# Time and Logical Clocks 1

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of Science and Technology

CS 240: Computing Systems and Concurrency
Lecture 5

Marco Canini

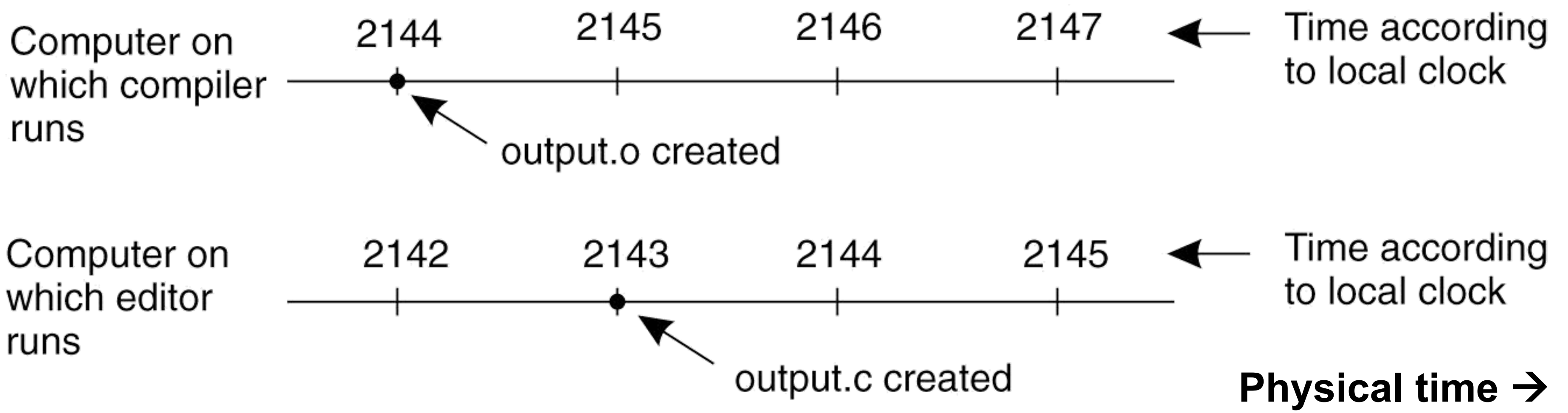
# Today

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

# Today

1. The need for time synchronization

2. **"Wall clock time" synchronization**
   – Cristian's algorithm

3. Logical time: Lamport clocks

# Just use Coordinated Universal Time?

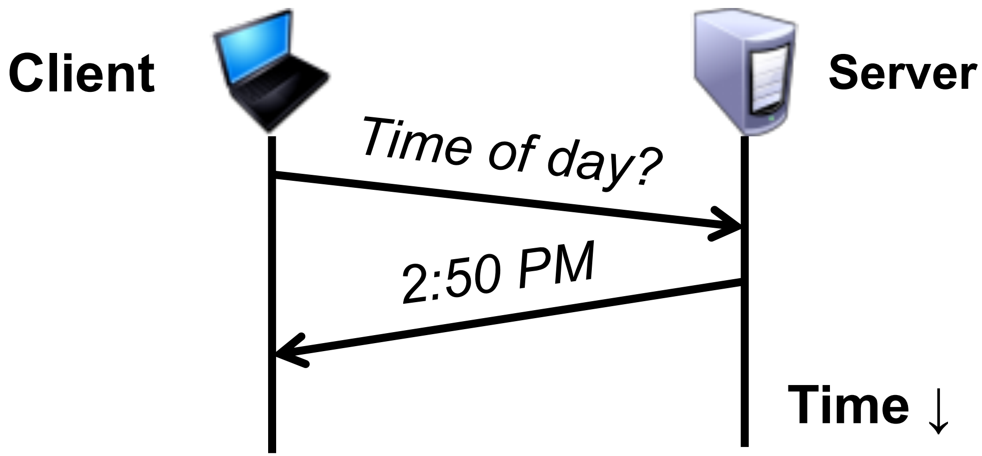
- UTC is broadcast from radio stations on land and satellite (*e.g.*, the Global Positioning System)
  - Computers with receivers can synchronize their clocks with these timing signals

- 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

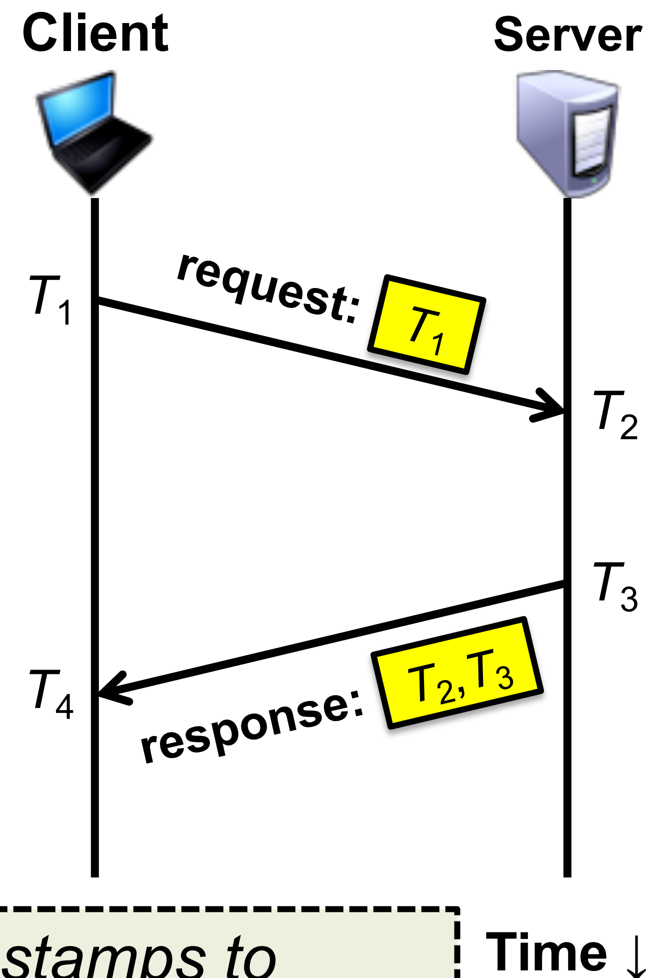
- Suppose a server with an accurate clock (*e.g.*, GPS-receiver)
  - Could simply issue an RPC to obtain the time:




- 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  - **Message delays** will have **outdated** server's answer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?*

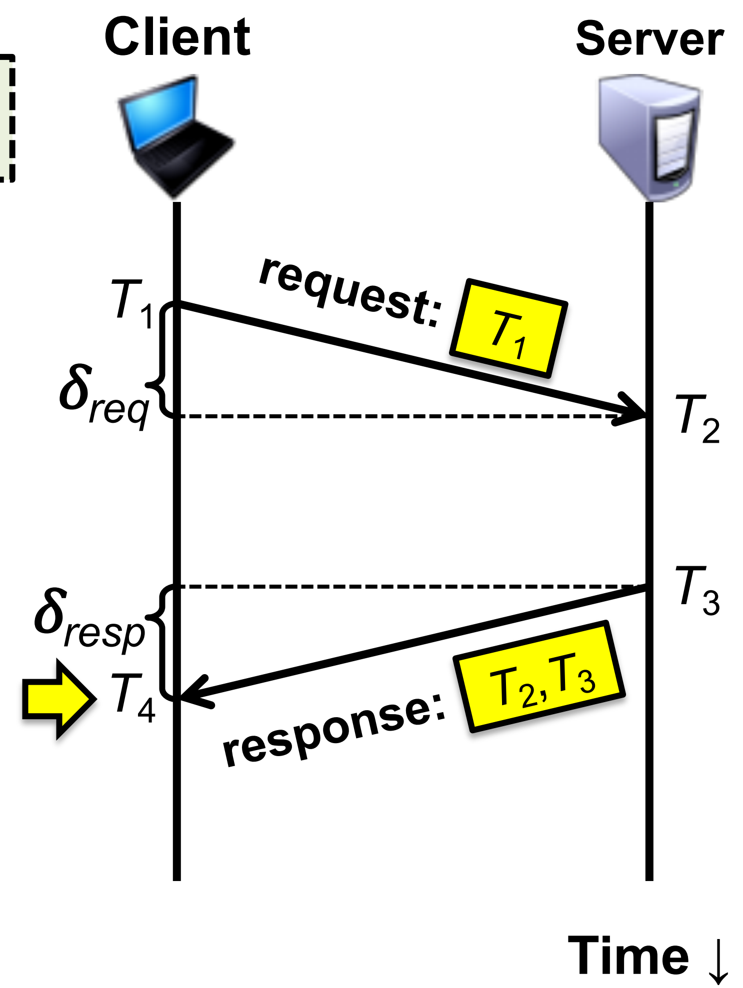
# Cristian's algorithm: Offset sample calculation

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

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

**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 $\mu$s−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

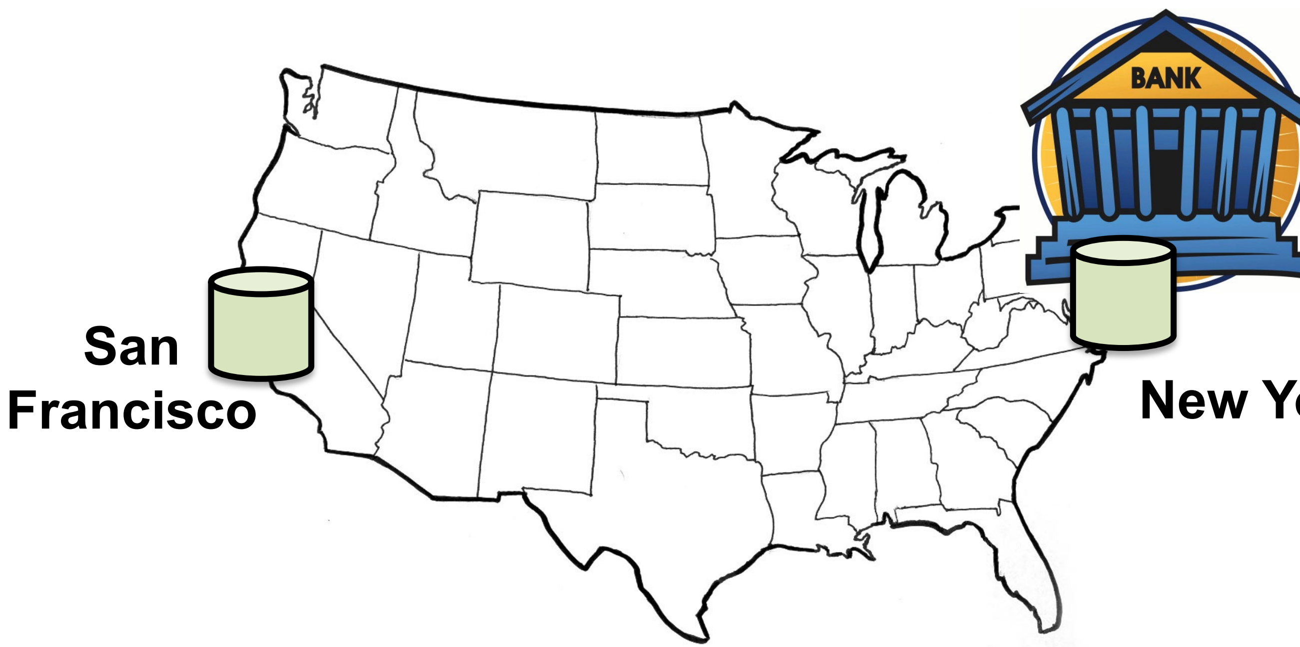
1. The need for time synchronization

2. "Wall clock time" synchronization
   – Cristian's algorithm

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

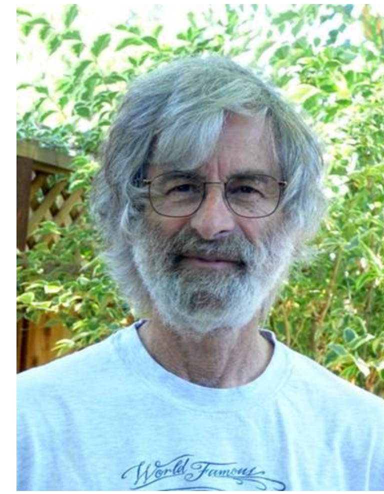
- **Replicate** the database, keep one copy in SF, one in NYC
  - Client sends **query** to the **nearest** copy
  - Client sends **update to both** copies


**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



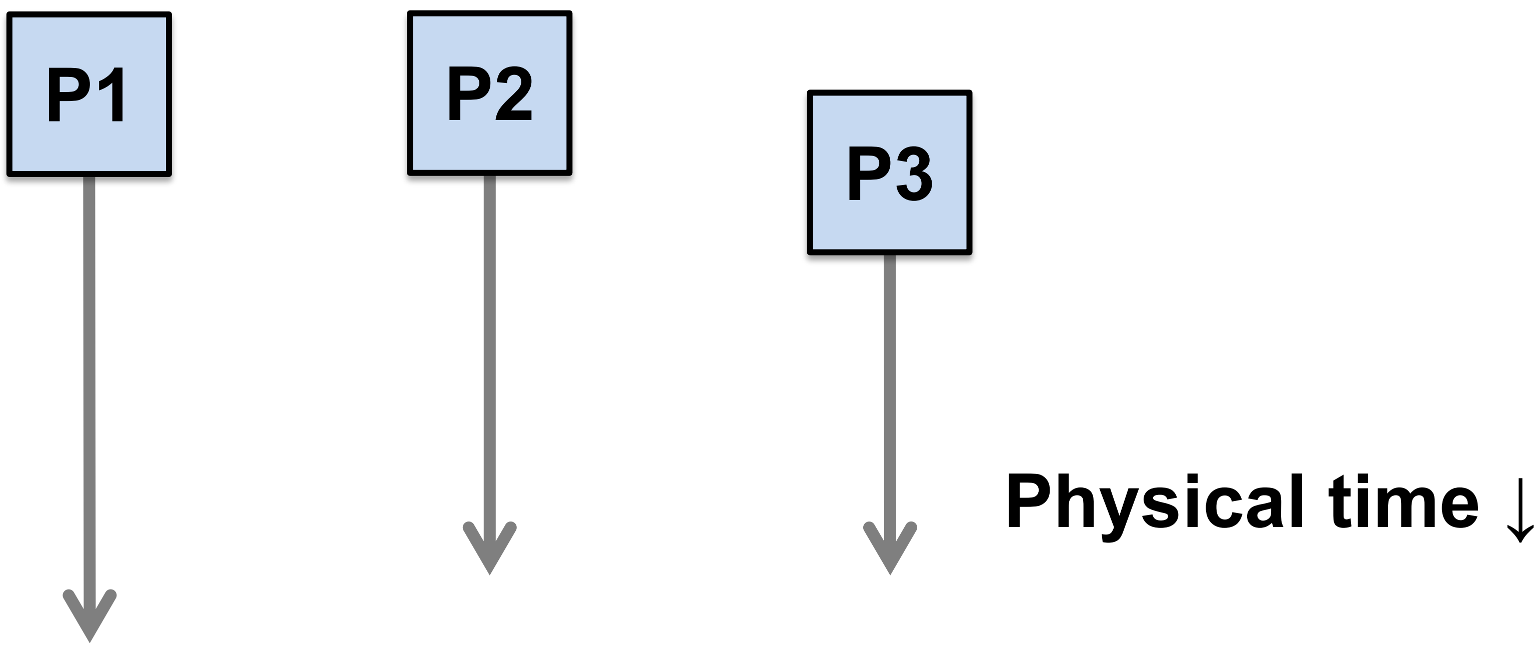

**Idea: Disregard** the precise clock time

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

# Defining "happens-before" (→)

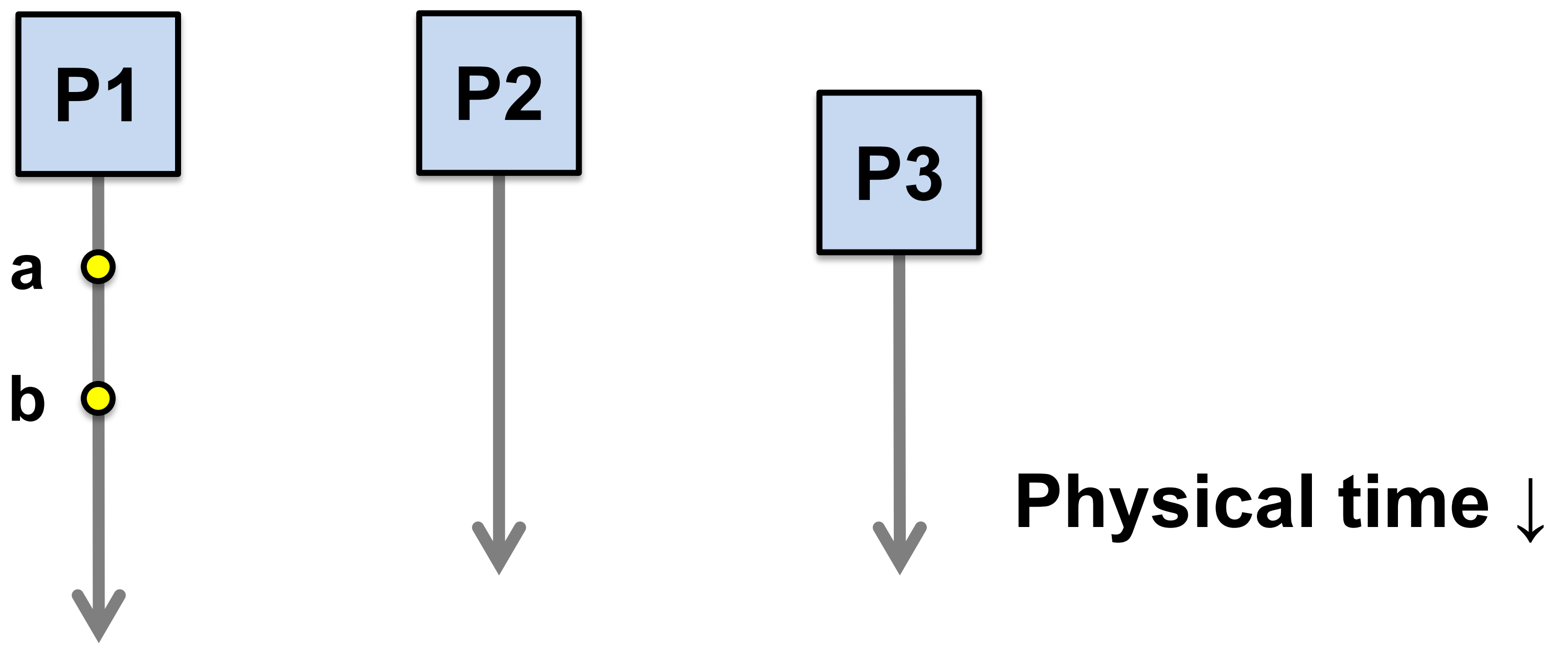
- Consider three processes: **P1**, **P2**, and **P3**

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



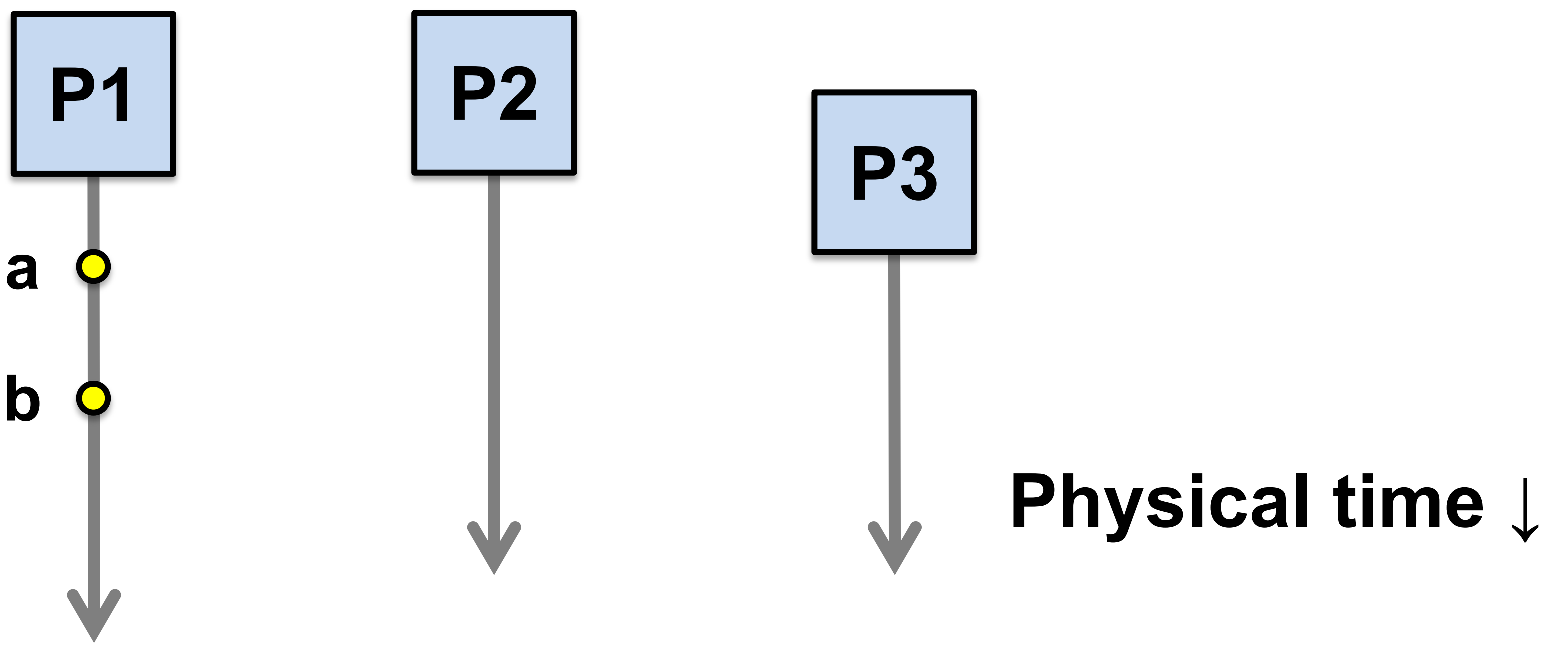
# Defining "happens-before" (→)

1. Can observe event order at a single process



# Defining "happens-before" (→)

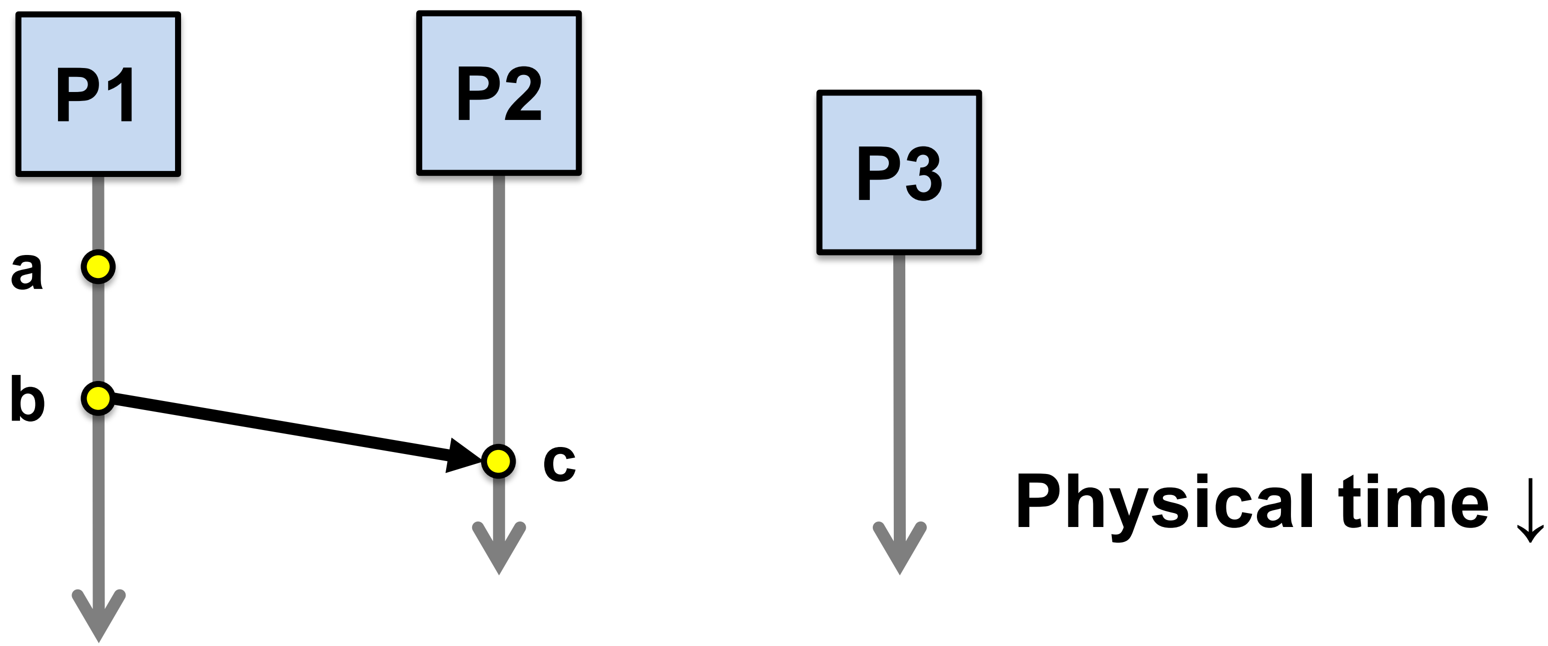
1. If **same process** and **a** occurs before **b**, then **a → b**



# Defining "happens-before" (→)

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

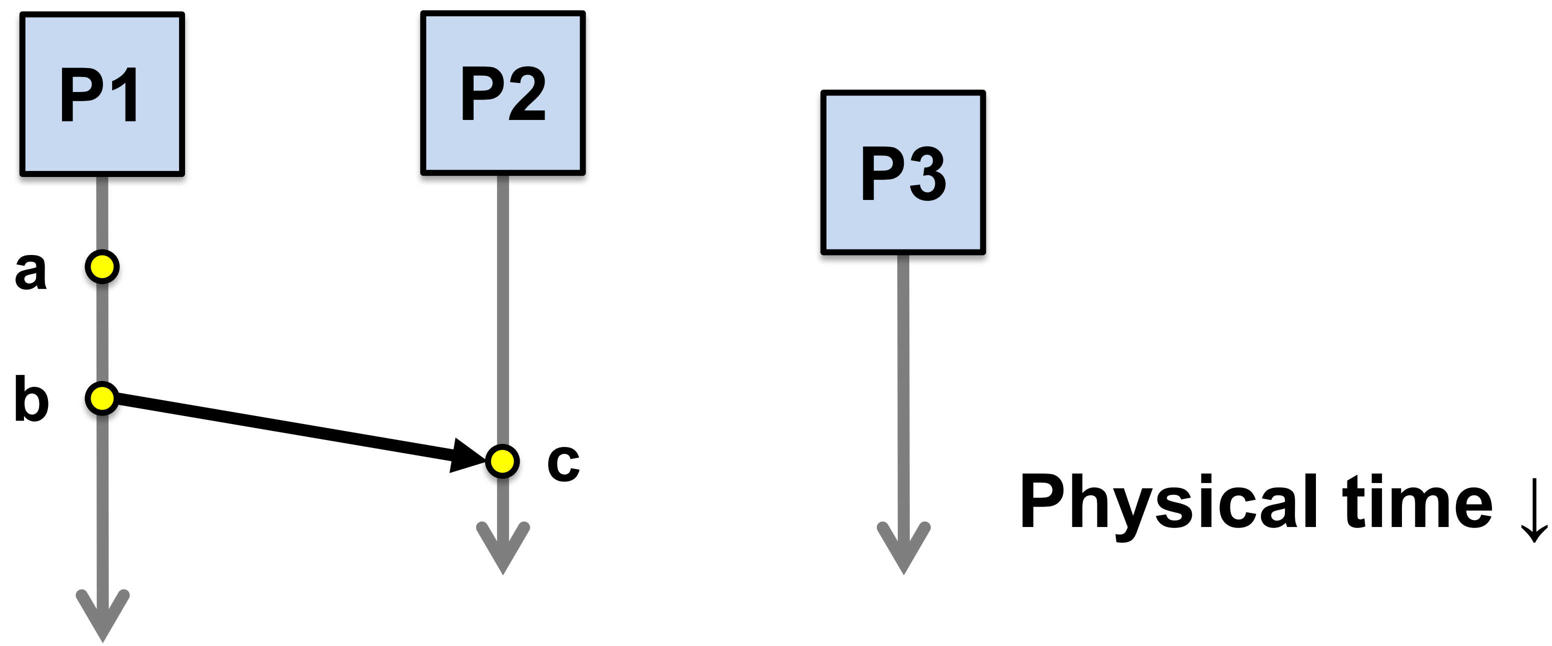
2. Can observe ordering when processes communicate



# 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**

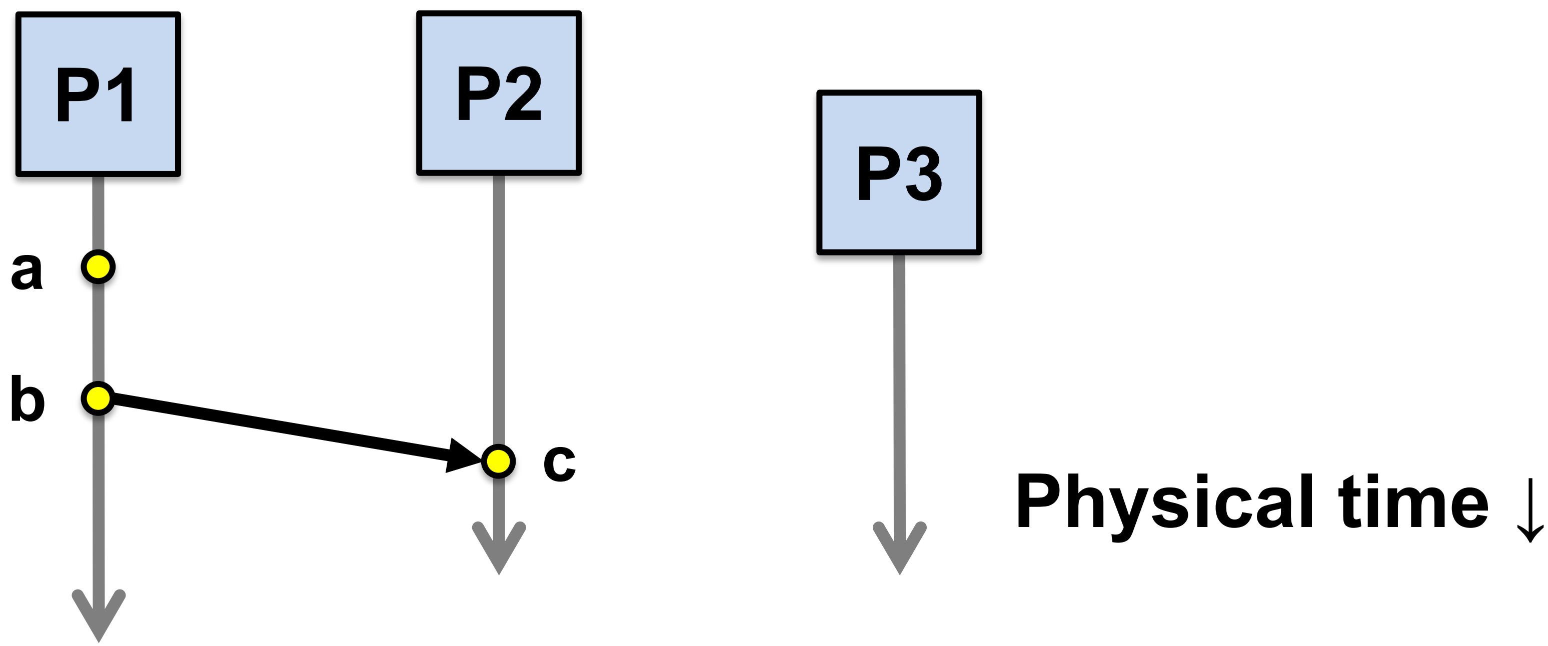


# Defining "happens-before" (→)

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

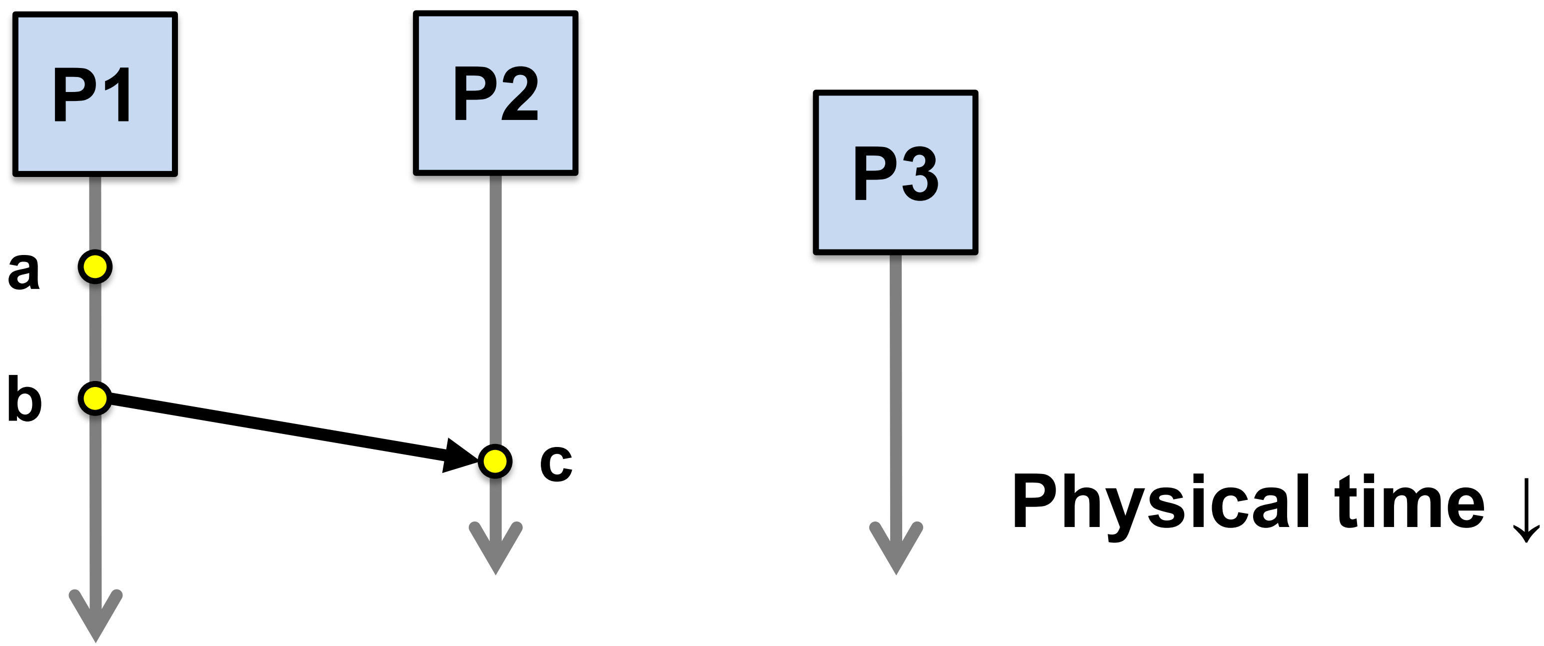
2. If **c** is a message receipt of **b**, then **b** → **c**

3. Can observe ordering transitively



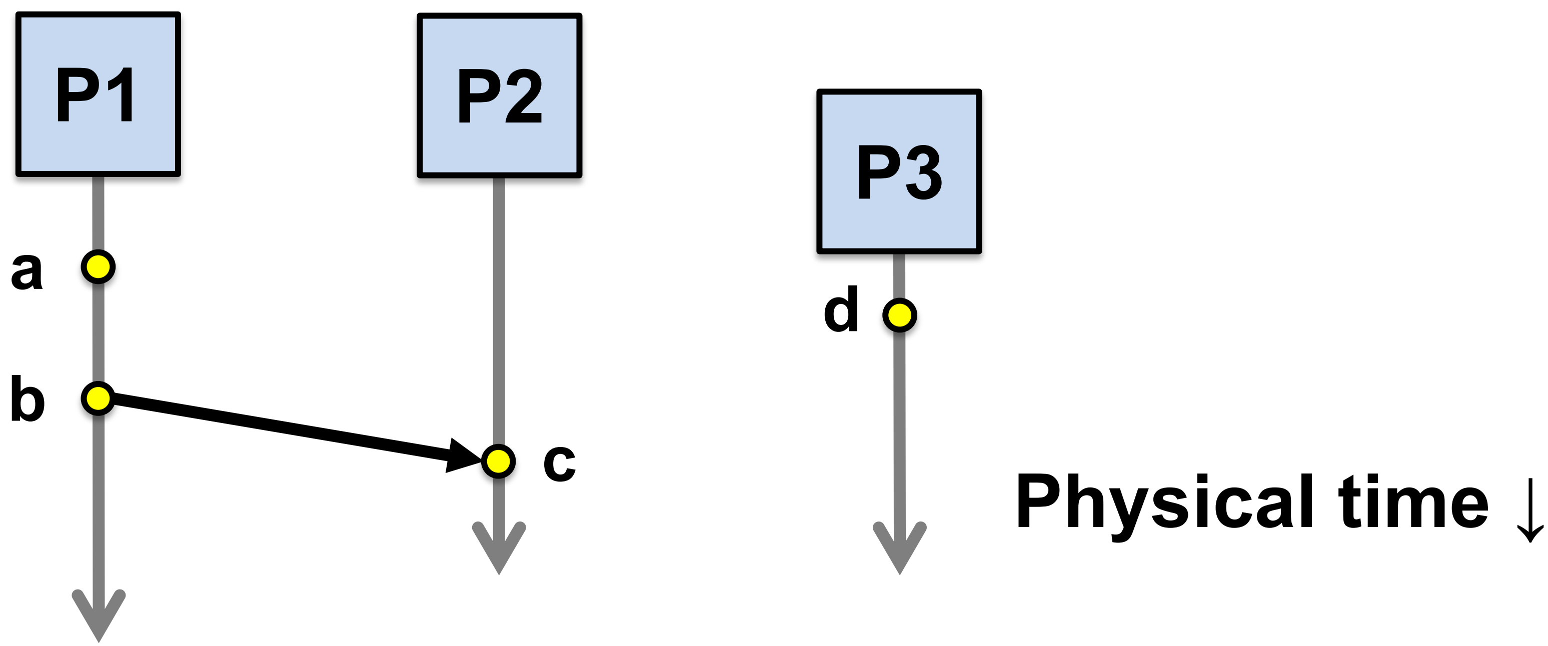
# Defining "happens-before"

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**

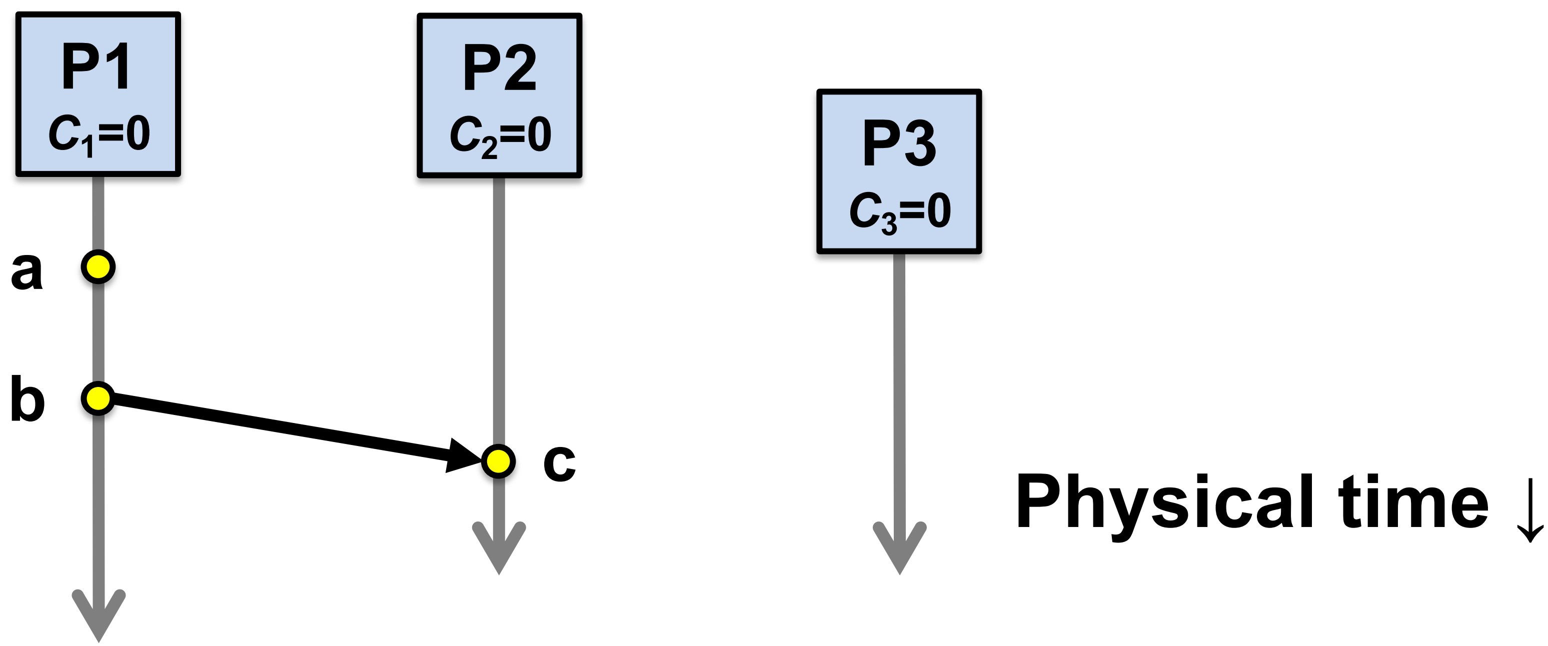
**Plan:** Tag events with clock times; use **clock times** to make distributed system correct

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

# The Lamport Clock algorithm

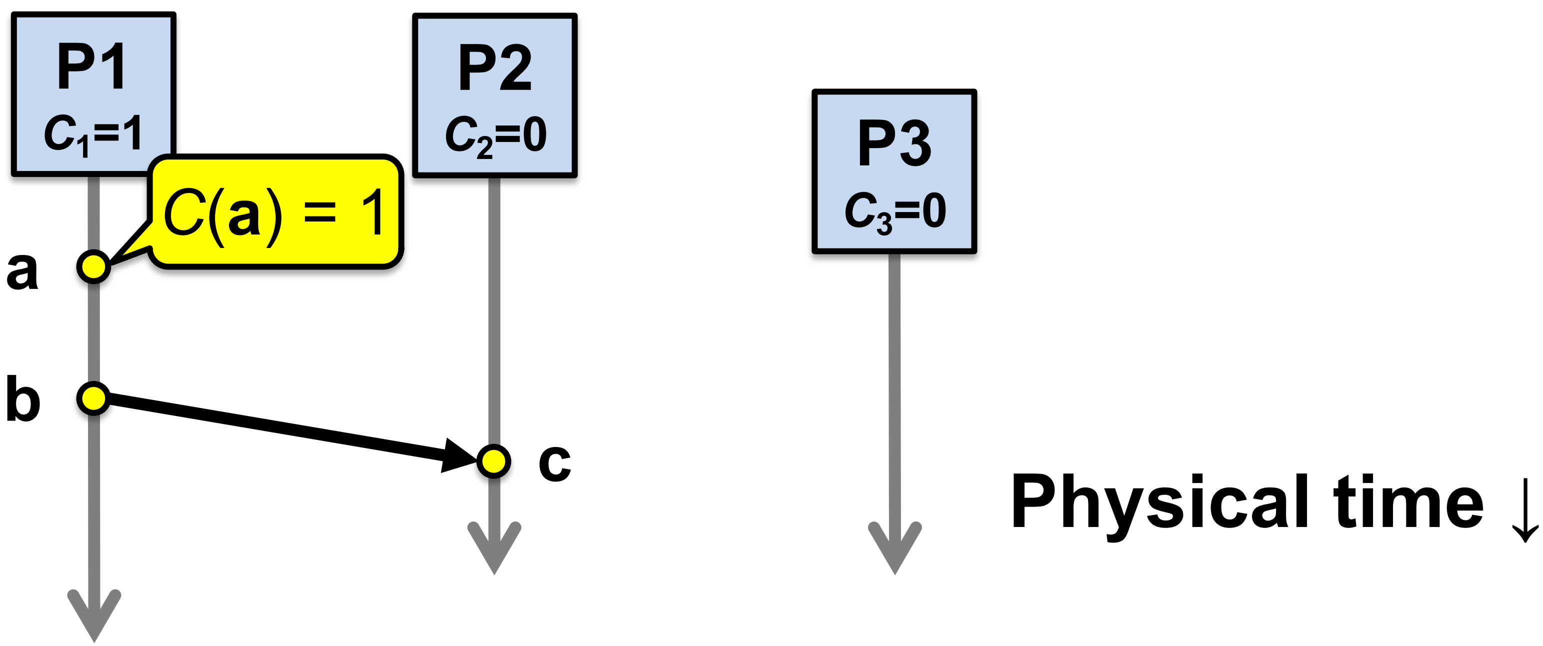
- Each process $\mathbf{P}_i$ maintains a local clock $C_i$

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



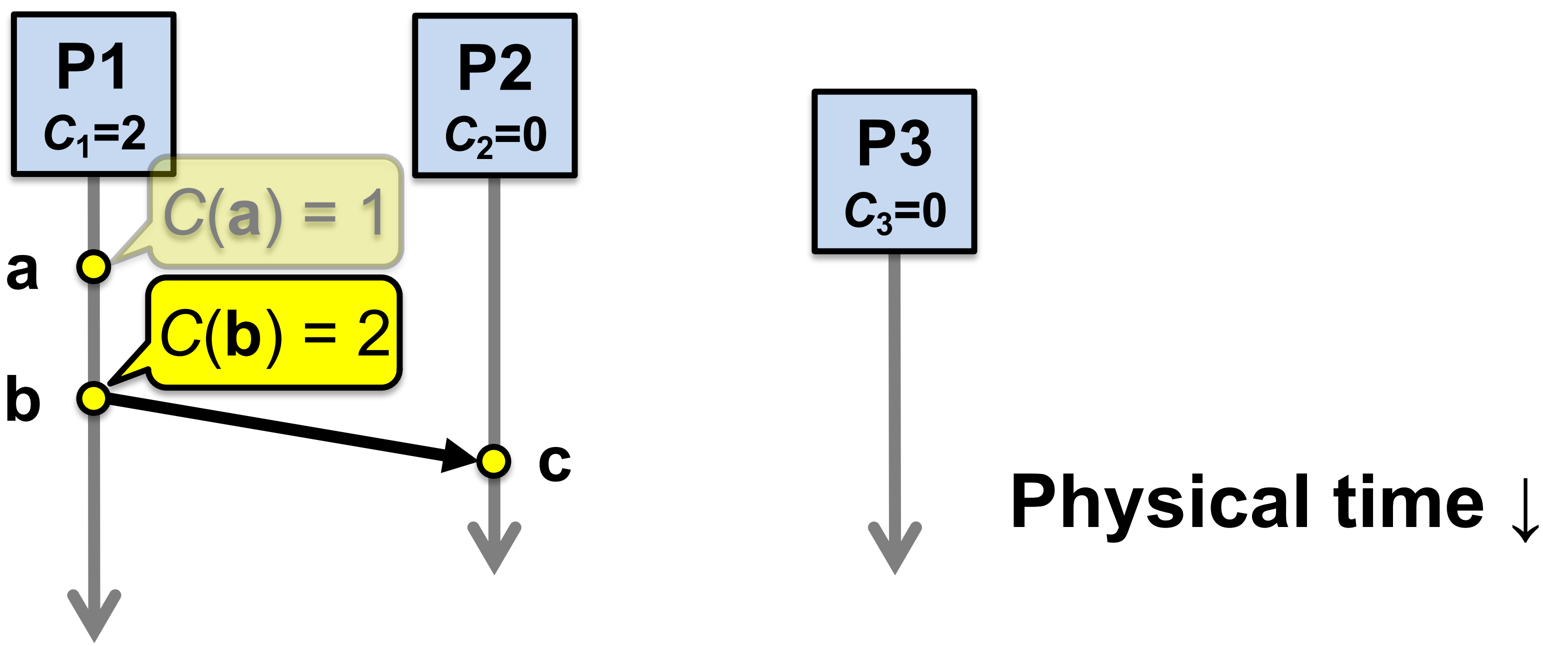
# The Lamport Clock algorithm

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

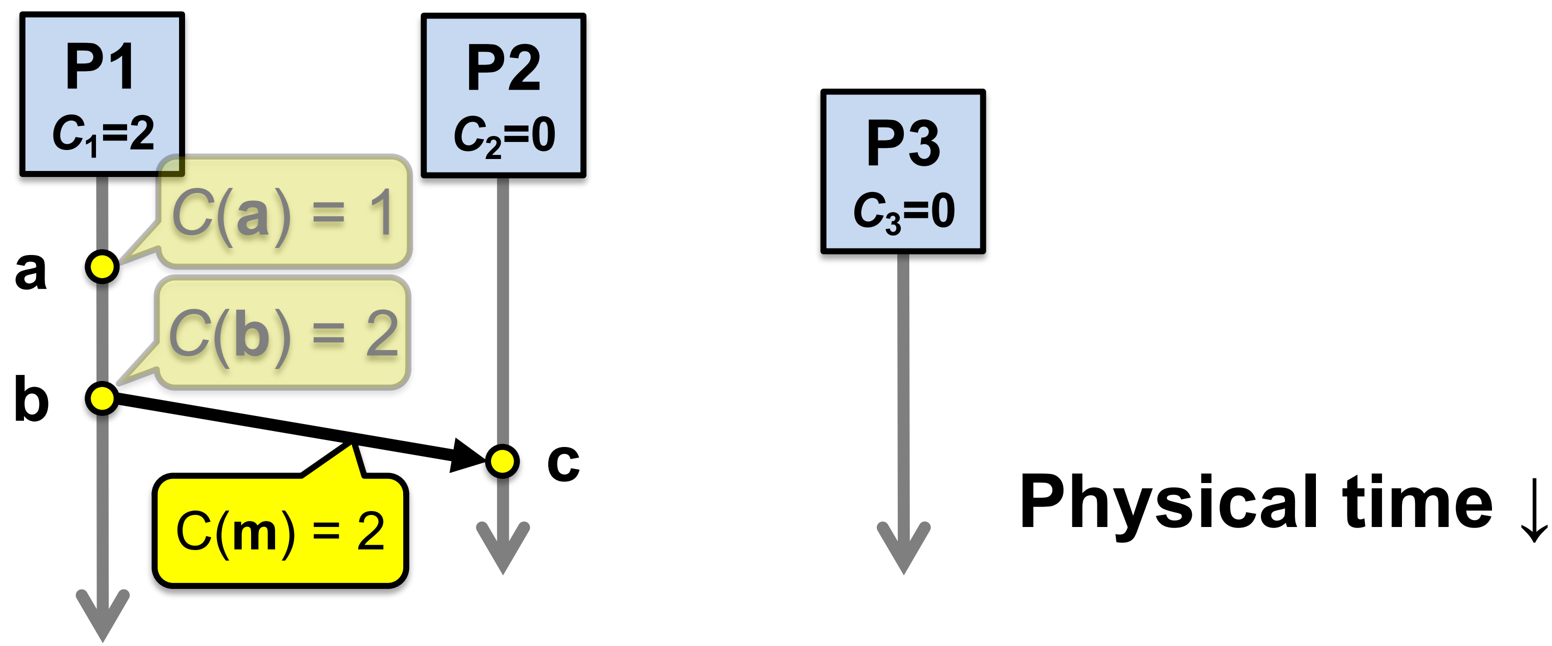
1. Before executing an event **b**, $C_i \leftarrow C_i + 1$:
   - Set event time $C(\mathbf{b}) \leftarrow C_i$



# The Lamport Clock algorithm

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

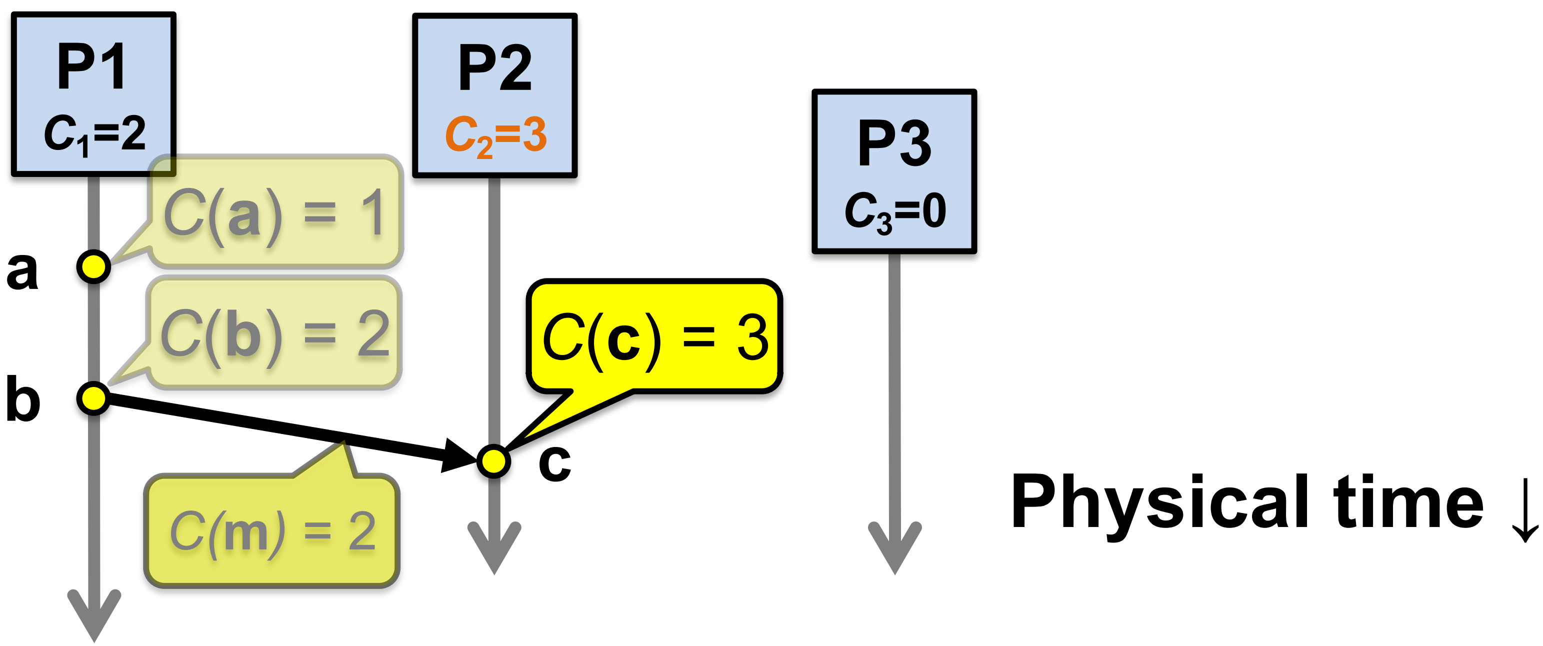
2. Send the local clock in the message **m**



# The Lamport Clock algorithm

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

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



# Lamport Timestamps: Ordering all events

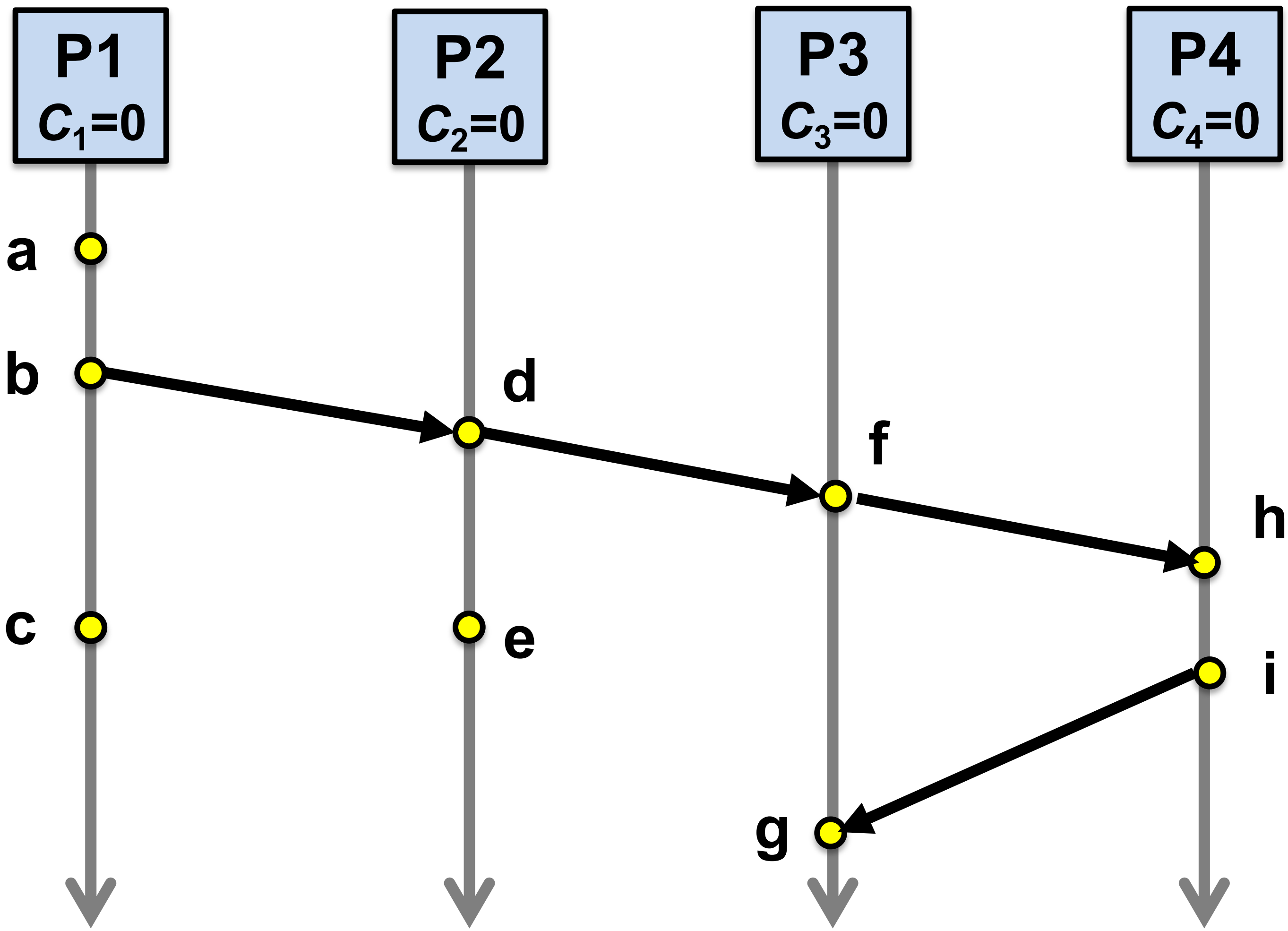
- **Break ties** by **appending the process number** to each event:

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

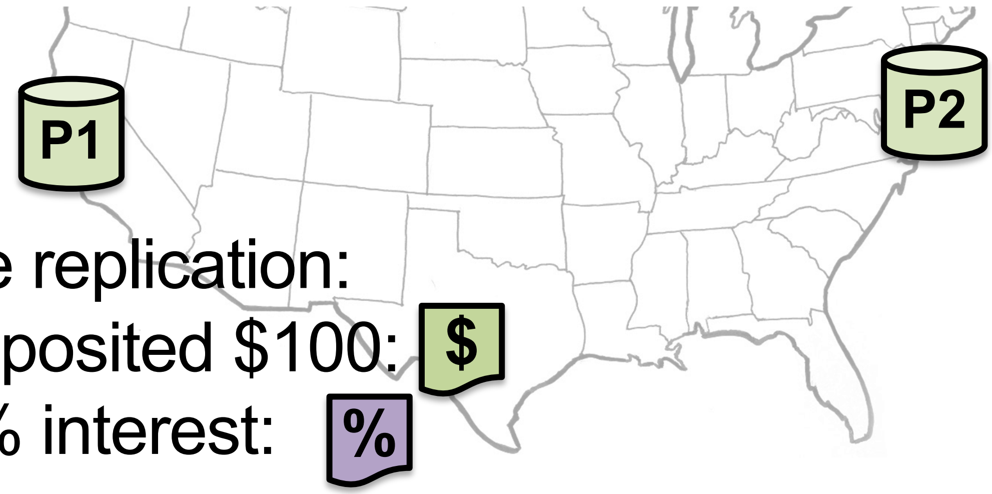
  2. $C(\mathbf{a}).i < C(\mathbf{b}).j$ when:
     - $C(\mathbf{a}) < C(\mathbf{b})$, **or** $C(\mathbf{a}) = C(\mathbf{b})$ and $i < j$

- Now, for any two events **a** and **b**, C(**a**) < C(**b**) or C(**b**) < C(**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?*

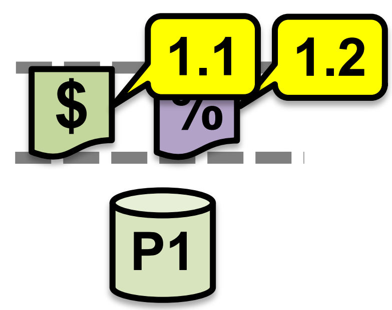
# Totally-Ordered Multicast

**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

**Example: P1's local queue:**




← **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)

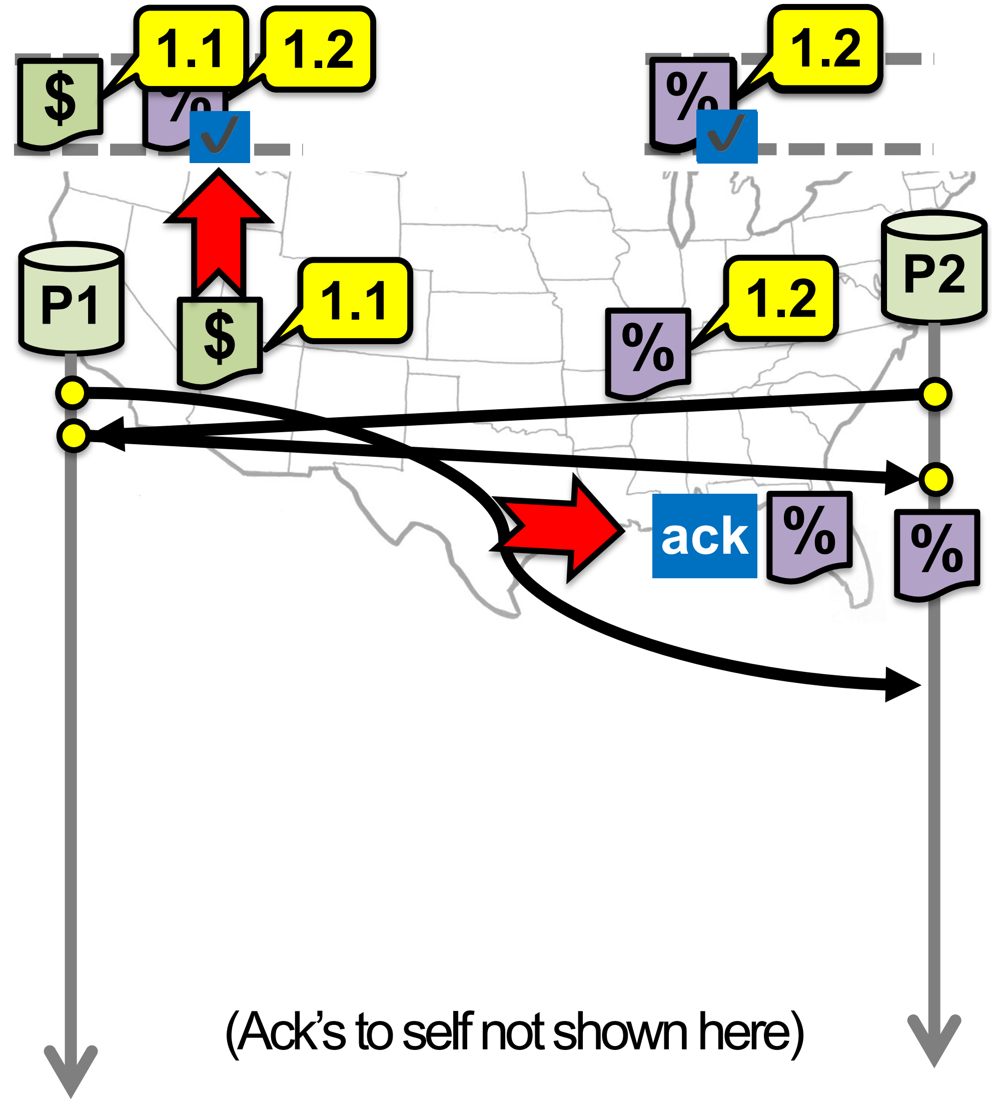
3. On **receiving** an **acknowledgement:**
   – Mark corresponding event ***acknowledged*** in your queue

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 %**



# Totally-Ordered Multicast (Correct version)

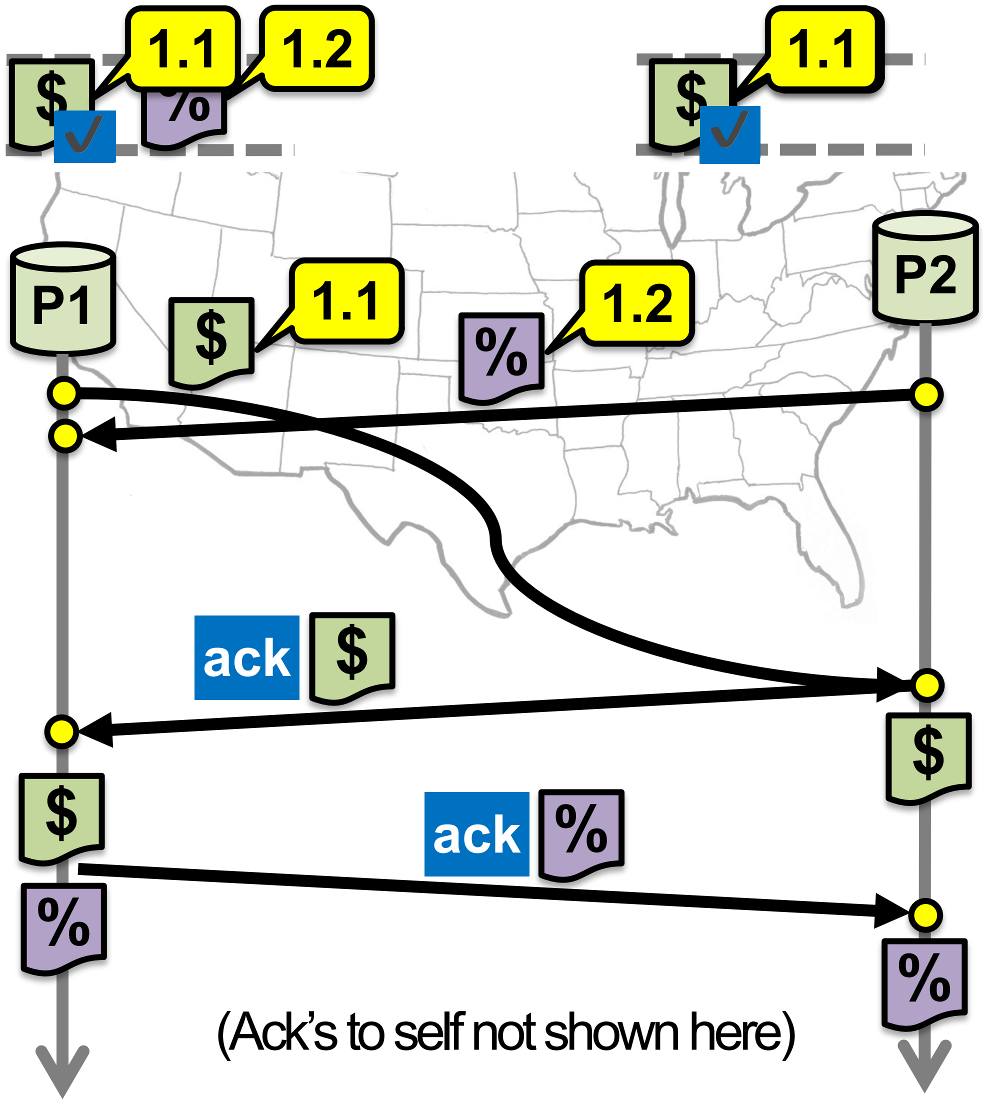
1. On **receiving** an update from **client**, broadcast to others (including yourself)

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)



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

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