# Eventual Consistency: Bayou

CS 240: Computing Systems and Concurrency
Lecture 6

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# Availability versus consistency

- Totally-Ordered Multicast **kept replicas consistent** but had **single points of failure**
  - **Not available** under failures

- (*Later*): **Distributed consensus algorithms**
  - **Strong consistency** (ops in same order everywhere)
  - But, **strong reachability requirements**

If the **network fails** (common case), **can we provide any consistency** when we replicate?

# Eventual consistency

- ***Eventual consistency:*** If no new updates to the object, **eventually** all reads will return the last updated value
- **Common:** git, iPhone sync, Dropbox, Amazon Dynamo
- Why do people like eventual consistency?
  - **Fast read/write** of **local** copy
  - **Disconnected operation**

**Issue:** **Conflicting writes** to different copies
**How to reconcile** them when discovered?

# Bayou: A Weakly Connected Replicated Storage System

- **Meeting room calendar application** as case study in ordering and conflicts in a distributed system with poor connectivity
- Each **calendar entry** = room, time, set of participants
- Want **everyone** to see the **same** set of entries, **eventually**
  - Else users may **double-book room**
    - or avoid using an **empty** room

# Paper context

- Early ’90s when paper was written: Dawn of PDAs, laptops, tablets
  - H/W clunky but showing clear potential

- Commercial devices **did not have wireless**

- **This problem has not gone away!**
  - Devices might be off, not have network access
    - Mainly outside the context of datacenters
  - Local write/reads still really fast
    - In datacenters when replicas are far away (geo-replicated)

# Why not just a central server?

- Want my calendar on a disconnected mobile phone
  - *i.e.,* each user wants database replicated on their mobile device
  - No master copy

- But phone has only **intermittent connectivity**
  - **Mobile data** expensive when roaming, **Wi-Fi** not everywhere, all the time
  - **Bluetooth** useful for direct contact with other calendar users' devices, but very short range

# Swap complete databases?

- Suppose two users are in Bluetooth range
  - Each sends entire calendar database to other
  - Possibly expend **lots of network bandwidth**

- What if the calendars **conflict**, *e.g.*, the two calendars have concurrent meetings in a room?
  - iPhone sync keeps both meetings

  - Want to do better: **automatic conflict resolution**

# Automatic conflict resolution: Granularity of "conflicts"

- **Can't** just view the calendar database as abstract **bits:**
  - **Too little information** to resolve conflicts:

1. "Both files have changed" can **falsely conclude** entire databases conflict
   - e.g., Mon 10am meeting in room 3 and Tuesday 11am meeting in room 4

2. "Distinct record in each database changed" can **falsely conclude** no conflict
   - e.g., Mon 10–11am meeting in room 3 Doug attending, Mon 10-11am meeting in room 4 Doug attending, …

# Application-specific conflict resolution

- Want intelligence that **knows how to resolve conflicts**
  - More like **users' updates:** read database, think, change request to eliminate conflict
  - Must ensure all nodes **resolve conflicts in the same way** to keep replicas consistent

# Application-specific update functions

- Suppose calendar update takes form:
  - "10 AM meeting, Room=305, CS-240 staff"
  - **How would this handle conflicts?**

- **Better:** write is an **update function** for the **app**
  - "1-hour meeting at 10 AM if room is free, else 11 AM, Room=305, CS-240 staff"

# Potential Problem: Permanently inconsistent replicas

- Node **A** asks for meeting **M1** at 10 AM, else 11 AM
- Node **B** asks for meeting **M2** at 10 AM, else 11 AM

- **X** syncs with **A,** then **B**
- **Y** syncs with **B,** then **A**

- **X** will put meeting **M1** at **10:00**
- **Y** will put meeting **M1** at **11:00**

**Can't just apply** update functions when replicas sync

# Totally order updates and replicate!

- Maintain an **ordered list of updates** at each node

  ***Write log***

  – Make sure every node holds **same updates**
    - And applies updates in the **same order**

  – Make sure updates are a **deterministic** function of database contents

- If we obey the above, "sync" is a **simple merge** of two ordered lists

# Agreeing on the update order

- **Timestamp:** ⟨local timestamp **T**, originating node **ID**⟩

- Ordering updates a and b:
  - a < b if a.T < b.T, or (a.T = b.T and a.ID < b.ID)

# Write log example

- ⟨701, A⟩: A asks for meeting **M1** at 10 AM, else 11 AM
- ⟨770, B⟩: B asks for meeting **M2** at 10 AM, else 11 AM

**Timestamp**

- **Pre-sync** database state:
  - A has M1 at 10 AM
  - B has M2 at 10 AM

- What's the **correct eventual outcome?**
  - The result of executing update functions in **timestamp order**: M1 at 10 AM, M2 at 11 AM

# Write log example: Sync problem

- ⟨701, A⟩: A asks for meeting **M1** at 10 AM, else 11 AM
- ⟨770, B⟩: B asks for meeting **M2** at 10 AM, else 11 AM

- **Now A and B sync with each other.** Then:
  - Each sorts new entries into its own log
    - Ordering by timestamp
  - **Both now know** the **full set** of updates

- **A** can just **run B's update function**
- But **B** has **already** run B's operation, **too soon!**

# Solution: Roll back and replay

- **B** needs to **“roll back”** the DB, and **re-run both ops** in the **correct order**

- Bayou User Interface: Displayed meeting room calendar entries are **“Tentative” at first**
  - B’s user saw M2 at 10 AM, then it moved to 11 AM

**Big point:** The **log** at each node holds the **truth**; the **DB** is just an **optimization**

# Does update order respect causality?

- ⟨701, A⟩: **A** asks for meeting **M1** at 10 AM, else 11 AM
- ⟨700, B⟩: **Delete update** ⟨701, A⟩
  - Possible if **B's** clock is **slow**, and using real-time timestamps

- Result: **delete will be ordered before add**
  - (Delete never has an effect.)

- Q: How can we assign timestamp to respect causality?

# Lamport clocks respect causality

- Want event timestamps so that **if** a node observes **E1** then generates **E2**, **then TS(E1) < TS(E2)**

- Use Lamport clocks!
  - If E1 → E2 then TS(E1) < TS(E2)

# Lamport clocks respect causality

- ⟨701, A⟩: A asks for meeting M1 at 10 AM, else 11 AM
- ~~⟨700, B⟩: Delete update ⟨701, A⟩~~
- ⟨706, B⟩: Delete update ⟨701, A⟩

- With Lamport clocks:
  - When A sends ⟨701, A⟩, it includes its clock, T (> 701)
  - When B receives ⟨701, A⟩, it updates its clock to T' > T
  - When B creates the delete, it timestamps it with clock T'' > T'
  - T'' > T' > T > 701
    - E.g., T'' is 706

Q: What if A and B are concurrent?
A: Lamport timestamps provide some total ordering of events

# Timestamps for write ordering: Limitations

- **Never know** whether **some write from "the past"** may yet reach your node…
    - So all entries in log must be **tentative forever**
    - And you must **store entire log forever**

Want to **commit** a tentative entry,
so we can **trim logs** and **have meetings**

# Fully decentralized commit

- **Strawman proposal:** Update ⟨10, A⟩ is **committed** when **all nodes** have seen all updates with TS ≤ 10

- Have sync always send in **log order**
- If you have seen updates with TS > 10 **from every node** then you'll never again see one < ⟨10, A⟩
  - So ⟨10, A⟩ is committed

- Why doesn't Bayou do this?
  - A server that **remains disconnected** could prevent writes from committing
    - So **many writes** may be **rolled back** on re-connect

# How Bayou commits writes

- Bayou uses a **primary commit** scheme
  - One designated node (the **primary**) commits updates
- Primary marks each write it receives with a permanent **CSN** (commit sequence number)
  - That write is **committed**
  - **Complete timestamp** = **⟨CSN, local TS, node-id⟩**

> **Advantage:** Can pick a **primary server** close to **locus of update activity**

# How Bayou commits writes (2)

- Nodes **exchange CSNs** when they **sync** with each other

- **CSNs define a total order** for committed writes
  - All nodes eventually agree on the total order
  - **Tentative** writes come **after** all **committed writes**

# Committed vs. tentative writes

- Suppose a node has seen every CSN up to a write, as guaranteed by propagation protocol

  - Can then **show user** the write has **committed**
    - Mark calendar entry "Confirmed"

- **Slow/disconnected** node **cannot prevent commits!**
  - Primary replica allocates CSNs

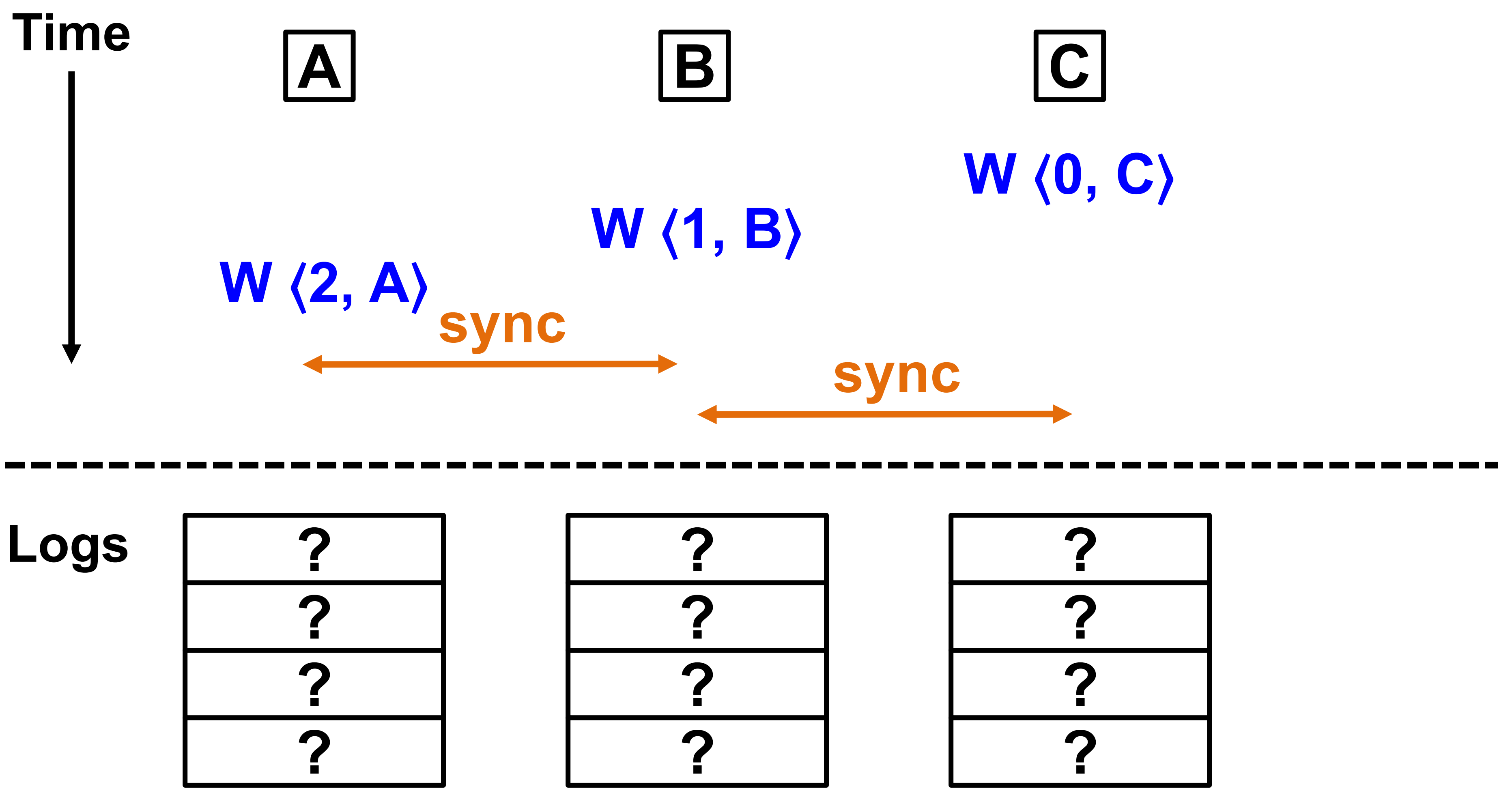
# Tentative writes

- What about **tentative writes**, though—how do they behave, as seen by users?

- Two nodes may **disagree** on meaning of **tentative writes**
  - Even if those two nodes have **synced** with each other!

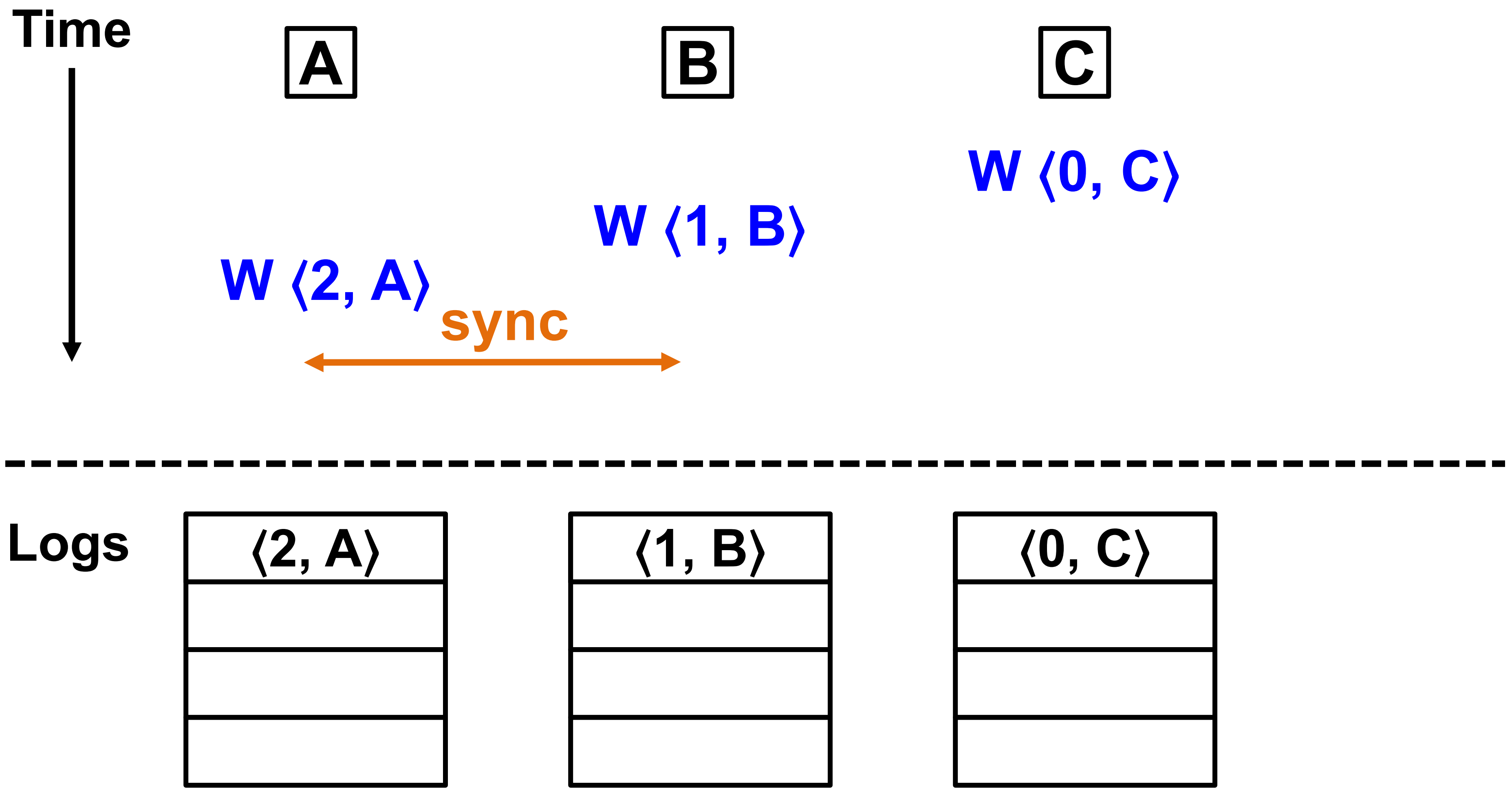
  - Only **CSNs** from primary replica can **resolve** these disagreements permanently

# Scenario 1: nodes that have synced disagree



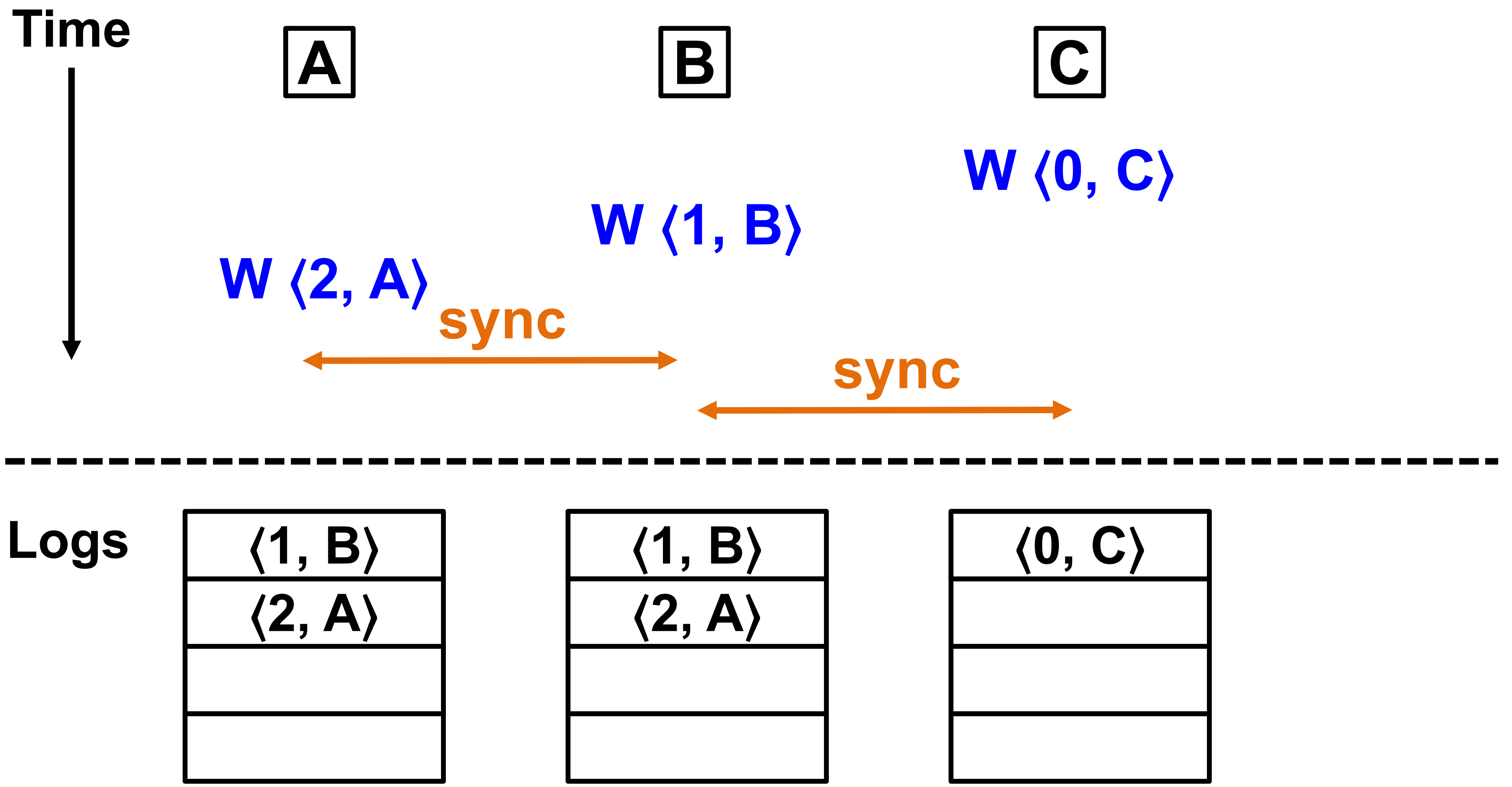

⟨local TS, node-id⟩

# Example: Disagreement on tentative writes



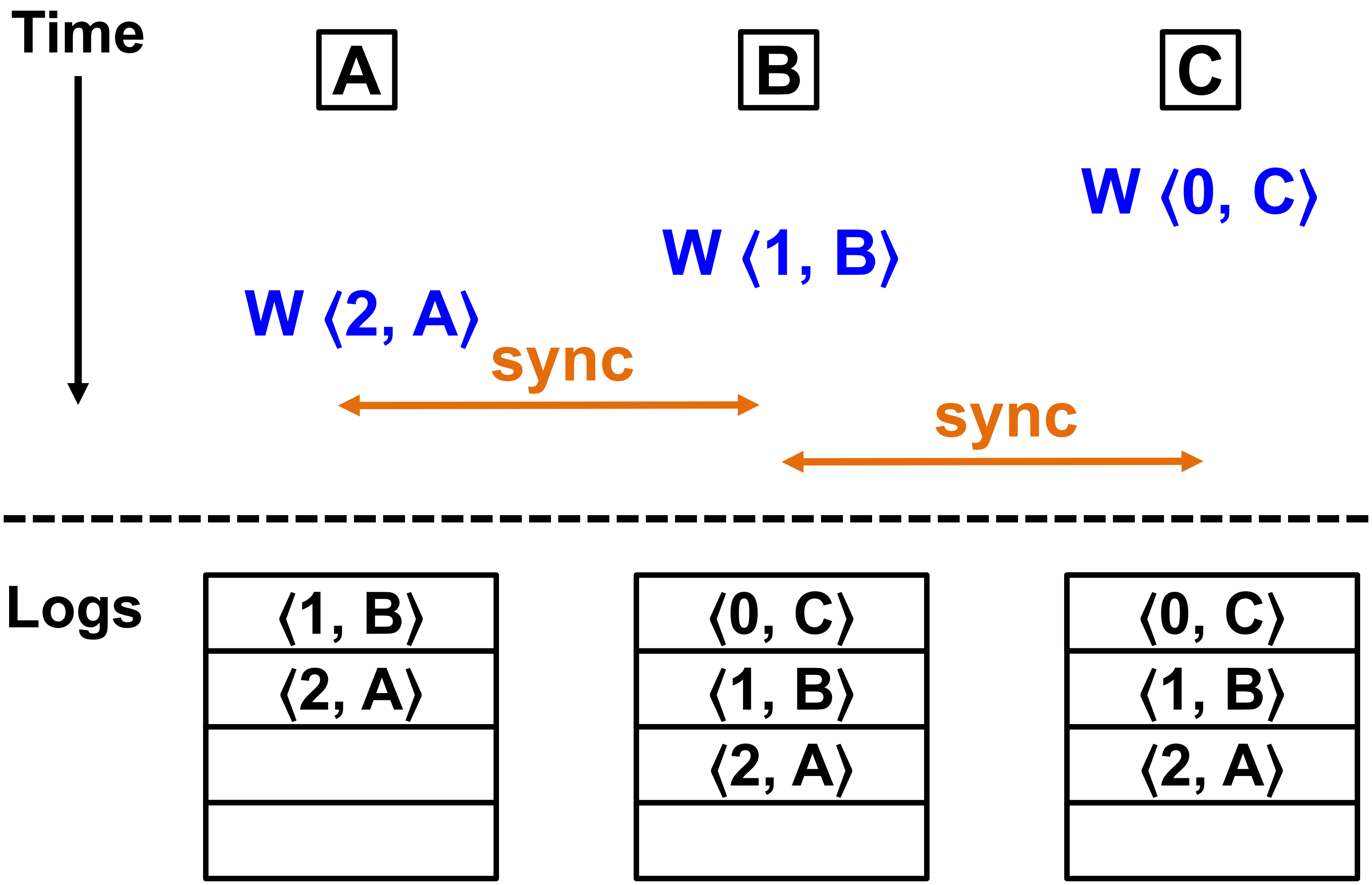

⟨local TS, node-id⟩

# Example: Disagreement on tentative writes



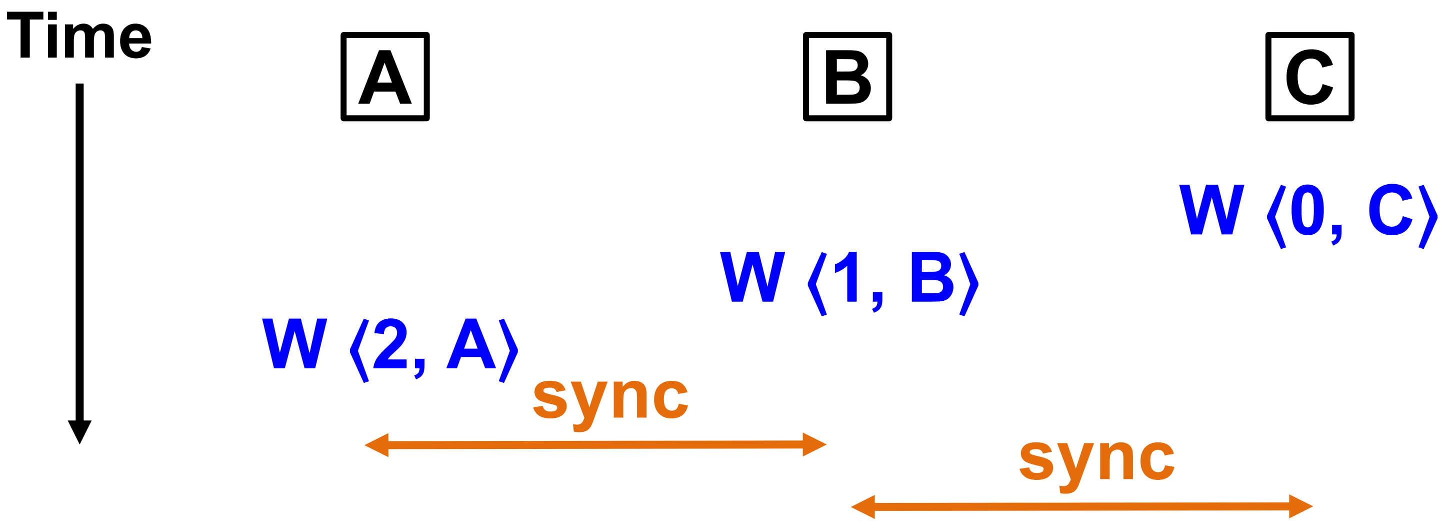

⟨local TS, node-id⟩

# Example: Disagreement on tentative writes




⟨local TS, node-id⟩

# Example: Disagreement on tentative writes



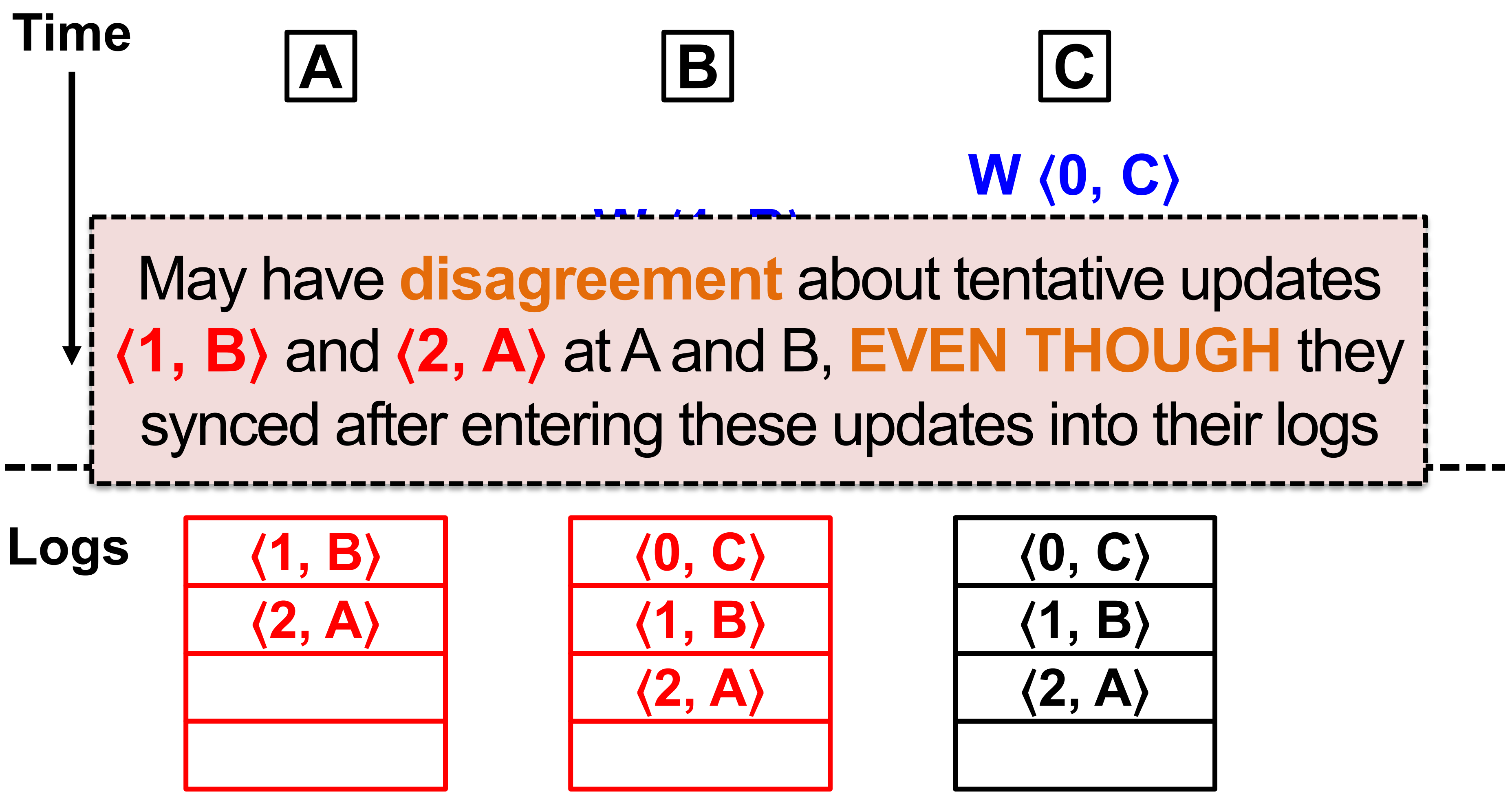

**Logs**

| A | B | C |
|---|---|---|
| ⟨1, B⟩ | ⟨0, C⟩ | ⟨0, C⟩ |
| ⟨2, A⟩ | ⟨1, B⟩ | ⟨1, B⟩ |
| | ⟨2, A⟩ | ⟨2, A⟩ |
| | | |

⟨local TS, node-id⟩

1

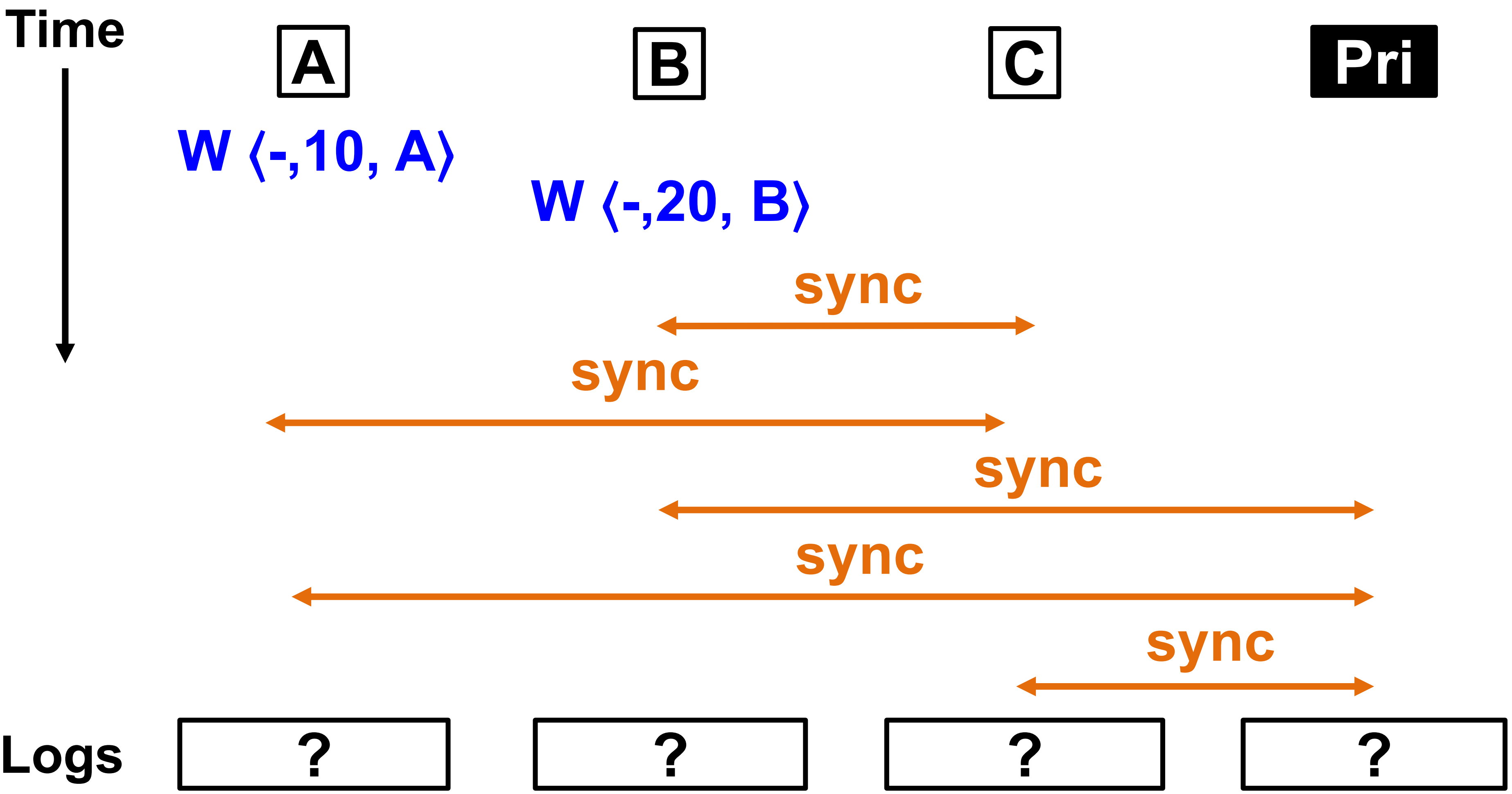
# Example: Disagreement on tentative writes




⟨local TS, node-id⟩

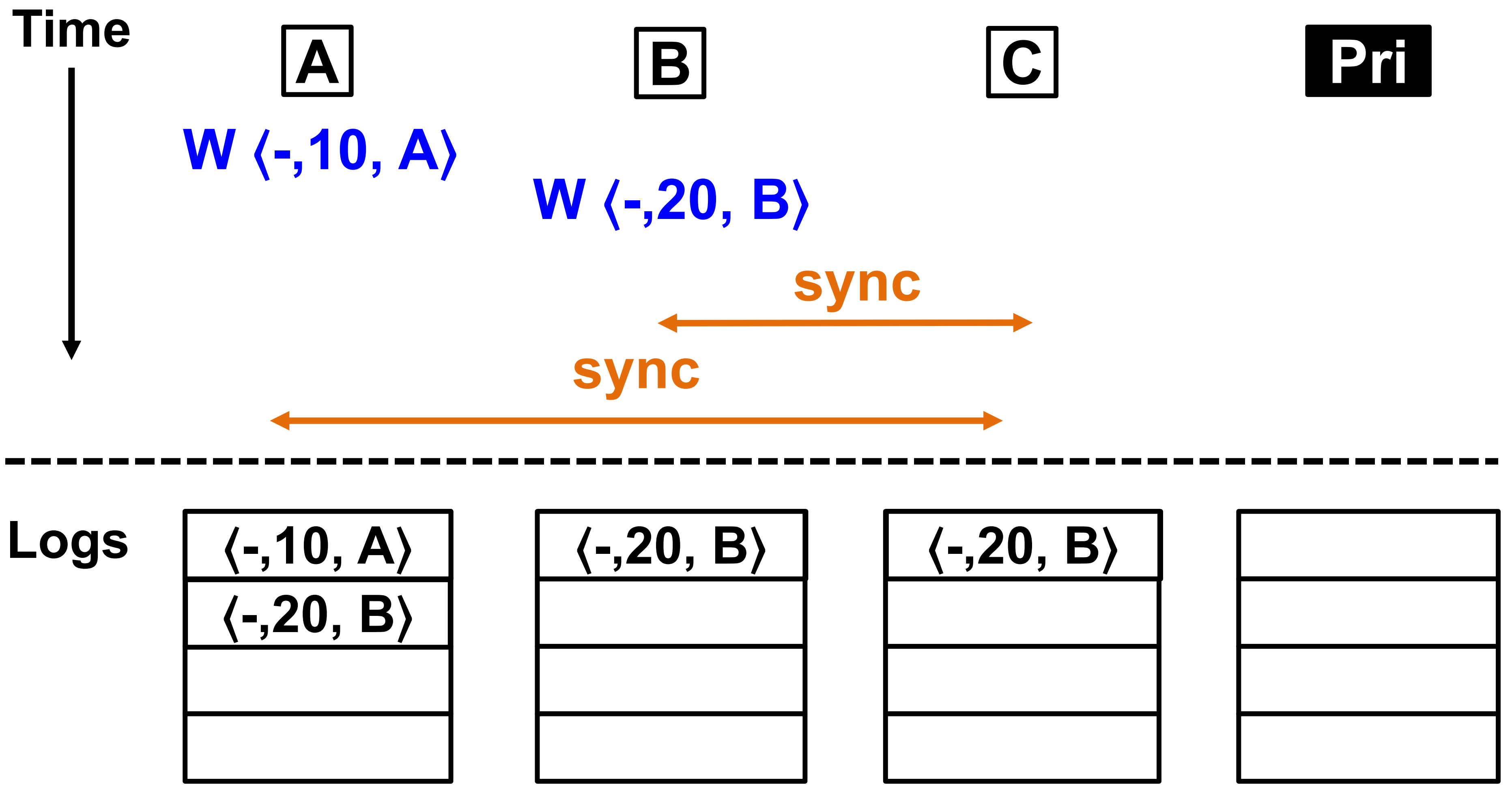
# Scenario 2: tentative order changes after commit

2




⟨CSN, local TS, node-id⟩

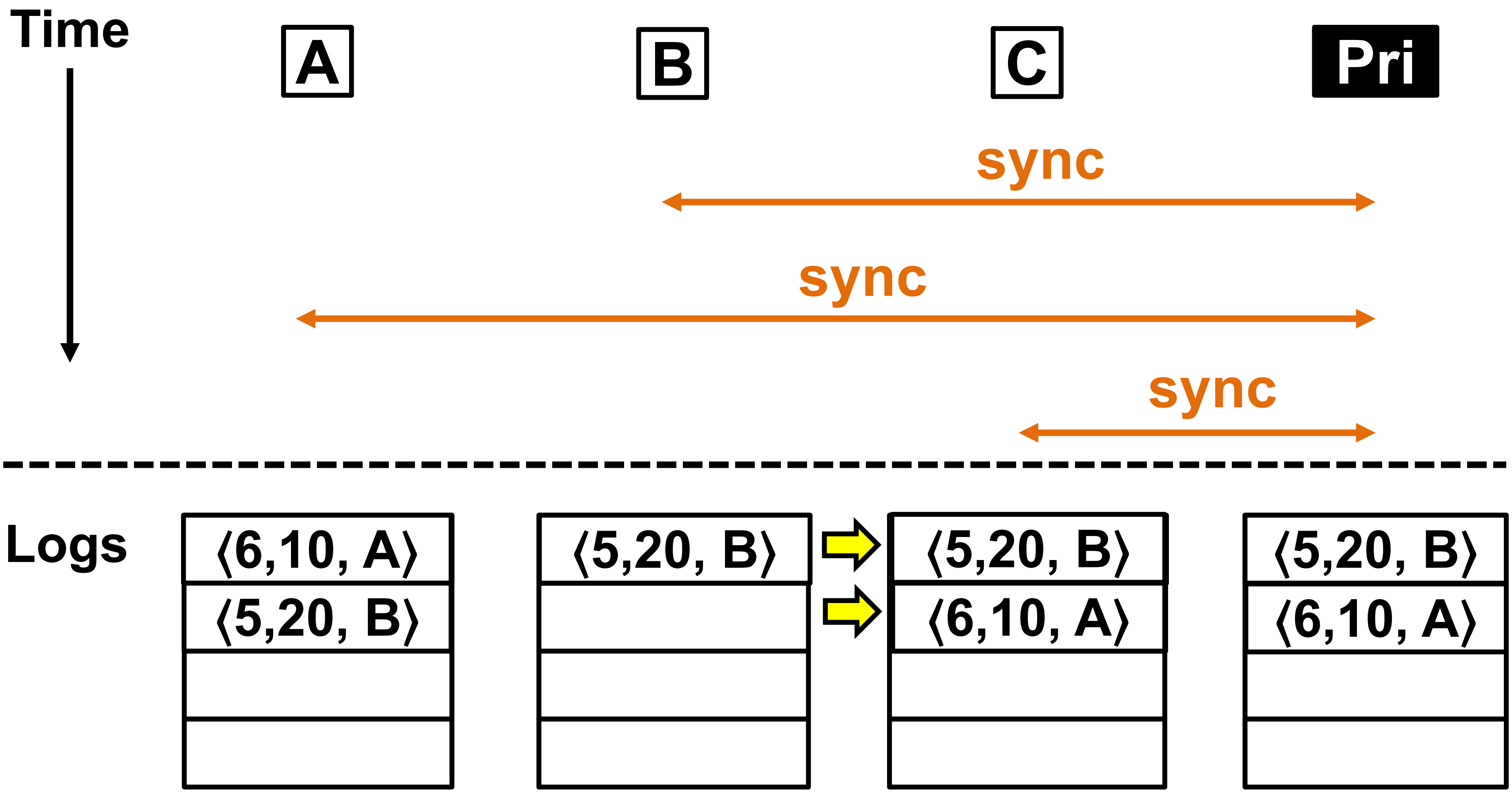
# Tentative order ≠ commit order




⟨CSN, local TS, node-id⟩

2

# Tentative order ≠ commit order




⟨CSN, local TS, node-id⟩

# Primary commit order constraint

- Suppose a user **creates meeting**, then decides to **delete or change it**
  - What **CSN order** must these ops have?
    - Create **first, then** delete or modify
    - Must be true in every node's view of tentative log entries, too

- **Rule:** Primary's total write order **must preserve causal order** of writes
  - Q: How?

# Primary preserves causal order

- **Rule:** Primary's total write order **must preserve causal order** of writes

- How?
  - Nodes sync **full** logs
    - If **A** → **B** then **A** is in all logs before **B**
  - Primary orders newly synced writes in **tentative order**
    - Primary will commit **A** and then commit **B**

# Trimming the log

- When nodes receive new CSNs, can **discard** all committed log entries seen up to that point
  - Update protocol → **CSNs received in order**

- Keep copy of whole database as of highest CSN

- **Result:** **No need** to keep years of **log data**

# Let’s step back

- *Is eventual consistency a useful idea?*
- **Yes:** people want **fast writes to local copies** iPhone sync, Dropbox, **Dynamo**, *…*

- *Are update conflicts a real problem?*
- Yes—all systems have some more or less awkward solution

# Is Bayou's complexity warranted?

- update functions, tentative ops, …
- Only critical if you want **peer-to-peer sync**
  - *i.e.* both **disconnected operation and ad-hoc connectivity**
- Only tolerable if humans are main consumers of data
  - Otherwise you can sync through a central server
  - Or read locally but send updates through a master

# What are Bayou's take-away ideas?

1. **Eventual consistency**, eventually if updates stop, all replicas are the same

2. **Update functions** for automatic application-driven conflict resolution

3. **Ordered update log** is the real truth, not the DB

4. Application of **Lamport clocks** for causal consistency