

Consistency and Replication

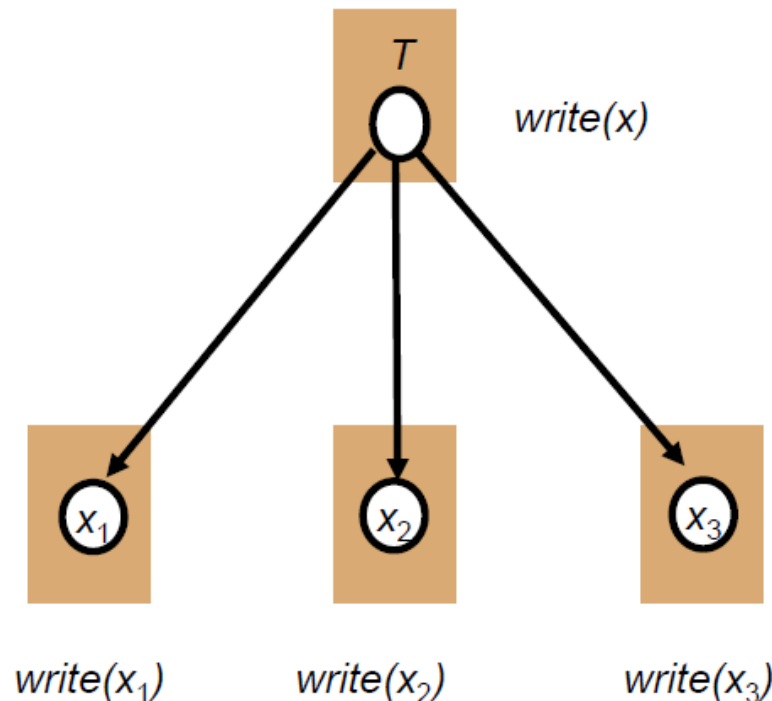
Distributed Systems [7]

Replication

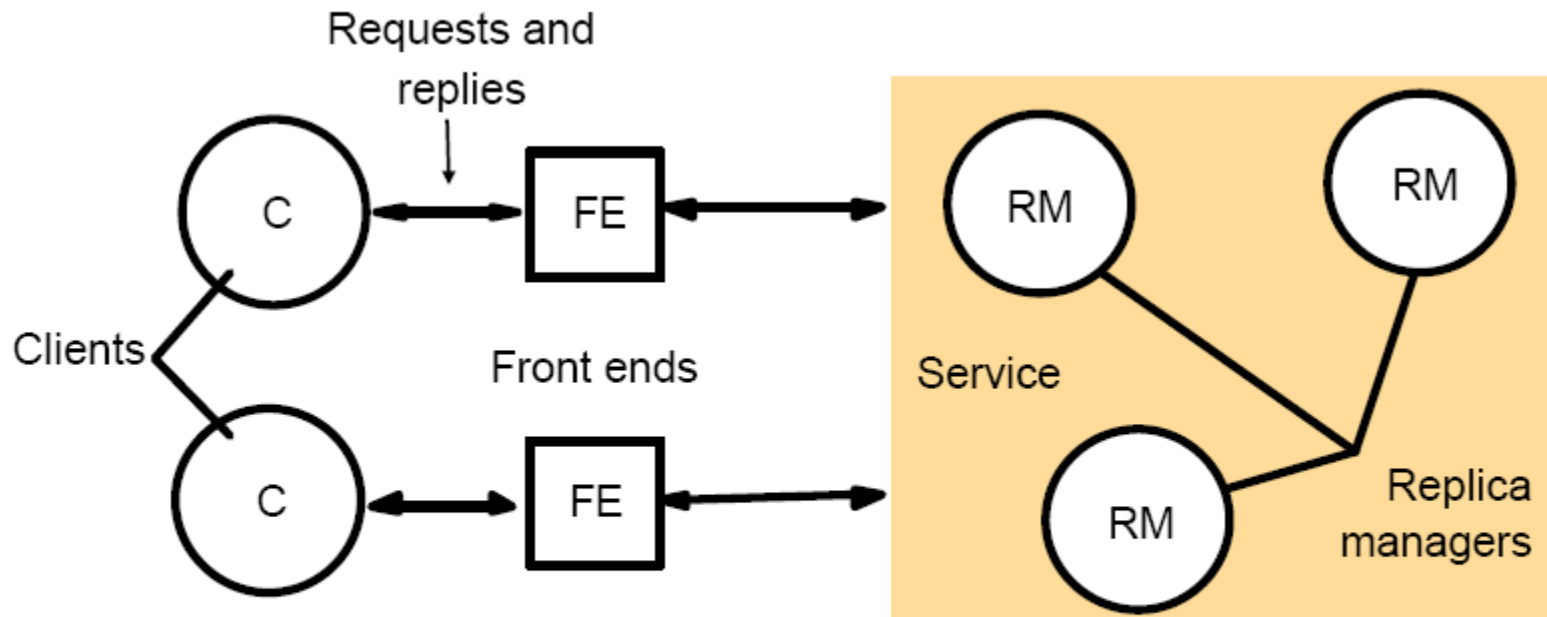
- Why replicate?
 - Reliability
 - Avoid single points of failure
 - Performance
 - Scalability in numbers and geographic area
- Why not replicate?
 - Replication transparency
 - Consistency issues
 - Updates are costly
 - Availability *may* suffer if not careful

Logical vs Physical Objects

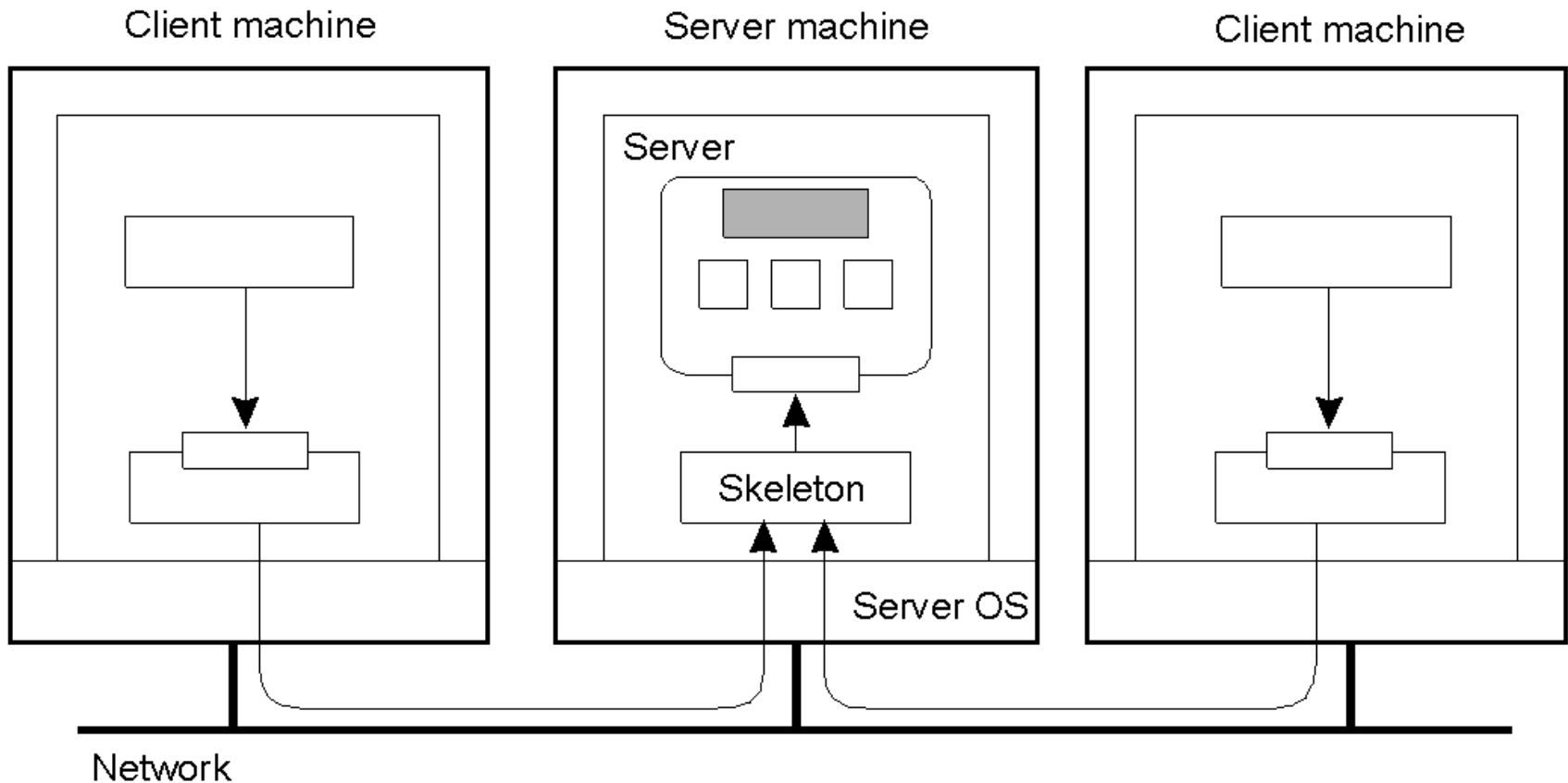
- There are physical copies of logical objects in the system.
 - Operations are specified on logical objects, but translated to operate on physical objects.



Replication Architecture

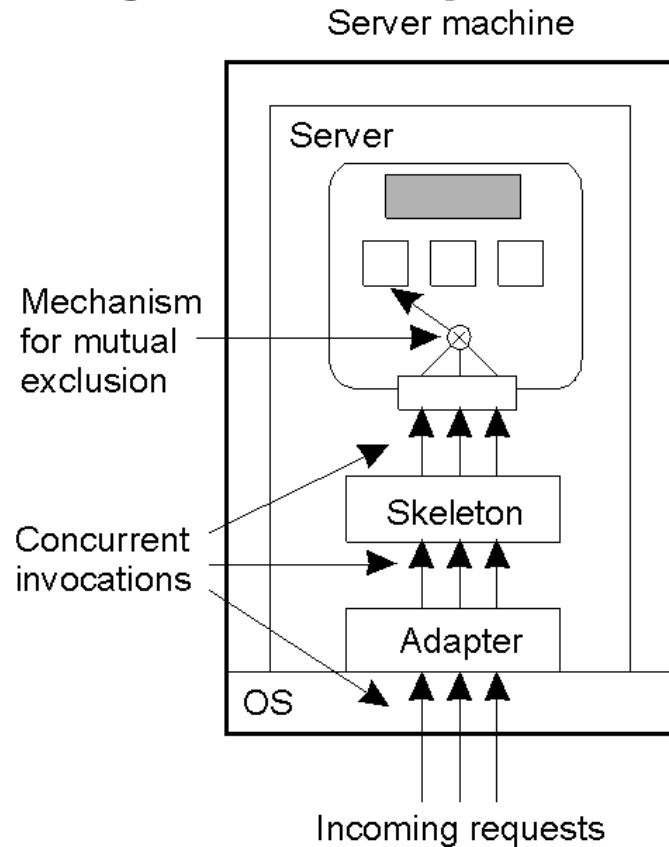


Object Replication (1)

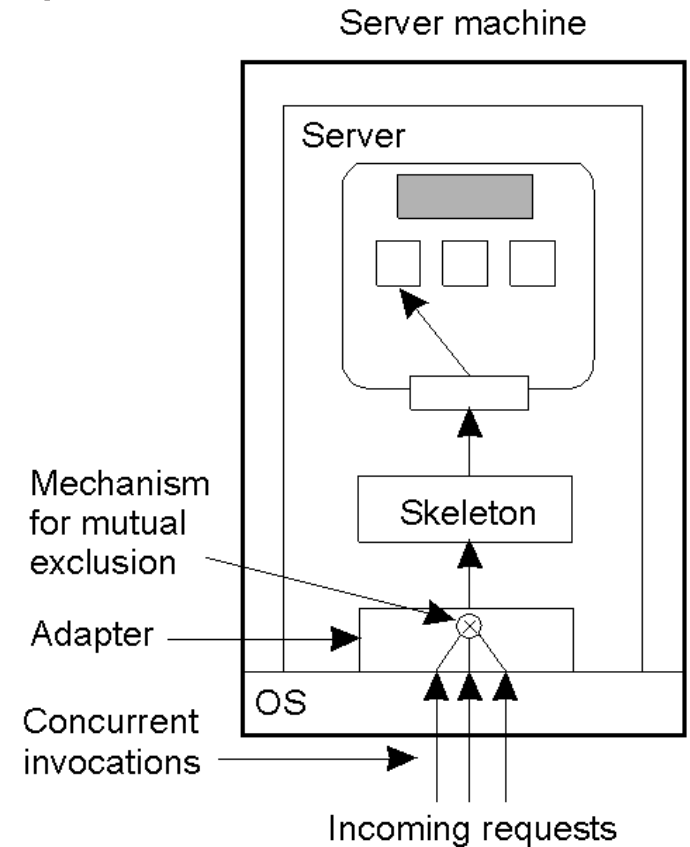


- Organization of a distributed remote object shared by two different clients.

Object Replication (2)



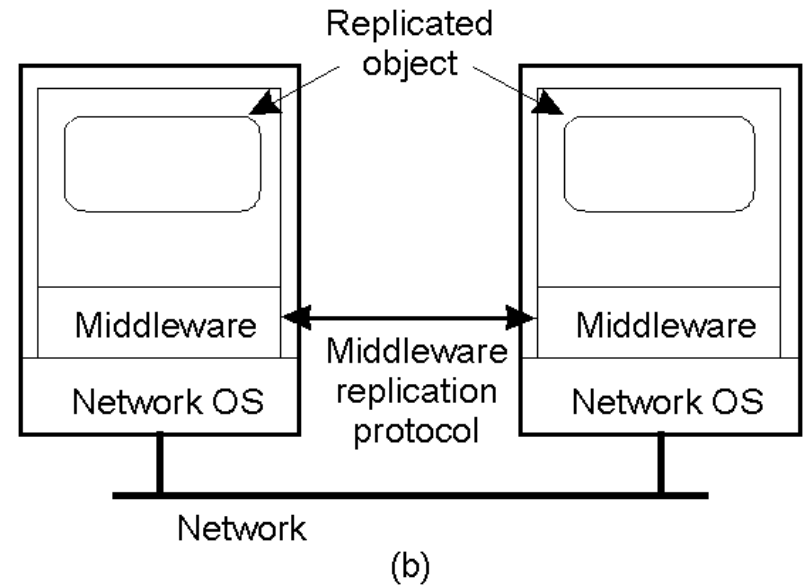
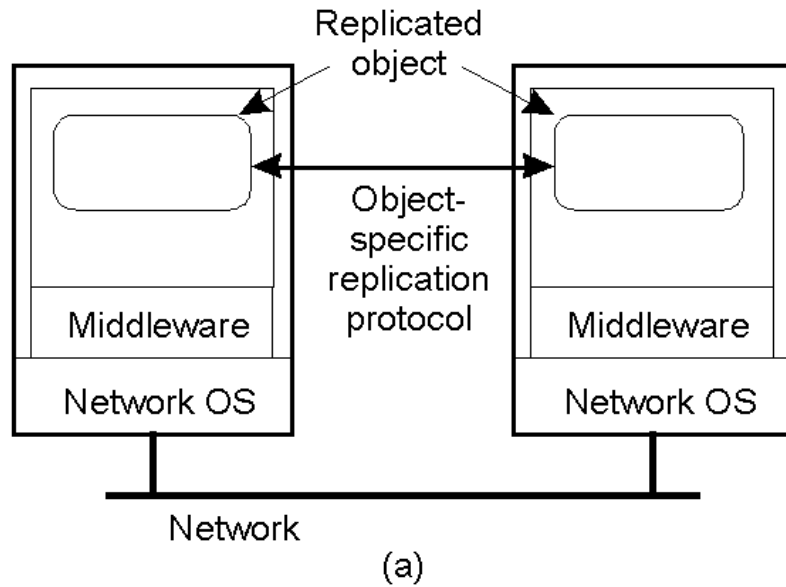
(a)



(b)

- a) A remote object capable of handling concurrent invocations on its own.
- b) A remote object for which an object adapter is required to handle concurrent invocations

Object Replication (3)



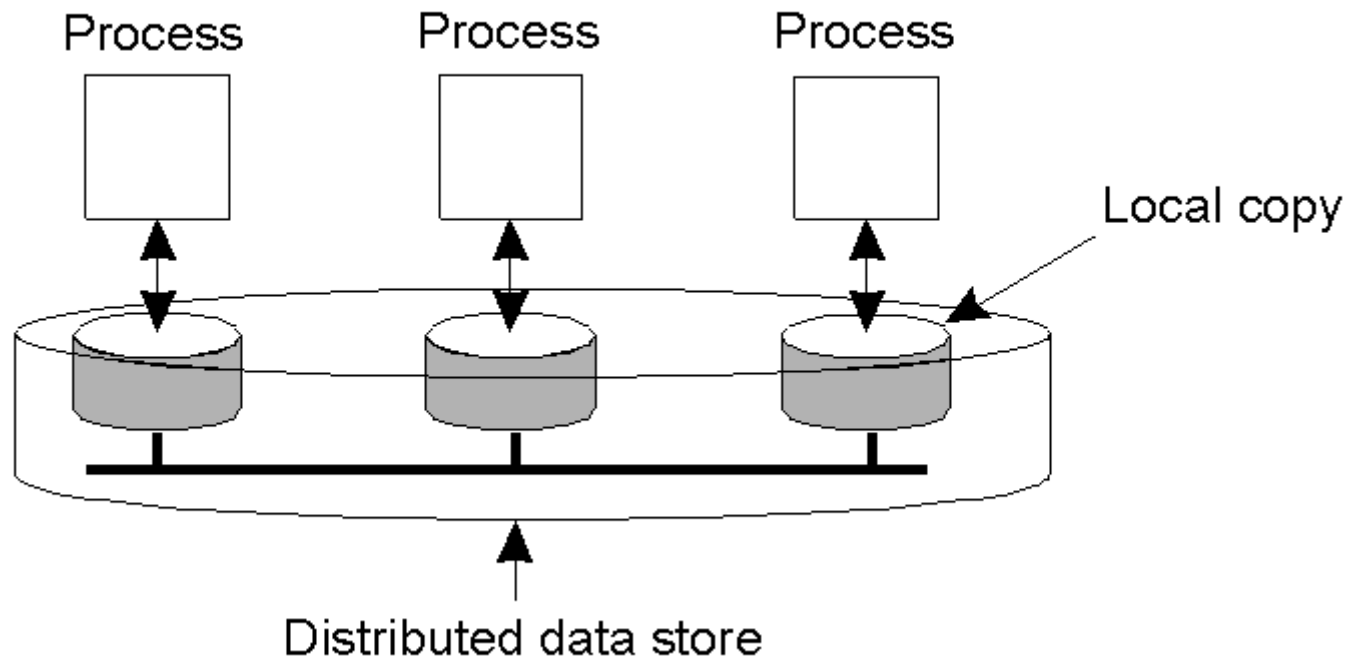
- a) A distributed system for replication-aware distributed objects.
- b) A distributed system responsible for replica management

What will we study

- Consistency models - How do we reason about the consistency of the “global state”?
 - Data-centric consistency
 - Strict consistency
 - Sequential consistency
 - Linearizability
 - Client-centric consistency
 - Eventual consistency
- Update propagation - How does an update to one copy of an item get propagated to other copies?
- Replication protocols - What is the algorithm that takes one update propagation method and enforces a given consistency model?

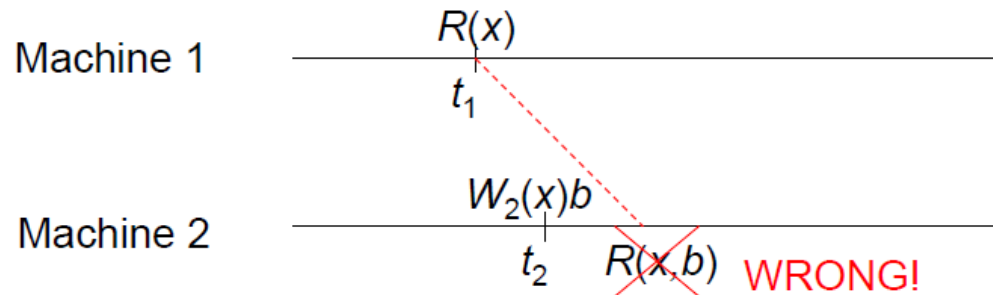
Data-Centric Consistency Models

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



Strict Consistency

- Any $read(x)$ returns a value corresponding to the result of the most recent $write(x)$.



- Relies on absolute global time; all writes are instantaneously visible to all processes and an absolute global time order is maintained.
- Cannot be implemented in a distributed system

P1:	W(x)a
P2:	R(x)a
Strictly consistent	

P1:	W(x)a
P2:	R(x)NIL R(x)a
Not strictly consistent	

Sequential Consistency

- Similar to linearizability, but no requirement on timestamp order.
- The result of execution should satisfy the following criteria:
 - Read and write operations by all processes on the data store were executed in some sequential order;
 - Operations of each individual process appear in this sequence in the order specified by its program.
- These mean that all processes see the same interleaving of operations similar to serializability.

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)

Linearizability

- The result of the execution should satisfy the following criteria:
 - Read and write by all processes were executed in some serial order and each process's operations maintain the order of specified;
 - If $ts_{op1}(x) < ts_{op2}(y)$ then $op1(x)$ should precede $op2(y)$ in this sequence. This specifies that the order of operations in interleaving is consistent with the real times at which the operations occurred in the actual implementation.
- Requires synchronization according to timestamps, which makes it expensive.
- Used only in formal verification of programs.

Sequences for the Processes

Process P1	Process P2	Process P3
x = 1; print (y, z);	y = 1; print (x, z);	z = 1; print (x, y);

- Four valid execution sequences for the processes of the previous slide. The vertical axis is time.

x = 1;
print ((y, z);
y = 1;
print (x, z);
z = 1;
print (x, y);

Prints: 001011
(a)

x = 1;
y = 1;
print (x,z);
print(y, z);
z = 1;
print (x, y);

Prints: 101011
(b)

y = 1;
z = 1;
print (x, y);
print (x, z);
x = 1;
print (y, z);

Prints: 010111
(c)

y = 1;
x = 1;
z = 1;
print (x, z);
print (y, z);
print (x, y);

Prints: 111111
(d)

Causal Consistency (1)

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

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

Causal Consistency (3)

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

(a)

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

(b)

- a) A violation of a causally-consistent store.
- b) A correct sequence of events in a causally-consistent store.

FIFO Consistency (1)

- Necessary Condition:
Writes done by a single process are seen by all other processes in the order in which they were issued, but writes from different processes may be seen in a different order by different processes.

FIFO Consistency (2)

P1: $\forall x (W(x) \rightarrow a)$

P2: R(x)a W(x)b W(x)c

P3: $R(x)b \quad R(x)a \quad R(x)c$

P4: $R(x)a \quad R(x)b \quad R(x)c$

- A valid sequence of events of FIFO consistency

FIFO Consistency (3)

Process P1	Process P2	Process P3
x = 1; print (y, z);	y = 1; print (x, z);	z = 1; print (x, y);

- The statements in bold are the ones that generate the output shown.

x = 1;
print (y, z);
y = 1;
print(x, z);
z = 1;
print (x, y);

Prints: 00

(a)

x = 1;
y = 1;
print(x, z);
print (y, z);
z = 1;
print (x, y);

Prints: 10

(b)

y = 1;
print (x, z);
z = 1;
print (x, y);
x = 1;
print (y, z);

Prints: 01

(c)

FIFO Consistency (4)

Process P1

`x = 1;`

`if (y == 0) kill (P2);`

Process P2

`y = 1;`

`if (x == 0) kill (P1);`

- Two concurrent processes.

Weak Consistency (1)

- Properties:
 - Accesses to synchronization variables associated with a data store are sequentially consistent
 - No operation on a synchronization variable is allowed to be performed until all previous writes have been completed everywhere
 - No read or write operation on data items are allowed to be performed until all previous operations to synchronization variables have been performed.

Weak Consistency (2)

```
int a, b, c, d, e, x, y;  
int *p, *q;  
int f( int *p, int *q);
```

```
a = x * x;  
b = y * y;  
c = a*a*a + b*b + a * b;  
d = a * a * c;  
p = &a;  
q = &b  
e = f(p, q)
```

```
/* variables */  
/* pointers */  
/* function prototype */  
  
/* a stored in register */  
/* b as well */  
/* used later */  
/* used later */  
/* p gets address of a */  
/* q gets address of b */  
/* function call */
```

- A program fragment in which some variables may be kept in registers.

Weak Consistency (3)

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

(a)

P1:	W(x)a	W(x)b	S		
P2:				S	R(x)a

(b)

- a) A valid sequence of events for weak consistency.
- b) An invalid sequence for weak consistency.

Release Consistency (1)

P1: Acq(L) W(x)a W(x)b Rel(L)

P2: Acq(L) R(x)b Rel(L)

P3: $R(x)a$

- A valid event sequence for release consistency.

Release Consistency (2)

- Rules:
 - Before a read or write operation on shared data is performed, all previous acquires done by the process must have completed successfully.
 - Before a release is allowed to be performed, all previous reads and writes by the process must have completed
 - Accesses to synchronization variables are FIFO consistent (sequential consistency is not required).

Entry Consistency (1)

- Conditions:
 - An acquire access of a synchronization variable is not allowed to perform with respect to a process until all updates to the guarded shared data have been performed with respect to that process.
 - Before an exclusive mode access to a synchronization variable by a process is allowed to perform with respect to that process, no other process may hold the synchronization variable, not even in nonexclusive mode.
 - After an exclusive mode access to a synchronization variable has been performed, any other process's next nonexclusive mode access to that synchronization variable may not be performed until it has performed with respect to that variable's owner.

Entry Consistency (2)

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

- A valid event sequence for entry consistency.

Summary of Consistency Models

Consistency	Description
Strict	Absolute time ordering of all shared accesses matters.
Linearizability	All processes must see all shared accesses in the same order. Accesses are furthermore ordered according to a (nonunique) global timestamp
Sequential	All processes see all shared accesses in the same order. Accesses are not ordered in time
Causal	All processes see causally-related shared accesses in the same order.
FIFO	All processes see writes from each other in the order they were used. Writes from different processes may not always be seen in that order

(a)

Consistency	Description
Weak	Shared data can be counted on to be consistent only after a synchronization is done
Release	Shared data are made consistent when a critical region is exited
Entry	Shared data pertaining to a critical region are made consistent when a critical region is entered.

(b)

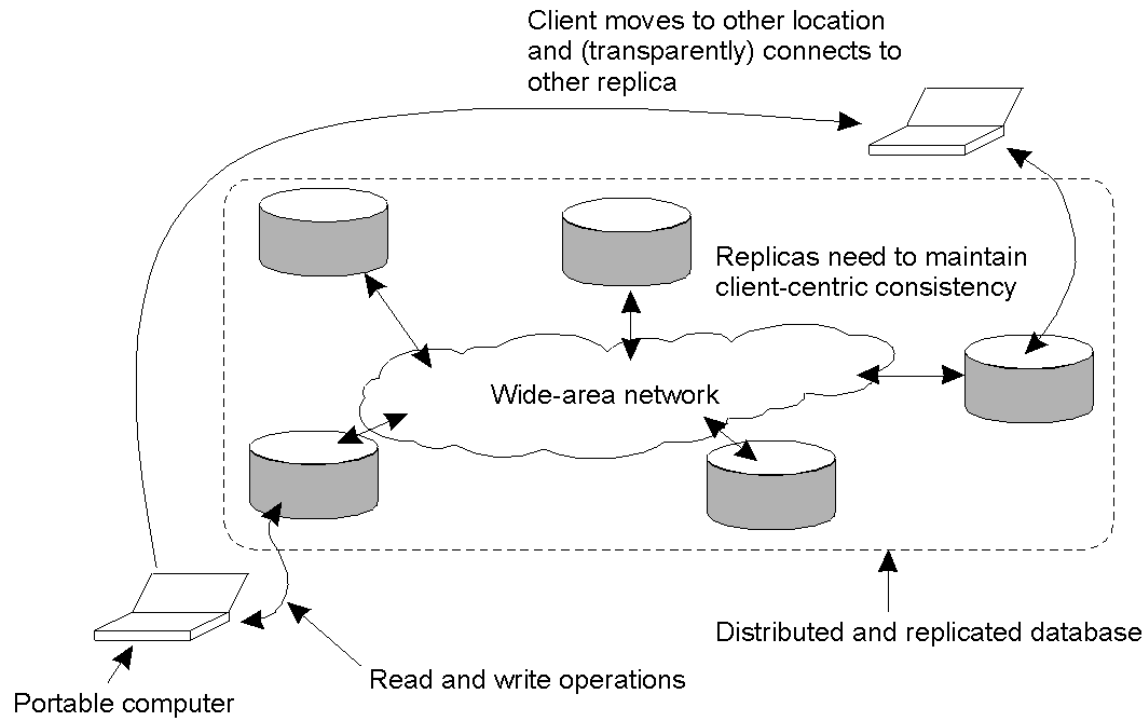
a) Consistency models not using synchronization operations.

b) Models with synchronization operations.

Client-Centric Consistency

- More relaxed form of consistency → only concerned with replicas being eventually consistent (eventual consistency).
- In the absence of any further updates, all replicas converge to identical copies of each other → only requires guarantees that updates will be propagated.
- Easy if a user always accesses the same replica; problematic if the user accesses different replicas.
 - Client-centric consistency: guarantees for a single client the consistency of access to a data store.

Eventual Consistency



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

Client-Centric Consistency (2)

- Monotonic reads
 - 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 writes
 - A write operation by a process on a data item x is completed before any successive write 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.
- 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 more recent value of x that was read.

Monotonic Reads

L1:	WS(x_1)	R(x_1)
<hr/>		
L2:	WS($x_1; x_2$)	R(x_2)

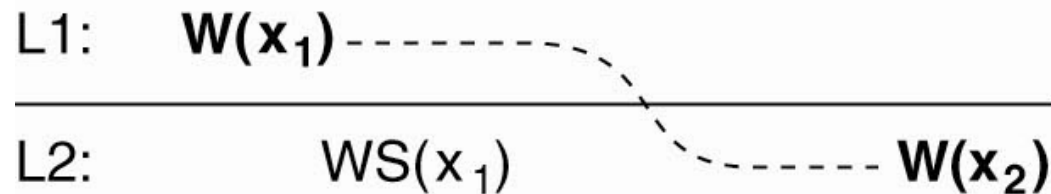
(a)

L1:	WS(x_1)	R(x_1)
<hr/>		
L2:	WS(x_2)	R(x_2)

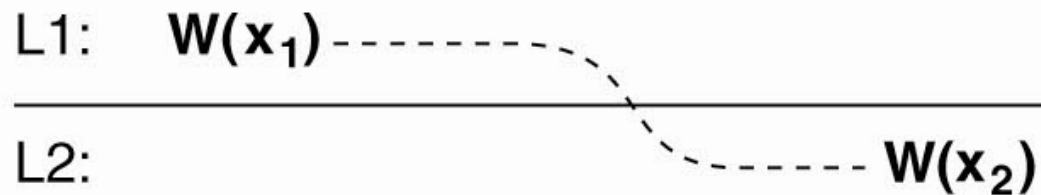
(b)

- 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
- b) A data store that does not provide monotonic reads.

Monotonic Writes



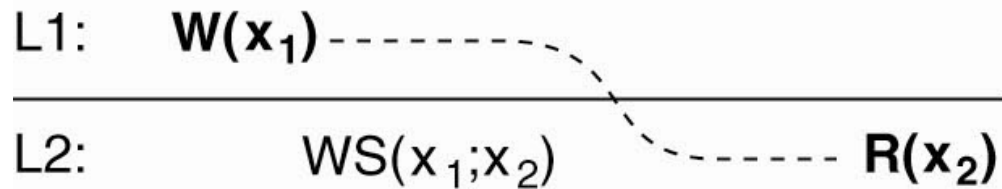
(a)



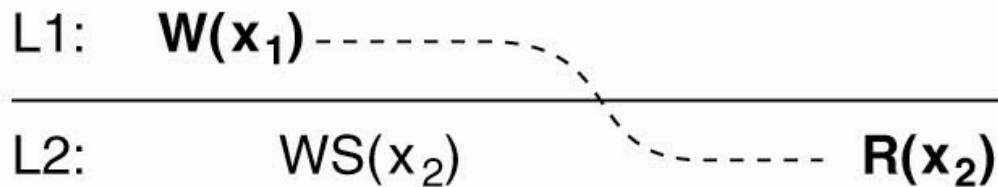
(b)

- 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.
- b) A data store that does not provide monotonic-write consistency.

Read Your Writes



(a)



(b)

- a) A data store that provides read-your-writes consistency.
- b) A data store that does not.

Writes Follow Reads

L1:	WS(x_1)	R(x_1)
<hr/>		
L2:	WS($x_1; x_2$)	W(x_2)

(a)

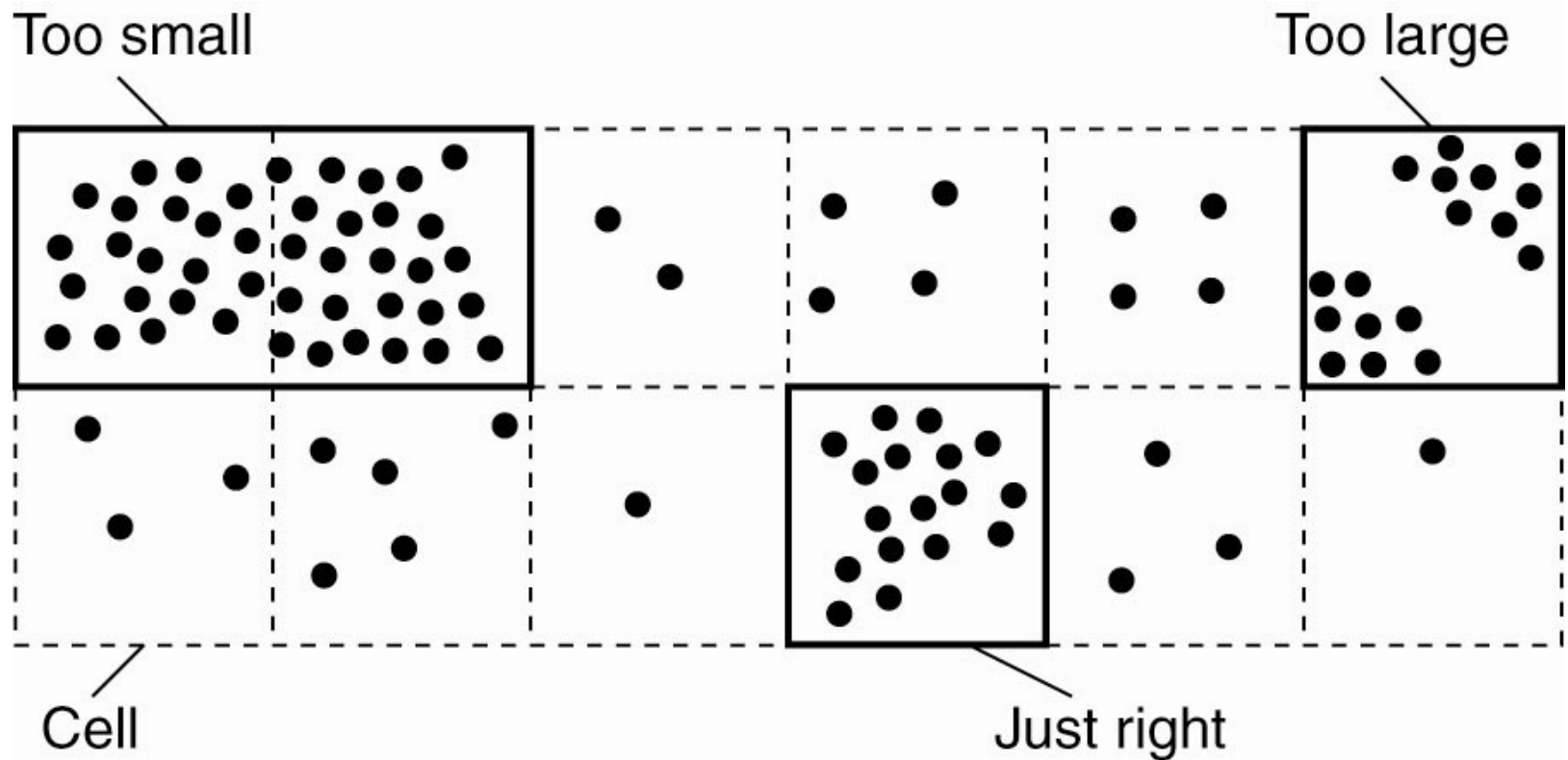
L1:	WS(x_1)	R(x_1)
<hr/>		
L2:	WS(x_2)	W(x_2)

(b)

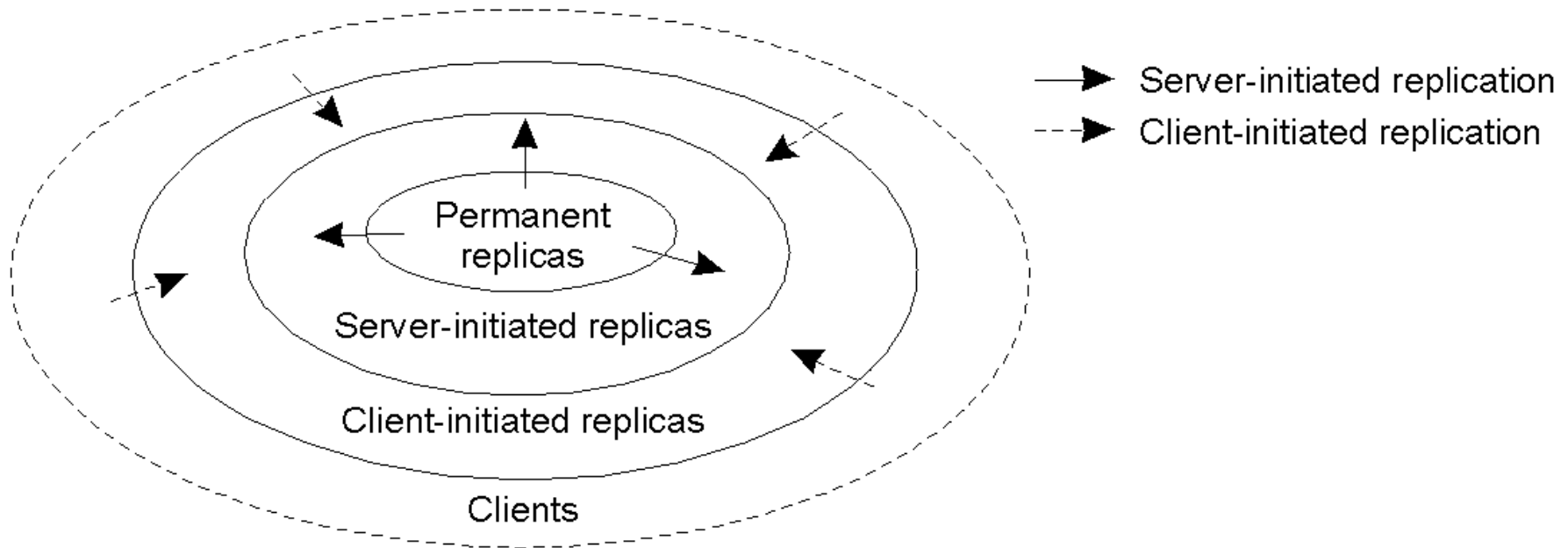
- a) A writes-follow-reads consistent data store
- b) A data store that does not provide writes-follow-reads consistency

Replica-Server Placement

- Choosing a proper cell size for server placement.



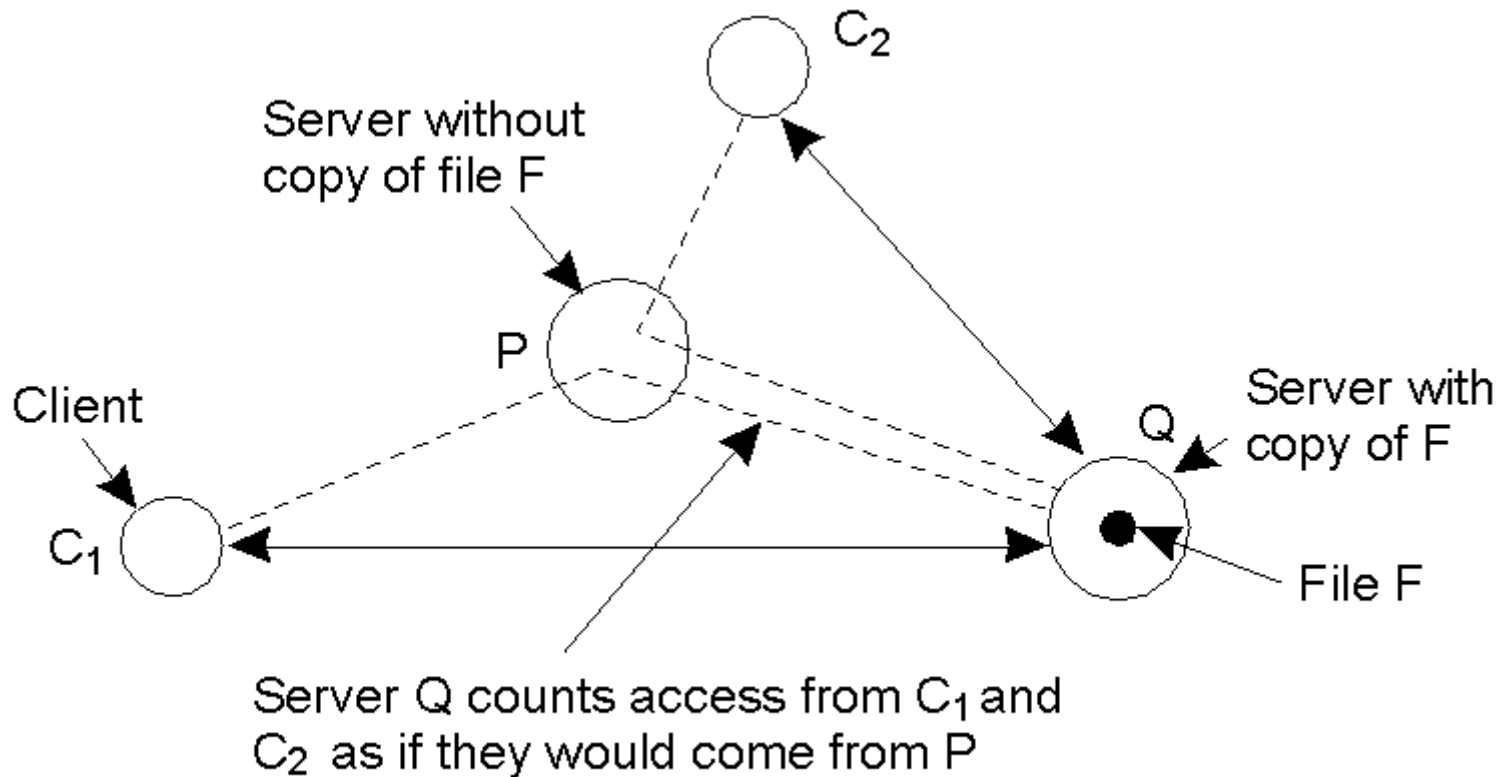
Replica Placement



- 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.



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 vs. Push Protocols

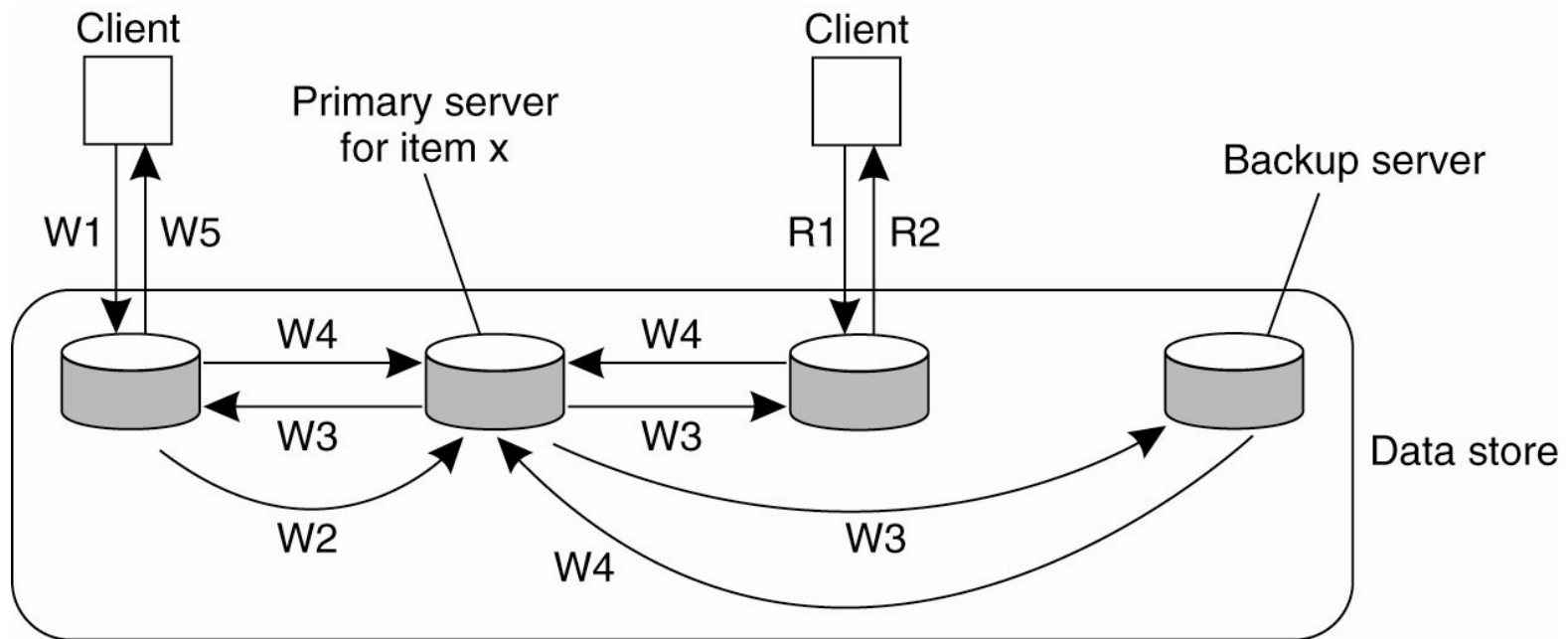
Issue	Push-based	Pull-based
State of server	List of client replicas and caches	None
Messages sent	Update (and possibly fetch update later)	Poll and update
Response time at client	Immediate (or fetch-update time)	Fetch-update time

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

Replication Protocols

- Linearizability
 - Primary-Backup
 - Chain Replication
- Sequential consistency
 - Primary-based protocols
 - Remote-Write protocols
 - Local-Write protocols
 - Replicated Write protocols
 - Active replication
 - Quorum-based protocols

Remote-Write Protocols

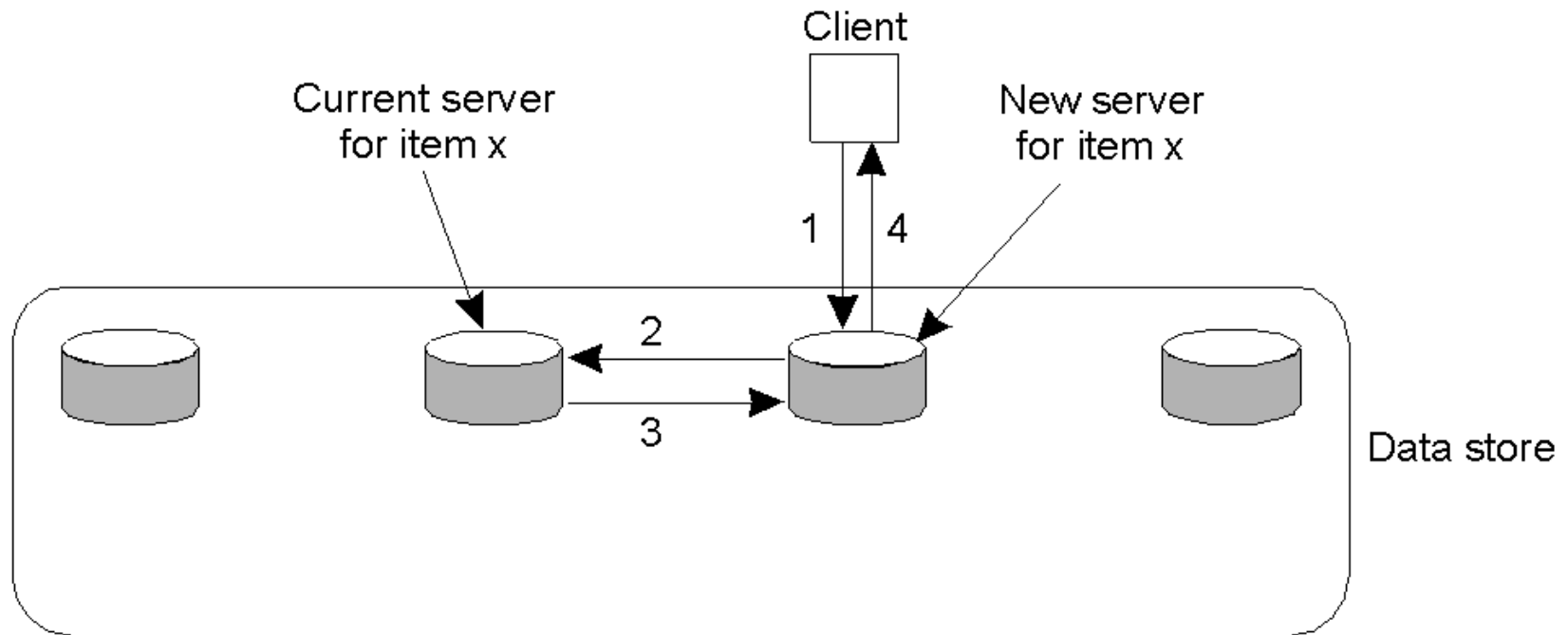


W1. Write request
W2. Forward request to primary
W3. Tell backups to update
W4. Acknowledge update
W5. Acknowledge write completed

R1. Read request
R2. Response to read

- Primary-based remote-write protocol with a fixed server to which all read and write operations are forwarded.

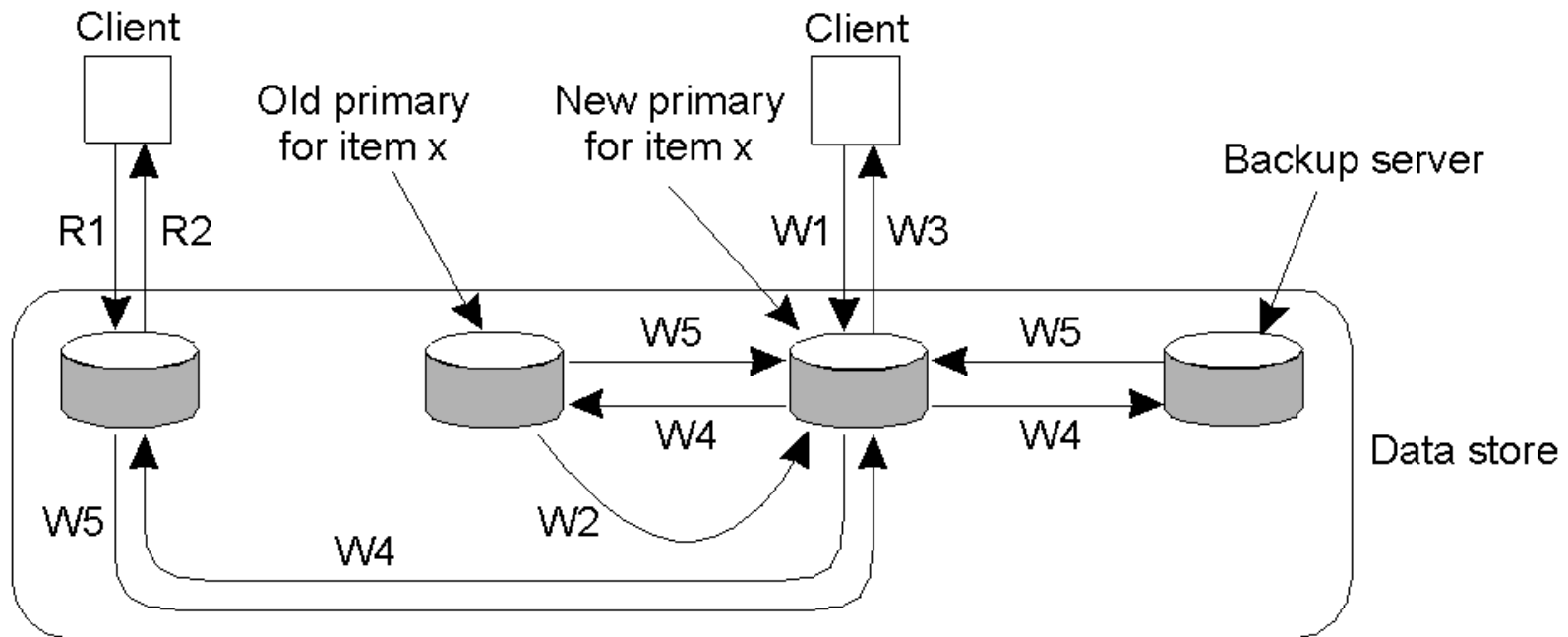
Local-Write Protocols (1)



1. Read or write request
2. Forward request to current server for x
3. Move item x to client's server
4. Return result of operation on client's server

- Primary-based local-write protocol in which a single copy is migrated between processes.

Local-Write Protocols (2)



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-backup protocol in which the primary migrates to the process wanting to perform an update.

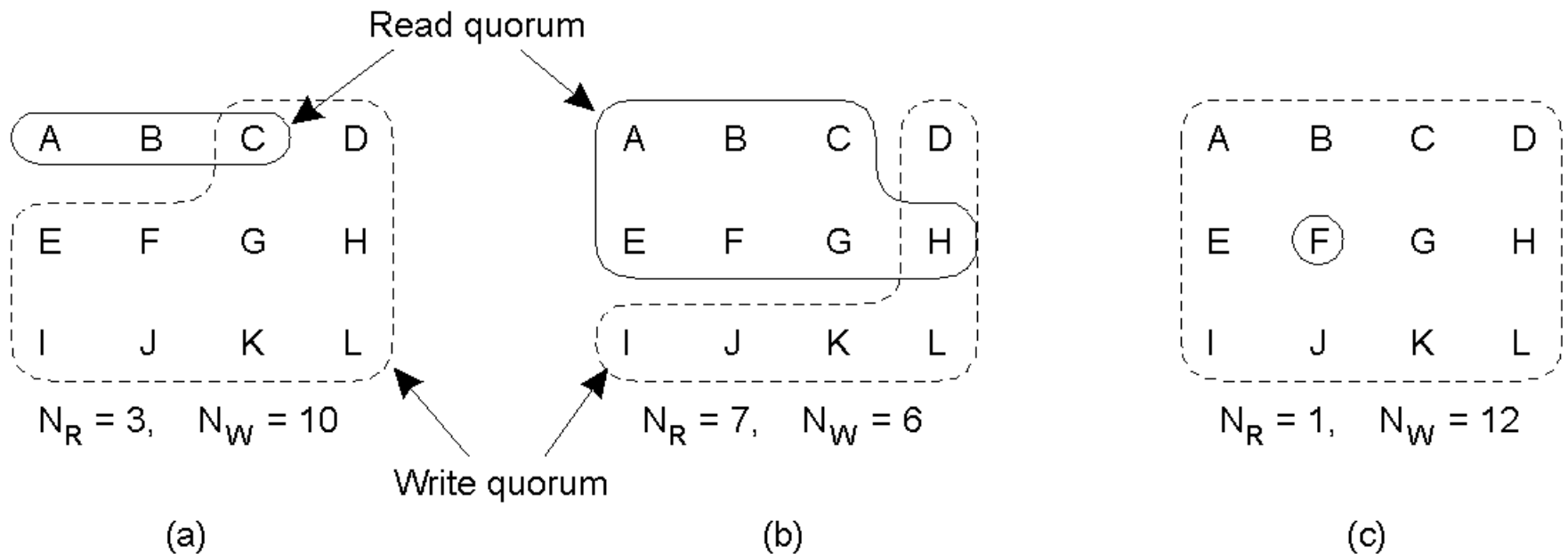
Active Replication

- Requires a process, for each replica, that can perform the update on it
- How to enforce the update order?
 - Totally-ordered multicast mechanism needed
 - Can be implemented by Lamport timestamps
 - Can be implemented by sequencer
- Problem of replicated invocations
 - If an object A invokes another object B , all replicas of A will invoke B (multiple invocations)

Quorum-Based Protocol

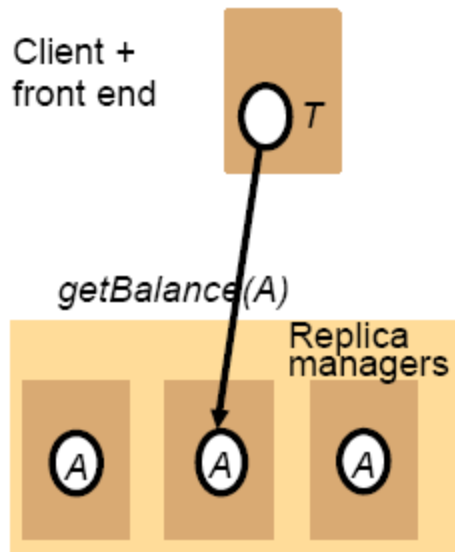
- Assign a vote to each *copy* of a replicated object (say V_i) such that $\sum_i V_i = V$
- Each operation has to obtain a *read quorum* (V_r) to read and a *write quorum* (V_w) to write an object
- Then the following rules have to be obeyed in determining the quorums:
 - $V_r + V_w > V$ an object is not read and written by two transactions concurrently
 - $V_w > V/2$ two write operations from two transactions cannot occur concurrently on the same object

Quorum-Based Protocols

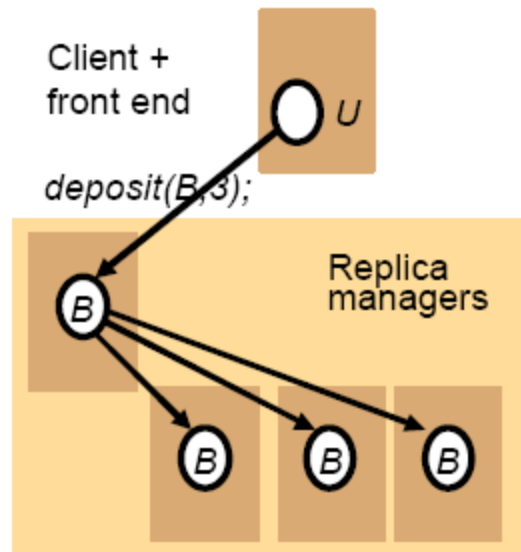


- Three examples of the voting algorithm:
 - a) A correct choice of read and write set
 - b) A choice that may lead to write-write conflicts
 - c) A correct choice, known as ROWA (read one, write all)

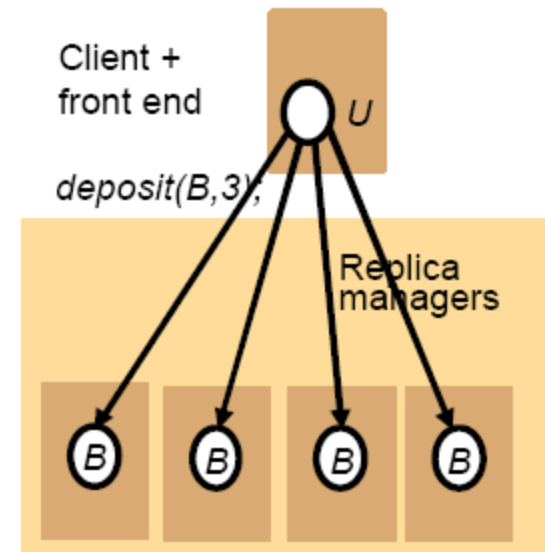
ROWA



Read

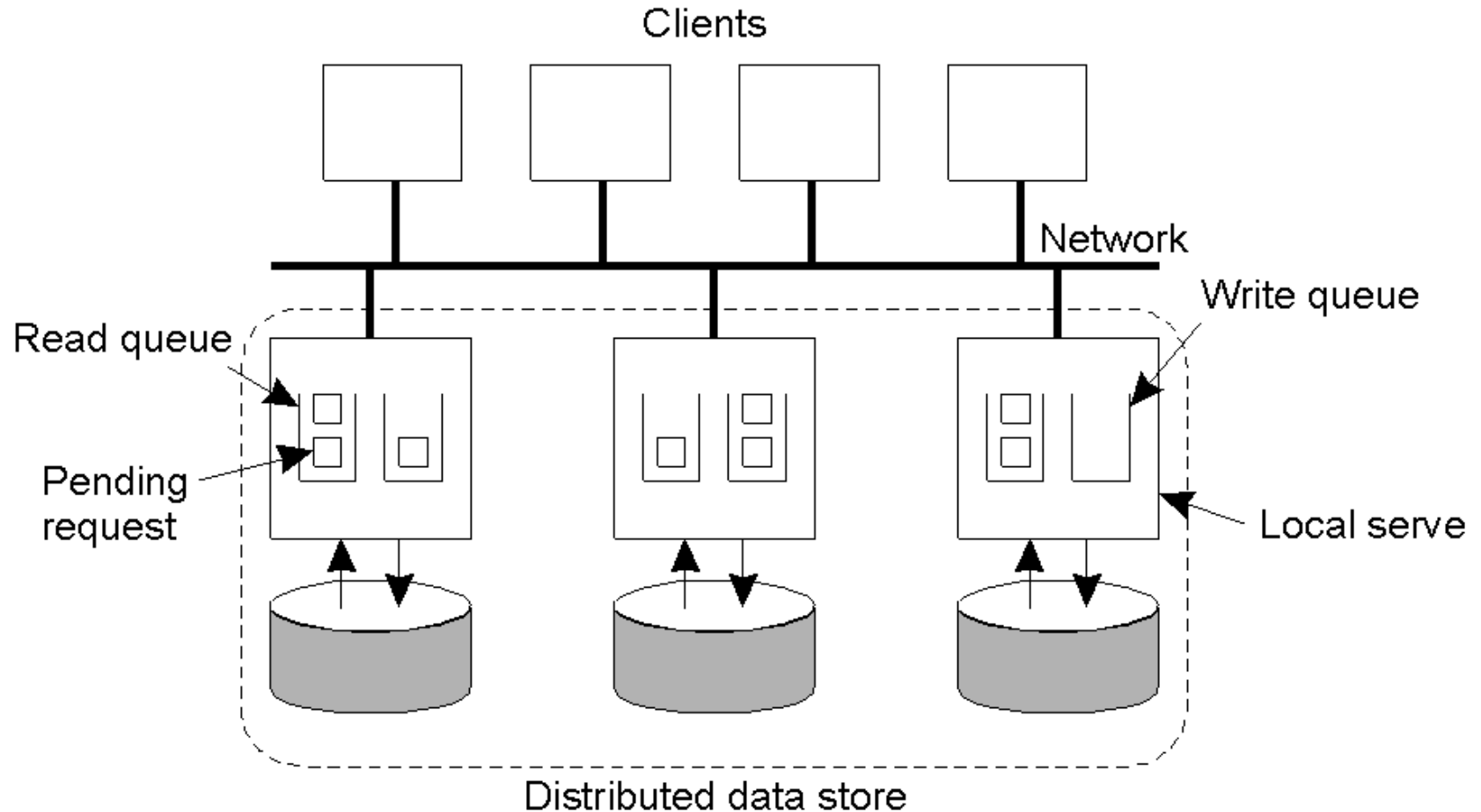


Write with a primary copy
A 2 level nested 2PC
protocol is implemented



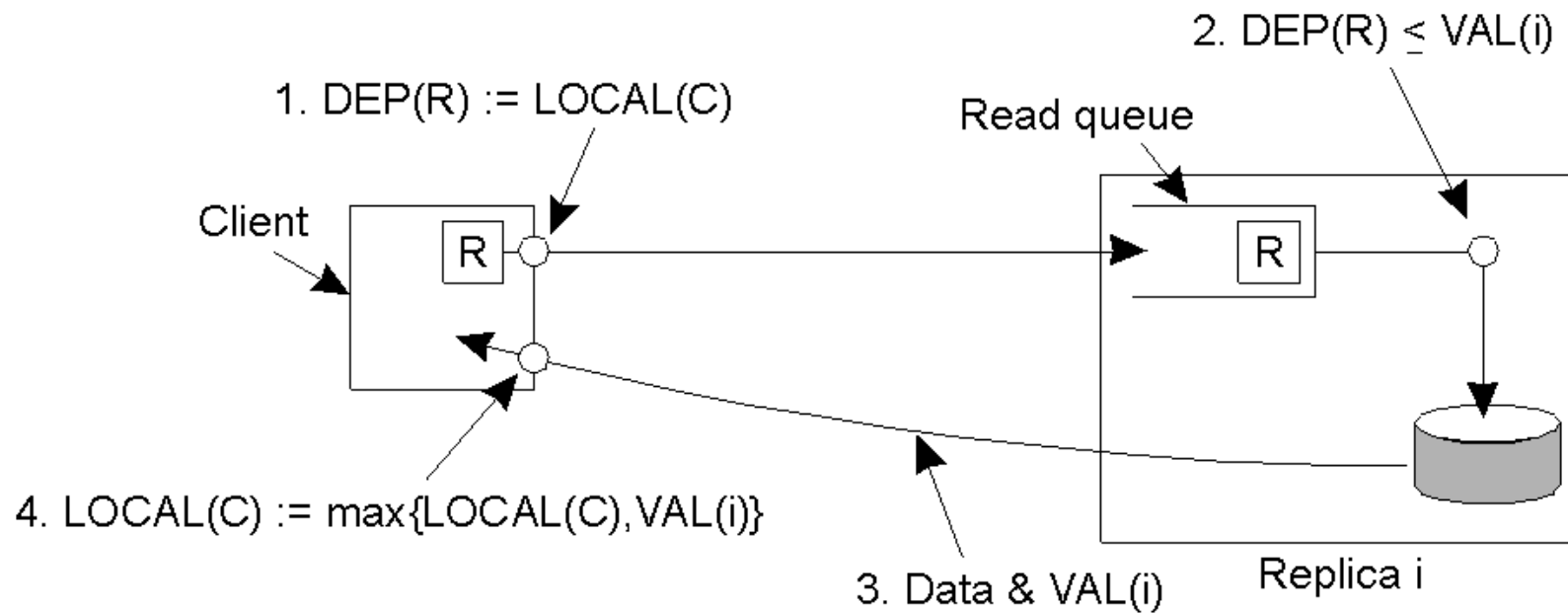
Write without a primary
copy
Regular 2PC implemented

Causally-Consistent Lazy Replication

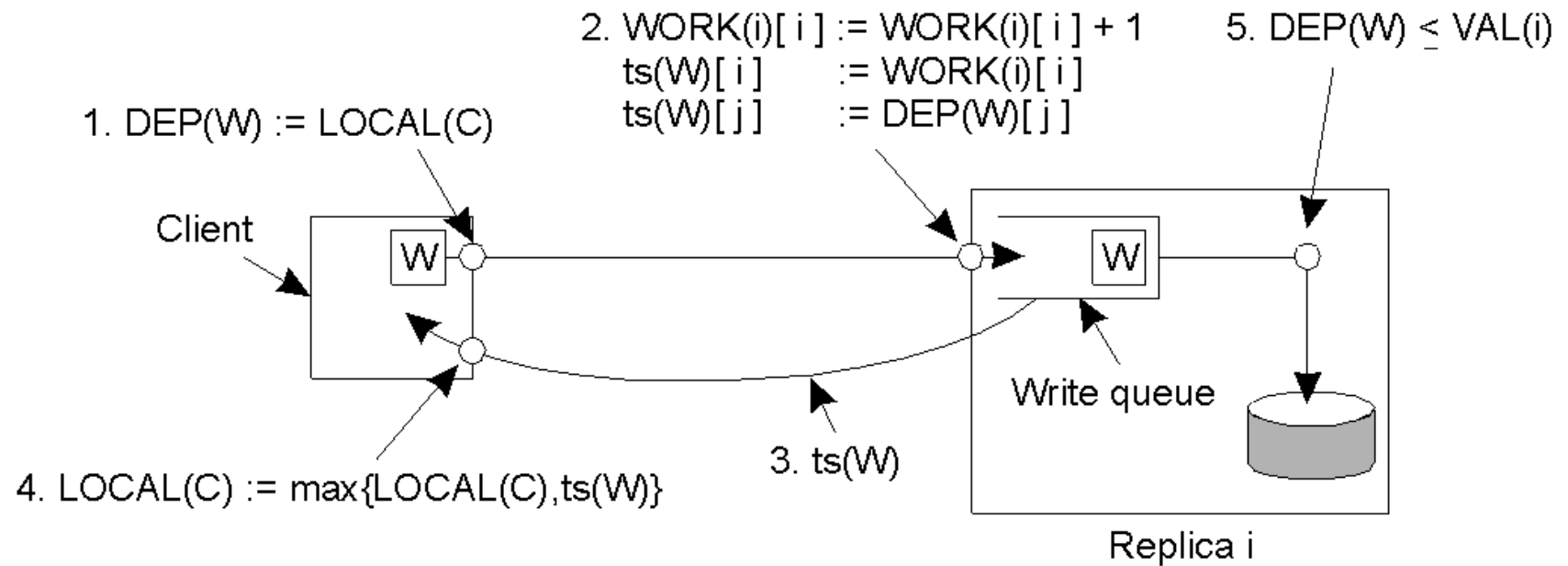


- The general organization of a distributed data store. Clients are assumed to also handle consistency-related communication.

Processing Read Operations



Processing Write Operations



- Performing a write operation at a local copy.