Time Synchronization and Logical Clocks

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CS 240: Computing Systems and Concurrency
Lecture 4

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Credits: Michael Freedman and Kyle Jamieson developed much of the original material.

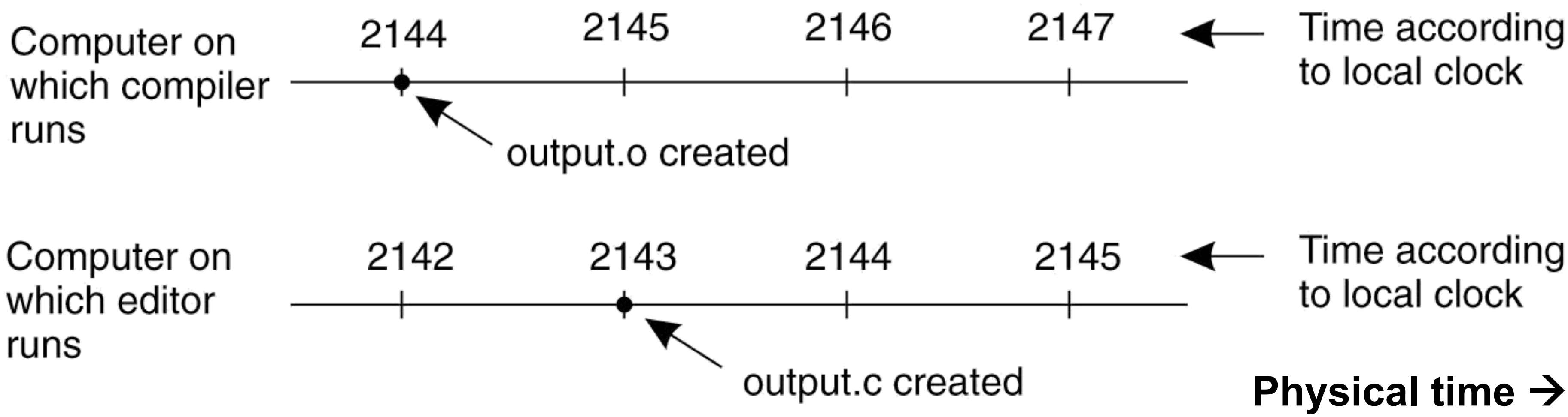
Today

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 network is:
   - ***Asynchronous:*** arbitrary message **delays**
   - ***Best-effort***: messages **don't always arrive**

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1. The need for time synchronization

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   – Cristian’s algorithm, NTP

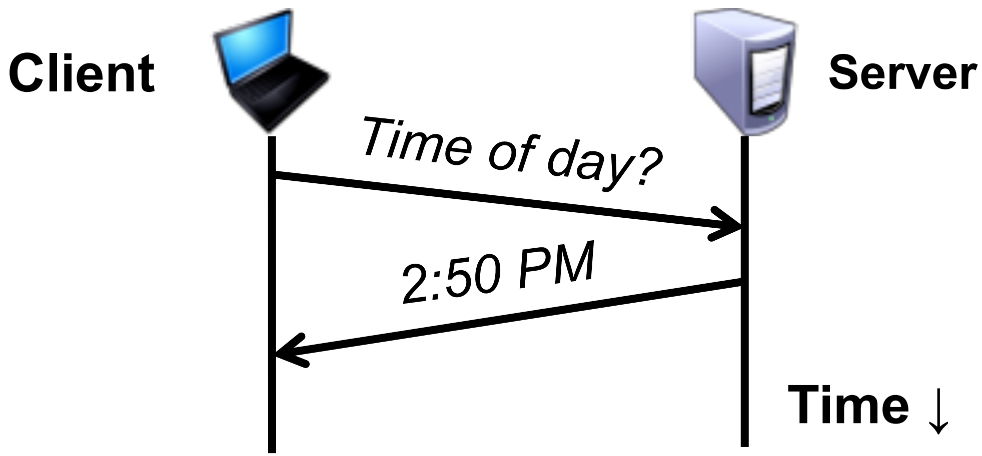
3. Logical time: Lamport clocks

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-disciplined crystal oscillator)
  - 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  - **Message delays** will have **outdated** server's answer

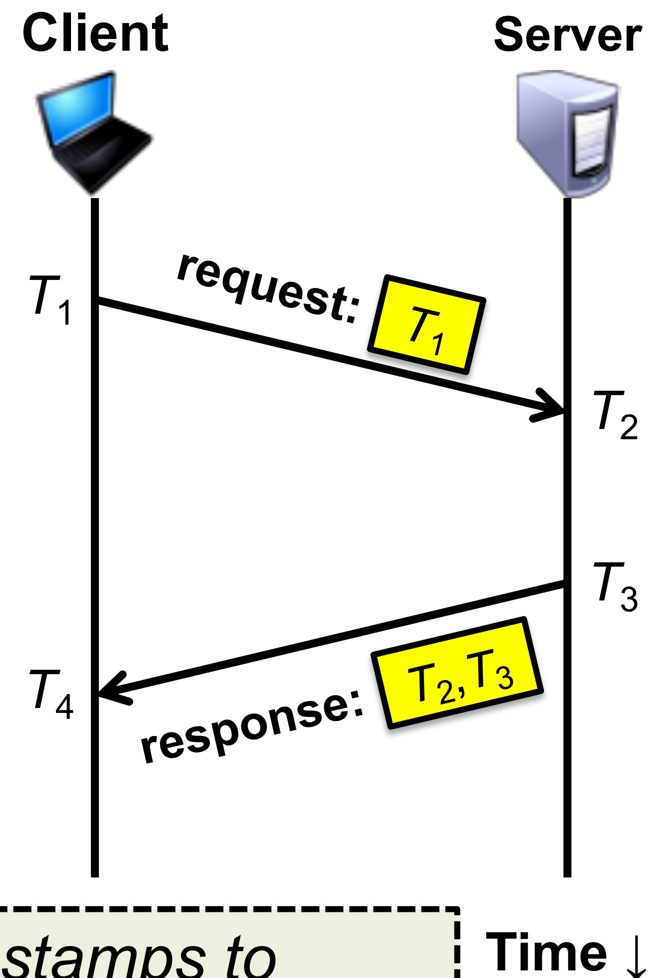
Cristian's algorithm: Outline

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

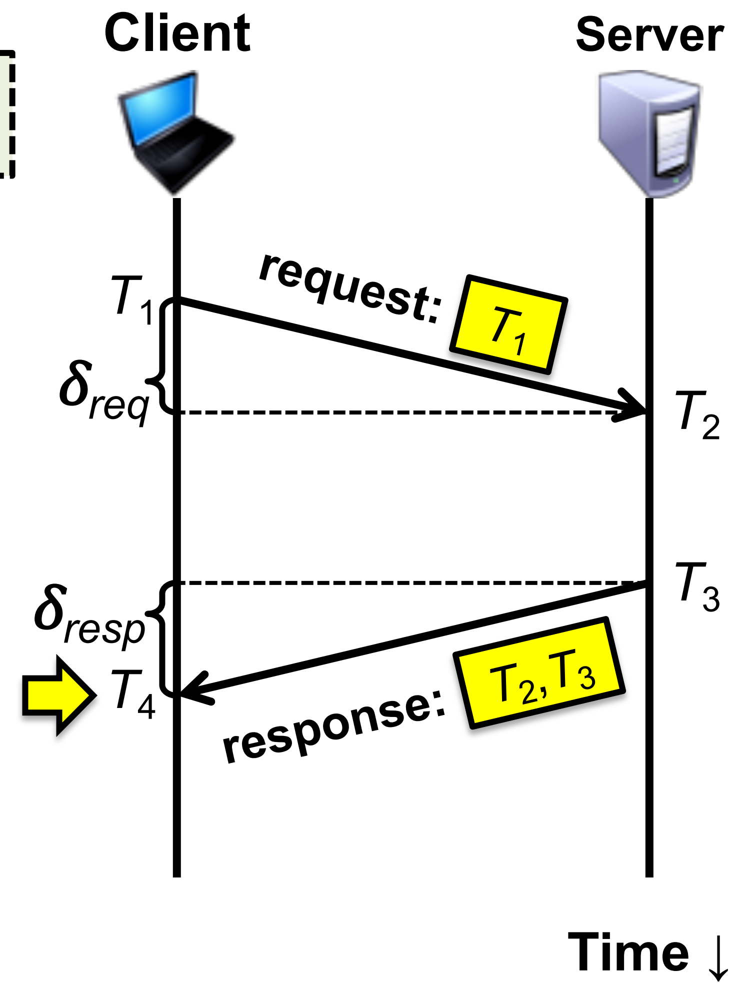
Cristian's algorithm: Offset sample calculation

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

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

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

Client sets clock ← $T_3 + ½\delta$



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

3. Logical time: Lamport clocks

The Network Time Protocol (NTP)

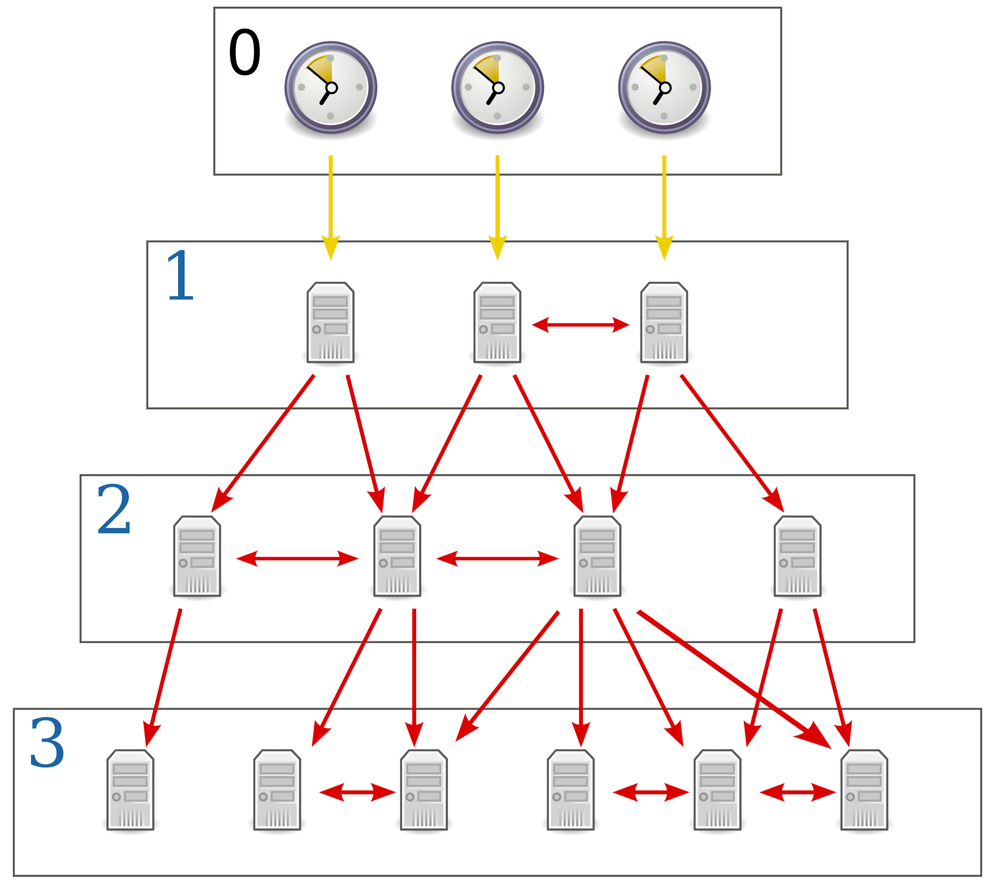
- Enables clients to be accurately synchronized to UTC despite message delays

- 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
  - Stratum 1-3: NTP 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 i^{th} 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**

NTP operation: How to change time

- 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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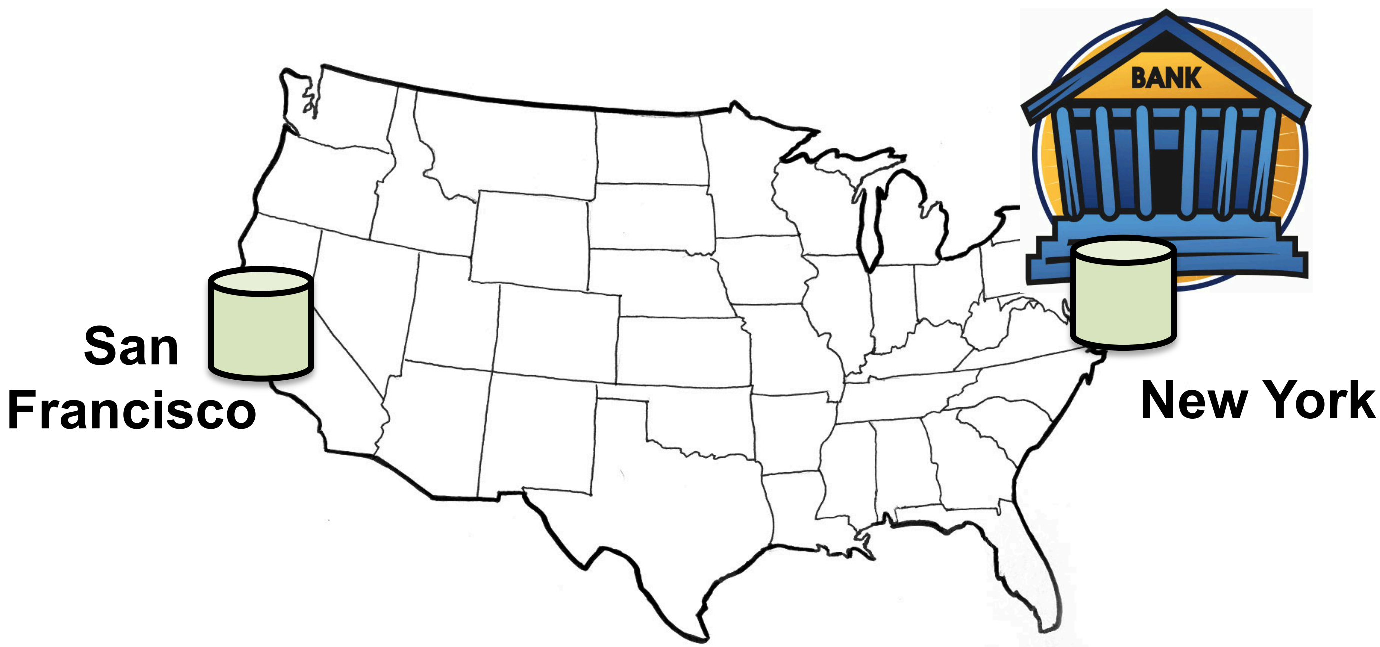
3. **Logical time: Lamport clocks**

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

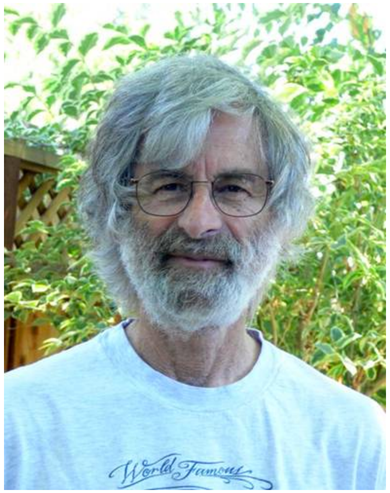
- **Replicate** the database, keep one copy in sf, one in nyc
  - Client sends **query** to the **nearest** copy
  - Client sends **update to both** copies

Inconsistent replicas!

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

Idea: *Logical* clocks

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



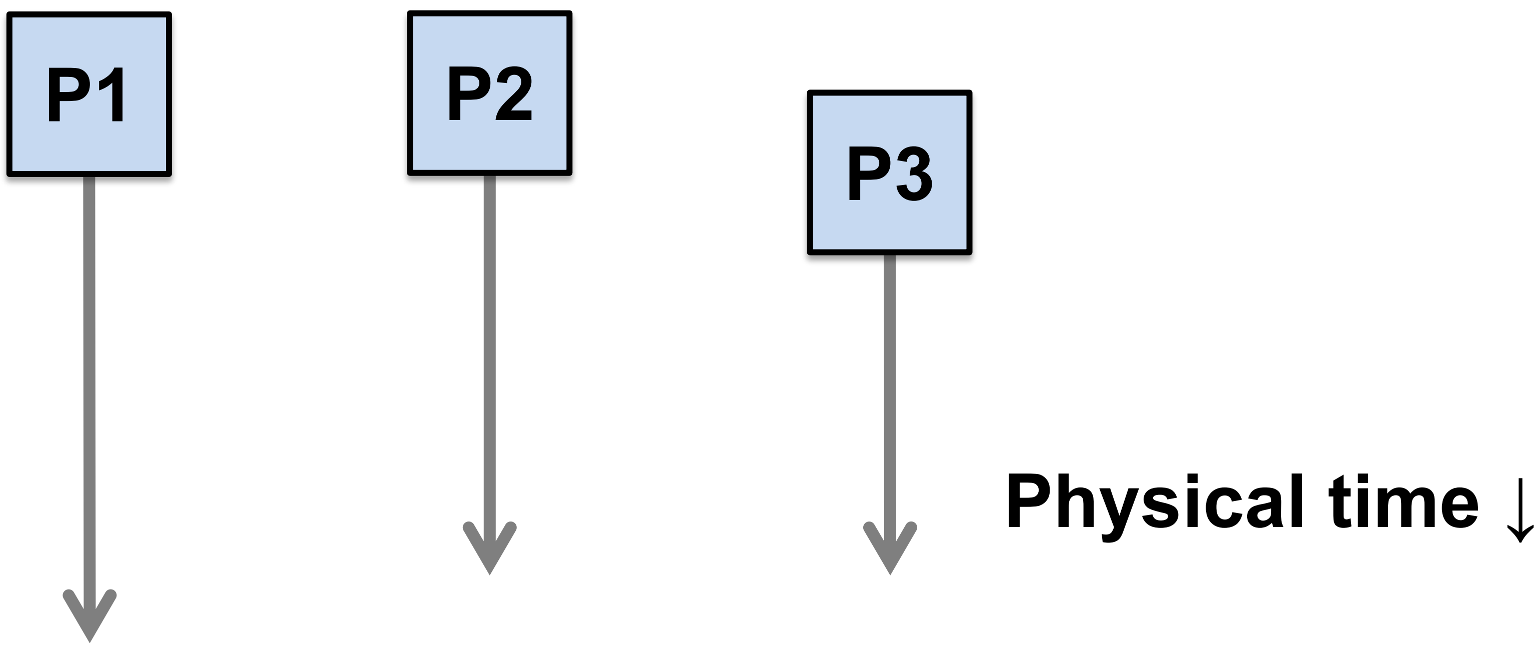
Idea: Disregard the precise clock time

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

Defining "happens-before" (→)

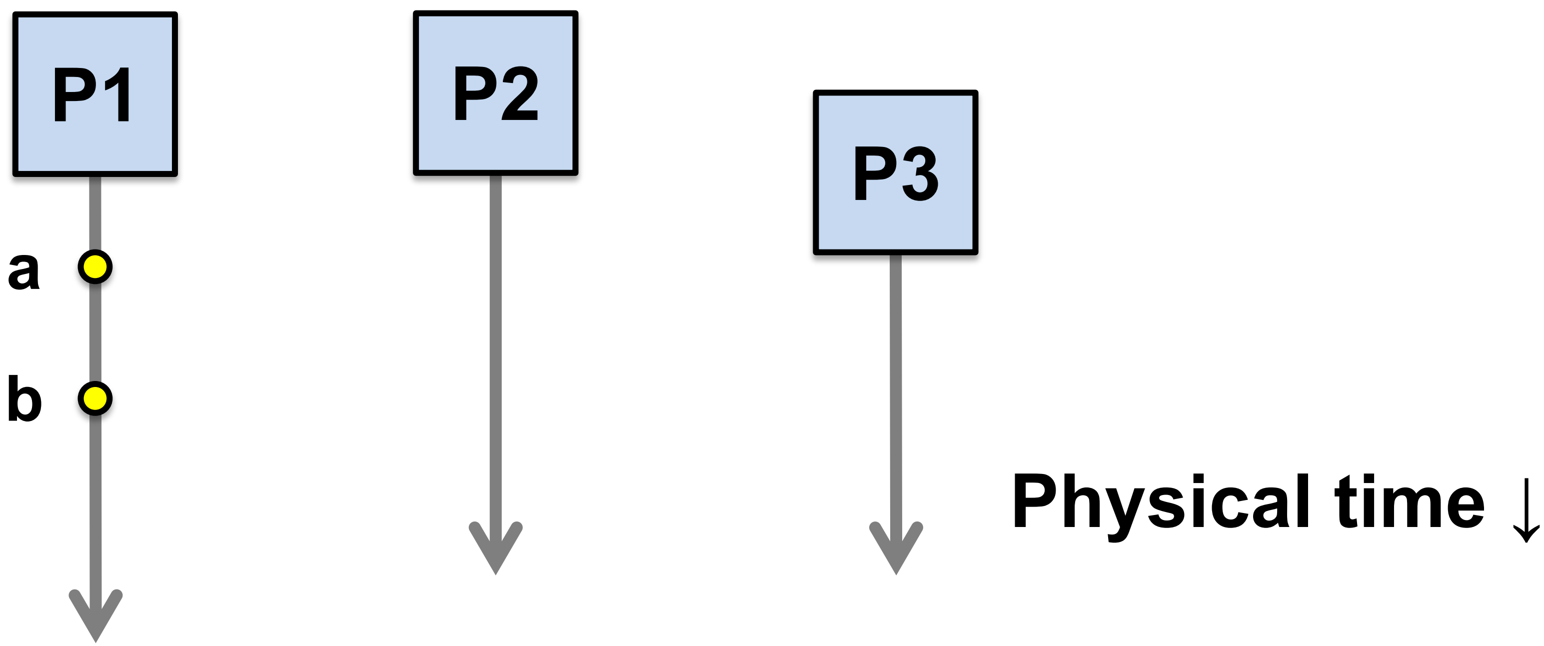
- Consider three processes: **P1**, **P2**, and **P3**

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



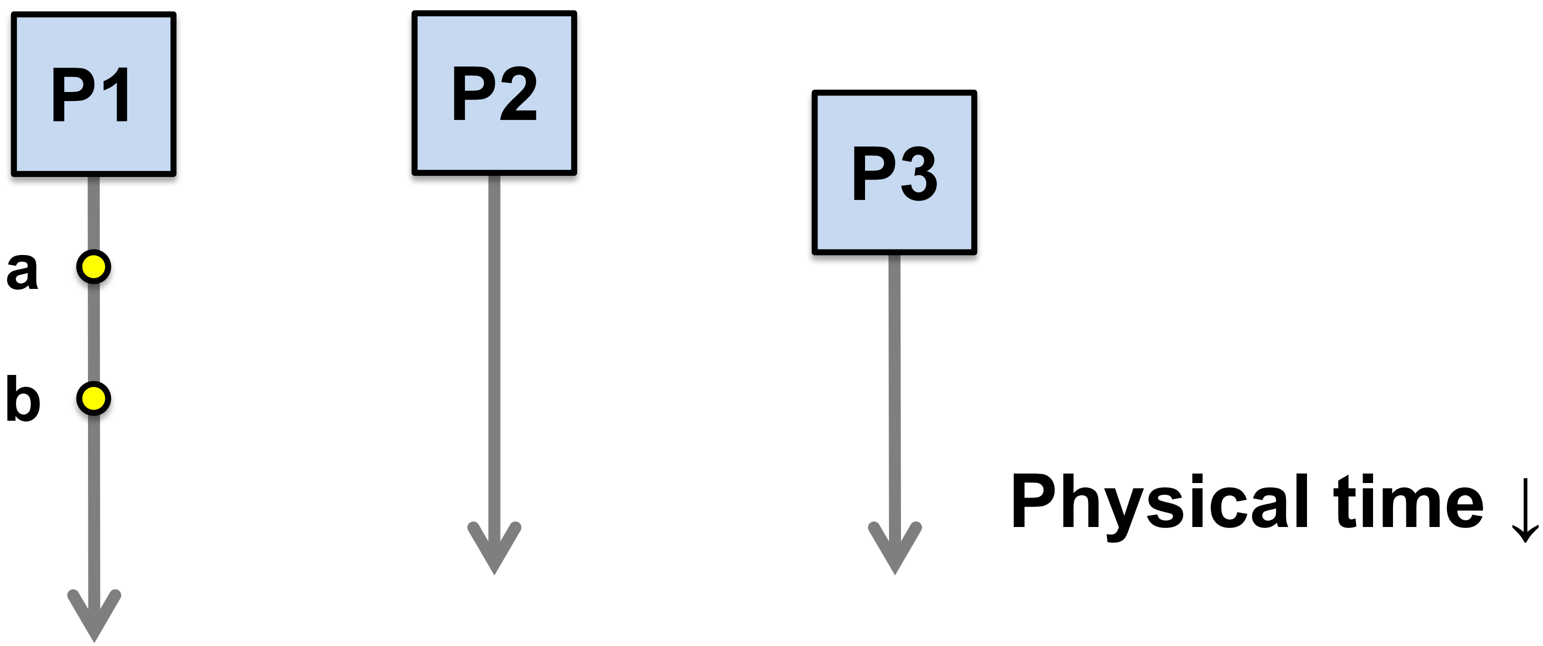
Defining "happens-before" (→)

1. Can observe event order at a single process



Defining "happens-before" (→)

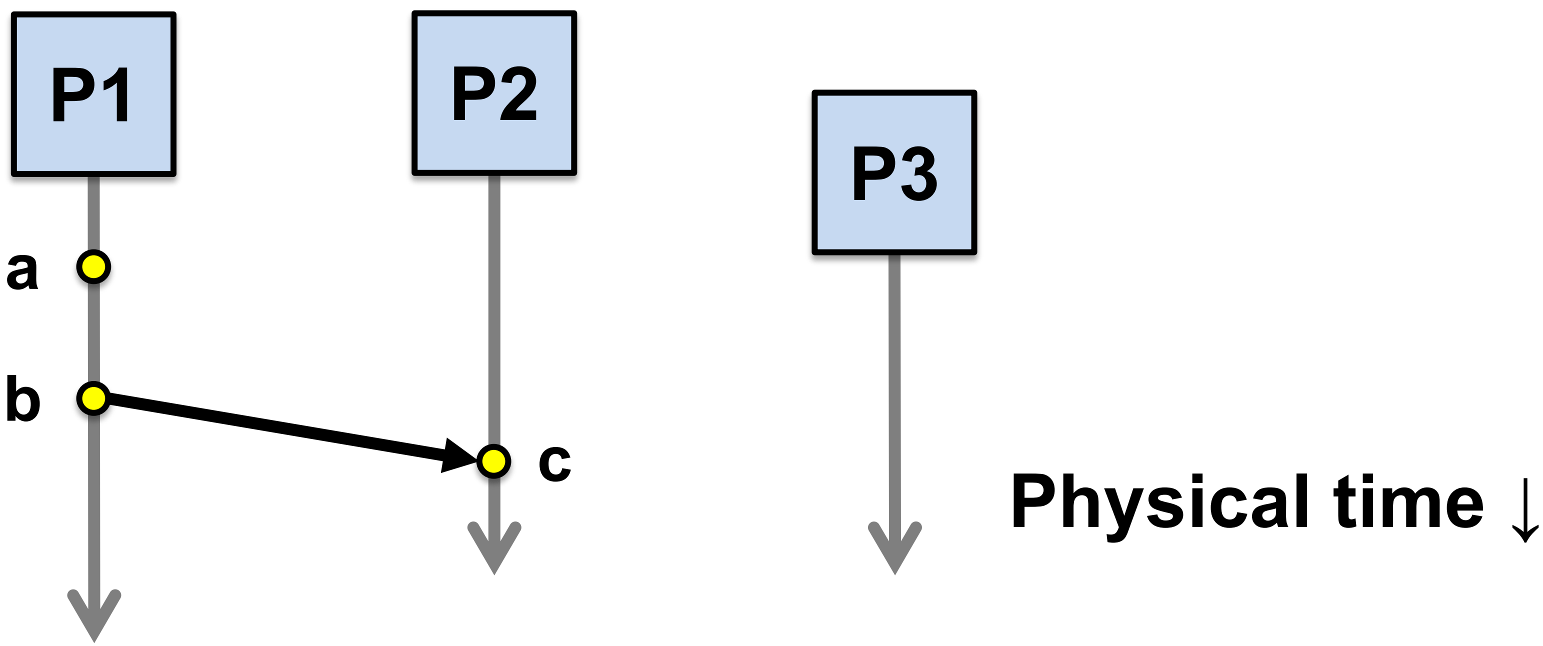
1. If **same process** and **a** occurs before **b**, then **a → b**



Defining "happens-before" (→)

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

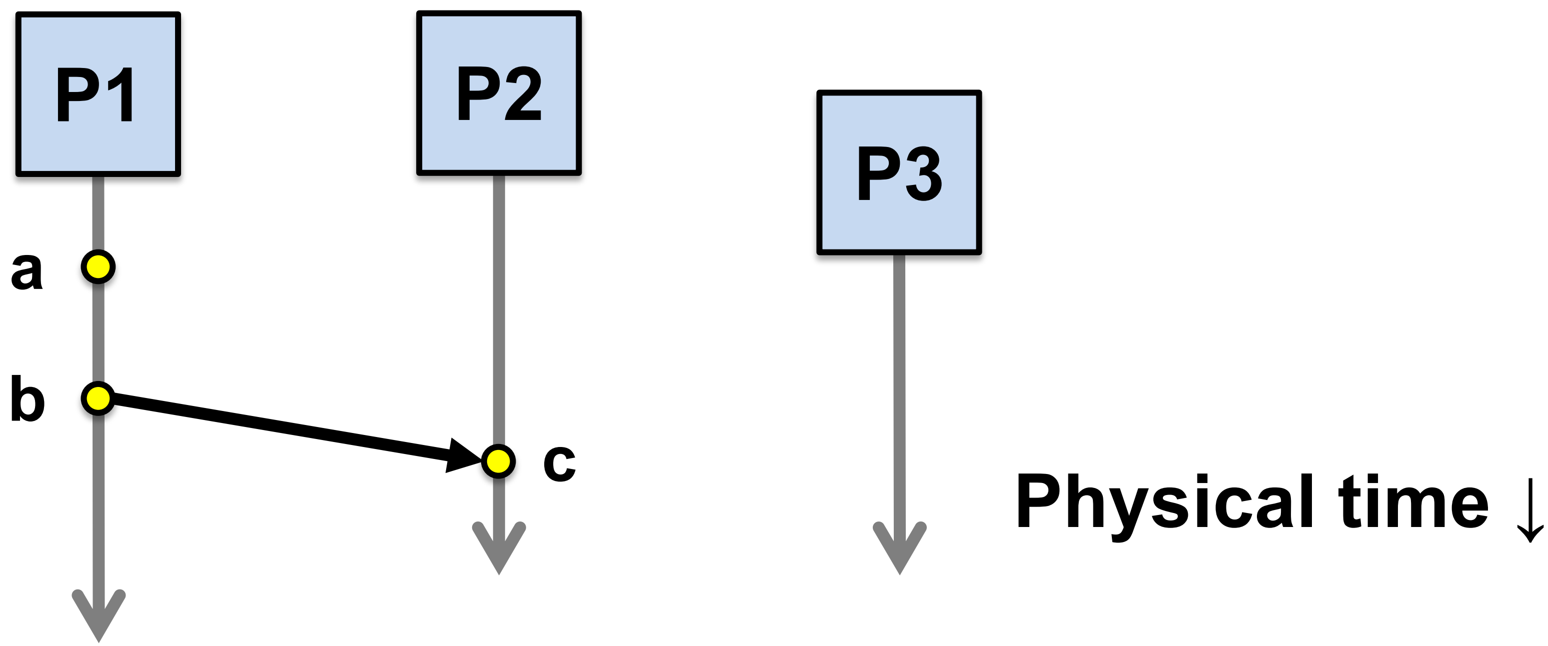
2. Can observe ordering when processes communicate



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**

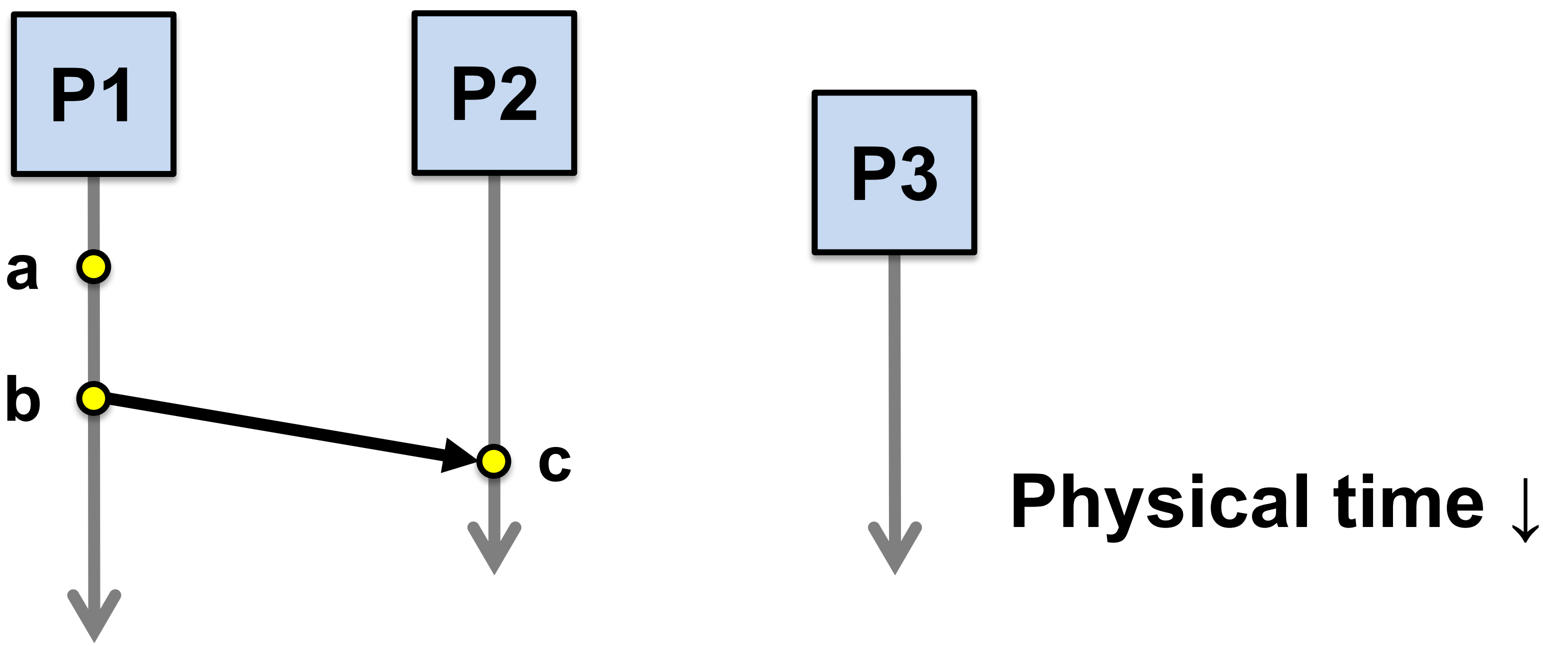


Defining "happens-before" (→)

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

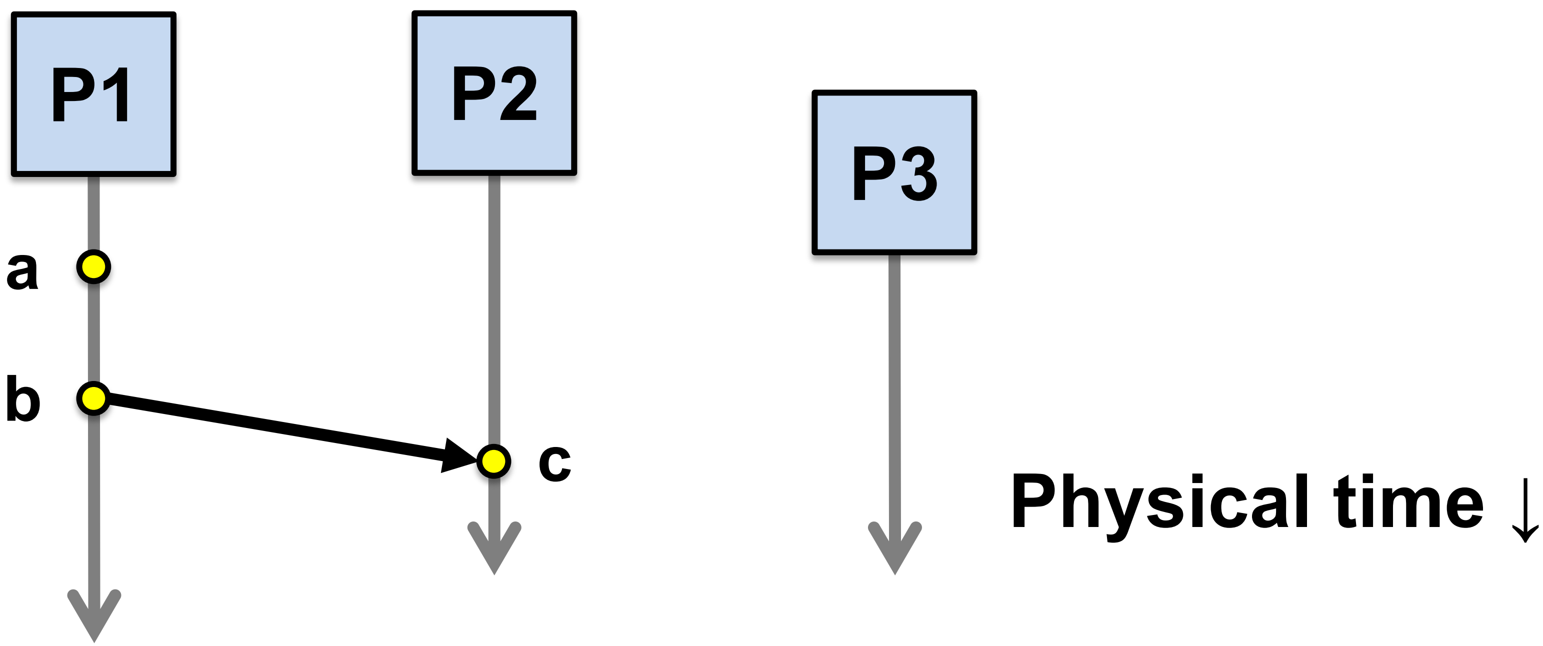
2. If **c** is a message receipt of **b**, then **b** → **c**

3. Can observe ordering transitively



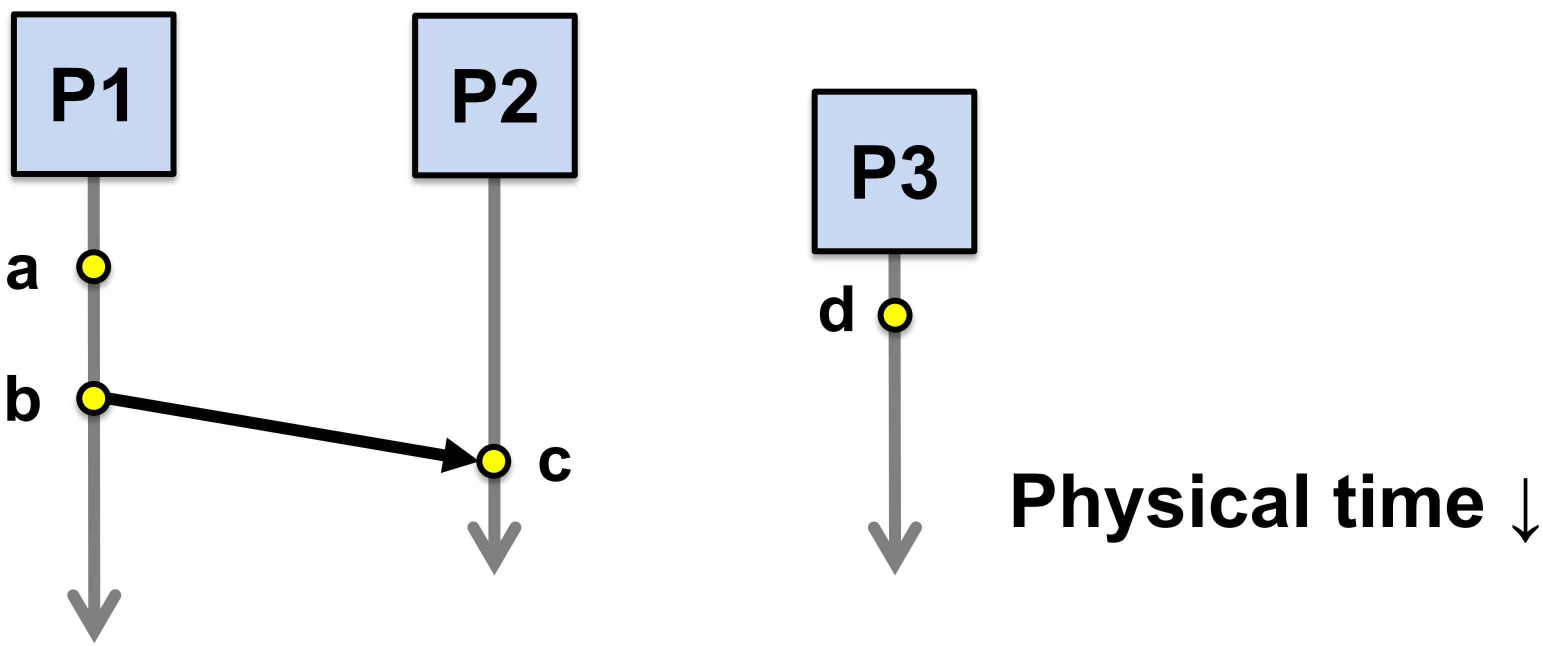
Defining "happens-before"

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**

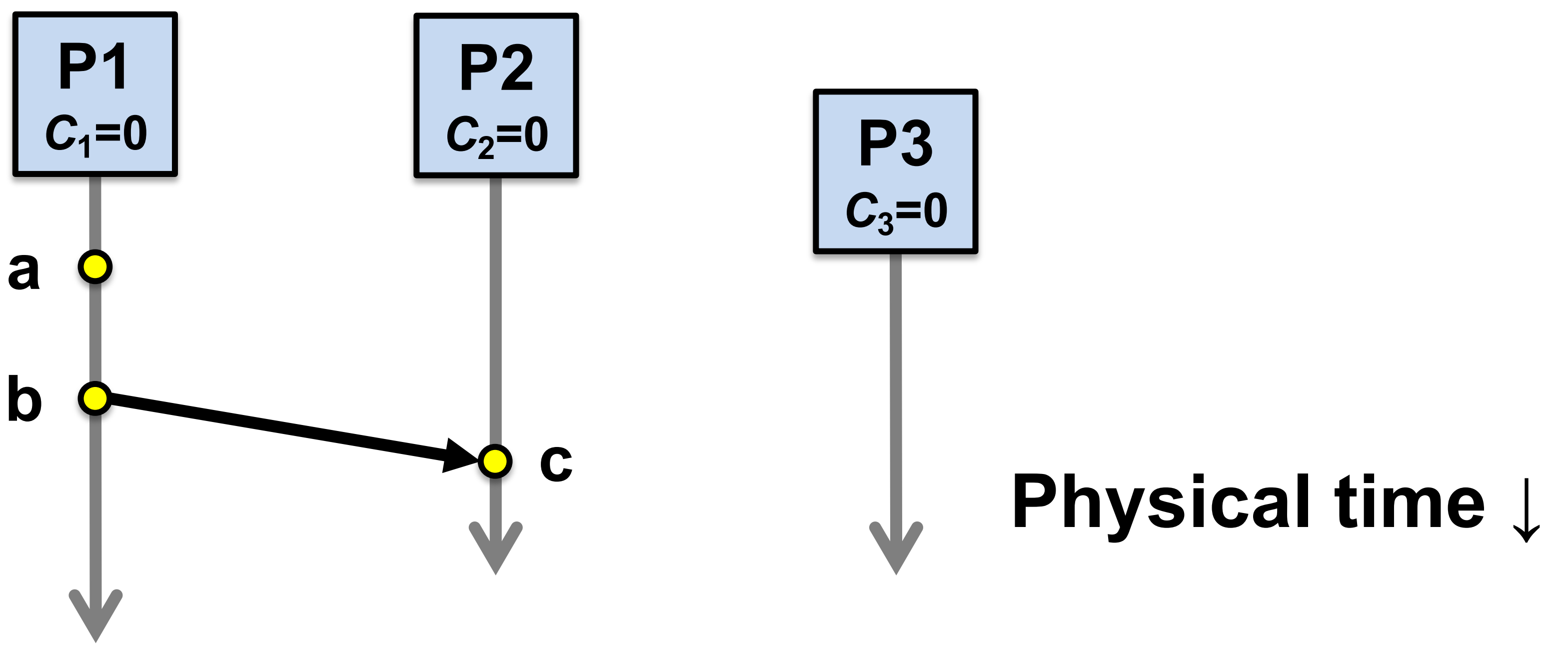
Plan: Tag events with clock times; use **clock times** to make distributed system correct

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

The Lamport Clock algorithm

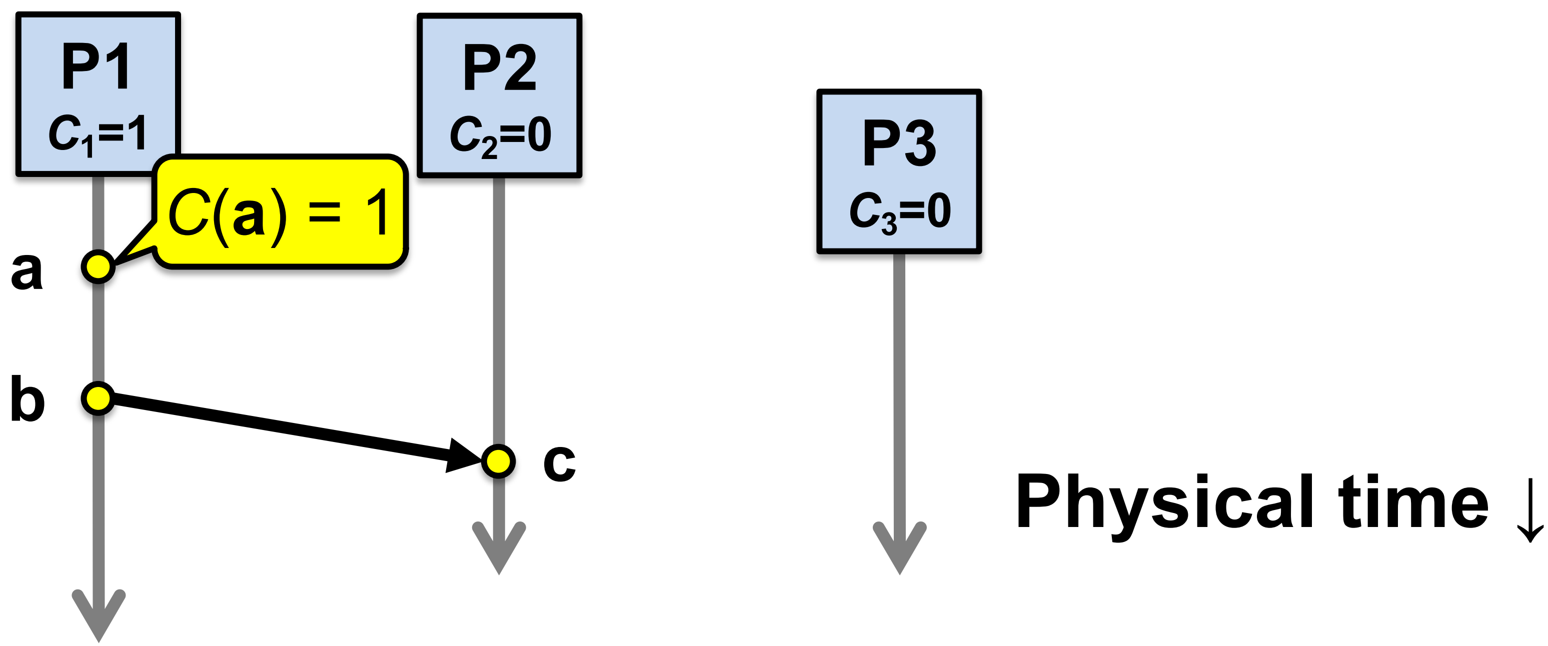
- Each process **P**$_i$ maintains a local clock C_i

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



The Lamport Clock algorithm

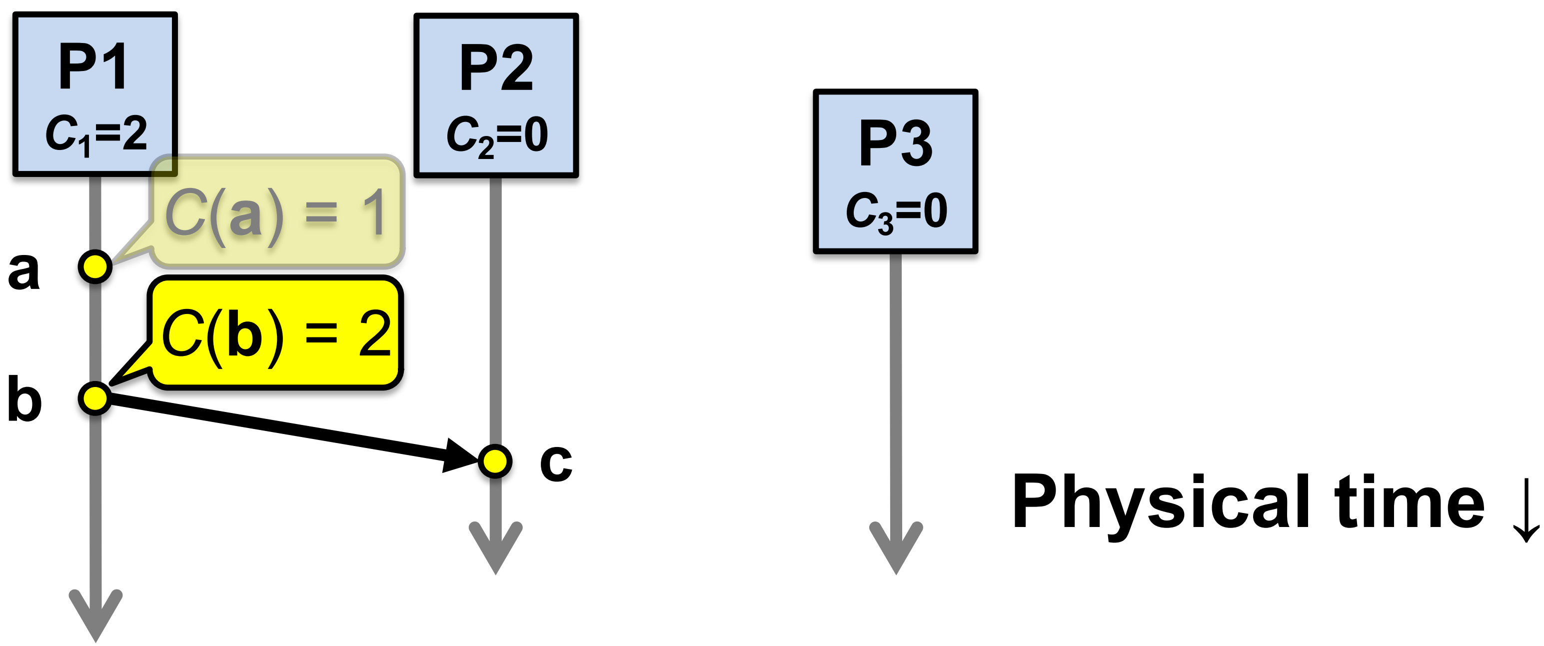
1. Before executing an event **a**, $C_i \leftarrow C_i + 1$:
   – Set event time $C(\mathbf{a}) \leftarrow C_i$



The Lamport Clock algorithm

1. Before executing an event **b**, $\boldsymbol{C_i} \leftarrow \boldsymbol{C_i} + 1$:

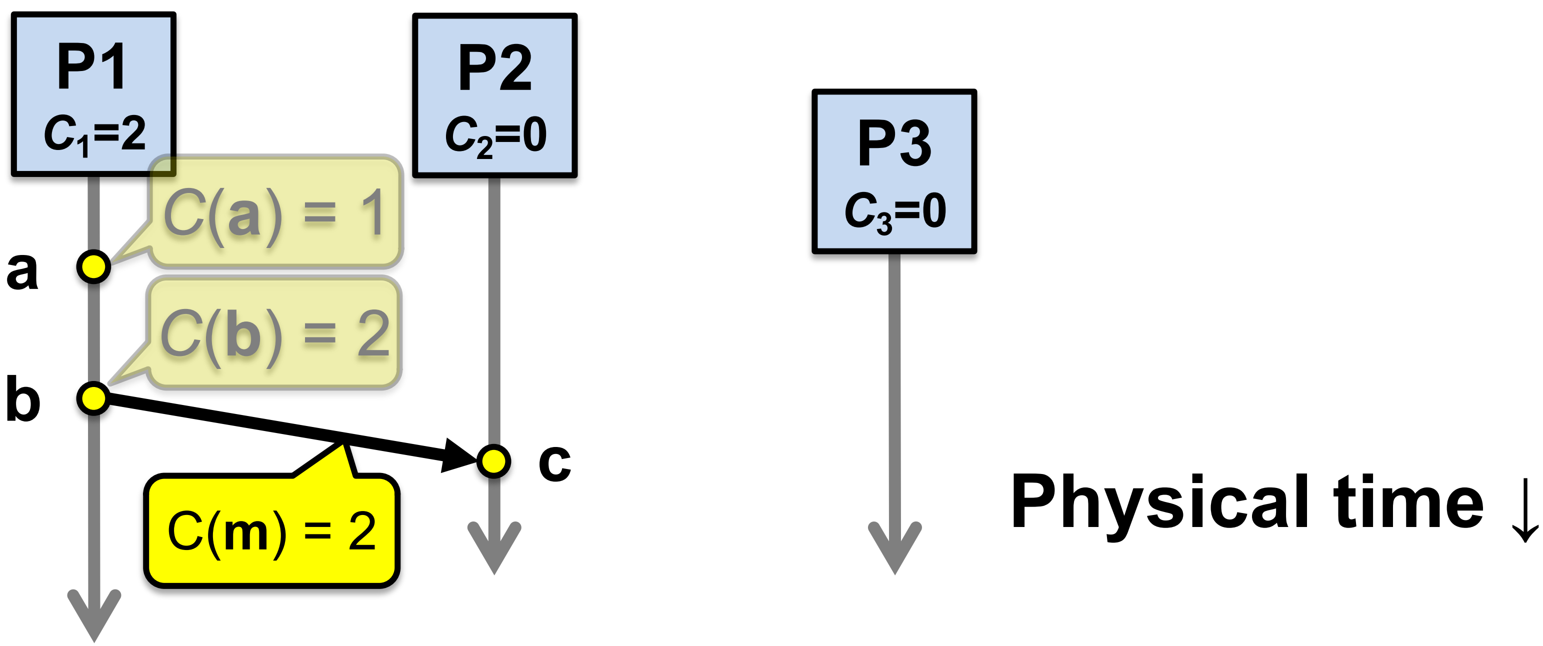
   – Set event time $C($**b**$) \leftarrow C_i$



The Lamport Clock algorithm

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

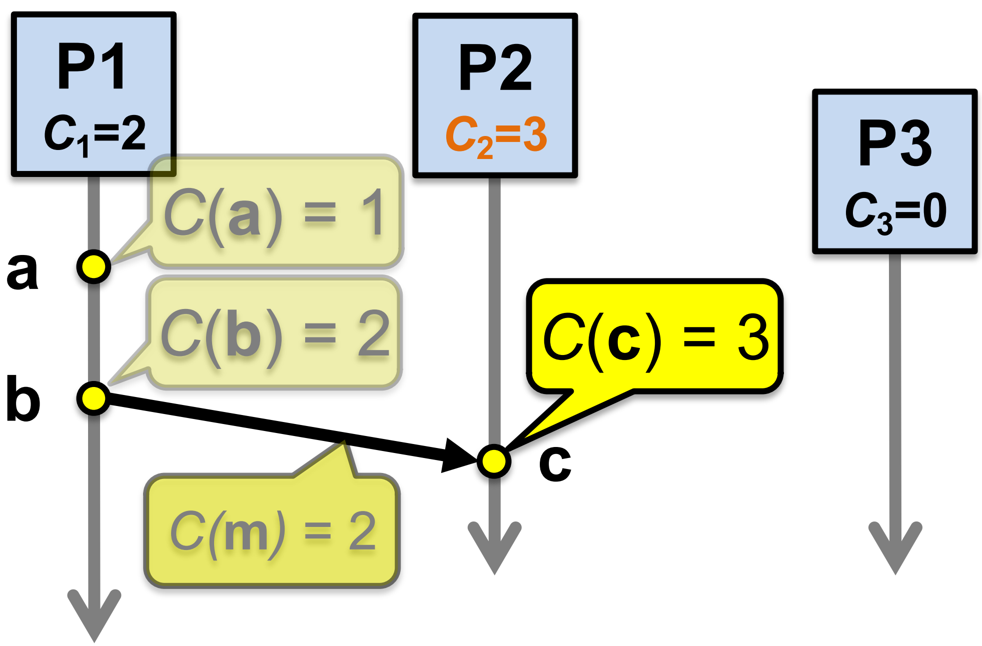
2. Send the local clock in the message **m**



The Lamport Clock algorithm

3. On process $\mathbf{P}_j$ receiving a message **m**:

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



Physical time ↓

Lamport Timestamps: Ordering all events

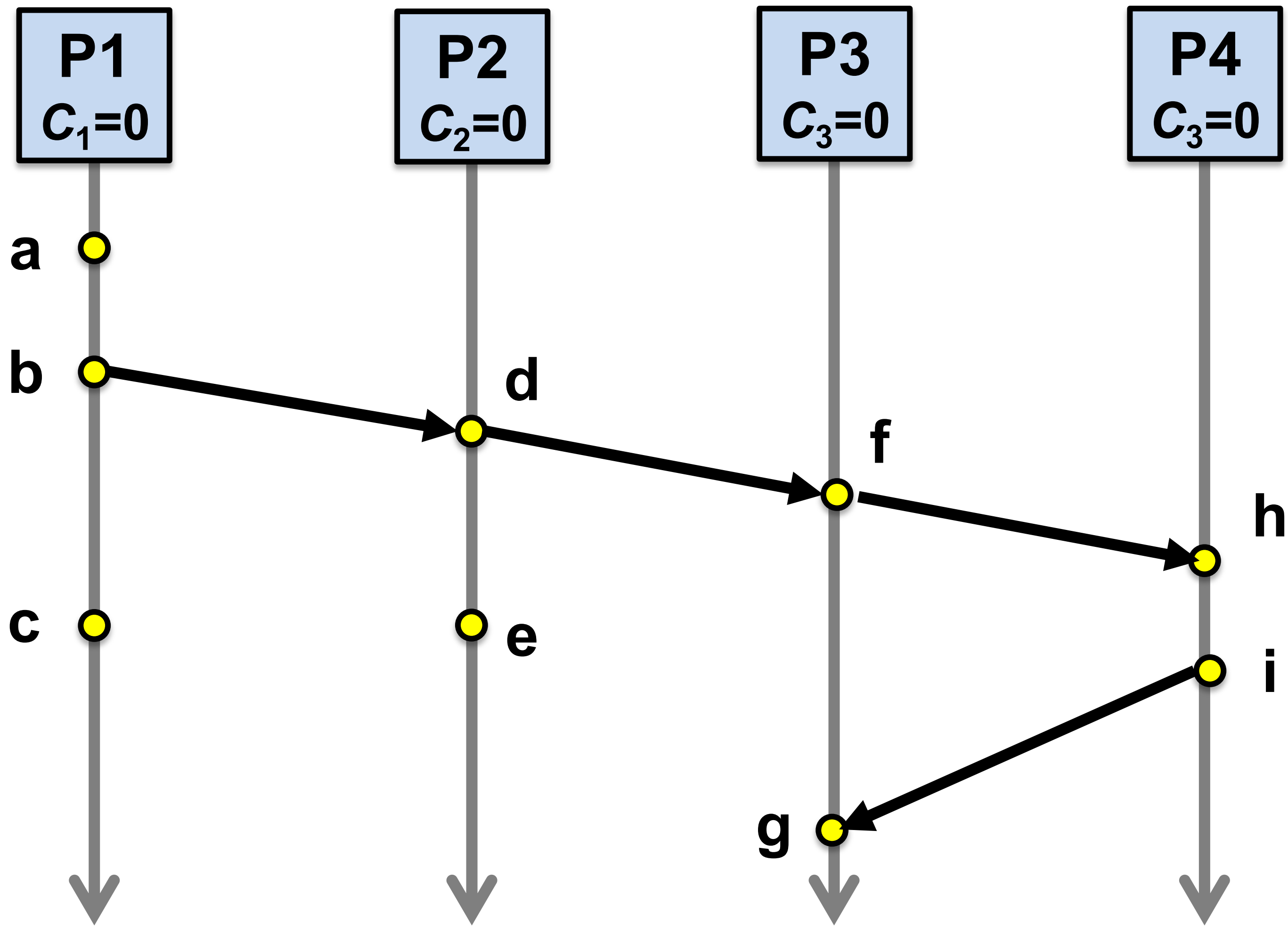
- **Break ties** by **appending the process number** to each event:

  1. Process $\mathbf{P}_i$ timestamps event **e** with $C_i(\mathbf{e}).i$

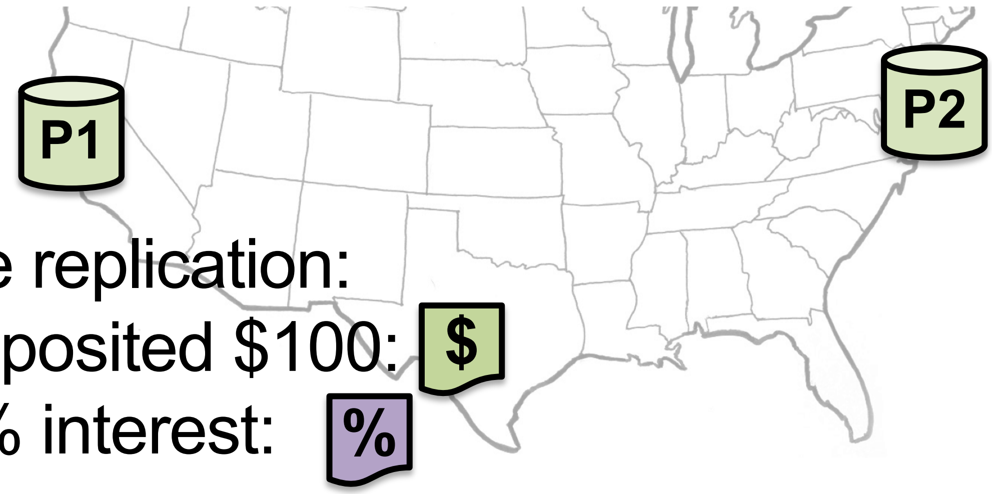
  2. $C(\mathbf{a}).i < C(\mathbf{b}).j$ when:
     - $C(\mathbf{a}) < C(\mathbf{b})$, **or** $C(\mathbf{a}) = C(\mathbf{b})$ and $i < j$

- Now, for any two events **a** and **b**, $C(\mathbf{a}) < C(\mathbf{b})$ or $C(\mathbf{b}) < C(\mathbf{a})$
  - This is called a **total ordering** of events

Order all these events



Making concurrent updates consistent



- Recall multi-site database replication:
  - San Francisco (**P1**) deposited $100:
  - New York (**P2**) paid 1% interest:

We reached an **inconsistent state**

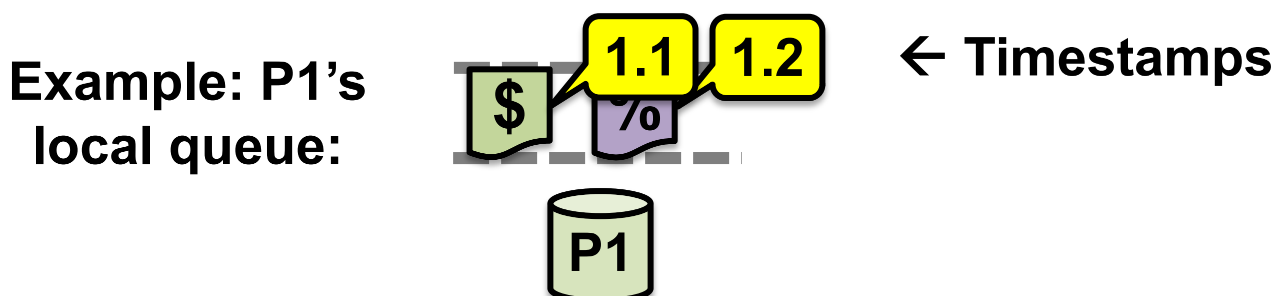
*Could we design a system that uses **Lamport Clock total order** to make multi-site updates consistent?*

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 $\mathbf{C_j.j}$

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



Totally-Ordered Multicast (Almost correct)

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

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

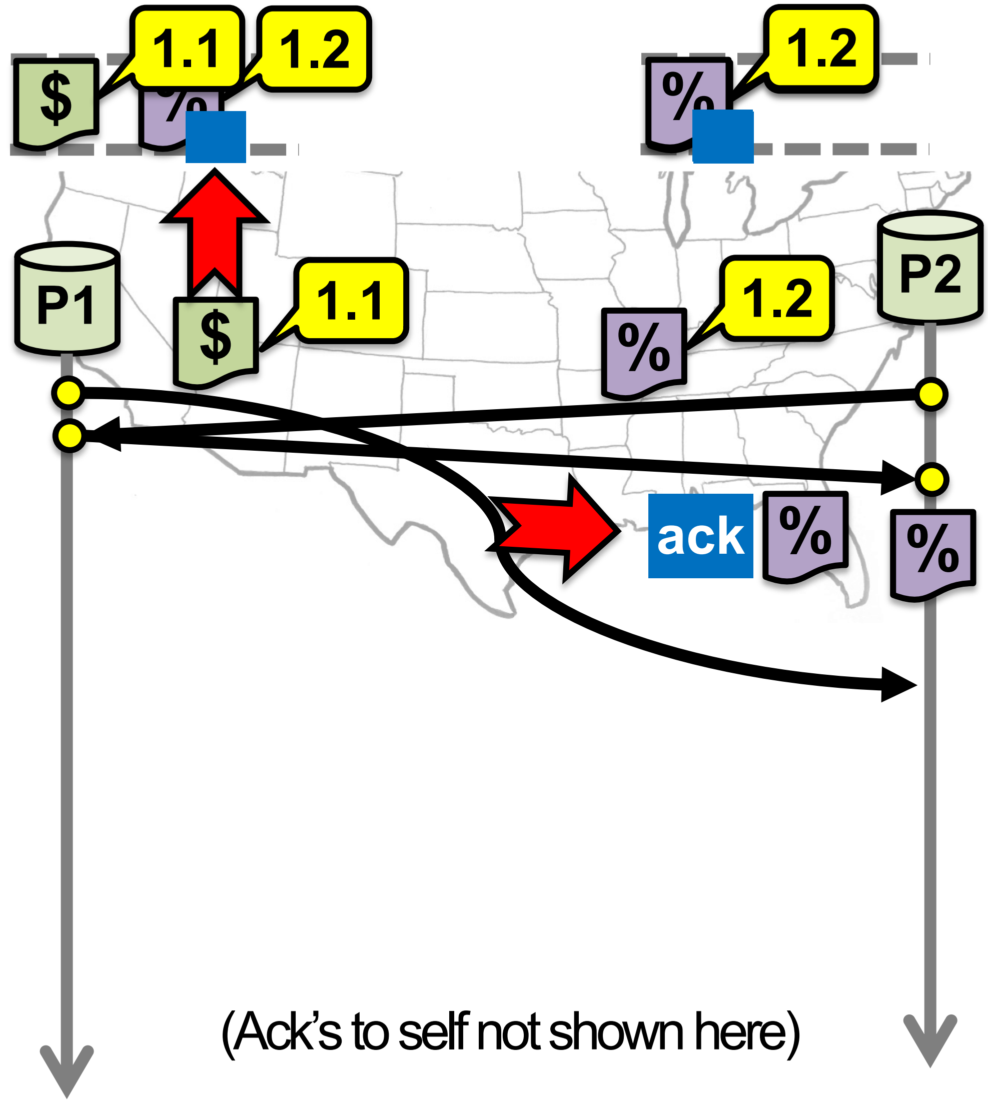
3. On **receiving** an **acknowledgement:**
   – Mark corresponding event ***acknowledged*** in your queue

4. **Remove and process** events **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 %**



(Ack's to self not shown here)

Totally-Ordered Multicast (Correct version)

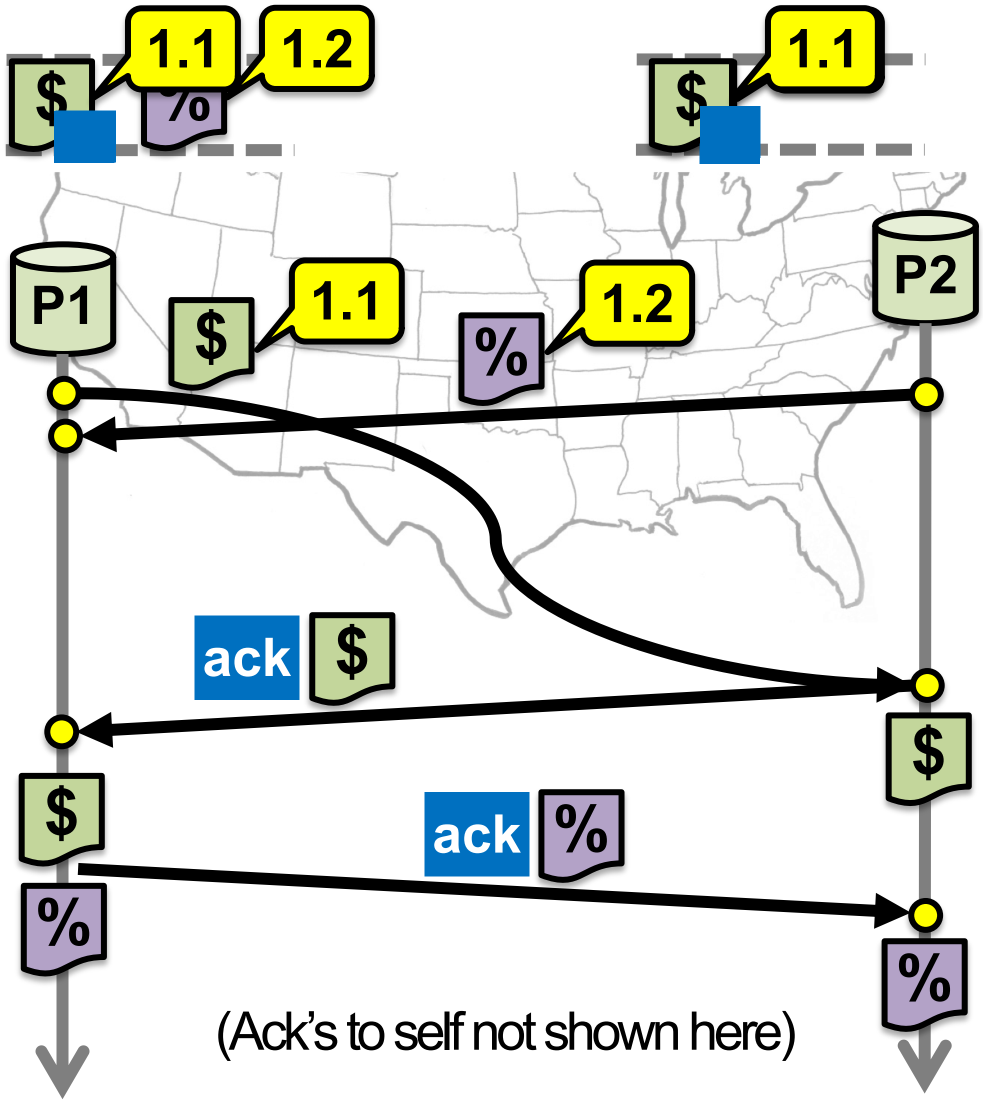
1. On **receiving** an update from **client**, broadcast to others (including yourself)

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)



(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

Next Topic:

Vector Clocks & Distributed Snapshots