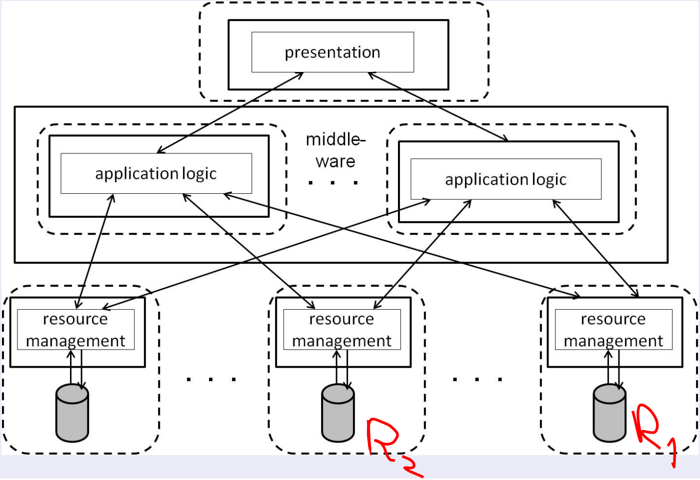
11. Replication and (Weaker) Consistency

Motivation

- Reliable and high-performance computation on a single instance of a data object is prone to failure.
- Replicate data to overcome single points of failure and performance bottlenecks.

Problem: Accessing replicas uncoordinatedly can lead to different values for each replica, jeopardizing consistency.

Basic architectural model

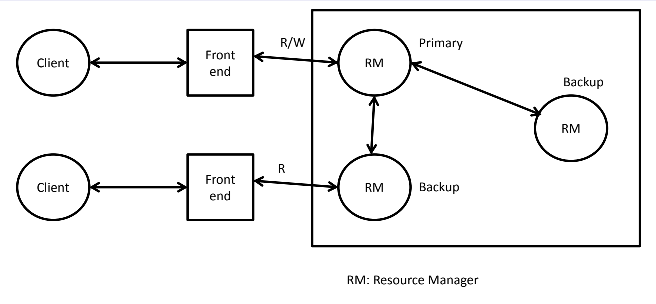


Classification of replication approaches

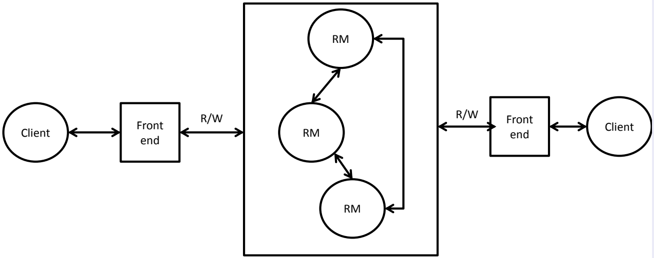
Two orthogonal dimensions

- Location of change:
  - Primary Copy: updates on a data item can only be performed on a single, dedicated replica
  - Write Anywhere: updates can be performed on any replica
- Propagation Speed
  - Immediate/Eager: At commit, all replicas contain the change
  - Delayed: only the modified replica contains the change at commit, the others will receive the changes later

Primary Copy replication model



Update anywhere replication model



RM: Resource Manager

Tradeoffs of application approaches

Overall Tradeoffs

- Location of change:
  - Primary Copy: Simple synchronization
  - Write Anywhere: flexible, no single bottleneck
- Propagation Speed
  - Immediate/Eager: strongly consistent, potentially long response times
  - Delayed/Lazy: fast response time, consistency problems

Method-Specific Tradeoffs

- Primary/Eager: resource contention on querying/updating/replication; strong consistency with simple implementation (e.g., with 2PC+local 2PL)
- Write anywhere/Eager: potentially prone to distributed deadlocks
- Primary/Lazy: typically fast (if not on multiple sites), outdated data
- Write anywhere/Lazy: fast, serializability not guaranteed

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Synchronous replication protocols (basic)

ROWA

- Write the change to all replicas
- Read on (any) single replica
- Expensive write coordination (2PC)
- Cheap, highly available reads
- Low write availability (lower than without replication)

Primary Copy

- Write the change initially to single replica
- Propagate changes in bulk to other replicas
- Coordination with read locks: request from primary
- Reduce write cost
- Increased read cost

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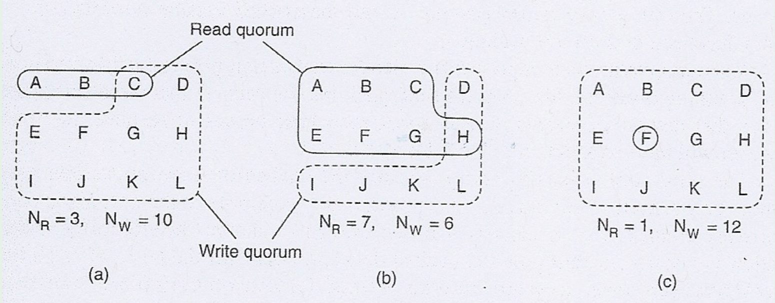
Quorum-Based Protocols

- Idea: Clients have to request and acquire the permission of multiple servers before either reading or writing a replicated data item.
- Assume an object has N replicas.
  - For update, a client must first contact at least $\frac{N}{2}+1$ servers and get them to agree to do the update. Once they have agreed, all contacted servers process the update assigning a new version number to the updated object.
  - For read, a client must first contact at least $\frac{N}{2}+1$ servers and ask them to send the version number of their local version. The client will then read the replica with the highest version number.
- This approach can be generalized to an arbitrary read quorum N_R and write quorum N_W such that holds:
  - $N_R + N_W > N$,
  - $N_W > \frac{N}{2}$.

  This approach is called *quorum consensus* method.

Example



(a) Correct choice of read and write quorum.

(b) Choice running into possible inconsistencies.

(c) ROWA by quorum

CAP Theorem

From the three desirable properties of a distributed shared-data system:

- atomic data consistency (i.e. operations on a data item look as if they were completed at a single instant),
- system availability (i.e. every request received by a non-failing node must result in a response), and
- tolerance to network partition (i.e. the system is allowed to lose messages),

only two can be achieved at the same time at any given time.

$\Longrightarrow$ Given that in distributed large-scale systems network partitions cannot be avoided, consistency and availability cannot be achieved at the same time.

Two basic options:

- Distributed ACID-transactions:

  Consistency has priority, i.e. updating replicas is part of the transaction - thus availability is not guaranteed.

- Large-scale distributed systems:

  Availability has priority - thus a weaker form of consistency is accepted, accpeting access to outdated replicas

  $\Longrightarrow$ Inconsistent updates may happen and have to be resolved on the application level, in general.

Eventual Consistency

- Specific form of weak consistency
- Guarantees
  - if no new updates are made to the object
  - eventually all accesses will return the last updated value
- Probabilistic inconsistency window duration, impacted
  - failures occur,
  - communication delays
  - the load on the system,
  - the number of replicas involved
- Originally popular in large-scale, no-DB systems (DNS)
- Major factor the NoSQL movement

Is this the end of the consistency story?

- Serializability and Eventual Consistency are (almost) at the extreme end of the spectrum
- Is there anything in between that would provide practically useful combinations of consistency and availability?
- In fact, there is wide of consistency models proposed in various communities
  - Database transaction models
  - Distributed systems single object models
- The CAP theorem does not talk about serializability, but linearizability
- Let's survey the space
- There is recent work that structures the space and makes proofs around the availability classes

Overview on Consistency

- We have a system with state and operations on the state
- Operations form a history
- Consistency models determine which histories are permissible
- Simplest model: cpu register
  - Instant application
  - strict order
- Challenges
  - Concurrent histories
  - Propagation delay

Database Consistency: Anomalies (1)

Dirty Writes

$w_1X \ldots w_2X \ldots (c_1 \text{ or } a_1)$ How to abort

Dirty Read

$w_1X \ldots r_2X \ldots (c_1 \text{ or } a_1)$ Uncommitted value read

Lost Update

$r_1X \ldots w_2X \ldots w_1X(c_1)$

?

Database Consistency: Anomalies (2)

Fuzzy Read

$r_1 X \ldots w_2 X \ldots r_1 X (c_1 \text{ or } a_1)$

set with predicate

Phantom

[P]

$r_1[P] \ldots w_2[yinP] \ldots r_1 X (c_1 \text{ or } a_1)$ → consistent aggregations

Write Skew

$r_1 X \ldots r_2 Y \ldots w_1 Y \ldots w_2 X \ldots c_1 c_2$ read others WS

Database Consistency Classes

ANSI SQL classes

Prevent typical anomalies from happening

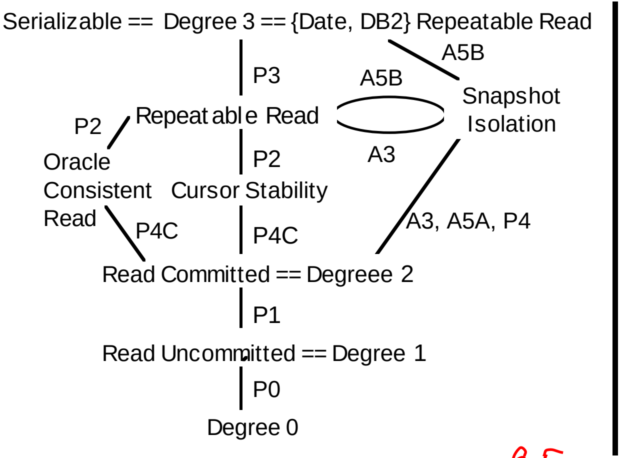
- Read Uncomitted: Dirty Read
- Read Committed: Lost Updates
- Repeatable Read: Phantoms
- Serializable: OK!

Modelled around typical locking strategies

Other classes

- Cursor Stability: Fuzzy Reads
- Snapshot Isolation: Write Skew
  - Perform all reads and writes on a snapshot created at t_s
  - At commit, check if any change by other TA on modified objects since t_s

Database Consistency: Classification



DS Consistency Classes

Session Guarantees

- Monotonic Reads: never return previous values
- Monotonic writes: writes in session appear in order
- Writes Follow Reads: happens-before on transactions

Sticky Session Guarantees → same replica

- Read Your Writes: get your updated value (or later)
- PRAM: serial execution within session (like RAM)
- Causal consistency/PL-2L: PRAM+WFR

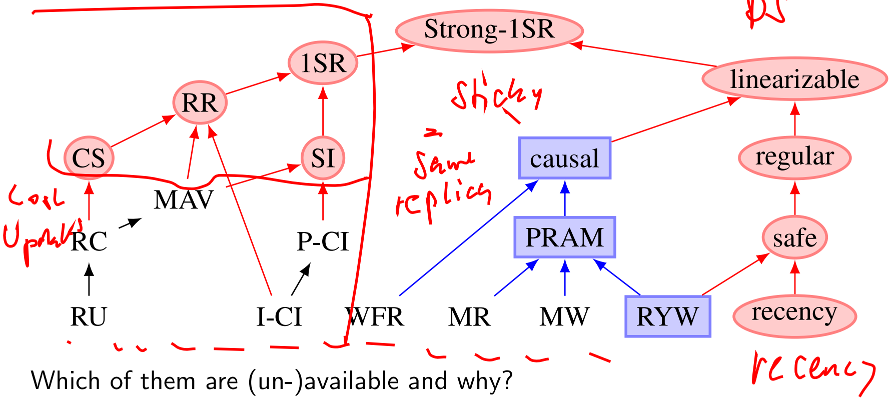
Overall Consistency Classification

2014

HAT not CAP

DS

→ 95 DB



Which of them are (un-)available and why?

Causes for unavailability

Preventing Lost Updates

Dectecting competing writes needs coordination

Preventing Write Skew

Generalization of Lost Updates

Recency Guarantess

Network splits may delay process arbitrarily long

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