Time

COS 418/518: Distributed Systems
Lecture 5

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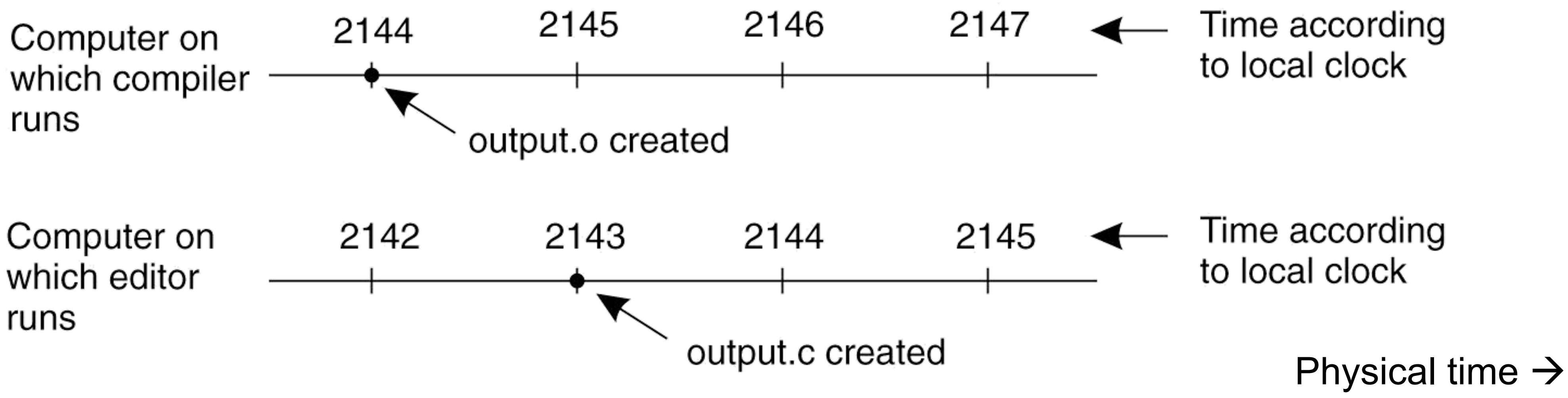
Today

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 ~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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2. "Wall clock time" synchronization
   - Cristian's algorithm, NTP

3. Logical Time: Lamport clocks

Just use Coordinated Universal Time?

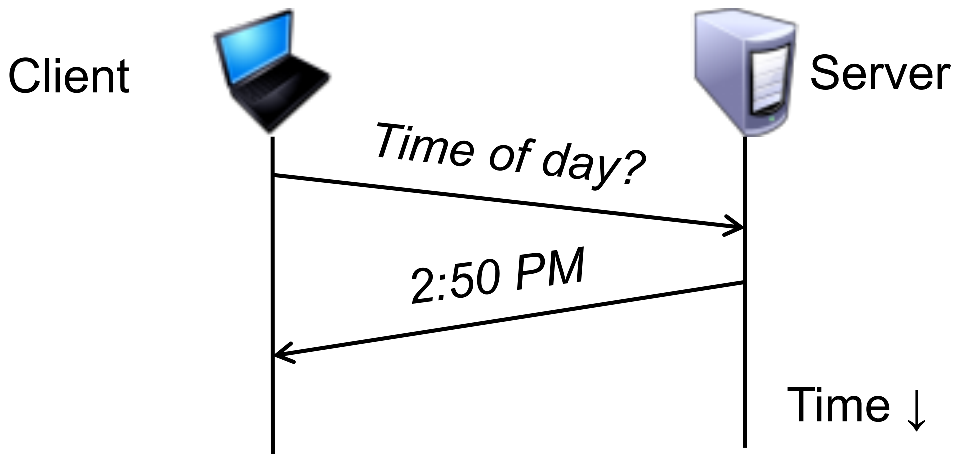
- UTC is broadcast from radio stations on land and satellite (e.g., the Global Positioning System)
  - Computers with receivers can synchronize their clocks with these timing signals

- 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

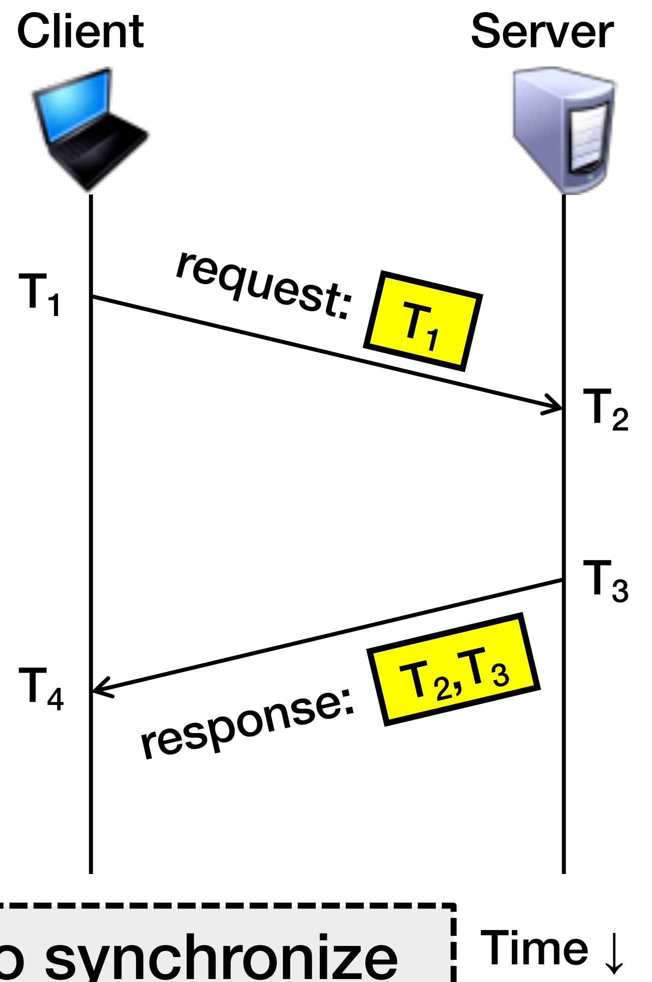
- Suppose a server with an accurate clock (e.g., GPS-receiver)
    - Could simply issue an RPC to obtain the time:



- 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    - Message delays will have outdated server's answer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

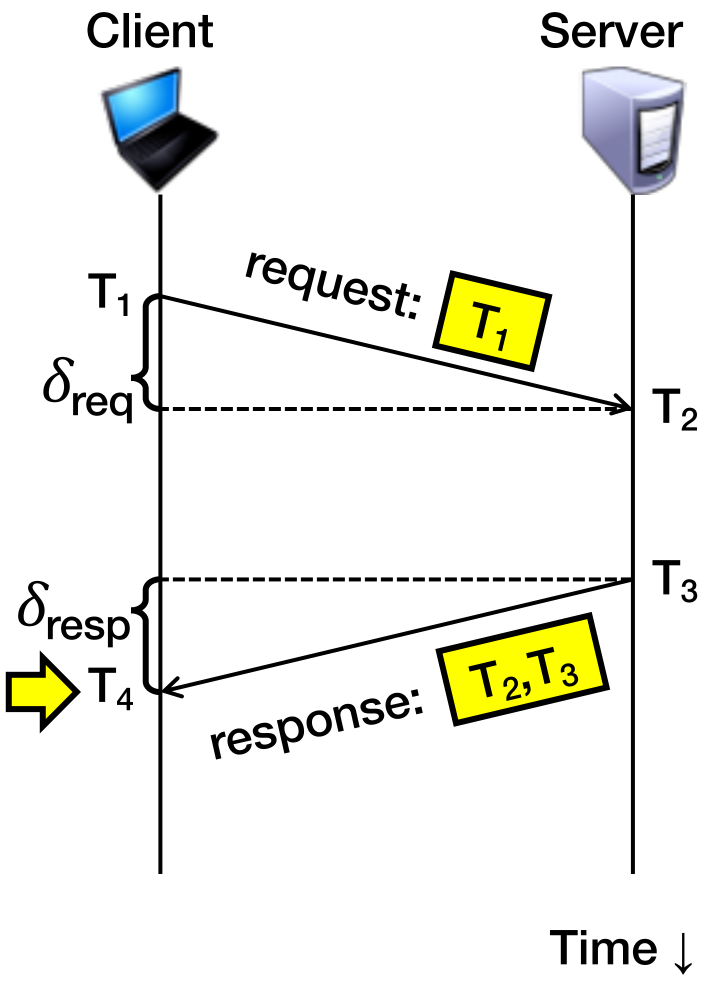
Goal: Client sets clock ← $T_3 + \delta_{resp}$

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

- But client knows δ, not δ_{resp}

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

Client sets clock ← $T_3 + ½\delta$



Clock synchronization: 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

Today

1. The need for time synchronization

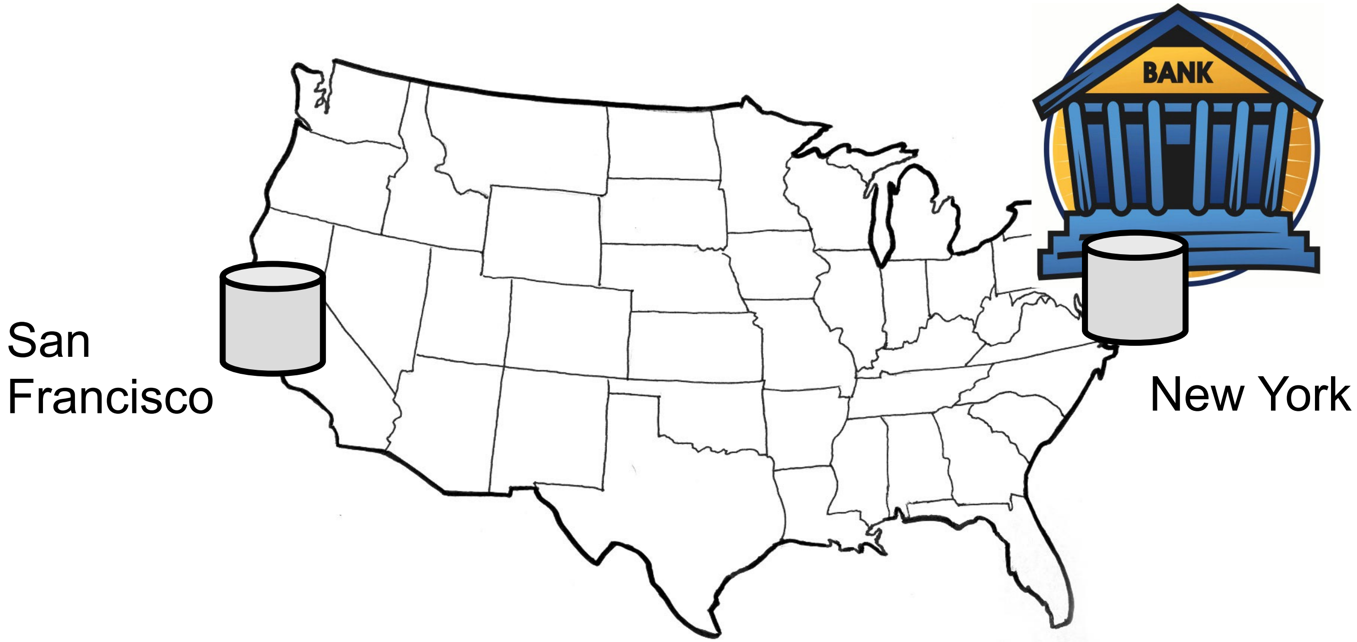
2. "Wall clock time" synchronization
   - Cristian's algorithm, NTP

3. Logical Time: Lamport clocks

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

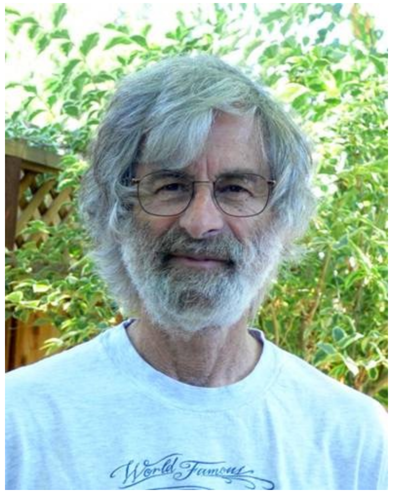
Inconsistent replicas!

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

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



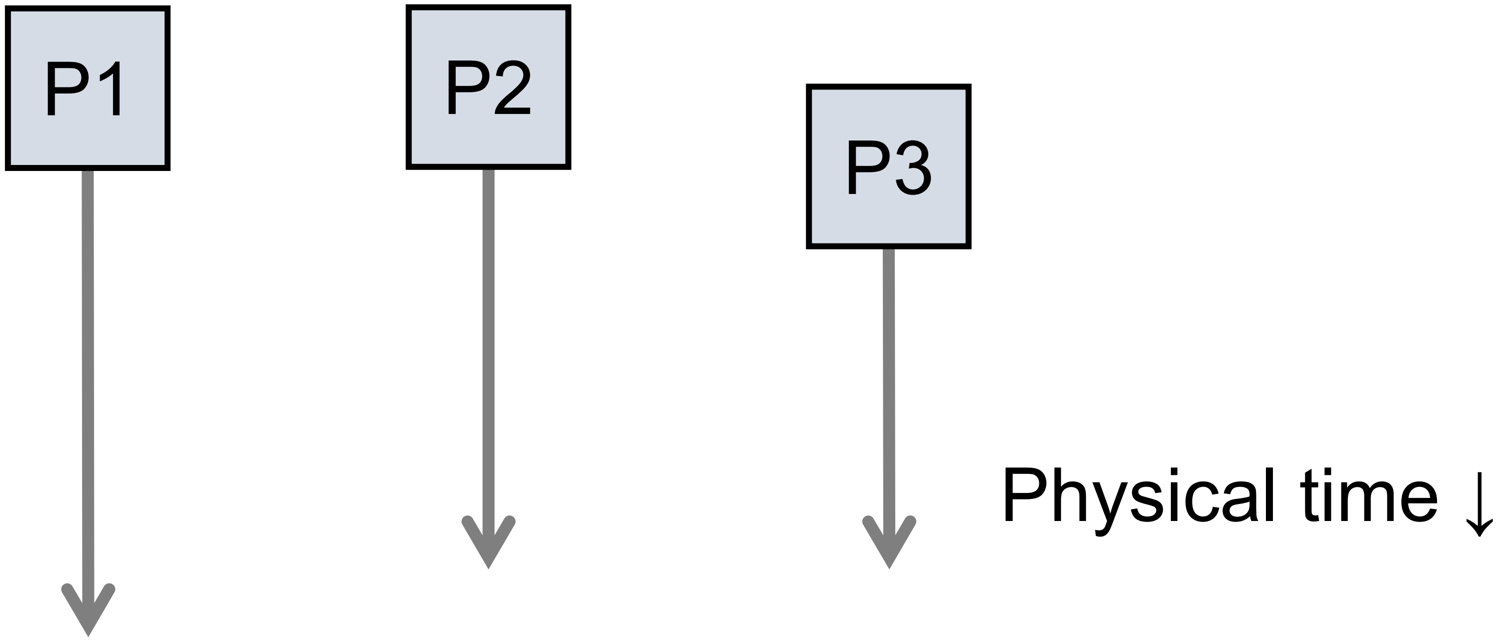
- Landmark 1978 paper by Leslie Lamport
- Insight: only the events themselves matter

Idea: Disregard the precise clock time

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

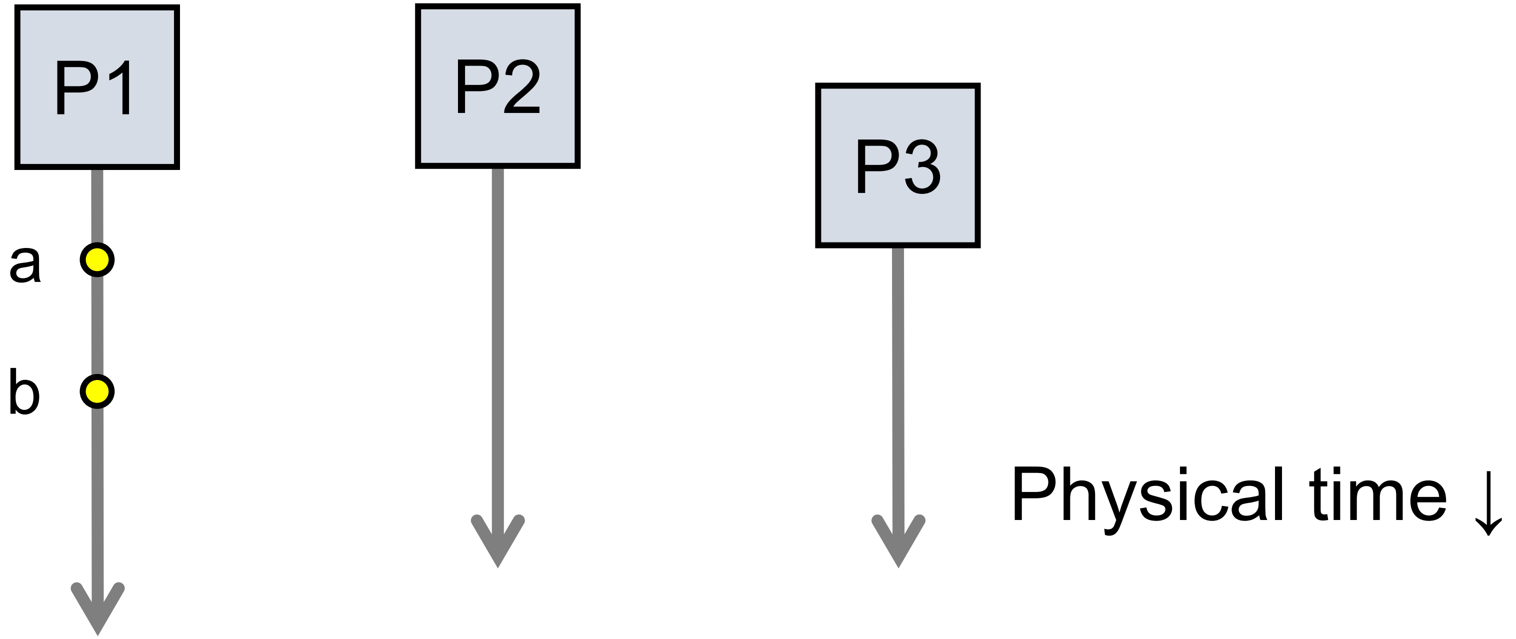
Defining "happens-before" (→)

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



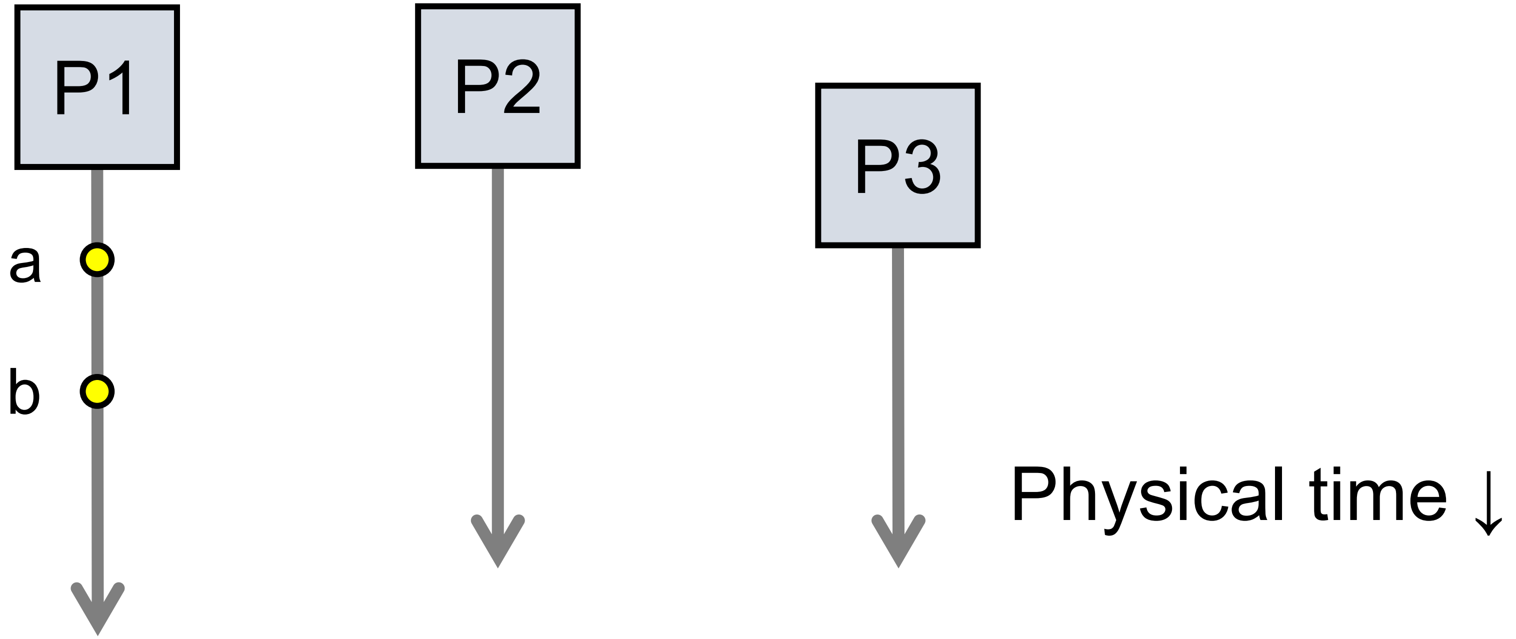
Defining "happens-before" (→)

- Can observe event order at a single process



Defining “happens-before” (→)

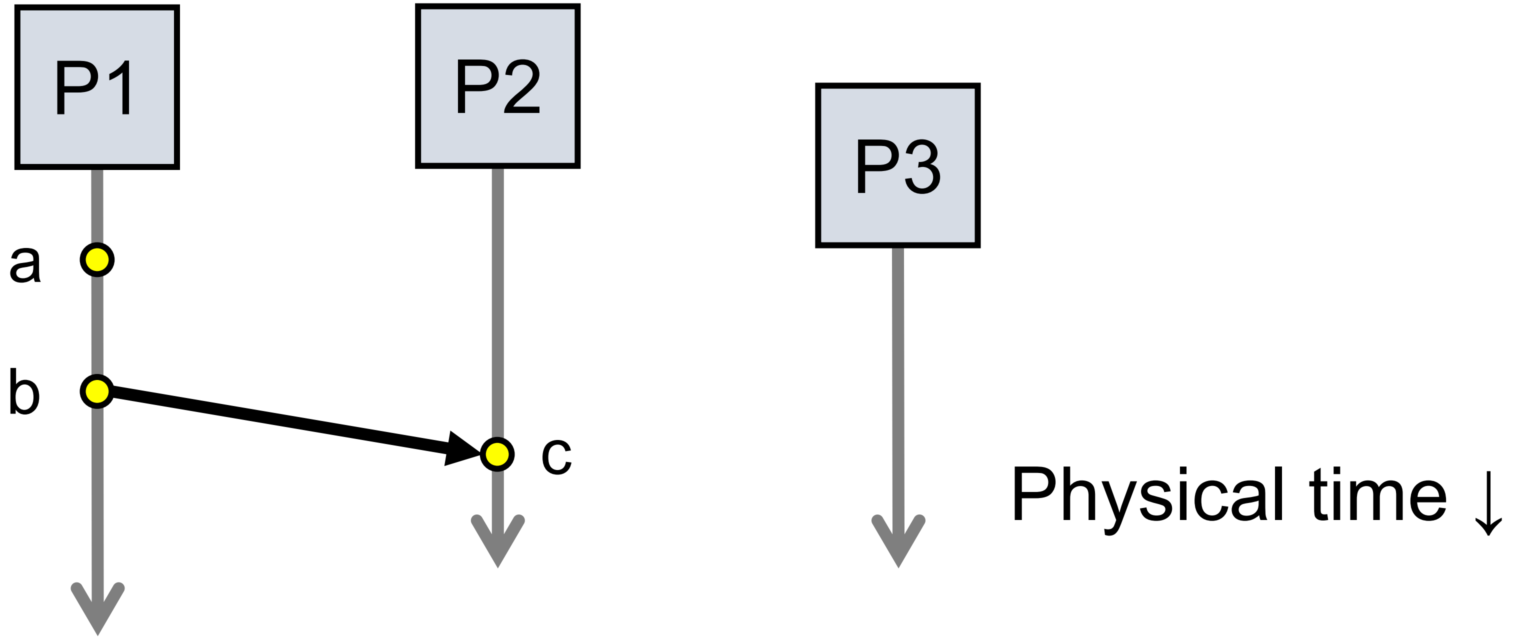
1. If **same process** and **a** occurs before **b**, then **a → b**



Defining “happens-before” (→)

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

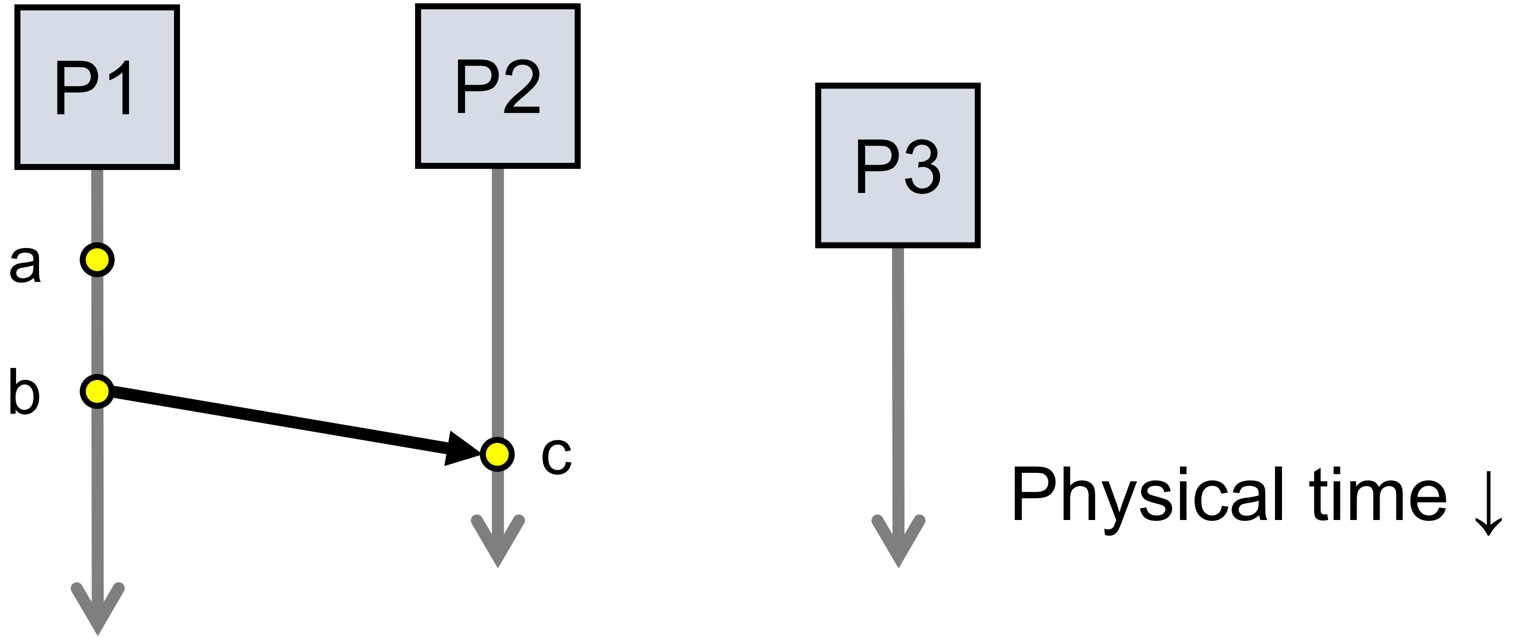
2. Can observe ordering when processes communicate



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**

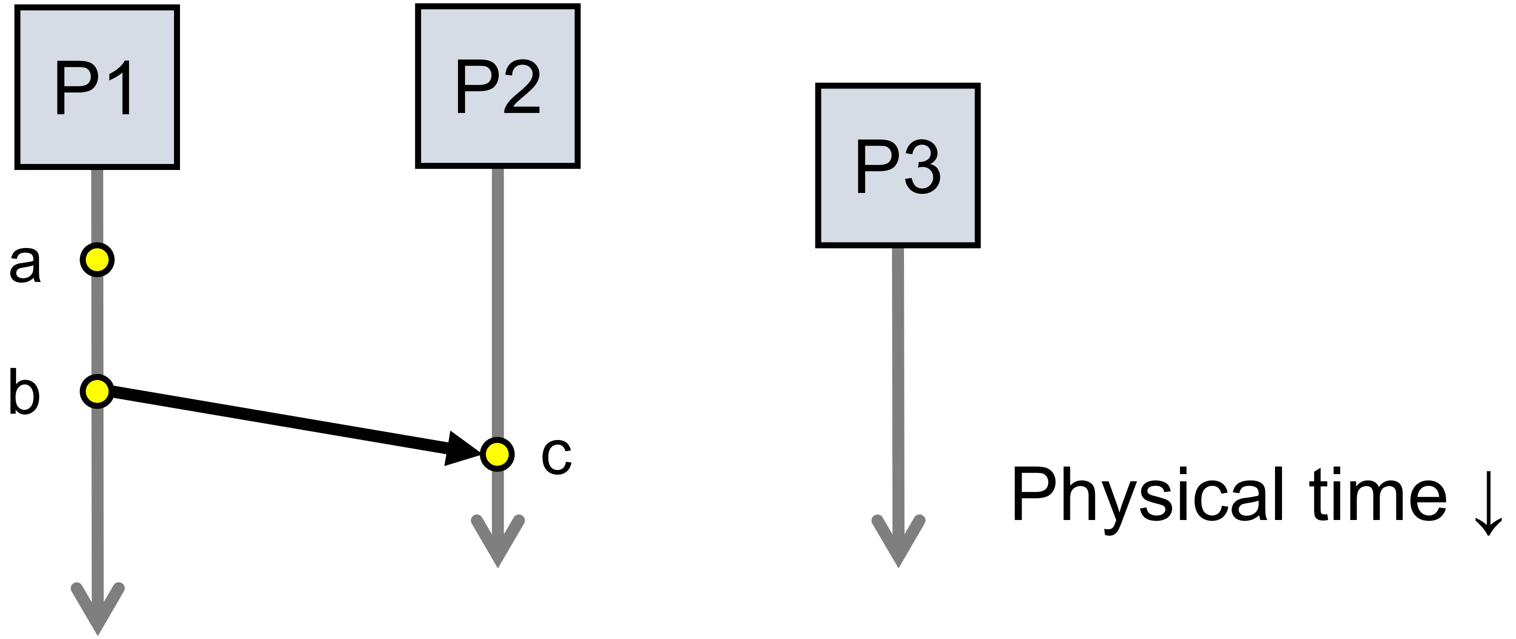


Defining "happens-before" (→)

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

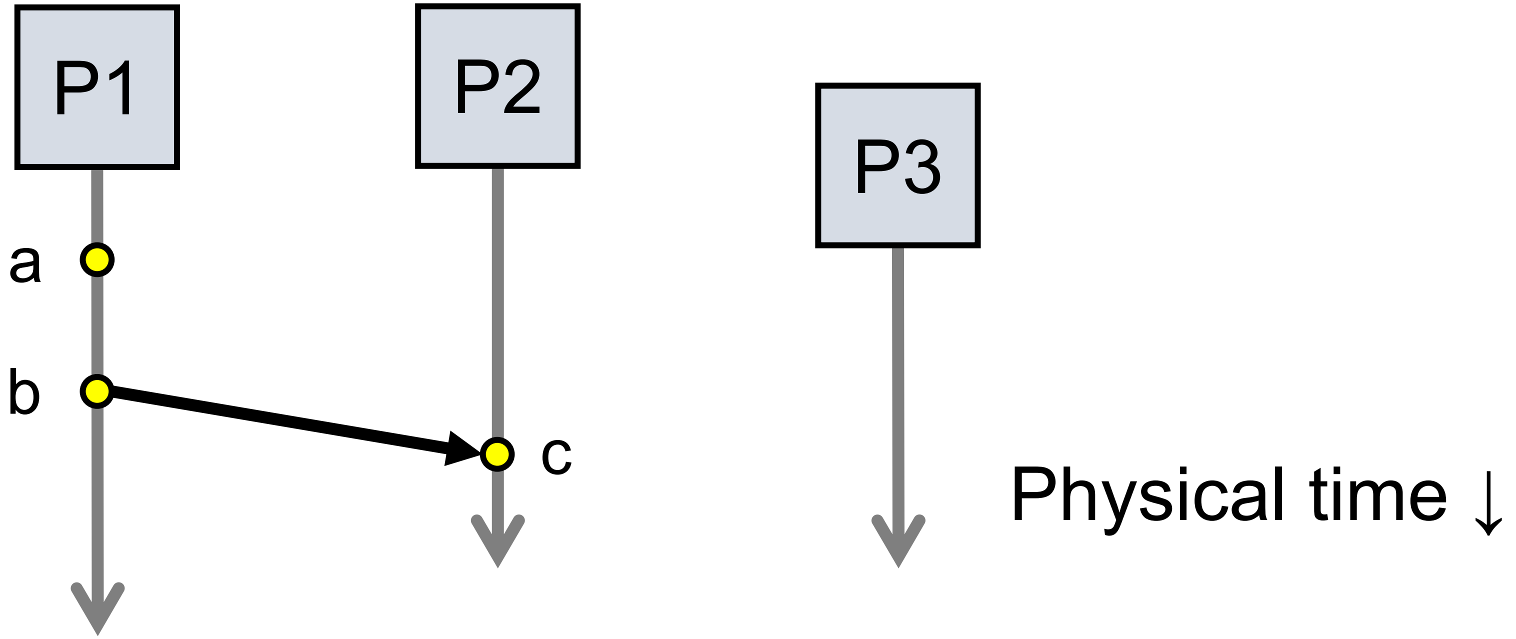


Defining "happens-before" (→)

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

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

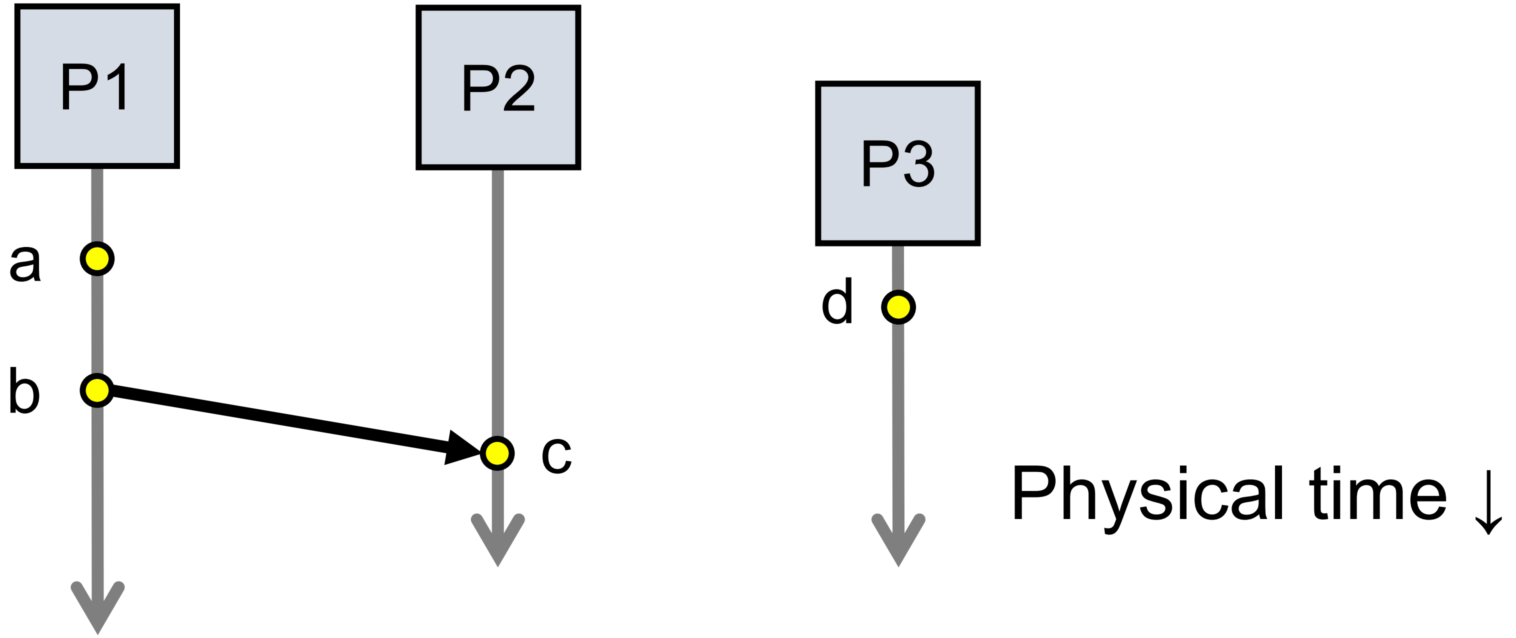
3. **If a → b and b → c, then a → c**



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

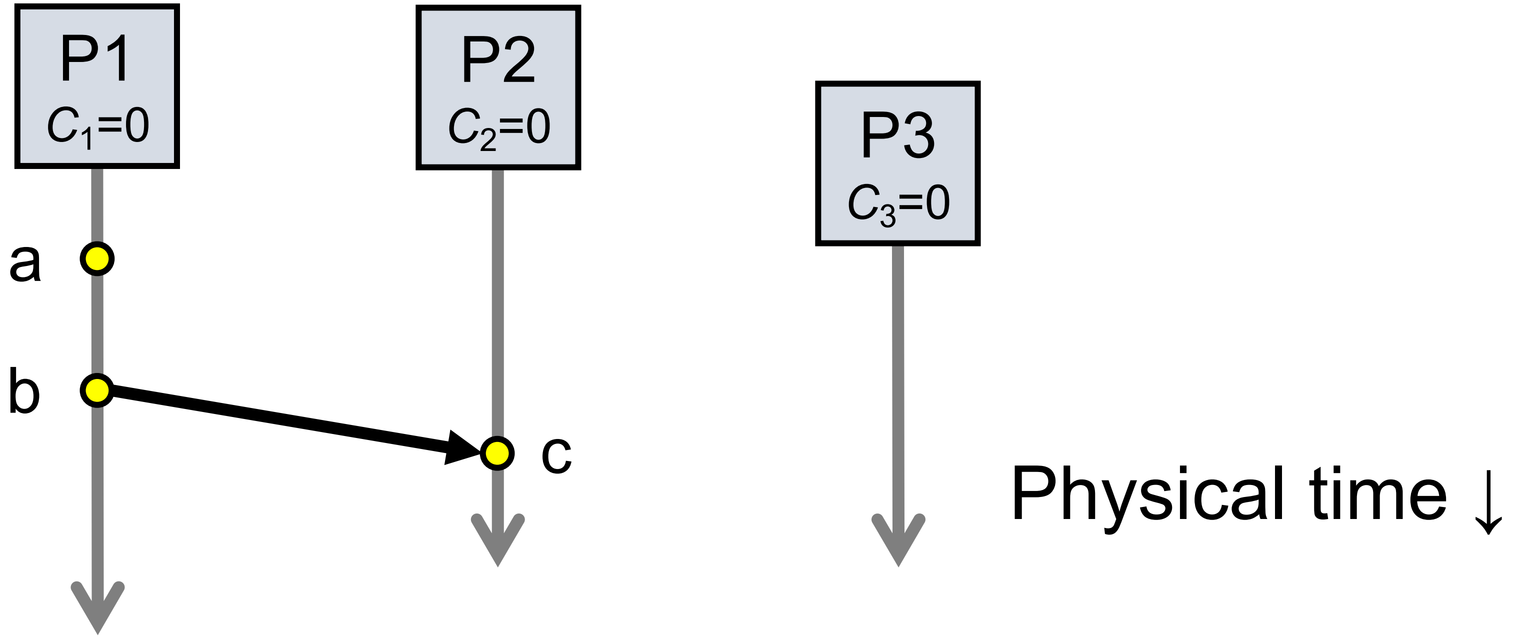
Plan: Tag events with clock times; use clock times to make distributed system correct

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

The Lamport Clock algorithm

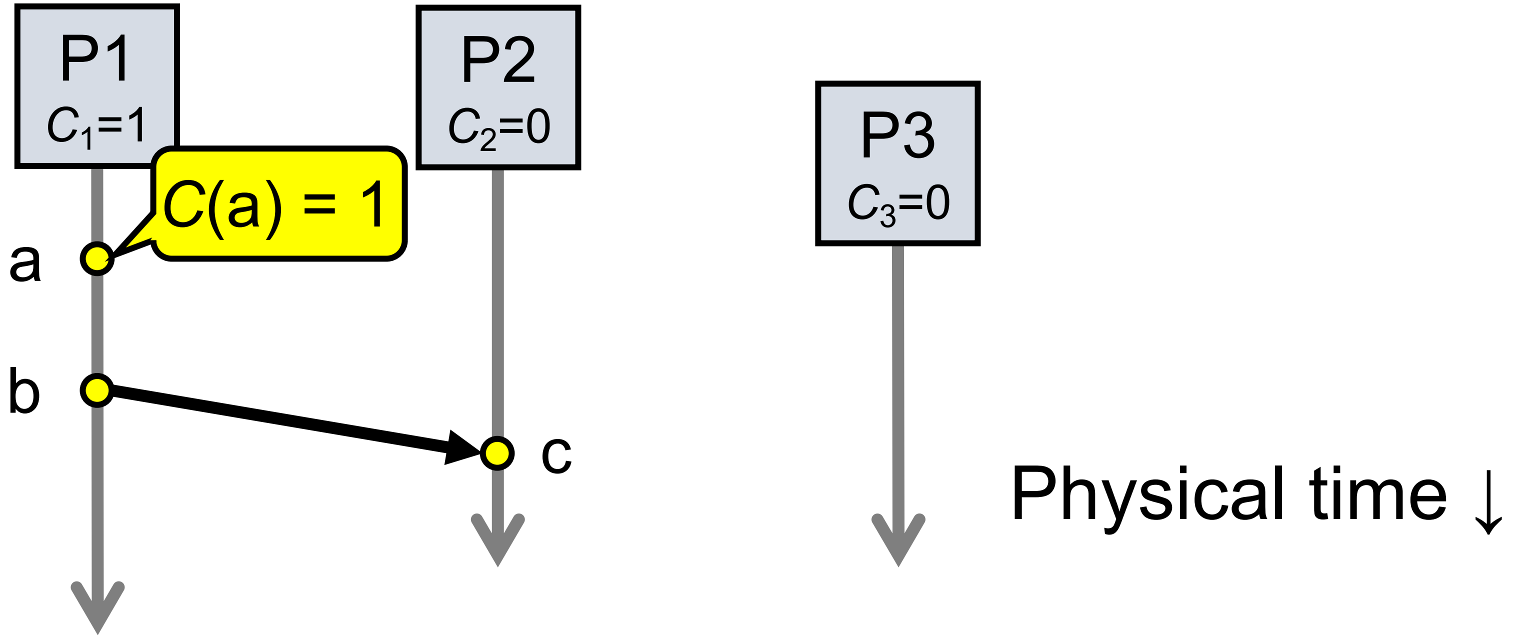
- Each process P_i maintains a local clock C_i

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



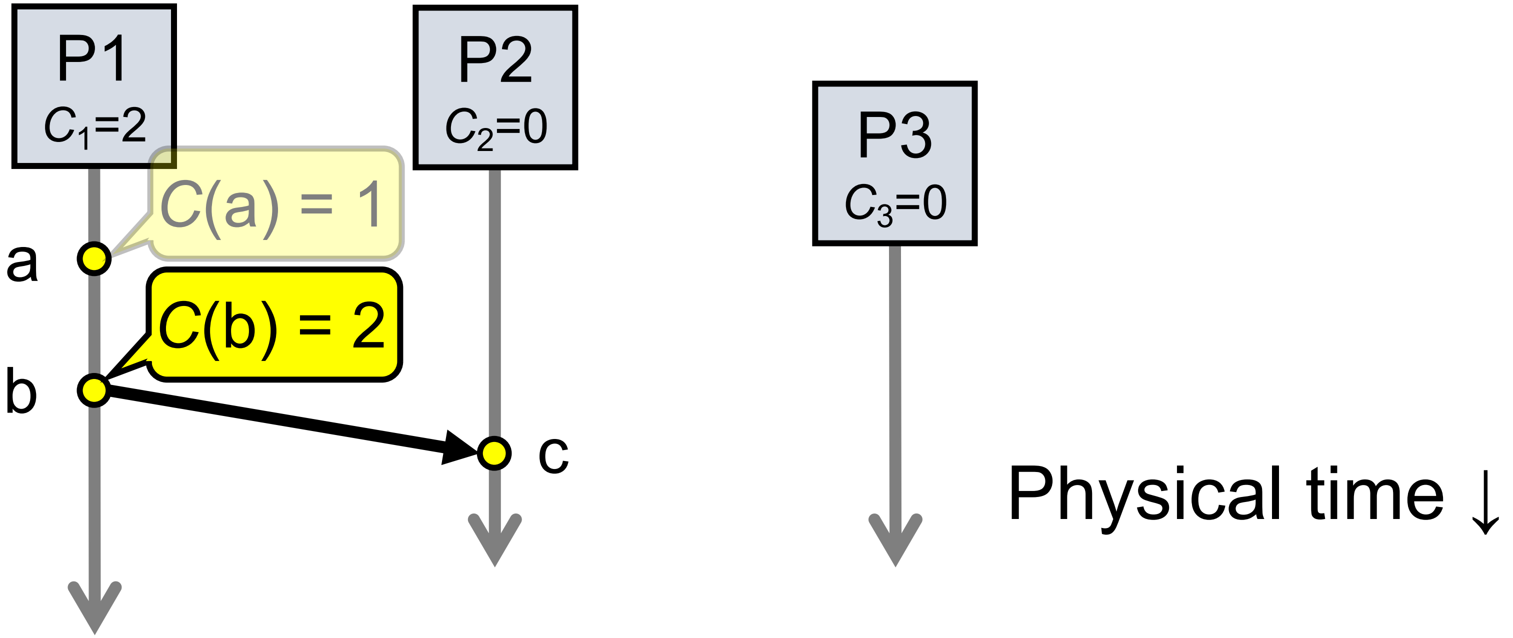
The Lamport Clock algorithm

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



The Lamport Clock algorithm

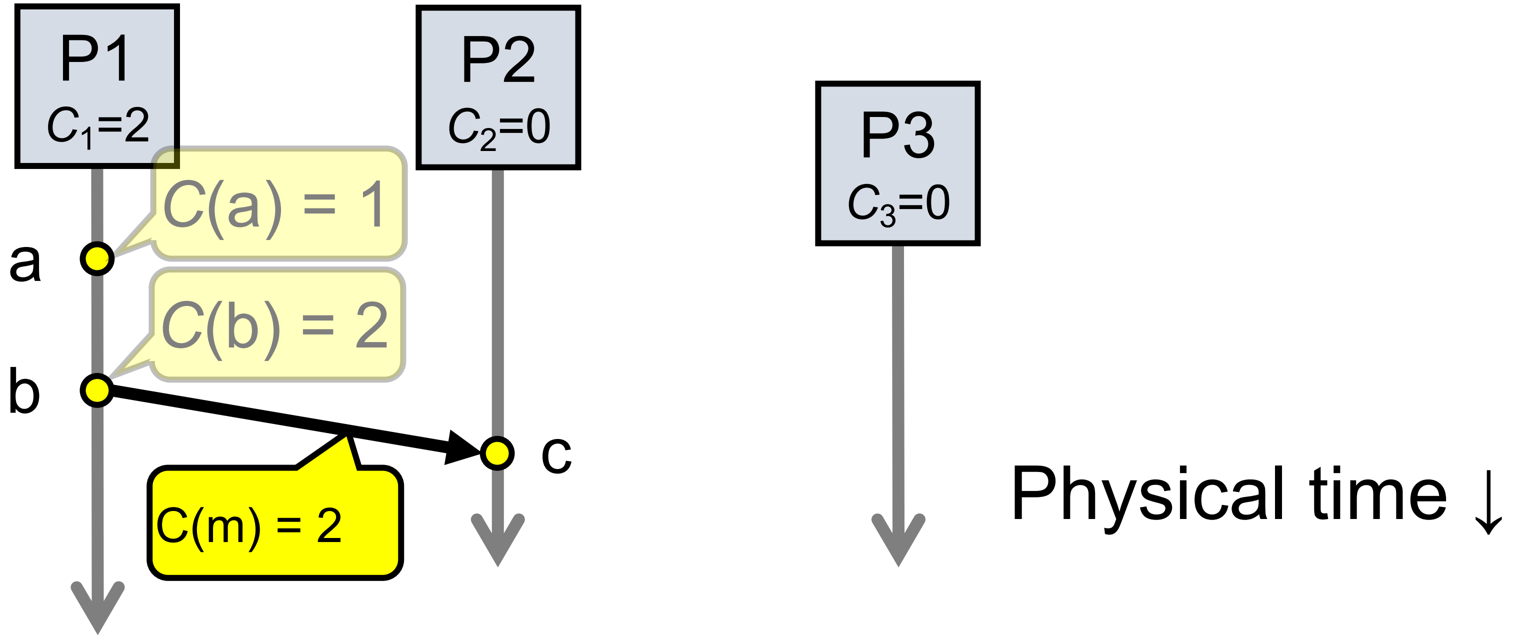
1. Before executing an event b, $C_i \leftarrow C_i + 1$:
   - Set event time $C(b) \leftarrow C_i$



The Lamport Clock algorithm

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

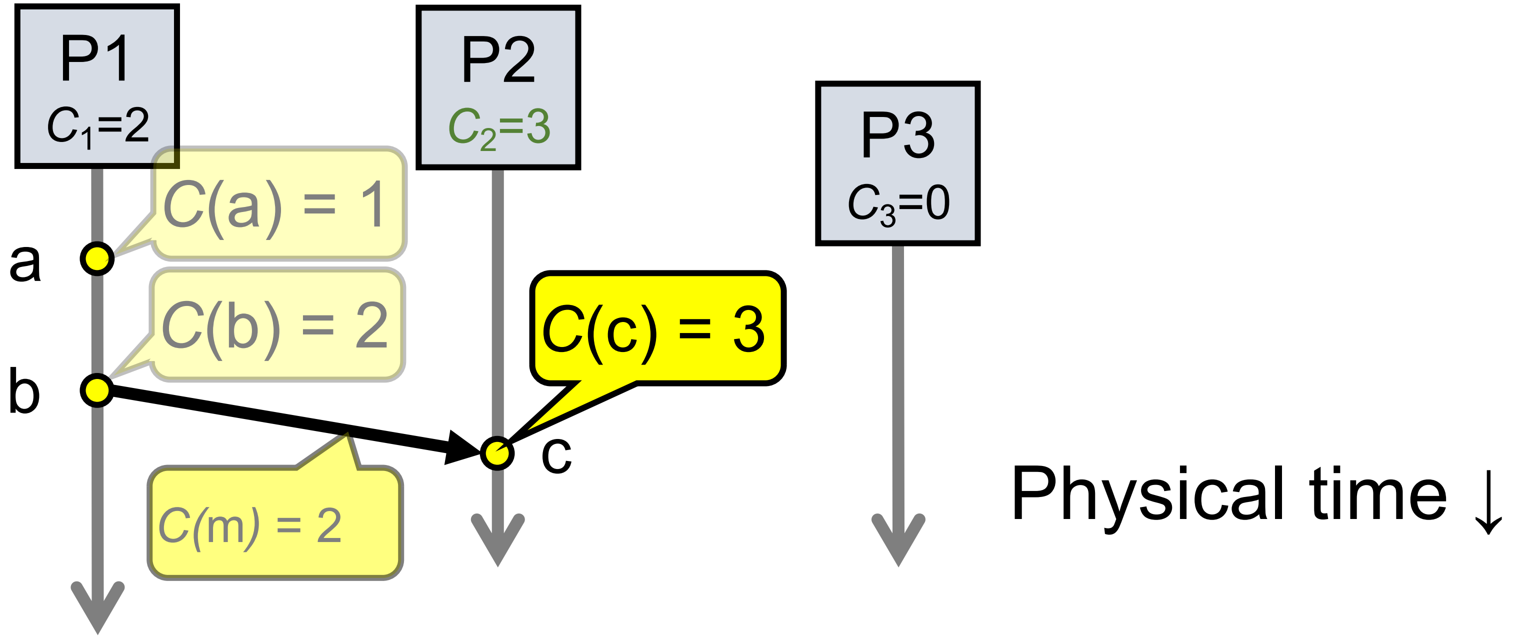
2. Send the local clock in the message m



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

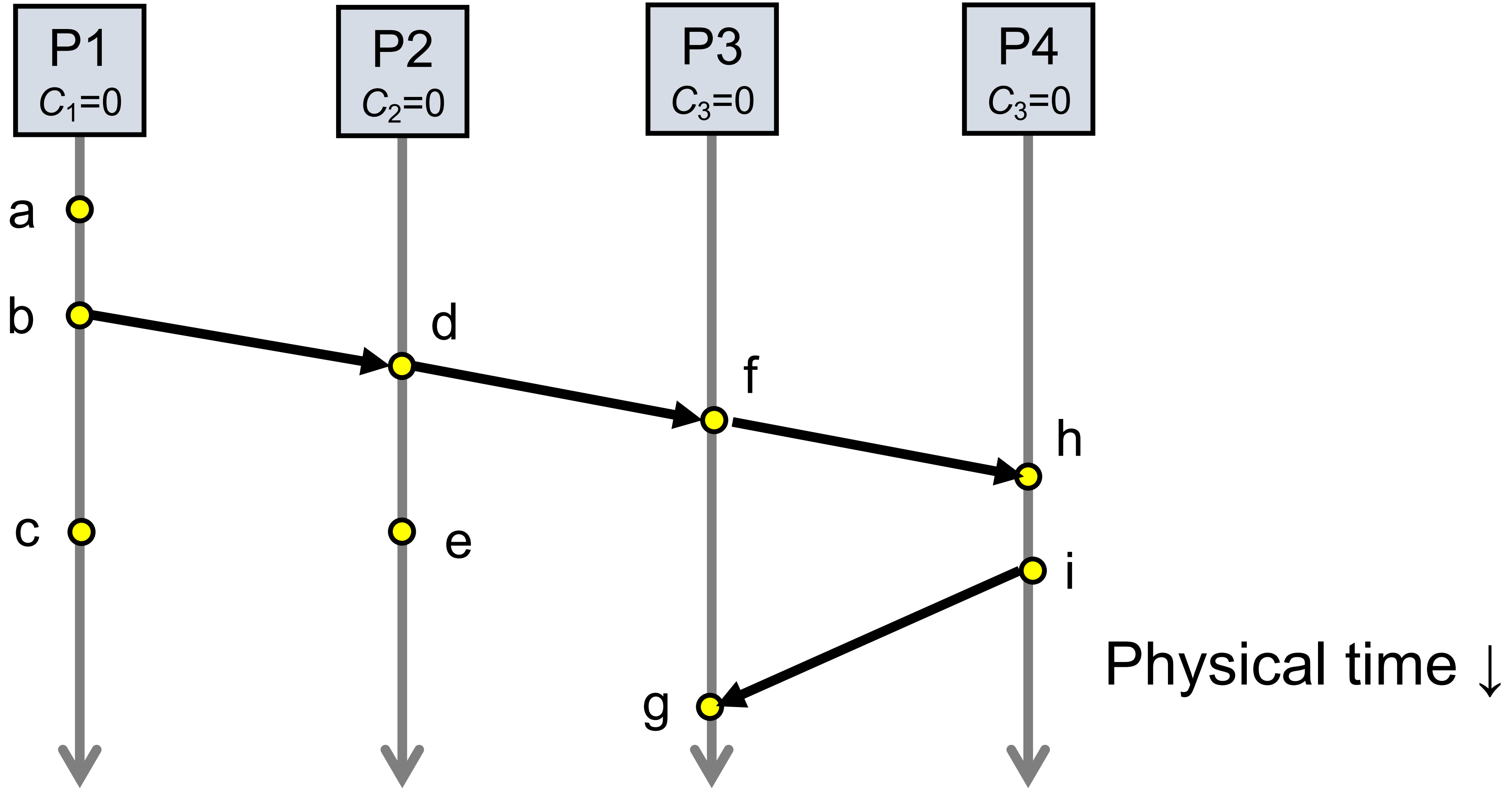
- Break ties by appending the process number to each event:

  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

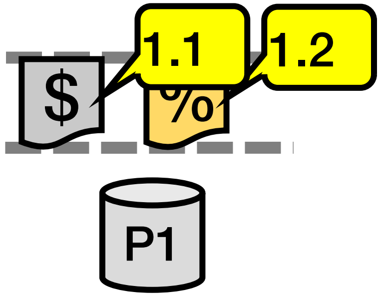


Totally-Ordered Multicast

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)

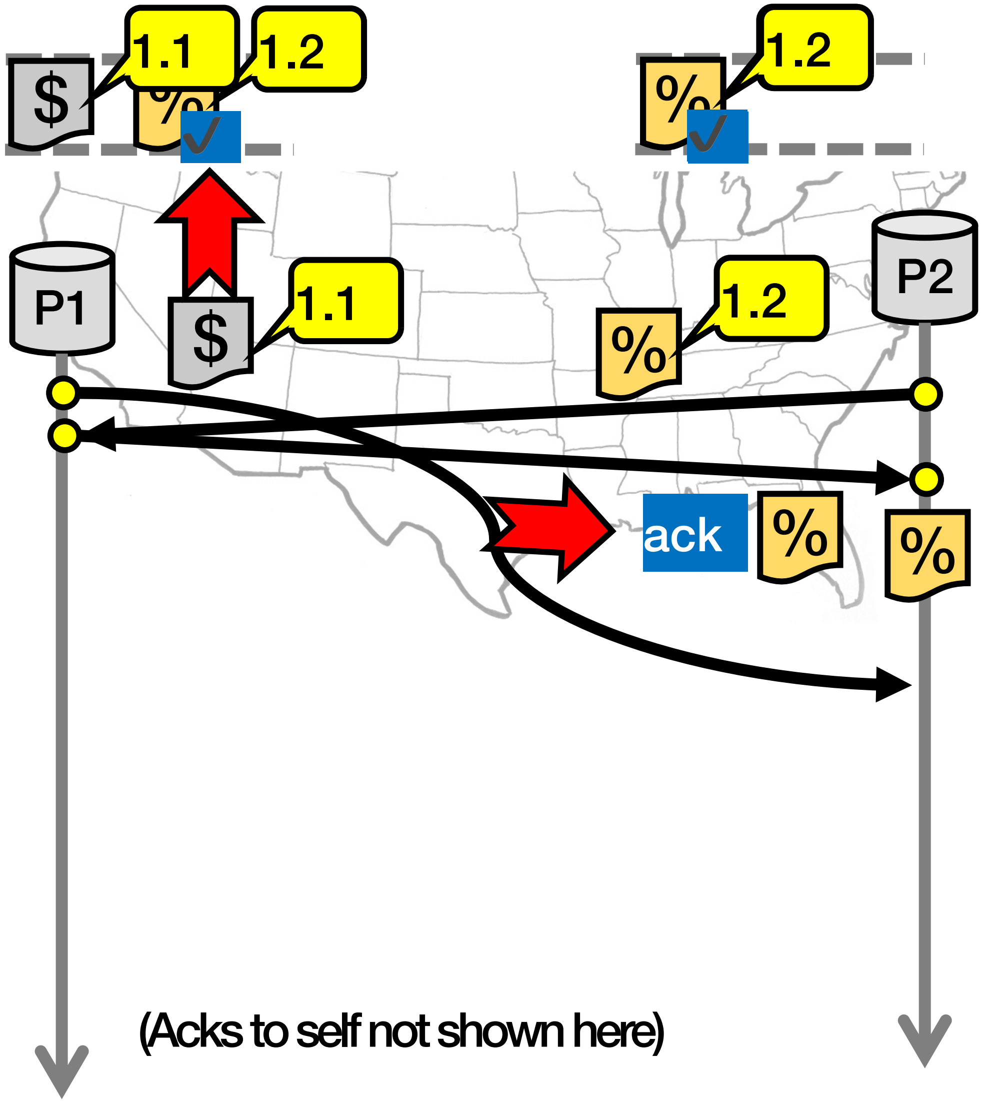
3. On receiving an acknowledgement:
   - Mark corresponding update acknowledged in your queue

4. Remove and process updates <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 %



(Acks to self not shown here)

Totally-Ordered Multicast (Correct version)

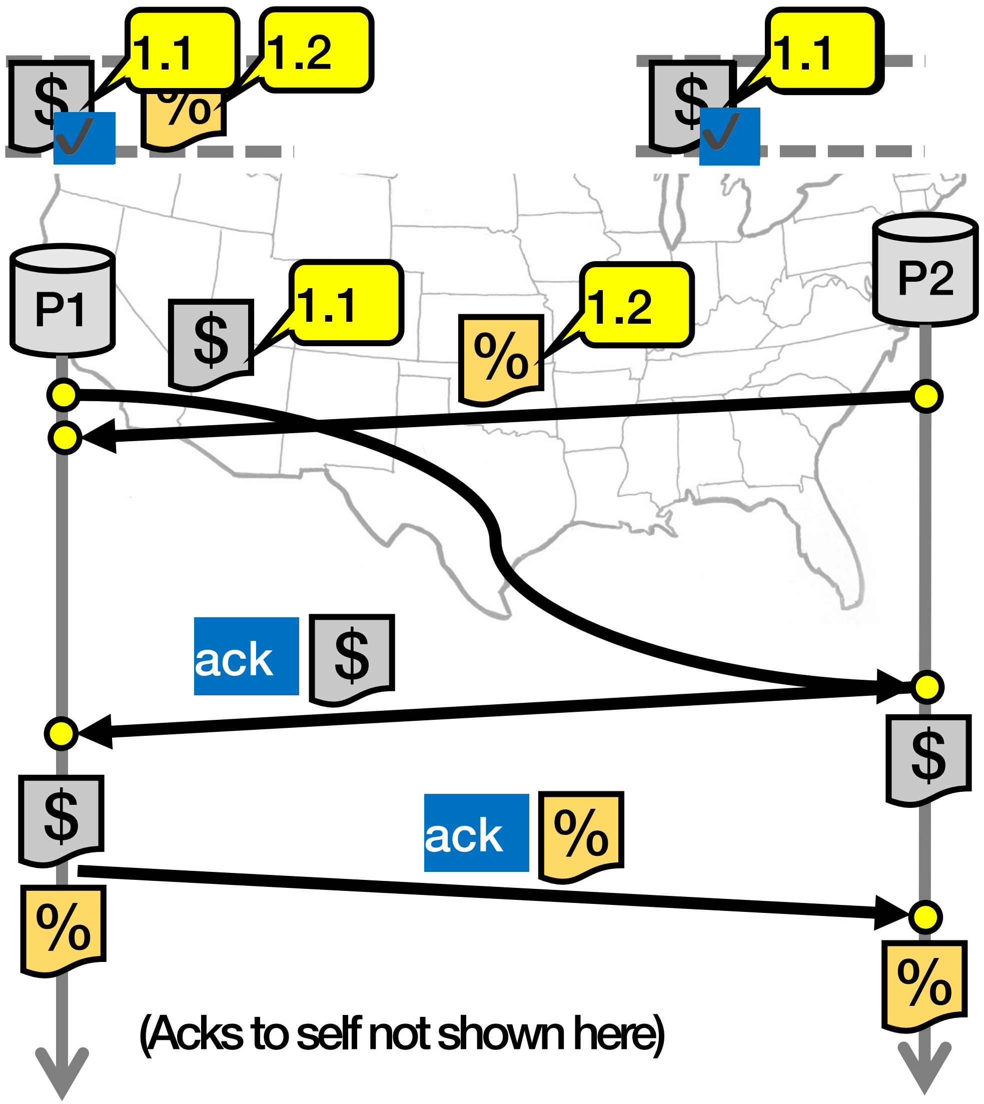
1. On receiving an update from client, broadcast to others (including yourself)

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)



(Acks 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 timestamps to infer causal relationships between events