Time & Clocks, Primary-Backup

CS 675: Distributed Systems (Spring 2020)

Lecture 4

Yue Cheng

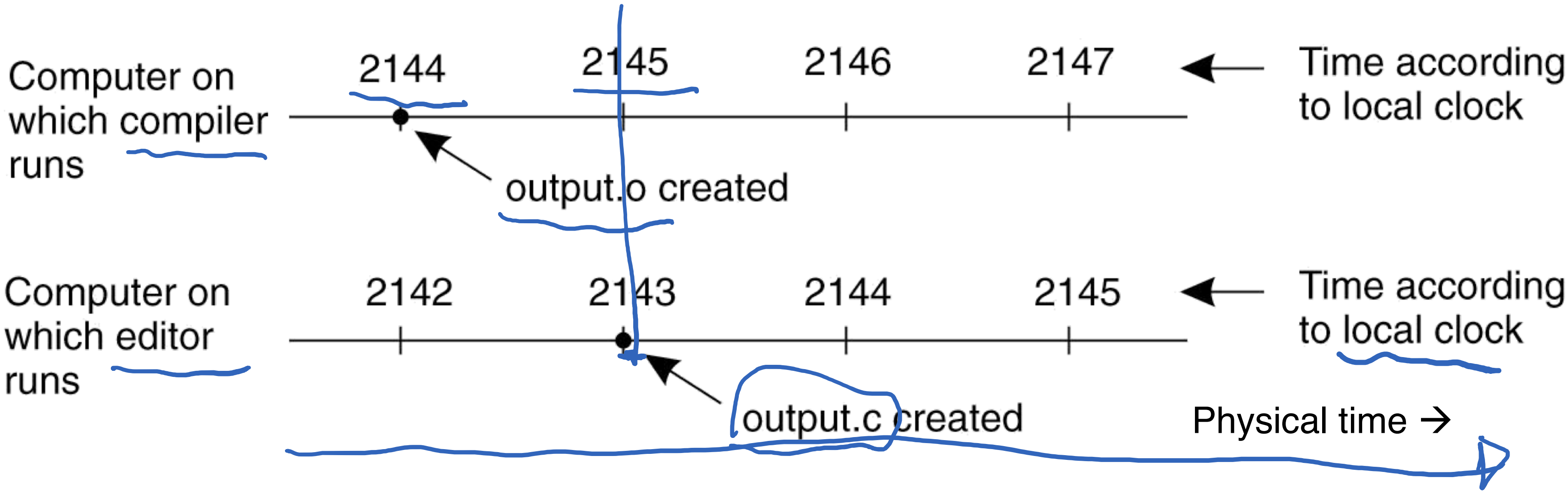
Some material taken/derived from:

- Princeton COS-418 materials created by Michael Freedman and Wyatt Lloyd.
- MIT 6.824 by Robert Morris, Frans Kaashoek, and Nickolai Zeldovich.
- Utah CS6450 by Ryan Stutsman.

Today's outline

1. Time and clocks
    - **The need for time synchronization**
    - "Wall clock time" synchronization
    - Logical Time: Lamport Clocks
    - Vector clocks
2. Primary-Back (P-B)

A distributed edit-compile workflow



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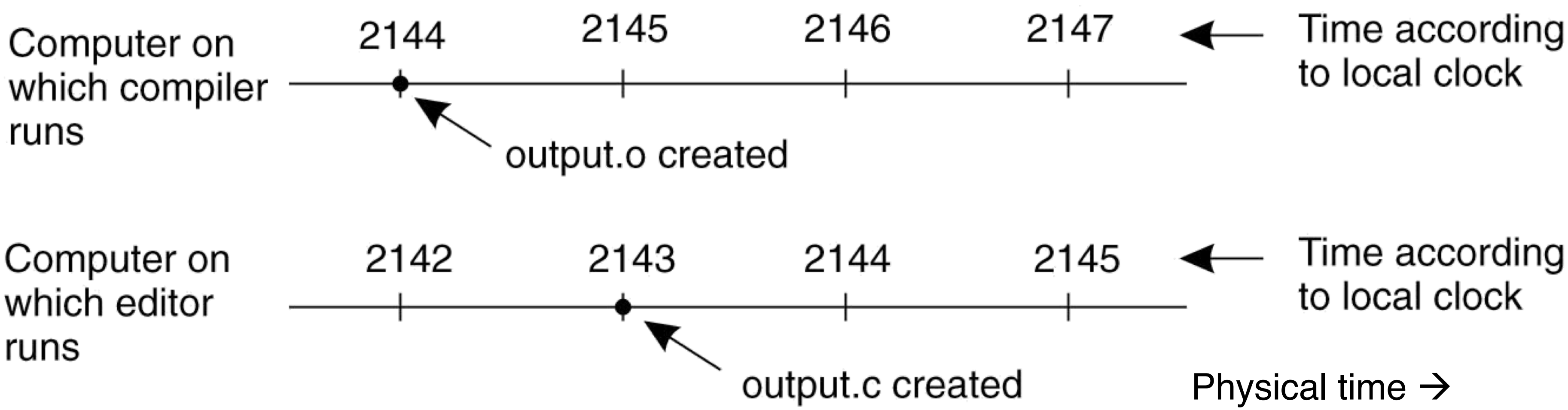

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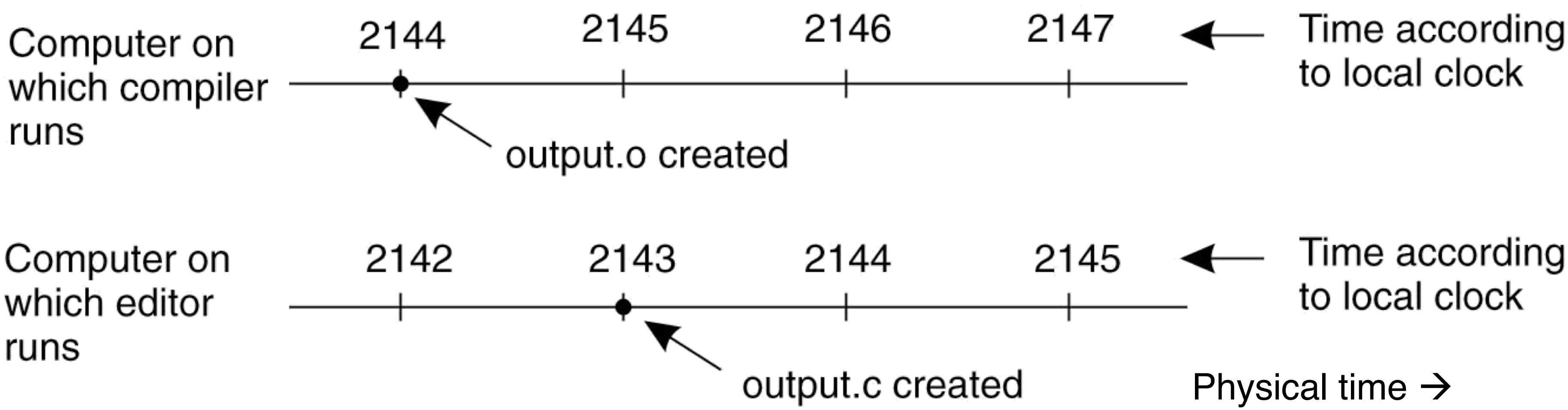

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Lack of time synchronization result – a possible object file mismatch

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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1. Time and clocks
    - The need for time synchronization
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        - Cristian's algorithm, NTP
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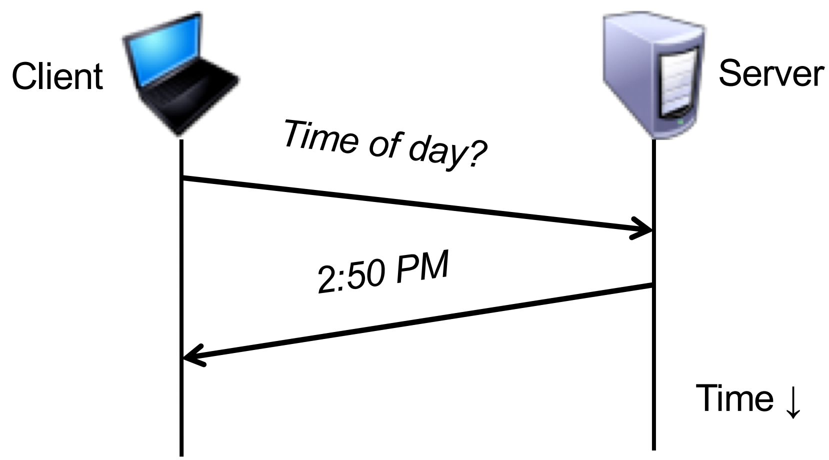
Just use Coordinated Universal Time?

- 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:



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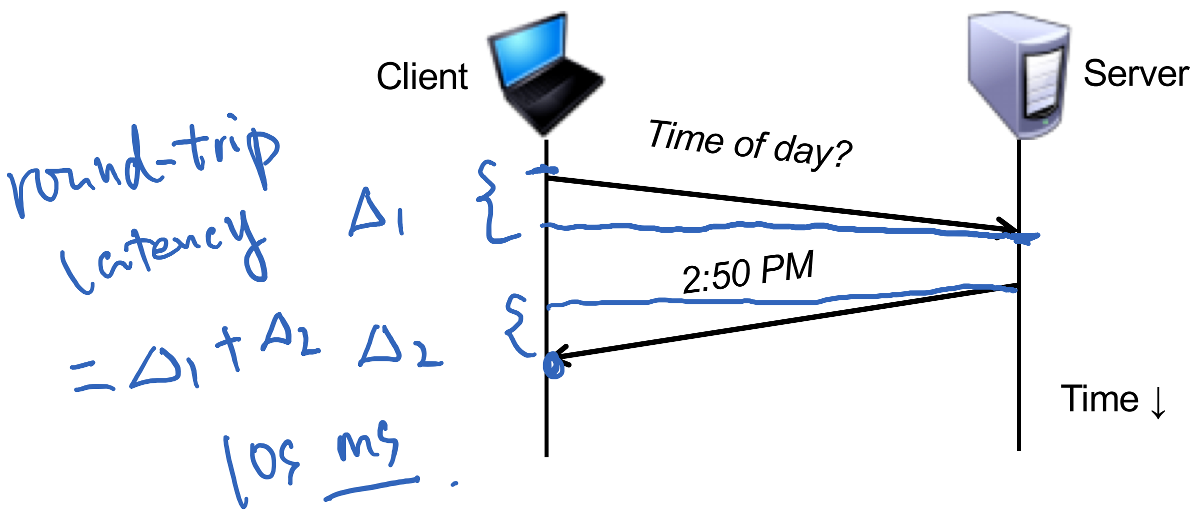
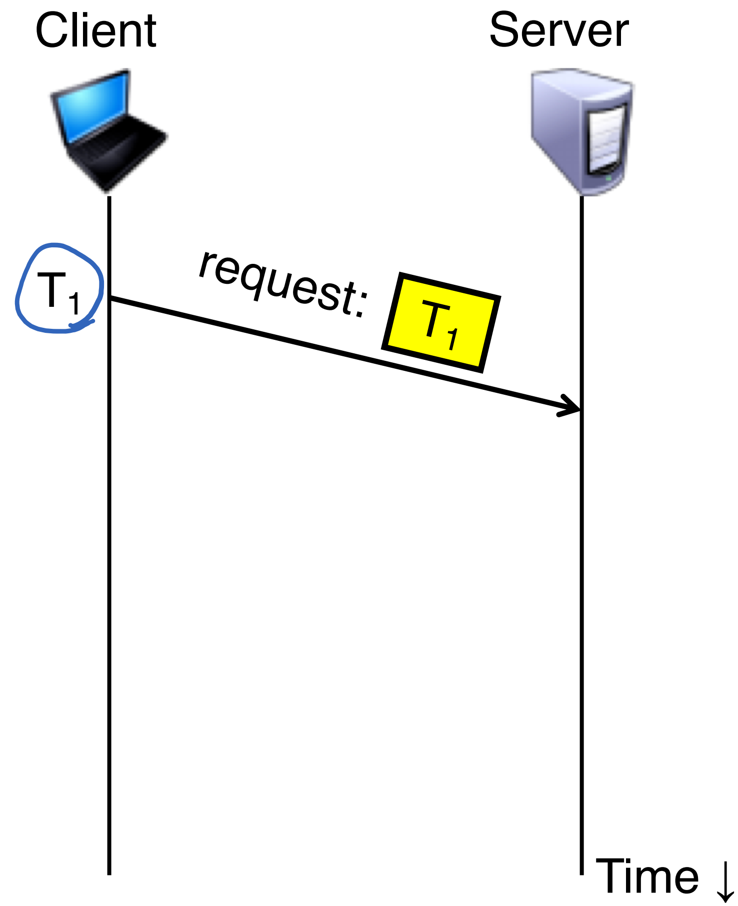


- But this doesn't account for network latency
  - Message delays will have outdated server's answer

Cristian's algorithm: Outline

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



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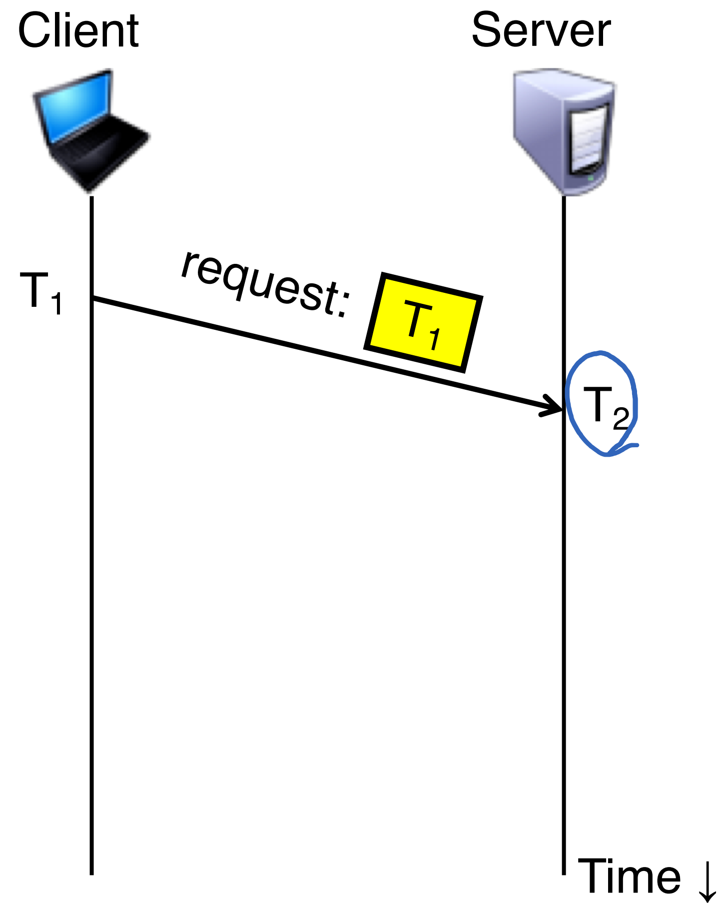

Cristian's algorithm: Outline

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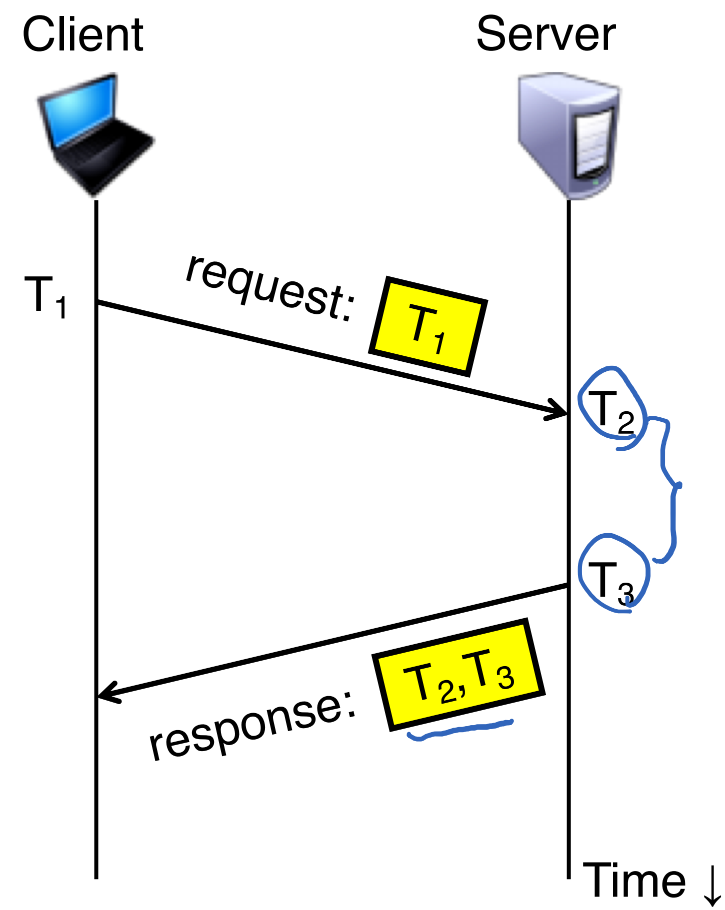
3. Server sends a response packet with its local clock T_3 and T_2



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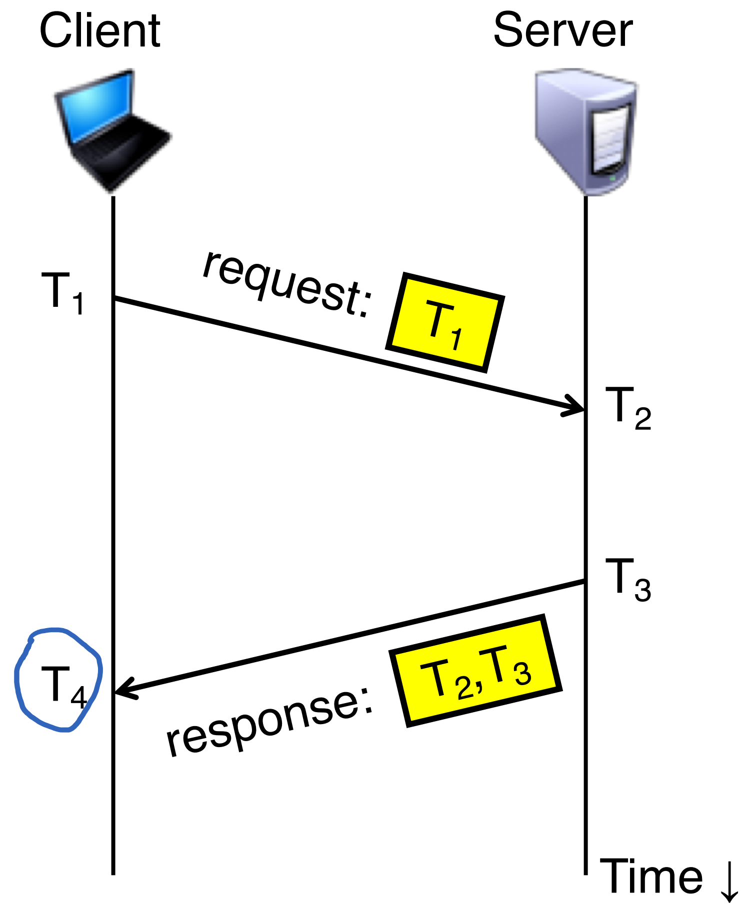

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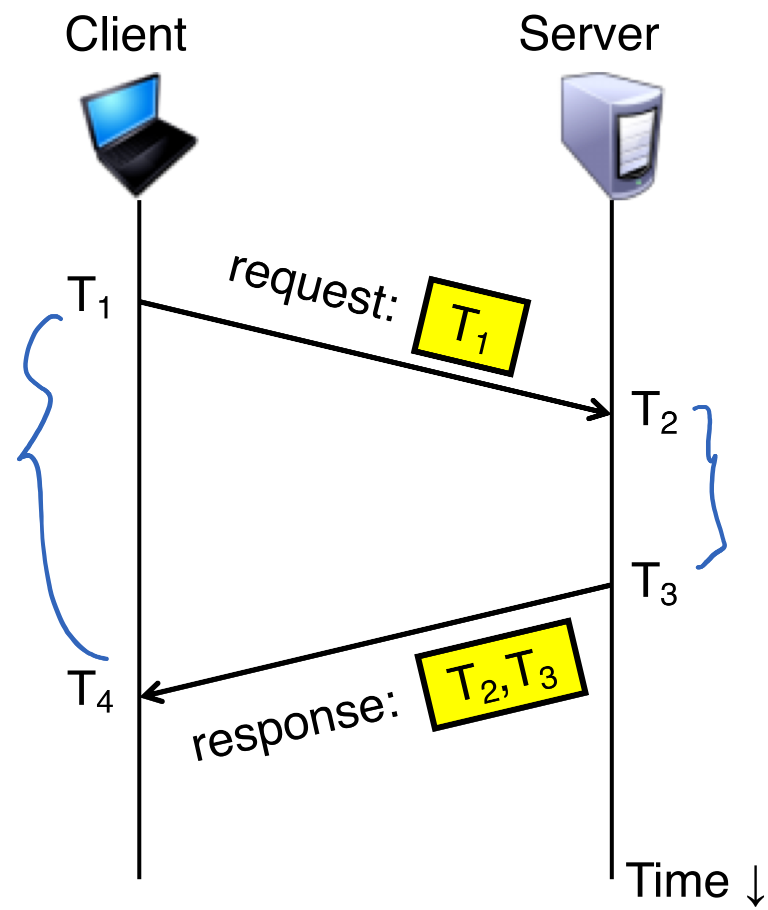


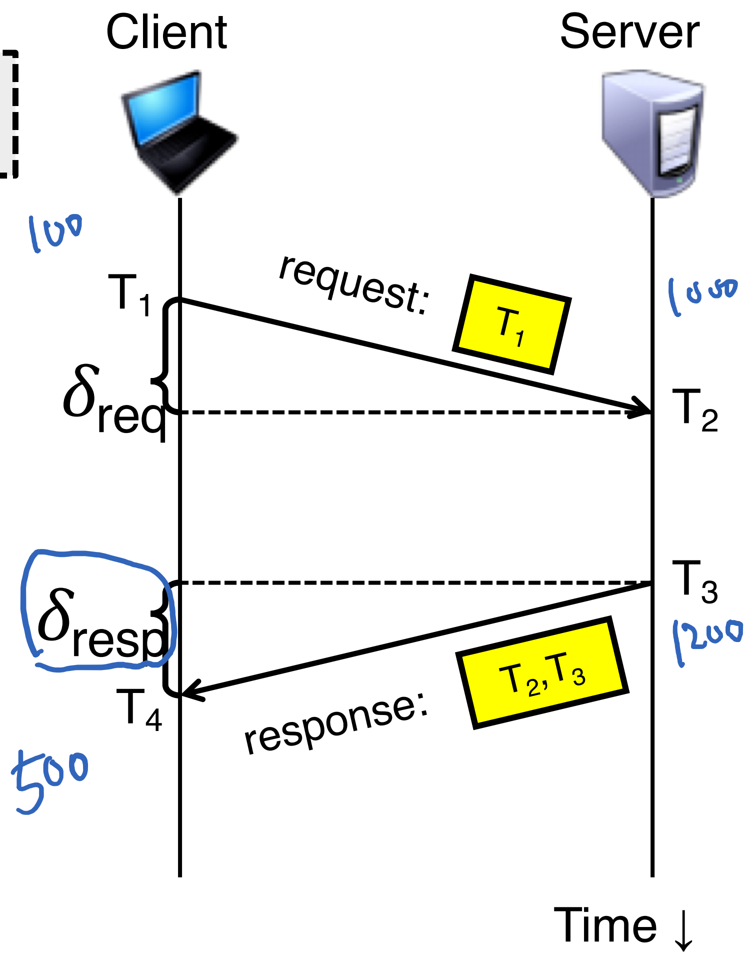
How can the client use these timestamps to synchronize its local clock to the server's local clock?

Cristian's algorithm: Offset sample calculation

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

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

offset client. offset server.



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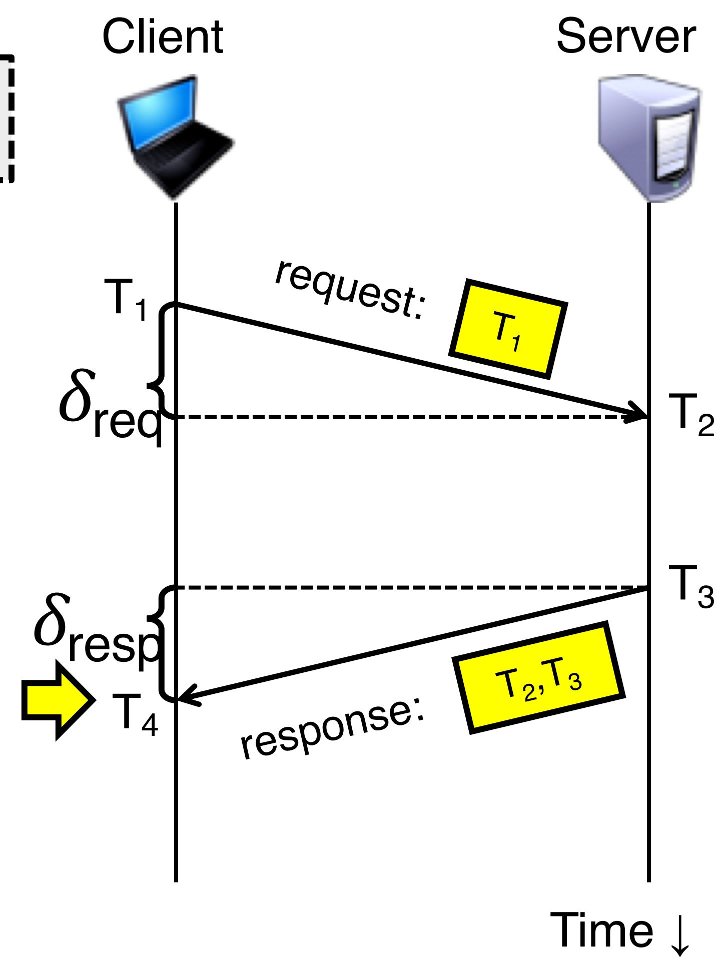

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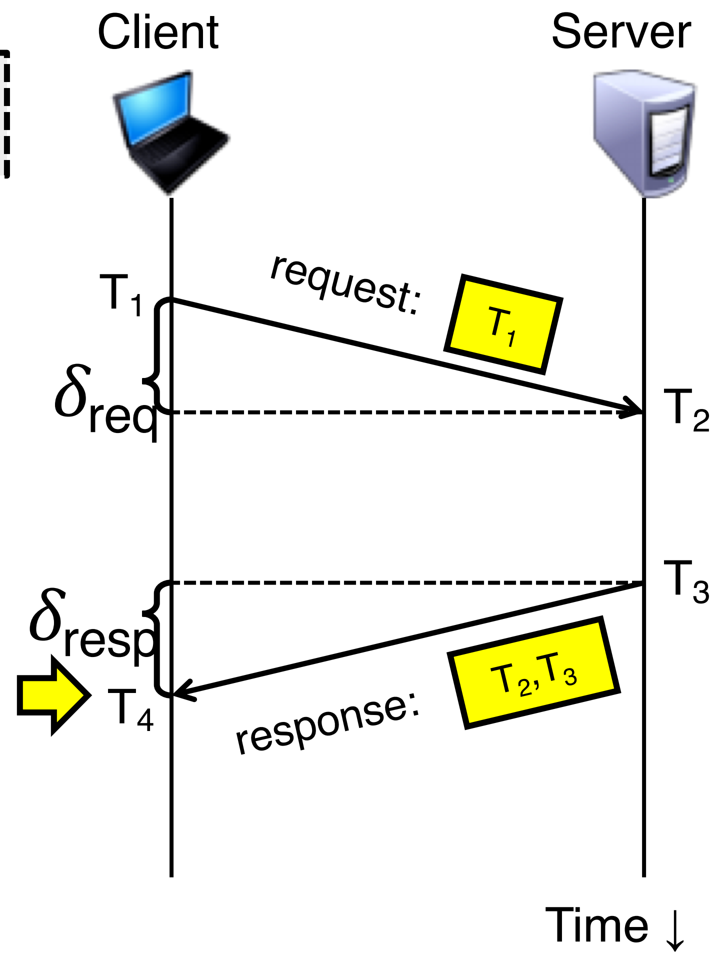

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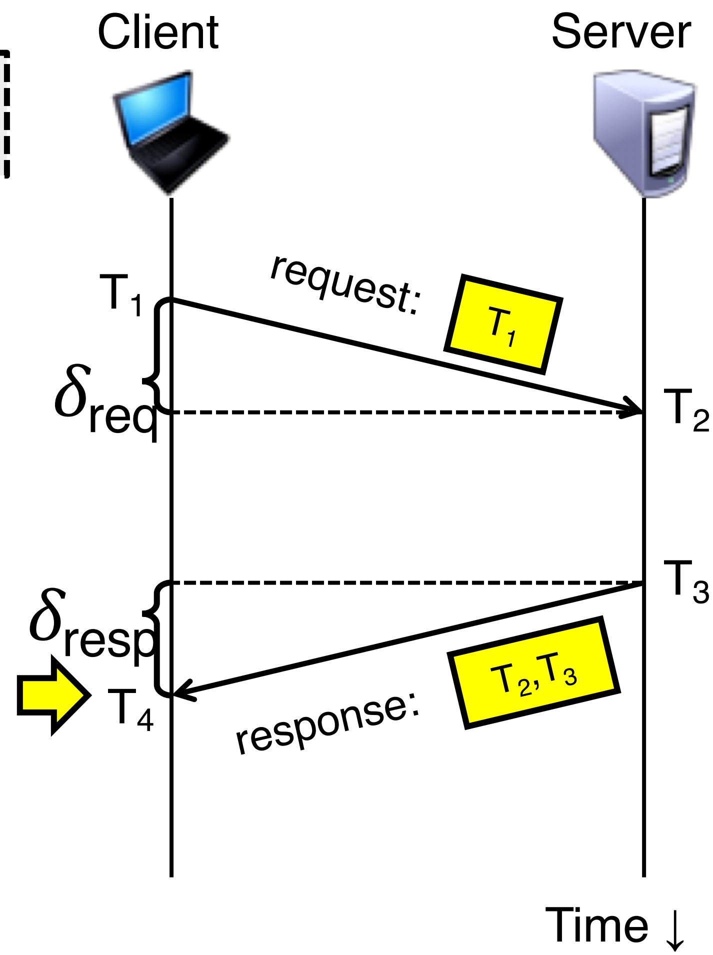

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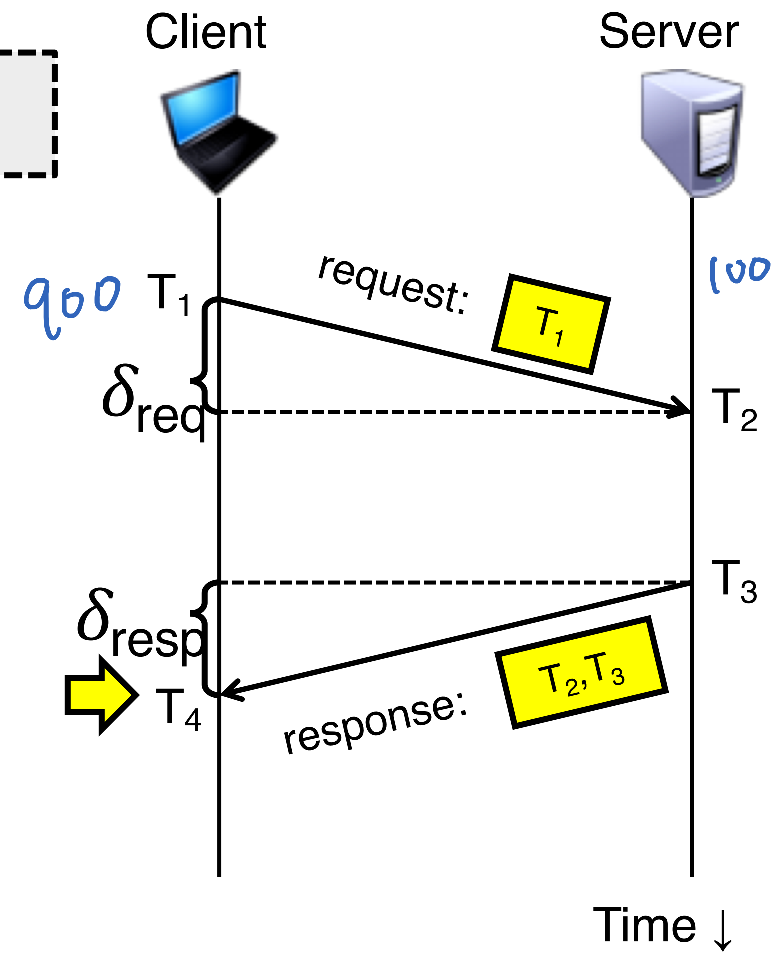
Client sets clock ← $T_3 + ½\delta$



Clock synchronization: Takeaway points

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

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

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- Clocks on different systems will always behave differently
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- 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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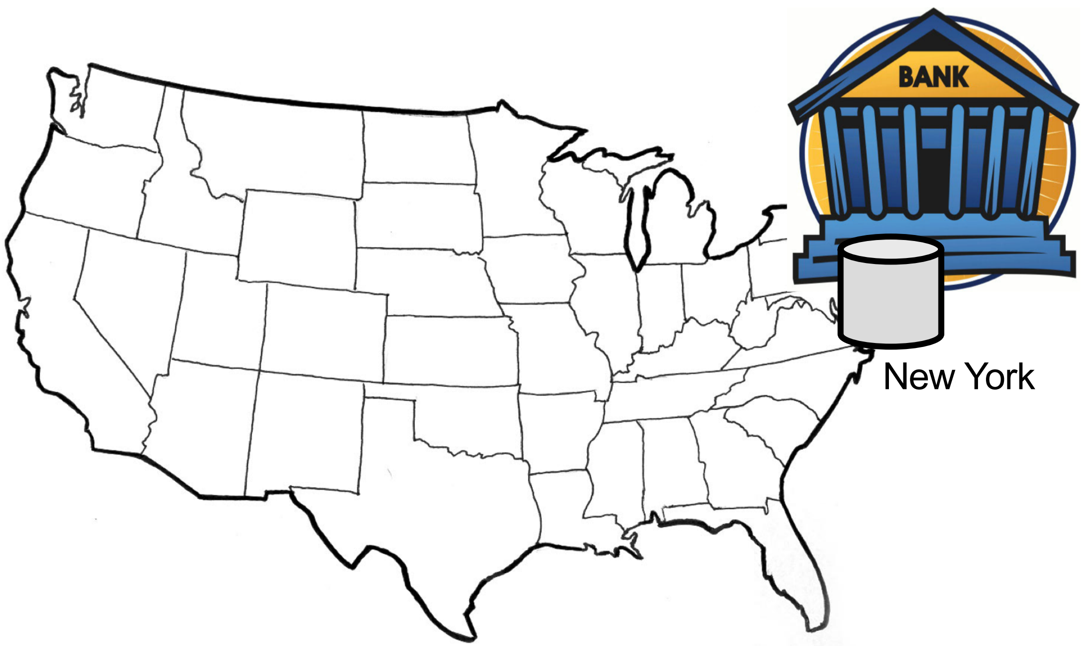
Motivation: Multi-site database replication

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



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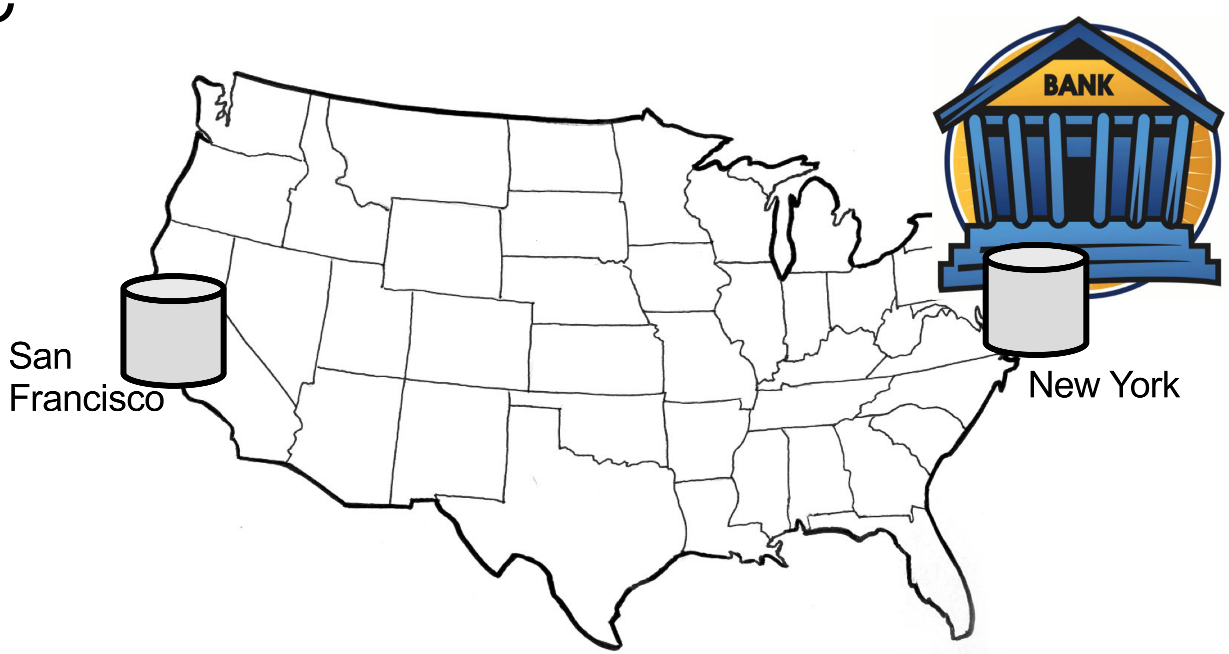
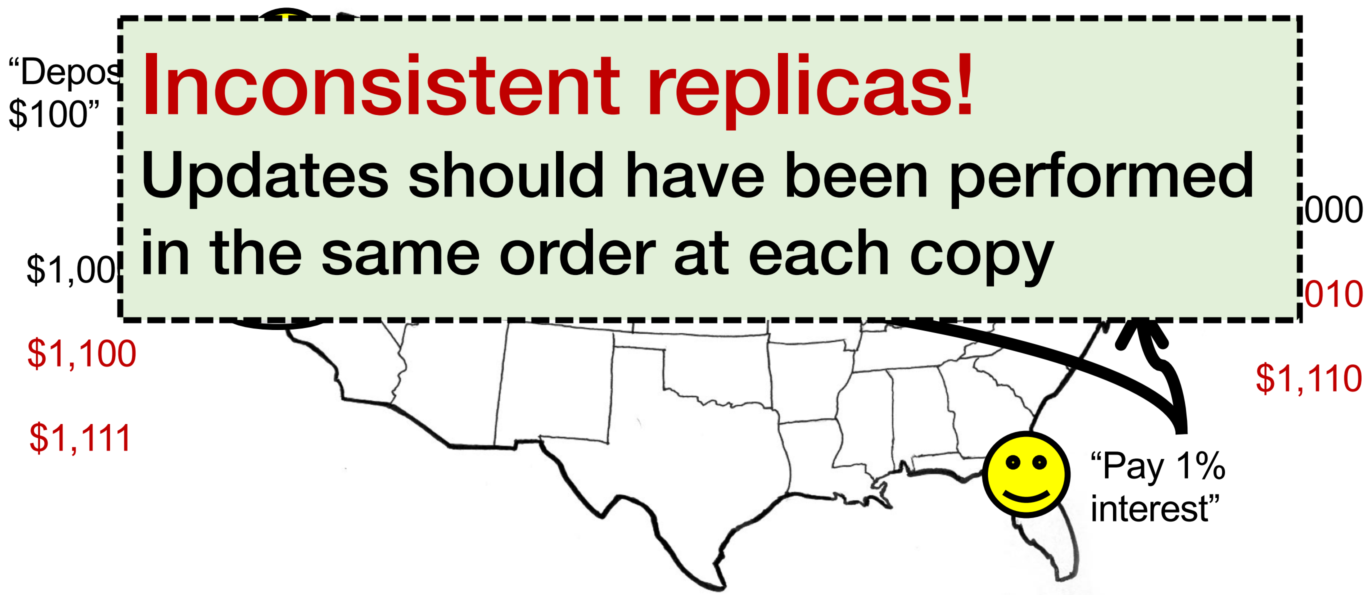
- A New York-based bank wants to make its transaction ledger database resilient to whole-site failures
- Replicate the database, keep one copy in **SF**, one in **NYC**



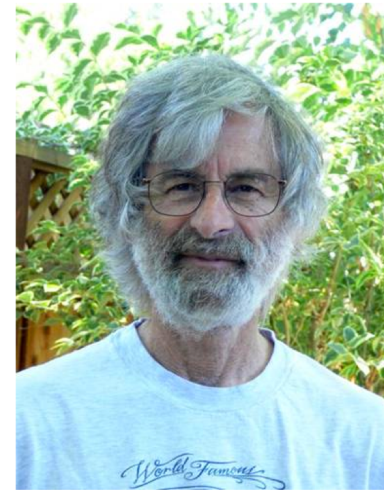
The consequences of concurrent updates

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



Idea: Logical clocks

- Landmark 1978 paper by Leslie Lamport



Idea: Logical clocks

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

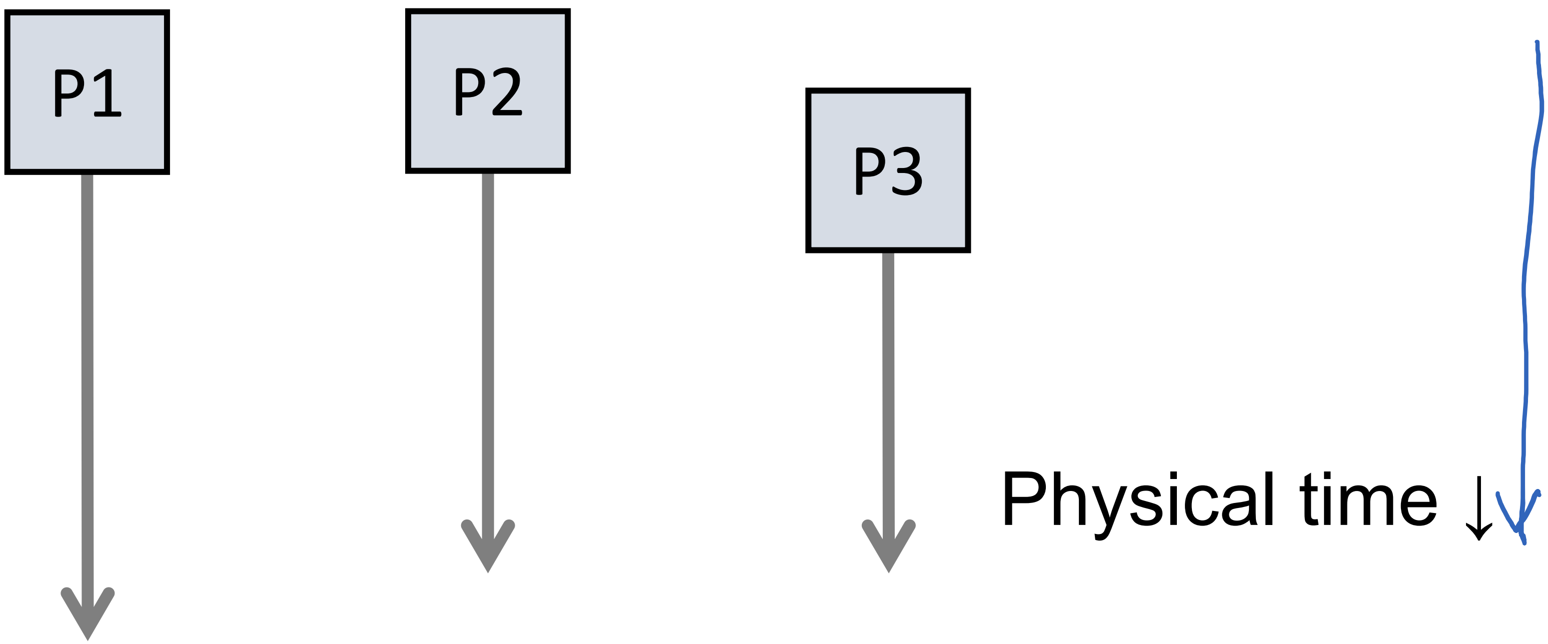
logical.

Idea: Disregard the precise clock time

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

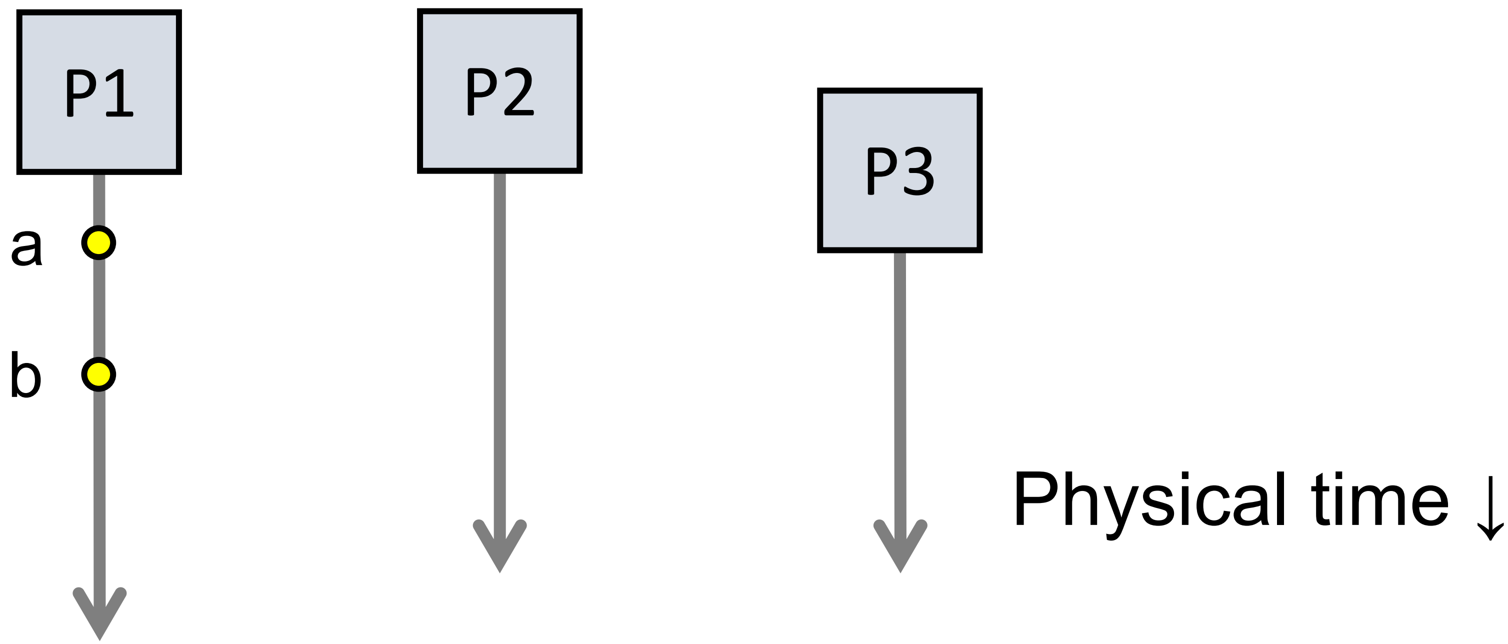
Defining "happens-before" (→)

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



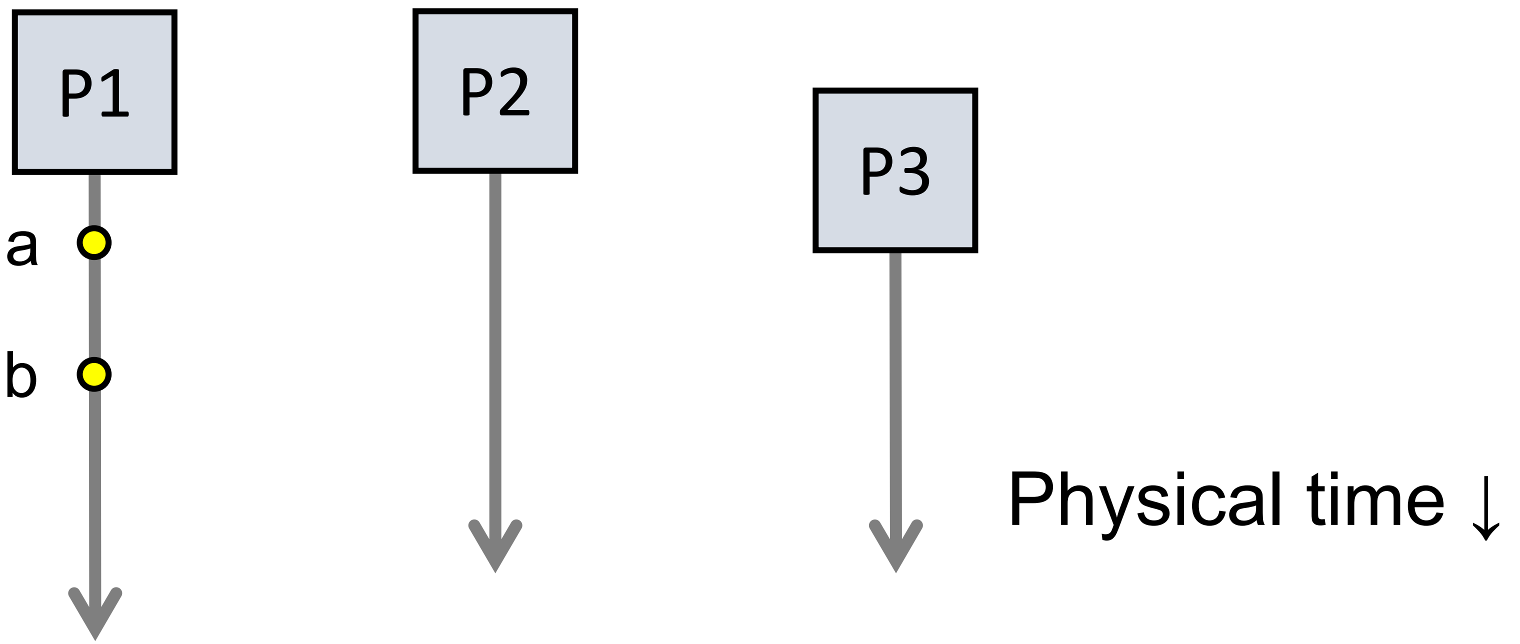
Defining "happens-before" (→)

- Can observe event order at a single process



Defining "happens-before" (→)

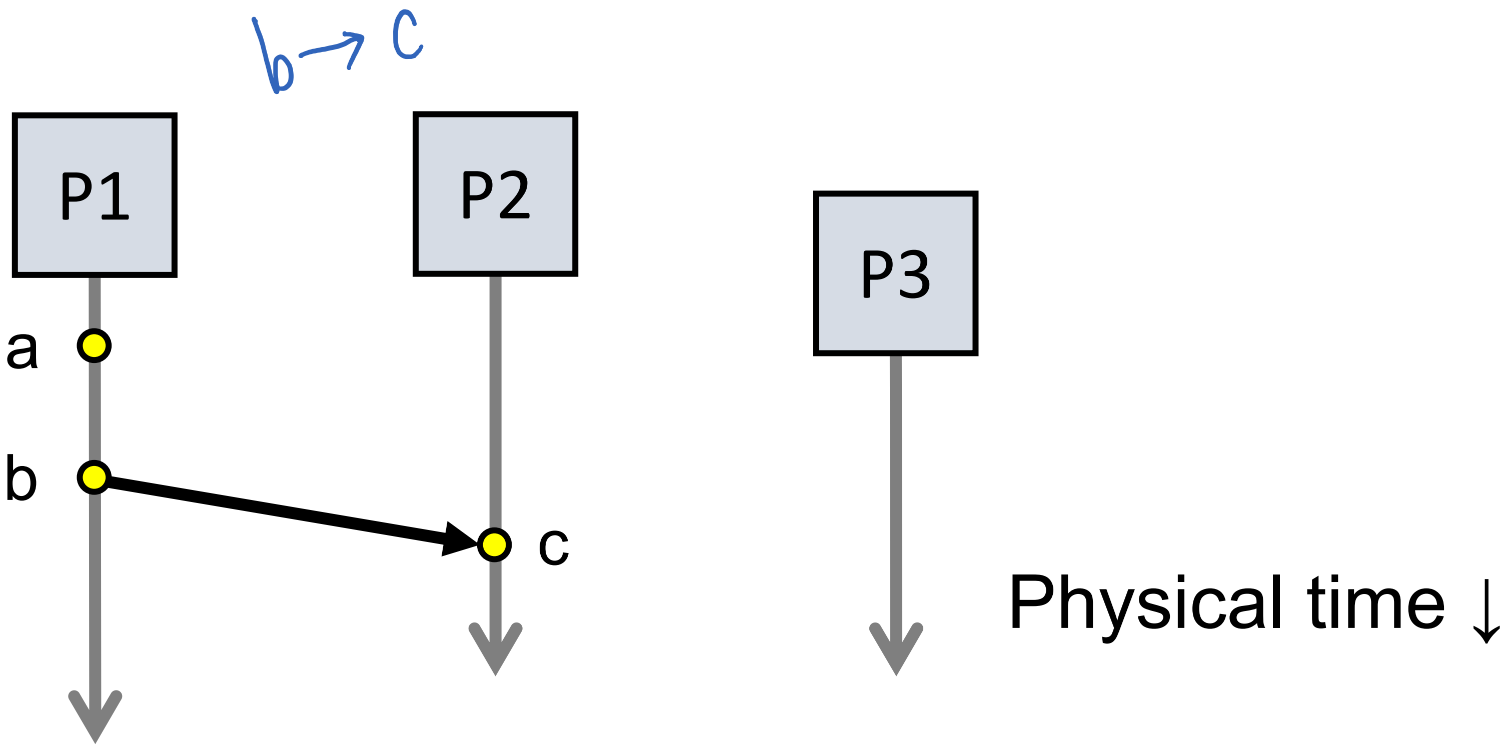
1. If **same process** and **a** occurs before **b**, then **a → b**



Defining "happens-before" (→)

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

2. Can observe ordering when processes communicate



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

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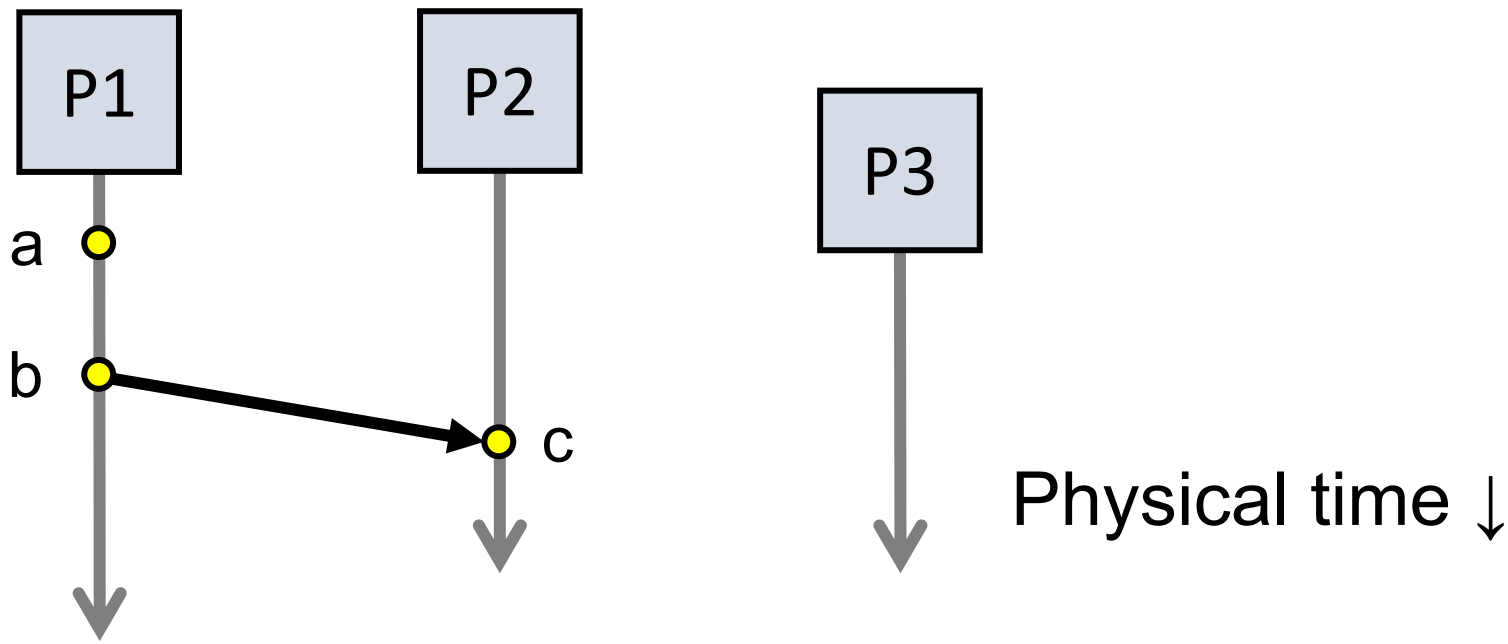

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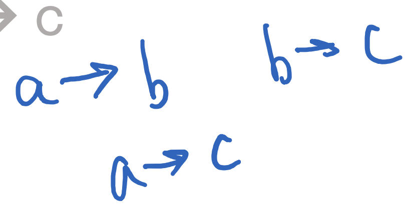
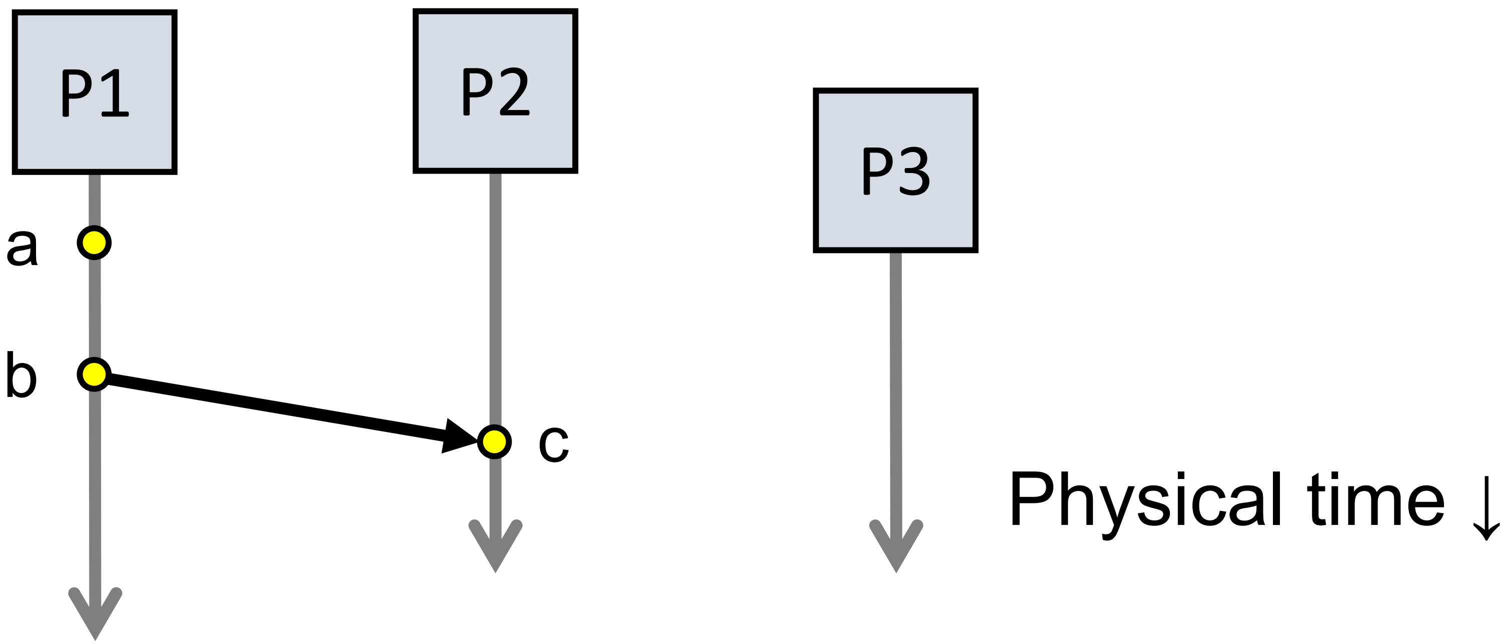


3. Can observe ordering transitively



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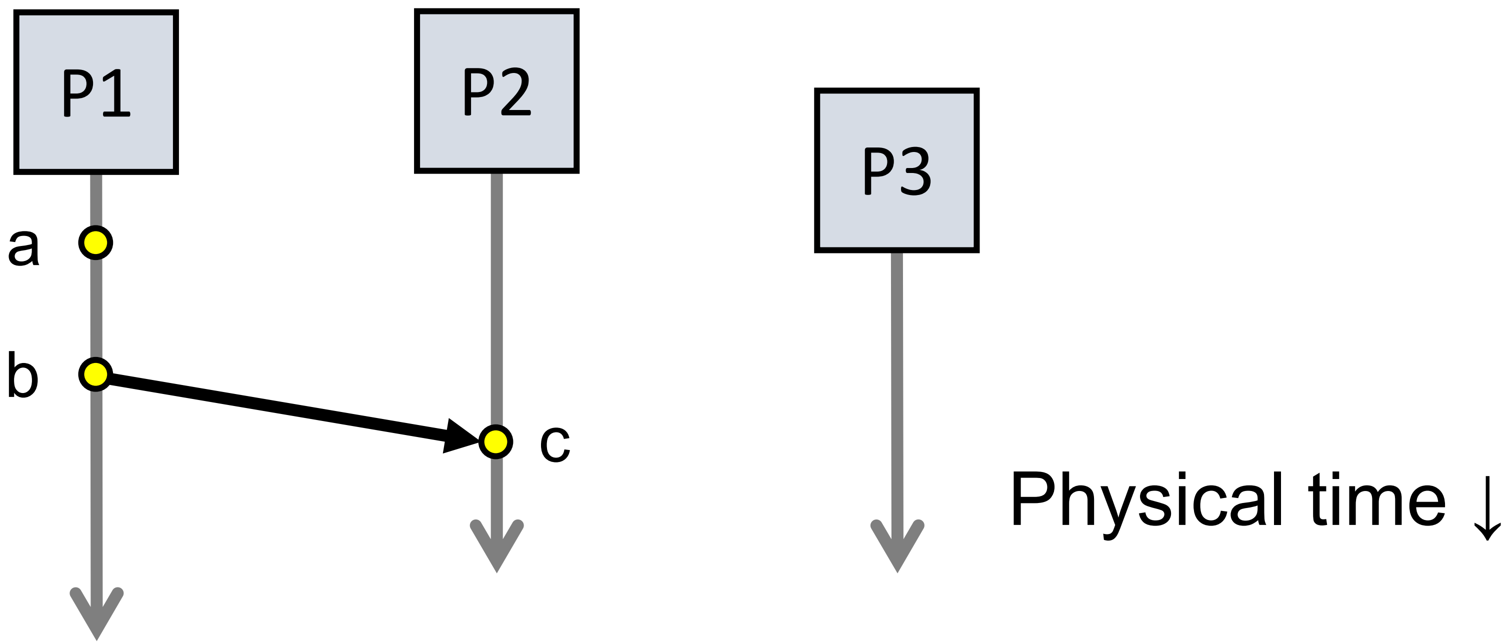
3. If a → b and b → c, then a → c



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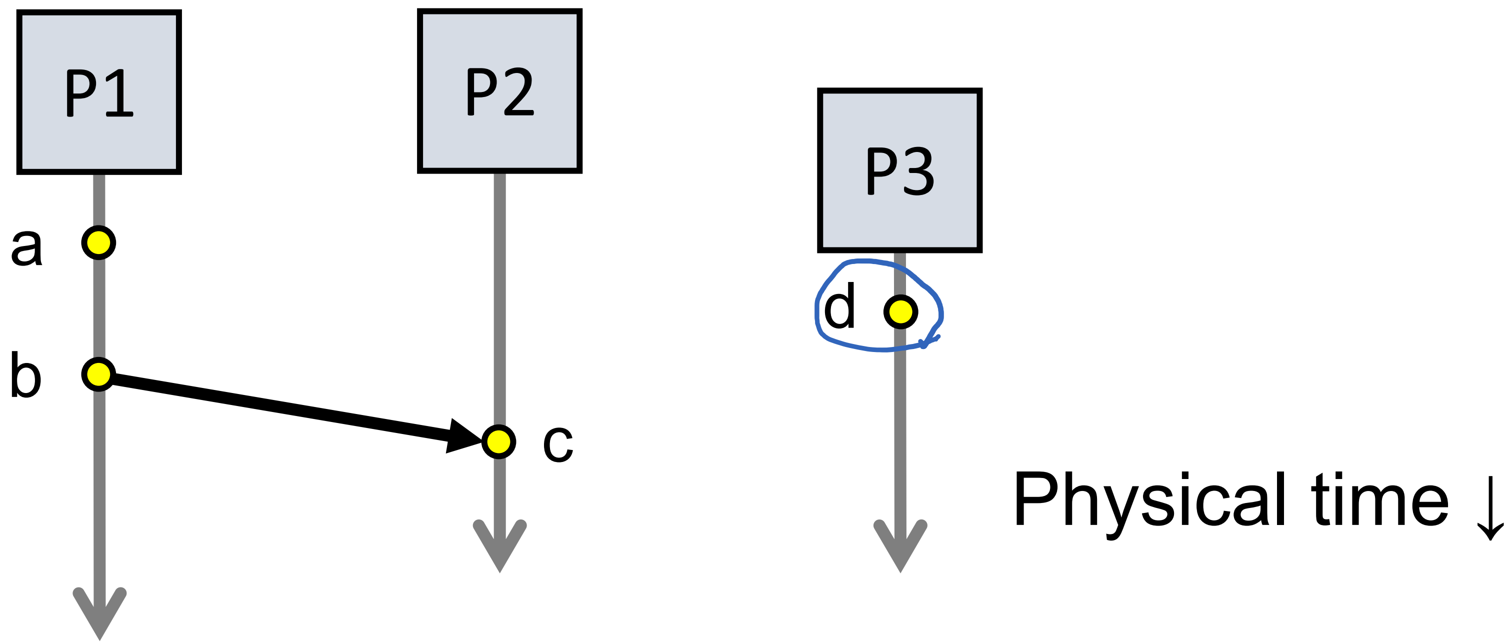

Defining "happens-before" (→)

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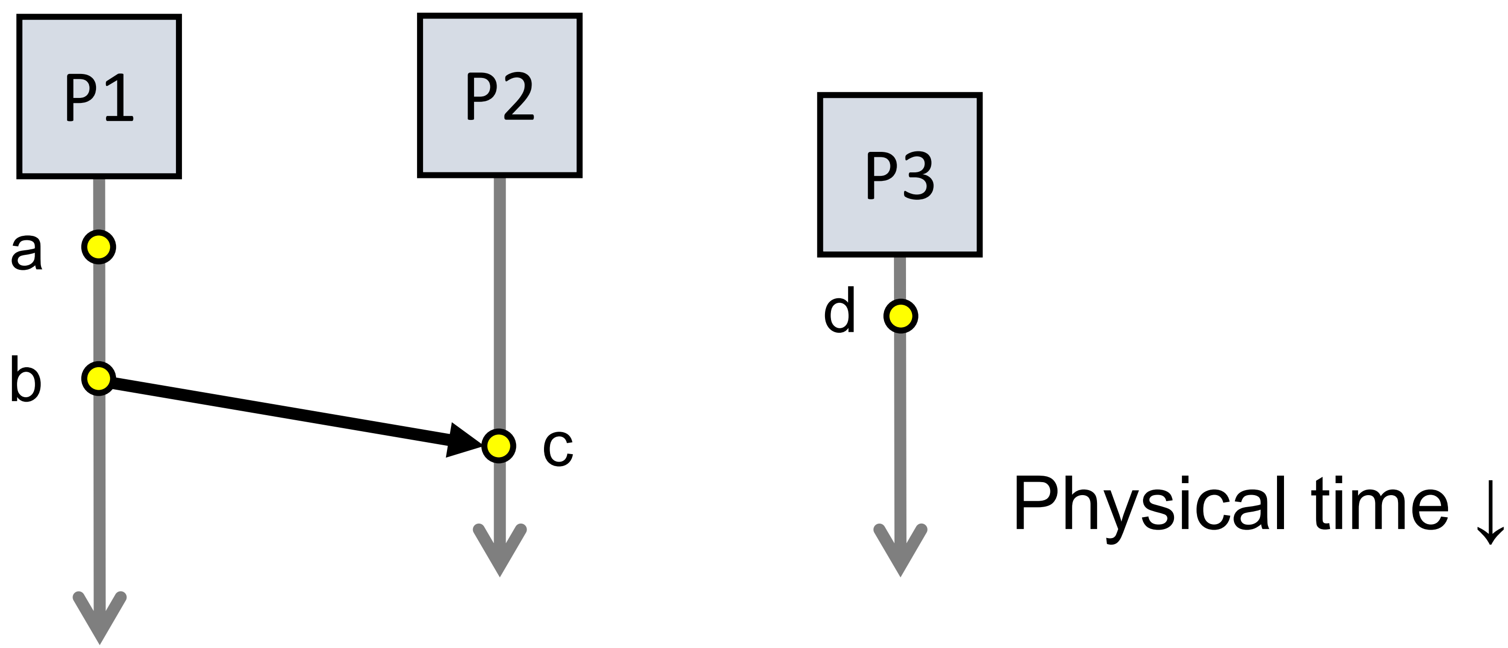
2. a, d not related by → so concurrent, written as a || d



Lamport clocks: Objective

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

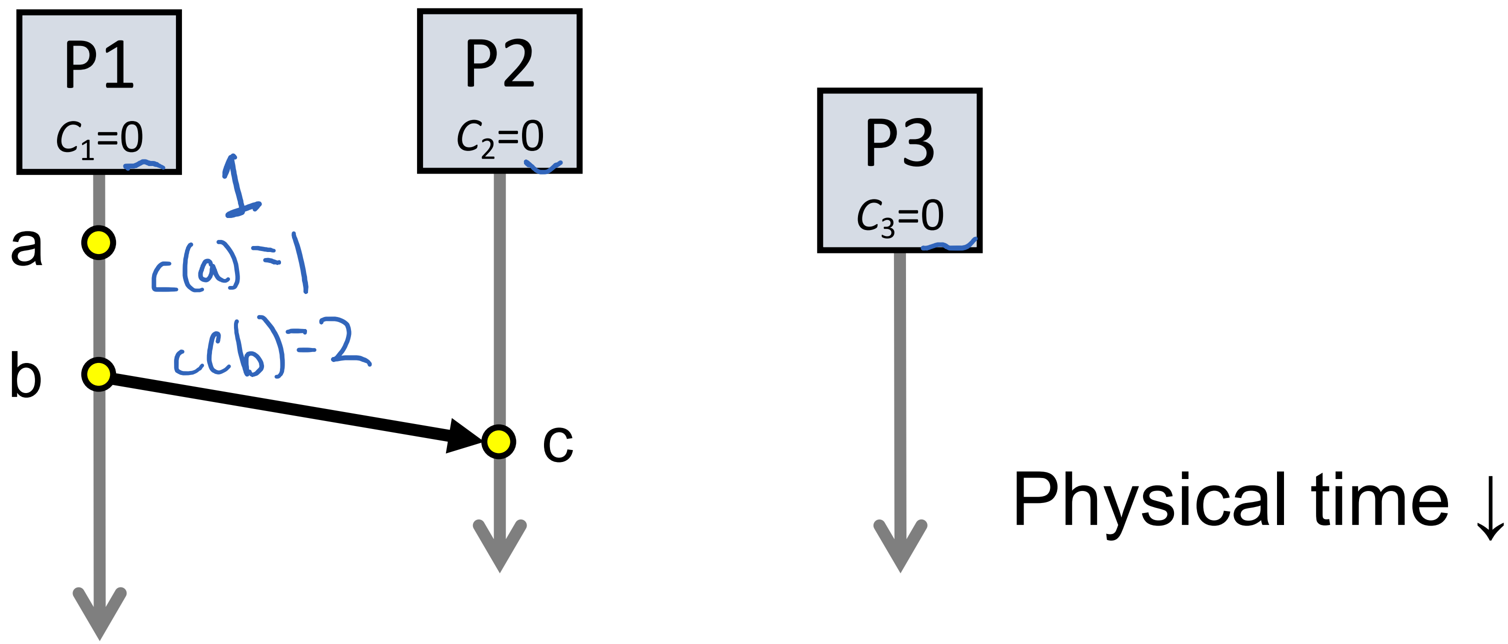
Plan: Tag events with clock times; use clock times to make distributed system correct

- 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, $C_i \leftarrow C_i + 1$:



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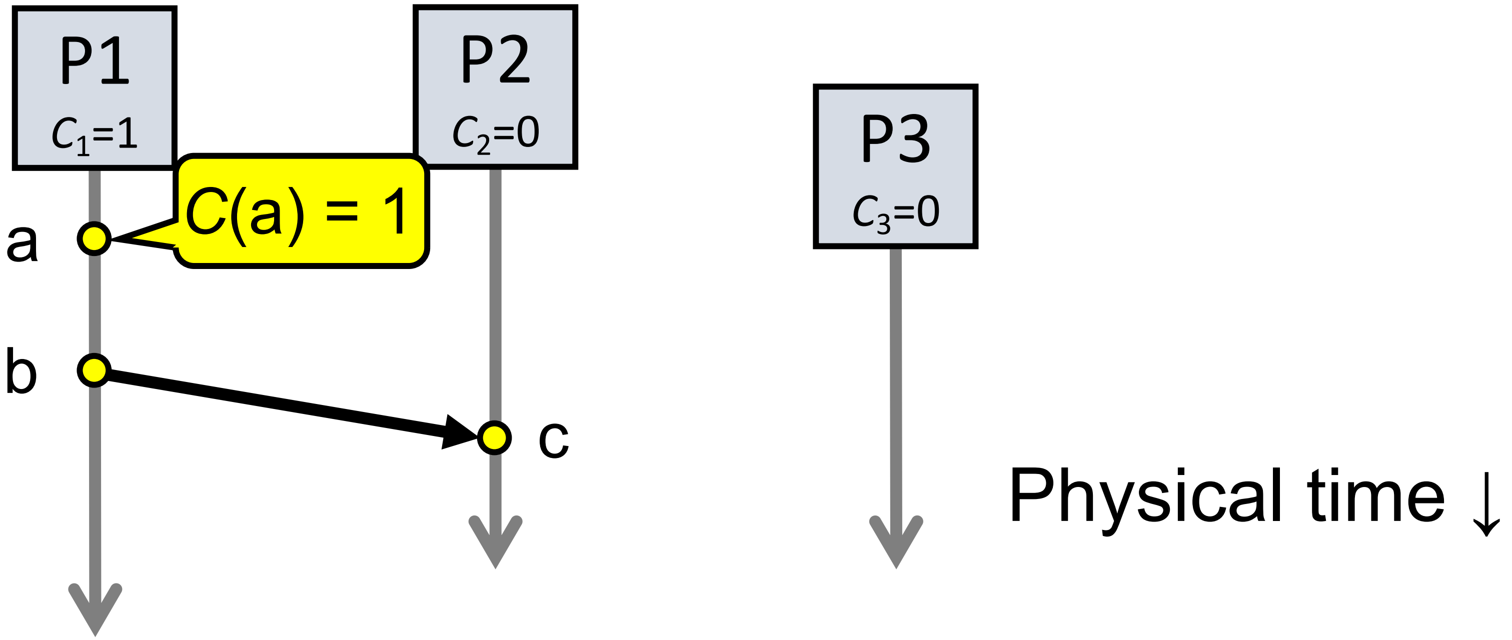

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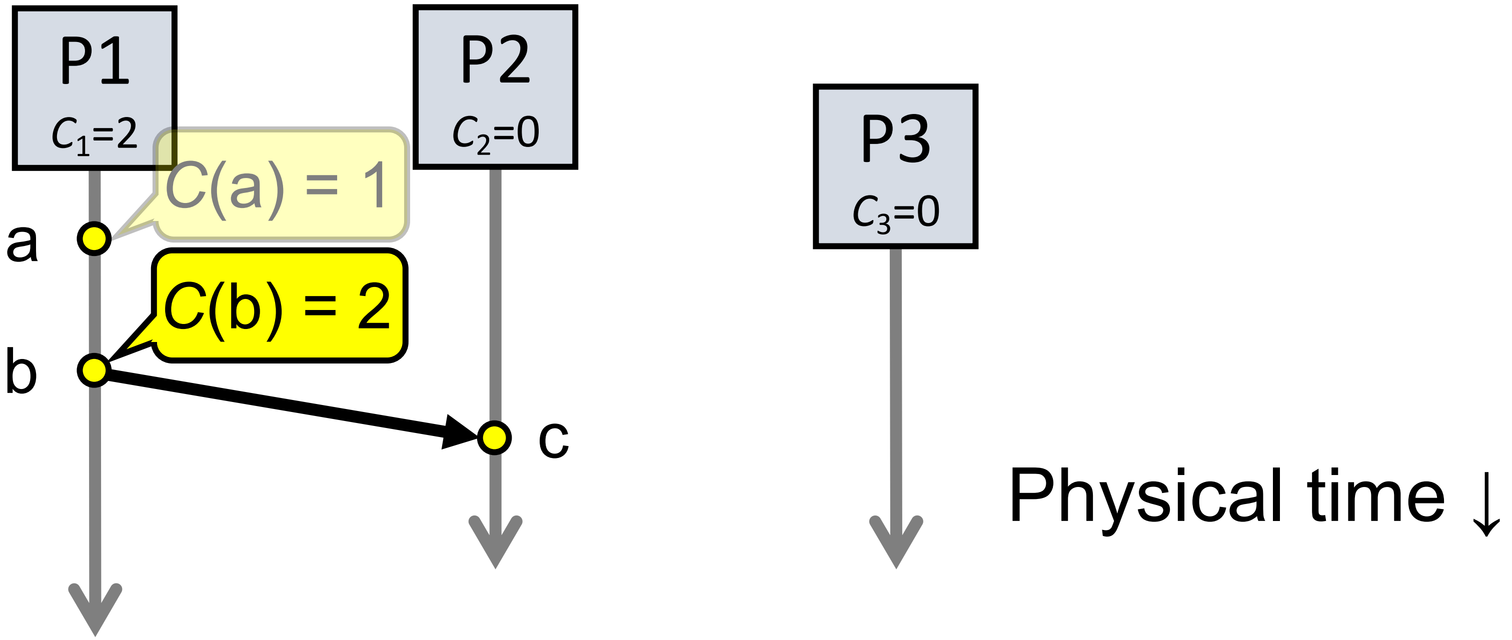

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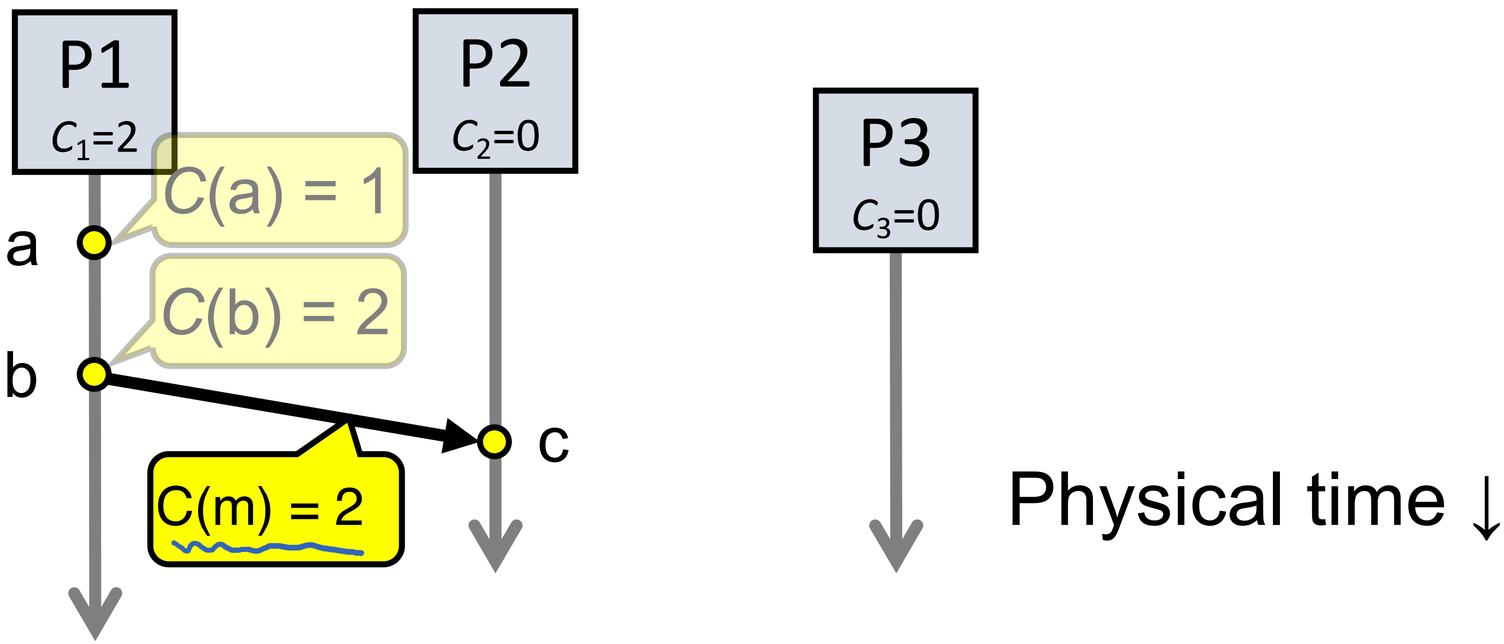
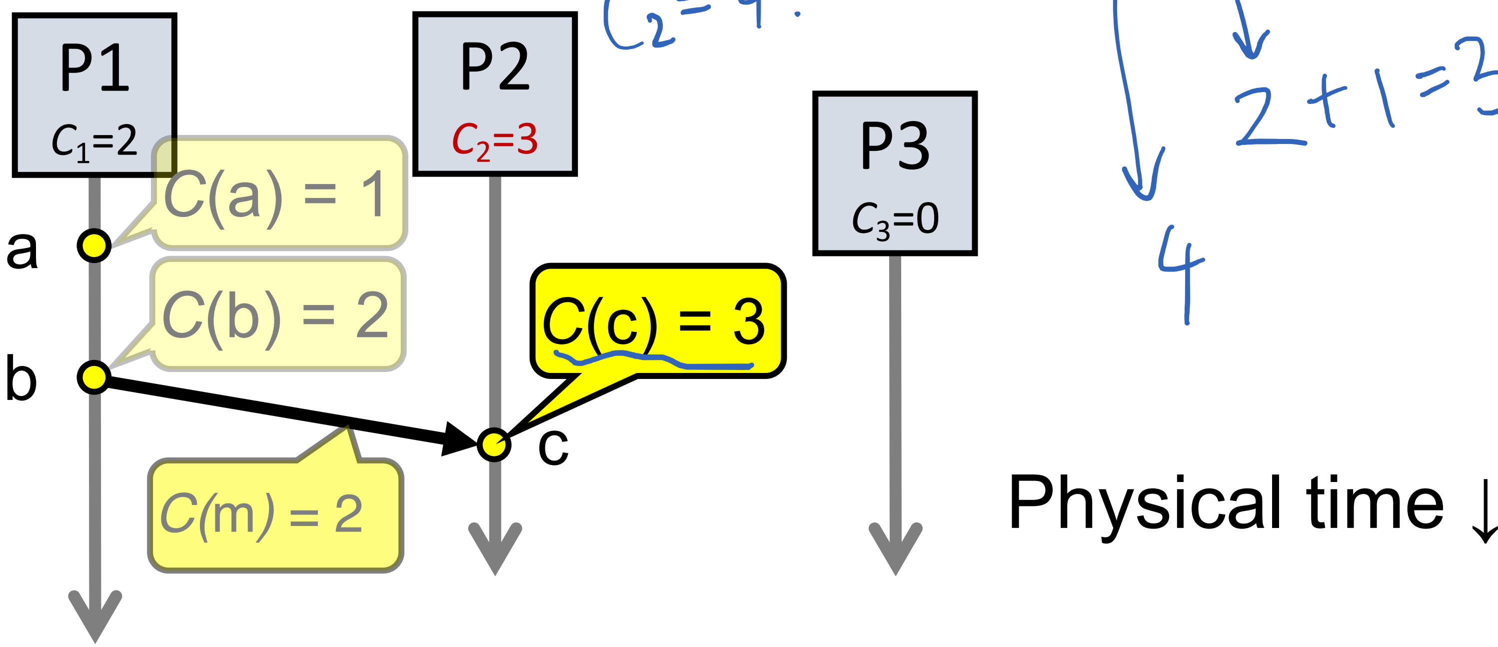
2. Send the local clock in the message m



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

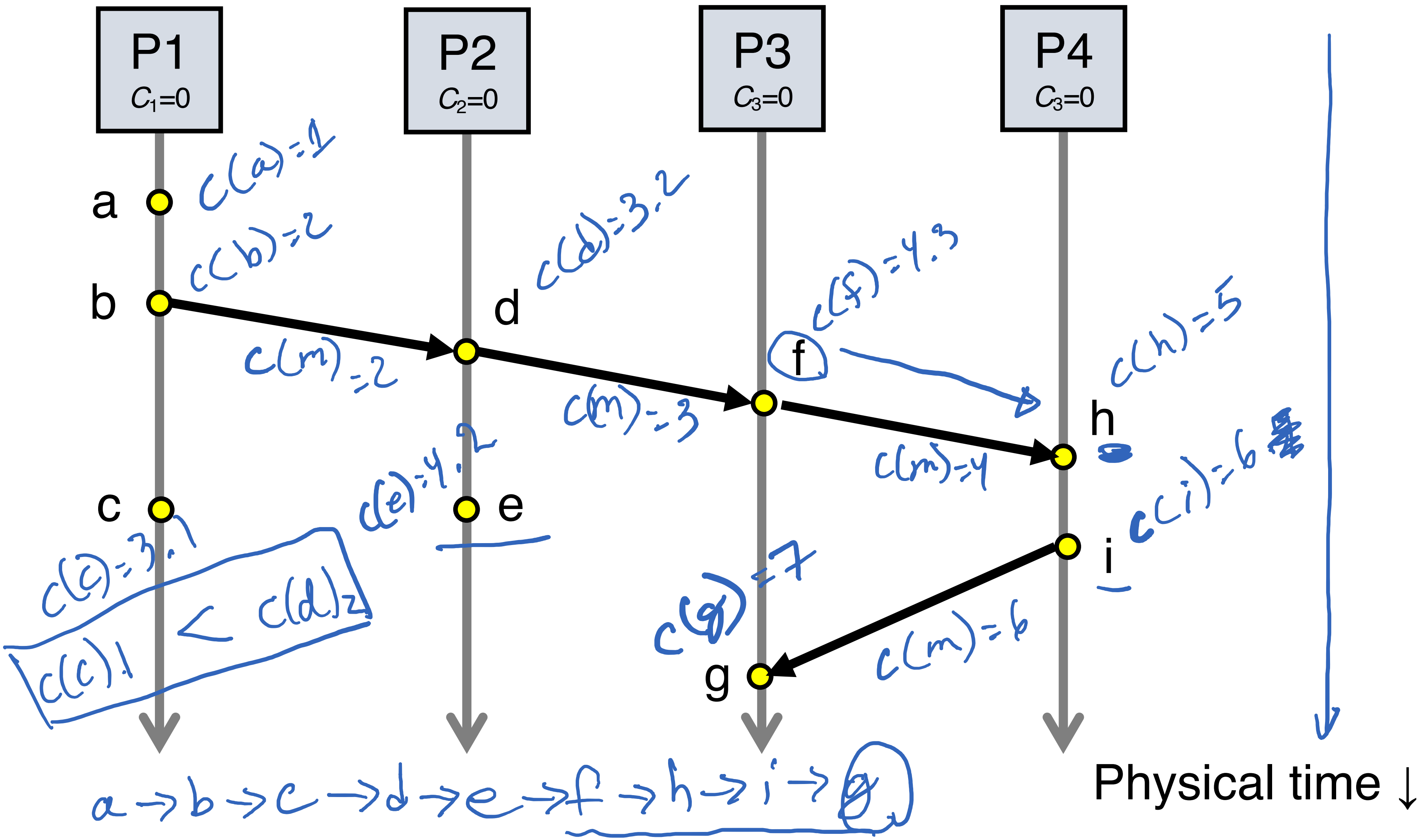
- Break ties by appending the process number to each event:

  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 $C_j \, . \, j$

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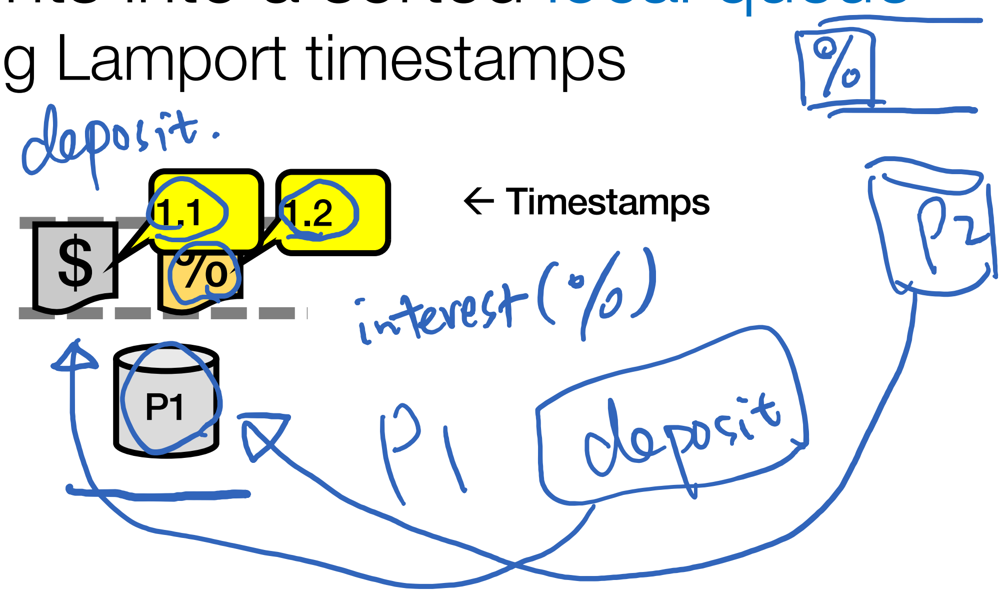
- Key idea: Place events into a sorted local queue
  - Sorted by increasing Lamport timestamps

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)

   ack

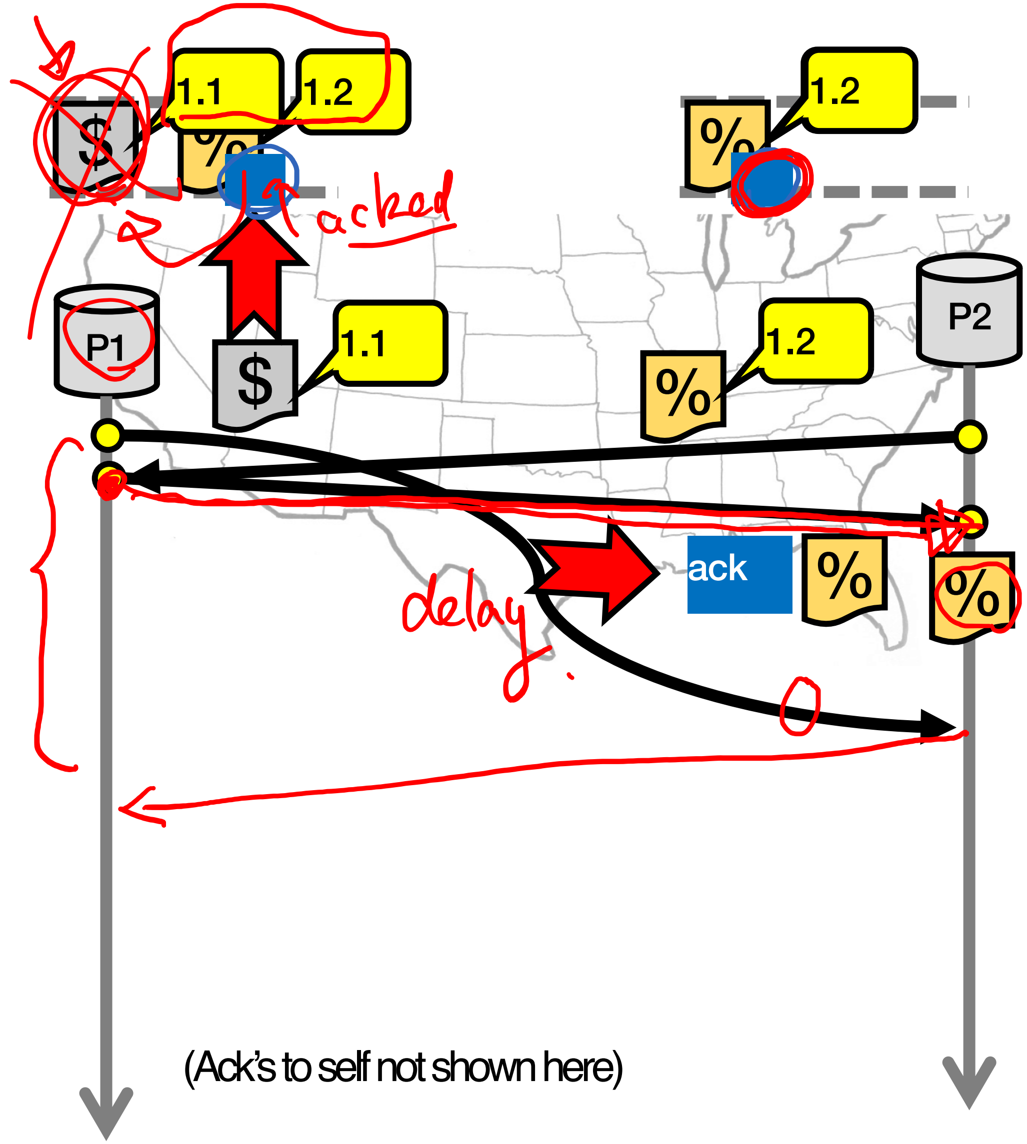
3. On receiving an acknowledgement:
   - Mark corresponding update acknowledged in your queue

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)

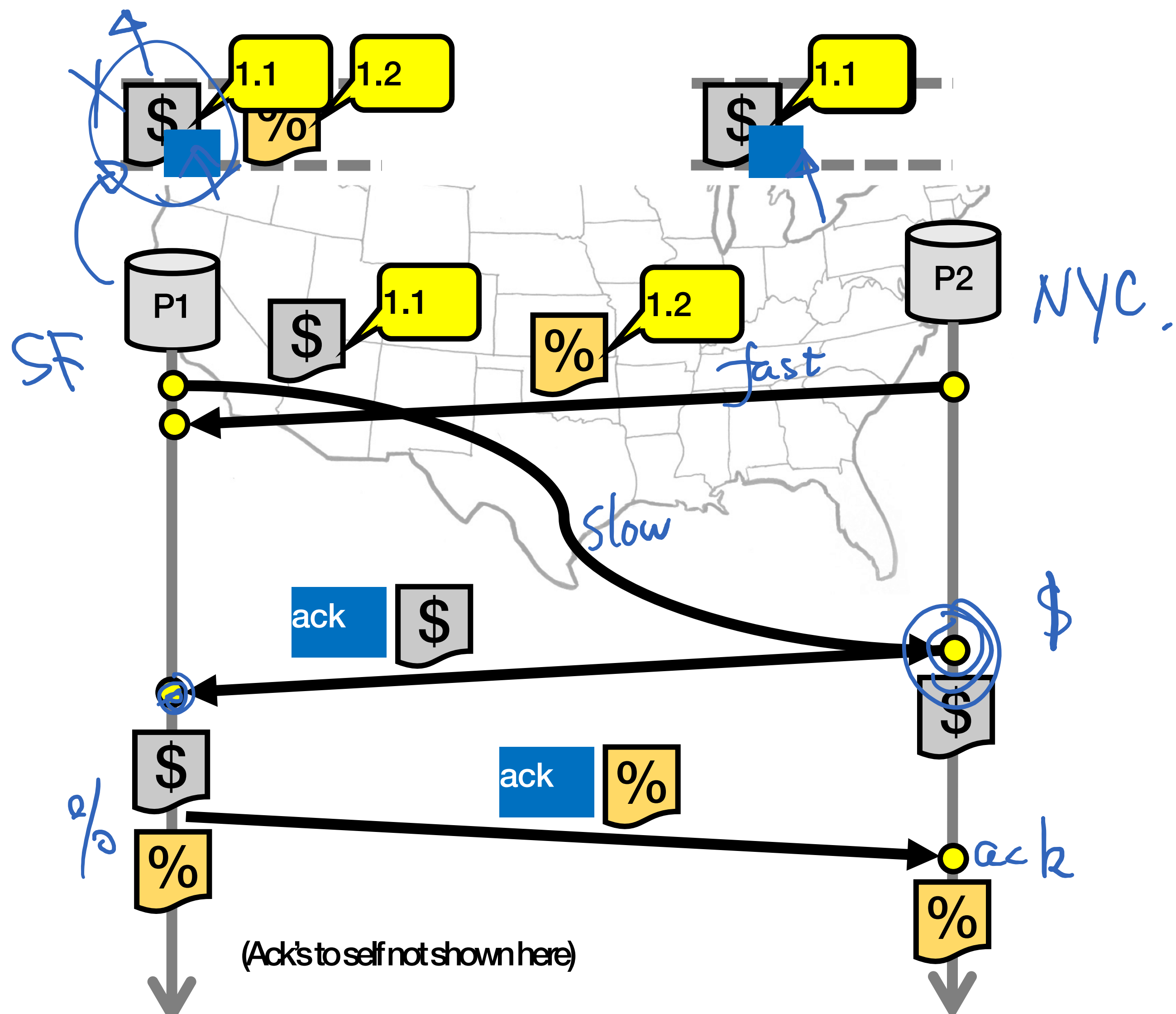
1. On receiving an update from client, broadcast to others (including yourself)

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)



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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

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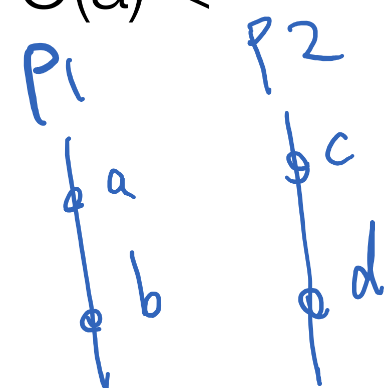

$c(a)_1 < c(c)_2$

$C(a)=1$ $\quad$ $c(c)=1$

$c(b)=2$ $\quad$ $c(d)=2.$

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

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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]

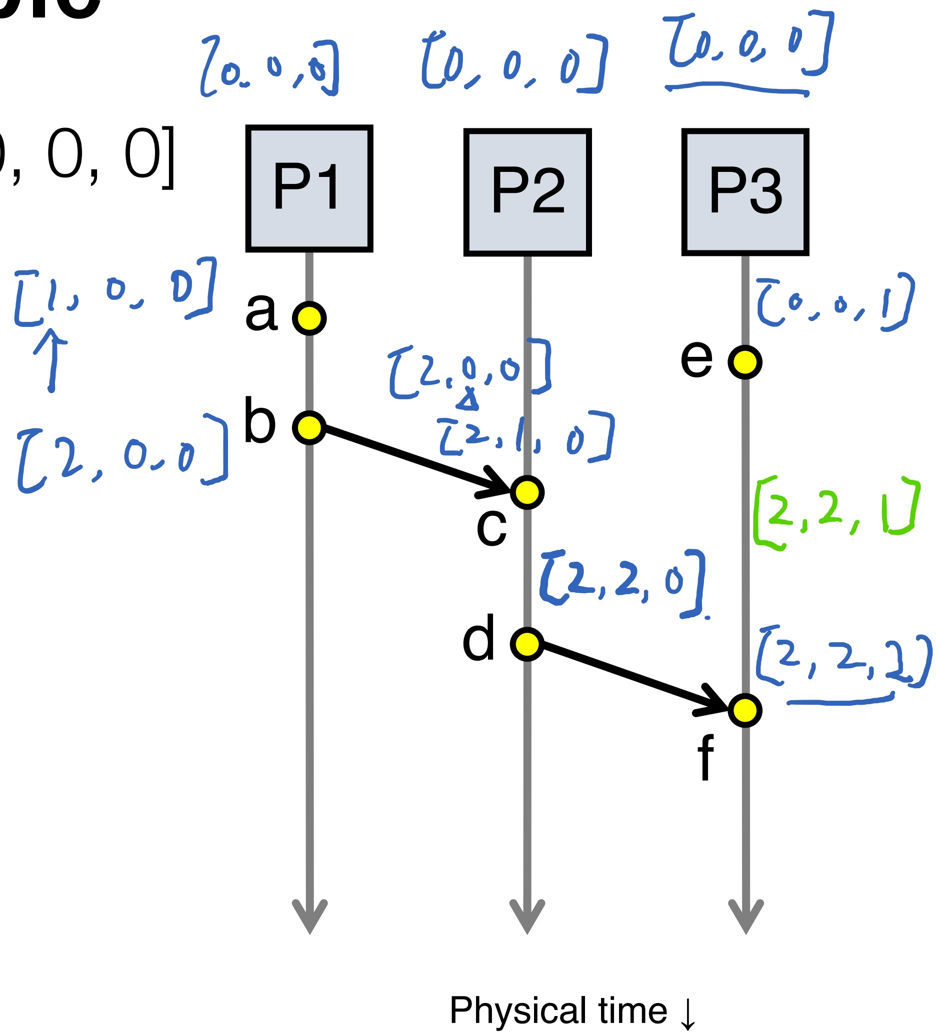
- Two update rules:

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]



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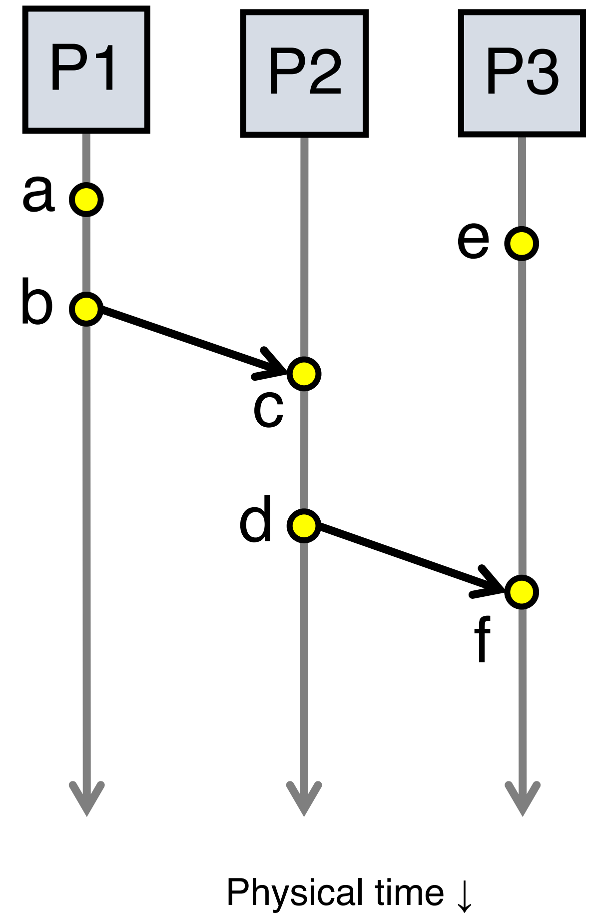

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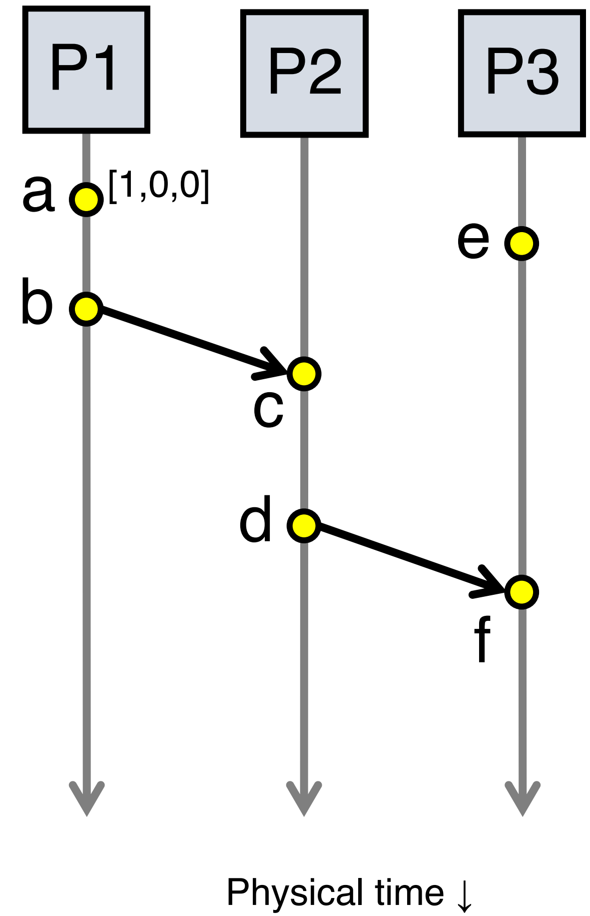

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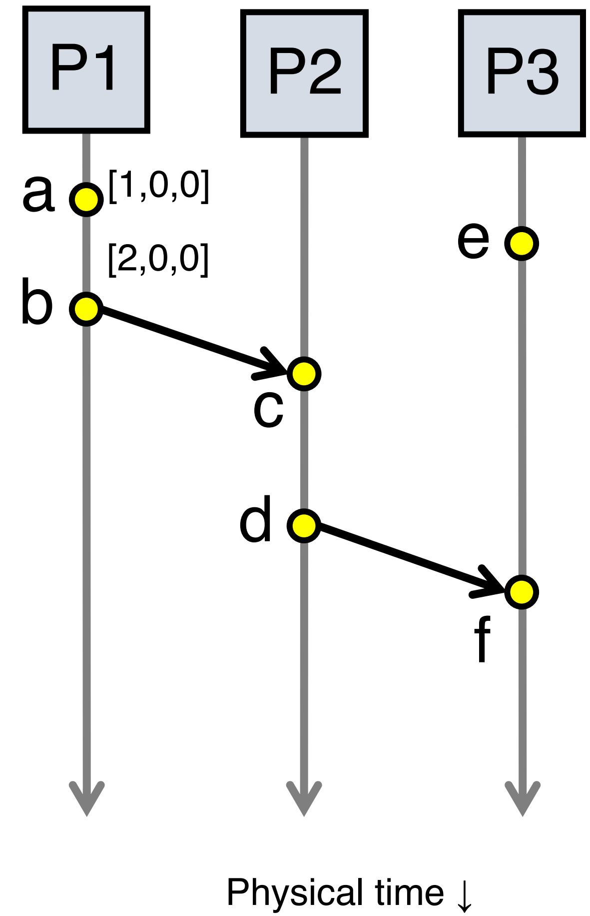

Vector clock: Example

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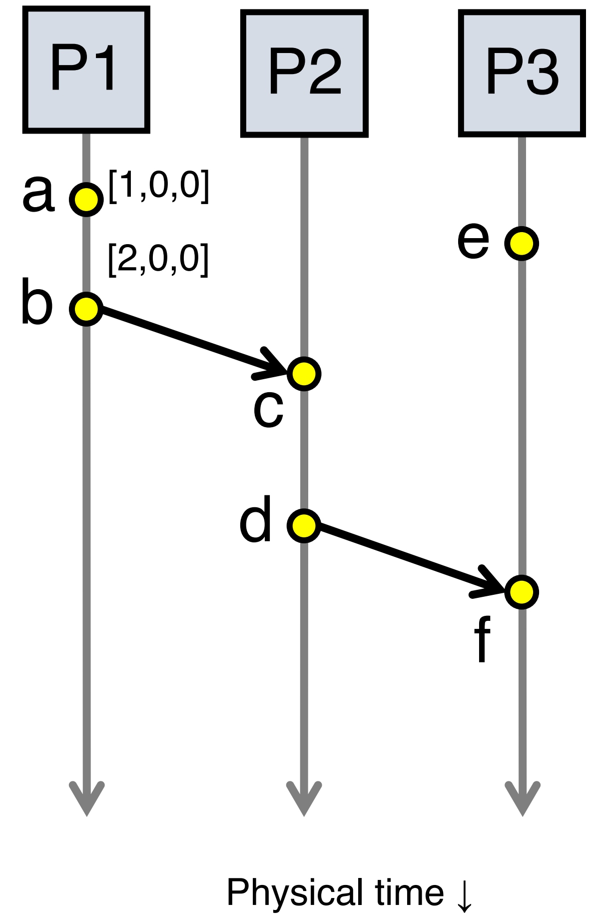
- Applying message rule
  - Local vector clock **piggybacks** on inter-process messages



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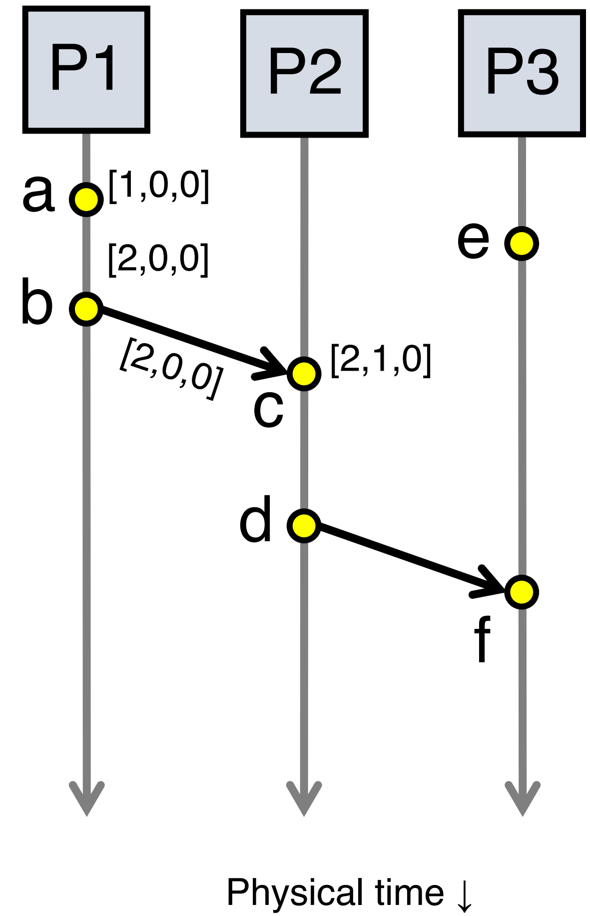

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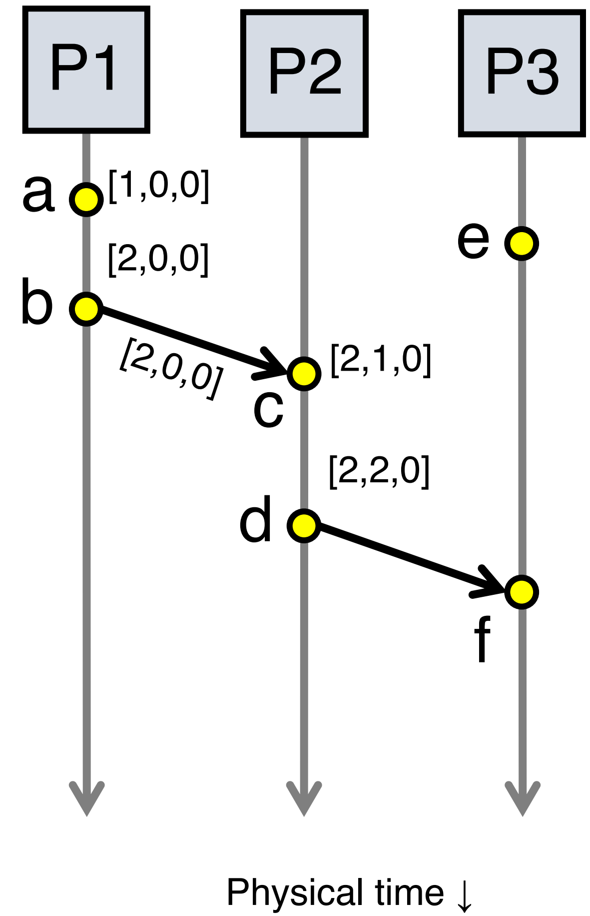

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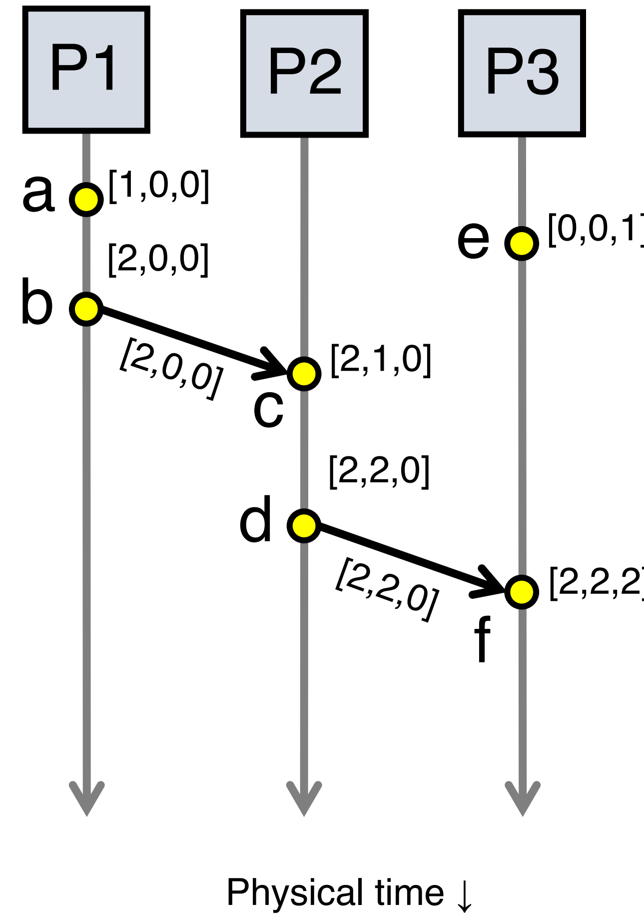


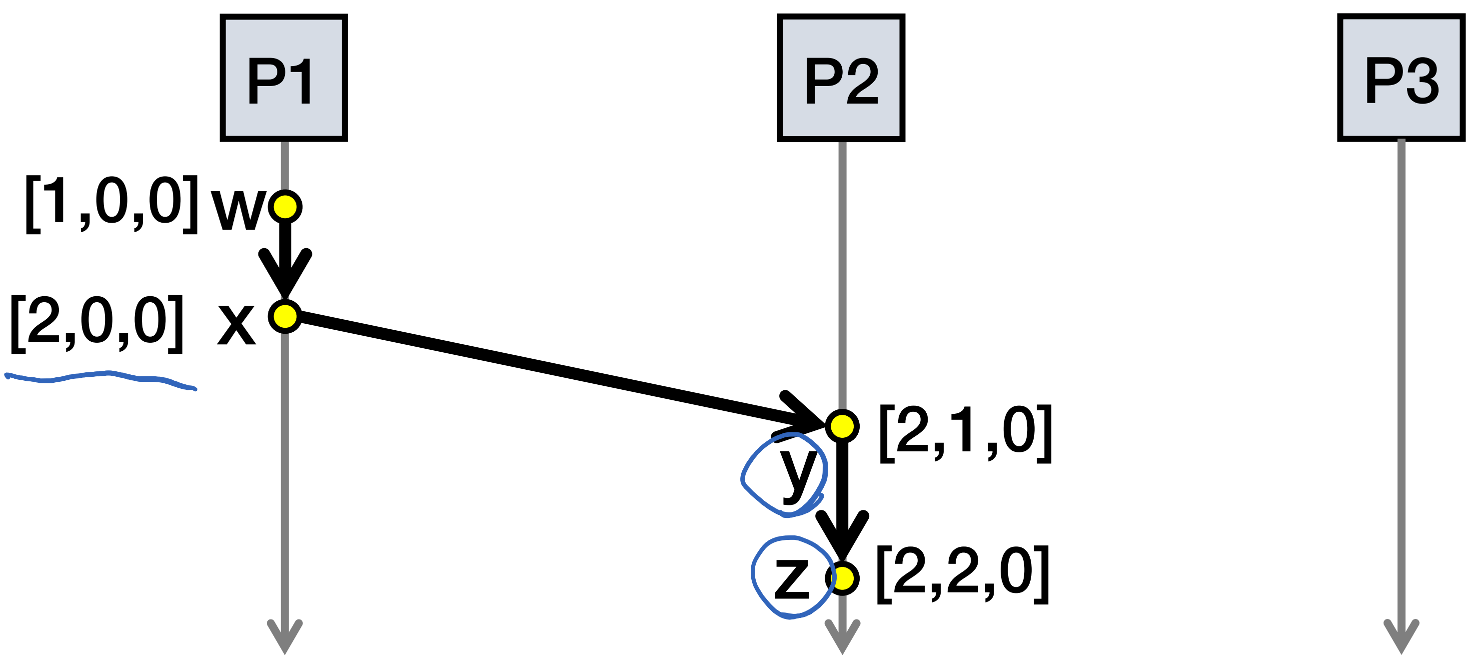
Comparing vector timestamps

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

Vector clocks capture causality

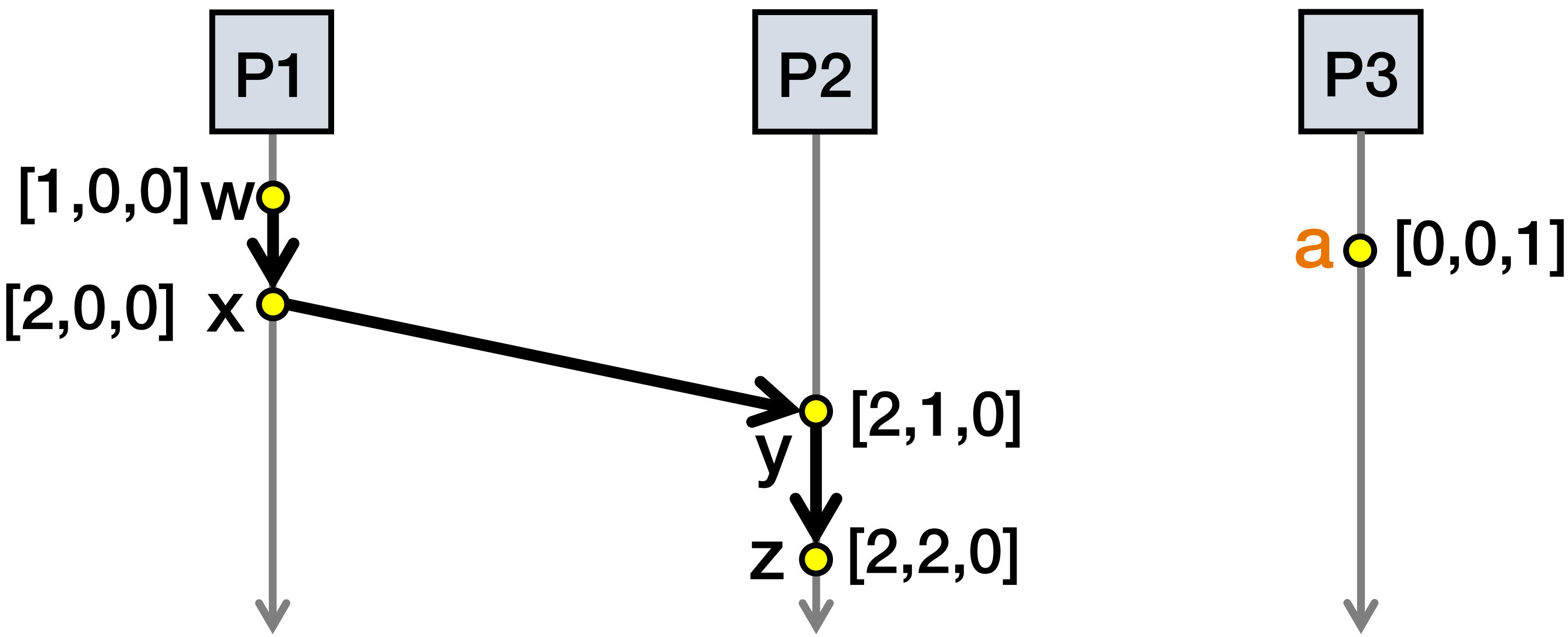
- V(w) < V(z) then there is a chain of events linked by Happens-Before (→) between a and z

w → 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

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Conclusion: a → z

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

Today's outline

1. Time and clocks
    - The need for time synchronization
    - "Wall clock time" synchronization
        - Cristian's algorithm, NTP
    - Logical Time: Lamport Clocks
    - Vector clocks
2. Primary-Back (P-B)

Limited fault tolerance in Totally-Ordered Multicast

- Stateful server replication for fault tolerance…

Limited fault tolerance in Totally-Ordered Multicast

- Stateful server replication for fault tolerance…
- But no story for server replacement upon a server failure → no replication

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Goal: Make stateful servers fault-tolerant?

Primary-Backup: Goals

- **Mechanism:** Replicate and separate servers

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    - Despite some server and network failures
        - Continue operation after failure

Primary-Backup: Goals

- **Mechanism:** Replicate and separate servers

- **Goal #1:** Provide a highly reliable service
  - Despite some server and network failures
    - Continue operation after failure

- **Goal #2:** Servers should behave just like a single, more reliable server

State machine replication

- **Any server** is essentially a *state machine*
  - Set of (key, value) pairs is **state**
  - Operations **transition** between states

- Need an op to be executed on all replicas, or none at all
  - *i.e.,* we need **distributed** all-or-nothing atomicity
  - If op is deterministic, replicas will end in same state

- **Key assumption:** Operations are deterministic

Primary-Backup (P-B) approach

- Nominate one server the *primary,* call the other the *backup*
  - Clients send all operations (get, put) to current primary
  - The primary **orders** clients' operations
- Should be only **one primary at a time**

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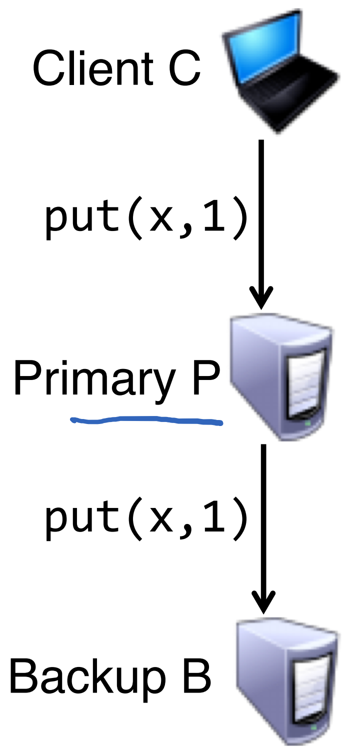
- Should be only **one primary at a time**

Need to keep clients, primary, and backup in sync: **who is primary** and **who is backup**

Primary-Backup replication



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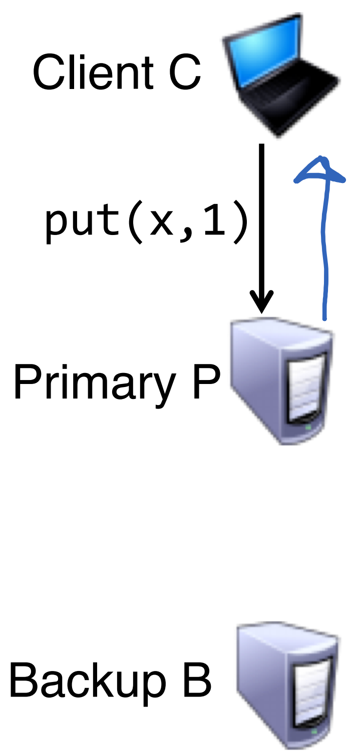
4. Backup exec's ops or writes to log

Primary-Backup replication



Asynchronous Replication

1. Primary gets operations
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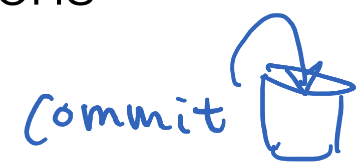

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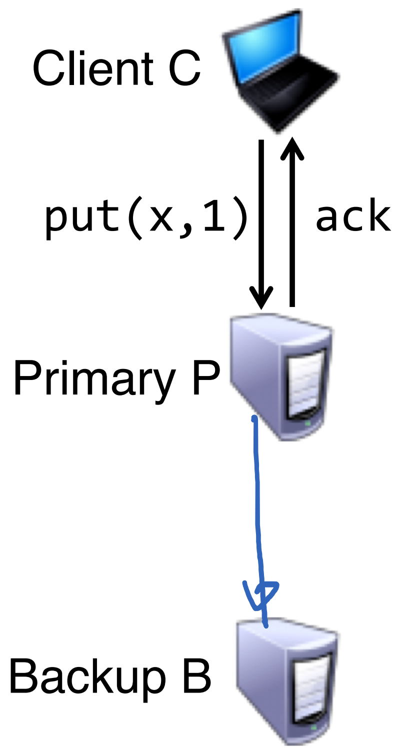

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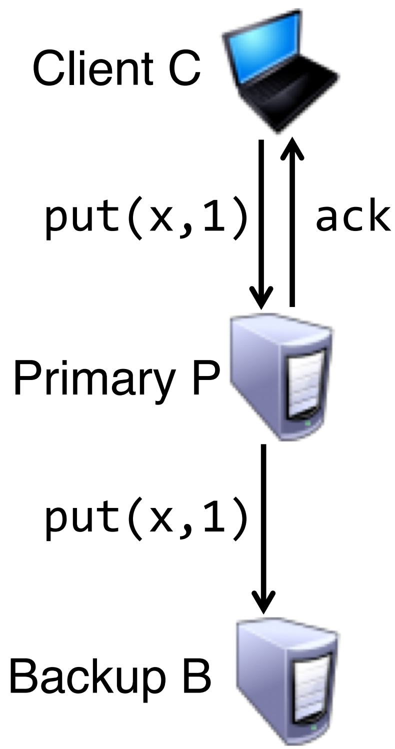

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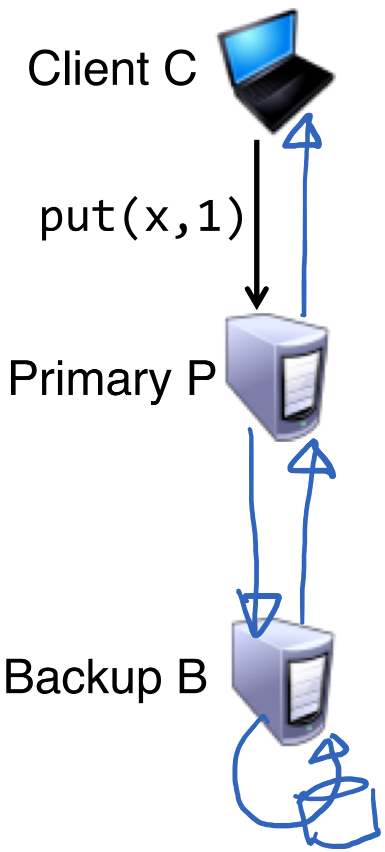

Synchronous Replication

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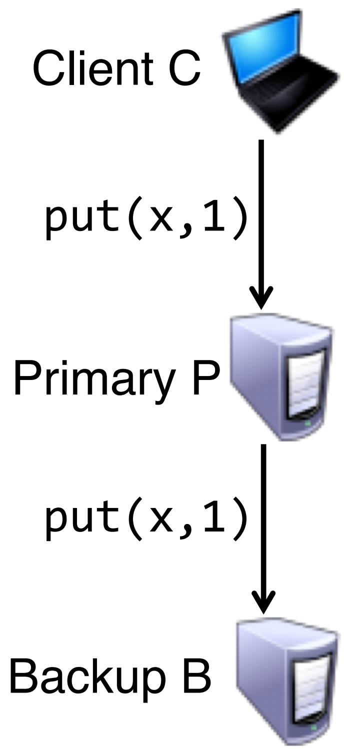
5. Primary gets ack, execs ops

Primary-Backup replication



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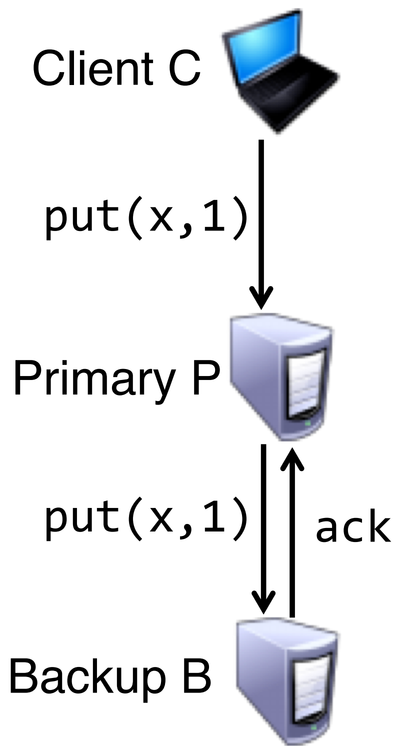

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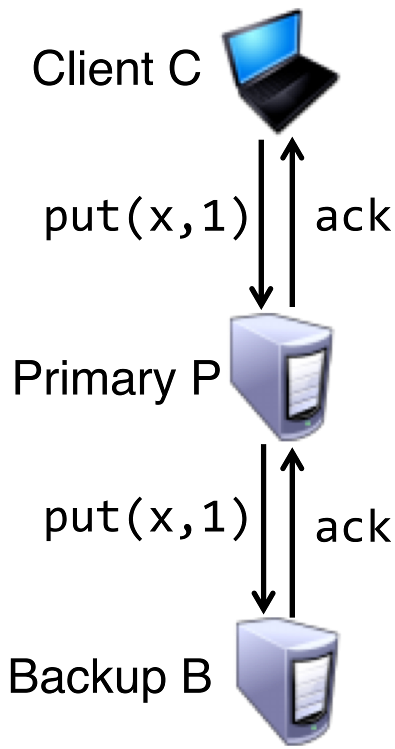

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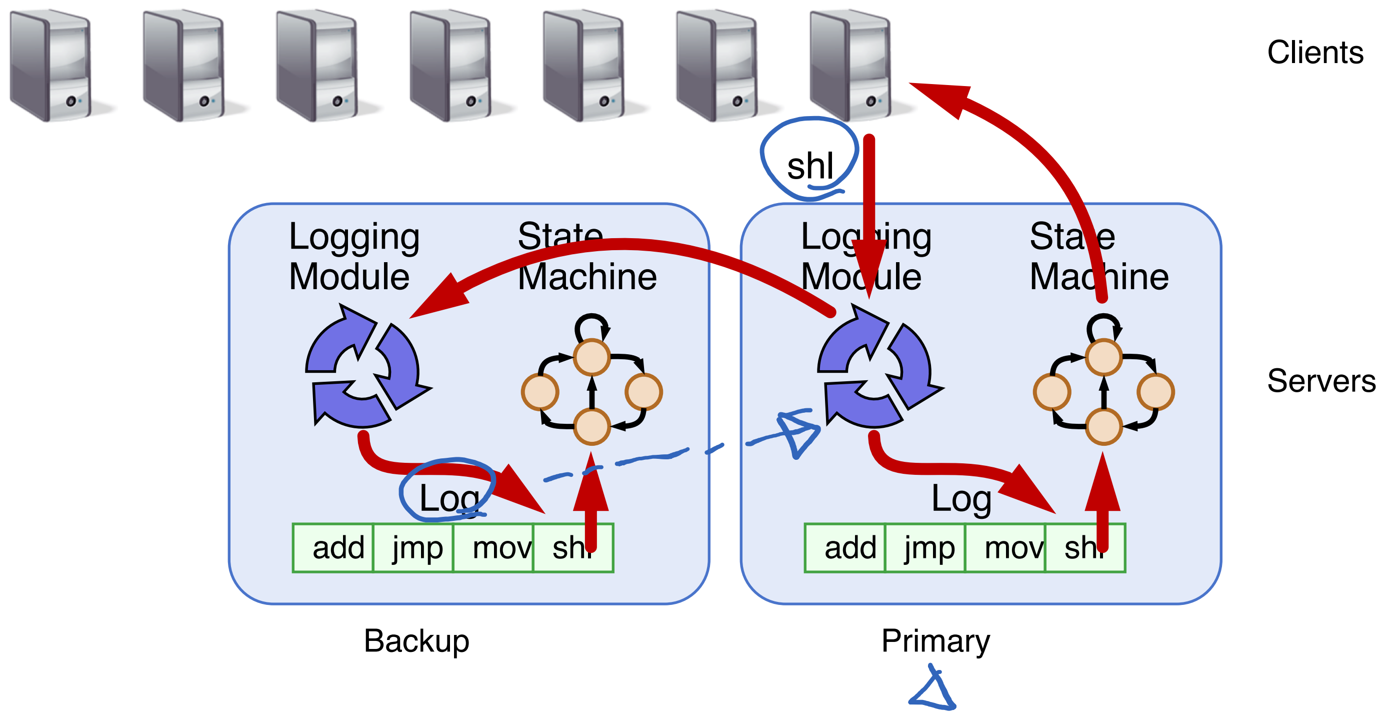

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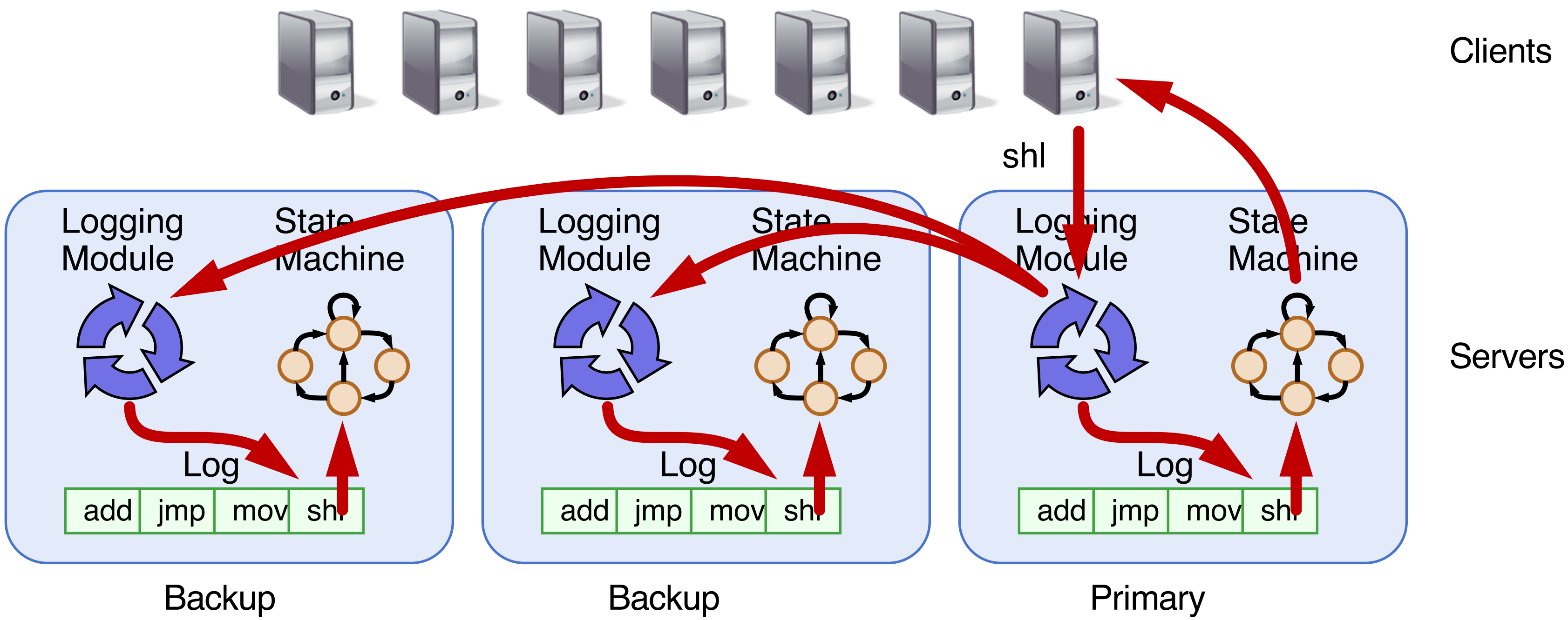

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Need determinism? Make it so!

- Operations are deterministic
  - No events with ordering based on local clock
    - Convert timer, network, user into logged events
  - Nothing using random inputs
- Execution order of ops is identical
  - Most RSMs are single threaded

Primary-Backup: Summary

- First step in our goal of making **stateful** replicas fault-tolerant
- Allows replicas to provide continuous service despite persistent net and machine failures
- Finds repeated application in practical systems (next lecture)