Consistency & Replication

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Based on slides by Maarten Van Steen

What is the problem?

Motivation

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- Problem: keeping replicas consistent.
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- Guaranteeing global ordering on conflicting operations may be a costly operation, downgrading scalability.

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- The placement problem is split into two subproblems:
  - Placing replica servers: finding the best locations to place a server.
  - Placing content: finding the best servers for placing content.

Distribution Protocols

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

Replica Placement

Replica Placement (1/2)

- Figure out what the best K places are out of N possible locations.
- The first chosen location minimizes the average distance to all clients.
- Select best location out of $N - k$ for which the average distance to clients is minimal. Then choose the next best server.

Replica Placement (2/2)

- Ignore the position of clients and only take the topology of the Internet as formed by the autonomous systems (AS).
- AS: the nodes all run the same routing protocol and which is managed by a single organization.
- Select the K-th largest autonomous system and place a server at the best-connected host.

Content Replication

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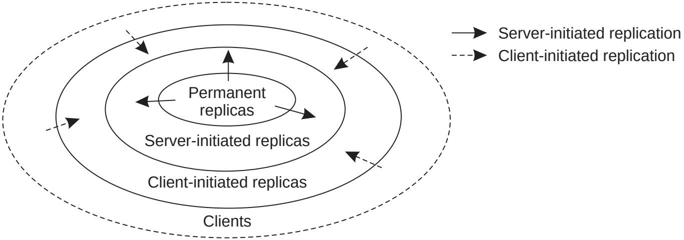
- Three different types of replicas:



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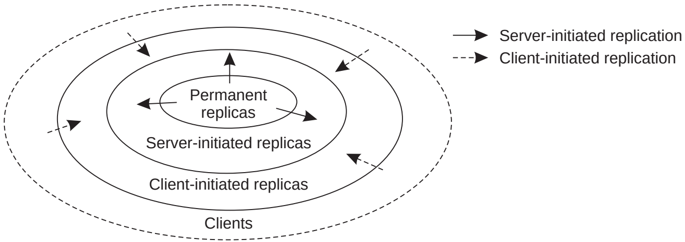

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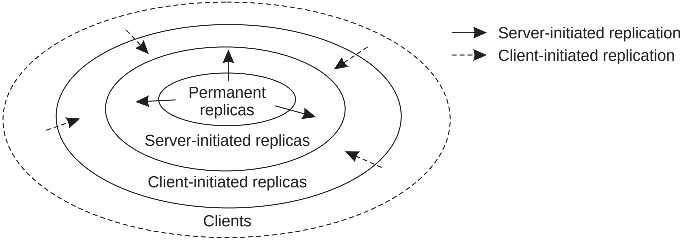

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- Three different types of replicas:
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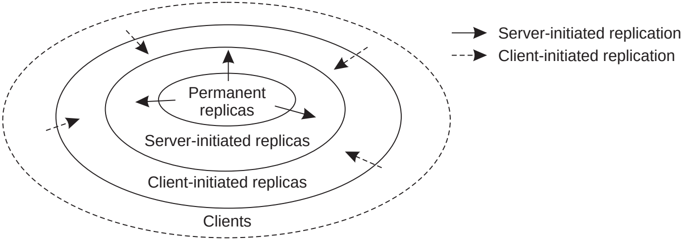
  - Server-initiated replica: process that can dynamically host a replica on request of another server in the data store.
  - Client-initiated replica: process that can dynamically host a replica on request of a client (client cache).

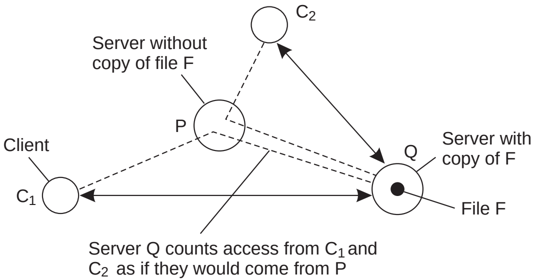


Permanent Replication

- Initial set of replicas that constitute a distributed data store.
- Example, web site:
  1. The web site files are replicated across a limited number of servers at a single location: the arrived requests are forwarded to one of the servers (round-robin strategy).
  2. Mirroring, where a web site is copied to a limited number of servers, which are geographically spread across the Internet.

Server-Initiated Replicas

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



Client-Initiated Replicas

- Client-initiated replicas are more commonly known as (client) caches.

- A cache is a local storage facility that is used by a client to temporarily store a copy of the data it has just requested.

- Managing the cache is left entirely to the client.

Content Distribution

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  - Propagate the update operation to other copies: active replication

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

Content Distribution (2/2)

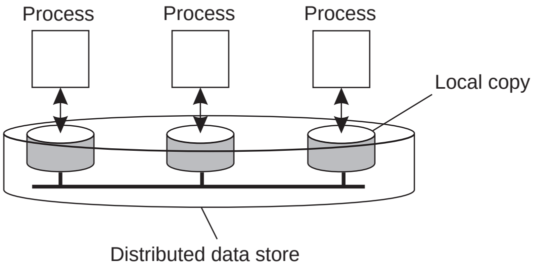
- Pushing updates: server-initiated approach, in which update is propagated regardless whether target asked for it.

- Pulling updates: client-initiated approach, in which client requests to be updated.

Data Centric Consistency Model

Data-Centric Consistency Models

- A data store is a distributed collection of storages:



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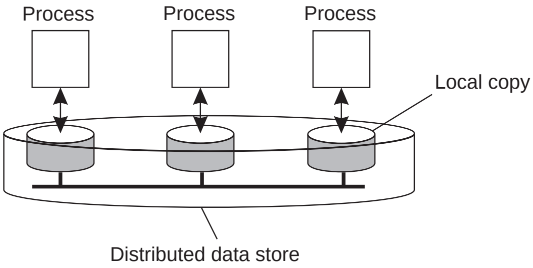

- Consistency model: a contract between a (distributed) data store and processes, in which the data store specifies precisely what the results of read and write operations are in the presence of concurrency.

Consistency Models

- Sequential consistency
- Causal consistency

Sequential Consistency

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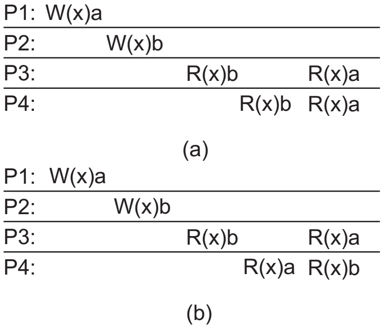

Sequential Consistency

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- Nothing is said about time: no reference to the most recent write operation on a data item.

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				
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(b)

Causal Consistency

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- It makes a distinction between events that are potentially causally related and those that are not.
- If event *b* is caused or influenced by an earlier event *a*, causality requires that everyone else first see *a*, then see *b*.
- On the other hand, if two processes spontaneously and simultaneously write two different data items, these are not causally related: concurrent processes

Causal Consistency (2/3)

- 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				
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(b)

Causal Consistency (3/3)

- This sequence is allowed with a causally-consistent store, but not with a sequentially consistent store.

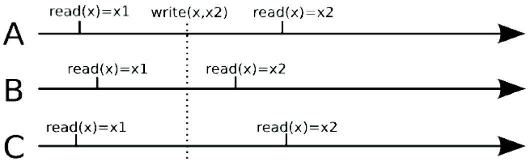
P1:	W(x)a			W(x)c		
P2:		R(x)a	W(x)b			
P3:		R(x)a			R(x)c	R(x)b
P4:		R(x)a			R(x)b	R(x)c

Client Centric Consistency Model

Client-Centric Consistency Models

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

Strong Consistency vs. Eventual Consistency



strong consistency

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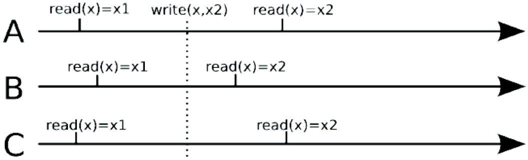

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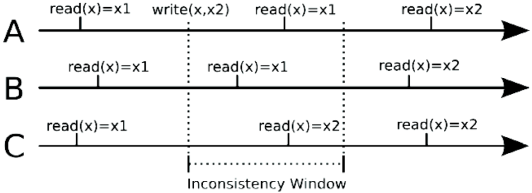


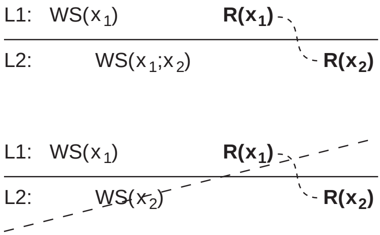
eventual consistency

Notation

- $WS(x_i[t])$ is the set of write operations (at local copy L_i) that lead to version x_i of x (at time t).
- $WS(x_i[t_1]; x_j[t_2])$ indicates that the operations in $WS(x_i[1])$ have also been performed at local copy L_j at a later time $t2$.
  - $WS(x_i[t_1])$ is part of $WS(x_j[t_2])$.
- Note: Parameter t is omitted from figures.

Monotonic Reads (1/2)

- 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.



Monotonic Reads (2/2)

- Example 1:
  - 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.

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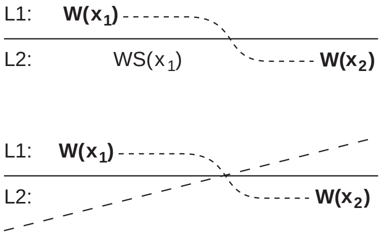
- Example 2:
  - Reading (not modifying) incoming mail while you are on the move.
  - Each time you connect to a different e-mail server, that server fetches (at least) all the updates from the server you previously visited.

Monotonic Writes (1/2)

- 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 (2/2)

- Example 1:
  - Updating a program at server S_2, and ensuring that all components on which compilation and linking depends, are also placed at S_2.

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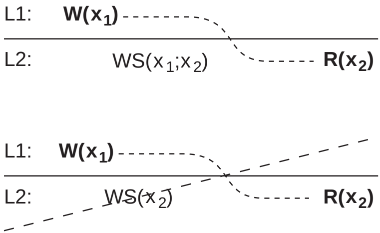
  - Updating a program at server S_2, and ensuring that all components on which compilation and linking depends, are also placed at S_2.

- Example 2:
  - 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

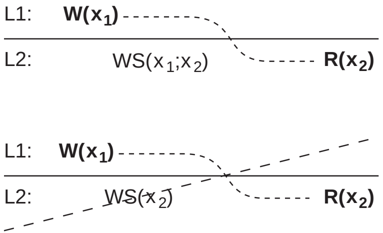
- The effect of a write operation by a process on data item x, will always be seen by a successive read operation on x by the same process.



Read Your Writes

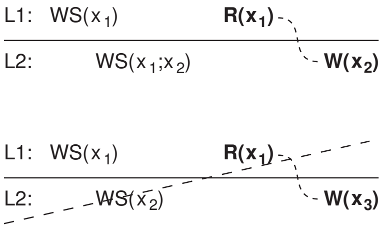
- The effect of a write operation by a process on data item x, will always be seen by a successive read operation on x by the same process.

- Example: updating your Web page and guaranteeing that your Web browser shows the newest version instead of its cached copy.



Writes Follow Reads

- 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.



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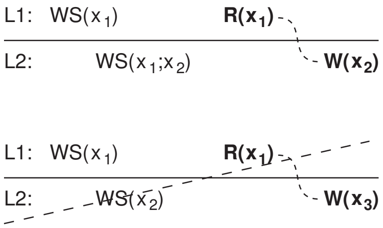
- Example: see reactions to posted articles only if you have seen the original posting.



Consistency Protocols

Consistency Protocols

- Consistency protocol: describes the implementation of a specific consistency model.
  - Primary-based protocols
  - Replicated-write protocols

Primary-Based Protocols

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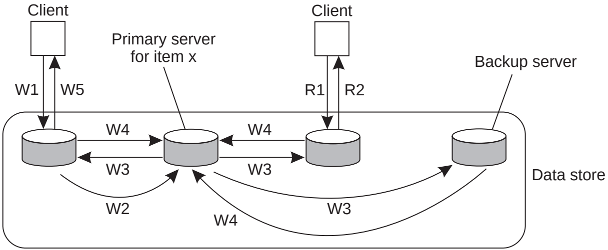
- In these protocols, each data item x in the data store has an associated primary, which is responsible for coordinating write operations on x.
- Primary-based protocols:
  - Remote-write protocols
  - Local-write protocols

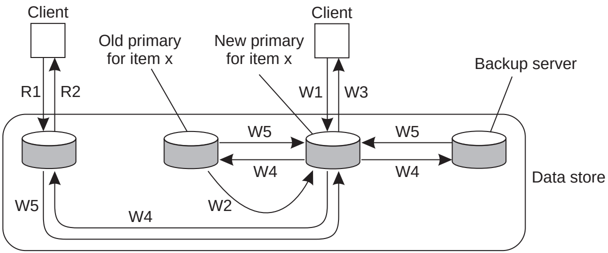
Remote-Write Protocols



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

Local-Write Protocols



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

Replicated-Write Protocols

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- Quorum Model
- N: the number of nodes to which a data item is replicated.
- R: the number of nodes a value has to be read from to be accepted.
- W: the number of nodes a new value has to be written to before the write operation is finished.

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- N: the number of nodes to which a data item is replicated.
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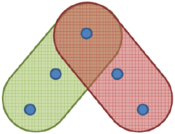
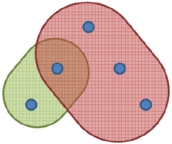
- To enforce consistency: $R + W > N$



R = 3, W = 3, N = 5



R = 4, W = 2, N = 5

Summary

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- Replication *rightarrow* problem: consistency
- Replica management: replica server placement, content placement, content distribution
- Data-centric consistency models: sequential, casual
- Client-centric consistency models: eventual consistency
- Monotonic reads, monotonic writes, read your write, writes follow reads
- Consistency protocols: primary-based, quorum

Reading

- Chapter 7 of the Distributed Systems: Principles and Paradigms.

Questions?