Distributed Systems
Principles and Paradigms

Chapter 07: Consistency & Replication

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Contents

Consistency & replication

- Introduction (what's it all about)
- Data-centric consistency
- Client-centric consistency
- Replica management
- Consistency protocols

Performance and scalability

Main issue

To keep replicas consistent, we generally need to ensure that all conflicting operations are done in the the same order everywhere

Conflicting operations

From the world of transactions:

- Read–write conflict: a read operation and a write operation act concurrently
- Write–write conflict: two concurrent write operations

Issue

Guaranteeing global ordering on conflicting operations may be a costly operation, downgrading scalability Solution: weaken consistency requirements so that hopefully global synchronization can be avoided

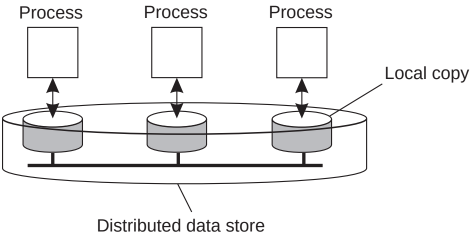
Data-centric consistency models

Consistency model

A contract between a (distributed) data store and processes, in which the data store specifies precisely what the results of read and write operations are in the presence of concurrency.

Essential

A data store is a distributed collection of storages:



Continuous Consistency

Observation

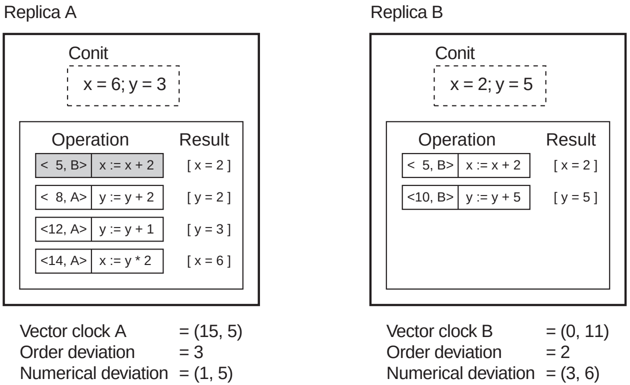
We can actually talk a about a degree of consistency:

- replicas may differ in their numerical value
- replicas may differ in their relative staleness
- there may be differences with respect to (number and order) of performed update operations

Conit

Consistency unit ⇒ specifies the data unit over which consistency is to be measured.

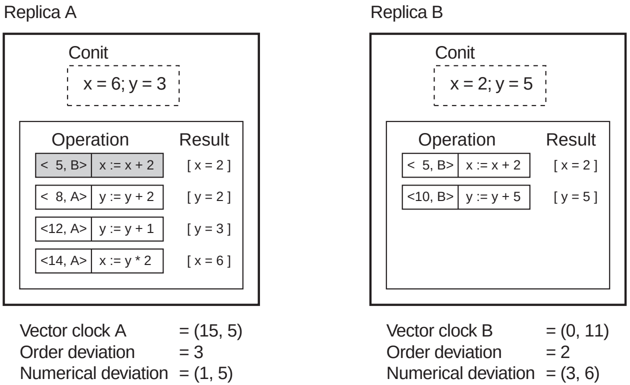
Example: Conit



Conit (contains the variables *x* and *y*)

- Each replica maintains a vector clock
- *B* sends *A* operation $[\langle 5, B\rangle : x := x + 2]$; *A* has made this operation permanent (cannot be rolled back)

Example: Conit



Conit (contains the variables *x* and *y*)

- *A* has three pending operations ⇒ order deviation = 3
- *A* has missed one operation from *B*, yielding a max diff of 5 units ⇒ $(1, 5)$

Sequential consistency

Definition

The result of any execution is the same as if the operations of all processes were executed in some sequential order, and the operations of each individual process appear in this sequence in the order specified by its program.

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

(a)

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

(b)

Causal consistency

Definition

Writes that are potentially causally related must be seen by all processes in the same order. Concurrent writes may be seen in a different order by different processes.

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		
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P4:		R(x)a	R(x)b

(b)

Grouping operations

Definition

- Accesses to synchronization variables are sequentially consistent.
- No access to a synchronization variable is allowed to be performed until all previous writes have completed everywhere.
- No data access is allowed to be performed until all previous accesses to synchronization variables have been performed.

Basic idea

You don't care that reads and writes of a series of operations are immediately known to other processes. You just want the effect of the series itself to be known.

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Grouping operations

P1:	Acq(Lx) W(x)a Acq(Ly) W(y)b Rel(Lx) Rel(Ly)
P2:	Acq(Lx) R(x)a R(y) NIL
P3:	Acq(Ly) R(y)b

Observation

Weak consistency implies that we need to lock and unlock data (implicitly or not).

Question

What would be a convenient way of making this consistency more or less transparent to programmers?

Client-centric consistency models

Overview

- System model
- Monotonic reads
- Monotonic writes
- Read-your-writes
- Write-follows-reads

Goal

Show how we can perhaps avoid systemwide consistency, by concentrating on what specific clients want, instead of what should be maintained by servers.

Consistency for mobile users

Example

Consider a distributed database to which you have access through your notebook. Assume your notebook acts as a front end to the database.

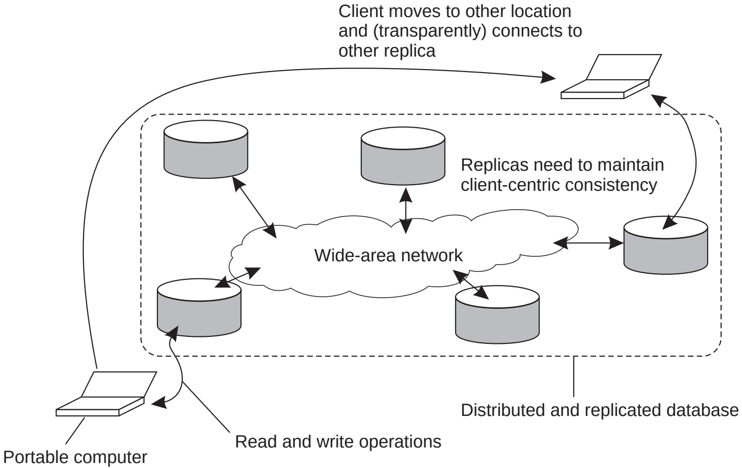
- At location *A* you access the database doing reads and updates.
- At location *B* you continue your work, but unless you access the same server as the one at location *A*, you may detect inconsistencies:
  - your updates at *A* may not have yet been propagated to *B*
  - you may be reading newer entries than the ones available at *A*
  - your updates at *B* may eventually conflict with those at *A*

Consistency for mobile users

Note

The only thing you really want is that the entries you updated and/or read at A, are in B the way you left them in A. In that case, the database will appear to be consistent to you.

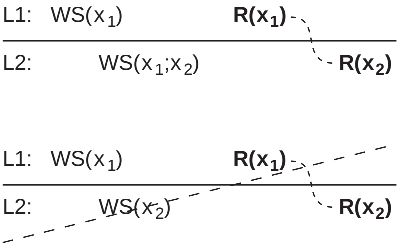
Basic architecture



Monotonic reads

Definition

If a process reads the value of a data item *x*, any successive read operation on *x* by that process will always return that same or a more recent value.



Client-centric consistency: notation

Notation

- $WS(x_i[t])$ is the set of write operations (at L_i) that lead to version x_i of x (at time t)
- $WS(x_i[t_1]; x_j[t_2])$ indicates that it is known that $WS(x_i[t_1])$ is part of $WS(x_j[t_2])$.
- Note: Parameter t is omitted from figures.

Monotonic reads

Example

Automatically reading your personal calendar updates from different servers. Monotonic Reads guarantees that the user sees all updates, no matter from which server the automatic reading takes place.

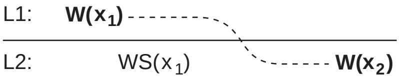
Example

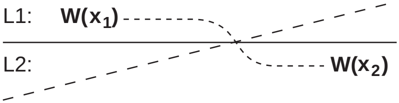
Reading (not modifying) incoming mail while you are on the move. Each time you connect to a different e-mail server, that server fetches (at least) all the updates from the server you previously visited.

Monotonic writes

Definition

A write operation by a process on a data item *x* is completed before any successive write operation on *x* by the same process.





Monotonic writes

Example

Updating a program at server S_2, and ensuring that all components on which compilation and linking depends, are also placed at S_2.

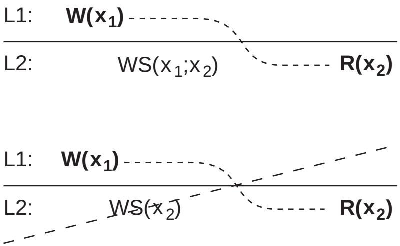
Example

Maintaining versions of replicated files in the correct order everywhere (propagate the previous version to the server where the newest version is installed).

Read your writes

Definition

The effect of a write operation by a process on data item x, will always be seen by a successive read operation on x by the same process.



Example

Updating your Web page and guaranteeing that your Web browser shows the newest version instead of its cached copy.

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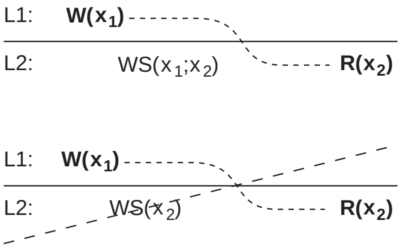

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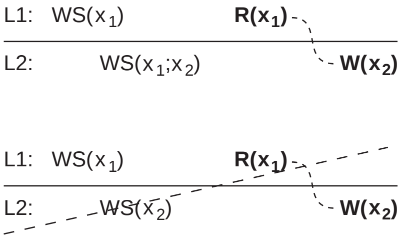

Example

See reactions to posted articles only if you have the original posting (a read "pulls in" the corresponding write operation).

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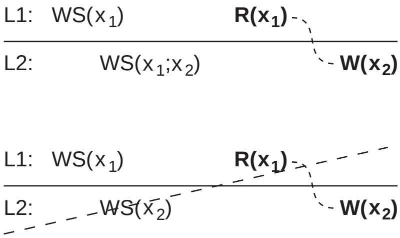

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Distribution protocols

- Replica server placement
- Content replication and placement
- Content distribution

Replica placement

Essence

Figure out what the best K places are out of N possible locations.

- Select best location out of $N-K$ for which the average distance to clients is minimal. Then choose the next best server. (Note: The first chosen location minimizes the average distance to all clients.) Computationally expensive.
- Select the K-th largest autonomous system and place a server at the best-connected host. Computationally expensive.
- Position nodes in a d-dimensional geometric space, where distance reflects latency. Identify the K regions with highest density and place a server in every one. Computationally cheap.

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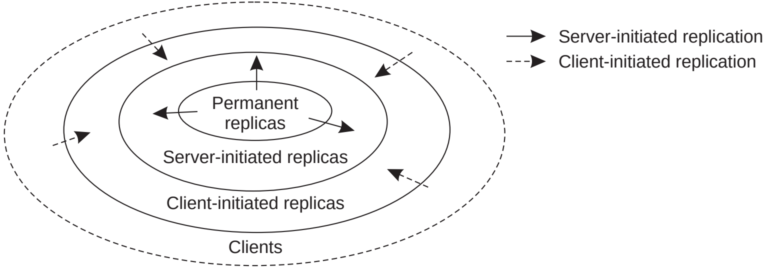
Content replication

Distinguish different processes

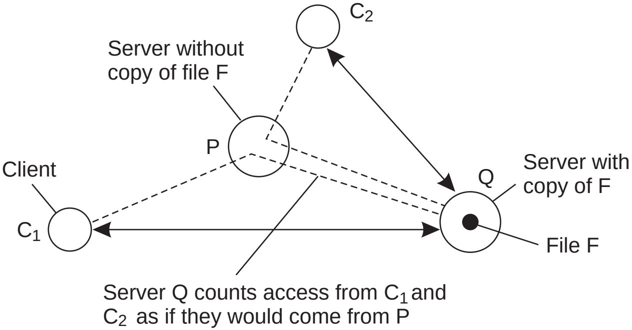
A process is capable of hosting a replica of an object or data:

- Permanent replicas: Process/machine always having a replica
- Server-initiated replica: Process that can dynamically host a replica on request of another server in the data store
- Client-initiated replica: Process that can dynamically host a replica on request of a client (client cache)

Content replication



Server-initiated replicas



- Keep track of access counts per file, aggregated by considering server closest to requesting clients
- Number of accesses drops below threshold $D \Rightarrow$ drop file
- Number of accesses exceeds threshold $R \Rightarrow$ replicate file
- Number of access between D and $R \Rightarrow$ migrate file

Content distribution

Model

Consider only a client-server combination:

- Propagate only notification/invalidation of update (often used for caches)
- Transfer data from one copy to another (distributed databases)
- Propagate the update *operation* to other copies (also called active replication)

Note

No single approach is the best, but depends highly on available bandwidth and read-to-write ratio at replicas.

Content distribution

- Pushing updates: server-initiated approach, in which update is propagated regardless whether target asked for it.
- Pulling updates: client-initiated approach, in which client requests to be updated.

Issue	Push-based	Pull-based
1:	List of client caches	None
2:	Update (and possibly fetch update)	Poll and update
3:	Immediate (or fetch-update time)	Fetch-update time

1: State at server

2: Messages to be exchanged

3: Response time at the client

Content distribution

Observation

We can dynamically switch between pulling and pushing using leases: A contract in which the server promises to push updates to the client until the lease expires.

Content distribution

Issue

Make lease expiration time dependent on system's behavior (adaptive leases):

- Age-based leases: An object that hasn't changed for a long time, will not change in the near future, so provide a long-lasting lease
- Renewal-frequency based leases: The more often a client requests a specific object, the longer the expiration time for that client (for that object) will be
- State-based leases: The more loaded a server is, the shorter the expiration times become

Question

Why are we doing all this?

Content distribution

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Consistency protocols

Consistency protocol

Describes the implementation of a specific consistency model.

- Continuous consistency
- Primary-based protocols
- Replicated-write protocols

Continuous consistency: Numerical errors

Principal operation

Consider a data item x and let $weight(W)$ denote the numerical change in its value after a write operation W. Assume that $\forall W : weight(W) > 0$.

W is initially forwarded to one of the N replicas, denoted as $origin(W)$. $TW[i,j]$ are the writes executed by server S_i that originated from S_j:

$$TW[i,j] = \sum\{weight(W) | origin(W) = S_j \ \& \ W \in log(S_i)\}$$

Continuous consistency: Numerical errors

Note

Actual value $v(t)$ of x:

$$v(t) = v_{init} + \sum_{k=1}^{N} TW[k,k]$$

value v_i of x at replica i:

$$v_i = v_{init} + \sum_{k=1}^{N} TW[i,k]$$

Continuous consistency: Numerical errors

Problem

We need to ensure that $v(t) - v_i < \delta_i$ for every server S_i.

Approach

Let every server S_k maintain a view $TW_k[i,j]$ of what it believes is the value of $TW[i,j]$. This information can be gossiped when an update is propagated.

Note

$0 \leq TW_k[i,j] \leq TW[i,j] \leq TW[j,j]$

Continuous consistency: Numerical errors

Solution

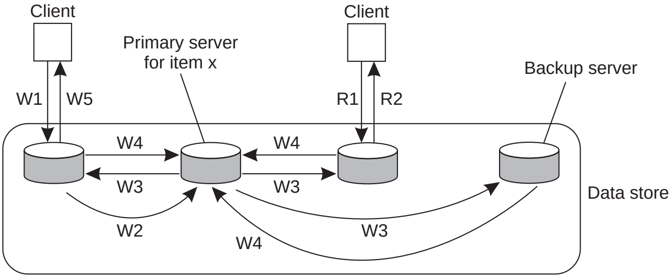
S_k sends operations from its log to S_i when it sees that $TW_k[i,k]$ is getting too far from $TW[k,k]$, in particular, when $TW[k,k] - TW_k[i,k] > \delta_i/(N-1)$.

Note

Staleness can be done analogously, by essentially keeping track of what has been seen last from S_i (see book).

Primary-based protocols

Primary-backup protocol



W1. Write request
W2. Forward request to primary
W3. Tell backups to update
W4. Acknowledge update
W5. Acknowledge write completed

R1. Read request
R2. Response to read

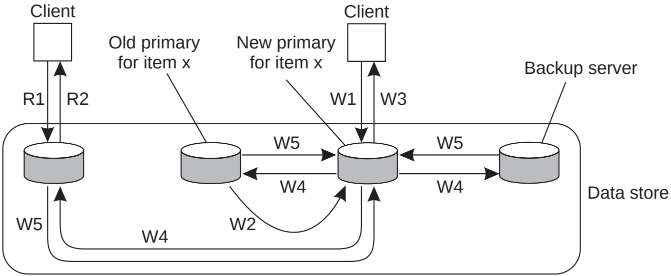
Primary-based protocols

Example primary-backup protocol

Traditionally applied in distributed databases and file systems that require a high degree of fault tolerance. Replicas are often placed on same LAN.

Primary-based protocols

Primary-backup protocol with local writes



W1. Write request
W2. Move item x to new primary
W3. Acknowledge write completed
W4. Tell backups to update
W5. Acknowledge update

R1. Read request
R2. Response to read

Primary-based protocols

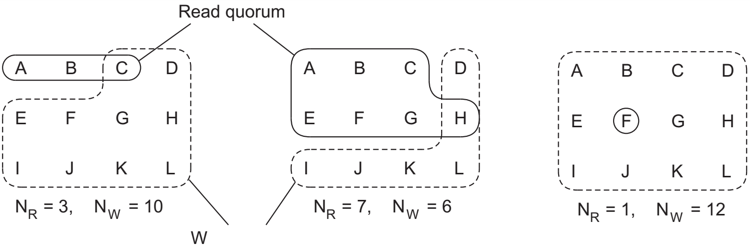
Example primary-backup protocol with local writes

Mobile computing in disconnected mode (ship all relevant files to user before disconnecting, and update later on).

Replicated-write protocols

Quorum-based protocols

Ensure that each operation is carried out in such a way that a majority vote is established: distinguish read quorum and write quorum:



required: $N_R + N_W > N$ and $N_W > N/2$