I Can't Believe It's Not Causal !

Scalable Causal Consistency with No Slowdown Cascades

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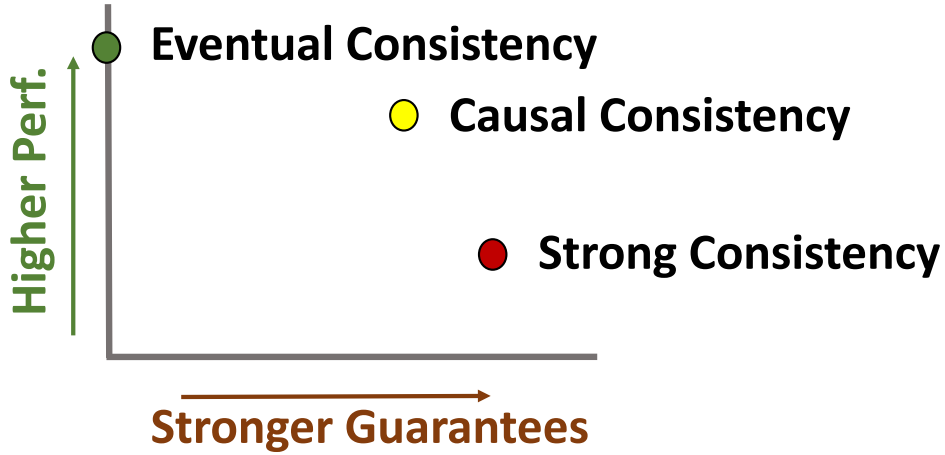
Causal Consistency: Great In Theory



- Lots of exciting research building scalable causal data-stores, e.g.,
  - COPS [SOSP 11]
  - Bolt-On [SIGMOD 13]
  - Chain Reaction [EuroSys 13]
  - Eiger [NSDI 13]
  - Orbe [SOCC 13]
  - GentleRain [SOCC 14]
  - Cure [ICDCS 16]
  - TARDiS [SIGMOD 16]

Causal Consistency: But In Practice …

The middle child of consistency models

Reality: Largest web apps use eventual consistency, e.g.,

Espresso

TAO

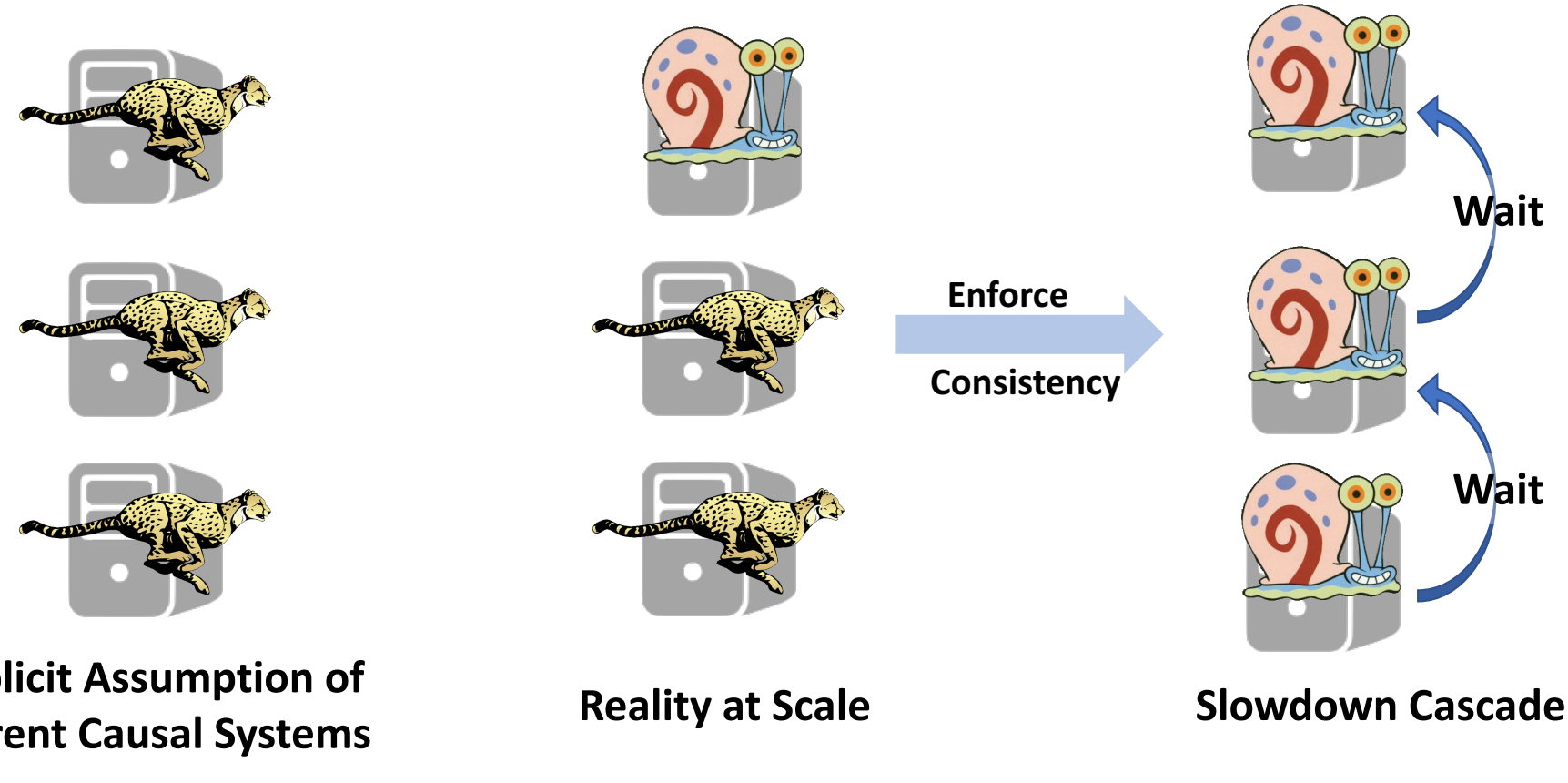
Manhattan

Key Hurdle: Slowdown Cascades

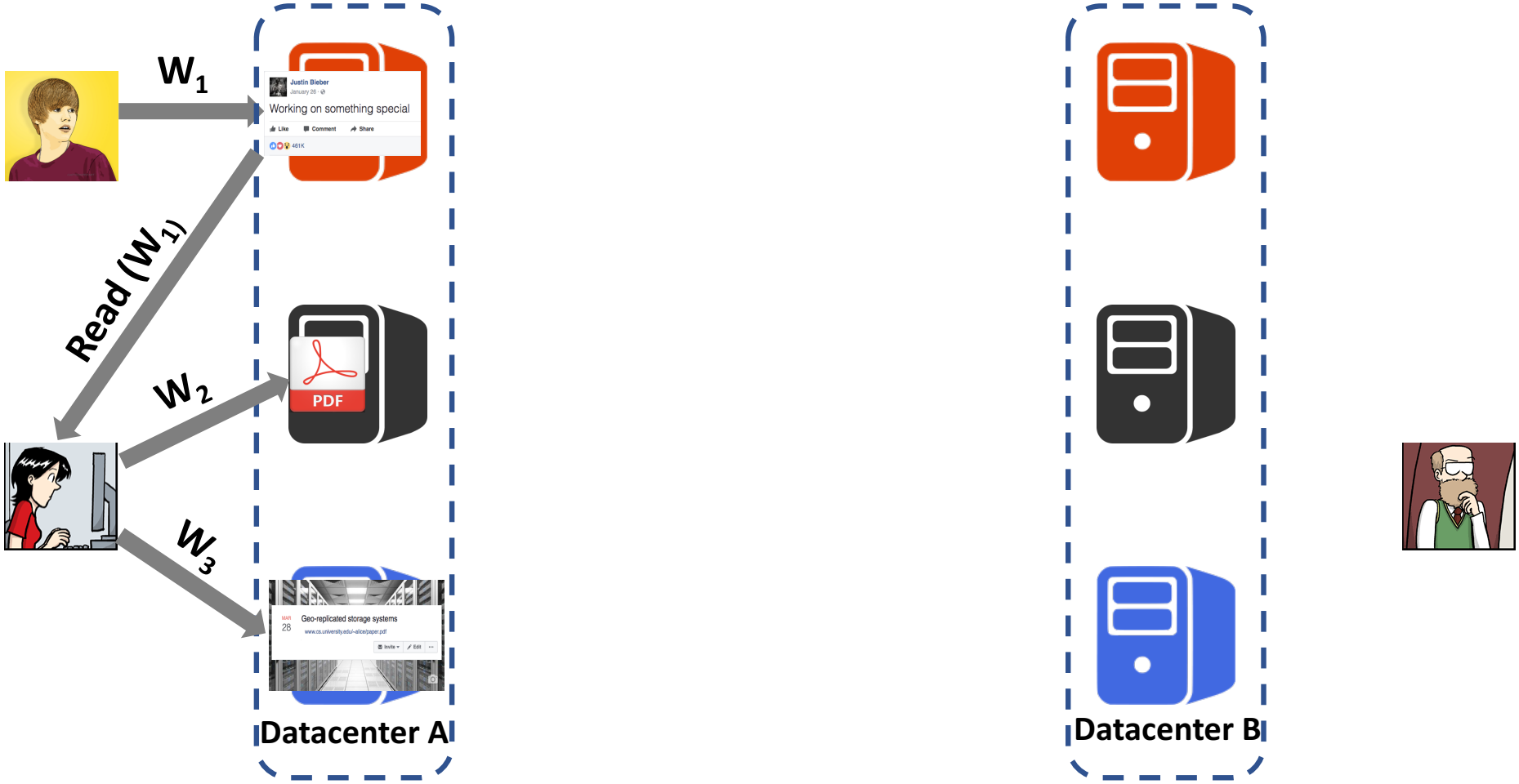
Implicit Assumption of Current Causal Systems

Reality at Scale

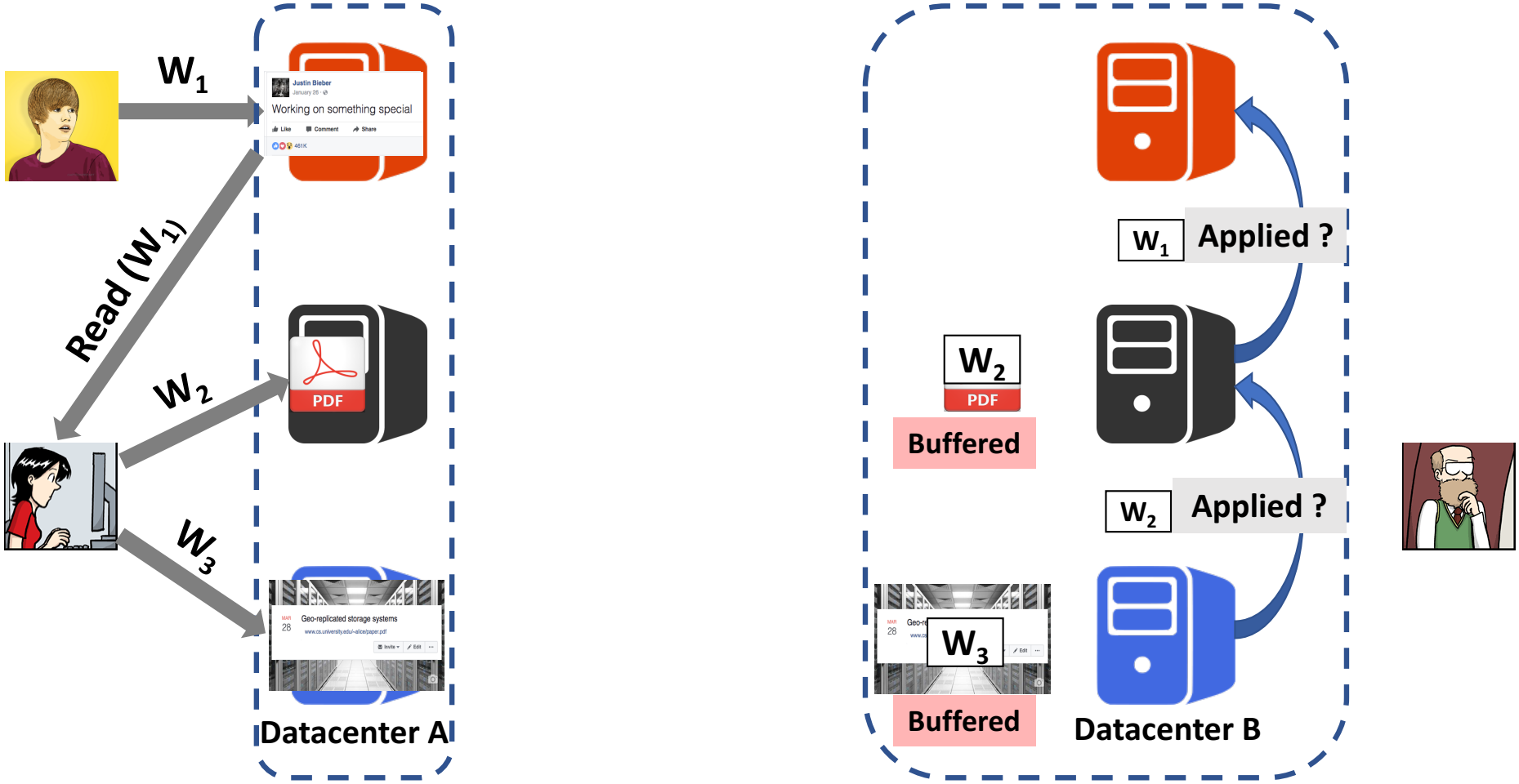
Key Hurdle: Slowdown Cascades



Replicated and sharded storage for a social network

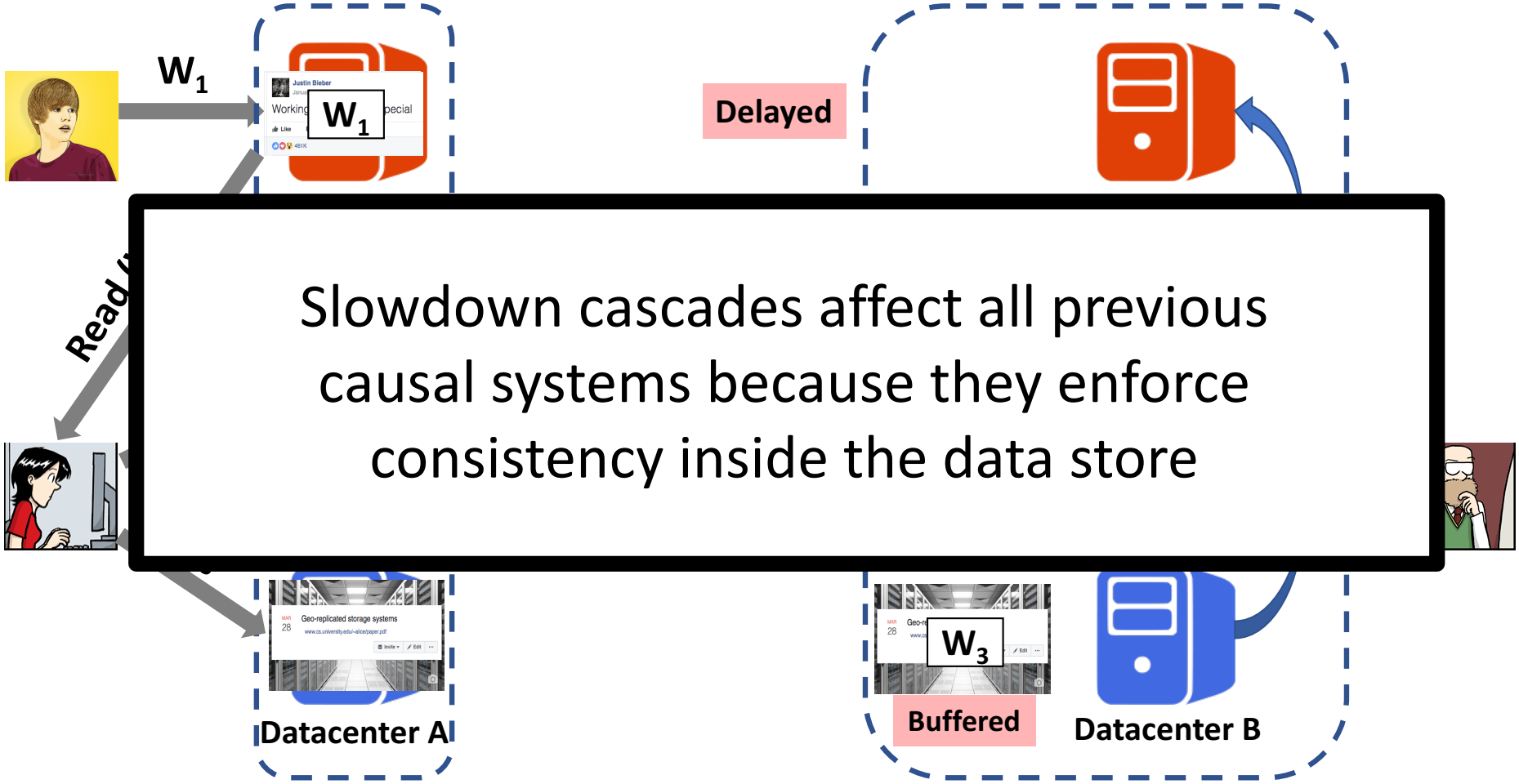


Writes causally ordered as $W_1 \rightarrow W_2 \rightarrow W_3$



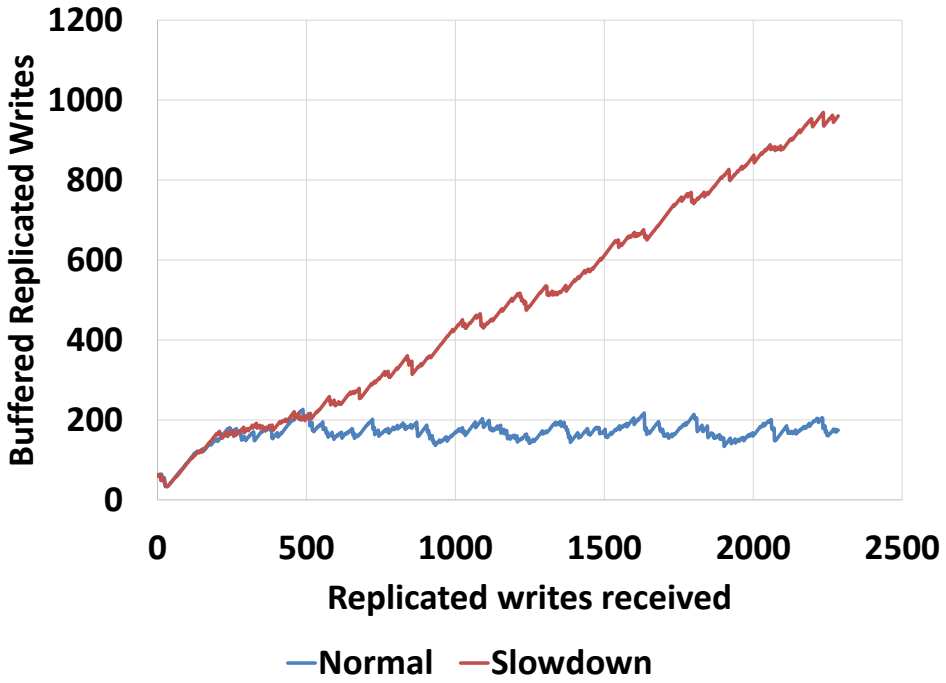
Current causal systems enforce consistency as a datastore invariant

Slowdown Cascade



Alice's advisor unnecessarily waits for Justin Bieber's update despite not reading it

Slowdown Cascades in Eiger (NSDI '13)



Replicated write buffers grow arbitrarily because Eiger enforces consistency inside the datastore

OCCULT

Observable Causal Consistency Using Lossy Timestamps

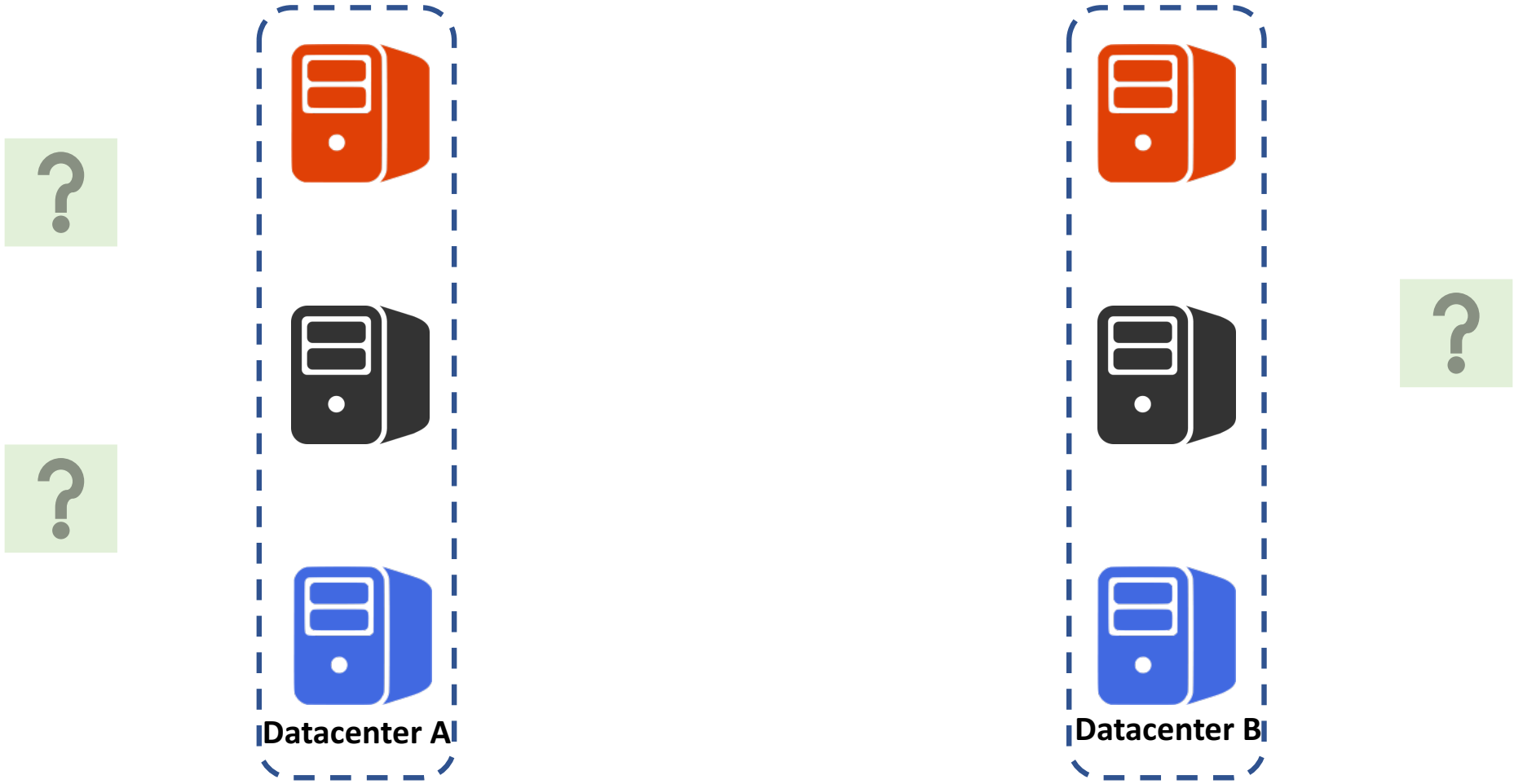
Observable Causal Consistency

Causal Consistency guarantees that each ***client observes*** a monotonically non-decreasing set of updates (including its own) in an order that respects potential causality between operations

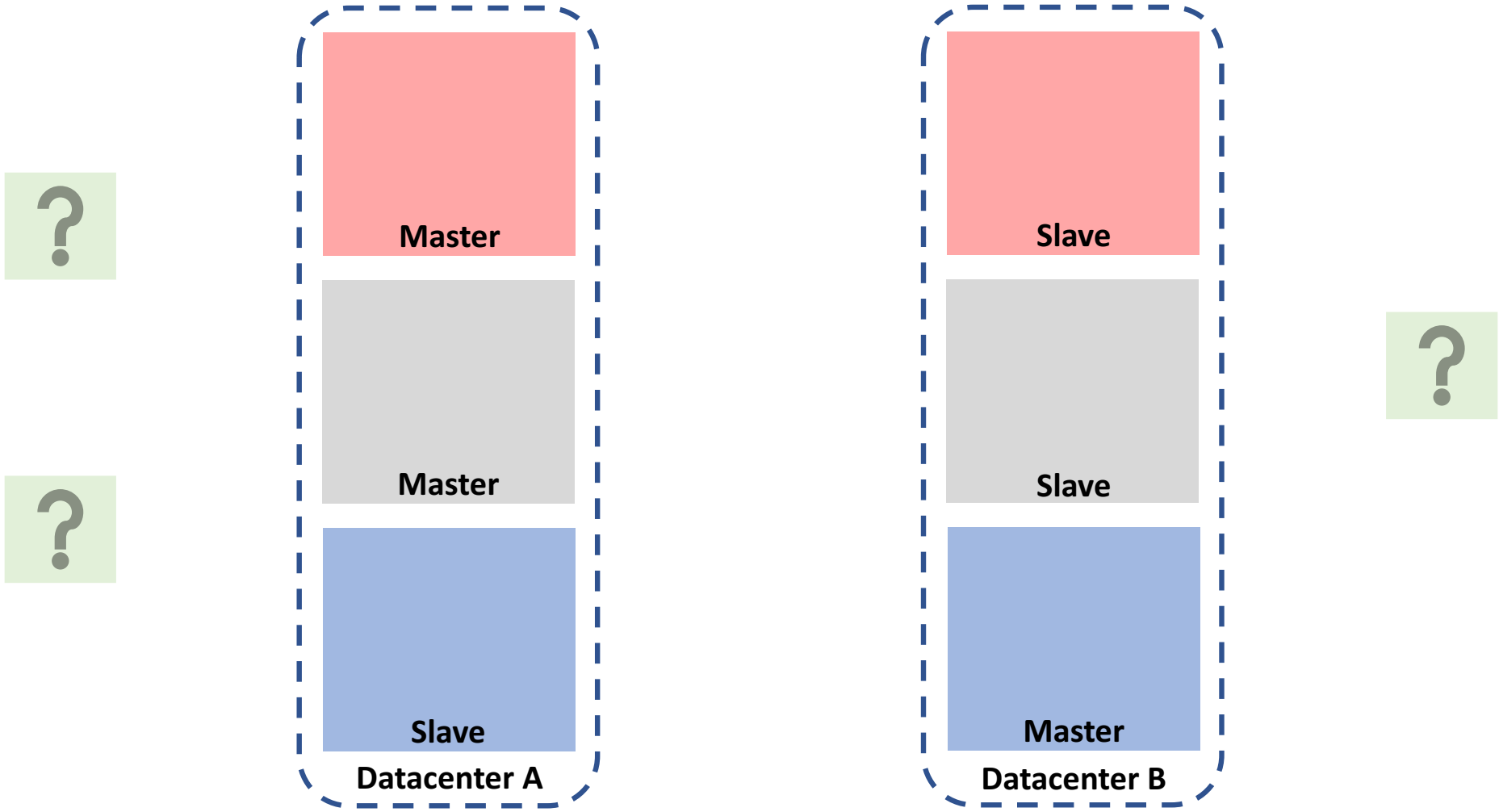
Key Idea:

Don't implement a causally consistent data store

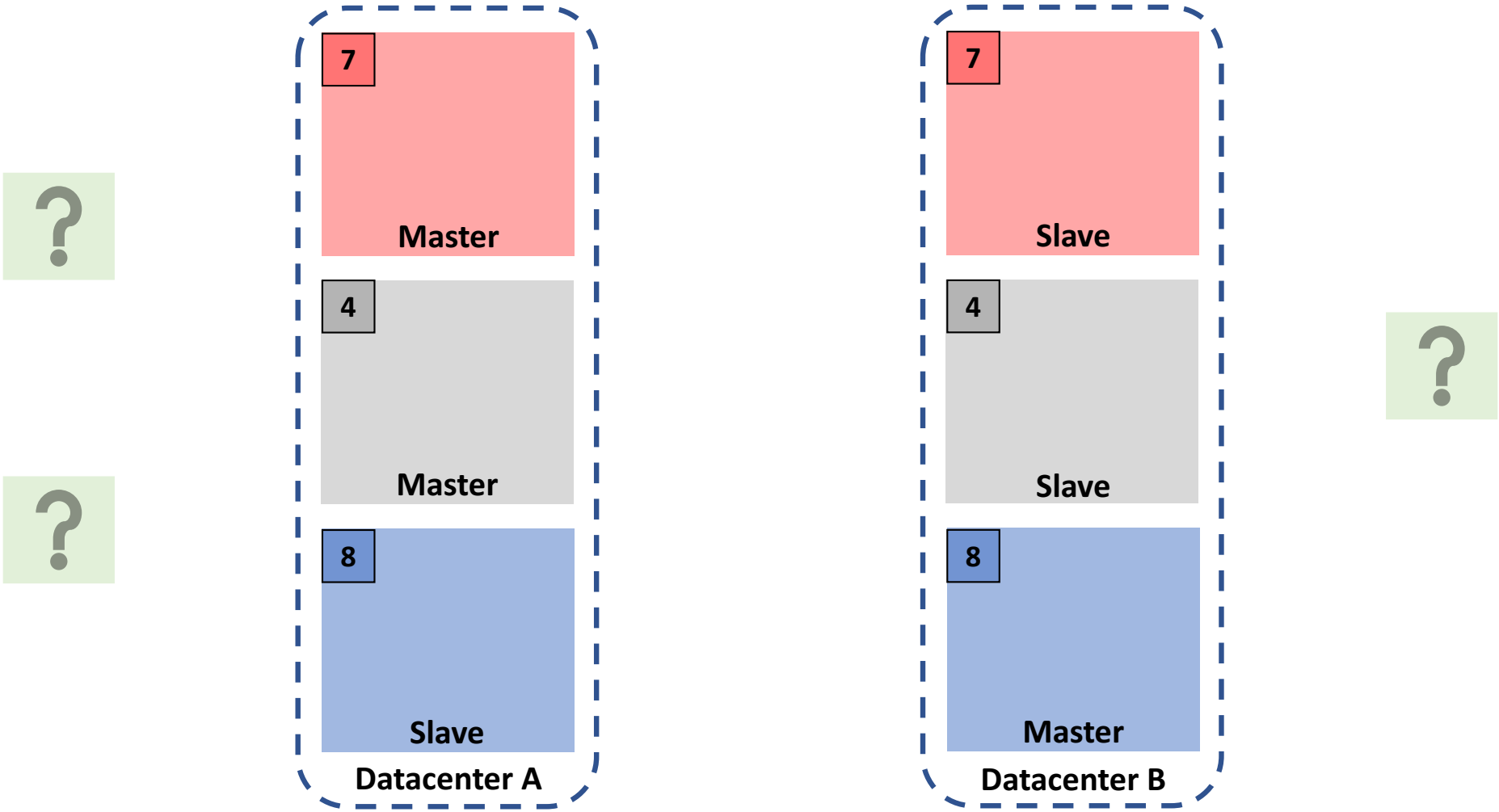
Let clients *observe* a causally consistent data store



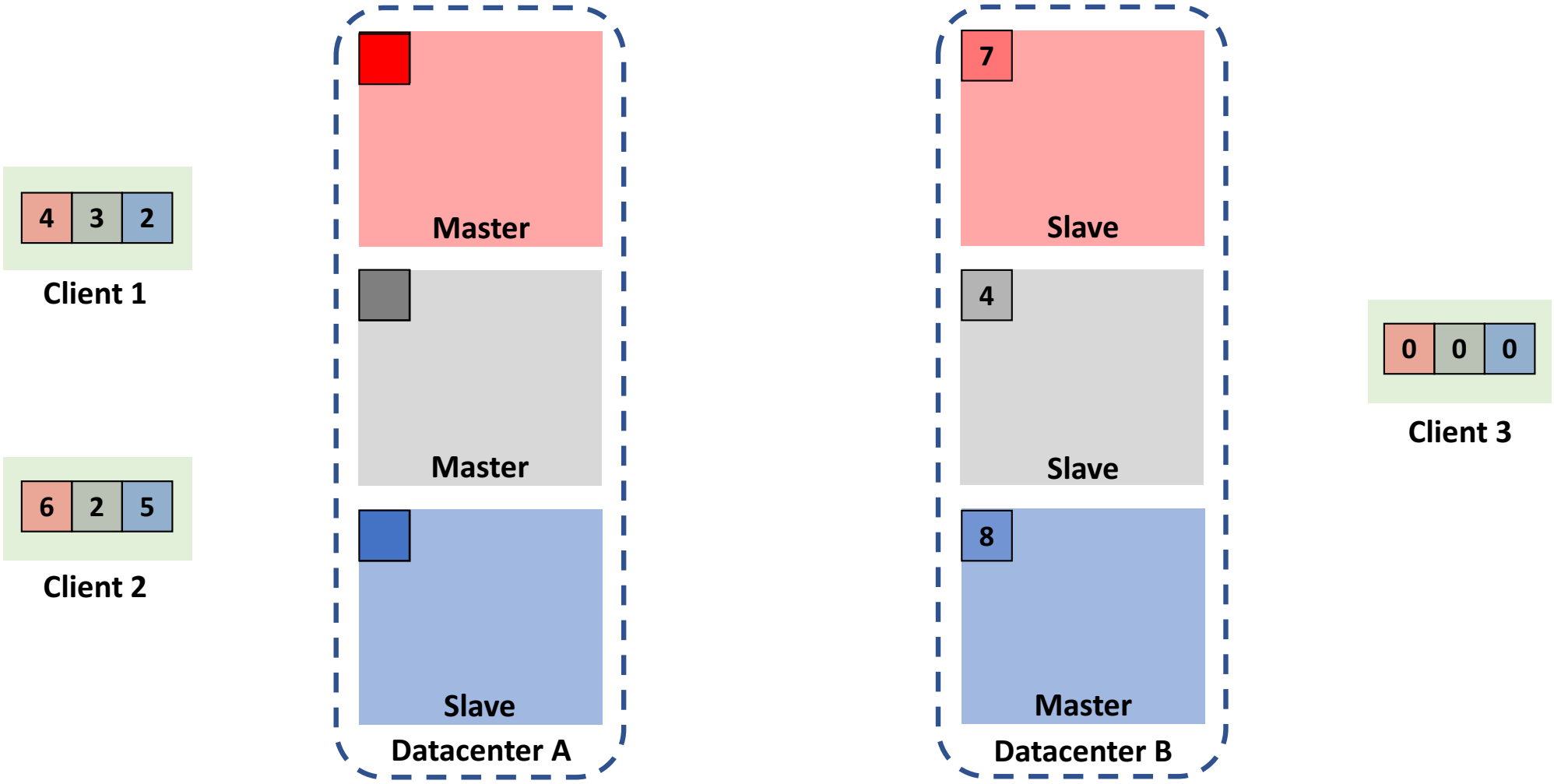
How do clients *observe* a causally consistent datastore ?



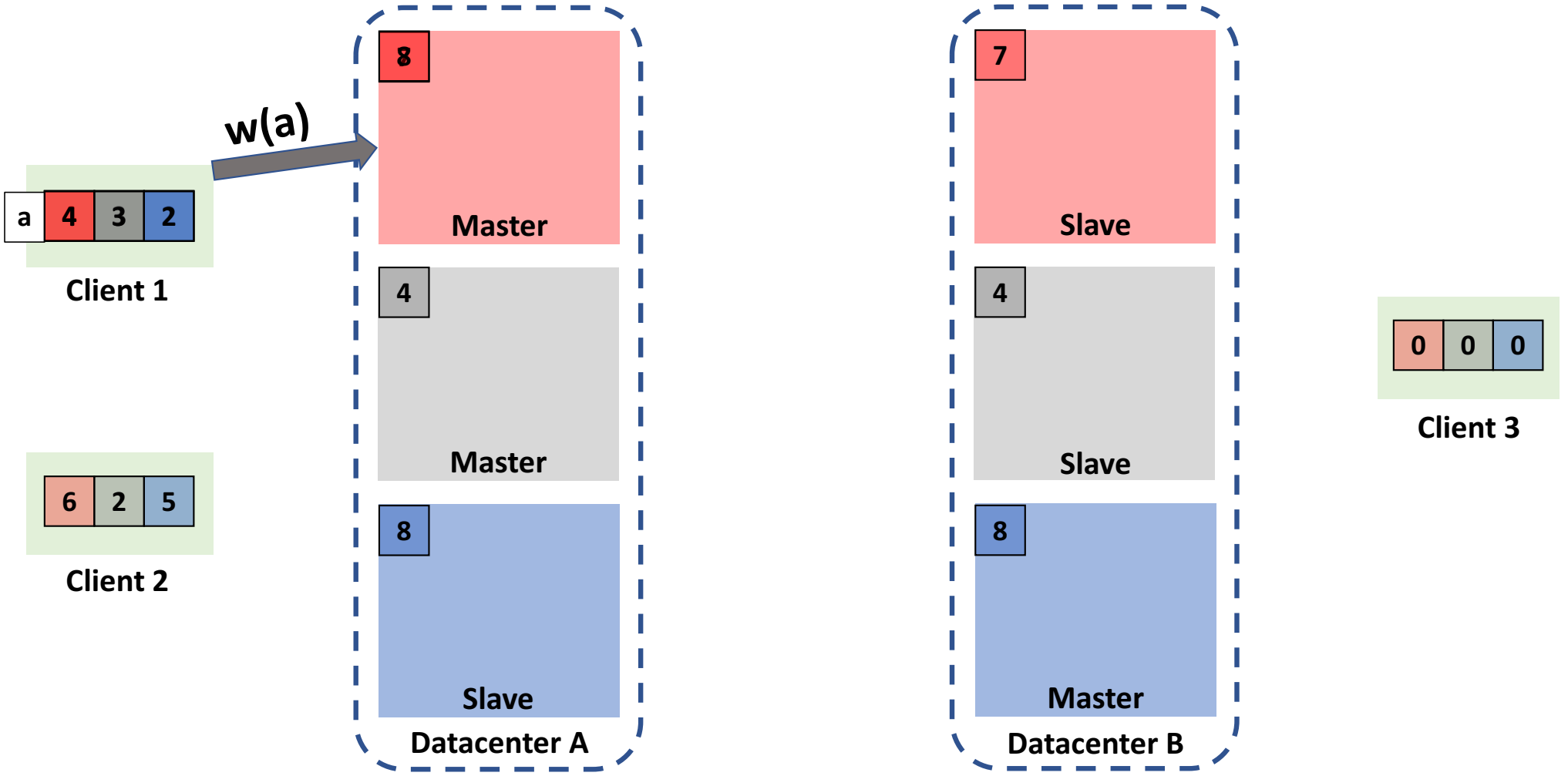
Writes accepted only by master shards and then replicated asynchronously in-order to slaves



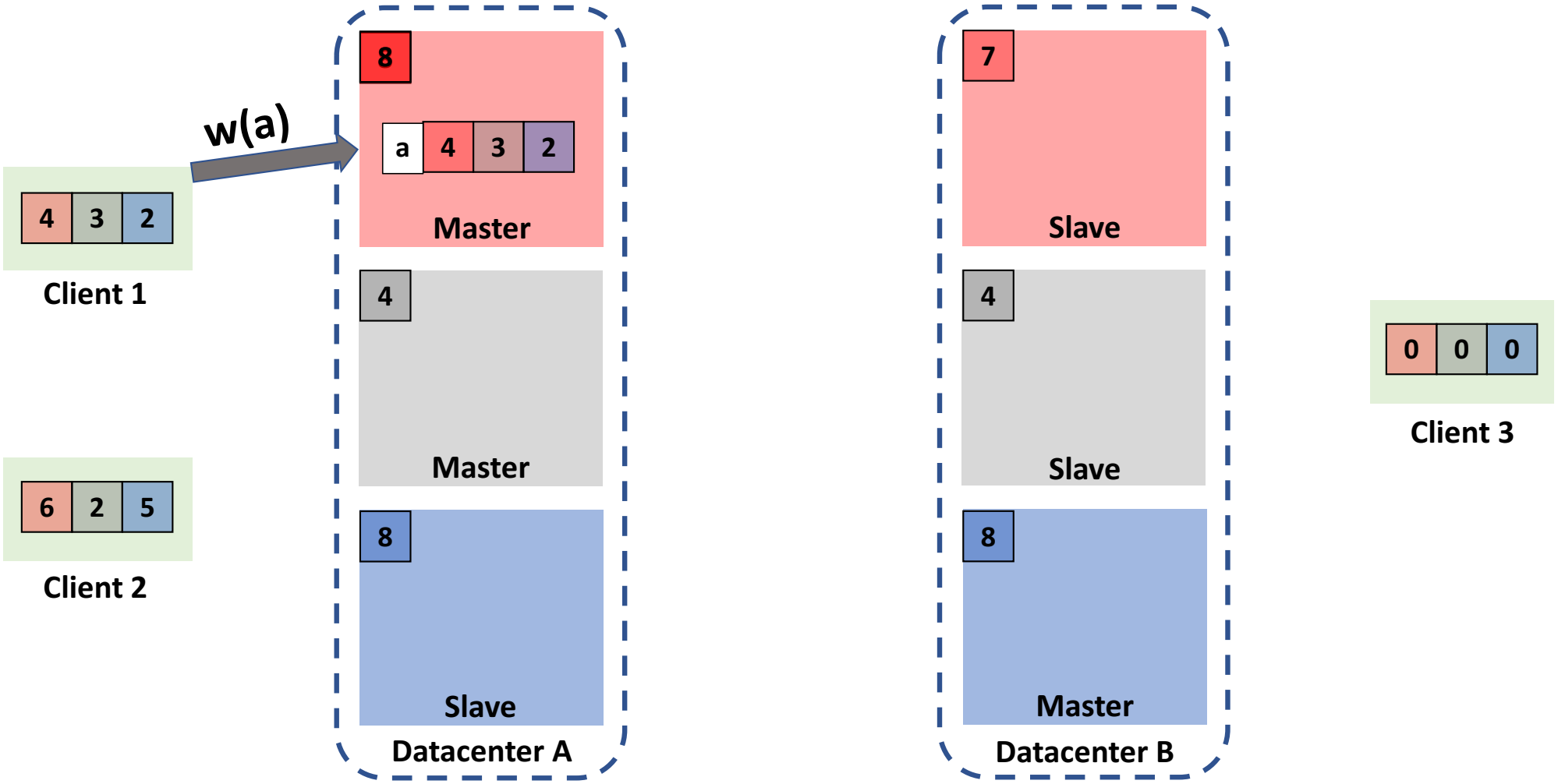
Each shard keeps track of a **shardstamp** which counts the writes it has applied



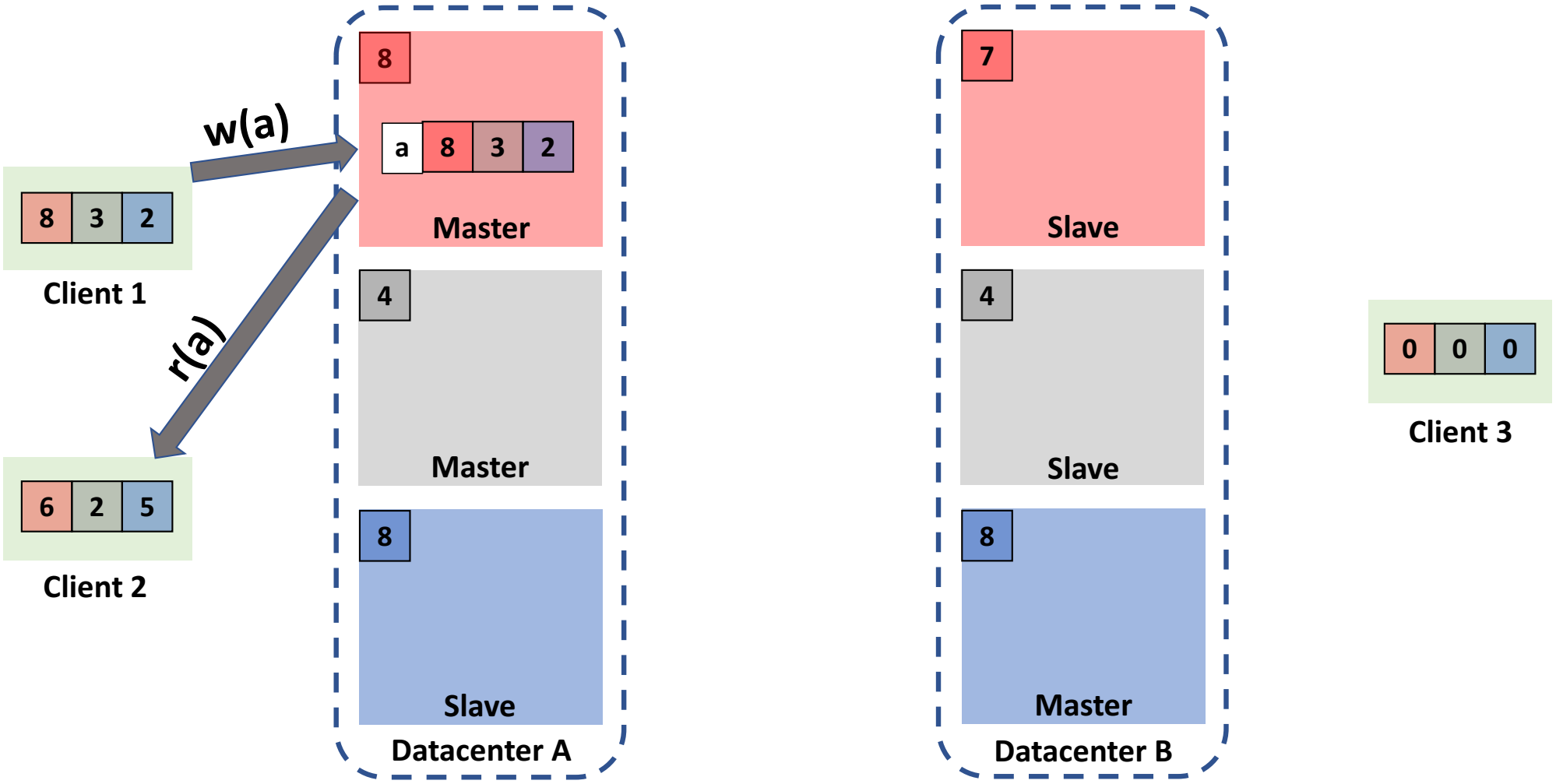
Causal Timestamp: Vector of shardstamps which identifies a global state across all shards



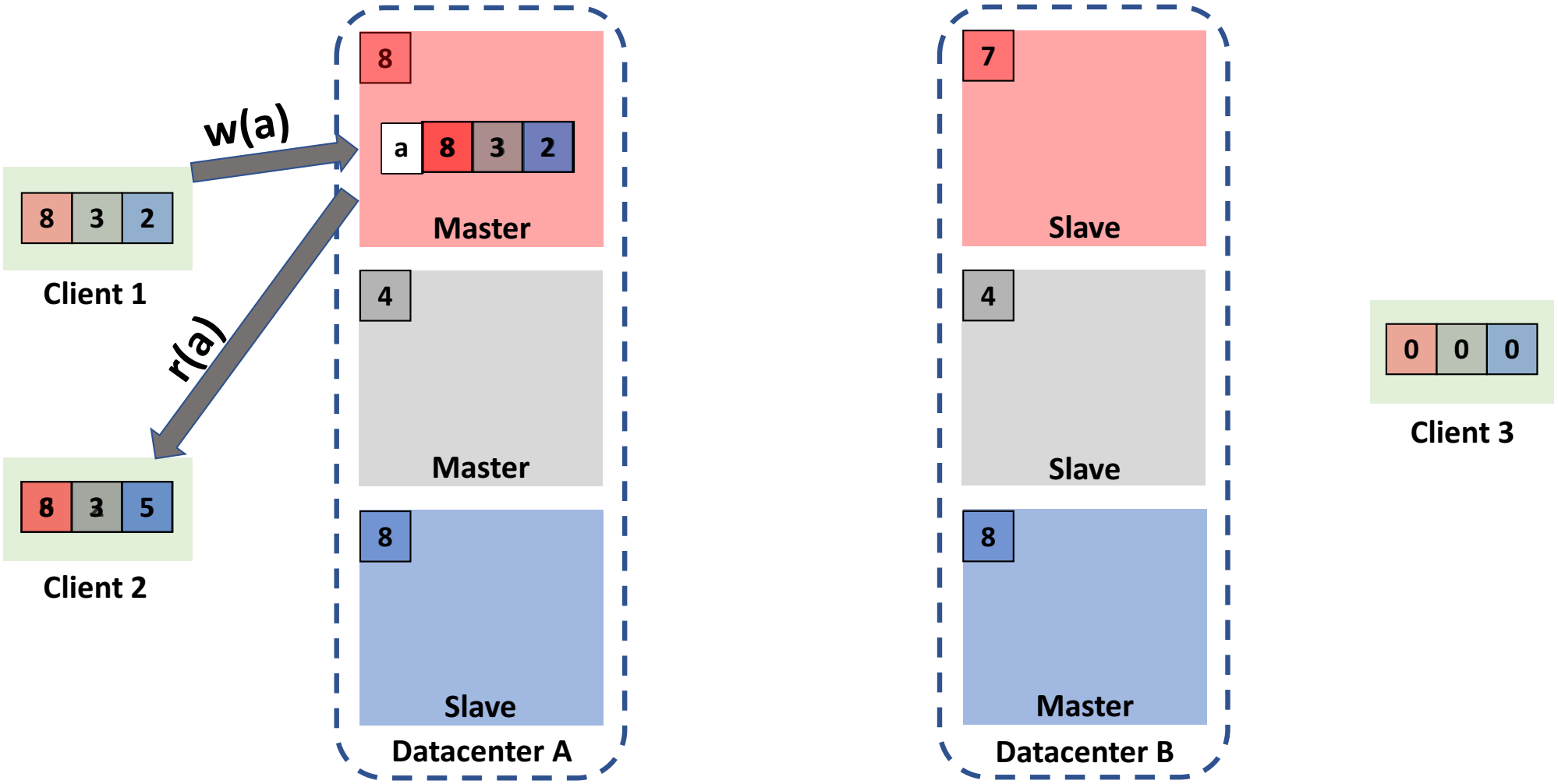
Write Protocol: Causal timestamps stored with objects to propagate dependencies



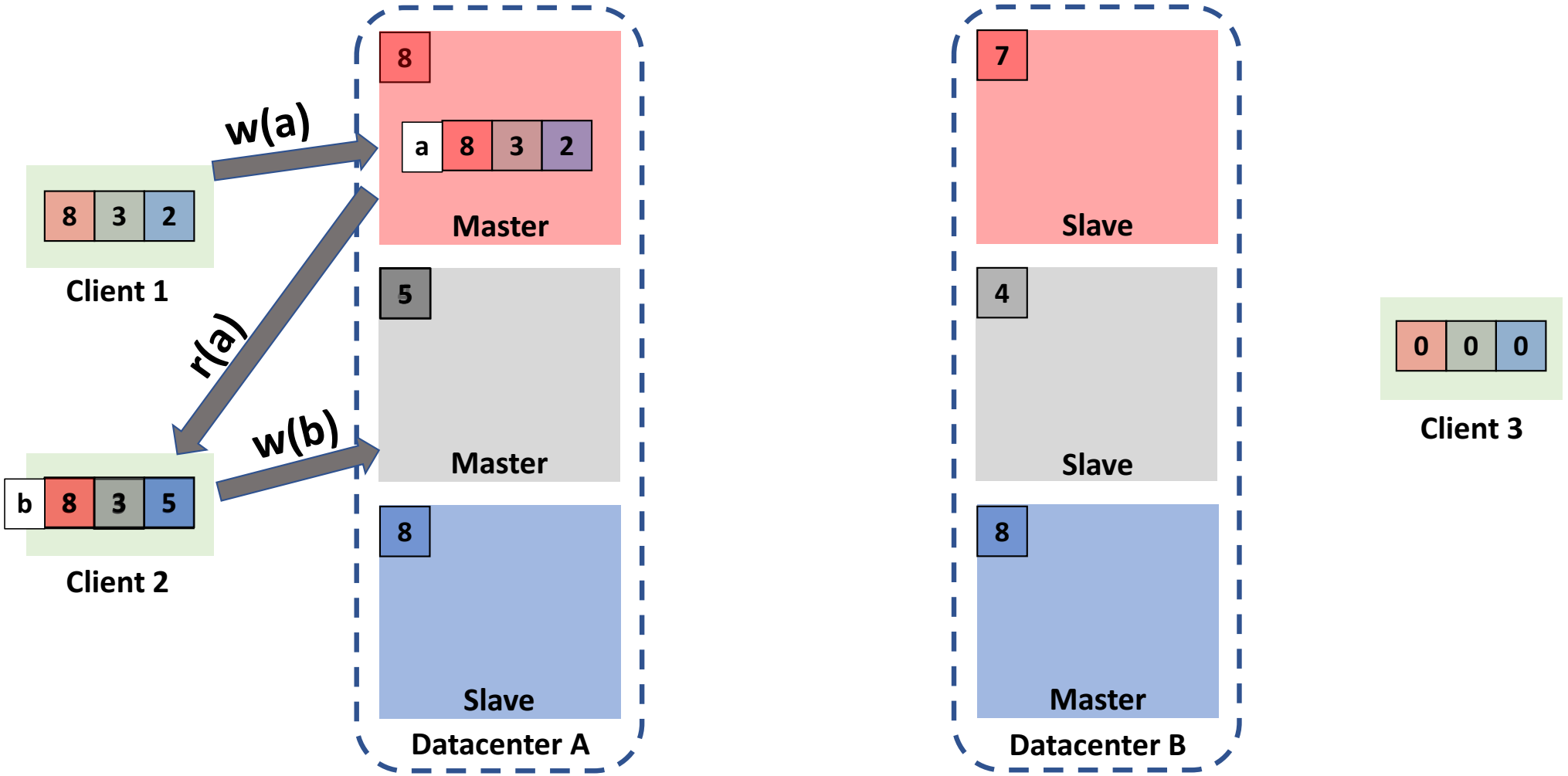
Write Protocol: Server shardstamp is incremented and merged into causal timestamps



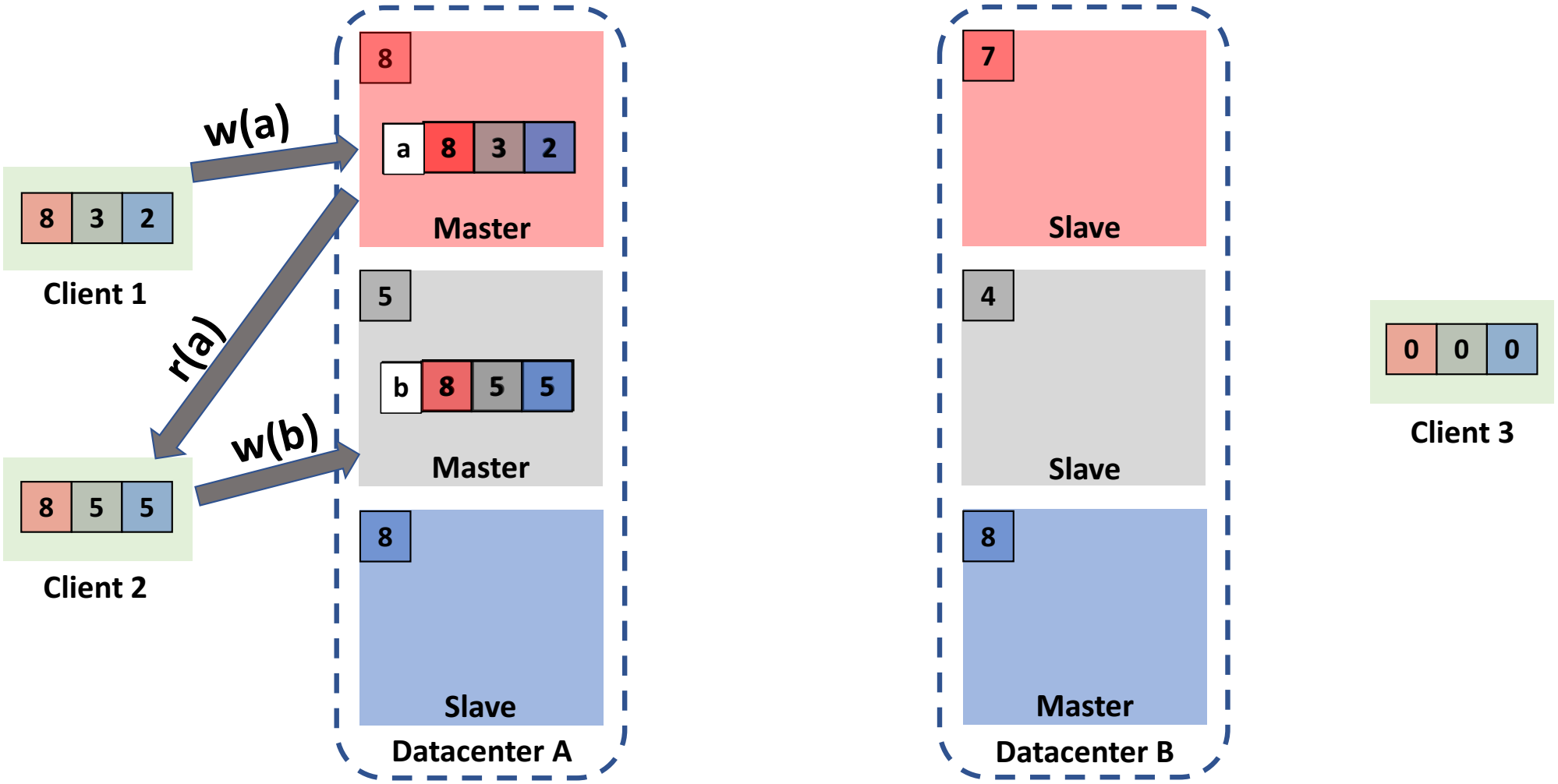
Read Protocol: Always safe to read from master



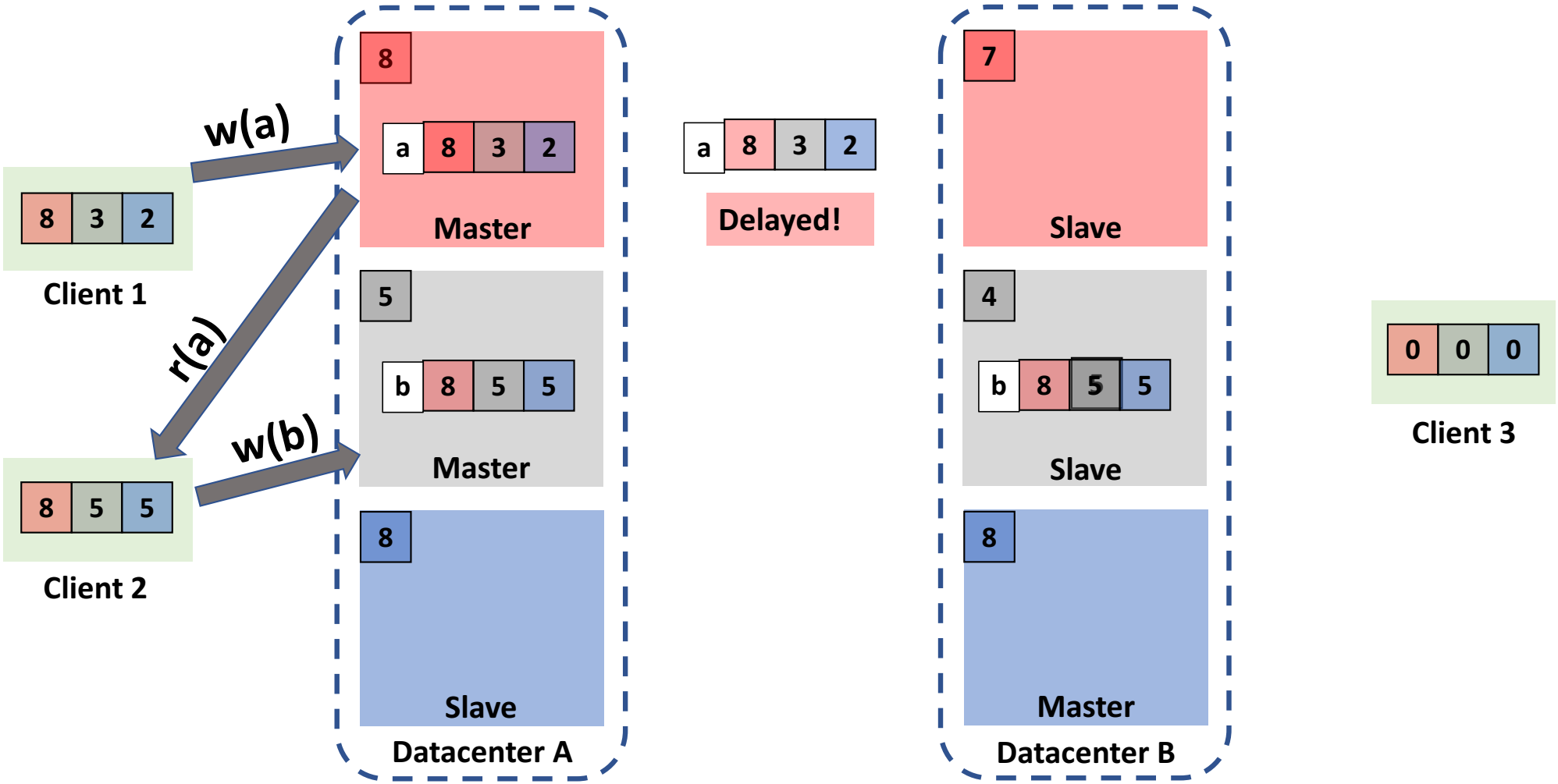
Read Protocol: Object's causal timestamp merged into client's causal timestamp



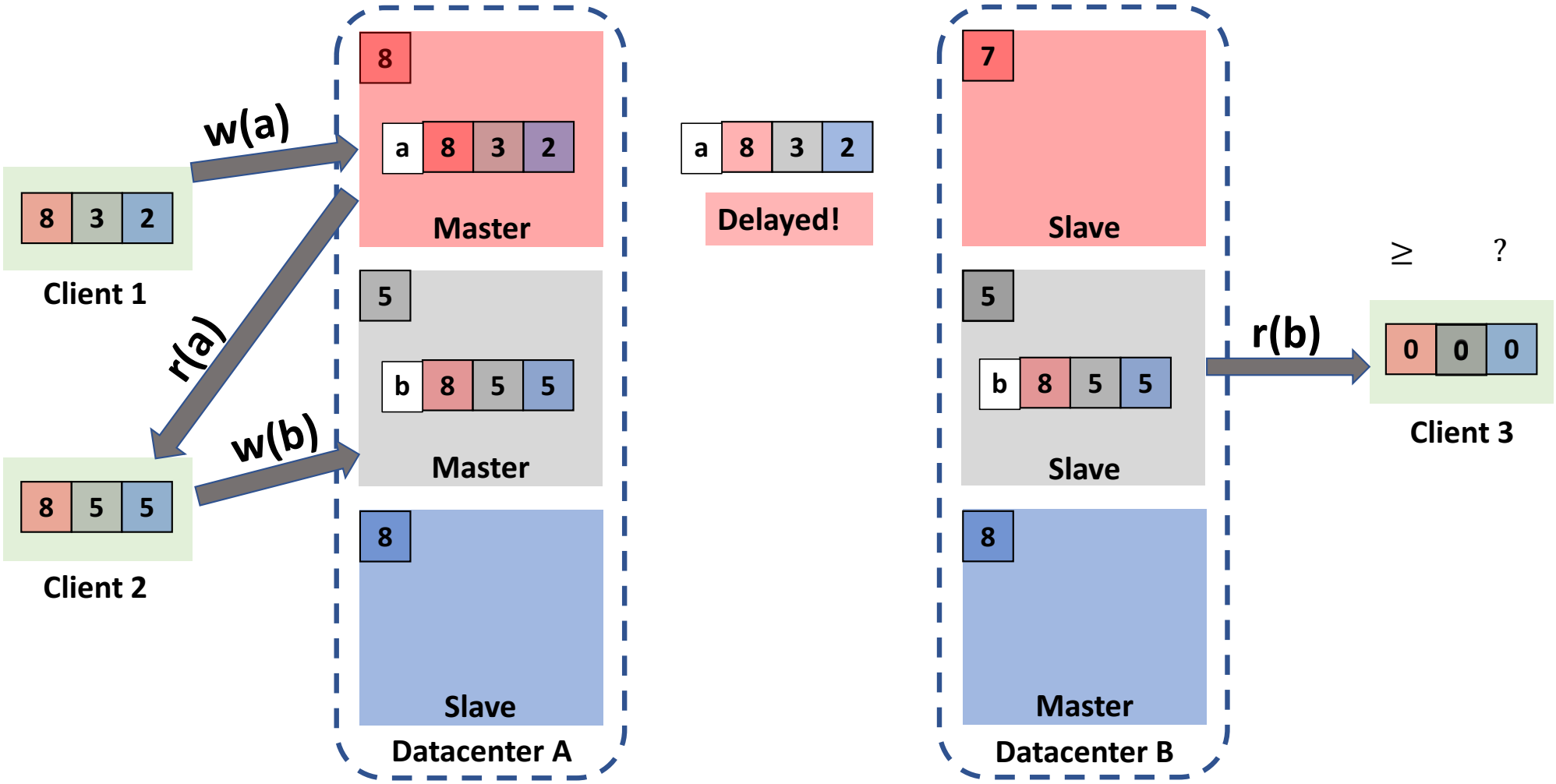
Read Protocol: Causal timestamp merging tracks causal ordering for writes following reads



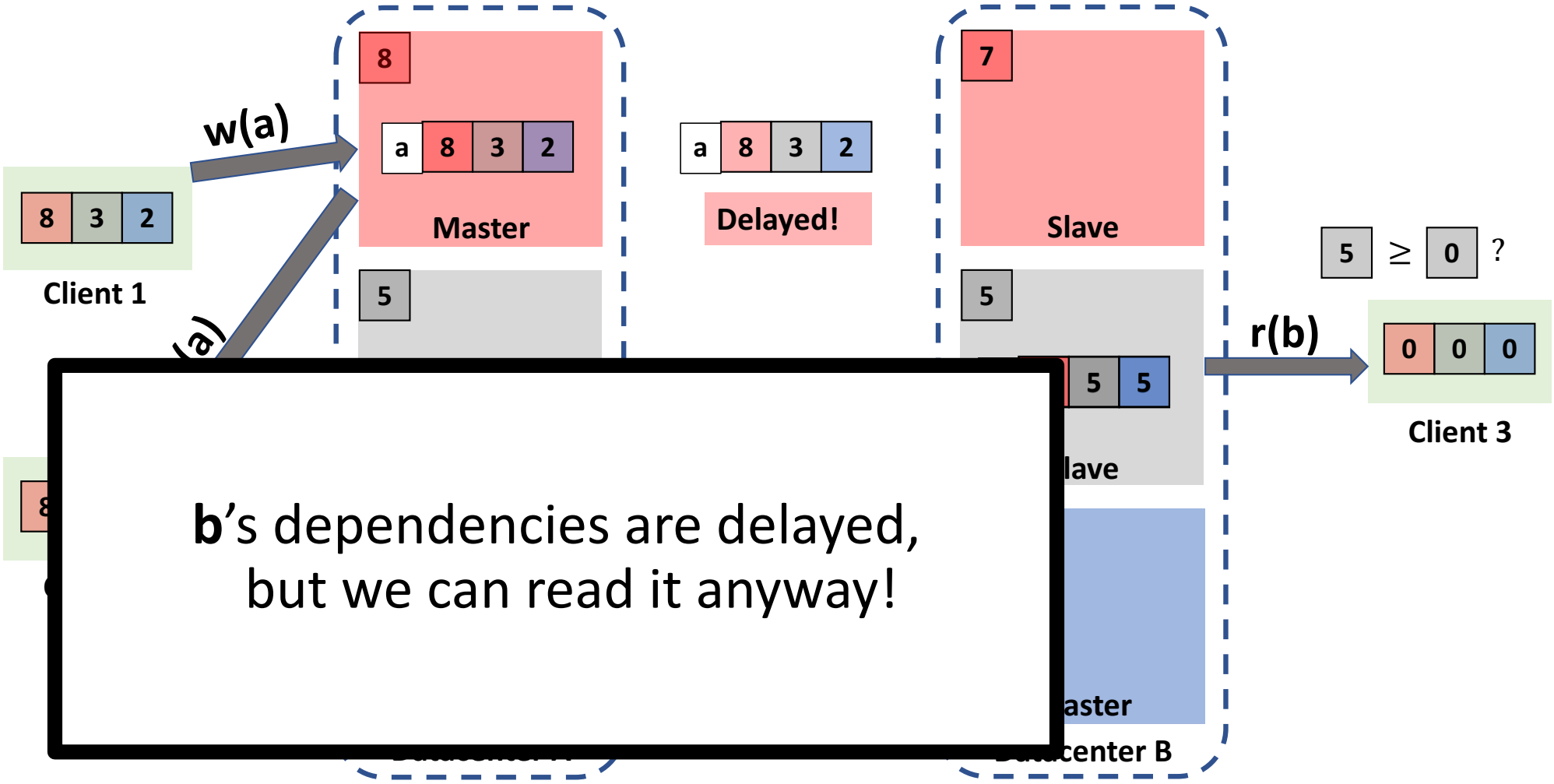
Replication: Like eventual consistency; asynchronous, unordered, writes applied immediately



Replication: Slaves increment their shardstamps using causal timestamp of a replicated write



Read Protocol: Clients do consistency check when reading from slaves



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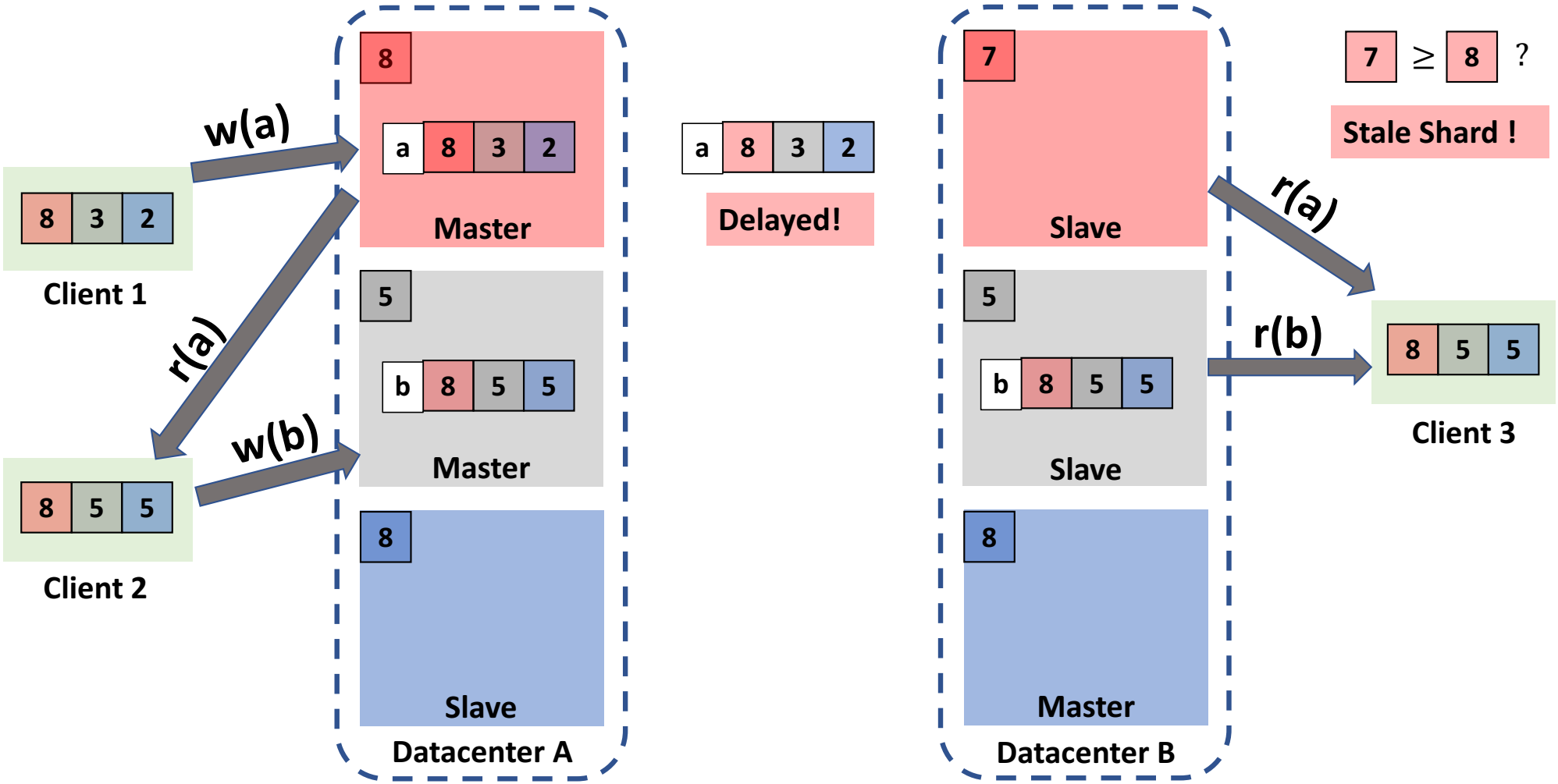
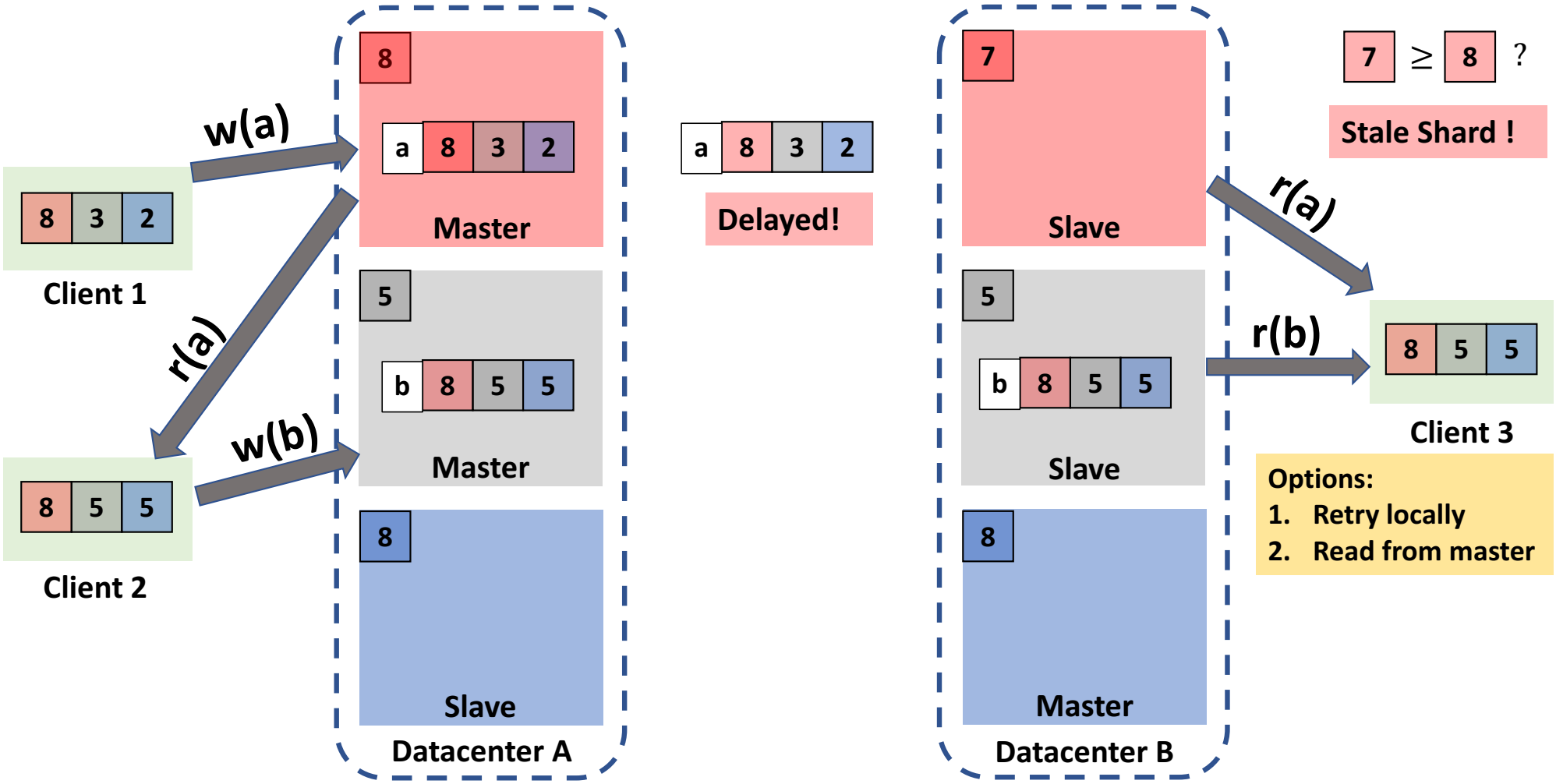


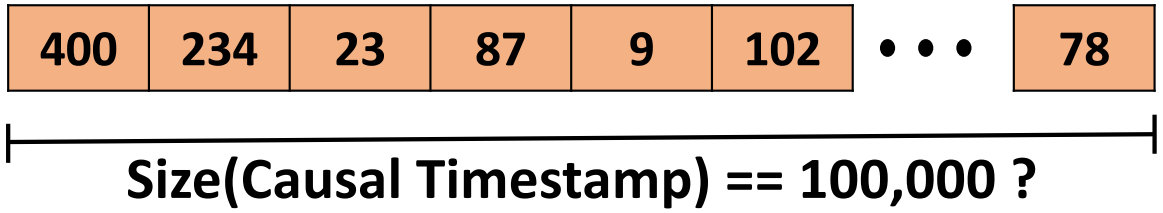
Read Protocol: Clients do consistency check when reading from slaves



Read Protocol: Resolving stale reads

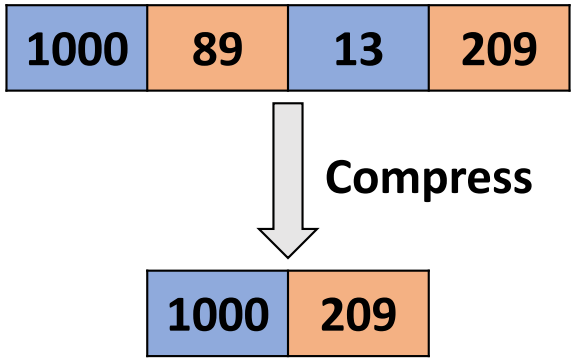
Causal Timestamp Compression

- What happens at scale when number of shards is (say) 100,000 ?



Causal Timestamp Compression: Strawman

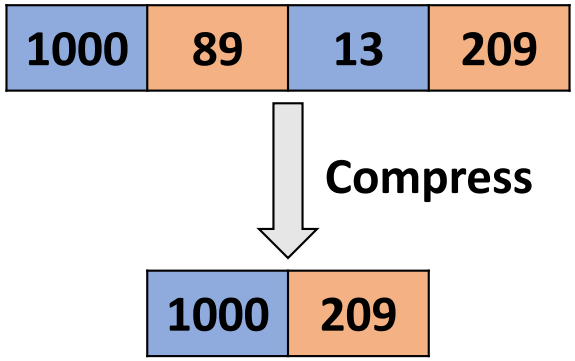
- To compress down to ***n***, conflate shardstamps with same ids modulo ***n***



- Problem: False Dependencies

Causal Timestamp Compression: Strawman

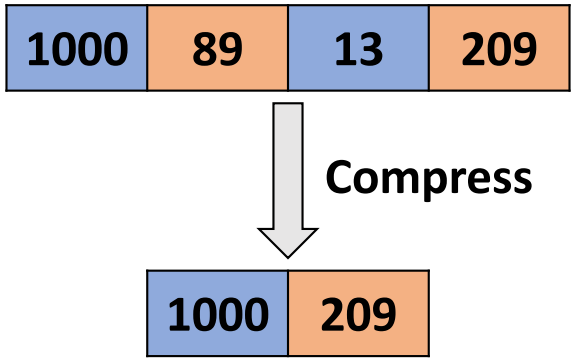
- To compress down to ***n***, conflate shardstamps with same ids modulo ***n***



- Problem: False Dependencies
- Solution:
  - **Use system clock as the next value of shardstamp on a write**
  - Decouples shardstamp value from number of writes on each shard

Causal Timestamp Compression: Strawman

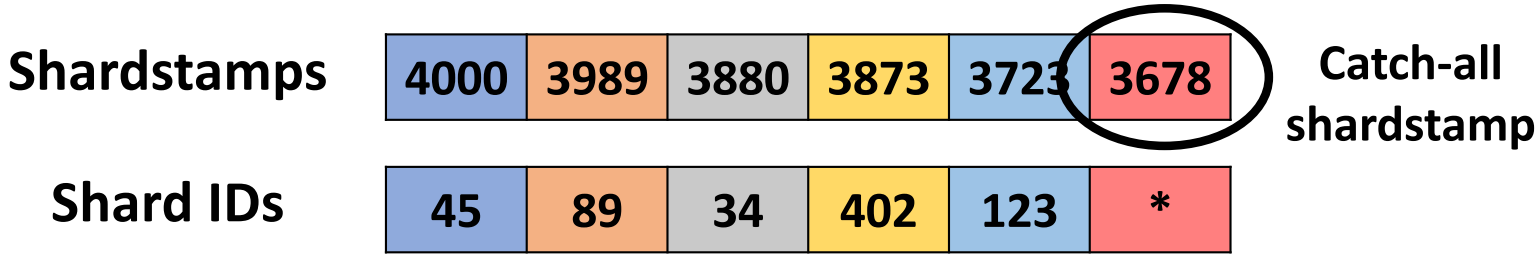
- To compress from ***N*** to ***n***, conflate shardstamps with same ids modulo ***n***



- Problem: Modulo arithmetic still conflates unrelated shardstamps

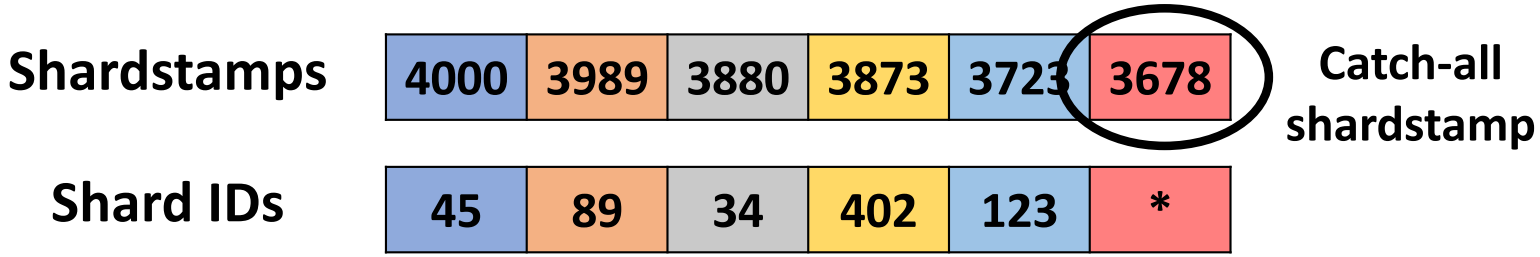
Causal Timestamp Compression

- **Insight**: Recent shardstamps more likely to create false dependencies
- Use high resolution for recent shardstamps and conflate the rest



Causal Timestamp Compression

- **Insight**: Recent shardstamps more likely to create false dependencies
- Use high resolution for recent shardstamps and conflate the rest



- 0.01 % false dependencies with just 4 shardstamps and 16K logical shards

Transactions in OCCULT

Scalable causally consistent general purpose transactions

Properties of Transactions

A. Atomicity
B. Read from a causally consistent snapshot
C. No concurrent conflicting writes

Properties of Transactions

A. ***Observable*** atomicity
B. ***Observably*** read from a causally consistent snapshot
C. No concurrent conflicting writes

Properties of Transactions

A. *Observable* Atomicity
B. *Observably* read from a causally consistent snapshot
C. No concurrent conflicting writes

Properties of Protocol

1. No centralized timestamp authorities (e.g. per-datacenter)
   - Transactions ordered using causal timestamps

Properties of Transactions

A. *Observable* Atomicity
B. *Observably* read from a causally consistent snapshot
C. No concurrent conflicting writes

Properties of Protocol

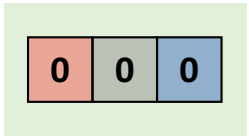
1. No centralized timestamp authority (e.g. per-datacenter)
   - Transactions ordered using causal timestamps
2. Transaction commit latency is independent of number of replicas

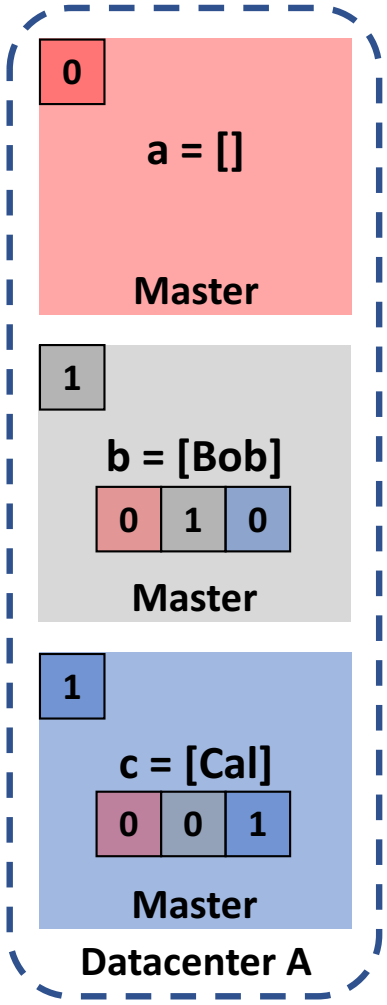
Properties of Transactions

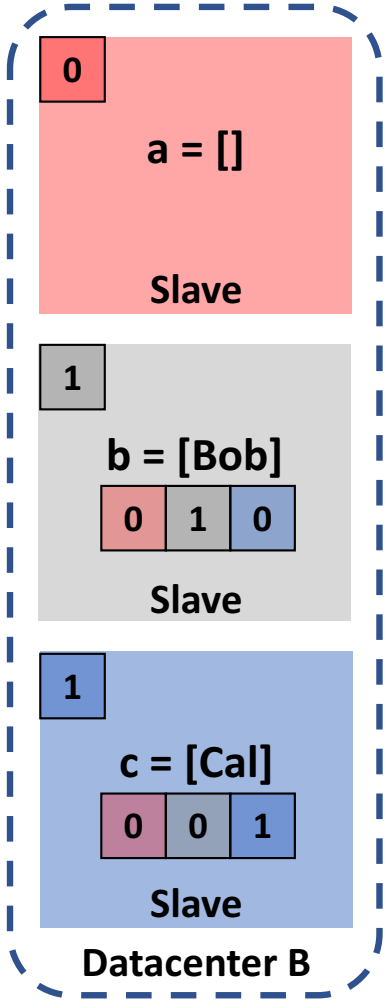
A. Observable Atomicity
B. Observably read from causally consistent snapshot
C. No concurrent conflicting writes

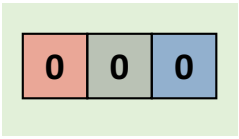
Three Phase Protocol

1. **Read Phase**
   - Buffer writes at client
2. **Validation Phase**
   - Client validates A, B and C using causal timestamps
3. **Commit Phase**
   - Buffered writes committed in an observably atomic way

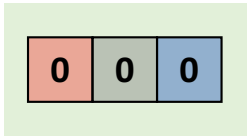


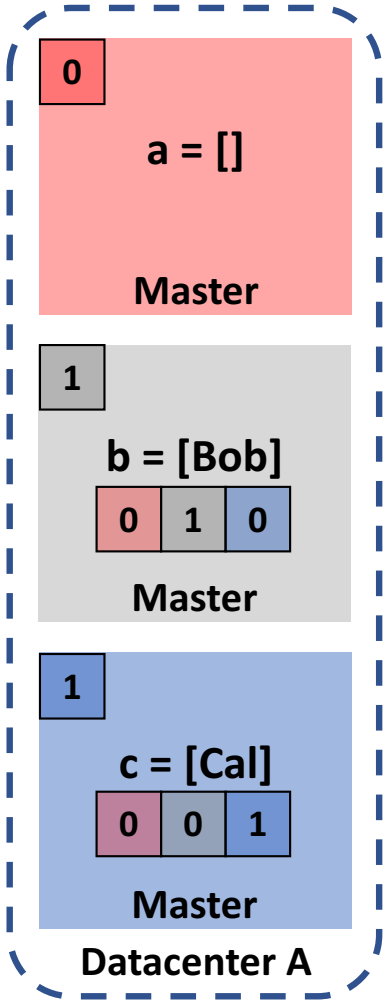


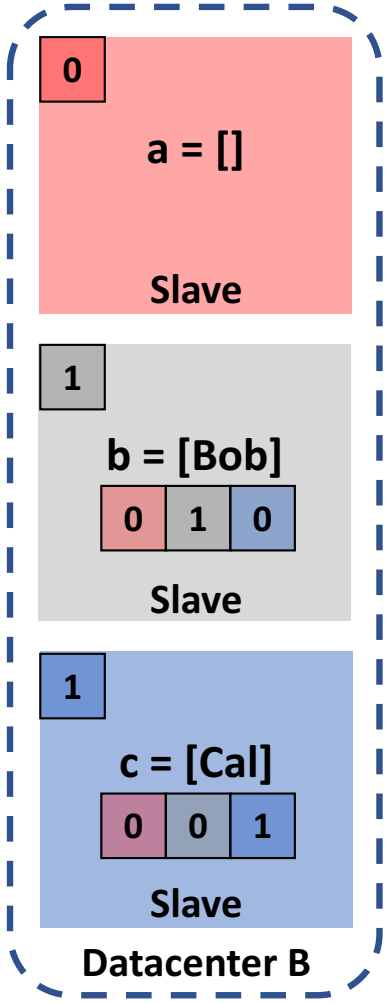


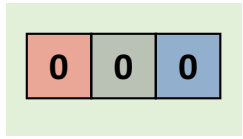


Alice and her advisor are managing lists of students for three courses

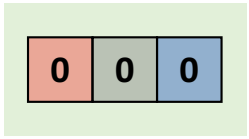




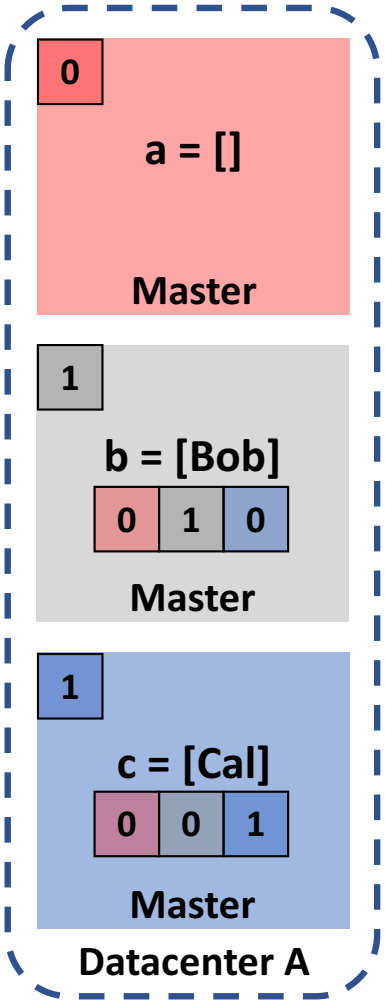


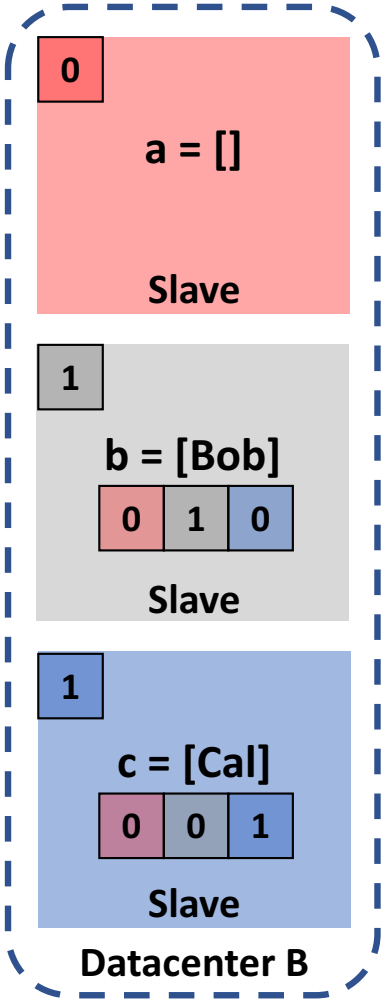


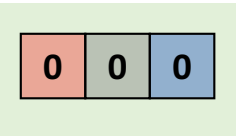
Observable atomicity and causally consistent snapshot reads enforced by same mechanism



Start T_1
r(a) = []
w(a = [Abe])







Transaction T_1 : Alice adding Abe to course **a**

1 0 0

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

1
a = [Abe]
1 0 0
Master

1
b = [Bob]
0 1 0
Master

1
c = [Cal]
0 0 1
Master

Datacenter A

0
a = []
Slave

1
b = [Bob]
0 1 0
Slave

1
c = [Cal]
0 0 1
Slave

Datacenter B

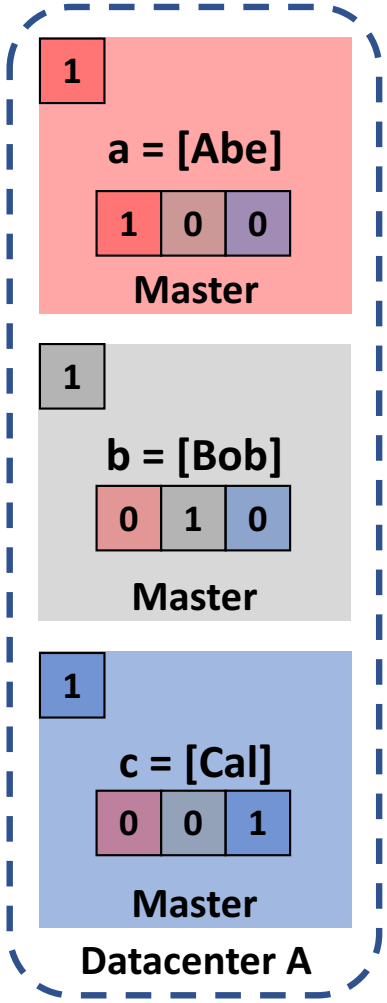
0 0 0

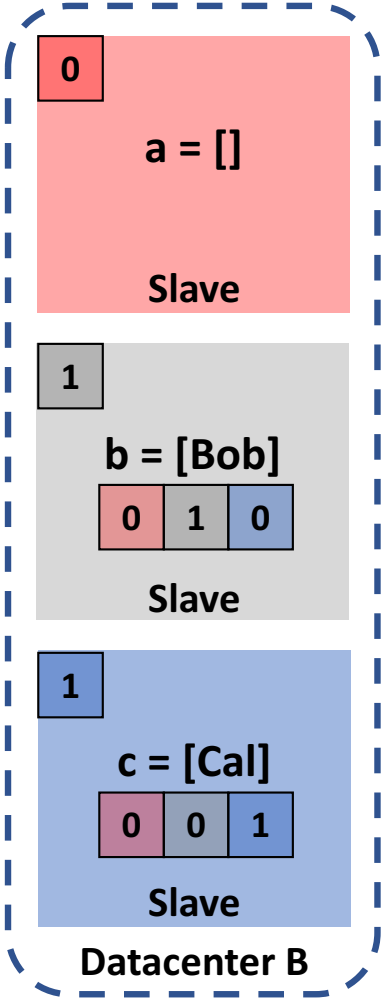
Transaction T_1 : After Commit

1 0 0

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

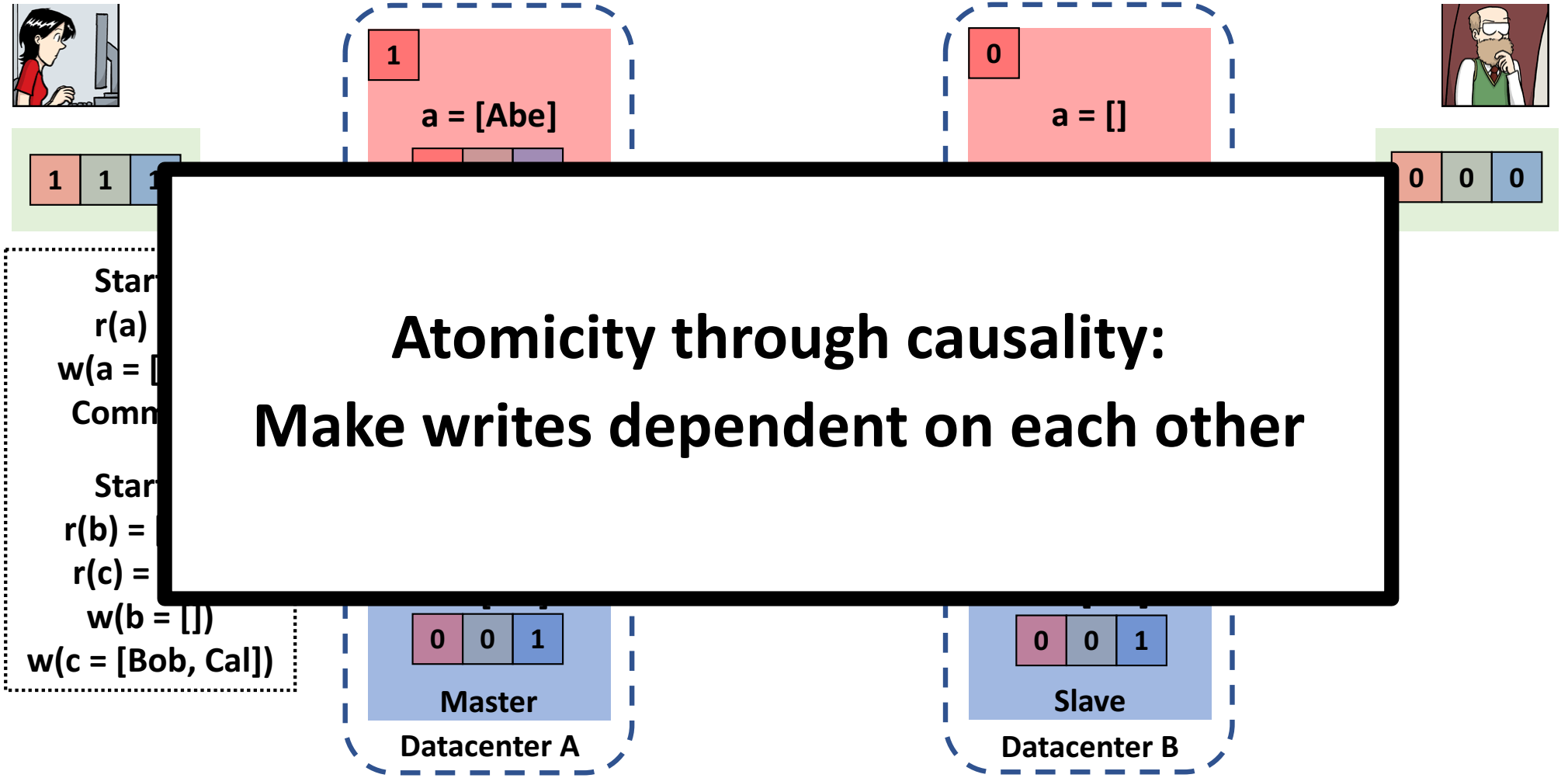
Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])



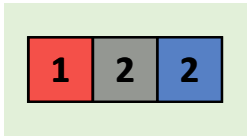


0 0 0

Transaction T_2 : Alice moving Bob from course **b** to course **c**

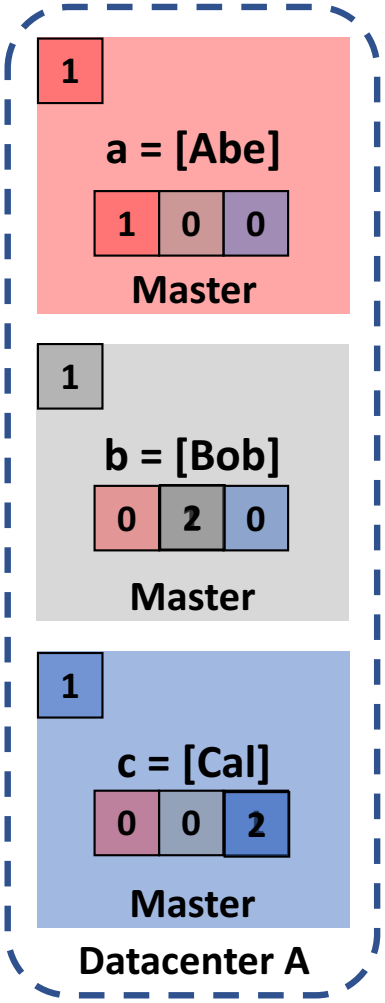


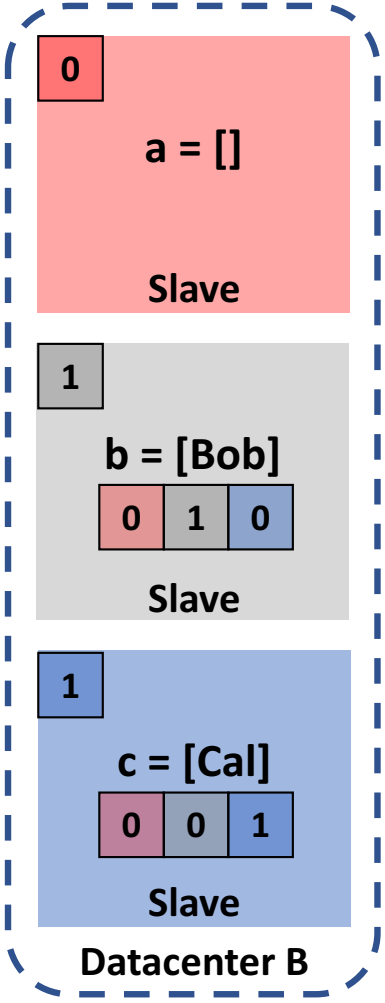
Observable Atomicity: Make writes causally dependent on each other

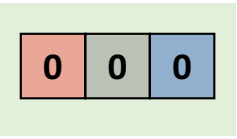


Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

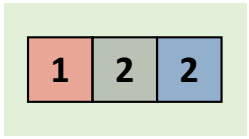
Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])





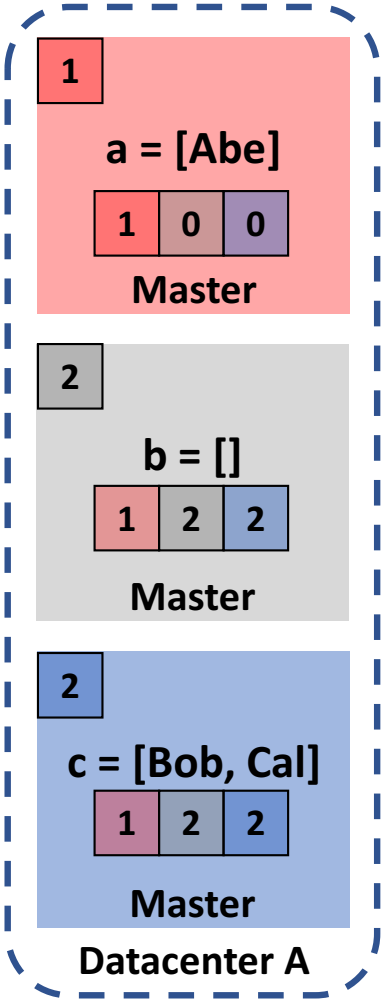


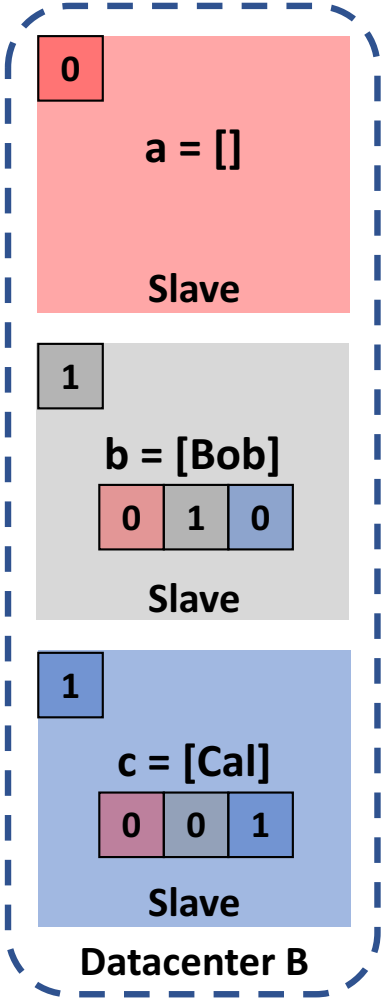
Observable Atomicity: Same commit timestamp makes writes causally dependent on each other

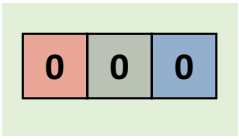


Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

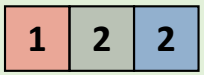
Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2

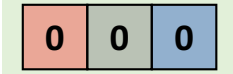






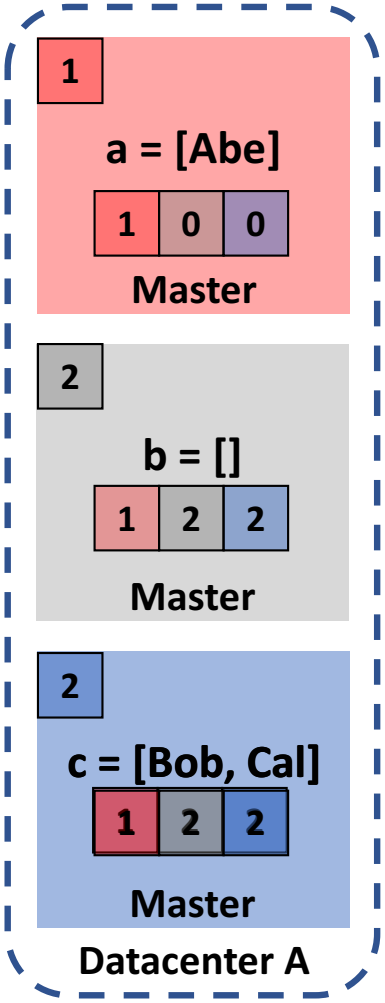
Observable Atomicity: Same commit timestamp makes writes causally dependent on each other

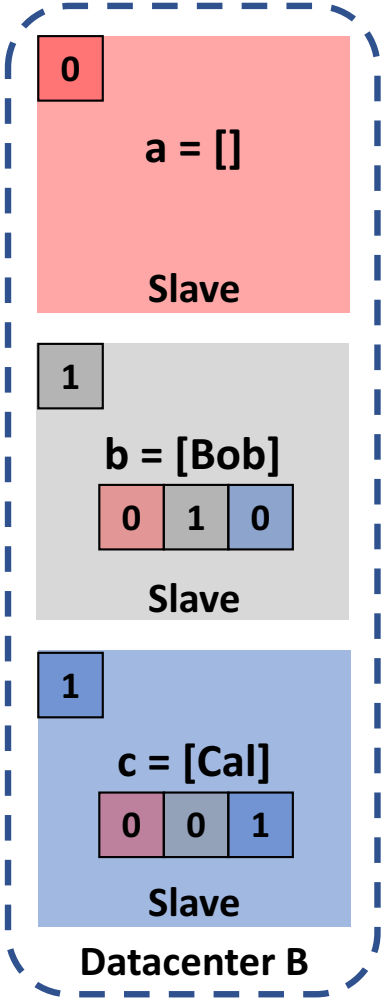




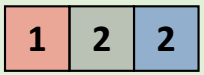
Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

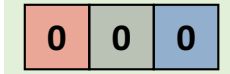
Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2





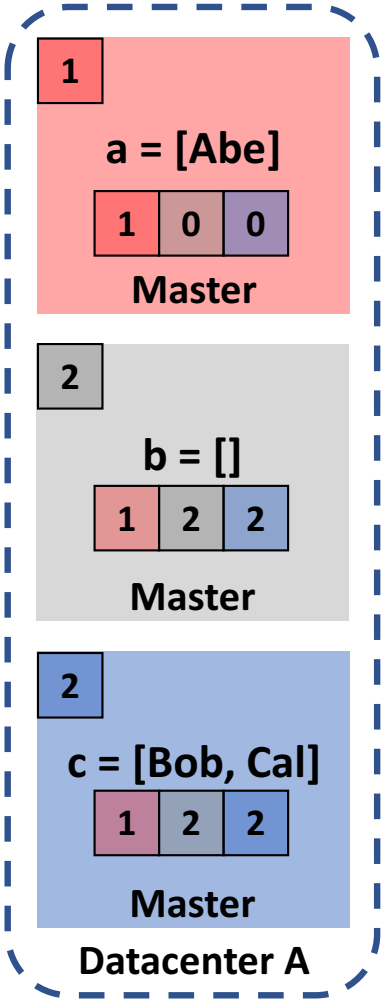
Transaction writes replicate asynchronously





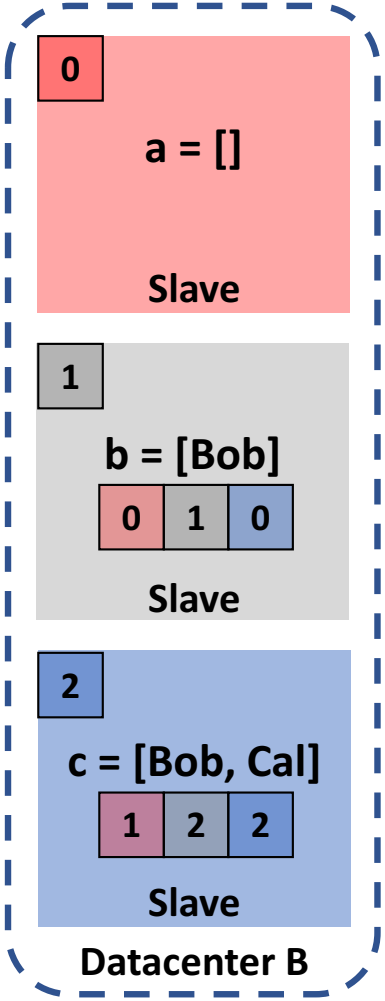
Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2



Delayed!

Delayed!



Transaction writes replicate asynchronously

1 2 2

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2

1
a = [Abe]
1 0 0
Master

2
b = []
1 2 2
Master

2
c = [Bob, Cal]
1 2 2
Master

Datacenter A

Delayed!

Delayed!

0
a = []
Slave

1
b = [Bob]
0 1 0
Slave

2
c = [Bob, Cal]
1 2 2
Slave

Datacenter B

0 0 0

Start T_3

Alice's advisor reads the lists in a transaction

1 2 2

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2

1
a = [Abe]
1 0 0
Master

2
b = [] Delayed!
1 2 2
Master

2
c = [Bob, Cal]
1 2 2
Master

Datacenter A

0
a = []
Slave

1
b = [Bob] Delayed!
0 1 0
Slave

2
c = [Bob, Cal]
1 2 2
Slave

Datacenter B

0 1 0

Start T_3
r(b) = [Bob]

Alice's advisor reads the lists in a transaction

1 2 2

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2

1
a = [Abe]
1 0 0
Master

2
b = []
1 2 2
Master

2
c = [Bob, Cal]
1 2 2
Master

Datacenter A

Delayed!

Delayed!

0
a = []
Slave

1
b = [Bob]
0 1 0
Slave

2
c = [Bob, Cal]
1 2 2
Slave

Datacenter B

0 1 0

Start T_3
r(b) = [Bob]

T_3 Read Set
b = [Bob]

Transactions maintain a Read Set to validate atomicity and causal snapshot reads

1 2 2

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2

1
a = [Abe]
1 0 0
Master

2
b = []
1 2 2
Master

2
c = [Bob, Cal]
1 2 2
Master

Datacenter A

Delayed!

Delayed!

0
a = []
Slave

1
b = [Bob]
0 1 0
Slave

2
c = [Bob, Cal]
1 2 2
Slave

Datacenter B

1 2 2

Start T_3
r(b) = [Bob]
r(c) = [Bob,Cal]

T_3 Read Set
b = [Bob]
1 0 1 0
c = [Bob, Cal]

Transactions maintain a Read Set to validate atomicity and read from causal snapshot

1 2 2

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2

1
a = [Abe]
1 0 0
Master

2
b = []
1 2 2
Master

2
c = [Bob, Cal]
1 2 2
Master

Datacenter A

Delayed!

Delayed!

0
a = []
Slave

1
b = [Bob]
0 1 0
Slave

2
c = [Bob, Cal]
1 2 2
Slave

Datacenter B

1 2 2

Start T_3
r(b) = [Bob]
r(c) = [Bob,Cal]

T_3 Read Set
b = [Bob]
1 0 1 0
c = [Bob, Cal]
2 1 2 2

Validation failure: **c** knows more writes from grey shard than applied at the time **b** was read

1 2 2

Start T_1
r(a) = []
w(a = [Abe])
Commit T_1

Start T_2
r(b) = [Bob]
r(c) = [Cal]
w(b = [])
w(c = [Bob, Cal])
Commit T_2

1
a = [Abe]
1 0 0
Master

2
b = []
1 2 2
Master

2
c = [Bob, Cal]
1 2 2
Master

Datacenter A

Delayed!

Delayed!

0
a = []
Slave

1
b = [Bob]
0 1 0
Slave

2
c = [Bob, Cal]
1 2 2
Slave

Datacenter B

1 2 2

Start T_3
r(b) = [Bob]
r(c) = [Bob,Cal]
r(a) = []

T_3 Read Set
b = [Bob]
1 0 1 0
c = [Bob, Cal]
2 1 2 2

Ordering Violation: Detected in the usual way. Red Shard is stale !

Properties of Transactions

A. Observable Atomicity
B. Observably read from causally consistent snapshot
C. No concurrent conflicting writes

Three Phase Protocol

1. **Read Phase**
   - Buffer writes at client
2. **Validation Phase**
   - Client validates A, B and C using causal timestamps
3. **Commit Phase**
   - Buffered writes committed in an observably atomic way

Properties of Transactions

A. Observable Atomicity
B. Observably read from causally consistent snapshot
C. No concurrent conflicting writes

Three Phase Protocol

1. **Read Phase**
   - Buffer writes at
2. **Validation Phase**
   - Client validates
3. **Commit Phase**
   - Buffered writes committed in an observably atomic way

2. Validation Phase

a. Validate Read Set to verify A and B
b. Validate Overwrite Set to verify C

Evaluation

Evaluation Setup

- Occult implemented by modifying Redis Cluster (baseline)
- Evaluated on CloudLab
  - Two datacenters in WI and SC
  - 20 server machines (4 server processes per machine)
  - 16K logical shards
- YCSB used as the benchmark
  - For graphs shown here read-heavy (95% reads) workload with zipfian distribution

Evaluation Setup

- Occult implemented by modifying Redis Cluster (baseline)
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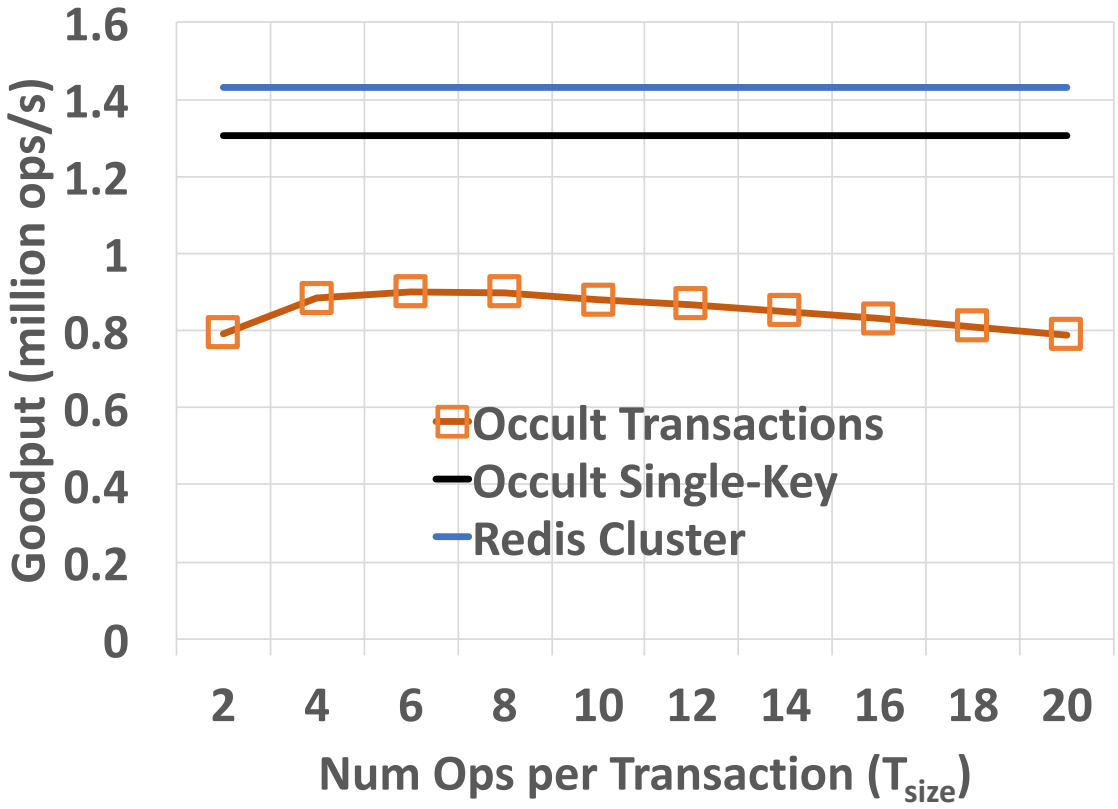
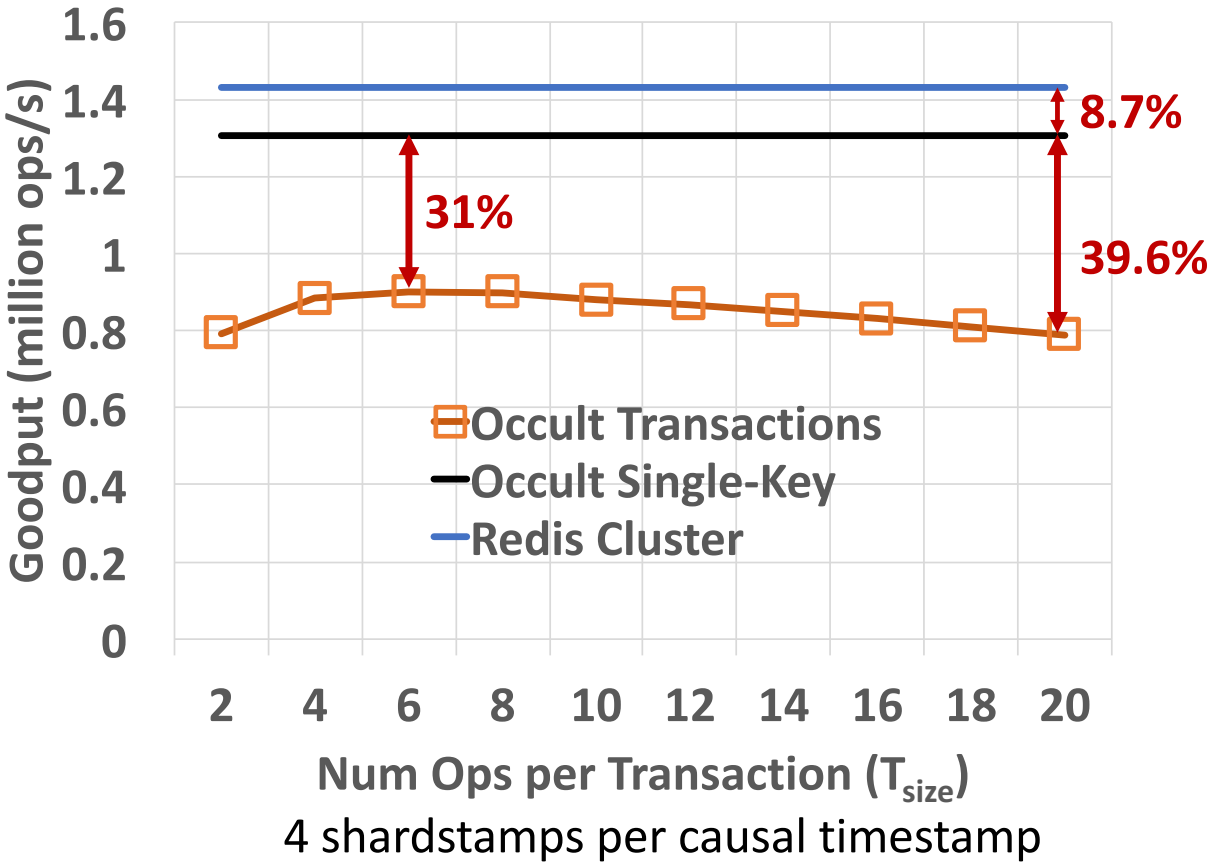
  - 20 server machines (4 server processes per machine)
  - 16K logical shards
- YCSB used as the benchmark
  - For graphs shown here read-heavy (95% reads) workload with zipfian distribution
- We show cost of providing consistency guarantees

Goodput Comparison

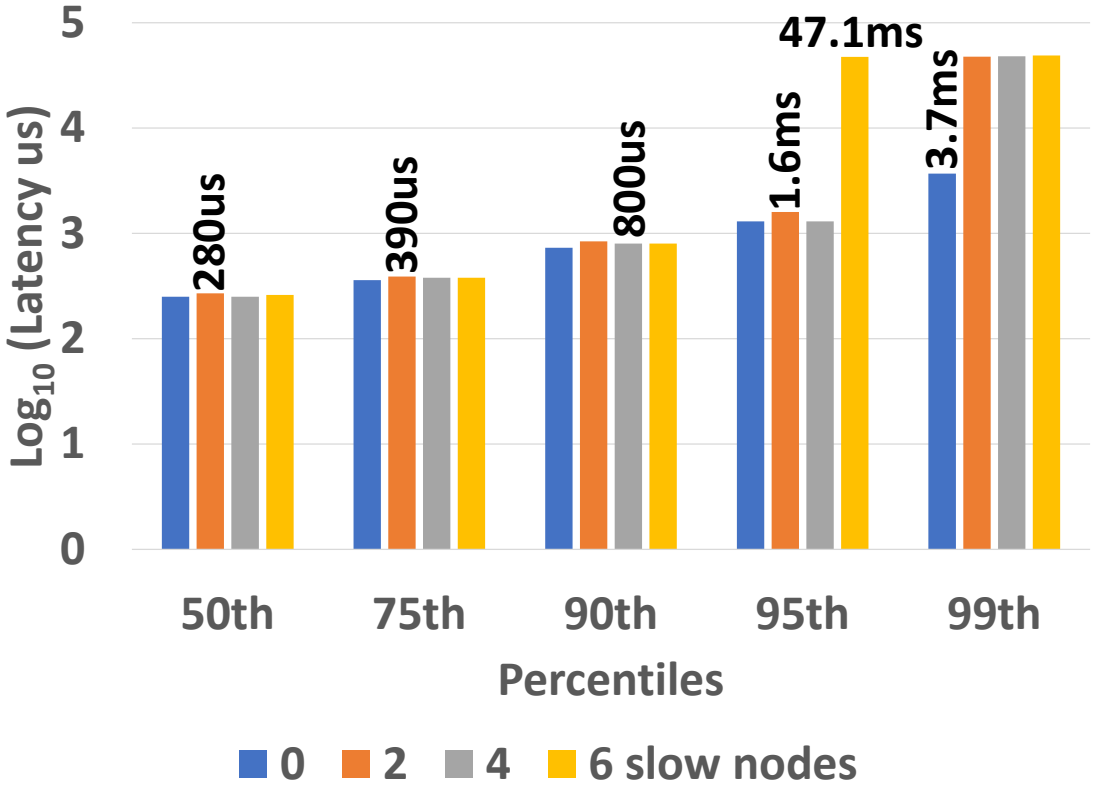


Goodput Comparison



4 shardstamps per causal timestamp

Effect of slow nodes on Occult Latency



Conclusions

- Enforcing **causal consistency** in the data store is vulnerable to slowdown cascades

- Sufficient to ensure that clients **observe** causal consistency:
  - Use lossy timestamps to provide the guarantee
  - Avoid slowdown cascades

- Observable enforcement can be extended to causally consistent transactions
  - Make writes causally dependent on each other to observe atomicity
  - Also avoids slowdown cascades