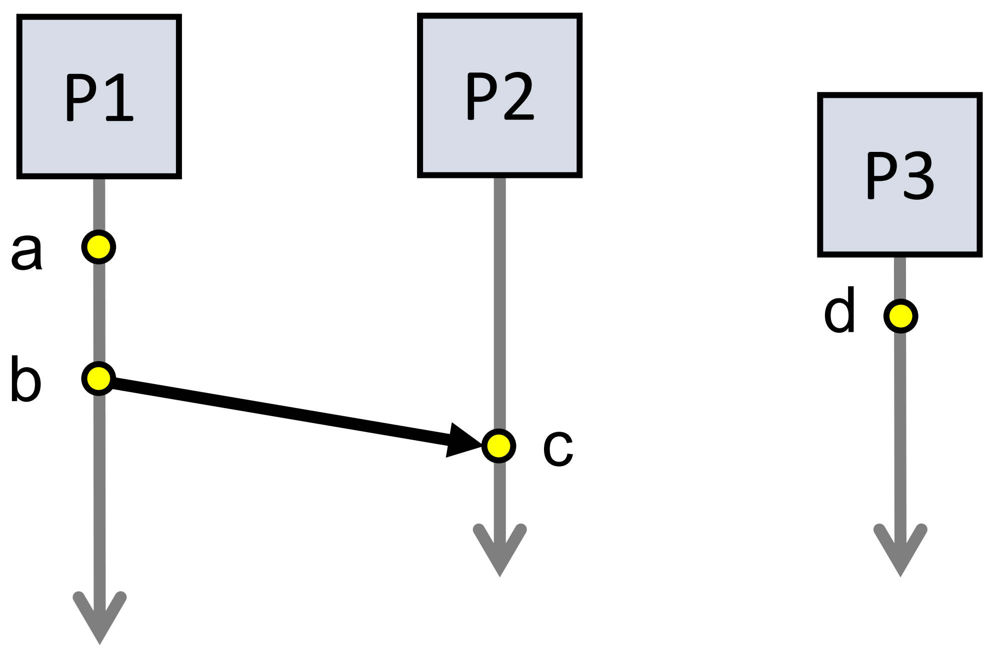
1. Not all events are related by →



Defining "happens-before" (→)

1. Not all events are related by →

2. a, d not related by → so concurrent, written as **a || d**



Physical time ↓

Lamport clocks: Objective

- We seek a clock time C(a) for every event a

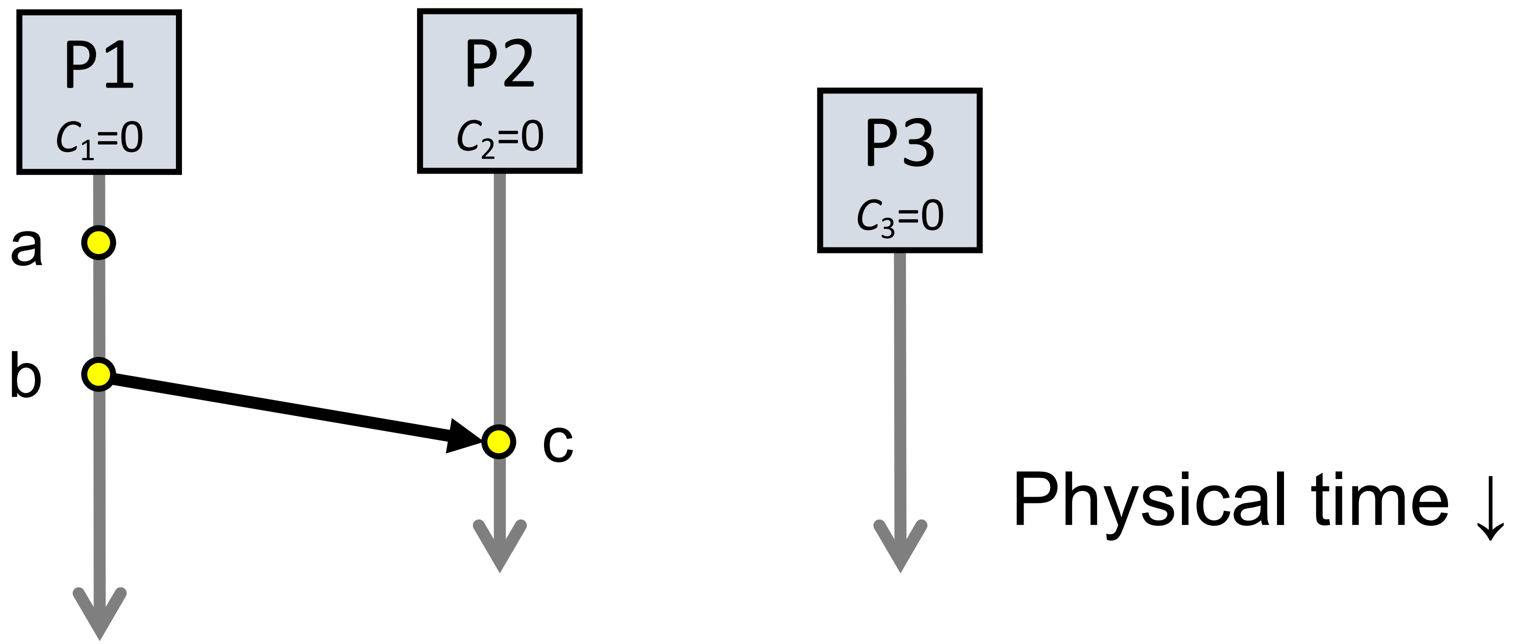
Plan: Tag events with clock times; use clock times to make distributed system correct

- Clock condition: If a → b, then C(a) < C(b)

The Lamport Clock algorithm

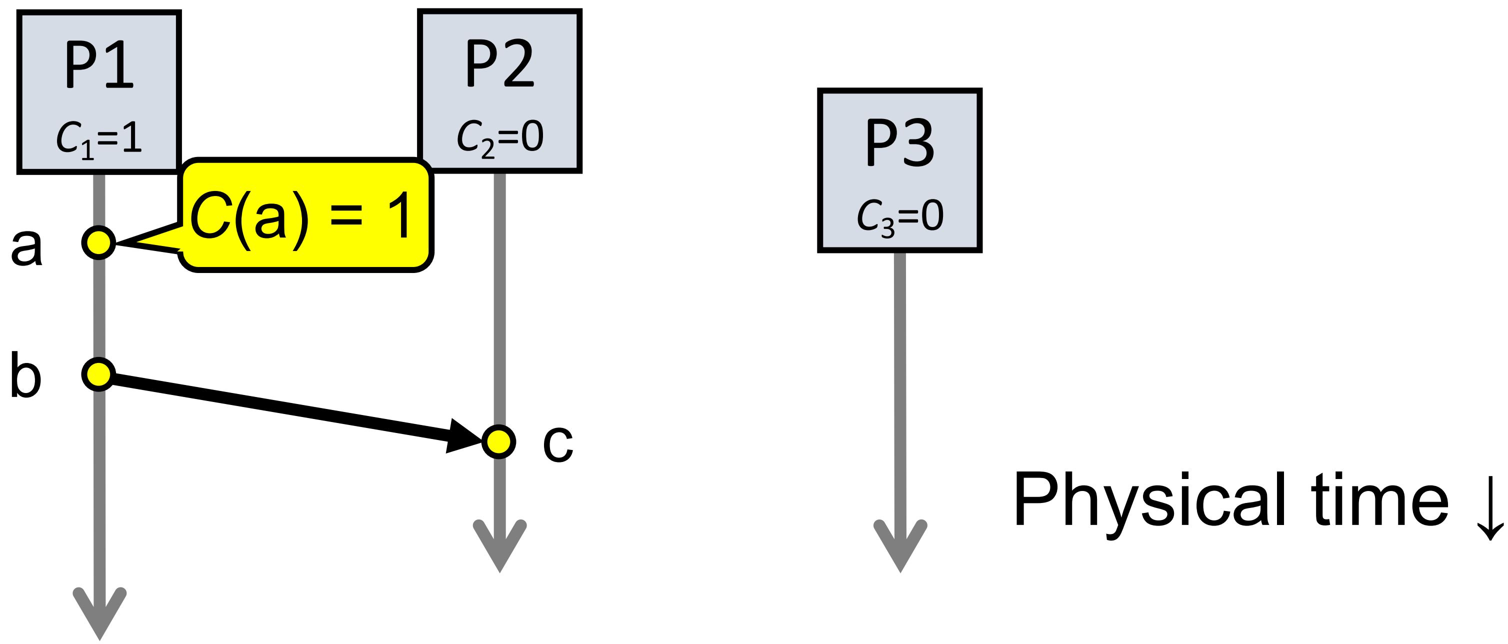
- Each process $\mathtt{P}_i$ maintains a local clock $\mathtt{C}_i$

1. Before executing an event, $C_i \leftarrow C_i + 1$:



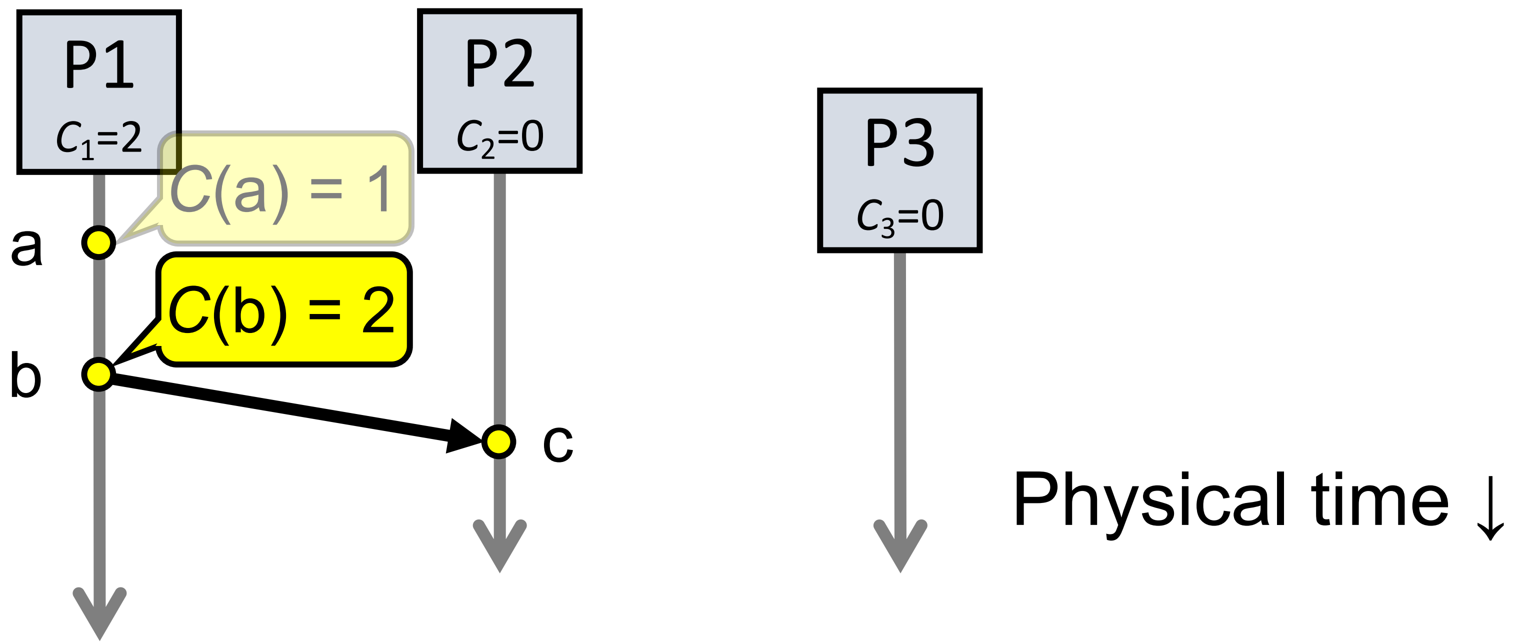
The Lamport Clock algorithm

1. Before executing an event a, $C_i \leftarrow C_i + 1$:
   - Set event time $C(a) \leftarrow C_i$



The Lamport Clock algorithm

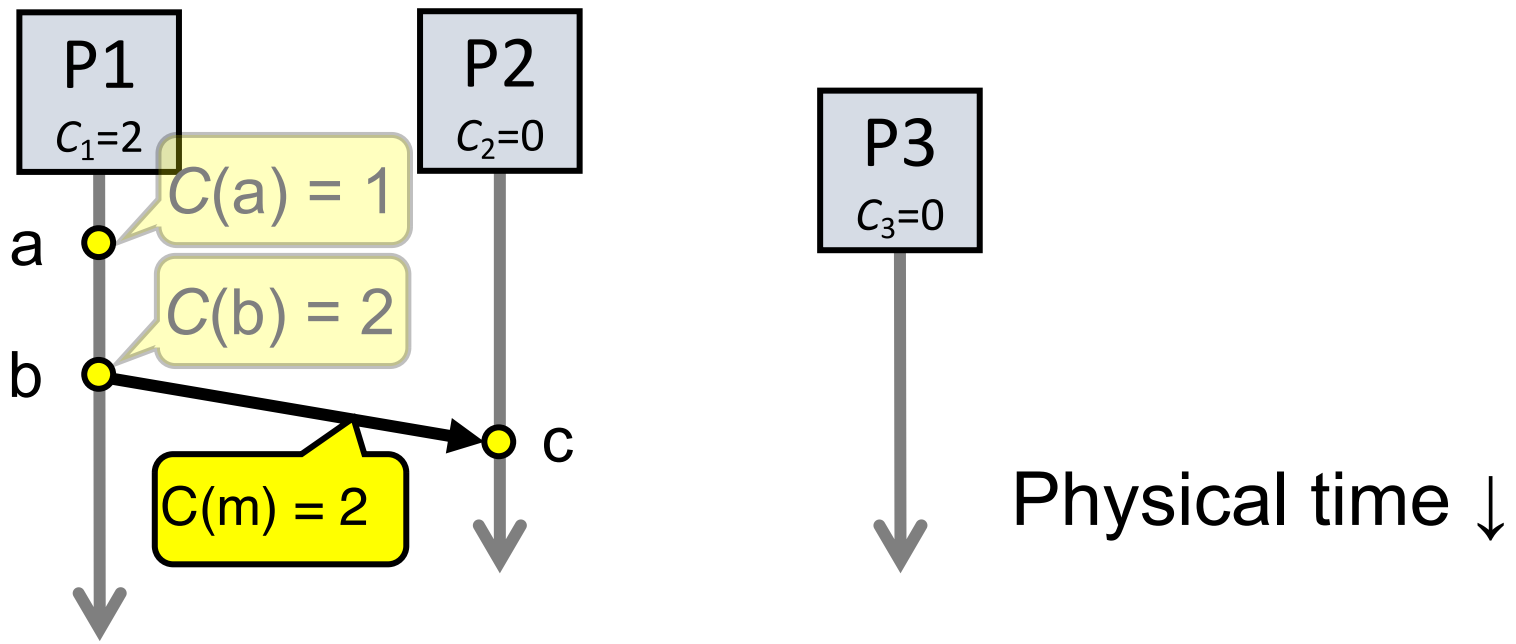
1. Before executing an event b, $C_i \leftarrow C_i + 1$:
   - Set event time $C(\text{b}) \leftarrow C_i$



The Lamport Clock algorithm

1. Before executing an event b, $C_i \leftarrow C_i + 1$

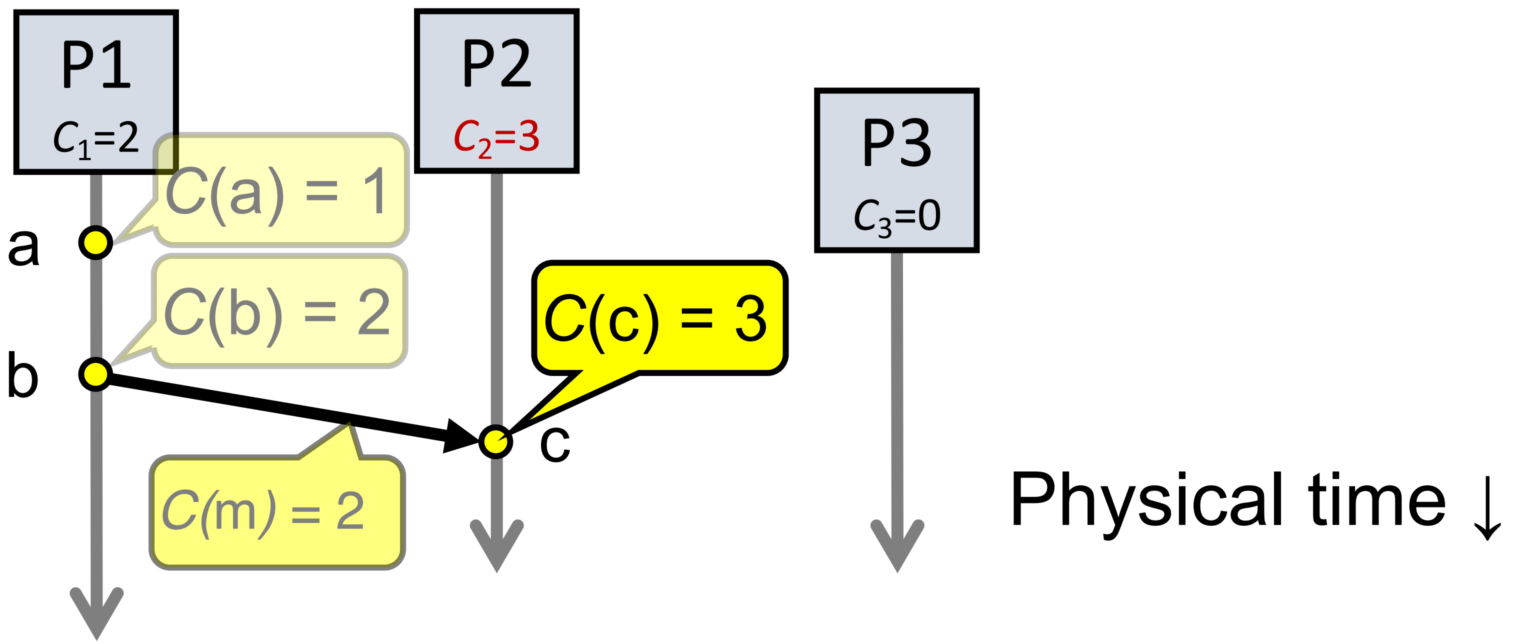
2. Send the local clock in the message m



The Lamport Clock algorithm

3. On process P_j receiving a message m:

   - Set C_j and receive event time C(c) ← 1 + max{ C_j, C(m) }



Lamport Timestamps: Ordering all events

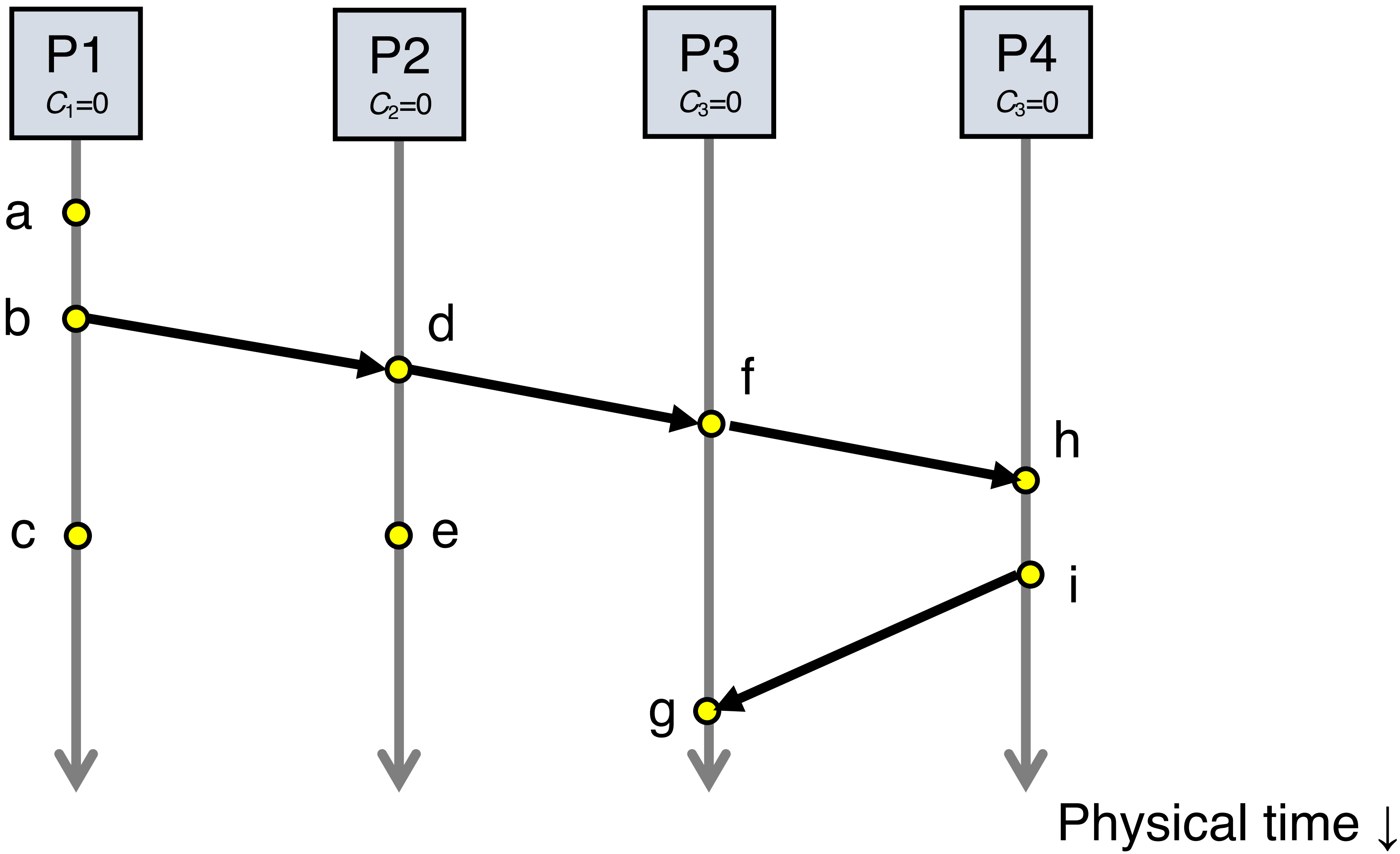
- Break ties by appending the process number to each event:

  1. Process P_i timestamps event e with $C_i(e).i$

  2. $C(a).i < C(b).j$ when:
     - $C(a) < C(b)$, or $C(a) = C(b)$ and $i < j$

- Now, for any two events a and b, C(a) < C(b) or C(b) < C(a)
  - This is called a total ordering of events

Order all these events



Totally-Ordered Multicast

Goal: All sites apply updates in (same) Lamport clock order

- Client sends update to one replica site *j*
  - Replica assigns it Lamport timestamp $C_j . j$

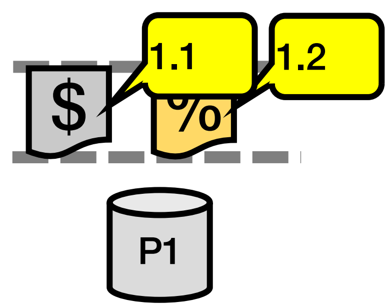
Totally-Ordered Multicast

Goal: All sites apply updates in (same) Lamport clock order

- Client sends update to one replica site *j*
  - Replica assigns it Lamport timestamp C_j . *j*

- Key idea: Place events into a sorted local queue
  - Sorted by increasing Lamport timestamps

Example: P1's local queue:



Totally-Ordered Multicast (Almost correct)

1. On receiving an update from client, broadcast to others (including yourself)

2. On receiving an update from replica:
   a) Add it to your local queue
   b) Broadcast an acknowledgement message to every replica (including yourself)

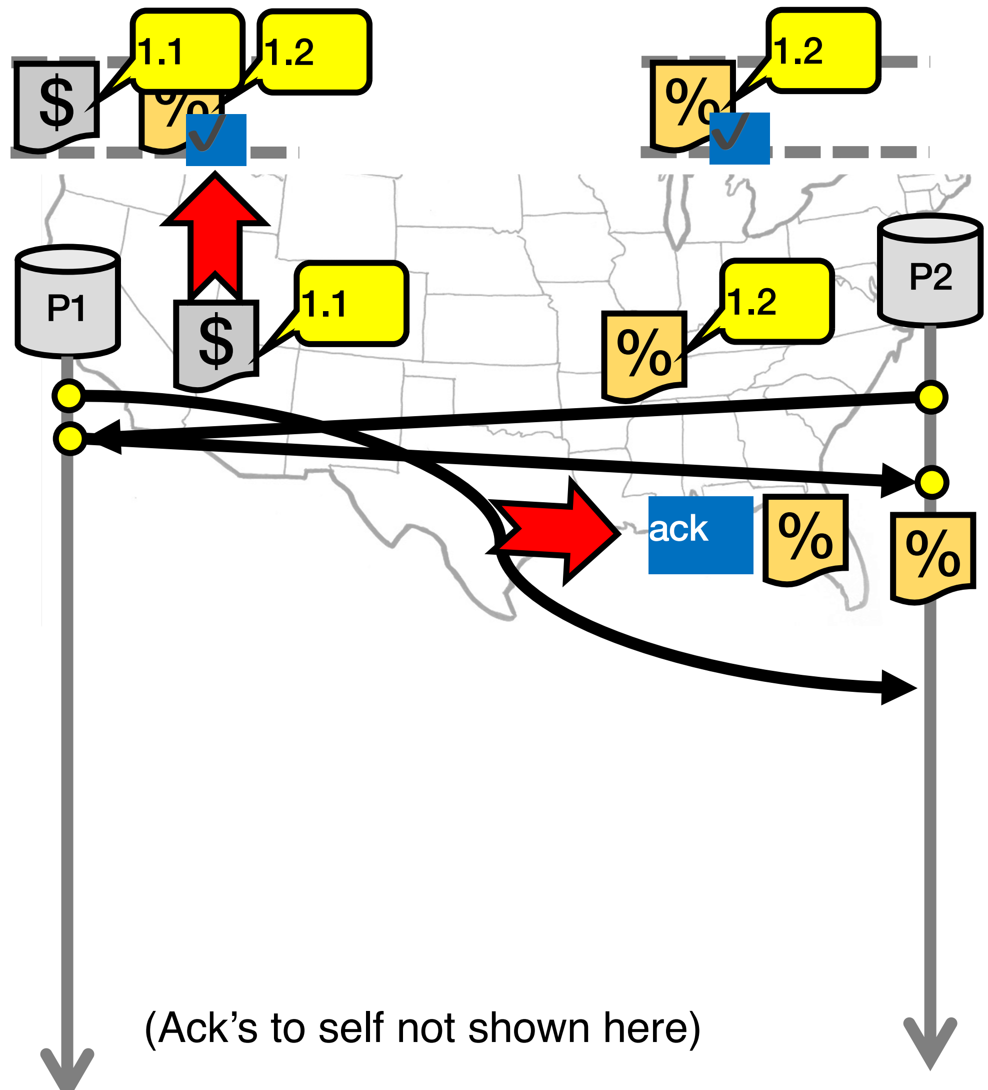
3. On receiving an acknowledgement:
   - Mark corresponding update acknowledged in your queue

4. Remove and process updates <u>everyone</u> has ack'ed from <u>head</u> of queue

Totally-Ordered Multicast (Almost correct)

- P1 queues $, P2 queues %
- P1 queues and ack's %
  - P1 marks % fully ack'ed
- P2 marks % fully ack'ed

✗ P2 processes %



Totally-Ordered Multicast (Correct version)

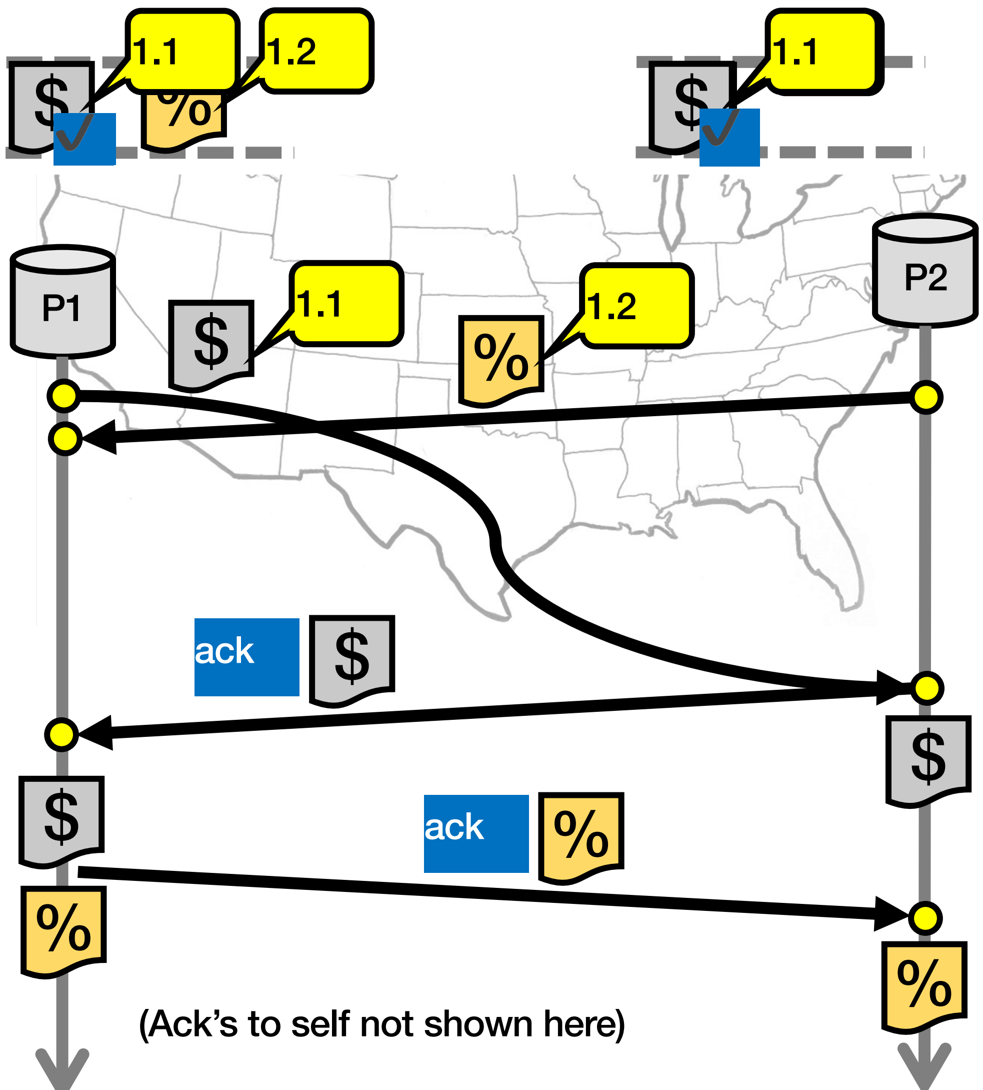
1. On receiving an update from client, broadcast to others (including yourself)

2. On receiving or processing an update:
   a) Add it to your local queue
   b) Broadcast an acknowledgement message to every replica (including yourself) only from head of queue

3. On receiving an acknowledgement:
   - Mark corresponding update acknowledged in your queue

4. Remove and process updates <u>everyone</u> has ack'ed from <u>head</u> of queue

Totally-Ordered Multicast (Correct version)



(Ack's to self not shown here)

So, are we done?

- *Does totally-ordered multicast solve the problem of multi-site replication in general?*

So, are we done?

- *Does totally-ordered multicast solve the problem of multi-site replication in general?*

- Not by a long shot!

1. Our protocol assumed:
   - No node failures
   - No message loss
   - No message corruption

So, are we done?

- *Does totally-ordered multicast solve the problem of multi-site replication in general?*

- Not by a long shot!

1. Our protocol assumed:
    - No node failures
    - No message loss
    - No message corruption
2. All-to-all communication does not scale

So, are we done?

- *Does totally-ordered multicast solve the problem of multi-site replication in general?*

- Not by a long shot!

1. Our protocol assumed:
   - No node failures
   - No message loss
   - No message corruption
2. All-to-all communication does not scale
3. Waits forever for message delays (performance?)

Lamport Clocks: Takeaway points

- Can totally-order events in a distributed system: that's useful!
  - We saw an application of Lamport clocks for totally-ordered multicast

Lamport Clocks: Takeaway points

- Can totally-order events in a distributed system: that's useful!
  - We saw an application of Lamport clocks for totally-ordered multicast

- But: while by construction,

  $$a \rightarrow b \text{ implies } C(a) < C(b),$$

  - The converse is not necessarily true:
    - $C(a) < C(b)$ does not imply $a \rightarrow b$ (possibly, $a \parallel b$)

Lamport Clocks: Takeaway points

- Can totally-order events in a distributed system: that's useful!
  - We saw an application of Lamport clocks for totally-ordered multicast

- But: while by construction,

$$a \rightarrow b \text{ implies } C(a) < C(b),$$

  - The converse is not necessarily true:
    - $C(a) < C(b)$ does not imply $a \rightarrow b$ (possibly, $a \parallel b$)

Can't use Lamport timestamps to infer causal relationships between events

Today’s outline

- The need for time synchronization
- “Wall clock time” synchronization
    - Cristian’s algorithm
- Logical Time: Lamport Clocks
- Vector clocks

Lamport Clocks and causality

- Lamport clock timestamps do not capture causality
- Given two timestamps C(a) and C(z), want to know whether there's a chain of events linking them:

$$a \rightarrow b \rightarrow \ldots \rightarrow y \rightarrow z$$

Vector clock: Introduction

- One integer can't order events in more than one process

- So, a Vector Clock (VC) is a vector of integers, one entry for each process in the entire distributed system

  - Label event e with $VC(e) = [c_1, c_2 \ldots, c_n]$
    - Each entry c_k is a count of events in process k that causally precede e

Vector clock: Update rules

- Initially, all vectors are [0, 0, …, 0]

- Two update rules:

1. For each local event on process i, increment local entry c_i

Vector clock: Update rules

- Initially, all vectors are [0, 0, …, 0]

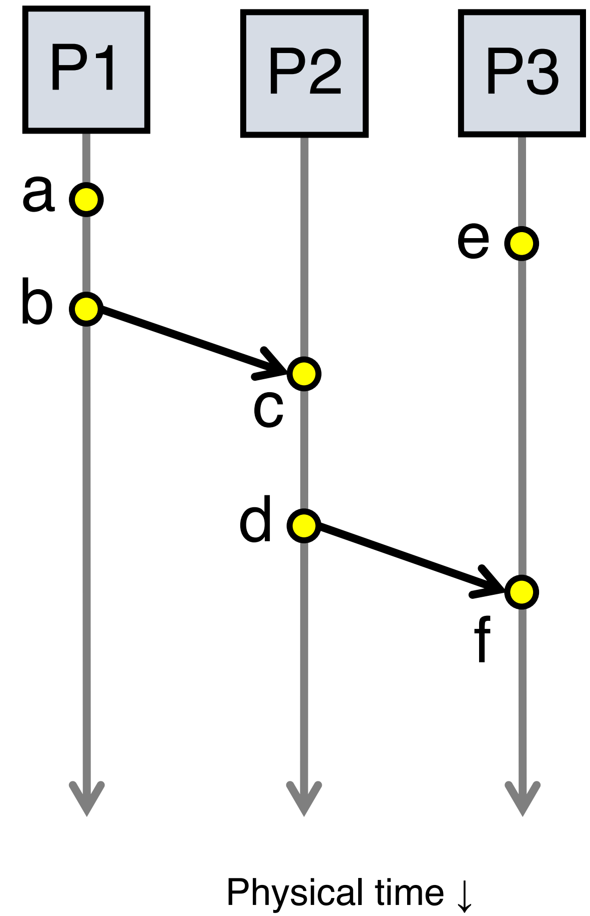
- Two update rules:

1. For each local event on process i, increment local entry c_i

2. If process j receives message with vector $[d_1, d_2, \ldots, d_n]$:
   - Set each local entry $c_k = \max\{c_k, d_k\}$
   - Increment local entry c_j

Vector clock: Example

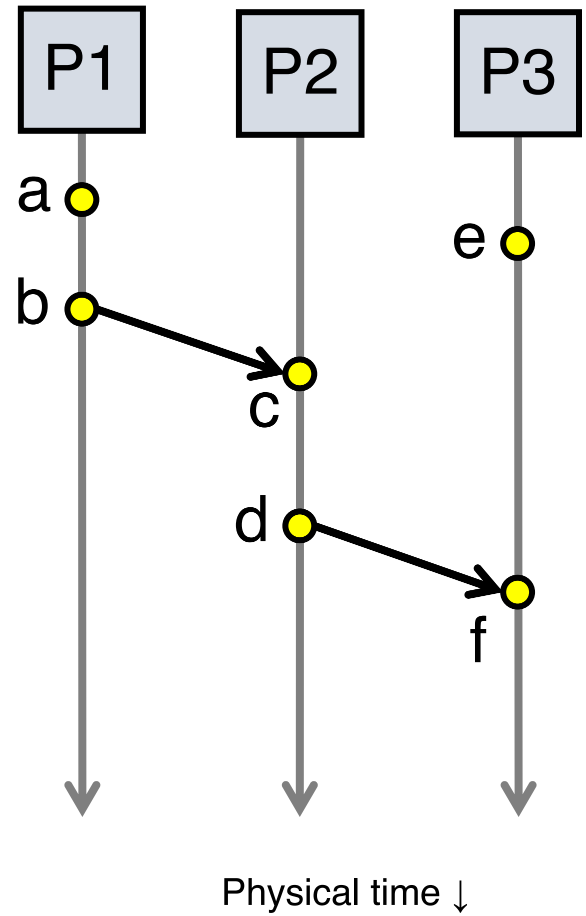
- All processes' VCs start at [0, 0, 0]



Vector clock: Example

- All processes' VCs start at [0, 0, 0]

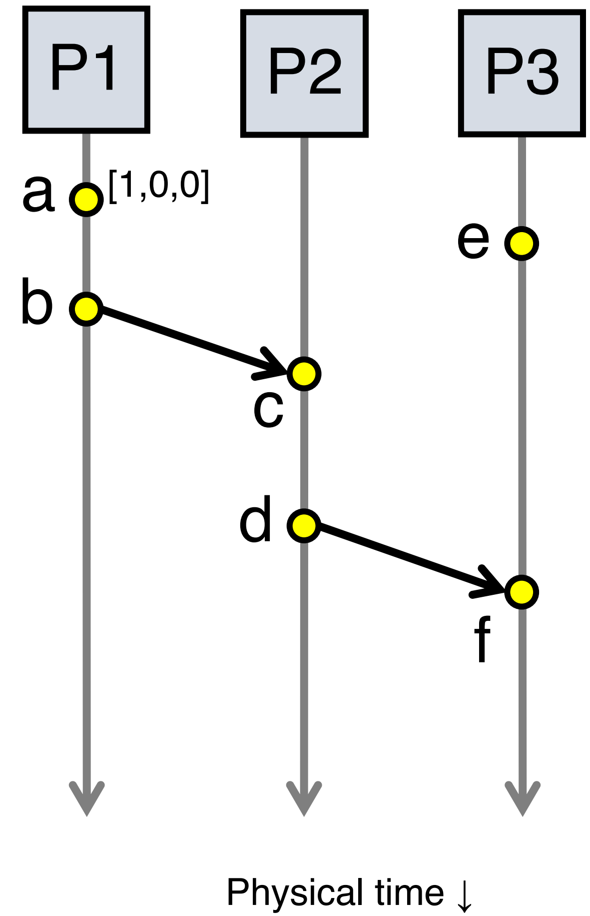
- Applying local update rule



Vector clock: Example

- All processes' VCs start at [0, 0, 0]

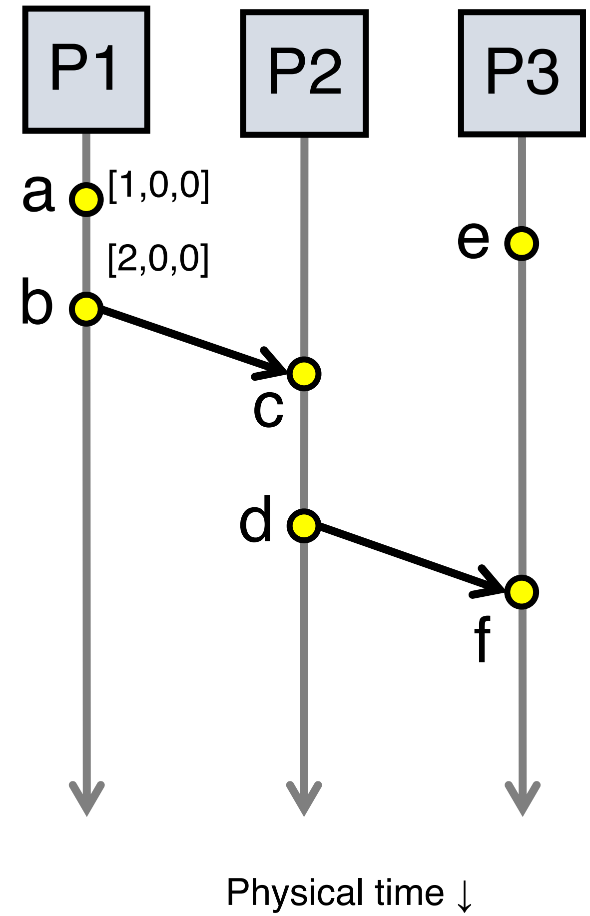
- Applying local update rule



Vector clock: Example

- All processes' VCs start at [0, 0, 0]

- Applying local update rule

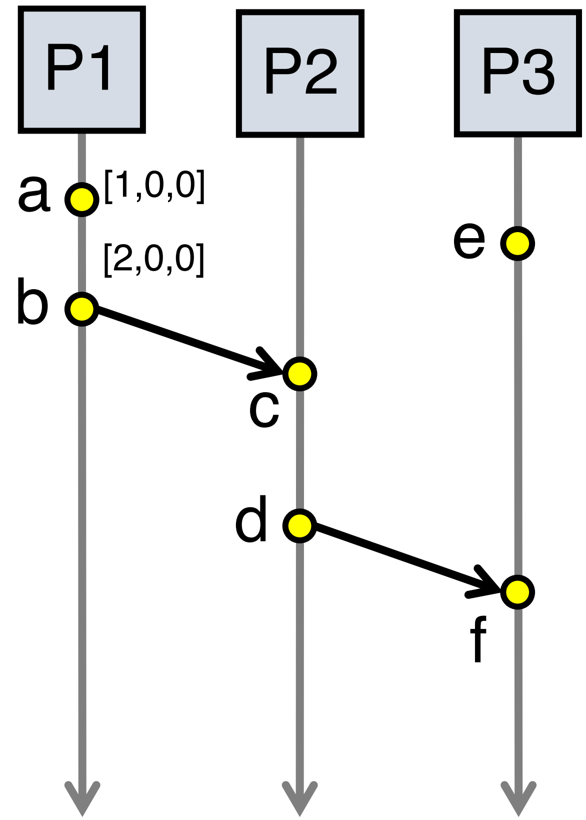


Vector clock: Example

- All processes' VCs start at [0, 0, 0]

- Applying local update rule

- Applying message rule
  - Local vector clock **piggybacks** on inter-process messages

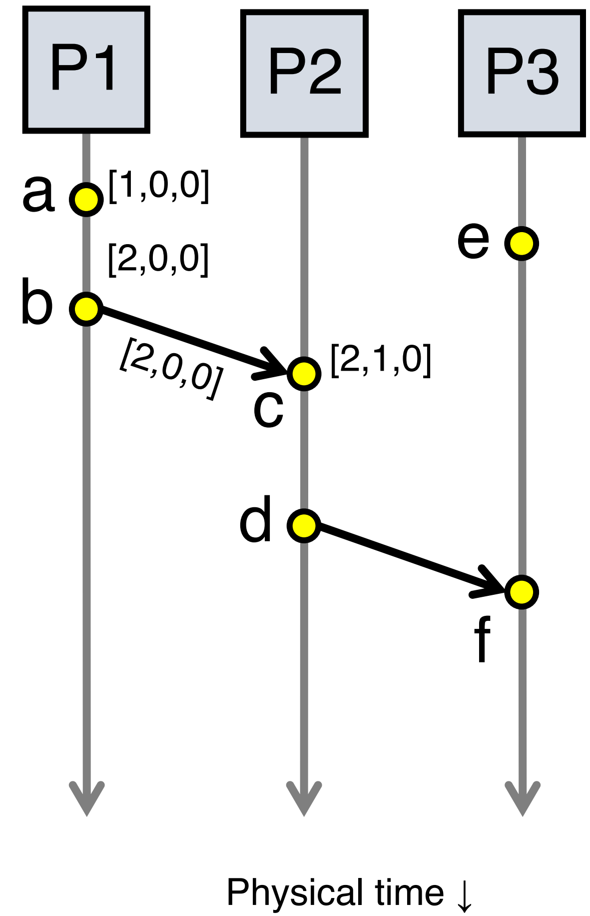


Vector clock: Example

- All processes' VCs start at [0, 0, 0]

- Applying local update rule

- Applying message rule
  - Local vector clock **piggybacks** on inter-process messages

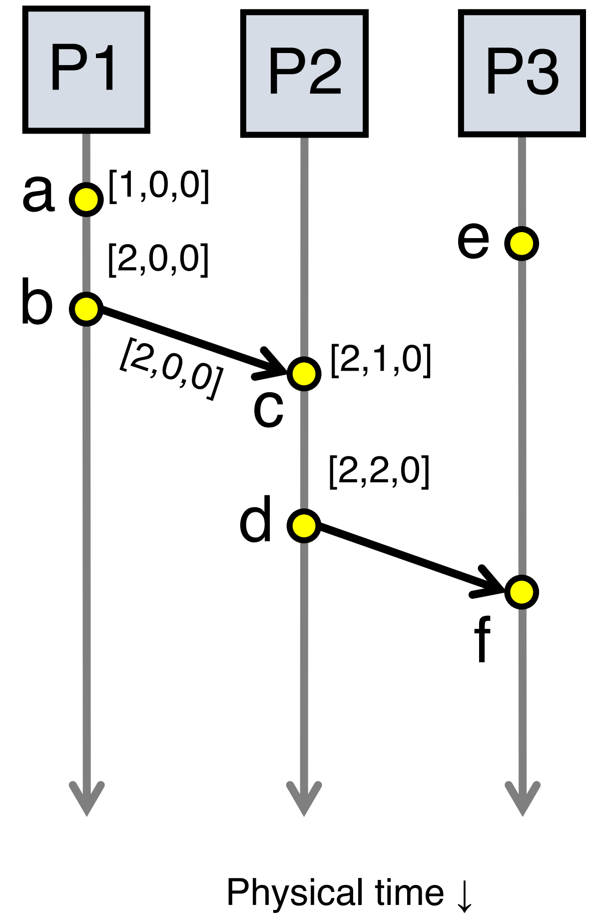


Vector clock: Example

- All processes' VCs start at [0, 0, 0]

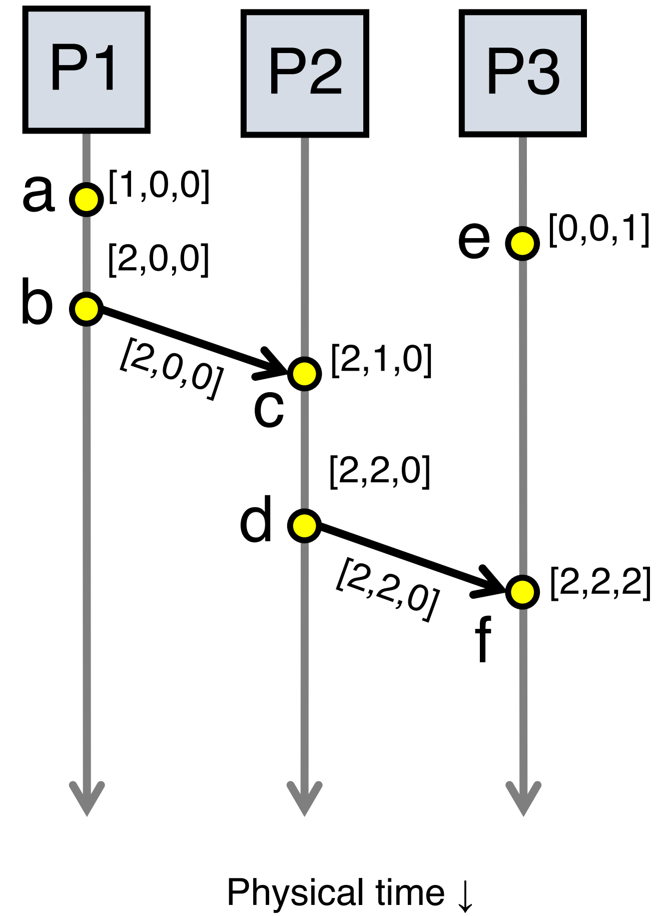
- Applying local update rule

- Applying message rule
  - Local vector clock **piggybacks** on inter-process messages



Vector clock: Example

- All processes' VCs start at [0, 0, 0]
- Applying local update rule
- Applying message rule
  - Local vector clock **piggybacks** on inter-process messages

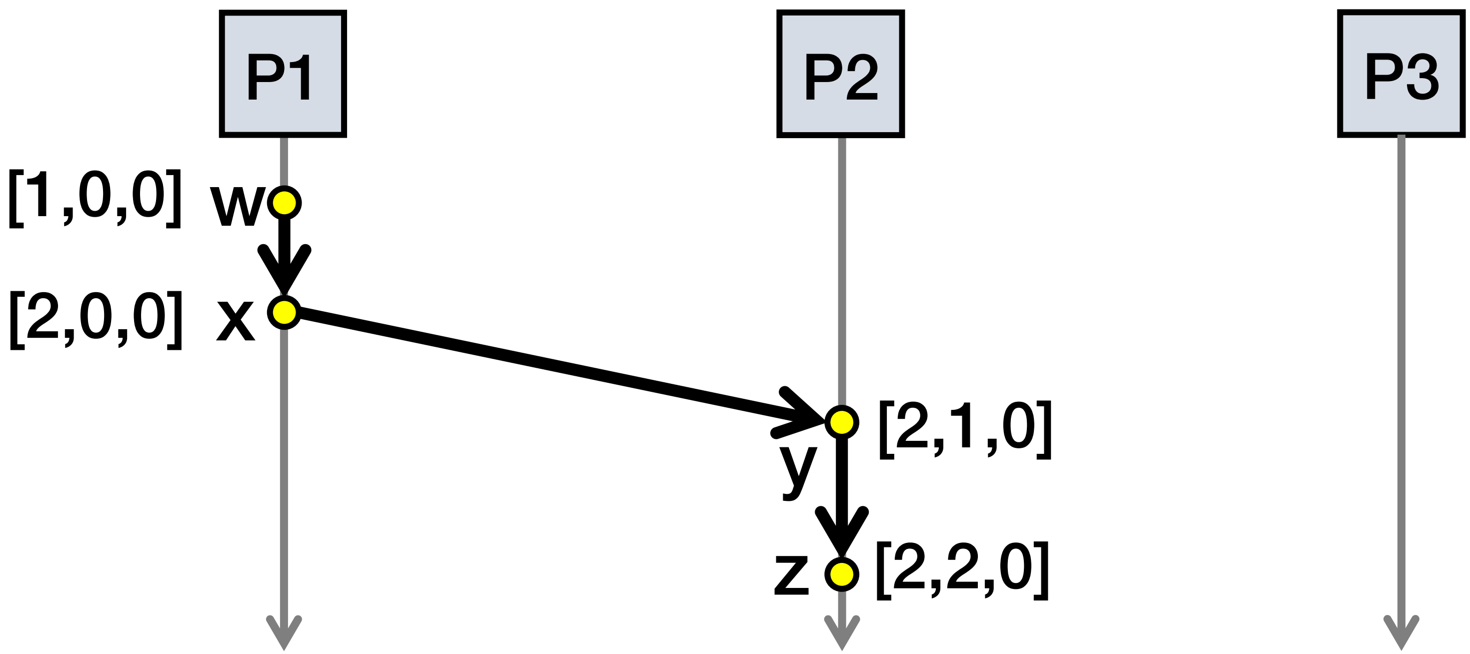


Comparing vector timestamps

- Rule for comparing vector timestamps:
  - $V(a) = V(b)$ when $a_k = b_k$ for all k
  - $V(a) < V(b)$ when $a_k \leq b_k$ for all k and $V(a) \neq V(b)$
- Concurrency:
  - $V(a) \parallel V(b)$ if $a_i < b_i$ and $a_j > b_j$, some i, j

Vector clocks capture causality

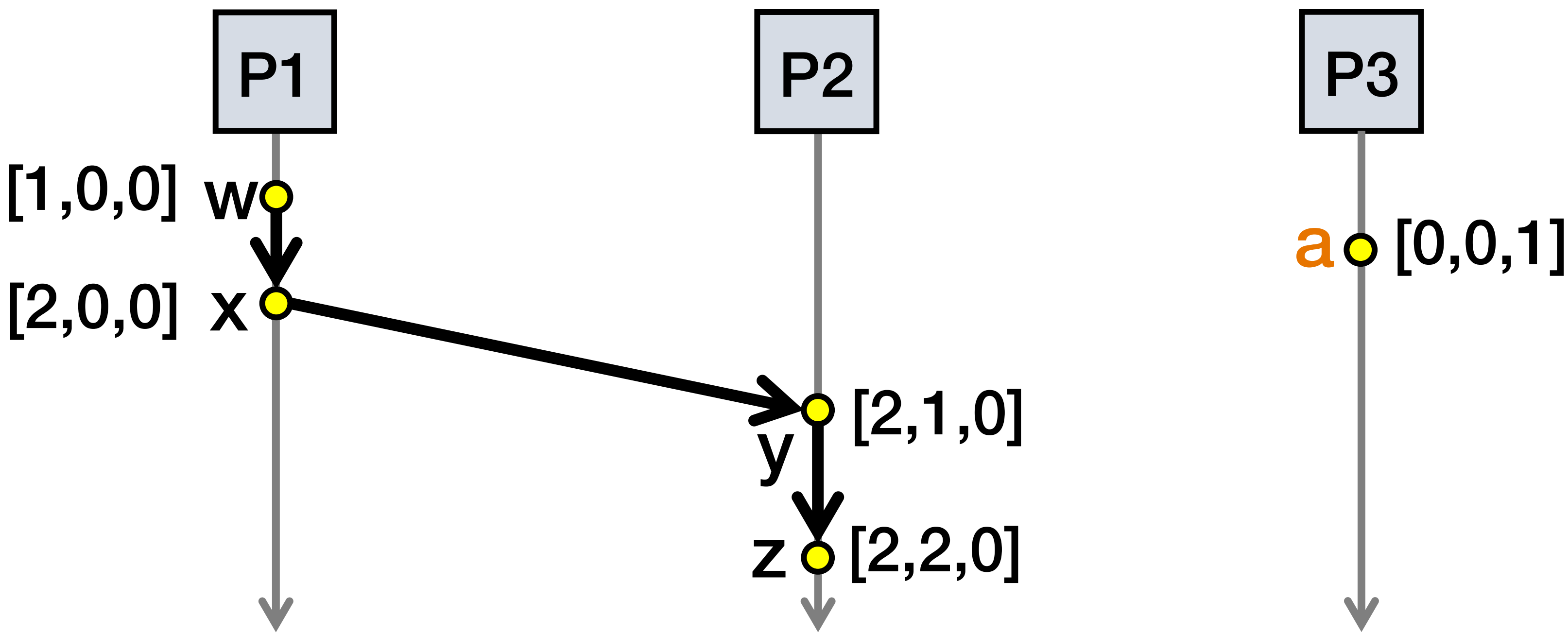
- V(w) < V(z) then there is a chain of events linked by Happens-Before (→) between a and z



Vector clocks capture causality

- V(w) < V(z) then there is a chain of events linked by Happens-Before (→) between a and z

- V(a) || V(w) then there is no such chain of events between a and w



Comparing vector timestamps

- Rule for comparing vector timestamps:
  - $V(a) = V(b)$ when $a_k = b_k$ for all k
    - They are the same event
  - $V(a) < V(b)$ when $a_k \leq b_k$ for all k and $V(a) \neq V(b)$
    - $a \rightarrow b$
- Concurrency:
  - $V(a) \parallel V(b)$ if $a_i < b_i$ and $a_j > b_j$, some i, j
    - $a \parallel b$

Two events a, z

Lamport clocks: C(a) < C(z)

Conclusion: z -/-> a, i.e., either a → z or a || z

Vector clocks: V(a) < V(z)

Conclusion: a → z

Two events a, z

Lamport clocks: $C(a) < C(z)$

Conclusion: z -/-> a, i.e., either $a \rightarrow z$ or $a \parallel z$

Vector clocks: $V(a) < V(z)$

Conclusion: $a \rightarrow z$

Vector clock timestamps precisely capture happens-before relation (potential causality)