10. Replication

CSEP 545 Transaction Processing

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Outline

1. Introduction
2. Primary-Copy Replication
3. Multi-Master Replication
4. Other Approaches
5. Products

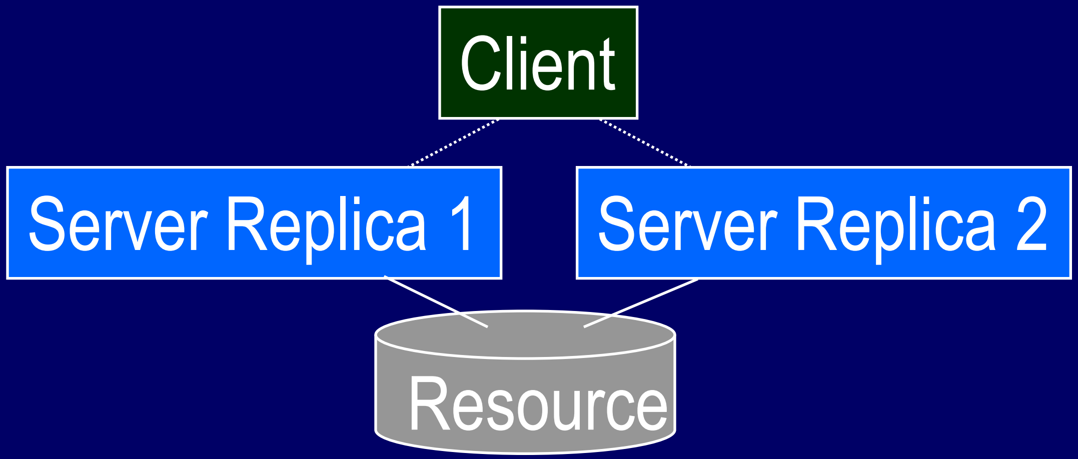
1. Introduction

- Replication - using multiple copies of a server or resource for better availability and performance.
  - Replica and Copy are synonyms

- If you're not careful, replication can lead to
  - worse performance - updates must be applied to all replicas and synchronized
  - worse availability - some algorithms require multiple replicas to be operational for any of them to be used

Replicated Server

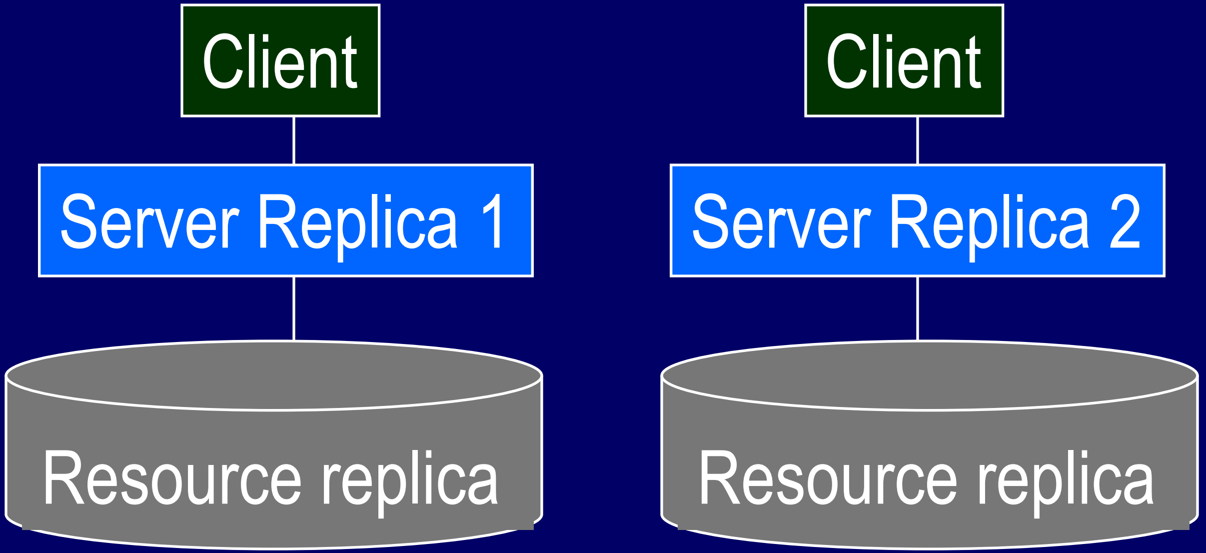
- Can replicate servers on a common resource
  - Data sharing - DB servers communicate with shared disk



- Helps availability for process (not resource) failure
- Requires a replica cache coherence mechanism, so this helps performance only if
  - little conflict between transactions at different servers or
  - loose coherence guarantees (e.g. read committed)

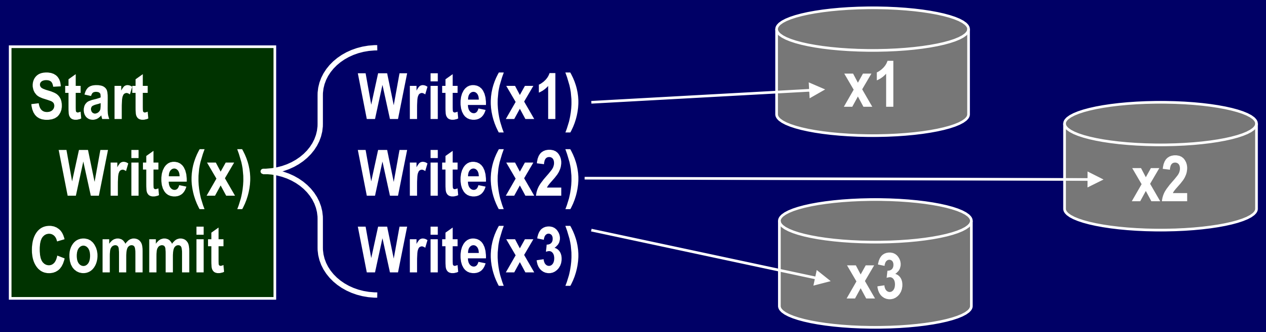
Replicated Resource

- To get more improvement in availability, replicate the resources (too)
- Also increases potential throughput
- This is what's usually meant by replication
- It's the scenario we'll focus on



Synchronous Replication

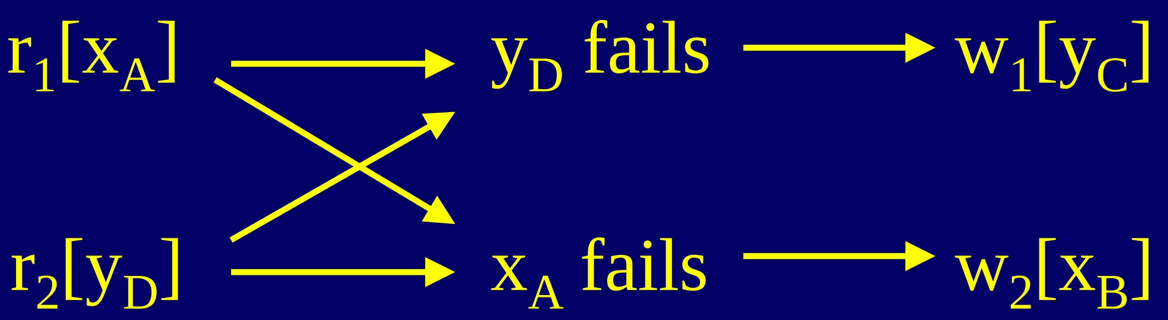
- Replicas function just like a non-replicated resource
  - Txn writes data item x. System writes all replicas of x.
  - Synchronous – replicas are written within the update txn
  - Asynchronous – One replica is updated immediately. Other replicas are updated later



- Problems with synchronous replication
  - Too expensive for most applications, due to heavy distributed transaction load (2-phase commit)
  - Can’t control when updates are applied to replicas

Synchronous Replication - Issues

- If you just use transactions, availability suffers.
- For high-availability, the algorithms are complex and expensive, because they require heavy-duty synchronization of failures.
- … of failures? How do you synchronize failures?
- Assume replicas x_A, x_B of x and y_C, y_D of y



Not equivalent to a one-copy execution, even if x_A and y_D never recover!

- DBMS products support it only in special situations

Atomicity & Isolation Goal

- One-copy serializability (abbr. *1SR*)
  - An execution of transactions on the replicated database has the same effect as a serial execution on a one-copy database.
- *Readset* (resp. *writeset*) - the set of data items (not copies) that a transaction reads (resp. writes).
- 1SR Intuition: the execution is SR *and* in an equivalent serial execution, for each txn T and each data item x in readset(T), T reads from the most recent txn that wrote into <u>any</u> copy of x.
- To check for 1SR, first check for SR (using SG), then see if there's equivalent serial history with the above property

Atomicity & Isolation (cont'd)

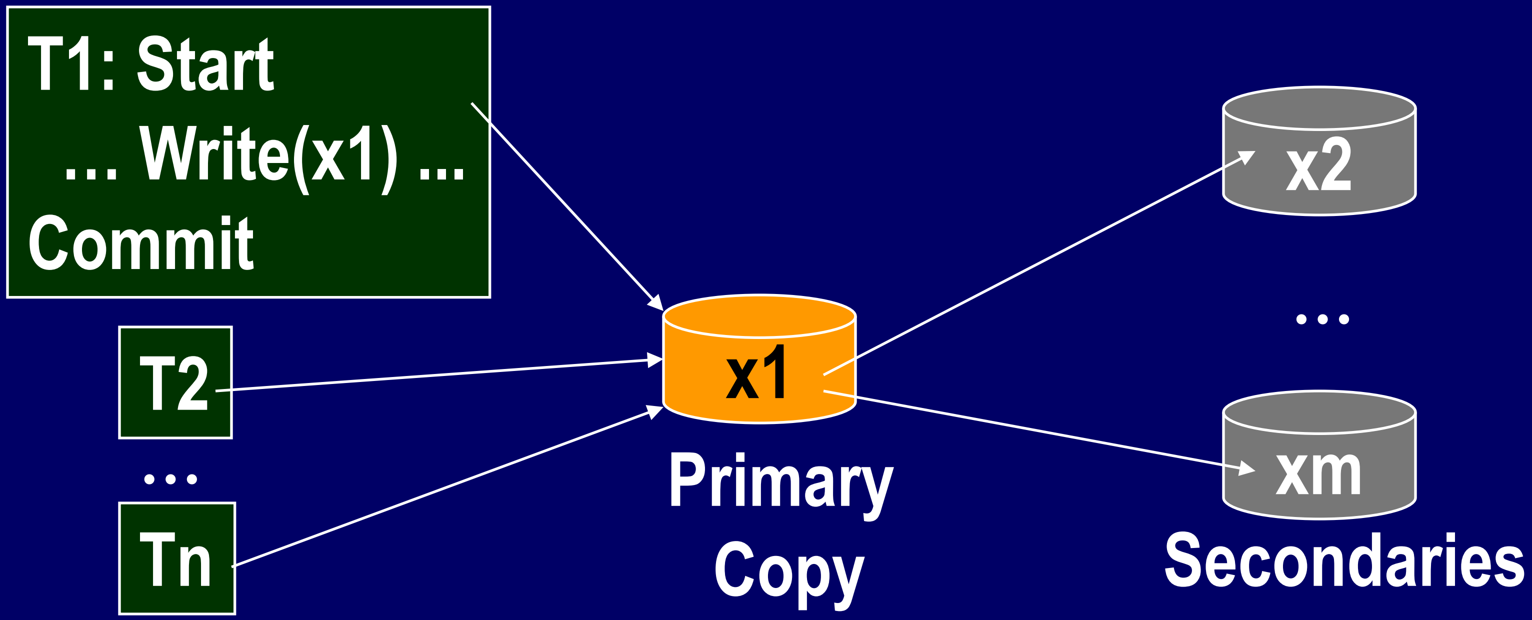
- Previous example was not 1SR. It is equivalent to
  - $r_1[x_A]\ w_1[y_C]\ r_2[y_D]\ w_2[x_B]$ and
  - $r_2[y_D]\ w_1[x_B]\ r_1[x_A]\ w_1[y_C]$
  - but in both cases, the second transaction does not read its input from the previous transaction that wrote that input.
- These are 1SR
  - $r_1[x_A]\ w_1[\mathbf{y_D}]\ r_2[y_D]\ w_2[x_B]$
  - $r_1[x_A]\ w_1[y_C]\ \mathbf{w_1[y_D]}\ r_2[y_D]\ w_2[x_A]\ w_2[x_B]$
- The previous history is the one you would expect
  - Each transaction reads one copy of its readset and writes into all copies of its writeset
- But it may not always be feasible, because some copies may be unavailable.

Asynchronous Replication

- Asynchronous replication
  - Each transaction updates one replica.
  - Updates are propagated later to other replicas.
- Primary copy: Each data item has a primary copy
  - All transactions update the primary copy
  - Other copies are for queries and failure handling
- Multi-master: Transactions update different copies
  - Useful for disconnected operation, partitioned network
- Both approaches ensure that
  - Updates propagate to all replicas
  - If new updates stop, replicas converge to the same state
- Primary copy ensures serializability, and often 1SR
  - Multi-master does not. … More later.

2. Primary-Copy Replication

- Designate one replica as the primary copy (publisher)
- Transactions may update only the primary copy
- Updates to the primary are sent later to secondary replicas (subscribers) in the order they were applied to the primary



Update Propagation

- Collect updates at the primary using triggers or by post-processing the log
  - Triggers: on every update at the primary, a trigger fires to store the update in the update propagation table.
  - Log post-processing: "sniff" the log to generate update propagations
- Log post-processing (vs. triggers)
  - Saves triggered update overhead during on-line txn.
  - But R/W log synchronization has a (small) cost
  - Requires admin (what if the log sniffer fails?)
- Optionally identify updated fields to compress log
- Most DB systems support this today.

Update Processing

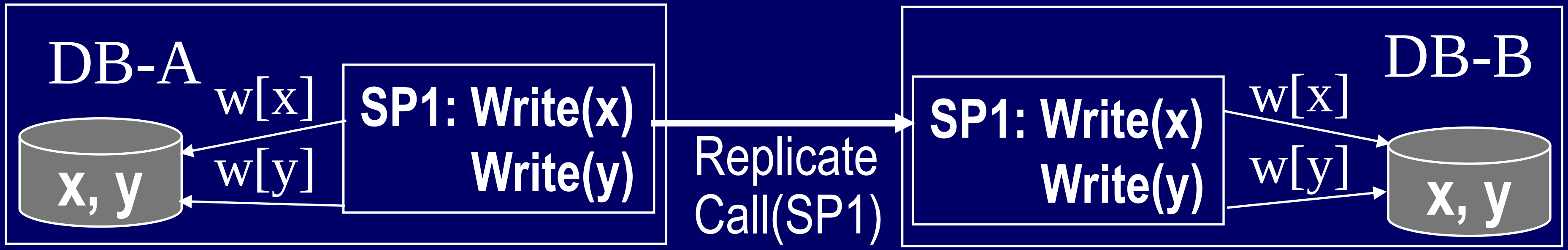
- At the replica, for each transaction T in the propagation stream, execute a transaction that applies T's updates to the replica.
- Process the stream serially
  - Otherwise, conflicting transactions may run in a different order at the replica than at the primary.
  - Suppose log contains $w_1[x]\ c_1\ w_2[x]\ c_2$. Obviously, T_1 must run before T_2 at the replica.
  - So the execution of update transactions is serial.

Update Processing (cont'd)

- To get a 1SR execution at the replica
  - Update transactions and read-only queries use an atomic and isolated mechanism (e.g., 2PL)
- Why this works
  - The execution is serializable
  - Each state in the serial execution is one that occurred at the primary copy
  - Each query reads one of those states.

Request Propagation

- An alternative to propagating updates is to propagate procedure calls (e.g., a DB stored procedure call).



- Or propagate requests (e.g. txn-bracketed stored proc calls)
- Must ensure requests run in the same order at primary and replica (same requirement as updates or procedure calls).
  - As for updates, can propagate requests asynchronously, or …
  - can run requests synchronously at all replicas, <u>but</u> commit even if one replica fails (need a recovery procedure for failed replicas).
  - If supported, it's often a txn middleware (not DB) feature.

Failure & Recovery Handling

- Secondary failure - nothing to do till it recovers
  - At recovery, apply the updates it missed while down
  - Needs to determine which updates it missed, just like non-replicated log-based recovery
  - If down for too long, may be faster to get a whole copy
- Primary failure
  - Normally, secondaries wait till the primary recovers
  - Can get higher availability by electing a new primary
  - A secondary that detects primary's failure starts a new election by broadcasting its unique replica identifier
  - Other secondaries reply with their replica identifier
  - The largest replica identifier wins

Failure Handling (cont'd)

- Primary failure (cont'd)
  - All replicas must now check that they have the same updates from the failed primary
  - During the election, each replica reports the id of the last log record it received from the primary
  - The most up-to-date replica sends its latest updates to (at least) the new primary.
  - Could still lose an update that committed at the primary and wasn't forwarded before the primary failed … but solving it requires synchronous replication (2-phase commit to propagate updates to replicas)

Communications Failures

- Secondaries can’t distinguish a primary failure from a communication failure that partitions the network.
- If the secondaries elect a new primary and the old primary is still running, there will be a reconciliation problem when they’re reunited. This is multi-master.
- To avoid this, one partition must know it’s the only one that can operate. It can’t communicate with other partitions to figure this out.
- Could make a static decision.
  E.g., the partition that has the primary wins.
- Dynamic solutions are based on Majority Consensus

Majority Consensus

- Whenever a set of communicating replicas detects a replica failure or recovery, they test if they have a majority (more than half) of the replicas.
- If so, they can elect a primary
- Only one set of replicas can have a majority.
- Doesn't work with an even number of copies.
  - Useless with 2 copies
- Quorum consensus
  - Give a weight to each replica
  - The replica set that has a majority of the weight wins
  - E.g. 2 replicas, one has weight 1, the other weight 2

3. Multi-Master Replication

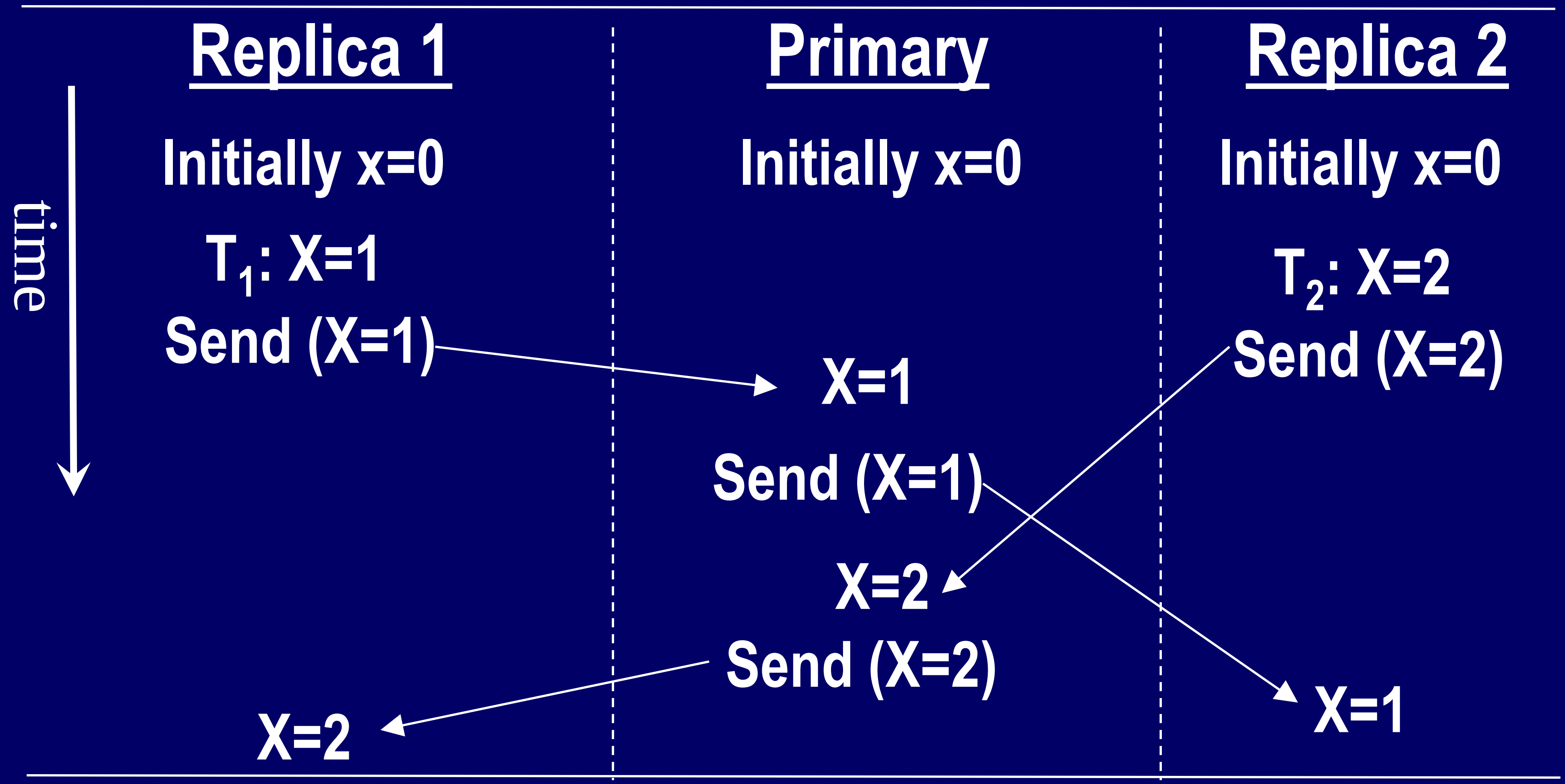
- Some systems must operate when partitioned.
  - Requires many updatable copies, not just one primary
  - Conflicting updates on different copies are detected late
- Classic example - salesperson's disconnected laptop

  Customer table (rarely updated) Orders table (insert mostly)

  Customer log table (append only)
  - So conflicting updates from different salespeople are rare
- Use primary-copy algorithm, with multiple masters
  - Each master exchanges updates ("gossips") with other replicas when it reconnects to the network
  - Conflicting updates require reconciliation (i.e. merging)
- In Lotus Notes, Access, SQL Server, Oracle, …

Example of Conflicting Updates

- Assume all updates propagate via the primary

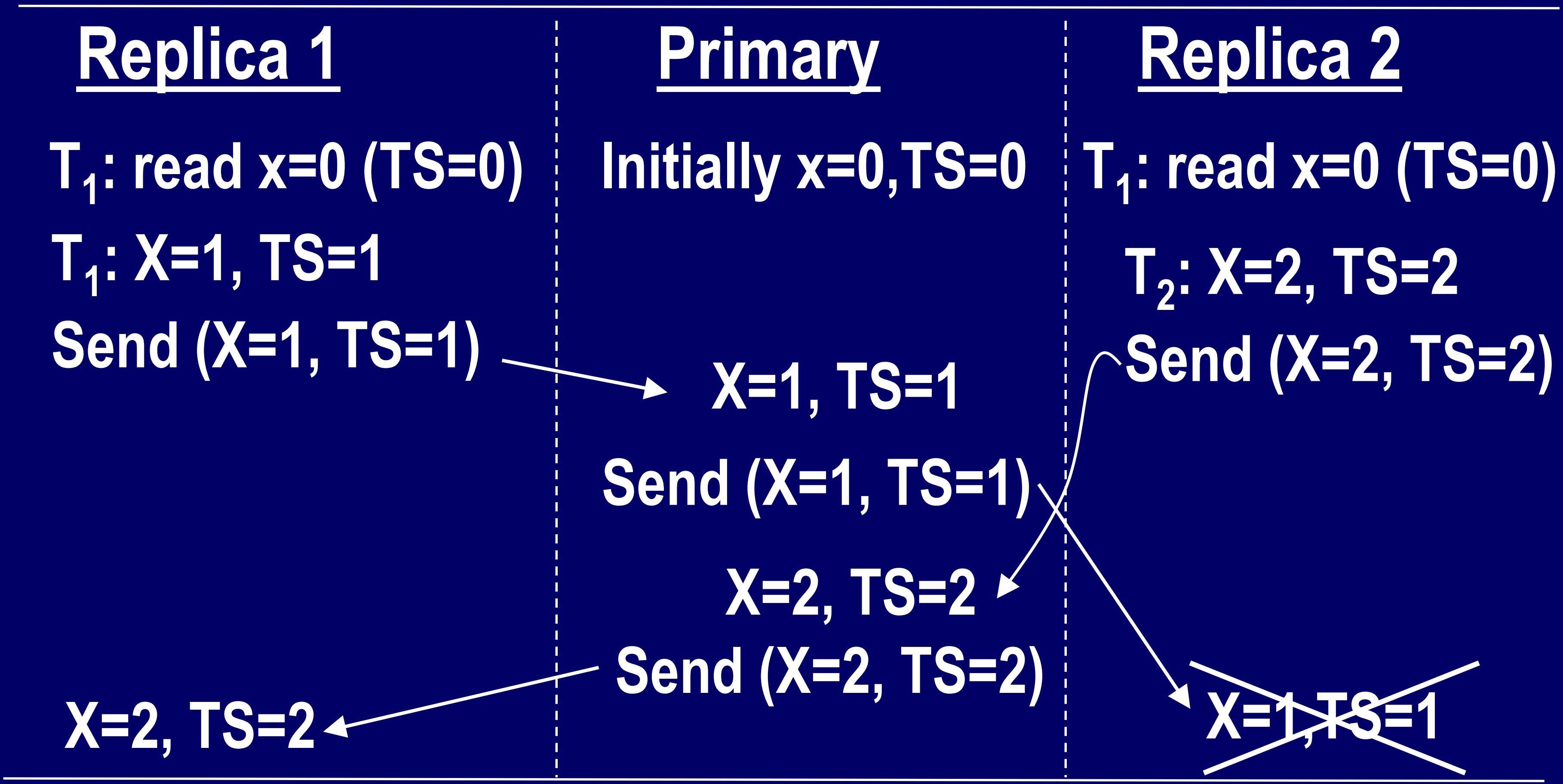


- Replicas end up in different states

Thomas' Write Rule

- To ensure replicas end up in the same state
  - Tag each data item with a timestamp
  - A transaction updates the value and timestamp of data items (timestamps monotonically increase)
  - An update to a replica is applied only if the update's timestamp is greater than the data item's timestamp
  - You only need timestamps of data items that were recently updated (where an older update could still be floating around the system)
- All multi-master products use some variation of this
- Robert Thomas, *ACM TODS*, June '79
  - Same article that invented majority consensus

Thomas Write Rule $\not\Rightarrow$ Serializability



- Replicas end in the same state, but neither T_1 nor T_2 reads the other's output, so the execution isn't serializable.
- This requires reconciliation

Multi-Master Performance

- The longer a replica is disconnected and performing updates, the more likely it will need reconciliation
- The amount of propagation activity increases with more replicas
  - If each replica is performing updates, the effect is quadratic

Microsoft Access and SQL Server

- Multi-master replication without a primary
- Each row R of a table has 4 additional columns
  - globally unique id (GUID)
  - generation number, to determine which updates from other replicas have been applied
  - version num = the number of updates to R
  - array of [replica, version num] pairs, identifying the largest version num it got for R from every other replica
- Uses Thomas' write rule, based on version nums
  - Access uses replica id to break ties. SQL Server 7 used subscriber priority or custom conflict resolution.

Generation Numbers (Access/SQL cont’d)

- Each replica has a current generation number
- A replica updates a row’s generation number whenever it updates the row
- A replica knows the generation number it had when it last exchanged updates with R´, for every replica R´.
- A replica increments its generation number every time it exchanges updates with another replica.
- So, when exchanging updates with R′, it should send all rows with a generation number larger than what it had when it last exchanged updates with R′.

Duplicate Updates (Access/SQL cont'd)

- Some rejected updates are saved for later analysis
- To identify duplicate updates to discard them
  - When applying an update to x, replace x's array of [replica, version#] pairs by the update's array.
  - To avoid processing the same update via many paths, check version num of arriving update against the array
- Consider a rejected update to x at R from R´, where
  - [R´, V] describes R´ in x's array, and
  - V´ is the version number sent by R´.
  - If V ≥ V´, then R saw R´'s updates
  - If V < V´, then R didn't see R´'s update, so store it in the conflict table for later reconciliation

4. Other Approaches

- Non-transactional replication using timestamped updates and variations of Thomas’ write rule
  – directory services are managed this way
- Quorum consensus per-transaction
  – Read and write a quorum of copies
  – Each data item has a version number and timestamp
  – Each read chooses a replica with largest version number
  – Each write increments version number one greater than any one it has seen
  – No special work needed for a failure or recovery

Other Approaches (cont'd)

- Read-one replica, write-all-available replicas
  - Requires careful management of failures and recoveries
- E.g., Virtual partition algorithm
  - Each node knows the nodes it can communicate with, called its view
  - Txn T can execute if its home node has a view including a quorum of T's readset and writeset
  - If a node fails or recovers, run a view formation protocol (much like an election protocol)
  - For each data item with a read quorum, read the latest version and update the others with smaller version #.

Summary

- State-of-the-art products have rich functionality.
  - It’s a complicated world for app designers
  - Lots of options to choose from
- Most failover stories are weak
  - Fine for data warehousing
  - For 24×7 TP, need better integration with cluster node failover

5. Products

- All major DBMS products have a rich primary-copy replication mechanism. These are *big* subsystems.
- Differences are in detailed features
  - performance
  - ease of management
  - richness of filtering predicates
  - push vs. pull propagation
  - stored procedure support
  - transports (e.g. Sybase SQLanywhere can use email!)
  - …
- The following summary is an incomplete snapshot of products as of May 2003.

Microsoft SQL Server 2000

- Publication - a collection of articles to subscribe to
- Article – a horiz/vertical table slice or stored proc
  - Customizable table filter (WHERE clause or stored proc)
  - Stored proc may be transaction protected (replicate on commit). Replicates the requests instead of each update.
- *Snapshot replication* makes a copy
- *Transactional replication* maintains the copy by propagating updates from publisher to subscribers
  - Post-processes log to store updates in Distribution DB
  - Distribution DB may be separate from the publisher DB
  - Updates can be pushed to or pulled from subscriber
  - Can customize propagated updates using stored procedures

SQL Server 2000 (cont'd)

- *Immediate updating subscriber* – Can update replicas
  - Queued updates are synchronized with publisher via 2PC.
  - Triggers capture *local* updates and forward them to the Subscriber (trigger must not fire for replicated updates from the publisher).
  - Subscriber's forwarded update has before-value of row version-id.
  - Publisher checks that its copy of row has the same version-id.
  - If so, it performs the update and asyncrhonously forwards it to other subscribers
  - If not, it aborts the transaction (subscriber updated the row lately)
- Access control lists protect publishers from unauthorized subscribers
- *Merge replication*- described later (multi-master)

Oracle 9i

- Like SQL Server, can replicate updates to table fragments or stored procedure calls at the master copy
- Uses triggers to capture updates in a deferred queue
  - Updates are row-oriented, identified by primary key
  - Can optimize by sending keys and updated columns only
- Group updates by transaction, which are propagated:
  - Either serially in commit order or
  - in parallel with some dependent transaction ordering: each read(x) reads the "commit number" of x; updates are ordered by dependent commit number
- Replicas are implemented as materialized views
- Replicas are updated in a batch refresh.
  - Pushed from master to snapshots, using queue scheduler
- Replicas can be updatable (similar to SQL Server)

Oracle 9i

- Materialized view replica is driven by one master
- Multi-master replication
  - Masters replicate entire tables
  - Push updates from master to masters (synch or asynch)
  - Updates include before values (you can disable if conflicts are impossible)
  - They recommend masters should always be connected
- Conflict detection
  - Before-value at replica is different than in update
  - Uniqueness constraint is violated
  - Row with the update’s key doesn’t exist

Oracle 9i Conflict Resolution

- Conflict resolution strategies (defined per column-group)
  - Add difference between the old and new values of the originating site to the destination site
  - Average the value of the current site and the originating site
  - Min or max of the two values
  - The one with min or max timestamp
  - The site or value with maximum priority
  - Can apply methods in sequence: e.g., by time , then by priority.
- Can call custom procs to log, notify, or resolve the conflict
  - Parameters - update's before/after value and row's current value
- For a given update, if no built-in or custom conflict resolution applies, then the entire transaction is logged.

IBM DB2

- Very similar feature set to SQL Server and Oracle
- Filtered subscriber
  - Create snapshot, then update incrementally (push or pull)
- Many table type options:
  - Read-only snapshot copy, optionally with timestamp
  - Aggregates, with cumulative or incremental values
  - Consistent change data, optionally with row versions
  - “Replica” tables, for multi-master updating
- Interoperates with many third party DBMS’s
- Captures DB2 updates from the DB2 log
  - For other systems, captures updates using triggers