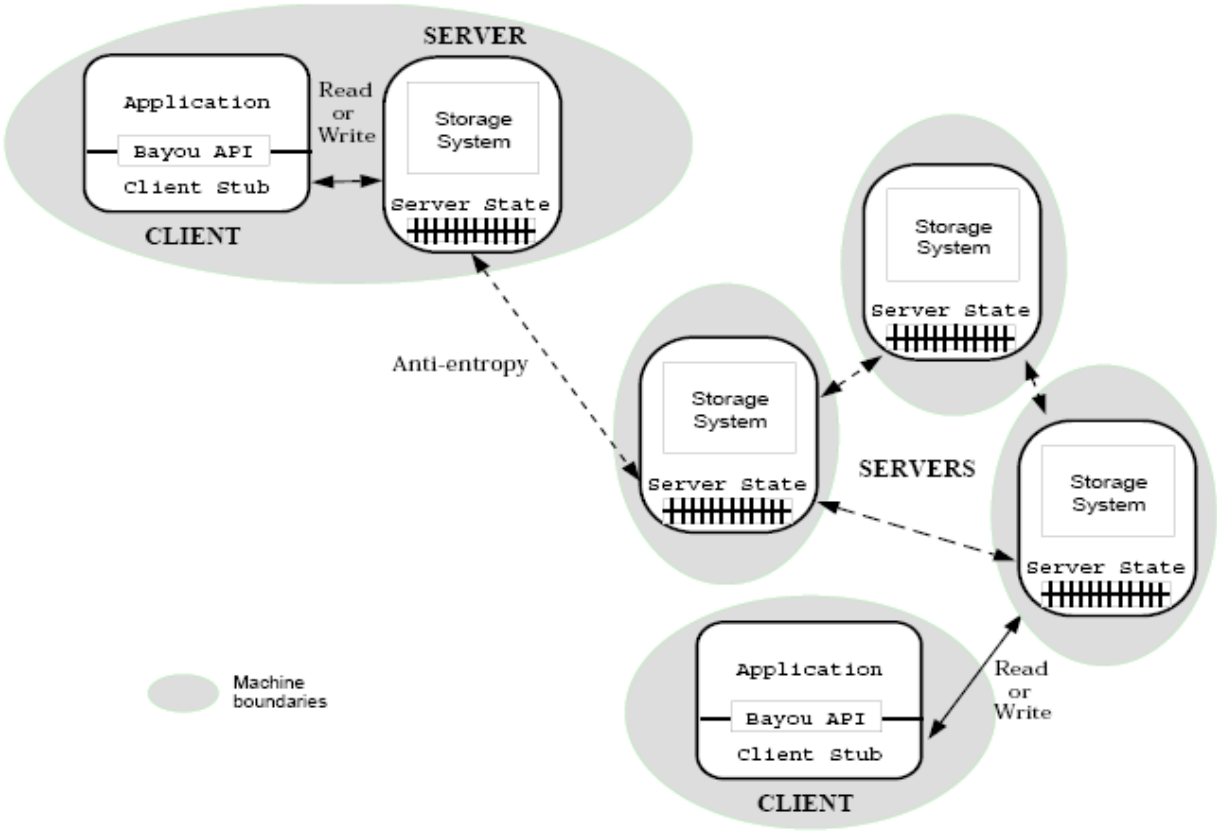
Managing Update Conflicts in Bayou, a Weakly Connected Replicated Storage System

Bayou

- assumptions:
  - read/write anywhere
  - DB fully replicated
  - disconnected operation
- goals
  - read anywhere/write anywhere
  - weak connectivity
  - eventual consistency
  - app-specific conflict resolution
- methods
  - optimism
  - anti-entropy sessions
  - session semantics
  - per-update **dependency checks** and **merge procedures**
  - committed vs tentative updates
  - security

System Model



Apps

- Apps:
  - Scheduler
    - users can specify multiple possible meeting times
  - Bib database
    - collisions on bib entry labels
    - duplicate entries
- If:
  - conflict detection far in future
- Then:
  - Need app-specific
    - conflict detection
    - resolution (merge procedures)

Fun Stuff

- Dependency Checks
  - Better than version vectors because:
    - read/write conflicts
    - arbitrary, multi-item constraints
  - Example 1: scheduler
    - checks to see if the requested time filled
  - Example 2: bank
    - Need to transfer $100 from A to B. If app checked first and saw $150, traditional opt approach would be to check for $150 before committing
    - Bayou can formalize real requirement, i.e., A >= $100

```
Bayou_Write (update, dependency_check, mergeproc) {
    IF (DB_Eval (dependency_check.query) <> dependency_check.expected_result)
        resolved_update = Interpret (mergeproc);
    ELSE
        resolved_update = update;
    DB_Apply (resolved_update);
}
```

A Complete Bayou Write

```
Bayou_Write(
    update = {insert, Meetings, 12/18/95, 1:30pm, 60min, "Budget Meeting"},
    dependency_check = {
        query = "SELECT key FROM Meetings WHERE day = 12/18/95
            AND start < 2:30pm AND end > 1:30pm",
        expected_result = EMPTY},
    mergeproc = {
        alternates = {{12/18/95, 3:00pm}, {12/19/95, 9:30am}};
        newupdate = {};
        FOREACH a IN alternates {
            # check if there would be a conflict
            IF (NOT EMPTY (
                SELECT key FROM Meetings WHERE day = a.date
                 AND start < a.time + 60min AND end > a.time))
                    CONTINUE;
            # no conflict, can schedule meeting at that time
            newupdate = {insert, Meetings, a.date, a.time, 60min, "Budget Meeting"};
            BREAK;
        }
        IF (newupdate = {})   # no alternate is acceptable
            newupdate = {insert, ErrorLog, 12/18/95, 1:30pm, 60min, "Budget Meeting"};
        RETURN newupdate;}
)
```

Replica Consistency

- Eventual consistency
  - writes must be committed in same order everywhere
- New writes **tentative**
  - ordered by local server timestamp
  - TS is mono-increasing: <TS, server ID>
  - immediately applied!
    - **must have undo**
    - **must have redo**
- Piecewise determinism:
  - no dep on anything but replica contents.

Write Stability

Write is **stable** when it has been executed for last time at that server.

- How to determine stability?
  - matrix clocks
  - timestamps
  - **cheat**
- Primary commit
  - one server responsible for final ordering of all updates
  - ordering?
    - not clear
    - hopefully consistent w/ timestamp order, but maybe not if some servers disconnected

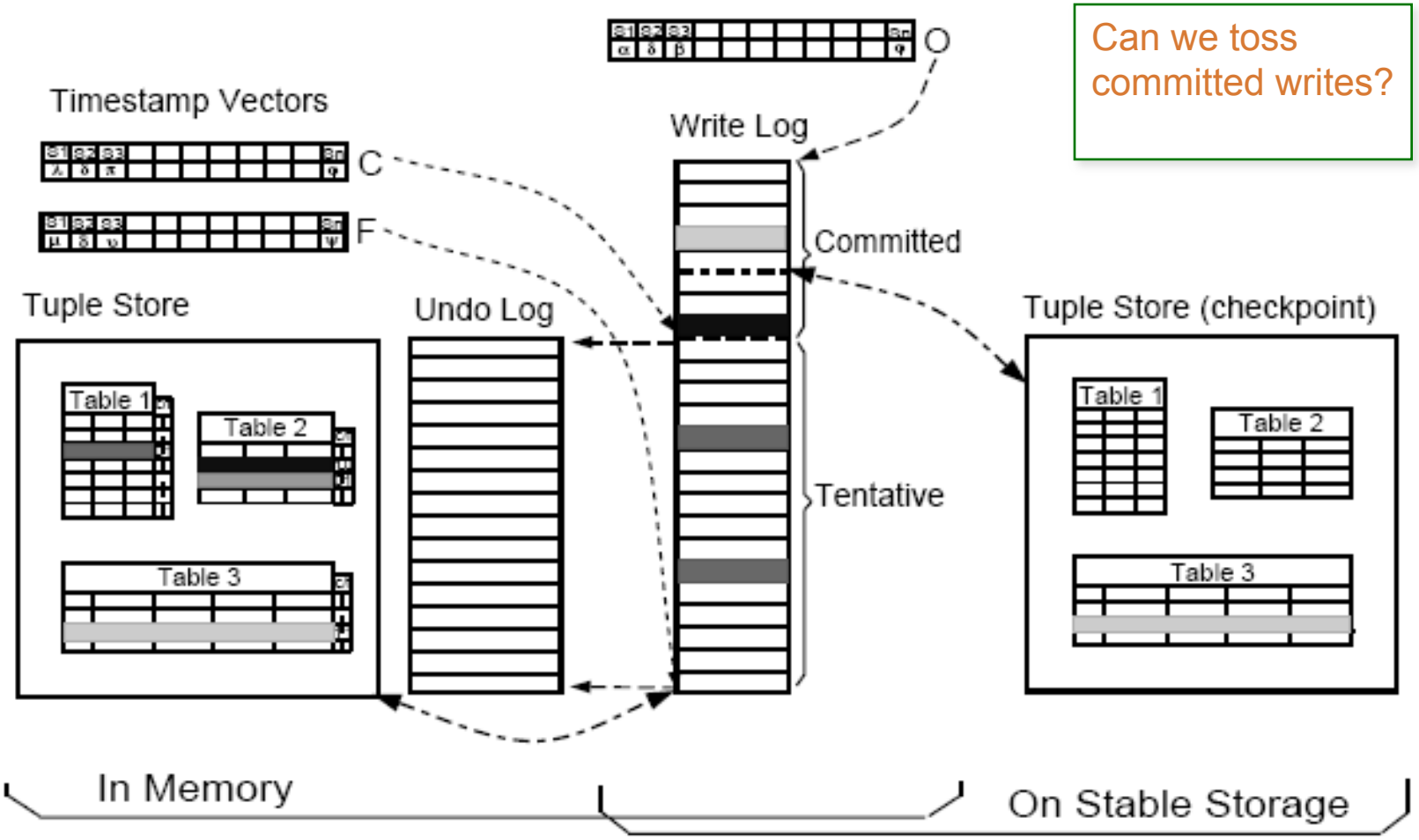
Applying Sets of Writes

```
Receive_Writes (writeset, received_from) {
    IF (received_from = CLIENT) {
        # Received one write from the client, insert at end of WriteLog
        # first increment the server's timestamp
        logicalclock = MAX(systemclock, logicalclock + 1);
        write = First(writeset);
        write.WID = {logicalclock, myServerID};
        write.state = TENTATIVE;
        WriteLog_Append(write);
        Bayou_Write(write.update, write.dependency_check, write.mergeproc);
    } ELSE {
        # Set of writes received from another server during anti-entropy,
        # therefore writeset is ordered
        write = First(writeset);
        insertionPoint = WriteLog_IdentifyInsertionPoint(write.WID);
        TupleStore_RollbackTo(insertionPoint);
        WriteLog_Insert(writeset);
        # Now roll forward
        FOREACH write IN WriteLog AFTER insertionPoint DO
            Bayou_Write(write.update, write.dependency_check, write.mergeproc);
        # Maintain the logical clocks of servers close
        write = Last(writeset);
        logicalclock = MAX(logicalclock, write.WID.timestamp);
    }
}
```

Details

- "O" vector
  - TS's of last tossed ('omitted') writes
  - works because writes tossed in order
  - writes from any server are propogated and committed in TS order
- Two more vectors
  - "C" : max TS's of committed writes
  - "F" : max TS's of tentative writes
  - used for anti-entropy, not conflict detection

Database Org



Can we toss committed writes?

Access Control

- We are:
  - potentially disconnected
  - and still need to make progress
- Outline:
  - public-key crypto
  - both clients/servers have signed certificates for rights
  - delegation certificates
  - revocation

Flexible Update Propagation for Weakly Consistent Replication

Basic Anti-entropy

- Servers assign **accept-stamps**
  - provide total order for writes accepted by a server, and
  - partial order "**accept-order**" over all writes
- Anti-entropy
  - one-way op between servers
  - consists of propagation of writes
  - write propagation constrained by accept-order
    - helps maintain "**prefix property**"
  - partner choice undefined

Anti-Entropy

```
anti-entropy(S,R) {
    Get R.V from receiving server R
    # now send all the writes unknown to R
    w = first write in S.write-log
    WHILE (w) DO
        IF R.V(w.server-id) < w.accept-stamp THEN
            # w is new for R
            SendWrite(R, w)
        w = next write in S.write-log
    END
}
```

Anti-Entropy W/ Commits

commit sequence number

```
anti-entropy(S,R) {
    Get R.V and R.CSN from receiving server R
    # first send all the committed writes that R does not know about
    IF R.CSN < S.CSN THEN
        w = first committed write that R does not know about
        WHILE (w) DO
            IF w.accept-stamp <= R.V(w.server-id) THEN
                # R has the write, but does not know it is committed
                SendCommitNotification(R, w.accept-stamp, w.server-id, w.CSN)
            ELSE
                SendWrite(R, w)
            END
            w = next committed write in S.write-log
        END
    END
    w = first tentative write
    # now send all the tentative writes
    WHILE (w) DO
        IF R.V(w.server-id) < w.accept-stamp THEN
            SendWrite(R, w)
        w = next write in S.write-log
    END
}
```

Anti-Entropy W/ Commits and Truncation

```
anti-entropy(S,R) {
    Request R.V and R.CSN from receiving server R
    #check if R's write-log does not include all the necessary writes to only send writes or
    # commit notifications
    IF (S.OSN > R.CSN) THEN
        # Execute a full database transfer
        Roll back S's database to the state corresponding to S.O
        SendDatabase(R, S.DB)
        SendVector(R, S.O) # this will be R's new R.O vector
        SendCSN(R, S.OSN) # R's new R.OSN will now be S.OSN
    END
    # now same algorithm as in Figure 2, send anything that R does not yet know about
    IF R.CSN < S.CSN THEN
        w = first committed write that R does not yet know about
        WHILE (w) DO
            IF w.accept-stamp <= R.V(w.server-id) THEN
                SendCommitNotification(R, w.accept-stamp, w.server-id, w.CSN)
            ELSE
                SendWrite(R, w)
            END
            w = next committed write in S.write-log
        END
    END
    w = first tentative write in S.write-log
    WHILE (w) DO
        IF R.V(w.server-id) < w.accept-stamp THEN
            SendWrite(R, w)
        w = next write in S.write-log
    END
}
```

Extensions

- Transportable media
  - parameters CSN and V define minimum state receiver must have in order to use
- Session guarantees
  - writes must be "**causally ordered**"
    - **A** precedes **B** iff *A* was already known to the server that received **B** from a client
    - scalar logical clock

Features enabled by specific anti-entropy design components

Feature \ Design Choices	One-way Peer-to-Peer	Operation-based	Partial Propagation Order	Causal Propagation Order	Stable Log Prefix
Arbitrary Communication Topologies	◆				
Arbitrary Policy Choices	◆				
Low-bandwidth Networks		◆			
Incremental Progress	◆*	◆	◆		
Eventual Consistency					◆**
Aggressive Storage Management					◆
Use of Transportable Media	◆		◆		
Light-weight Dynamic Replica Sets	◆	◆		◆	
Per Update Conflict Management		◆			
Session Guarantees				◆	

Policy Choices

- when to reconcile
  - periodically, manual, system trigger
- who to reconcile w/
  - network characteristics, up-to-dateness of replicas, truncations
- how aggressively to truncate write log
  - eh.
- who to create new server from
  - up-to-dateness, identifier length?

Creation and Retirement Writes

- Bayou server S_i creates itself by sending **creation write** to another server S_k
  - gives S_i name $\langle T_{k,I}, S_k \rangle$
  - tells others of $\langle T_{k,I}, S_k \rangle$'s existance
- Disappearing servers issue "**retirement writes**"
- What do we know if target of anti-entropy, S_L, doesn't have an entry for some server $\langle T_{k,I}, S_k \rangle$?
  - either S_L hasn't heard of $\langle T_{k,I}, S_k \rangle$, or knows that it is gone
  - tell by looking $S_L.V[S_k]$

My Summary

- Dynamite stuff
  - flexibility on all levels
  - lots of knobs to be tweaked
- Downsides
  - not at all clear that merge procs etc. that useful
  - primary copy is a cop-out