Time

COS 418: Distributed Systems
Lecture 3

Wyatt Lloyd

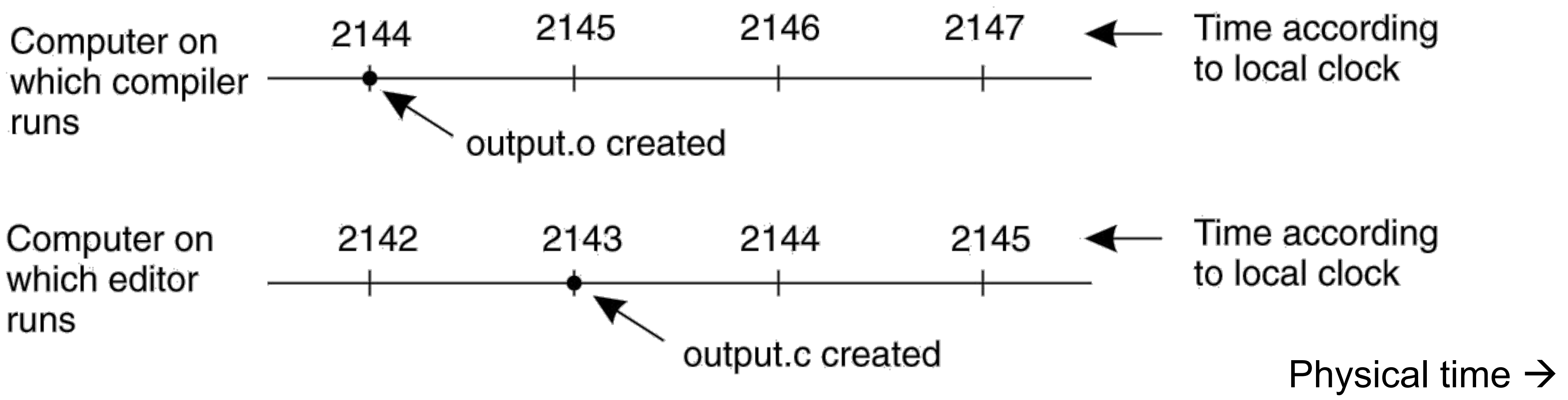
Today

1. The need for time synchronization

2. “Wall clock time” synchronization

3. Logical Time: Lamport Clocks

A distributed edit-compile workflow



- 2143 < 2144 ➔ make doesn't call compiler

Lack of time synchronization result – a possible object file mismatch

What makes time synchronization hard?

1. Quartz oscillator sensitive to temperature, age, vibration, radiation
   - Accuracy circa 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

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   - Cristian’s algorithm, NTP

3. Logical Time: Lamport clocks

Just use Coordinated Universal Time?

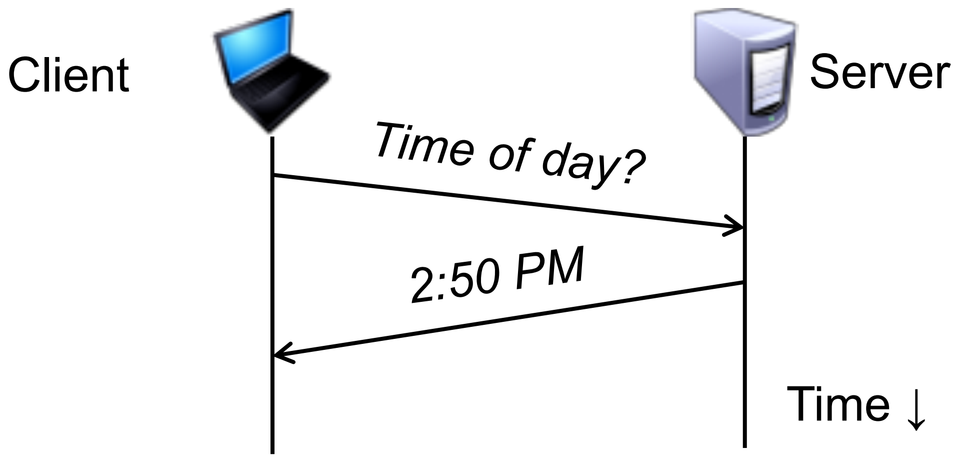
- UTC is broadcast from radio stations on land and satellite (e.g., the Global Positioning System)
  - Computers with receivers can synchronize their clocks with these timing signals

- 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

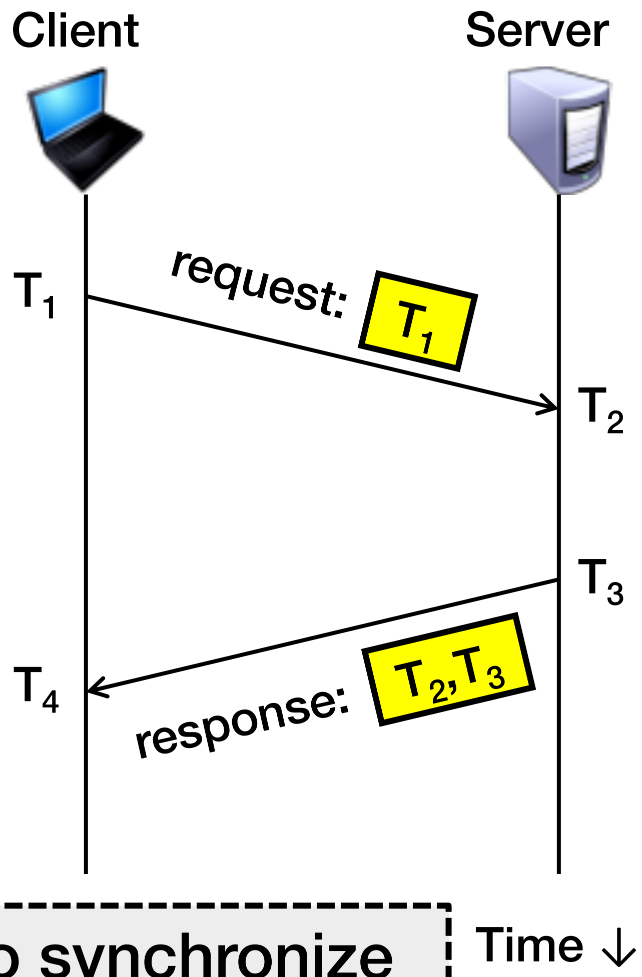
- Suppose a server with an accurate clock (e.g., GPS-receiver)
  - Could simply issue an RPC to obtain the time:



- 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  - Message delays will have outdated server's answer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
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

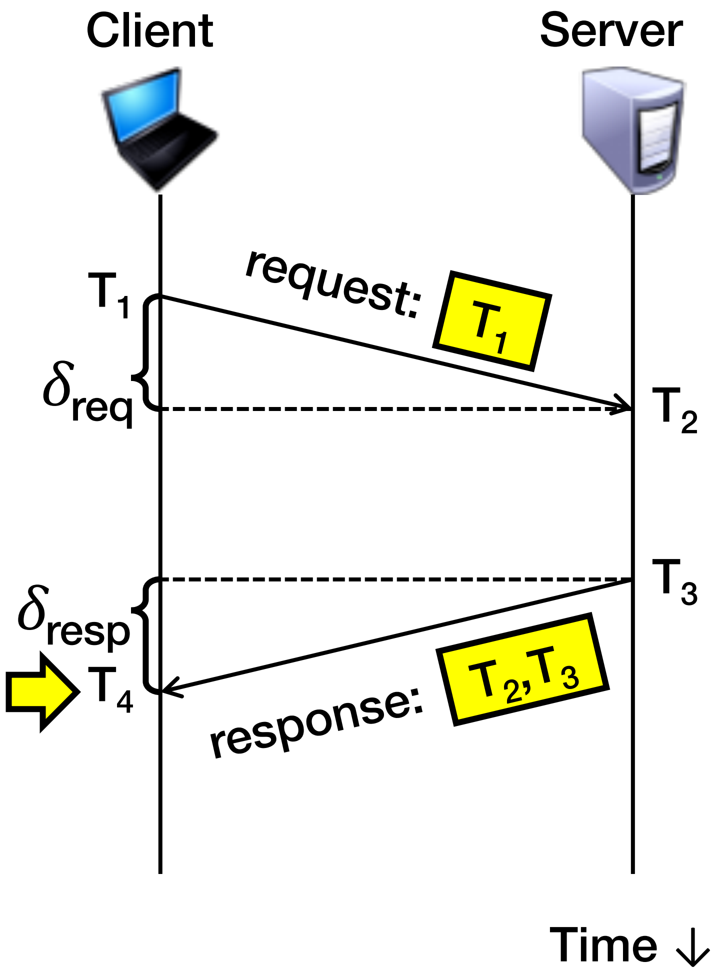
Goal: Client sets clock ← $T_3 + \delta_{resp}$

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

- But client knows δ, not δ_{resp}

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

Client sets clock ← $T_3 + ½\delta$



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    - Cristian’s algorithm, Berkeley algorithm, NTP

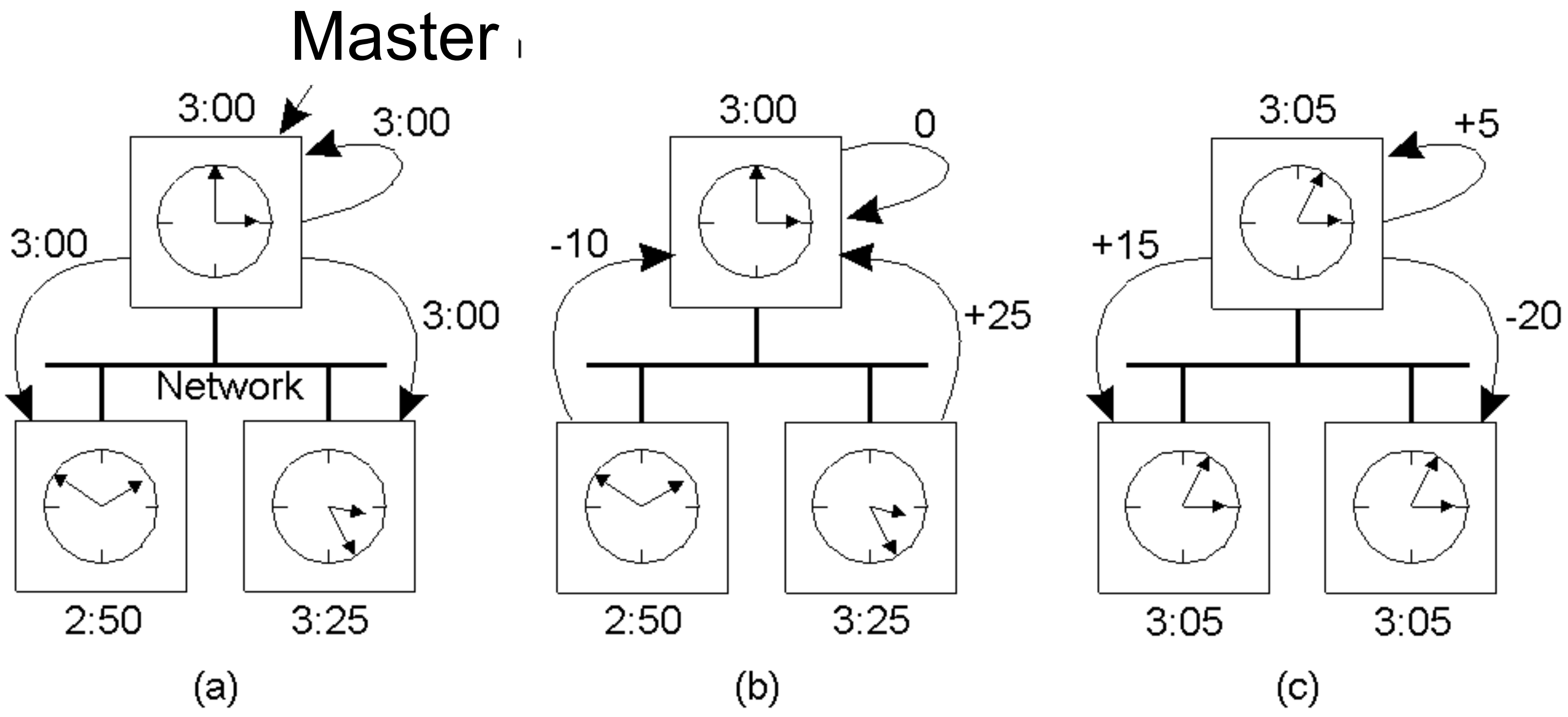
3. Logical Time: Lamport clocks

Berkeley algorithm

- A single time server can fail, blocking timekeeping
- The Berkeley algorithm is a distributed algorithm for timekeeping
  - Assumes all machines have equally-accurate local clocks
  - Obtains average from participating computers and synchronizes clocks to that average

Berkeley algorithm

- Master machine: polls L other machines using Cristian's algorithm → { θ_i } (i = 1…L)



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The Network Time Protocol (NTP)

- Enables clients to be accurately synchronized to UTC despite message delays

- Provides reliable service
  - Survives lengthy losses of connectivity
  - Communicates over redundant network paths

- Provides an accurate service
  - Unlike the Cristian's algorithm, leverages heterogeneous accuracy in clocks

NTP: System structure

- Servers and time sources are arranged in layers (strata)
    - Stratum 0: High-precision time sources themselves
        - e.g., atomic clocks, shortwave radio time receivers
    - Stratum 1: NTP servers directly connected to Stratum 0
    - Stratum 2: NTP servers that synchronize with Stratum 1
        - Stratum 2 servers are clients of Stratum 1 servers
    - Stratum 3: NTP servers that synchronize with Stratum 2
        - Stratum 3 servers are clients of Stratum 2 servers
- Users' computers synchronize with Stratum 3 servers

NTP operation: Server selection

- Messages between an NTP client and server are exchanged in pairs: request and response
  - Use Cristian's algorithm

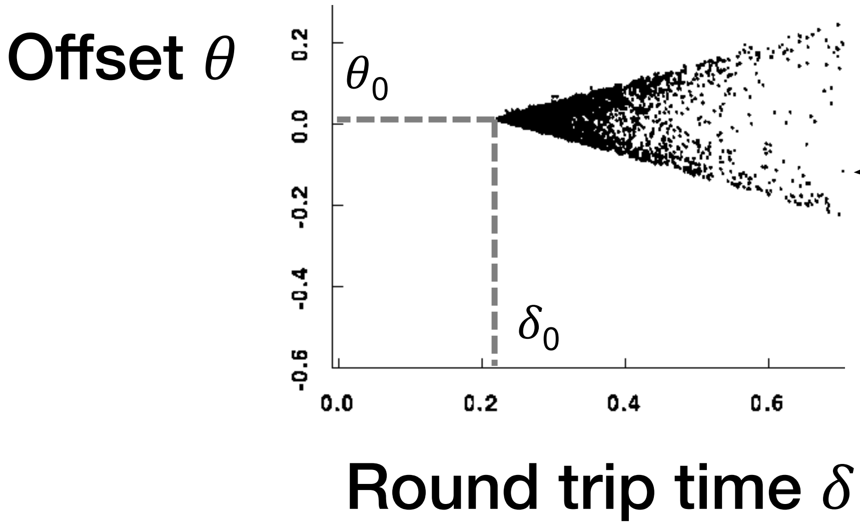
- For ith message exchange with a particular server, calculate:
  1. Clock offset θ_i from client to server
  2. Round trip time δ_i between client and server

- Over last eight exchanges with server k, the client computes its dispersion $\sigma_k = \max_i \delta_i - \min_i \delta_i$
  - Client uses the server with minimum dispersion

- Then uses a best estimate of clock offset

NTP operation : Clock offset calculation

- Client tracks minimum round trip time and associated offset over the last eight message exchanges (δ_0, θ_0)
  - θ_0 is the best estimate of offset: client adjusts its clock by θ_0 to synchronize to server



Each point represents one sample

NTP: How to change time (slewing)

- Can’t just change time: Don’t want time to run backwards
    - Recall the make example

- Instead, change the update rate for the clock
    - Changes time in a more gradual fashion
    - Prevents inconsistent local timestamps

Clock synchronization: Take-away points

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

- NTP clock synchronization
    - 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

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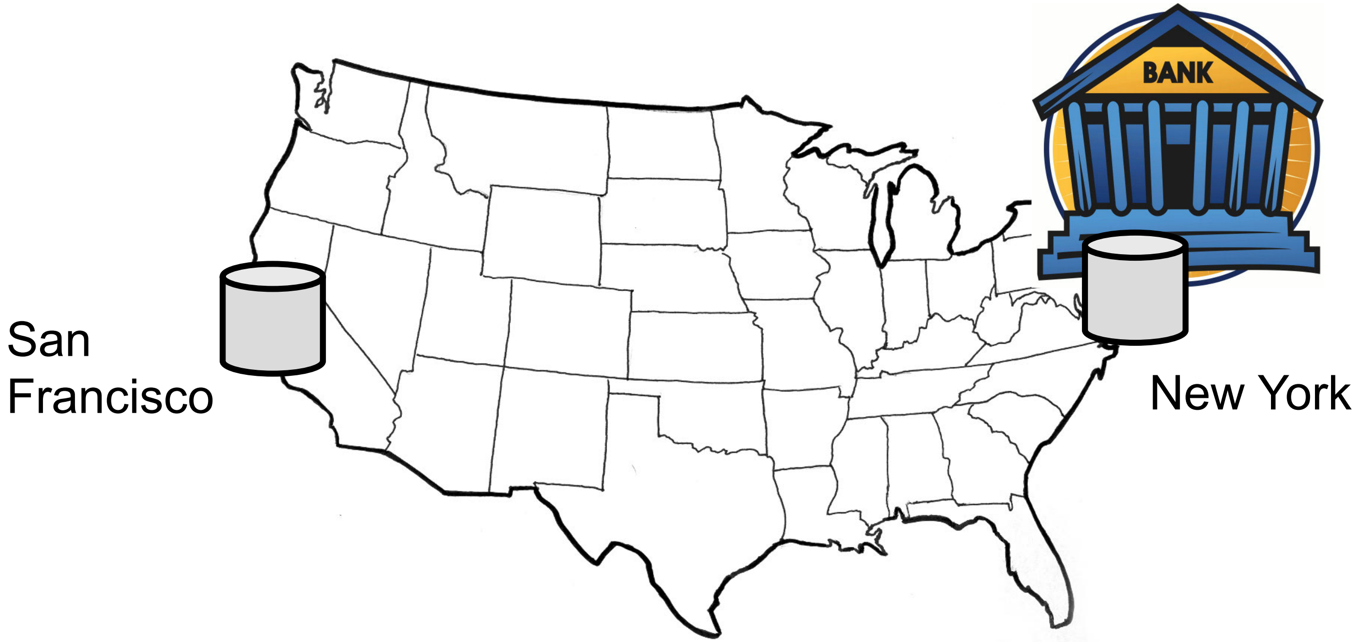
Motivation: Multi-site database replication

- 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 query to the nearest copy
  - Client sends update to both copies

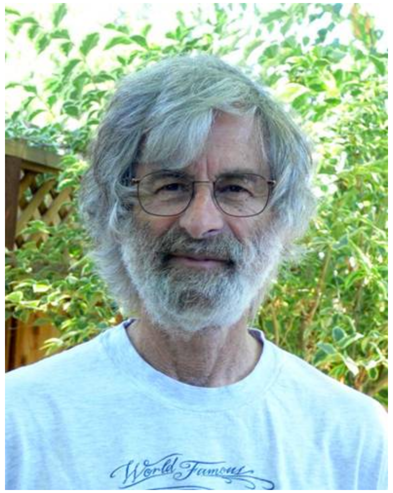
Inconsistent replicas!

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

RFC 677 “The Maintenance of Duplicate Databases” (1975)

- “To the extent that the communication paths can be made reliable, and the clocks used by the processes kept close to synchrony, the probability of seemingly strange behavior can be made very small. However, *the distributed nature of the system dictates that this probability can never be zero*.”

Idea: Logical clocks



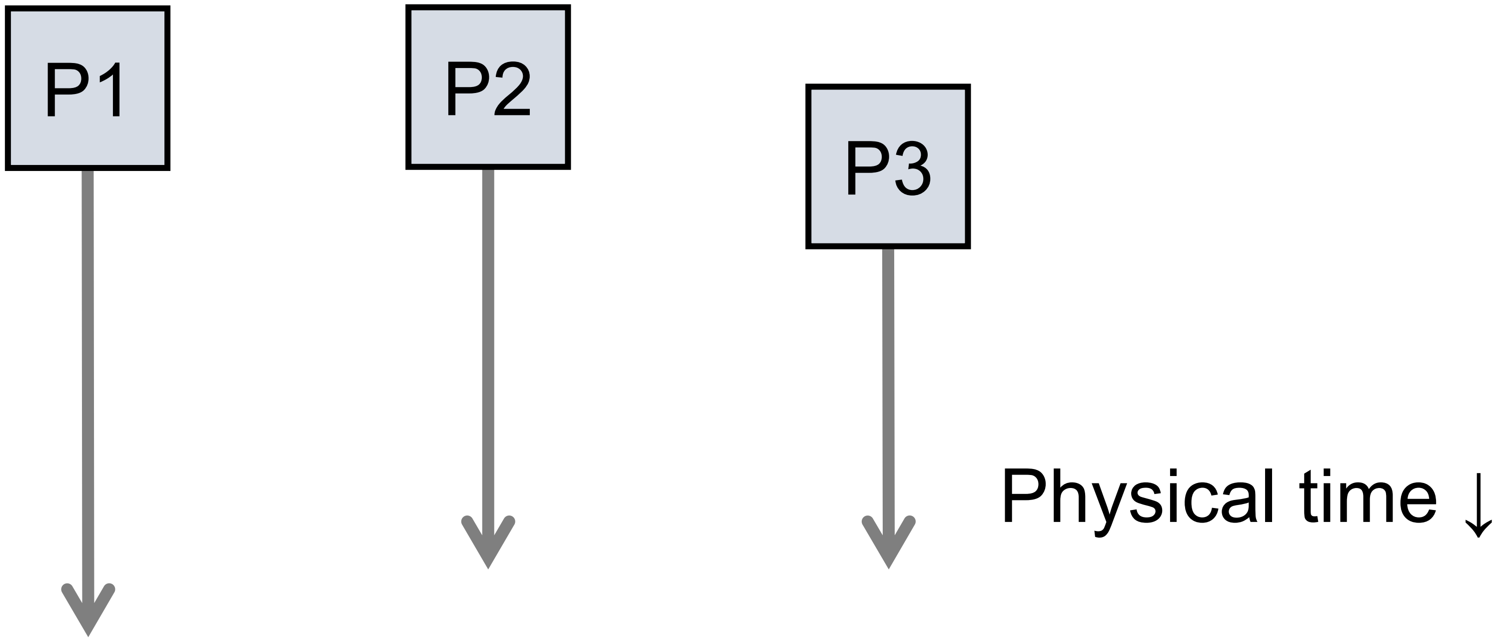
- Landmark 1978 paper by Leslie Lamport
- Insight: only the events themselves matter

Idea: Disregard the precise clock time

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

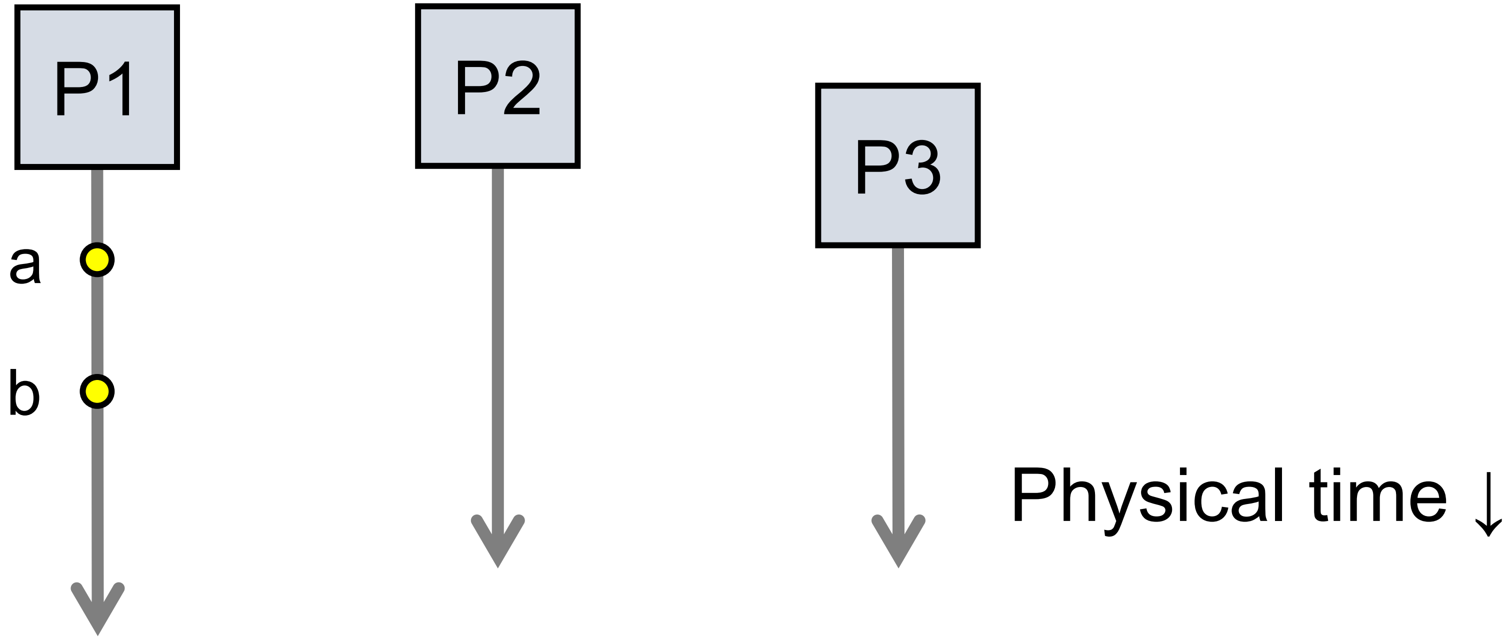
Defining “happens-before” (→)

- Consider three processes: P1, P2, and P3
- Notation: Event a happens before event b (a → b)



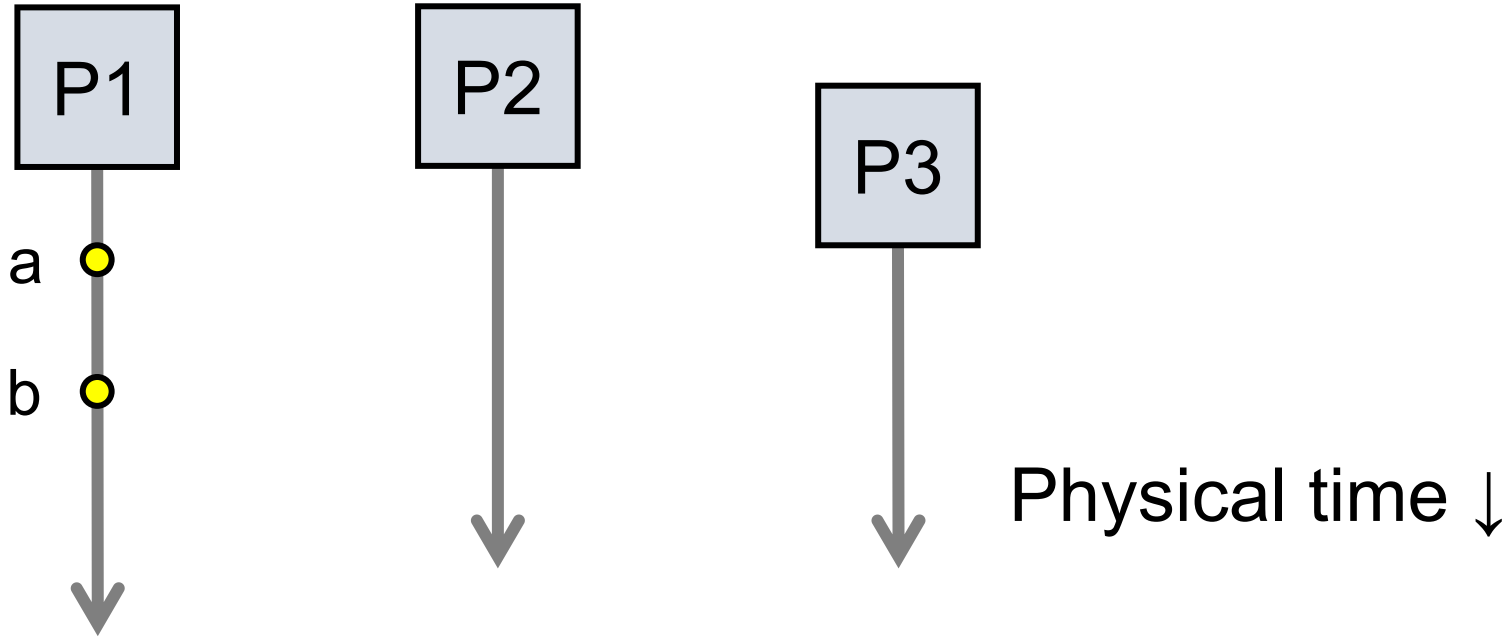
Defining “happens-before” (→)

- Can observe event order at a single process



Defining “happens-before” (→)

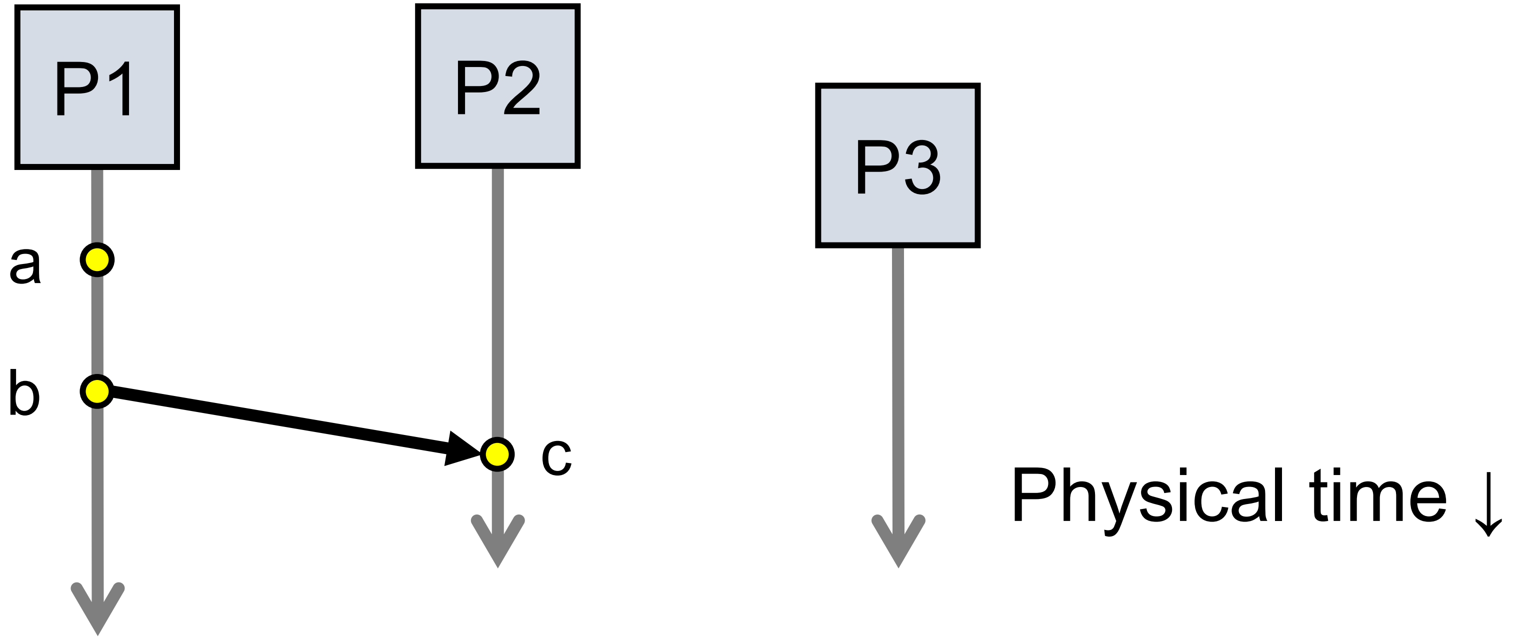
1. If **same process** and **a** occurs before **b**, then **a → b**



Defining "happens-before" (→)

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

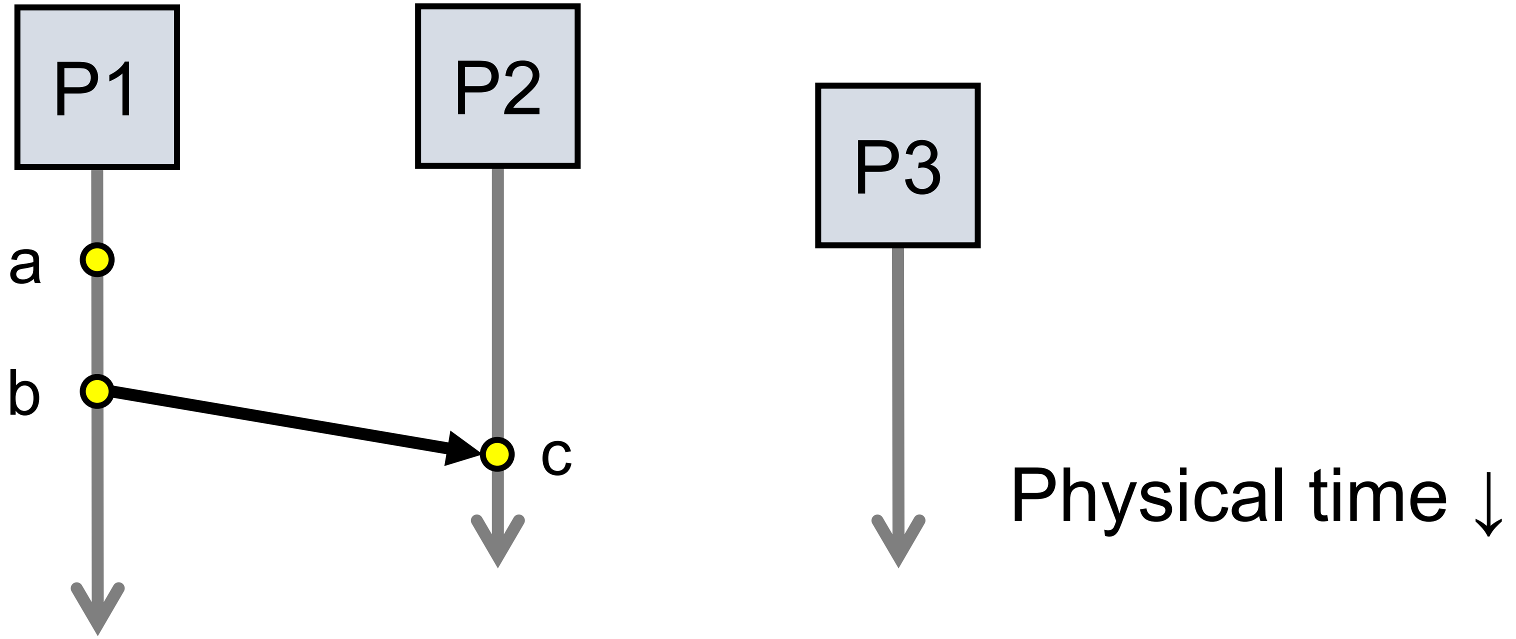
2. Can observe ordering when processes communicate



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**

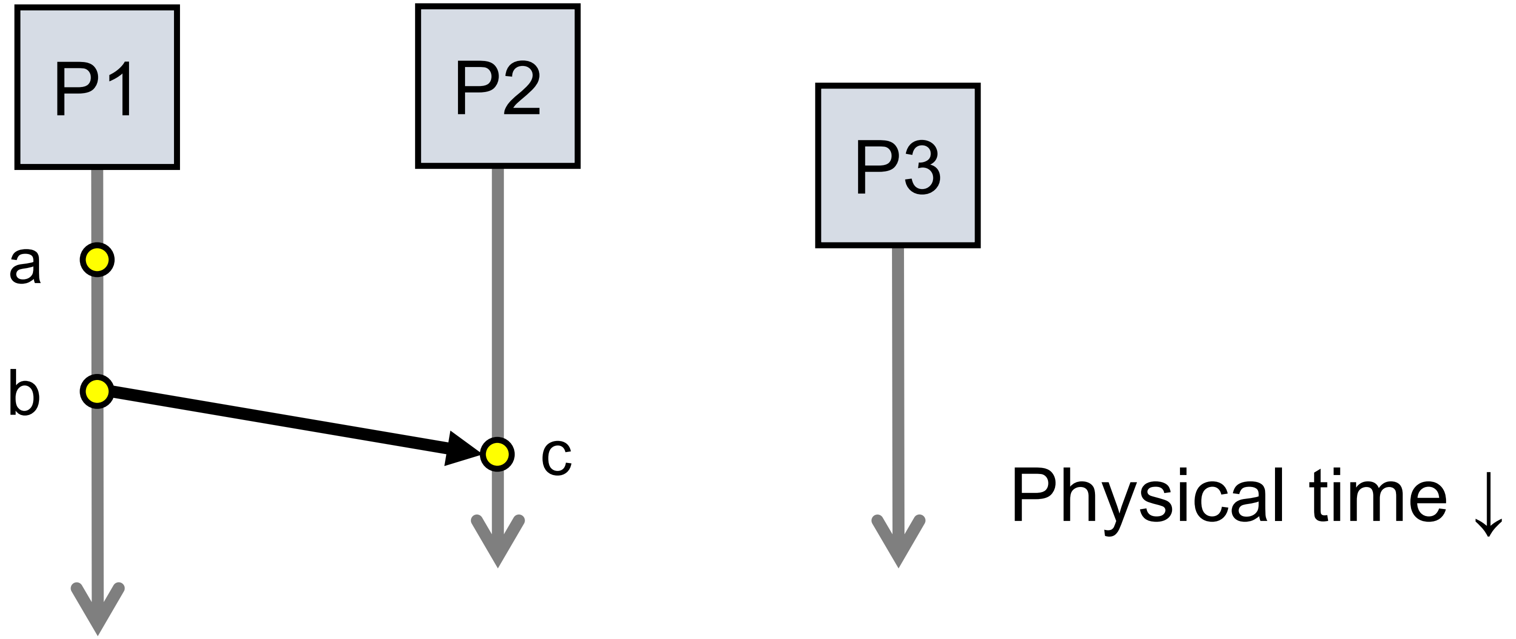


Defining "happens-before" (→)

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

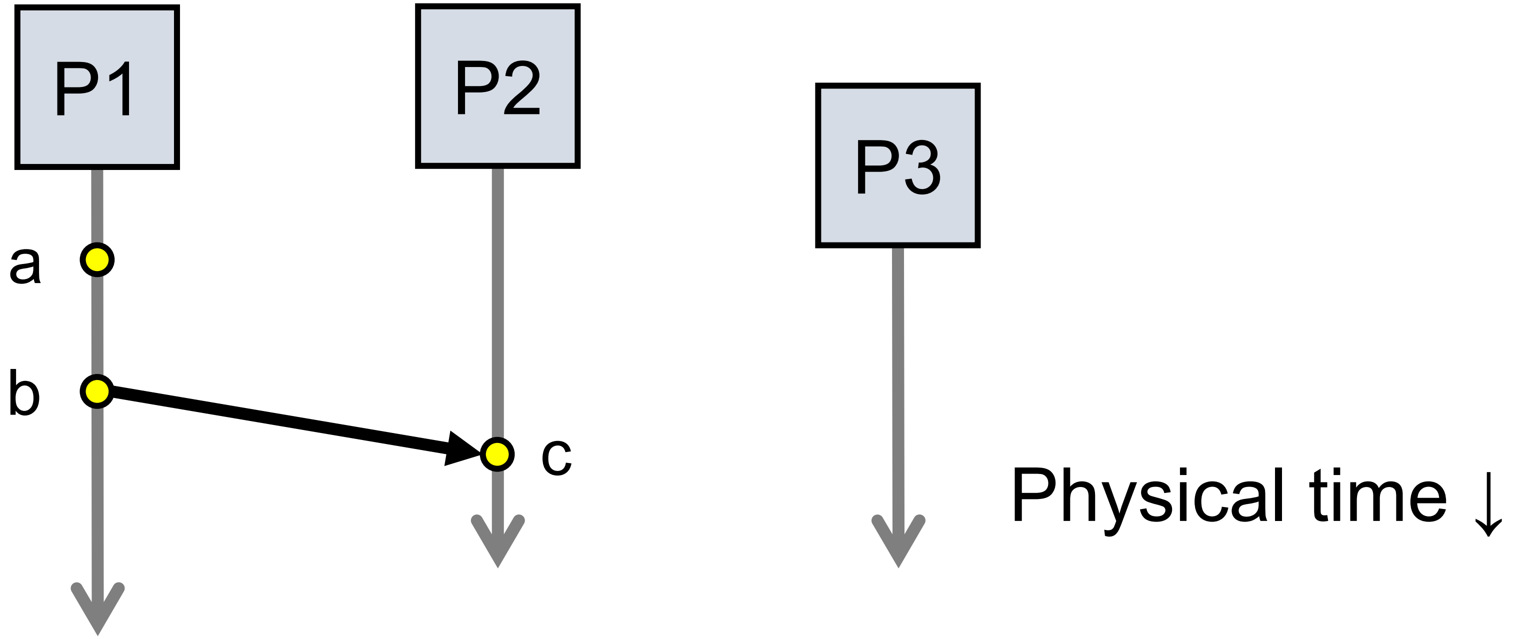


Defining “happens-before” (→)

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

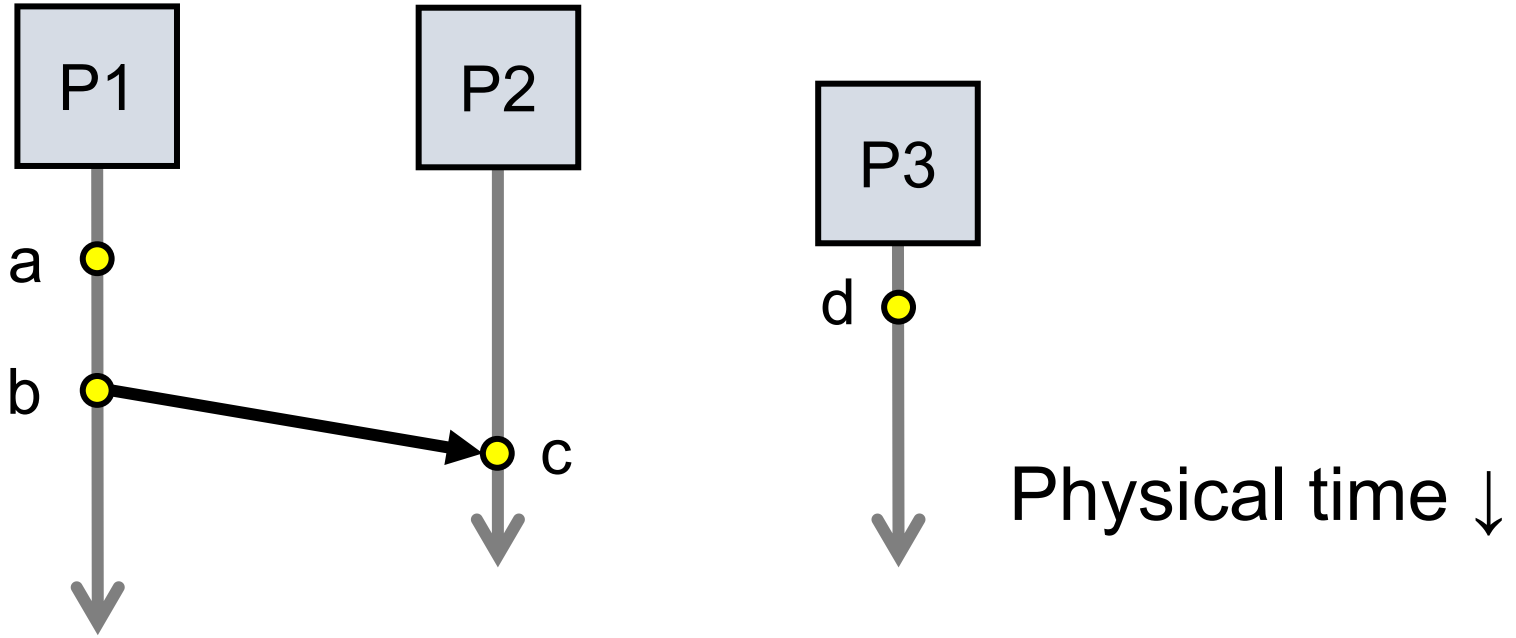
2. If **c** is a message receipt of **b**, then **b** → **c**

3. **If a → b and b → c, then a → c**



Concurrent events

- Not all events are related by →
- a, d not related by → so concurrent, written as a || d



Lamport clocks: Objective

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

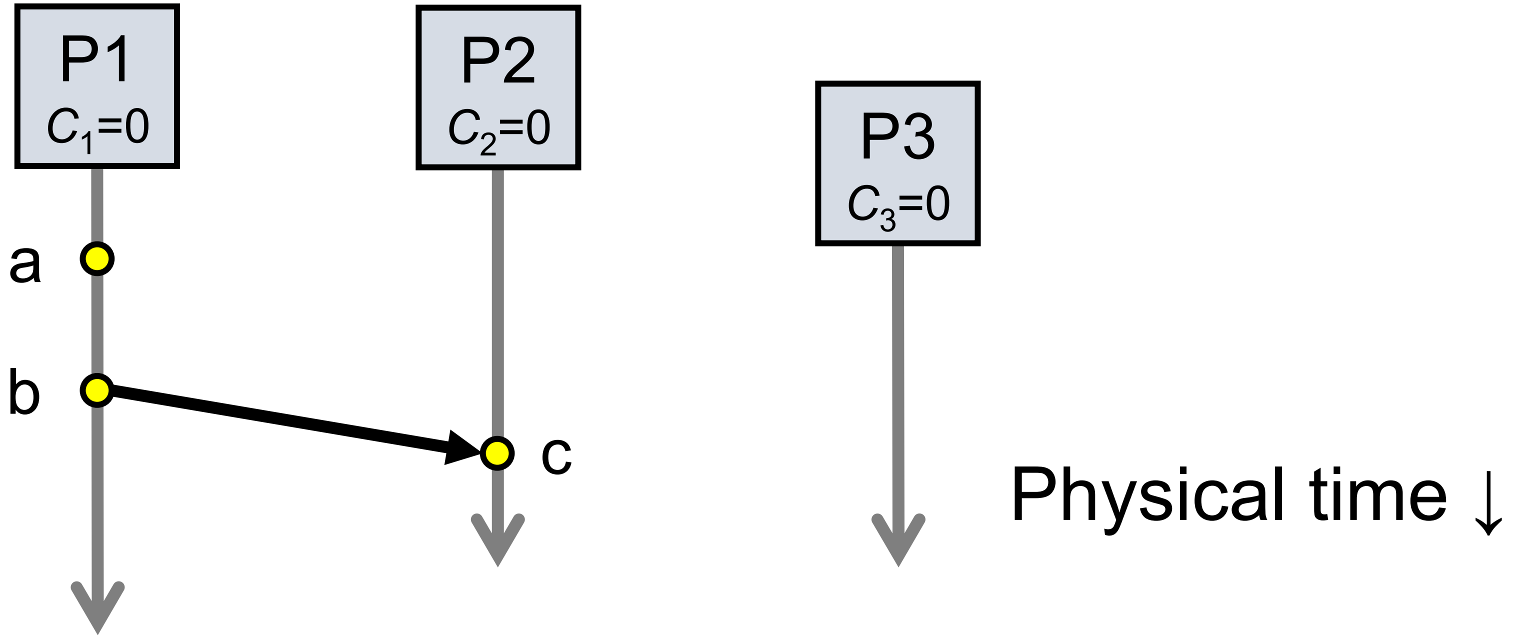
Plan: Tag events with clock times; use clock times to make distributed system correct

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

The Lamport Clock algorithm

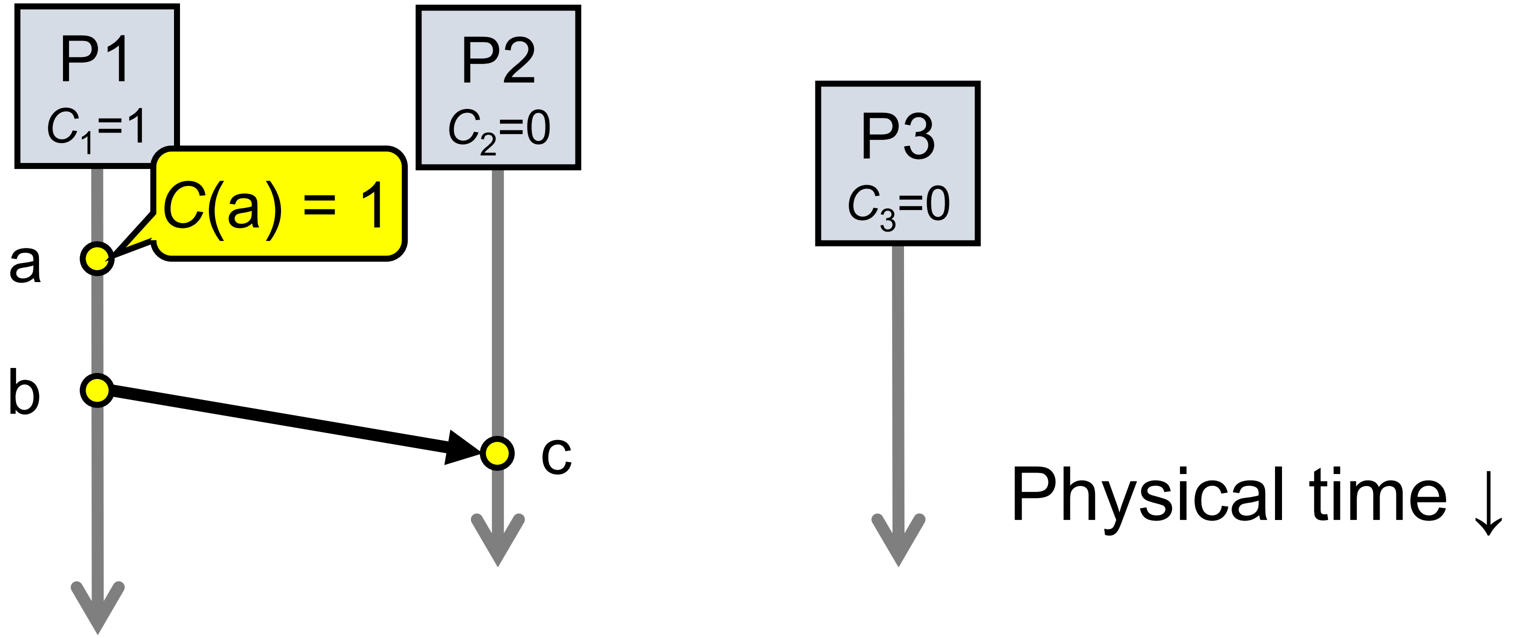
- Each process P_i maintains a local clock C_i

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



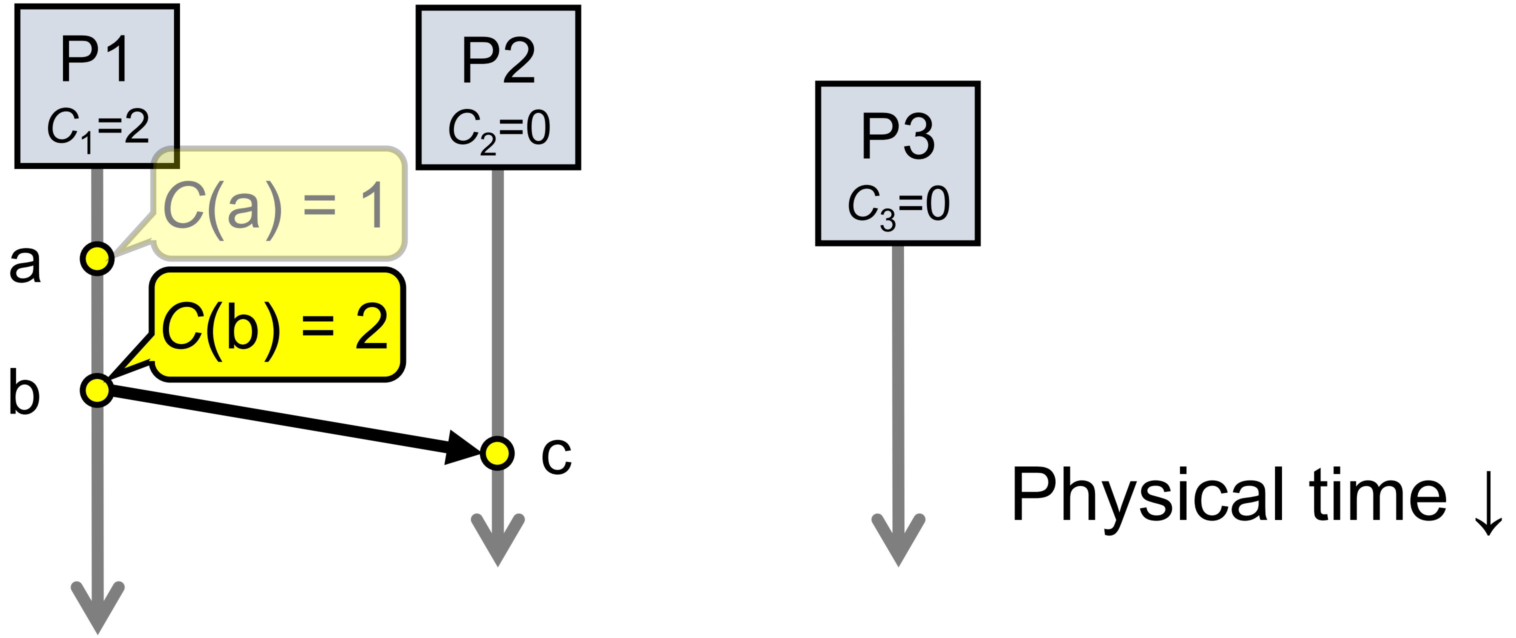
The Lamport Clock algorithm

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



The Lamport Clock algorithm

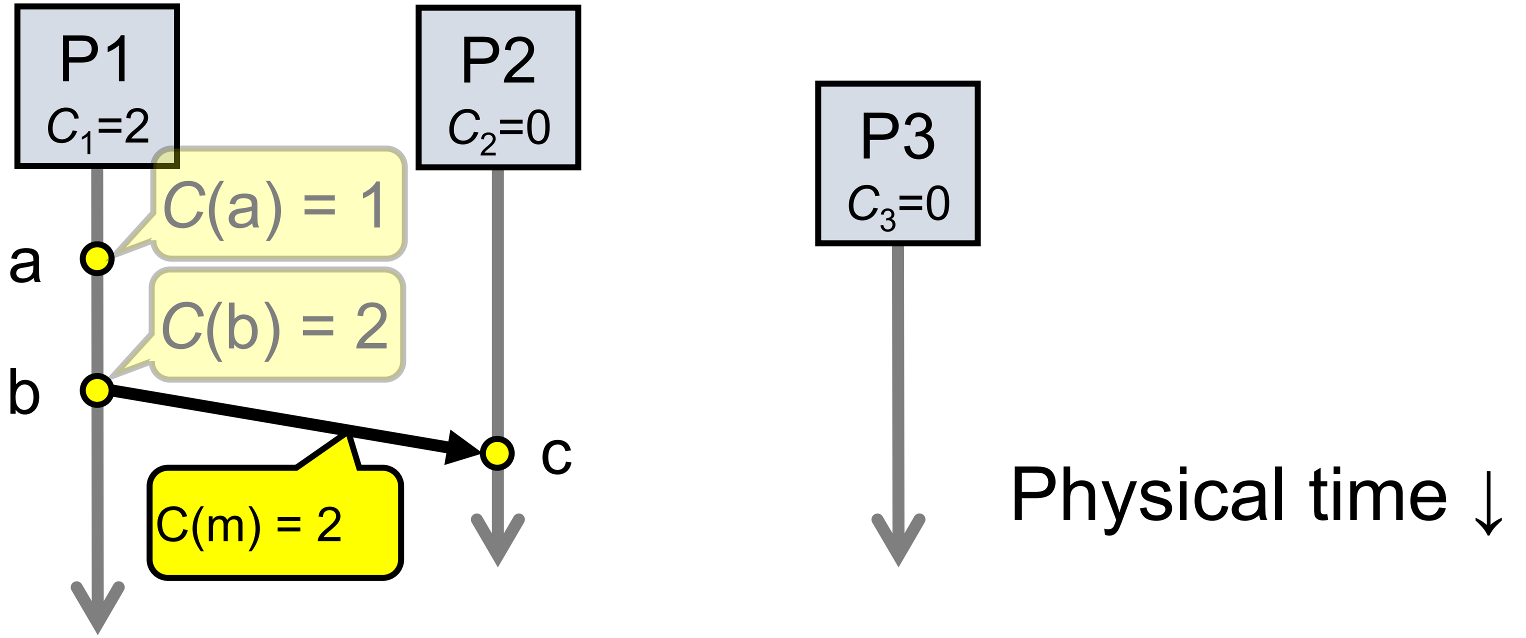
1. Before executing an event b, $C_i \leftarrow C_i + 1$:
   - Set event time $C(b) \leftarrow C_i$



The Lamport Clock algorithm

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

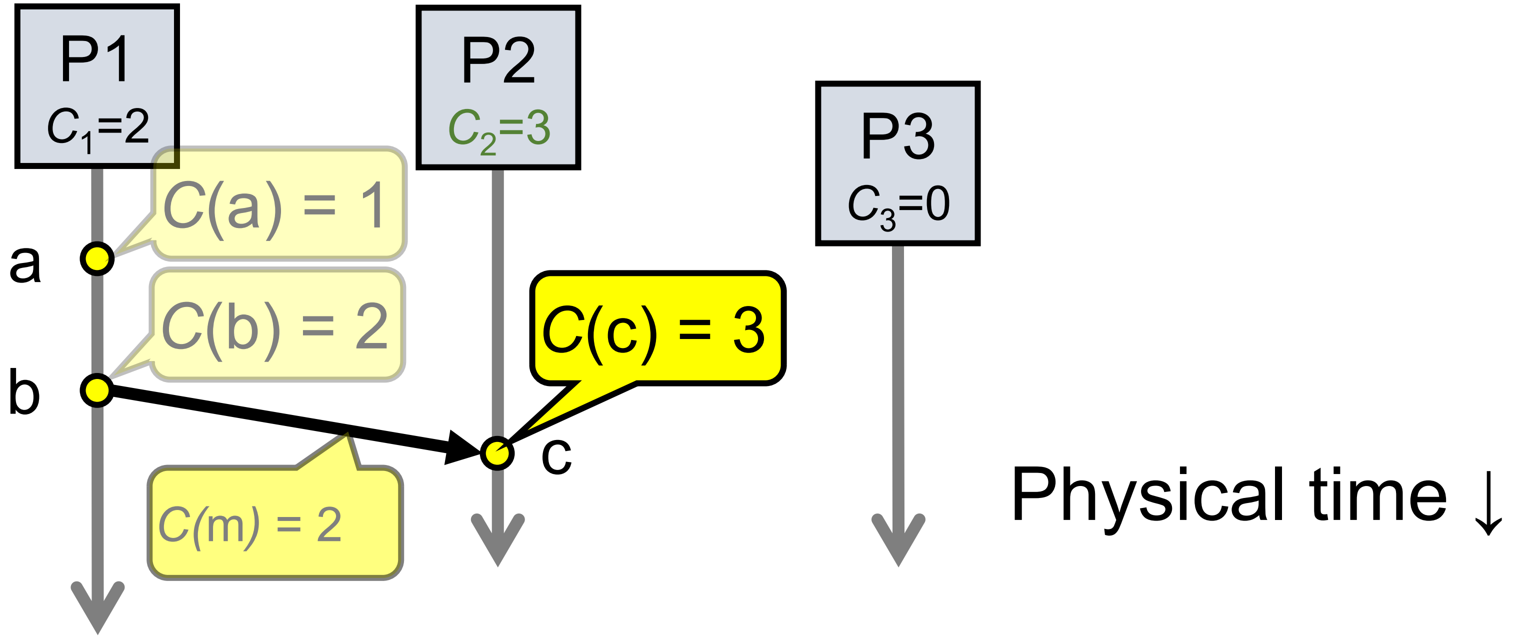
2. Send the local clock in the message m



The Lamport Clock algorithm

3. On process P_j receiving a message m:

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



Lamport Timestamps: Ordering all events

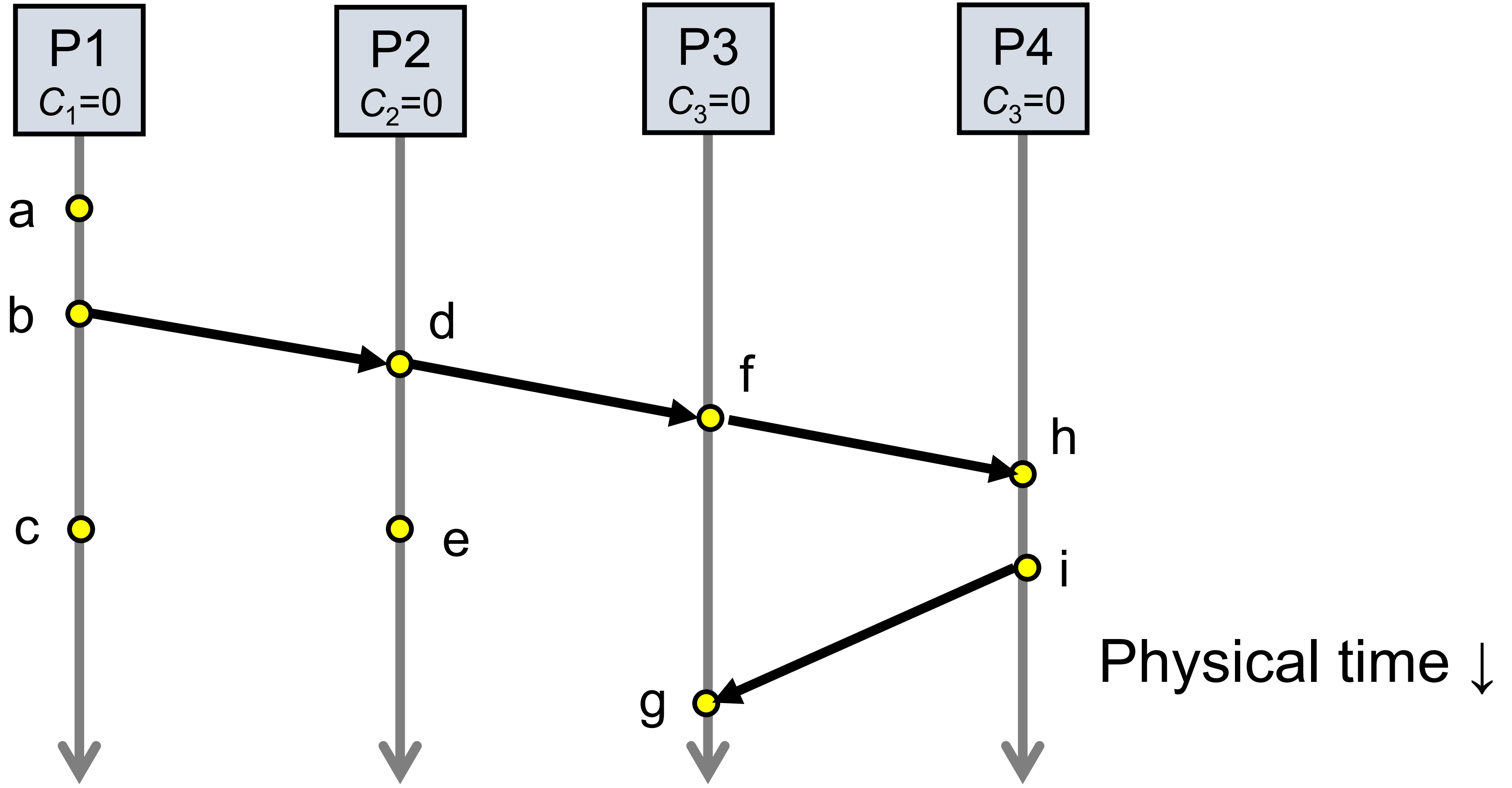
- Break ties by appending the process number to each event:

  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



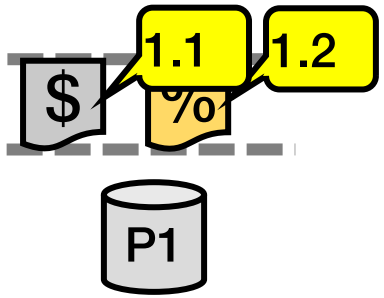
Totally-Ordered Multicast

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

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

Example: P1's local queue:



← Timestamps

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)

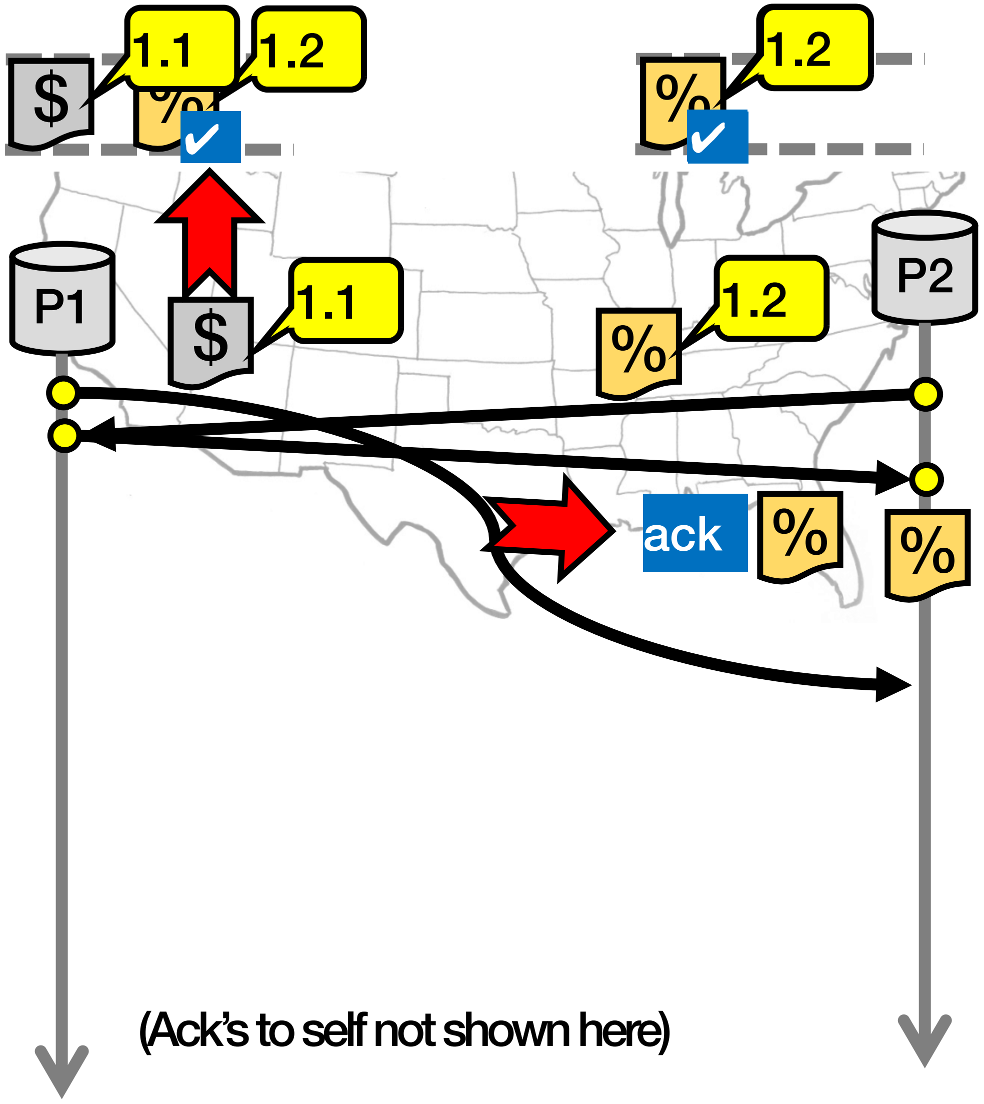
3. On receiving an acknowledgement:
   - Mark corresponding update acknowledged in your queue

4. Remove and process updates everyone has ack'ed from head 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)

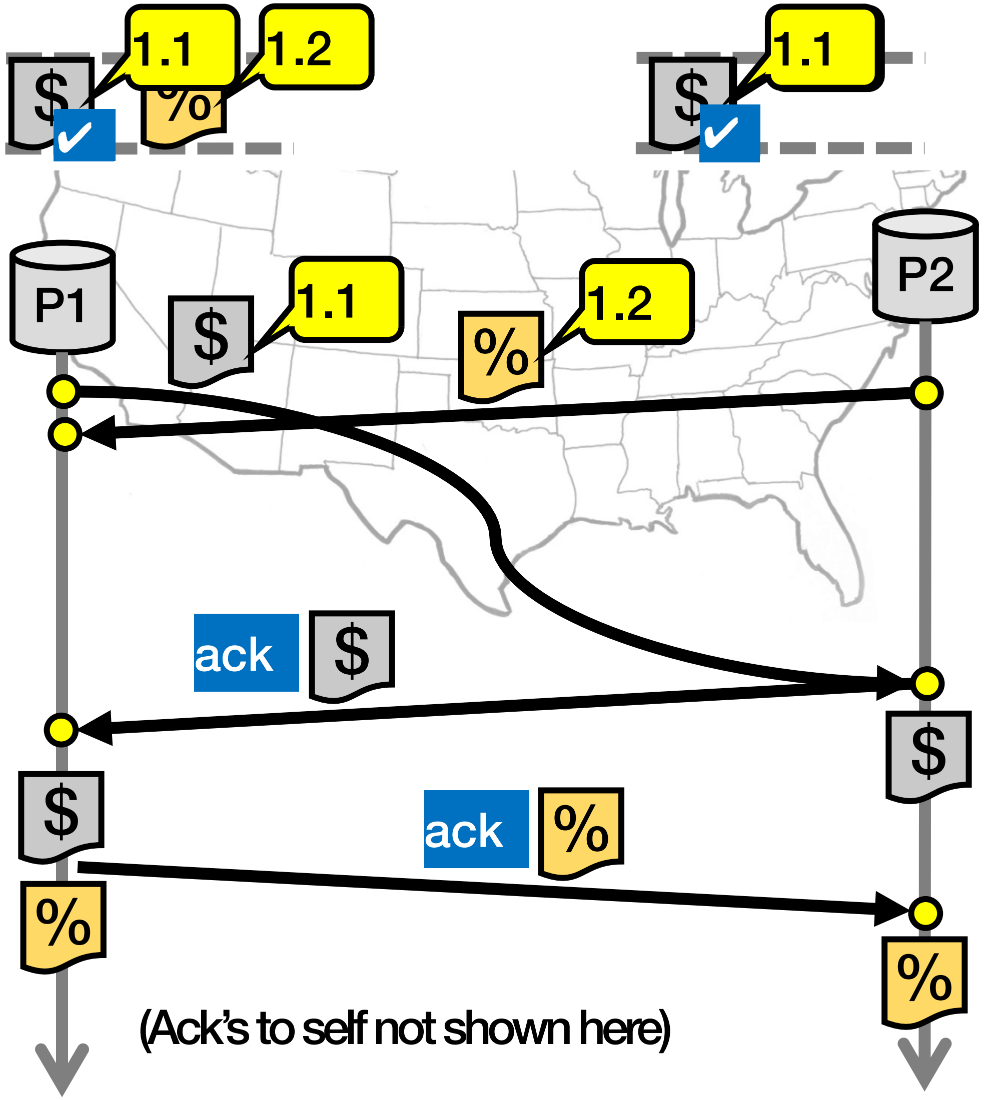
1. On receiving an update from client, broadcast to others (including yourself)

2. On receiving or processing an update:
   a) Add it to your local queue, if received update
   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 everyone has ack'ed from head 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?*

- 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?)

Take-away points: Lamport clocks

- 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 → b implies *C*(a) < *C*(b),
  - The converse is not necessarily true:
    - *C*(a) < *C*(b) does not imply a → b (possibly, a || b)

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