Logical Time 2

COS 316: Principles of Computer System Design

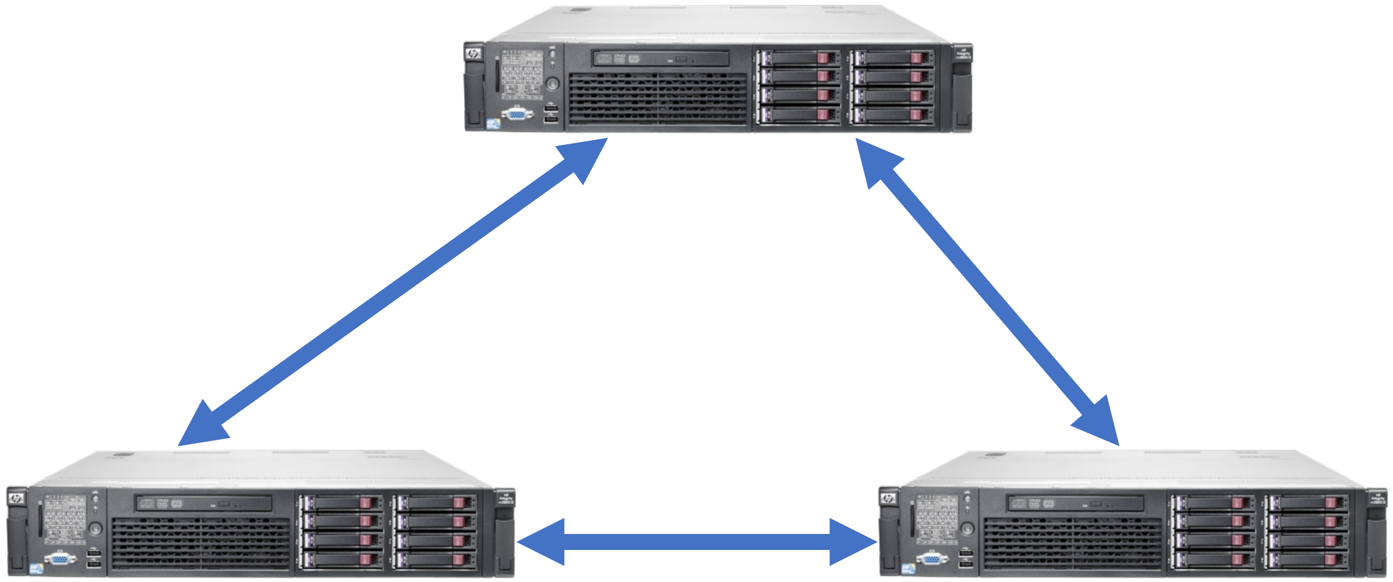
Lecture 16

Amit Levy & Ravi Netravali

Concurrency

- Multiple things happening at the same time
- Primary benefit is better performance
  - Do more work in the same amount of time
  - Complete fixed amount work in less time
  - Better utilize resources
- Primary cost is complexity
  - Hard to reason about
  - Hard to get right
  - (Systems deal with it, not applications, … to some extent)

Distributed Systems, What?



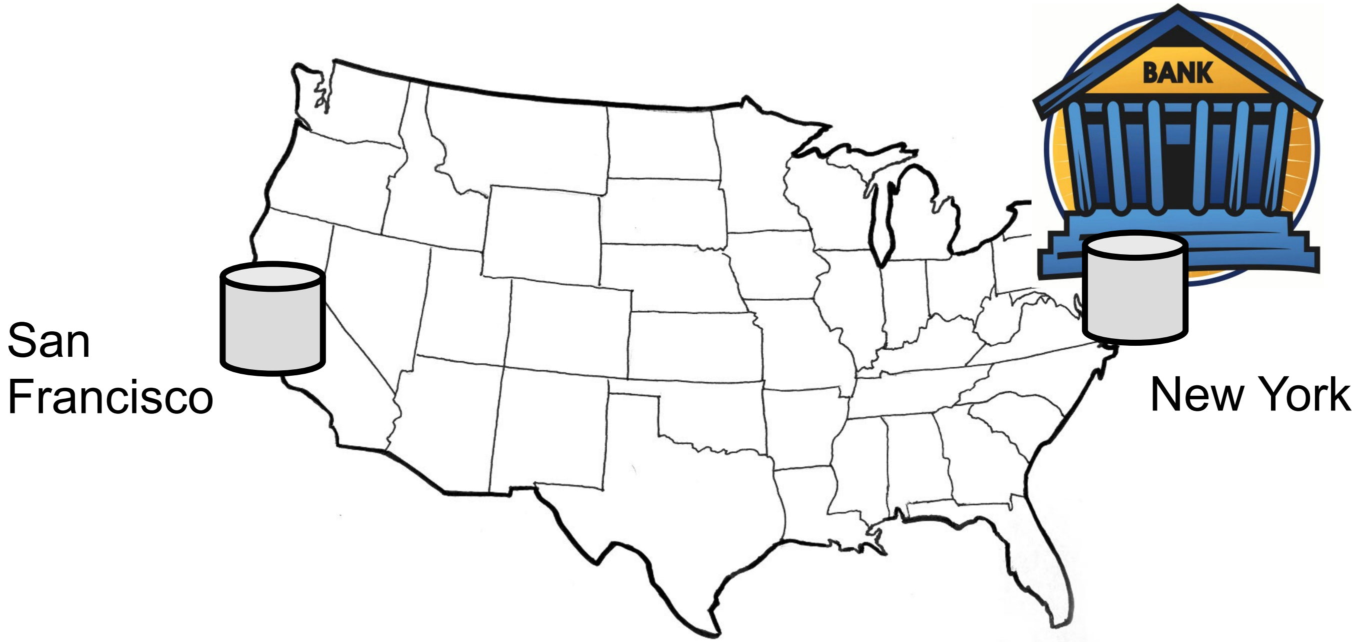
1) Multiple computers
2) Connected by a network
3) Doing something together

Concurrency is Inevitable!

Motivation: Multi-site database replication

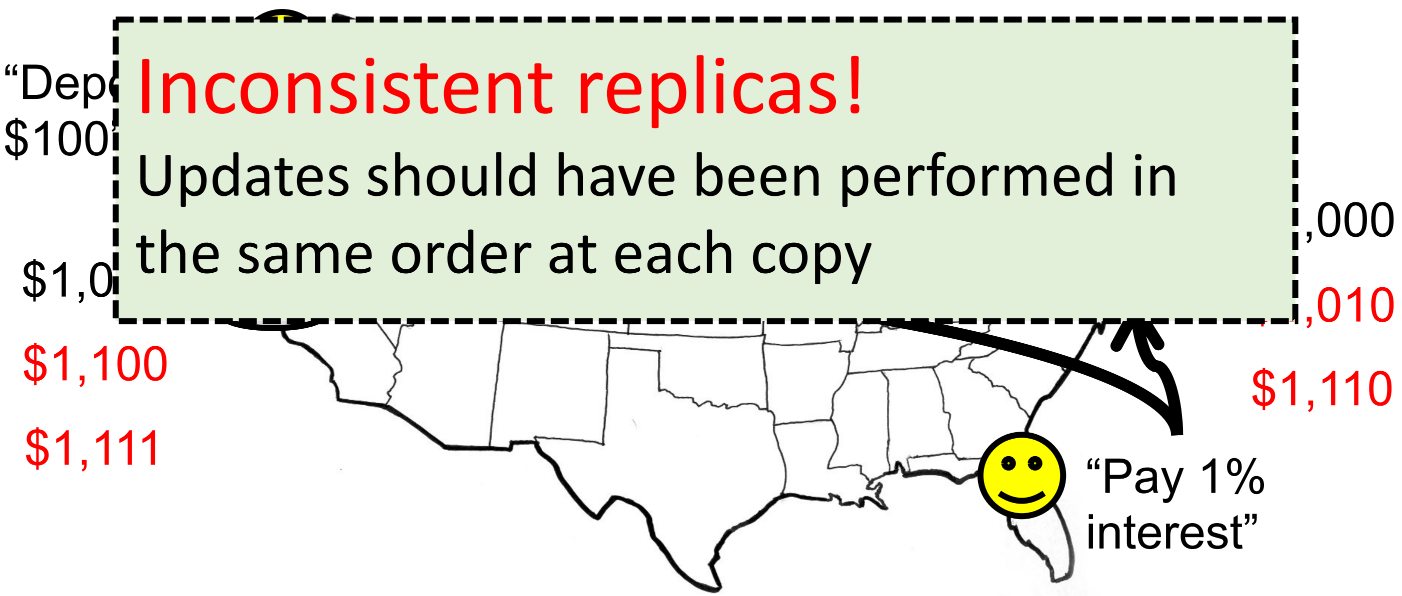
- A New York-based bank wants to make its transaction ledger database resilient to whole-site failures

- 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

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 $i < j$

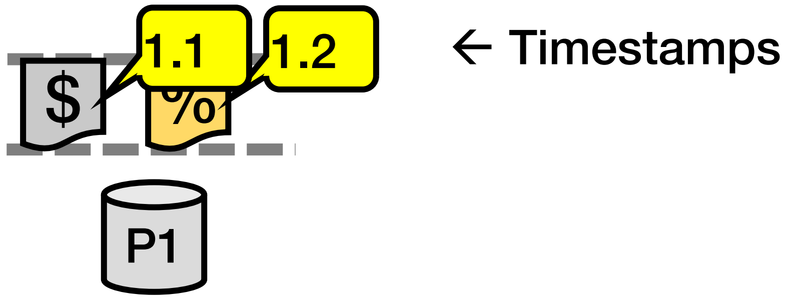
- Now, for any two events a and b, C(a) < C(b) or C(b) < C(a)
    - This is called a total ordering of events

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:



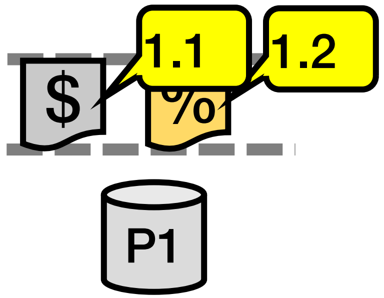
Totally-Ordered Multicast

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)

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)

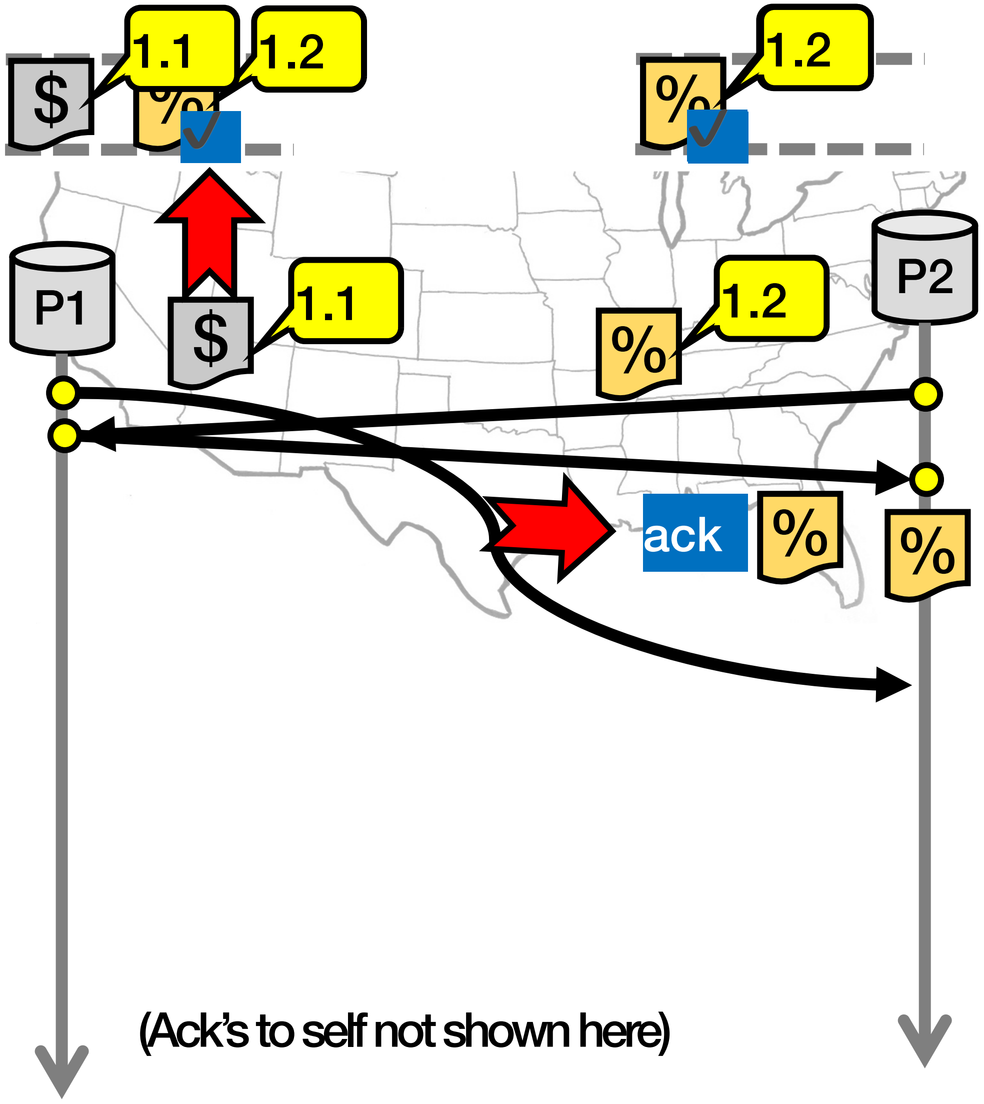
3. On receiving an acknowledgement:
   - Mark corresponding update acknowledged in your queue

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 %



(Ack's to self not shown here)

Totally-Ordered Multicast (Correct version)

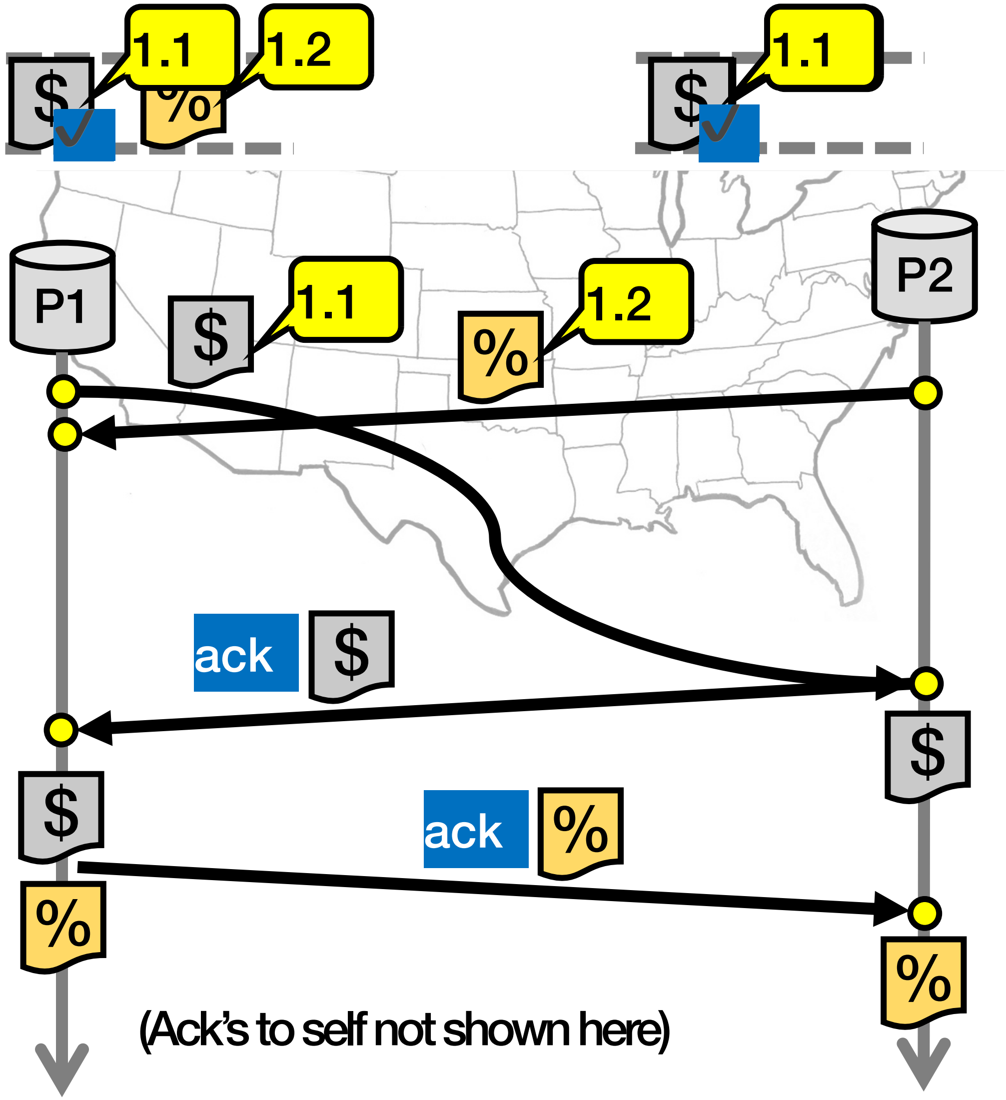
1. On receiving an update from client, broadcast to others (including yourself)

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 <u>everyone</u> has ack'ed from <u>head</u> 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?)

Lamport Clocks Review

Q: a → b => LC(a) < LC(b)

Q: LC(a) < LC(b) => b -/-> a (a → b or a || b)

Q: a || b => nothing

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 precisely 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

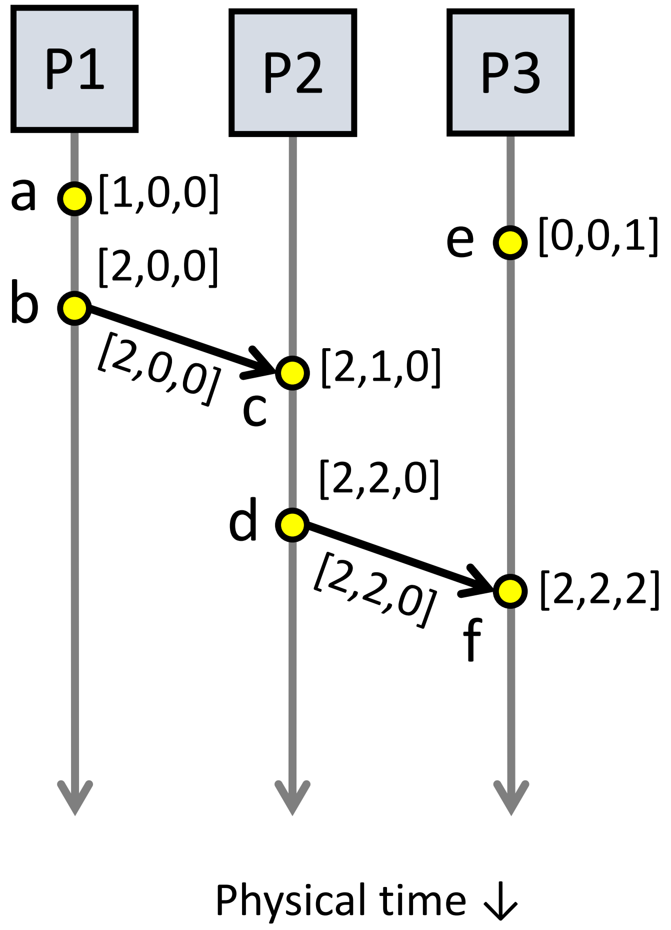
2. If process j receives message with vector $[d_1, d_2, \ldots, d_n]$:
    - Set each local entry $c_k = \max\{c_k, d_k\}$
    - Increment local entry c_j

Vector clock: Example

- All processes' VCs start at [0, 0, 0]

- Applying local update rule

- Applying message rule
  - Local vector clock piggybacks on inter-process messages



Comparing vector timestamps

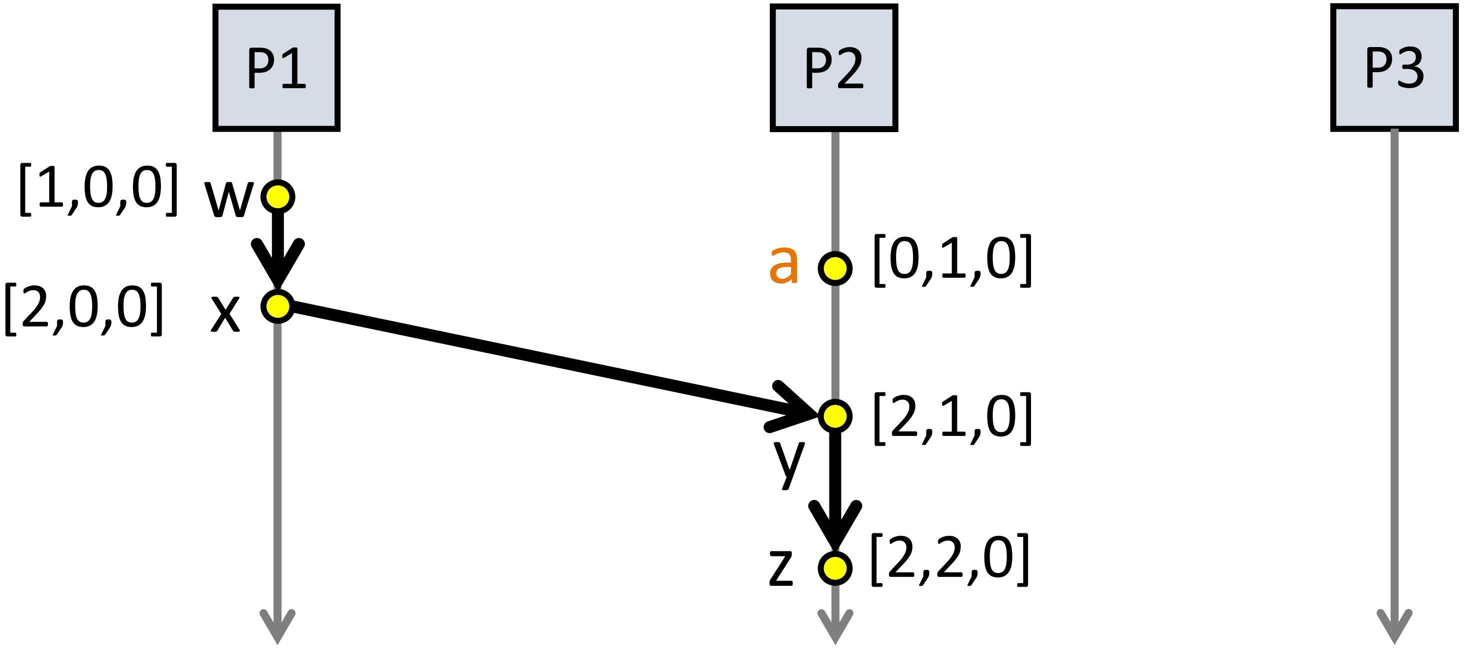
- Rule for comparing vector timestamps:
  - $V(a) = V(b)$ when $a_k = b_k$ for all k
  - $V(a) < V(b)$ when $a_k \leq b_k$ for all k and $V(a) \neq V(b)$

- Concurrency:
  - $a \mid\mid b$ 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

- V(a) || V(w) then there is no such chain of events between a and w



Two events a, z

Lamport clocks: C(a) < C(z)

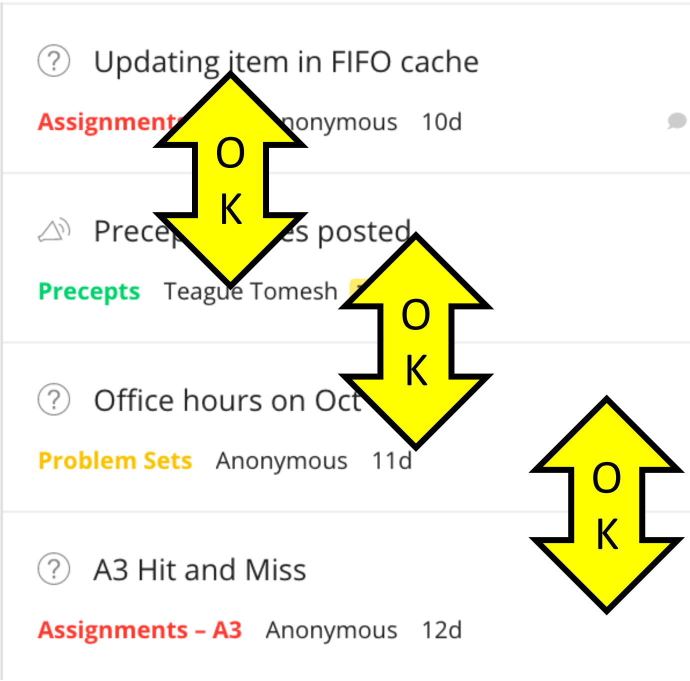
Conclusion: z -/-> a, i.e., either a → z or a || z

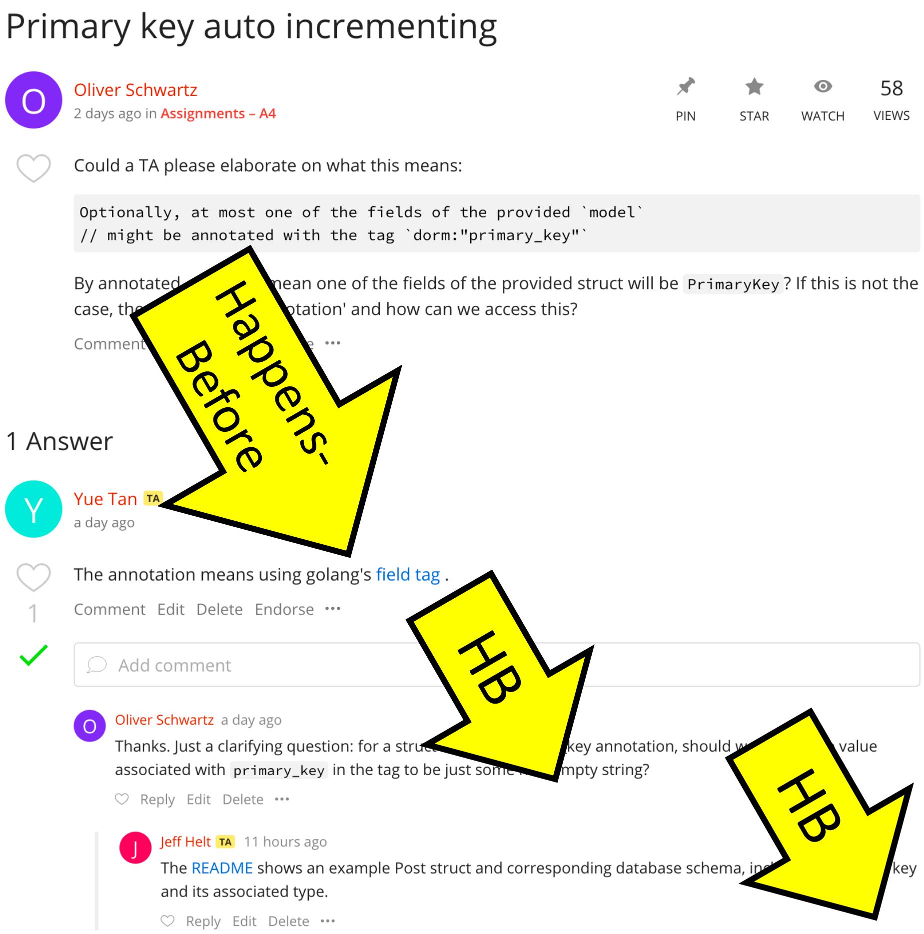
Vector clocks: V(a) < V(z)

Conclusion: a → z

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

Motivation: Distributed discussion board



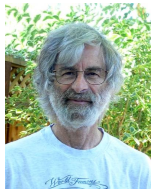


Distributed discussion board

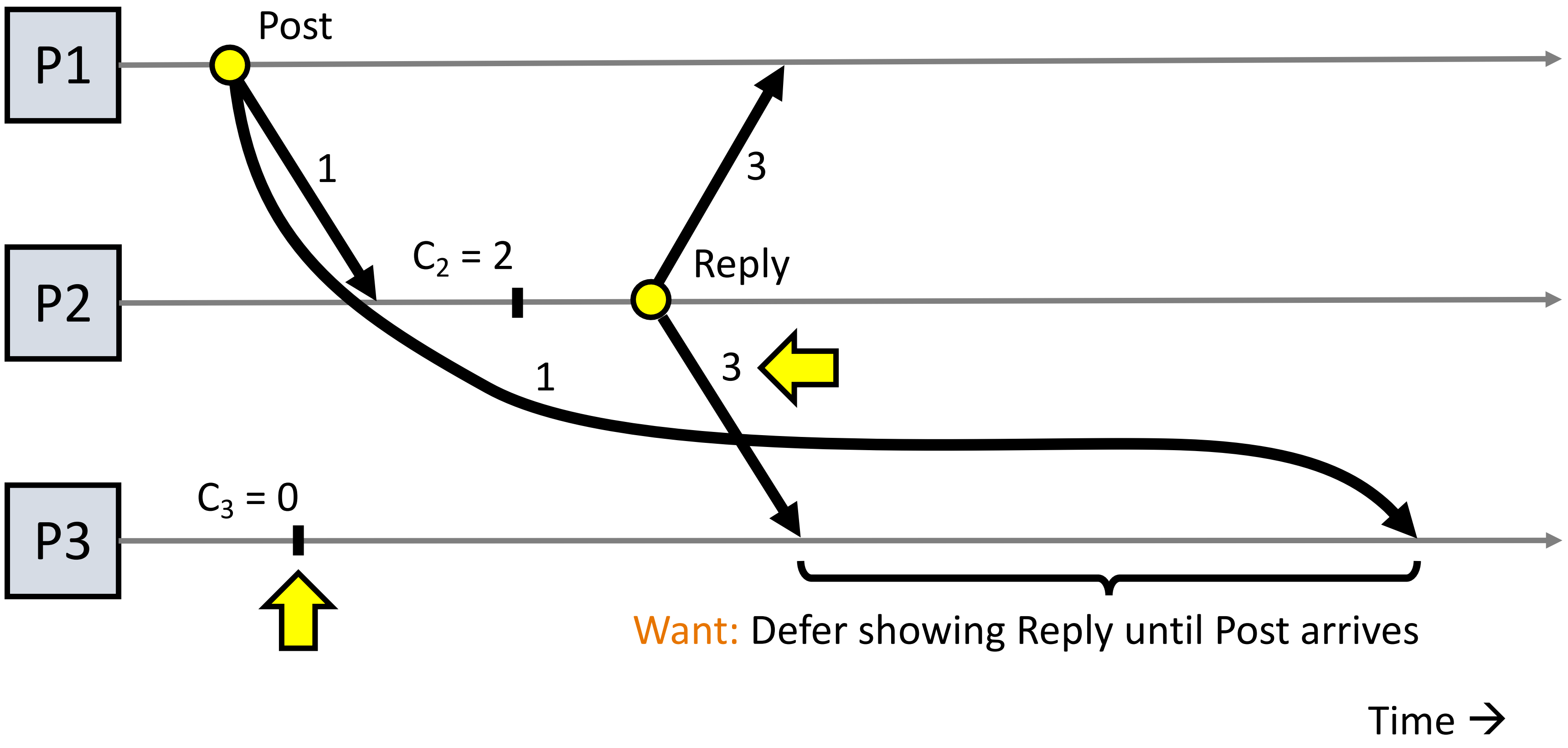
- Users join specific discussion groups
  - Each user runs a process on a different machine
  - Messages (posts or replies) sent to all users in group

- Goal: Ensure replies follow posts
- Non-goal: Sort posts and replies chronologically

- Q: Can Lamport Clocks help here?

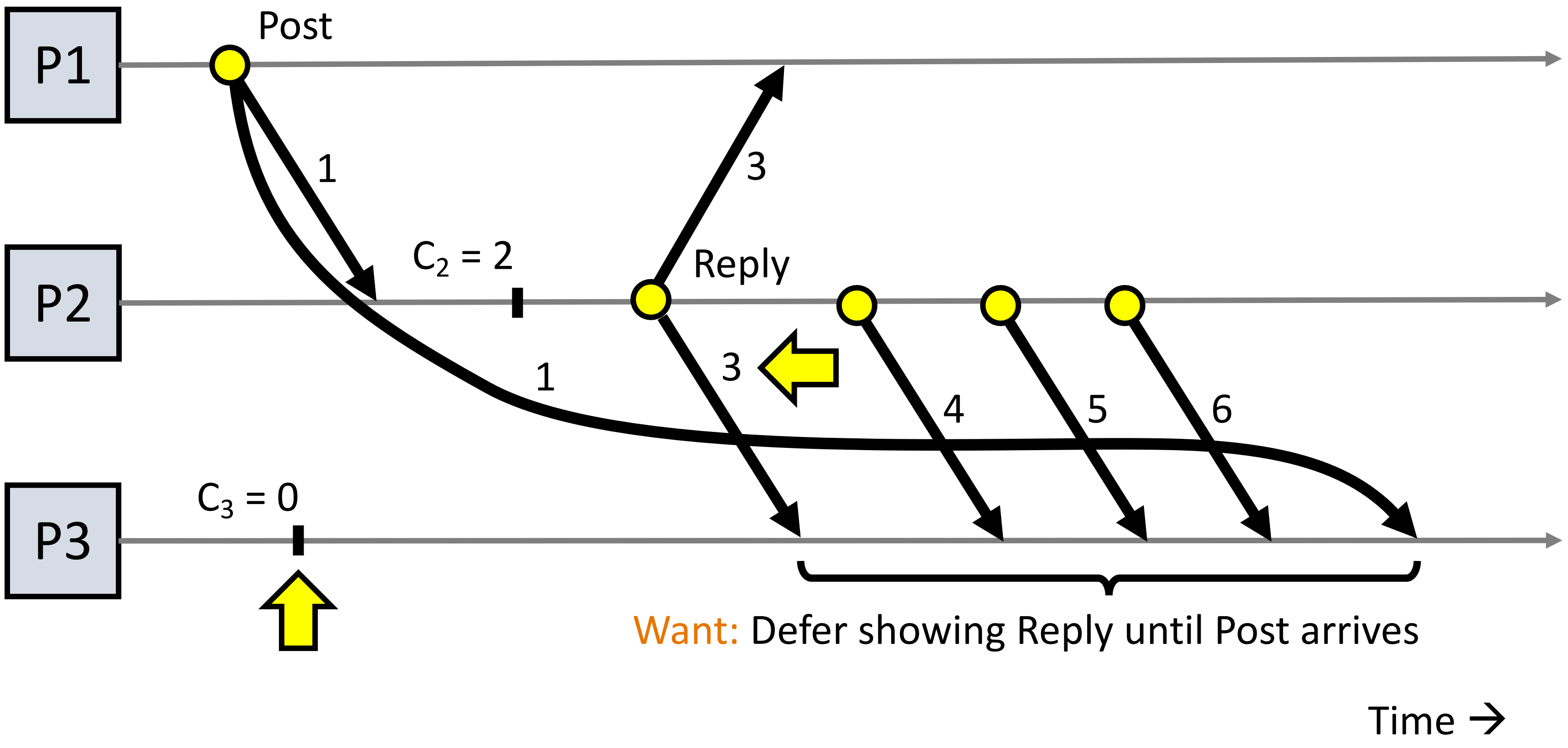


Lamport Clock-based discussion board



Proposal 1 : Defer showing message if C(message) > local clock + 1?

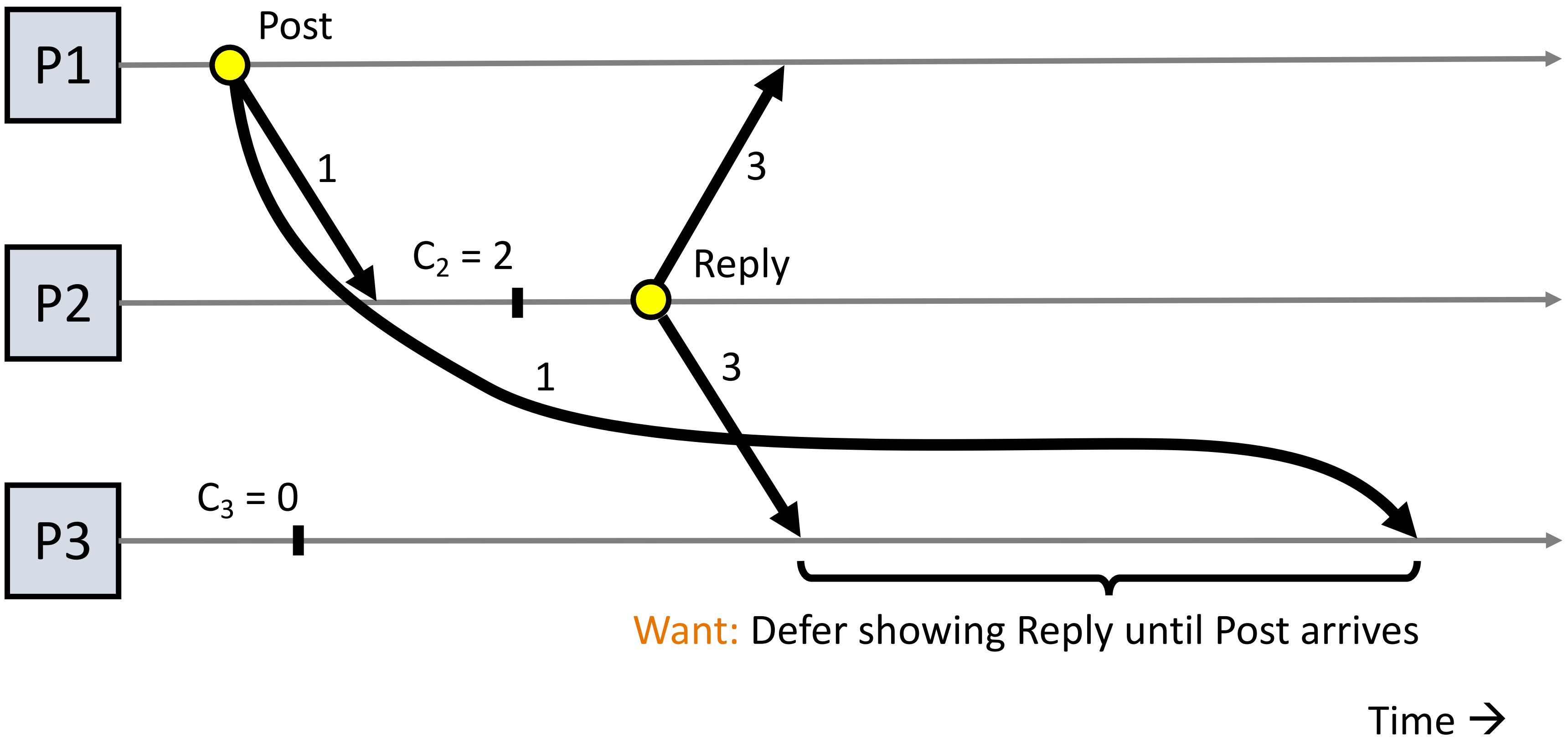
Lamport Clock-based discussion board



Proposal 1 : Defer showing message if C(message) > local clock + 1?

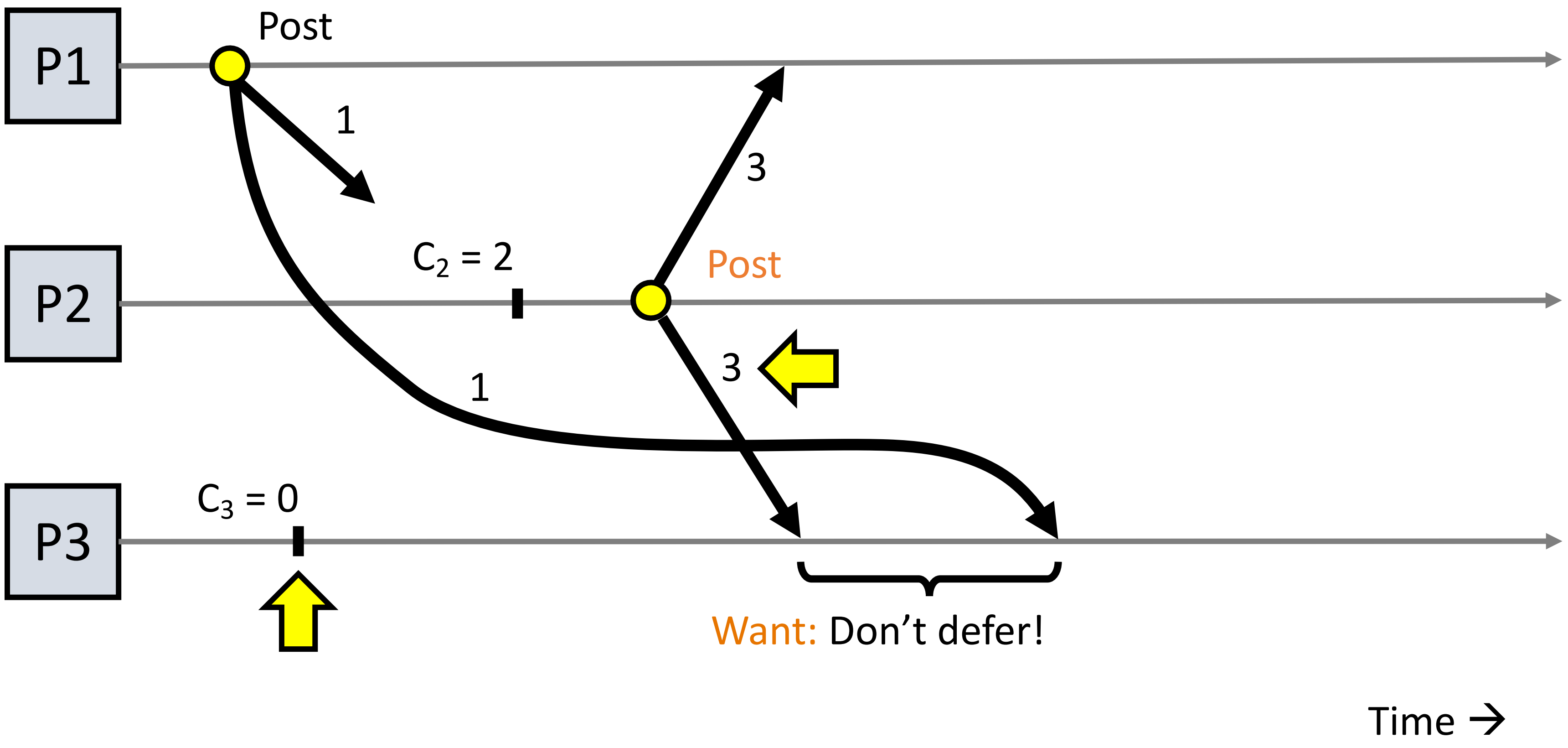
No! Local clock can be advanced by independent messages

Lamport Clock-based discussion board



Proposal 2: Use totally ordered multicast?

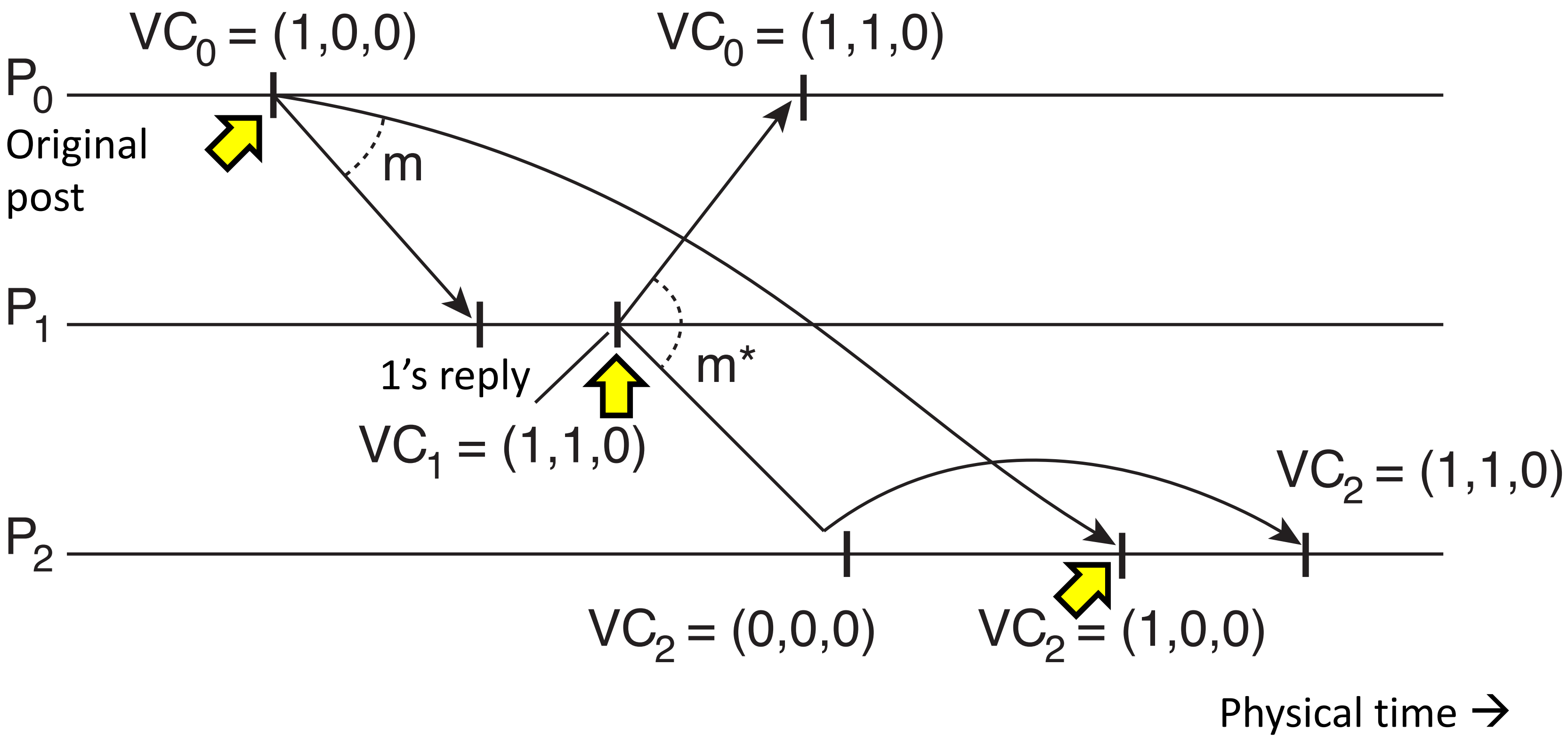
Lamport Clock-based discussion board



Proposal 2: Use totally ordered multicast?

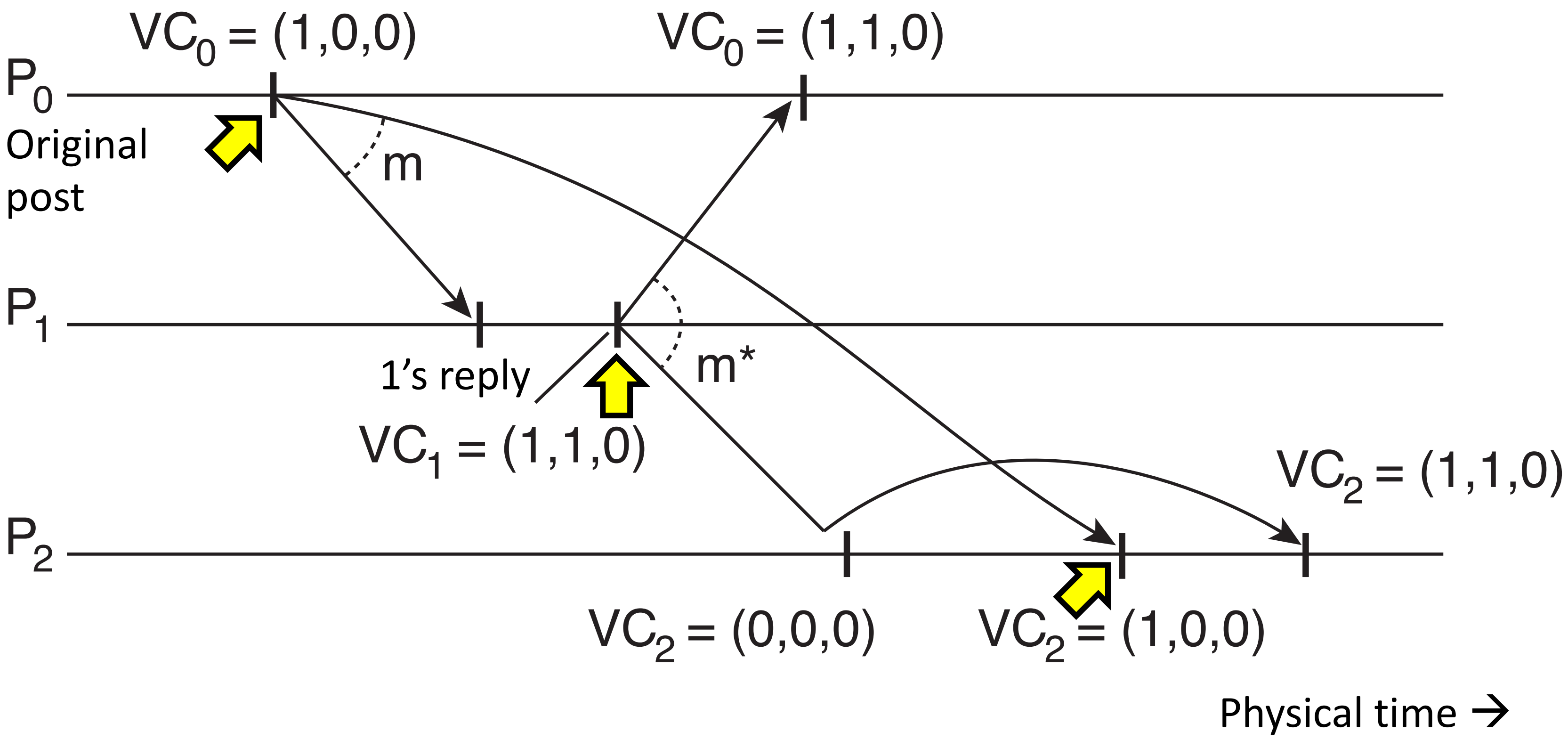
No! It's quite slow & gap could be due to other independent posts

VC application: Causally-ordered discussion board



Proposal 3: Defer showing message if C(message) > local clock + 1?

VC application: Causally-ordered discussion board



User 0 posts, user 1 replies to 0's post; user 2 observes

Logical Time Day 2 Conclusion

- Lamport clocks agree with happens-before
  - Easily extended to a total order
- Totally ordered multicast used lamport clocks!
  - Lamport clocks + careful protocol = correct replication
- Vector clocks capture happens-before (causality)
- Causally ordered discussion board
  - Totally ordered multicast correct … but loses performance (concurrency)
  - Vector clocks for precise causal ordering with more concurrency