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 PDA
  – i.e., each user wants database replicated on his PDA or laptop
  – No master copy

• PDA has only intermittent connectivity
  – GPRS/EDGE/3G expensive, WiFi not everywhere; nothing on Tube
  – 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 Palm sync
• Possibly lots of network bandwidth
• What if conflict, i.e., two concurrent meetings?
  – Palm 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

A  B  C

W <0, C>

logs
Example: Disagreement on Tentative Writes

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>W &lt;0, C&gt;</td>
<td>W &lt;1, B&gt;</td>
<td>W &lt;0, C&gt;</td>
</tr>
</tbody>
</table>

logs

---
Example: Disagreement on Tentative Writes

\[
\text{time} \\
A \quad B \quad C
\]

\[
W <1, B>
\]

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

```
  time

A   B   C

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

logs
```
Example: Disagreement on Tentative Writes

A

B

C

\[ W <0, C> \]
\[ W <1, B> \]
\[ W <2, A> \]

\text{sync (3)}

\begin{align*}
\text{logs} & \\
\hline
<2, A> & <1, B> & <0, C> \\
\hline
\end{align*}
Example: Disagreement on Tentative Writes

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

<table>
<thead>
<tr>
<th>time</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>W &lt;0, C&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W &lt;1, B&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W &lt;2, A&gt;</td>
</tr>
</tbody>
</table>

logs

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

sync (3)  
sync (4)
Example: Disagreement on Tentative Writes

<table>
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<th>time</th>
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<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>W &lt;0, C&gt;</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>W &lt;1, B&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>W &lt;2, A&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Logs:

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

Sync points:
- Sync (3) between A and B
- Sync (4) between A and C
Example: Disagreement on Tentative Writes

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

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

Syncs:
- Sync (3) between B and A
- Sync (4) between A and C
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 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!