CS 138: Replication and Gossip
## Example

<table>
<thead>
<tr>
<th>Client 1</th>
<th>Client 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{setBalance}_B(x, 1) )</td>
<td></td>
</tr>
<tr>
<td>( \text{setBalance}_A(y, 2) )</td>
<td></td>
</tr>
<tr>
<td>( \text{getBalance}_A(y) \rightarrow 2 )</td>
<td></td>
</tr>
<tr>
<td>( \text{getBalance}_A(x) \rightarrow 0 )</td>
<td></td>
</tr>
</tbody>
</table>
Linearizability

The diagram illustrates the concept of linearizability in distributed systems. It shows a Client communicating with Replica Managers. The Replica Managers are responsible for maintaining consistency across different replicas of the data. The arrows indicate the flow of communication between the Client and the Replica Managers.
Linearizability Definition

• Clients perform sequences of operations
  – each operation consists of request, arguments, and result

• A system is *linearizable* iff
  – for any execution of the system, the operations of all the clients can be put into a sequence such that
    - the sequence could have taken place in a system with only one replica manager
    - the operations in the sequence are partially ordered by the real times of their actual occurrences
Another Example

<table>
<thead>
<tr>
<th>Client 1</th>
<th>Client 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>setBalance(_B)(x, 1)</td>
<td></td>
</tr>
<tr>
<td>getBalance(_A)(y) → 0</td>
<td>getBalance(_A)(x) → 0</td>
</tr>
<tr>
<td>setBalance(_A)(y, 2)</td>
<td></td>
</tr>
</tbody>
</table>
Sequential Consistency

- Clients perform sequences of operations
  - each operation consists of request, arguments, and result
- A system is sequential consistent iff
  - for any execution of the system, the operations of all the clients can be put into a sequence such that
    - the sequence could have taken place in a system with only one replica manager
    - the operations in the sequence are partially ordered by their order in each client
Passive Replication

Client → Replica Manager

Replica Manager → Replica Manager

Replica Manager → Replica Manager

Client → Replica Manager
Passive Replication Sequence

1) Request: client issues request to primary
2) Coordination: primary takes each request atomically, in order received
3) Execution: primary executes request and stores response
4) Agreement: if request is an update, primary sends request to backups
5) Response: once all backups respond, primary sends response to client
Passive Replication
Raft to the Rescue

• New primary is elected
• Clients communicate with it
Active Replication
Gossip

From “Providing High Availability Using Lazy Replication”
Rivka Ladin, Barbara Liskov, Liuba Shrira, and Sanjay Ghemawat
Scenario

• Distribution-list service
  – multiple, geographically distributed servers
  – replicated database
  – operations
    - post a message
    - add a user
    - ostracize a user
Posting a Message

• Client posts a message
  – contacts nearest server
  – wants quick confirmation

• However …
  – server could crash at any moment
    - message should be replicated at other servers
    - causality constraints must be satisfied
      • but these are pretty weak
Example

• I send a message to Rodrigo
  – via the Providence replica

• Rodrigo reads message
  – via Providence replica

• Rodrigo sends response
  – via Rio de Janeiro replica

• I read response
  – still in Providence (sigh)

• George sends Jake message
  – via San Francisco replica

• Jake reads message
  – via Miami replica

• Jake sends response
  – via Grand Cayman replica

• George reads response
  – via Honolulu replica
Adding a User

- Two different people want to register for the CS138 list as “JCarberry”
- One asks Jordan, the other asks Vivek
- Jordan and Vivek each attempt to add their person
  - simultaneously
- First one to reach the server succeeds, second one fails
- But there are multiple servers
  - each contacts a different server
- Want the same total order at all servers
Ostracizing a User

• Junyang defects to CS166
• No longer trusted to receive confidential CS138tas email
• Must be removed from list immediately (if not sooner) at all servers
  – urgent!
Desired Features

• Causal ordering
  – needed for updates

• Forced ordering
  – both causal and total order
  – needed for adding JCarberry

• Immediate ordering
  – forced ordering with minimal delay
  – needed for ostracizing Jake
Clients normally communicate with one RM
- but it might be busy
  - communicate with another
  - communicate with many
Rough Outline
(Causal Ordering)

• Query
  – client sends request to one or more RMs
  – respond when causally possible

• Update
  – client sends request to one or more RMs
  – update and respond when causally possible
  – propagate changes to others via “gossip” messages
    - not specified how this is done
    - allows many possibilities
Query Model

Client

Distributed Service

App

front end

TS

Replica Manager

TS

Value

Replica Manager

Replica Manager

App

front end

Client
Query

• Client sends query q
  – request (q.op)
  – causal dependencies
    - q.prev = client.ts

• RM $i$ responds
  – receives query
  – holds it until
    - q.prev $\leq$ rm$_i$.val.ts
  – returns value and timestamp (rm.val.ts)

• Client
  – updates its own timestamp
    - client.ts = merge (client.ts, rm.val.ts)
Update Model

Distributed Service

Replica Manager

Replica Manager

TS

Value

Log

Replica Manager

Client

App

front end

TS

Replica Timestamp

Client

App

front end

TS

TS
Update (1)

• Client sends
  – request (u.op)
  – causal dependencies
    - u.prev = client.ts
Update (2)

- RM i responds
  - receives update
    - assigns timestamp
      - \( rm_i\.replica.ts[i] += 1 \)
      - \( TS = u\.prev; \ TS[i] = rm_i\.replica.ts[i] \)
    - puts in log
      - \(<u, i, TS> (update, node, timestamp)>\)
    - returns TS
  - when \( u\.prev \leq rm_i\.val.ts \)
    - updates val (by applying \( u\.op \))
    - \( rm_i\.val.ts = merge(rm_i\.val.ts, TS) \)
Update (3)

• Client
  – updates its own timestamp
    - client.ts = merge (client.ts, TS)
Gossipping

- RM a initiates gossip
  - sends to RM b:
    - contents of log (rm_a.log)
    - replica timestamp (rm_a.replica.ts)
- RM b receives gossip
  - merges rm_a.log into rm_b.log
  - rm_b.replica.ts = merge(rm_a.replica.ts, rm_b.replica.ts)
  - while there exists request r in rm_b.log such that
    r.u.prev ≤ rm_b.val.ts && r.processed == false
    • r.processed = true
    • update val (by applying r.u.op)
    • rm_b.val.ts = merge(rm_b.val.ts, r.TS)
Forced Updates (1)

- Need a causal order that’s also total
  - all clients go through same RM
Forced Updates (2)

• What if primary crashes?
  – elect new primary

Diagram:
- App (front end)
- Client
- Distributed Service
  - Primary Replica Manager
  - Backup Replica Manager
  - Primary Replica Manager (with crown)
Immediate Updates (1)

- Primary requests logs and replica timestamps
  - backups respond and stop processing queries
  - updates are accepted but not executed
Immediate Updates (2)

- Backups respond with logs and timestamps
  - primary stops processing queries and updates
  - processes logs and timestamps
Immediate Updates (3)

- Primary assigns timestamp to update
- Primary sends update to backups
Immediate Updates (4)

- Backups acknowledge updates
Immediate Updates (5)

- After half the backups respond, primary commits (updates val) and responds to client
  - half the backups + primary = majority
Immediate Updates (6)

- Primary sends log to each backup (gossips)
Problem?

• What if client sends update request to multiple RMs?
  – multiple copies of the request are propagated
  – all are executed
  – probably aren’t idempotent
Solution

• Client assigns unique ID (CID) to each request
• RMs keep track of CIDs of completed requests
  – completed requests go to invalid CIDs list
  – check list before doing a request
    - don’t perform requests that have already been performed
Updated Update Model

Graphical representation:
- Client: App and front end
- Distributed Service: Replica Manager, TS, Value, Log, Invalid CIDs
- Replica Timestamp

Diagram showing the interaction between App and front end with Replica Manager, TS, Value, Log, and Invalid CIDs in the Distributed Service.
Another Problem?

• Won’t logs and invalid CID lists grow without bound?
  – yes …
Bounding Logs (1)

- Each log entry $r$ must be kept on RM $i$ until it is present on all RMs
  - so that gossip from $i$ will inform other RMs
- $r$.node is the node that created the log entry $r$
- $r$.ts is the vector timestamp assigned to the log entry by $r$.node
- $r$.ts[$r$.node] is the logical time on $r$.node when the entry was created
- $r$ may be removed from $i$’s log when:
  - $\forall k: r$.ts[$r$.node] $\leq$ $rm_k$.replica.ts[$r$.node]
Bounding Logs (2)

• How does RM i know \( rm_k.replica.ts[r.node] \)?
  – gossip messages contain replica timestamps
    - timestamps on logs
  – each RM keeps a table of the most recent timestamps obtained from all other RMs
    - \( rm_i.ts_table \)
      - \( \forall k \) \( rm_i.ts_table[k] \leq rm_k.replica.ts \)
  – RM i may remove log entry r when:
    - \( \forall k: r.ts[r.node] \leq rm_i.ts_table[k][r.node] \)
Trimming the Invalid CID List

• When can an entry be removed?
  – when it will never be received again

• Assuming perfect communication, how can you tell?
  – you can’t: client’s front-end might send same update to multiple RMs
  – what’s more, communication might not be perfect

• More machinery needed …
More Machinery …

• Client front-end puts (real-time) timestamps on all update requests
• After successful transmission of last transmission of an update, it sends “that’s all” (TA) message to at least one RM
  – contains CID of update and (real-time) timestamp
    - timestamp of TA is later than that of updates
  – RM puts it in log (and includes it in gossips)
• Assume maximum real time required for any RM i to notify RM j of new info via gossip is $\delta$
  – takes into account clock skew, etc.
Yet More Machinery ...

- **General idea**
  - all equivalent update messages terminated by TA $a$ must be received by $a.\text{timestamp} + \delta$

- **Details**
  - discard CID $c$ from invalid CID list if its TA is in log and no update records for $c$ in log
    - all RMs have seen $c$
  - ignore updates if $m.\text{time} + \delta < \text{replica’s local time}$
  - discard TA $a$ from log if it appears in all logs and $a.\text{timestamp} + \delta < \text{replica’s local time}$
    - no other instances of updates terminated by $a$ are still circulating