Time 2: Totally Ordered Multicast & Vector Clocks

COS 418/518: Distributed Systems
Lecture 6

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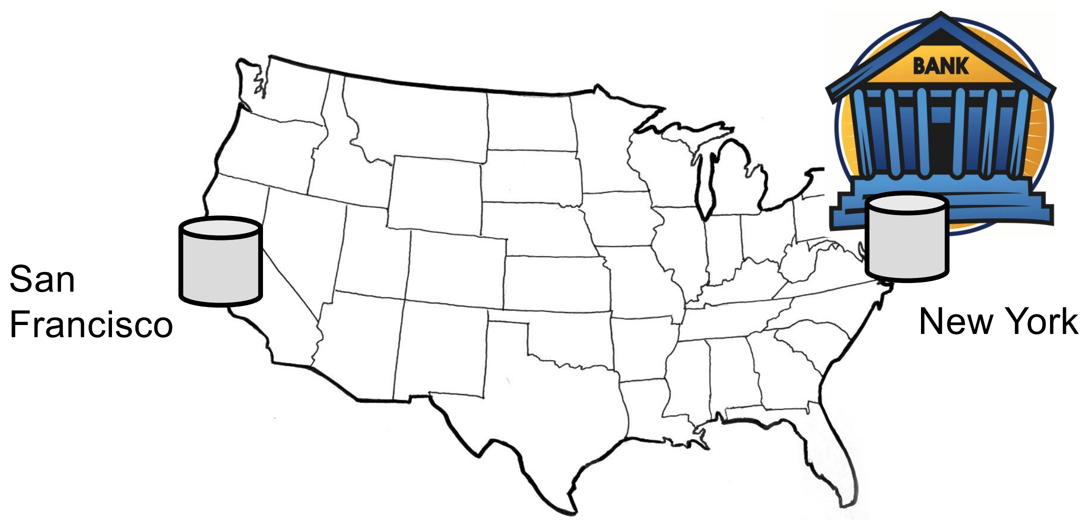
Motivation: Multi-site database replication

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

- 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

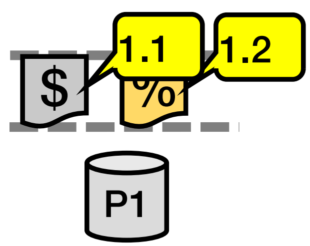
Totally-Ordered Multicast

Goal: All sites apply updates in (same) Lamport clock order

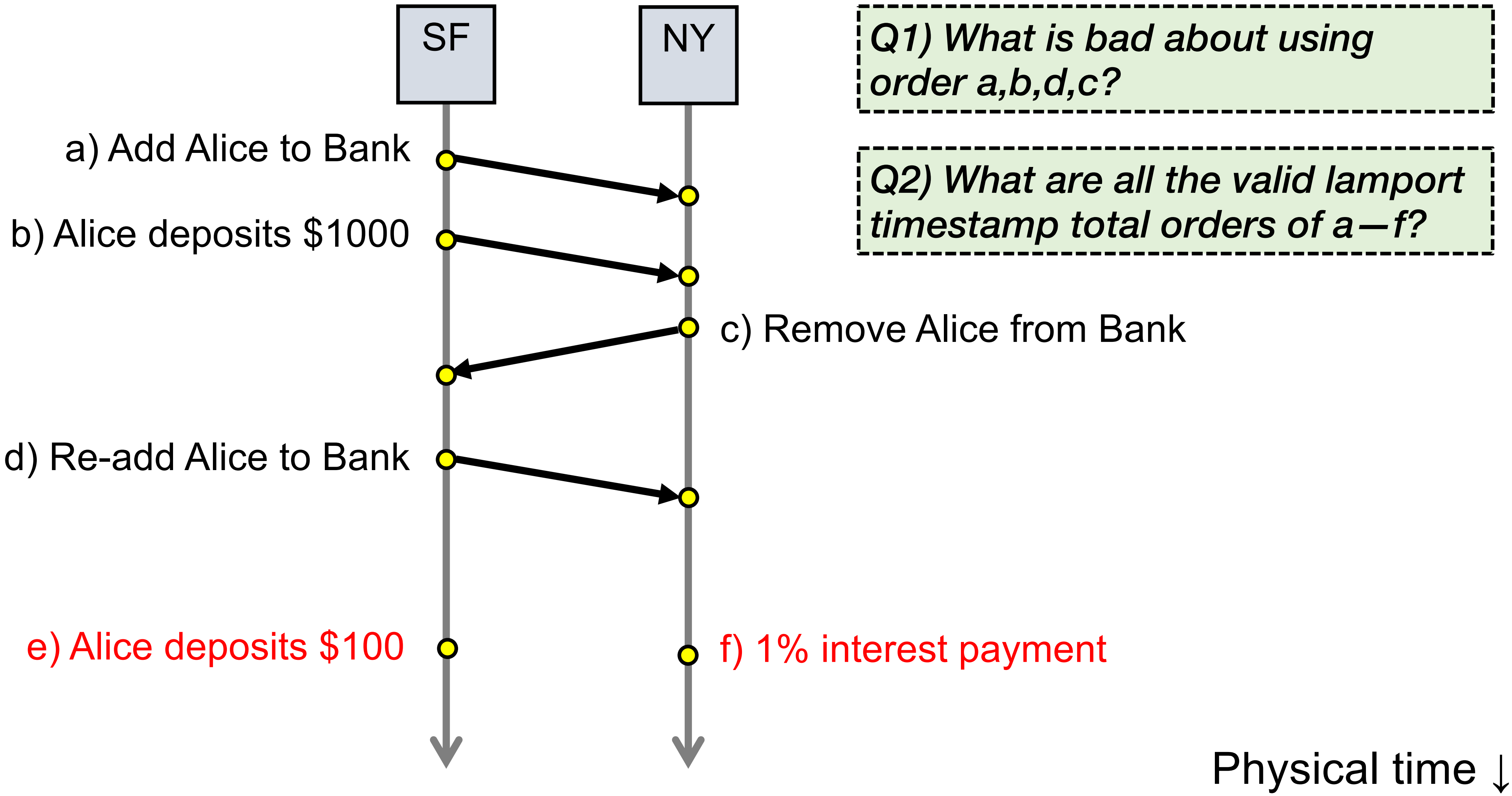
- Client sends update to one replica site *j*
  - Replica assigns it Lamport timestamp C_j . *j*

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

Example: P1's local queue:



← Timestamps


SF
NY
a) Add Alice to Bank
b) Alice deposits $1000
c) Remove Alice from Bank
d) Re-add Alice to Bank
e) Alice deposits $100
f) 1% interest payment
Physical time ↓
Q1) What is bad about using order a,b,d,c?
Q2) What are all the valid lamport timestamp total orders of a—f?

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)

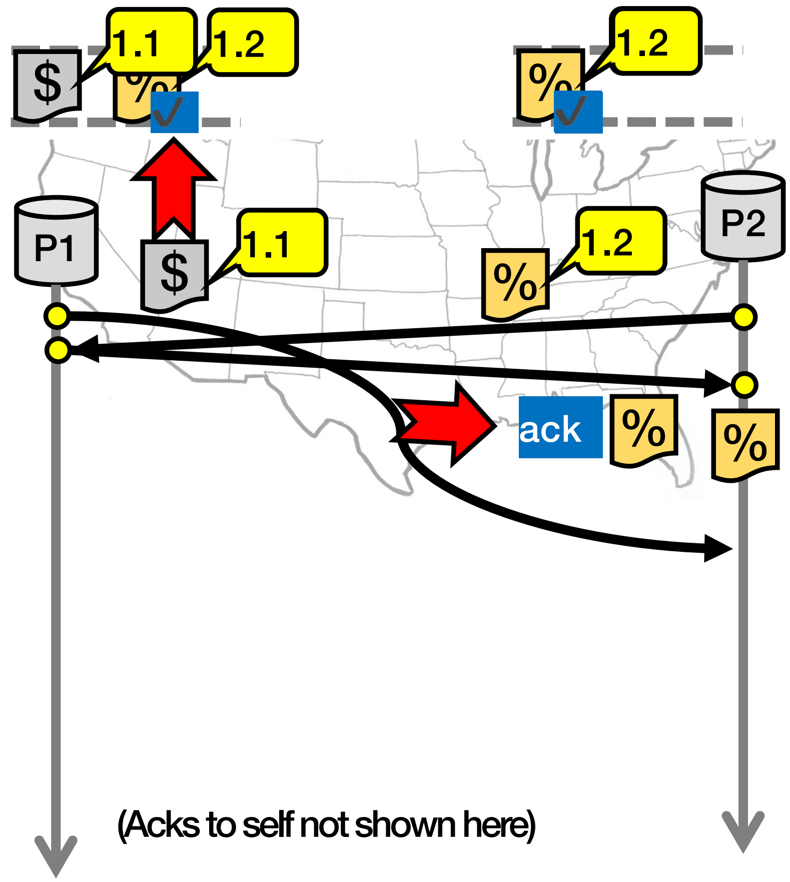
3. On receiving an acknowledgement:
   - Mark corresponding update acknowledged in your queue

4. Remove and process updates 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)

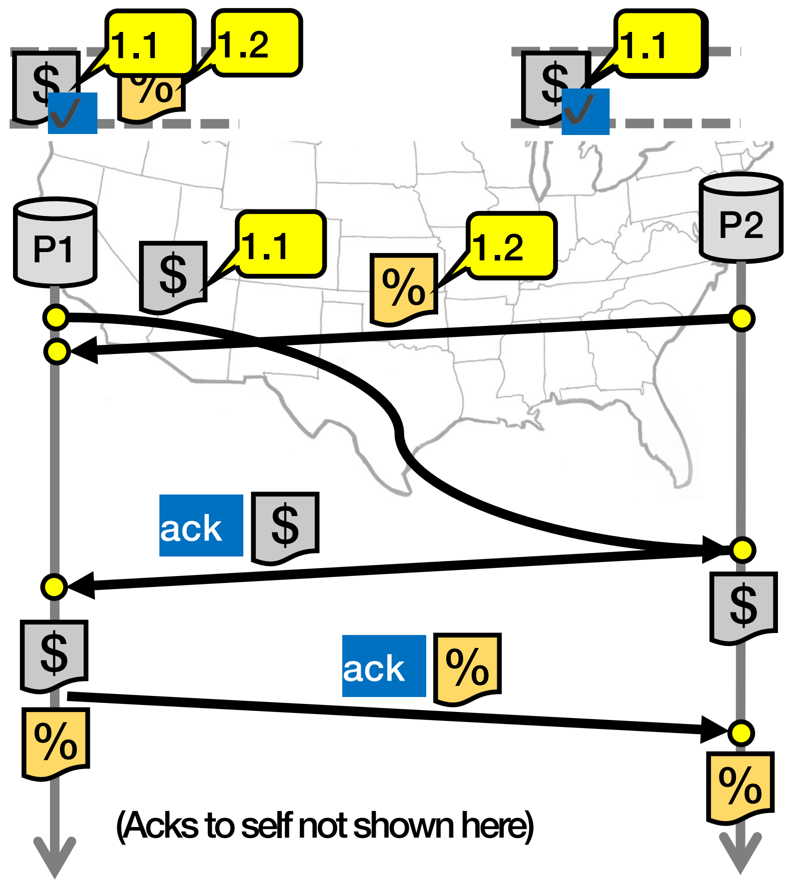
2. On receiving or processing an update:
   a) Add it to your local queue, if received update
   b) Broadcast an acknowledgement message to every replica (including yourself) only from head of queue

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

4. Remove and process updates <u>everyone</u> has ack'ed from <u>head</u> of queue

Why is this correct?

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?)

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 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 …, 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]

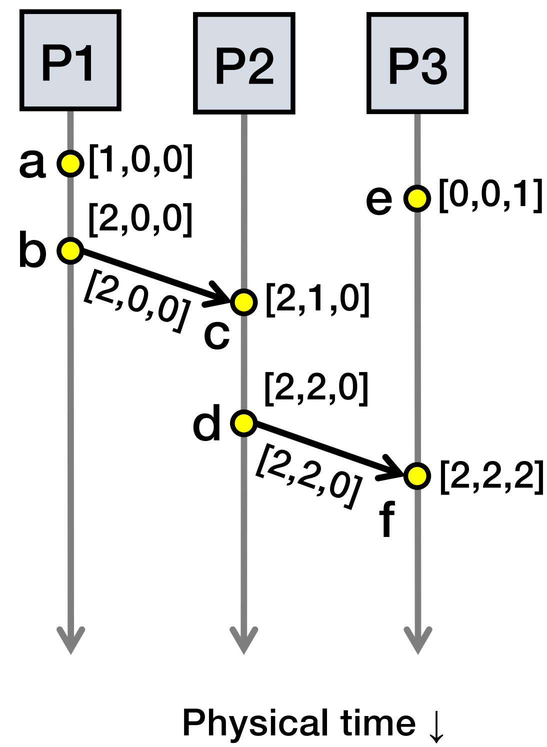
- Two update rules:

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

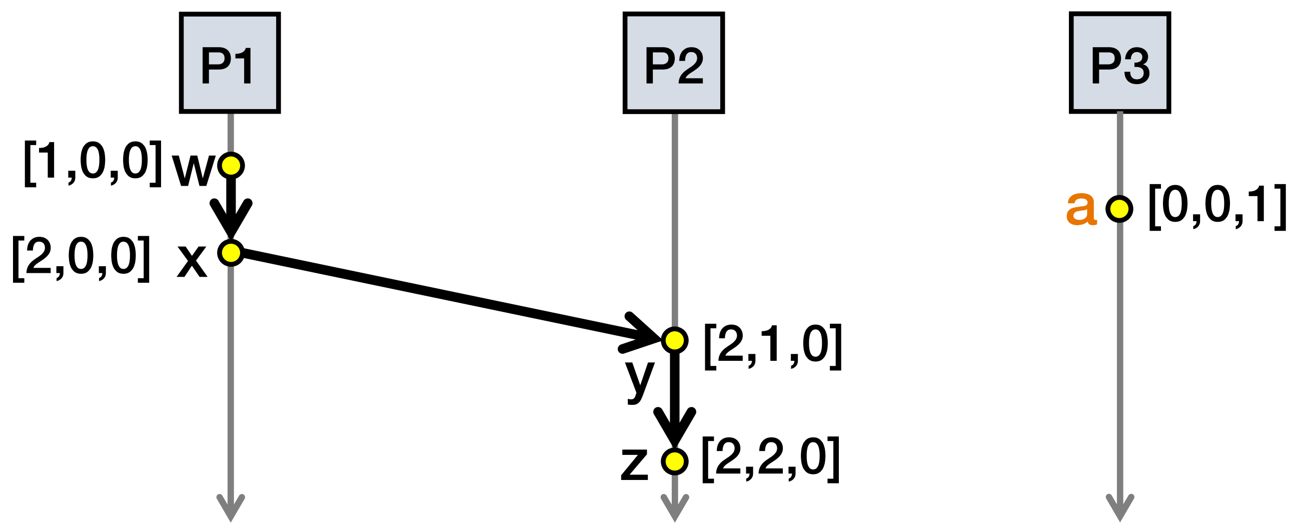
- Rule for comparing vector timestamps:
  - $V(a) = V(b)$ when $a_k = b_k$ for all k
  - $V(a) < V(b)$ when $a_k \leq b_k$ for all k and $V(a) \neq V(b)$

- Concurrency:
  - $V(a) \| V(b)$ 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

- 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

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

Conclusion: a → z

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