Eventual Consistency: Bayou

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

CS 240: Computing Systems and Concurrency
Lecture 7

Marco Canini

Credits: Michael Freedman and Kyle Jamieson developed much of the original material.
Selected content adapted from B. Karp, R. Morris.

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 accesses 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 (no primary, no consensus)
  - **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
- iPhone sync, Dropbox sync, Dynamo

What's wrong with a central server?

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

- 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 conflict, *i.e.*, two concurrent meetings?
  - iPhone sync keeps both meetings
  - Want to do better: **automatic conflict resolution**

Automatic conflict resolution

- **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

2. "Distinct record in each database changed" can **falsely conclude** no conflict

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

What's in a write?

- 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"

Want all nodes to execute **same instructions** in **same order, eventually**

Problem

- 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 to DB replicas

Insight: Total ordering of updates

- 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**

- So, in the 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**

Is update order consistent with wall clock?

- ⟨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

- Maybe **B** asked first by the wall clock
  - But because of clock skew, **A's** meeting has **lower timestamp**, so gets priority

- No, **not "externally consistent"**

Does update order respect causality?

- Suppose **another example:**

- ⟨701, A⟩: **A** asks for meeting **M1** at 10 AM, else 11 AM
- ⟨700, B⟩: **Delete update** ⟨701, A⟩
  - **B's** clock was **slow**

- Now **delete will be ordered before add**

Lamport logical clocks respect causality

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

- **Tmax** = highest TS seen from any node (including self)
- T = max(T_{max}+1, wall-clock time), to generate TS

- Recall properties:
  - **E1** then **E2** on same node ➔ TS(E1) < TS(E2)
  - But TS(E1) < TS(E2) **does not imply** that E1 necessarily came before E2

Lamport clocks solve causality problem

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

- Now when **B** sees ⟨701, A⟩ it sets $\mathbf{T_{max} \leftarrow 701}$
  - So it will then generate a **delete update** with a **later timestamp**

Timestamps for write ordering: Limitations

- Ordering by timestamp **arbitrarily constrains order**
  - **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**

Problem: How can we allow committing a tentative entry, so we can **trim logs** and **have meetings**

Fully decentralized commit

- **Strawman proposal:** Update ⟨10, A⟩ is **stable** if **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 stable

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

Criteria for committing writes

- For log entry **X** to be committed, all servers must agree:

1. On the **total order** of all **previous** committed writes

2. That **X** is **next** in the total order

3. That all **uncommitted** entries are **“after” X**

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
  - **Uncommitted** writes come **after** all **committed writes**

Showing users that writes are committed

- **Still not safe** to show users that an appointment request has committed!

- Entire **log up to newly committed write** must be **committed**
  - Else there might be **earlier committed write** a node doesn’t know about!
    - And upon learning about it, would have to **re-run conflict resolution**

- Bayou propagates writes between nodes to enforce this invariant, *i.e.* Bayou **propagates writes in CSN order**

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**
- **Slow/disconnected** node **cannot prevent commits!**
  - Primary replica allocates CSNs; global order of writes may not reflect real-time write times

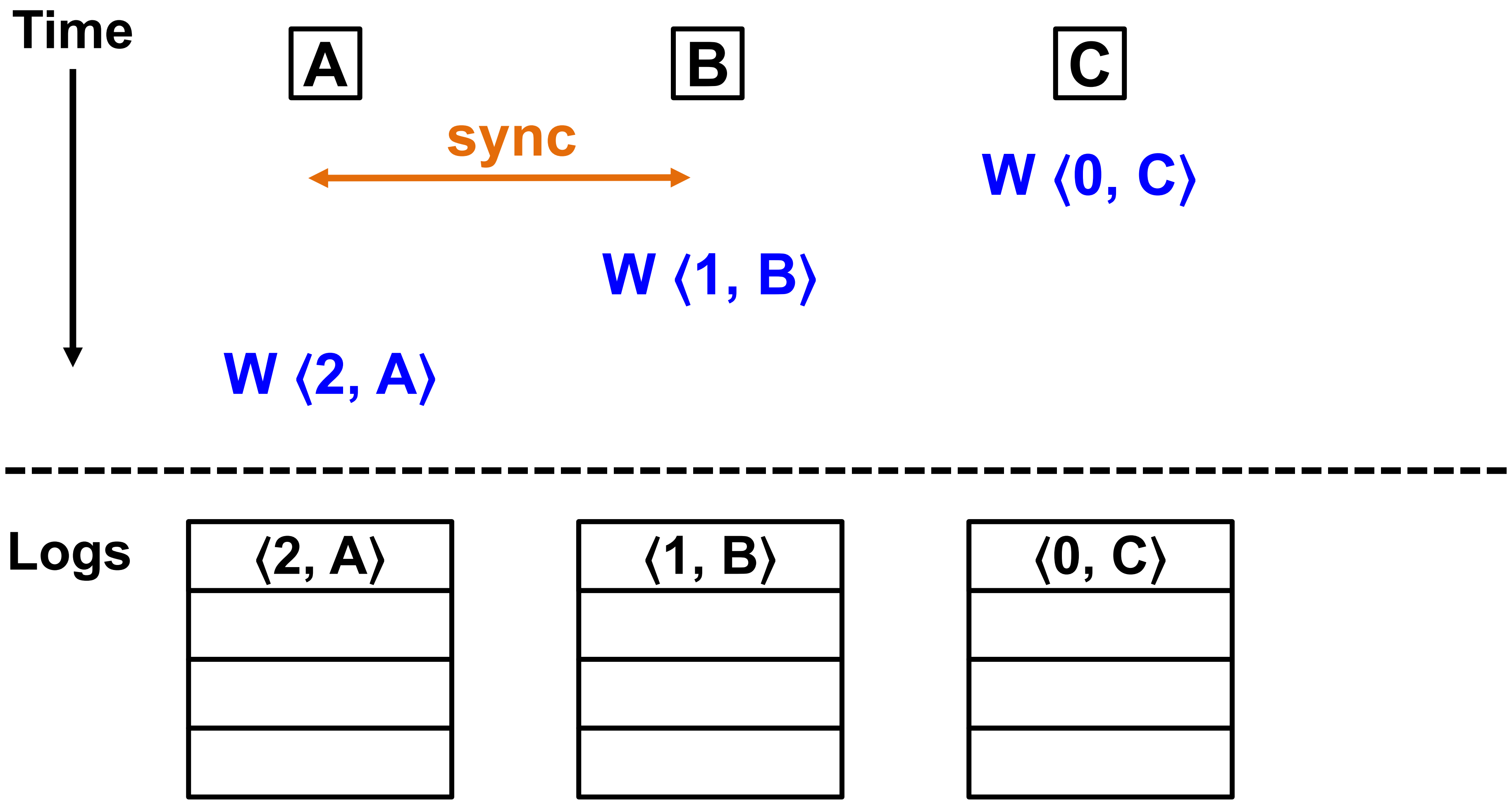
Tentative writes

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

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

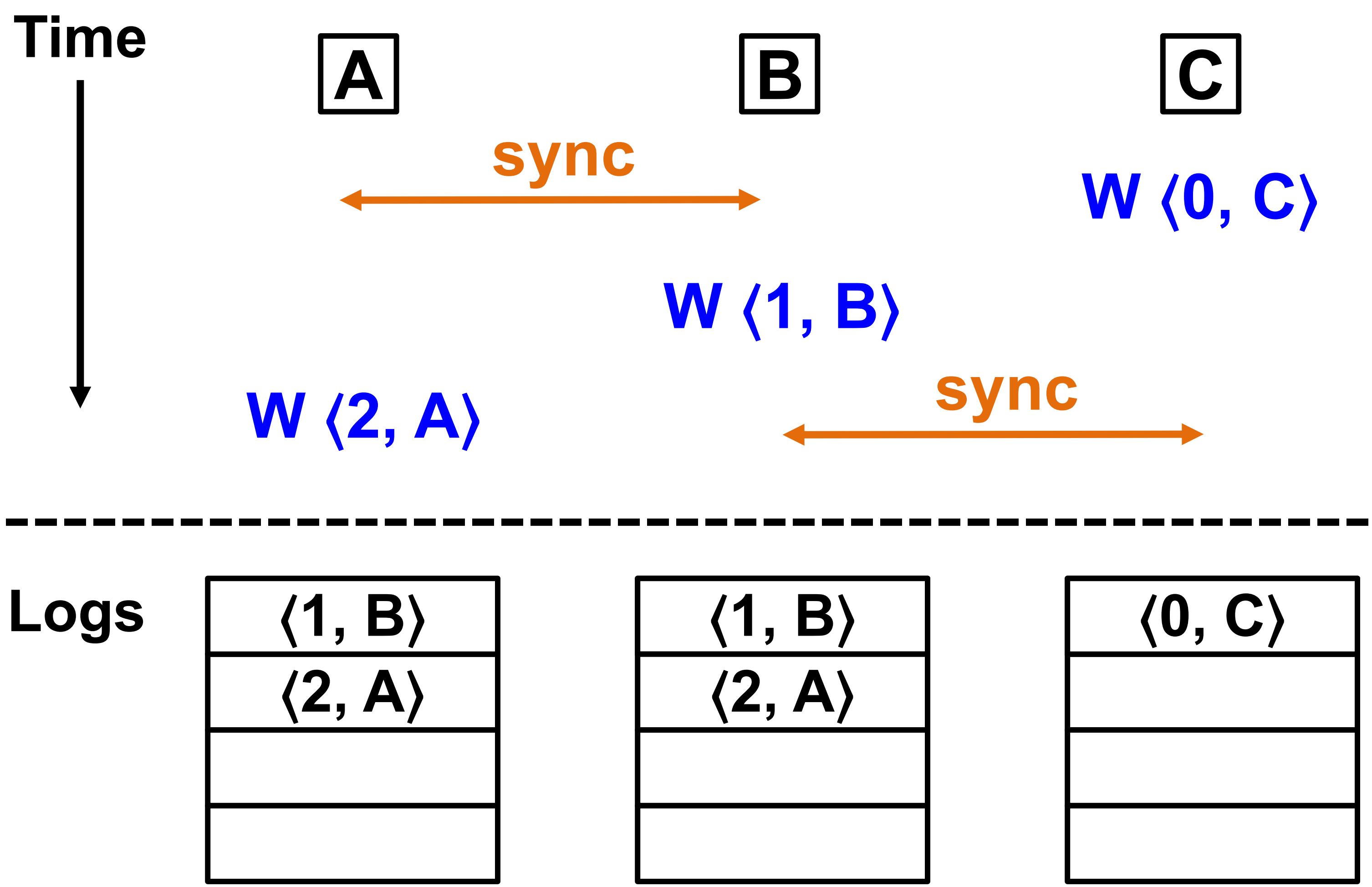
  - Only **CSNs** from primary replica can **resolve** these disagreements permanently

Example: Disagreement on tentative writes



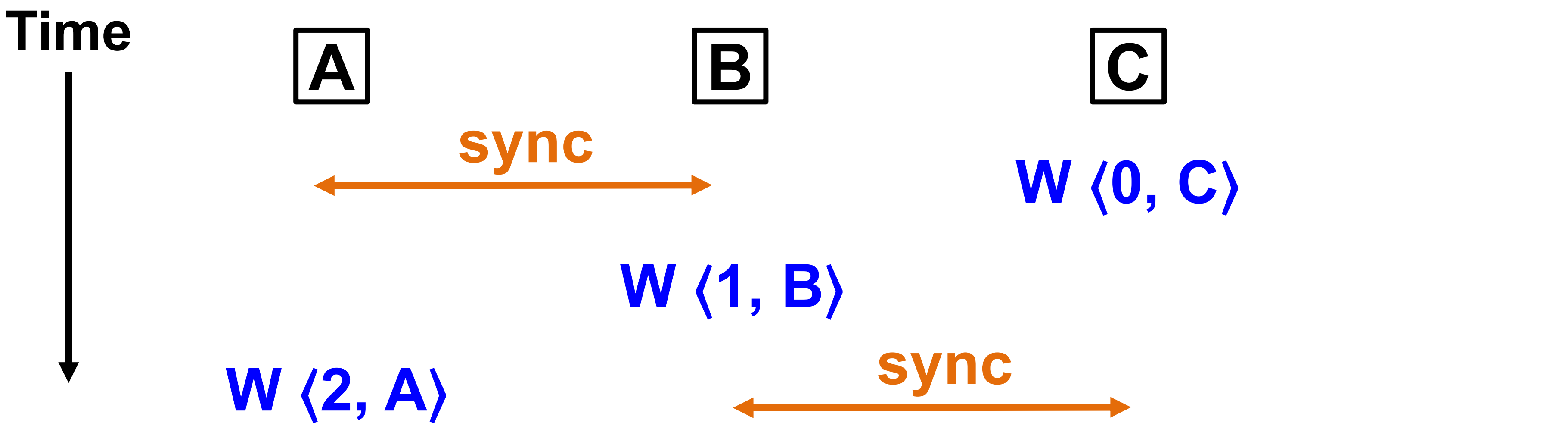
⟨local TS, node-id⟩

Example: Disagreement on tentative writes



⟨local TS, node-id⟩

Example: Disagreement on tentative writes

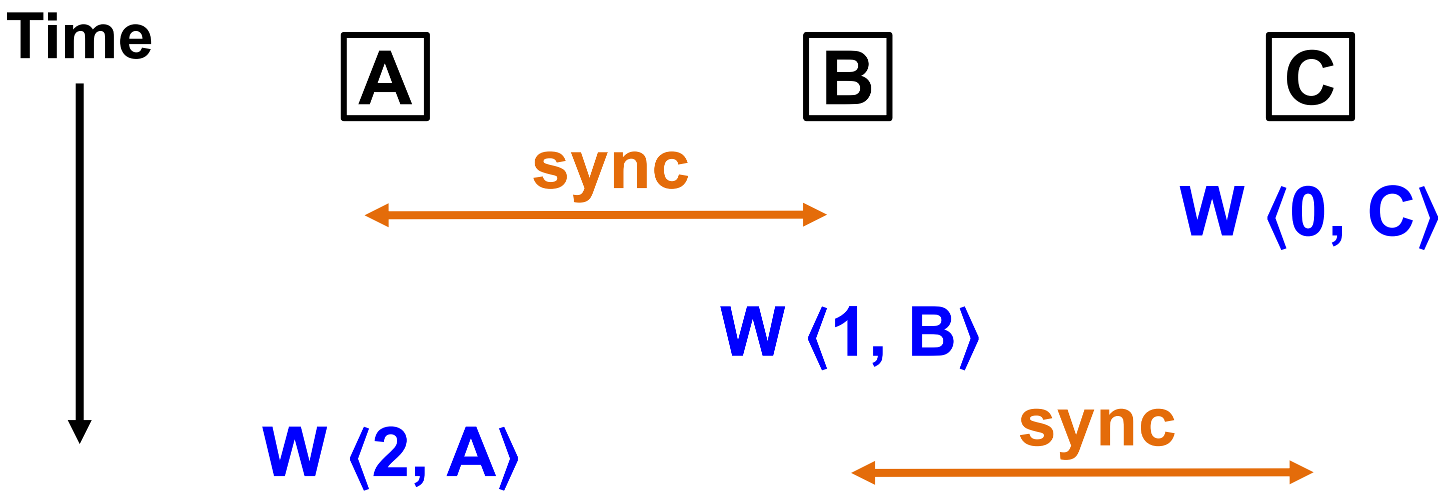


Logs

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

⟨local TS, node-id⟩

Example: Disagreement on tentative writes

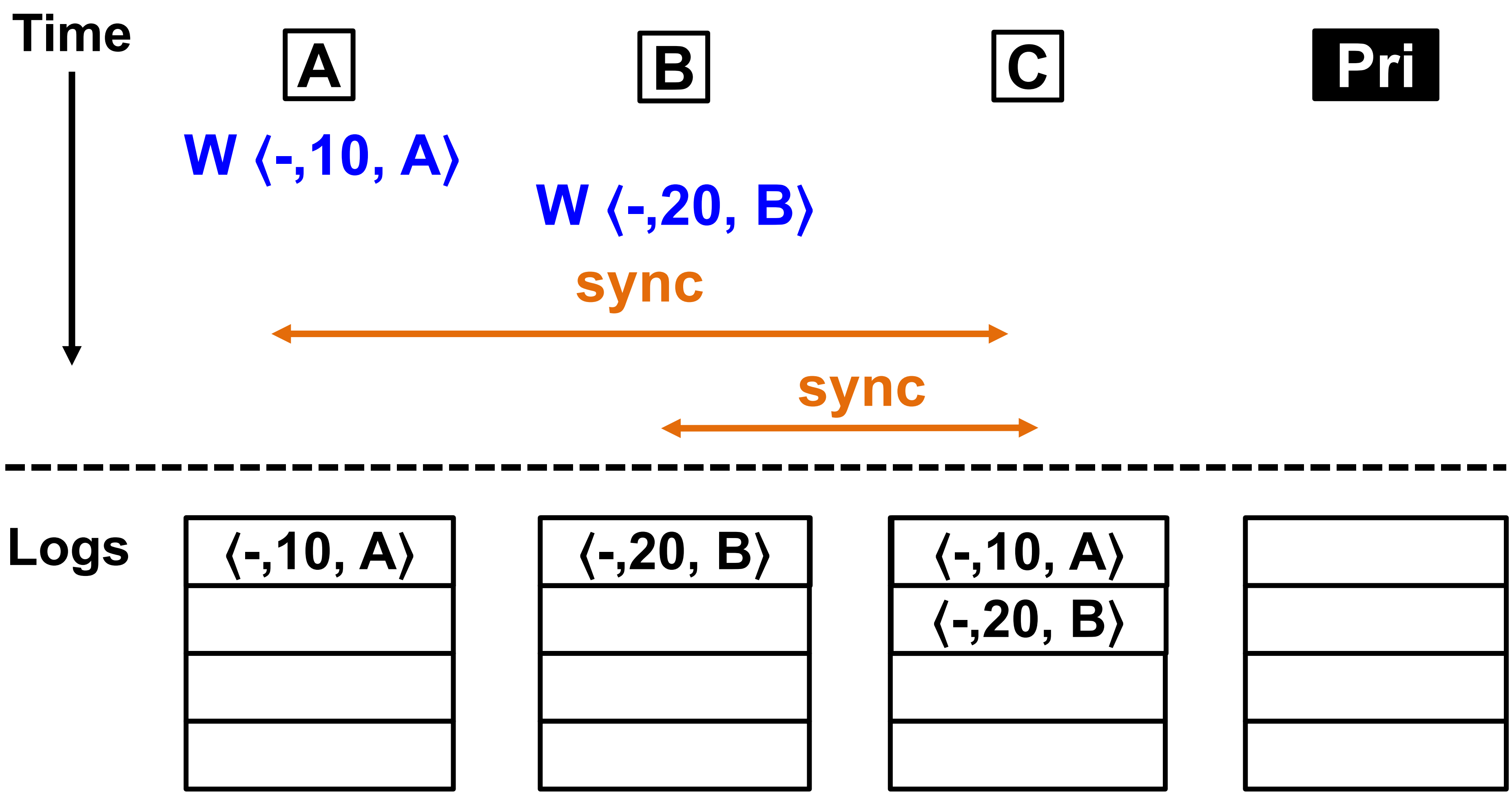


Logs

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

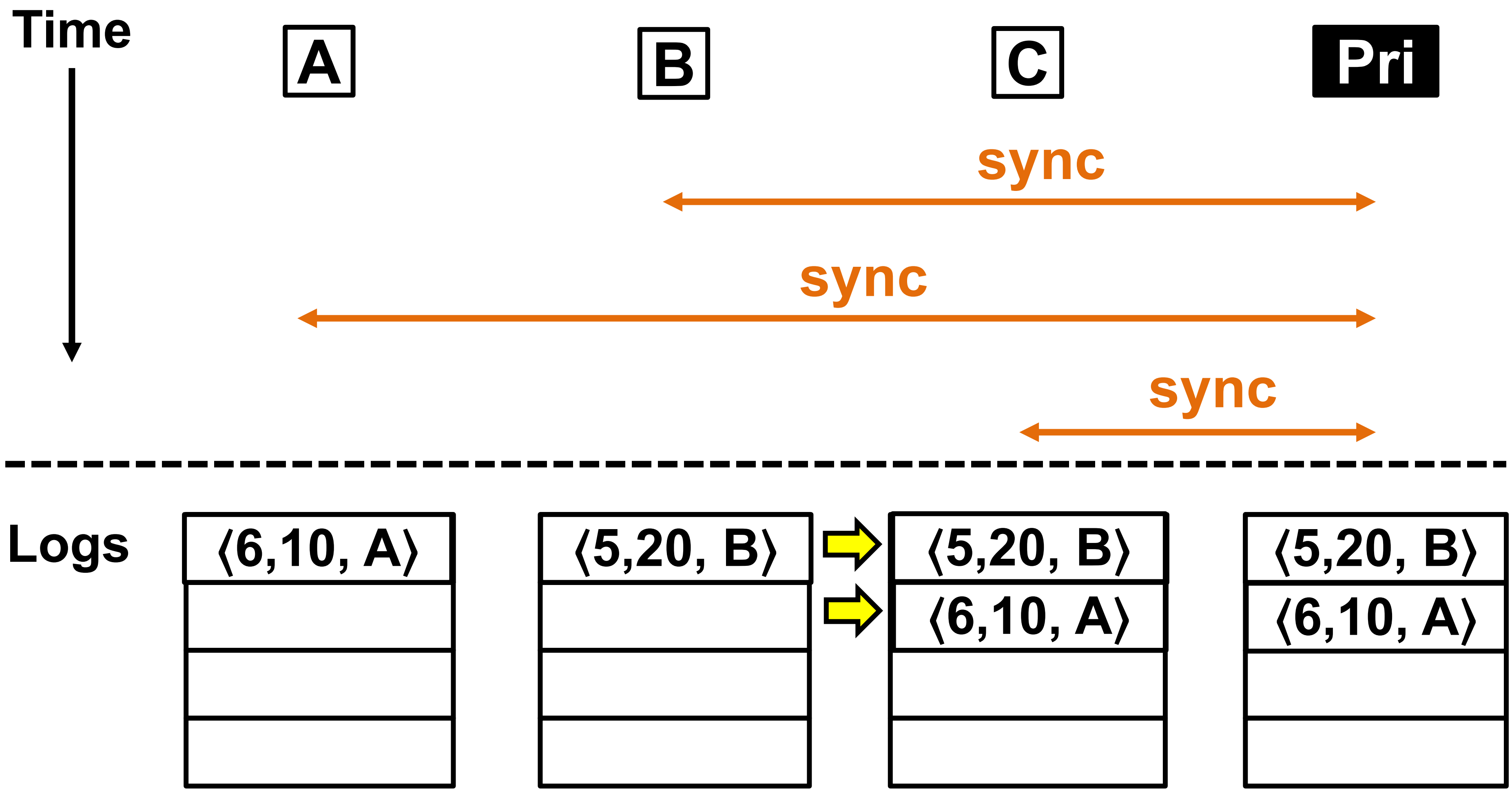
⟨local TS, node-id⟩

Tentative order ≠ commit order



⟨CSN, local TS, node-id⟩

Tentative order ≠ commit order



⟨CSN, local TS, node-id⟩

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**

Can primary commit writes in any order?

- 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 made **at each node**
  - Not necessarily order among different nodes' writes

Syncing with trimmed logs

- Suppose nodes discard all writes in log with CSNs
  - Just keep a copy of the **"stable" DB**, reflecting discarded entries

- **Cannot** receive writes that **conflict** with stable DB
  - Only could be if write had CSN less than a discarded CSN
  - **Already saw** all writes with lower CSNs in right order: if see them again, **can discard!**

Syncing with trimmed logs (2)

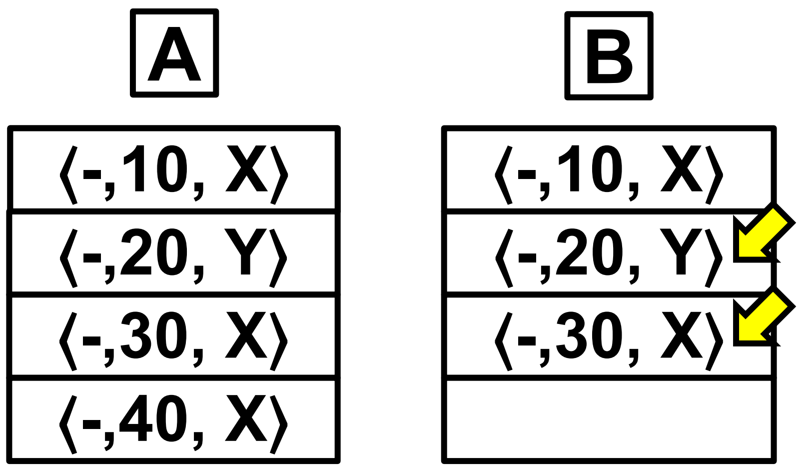
- To propagate to node **X:**

- If **X's** highest CSN **less than mine,**
  - Send **X** full stable DB; X uses that as starting point
  - **X can discard** all his **CSN** log entries
  - **X** plays his **tentative writes** into that DB

- If **X's** highest CSN **greater than mine,**
  - **X can ignore** my DB!

How to sync, quickly?

- What about **tentative updates?**



- B tells A: **highest local TS for each other node**

This is a **version vector** (“F” vector in Figure 4)
A’s F: [X:40,Y:20] **B’s F:** [X:30,Y:20]

New server

- New server **Z** joins. Could it just start generating writes, *e.g.* ⟨-, 1, Z⟩?
  - And other nodes just start including **Z** in their version vectors?

- If **A** syncs to **B**, **A** has ⟨-, 10, Z⟩
  - But, **B** **has no Z** in its version vector

  - A **should pretend** B's version vector was [**Z:0**,...]

Server retirement

- We want to stop including **Z** in version vectors!
- **Z** sends update: **⟨-, ?, Z⟩"retiring"**
  - If you see a retirement update, omit **Z** from VV
- **Problem:** How to deal with a VV that's missing Z?
  - A has log entries from Z, but B's VV has no Z entry
    - *e.g.* A has ⟨-, 25, Z⟩, B's VV is just [A:20, B:21]
  - Maybe **Z** has **retired,** B knows, A does not
  - Maybe **Z** is **new,** A knows, B does not

Need a way to **disambiguate**

Bayou's retirement plan

- **Idea:** Z joins by contacting some server X
  - **New server identifier:** id now is **⟨T_z, X⟩**
    - T_z is **X's logical clock** as of when Z joined

- **X** issues update **⟨-, T_z, X⟩ "new server Z"**

Bayou's retirement plan

- Suppose Z's ID is ⟨20, X⟩
  - A syncs to B
  - **A** has log entry from **Z: ⟨-, 25, ⟨20,X⟩⟩**
  - **B's** VV has **no Z entry**

- One case: B's VV: [**X:10**, ...]
  - 10 < 20, so B hasn't yet seen X's "new server Z" update

- The other case: B's VV: [**X:30**, ...]
  - 20 < 30, so B once knew about Z, but then saw a retirement update

Let's step back

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

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

Is Bayou's complexity warranted?

- *i.e.* update function log, version vectors, 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. **Update functions** for automatic application-driven conflict resolution

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

3. Application of **Lamport logical clocks** for causal consistency

Next topic:

Peer to Peer Systems and Distributed Hash Tables