Bayou: Replication with Weak Inter-Node Connectivity

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Context: Availability vs. Consistency

- NFS, Ivy, 2PC all had single points of failure; **not available under failures**
- Paxos allows view-change to elect primary, thus state machine replication
  - **Strong consistency model**: all operations in same order at all replicas, always appearance of single system-wide order for all operations
  - **Strong reachability requirement**: majority of nodes must be reachable by leader
- **If reachability weaker, can we provide any consistency when we replicate?**
Bayou: Calendar Application Case Study

• Today’s lecture:
  – Bayou’s office calendar application as case study in ordering and conflicts in a distributed system with poor connectivity

• Each calendar entry: room, time, and set of participants

• Want everyone to see same set of entries (eventually)
  – else, users may double-book room, avoid using unoccupied room, &c.
Traditional Calendar Application: One Central Server

- Ordering of users’ requests: only one copy, server picks order
- Conflict resolution: server checks for conflicts (i.e., “is this room already booked during this period?”) before accepting updates
  - Returns error to user if conflict; user decides what to do
What’s Wrong with Central Server?

- Want my calendar on my iPhone
  - i.e., each user wants database replicated on his PDA or laptop
  - No master copy
- iPhone has only intermittent connectivity
  - 3G expensive when roaming, WiFi not everywhere; no connectivity on many flights
  - Bluetooth useful for direct contact with other calendar users’ PDAs, but very short range
Simple Proposal: Swap Complete DBs

• Suppose two users in Bluetooth range
• Each sends entire calendar DB to other, as with “classic” Palm or iPhone sync
• Possibly lots of network bandwidth
• What if conflict, i.e., two concurrent meetings?
  – iPhone sync just keeps both meetings!
  – Want to do better: automatic conflict resolution
Automatic Conflict Resolution

- Can’t just view DB items as bits—too little information to resolve conflicts!
  - “Both files have changed” can falsely conclude entire DBs conflict
  - “Distinct record in each DB changed” can falsely conclude no conflict
- Want to build intelligent DB app that knows how to resolve conflicts
  - More like users’ updates: read DB, think, change request to eliminate conflict
  - Must ensure all nodes resolve conflicts in same way to keep replicas consistent
Insight: Ordering of Updates

• Maintain ordered list of updates at each node
• Make sure every node holds same updates
• Make sure every node applies updates in same order
• Make sure updates are deterministic function of DB contents
• If we obey above, “sync” really just a simple merge of two ordered lists!
What’s in a Write?

• Each node’s ordered list of writes: write log

• Suppose calendar update takes form:
  – “10 AM meeting, Room 6.12, Mark and Brad”
  – Sufficient for our goal?

• Better: “1-hour meeting, Room 6.12, Mark and Brad, at 9, else 10, else 11”
  – Also include unique ID: <local-time-stamp, originating-node-ID>
What’s in a Write?

Instructions for write more than data to write
Write log really an “instruction” for calendar program
Want all nodes to execute same instructions in same order, eventually

• Better: “1-hour meeting, Room 6.12, Mark and Brad, at 9, else 10, else 11”
  – Also include unique ID: <local-time-stamp, originating-node-ID>
Write Log Example

• <701, A>: Node A asks for meeting M1 to occur at 10 AM, else 11 AM
• <770, B>: Node B asks for meeting M2 to occur at 10 AM, else 11 AM
• Let’s agree to sort by write ID (e.g., <701, A>)
• As “writes” spread from node to node, nodes may initially apply updates in different orders
Write Log Example (2)

• Each newly seen write merged into log

• Log replayed
  – May cause calendar displayed to user to change!
  – i.e., all entries really “tentative,” nothing stable

• After everyone has seen all writes, everyone will agree (contain same state)
Global Time Synchronization Impossible

- Does this mean that globally ordering writes by local timestamps impossible?
- No—timestamps just allow agreement on order
  - Nodes may have wrong clocks
  - OK, so long as users don’t expect writes to reach calendar in real-time order made
Timestamps for Write Ordering: Limitations

• Ordering by write ID arbitrarily constrains order
  – Never know if some write from past hasn’t yet reached 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 have meetings and trim logs
Criteria for Committing Writes

• For log entry X to be committed, everyone must agree on:
  – Total order of all previous committed entries
  – Fact that X is next in total order
  – Fact that all uncommitted entries are “after” X
How Bayou Agrees on Total Order of Committed Writes

- One node designated “primary replica”
- Primary marks each write it receives with permanent CSN (commit sequence number)
  - That write is committed
  - Complete timestamp is <CSN, local-TS, node-id>
- Nodes exchange CSNs
- CSNs define total order for committed writes
  - All nodes eventually agree on total order
  - Uncommitted writes come after all committed writes
Showing Users that Writes Have Committed

• Still not safe to show users that an appointment request has committed

• Entire log up to newly committed entry 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

• Result: committed write not stable unless node has seen all prior committed writes
Showing Users that Writes Have Committed

Bayou propagates writes between nodes to enforce this invariant.

**i.e., Bayou propagates writes in order**

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

• Result: committed write not stable unless node has seen all prior committed writes
Committed vs. Tentative Writes

• Can now show user if a write has committed
  – When node has seen every CSN up to that point, as guaranteed by propagation protocol

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

• What about tentative writes, though—how do they behave, as seen by users?
Tentative Writes

• 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
Example: Disagreement on Tentative Writes

\[ W <0, C> \]
Example: Disagreement on Tentative Writes

 logs

 A

 B

 C

 W <0, C>

 time
Example: Disagreement on Tentative Writes

`time`

A

B

C

\[ W <0, C> \]
\[ W <1, B> \]

logs

\[ <0, C> \]
Example: Disagreement on Tentative Writes

W <0, C>
W <1, B>
W <1, B>
logs
Example: Disagreement on Tentative Writes

W <0, C>

W <1, B>

W <2, A>

A

B

C

time

logs
Example: Disagreement on Tentative Writes

```plaintext
Example:

Disagreement on Tentative Writes

<table>
<thead>
<tr>
<th>Time</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2, A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1, B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;0, C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

**Explanation:**
- A makes a write at time <2, A>, B makes a write at time <1, B>, and C makes a write at time <0, C>.
- There is disagreement on the tentative writes as they are not logged in the same order across the nodes.
Example: Disagreement on Tentative Writes

- A
- B
- C

Records:
- W <2, A>
- W <1, B>
- W <0, C>

Logs:
- <2, A>
- <1, B>
- <0, C>

Time points:
- sync (3)
Example: Disagreement on Tentative Writes

A
B
C

W <0, C>
W <1, B>
W <2, A>

logs

sync (3)
Example: Disagreement on Tentative Writes

- **Time:**
  - A
  - B
  - C

- **Writes:**
  - A
  - B
  - C

- **Logs:**
  - <1, B>
  - <2, A>

- **Synchronization Events:**
  - sync (3)
  - sync (4)
Example: Disagreement on Tentative Writes

logs

<table>
<thead>
<tr>
<th>time</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1, B&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;2, A&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sync (3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sync (4)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

W <0, C>
W <1, B>
W <2, A>
Example: Disagreement on Tentative Writes

A

B

C

W <0, C>

W <1, B>

W <2, A>

sync (3)

sync (4)

time

logs

<1, B>

<2, A>

<0, C>

<1, B>

<2, A>

<0, C>

<1, B>

<2, A>
Trimming the Log

- When nodes receive new CSNs, can discard all committed log entries seen up to that point
  - Update protocol guarantees CSNs received in order
- Instead, keep copy of whole database as of highest CSN
  - By definition, official committed database
  - Everyone does (or will) agree on contents
  - Entries never need go through conflict resolution
Trimming the Log

- When nodes receive new CSNs, can discard all committed log entries seen up to that point

**Result: no need to keep years of log data!**

- Instead, keep copy of whole database as of highest CSN
  - By definition, official committed database
  - Everyone does (or will) agree on contents
  - Entries never need go through conflict resolution
Ordering of Commits by Primary Replica

• **Can primary commit writes in any order it pleases?**
  – Suppose user creates appointment, then decides to delete it, or change attendee list
  – **What order must these ops take in CSN order?**
    • Create first, then delete or modify
    • Must be true in every node’s view of tentative log entries, too!

• **Total order of writes must preserve order of writes made at each node**
  – Not necessarily order among different nodes’ writes
How Does Primary Replica Commit Each Node’s Writes in Order?

• Nodes don’t quite use real-time clocks for timestamps—use Lamport logical clocks
  – Anytime see message with later timestamp than current time, set clock to after that timestamp

• All nodes send updates in order

• So primary receives updates in per-node causal order, and commits them in that order
Syncing with Trimmed Logs

- Suppose nodes discard all writes in log with CSNs
  - Just keep copy of “stable” DB, reflecting discarded entries
- Cannot receive writes that conflict with DB
  - Only could be if write has 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 node X’s highest CSN less than mine:
  – Send X full stable DB
  – X uses that DB as starting point
  – X can discard all his CSN log entries
  – X can play his tentative writes into that DB

• If node X’s highest CSN greater than mine:
  – X can ignore my DB!
Bayou: Summary

• Seems more useful than old Palm’s calendar!
  – Often disconnected when making appointments
  – Automatic conflict resolution convenient

• Not at all transparent to applications!
  – Very strange programming practices
  – Writes are code, not just bits!
  – Check for conflicts, resolve conflicts

• Doesn’t work for all apps
  – Bank account may be OK
  – But hard to imagine for source code repository!