Principles of Distributed Systems

inft-3507

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Section 7: Consistency and Replication

This content is based on the following public resources: https://www.distributed-systems.net/index.php/books/ds4/

Introduction

Replication

Assume a simple model in which we make a copy of a specific part of a system (meaning code and data).

Why replicate

- Increase reliability: if one copy does not live up to specifications, switch over to the other copy while repairing the failing one.
- Performance: simply spread requests between different replicated parts to keep load balanced, or to ensure quick responses by taking proximity into account.

The problem

Having multiple copies, means that when any copy changes, that change should be made at all copies: replicas need to be kept the same, that is, be kept consistent.

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

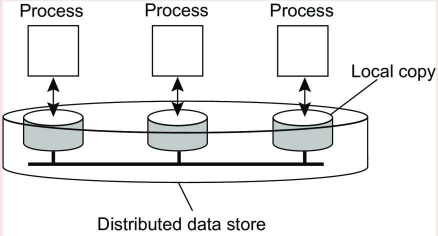
Data-centric consistency models

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:



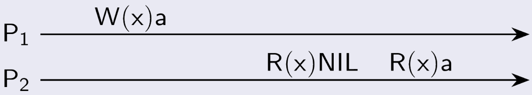
Some notations

Read and write operations

- $W_i(x)a$: Process P_i writes value a to x
- $R_i(x)b$: Process P_i reads value b from x
- All data items initially have value NIL

Possible behavior

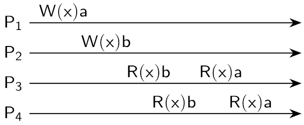
We omit the index when possible and draw according to time (x-axis):



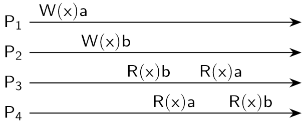
Sequential consistency

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.



A sequentially consistent data store



A data store that is not sequentially consistent

Example

Three concurrent processes (initial values: 0)

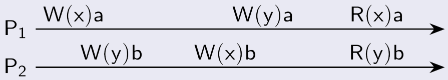
Process P_1	Process P_2	Process P_3
x ← 1;	y ← 1;	z ← 1;
print(y,z);	print(x,z);	print(x,y);

Example execution sequences

Execution 1	Execution 2	Execution 3	Execution 4
P_1: x ← 1;	P_1: x ← 1;	P_2: y ← 1;	P_2: y ← 1;
P_1: print(y,z);	P_2: y ← 1;	P_3: z ← 1;	P_1: x ← 1;
P_2: y ← 1;	P_2: print(x,z);	P_3: print(x,y);	P_3: z ← 1;
P_2: print(x,z);	P_1: print(y,z);	P_2: print(x,z);	P_2: print(x,z);
P_3: z ← 1;	P_3: z ← 1;	P_1: x ← 1;	P_1: print(y,z);
P_3: print(x,y);	P_3: print(x,y);	P_1: print(y,z);	P_3: print(x,y);
Prints: 001011	*Prints:* 101011	*Prints:* 010111	*Prints:* 111111
Signature: 00 10 11	*Signature:* 10 10 11	*Signature:* 11 01 01	*Signature:* 11 11 11
(a)	(b)	(c)	(d)

How tricky can it get?

Seemingly okay



But not really (don't forget that P_1 and P_2 act concurrently)

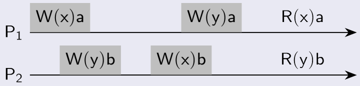
Possible ordering of operations	**Result**	
$W_1(x)a;\ W_1(y)a;\ W_2(y)b;\ W_2(x)b$	$R_1(x)b$	$R_2(y)b$
$W_1(x)a;\ W_2(y)b;\ W_1(y)a;\ W_2(x)b$	$R_1(x)b$	$R_2(y)a$
$W_1(x)a;\ W_2(y)b;\ W_2(x)b;\ W_1(y)a$	$R_1(x)b$	$R_2(y)a$
$W_2(y)b;\ W_1(x)a;\ W_1(y)a;\ W_2(x)b$	$R_1(x)b$	$R_2(y)a$
$W_2(y)b;\ W_1(x)a;\ W_2(x)b;\ W_1(y)a$	$R_1(x)b$	$R_2(y)a$
$W_2(y)b;\ W_2(x)b;\ W_1(x)a;\ W_1(y)a$	$R_1(x)a$	$R_2(y)a$

How tricky can it get?

Linearizability

Each operation should appear to take effect instantaneously at some moment between its start and completion.

Operations complete within a given time (shaded area)



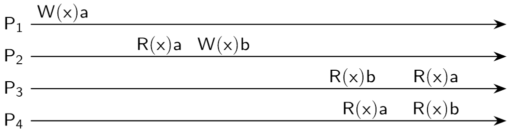
With better results

Possible ordering of operations	**Result**	
$W_1(x)a;\ W_2(y)b;\ W_1(y)a;\ W_2(x)b$	$R_1(x)b$	$R_2(y)a$
$W_1(x)a;\ W_2(y)b;\ W_2(x)b;\ W_1(y)a$	$R_1(x)b$	$R_2(y)a$
$W_2(y)b;\ W_1(x)a;\ W_1(y)a;\ W_2(x)b$	$R_1(x)b$	$R_2(y)a$
$W_2(y)b;\ W_1(x)a;\ W_2(x)b;\ W_1(y)a$	$R_1(x)b$	$R_2(y)a$

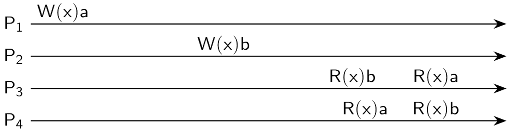
Causal consistency

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.



A violation of a causally-consistent store



The second example is **Causally Consistent**, but not **Sequentially Consistent** because it cannot be explained by any one total ordering of operations.

Consistency models, serializability, transactions

Overwhelming, but often already known

Again, from the world of transactions: can we order the execution of all operations in a set of transactions in such a way that the final result matches a serial execution of those transactions? The keyword is serializability.

```
BEGIN_TRANSACTION
  x = 0
  x = x + 1
END_TRANSACTION
```
Transaction T_1

```
BEGIN_TRANSACTION
  x = 0
  x = x + 2
END_TRANSACTION
```
Transaction T_2

```
BEGIN_TRANSACTION
  x = 0
  x = x + 3
END_TRANSACTION
```
Transaction T_3

A number of schedules

	Time $\longrightarrow$						
S1	$x = 0$	$x = x + 1$	$x = 0$	$x = x + 2$	$x = 0$	$x = x + 3$	Legal
S2	$x = 0$	$x = 0$	$x = x + 1$	$x = x + 2$	$x = 0$	$x = x + 3$	Legal
S3	$x = 0$	$x = 0$	$x = x + 1$	$x = 0$	$x = x + 2$	$x = x + 3$	Illegal
S4	$x = 0$	$x = 0$	$x = x + 3$	$x = 0$	$x = x + 1$	$x = x + 2$	Illegal

Grouping operations

Entry consistency: Definition

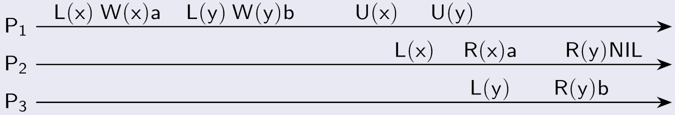
- Lock operations follow a sequentially consistent order.
- When a lock is acquired, all work done before the previous release is considered to have happened first.
- Work done after acquiring the lock will see the results of that earlier work.

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.

Grouping operations

A valid event sequence for entry consistency



Observation

Entry 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?

Eventual consistency

Definition

Consider a collection of data stores and (concurrent) write operations. The strores are eventually consistent when in lack of updates from a certain moment, all updates to that point are propagated in such a way that replicas will have the same data stored (until updates are accepted again).

Srong eventual consistency

Basic idea: if there are conflicting updates, have a globally determined resolution mechanism (for example, using NTP, simply let the "most recent" update win).

Program consistency

P is a monotonic problem if for any input sets S and T, $P(S) \subseteq P(T)$.
Observation: A program solving a monotonic problem can start with incomplete information, but is guaranteed not to have to roll back when missing information becomes available. Example: filling a shopping cart. NOTE: *In all cases, we are avoiding global synchronization.*

Continuous Consistency

We can actually talk about a degree of consistency

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

Conit

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

Example: Conit

Replica A

Conit
- d = 558 // distance
- g = 95 // gas
- p = 78 // price

Operation		Result
< 5, B>	g ← g + 45	[g = 45]
< 8, A>	g ← g + 50	[g = 95]
< 9, A>	p ← p + 78	[p = 78]
<10, A>	d ← d + 558	[d = 558]

Vector clock A = (11, 5)
Order deviation = 3
Numerical deviation = (2, 482)

Replica B

Conit
- d = 412 // distance
- g = 45 // gas
- p = 70 // price

Operation		Result
< 5, B>	g ← g + 45	[g = 45]
< 6, B>	p ← p + 70	[p = 70]
< 7, B>	d ← d + 412	[d = 412]

Vector clock B = (0, 8)
Order deviation = 1
Numerical deviation = (3, 686)

Conit (contains the variables g, p, and d)

- Each replica has a vector clock: ([known] time @ A, [known] time @ B)
- B sends A operation $[\langle 5, B\rangle : g \leftarrow d + 45]$; A has made this operation permanent (cannot be rolled back)

Example: Conit

Replica A

Conit

d = 558 // distance
g = 95 // gas
p = 78 // price

Operation		Result
< 5, B>	g ← g + 45	[g = 45]
< 8, A>	g ← g + 50	[g = 95]
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<10, A>	d ← d + 558	[d = 558]

Vector clock A = (11, 5)
Order deviation = 3
Numerical deviation = (2, 482)

Replica B

Conit

d = 412 // distance
g = 45 // gas
p = 70 // price

Operation		Result
< 5, B>	g ← g + 45	[g = 45]
< 6, B>	p ← p + 70	[p = 70]
< 7, B>	d ← d + 412	[d = 412]

Vector clock B = (0, 8)
Order deviation = 1
Numerical deviation = (3, 686)

Conit (contains the variables g, p, and d)

- A has three pending operations $\Rightarrow$ order deviation $= 3$
- A missed two operations from B; max diff is $70 + 412$ units $\Rightarrow (2, 482)$

Granualarit Granularity of Conits Trade-offs

We need to pay attention to the **granularity** of our Conits: The trade-off is fine-grained vs. coarse-grained conits

- Coarse-grained conit $=$ large data set (e.g., entire database)
- Updates are aggregated over all data inside the same conit
- Consequence: replicas enter inconsistent state earlier
- Example: if max deviation $= 1$ update and conit $=$ whole DB $\rightarrow$ one local update forces immediate propagation
- Fine-grained conits (per data item) keep replicas "up-to-date" longer
- Worst case: unrelated data items falsely share the same conit $\rightarrow$ unnecessary synchronization and staleness

Summary

We can arrange the consistency models from strongest to weakest:

1. **Linearizability**: Single atomic global timeline. Every operation appears to take effect instantly at one point in real time. All clients see the same order respecting real-time.
2. **Serializability**: Transactions appear as if executed in some sequential order, but that order can differ from real-time wall-clock order
3. **Sequential Consistency**: One global total order of all operations that respects each process's own program order, but not necessarily real-time
4. **Causal Consistency**: All causally related operations (happens-before via reads/writes or messages) are seen in the same order by everyone
5. **Entry Consistency**: Consistency guaranteed only for data protected by a lock
6. **Eventual Consistency**: If no new writes, all replicas eventually converge. No ordering or timeliness guarantees

Client-centric consistency models

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.

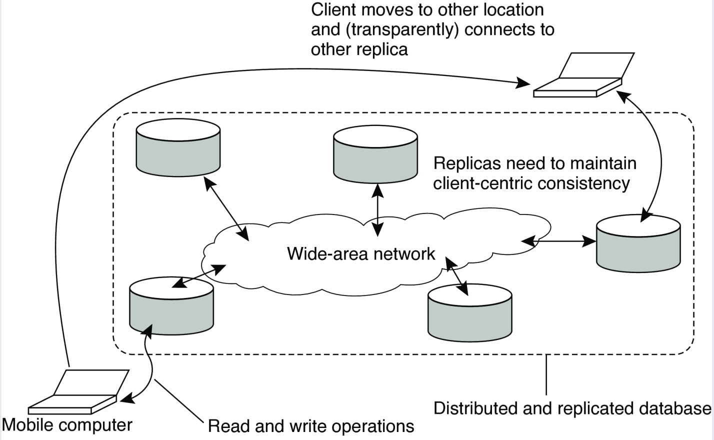
- At location A you access the database doing reads and updates.
- At location B you continue your work, but unless you access the same server as the one at location A, you may detect inconsistencies:
  - your updates at A may not have yet been propagated to B
  - you may be reading newer entries than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

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

The principle of a mobile user accessing different replicas of a distributed database



Client-centric consistency: notation

Notations

- $W_1(x_2)$ is the write operation by process P_1 that leads to version x_2 of x
- $W_1(x_i;x_j)$ indicates P_1 produces version x_j based on a previous version x_i.
- $W_1(x_i|x_j)$ indicates P_1 produces version x_j concurrently to version x_i.

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 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.

L_1: $W_1(x_1)$ $R_1(x_1)$

L_2: $W_2(x_1;x_2)$ $R_1(x_2)$

A monotonic-read consistent data store

L_1: $W_1(x_1)$ $R_1(x_1)$

L_2: $W_2(x_1|x_2)$ $R_1(x_2)$

A data store that does not provide monotonic reads

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.

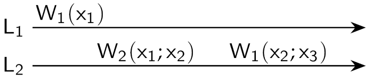
Example

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

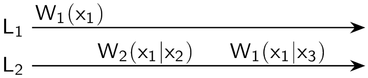
Monotonic writes

Definition

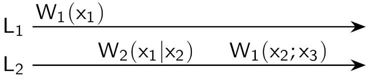
A write operation by a process on a data item x is completed before any successive write operation on x by the same process.



OK



Not OK



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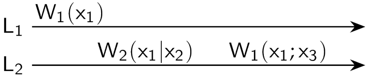
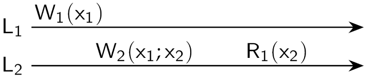


OK

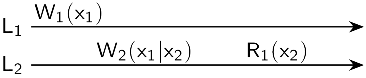
Read your writes

Definition

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



OK



Not OK

Example

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

Writes follow reads

Definition

A write operation by a process on a data item x following a previous read operation on x by the same process, is guaranteed to take place on the same or a more recent value of x that was read.

L_1: $W_1(x_1)$ — $R_2(x_1)$

L_2: $W_3(x_1;x_2)$ — $W_2(x_2;x_3)$

OK

L_1: $W_1(x_1)$ — $R_2(x_1)$

L_2: $W_3(x_1|x_2)$ — $W_2(x_2|x_3)$

Not OK

Example

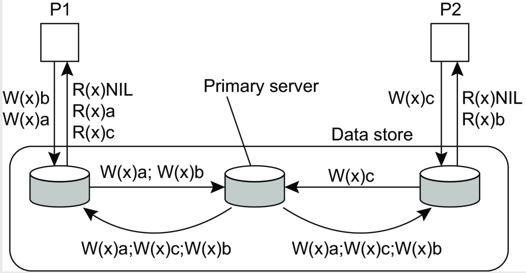
See reactions to posted articles only if you have the original posting (a read "pulls in" the corresponding write operation).

Example: ZooKeeper consistency

Yet another model?

ZooKeeper's consistency model mixes elements of data-centric and client-centric models

Take a naive example



Replica management

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.

Content replication

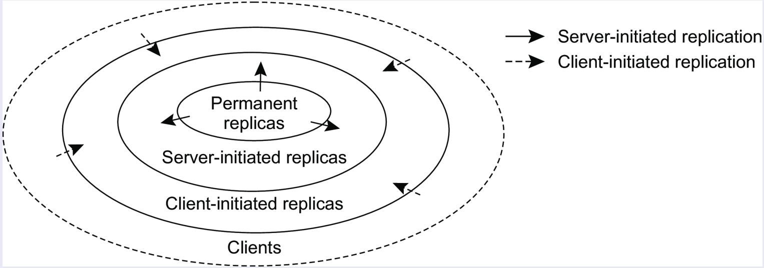
Distinguish different processes

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)

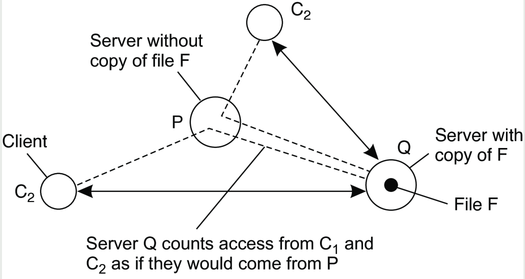
Content replication

The logical organization of different kinds of copies of a data store into three concentric rings



Server-initiated replicas

Counting access requests from different clients



- 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

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): passive replication
- Propagate the update operation to other copies: active replication

Note

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

Content distribution: client/server system

A comparison between push-based and pull-based protocols in the case of multiple-client, single-server systems

- 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.

Make lease expiration time adaptive

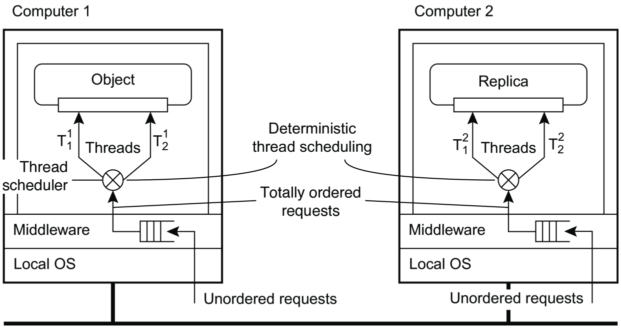
- Age-based leases: An object that hasn't changed for a long time, will not change in the near future, so provide a long-lasting lease
- Renewal-frequency based leases: The more often a client requests a specific object, the longer the expiration time for that client (for that object) will be
- State-based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

Question

Why are we doing all this?

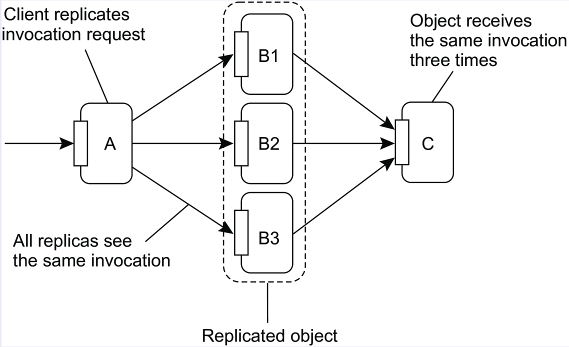
Managing replicated objects

- Prevent concurrent execution of multiple invocations on the same object: access to the internal data of an object has to be serialized. Using local locking mechanisms are sufficient.
- Ensure that all changes to the replicated state of the object are the same: no two independent method invocations take place on different replicas at the same time: we need deterministic thread scheduling.

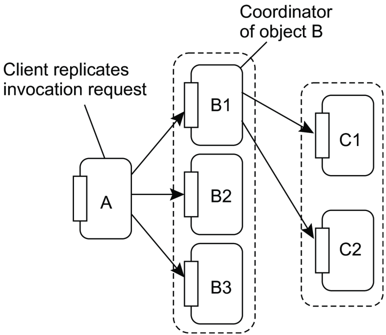


Replicated-object invocations

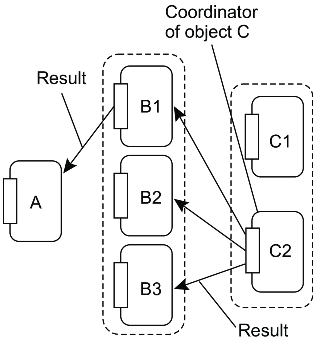
Problem when invocating a replicated object



Replicated-object invocations



Forwarding a request

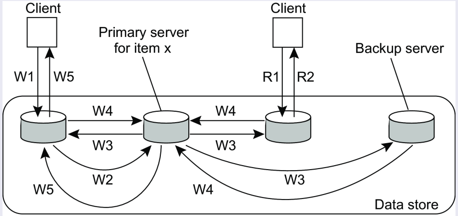


Returning the reply

Consistency protocols

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

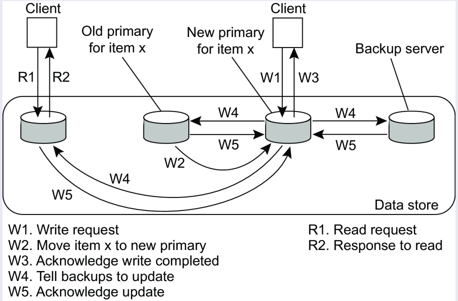
R1. Read request
R2. Response to read

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 the same LAN.

Primary-based protocols

Primary-backup protocol with local writes



Example primary-backup protocol with local writes

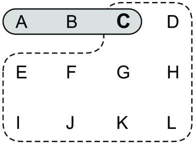
Mobile computing in disconnected mode (ship all relevant files to user before disconnecting, and update later on).

Replicated-write protocols

Quorum-based protocols

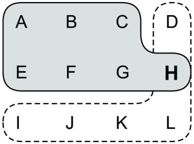
Assume N replicas. Ensure that each operation is carried out in such a way that a majority vote is established: distinguish read quorum N_R and write quorum N_W. Ensure:

1. $N_R + N_W > N$ (prevent read-write conflicts)
2. $N_W > N/2$ (prevent write-write conflicts)



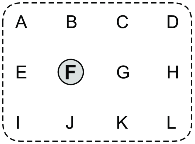
$N_R = 3$, $N_W = 10$

Correct



$N_R = 3$, $N_W = 10$

Write-write conflict



$N_R = 1$, $N_W = 12$

Correct (ROWA)

Continuous consistency: Numerical errors

Principal operation

- Every server S_i has a log, denoted as L_i.
- Consider a data item x and let $val(W)$ denote the numerical change in its value after a write operation W. Assume that

$$\forall W : val(W) > 0$$

- 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:

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

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 server S_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

$$TW[k,k] - TW_k[i,k] > \delta_i/(N-1)$$

Question

To what extent are we being pessimistic here: where does $\delta_i/(N-1)$ come from?

Note

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

Implementing client-centric consistency

Keeping it simple

Each write operation W is assigned a globally unique identifier by its origin server. For each client, we keep track of two sets of writes:

- Read set: the (identifiers of the) writes relevant for that client's read operations
- Write set: the (identifiers of the) client's write operations.

Monotonic-read consistency

When client C wants to read at server S, C passes its read set. S can pull in any updates before executing the read operation, after which the read set is updated.

Monotonic-write consistency

When client C wants to write at server S, C passes its write set. S can pull in any updates, executes them in the correct order, and then executes the write operation, after which the write set is updated.

Implementing client-centric consistency

Read-your-writes consistency

When client C wants to read at server S, C passes its write set. S can pull in any updates before executing the read operation, after which the read set is updated.

Writes-follows-reads consistency

When client C wants to write at server S, C passes its read set. S can pull in any updates, executes them in the correct order, and then executes the write operation, after which the write set is updated.

Example: Caching and replication in the Web

Example: replication in the Web

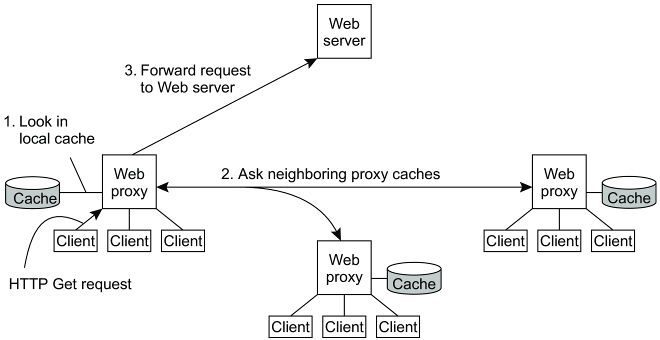
Client-side caches

- In the browser
- At a client's site, notably through a Web proxy

Caches at ISPs

Internet Service Providers also place caches to (1) reduce cross-ISP traffic and (2) improve client-side performance. May get nasty when a request needs to pass many ISPs.

Cooperative caching



Web-cache consistency

How to guarantee freshness?

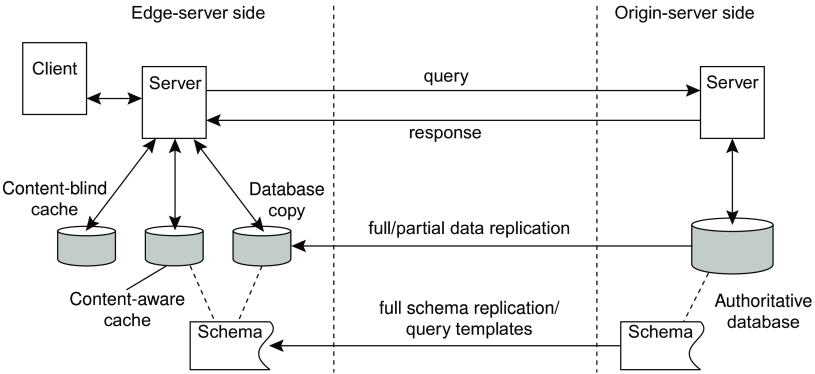
To prevent that stale information is returned to a client:

- Option 1: let the cache contact the original server to see if content is still up to date.
- Option 2: Assign an expiration time T_{expire} that depends on how long ago the document was last modified when it is cached. If $T_{last\_modified}$ is the last modification time of a document (as recorded by its owner), and T_{cached} is the time it was cached, then

$$T_{expire} = \alpha(T_{cached} - T_{last\_modified}) + T_{cached}$$

  with $\alpha = 0.2$. Until T_{expire}, the document is considered valid.

Alternatives for caching and replication



- Database copy: the edge has the same as the origin server
- Content-aware cache: check if a (normal query) can be answered with cached data. Requires that the server knows about which data is cached at the edge.
- Content-blind cache: store a query, and its result. When the exact same query is issued again, return the result from the cache.

Summary

Summary

In this section on *Consistency and Replication*, we discussed the following topics

- Data-centric consistency models
- Client-centric consistency models
- Replica Management
- Consistency Protocols
- Caching Example