Practical Replication

Purposes of Replication

- Improve Availability
  - Replicated databases can be accessed even if several replicas are unavailable
- Improve Performance
  - Replicas can be geographically diverse, with closest replica serving each client

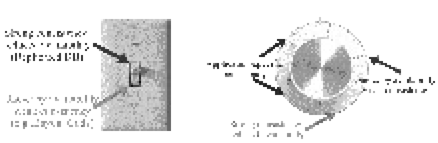
Problems with Replication

- Consistency of the replicated data
  - Many applications require consistency regardless of which replica is read from or inserted into
  - Consistency is expensive
  - Some replication schemes will reduce update availability
  - Others require reconciliation after inconsistency occurs
  - Performance may suffer as agreement across replicas may be necessary

The Costs and Limits of Availability for Replicated Services

- Consistency vs. Availability
  - Many applications don’t need strong consistency
    - Can specify a maximum deviation
  - Consistency don’t need to be sacrificed during normal operation
    - Only perform tradeoff when failure occurs
- Typically two choices of consistency
  - Strong consistency
    - Low availability, high data accuracy
  - Weak consistency
    - High availability, low accuracy (lots of conflicts and stale access)
- Continuous Consistency Model
  - A spectrum of different levels of consistency
  - Dynamically adapt consistency bounds in response to environmental changes

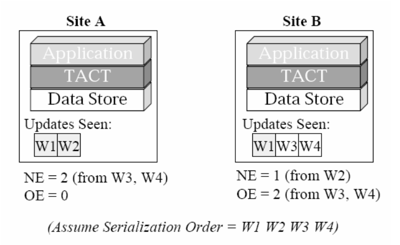
Continuous Consistency Model



Metrics of Consistency

- Three categories of errors in consistency at a replica
  - *Numerical error*
    - The total number of writes accepted by the system but not seen by the replica
  - *Staleness*
    - Difference between current time and the acceptance time of the oldest write not seen locally
  - *Order error*
    - Number of writes that have not established their commit order at the local replica

Example of Numerical and Order Error



Deriving tight upper bound on availability

- Want to derive a tight upper bound on the $Avail_{service}$ based on a given level of consistency, workload, and faultload
  - $Avail_{service} \le$ F(consistency, workload, faultload)
- Upper bound helps evaluate existing consistency protocols
  - Reveal inherent impact of consistency on availability
  - Optimize existing consistency protocols
- Questions:
  - Must determine which write to accept or reject
    - Accepting all writes that do not violate consistency may preclude acceptance of a larger number of write in the future
  - Determine when and where to propagate writes
    - Write propagation decreases numerical error but can increase order error
  - Must decide serialization order
    - Can affect the order error

Upper bound as a function of Numerical error and staleness

- Questions on write propagation
  - When and where to propagate writes
  - Simply propagate writes to all replicas whenever possible – *Aggressive write propagation*
    - Always help reduce both numerical error and staleness
- Questions on write acceptance
  - Must perform a exhaustive search on all possible sets of accepted writes
    - To maximize availability and ensure numerical and staleness bounds are not violated
  - Search space can be reduced by collapsing all writes in an interval to a single logical write
    - Due to *Aggressive write propagation*

Upper bound as a function of order error

- To commit a write, a replica must see all preceding writes in the global serialization order
  - Must determine the global serialization order
- Factorial number of serialization order
  - Search space can be reduced
    - Causal order
      - Serialization orders compatible with causal order
    - Cluster order
      - Writes accepted by the same partition during a particular interval cluster together

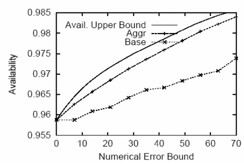
Serialization order

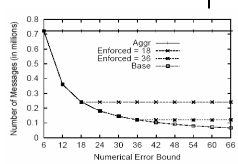
- Example:
  - Suppose Replica 1 receives transaction W_1 and W_2 and Replica 2 receives W_3 and W_4
  - Causal
    - S = $W_1W_2W_3W_4$ better than S' = $W_2W_1W_3W_4$
    - Whenever W_2 can be committed using S', the replica must bave already seen W_1 and thus can also commit W_2 in S. The same is true for W_1, W_3, W_4
  - Cluster
    - Only 2 possible clusters
    - S = $W_1W_2W_3W_4$ and $W_3W_4W_1W_2$
    - Intuition is that it does not expedite write commitment on any replica if the writes accepted by the same partition during a particular interval are allowed to split into multiple sections in the serialization order
  - Cluster has smallest search space

What can we get from this?

- Modify an existing protocol with ideas from proof
  - Each replica ensure that the error bound on other replicas are not violated
    - Replica may push writes to other replicas before accepting a new write
  - Added aggressive write propagation
- Analyze other protocols for order error
  - Primary copy protocol
    - A write is committed when it reaches the primary replica
    - Serialization order is the write order as seen by primary replica
  - Golding's algorithm
    - Each write assigned a logical timestamp that determines serialization order
    - Each replica maintains a version vector to determine whether it has seen all writes with time less than t
    - Pulls in writes from other replicas to advance version vector
  - Voting
    - Order is determining by voting of members
- Is there anything else other than Aggressive Write Propagation that we can get from this proof?

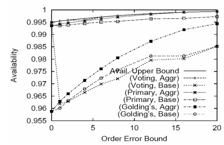
Numerical Error Bound

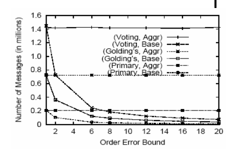




- As predicted, aggressive write propagation improves availability
- Also increases the number of messages required
  - Removes the optimization of combining multiple updates to amortize communication costs
    - Packet header overhead, packet boundaries, ramping up to the bottleneck bandwidth in TCP

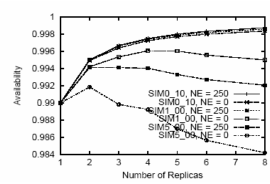
Order Error Bound





- Aggressive Voting also performs well
  - Base voting is awful
    - Lazy replication can cause each replica to casts a vote for a different uncommitted write
    - Each replica must collect votes from all replicas to determine winner and any unknown vote can be the deciding one
  - Aggressive ensures most votes for the same uncommitted write
    - Only need to contact a subset of nodes

Effects of Replication Scale



Faultload	Description	Avg. Fail. Rate
SAMPLED1	First day of the RMI-ping trace	0.17%
SIM0_10	Simulated trace	0.11%
SIM1_00	Simulated trace	1.05%
SIM5_00	Simulated trace	4.12%

- Adding more replicas
  - Reduces network failure rate
  - Increases replica rejection rate
- Availability =

  (1 – Network Failure Rate) *

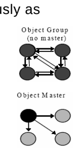
  (1 – Rejection Rate)

The Dangers of Replication and a Solution

- Replication works well with a few nodes
  - Limited deadlocks and reconciliation needed
- Does not scale well or handle mobile nodes that are normally disconnected
  - Cubic growth of deadlock and reconciliation rates predicated in this paper
  - Is this a fundamental limitation?
- Eventually reaches *system delusion*
  - Database is inconsistent and there is no obvious way to repair it
- What about mobile nodes?
  - Does replication currently work well with nodes that can be disconnected?

How does replication models affect deadlock/reconciliation rates

- Models to propagate updates to replica
  - Eager replication
    - Updates applied to all replicas of an object as part of original transaction
  - Lazy replication
    - One replica is updated by the original transaction
    - Updates to other replicas propagate asynchronously as separate transactions
- Models to regulate replica updates
  - Group
    - Any node with a copy of the data can update it
  - Master
    - Each object has a master node
    - Only master can update the primary copy



Eager Replication

- Updates all replicas in same transaction
- No serialization anomalies, no need for reconciliation
- Not an option for mobile systems
- Updates may fail even if all nodes are connected all the time
- When replicated, deadlock rate grows cubic to the rate number of nodes
  - Each node must do its own work and also apply updates generated by other nodes
  - Probability of a wait also increases

$$\approx \frac{TPS^2 \times Action\_Time \times Actions^5 \times Nodes^3}{4 \times DB\_Size^2}$$

- Deadlocks can be removed if used with an object-master approach
  - Lower throughput due to synchronous updates

Lazy Group Replication

- Any node can update any local data
- Updates are propagated asynchronously in separate transactions
- Timestamps are used to detect and reconcile updates
  - Each object carries the timestamp of its most recent update
  - Each replica update carries the new value and is tagged the old object timestamp
  - Receiving replica tests if local timestamp and the update's old timestamp are equal
    - If so, update is safe, local timestamp advances to the new transaction timestamp
    - Else, update may be dangerous, and requires reconciliation on the transaction

Lazy Group Replication

- Waits in a eager replication system faces reconciliation in a lazy group system
  - Waits much more frequent than deadlocks

$$\approx \frac{Disconnect\_Time \times (TPS \times Actions \times Nodes)^2}{DB\_Size}$$

- Can be used for mobile systems

Lazy Master Replication

- Updates are propagated asynchronously in separate transactions
  - Only object master can update object
  - No reconciliation required
    - Deadlock possible

$$\approx \frac{(TPS \times Nodes)^2 \times Action\_Time \times Actions^5}{4 \times DB\_Size^2}$$

- Not appropriate for mobile applications
  - Requires atomic transaction with the owner

Non-Transactional Schemes

- Let's be less ambitious and reduce the domain
  - Abandon serializability for convergence
- Add timestamps to each update
  - Lotus Notes approach:
    - If update has a greater timestamp than current, replace current
    - Else, discard update
- System works if updates are commutative
  - Value is completely replaced
  - Adding or subtracting constants
    - May not even need timestamp

Two-tier system

- Two node types
  - Mobile Nodes
    - Often disconnected
    - May originate tentative transactions
  - Base nodes
    - Always connected
- Two version types
  - Master Version
    - Most recent value received from object master
  - Tentative Version
    - Local version and may be updated by tentative transactions

Two-tier system

- Base Transaction
  - Work on master data and produces new master data
  - Involved with at most one mobile node, and several base nodes
- Tentative Transaction
  - Work on local tentative data
  - Produces tentative version and a base transaction to be run later on the base nodes
    - Base transaction generated by tentative transaction may fail or produce different results
    - Based on a user specified acceptance criteria
      - E.g. The bank balance must not go negative

Two-tier system

- If tentative transaction fails
  - Originating node informed of failure
  - Similar to lazy-group replication except
    - Master database is always converged
    - Originating node need to only contact a base node to discover whether the tentative transaction is acceptable

Example

- When Mobile node connects
  - Discard tentative object version since it will be soon refreshed
  - Send its master object updates
    - Objects that the mobile node is master
  - Send all tentative transactions
  - Accept replica updates from the base node
  - Accept notice of success or failure of each tentative transaction

Example

- On host
  - Send delayed replica updates to mobile node
  - Accepts delayed mobile-mastered objects
  - Accepts list of tentative transactions with acceptance criteria
  - After base node commits, propagate update to other replicas
  - Converge mobile node state with base state

Two-tier system

- Does the two-tier system solve the scalability of replication problem
  - Yes, but only if we can restrict the domain
- Can we do better?
  - Or is this a fundamental problem that can't be solved entirely?