DISTRIBUTED SYSTEMS
Principles and Paradigms
Second Edition
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Chapter 7
Consistency And Replication

Data-centric Consistency Models

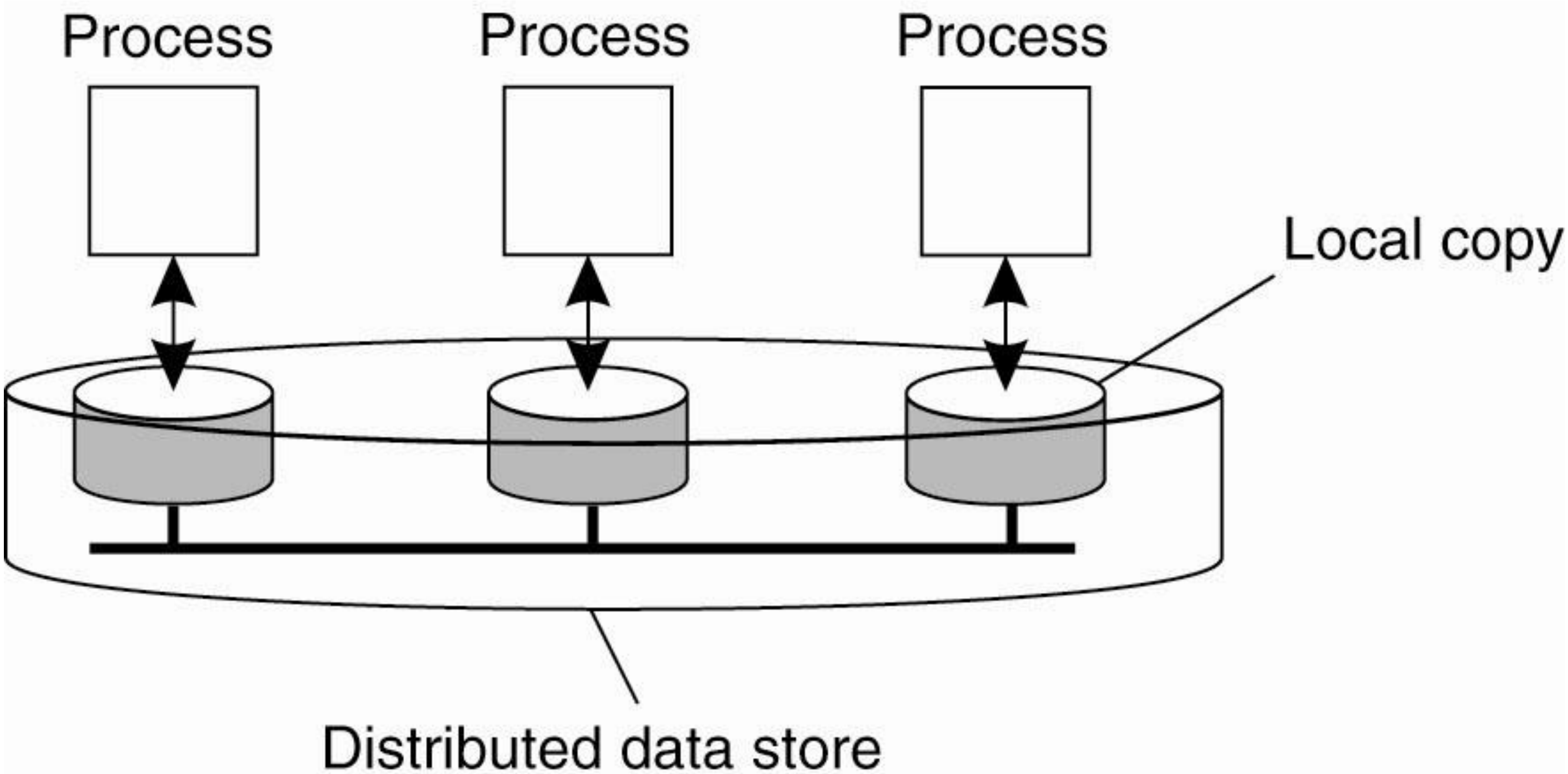


Figure 7-1. The general organization of a logical data store, physically distributed and replicated across multiple processes.

Sequential Consistency (1)

Figure 7-4. Behavior of two processes operating on the same data item. The horizontal axis is time.

Sequential Consistency (2)

A data store is sequentially consistent when:

The result of any execution is the same as if the (read and write) operations by all processes on the data store

- were executed in some sequential order and
- the operations of each individual process appear
  - in this sequence
  - in the order specified by its program.

Sequential Consistency (3)

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)

Figure 7-5. (a) A sequentially consistent data store.
(b) A data store that is not sequentially consistent.

Sequential Consistency (4)

Process P1	Process P2	Process P3
$x \leftarrow 1;$	$y \leftarrow 1;$	$z \leftarrow 1;$
print(y, z);	print(x, z);	print(x, y);

Figure 7-6. Three concurrently-executing processes.

Sequential Consistency (5)

x ← 1;	x ← 1;	y ← 1;	y ← 1;
print(y, z);	y ← 1;	z ← 1;	x ← 1;
y ← 1;	print(x, z);	print(x, y);	z ← 1;
print(x, z);	print(y, z);	print(x, z);	print(x, z);
z ← 1;	z ← 1;	x ← 1;	print(y, z);
print(x, y);	print(x, y);	print(y, z);	print(x, y);
Prints: 001011	Prints: 101011	Prints: 010111	Prints: 111111
Signature: 001011	Signature: 101011	Signature: 110101	Signature: 111111
(a)	(b)	(c)	(d)

Figure 7-7. Four valid execution sequences for the processes of Fig. 7-6. The vertical axis is time.

Causal Consistency (1)

For a data store to be considered causally consistent, it is necessary that the store obeys the following condition:

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
- on different machines.

Causal Consistency (2)

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

Figure 7-8. This sequence is allowed with a causally-consistent store, but not with a sequentially consistent store.

Causal Consistency (3)

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)

Figure 7-9. (a) A violation of a causally-consistent store.

Causal Consistency (4)

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

(b)

Figure 7-9. (b) A correct sequence of events in a causally-consistent store.

Eventual Consistency

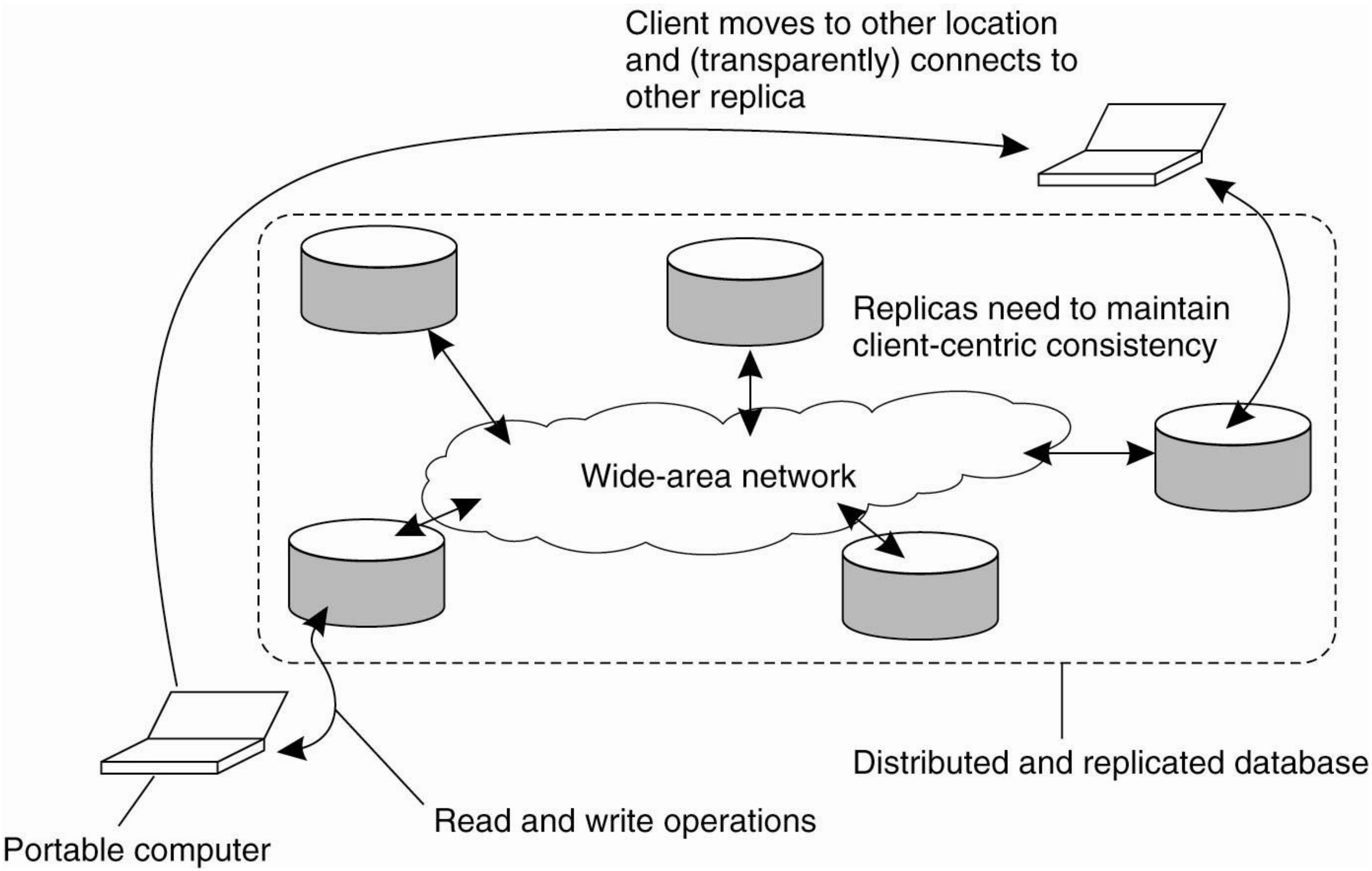


Figure 7-11. The principle of a mobile user accessing different replicas of a distributed database.

Monotonic Reads (1)

A data store is said to provide monotonic-read consistency if the following condition holds:

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 value
- or a more recent value.

Monotonic Reads (2)

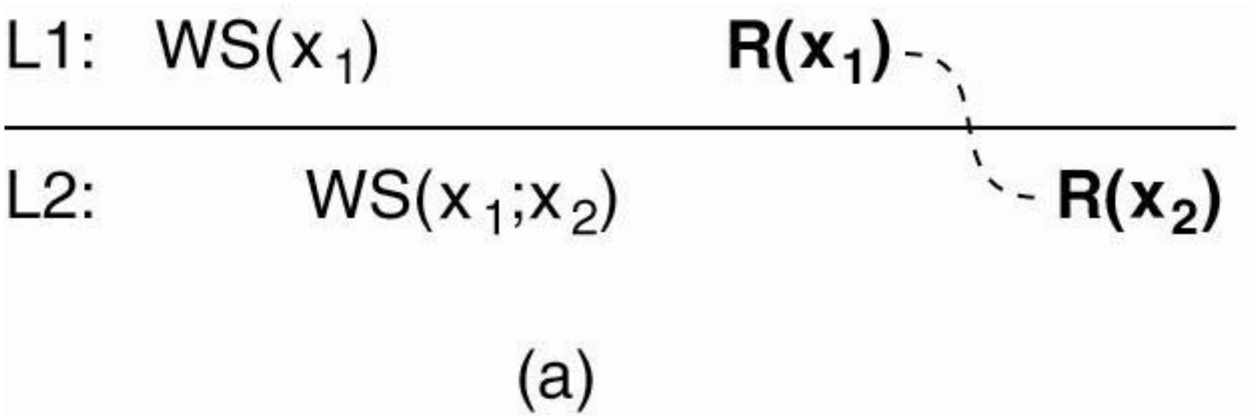


Figure 7-12. The read operations performed by a single process P at two different local copies of the same data store.
(a) A monotonic-read consistent data store.

Monotonic Reads (3)

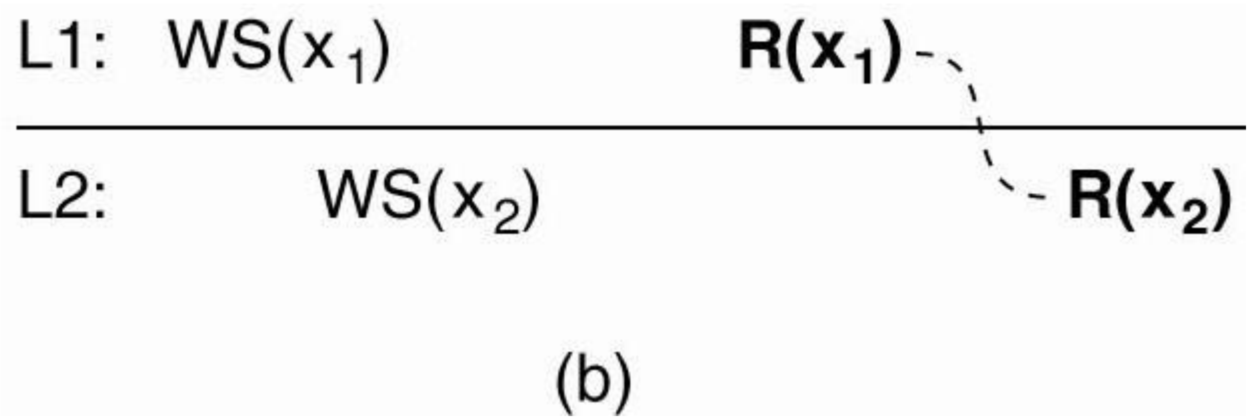


Figure 7-12. The read operations performed by a single process P at two different local copies of the same data store. (b) A data store that does not provide monotonic reads.

Monotonic Writes (1)

In a monotonic-write consistent store, the following condition holds:

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)

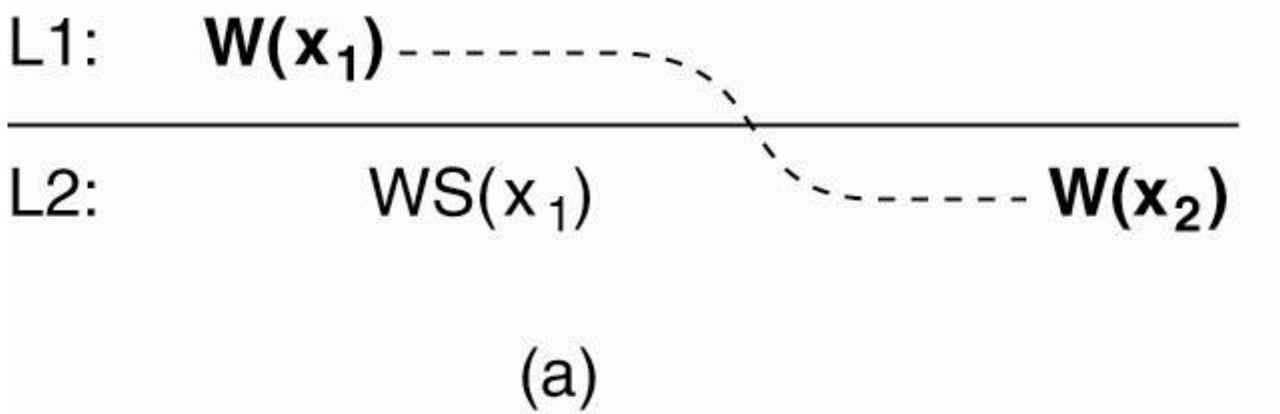


Figure 7-13. The write operations performed by a single process P at two different local copies of the same data store. (a) A monotonic-write consistent data store.

Monotonic Writes (3)

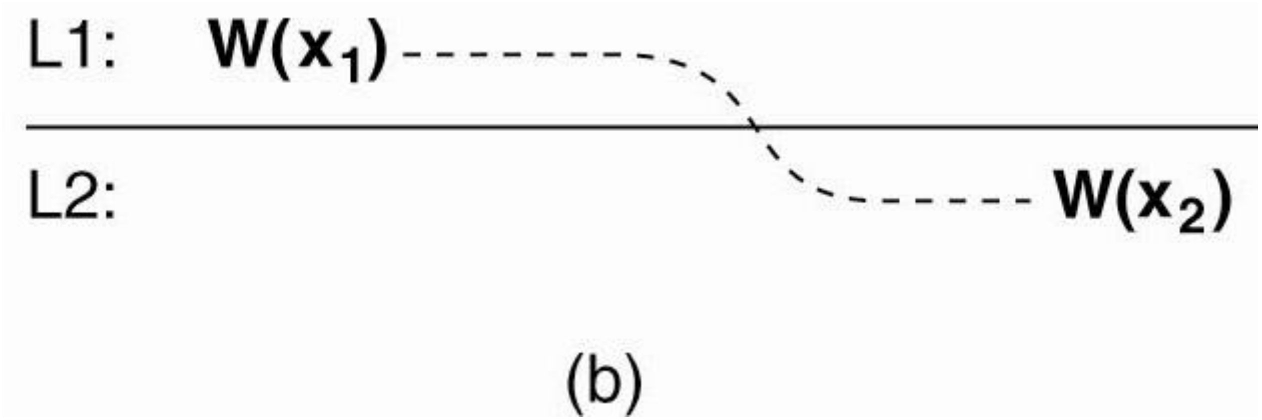


Figure 7-13. The write operations performed by a single process P at two different local copies of the same data store. (b) A data store that does not provide monotonic-write consistency.

Read Your Writes (1)

A data store is said to provide read-your-writes consistency, if the following condition holds:

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 (2)

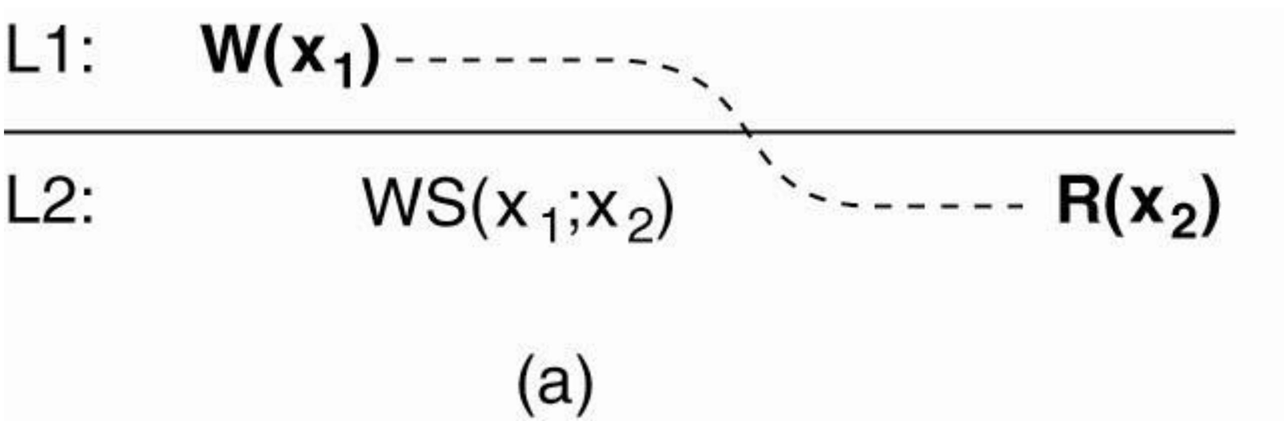


Figure 7-14. (a) A data store that provides read-your-writes consistency.

Read Your Writes (3)

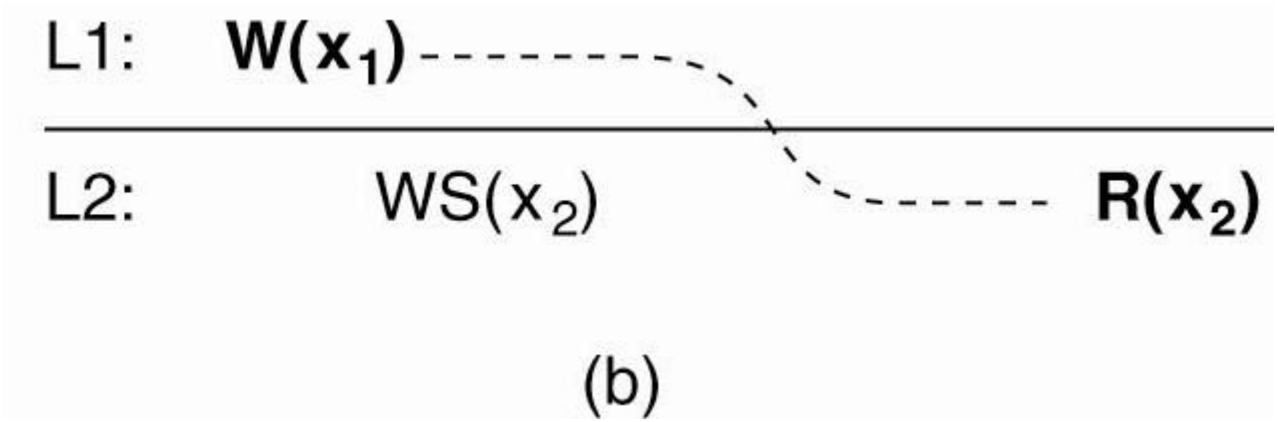


Figure 7-14. (b) A data store that does not.

Writes Follow Reads (1)

A data store is said to provide writes-follow-reads consistency, if the following holds:

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.

Writes Follow Reads (2)

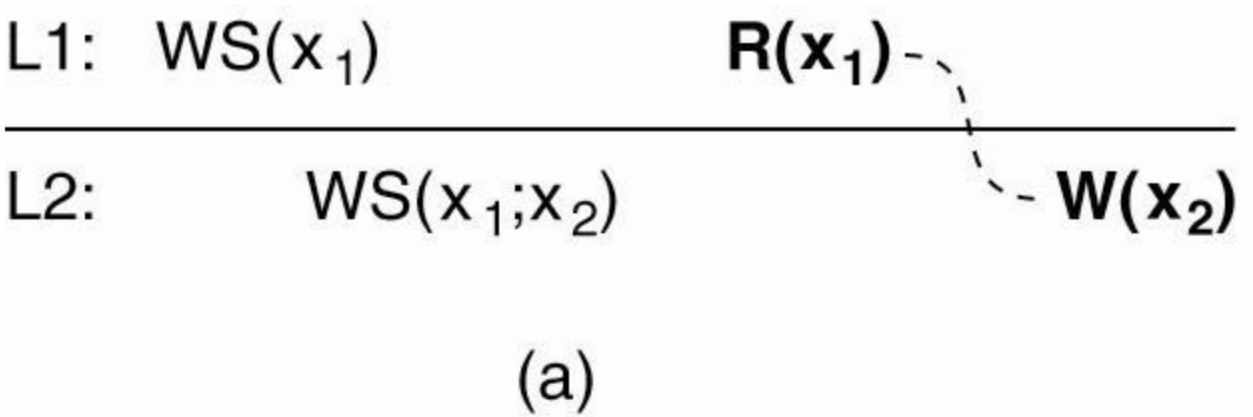


Figure 7-15. (a) A writes-follow-reads consistent data store.

Writes Follow Reads (3)

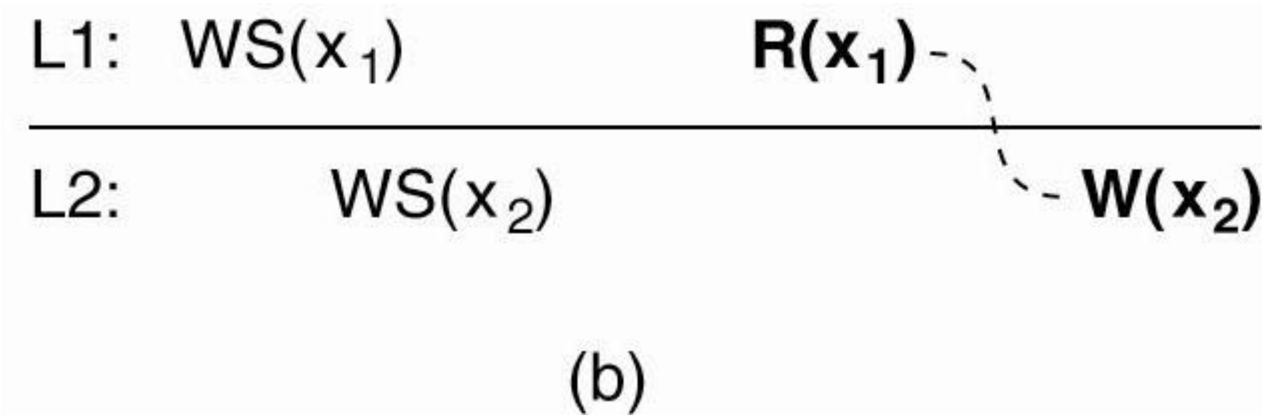


Figure 7-15. (b) A data store that does not provide writes-follow-reads consistency.

Replica-Server Placement

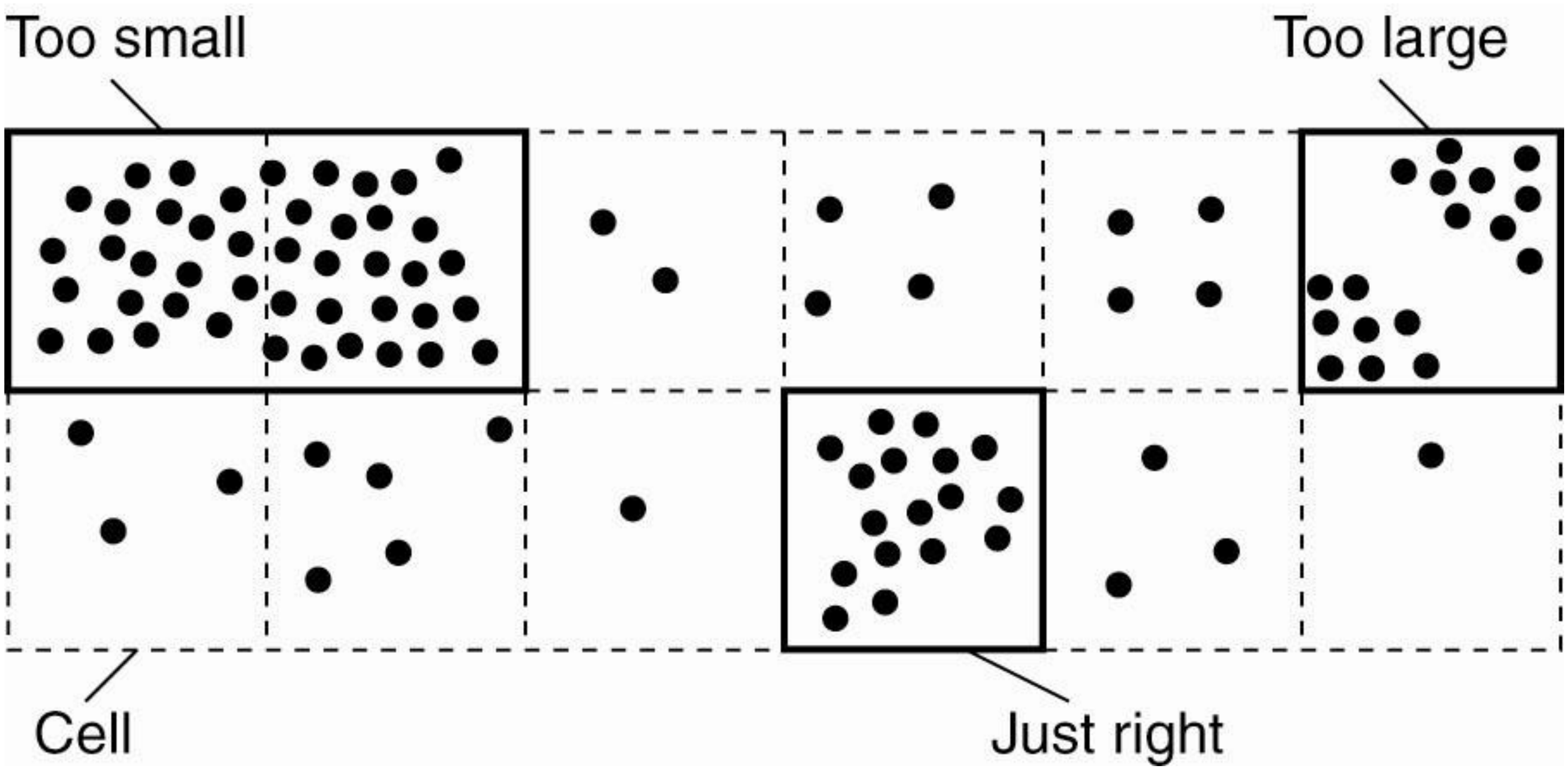


Figure 7-16. Choosing a proper cell size for server placement.

Content Replication and Placement

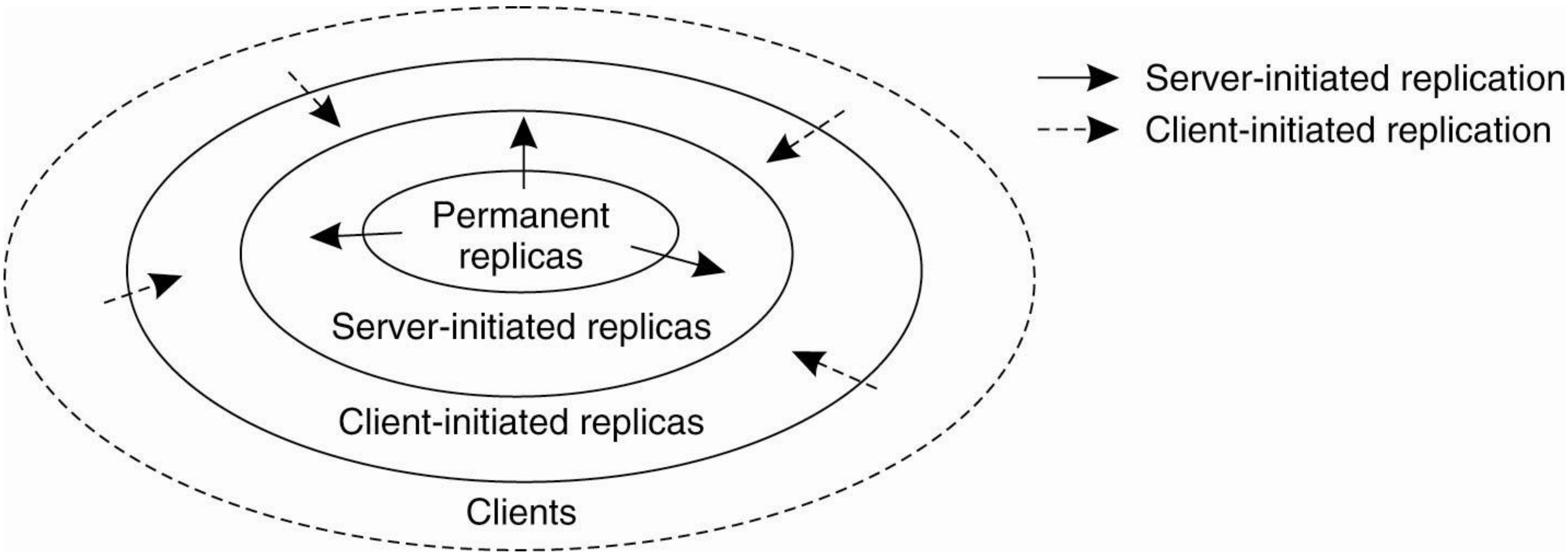


Figure 7-17. The logical organization of different kinds of copies of a data store into three concentric rings.

Server-Initiated Replicas

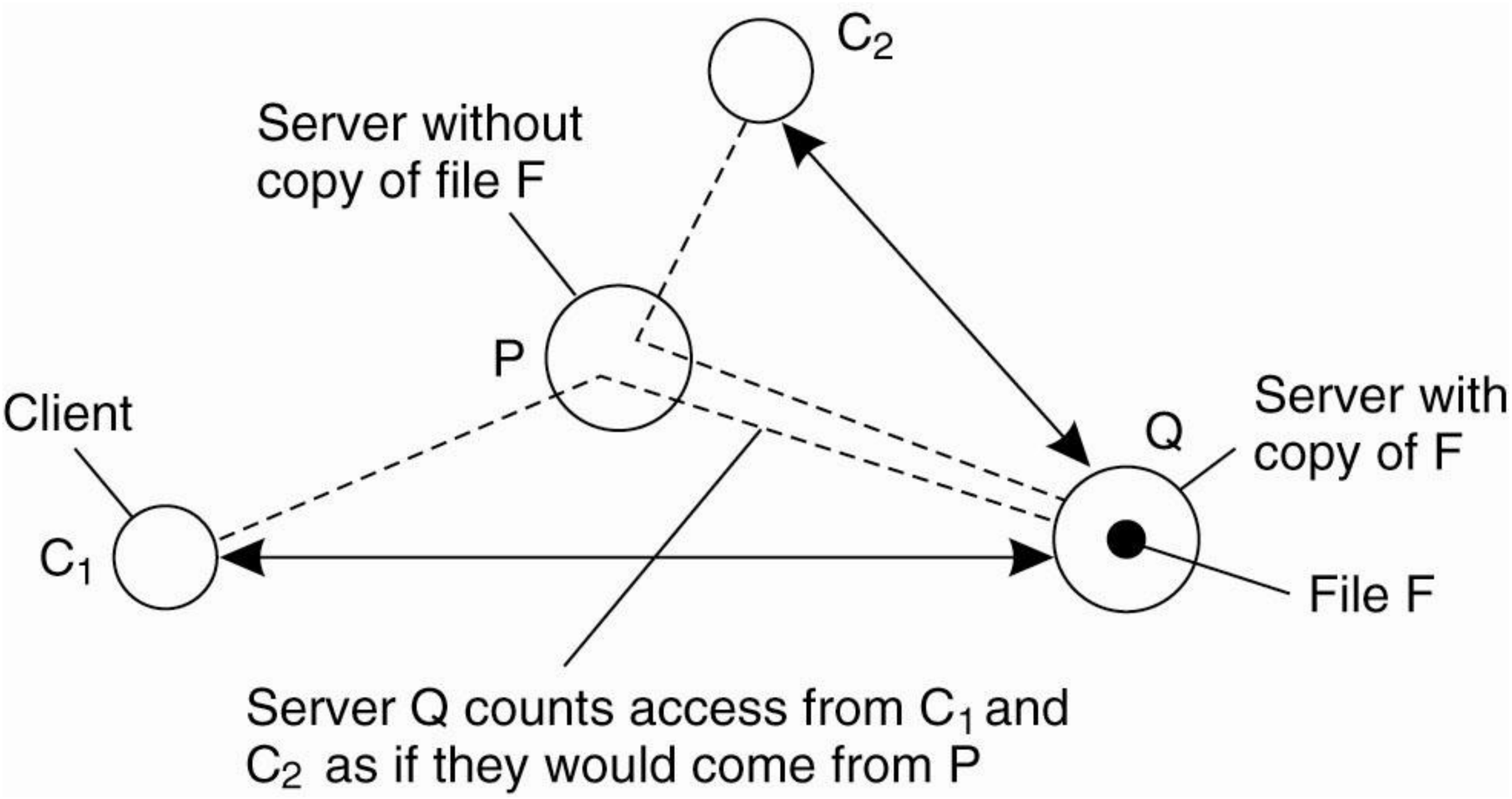


Figure 7-18. Counting access requests from different clients.

State versus Operations

Possibilities for what is to be propagated:

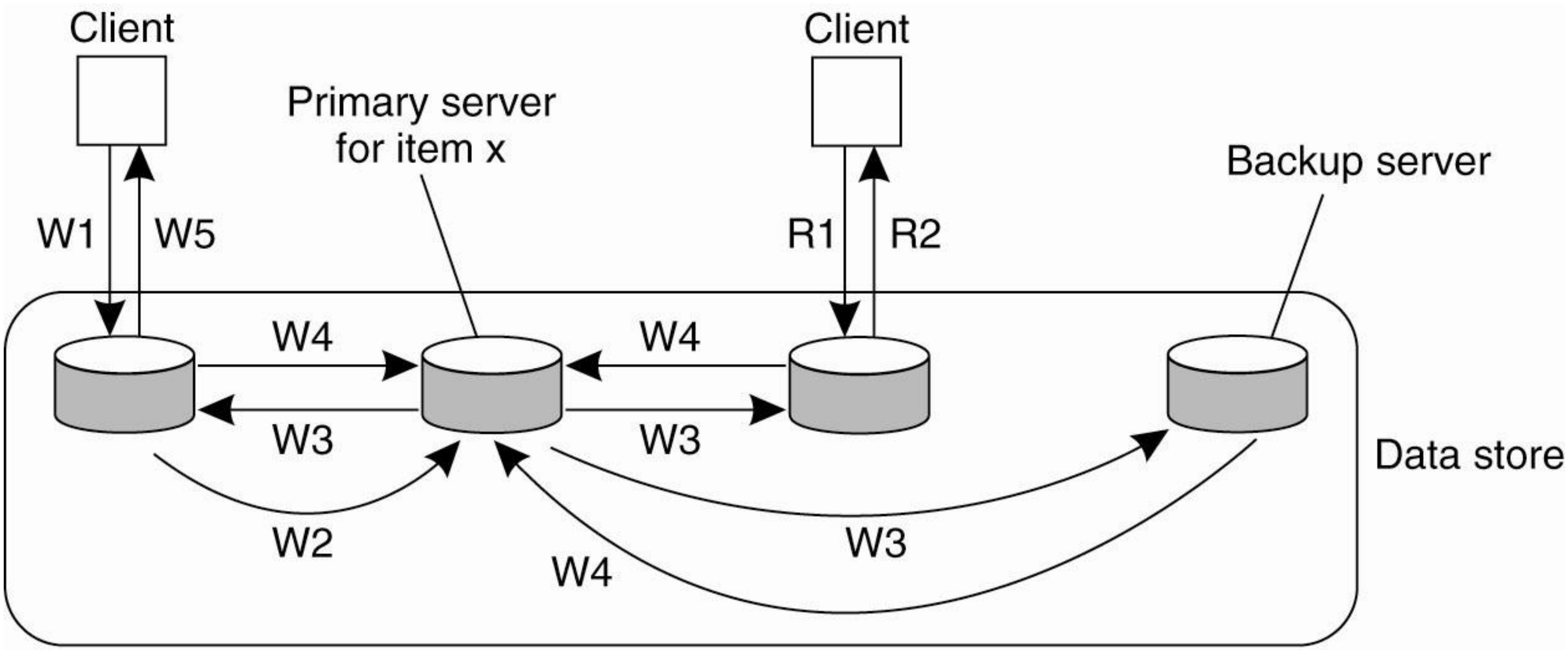
1. Propagate only a notification of an update.
2. Transfer data from one copy to another.
3. Propagate the update operation to other copies.

Pull versus Push Protocols

Issue	Push-based	Pull-based
State at server	List of client replicas and caches	None
Messages sent	Update (and possibly fetch update later)	Poll and update
Response time at client	Immediate (or fetch-update time)	Fetch-update time

Figure 7-19. A comparison between push-based and pull-based protocols in the case of multiple-client, single-server systems.

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

Figure 7-20. The principle of a primary-backup protocol.

Local-Write Protocols

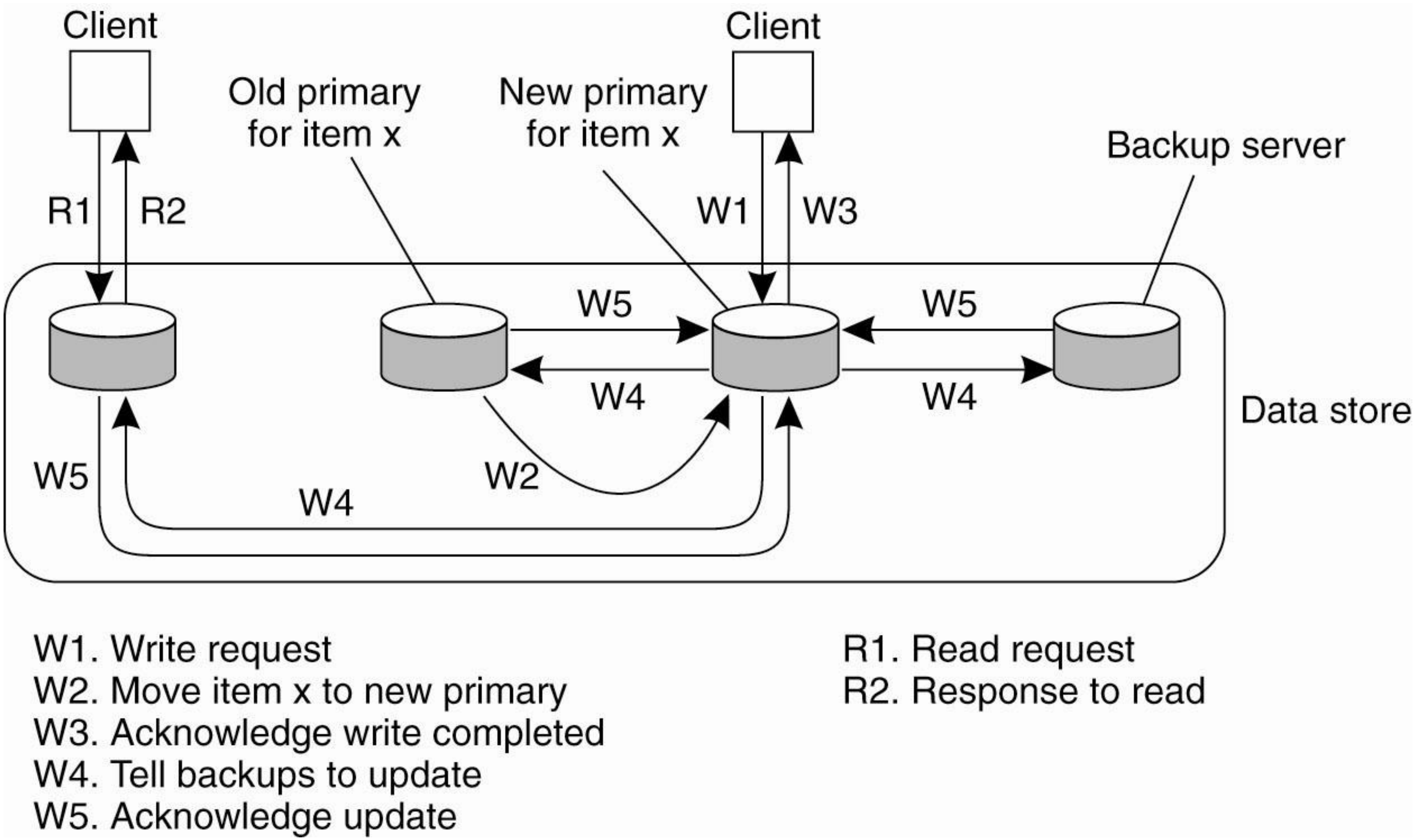


Figure 7-21. Primary-backup protocol in which the primary migrates to the process wanting to perform an update.

Quorum-Based Protocols

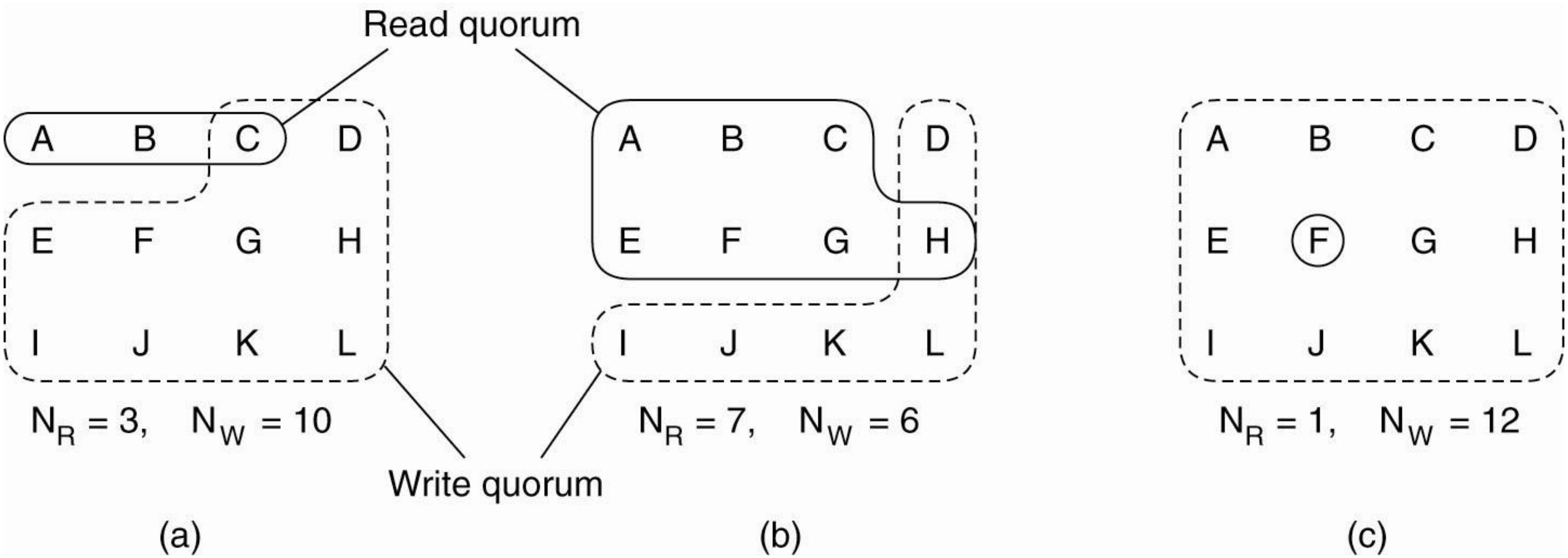


Figure 7-22. Three examples of the voting algorithm. (a) A correct choice of read and write set. (b) A choice that may lead to write-write conflicts. (c) A correct choice, known as ROWA (read one, write all).