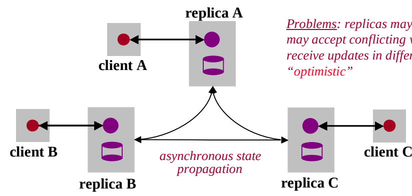
Asynchronous Replication and Bayou

Asynchronous Replication

Idea: build available/scalable information services with *read-any-write-any* replication and a weak consistency model.

- no denial of service during transient network partitions
- supports massive replication without massive overhead
- "ideal for the Internet and mobile computing" [Golding92]

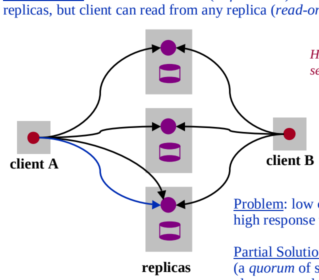


Problems: replicas may be out of date, may accept conflicting writes, and may receive updates in different orders. "optimistic"

Synchronous Replication

Basic scheme: connect each client (or *front-end*) with every replica: writes go to all replicas, but client can read from any replica (*read-one-write-all replication*).

How to ensure that each replica sees updates in the "right" order?



Problem: low concurrency, low availability, and high response times.

Partial Solution: Allow writes to any *N* replicas (a *quorum* of size *N*). To be safe, reads must also request data from a quorum of replicas.

Grapevine and Clearinghouse (Xerox)

Weakly consistent replication was used in earlier work at Xerox PARC:

- Grapevine and Clearinghouse name services
  - Updates were propagated by unreliable multicast ("direct mail").
- Periodic *anti-entropy exchanges* among replicas ensure that they eventually converge, even if updates are lost.
  - Arbitrary pairs of replicas periodically establish contact and resolve all differences between their databases.
  - Various mechanisms (e.g., MD5 digests and update logs) reduce the volume of data exchanged in the common case.
  - Deletions handled as a special case via "death certificates" recording the delete operation as an update.

Epidemic Algorithms

PARC developed a family of weak update protocols based on a disease metaphor (*epidemic algorithms* [Demers et. al. OSR 1/88]):

- Each replica periodically "touches" a selected "susceptible" peer site and "infects" it with updates.
  - Transfer every update known to the carrier but not the victim.
  - Partner selection is randomized using a variety of heuristics.
- Theory shows that the epidemic eventually infects the entire population with high probability (assuming it is connected).
  - Probability that replicas that have not yet converged decreases exponentially with time.
  - Heuristics (e.g., push vs. pull) affect traffic load and the expected time-to-convergence.

How to Ensure That Replicas Converge

1. Using any form of epidemic (randomized) anti-entropy, all updates will (eventually) be known to all replicas.
2. Imposing a global order on updates guarantees that all sites (eventually) apply the same updates in the same order.
3. Assuming conflict *detection* is deterministic, all sites will detect the same conflicts.
   - Write conflicts cannot (generally) be detected when a site *accepts* a write; they appear when updates are *applied*.

3. Assuming conflict *resolution* is deterministic, all sites will resolve all conflicts in exactly the same way.

Issues and Techniques for Weak Replication

1. How should replicas choose partners for anti-entropy exchanges?
   Topology-aware choices minimize bandwidth demand by "flooding", but randomized choices survive transient link failures.
2. How to impose a global ordering on updates?
   logical clocks and delayed delivery (or delayed commitment) of updates
3. How to integrate new updates with existing database state?
   Propagate updates rather than state, but how to detect and reconcile conflicting updates? Bayou: user-defined checks and *merge rules.*
4. How to determine which updates to propagate to a peer on each anti-entropy exchange?
   vector clocks or *vector timestamps*
5. When can a site safely *commit* or *stabilize* received updates?
   receiver acknowledgement by vector clocks (TSAE protocol)

Bayou Basics

1. Highly available, weak replication for mobile clients.
   Beware: every device is a "server"... let's call 'em *sites*.
2. Update conflicts are detected/resolved by rules specified by the application and transmitted with the update.
   interpreted dependency checks and merge procedures
3. Stale or tentative data may be observed by the client, but may mutate later.
   The client is aware that some updates have not yet been *confirmed*.
   "An inconsistent database is marginally less useful than a consistent one."

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Clocks

1. physical clocks
   Protocols to control drift exist, but physical clock timestamps cannot assign an ordering to "nearly concurrent" events.
2. logical clocks
   Simple timestamps guaranteed to respect causality: "*A*'s current time is later than the timestamp of any event *A* knows about, no matter where it happened or who told *A* about it."
3. vector clocks
   Order(N) timestamps that say exactly what *A* knows about events on *B*, even if *A* heard it from *C*.
4. matrix clocks
   Order(N^2) timestamps that say what *A* knows about what *B* knows about events on *C*.
   Acknowledgement vectors: an O(N) approximation to matrix clocks.

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Update Ordering

Problem: how to ensure that all sites recognize a fixed order on updates, even if updates are delivered out of order?

Solution: Assign timestamps to updates at their accepting site, and order them by source timestamp at the receiver.

Assign nodes unique IDs: break ties with the origin node ID.

- What (if any) ordering exists between updates accepted by different sites?
  Comparing physical timestamps is arbitrary: physical clocks drift.
  Even a protocol to maintain loosely synchronized physical clocks cannot assign a meaningful ordering to events that occurred at "almost exactly the same time".
- In Bayou, received updates may affect generation of future updates, since they are immediately visible to the user.

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Causality and Logical Time

Constraint: The update ordering must respect *potential causality*.

- Communication patterns establish a ***happened-before*** order on events, which tells us when ordering *might* matter.
- Event e_1 ***happened-before*** e_2 iff e_1 could possibly have affected the generation of e_2: we say that $e_1 < e_2$.
  $e_1 < e_2$ iff e_1 was "known" when e_2 occurred.
  Events e_1 and e_2 are *potentially causally related.*
- In Bayou, users or applications may perceive inconsistencies if causal ordering of updates is not respected at all replicas.
  An update *u* should be ordered after all updates *w* known to the accepting site at the time *u* was accepted.
  e.g., the newsgroup example in the text.

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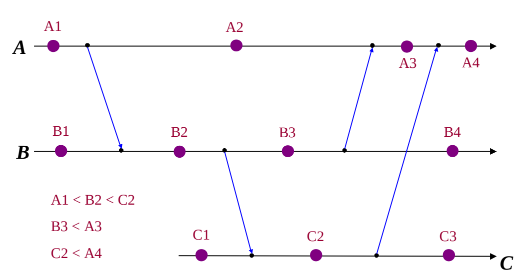
Causality: Example



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Logical Clocks

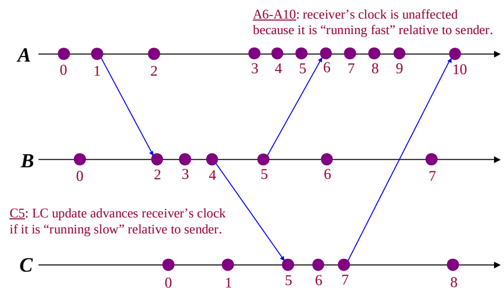
Solution: timestamp updates with *logical clocks* [Lamport]

Timestamping updates with the originating node's logical clock *LC* induces a partial order that respects potential causality.

Clock condition: $e_1 < e_2$ implies that $LC(e_1) < LC(e_2)$

1. Each site maintains a monotonically increasing clock value ***LC***.
2. Globally visible events (e.g., updates) are timestamped with the current ***LC*** value at the generating site.
   Increment local ***LC*** on each new event: ***LC = LC + 1***
3. Piggyback current clock value on all messages.
   Receiver resets local LC: **if** $LC_s > LC_r$ **then** $LC_r = LC_s + 1$

Logical Clocks: Example



Flooding and the Prefix Property

In Bayou, each replica's knowledge of updates is determined by its pattern of communication with other nodes.

Loosely, a site knows everything that it *could* know from its contacts with other nodes.

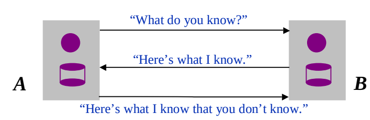
- Anti-entropy *floods* updates.
  Tag each update originating from site *i* with *accept stamp* (i, LC_i).
  Updates from each site are bulk-transmitted *cumulatively* in an order consistent with their source accept stamps.
- Flooding guarantees the *prefix property* of received updates.
  If a site knows an update *u* originating at site *i* with accept stamp LC_u, then it also knows all preceding updates *w* originating at site *i*: those with accept stamps $LC_w < LC_u$.

Which Updates to Propagate?

In an anti-entropy exchange, ***A*** must send ***B*** all updates known to ***A*** that are not yet known to ***B***.

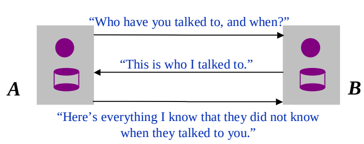
Problem: which updates are those?

one-way "push" anti-entropy exchange (Bayou reconciliation)



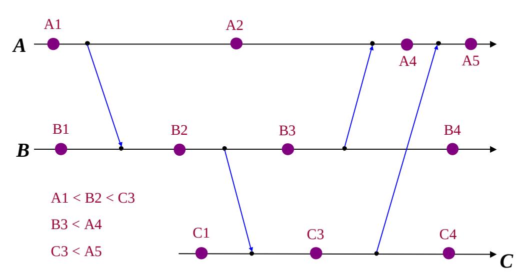
Causality and Reconciliation

In general, a transfer from ***A*** must send ***B*** all updates that did not ***happen-before*** any update known to ***B***.



Can we determine which updates to propagate by comparing logical clocks ***LC(A)*** and ***LC(B)***? NO.

Causality and Updates: Example



Motivation for Vector Clocks

Logical clocks induce an order consistent with causality, but it is actually stronger than causality.

- The converse of the *clock condition* does not hold: it may be that $LC(e_1) < LC(e_2)$ even if e_1 and e_2 are concurrent.
  - If *A* could know anything *B* knows, then $LC_A > LC_B$, but if $LC_A > LC_B$ then that doesn't make it so: "false positives".
  - Concurrent updates may be ordered unnecessarily.
- In Bayou, logical clocks tell us that *A* has *not* seen any update *u* with $LC(u) > LC_A$, but what has *A* seen?
  - LC_A does not say if *A* saw a given update *w* with $LC(w) < LC_A$.

We need a clock mechanism that is not so sloppy about capturing causality.

Vector Clocks

Vector clocks (aka *vector timestamps* or *version vectors*) are a more detailed representation of what a site might know.

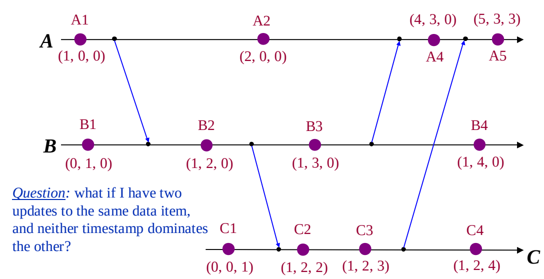
1. In a system with ***N*** nodes, each site keeps a vector timestamp *TS[N]* as well as a logical clock *LC*.
   - *TS[j]* at site *i* is the most recent value of site *j*'s logical clock that site *i* "heard about".
   - $TS_i[i] = LC_i$: each site *i* keeps its own *LC* in *TS[i]*.
2. When site *i* generates a new event, it increments its logical clock.
   - $TS_i[i] = TS_i[i] + 1$
3. A site *r* observing an event (e.g., receiving a message) from site *s* sets its TS_r to the pairwise maximum of TS_s and TS_r.
   - For each site *i*, $TS_r[i] = \text{MAX}(TS_r[i], TS_s[i])$

Vector Clocks and Causality

Vector clocks induce an order that *exactly* reflects causality.

- Tag each event *e* with current *TS* vector at originating site.
  - vector timestamp *TS(e)*
- e_1 ***happened-before*** e_2 *if and only if* $TS(e_2)$ ***dominates*** $TS(e_1)$
  - $e_1 < e_2$ iff $TS(e_1)[i] <= TS(e_2)[i]$ for each site *i*
  - "Every event or update visible when e_1 occurred was also visible when e_2 occurred.
- Vector timestamps allow us to ask if two events are concurrent, or if one ***happened-before*** the other.
  - If $e_1 < e_2$ then $LC(e_1) < LC(e_2)$ **and** $TS(e_2)$ dominates $TS(e_1)$.
  - If $TS(e_2)$ does **not** dominate $TS(e_1)$ then it is not true that $e_1 < e_2$.

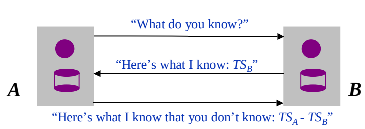
Vector Clocks: Example



Reconciliation with Vector Clocks

A can determine which updates to pass to ***B*** by comparing their current vector clocks.

- Tag each update originating from site *i* with *accept stamp* (i, LC_i).
- If $TS_A[i] > TS_B[i]$, then *A* has updates from *i* that *B* has not seen, i.e., they did not ***happen-before*** any updates known to *B*.
- *A* sends *B* all updates from site *i* tagged with accept stamps *LC* such that $TS_B[i] < LC <= TS_A[i]$.



The Prefix Property and Reconciliation

Vector clocks work for anti-entropy transfers because they precisely encapsulate which updates a site has seen.

- The *prefix property* must hold for this to work.
  - If a site knows an update *u* originating at site *i* with accept stamp LC_u, then it also knows all preceding updates *w* originating at site *i*: those with accept stamps $LC_w < LC_u$.
- $TS_B[i]$ exceeds the origin timestamp (*LC*) of the *latest* update generated by *i* and received at *B*.
- Updates *w* from *i* with origin timestamps $LC(w) > TS_B[i]$ are exactly those updates that did not ***happen-before*** TS_B.
  - If $LC(w) > TS_B[i]$, then TS_B cannot dominate $TS_i(w)$, so *w* cannot be known to *B*.
  - (Converse left as an exercise.)

When to Discard or Stabilize Updates?

Problem 1: when can a site discard its pending updates?

When can A know that every other site has seen some update u?

Problem 2: when to commit (stabilize) pending updates?

A *committed* update w is *stable*: no other update u can arrive with $u < w$; w will never need to be rolled back.

These two questions are equivalent:

Suppose we know that each peer site s has received this update w.

We had transitive contact with s since it received w.

We have received all updates known by s when it received w.

We have received all updates generated by s before it received w.

We have received all updates generated before w: w is stable.

One approach: propagate "knowledge about knowledge" with the AE.

The Need for Propagating Acknowledgments

Vector clocks tell us what B knows about C, but they do not reflect what A knows about what B knows about C.

Nodes need this information to determine when it is safe to discard/stabilize updates.

- A can always tell if B has seen an update u by asking B for its vector clock and looking at it.

  If u originated at site i, then B knows about u if and only if TS_B *covers* its accept stamp LC_u: $TS_B[i] >= LC_u$.

- A can only know that *every* site has seen u by looking at the vector clocks for *every* site.

  Even if B recently received updates from C, A cannot tell (from looking at B's vector clock) if B got u from C or if B was already aware of u when C contacted it.

Solution 1: Matrix Clocks

Matrix clocks extend vector clocks to capture "what A knows about what B knows about C".

- Each site i maintains a matrix $MC_i(N,N)$.

  Row j of i's matrix clock MC_i is the most recent value of j's vector clock TS_j that i has heard about.

  $MC_i[i, i] = LC_i$ and $MC_i[i, *] = TS_i$

  $MC_i[j,k]$ = what i knows about what j knows about what happened at k.

- If A sends a message to B, then MC_B is set to the pairwise maximum of MC_A and MC_B.

  If A knows that B knows u, then after A talks to C, C knows that B knows u too.

Solution 2: Acknowledgment Stamps

Matrix clocks require N^3 state for a system with N nodes.

Propagate N^2 state on each exchange.

For anti-entropy, we can conservatively approximate the matrix clock using only N^2 state. [Golding]

- After A passes updates to B, compute B's *ack stamp* as the *lowest LC* entry in TS_B.
- Each node keeps an *acknowledgment summary vector AS(N)* of ack stamps for every other node "last it heard".

  (AS vector just has the min value of each row in the matrix clock.)

- In an anti-entropy exchange from A to B, compute AS_B as a pairwise maximum of AS_A and AS_B.

  $AS_i[j]$ does not tell i what j knows about k, but it does say that j knows about every event at k prior to $AS_i[j]$, *for every k*.

Golding's TSAE Protocol

Golding defined a *T*imestamped *A*nti-*E*ntropy (TSAE) protocol that predates Bayou.

- designed for replicated Internet services (e.g., *refdbms*)
- reconciliation by two-way pairwise anti-entropy exchanges

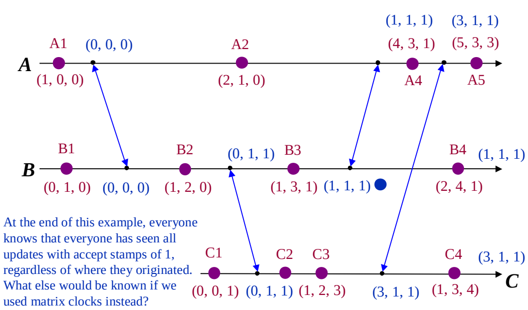
  flooded updates

- studied role of network topology in partner selection
- uses logical clocks for accept stamps

  total commit ordering defined by logical clocks

- propagates knowledge of peer replica state by ack stamps and ack vectors

Ack Vectors in TSAE: Example



At the end of this example, everyone knows that everyone has seen all updates with accept stamps of 1, regardless of where they originated. What else would be known if we used matrix clocks instead?

The Trouble With Ack Vectors

Matrix clocks and ack vectors can impede forward progress in the presence of failures.

- If a replica *A* fails or becomes disconnected, other nodes recognize that it is "getting behind".
  - No node's ack stamp can advance beyond the accept stamp *LC(w)* of the last update *w* received by *A*.
- If a replica gets behind, other nodes cannot retire (discard) received updates *u* with *LC(u)* > *LC(w)*.
- One solution is to forcibly remove the disconnected node *A* from the replica set.
  - How to bring *A* up to date if it later rejoins the replica set? How to order updates generated by *A* while disconnected?

Committing Updates in Bayou

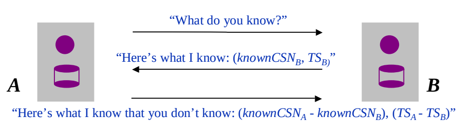
Bayou commits updates more aggressively using a *primary-commit protocol.*

- A single site is designated as the *primary*.
- The primary *commits* updates as it receives them.
  - Primary assigns a *commit sequence number* (CSN) to each committed update.
  - The final total update order is defined by CSN order.
- Sites learn of commitment through anti-entropy transfers.
  - A site may learn of an update before learning that the update has been committed by the primary.
  - Sites learn of commitment in CSN order. Updates known to be committed are *stable*: their order will never change.

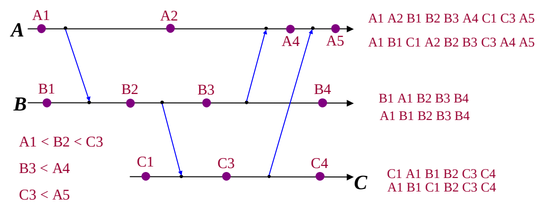
Reconciliation with CSNs

Each site also maintains a *knownCSN* counter, the CSN of the latest committed update the site knows has committed.

- In an anti-entropy transfer, *A* looks at *B*'s *knownCSN*.
- If *A* knows update *w* has committed, and $CSN(w) > knownCSN_B$, then *A* notifies *B* that *w* has committed.
- B updates $knownCSN_B$ as it learns of committed updates.
- (This assumes that sites learn of commitment in CSN order.)



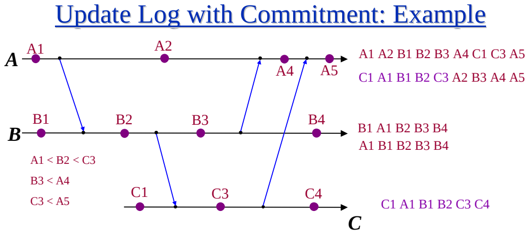
Bayou Update Logs: Example



ordering properties (so far)

1. Each site sees/logs its own updates in accept order.
2. Each site sees/logs updates from each peer site in accept order.
3. Each site sees all updates in a causal order.
4. Each site reorders received updates to total accept stamp order.
5. Each site sends updates in its update log order.

Update Log with Commitment: Example



Suppose *C* is the primary

1. *C* commits updates in its update-log order.
2. *New constraint*: all sites order known-committed updates before all tentative updates.
3. Sites propagate updates/knowledge in update log order: known-committed updates propagate before tentative updates, and commit knowledge propagates in CSN order.
4. Can CSN order violate causality? Can it violate a total order based on accept stamps?

Discarding Updates in Bayou

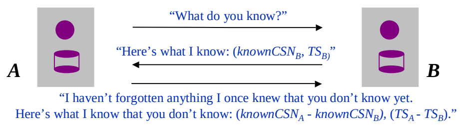
Any site *A* may truncate any prefix of the stable (committed) portion of its update log to reclaim space.

- *A* needs no record of known-committed updates for itself.
  - Committed updates are never rolled back, since commits are received in CSN order, the same as the final order.
- *A* keeps stable updates in its log only so it can tell other sites about those updates.
- How can *A* reconcile with peers needing discarded updates?
  - Easy: may discard stable updates *if* there is some other way to reconcile, e.g., send entire committed database state before sending updates.
  - *Truncation is a tradeoff*: it reclaims local storage, but may make later reconciliations more expensive.

Reconciliation with Update Log Truncation

Each site maintains an *omitCSN* stamp to characterize the omitted log prefix.

- $omitCSN_A$ is the latest CSN omitted from *A*'s log.
- An incremental update transfer is insufficient if $omitCSN_A > knownCSN_B$.



Reconciling a Lagging Server

What if a server is too far out of date for an incremental transfer?

- ***A*** can't just send its entire database state.
  - ***B*** must know about ***A***'s pending tentative updates in case they must be rolled back.
  - ***B*** may possess updates not known to ***A***: these cannot be discarded.
- Instead, ***A*** must send a "committed view" of its database with all tentative updates rolled back.
  - ...then complete the protocol as before by sending logged updates and commit records unknown to ***B***.
    - As described in the paper, Bayou rolls back *all* logged updates including committed updates, but I don't see why this is necessary.
  - ***B*** then rolls its log forward in the usual way, including any new updates from ***A***, possibly interleaved with updates ***B*** already had.

That Pesky "O-Vector"

Problem: what if ***B*** has a logged update *w* that was already committed and discarded by ***A***?

- *B* saw *w*, but did not know that it was committed.
- *B* cannot tell from $omitCSN_A$ that ***A***'s committed view reflects *w*.
- *B* must be prevented from reapplying *w*.

- Solution: Each site also keeps an *omitTS* timestamp vector to characterize the omitted prefix of its update log.
  - $omitTS_A[i]$ is the highest accept stamp of any update originating at site *i* that was omitted from ***A***'s log.
  - On a full database transfer, roll back ***A***'s state to $omitTS_A$, send that state with $omitTS_A$, then set $omitTS_B = omitTS_A$. This is safe because $omitTS_A$ must dominate the "old" $omitTS_B$.
- *B* strikes from its log any updates *w* covered by $omitTS_A$.

Reconciliation Using Transportable Media

1. "Sender" dumps its replica state on media (e.g., a floppy).
   - E.g., *A* dumps its update log to the disk, prefixed by ($omitCSN_A$, $omitTS_A$) and (CSN_A, TS_A).
2. "Receiver" must ask two questions:
   - Am I advanced enough to accept the updates on this disk?
     - Is $CSN_I > omitCSN_A$?
   - Will I learn anything from the updates on this disk?
     - Is $CSN_A > CSN_I$? Or is $TS_A[k] > TS_I[k]$, for any *k*?
3. This is exactly like network anti-entropy transfer...
   - ...except the receiver has access to the sender's state, and executes both sides of the protocol.

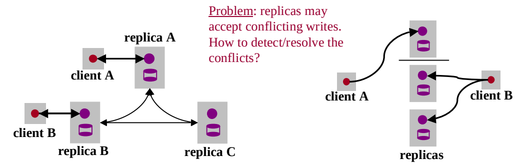
Questions About Bayou

1. What is the effect of a failed primary?
2. What will happen when you reconnect your laptop after you return from a long vacation on a tropical island?
3. If it was a working vacation with some buddies, can you assume that your replicas will converge in the absence of the primary to define the commit order?
4. Can you assume that the interleaving of updates observed during your vacation will be preserved when you reconnect?
5. What if one person goes home and reconnects before the others?
6. How to create/retire replicas and notify peers that they exist?

Write Conflicts in Optimistic Replication

Asynchronous replication is *optimistic*: since replicas can accept writes independently, it assumes that concurrent writes accepted by different replicas will be *nonconflicting*.

Systems with synchronous replication may choose to be optimistic to improve availability, e.g., to accept writes issued to a subset of replicas that do not constitute a quorum.



Detecting Update Conflicts: Traditional View

Many systems view updates *u* and *w* as *nonconflicting* iff:

- *u* and *w* update different objects (e.g., files or records)
- *u* and *w* update the same object, but one writer had observed the other's update before making its own.

In other words, an update conflict occurs when two processes *p* and *q* generate "concurrent" updates to the same object.

- *p* and *q* updated the same object, but neither update ***happened-before*** the other.
- Updates to an object must follow a well-defined causal chain.
  - Potential causality must induce a total order on the updates.

Example: Coda

Coda is a highly-available replicated file system (successor to AFS) that supports disconnected operation.

- Data is stored in *files*, which are grouped in *volumes*, which are stored on *servers*.
  - Files are the granularity of caching by clients.
- Volumes are the granularity of replication.
  - VSG = ***V***olume ***S***torage ***G***roup == set of servers for a volume.
- Availability by *read-any/write-all-available* replication.
  - On an *open*, read the file from the "most up-to-date" member of the ***A***vailable VSG (*AVSG*).
  - On a *close* after *write*, send the new version of the file to *all* members of the AVSG.

Version Vectors in Coda

How to characterize the "up-to-dateness" of a file version?

Solution: *Coda Version Vectors.*

- Coda nodes maintain a version vector *CVV* for each file *F*.
  - *CVV* has one element for each server in the file's VSG.
  - *CVV[i]* is the # of writes received on *this version* of *F* at server *i*.
- On an *open*, client sets *CVV* to the server's *CVV*.
- On a *close*, client updates *CVV* and propagates it to the AVSG.
  - Increment *CVV[i]* for each server *i* that acknowledges the write.
- We can compare the *CVV*s to tell if one version of *F* has updates not reflected in the other.
  - Two versions *conflict* if neither *CVV* dominates the other.

Update Conflicts: the Bayou Approach

Bayou rejects the traditional "blind" view of conflicts:

- Updates might conflict even if they affect different records.
  - *Example*: two meeting-room records that contain the same room number and overlapping times.
  - *Example*: two bibliography database entries that describe the same document.
  - *Example*: two bibliography database entries that describe different documents using the same tag.
- Concurrent updates to the same record might not conflict.
  - Writes don't conflict if they *commute*, e.g., they update different fields of the same record.

Detecting/resolving conflicts is *application-specific*.

Application-Specific Reconciliation

Only the application can decide how to reconcile conflicting updates detected as writes are applied.

E.g., *refdbms.*

- Discard updates and deletions for already-deleted records.
- Change entry tag names to resolve add/add conflicts.
  - e.g., change *Lamport75* to *Lamport75a*
- field-specific update conflict resolution

Handling Update Conflicts in Bayou

- The primary commit protocol ensures that all sites commit the same writes in the same order.
- But this is not sufficient to guarantee that replicas converge.
  - *Dependency checks* and *merge procedures* handle conflicts.
  - Check/merge can examine any state in the replica.
- Check and merge procedures must be deterministic.
  - Limit inputs to the current contents of the database.
  - Execute with fixed resource bounds so they fail deterministically.
- Check/merge is executed every time a write is applied.
  - Rollback must be able to undo the effects of a merge.