Carnegie Mellon University

Intro to Database Systems (15-445/645)

Lecture #23

Distributed OLTP Databases

SPRING 2024 ❯❯ Prof. Jignesh Patel

LAST CLASS

System Architectures
→ Shared-Everything, Shared-Disk, Shared-Nothing

Partitioning/Sharding
→ Hash, Range, Round Robin

Transaction Coordination
→ Centralized vs. Decentralized

OLTP VS. OLAP

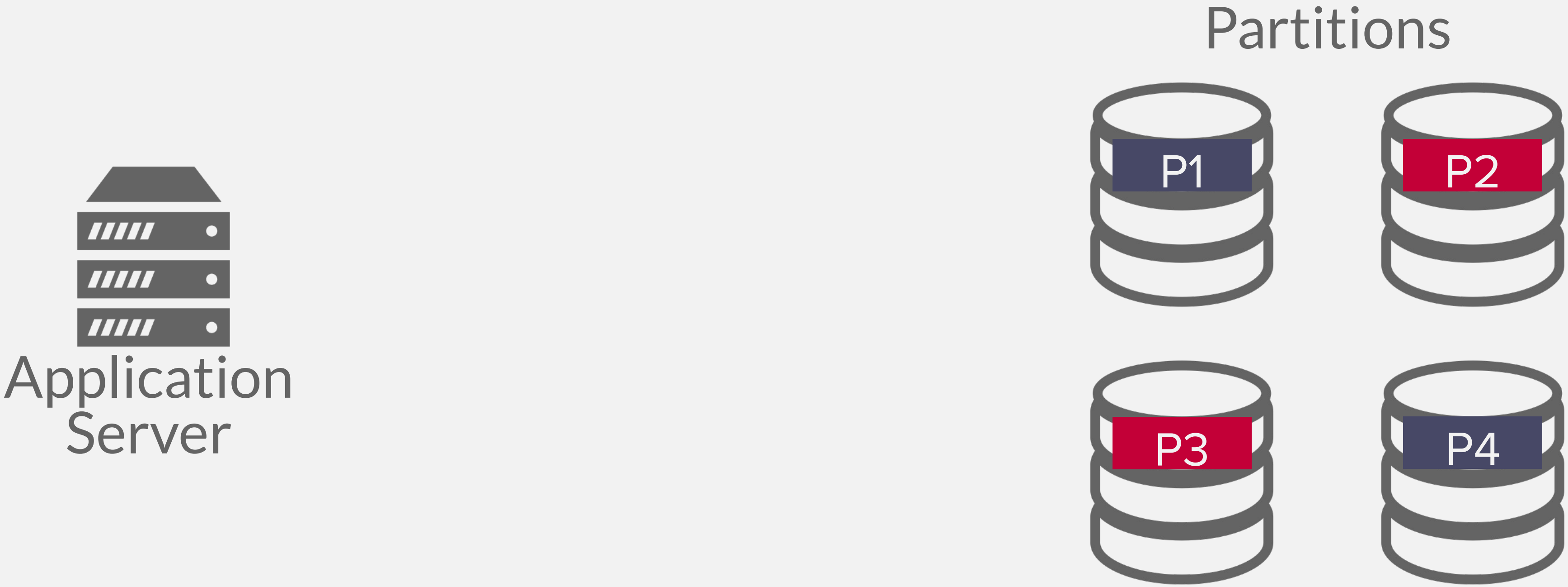
On-line Transaction Processing (OLTP):

→ Short-lived read/write txns.
→ Small footprint.
→ Repetitive operations.

On-line Analytical Processing (OLAP):

→ Long-running, read-only queries.
→ Complex joins.
→ Exploratory queries.

DECENTRALIZED COORDINATOR



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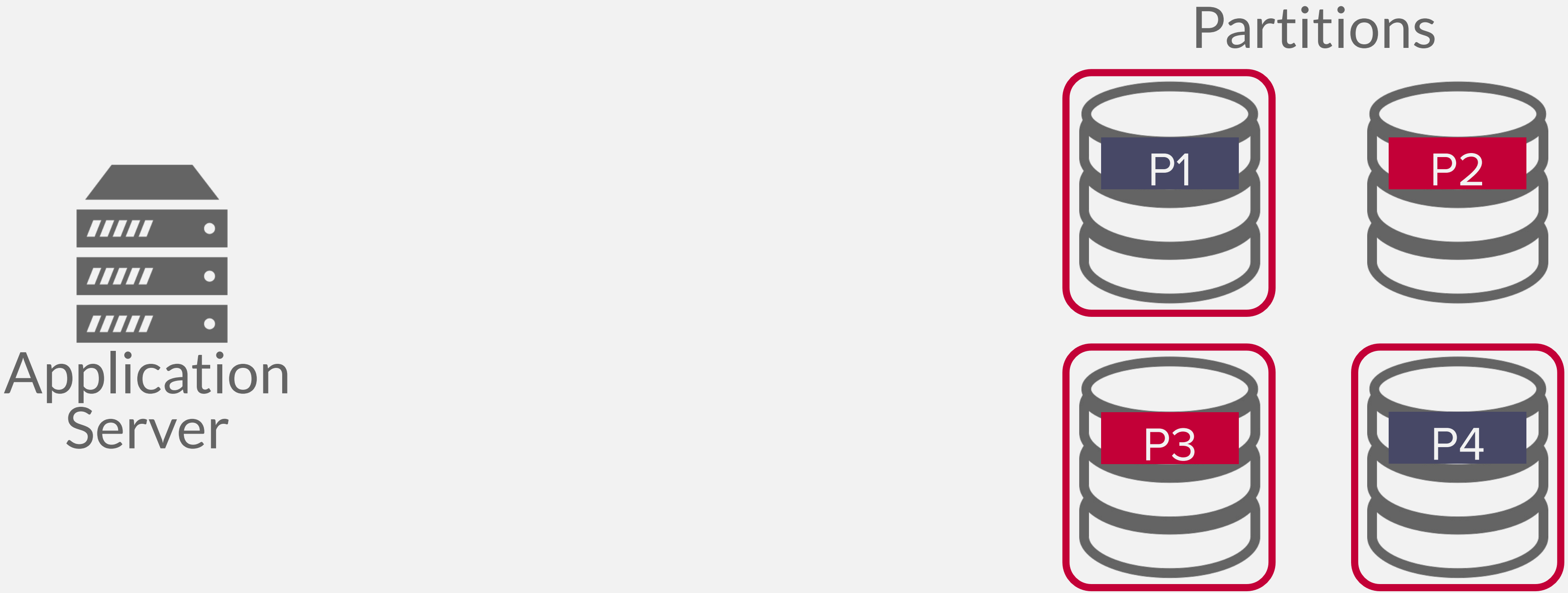

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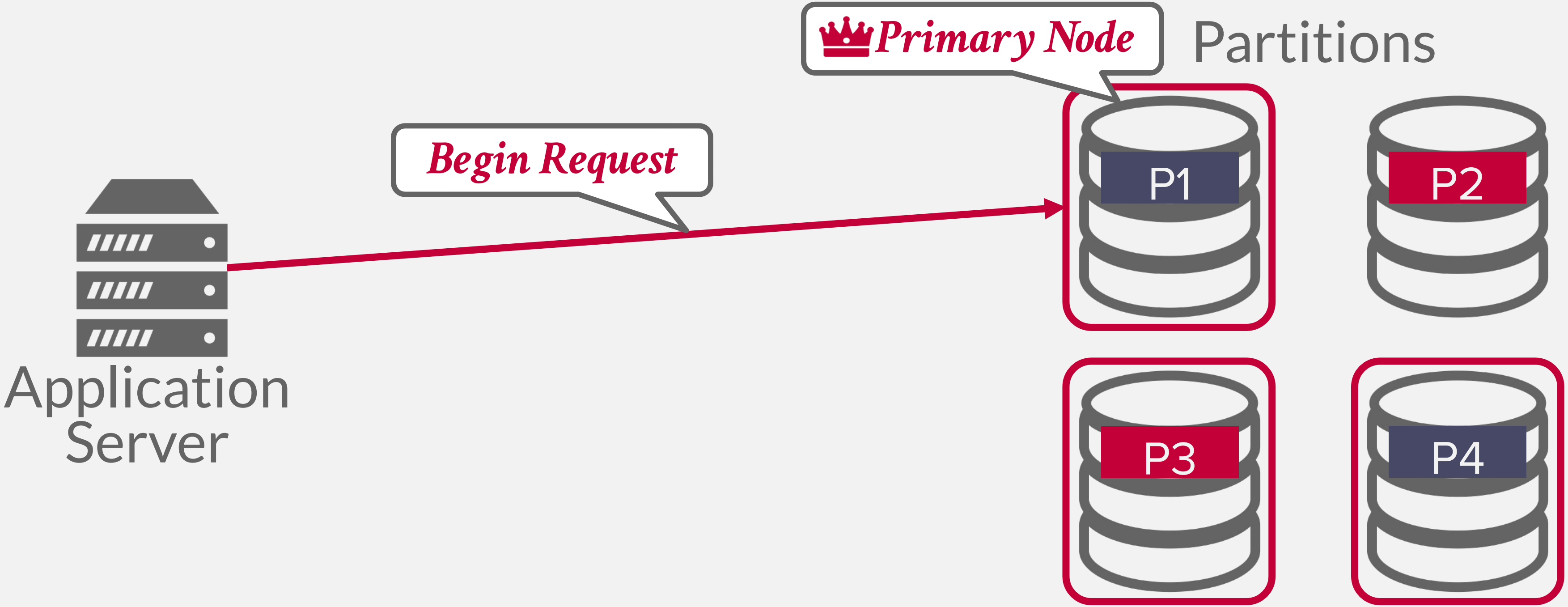

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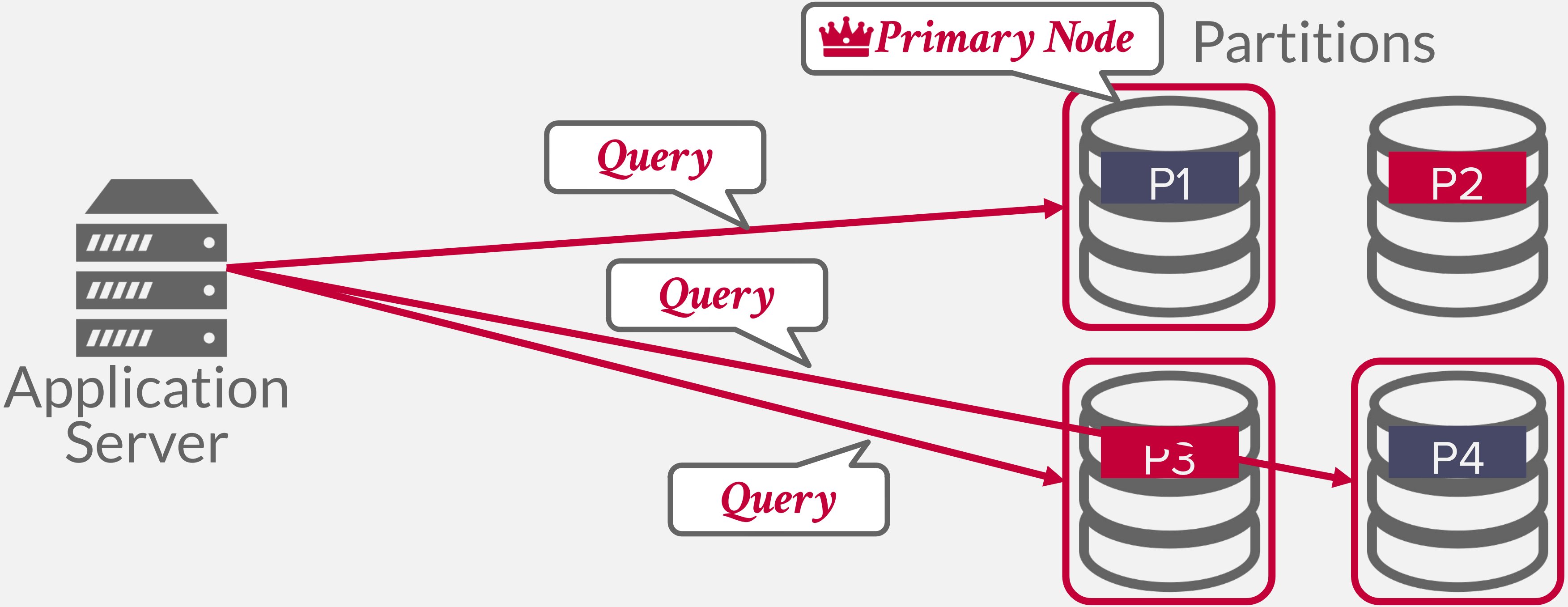

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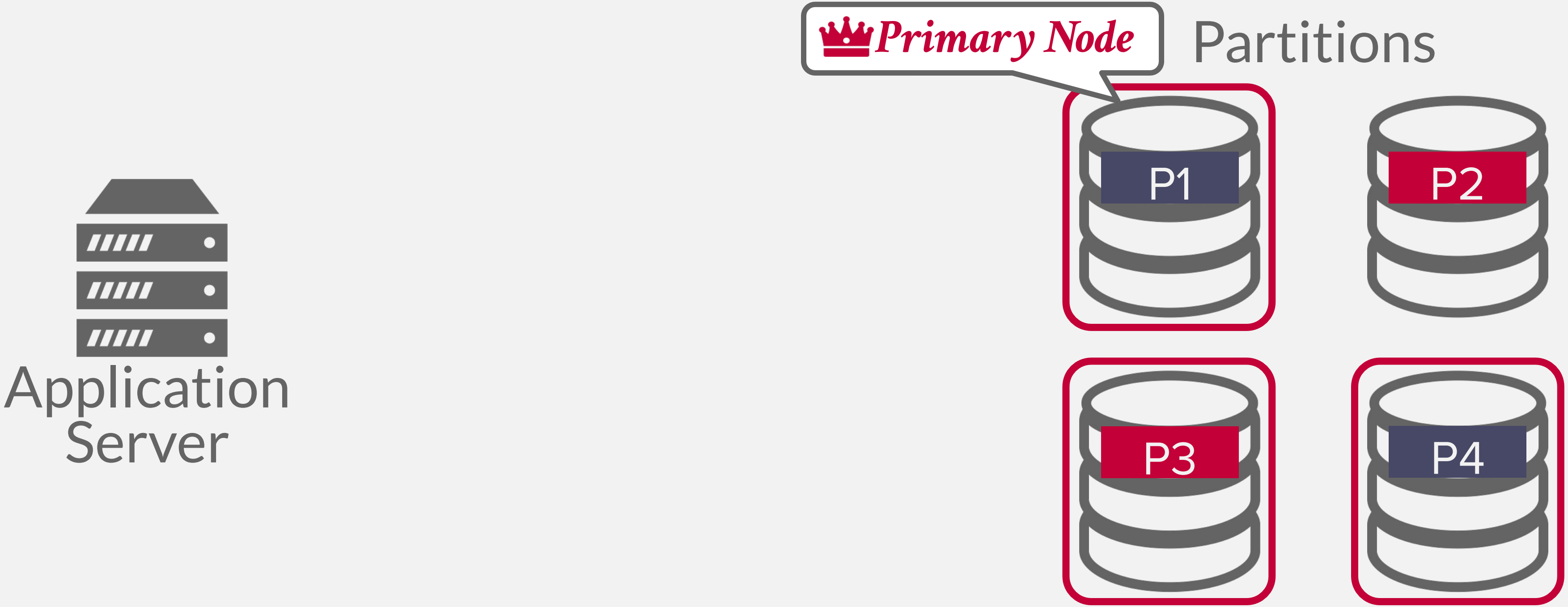

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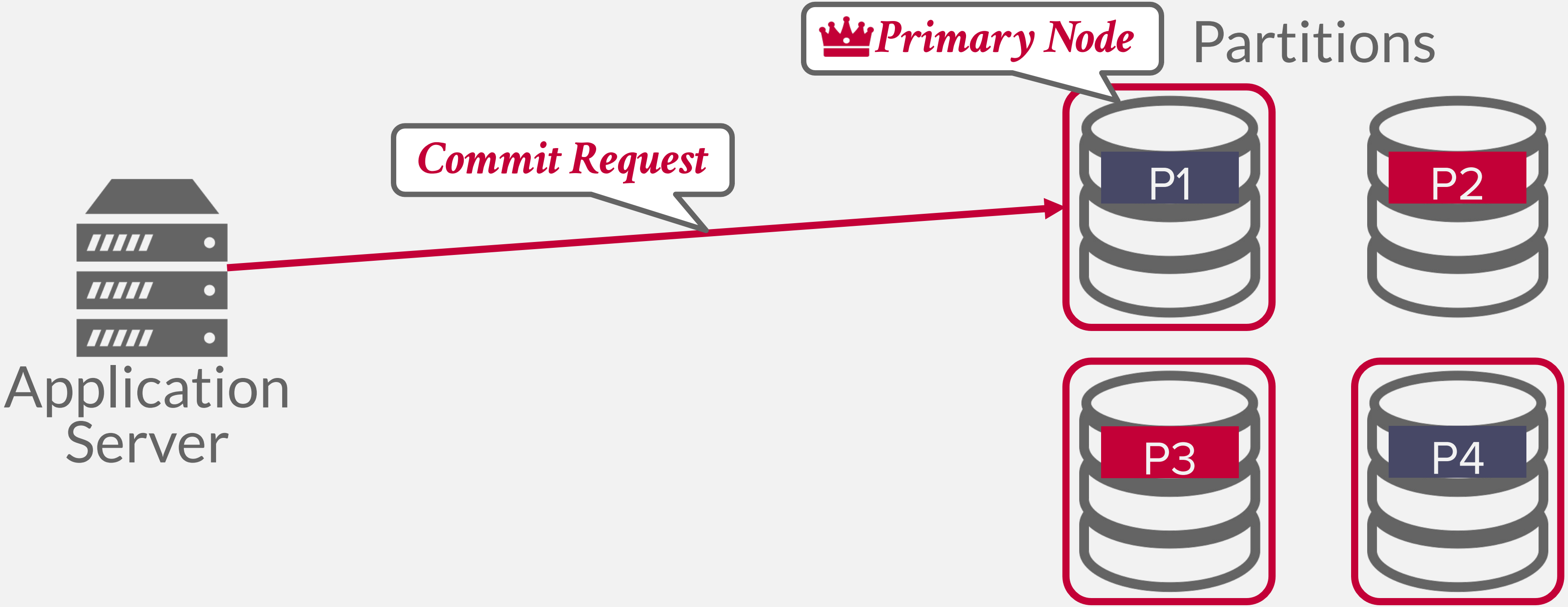

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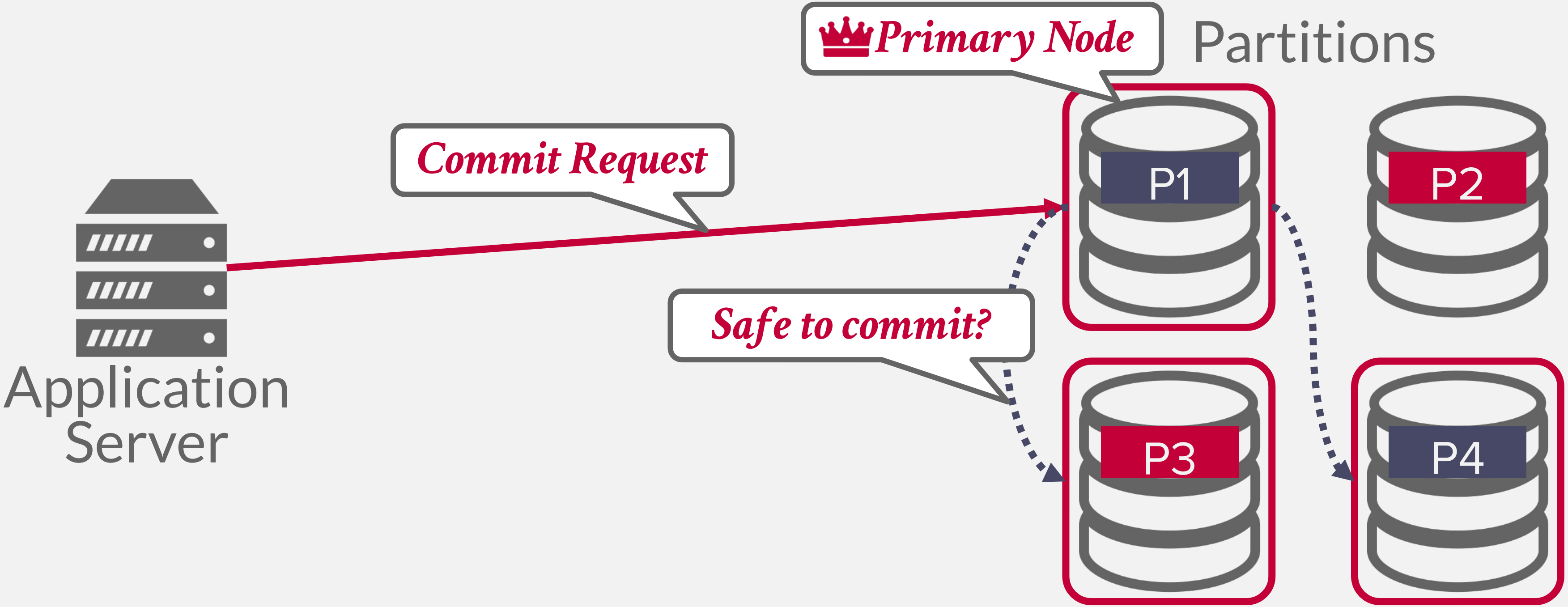


OBSERVATION

Recall that our goal is to have multiple physical nodes appear as a single logical DBMS.

We have not discussed how to ensure that all nodes agree to commit a txn and then to make sure it does commit if the DBMS decides it should.

→ What happens if a node fails?
→ What happens if messages show up late?
→ What happens if the system does not wait for every node to agree to commit?

IMPORTANT ASSUMPTION

We will assume that all nodes in a distributed DBMS are well-behaved and under the same administrative domain.

→ If we tell a node to commit a txn, then it will commit the txn (if there is not a failure).

If you do not trust the other nodes in a distributed DBMS, then you need to use a Byzantine Fault Tolerant protocol for txns (blockchain).

→ Blockchains are NOT good for high-throughput OLTP workloads (also they are not good for OLAP).

TODAY'S AGENDA

Replication

Atomic Commit Protocols

Consistency Issues (CAP / PACELC)

Google Spanner

REPLICATION

The DBMS can replicate a database across redundant nodes to increase availability.

→ Partitioned vs. Non-Partitioned
→ Shared-Nothing vs. Shared-Disk

Design Decisions:

→ Replica Configuration
→ Propagation Scheme
→ Propagation Timing
→ Update Method

REPLICA CONFIGURATIONS

Approach #1: Primary-Replica

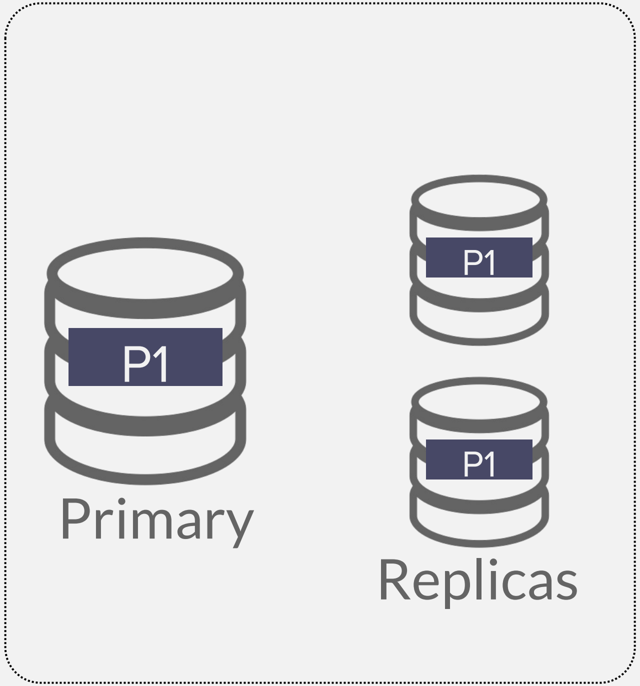
- → All updates go to a designated primary for each object.
- → The primary propagates updates to its replicas by shipping logs.
- → Read-only txns may be allowed to access replicas.
- → If the primary goes down, then hold an election to select a new primary.

Approach #2: Multi-Primary

- → Txns can update data objects at any replica.
- → Replicas must synchronize with each other using an atomic commit protocol.

REPLICA CONFIGURATIONS

Primary-Replica



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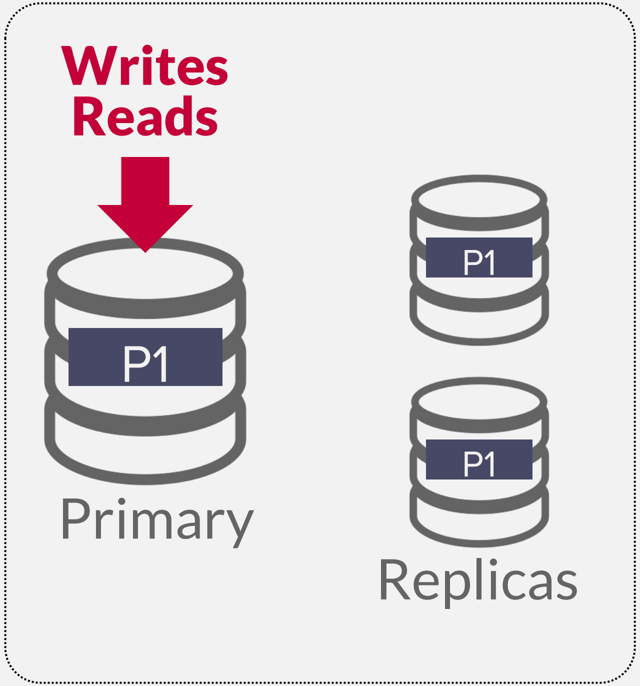

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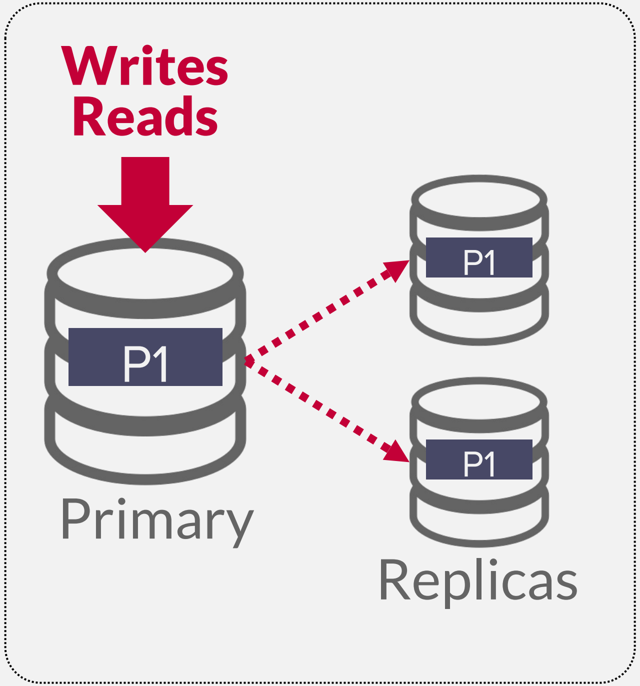

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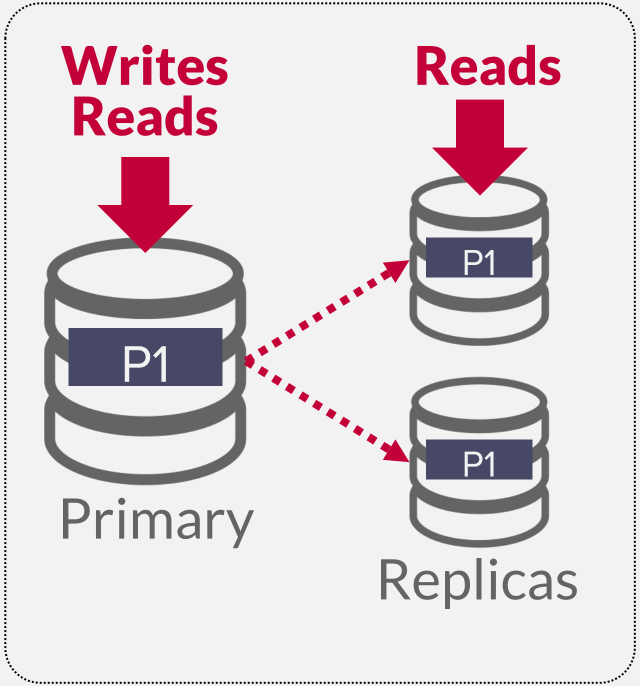

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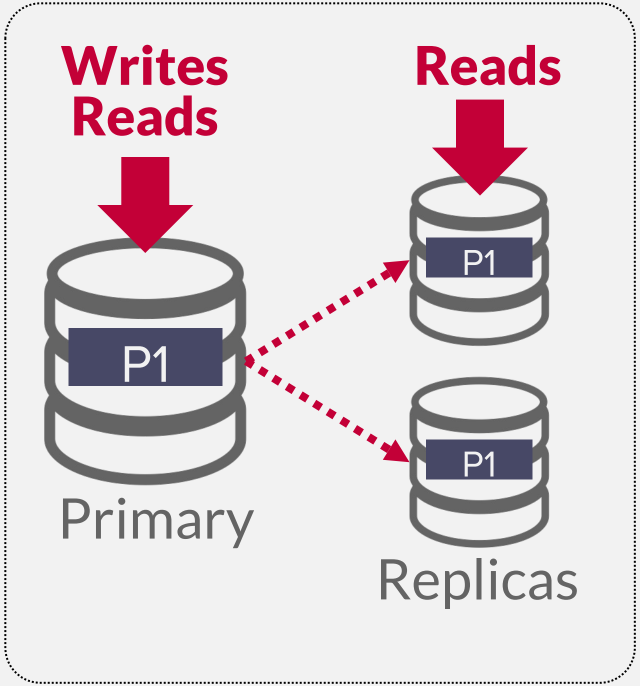
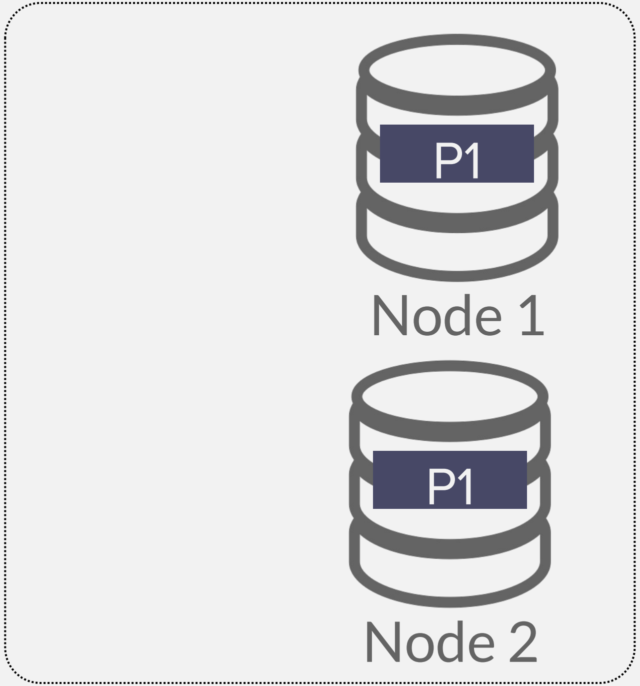


Multi-Primary



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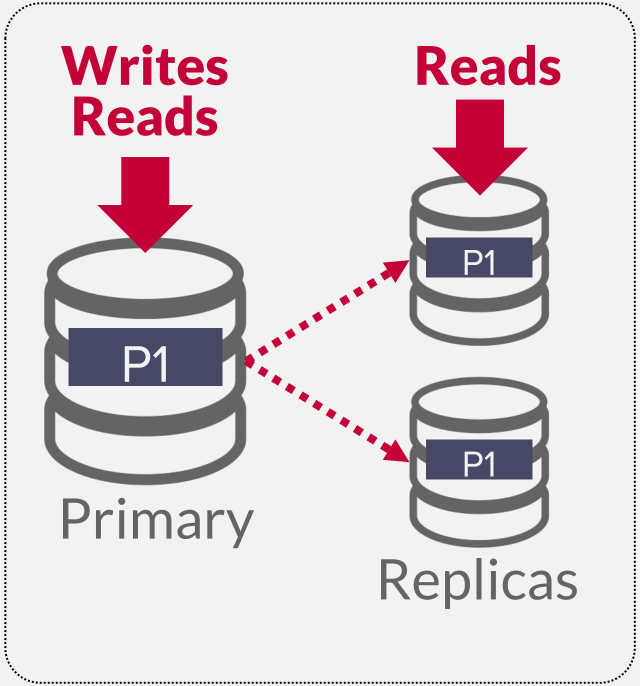

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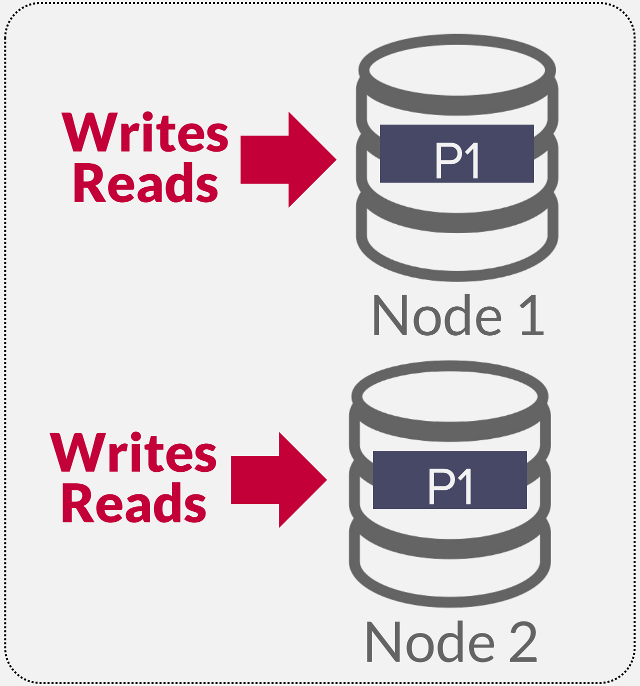

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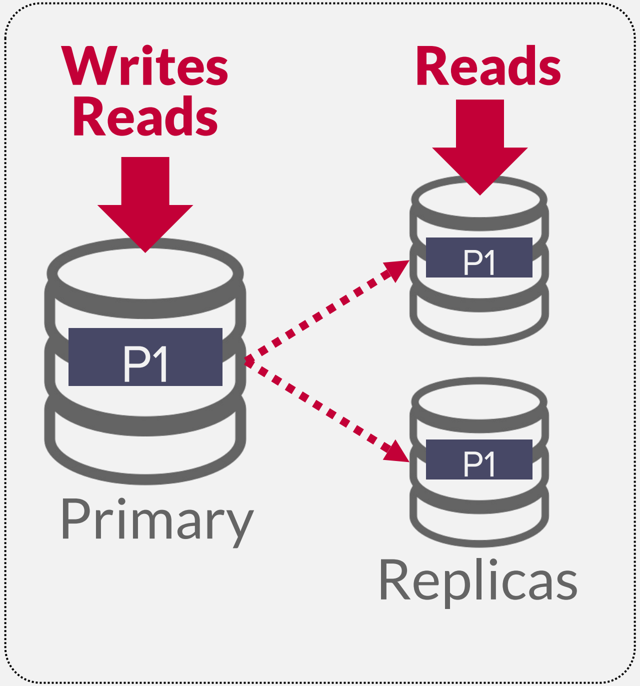

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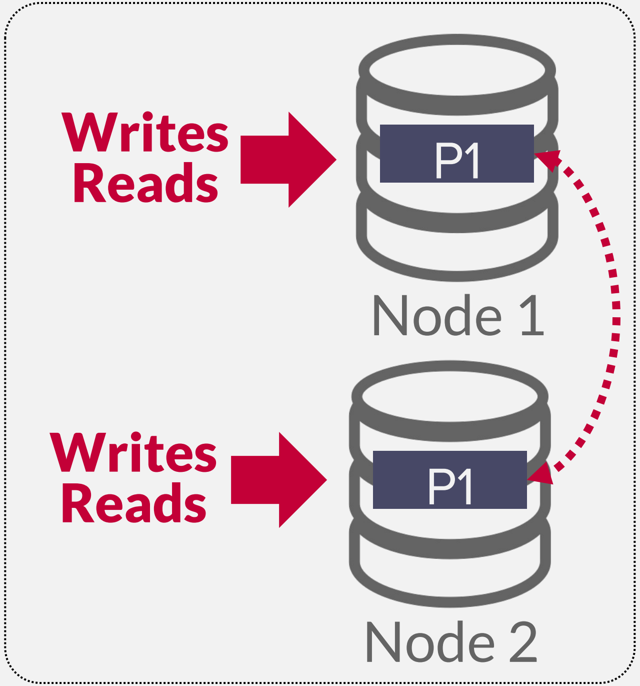

K-SAFETY

K**-safety** is a threshold for determining the fault tolerance of the replicated database.

The value ***K*** represents the number of replicas per data object that must always be available.

If the number of replicas goes below this threshold, then the DBMS halts execution and takes itself offline.

PROPAGATION SCHEME

When a txn commits on a replicated database, the DBMS decides whether it must wait for that txn's changes to propagate to other nodes before it can send the acknowledgement to application.

Propagation levels:

→ Synchronous (*Strong Consistency*)
→ Asynchronous (*Eventual Consistency*)

PROPAGATION SCHEME

Approach #1: Synchronous

→ The primary sends updates to replicas and then waits for them to acknowledge that they fully applied (i.e., logged) the changes.

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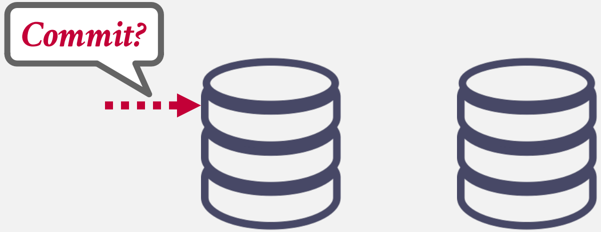

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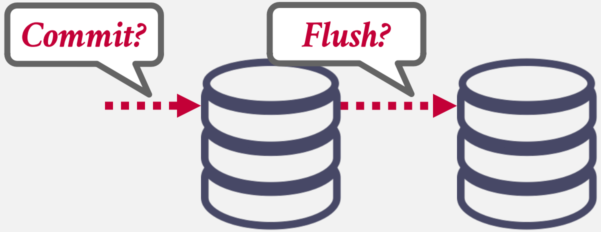

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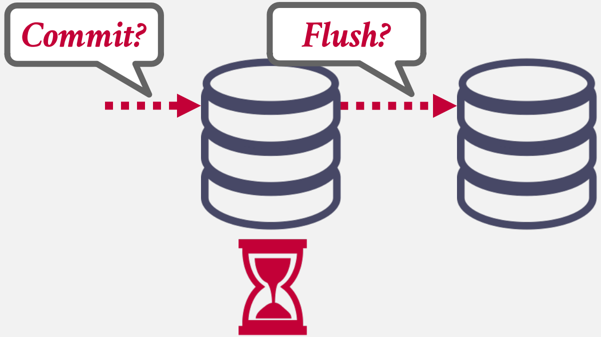

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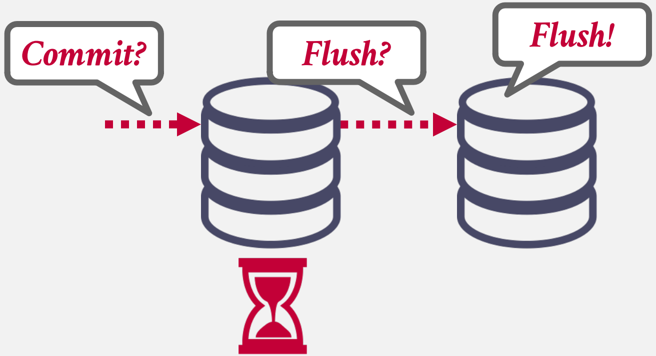

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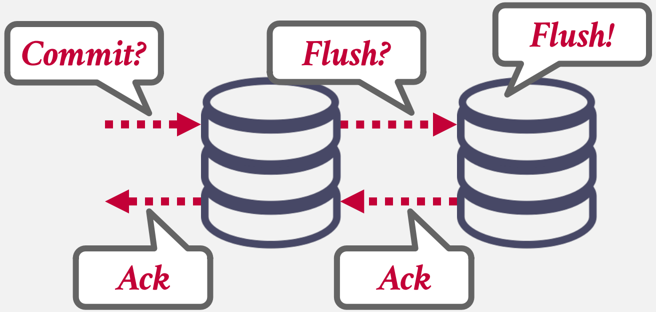

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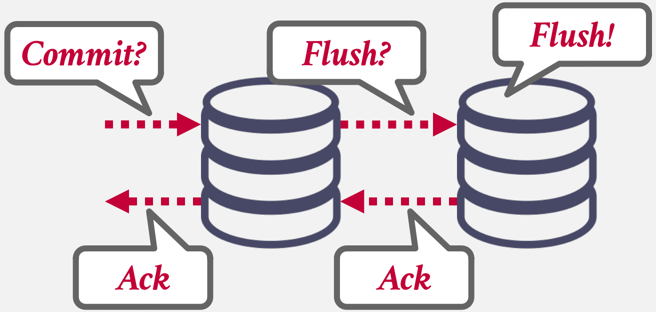

Approach #2: Asynchronous

→ The primary immediately returns the acknowledgement to the client without waiting for replicas to apply the changes.

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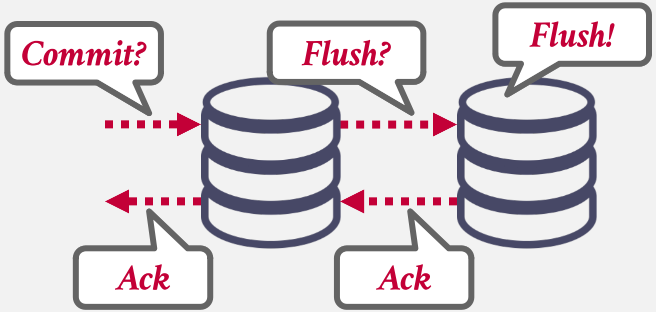

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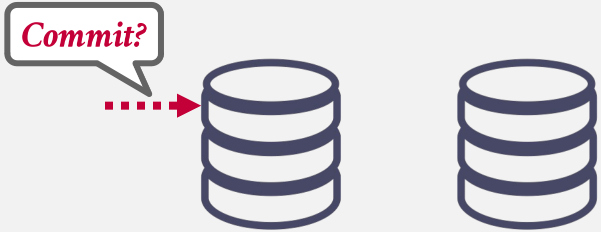

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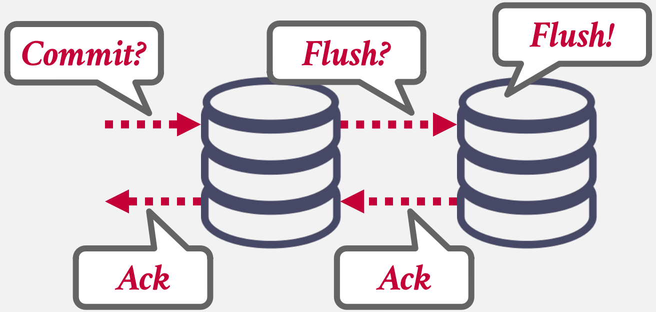

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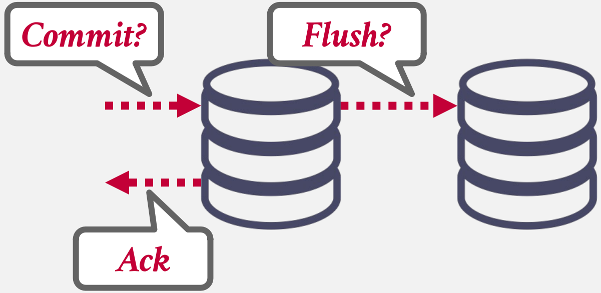


PROPAGATION TIMING

Approach #1: Continuous

→ The DBMS sends log messages immediately as it generates them.

→ Also need to send a commit/abort message.

Approach #2: On Commit

→ The DBMS only sends the log messages for a txn to the replicas once the txn is commits.

→ Do not waste time sending log records for aborted txns.

ACTIVE VS. PASSIVE

Approach #1: Active-Active

→ A txn executes at each replica independently.
→ Need to check at the end whether the txn ends up with the same result at each replica.

Approach #2: Active-Passive

→ Each txn executes at a single location and propagates the changes to the replica.
→ Can either do physical or logical replication.
→ Not the same as Primary-Replica vs. Multi-Primary

ATOMIC COMMIT PROTOCOL

Coordinating the commit order of txns across nodes in a distributed DBMS.

- → Commit Order = State Machine
- → It does not matter whether the database's contents are replicated or partitioned.

Examples:

- → Two-Phase Commit (1970s)
- → Three-Phase Commit (1983)
- → Viewstamped Replication (1988)
- → Paxos (1989)
- → ZAB (2008?)
- → Raft (2013)

ATOMIC COMMIT PROTOCOL

Resource Managers (RMs)

→ Execute on different nodes

→ Need to coordinate to decide on the fate of a txn: Commit or Abort

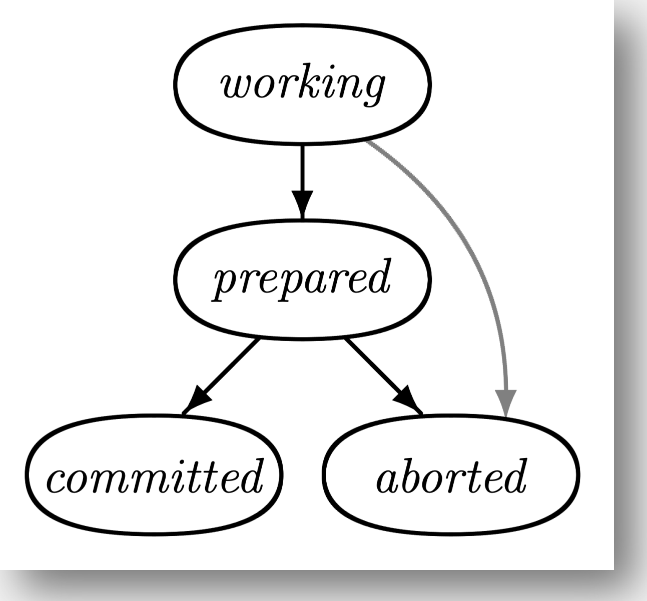
Properties of the Commit Protocol

→ **Stability**: Once the fate is decided, it can't be changed.

→ **Consistency**: All RMs end up in the same state.

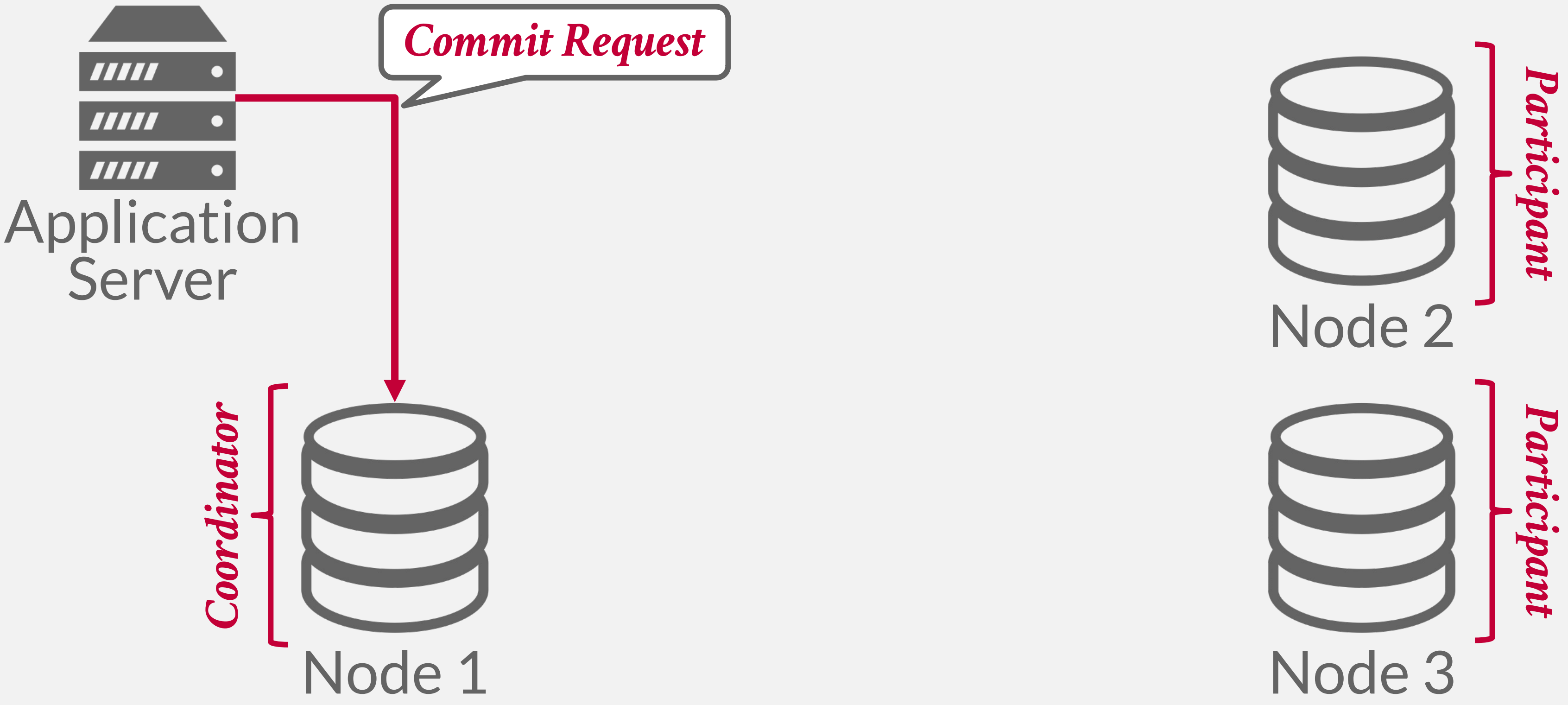
Assumes "Liveness":

→ Informally, there is some way of progressing forward; e.g., enough nodes are alive and connected for the duration of the protocol.



https://www.microsoft.com/en-us/research/publication/consensus-on-transaction-commit/

TWO-PHASE COMMIT (SUCCESS)



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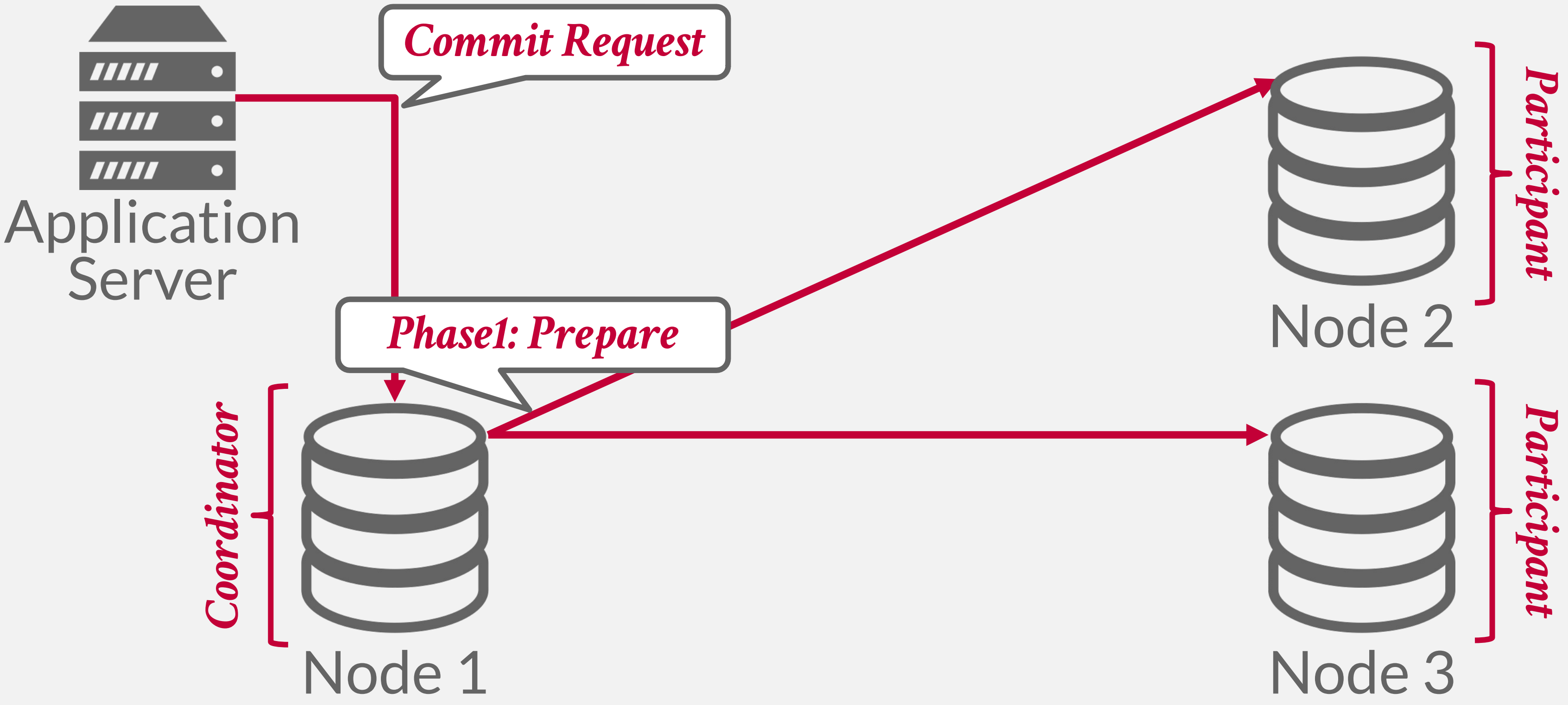

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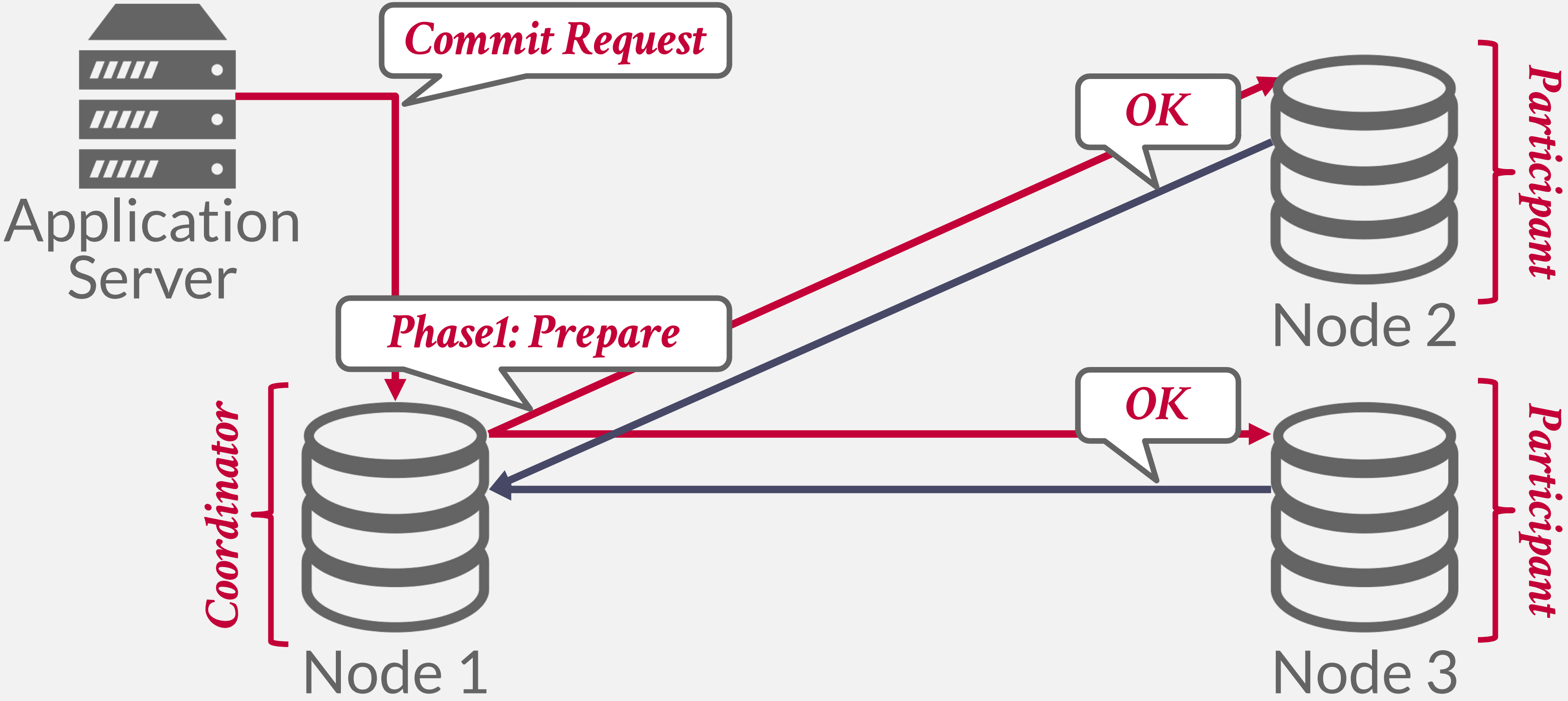

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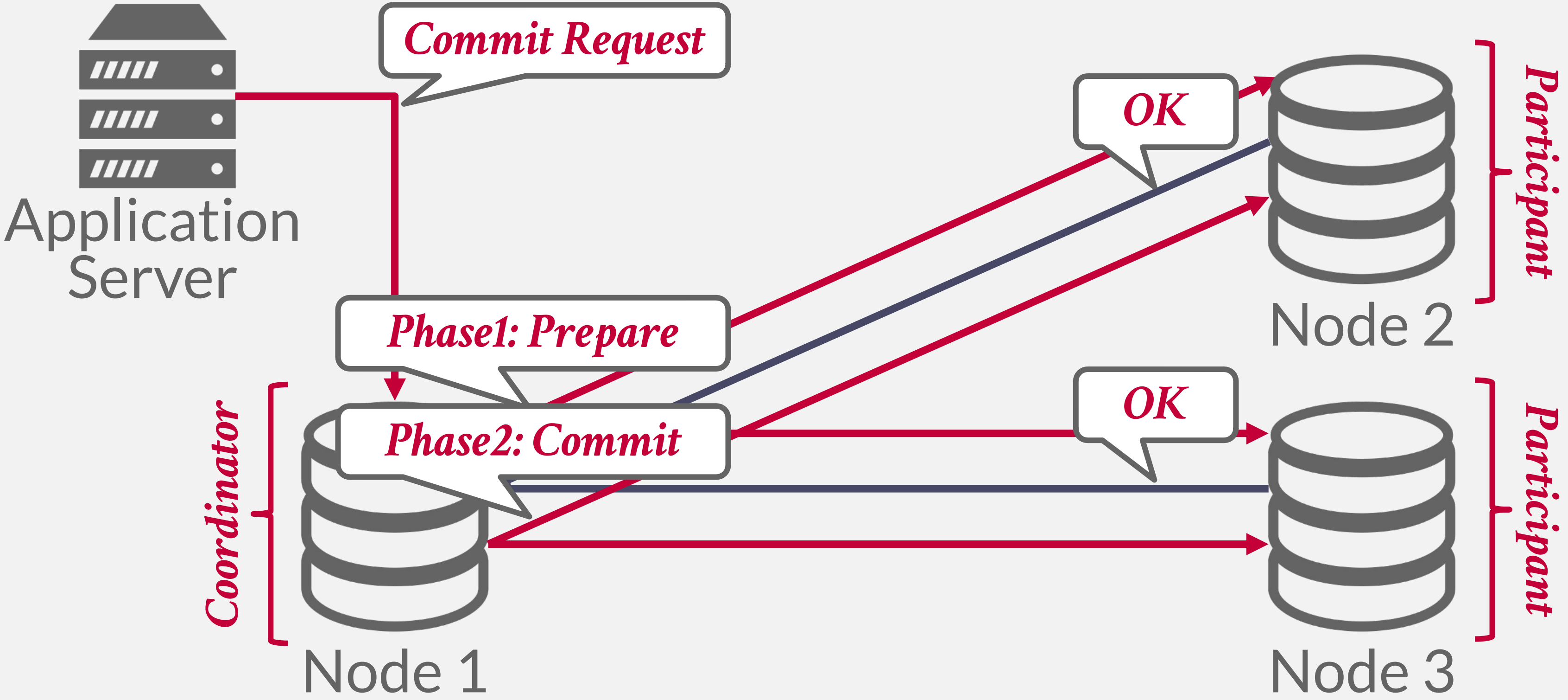

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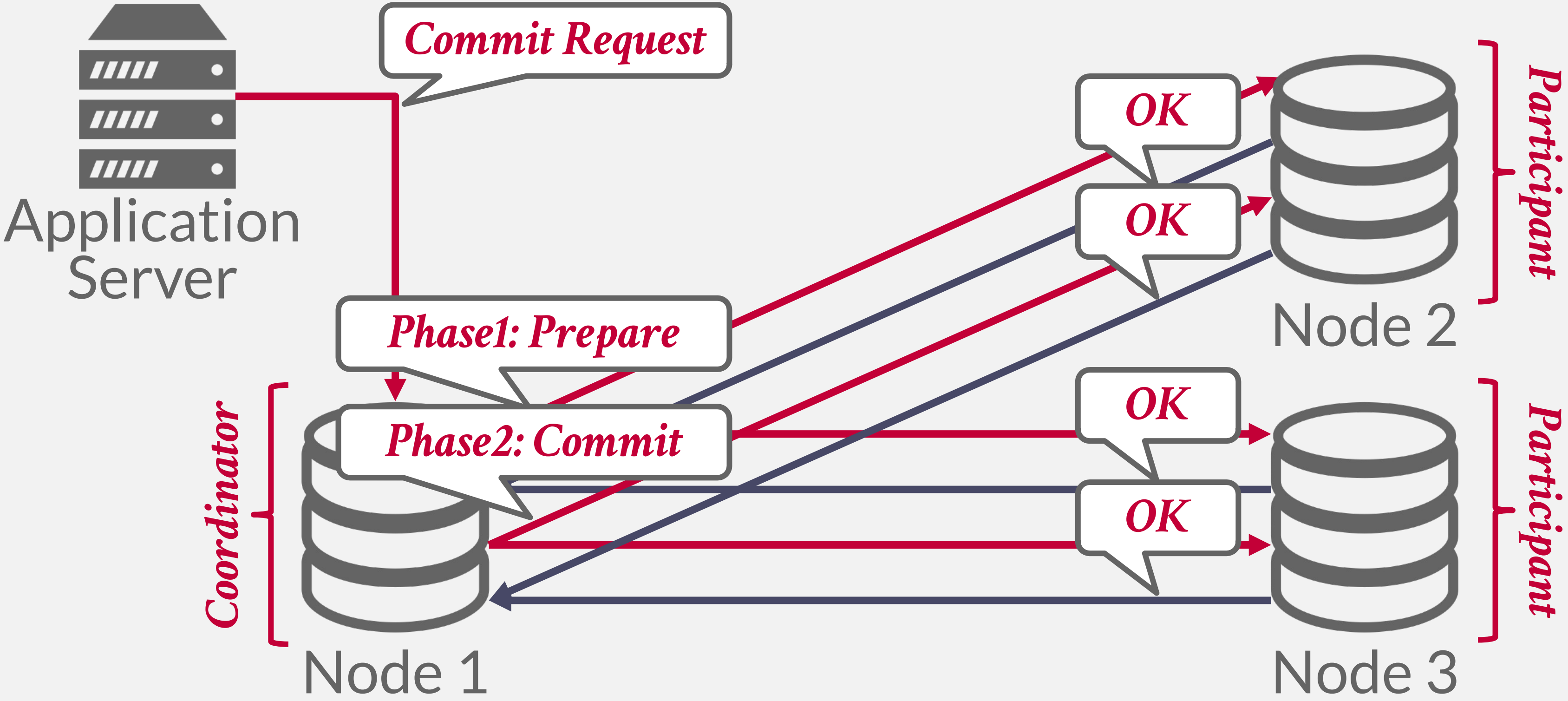

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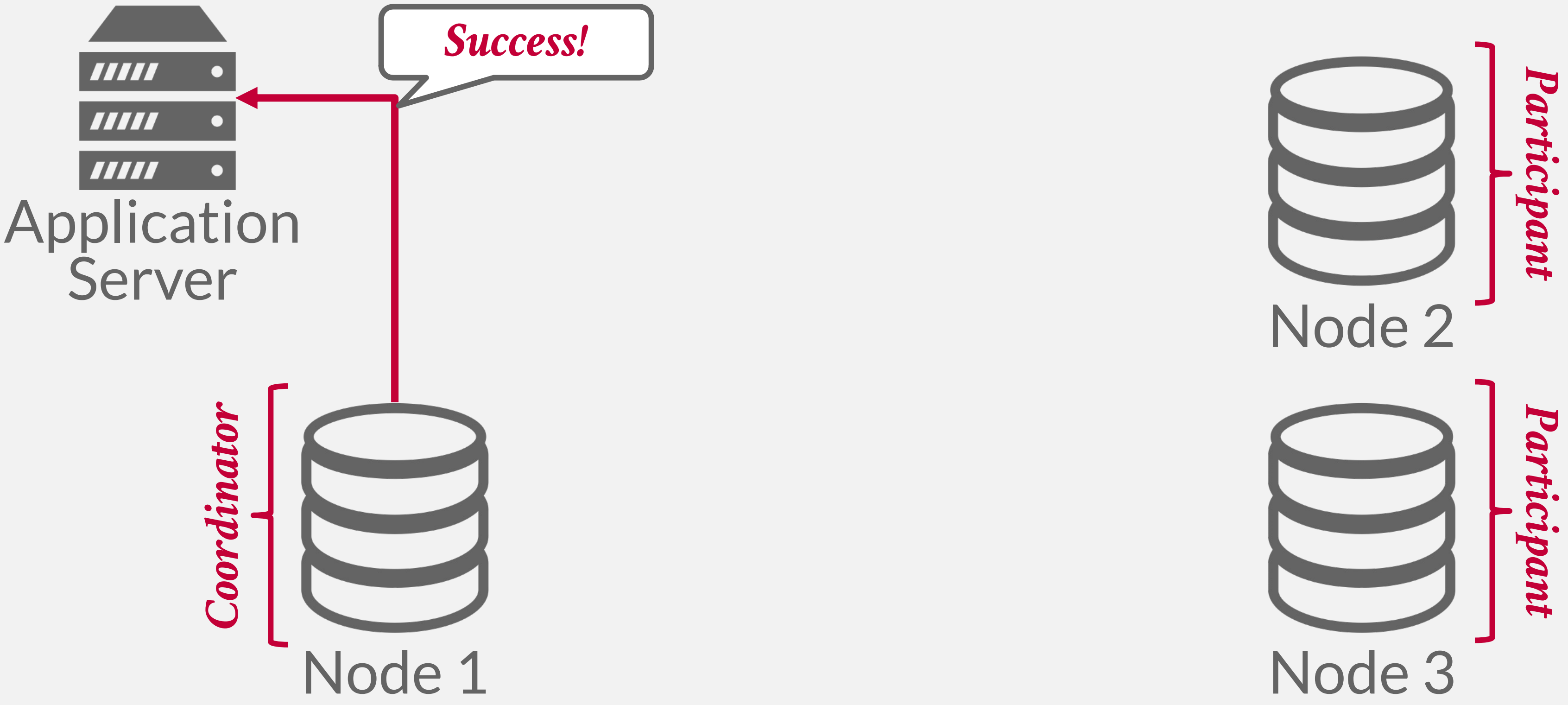
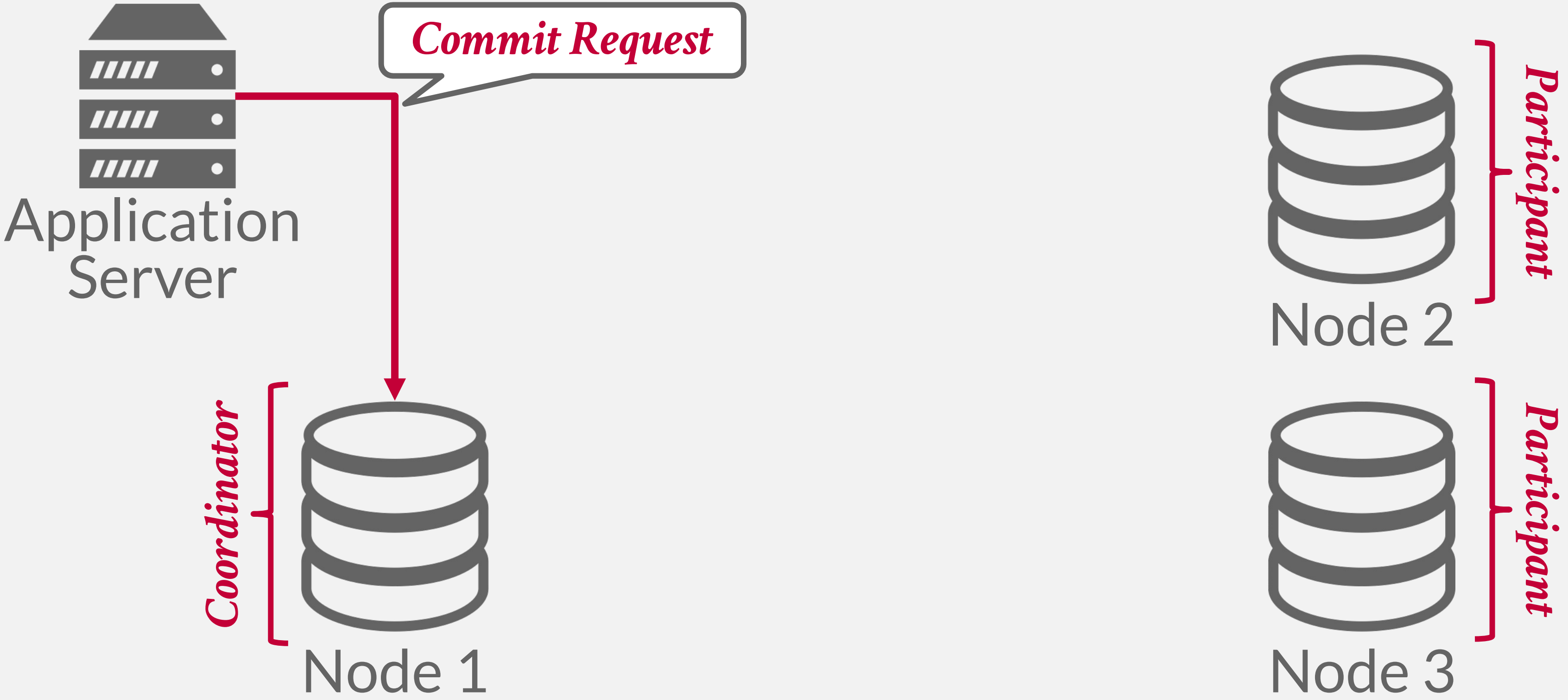


TWO-PHASE COMMIT (ABORT)



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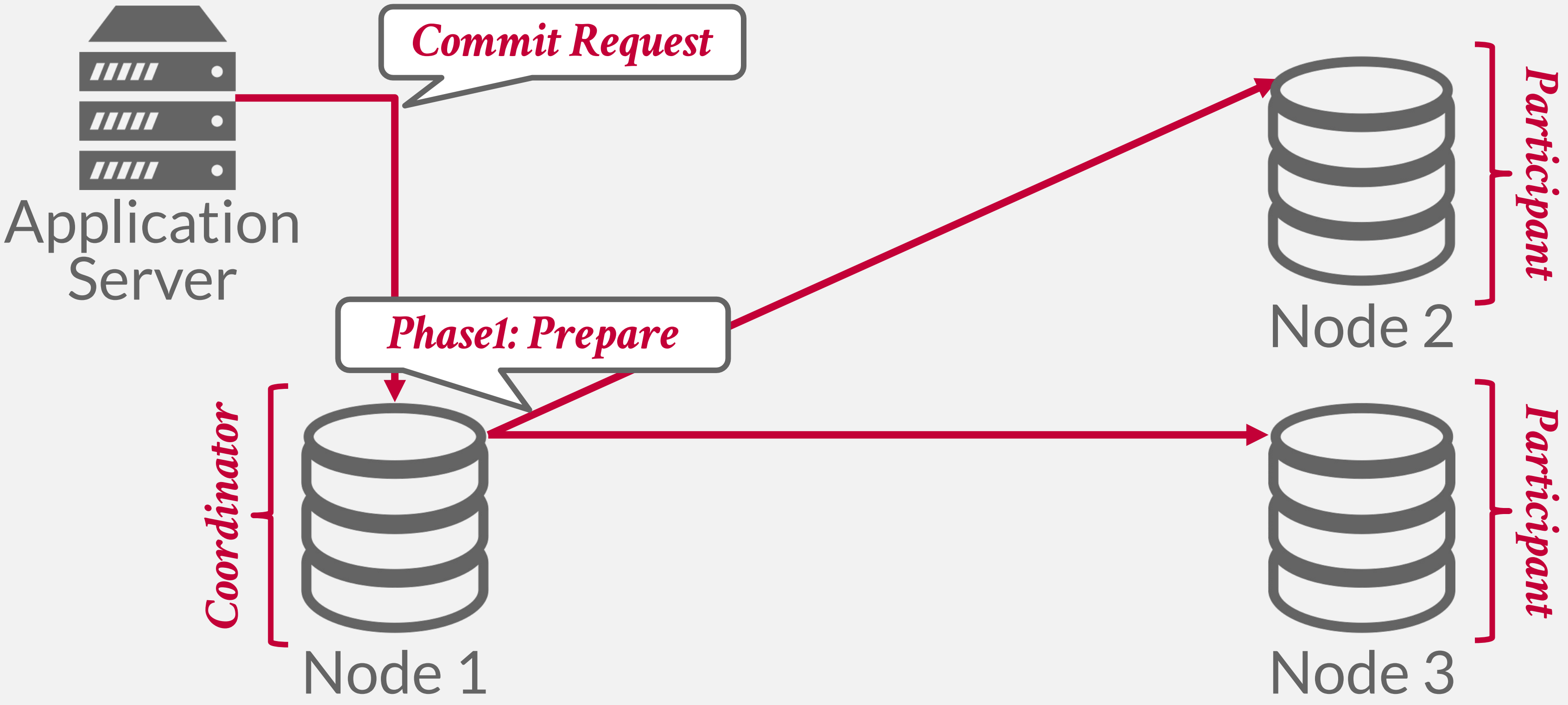

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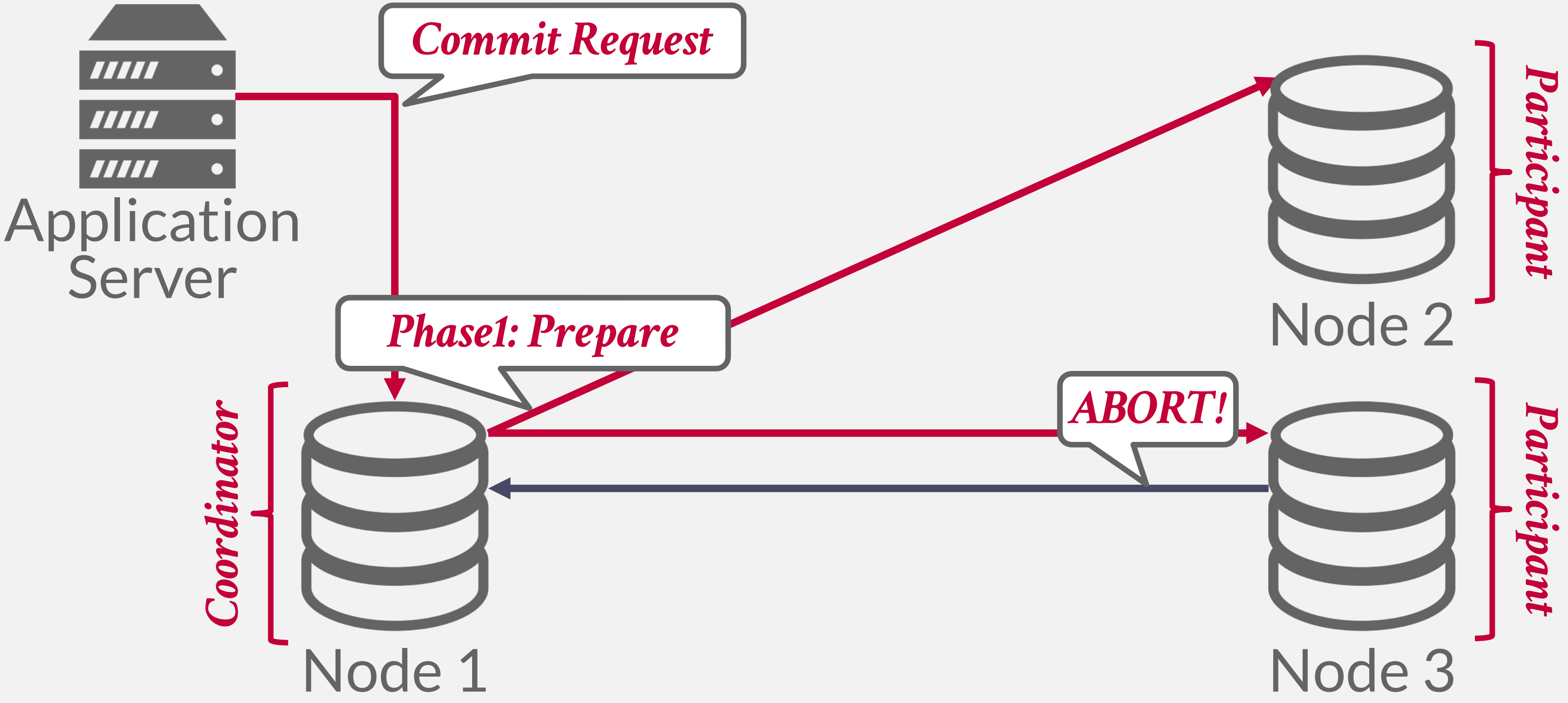

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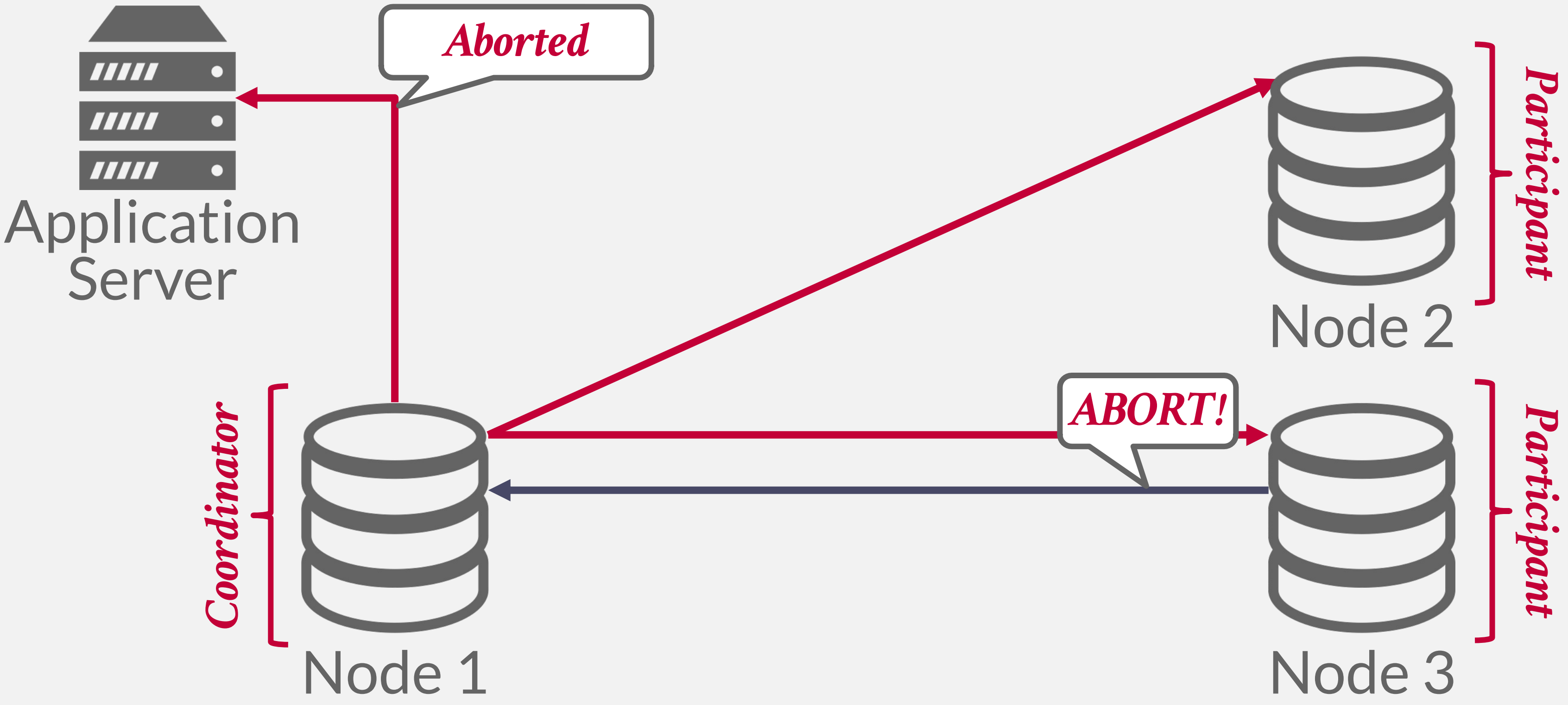

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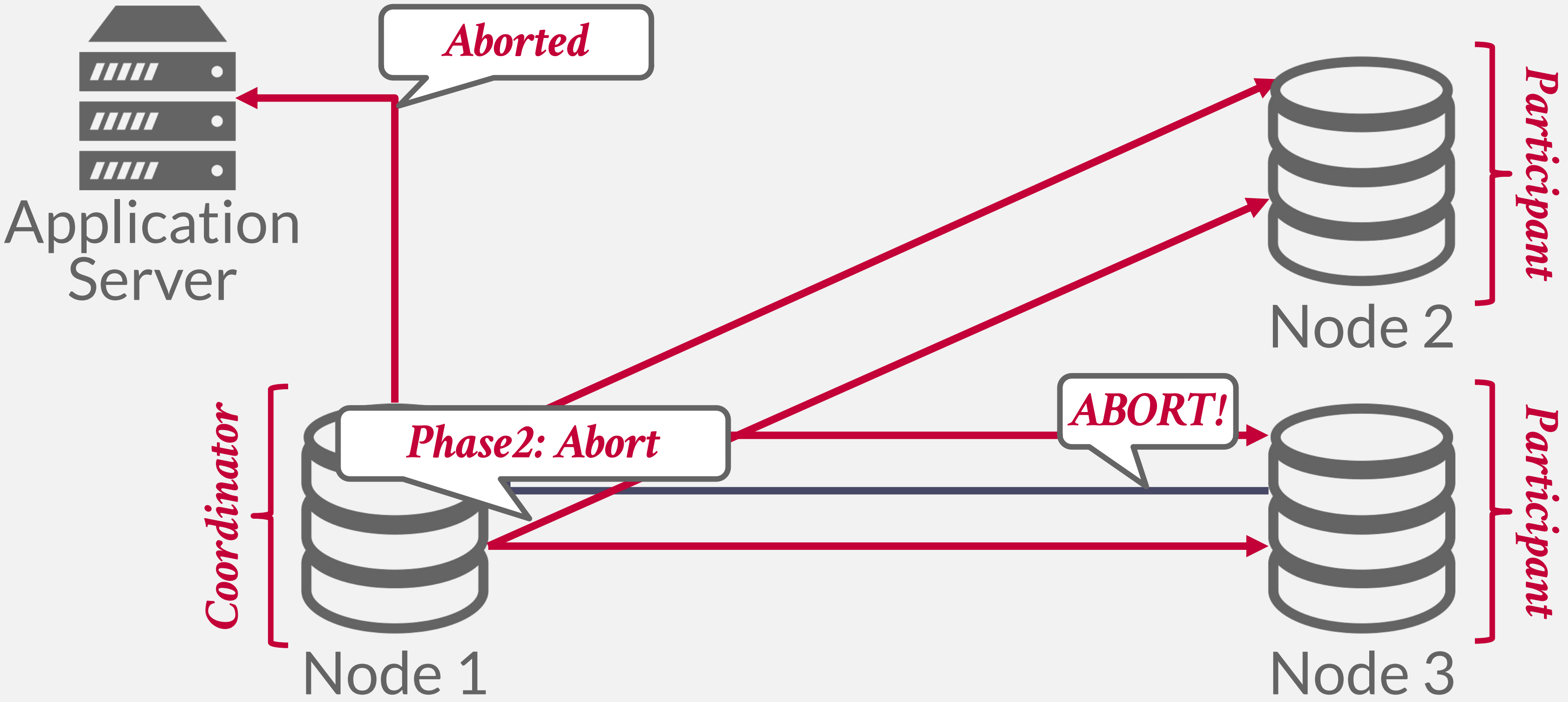

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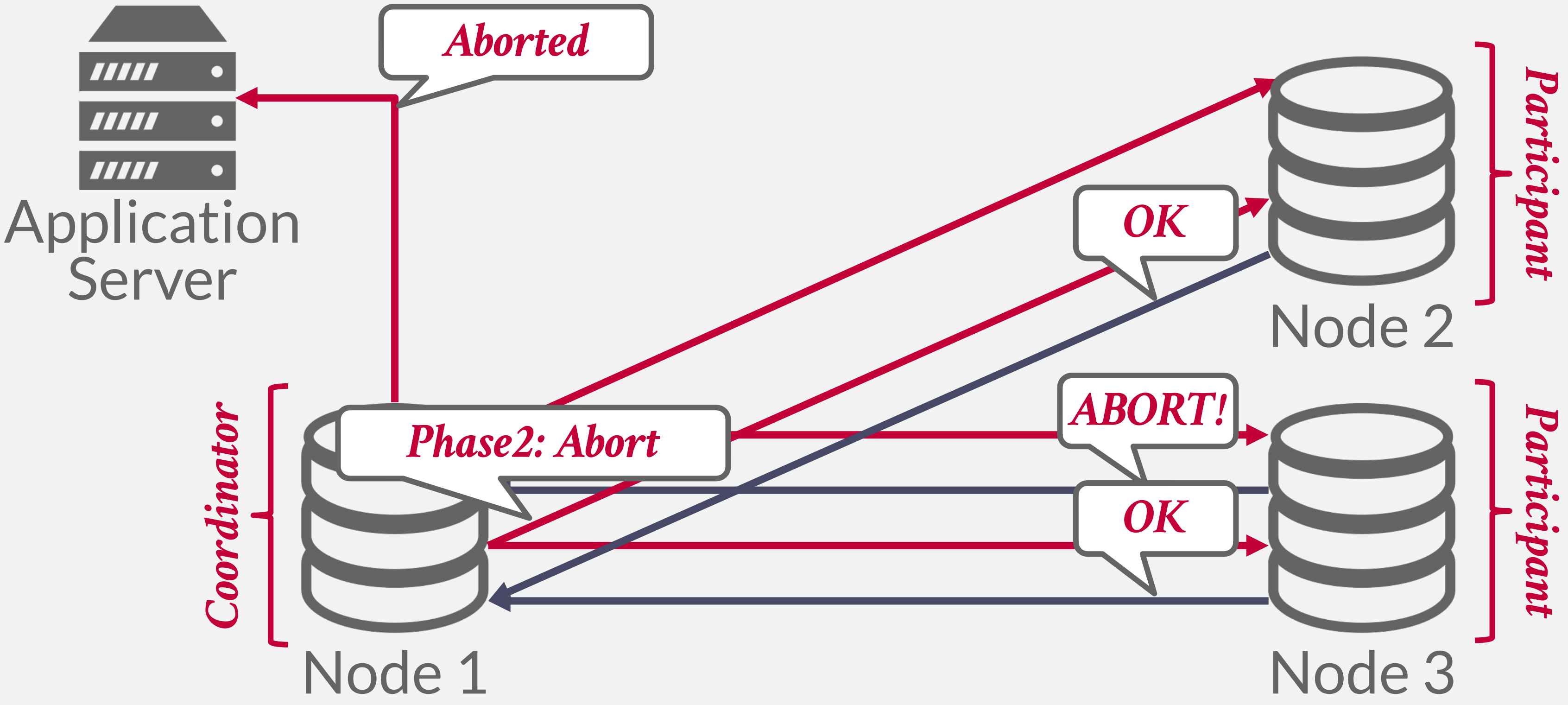

TWO-PHASE COMMIT

Each node records the inbound/outbound messages and outcome of each phase in a non-volatile storage log.

On recovery, examine the log for 2PC messages:

→ If local txn in prepared state, contact coordinator.

→ If local txn not in prepared, abort it.

→ If local txn was committing and node is the coordinator, send `COMMIT` message to nodes.

TWO-PHASE COMMIT FAILURES

What happens if coordinator crashes?

→ Participants must decide what to do after a timeout.
→ System is not available during this time.

What happens if participant crashes?

→ Coordinator assumes that it responded with an abort if it has not sent an acknowledgement yet.
→ Again, nodes use a timeout to determine whether a participant is dead.

2PC OPTIMIZATIONS

Early Prepare Voting *(Rare)*

→ If you send a query to a remote node that you know will be the last one to execute in this txn, then that node will also return their vote for the prepare phase with the query result.

Early Ack After Prepare *(Common)*

→ If all nodes vote to commit a txn, the coordinator can send the client an acknowledgement that their txn was successful before the commit phase finishes.

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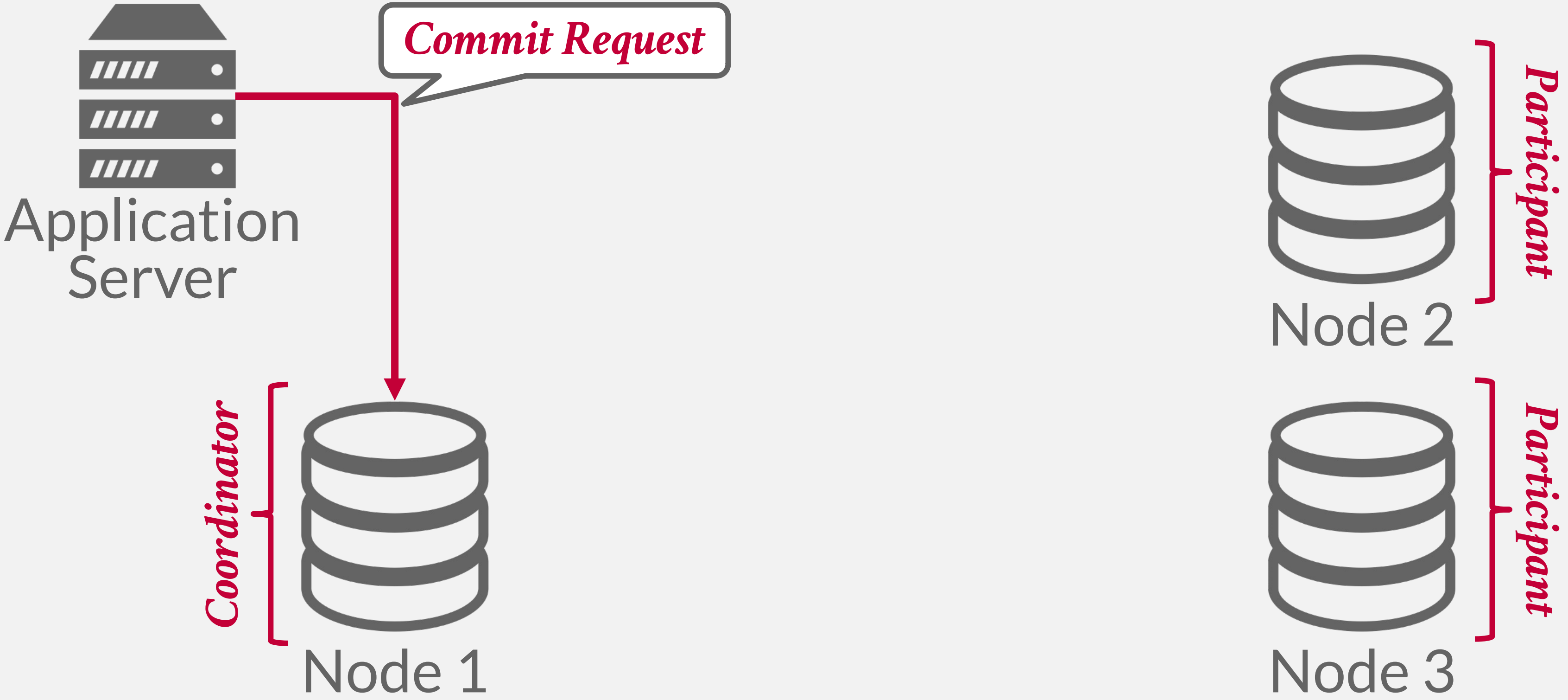

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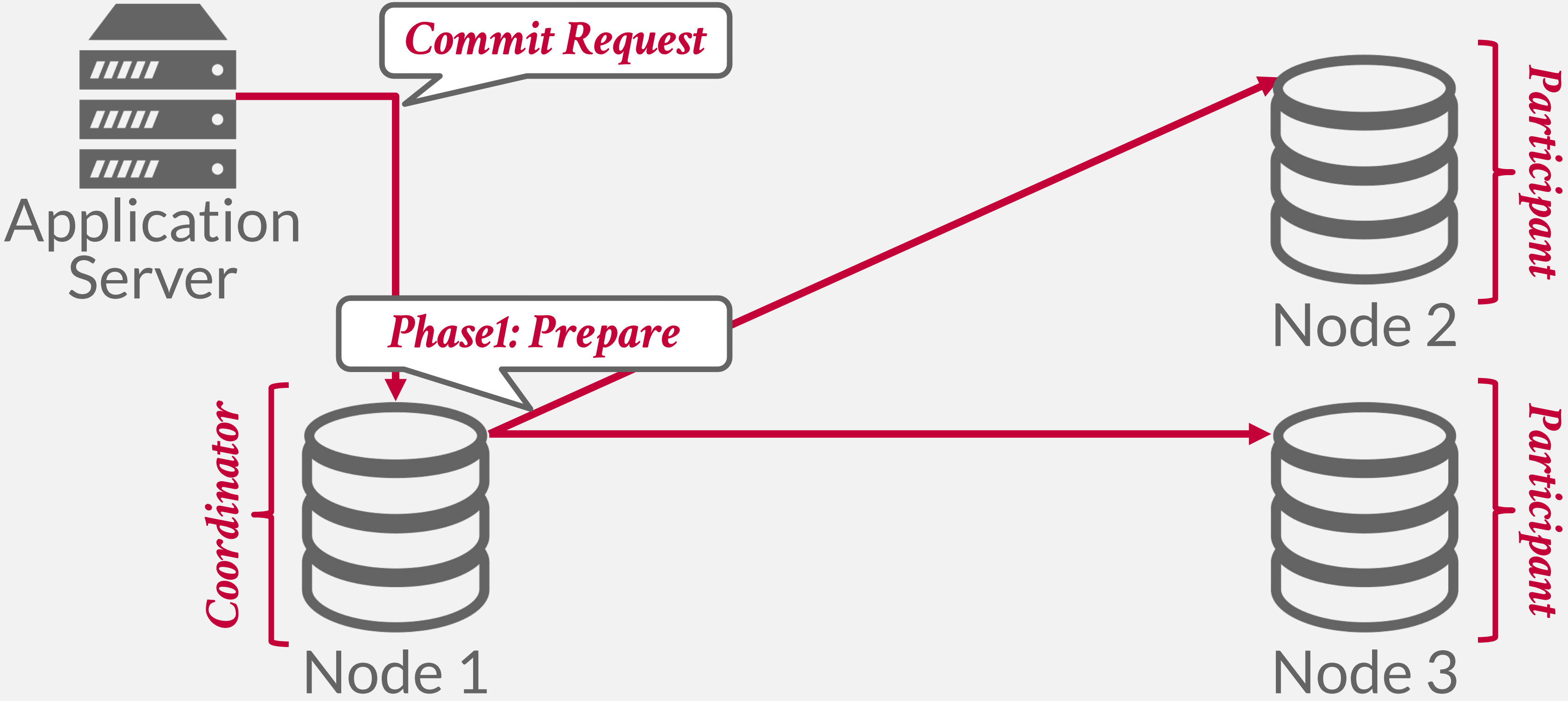

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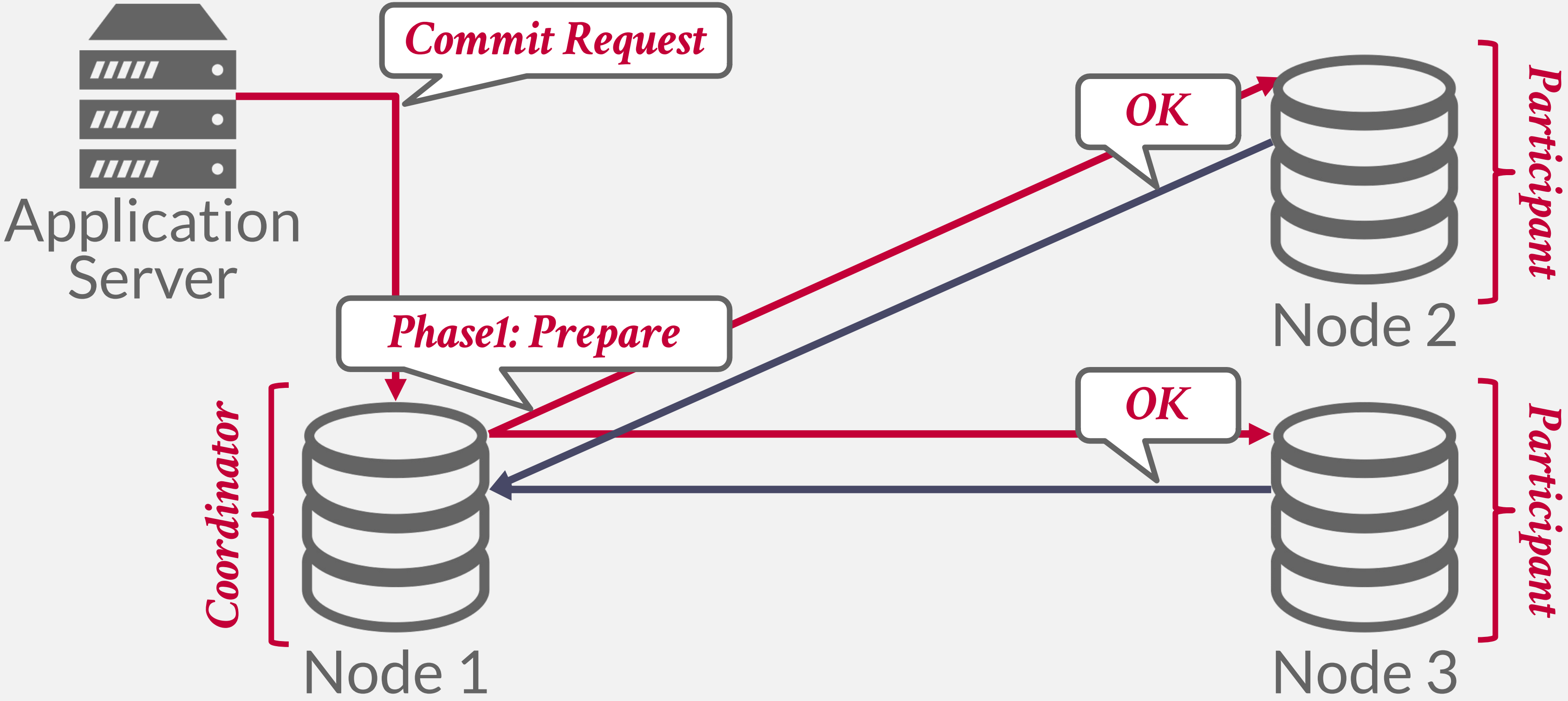

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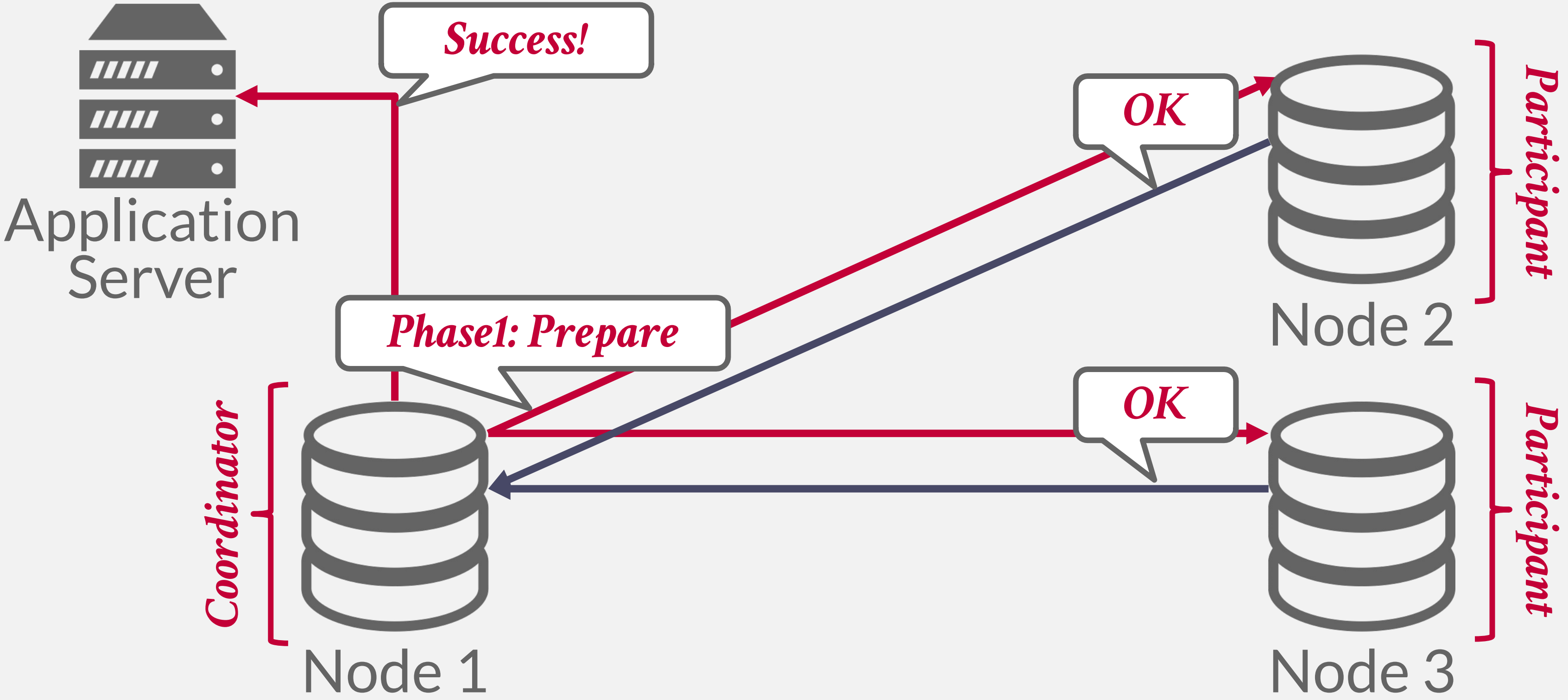

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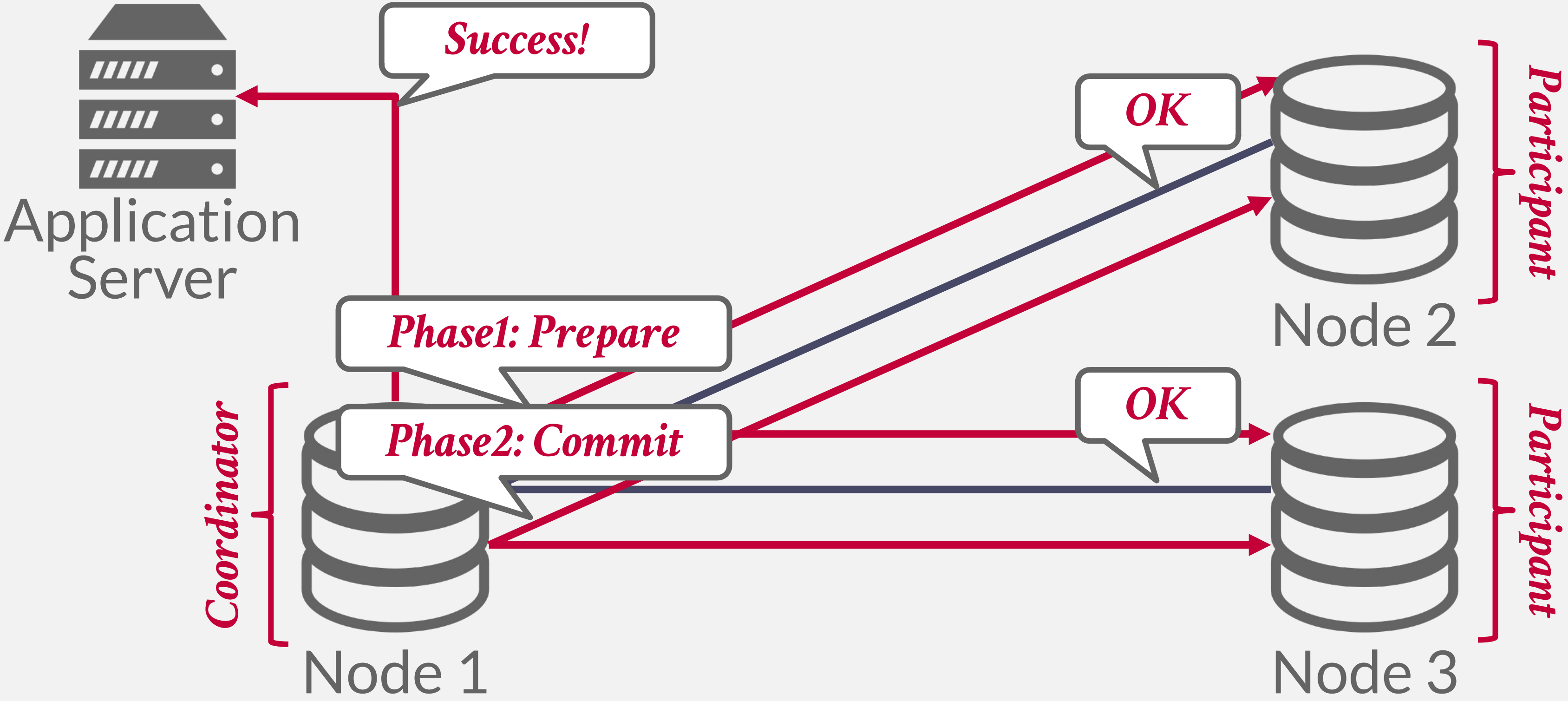

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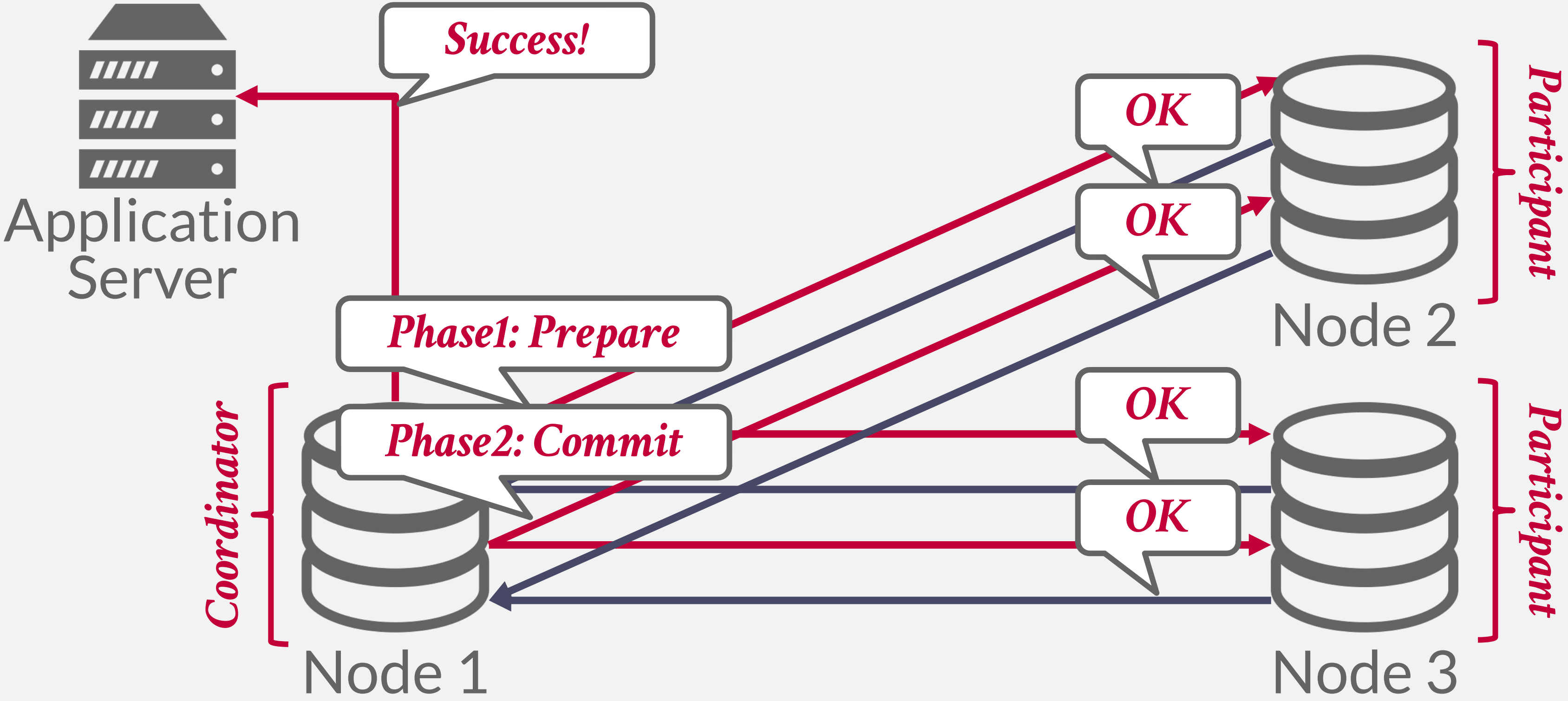
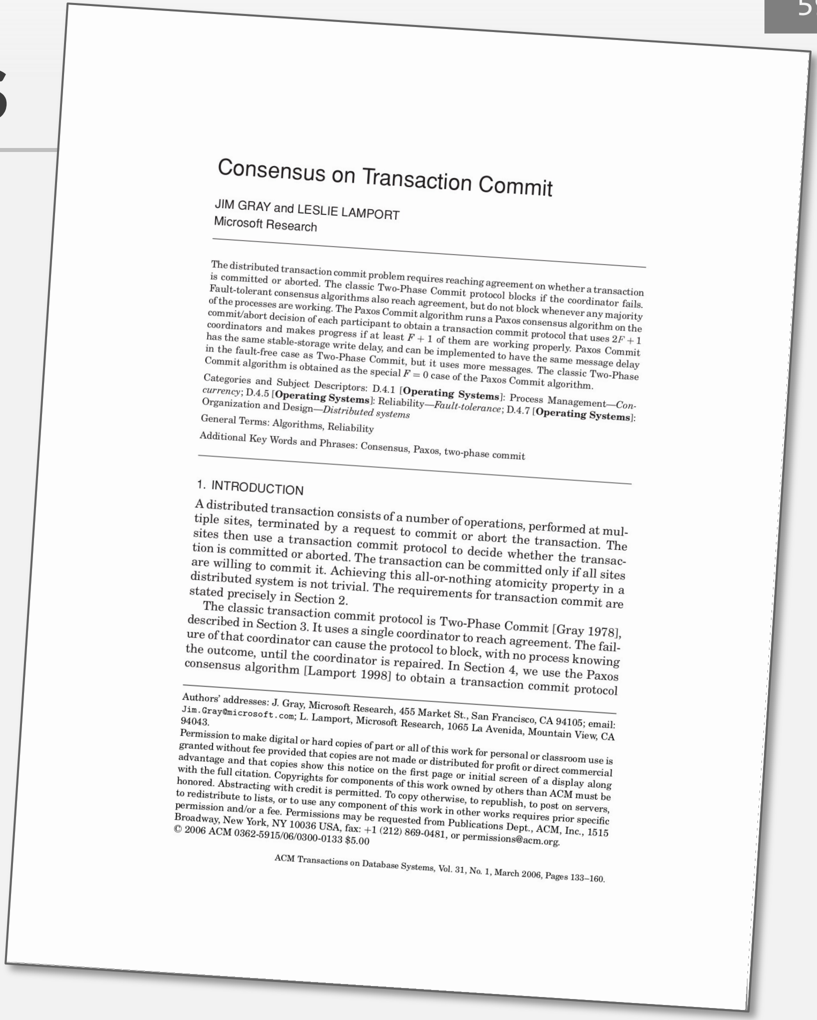


PAXOS

Consensus protocol where a coordinator proposes an outcome (e.g., commit or abort) and then the participants vote on whether that outcome should succeed.

Does not block if a majority of participants are available and has provably minimal message delays in the best case.



Consensus on Transaction Commit

JIM GRAY and LESLIE LAMPORT
Microsoft Research

The distributed transaction commit problem requires reaching agreement on whether a transaction is committed or aborted. The classic Two-Phase Commit protocol blocks if the coordinator fails. Fault-tolerant consensus algorithms also reach agreement, but do not block whenever any majority of the processes are working. The Paxos Commit algorithm runs a Paxos consensus algorithm on the commit/abort decision of each participant to obtain a transaction commit protocol that uses $2F+1$ coordinators and makes progress if at least $F+1$ of them are working properly. Paxos Commit has the same stable-storage write delay, and can be implemented to have the same message delay in the fault-free case as Two-Phase Commit, but it uses more messages. The classic Two-Phase Commit algorithm is obtained as the special $F=0$ case of the Paxos Commit algorithm.

Categories and Subject Descriptors: D.4.1 [**Operating Systems**]: Process Management—*Concurrency*; D.4.5 [**Operating Systems**]: Reliability—*Fault-tolerance*; D.4.7 [**Operating Systems**]: Organization and Design—*Distributed systems*

General Terms: Algorithms, Reliability

Additional Key Words and Phrases: Consensus, Paxos, two-phase commit

1. INTRODUCTION

A distributed transaction consists of a number of operations, performed at multiple sites, terminated by a request to commit or abort the transaction. The sites then use a transaction commit protocol to decide whether the transaction is committed or aborted. The transaction can be committed only if all sites are willing to commit it. Achieving this all-or-nothing atomicity property in a distributed system is not trivial. The requirements for transaction commit are stated precisely in Section 2.

The classic transaction commit protocol is Two-Phase Commit [Gray 1978], described in Section 3. It uses a single coordinator to reach agreement. The failure of that coordinator can cause the protocol to block, with no process knowing the outcome, until the coordinator is repaired. In Section 4, we use the Paxos consensus algorithm [Lamport 1998] to obtain a transaction commit protocol

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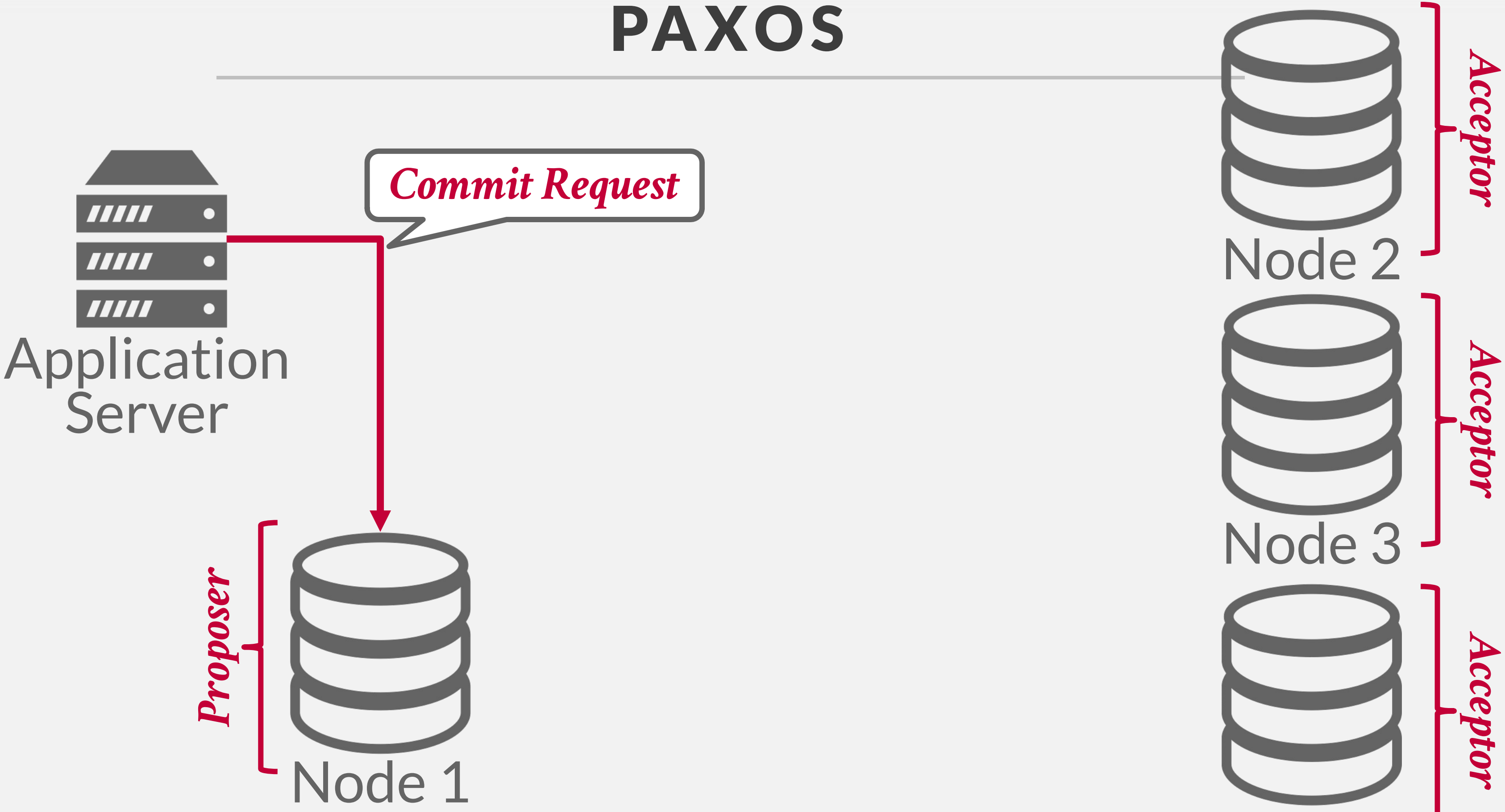
ACM Transactions on Database Systems, Vol. 31, No. 1, March 2006, Pages 133–160.

PAXOS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Commit Request
Proposer
Node 1
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Node 2
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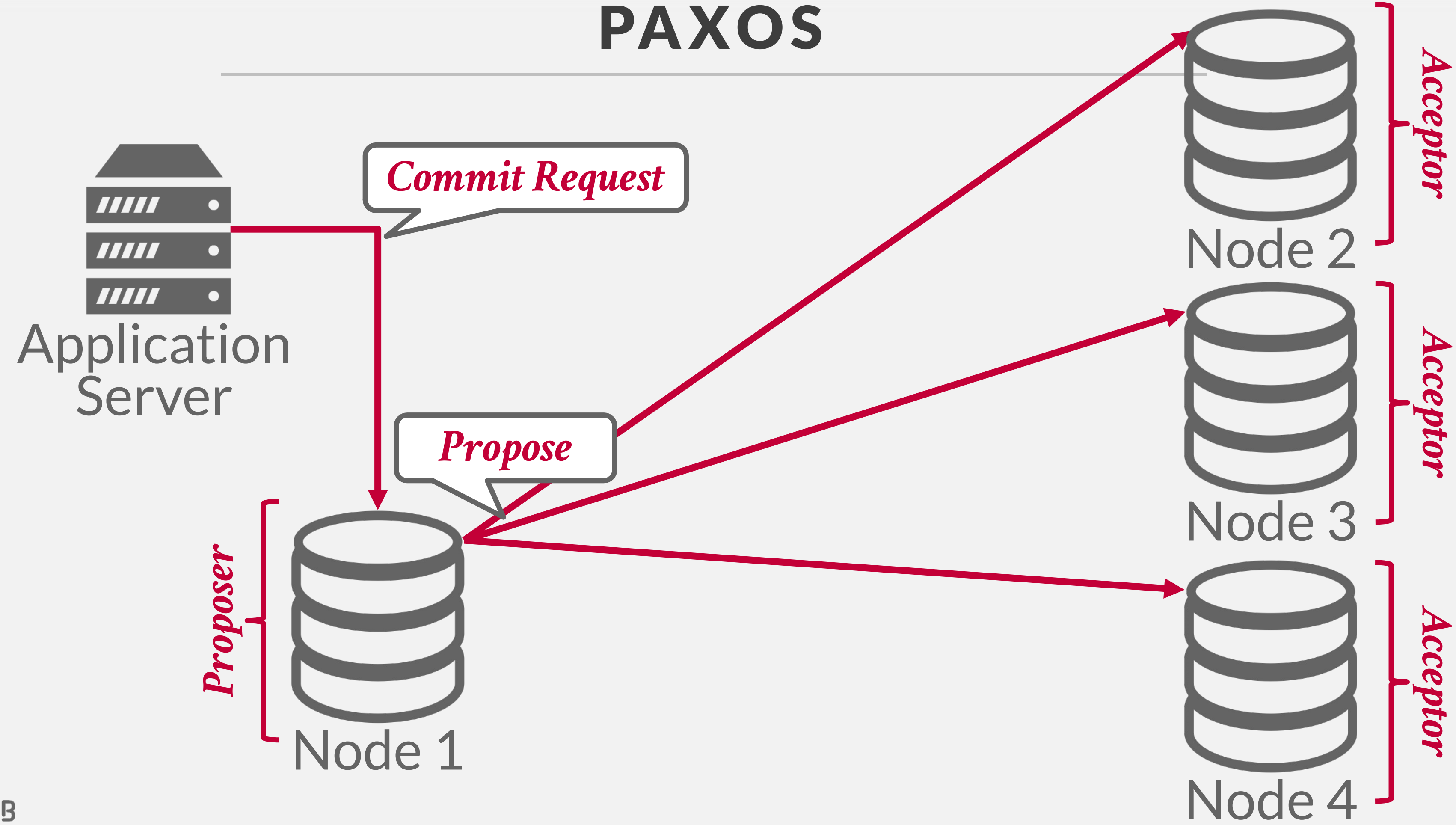
Node 3
Acceptor
Node 4

PAXOS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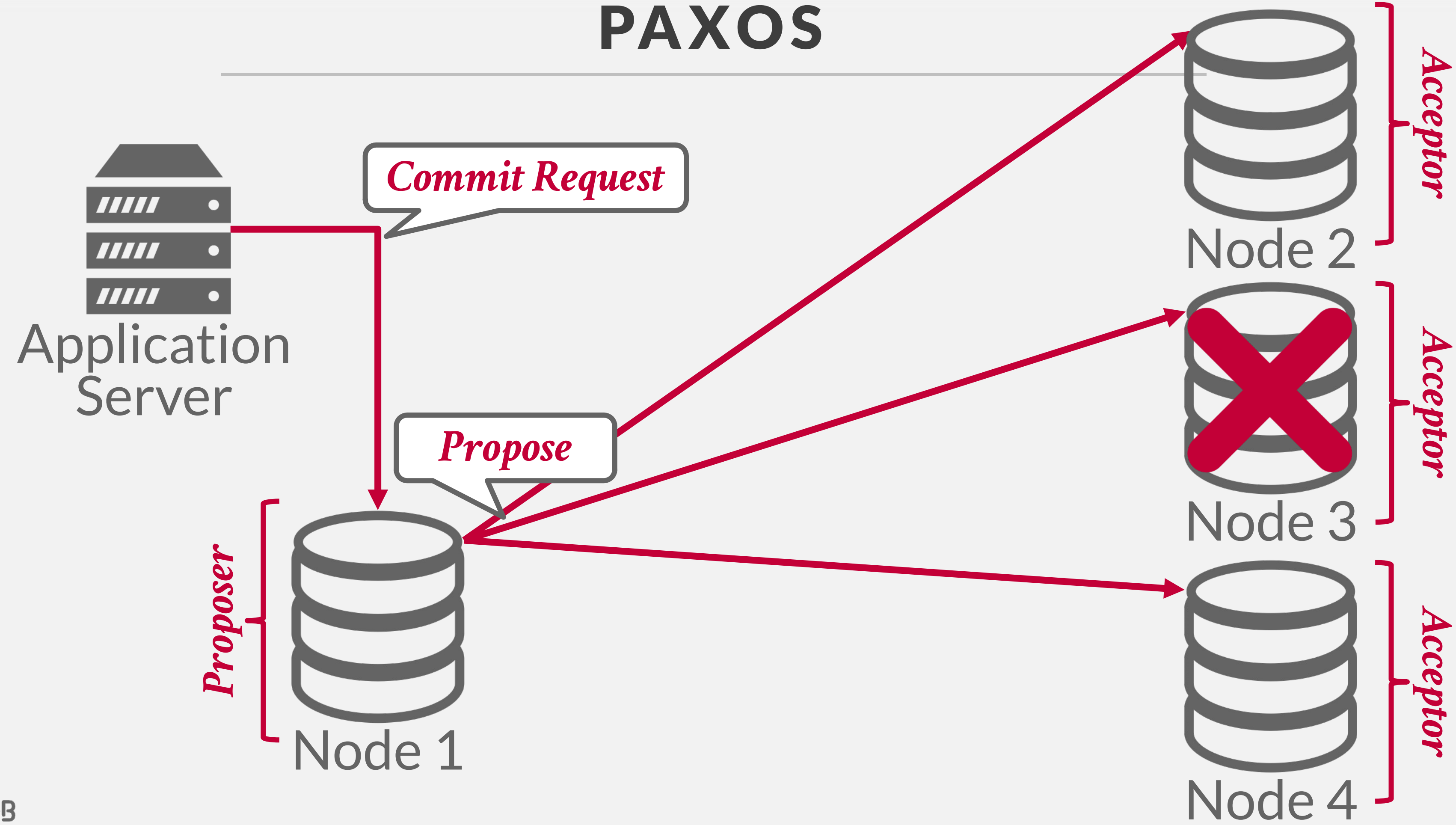
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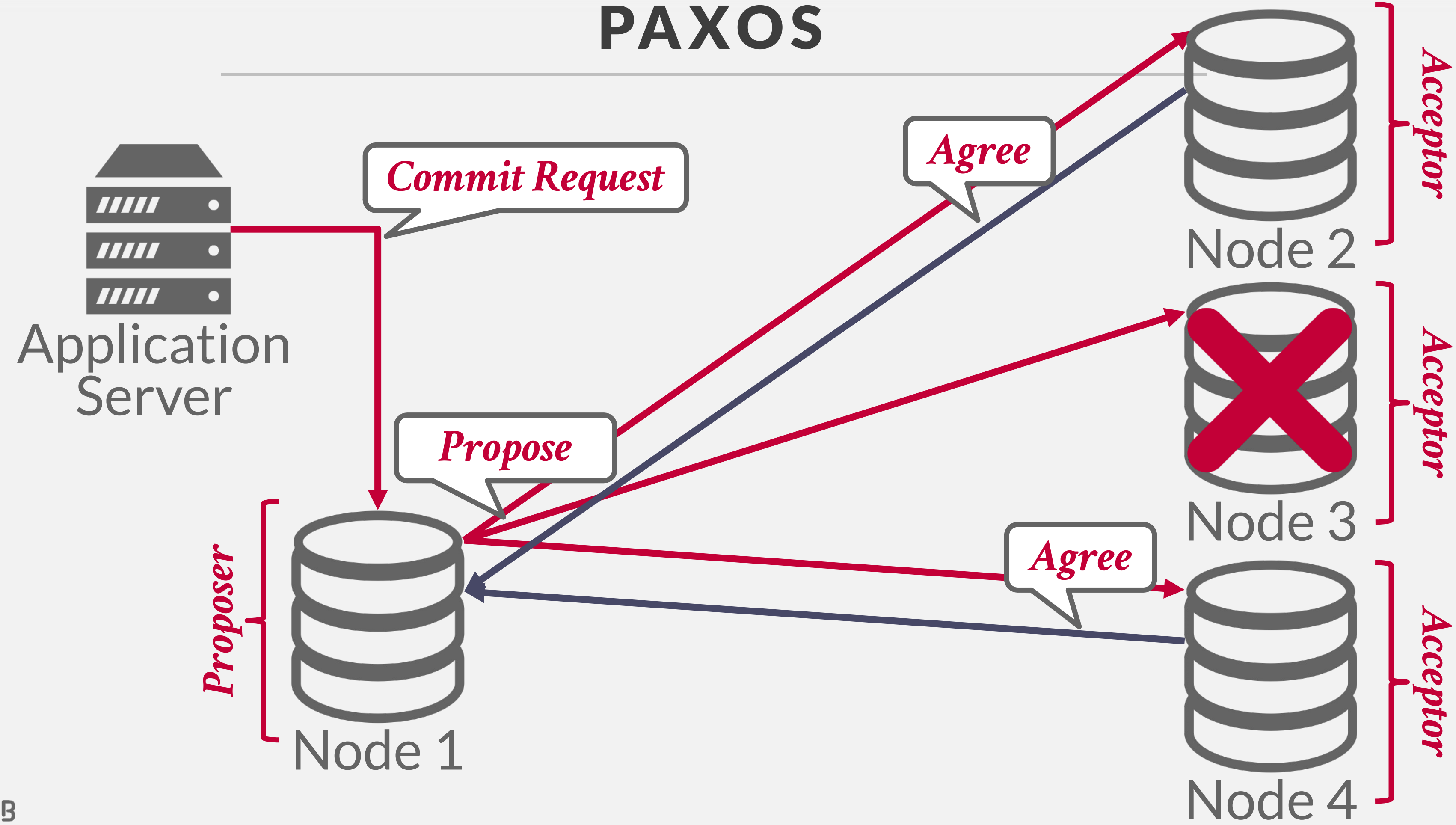
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Node 1
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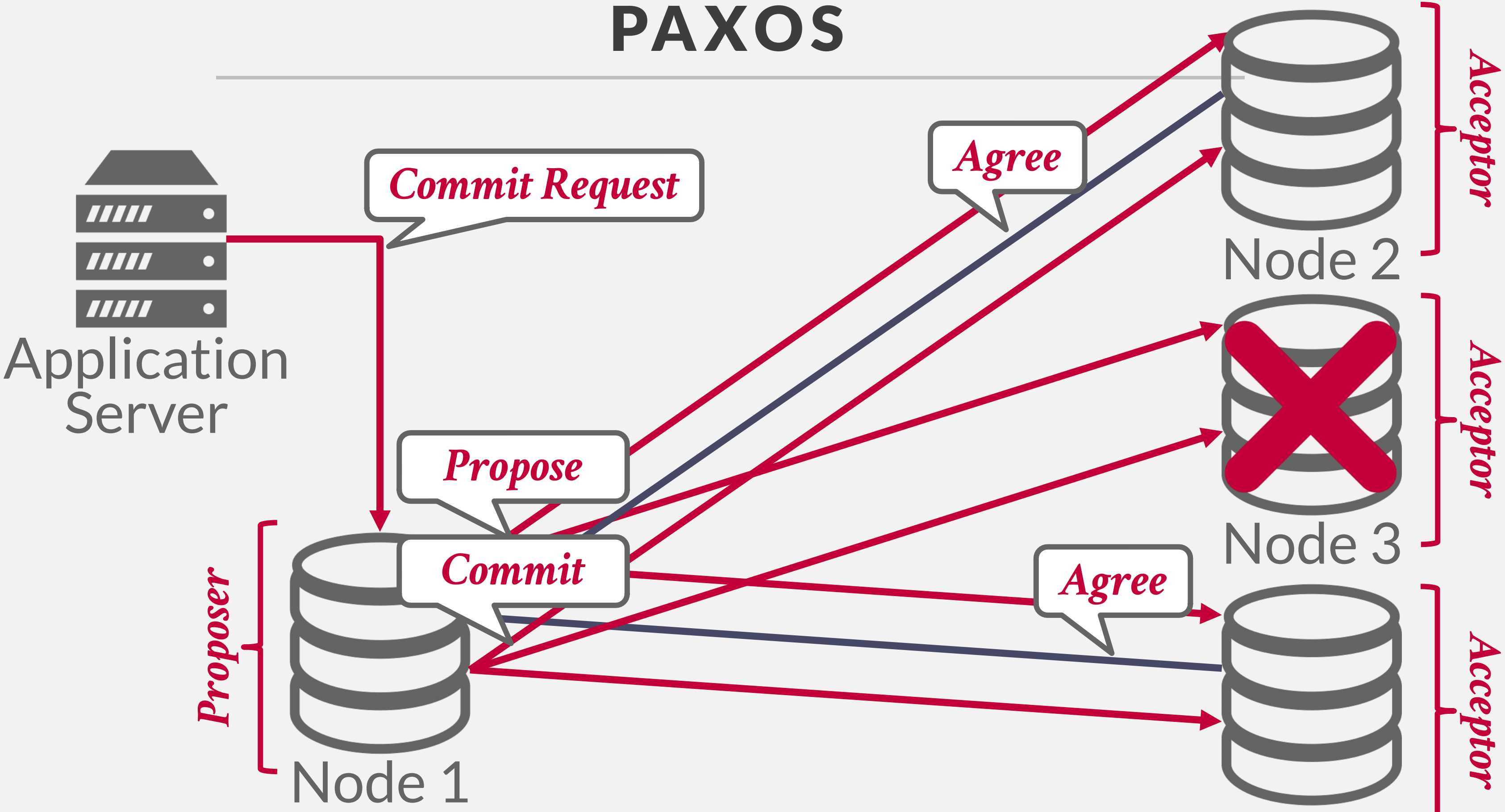
PAXOS


Commit Request
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Application Server
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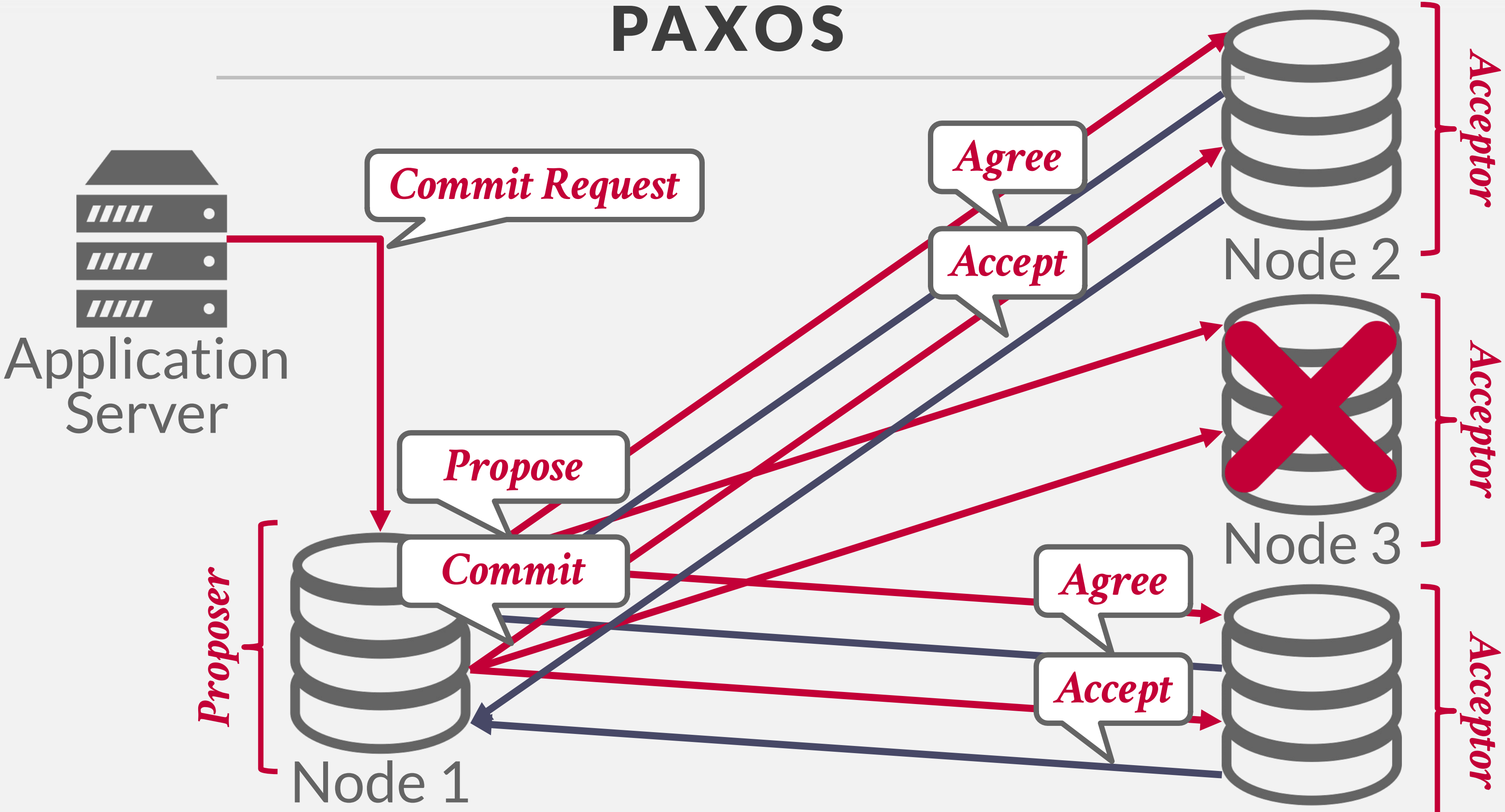
PAXOS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Node 1
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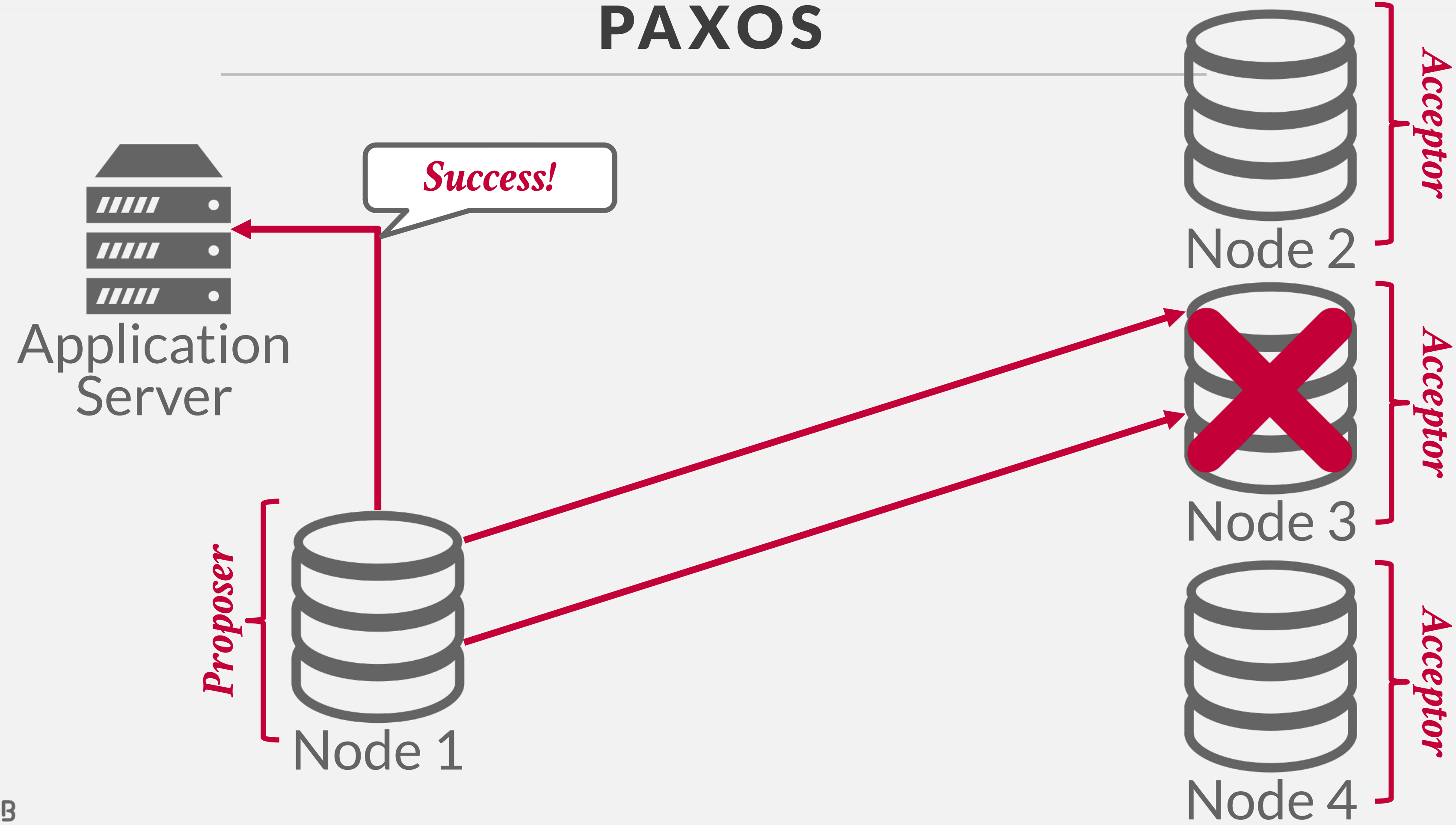
PAXOS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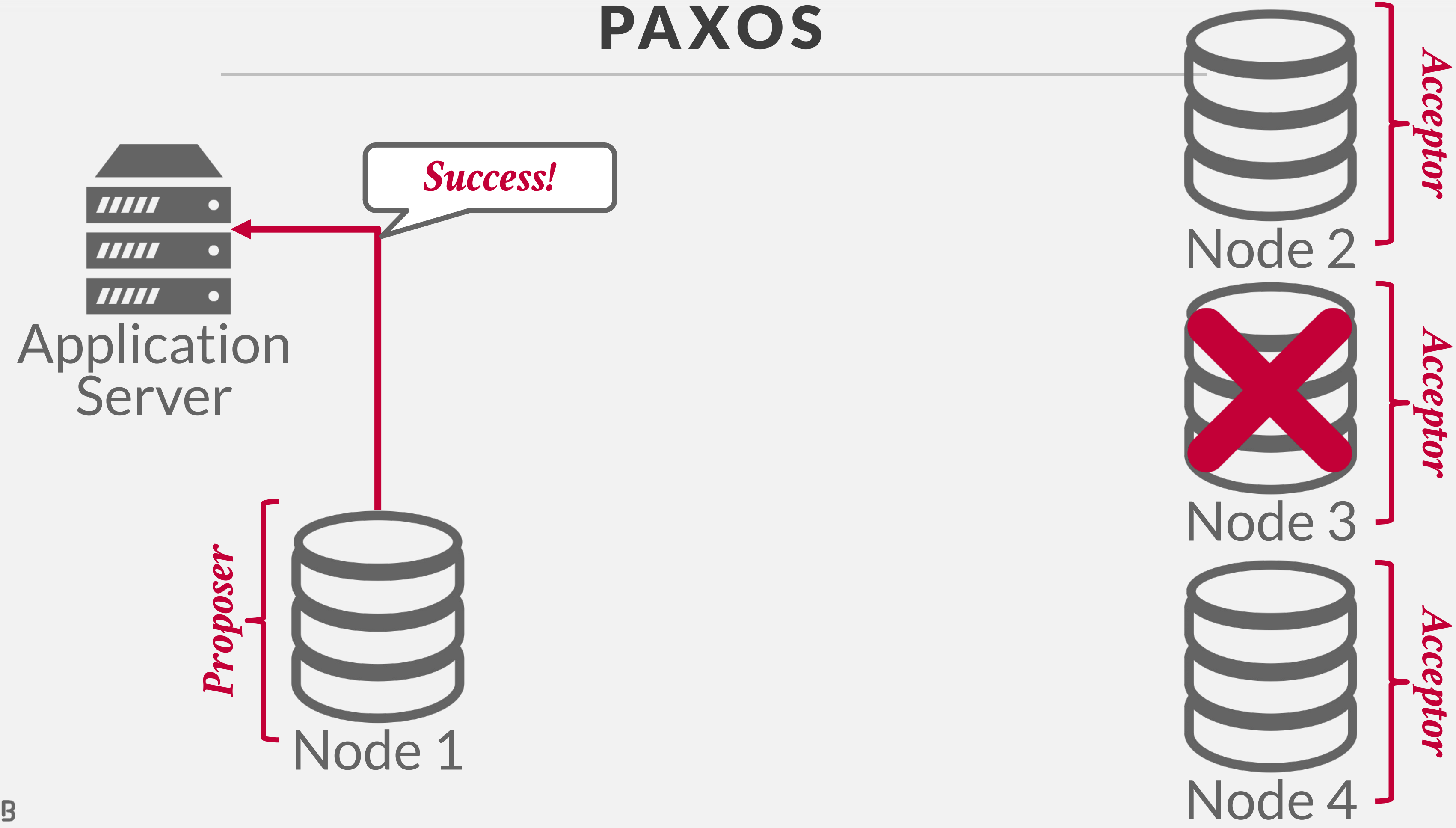
Node 4

PAXOS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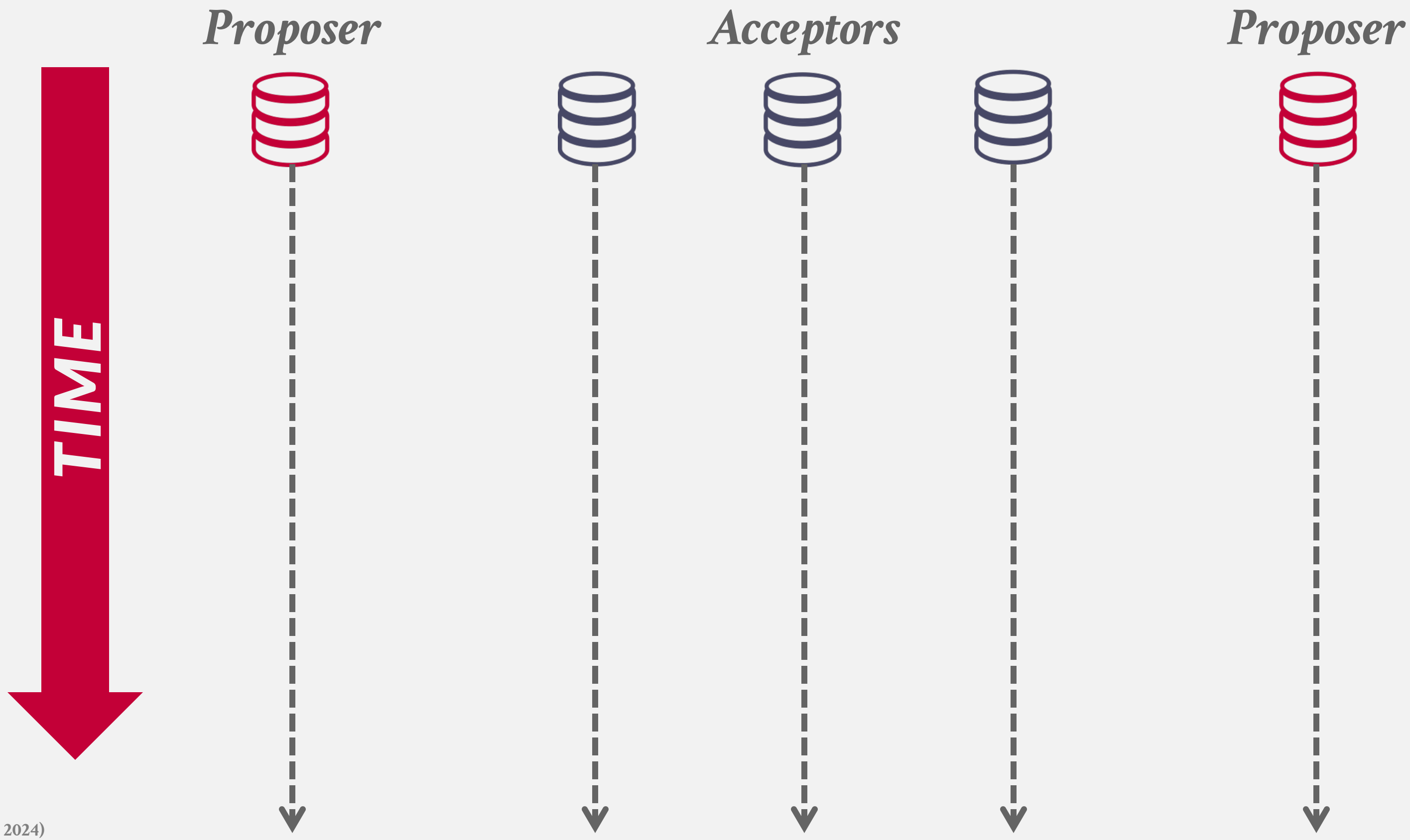
PAXOS



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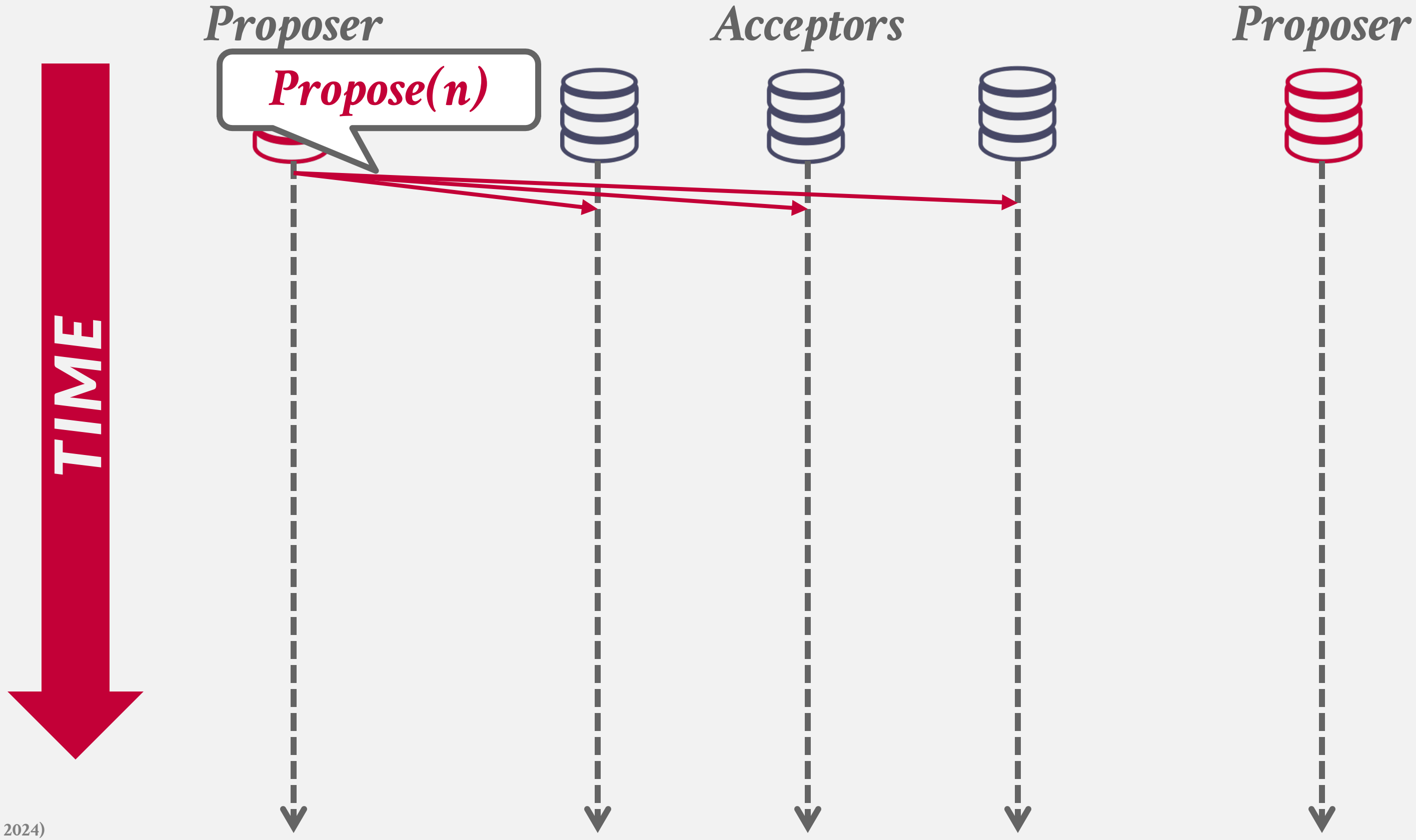

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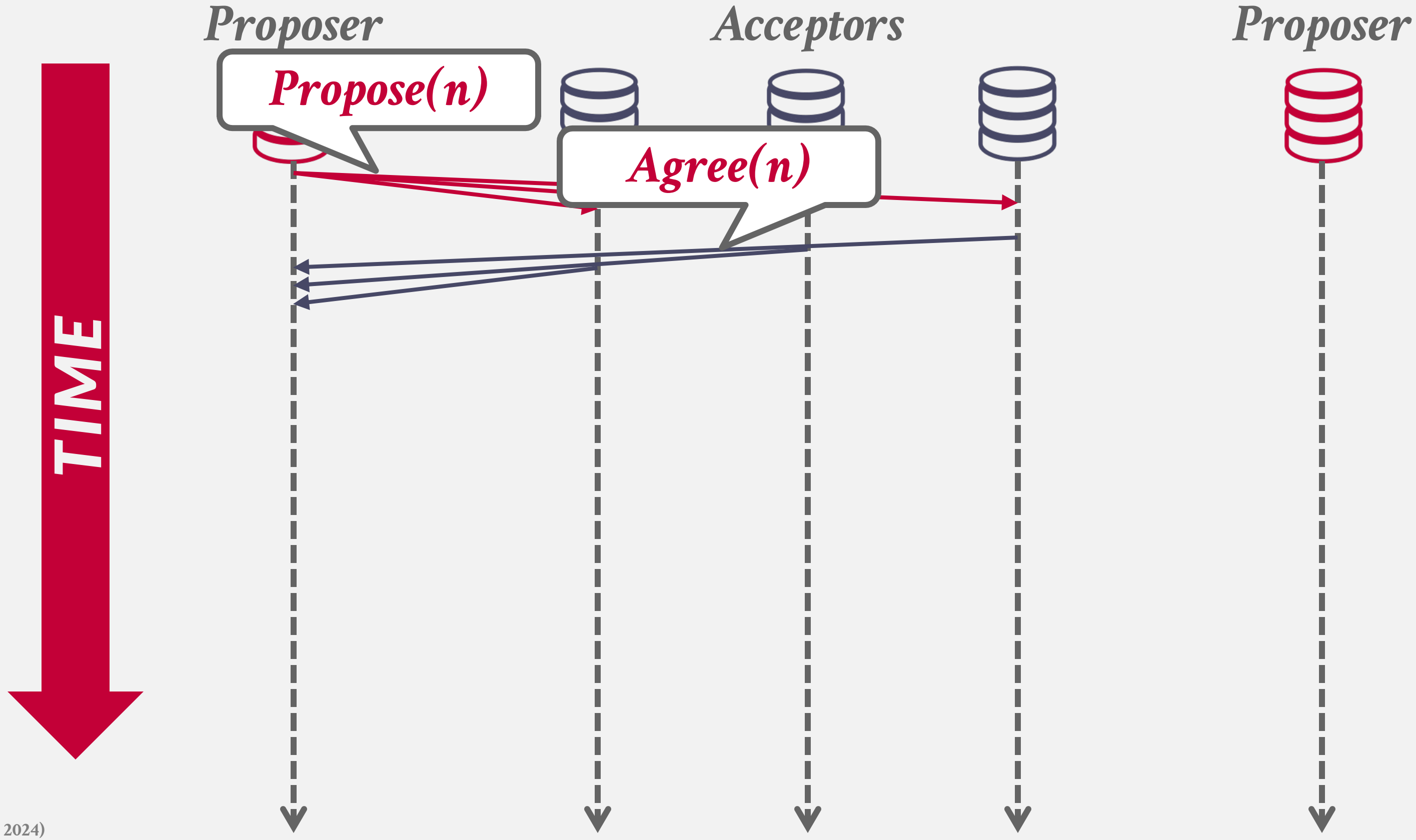

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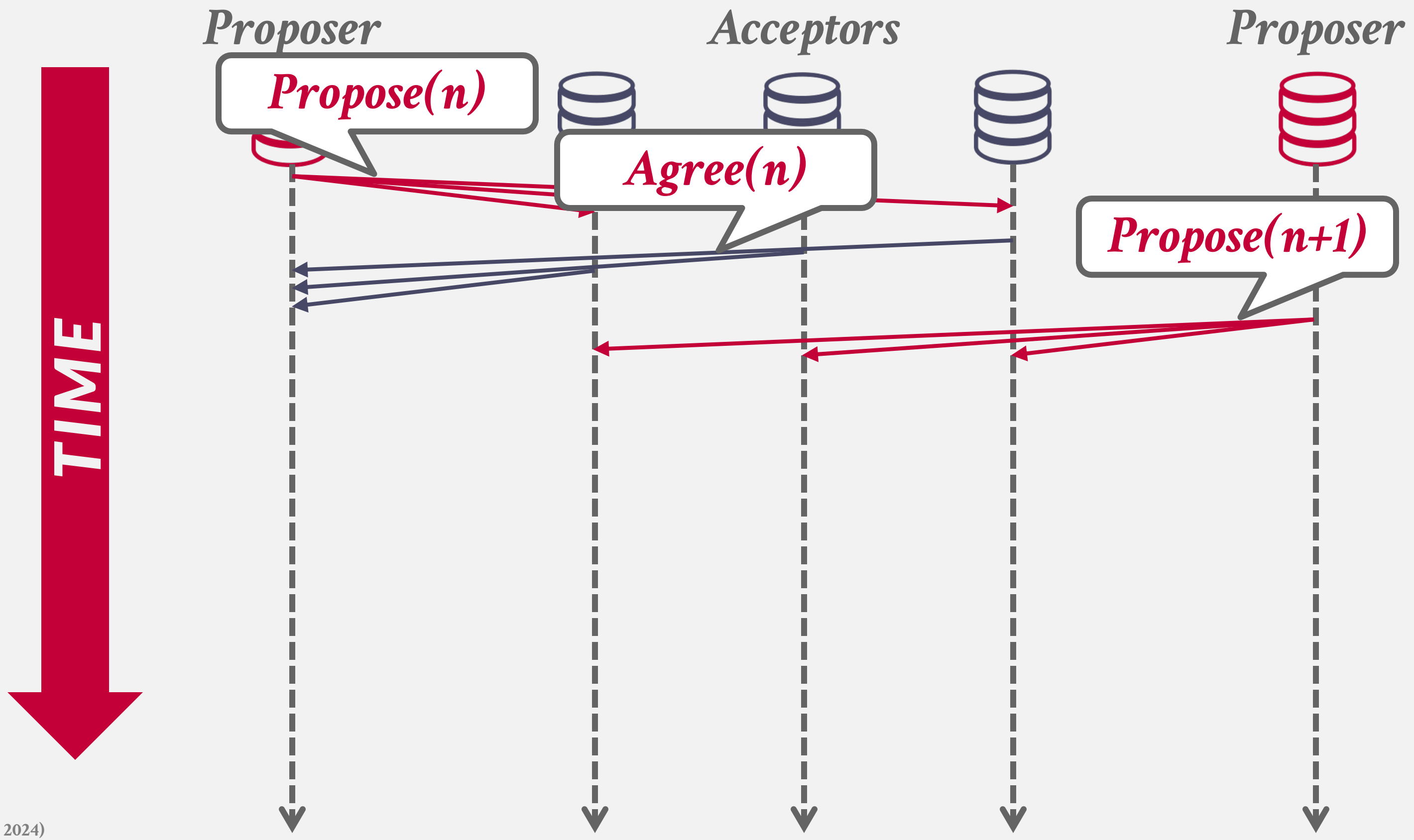
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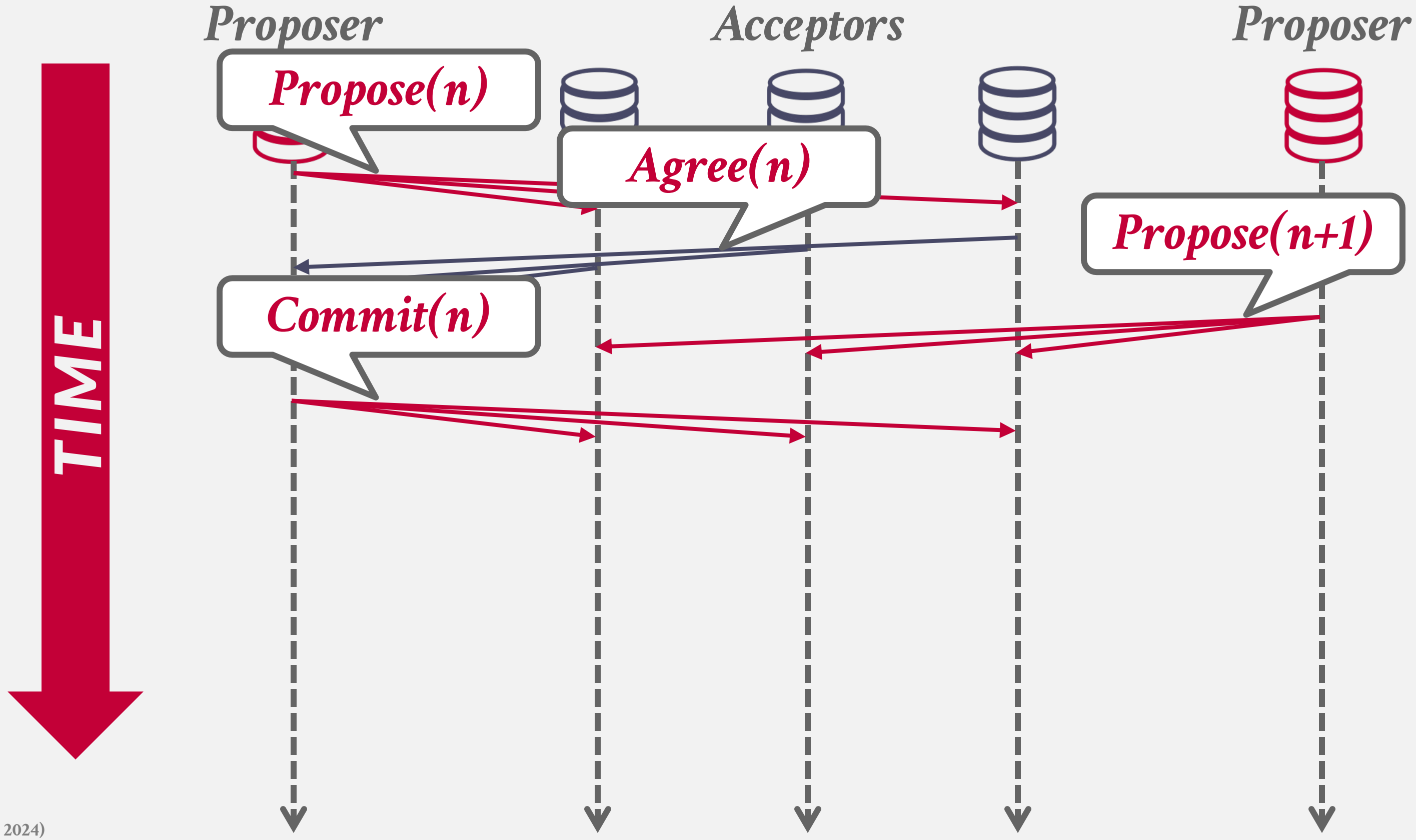
Acceptors
Proposer
Propose(n)
Agree(n)
Propose(n+1)
TIME

PAXOS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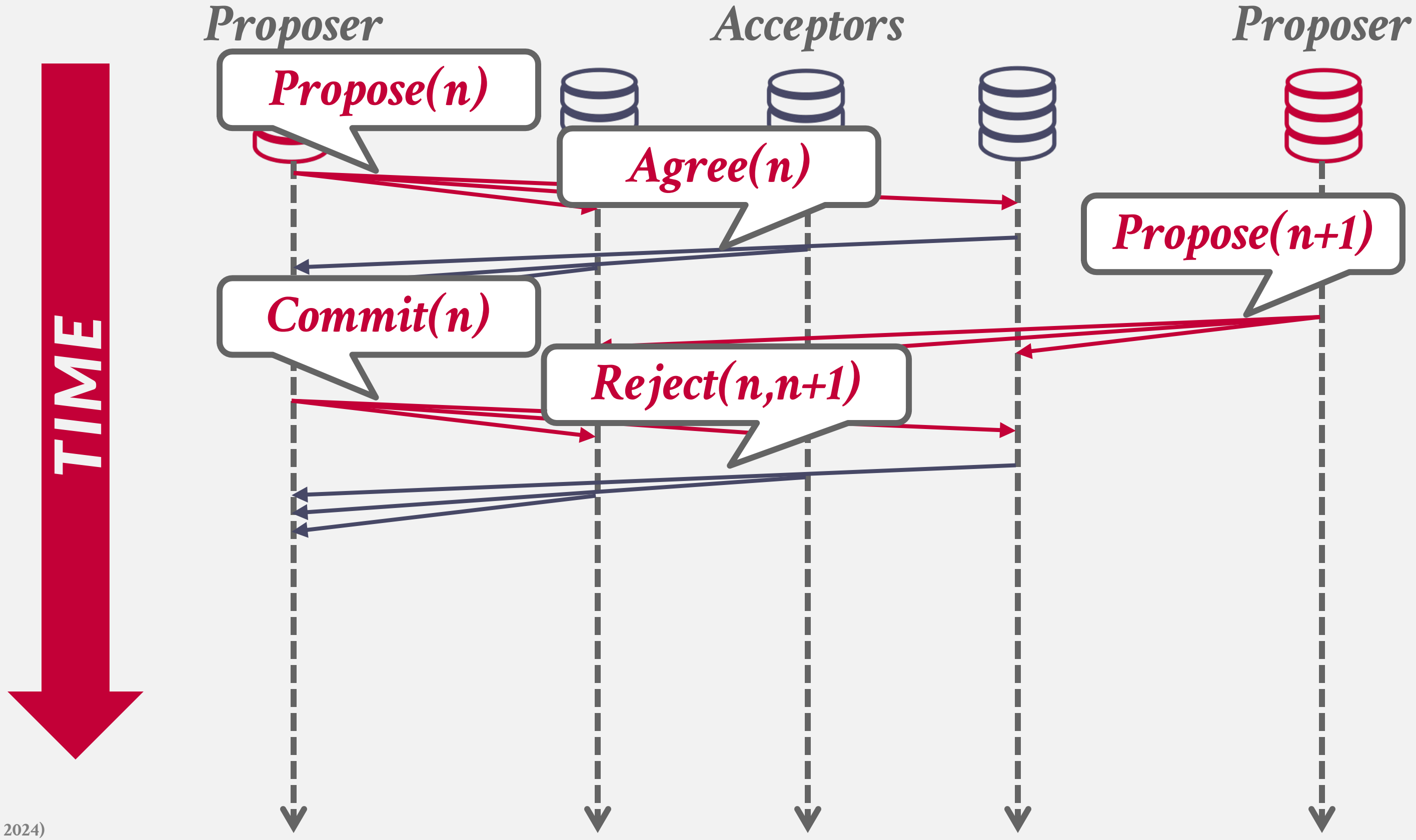
Commit(n)

PAXOS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TIME
Propose(n)
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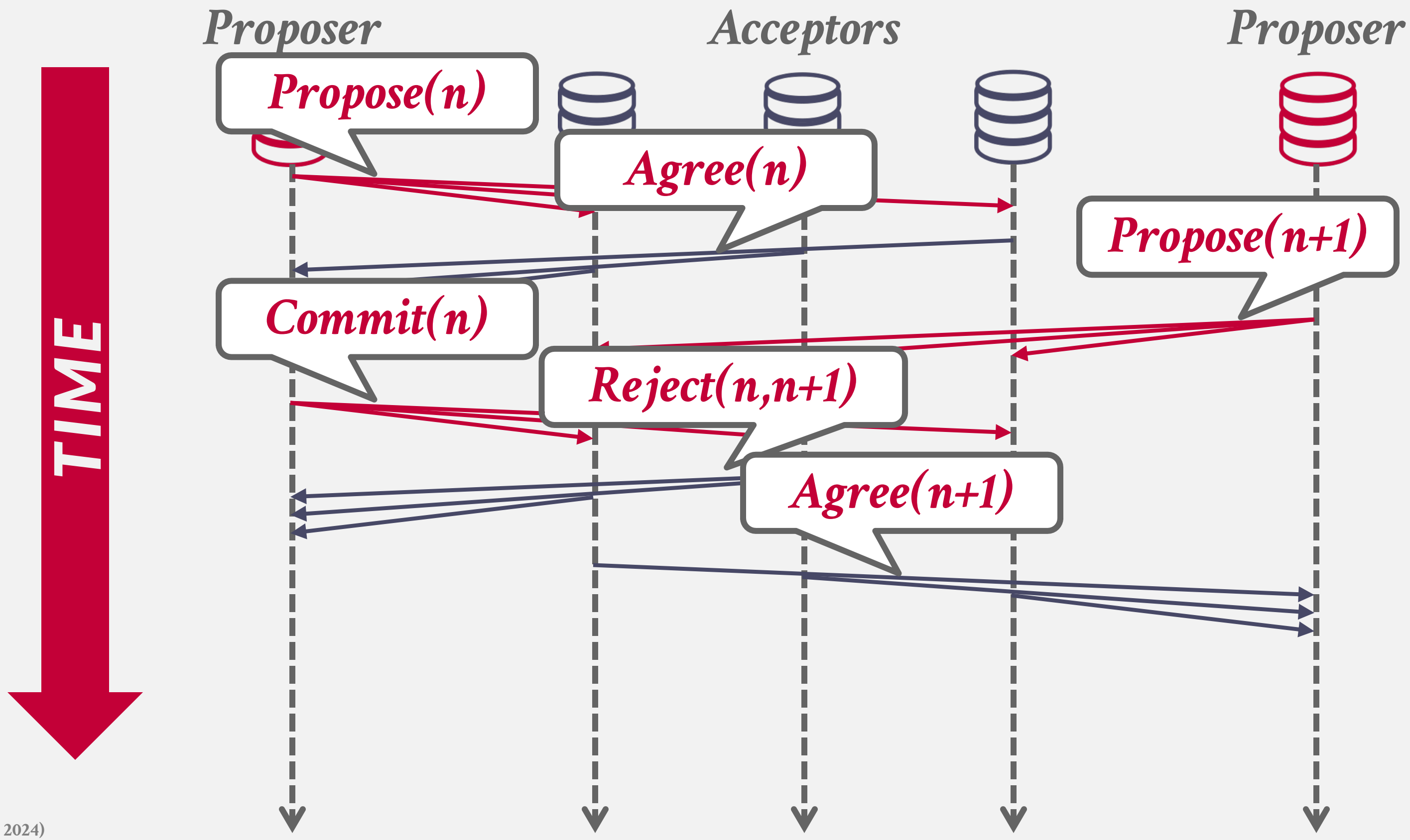
Commit(n)
Reject(n,n+1)

PAXOS


Proposer
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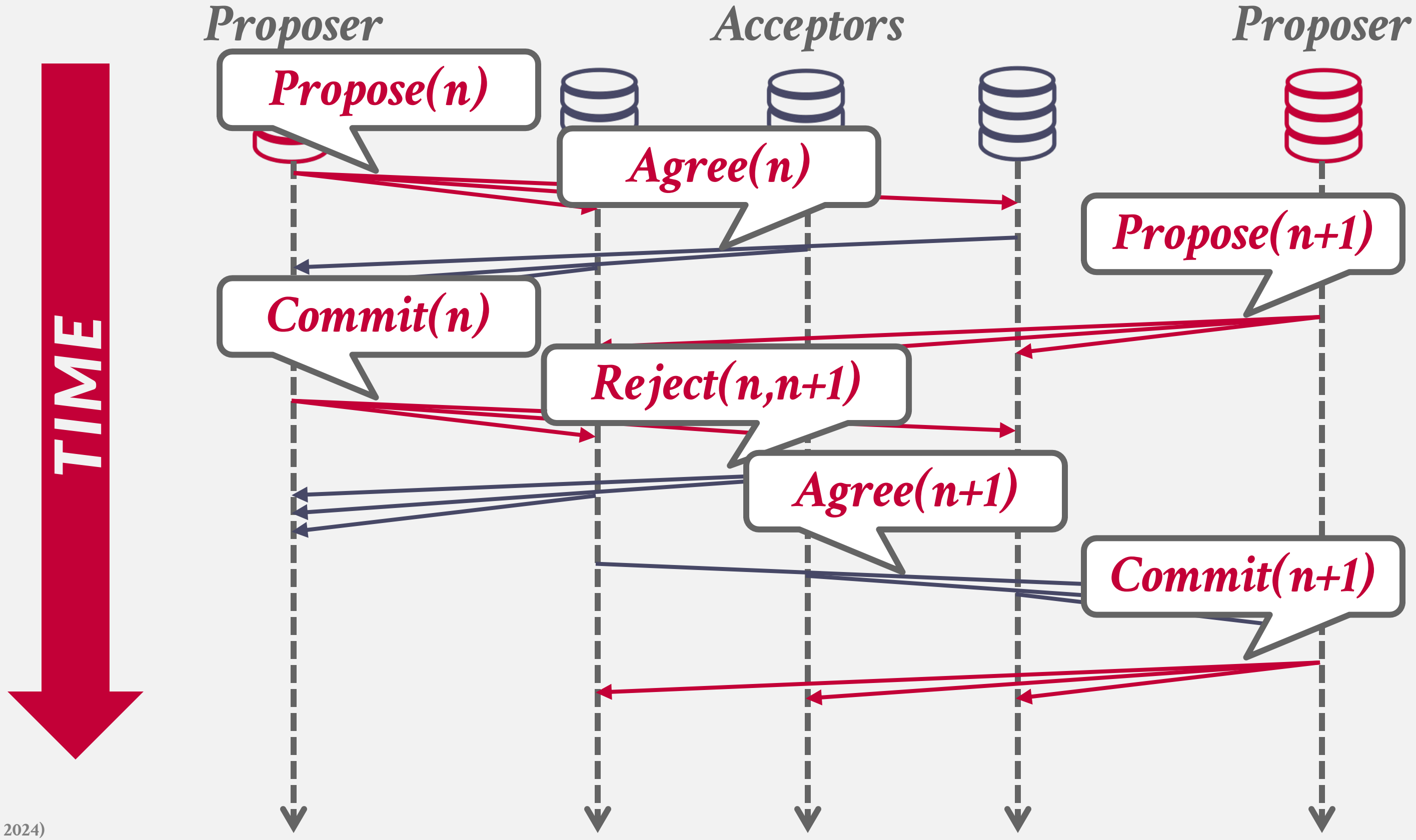
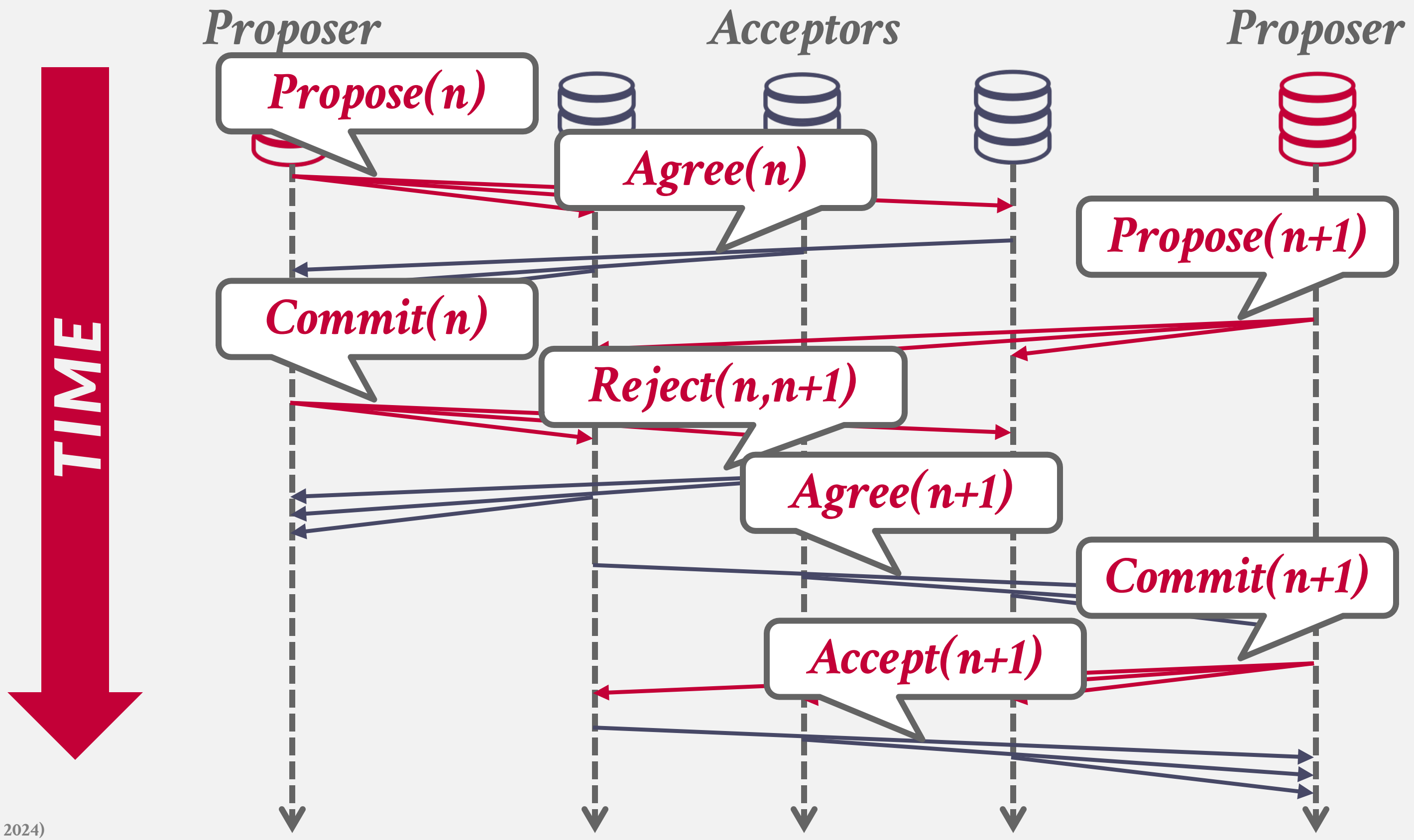
Propose(n+1)
Commit(n)
Reject(n,n+1)
Agree(n+1)

PAXOS


Proposer
Acceptors
Proposer
TIME
Propose(n)
Agree(n)
Propose(n+1)
Commit(n)
Reject(n,n+1)
Agree(n+1)
Commit(n+1)

PAXOS


Proposer
Acceptors
Proposer
TIME
Propose(n)
Agree(n)
Propose(n+1)
Commit(n)
Reject(n,n+1)
Agree(n+1)
Commit(n+1)
Accept(n+1)

MULTI-PAXOS

If the system elects a single leader that oversees proposing changes for some period, then it can skip the **Propose** phase.

→ Fall back to full Paxos whenever there is a failure.

The system periodically renews the leader (known as a *lease*) using another Paxos round.

→ Nodes must exchange log entries during leader election to make sure that everyone is up-to-date.

2PC VS. PAXOS VS. RAFT

Two-Phase Commit

→ Blocks if coordinator fails after the prepare message is sent, until coordinator recovers.

Paxos

→ Non-blocking if a majority participants are alive, provided there is a sufficiently long period without further failures.

Raft:

→ Similar to Paxos but with fewer node types.
→ Only nodes with most up-to-date log can become leaders.

CAP THEOREM

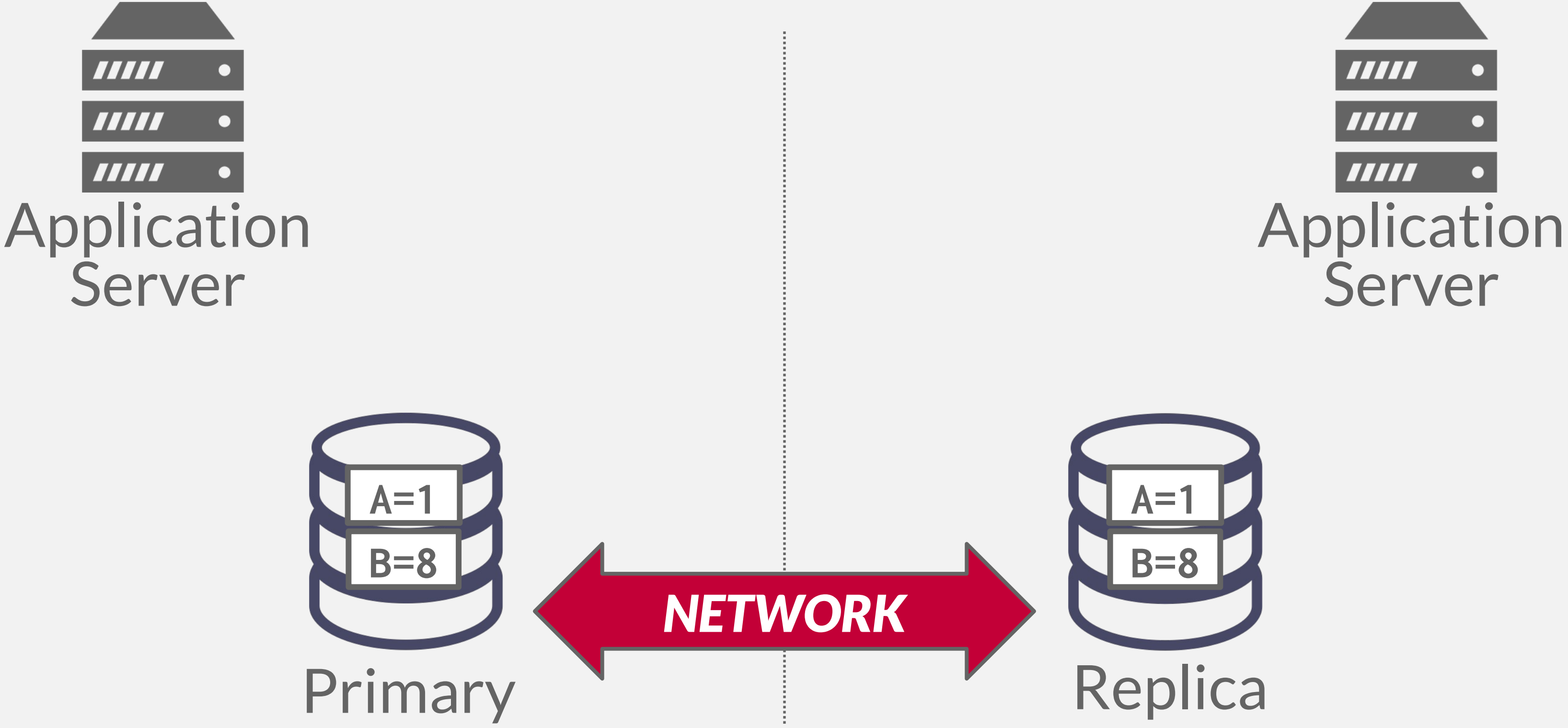
Proposed in the late 1990s that is impossible for a distributed database to always be:

- → **C**onsistent
- → **A**lways Available
- → **N**etwork Partition Tolerant

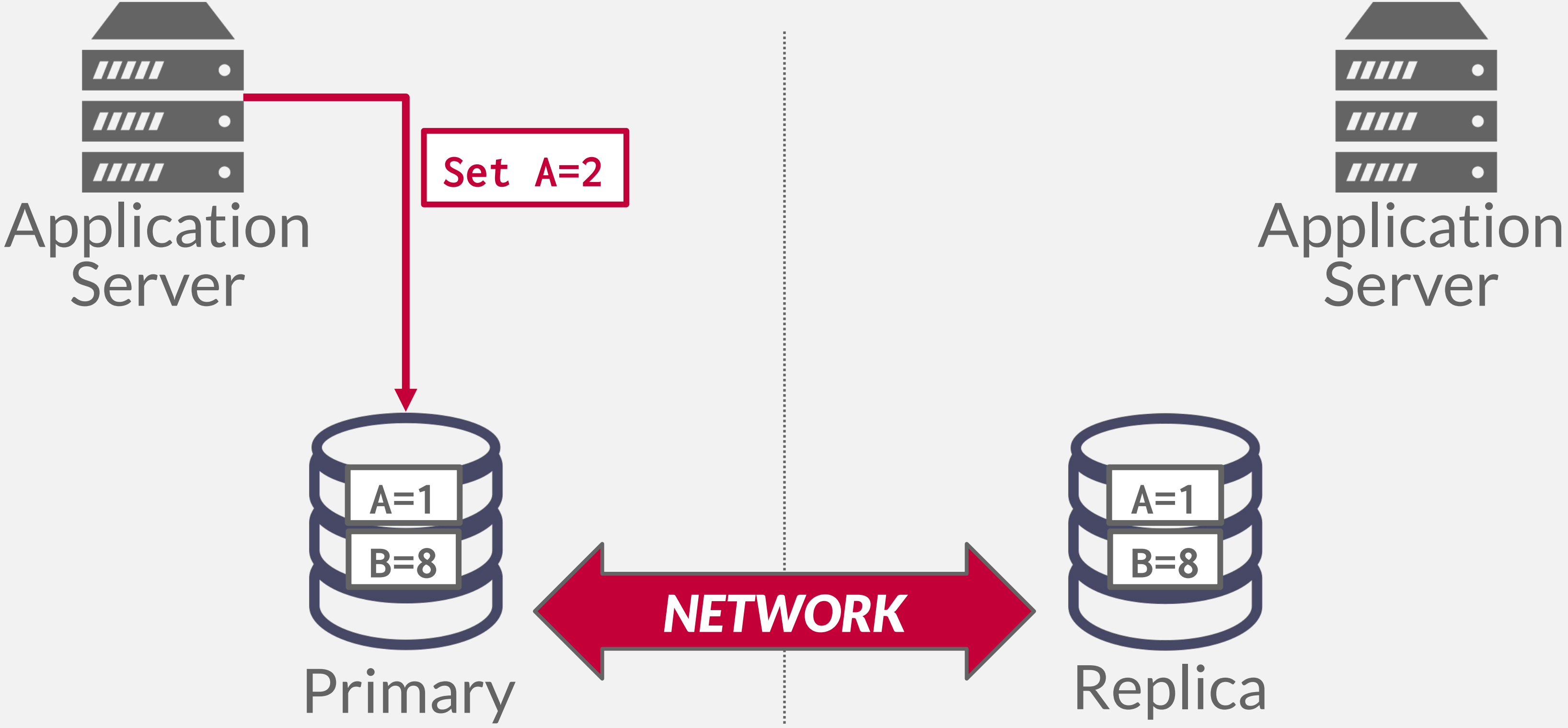
Extended in 2010 (PACELC) to include consistency vs. latency trade-offs:

- → **P**artition Tolerant
- → **A**lways Available
- → **C**onsistent
- → **E**lse, choose during normal operations
- → **L**atency
- → **C**onsistency

CONSISTENCY



CONSISTENCY



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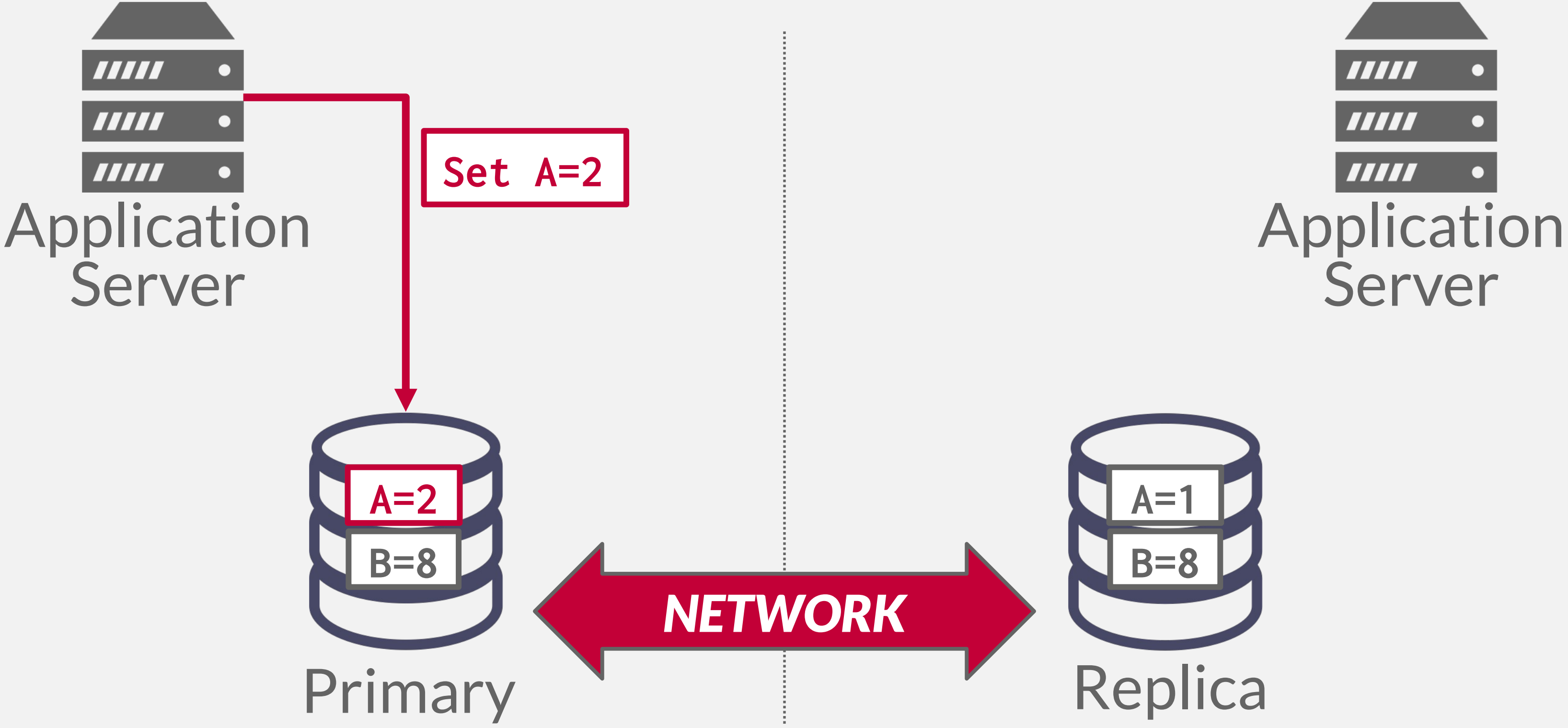
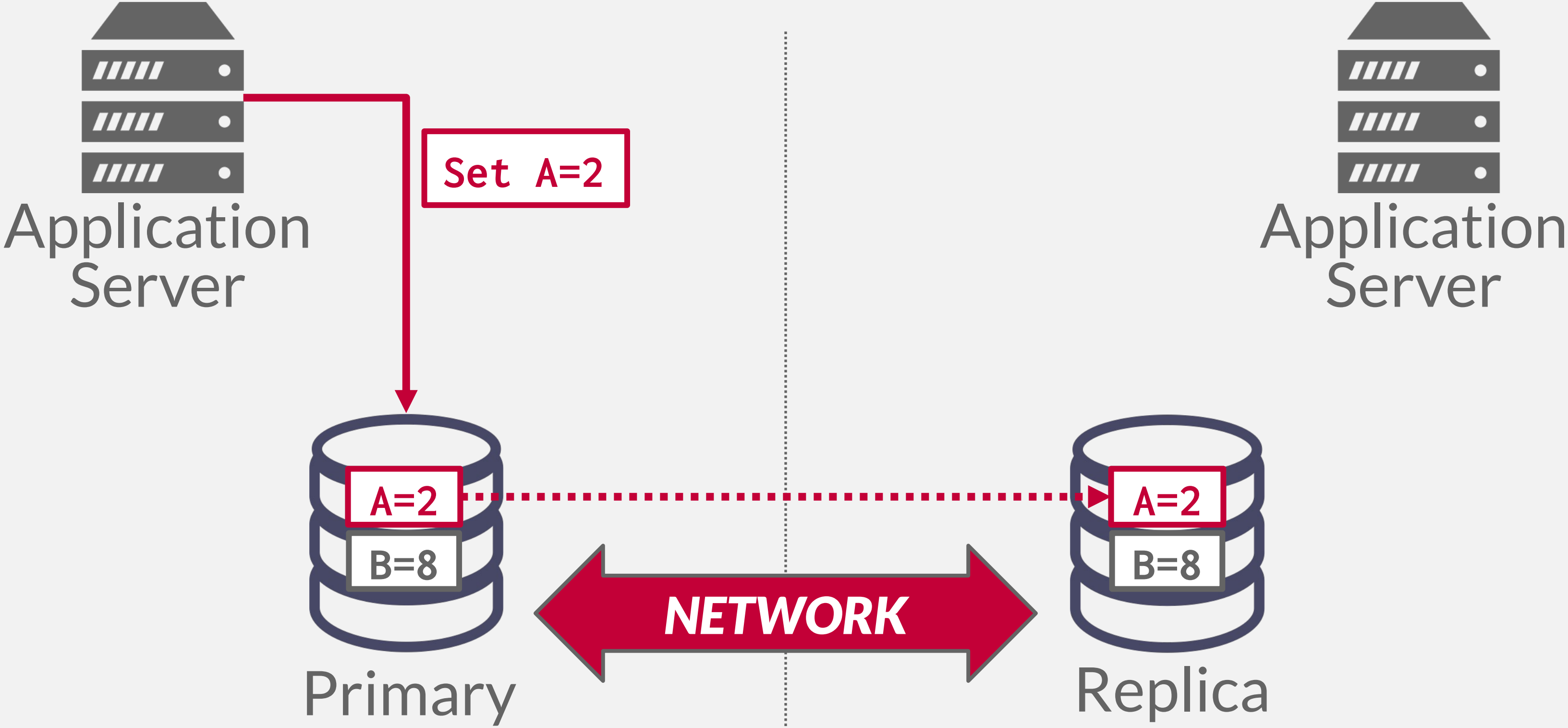


CONSISTENCY



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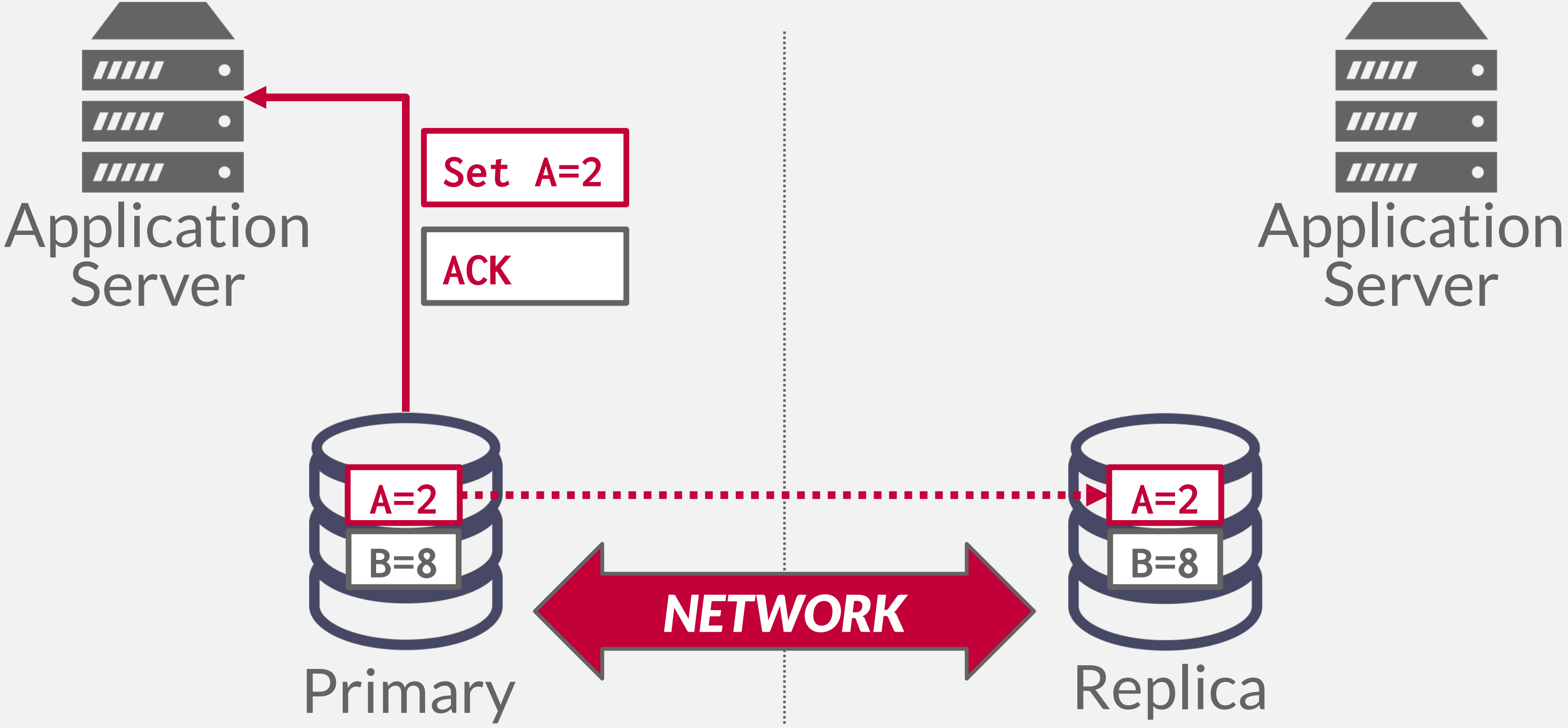

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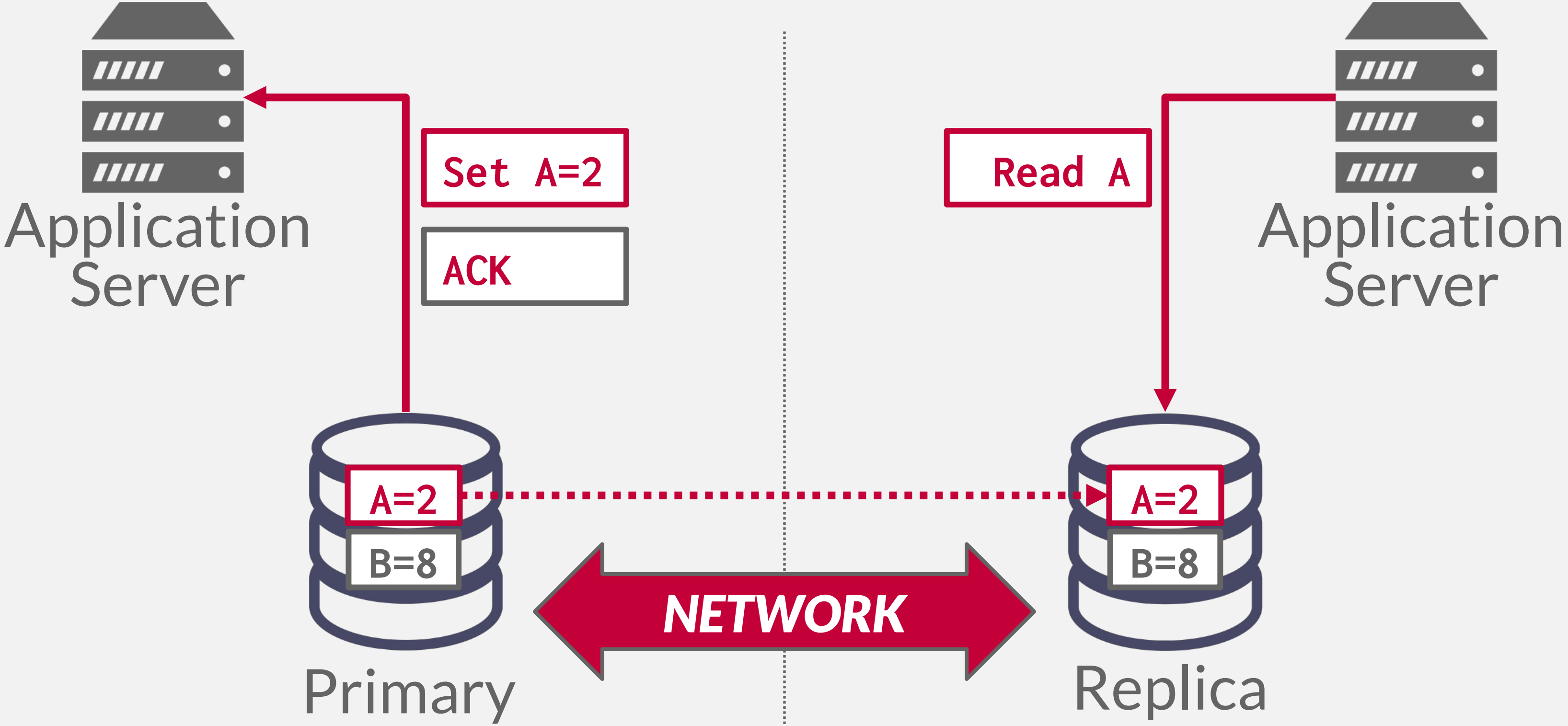

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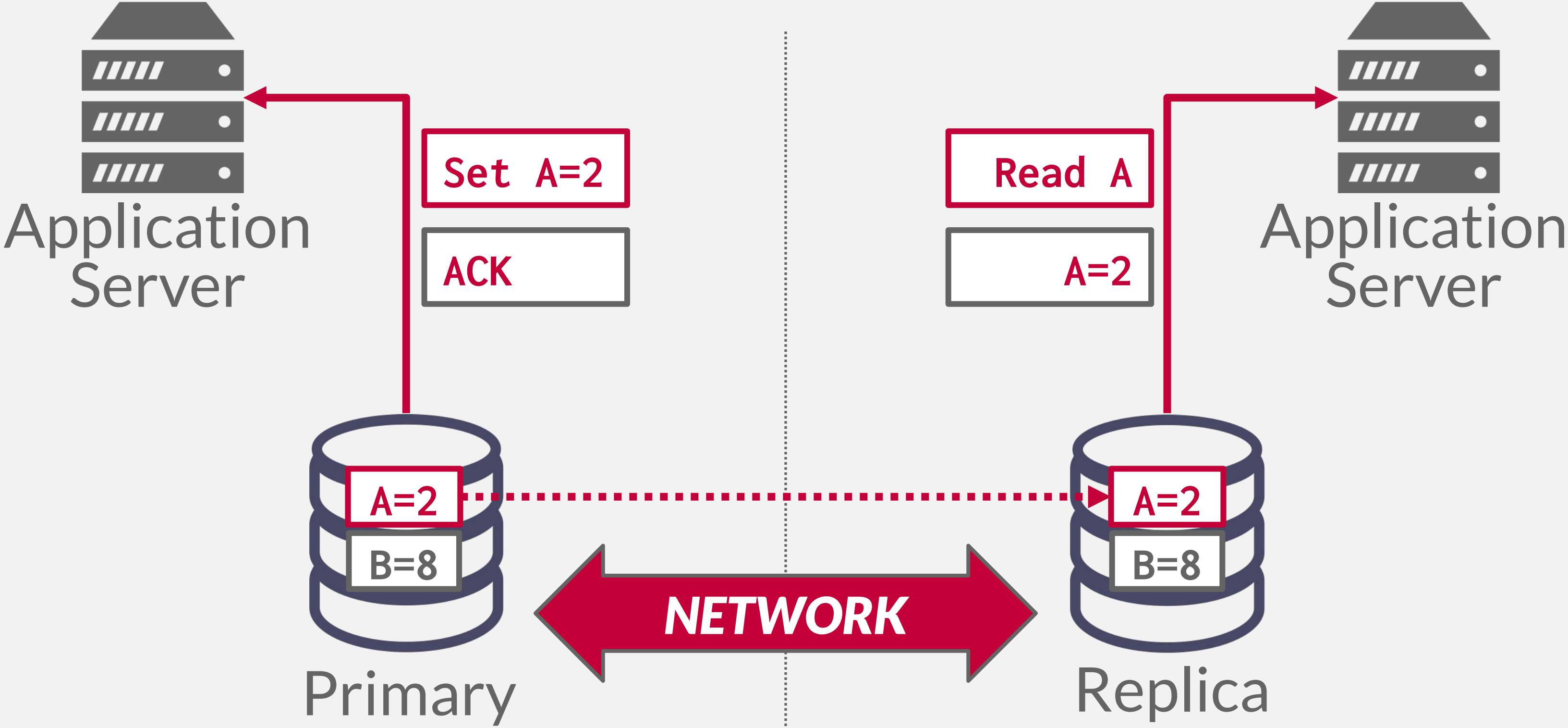
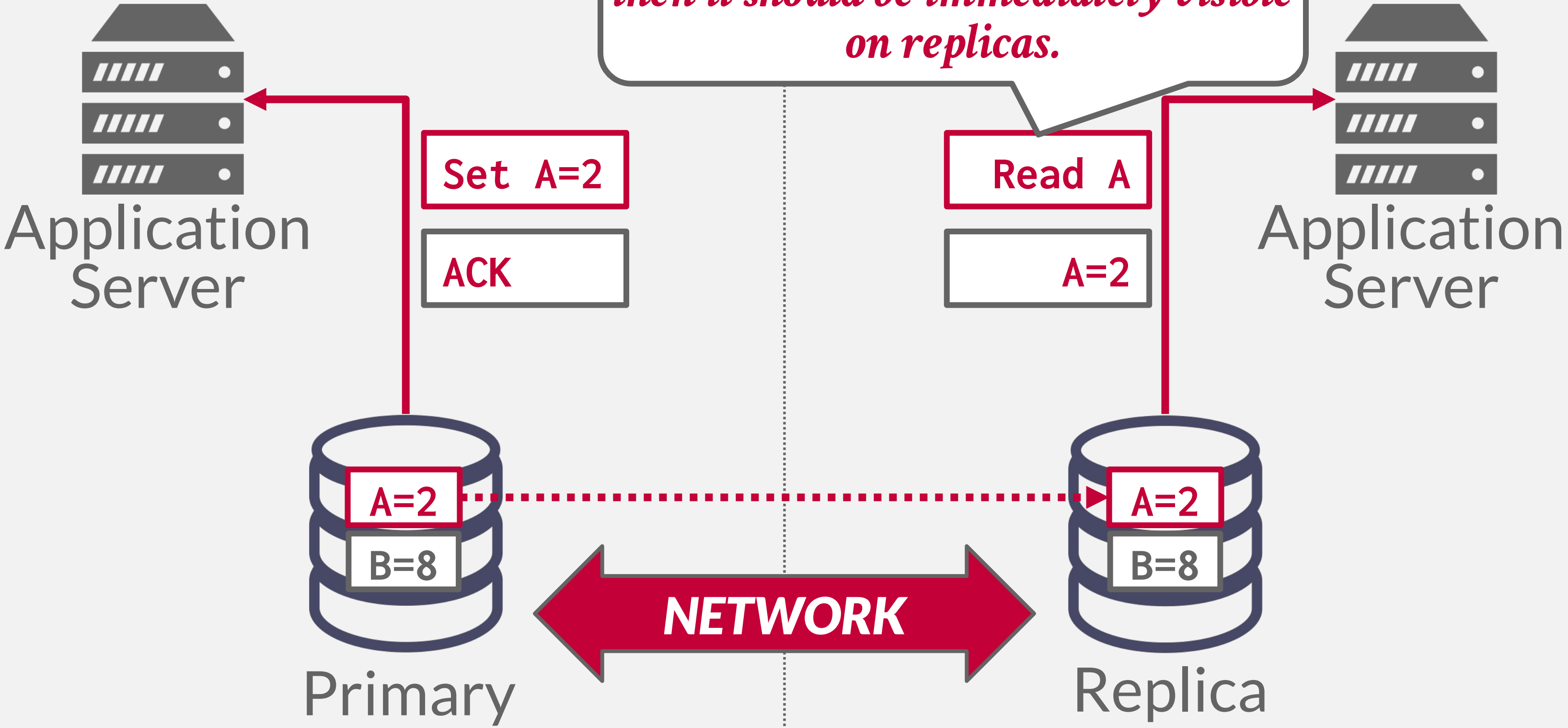
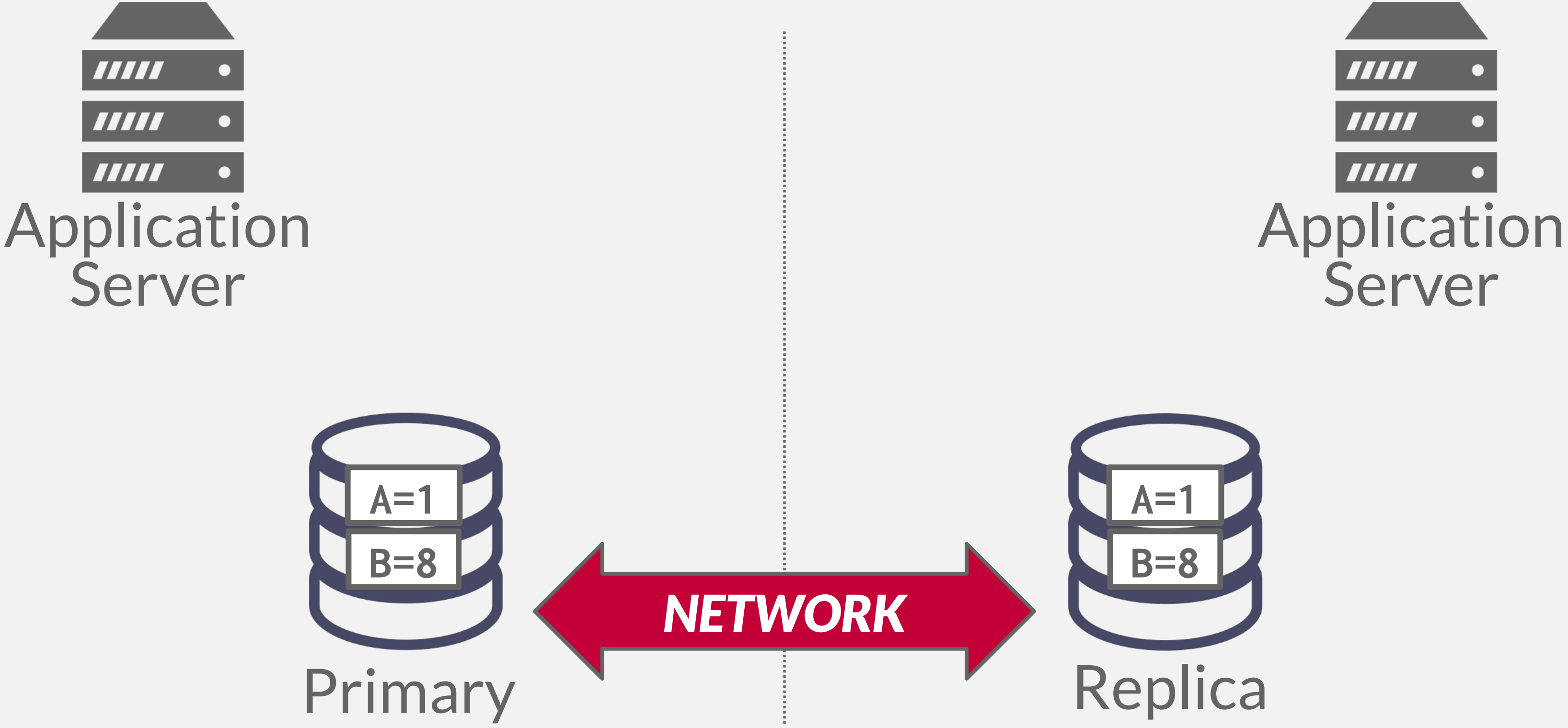


CONSISTENCY

If Primary says the txn committed, then it should be immediately visible on replicas.



AVAILABILITY



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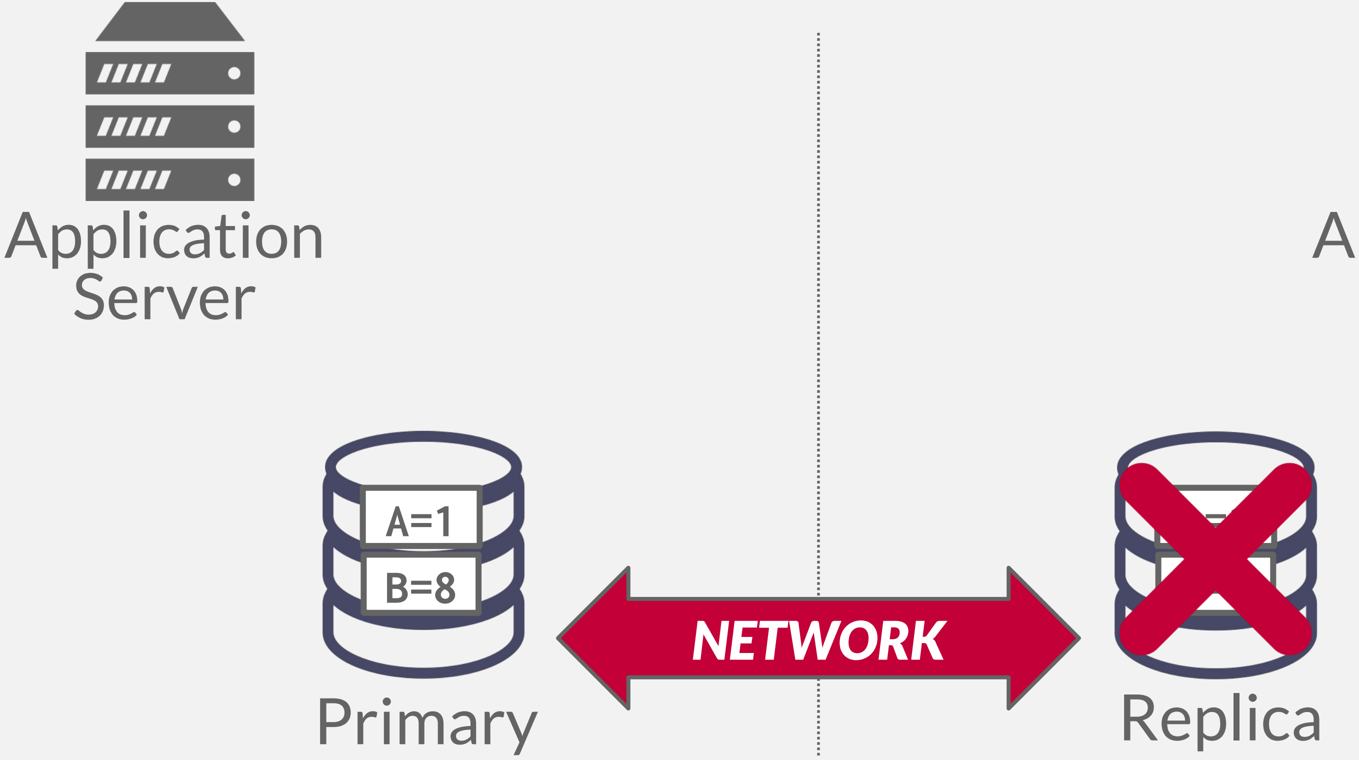

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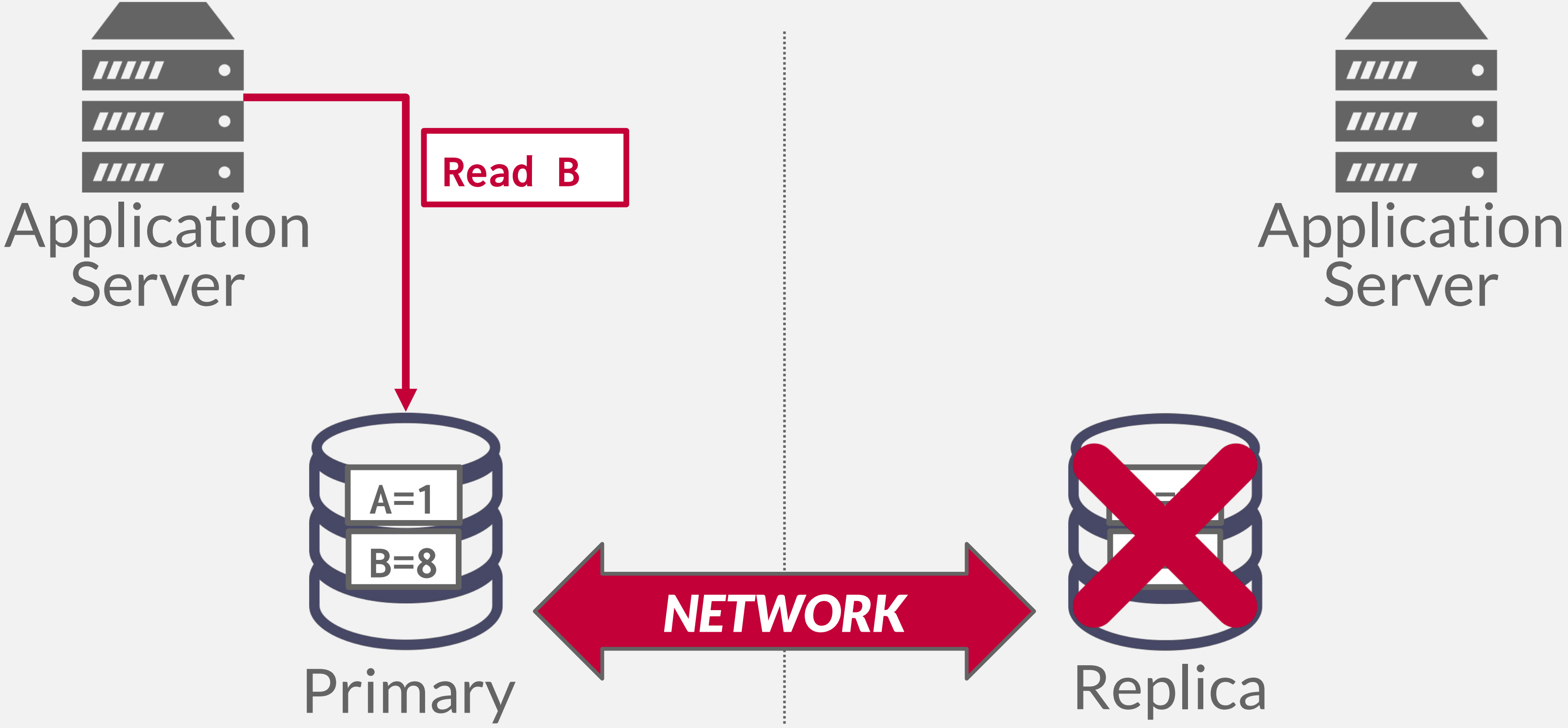

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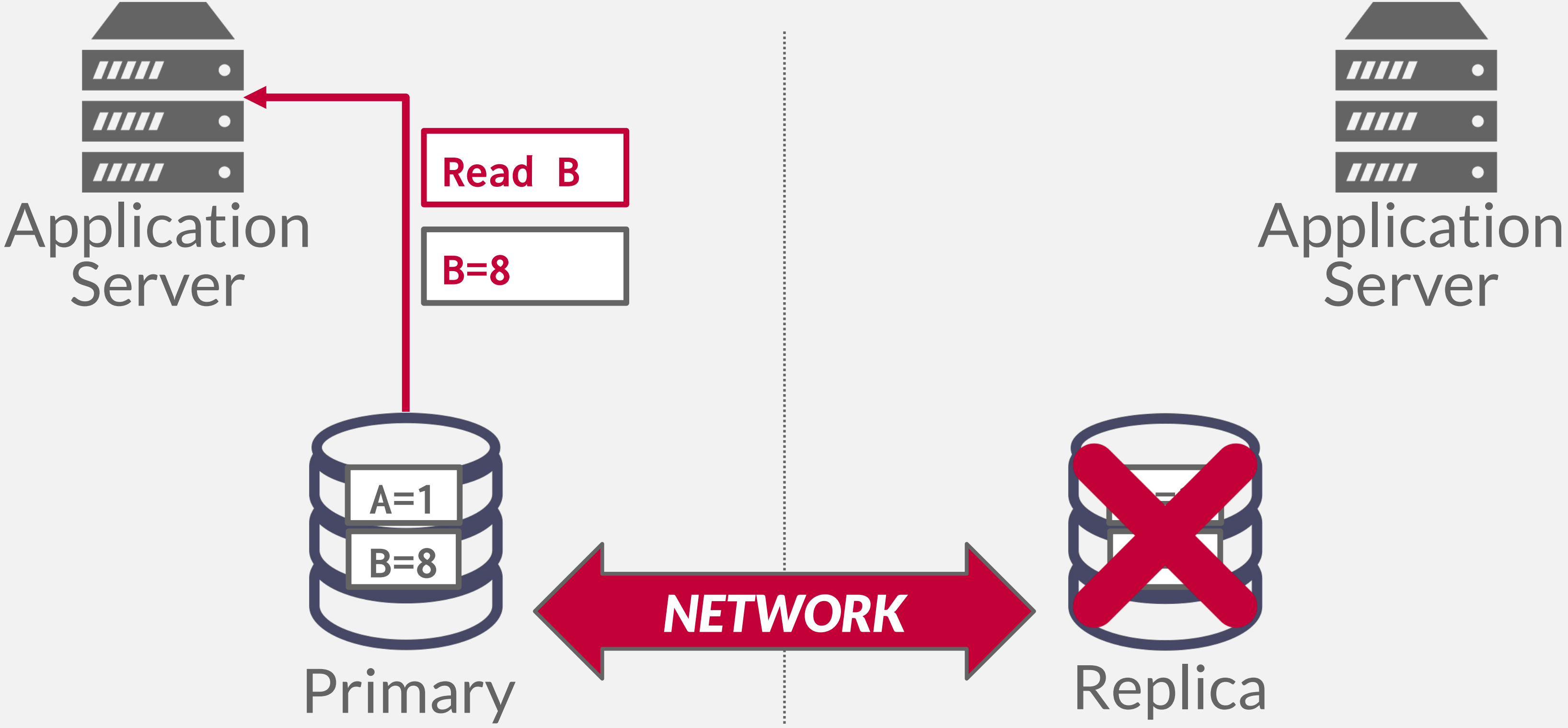

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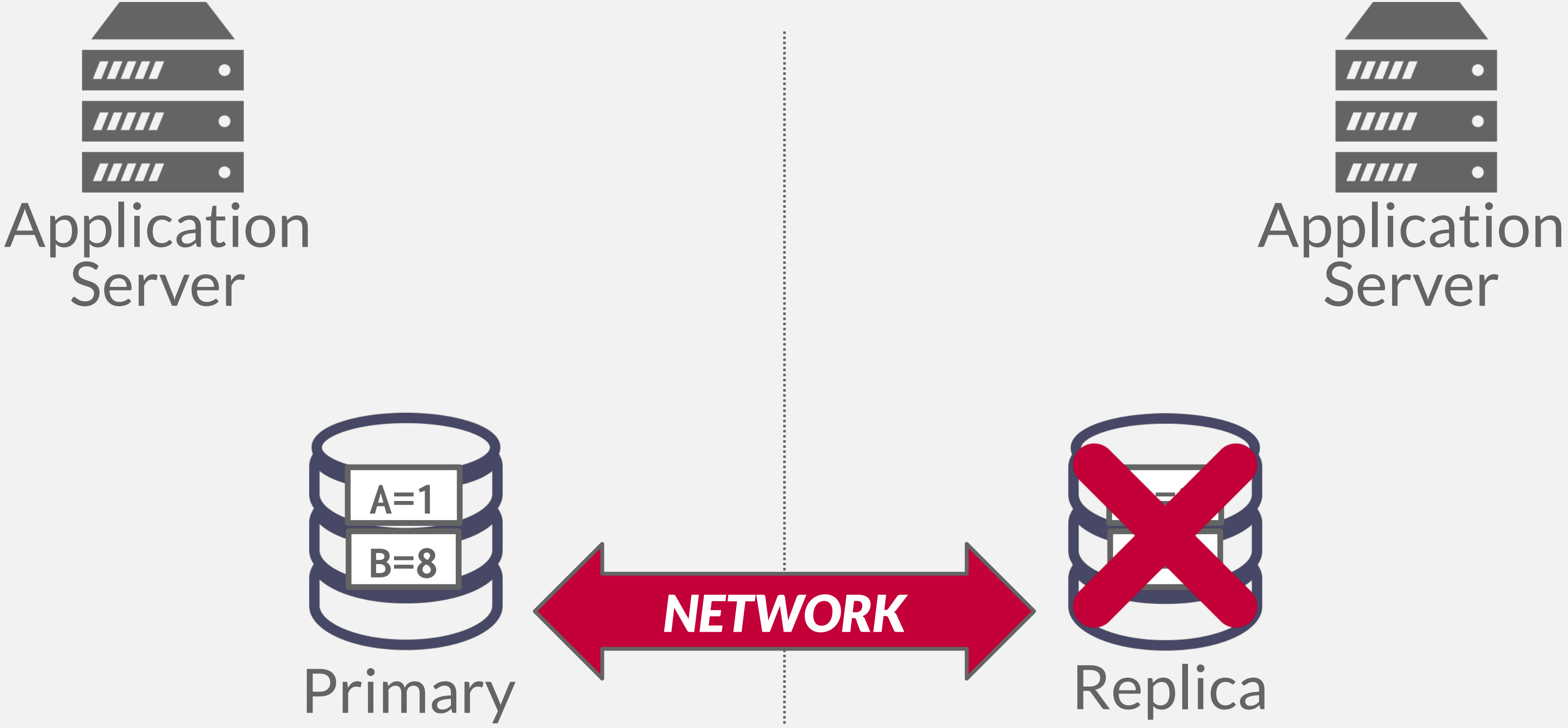

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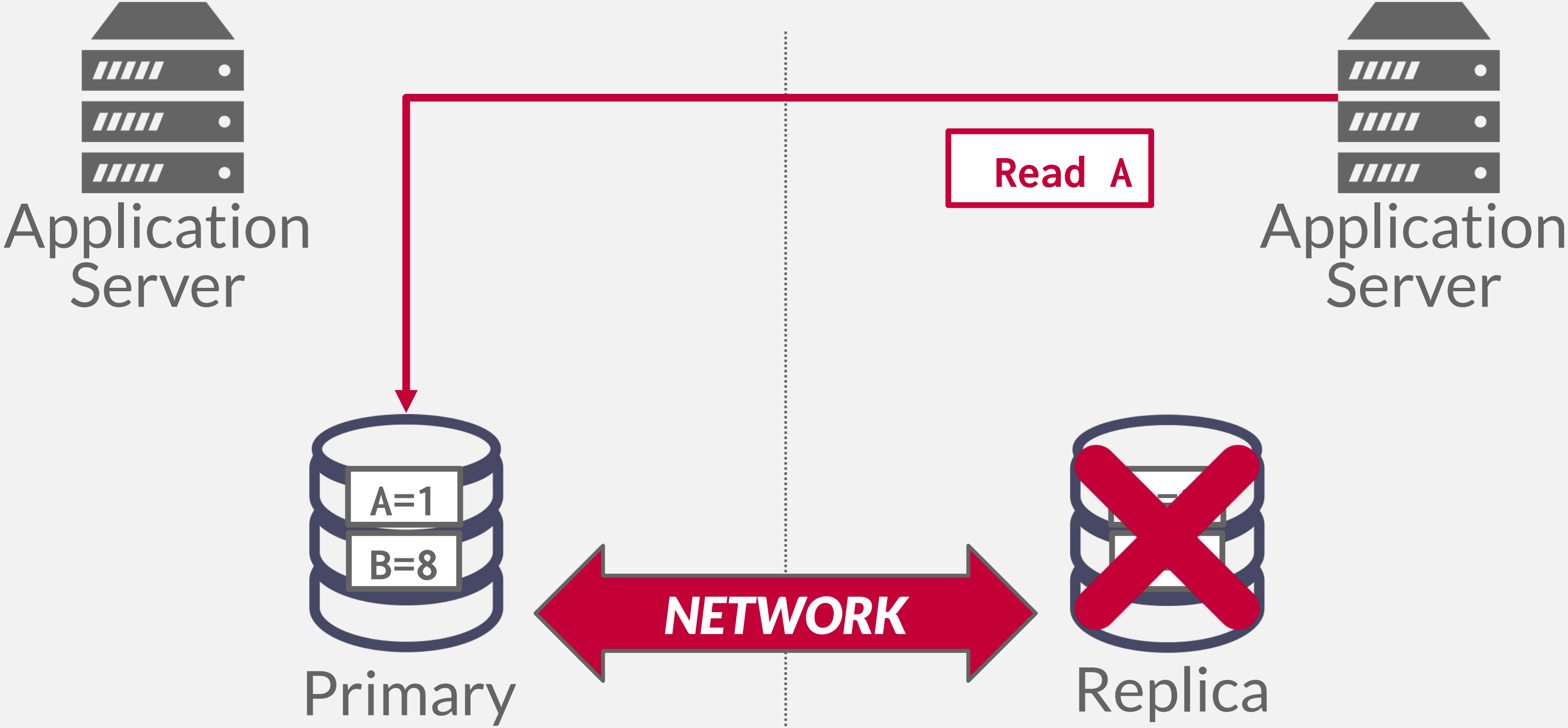

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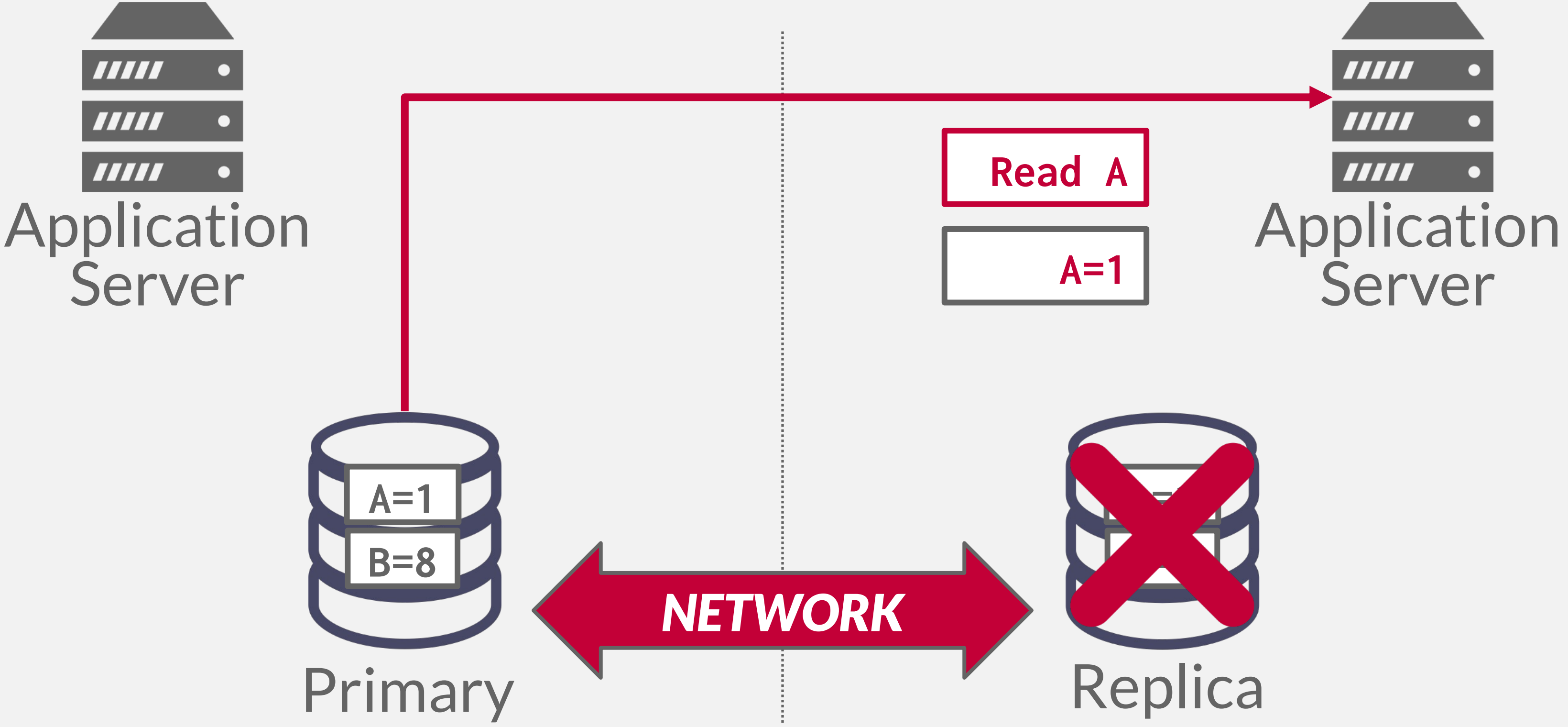
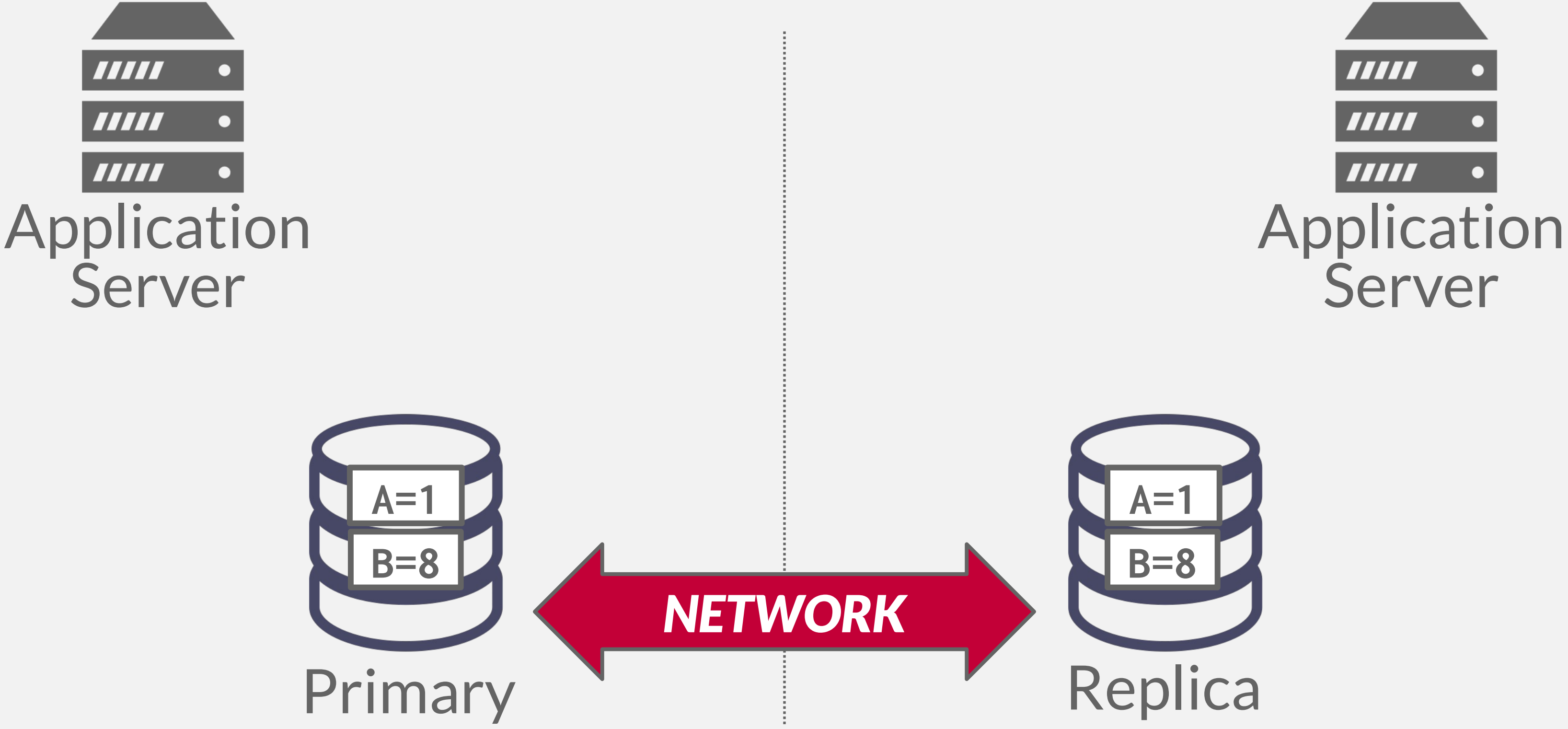


PARTITION TOLERANCE



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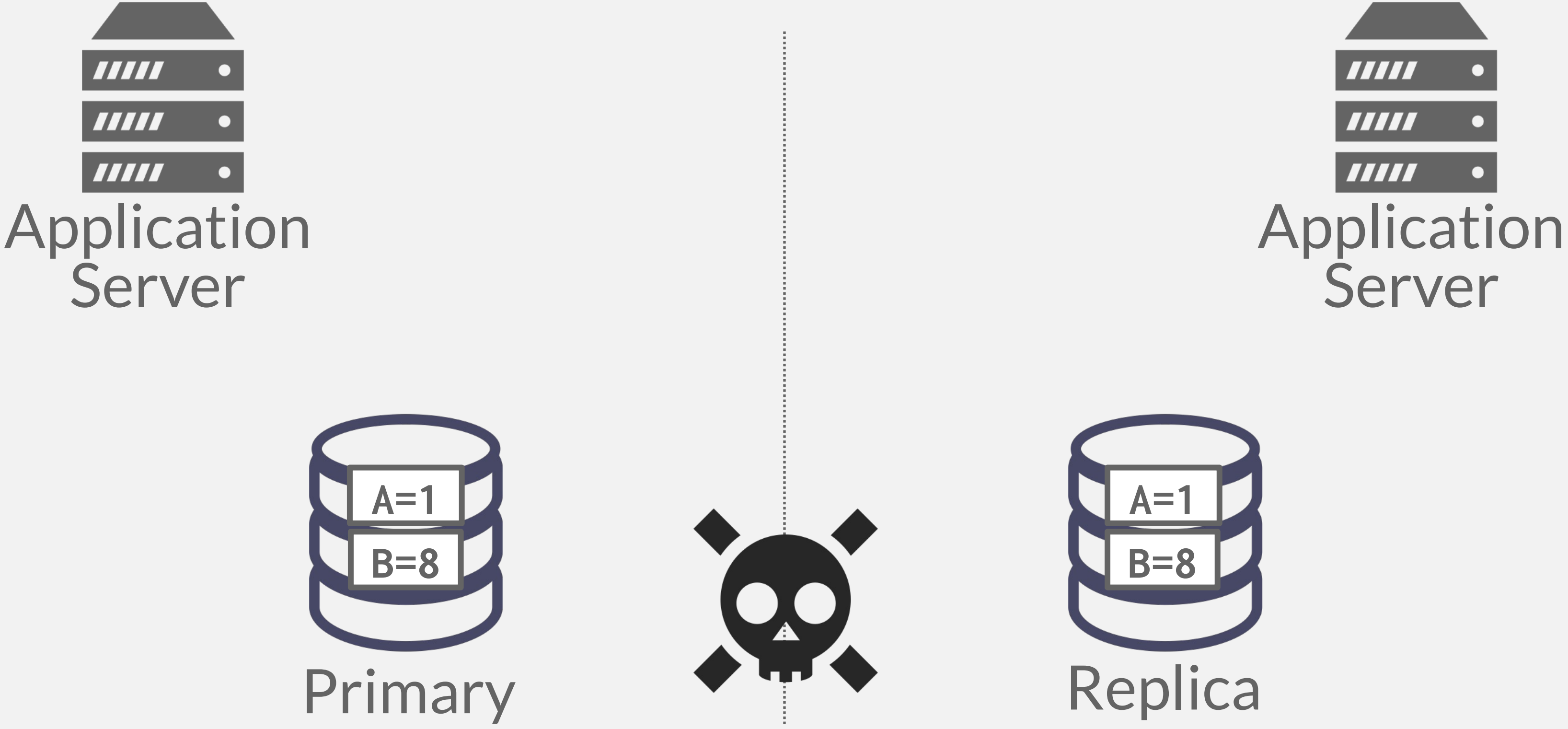

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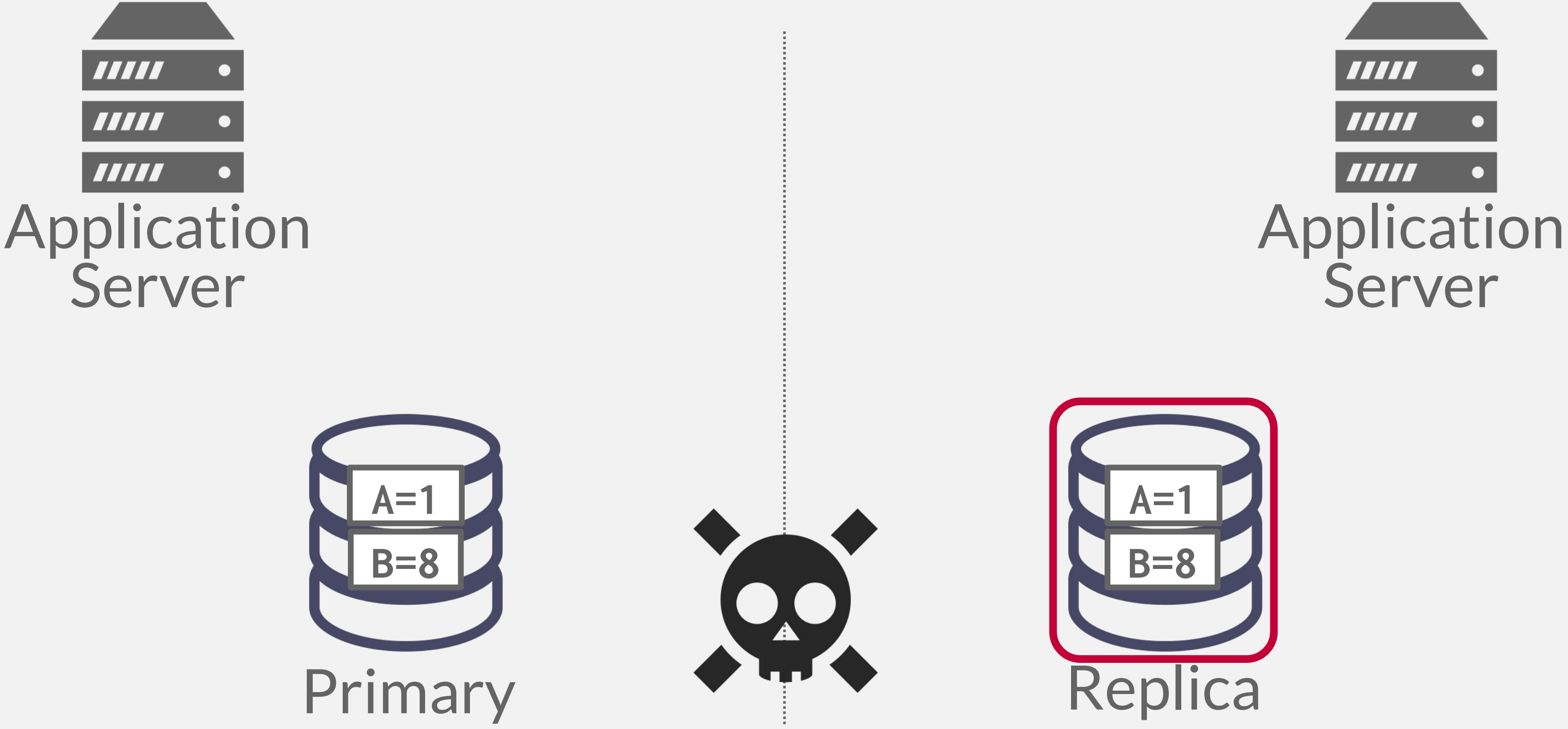

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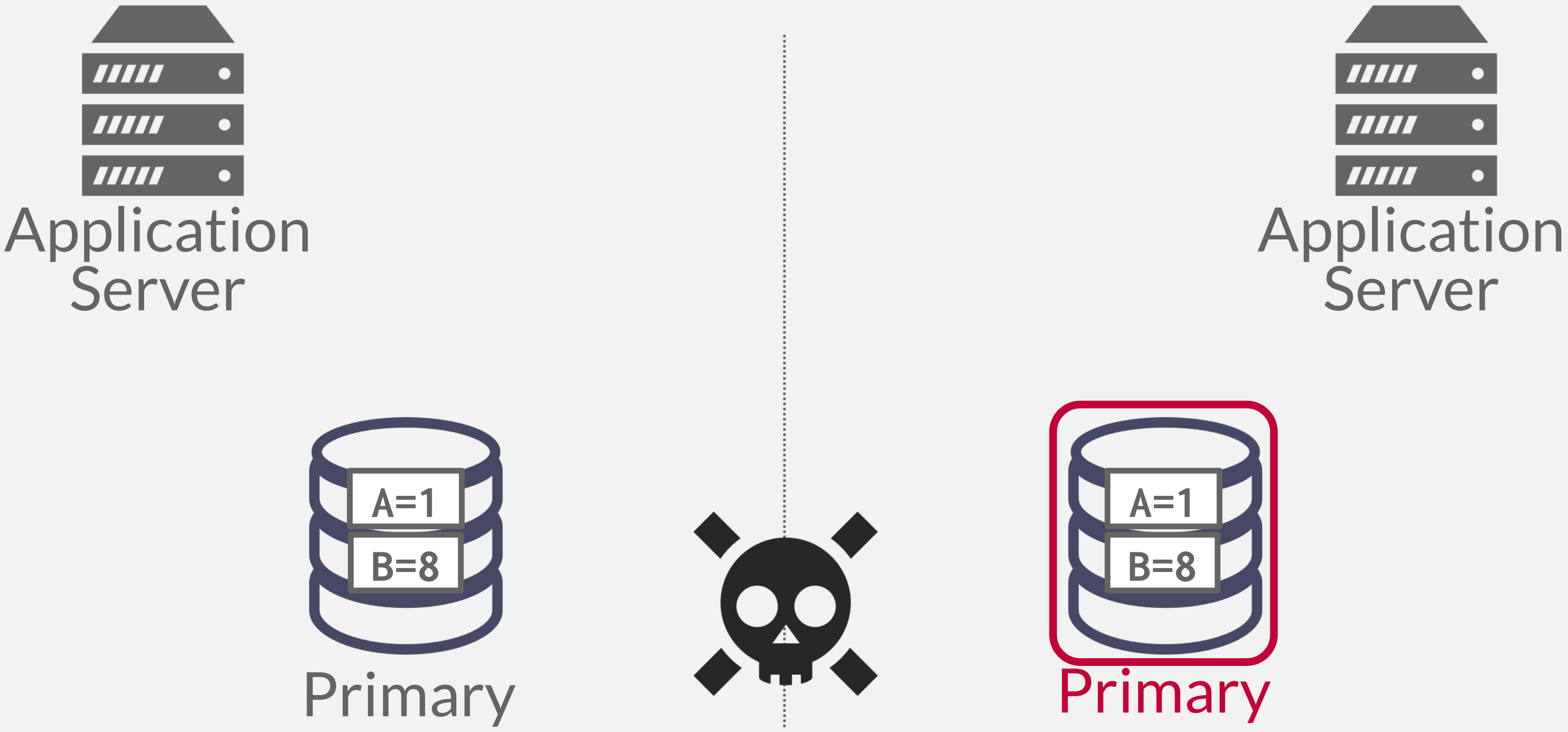

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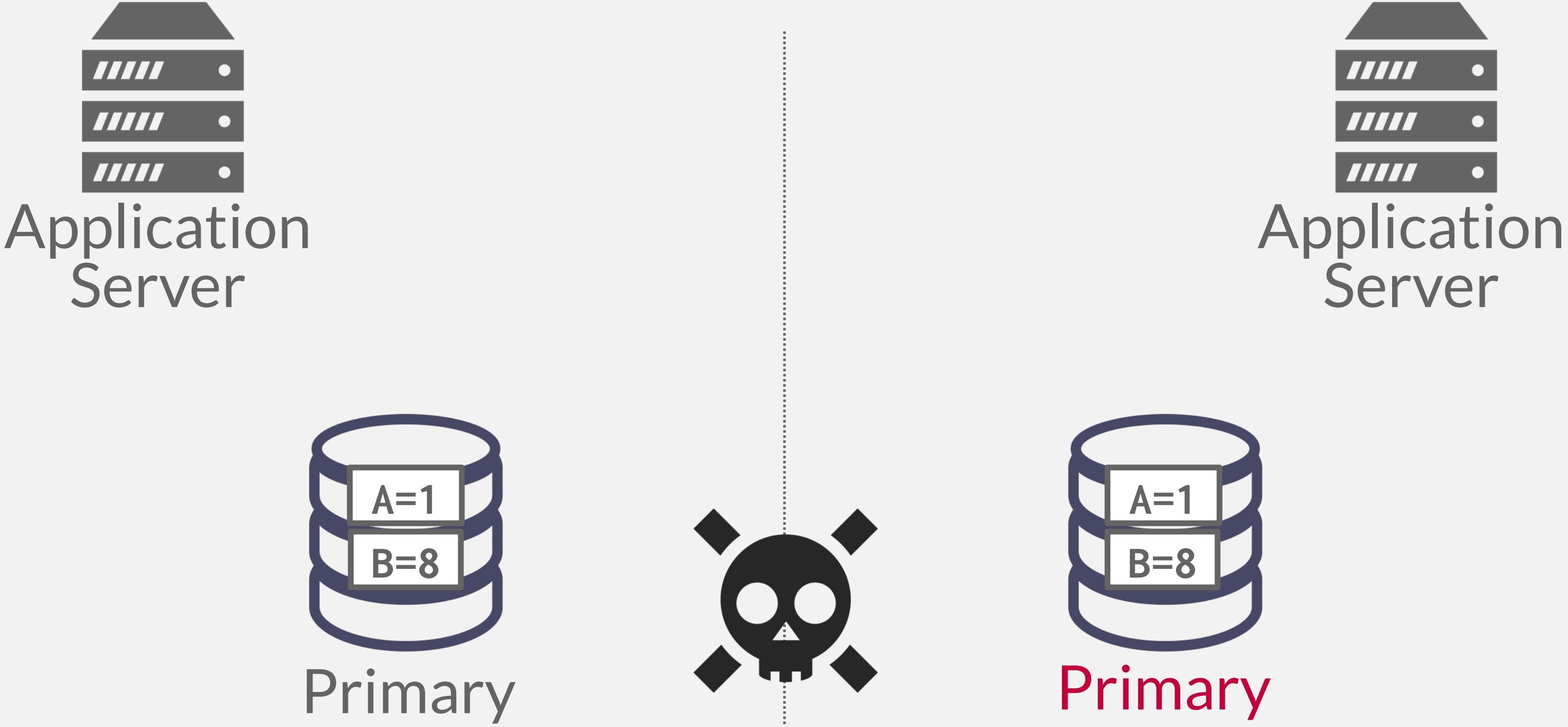

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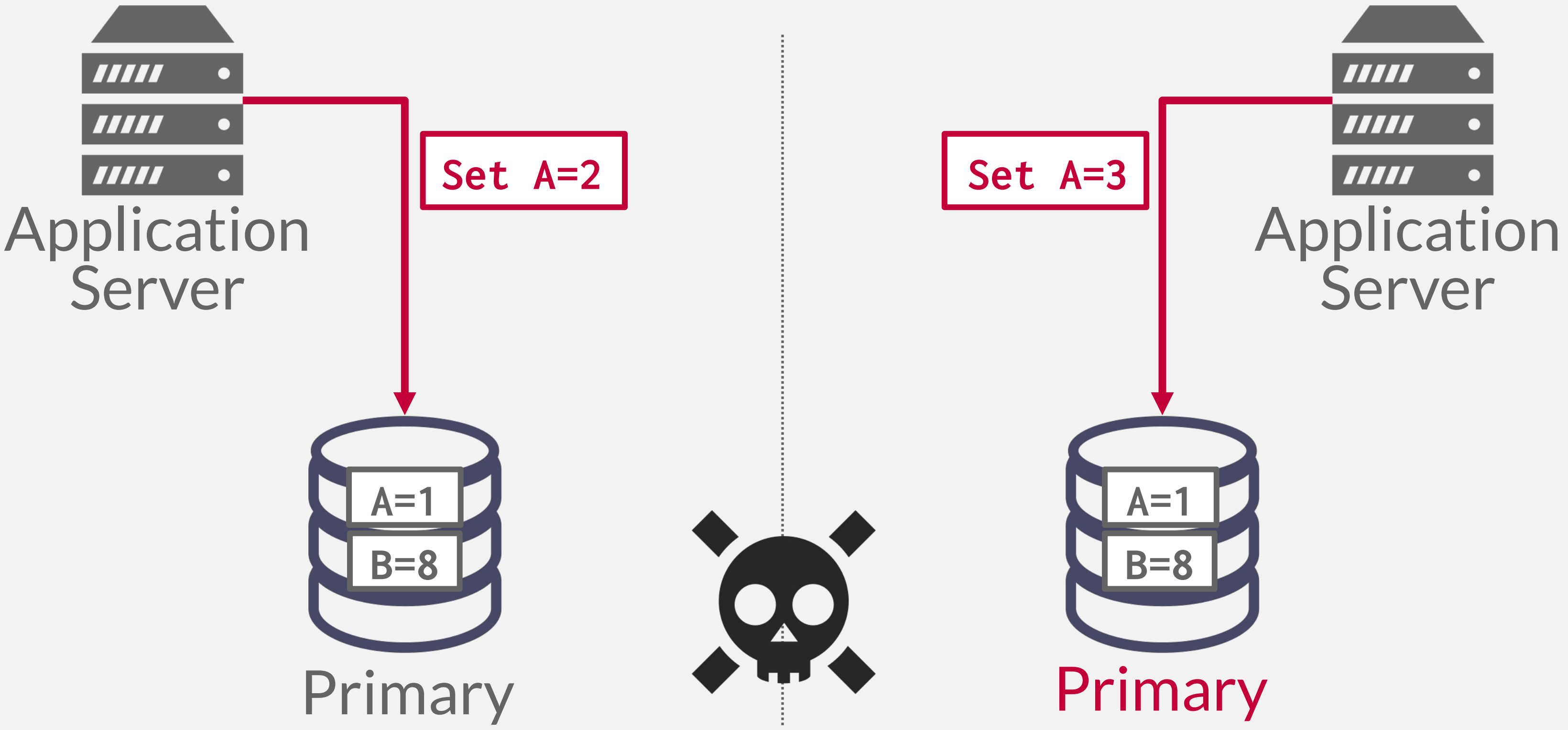

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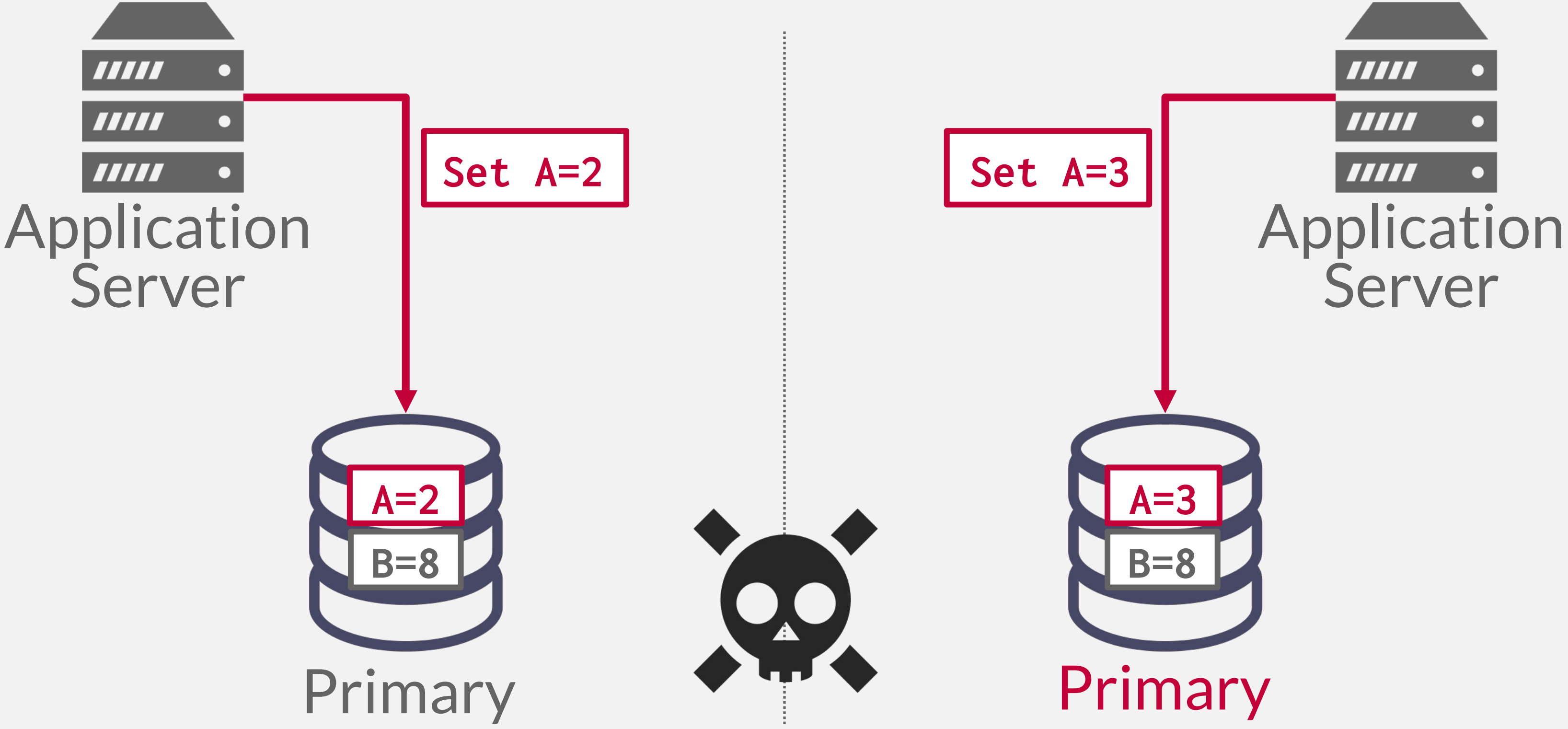

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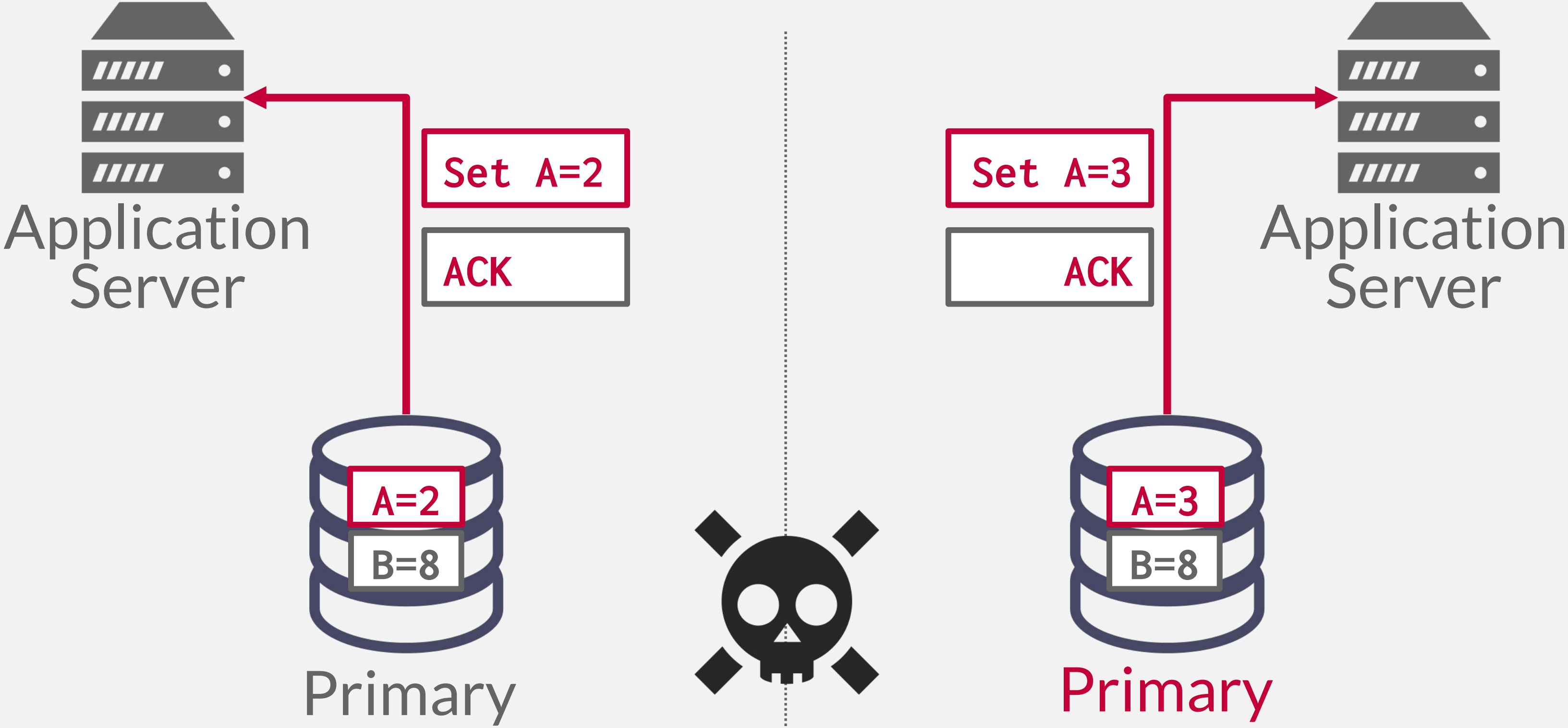

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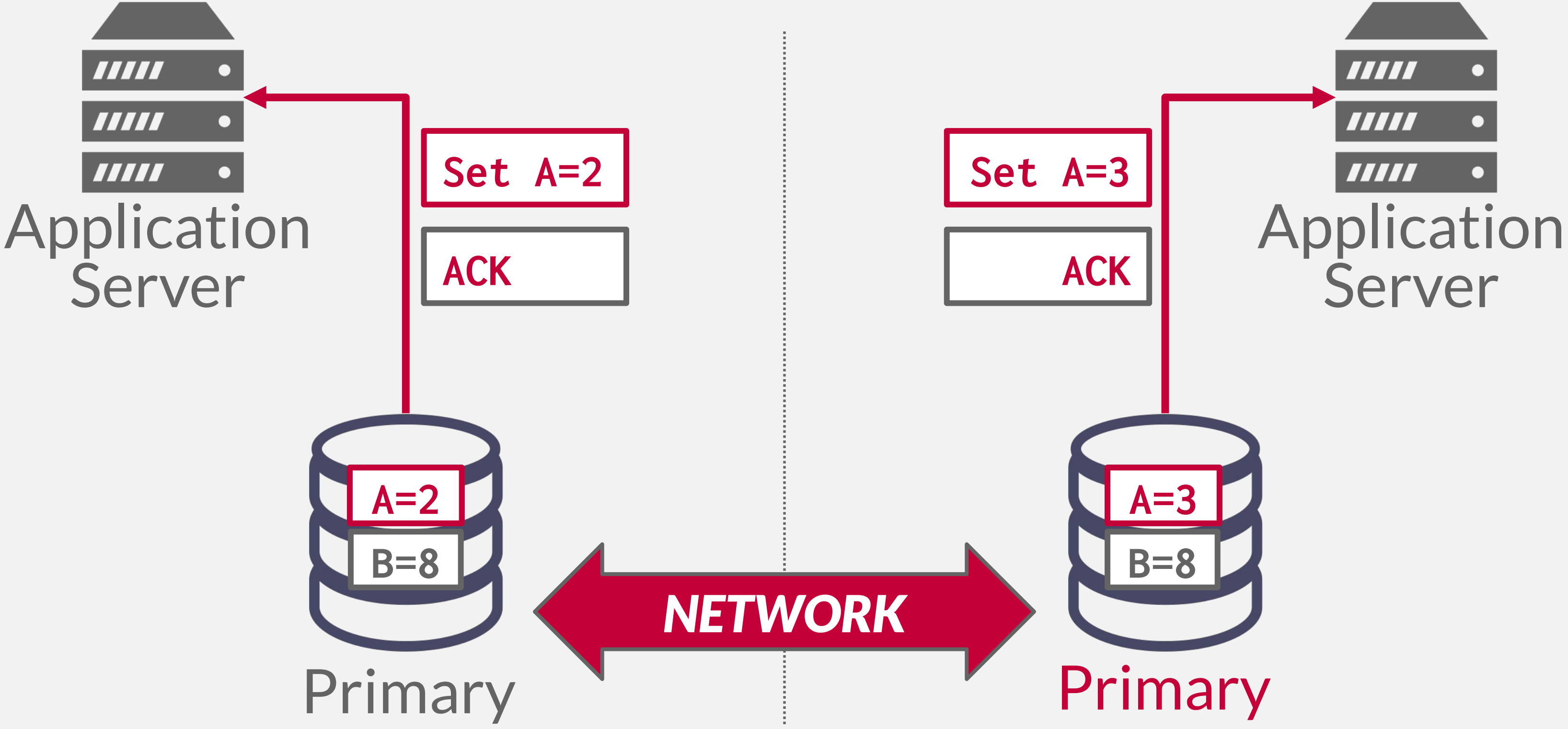

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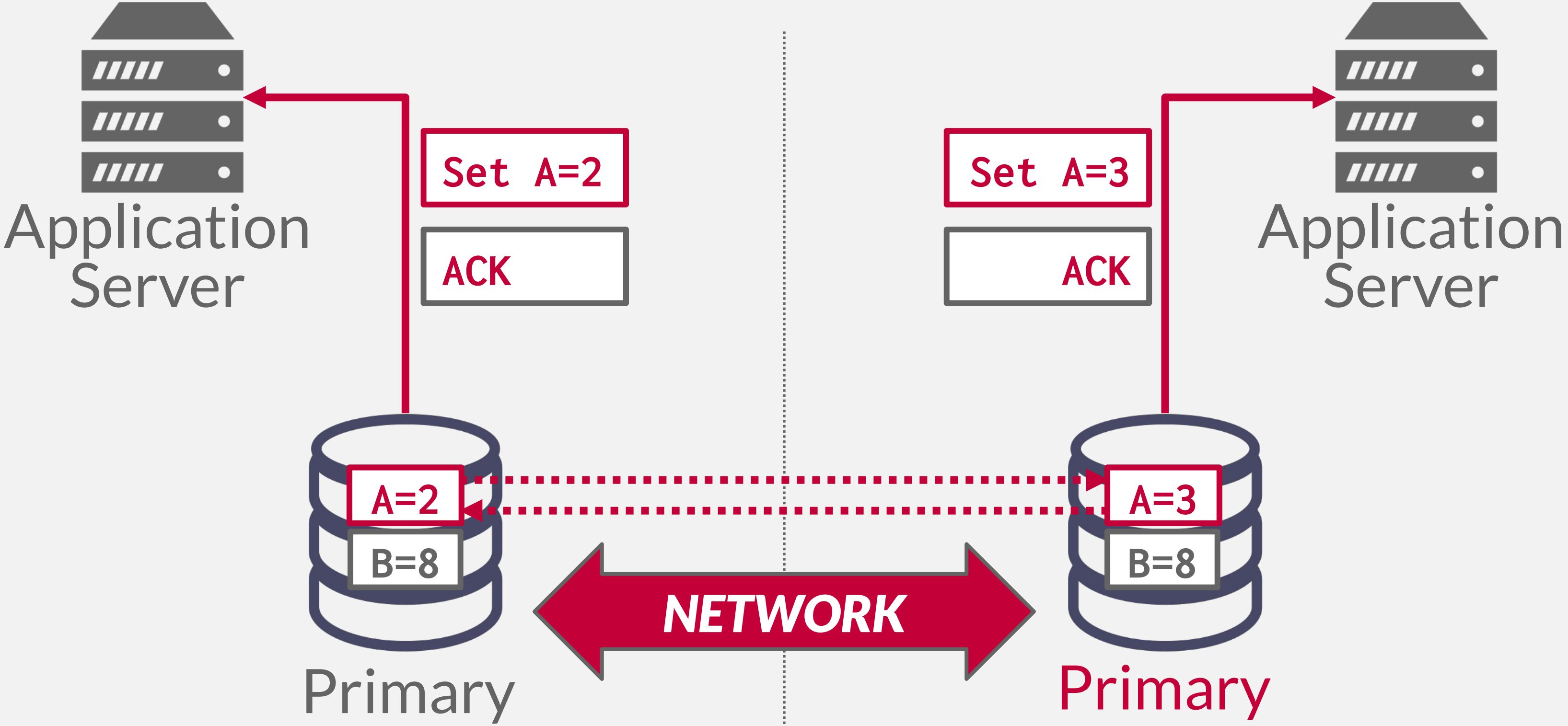
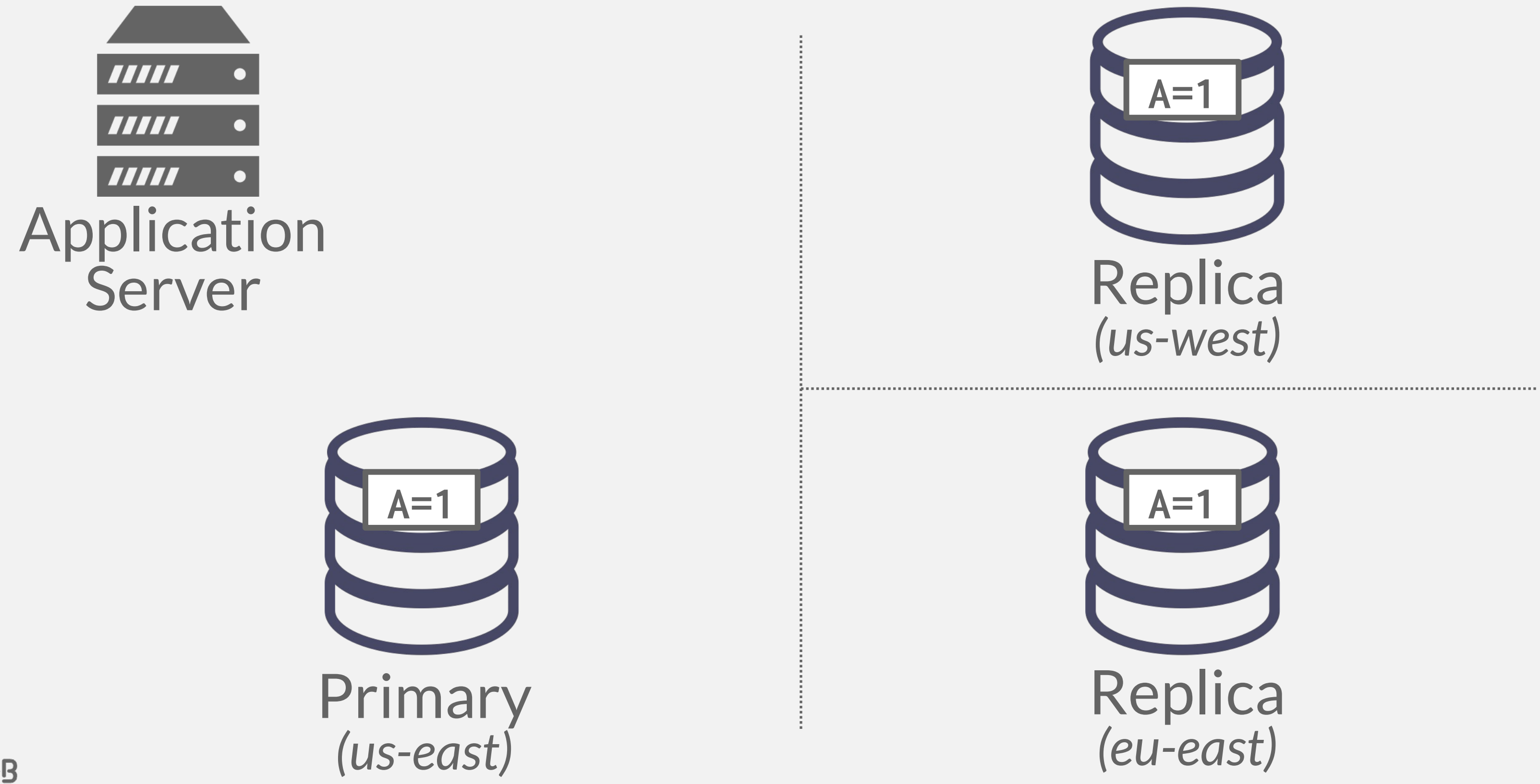


LATENCY VS. CONSISTENCY



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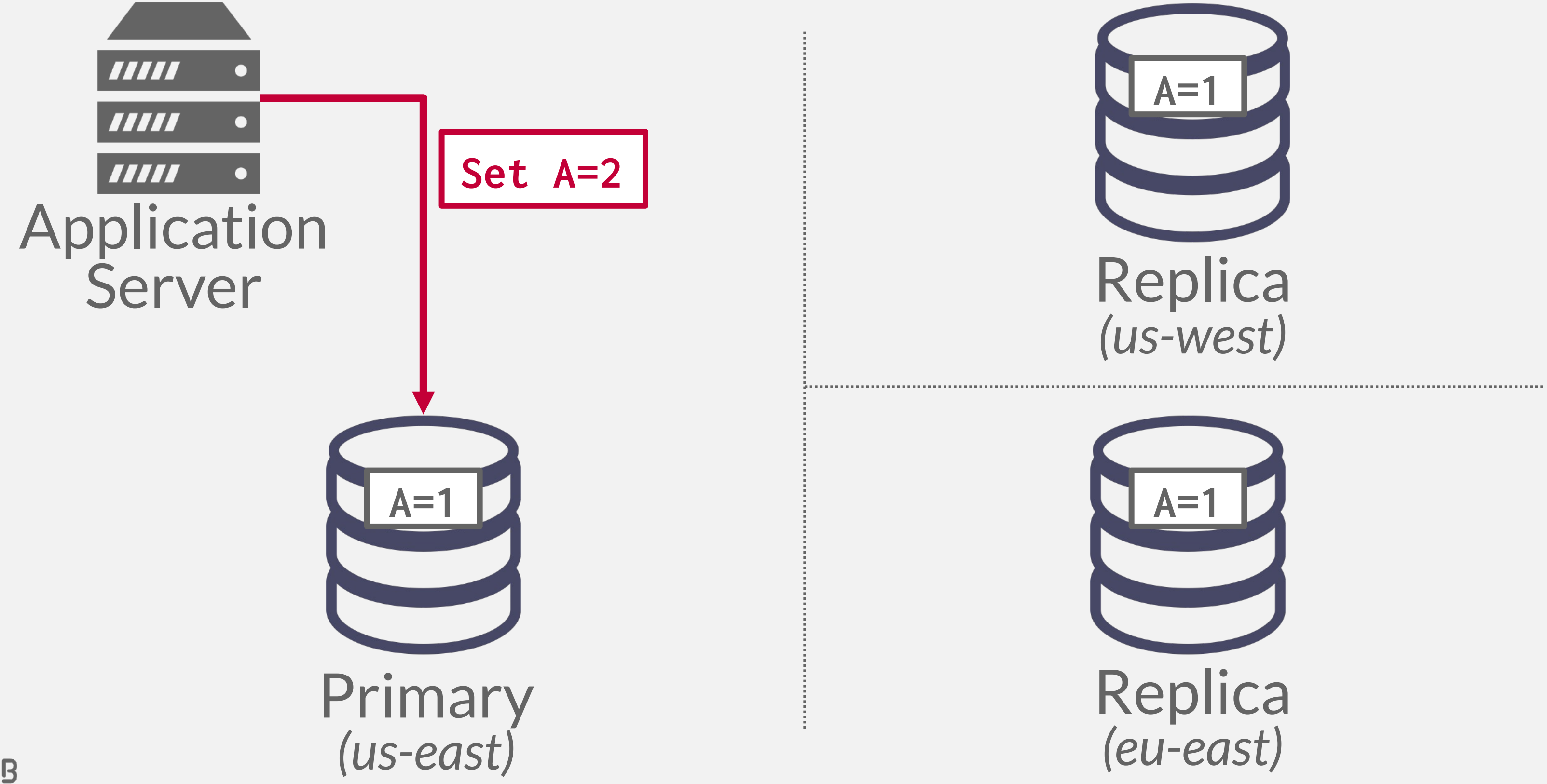

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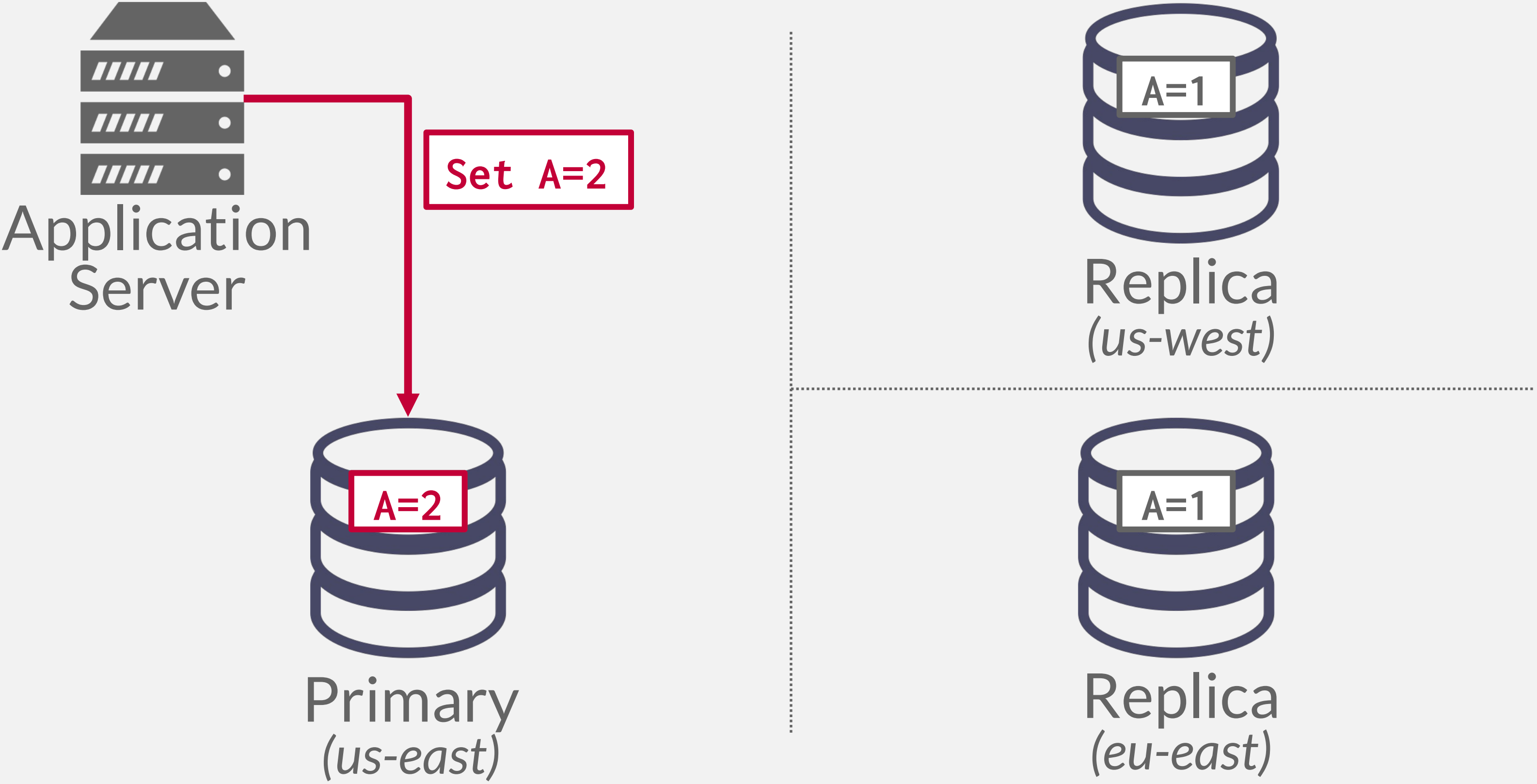

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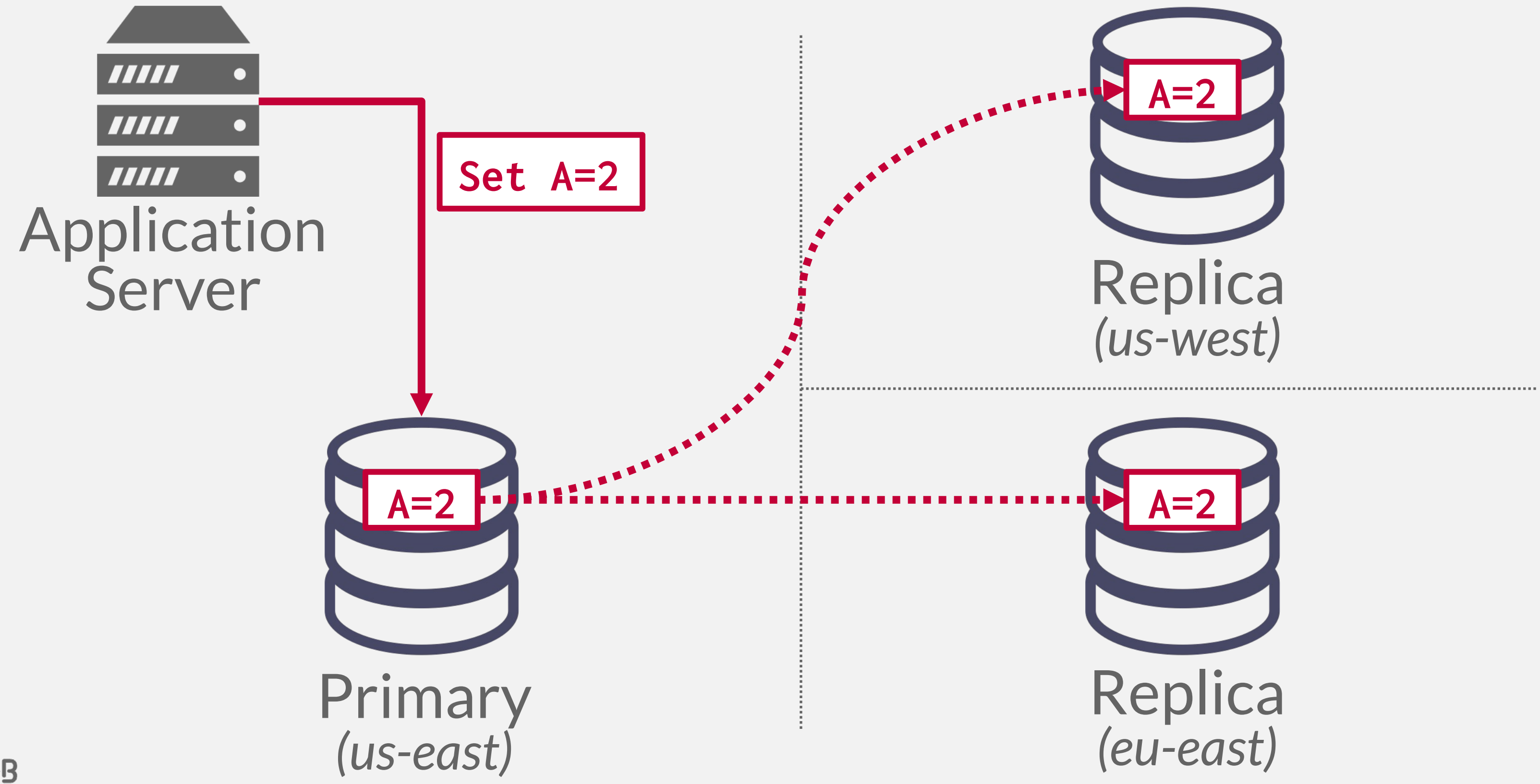
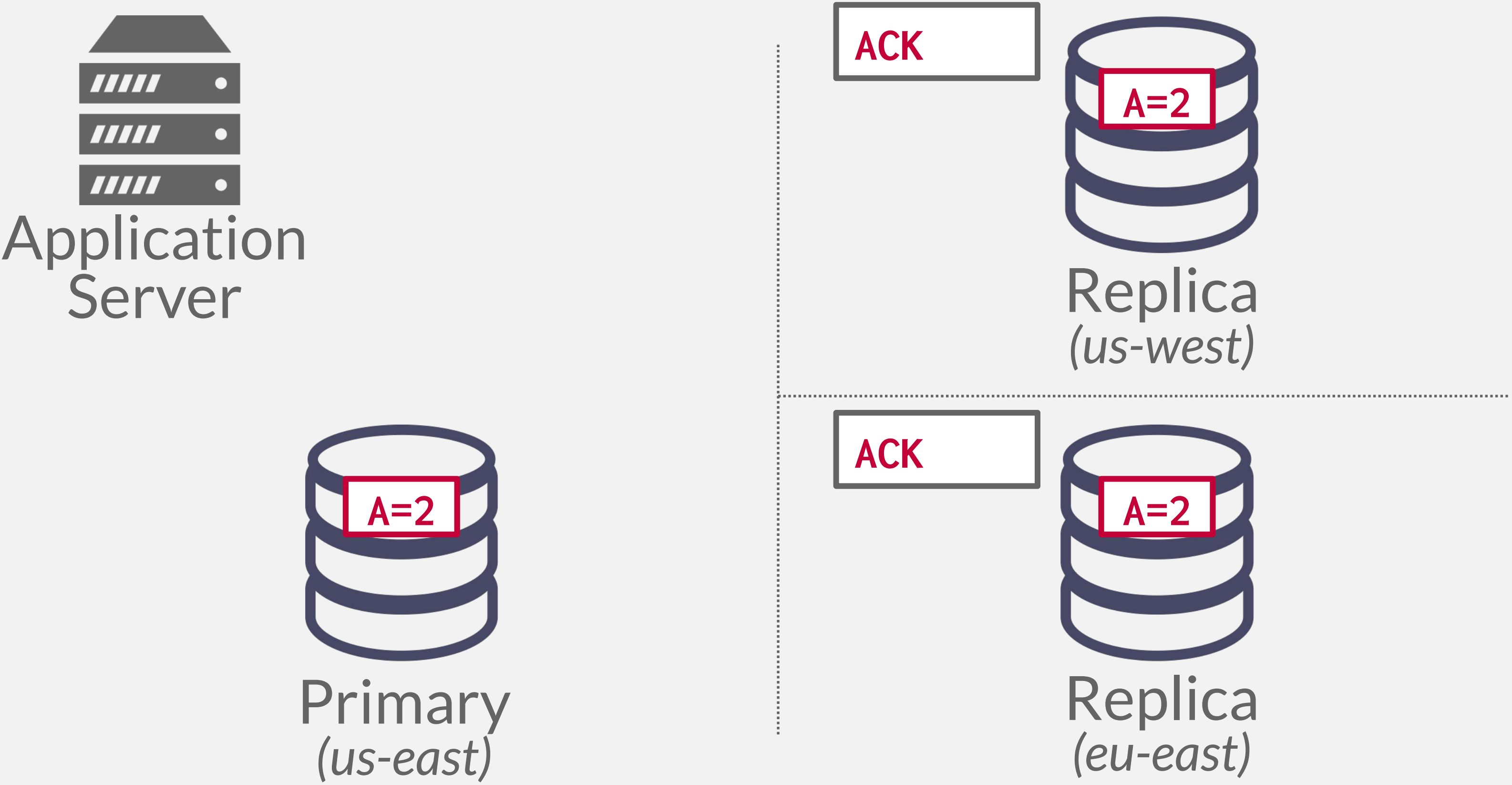


LATENCY VS. CONSISTENCY



Application Server

ACK

A=2

Replica *(us-west)*

ACK

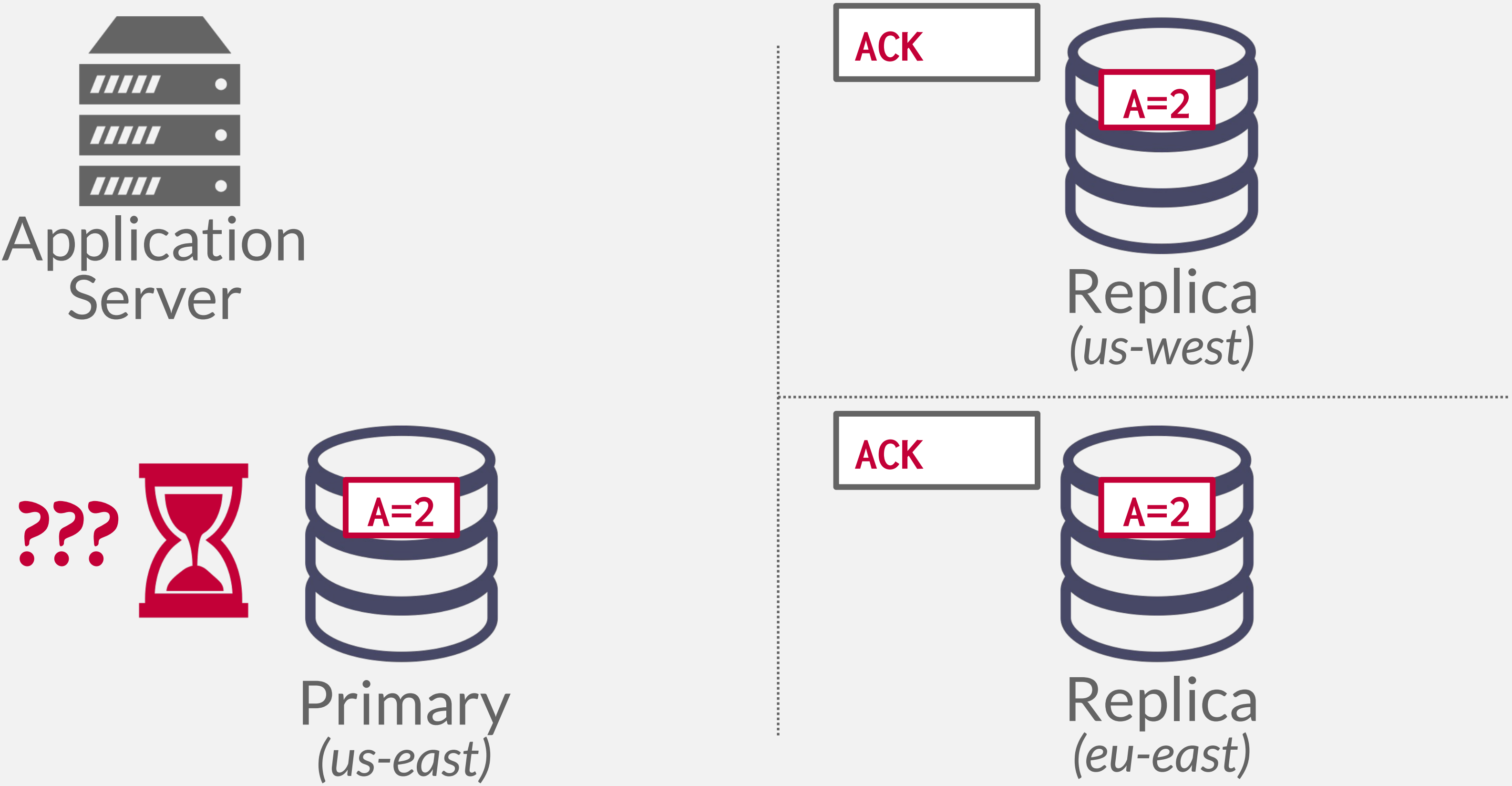
A=2

Replica *(eu-east)*

A=2

Primary *(us-east)*

LATENCY VS. CONSISTENCY



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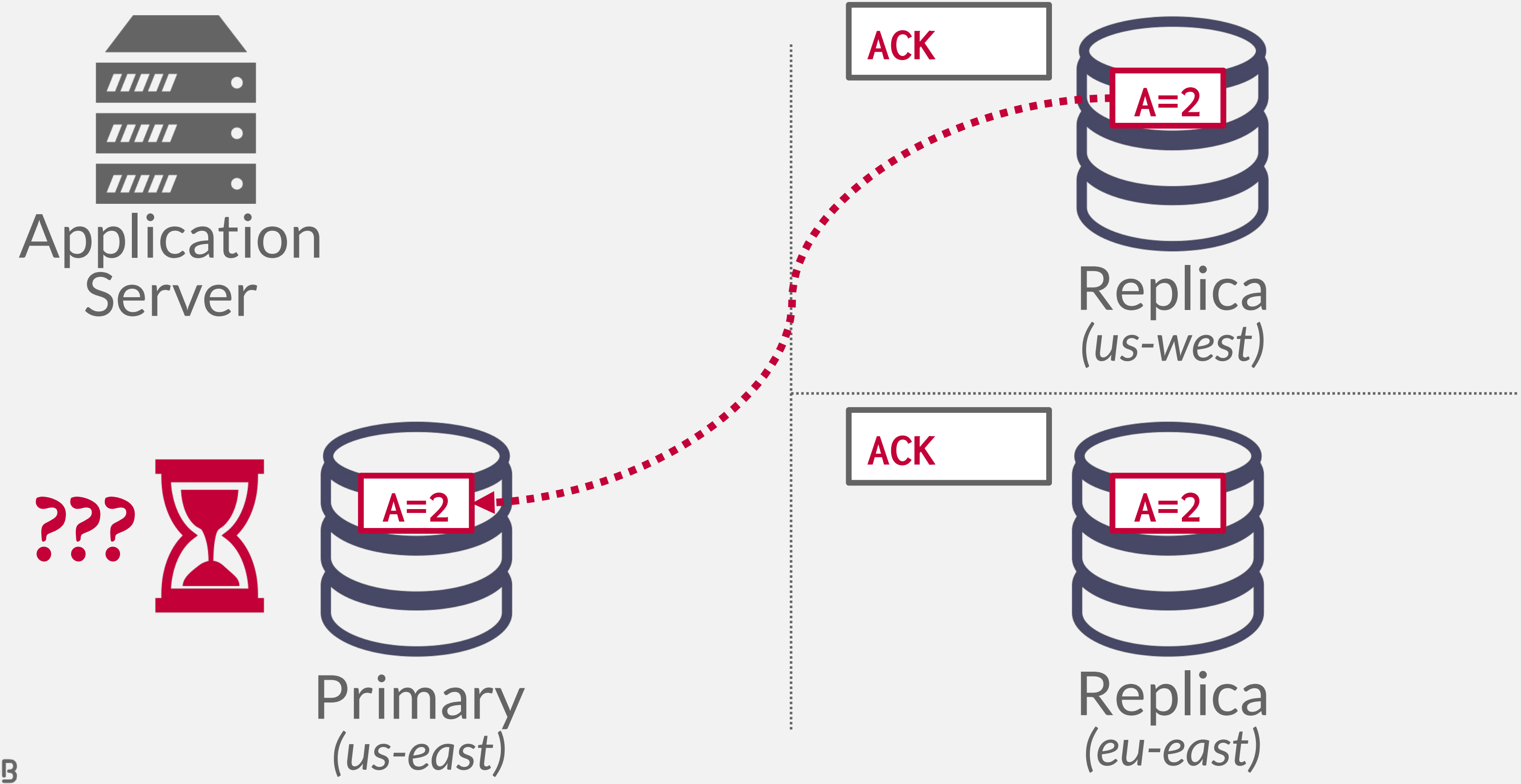

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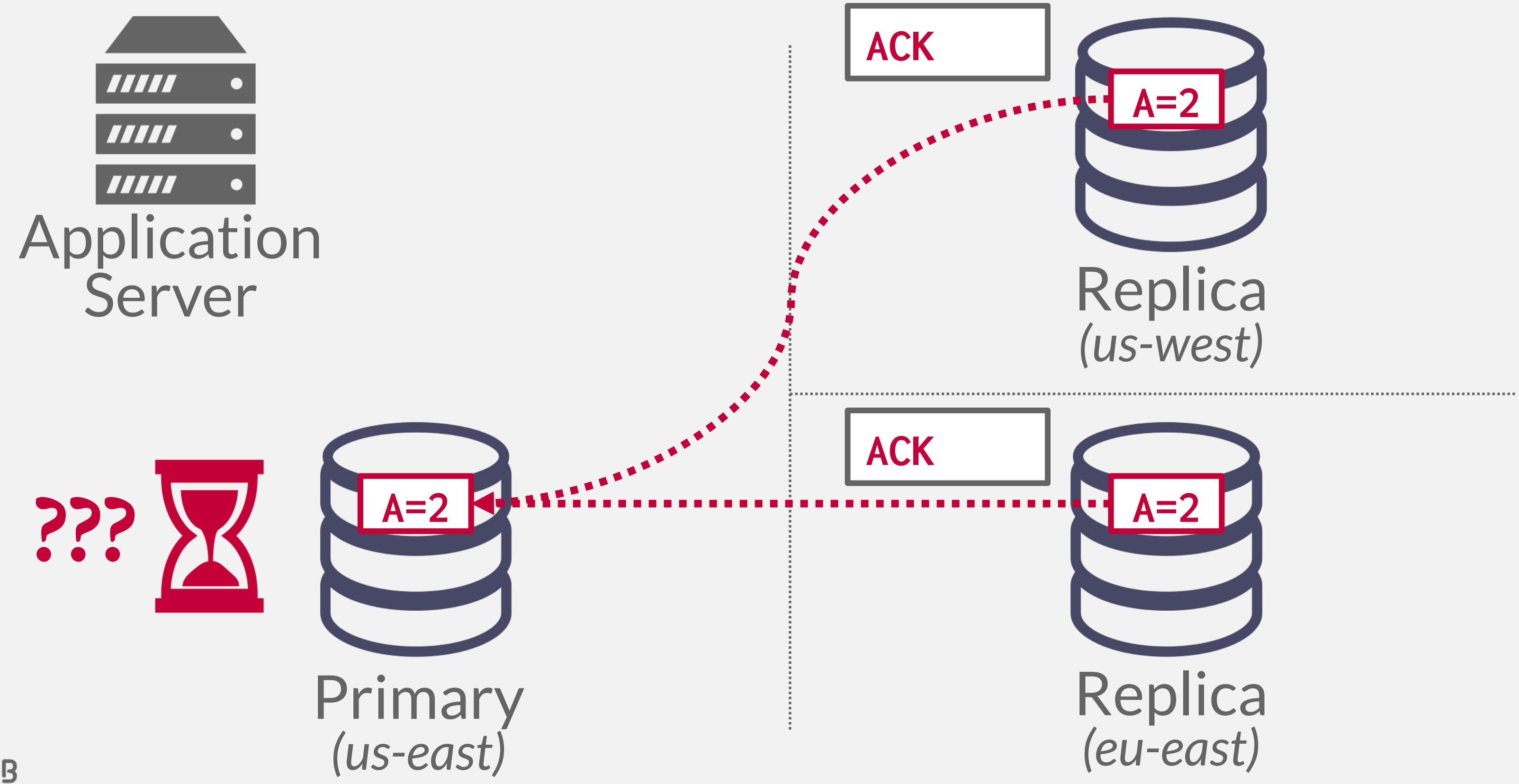

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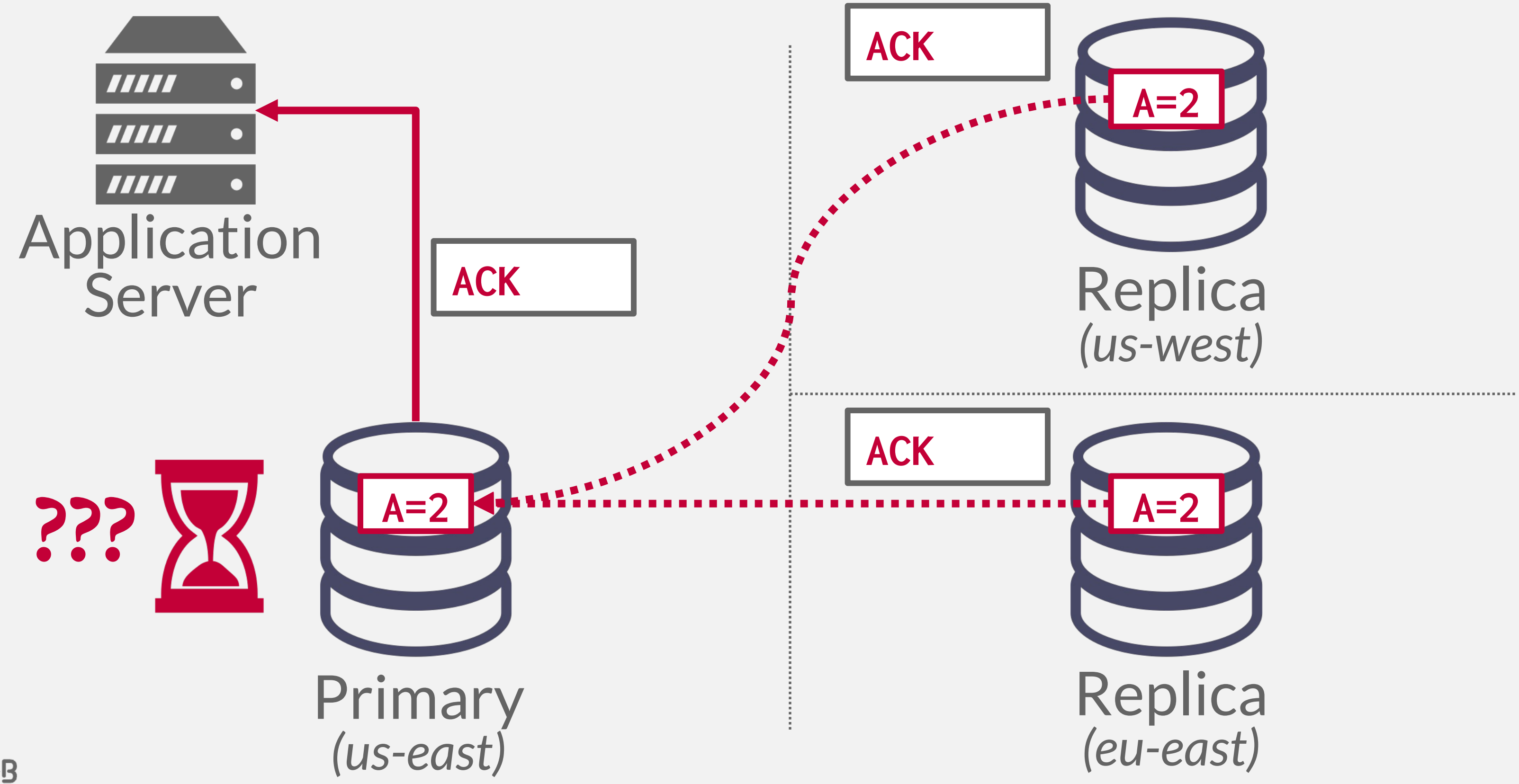


CAP/PACELC FOR OLTP DBMSs

How a DBMS handles failures determines which elements of the CAP theorem they support.

Distributed Relational DBMSs

→ Stop allowing updates until a majority of nodes are reconnected.

NoSQL DBMSs

→ No multi-node consistency. Last update wins (*common*).

→ Provide client-side API to resolve conflicts after nodes are reconnected (*rare*).

GOOGLE SPANNER

Google's geo-replicated DBMS (>2011)

Schematized, semi-relational data model.

Decentralized shared-disk architecture.

Log-structured on-disk storage.

Concurrency Control:

- → Strict 2PL + MVCC + Multi-Paxos + 2PC
- → **Externally consistent** global write-transactions with synchronous replication.
- → Lock-free read-only transactions.

SPANNER: CONCURRENCY CONTROL

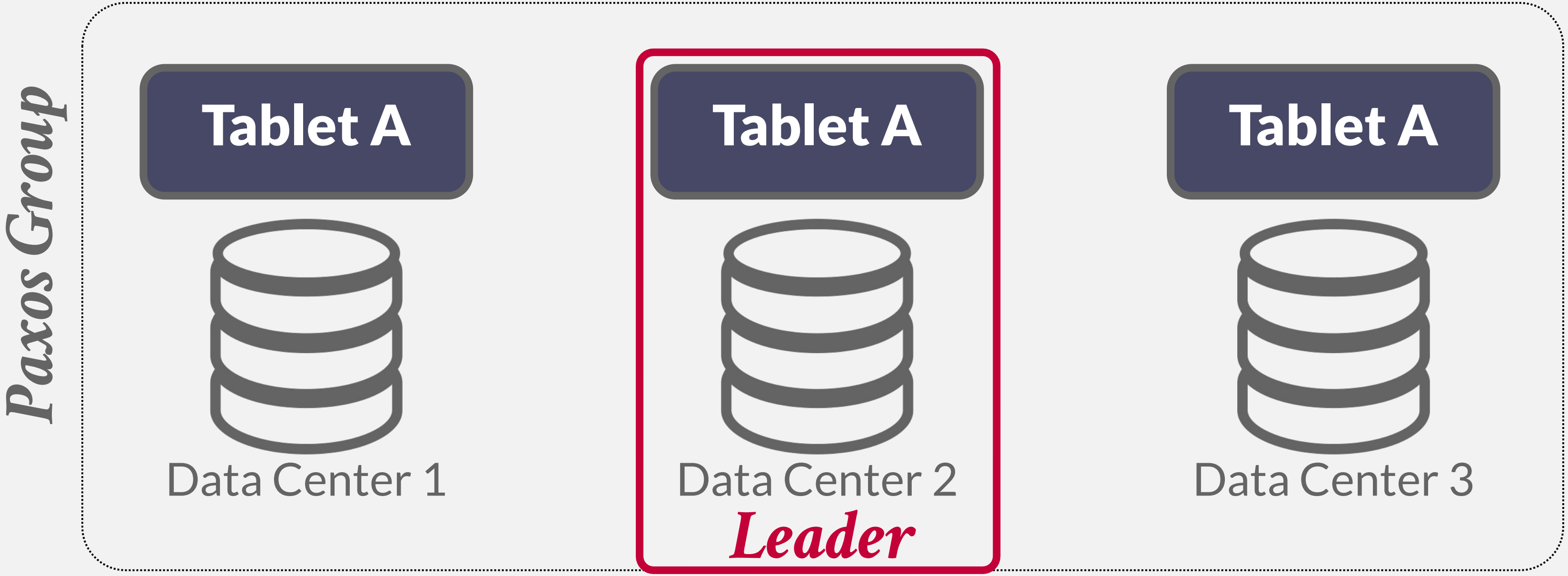
MVCC + Strict 2PL with Wound-Wait Deadlock Prevention

DBMS ensures ordering through globally unique timestamps generated from atomic clocks and GPS devices.

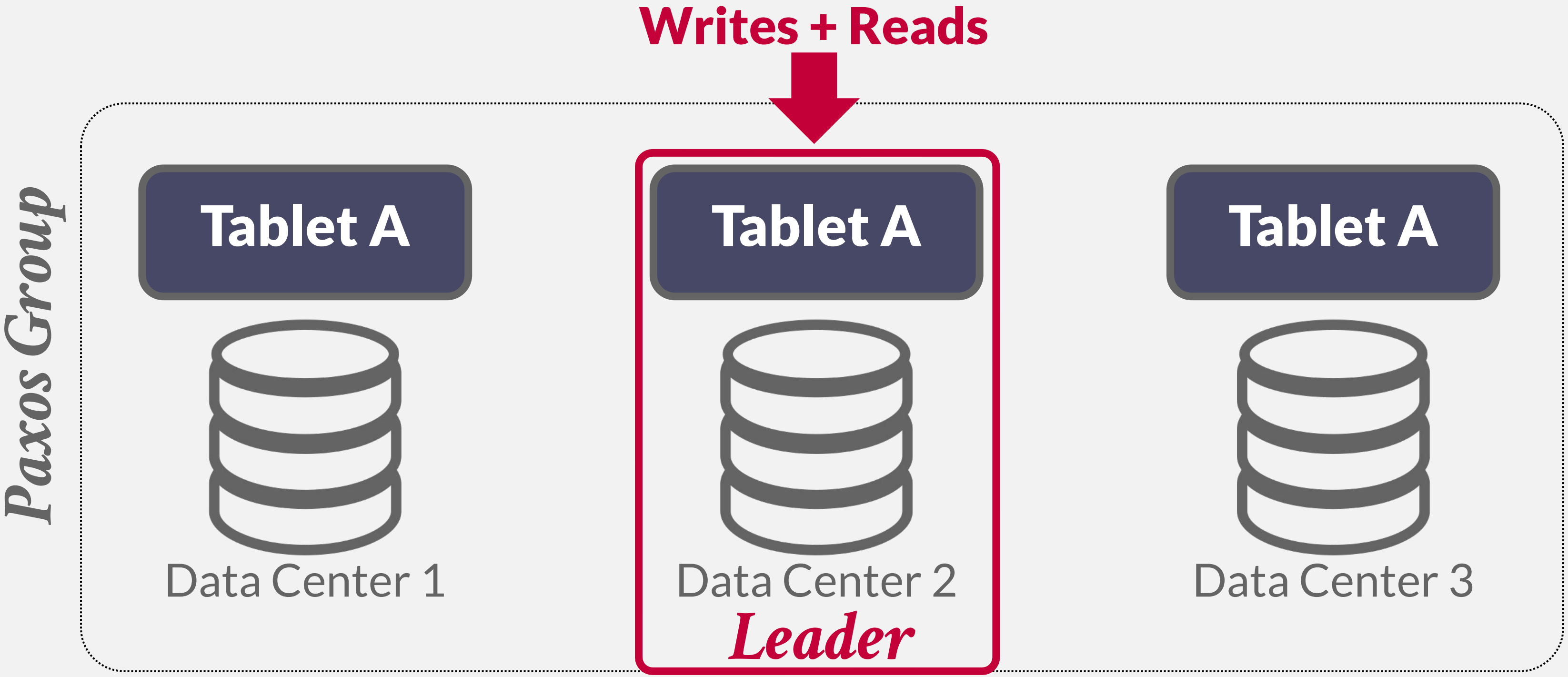
Database is broken up into tablets (partitions):

→ Use Paxos to elect leader in tablet group.
→ Use 2PC for txns that span tablets.

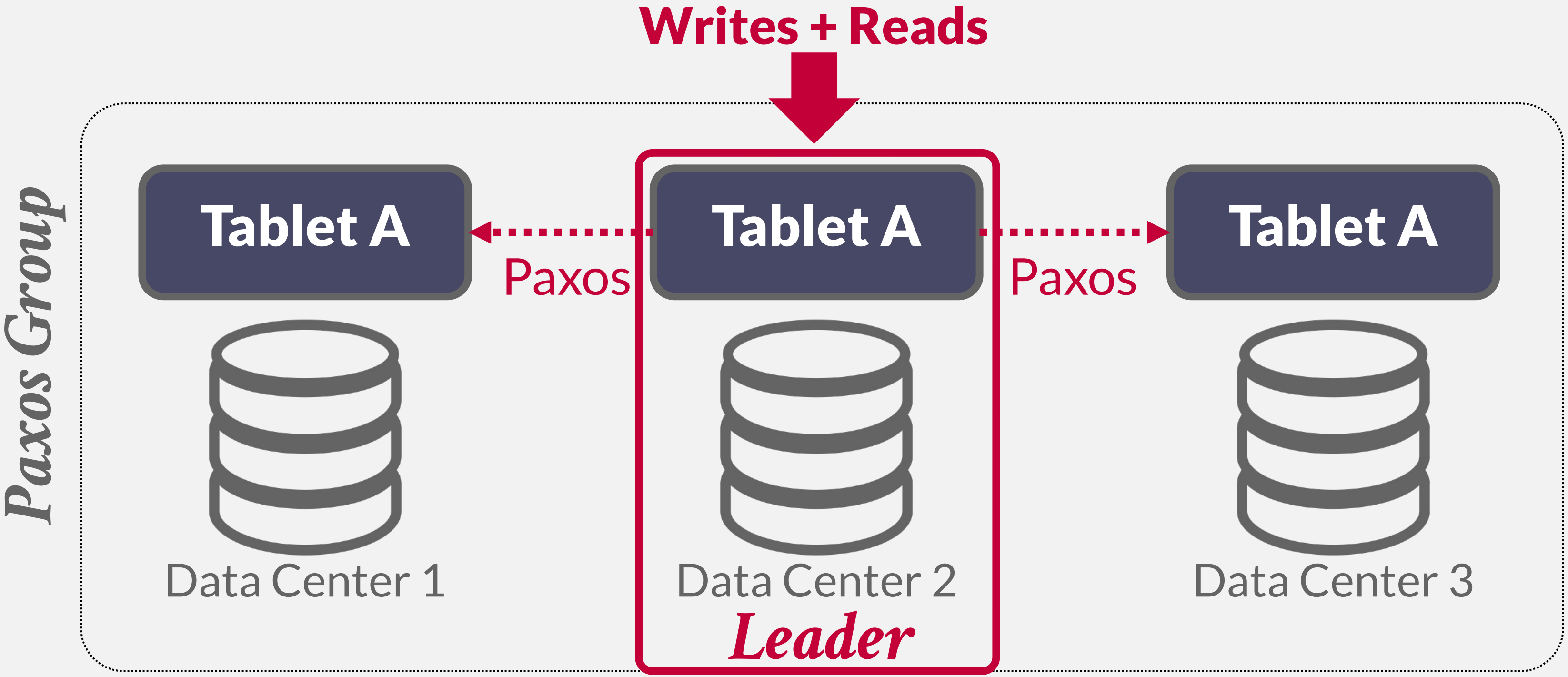
SPANNER TABLETS



SPANNER TABLETS



SPANNER TABLETS



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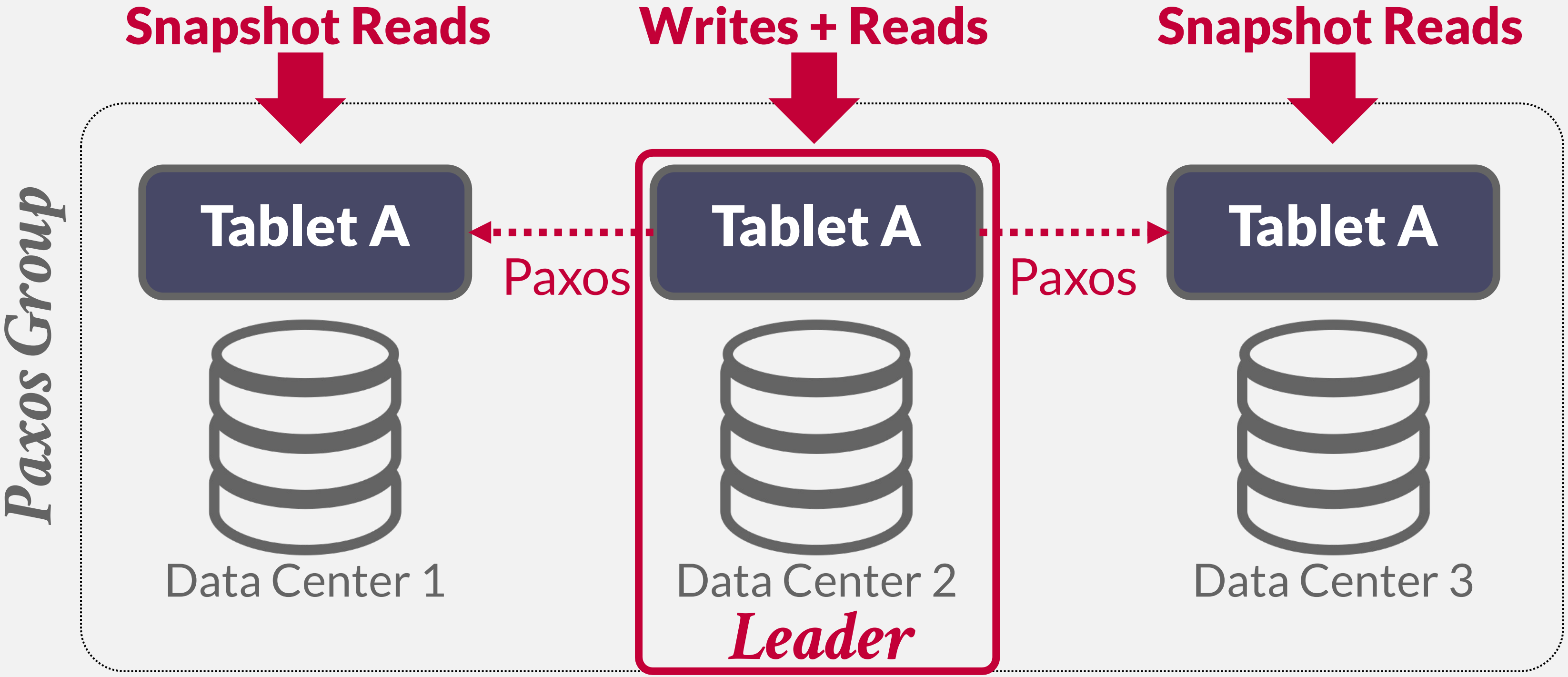

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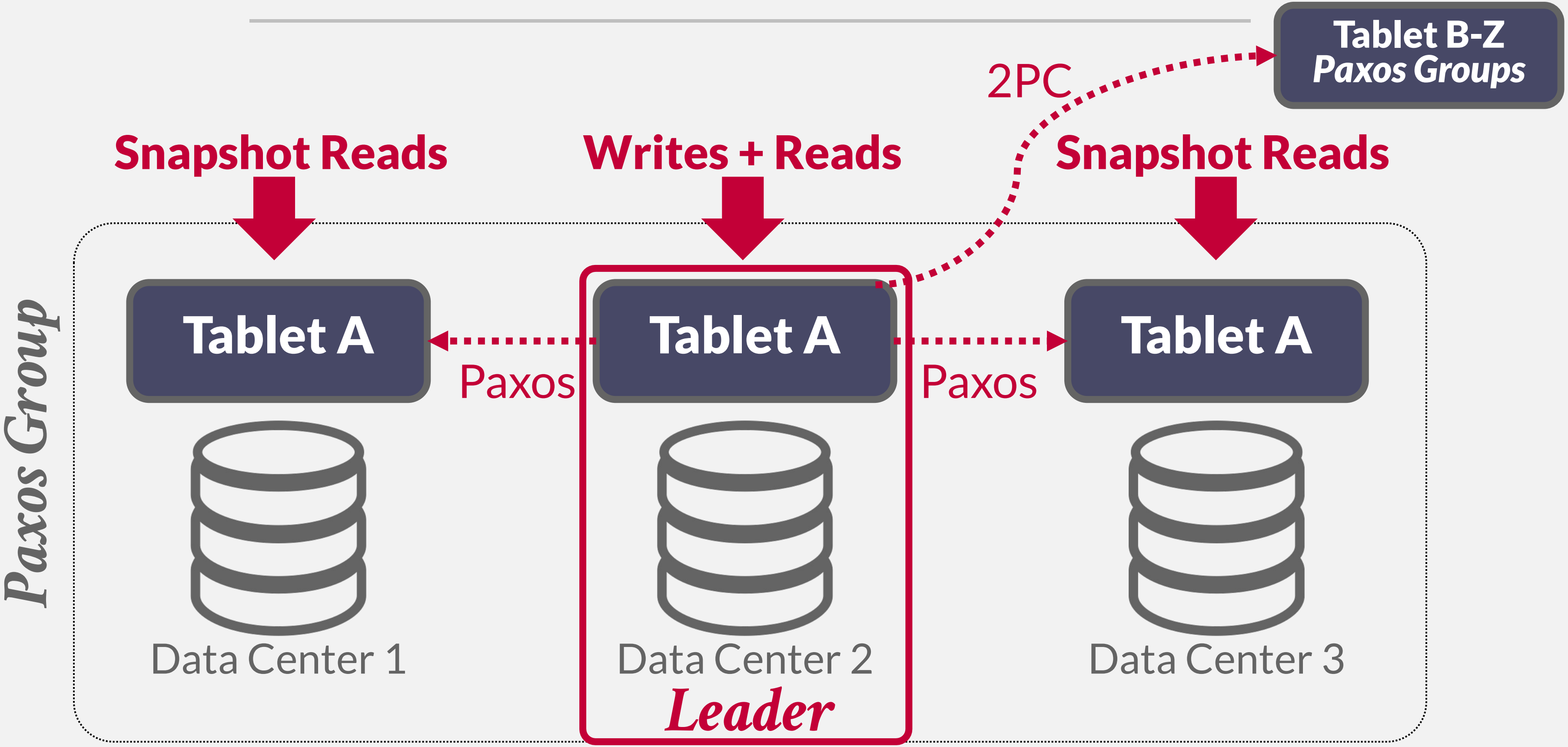

SPANNER: TRANSACTION ORDERING

DBMS orders transactions based on physical "wall-clock" time.

→ This is necessary to guarantee strict serializability.

→ If T_1 finishes before T_2, then T_2 should see the result of T_1.

Each Paxos group decides in what order transactions should be committed according to the timestamps.

→ If T_1 commits at $\texttt{time}_1$ and T_2 starts at $\texttt{time}_2$ > $\texttt{time}_1$, then T_1's timestamp should be less than T_2's.

CONCLUSION

Maintaining transactional consistency across multiple nodes is hard. Bad things will happen.

Blockchain databases assume that the nodes are adversarial. You must use different protocols to commit transactions. Not suitable for database workloads.

More info (and humiliation):

→ Kyle Kingsbury's Jepsen Project

NEXT CLASS

Distributed OLAP Systems