Distributed Systems

Winter Term 2024/25

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Stand: December 12, 2024

Distributed Systems

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8 Replication and Consistency

Contents

- Introduction, motivation
- Data-centered consistency models
- Client-centered consistency models
- Distribution protocols
- Consistency protocols

Literature

- Tanenbaum, van Steen: Kap. 6

8.1 Introduction and Motivation

- **Replication**: several (identical) copies of data objects are stored in the distributed system
  - processes can access an arbitrary copy
- Reasons for the replication:
  - increase in availability and reliability
    - if a replica is not available, use another one
    - reading multiple replicas with majority vote
  - increase in read performance
    - for large systems: concurrent read access can be serviced by different replicas
    - with systems spread over a large area: access request is sent to a replica in the vicinity

Central Problem of Replication: Consistency

- When data is changed, **all** replicas must be kept consistent
- Simplest option: all updates are done via totally ordered atomic multicast
  - high overhead when frequent updates occur
    - in some replicas these may actually never be read
  - totally ordered atomic multicast is very expensive with many / widely dispersed replicas
- Strict consistency maintenance of replicas always deteriorates performance and scalability
- Solution: weakened consistency requirements
  - often only very weak demands, e.g. News, Web, ...

Consistency Models

- A consistency model determines the order in which the write operations (updates) of the processes are “seen” by the other processes
- Intuitive expectation: a read operation always returns the result of the last write operation (**strict consistency**)
  - problem: there is no global time
    - pointless to speak of the “last” write operation
  - therefore: other consistency models necessary
- **Data-centric consistency models**: view of the data storage
- **Client-centric consistency models**: view of **one** process
  - assumption: (essentially) no update by multiple processes

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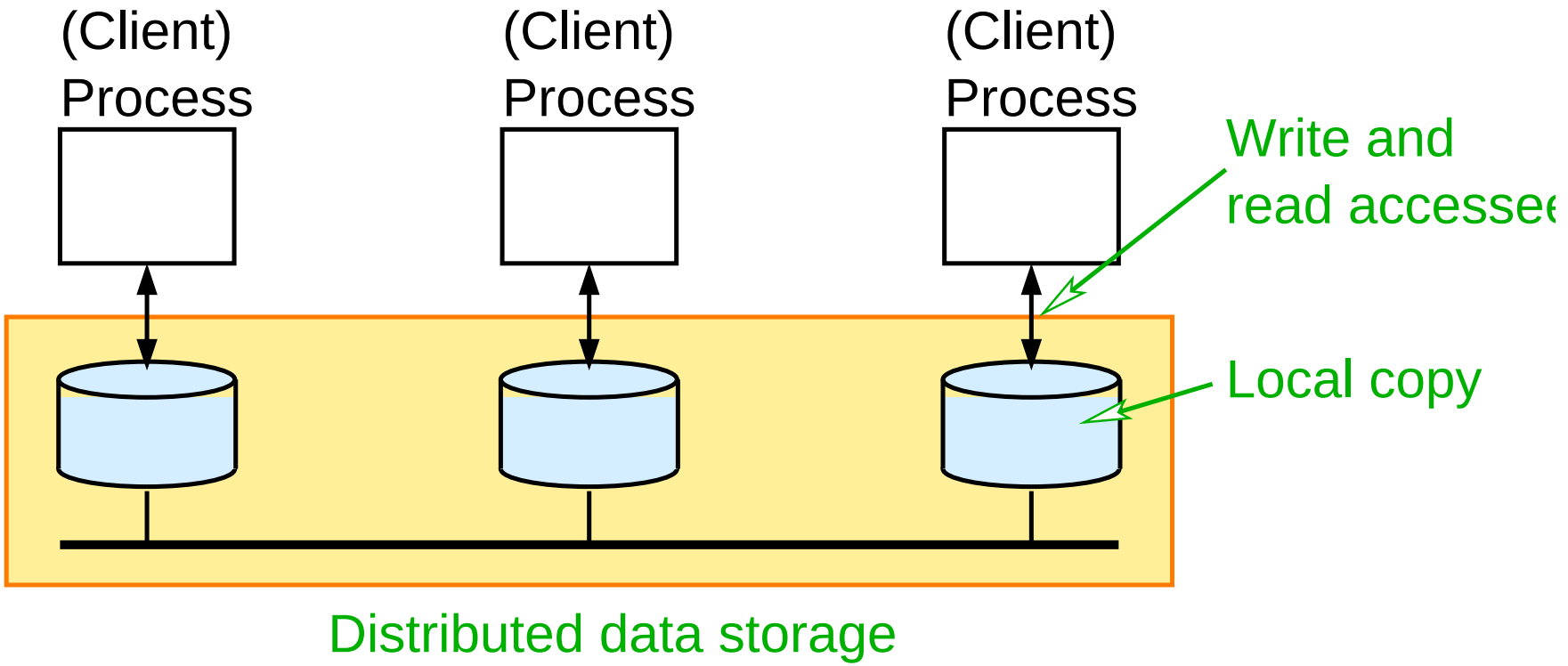
8.2 Data Centric Consistency Models

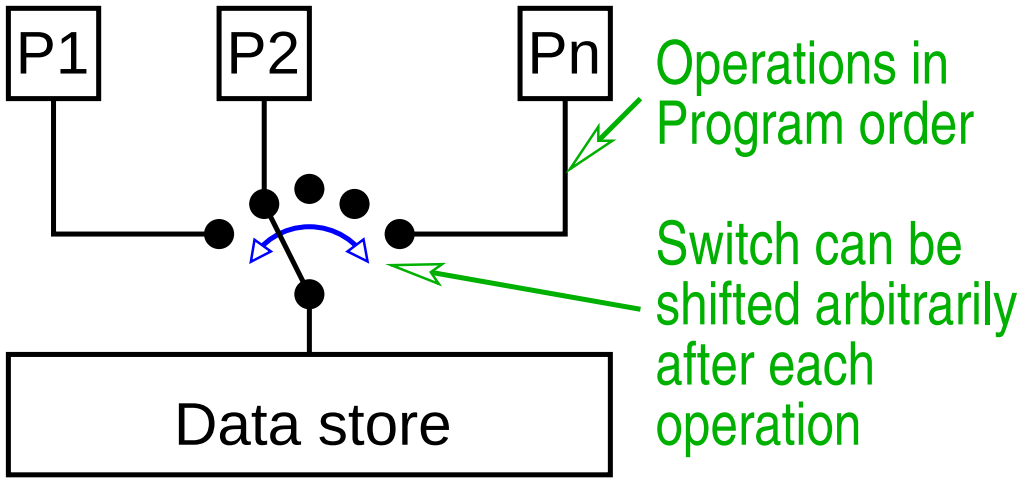
- Model of a distributed data store:



- logical, shared data memory
- physically distributed and replicated across multiple nodes

Sequential Consistency

- A data store is **sequentially consistent** if the result of each program execution is as if:
  - the (read/write) operations of all processes are executed in a (random) sequential order,
  - in which the operations of each individual process appear in the order specified by the program.
- I.e. the execution of the operations of the individual processes can be interleaved arbitrarily
- Independent of time or clocks



- All processes see the (write) accesses in the same order

Sequential Consistency: Examples

Allowed sequence:

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

Forbidden Sequence:

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

- Notation:
  - W(x)a : the value 'a' is written into the variable 'x'
  - R(x)a : variable 'x' will be read, result is 'a'
- A possible sequential order of the left sequence:
  - $W_2(x)b$, $R_3(x)b$, $R_4(x)b$, $W_1(x)a$, $R_3(x)a$, $R_4(x)a$

Sequential Consistency: Examples

Allowed sequence:

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

Forbidden Sequence:

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

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Linearizability

- Stronger than sequential consistency
- Assumption: the nodes (processes) have synchronized clocks
  - i.e. an approximation of a global time
- Operations have time stamps based on these clocks
- In comparison with sequential consistency additionally required:
  - the sequential order of operations is consistent with their timestamps
- Complex implementation
- Used for formal verification of concurrent algorithms

Causal Consistency

- Weakening of sequential consistency
- (Only) write operations that are potentially causally dependent must be visible to all processes in the same order

Causally, but not seq. consistent:

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

Not causally consistent:

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

Weak Consistency

- In practice: access to shared resources is coordinated via synchronization variables (SV)
- Then: weaker consistency requirements are sufficient:
  - accesses to SVs are sequentially consistent
  - an operation on a SV is not allowed until all previous write accesses to data have been completed everywhere
  - no operation on data is allowed before all previous operations on SVs have been completed

Allowed event sequence:

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

Invalid event sequence:

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

Release Consistency (*Freigabe-Konsistenz*)

- Idea as with weak consistency, but distinction between *acquire* and *release* operations (mutual exclusion!)
  - before an operation on the data is performed all *acquire*-operations of the process must be completed
  - before the end of a *release* operation all operations of the process on the data must be completed
  - *acquire* / *release* operations of a process are seen everywhere in the same order

Allowed event sequence:

P1:	acq(L)	W(x)a		W(x)b		rel(L)					
P2:							acq(L)		R(x)b		rel(L)
P3:											R(x)a

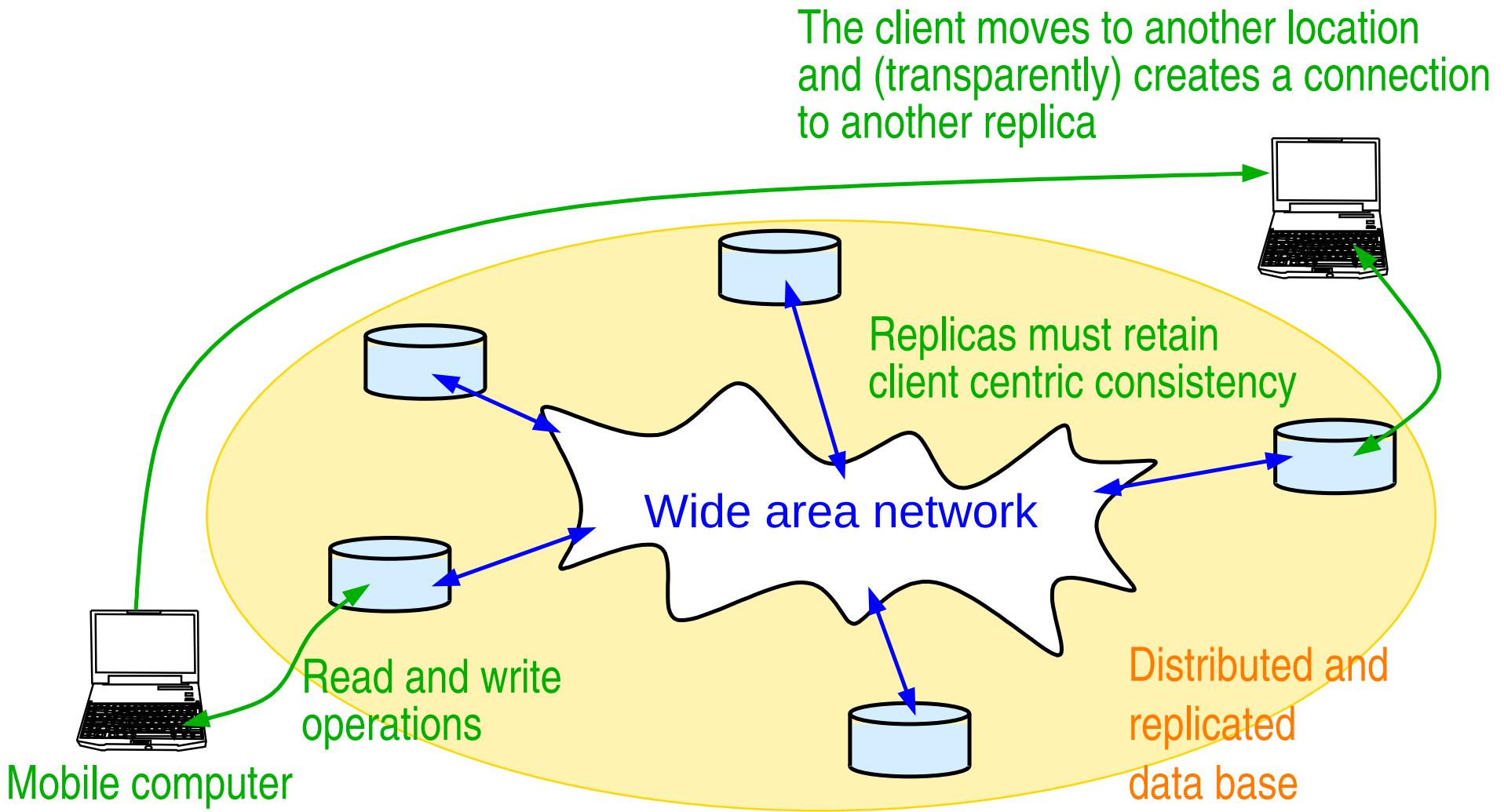
Comparison of models

Strict	Absolute time sequence of all shared accesses (physically not useful!)
Linearization	All processes see all (write) accesses in the same order. Accesses are sorted by a (non-unique) global timestamp.
Sequential	All processes see all (write) accesses in the same order. Accesses sre not sorted by time.
Causal	All processes see causally linked (write) accesses in the same order.
Weak	Data is only reliably consistent after a synchro-nization has been performed.
Release	Data is made consistent when leaving the critical region.

8.3 Client Centric Consistency Models

- In practice:
  - clients are usually independent from each other
  - changes to the data are mostly rare
  - because of partitioning often no write/write conflicts
    - e.g., DNS, WWW (Caches), ...
- **Eventual consistency**: all replicas will eventually become consistent if no updates take place for a long time
- Problem if a client changes the replica it is accessing
  - updates may not have arrived there yet
  - client detects inconsistent behavior
- Solution: client-centric consistency models
  - guarantee consistency for an **individual** client
  - but not for concurrent accesses by multiple clients

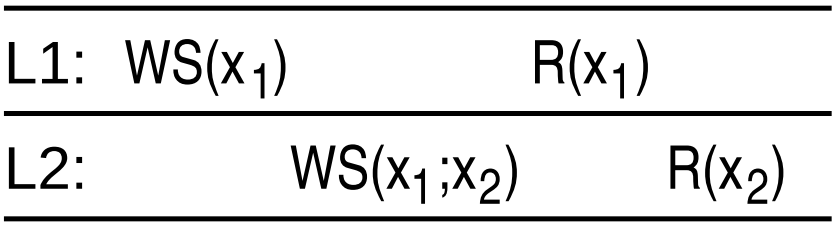
Illustration of the problem



Monotonic Read

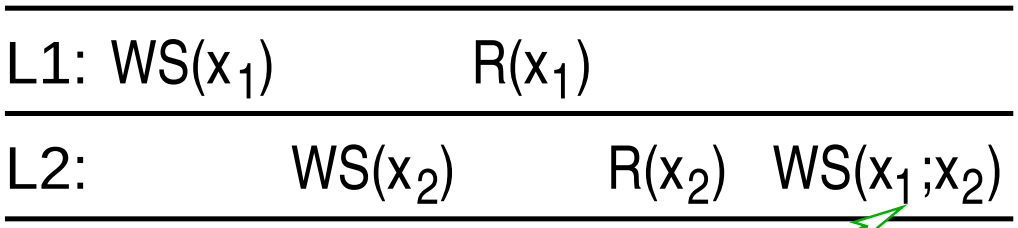
- Example for a client centric consistency model
  - more: see Tanenbaum / van Steen, Ch. 6.3
- Rule: When a process reads the value of a variable x, every subsequent read operation for x returns the same or a more recent value
- Example: access to a mailbox at different locations

With monotonic read



L1/L2: local copies
WS(...) set of write operations

Without monotonic read:

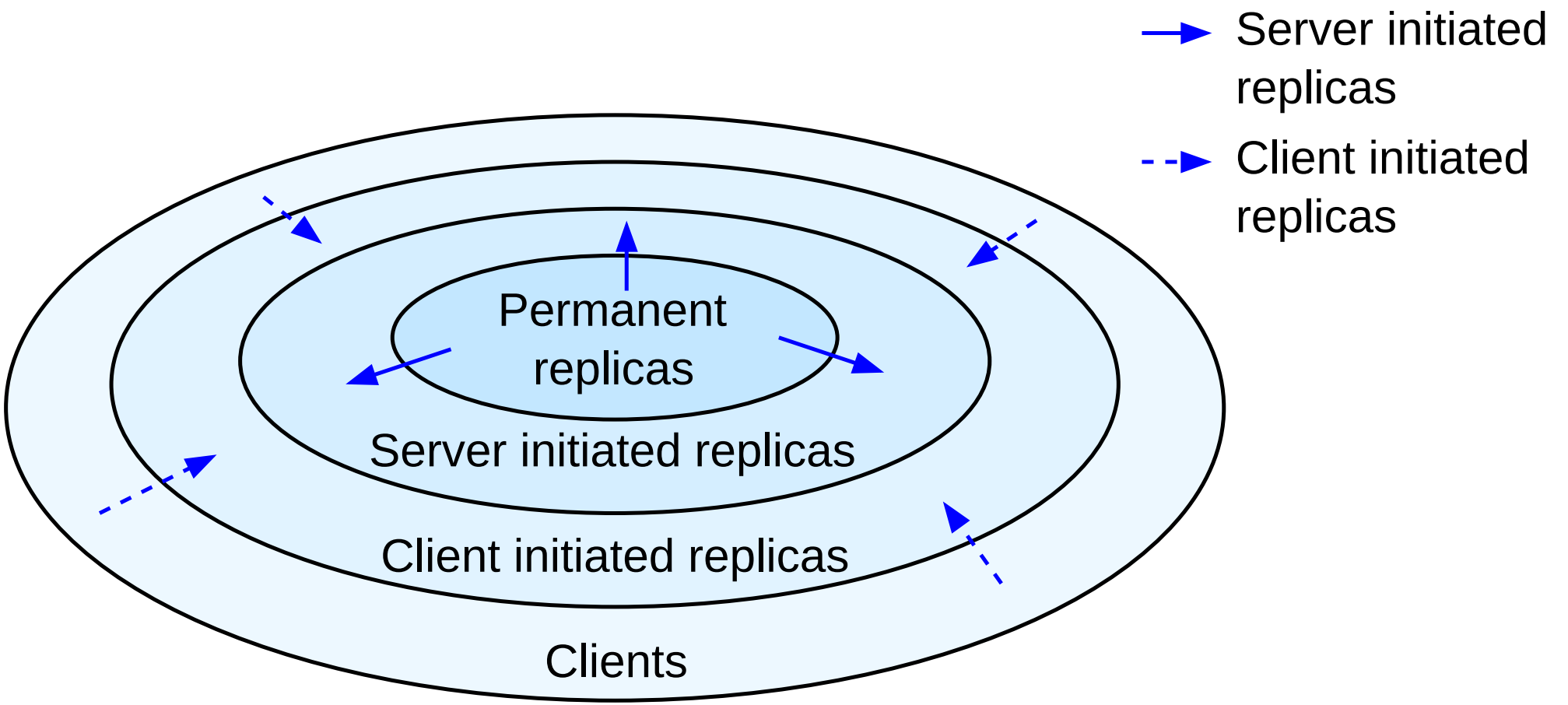


Write operations to x in L1
are now executed on x in L2

8.4 Distribution Protocols

- Question: where, when and by whom are replicas placed?
  - permanent replicas
  - server initiated replicas
  - client initiated replicas
- Question: how are updates distributed (regardless of consistency protocol, ☞ **8.5**)?
  - sending invalidations, status or operations
  - pull or push protocols
  - unicast or multicast

Placing the Replicas



➥ All three types can occur simultaneously

Permanent Replicas

- Initial set of replicas, static, mostly small
- Examples:
  - replicated web site (transparent to client)
  - mirroring (client deliberately chooses a replica)

Server Initiated Replicas

- Server creates additional replicas on demand (*Push-Cache*)
  - e.g., for web hosting services
- Difficult: deciding when and where replicas will be created
  - usually access counter for each file, additional information about the origin of the requests ($\rightarrow$ nearest server)

Client initiated Replicas

- Other term: ***Client Cache***
- Client cache locally stores (frequently) used data
- Goal: improving access time
- Management of the cache is completely left to the client
  - server doesn't care about consistency
- Data is usually kept in the cache for a limited time only
  - prevents use of extremely obsolete data
- Cache usually placed on client machines, or shared cache for multiple clients in their proximity
  - e.g., Web proxy caches

Forwarding Updates: What's Being Sent?

- The new value of the data object
  - good with high read/update ratio
- The update operation (active replication)
  - saves bandwidth (operation with parameters is usually small)
  - but more computing power required
- Just a notification (invalidation protocols)
  - notification makes the copy of the data object invalid
    - on next access a new copy will be requested
  - requires very little network bandwidth
  - good at low read/update ratio

Pull and Push Protocols

- **Push**: updates are distributed on the initiative of the server that made the change
  - replicas don't have to request updates
  - common in permanent and server-initiated replicas
  - when a relatively high degree of consistency is required
  - at high read/update ratio
  - problem: server must know all replicas
- **Pull**: replicas actively request data updates
  - common with client caches
  - at low read/update ratio
  - disadvantage: higher response time for cache access
- **Leases**: mixed form: first push for some time, then pull later

Unicast vs. Multicast

- Unicast: send update individually to each replica server
- Multicast: send one message and leave the distribution to the network (e.g. IP multicast)
  - often much more efficient
  - especially in LANs: hardware broadcast possible
- Multicast is useful for push protocols
- Unicast is better with pull protocols
  - only a single client/server requests an update

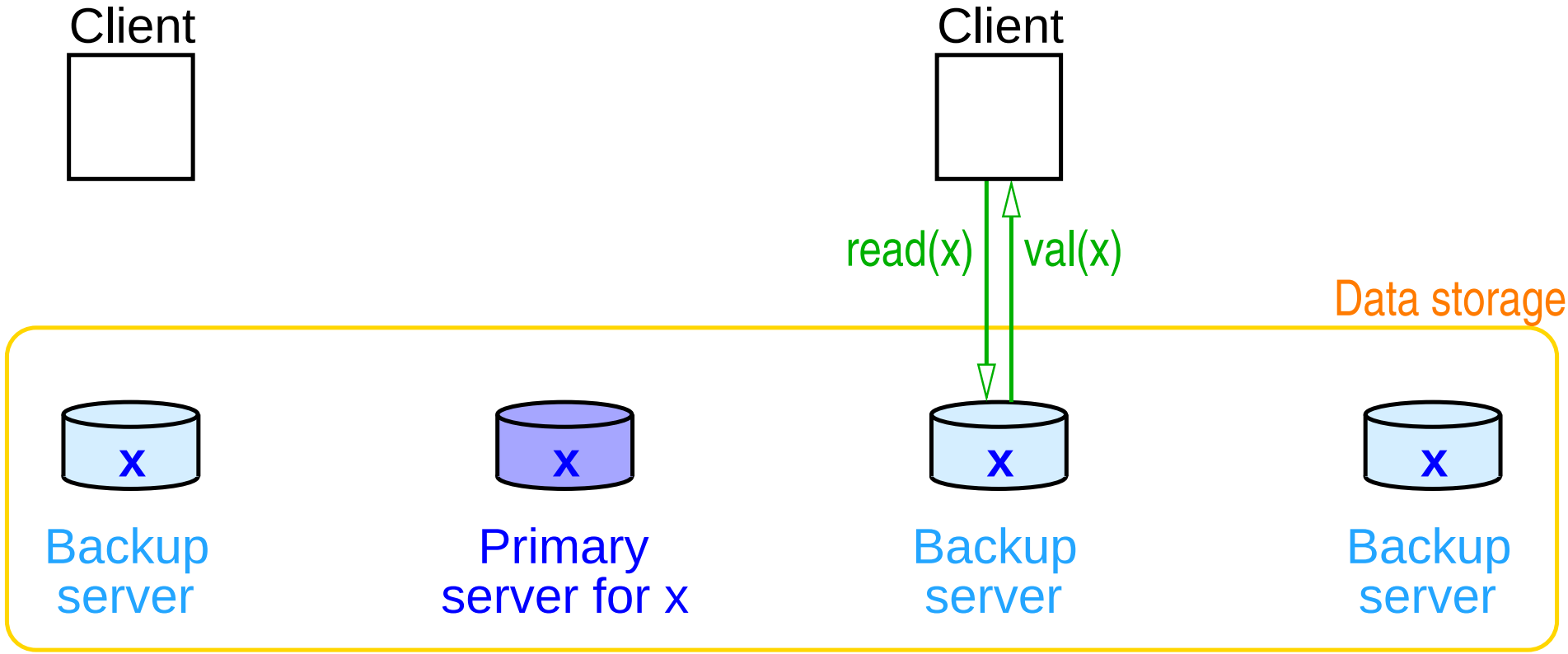
8.5 Consistency Protocols

- Describe how replica servers coordinate with each other to implement a specific consistency model
- Here specifically considered:
  - consistency models that serialize operations globally
  - e.g., sequential, weak and release consistency
- Two basic approaches:
  - **primary-based** (*primärbasierte*) **protocols**
    - write operations are always coordinated by a special copy (**primary copy**)
  - **replicated-write protocols**
    - write operations go to multiple copies

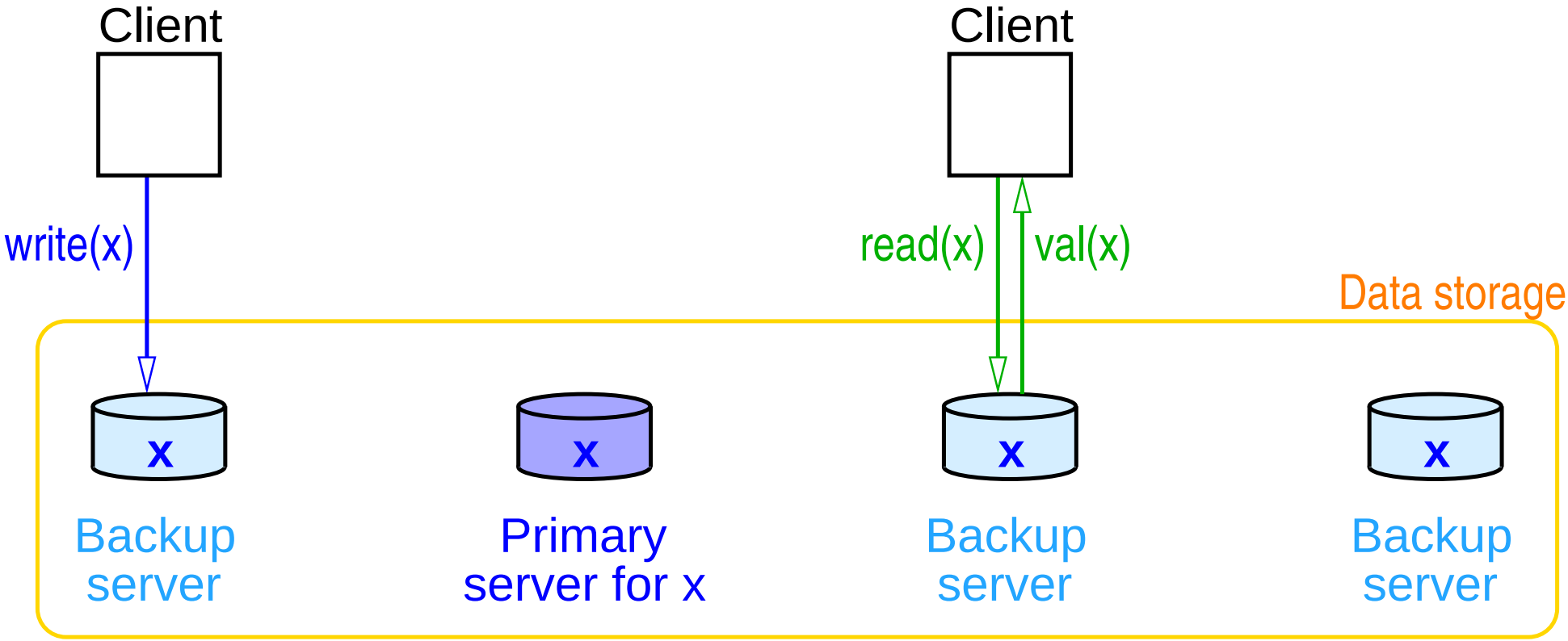
Primary-Based Protocols

- Read operations are possible on arbitrary (local) copies
- Write operations must be handled by the primary copy
  - e.g., to realize a sequential consistency:
    - the primary copy updates all other copies and waits for acknowledgements, only then it replies to the client
    - problem: performance
- **Remote-write protocols**
  - the writer forwards the operation to a fixed primary copy
- **Local-write protocols**
  - writer must become primary copy before it can do the update
    - i.e., the primary copy is migrated between servers
  - good model also for mobile users

Remote Write Protocol: Workflow (Sequential Consistency)

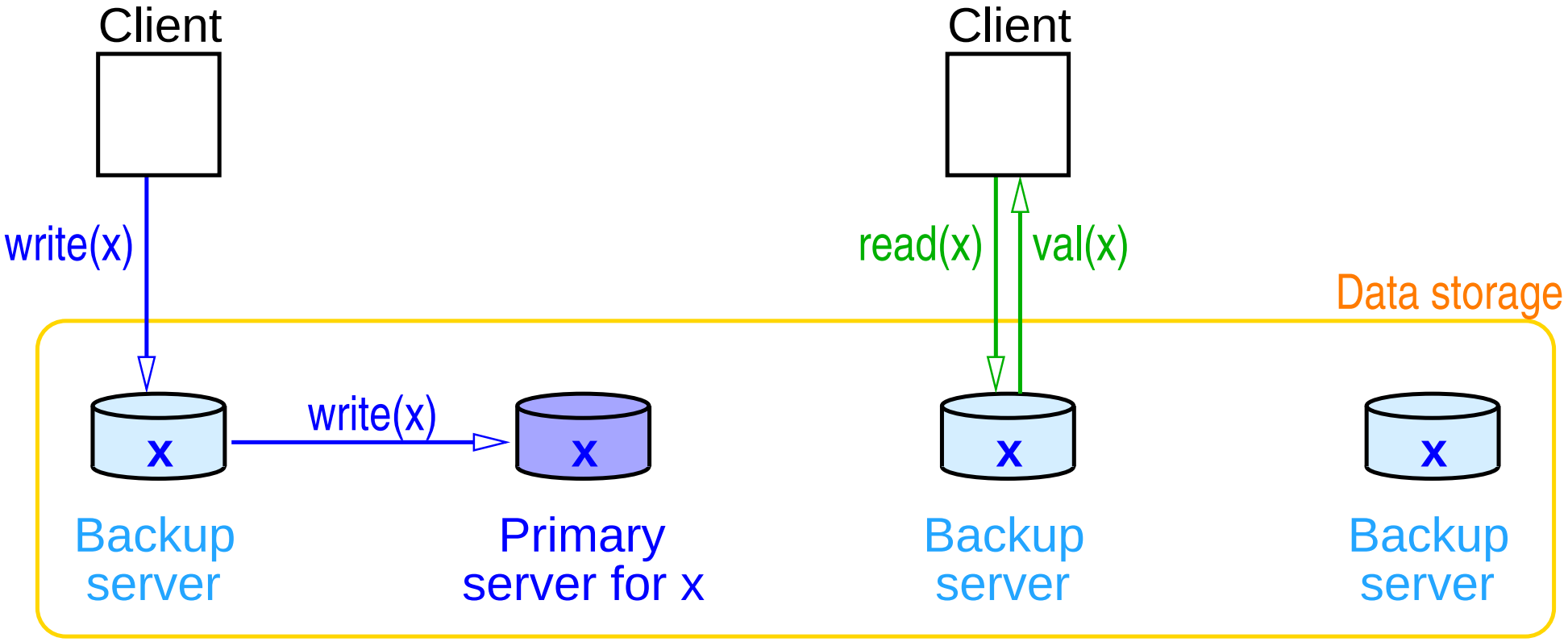


Remote Write Protocol: Workflow (Sequential Consistency)



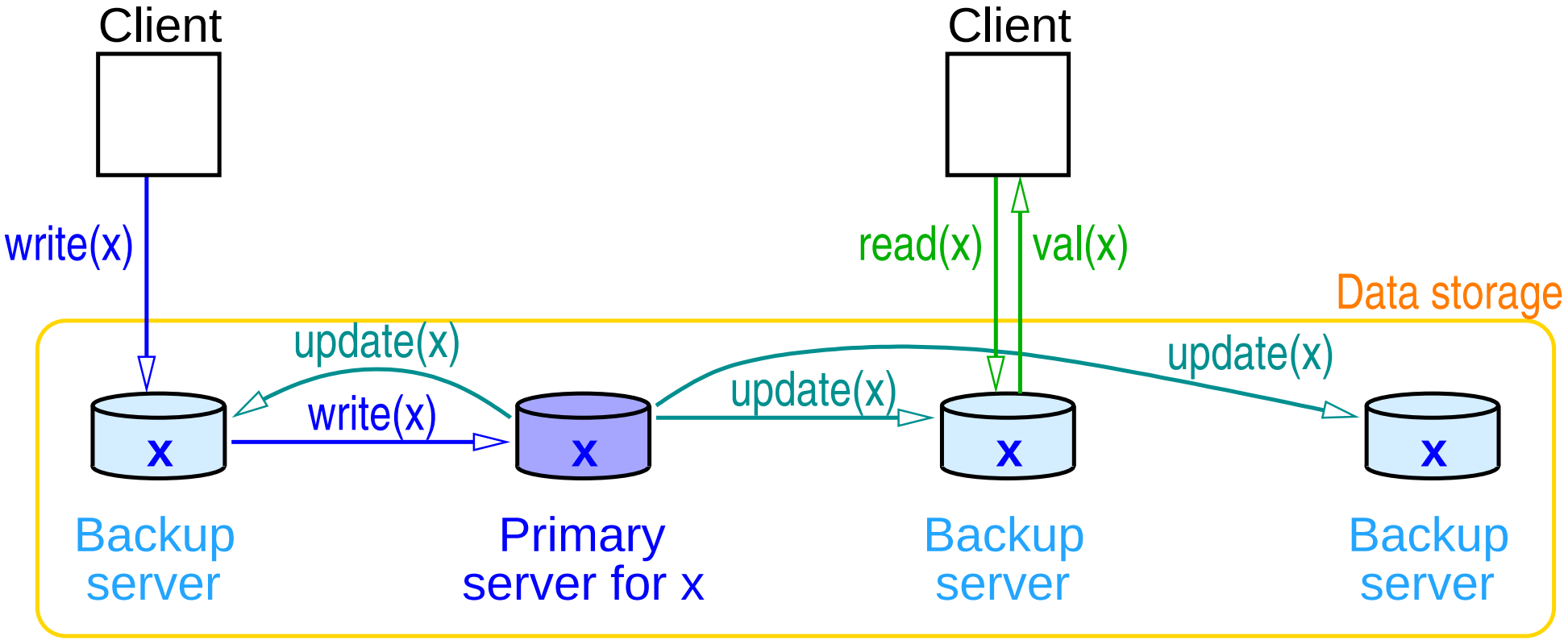
(1) Write request

Remote Write Protocol: Workflow (Sequential Consistency)



(1) Write request is forwarded to primary server

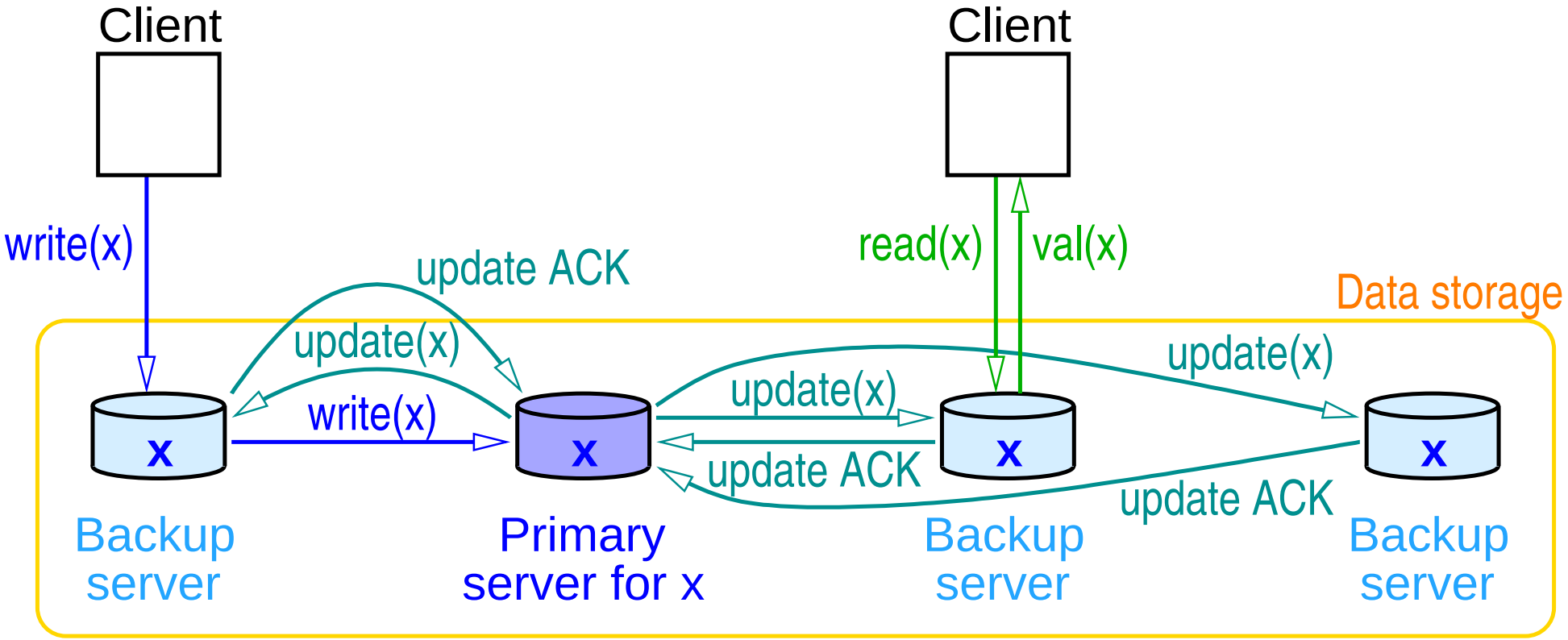
Remote Write Protocol: Workflow (Sequential Consistency)



(1) Write request is forwarded to primary server

(2) Primary server updates all backups

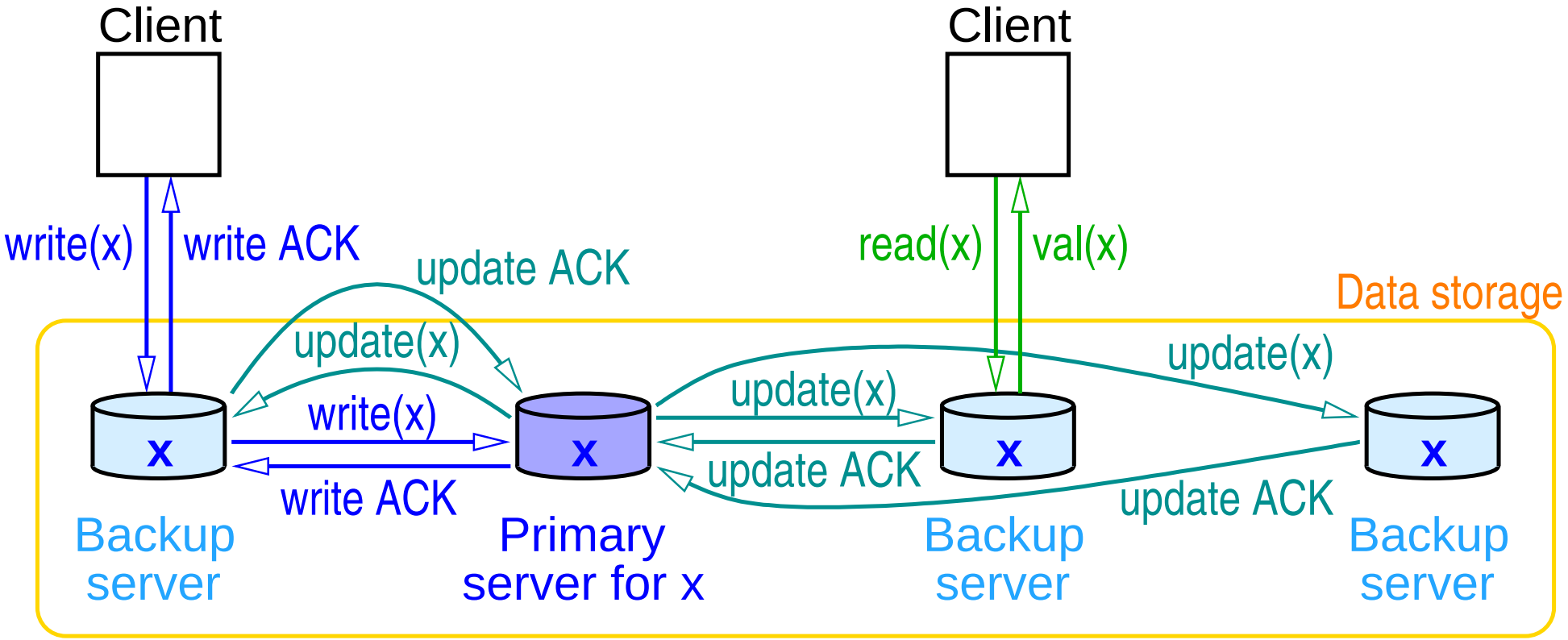
Remote Write Protocol: Workflow (Sequential Consistency)



(1) Write request is forwarded to primary server

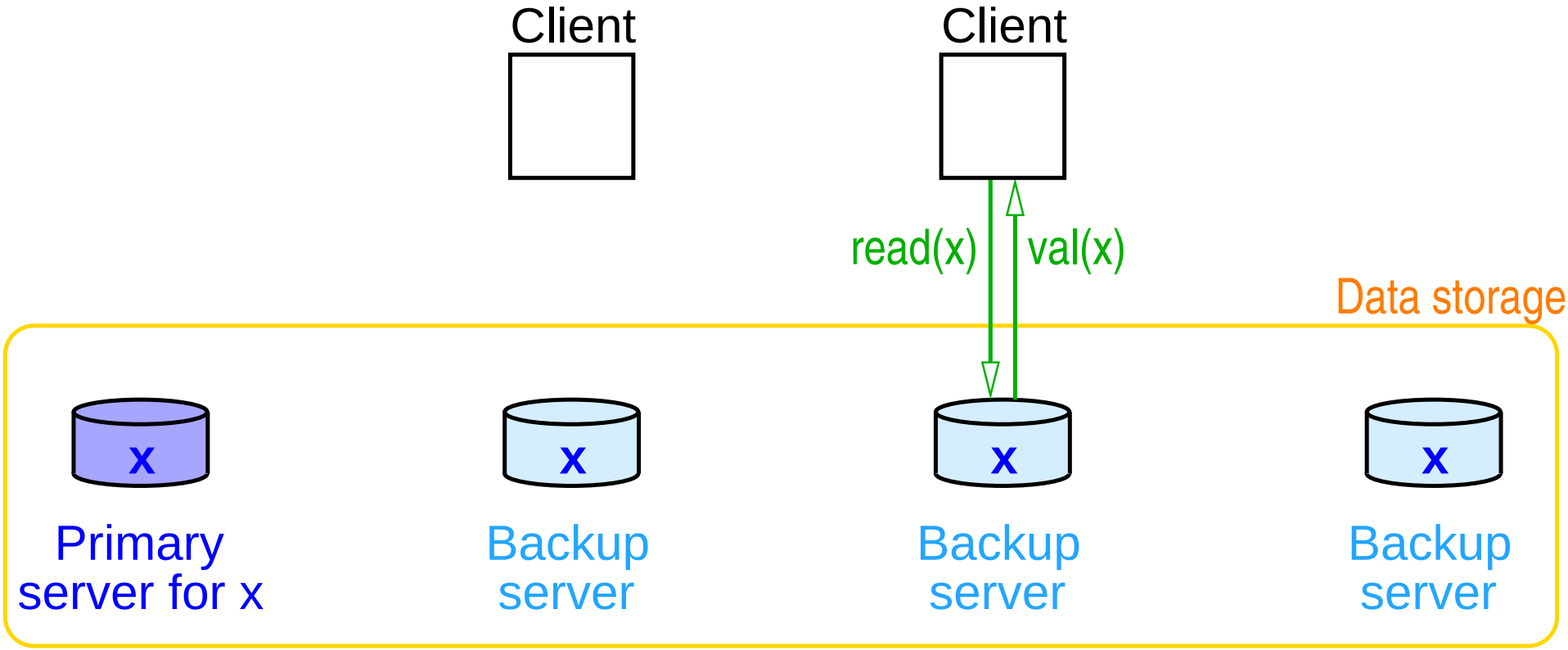
(2) Primary server updates all backups and waits for acknowledgements

Remote Write Protocol: Workflow (Sequential Consistency)

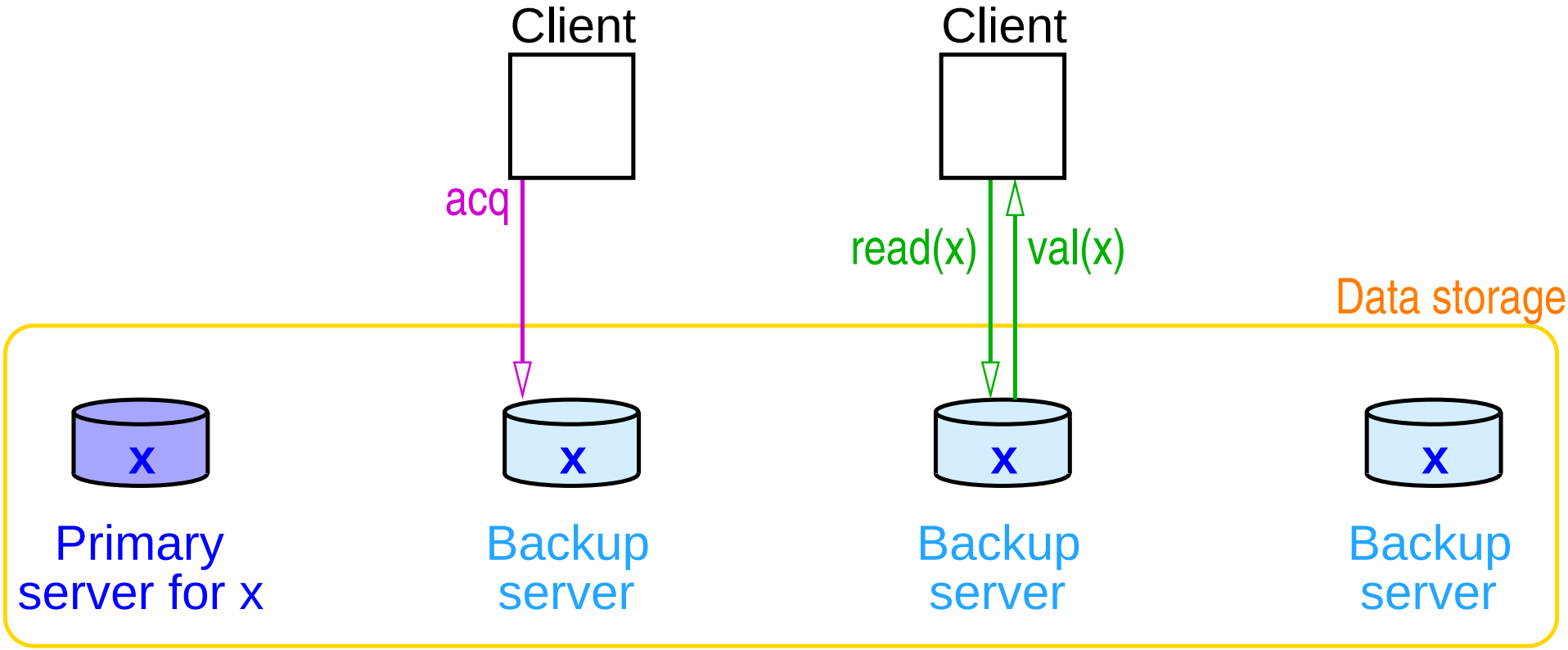


(1) Write request is forwarded to primary server
(2) Primary server updates all backups and waits for acknowledgements
(3) Acknowledge the end of the write operation

Local Write Protocol: Workflow (Release Consistency)

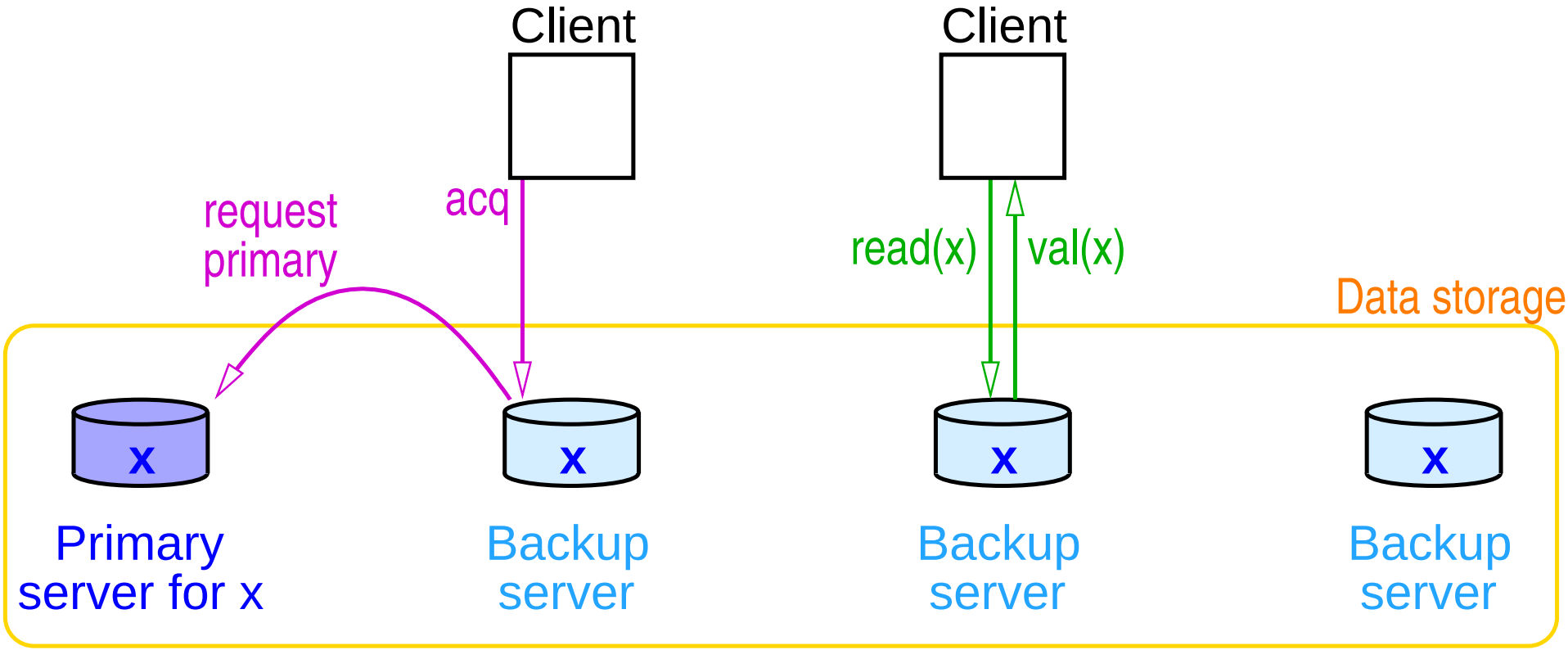


Local Write Protocol: Workflow (Release Consistency)



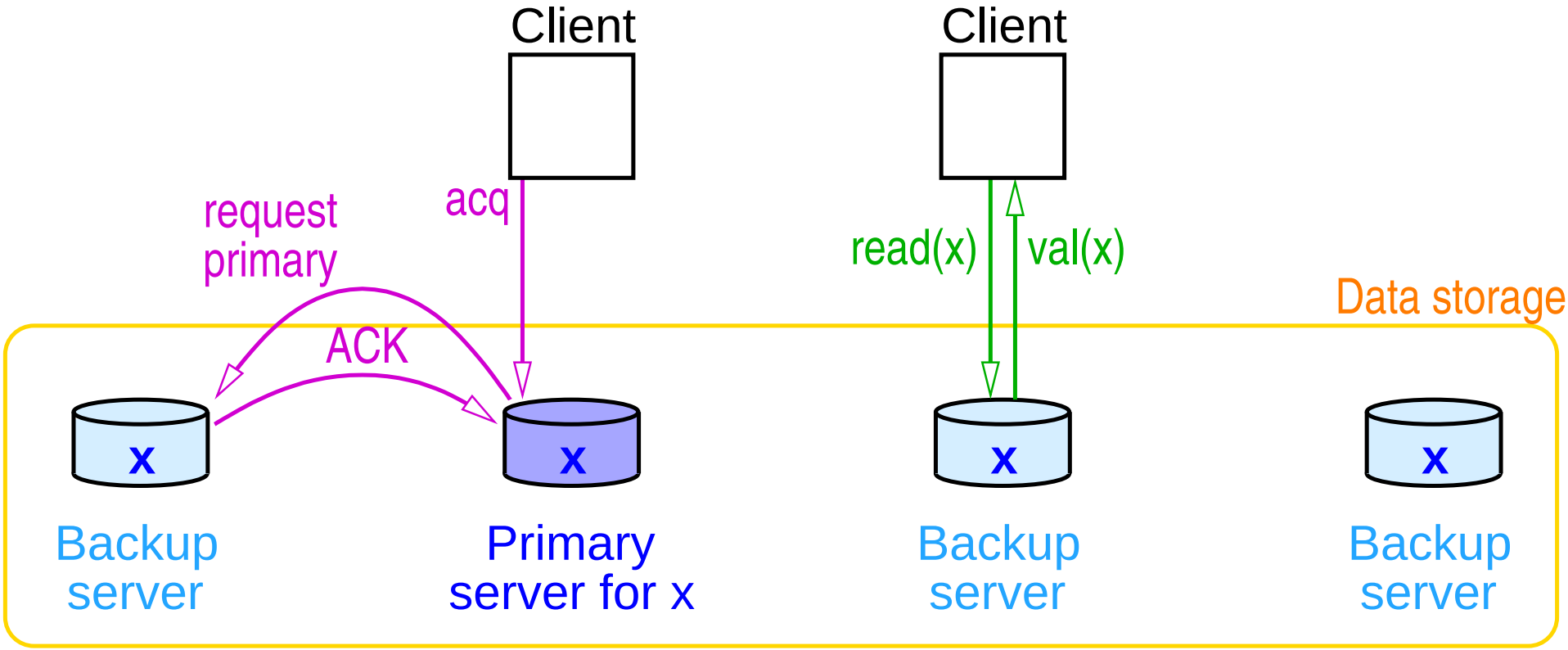
(1) Acquire lock;

Local Write Protocol: Workflow (Release Consistency)



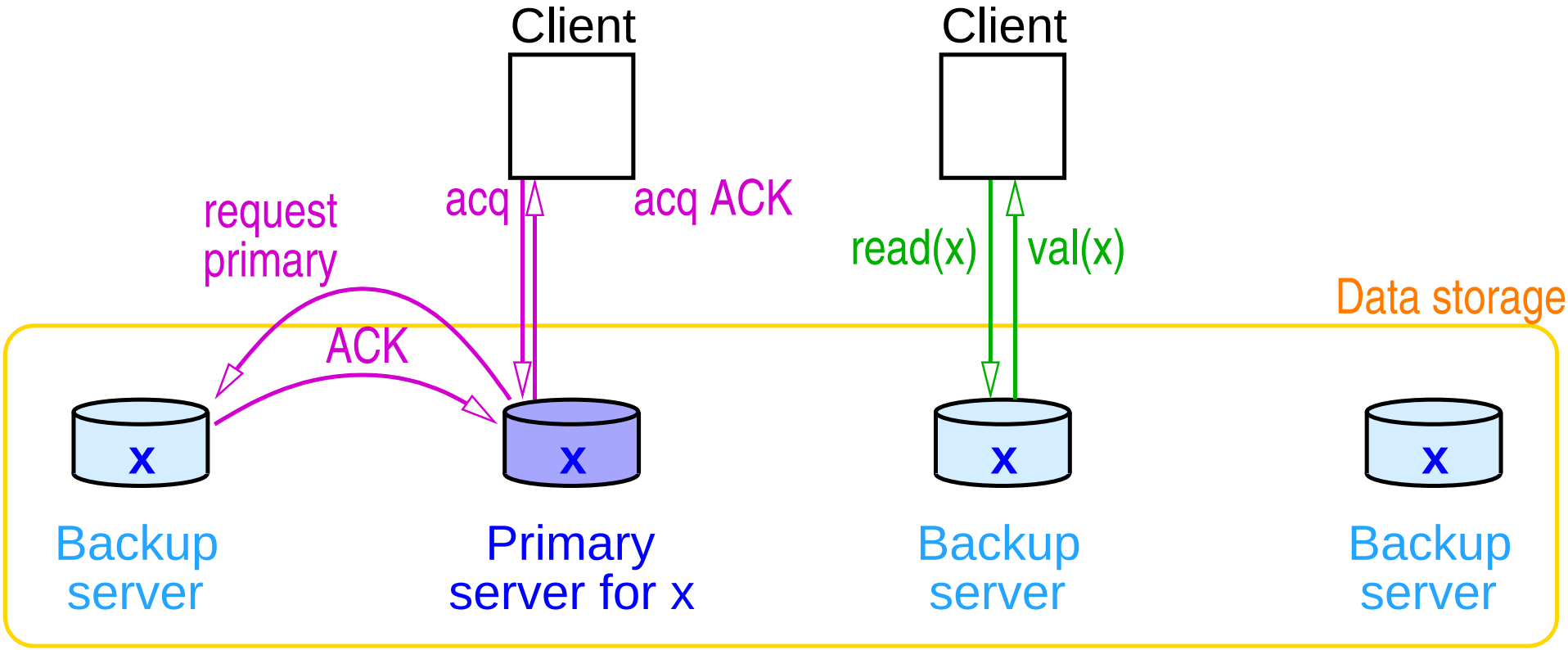
(1) Acquire lock; Move primary copy to new server

Local Write Protocol: Workflow (Release Consistency)



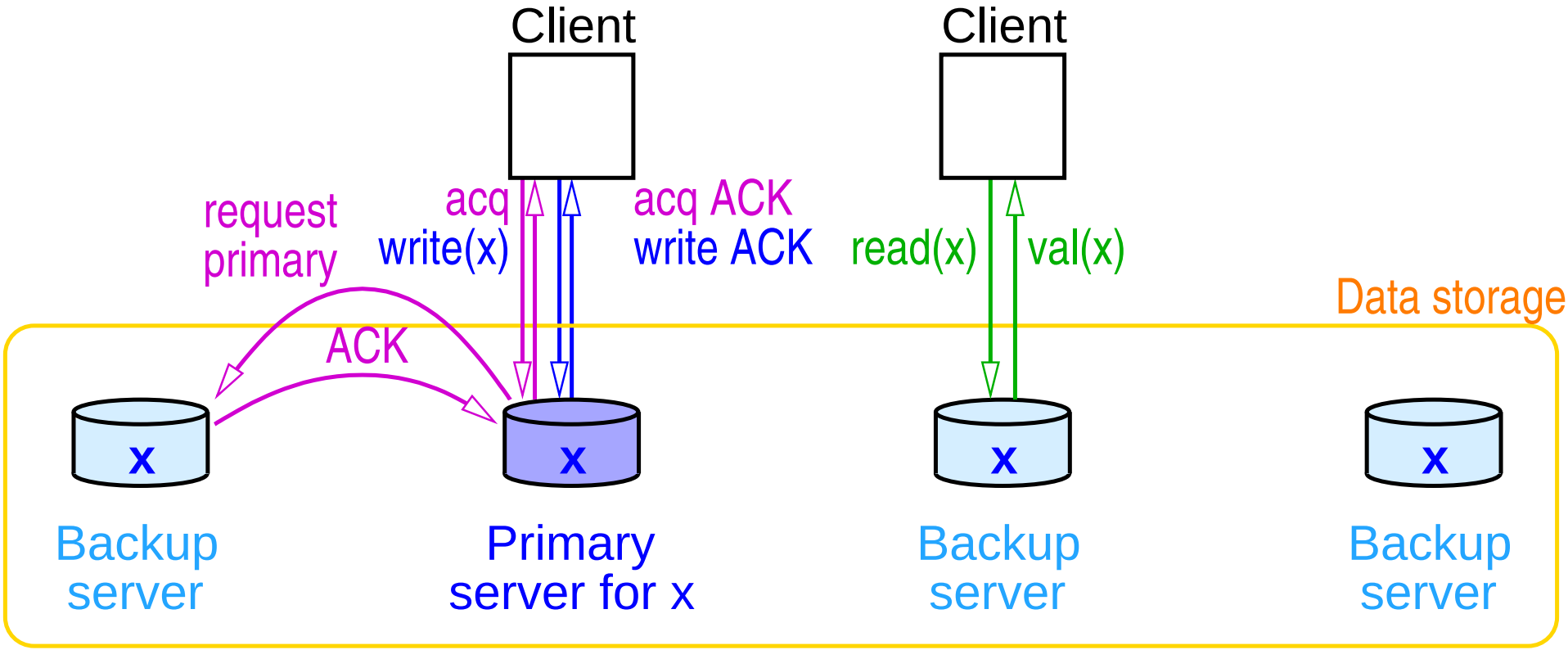
(1) Acquire lock; Move primary copy to new server

Local Write Protocol: Workflow (Release Consistency)



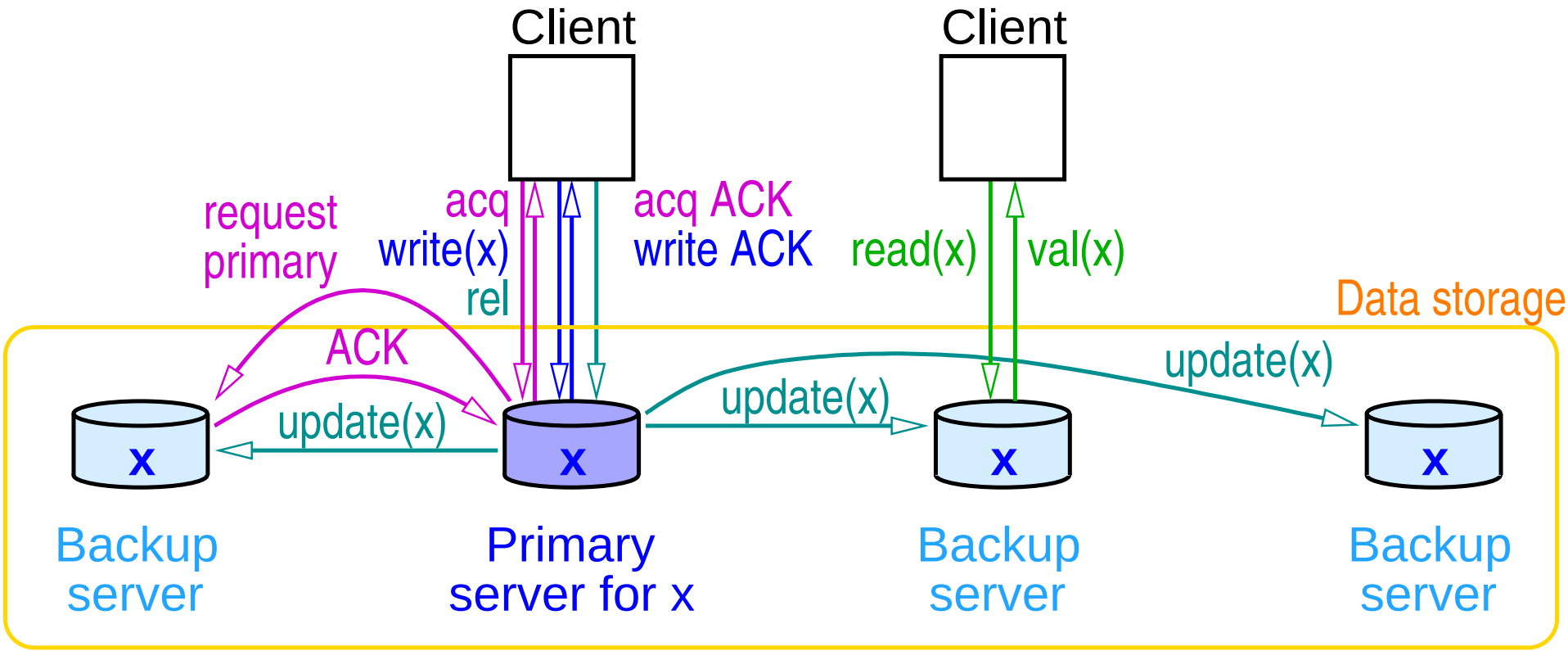
(1) Acquire lock; Move primary copy to new server
(2) Acknowledge the end of the write operation

Local Write Protocol: Workflow (Release Consistency)



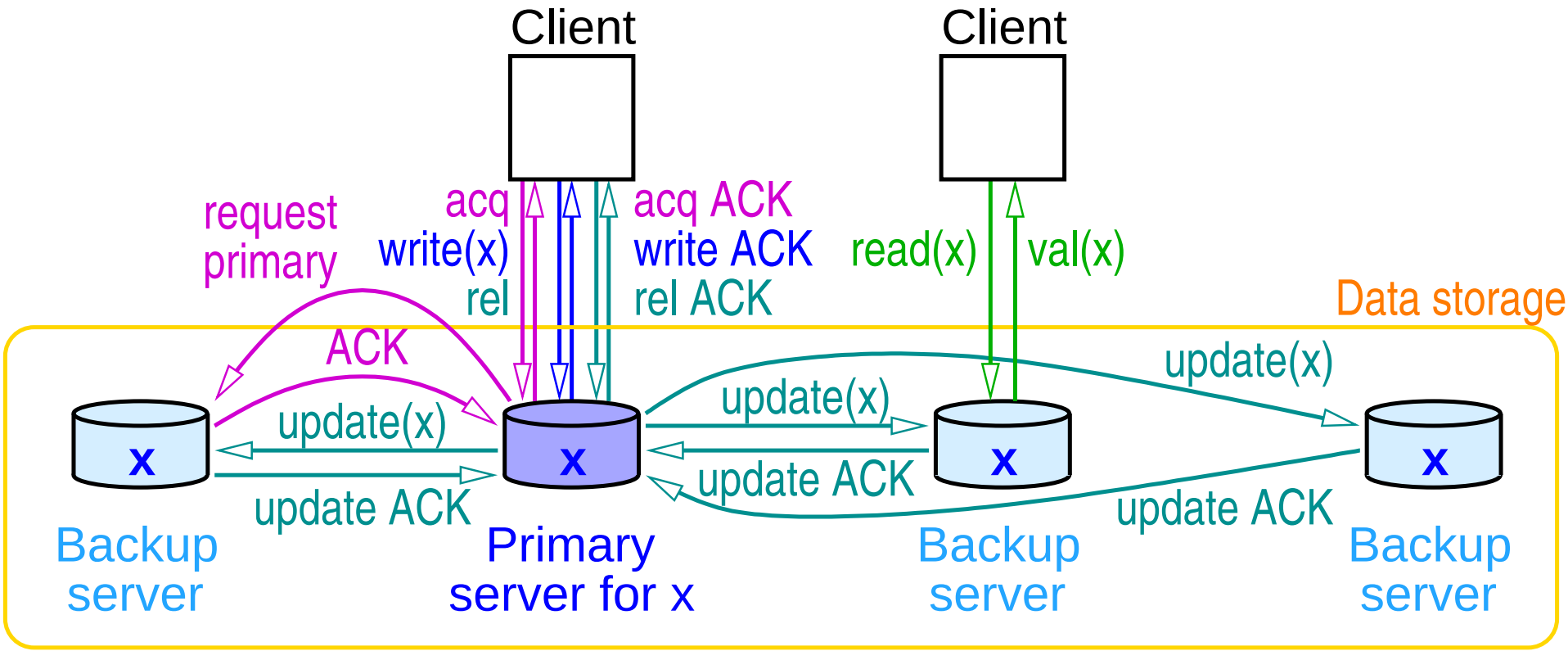
(1) Acquire lock; Move primary copy to new server
(2) Acknowledge the end of the write operation
(3) Write operations are executed (only) on the local server

Local Write Protocol: Workflow (Release Consistency)



(1) Acquire lock; Move primary copy to new server
(2) Acknowledge the end of the write operation
(3) Write operations are executed (only) on the local server
(4) New primary server updates backups

Local Write Protocol: Workflow (Release Consistency)



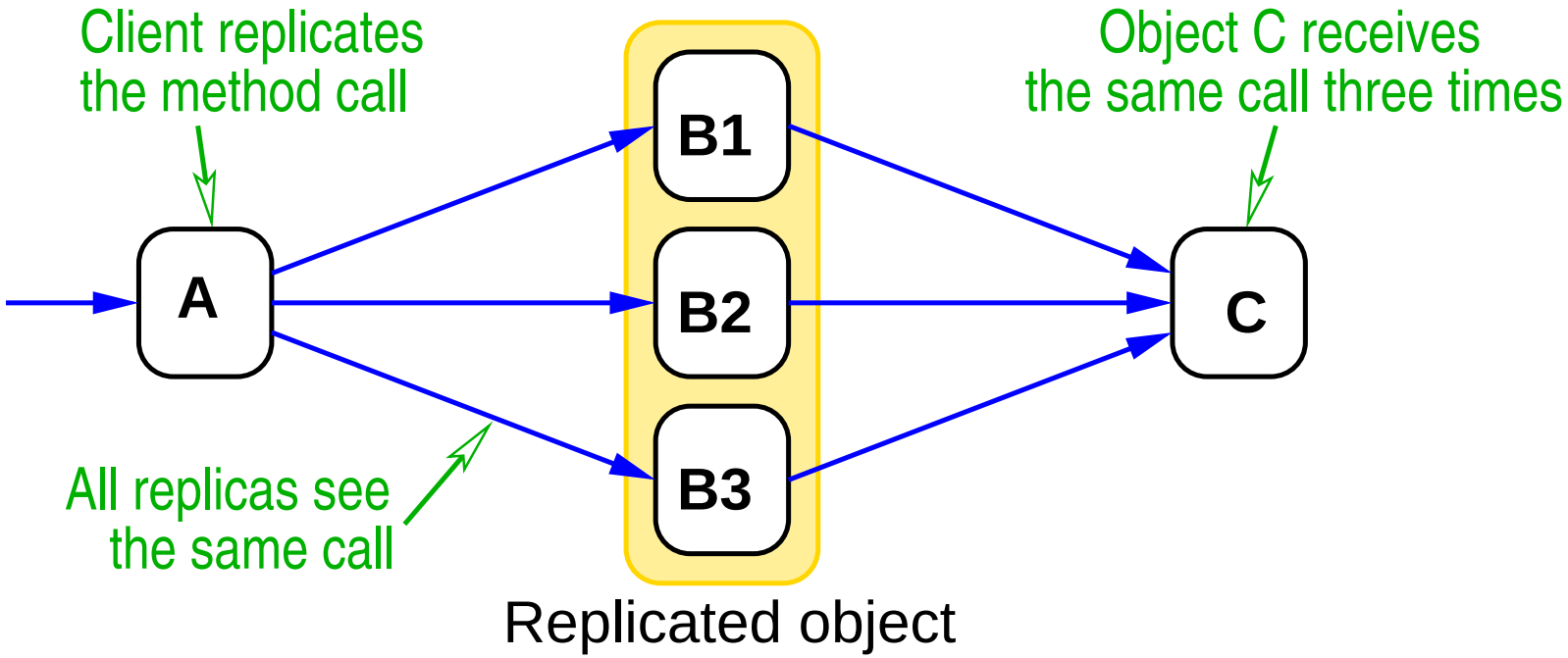
(1) Acquire lock; Move primary copy to new server
(2) Acknowledge the end of the write operation
(3) Write operations are executed (only) on the local server
(4) New primary server updates backups and waits for acknowledgements

Replicated Write Protocols

- Allow execution of write operations on (multiple) arbitrary replicas
- In the following, two approaches:
  - active replication
    - update operations are passed on to all copies
    - requirement: globally unique sequence of operations
      - using totally ordered multicast
      - or via central sequencer process
  - quorum-based protocols
    - only a portion of the replicas needs to be modified
    - however, also multiple copies need to be read

Problem With Replicated Object Calls

- What happens when a replicated object calls another?

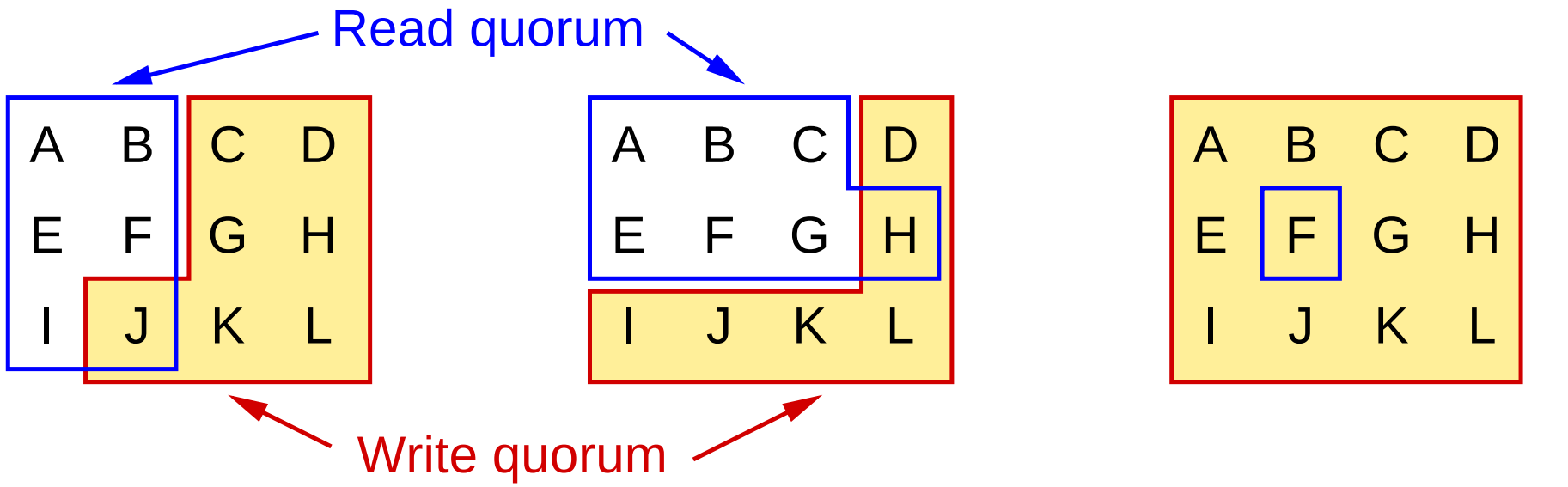


- Solution: middelware that is aware of replication
  - coordinator of B makes sure that only one call is sent to C and its result is distributed to all replicas of B

Quorum-based Protocols (Sequential Consistency)

- Clients need the permission of multiple servers for writing **and** for reading
- When writing: send the request to (at least) N_W copies
  - their servers must agree to the change
  - data gets a new version number when changed
  - condition: $N_W > N/2$ (N = total number of copies)
    - prevents write/write conflicts
- When reading: send the request to (at least) N_R copies
  - client selects the latest version (highest version number)
  - condition: $N_R + N_W > N$
    - ensures that in any case the latest version is read

Quorum-based Protocols: Examples



$N_R = 6$ $N_W = 7$

correct

$N_R = 7$ $N_W = 6$

Write/write conflicts are possible

($N_W \leq N/2$)

$N_R = 1$ $N_W = 12$

correct

8.6 Summary

- Replication due to availability and performance
- Problem: consistency of copies
  - strictest model: sequential consistency
  - waekenings: causal consistency, weak ∼, release ∼
  - client-centric consistency models
- Implementation of replication and consistency:
  - replication scheme: static, server initiated, client initiated
  - distribution protocols
    - type of update, push / pull, unicast / multicast
  - consistency protocols
    - primary based / replicated write protocols