Replication in Distributed Systems

Replication Basics

- Multiple copies of data kept in different nodes
  - A set of replicas holding copies of a data
    - Nodes can be physically very close or distributed all over the world
  - A set of clients that make requests (read/write) of the data in a replica
- Why replicate?
  - Fault Tolerance
    - Service can be provided from a different replica if one replica fails
  - Load Balancing
    - Load can be shared by multiple replicas (ex. web servers)
  - Reduced latency
    - Replicas placed closer to request source for faster access

- Ideally, the user should think that there is a single copy of the data (replication transparency)
  - Requires a write at one replica to propagate instantaneously to another replica as if it is done on a single copy
    - Impossible if real time ordering of read/write operations is to be maintained as in a single copy
- Then how should we keep replicas updated in the presence of writes?
  - Should all copies of the data have the same value always, or are intermediate differences allowed?
    - Depends on consistency model to be satisfied depending on application need
      - What is a consistency model?

Design Issues in Replication

- Consistency model to be enforced
- Where can updates happen?
  - One designated replica or any replica?
- When to propagate updates?
  - Eager (immediately, before response to client) or lazy (sometime after response is sent to client)?
  - Depends on consistency model to be supported
- How many replicas to install?
- When to Install a replica
  - Static or On-demand?
- Where to place the replicas?

Consistency Models

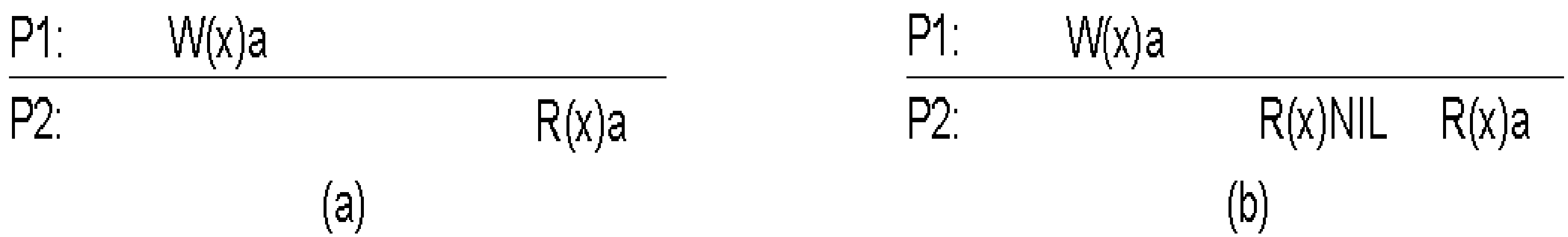
Consistency Models

- Defines what guarantees are provided on reads on a shared data in the presence of possibly interleaved/overlapped access
- Replicas of a data accessed at multiple sites can be viewed as a single shared data
- Tradeoff
  - Should be strong enough to be useful
  - Should be weak enough to be efficiently implementable

- Examples of consistency models
  - Linearizability
  - Sequential consistency
  - Causal consistency
  - Eventual consistency
- Many other models exist…
- Why so many models?
  - Application requirements are different
  - Stronger models require more overheads to implement, so many weaker models have evolved if strong guarantees are not needed for an application
  - Even within a single application, different types of data may require different consistency models

Linearizability

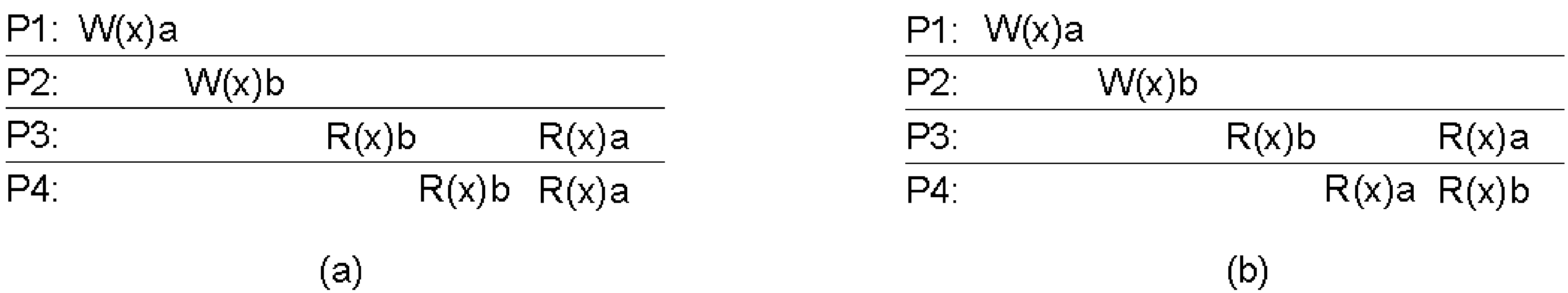
- Satisfied if there exists some sequential ordering of the reads and writes in which
  1. Operations of individual processes are ordered in the same way as in the actual order
  2. For two operations by two different processes, if times in actual order are t1 and t2, and times in the sequential order are t1' and t2', then if t1 < t2, then t1' < t2'
  3. Each read gets the value of the latest write before it in the sequential ordering
- Time can be based on any global timestamping scheme
- Used mostly for formal verification etc.



(a) is linearizable, (b) is not

Sequential Consistency

- Requires only the first and third conditions of Linearizability
  - No ordering of events at different processes required
  - Linearizability implies sequential consistency but not vice-versa
- No notion of time, and hence no notion of "most recent" write
- Ordering of events at different processes may not be important as they could have happened in some other order in practice anyway due to different reasons (server speed, message delays,…)
- Widely used in practice
- Still costly to implement



- (a) is sequentially consistent (Is (a) Linearizable?)
- (b) is not sequentially consistent
- Sequential consistency means all processes see all writes in the same order ("seeing" means the results returned by reads)

Causal Consistency

- Causally related writes
  - Writes in the same process
  - Writes in different processes linked by reads in between
- Writes not causally related are concurrent
- All writes that are causally related must be seen (results of read) by every process in the same order
- Writes that are not causally related can be seen in any order by different processes
- Value returned by the reads must be consistent with this causal order

- Example

P1:	W(x)a			W(x)c		
P2:		R(x)a	W(x)b			
P3:		R(x)a			R(x)c	R(x)b
P4:		R(x)a			R(x)b	R(x)c

- Is this sequentially consistent?

- What about these?

P1:	W(x)a				
P2:		R(x)a	W(x)b		
P3:				R(x)b	R(x)a
P4:				R(x)a	R(x)b

(a)

P1:	W(x)a			
P2:		W(x)b		
P3:			R(x)b	R(x)a
P4:			R(x)a	R(x)b

(b)

Eventual Consistency

- Only requires that all replicas are eventually consistent
  - If no further updates to a data happens, all reads of the data at any replica should eventually get the same value
  - Temporarily, different clients can see different values
    - Say client X updates at replica A, and client Y reads from replica B before the update by X propagates to B
  - Temporarily, even same client can see different value
    - Say client X updates at replica A, and then reads from replica B before the update propagates to B
    - So may not even guarantee that a single client always sees its last write
  - Other intermediate models exist

- Good if most operations are read, writes are infrequent, and some temporary inconsistencies can be tolerated
  - Good for many applications. Ex. DNS, NIS,….

Implementing Consistency Models

Replication Architectures

- Consistency models are fine, but how do systems implement them?
  - Depends on replication architecture and the specific model
- Replication Architectures
  - Passive Replication
    - All requests made to a single replica (primary)
  - Active Replication
    - Requests made to all replicas

Passive Replication

- Each client requests to a single replica (primary)
  - A unique identifier assigned by primary for each request
- Other replicas are backup
- Master-slave like relation between primary and backups
- Reads are returned from primary
- On write,
  - Primary executes the write and sends the updated state to all replicas
  - Receive reply from all replicas
  - Reply success to client
- Primary also sends periodic heartbeat messages to all backups to indicate it is alive

- If primary dies (no heartbeat message detected at backup)
  - Backups elect a new leader that starts to act as primary
  - Client may fail to access a service during the duration between primary crash and new primary election (failover time)
- Need to ensure
  - Exactly one primary at all times (except failover time)
  - All backups agree on the primary
  - No backups respond to client requests
- Problem: what happens if there is a failure during update of replicas?

- Consistency models enforced in passive replication
  - Linearizability, as primary acts as sequencer, serializing all access to the data
  - Enforcing Linearizability implies sequential consistency

Active Replication

- No master-slave relation among replicas
- A client makes requests to all replicas
  - In practice, client can send request to one replica, that replica can act as front end to send requests to all replicas
  - Client must know what replica to go to if the front end fails
- All replicas replies to client, client can take
  - First response for crash failure model (requires f+1 replicas to tolerate f faults)
  - Majority for byzantine faults (requires 2f+1 replicas to tolerate f faults)
- Need to ensure that all replicas agree on the order of client requests
  - If all requests are applied in the same order at all replicas, their final state is consistent
  - Consensus problem

State Machine Replication

- A general strategy proposed to build fault-tolerant systems by replication
  - Basis for active replication in practice
- Each replica is represented by a state machine
- All replicas start with the same initial state
- Client requests are made to the state machines
- Need to ensure
  - All non-faulty state machines receive all requests (Agreement)
  - All non-faulty state machines processes the requests in the same order (Order)

Ensuring Agreement and Order

- Using atomic multicast
  - Read/write request sent to all replicas using atomic multicast
  - How to implement atomic multicast?
  - Atomic multicast is equivalent to consensus
- Using other specialized consensus protocols (Paxos/Raft)
  - We will study Raft

Implementing Linearizability

- Client makes read/write request
- Read/write request sent by local replica to all others using atomic multicast
- On receiving this, replica servers (a) update copy on write and send back ack, (b) only send ack on read
- On completion of total order multicast, the local copy given to client on read or success returned to client on write

Implementing Sequential Consistency

- Using atomic multicast
  - Client makes read/write request
  - On read, just return the local copy (no atomic multicast)
  - On write, request sent by local replica to all others using atomic multicast
    - On receiving this, replica servers update copy on write and send back ack
    - On completion of atmic multicast, success returned to client on write
- Using Quorum-based protocols/Voting protocols

Voting Protocols

- Each replica is given a number of votes
  - Let V = sum of all replica votes
- Choose read quorum Q_r and write quorum Q_w such that
  - $Q_r + Q_w > V$, and
  - $2 * Q_w > V$
- To read, each replica must get Q_r votes
- To write, each replica must get Q_w votes
- Guarantees
  - A read and a write do not occur together
  - Two writes do not occur together

- Data items are tagged with a version
  - Incremented on each write
- To read data
  - client gets read quorum from replica sites
  - chooses the copy with the highest version no. from those replicas
  - Most updated copy (why?)
- To write data
  - Client gets read quorum from replica sites
  - Chooses the copy with highest version number (say t)
  - Client gets write quorum from replica sites
  - Writes the data with version number > t in all replicas of write quorum

Special Cases

- Let N = no. of replicas
- ROWA (Read One Write All)
  - Each replica has one vote, $Q_r = 1$, $Q_w = N$
  - Fast reads, slow writes
  - Cannot tolerate even one replica failure for writes
- Majority
  - Each replica has one vote, $Q_r = Q_w = N/2 + 1$
  - Equal read/write overhead

Questions

- How to assign votes?
  - More reliable servers can be assigned more votes
  - More powerful servers may be assigned more votes
- What if one or more replicas fail?
  - No combination of votes may satisfy the quorum constraints
- What if there is a network partition?
  - No majority may exist in any of the partitions

Problems with Sequential Consistency

- Not scalable
  - Atomic Multicast requires all replicas to contact all other replicas
  - Voting based protocols still require a replica to contact a large no. of other replicas (majority in the worst case)
- Good for small systems that require such strong consistency
- Many systems do not need such strong consistency guarantees

Implementing Eventual Consistency

- Easy if a client always connects to a single replica
- Hard otherwise
  - Ex. mobile systems
- Generally goal is to ensure that all replicas have the same state eventually
  - Epidemic protocol to replicate
  - Replication topology
    - Form a replication topology to decide who replicates from who
  - Scheduled Replication
  - Push vs. pull models

Replica Placement

- Mirroring
  - Static replicas created a-priori
  - May mirror all data or part depending on need
- Server-generated
  - Dynamic replicas created by a server when load increases
- Client caching
  - Replicas created by caching frequently used data at/near client
- Pros/Cons of each? When should you use what?