Carnegie Mellon University

DATABASE SYSTEMS

Distributed Databases II

LECTURE #24 » 15-445/645 FALL 2025 » PROF. ANDY PAVLO

ADMINISTRIVIA

Project #4 is due Sunday Dec 7th @ 11:59pm
→ Recitation Slides + Video (**@300**)

Homework #6 is due Sunday Dec 7th @ 11:59pm

Final Exam is on Thursday Dec 11th @ 1:00pm
→ Do not make travel plans before this date!

We are recruiting TAs for the next semester
→ Apply at: https://www.ugrad.cs.cmu.edu/ta/S26/

UPCOMING DATABASE TALKS

Apache Polaris (DB Seminar)
→ Monday Dec 1st @ 12:00pm
→ Zoom

Apache Fluss (DB Seminar)
→ Monday Dec 7th @ 12:00pm
→ Zoom

LAST CLASS

System Architectures
→ Shared-Nothing vs. Shared-Disk

Partitioning
→ Horizontal: Hash, Range, Round Robin

Replication
→ Primary-Replica vs. Multi-Primary

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.

TODAY'S AGENDA

Atomic Commit Protocols

Consistency Issues (CAP / PACELC)

Distributed Join Algorithms

Shuffle

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 assume 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 workloads.

Don't Do This!

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.

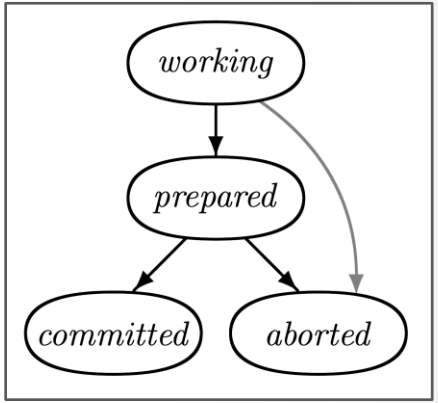
Examples:

→ 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
→ Coordinate to decide fate of a txn.



Properties of the Commit Protocol:

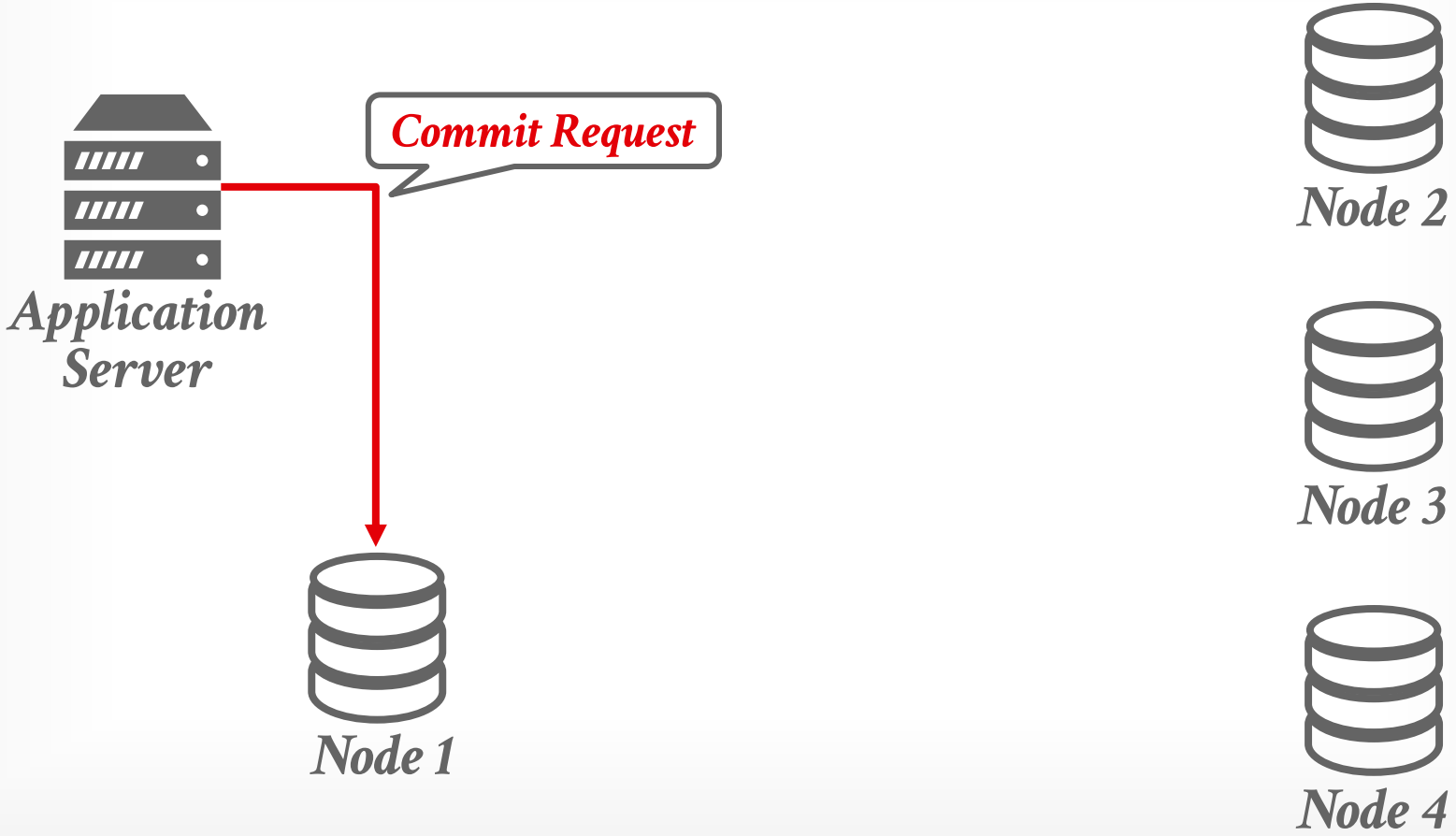
→ **Stability**: Once fate is decided, it cannot be changed.
→ **Consistency**: All RMs end in the same state.

Assumes Liveness:

→ There is some way of progressing forward.
→ Enough nodes are alive and connected for the duration of the protocol.

Source: Jim Gray + Lesile Lamport

TWO-PHASE COMMIT (SUCCESS)



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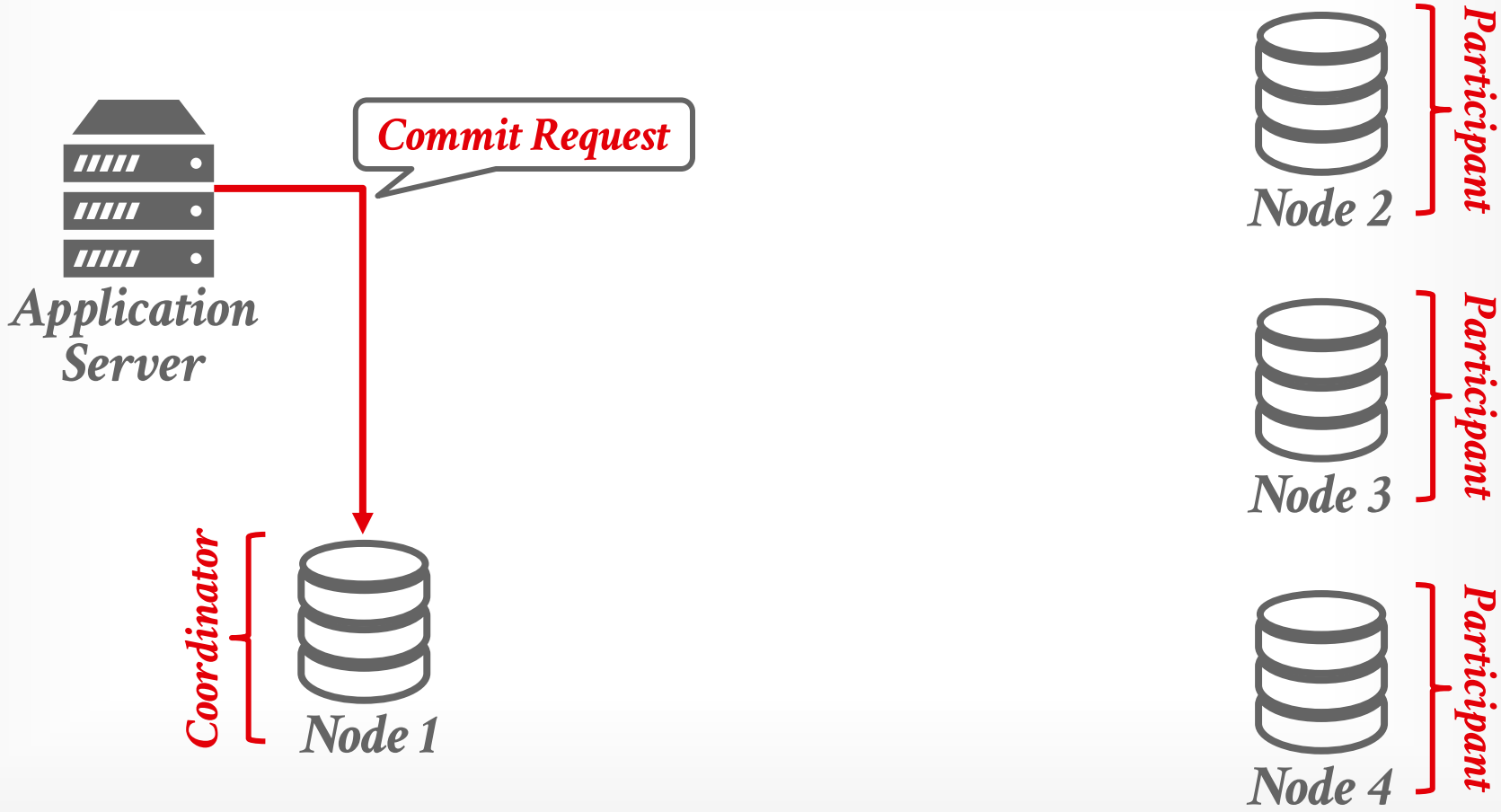

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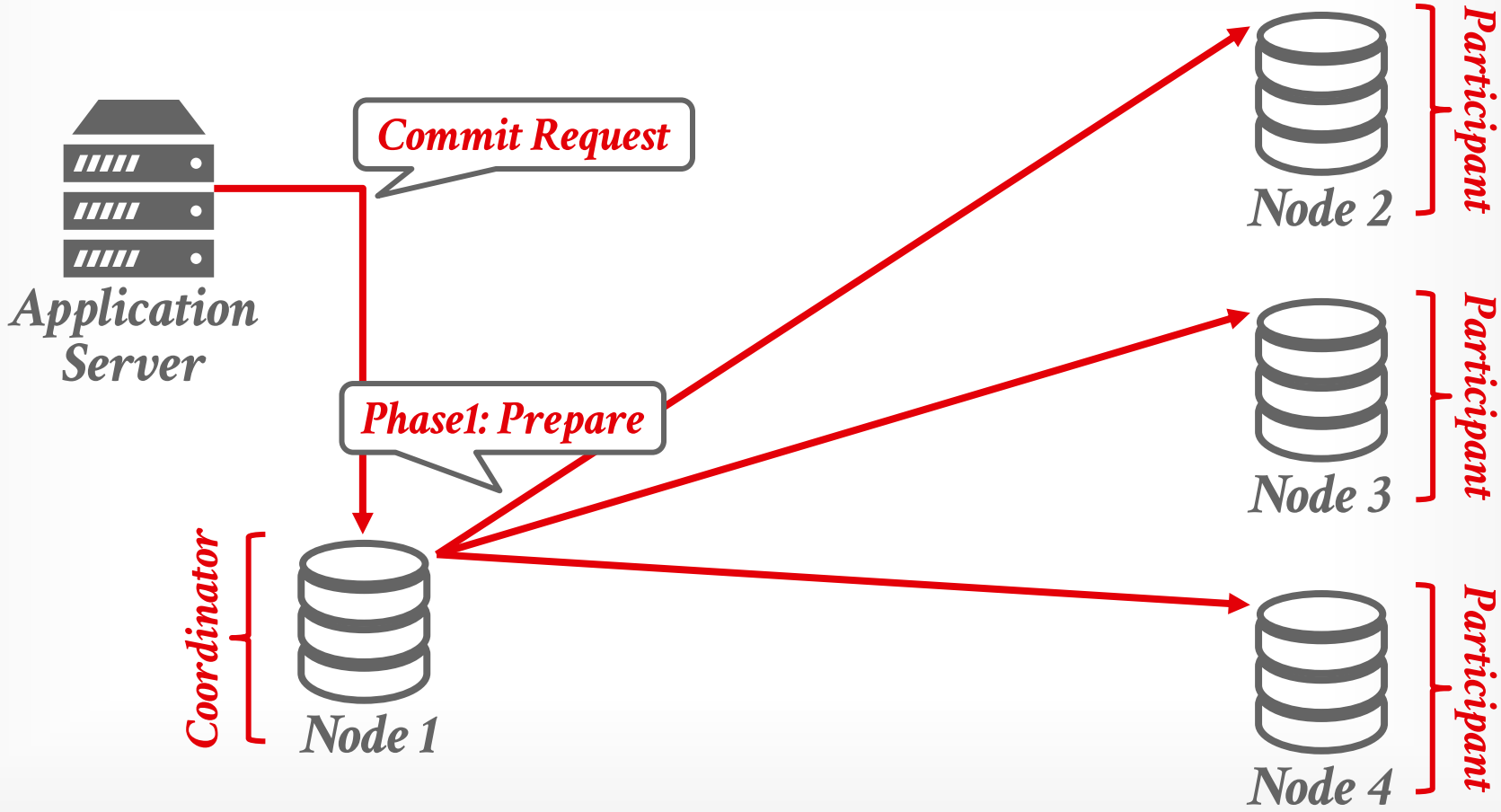

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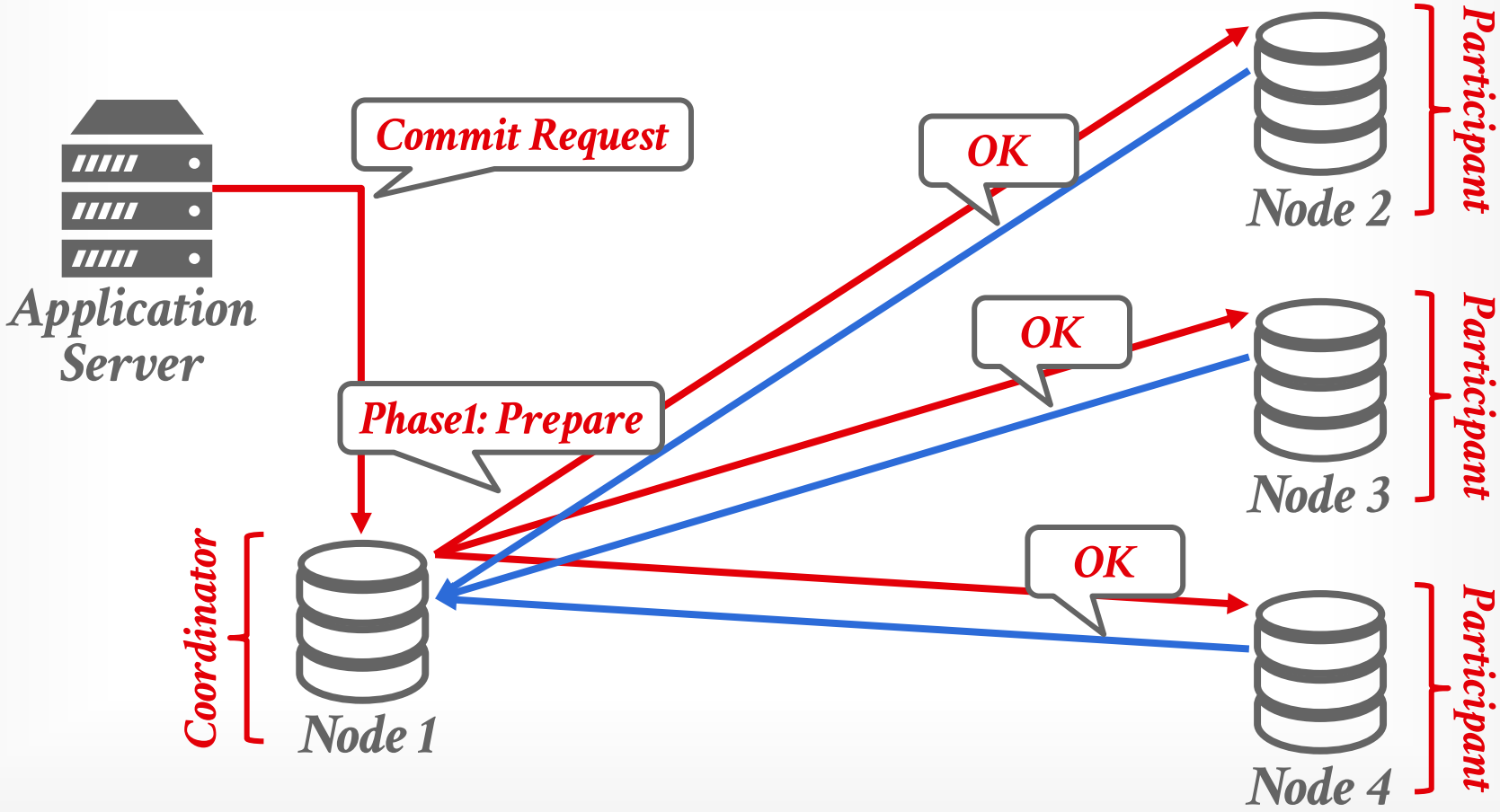

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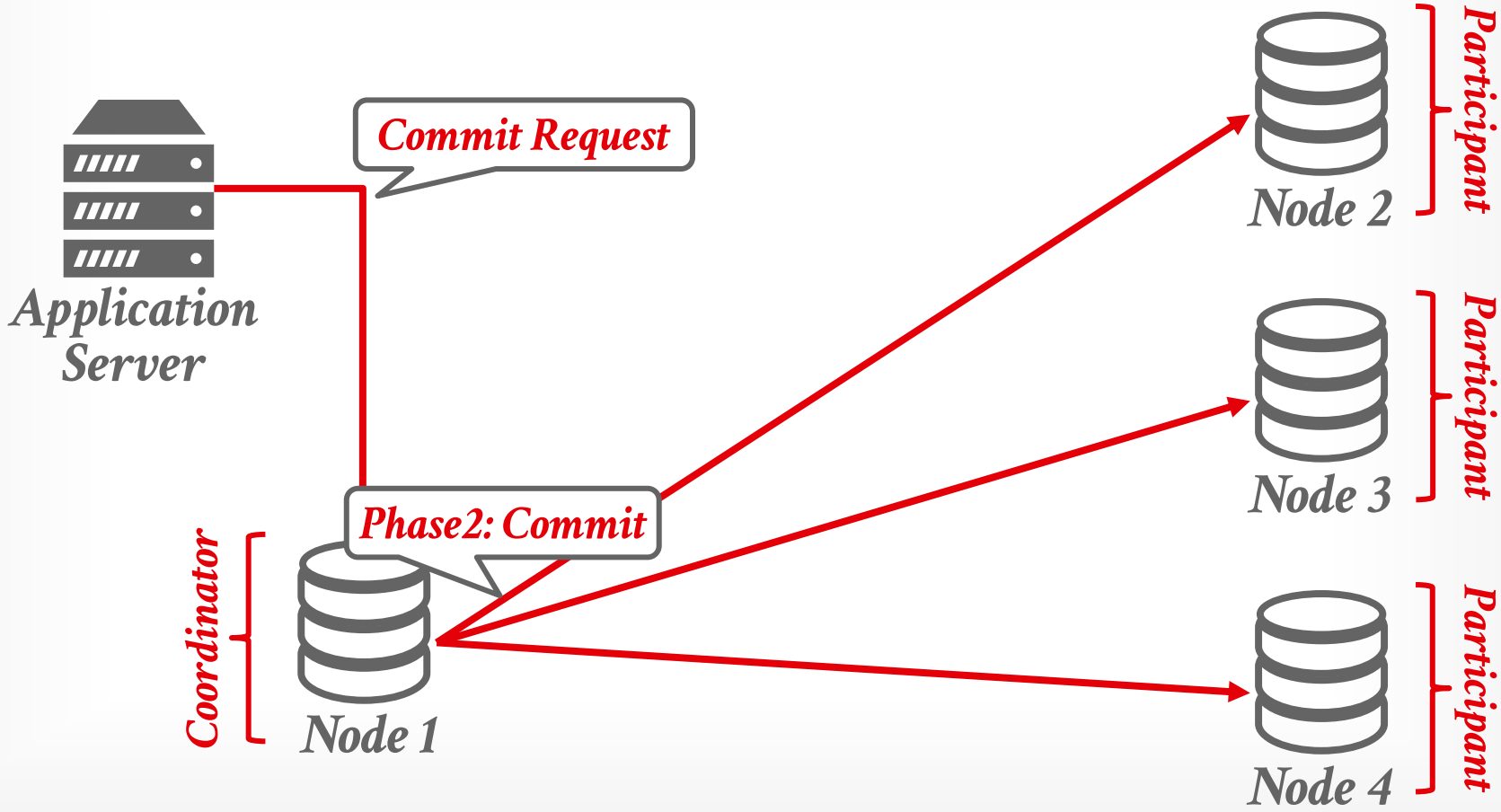

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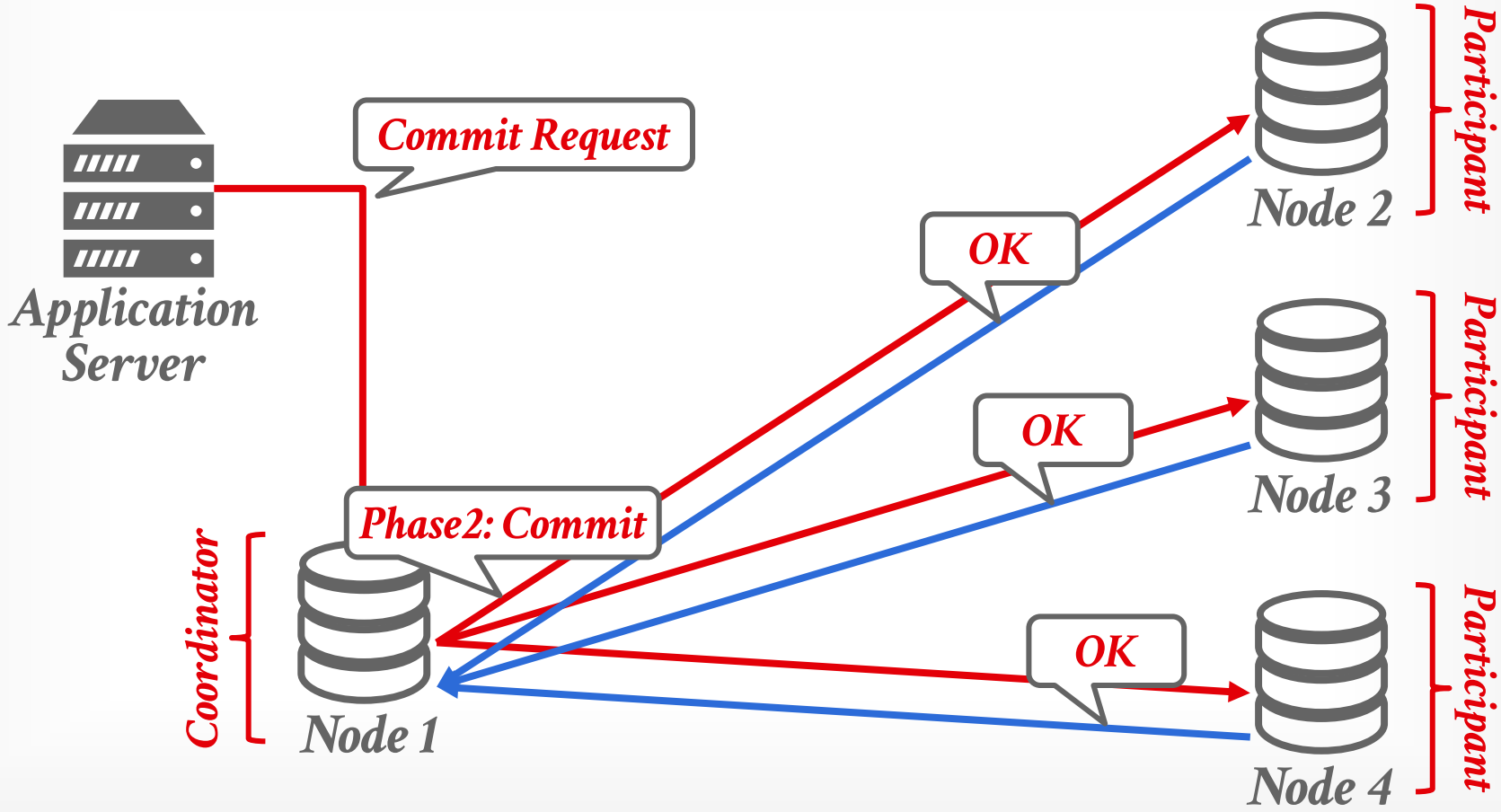

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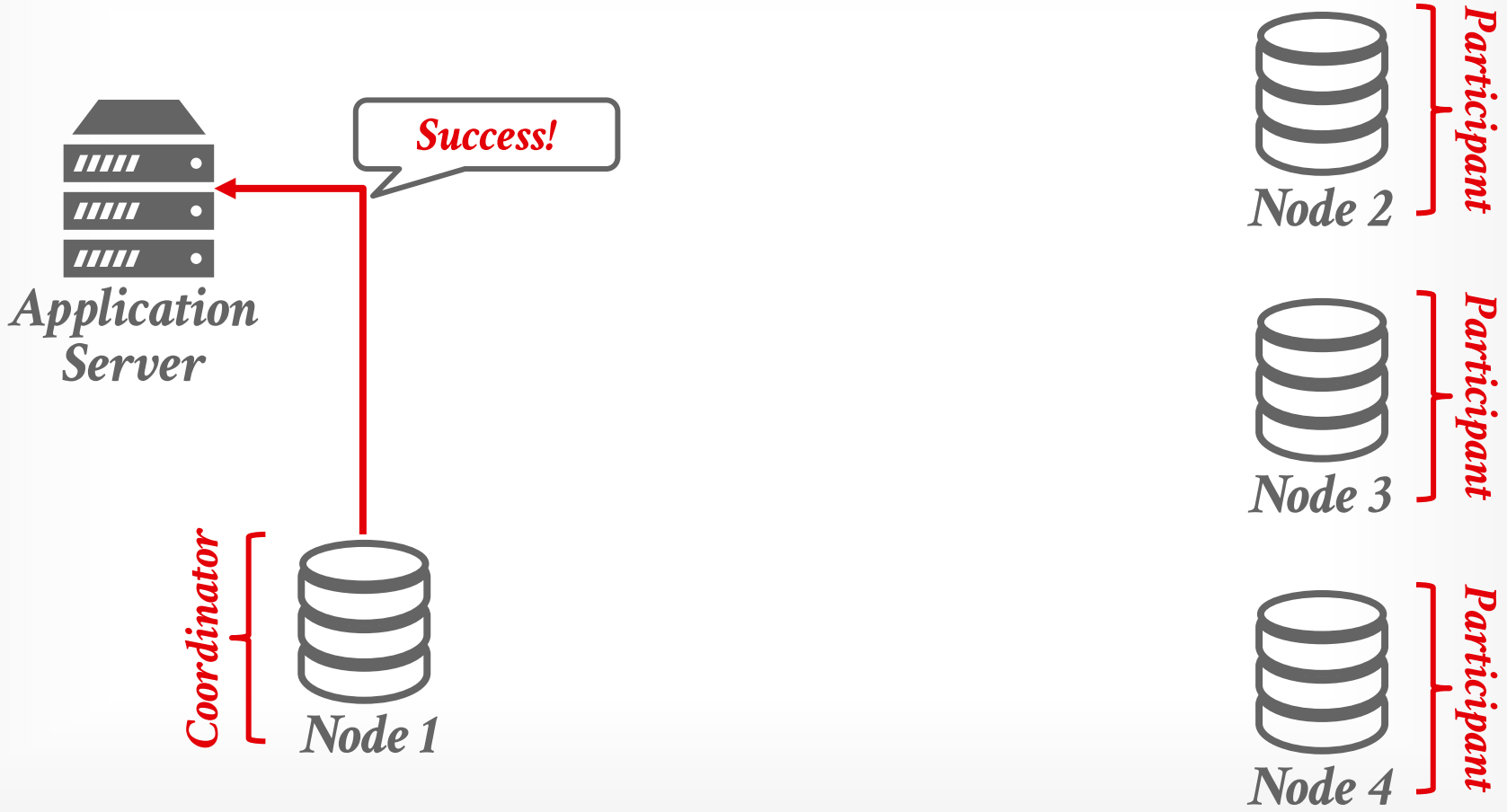

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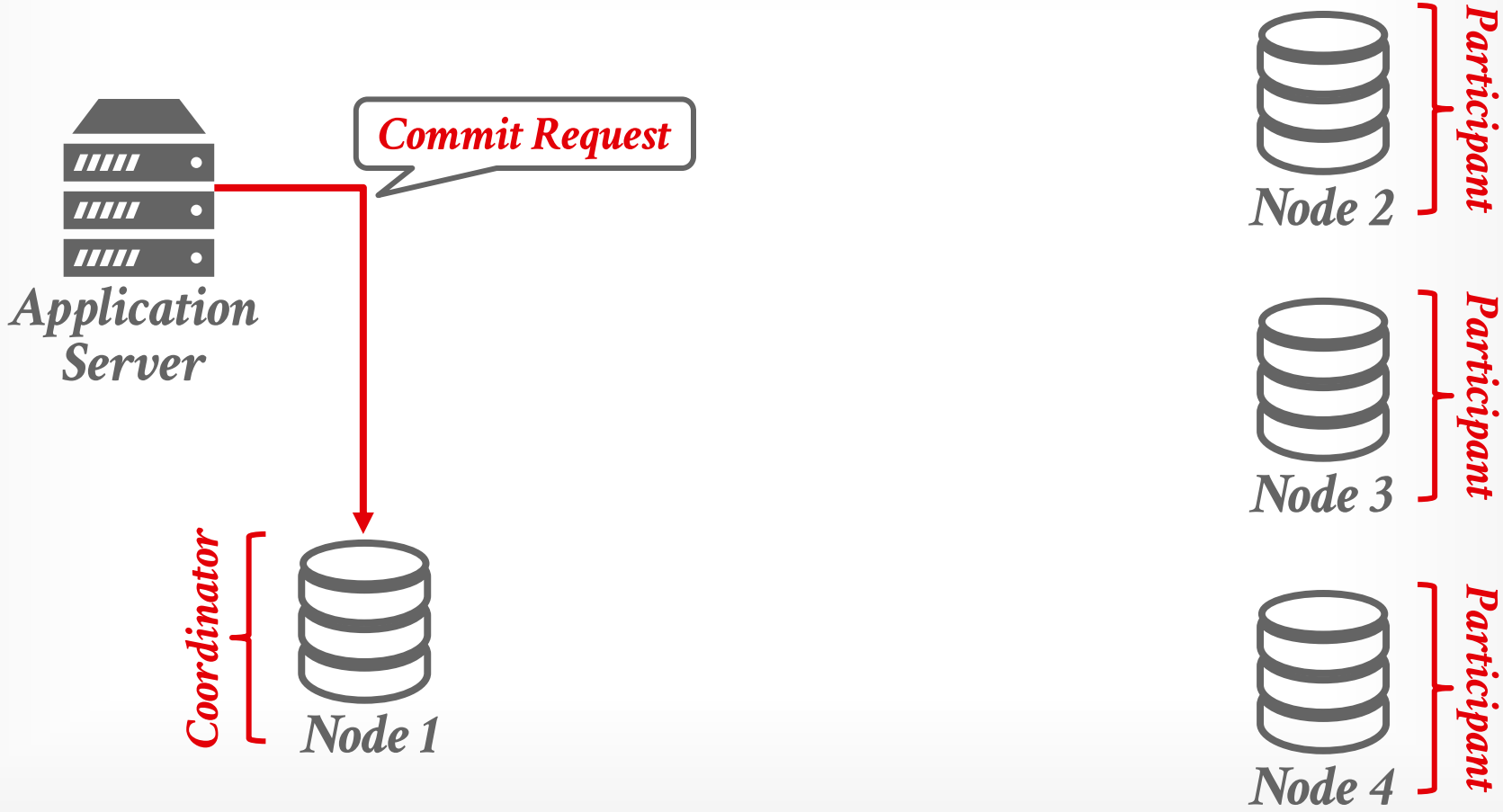

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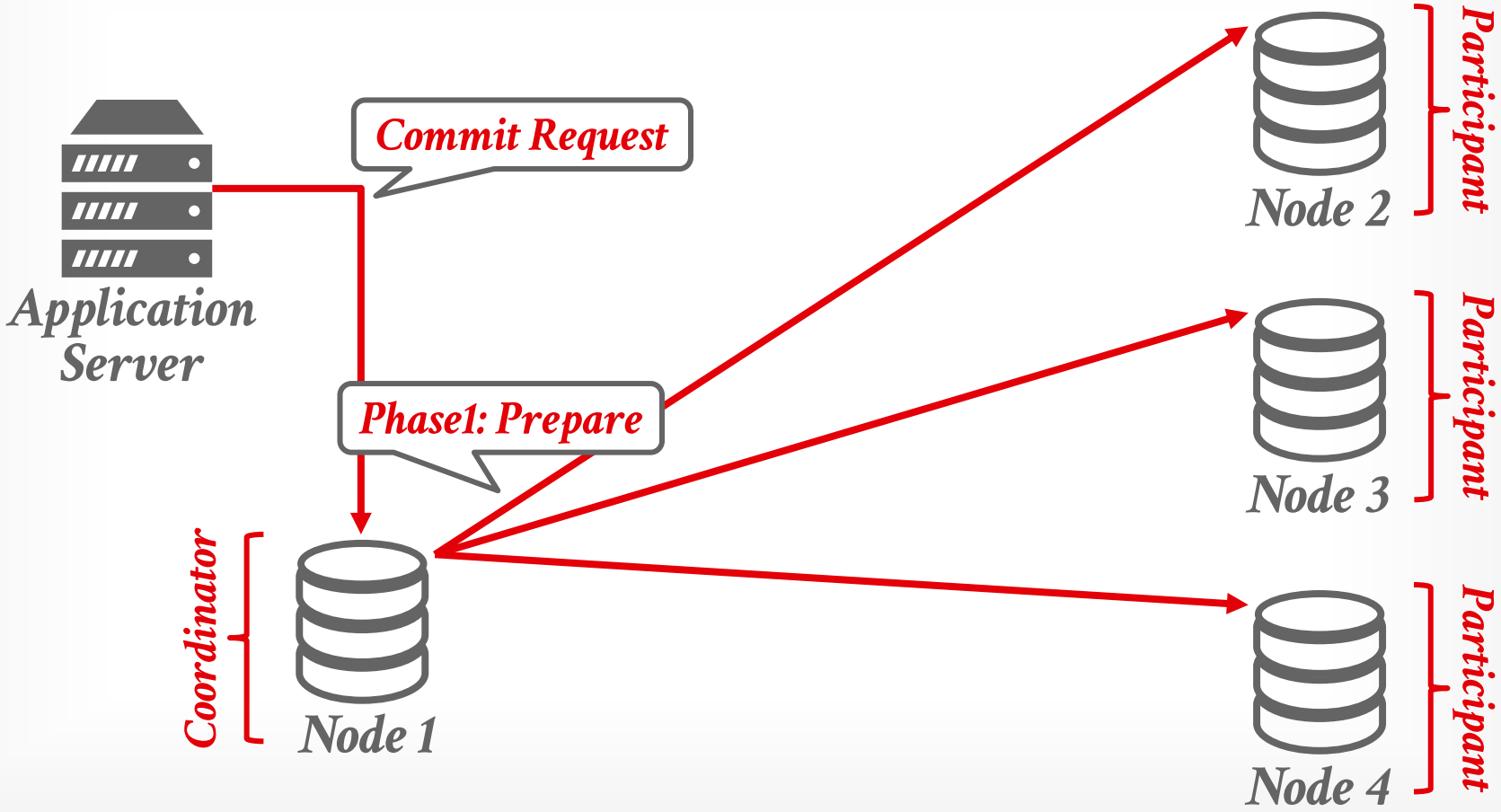

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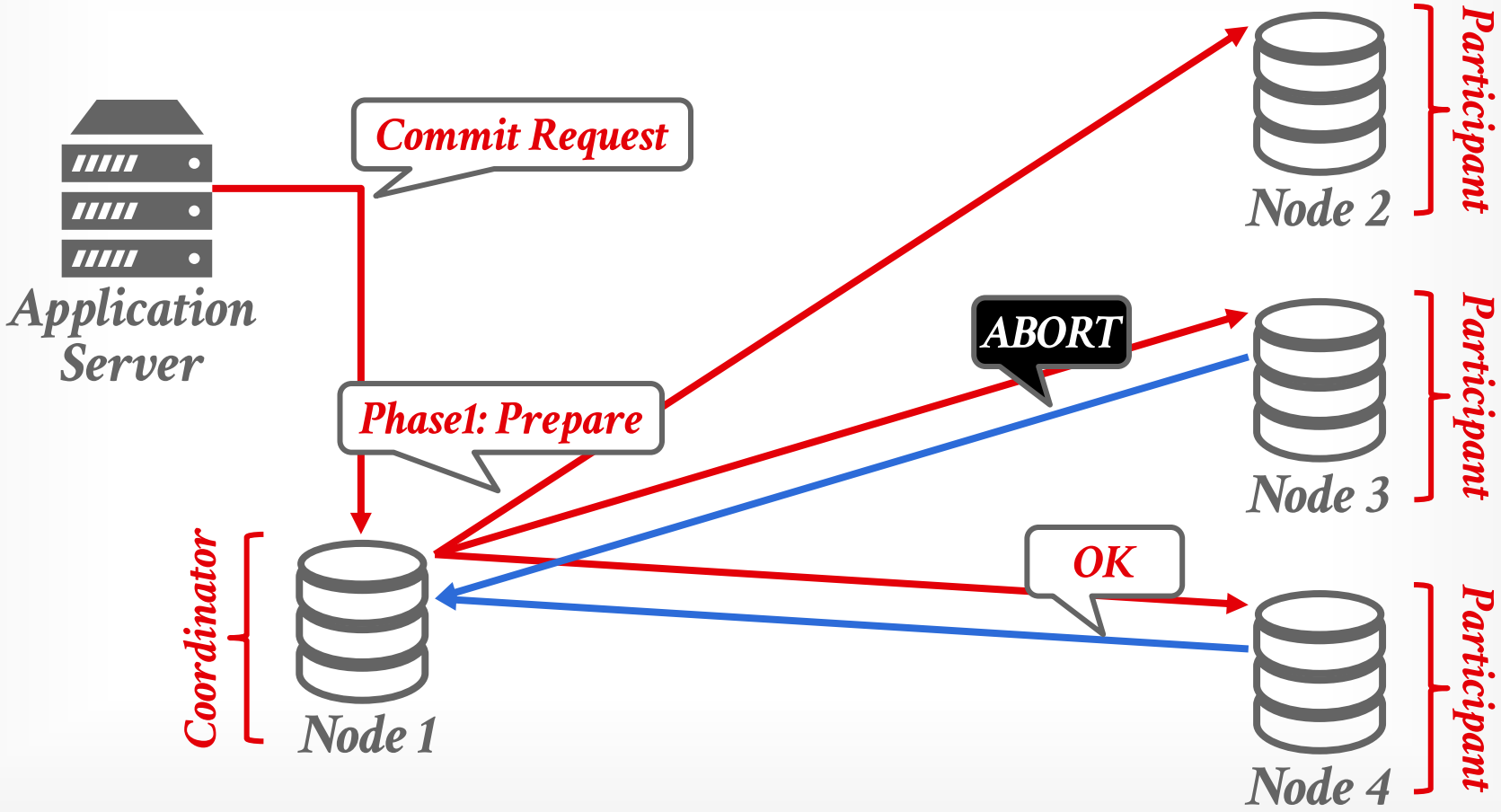

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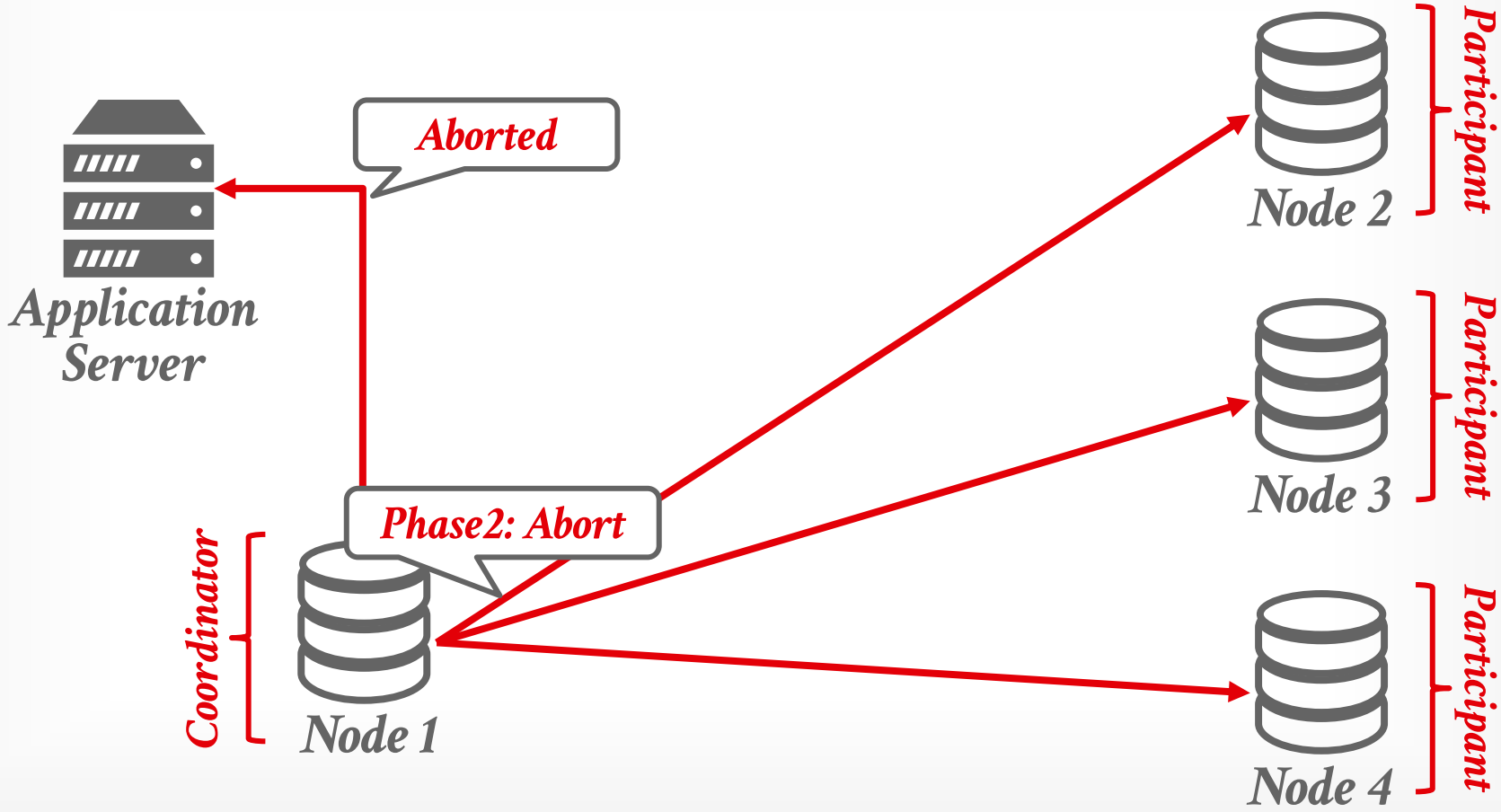

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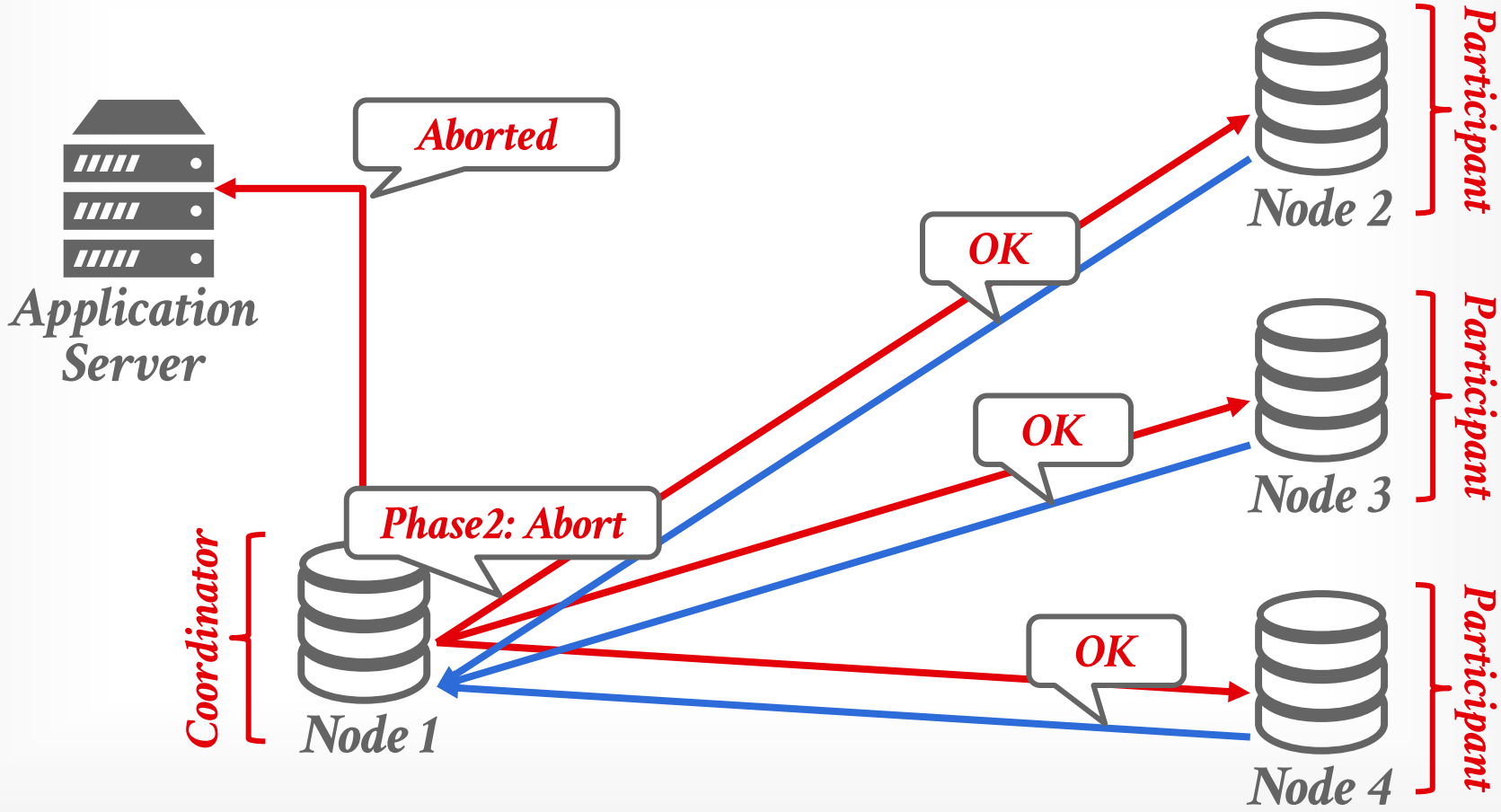

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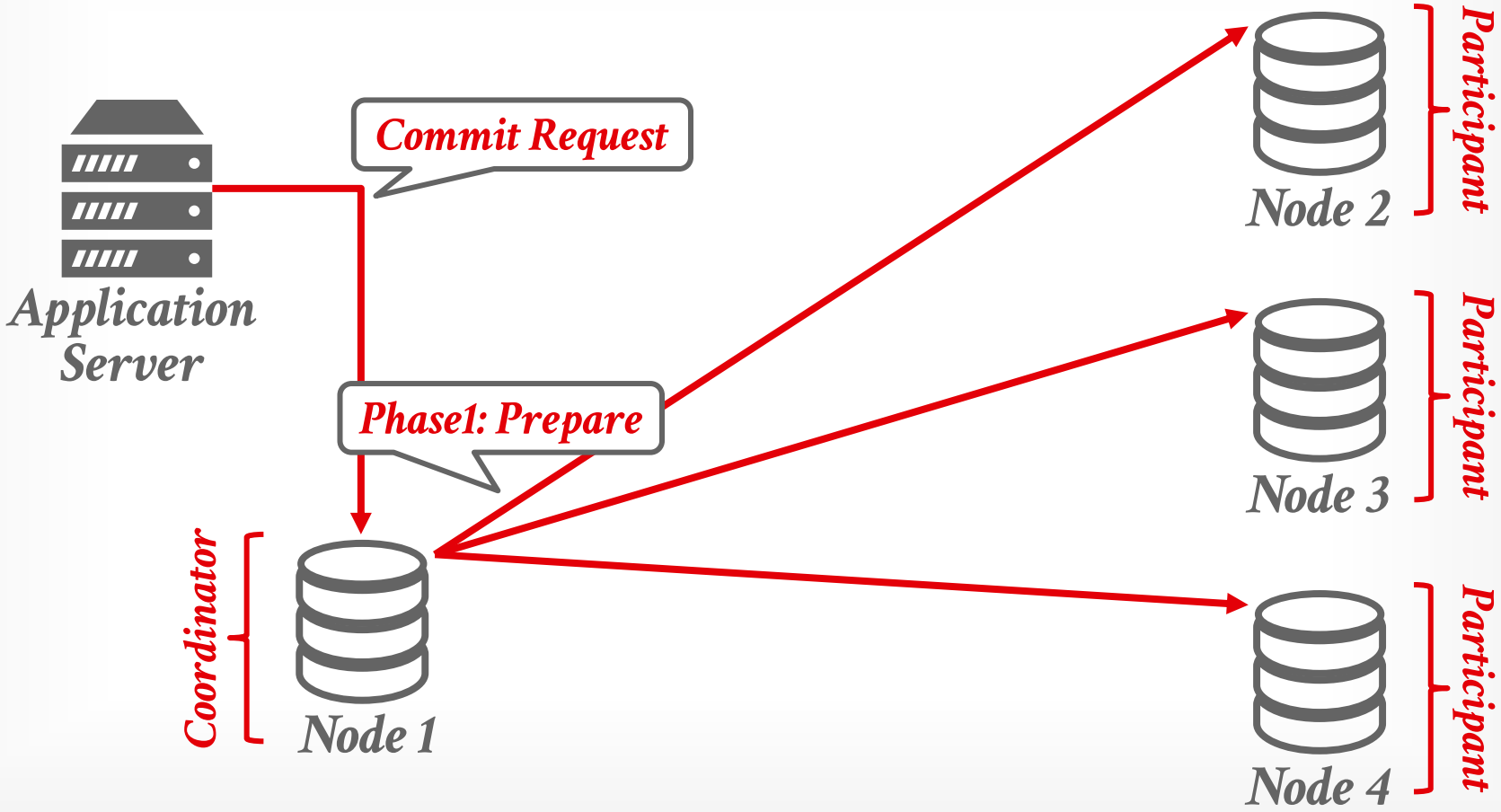

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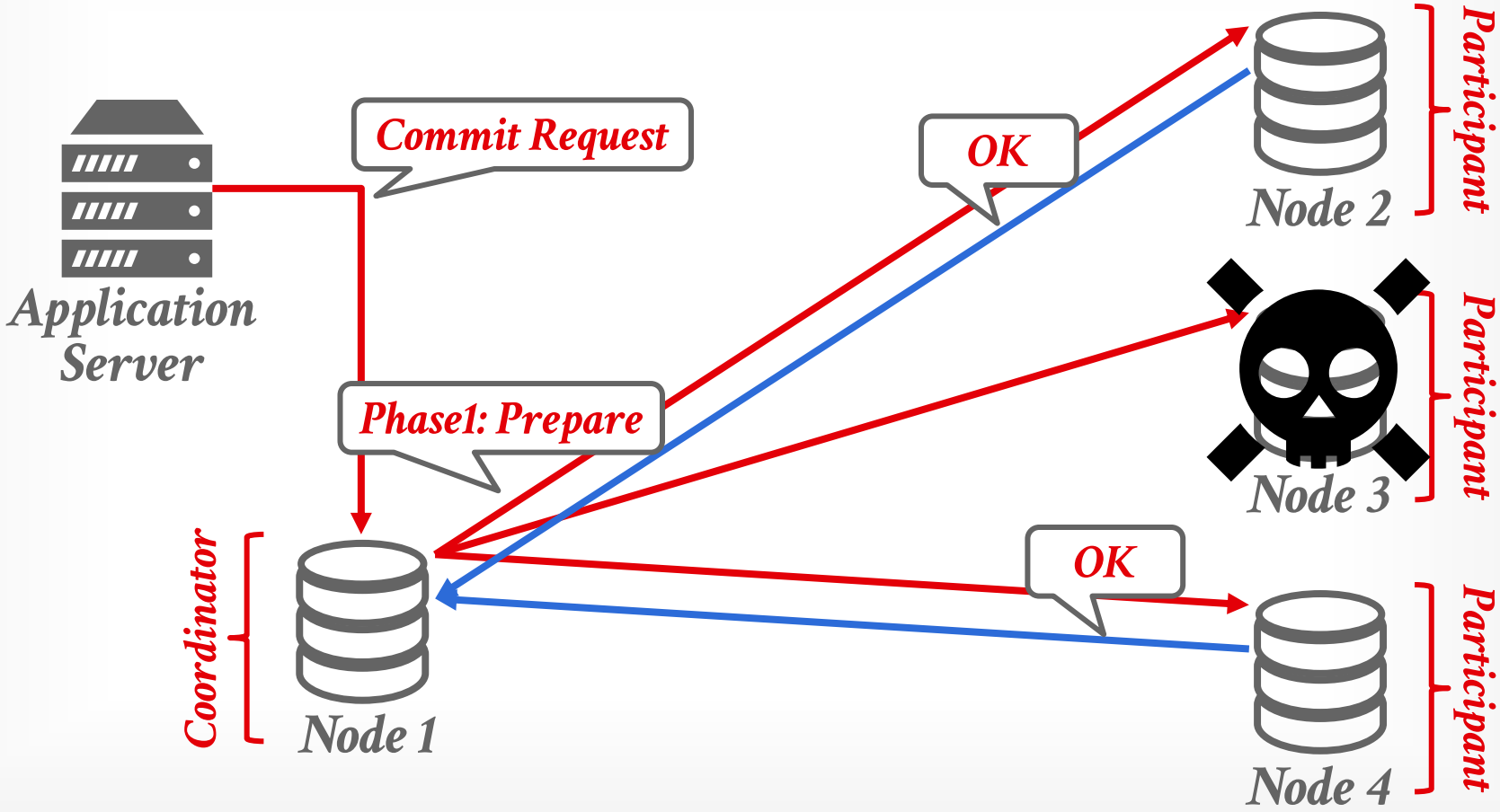

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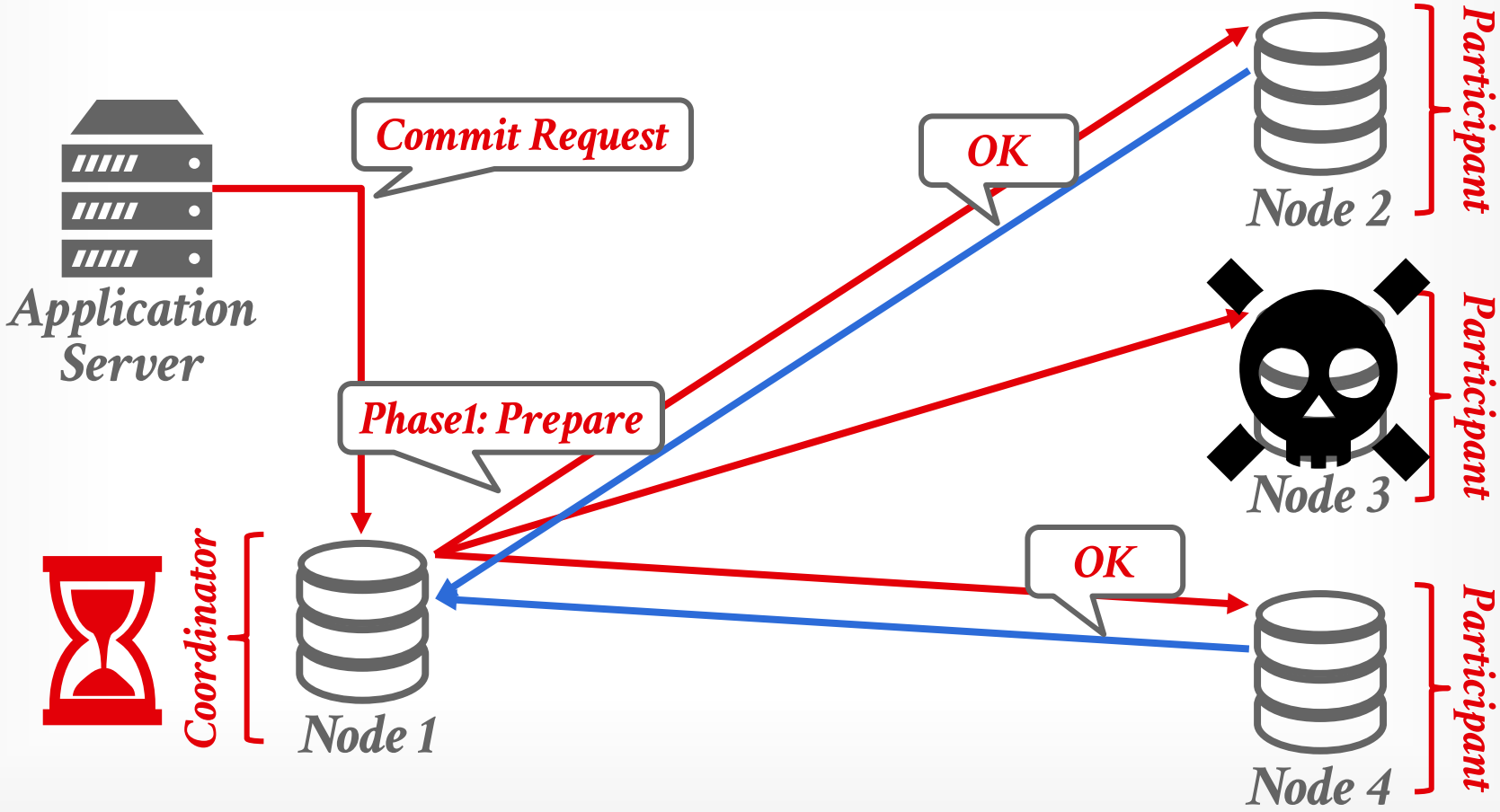

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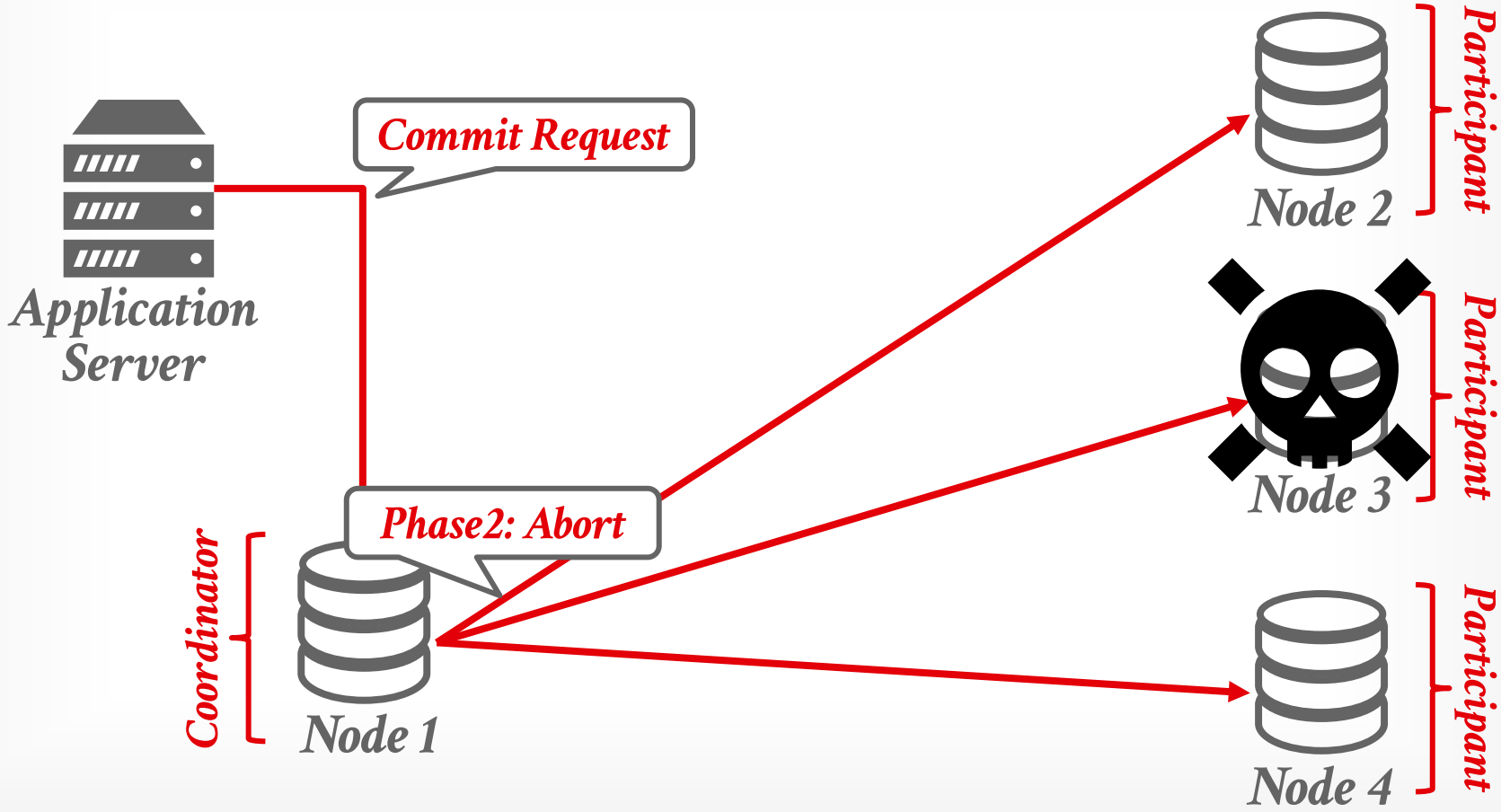

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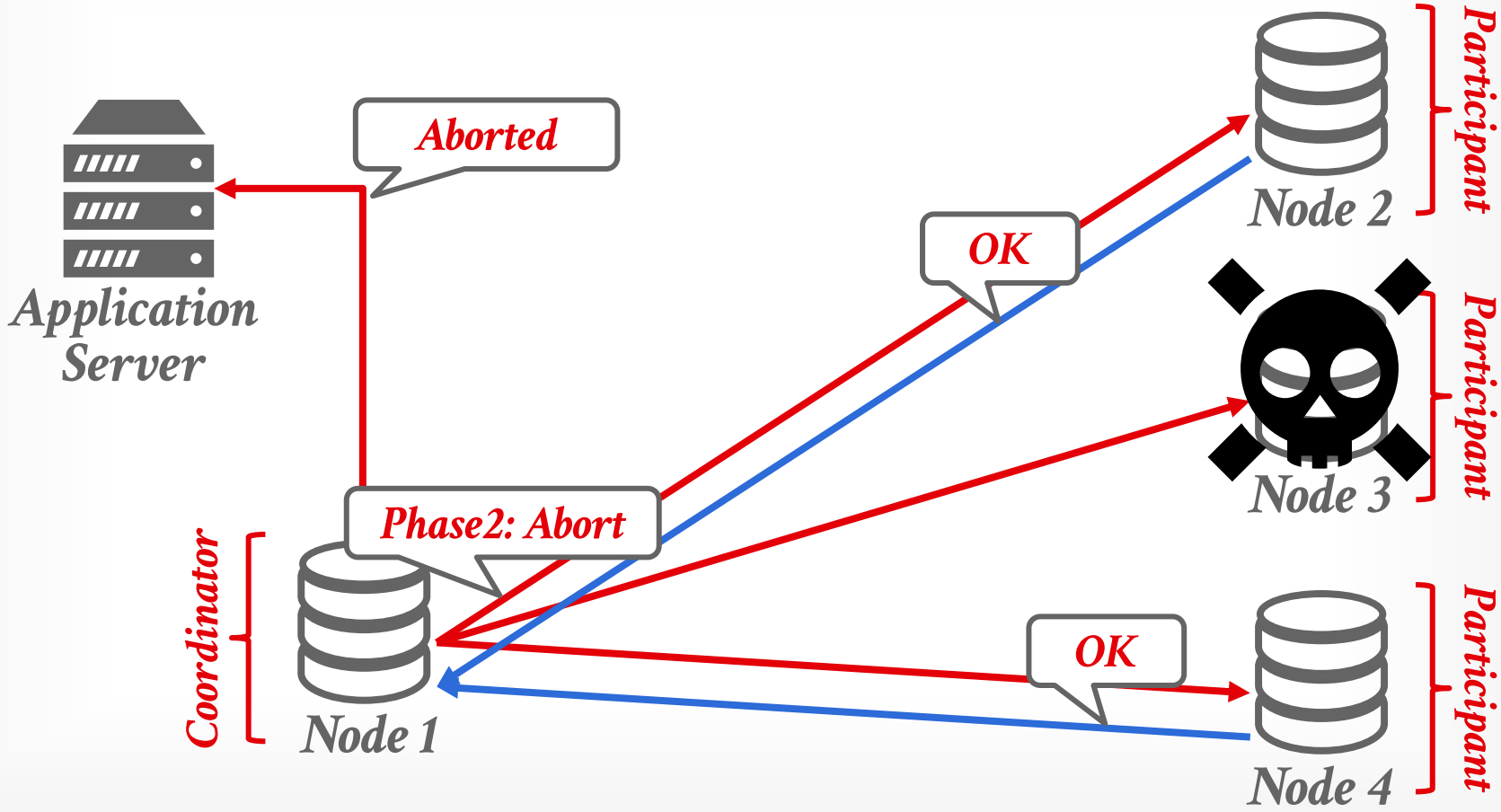

TWO-PHASE COMMIT

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 the coordinator crashes?

→ Participants must decide what to do after a timeout
(this only applies if the participants know of all other participants).

→ System is not available during this time.

What happens if the 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/request 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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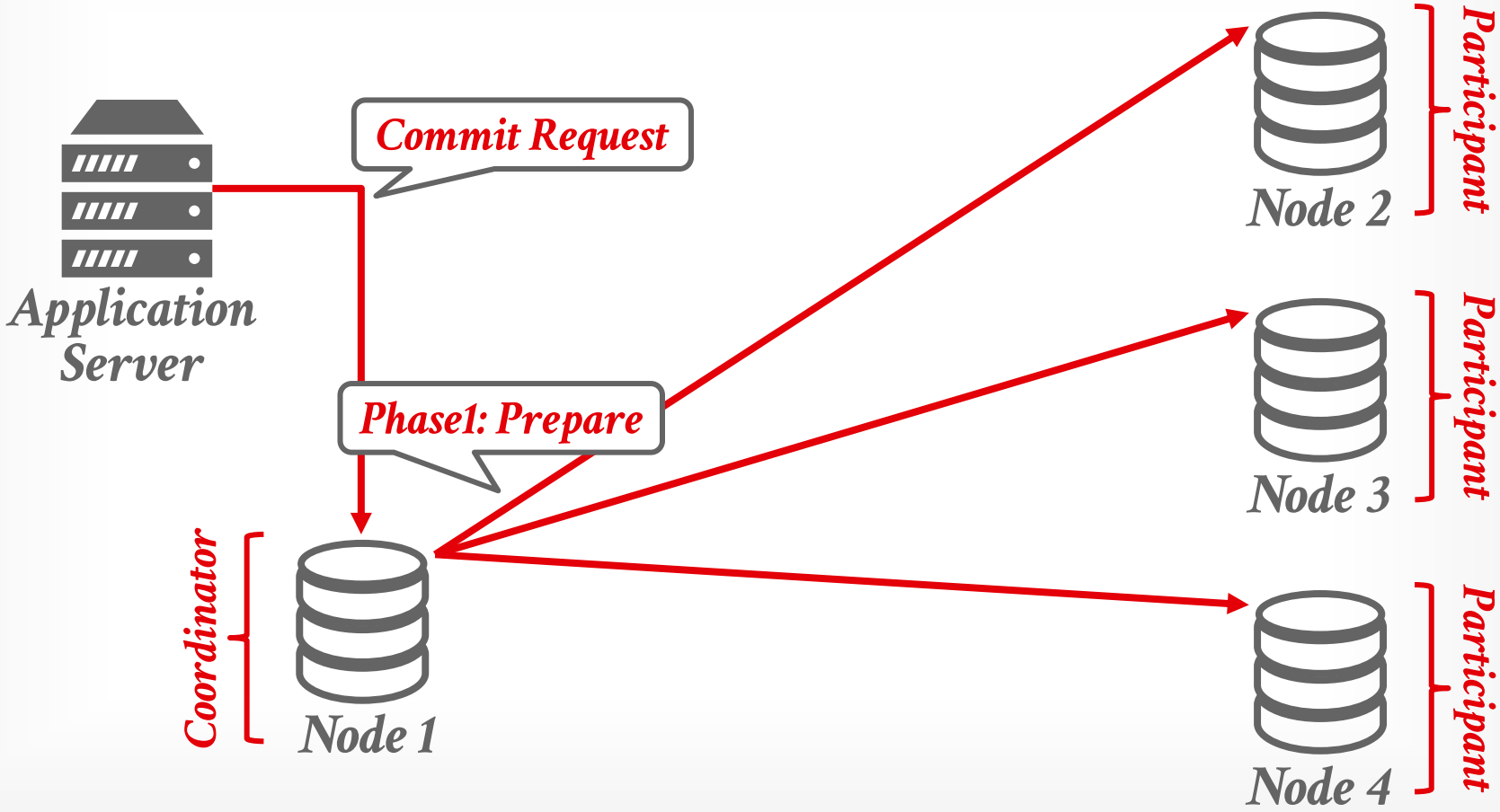

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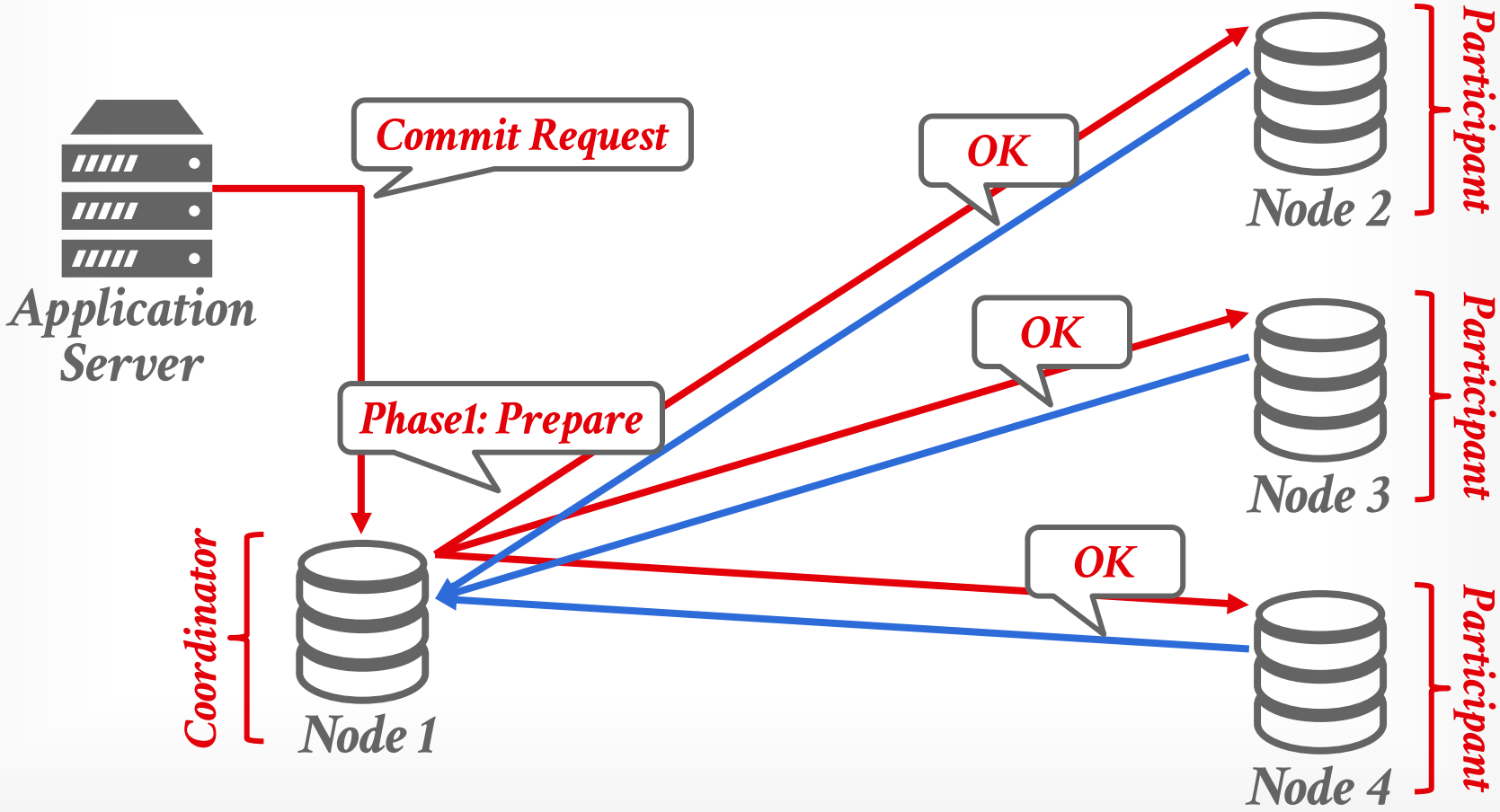

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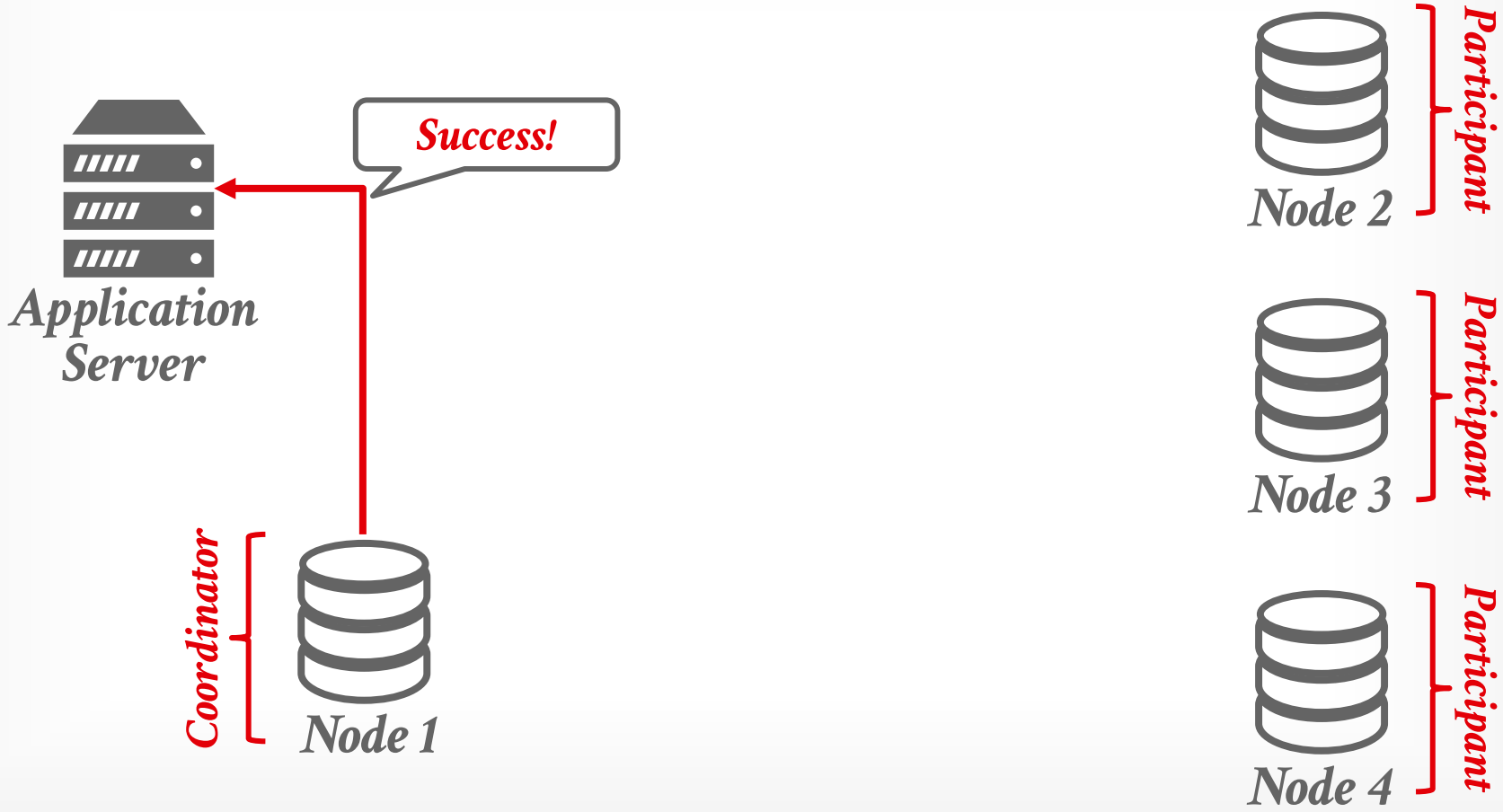

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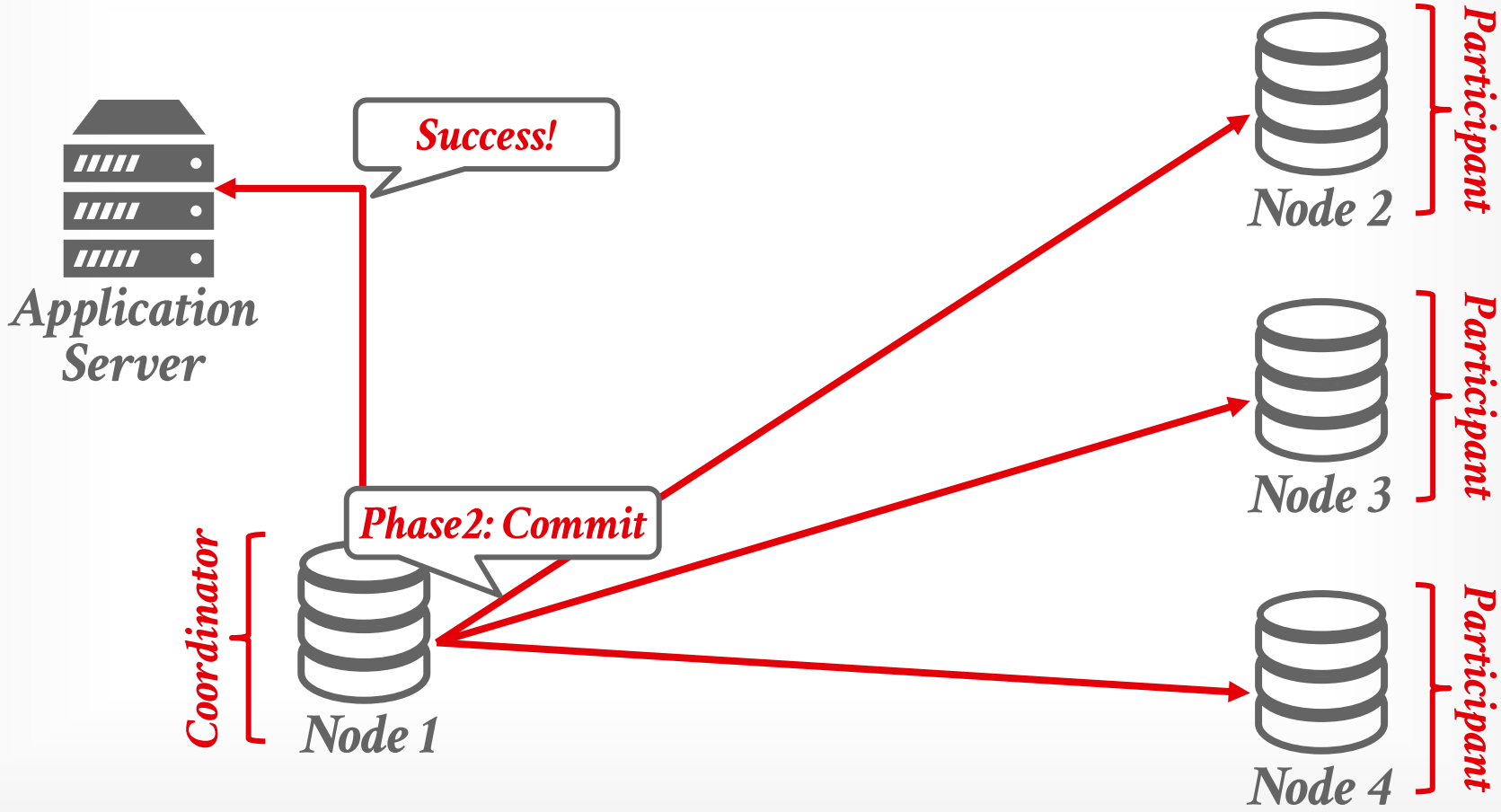

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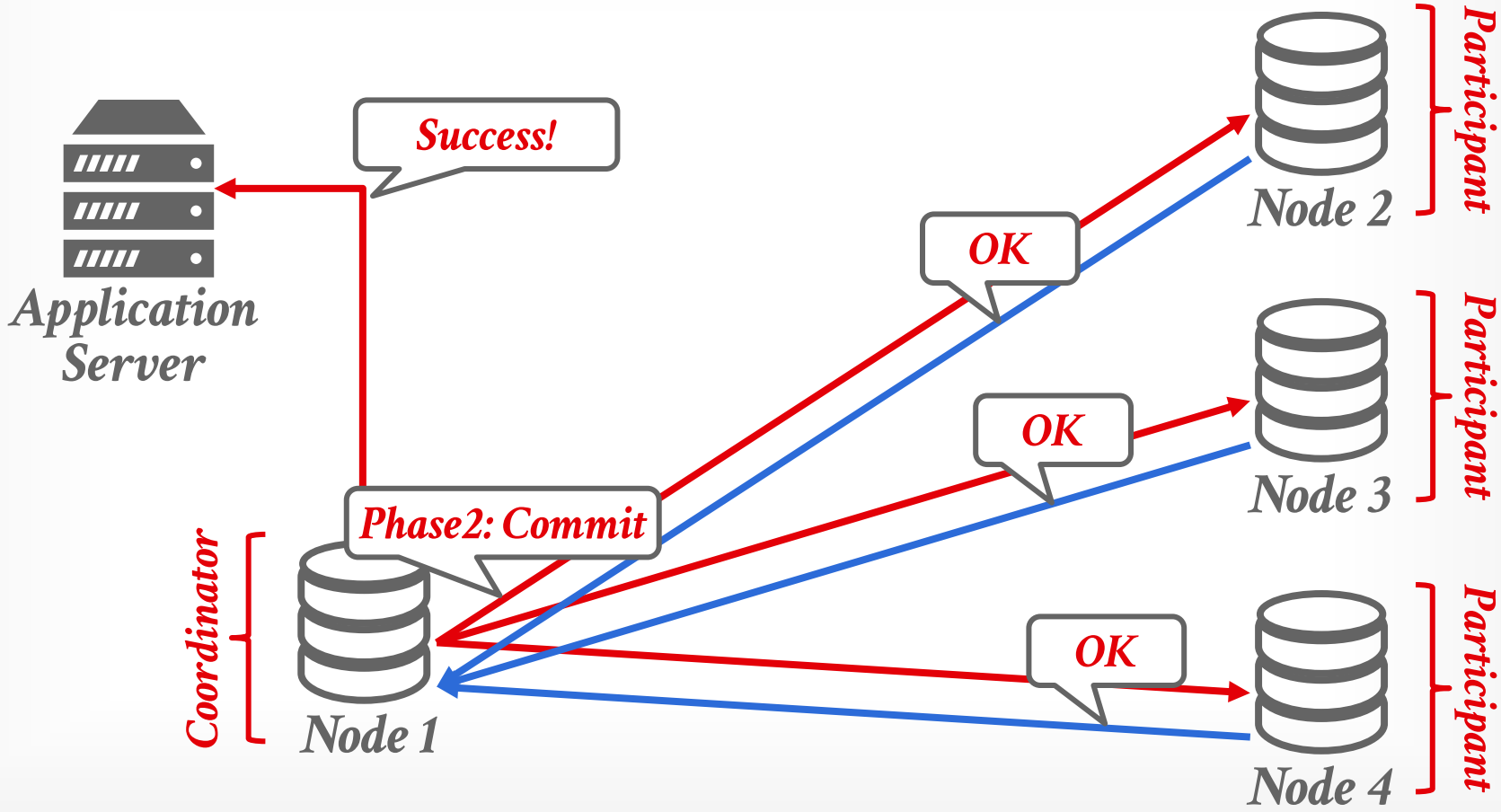


EARLY ACKNOWLEDGEMENT

Application Server

Participant

Node 2

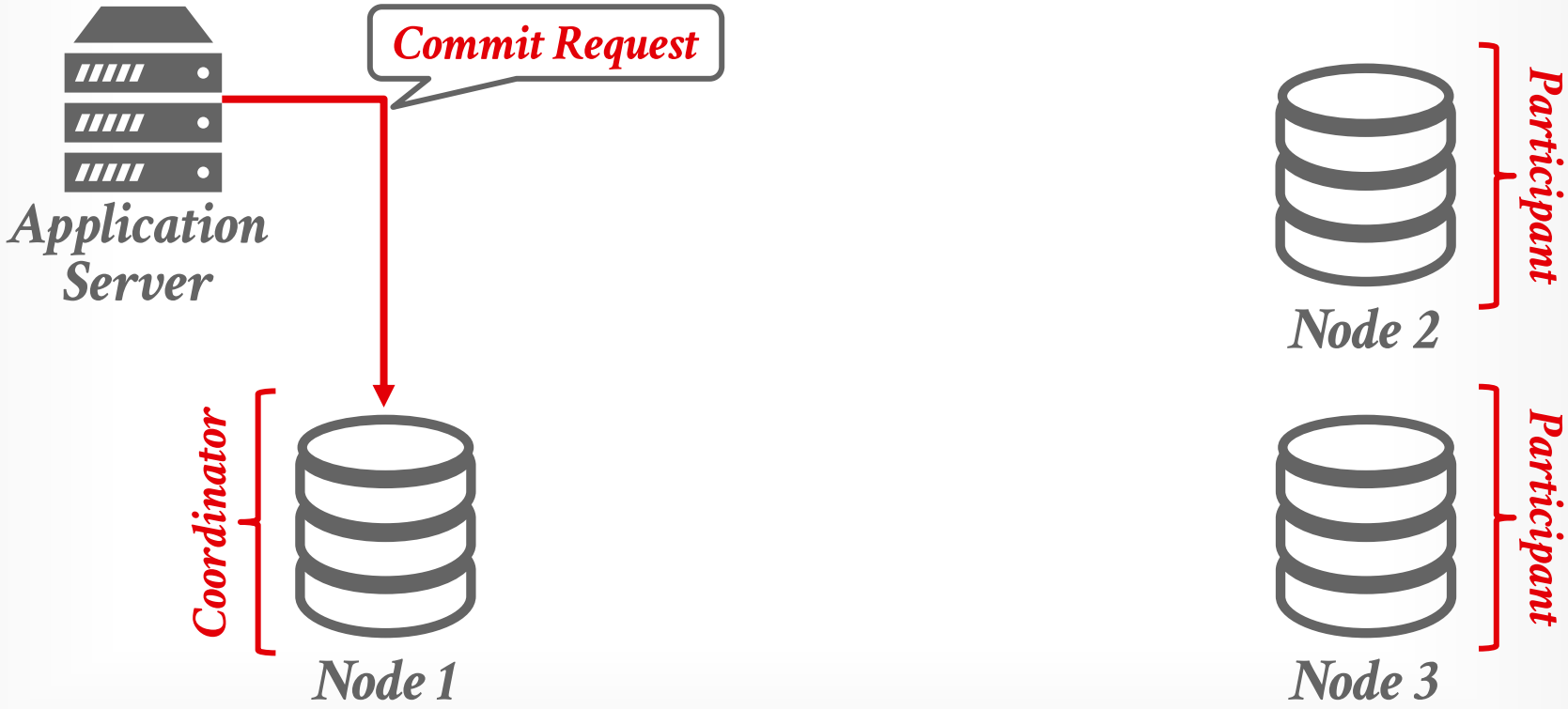
Coordinator

Node 1

Participant

Node 3

EARLY ACKNOWLEDGEMENT



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.

The Part-Time Parliament

LESLIE LAMPORT
Digital Equipment Corporation

Recent archaeological discoveries on the island of Paxos reveal that the parliament functioned despite the peripatetic propensity of its part-time legislators. The legislators maintained consistent copies of the parliamentary record, despite their frequent forays from the chamber and the forgetfulness of their messengers. The Paxon parliament's protocol provides a new way of implementing the state-machine approach to the design of distributed systems.

Categories and Subject Descriptors: C2.4 [**Computer-Communications Networks**]: Distributed Systems—*Network operating systems*; D4.5 [**Operating Systems**]: Reliability—*Fault-tolerance*; J.1 [**Administrative Data Processing**]: Government

General Terms: Design, Reliability

Additional Key Words and Phrases: State machines, three-phase commit, voting

This submission was recently discovered behind a filing cabinet in the *TOCS* editorial office. Despite its age, the editor-in-chief felt that it was worth publishing. Because the author is currently doing field work in the Greek isles and cannot be reached, I was asked to prepare it for publication.

The author appears to be an archeologist with only a passing interest in computer science. This is unfortunate; even though the obscure ancient Paxon civilization he describes is of little interest to most computer scientists, its legislative system is an excellent model for how to implement a distributed computer system in an asynchronous environment. Indeed, some of the refinements the Paxons made to their protocol appear to be unknown in the systems literature.

The author does give a brief discussion of the Paxon Parliament's relevance to distributed computing in Section 4. Computer scientists will probably want to read that section first. Even before that, they might want to read the explanation of the algorithm for computer scientists by Lampson [1996]. The algorithm is also described more formally by De Prisco et al. [1997]. I have added further comments on the relation between the ancient protocols and more recent work at the end of Section 4.

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University of California, San Diego

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PAX

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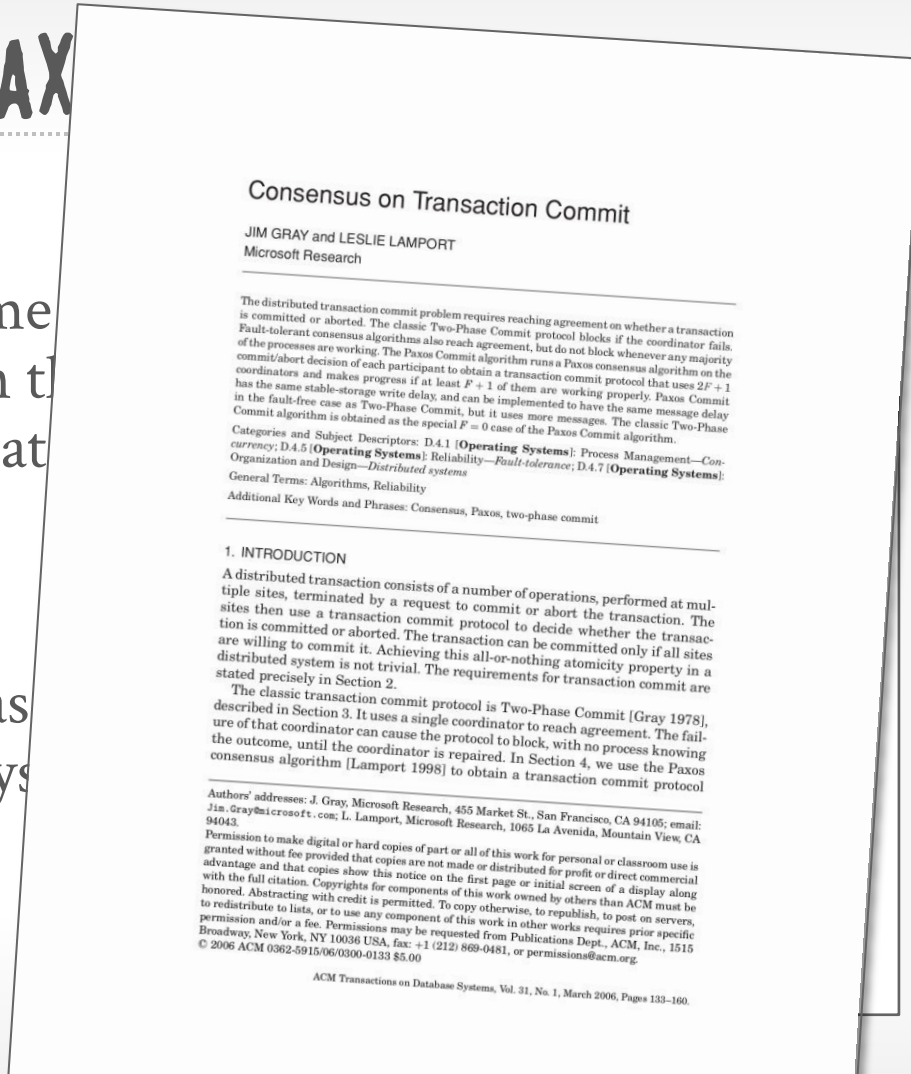

Consensus on Transaction Commit

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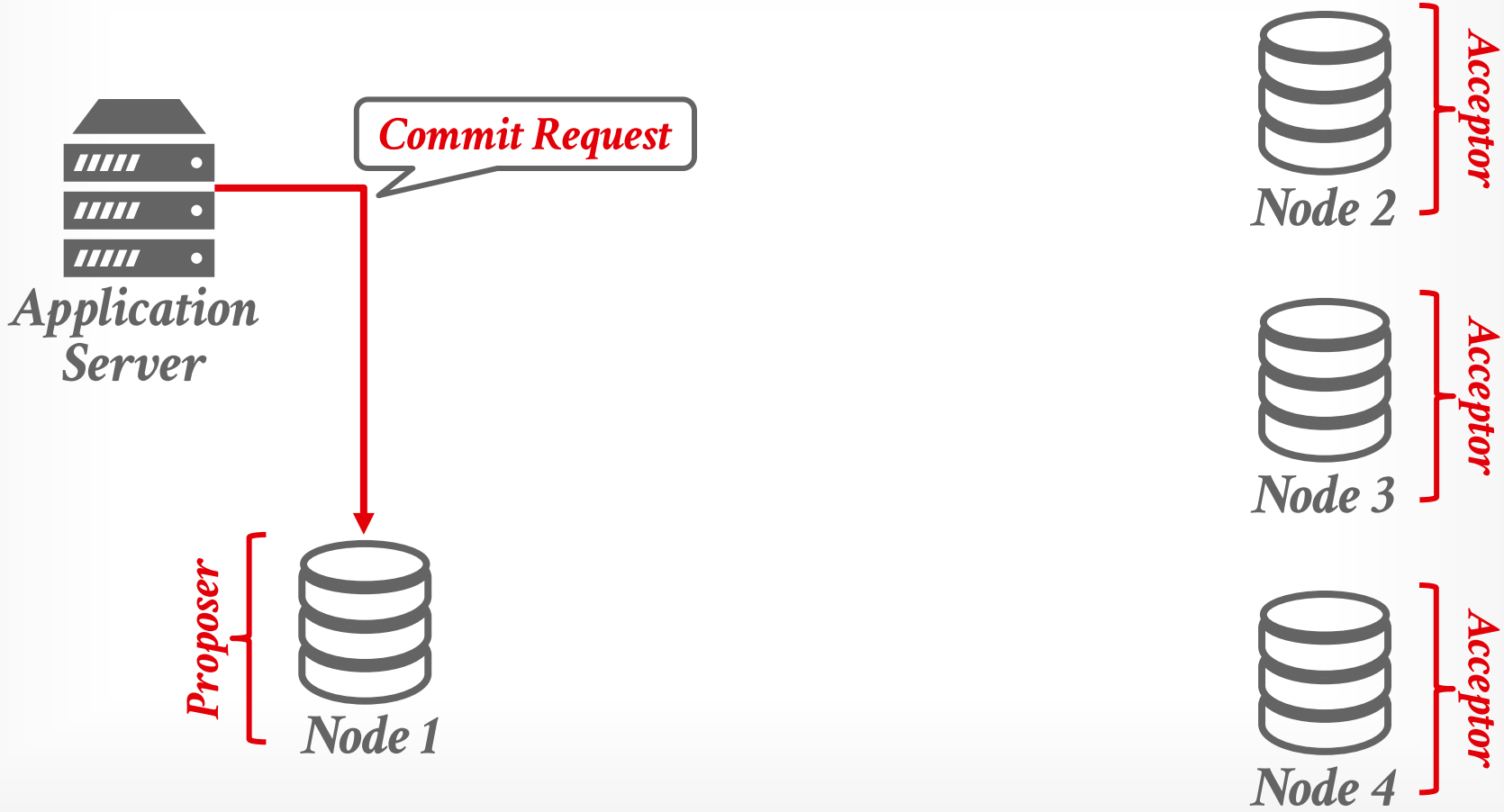
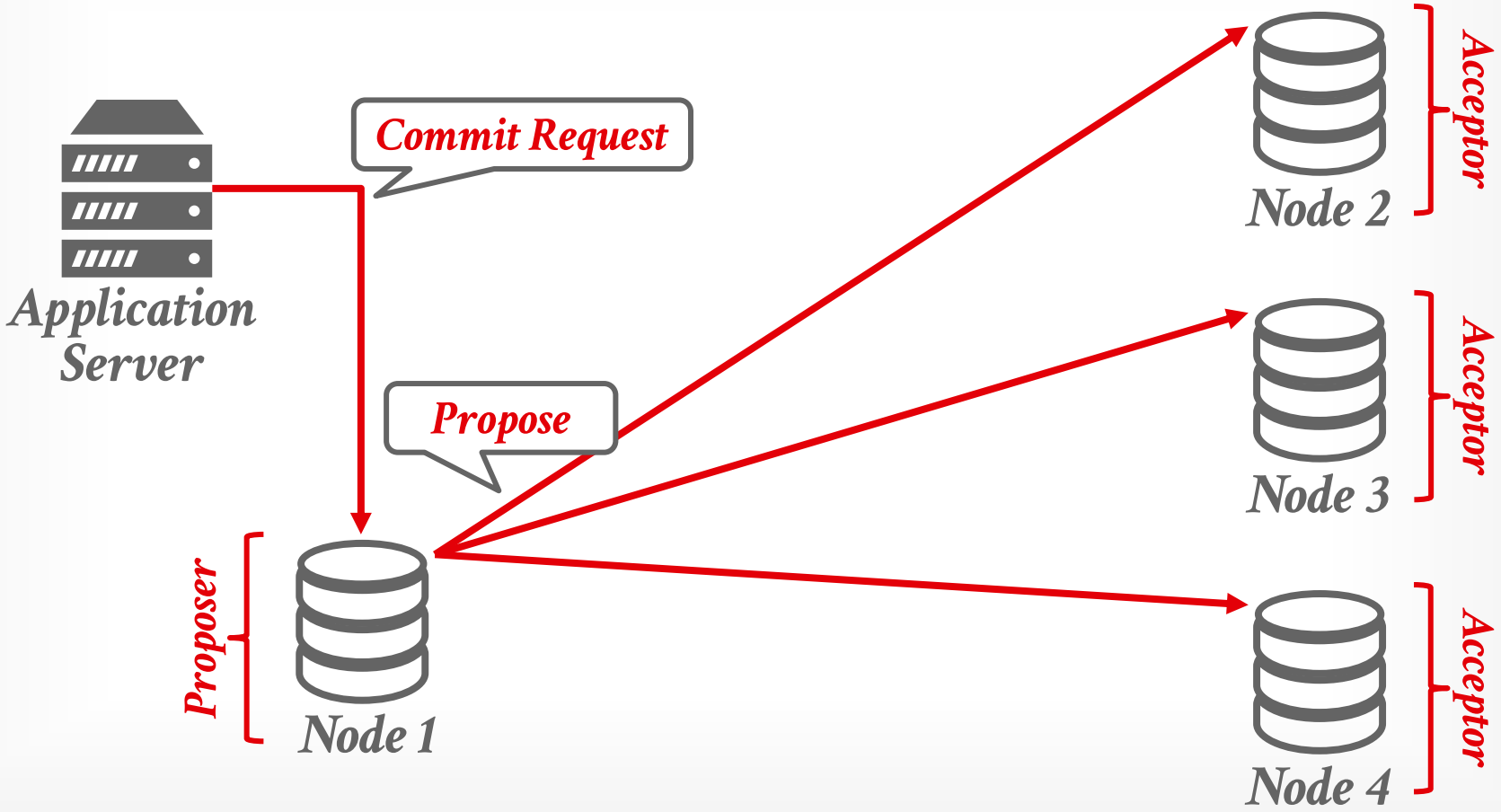
ACM Transactions on Database Systems, Vol. 31, No. 1, March 2006, Pages 133–160.

PAXOS


Commit Request
Application Server
Proposer
Node 1
Node 2
Acceptor
Node 3
Acceptor
Node 4
Acceptor

PAXOS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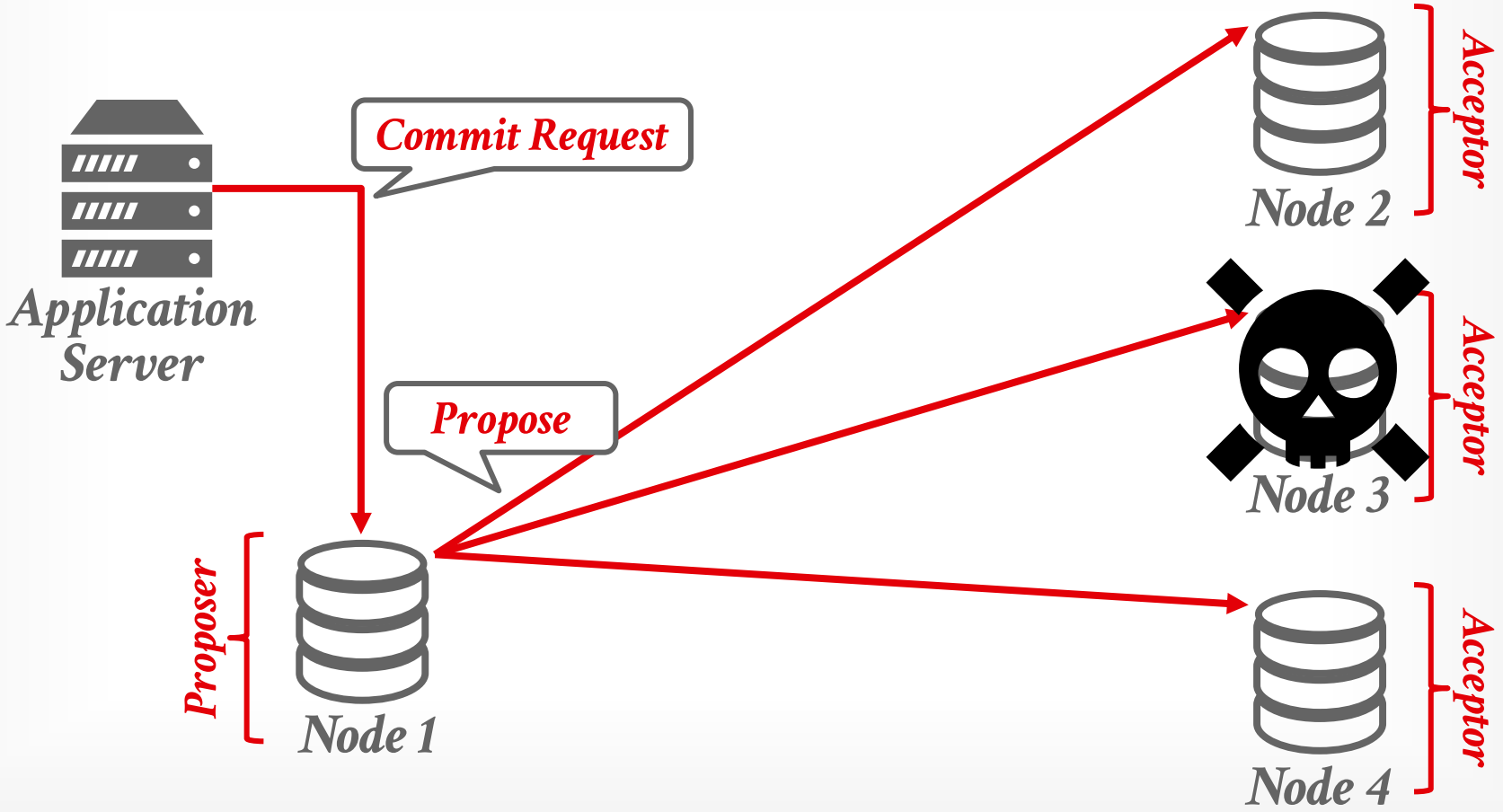
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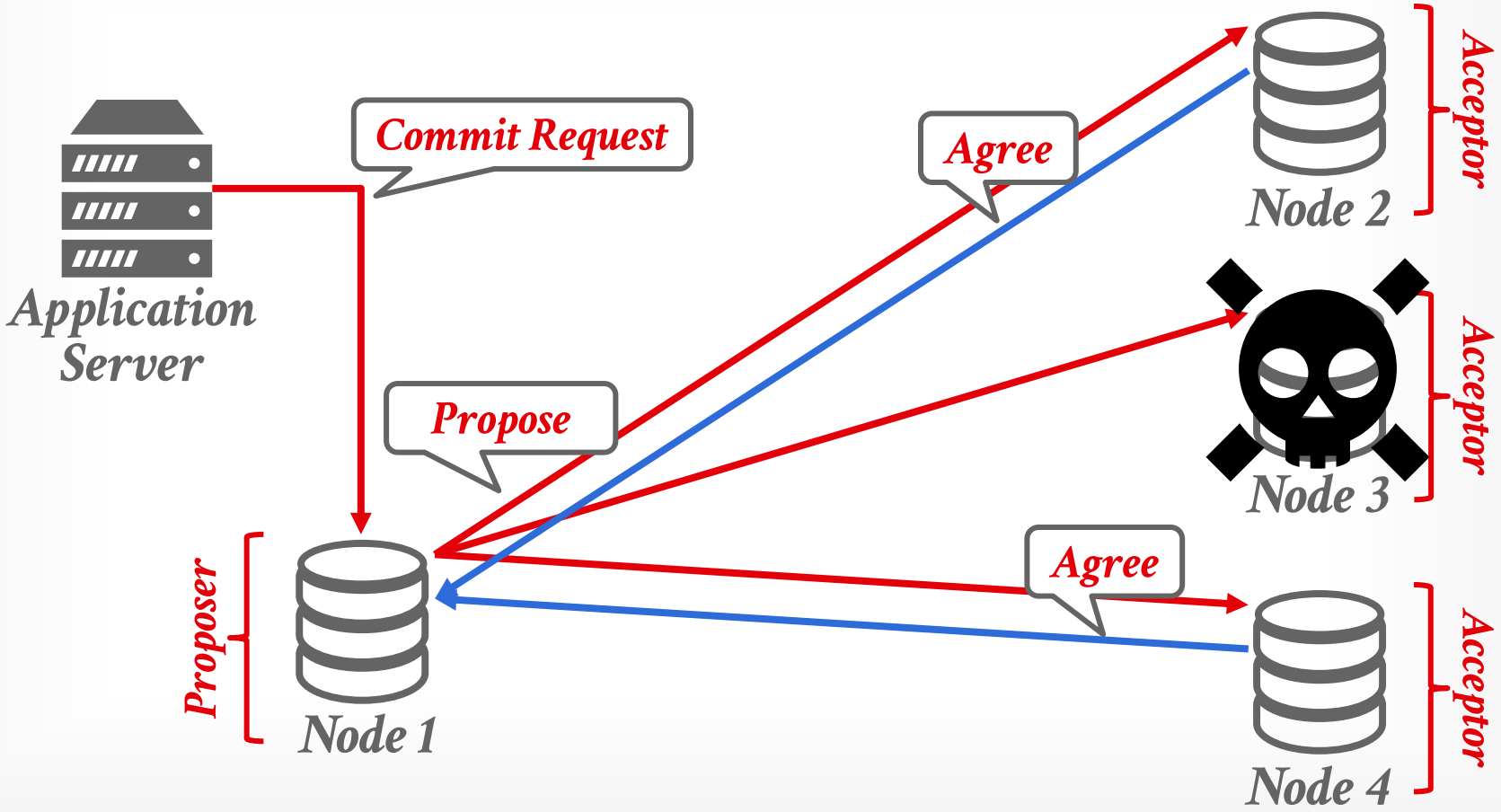
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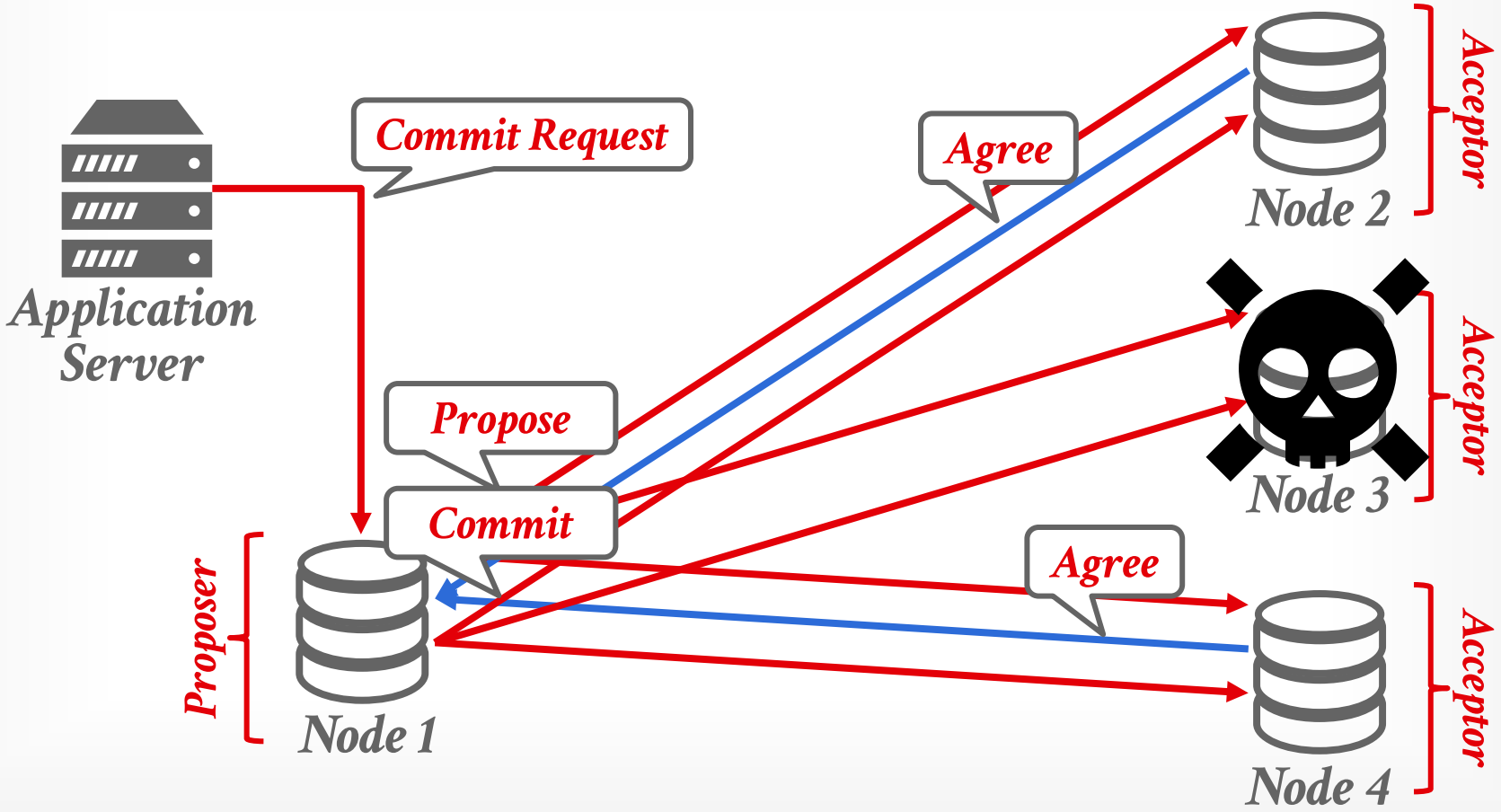
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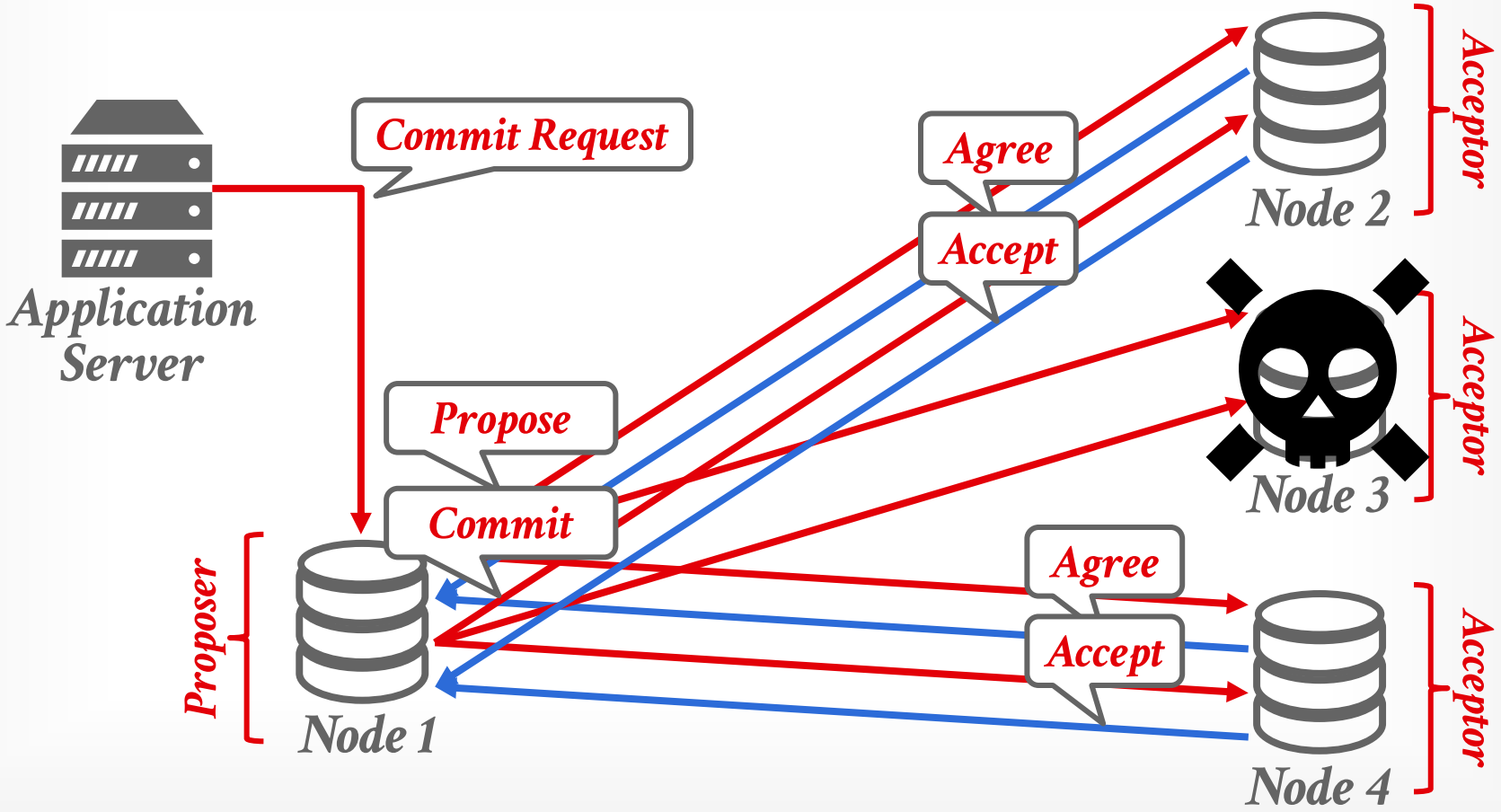
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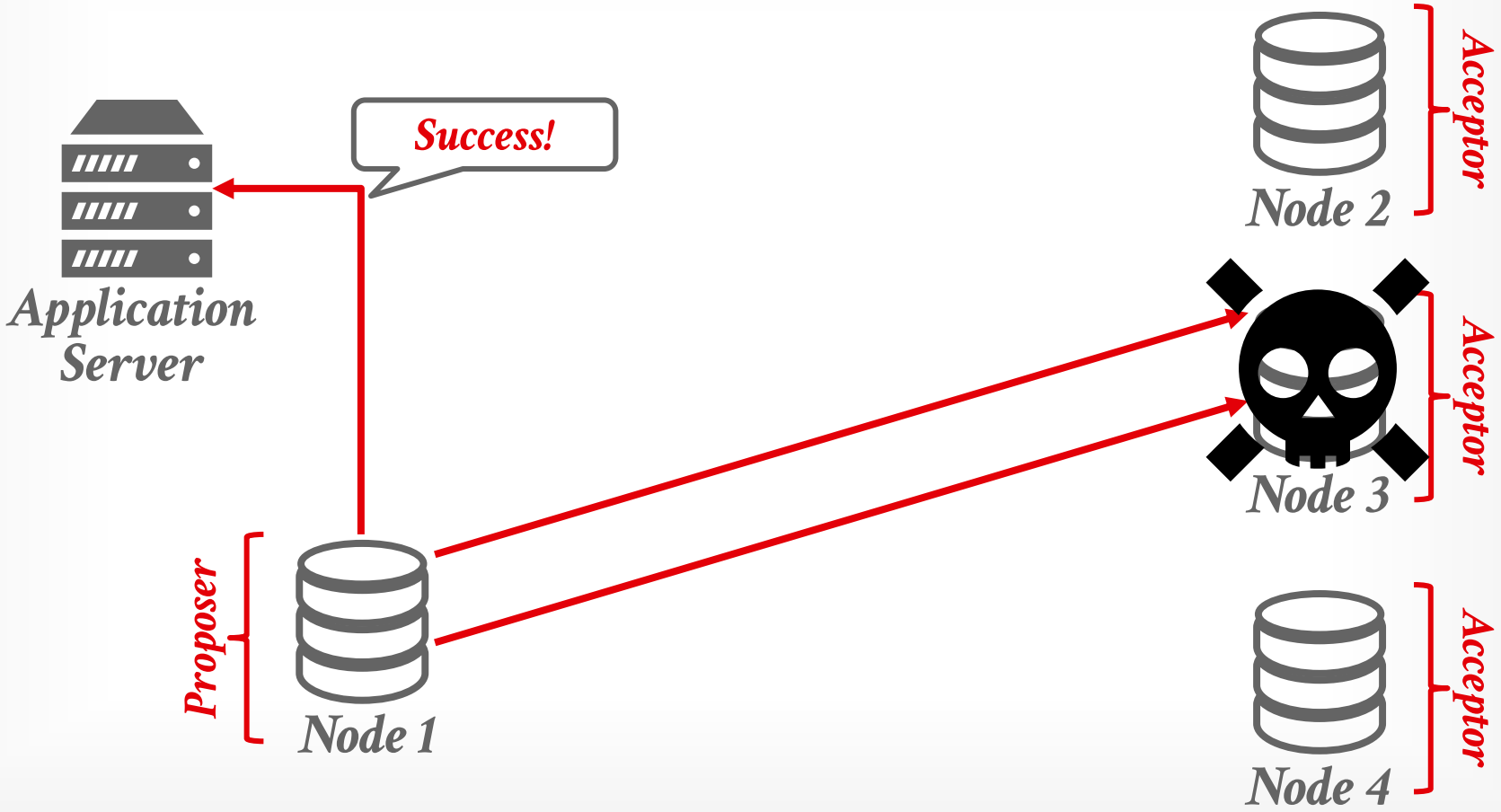
PAXOS


Success!
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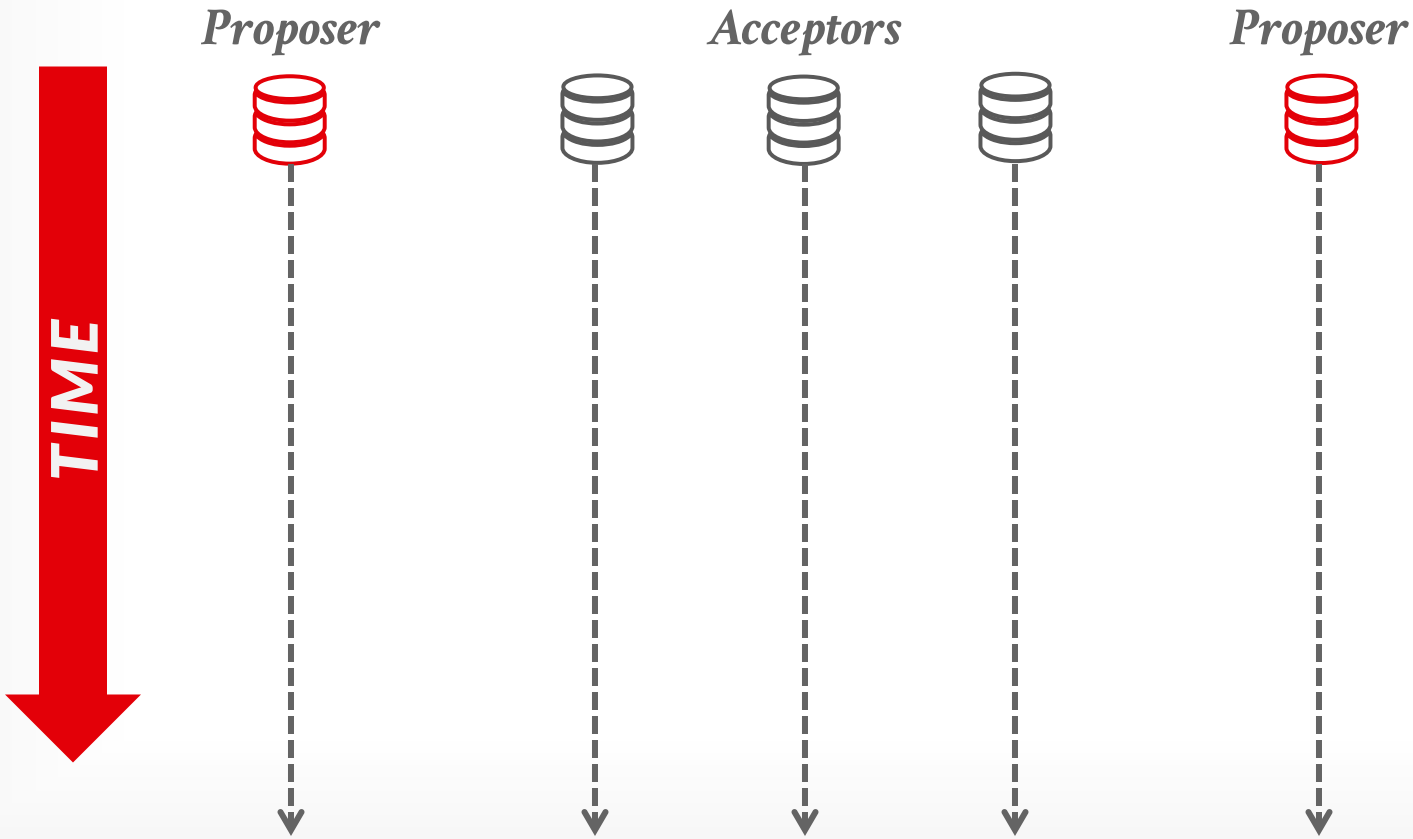
PAXOS



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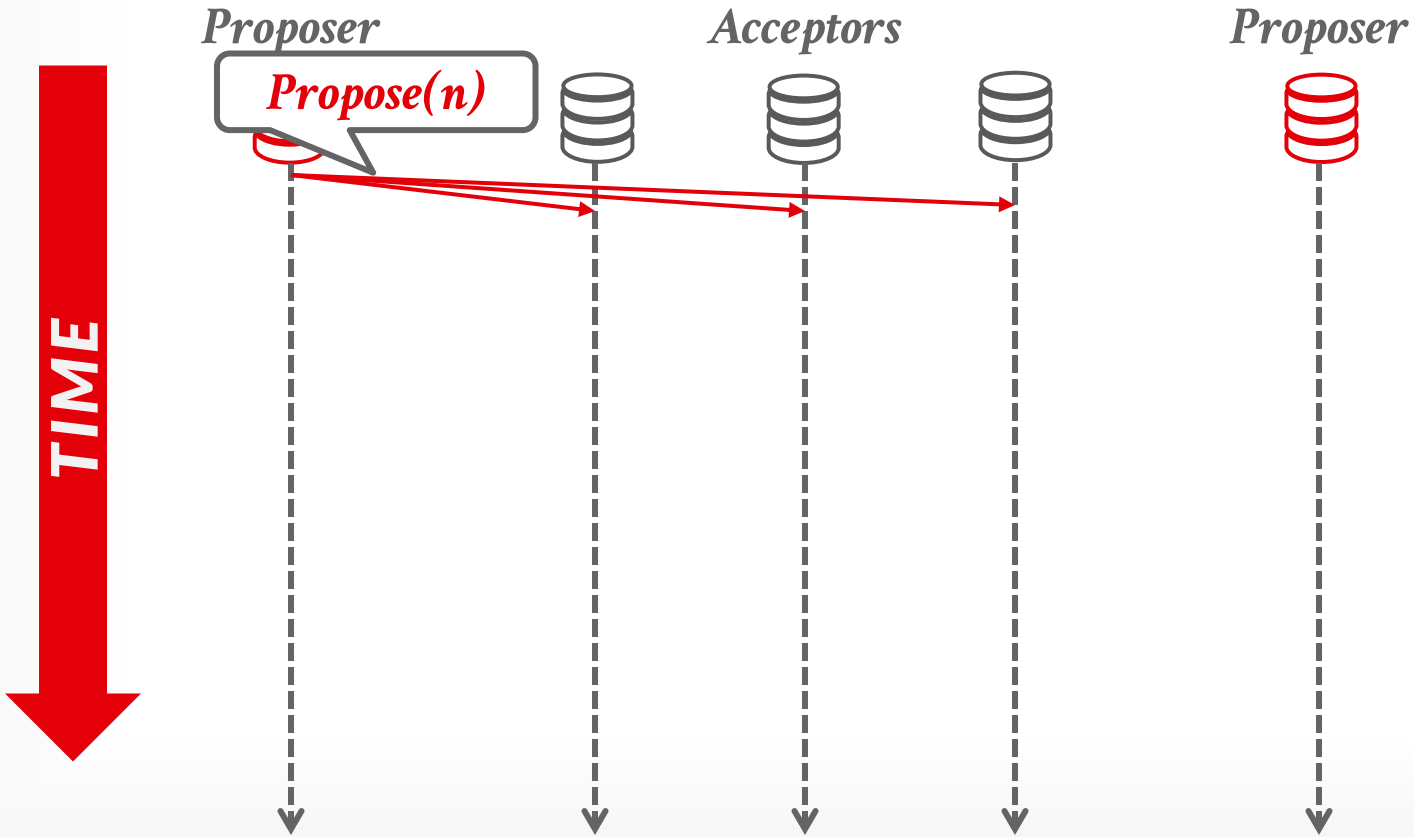

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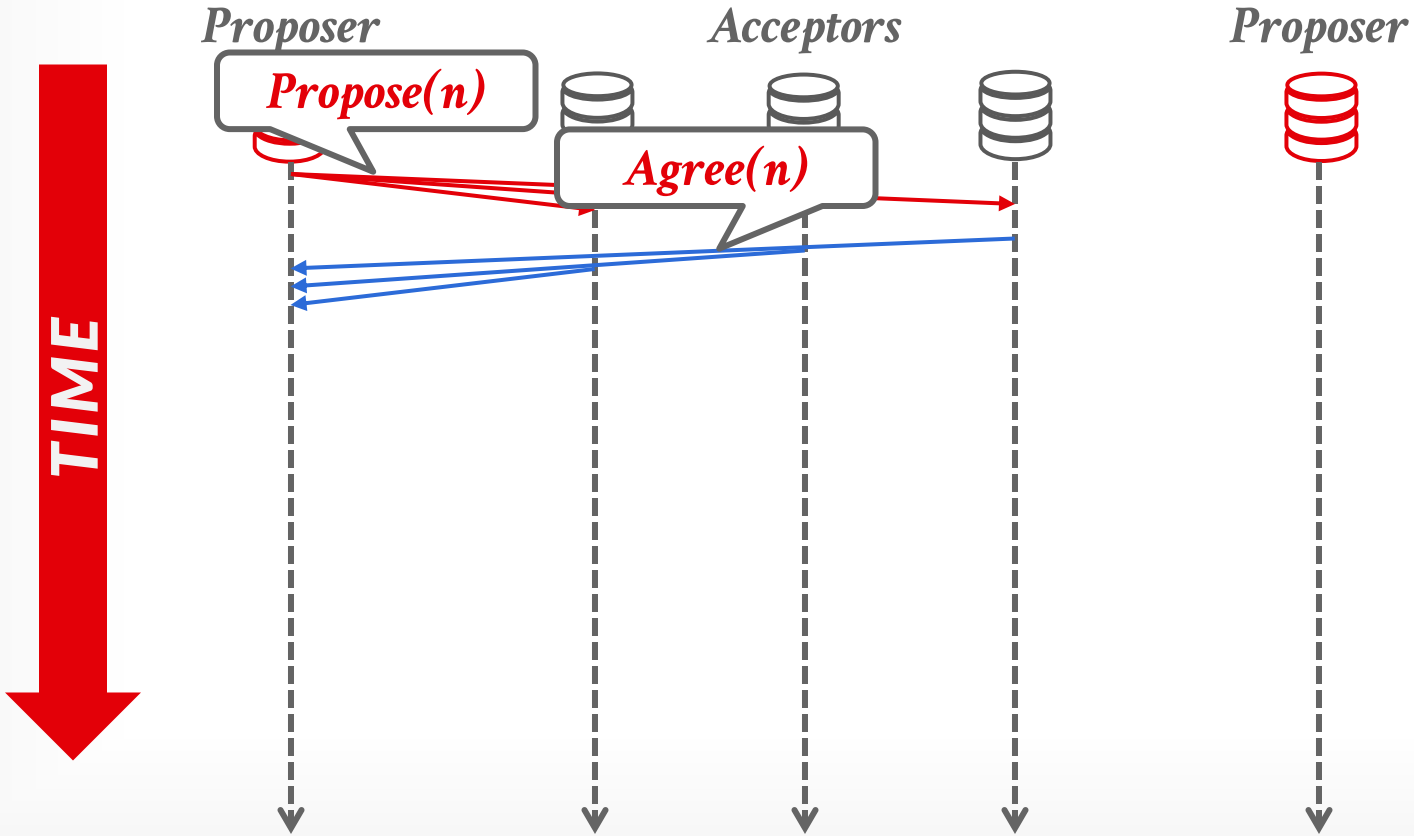

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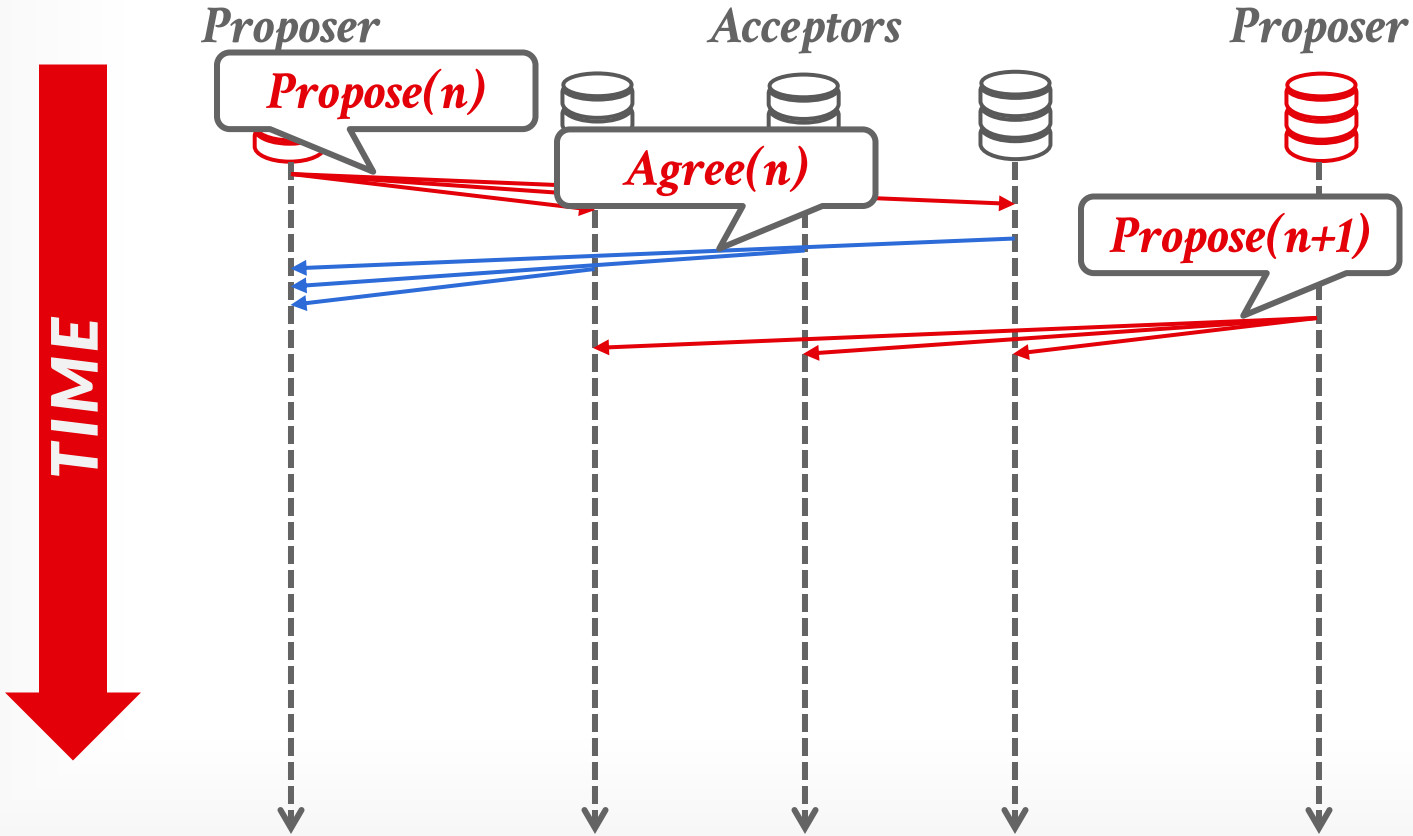
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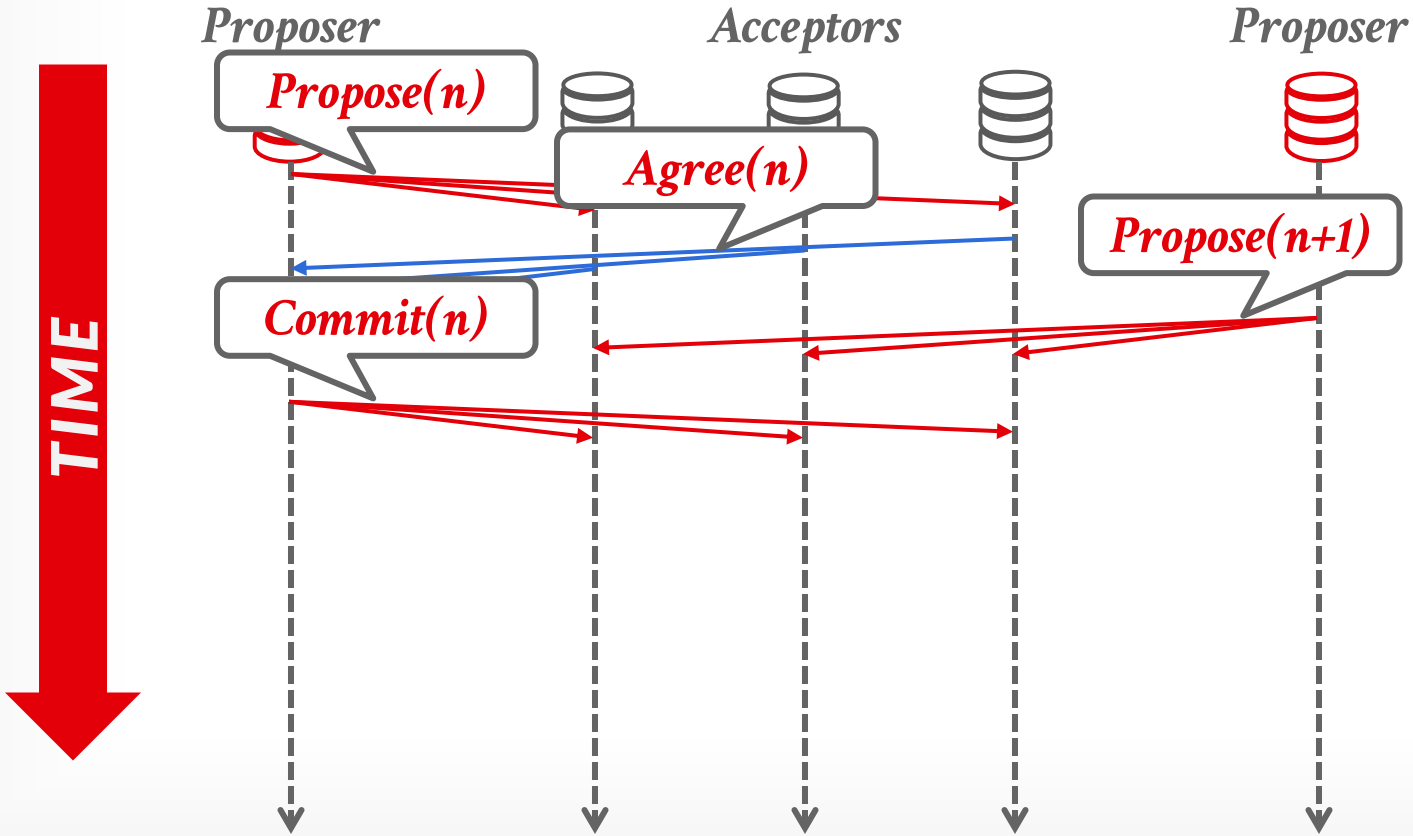
Acceptors
Proposer
Propose(n)
Agree(n)
Propose(n+1)
TIME

PAXOS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Proposer
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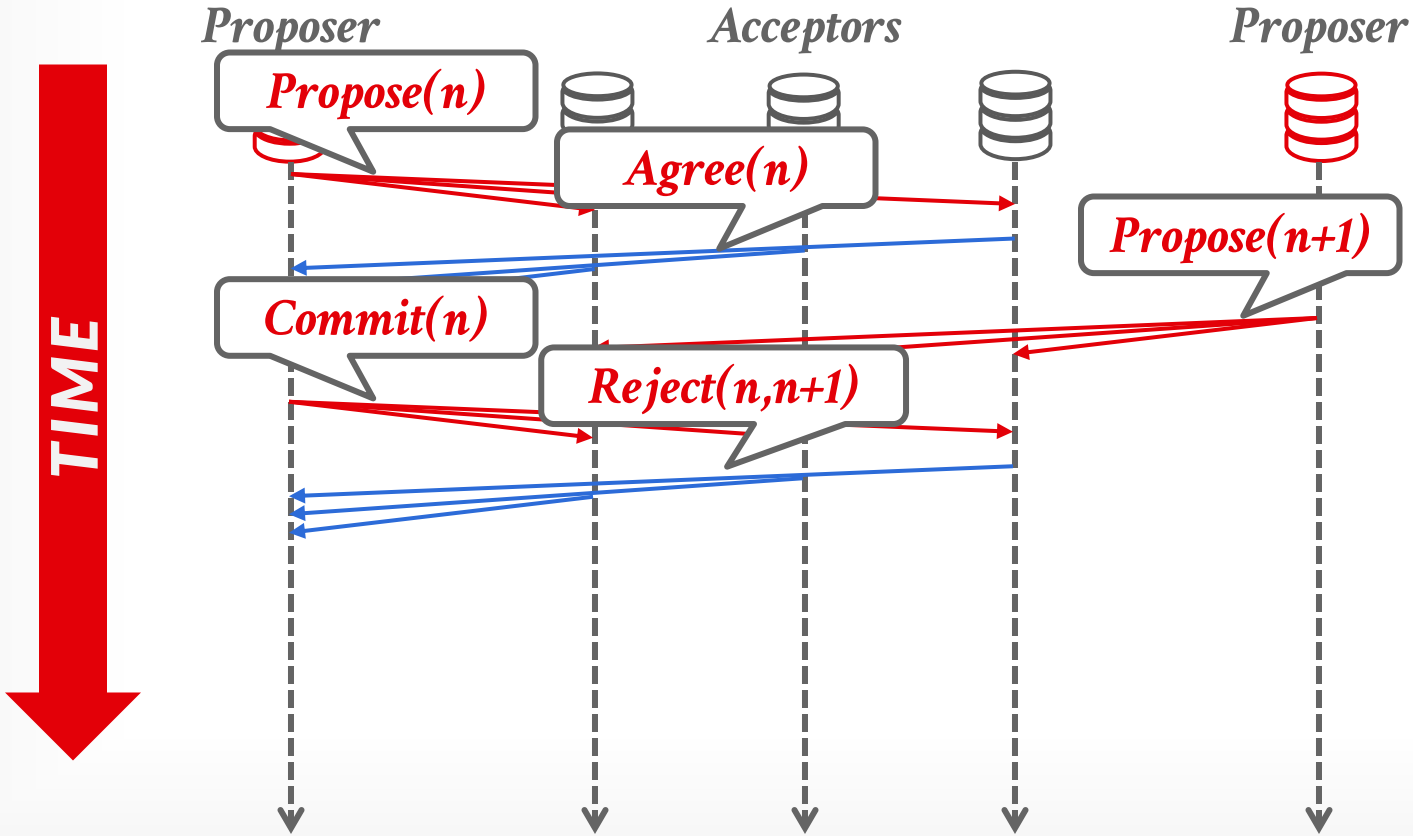
Agree(n)
Propose(n+1)
Commit(n)
TIME

PAXOS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TIME

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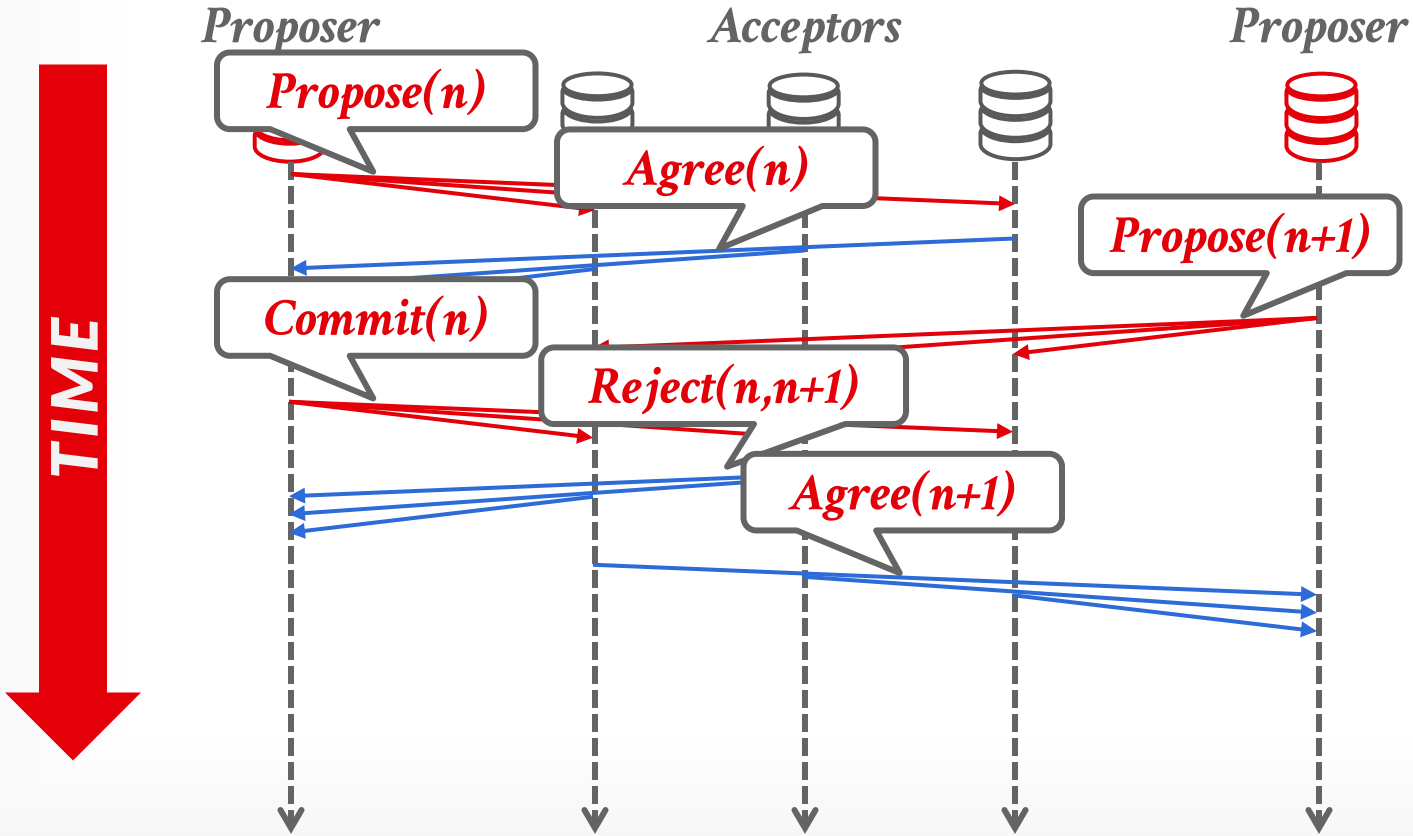
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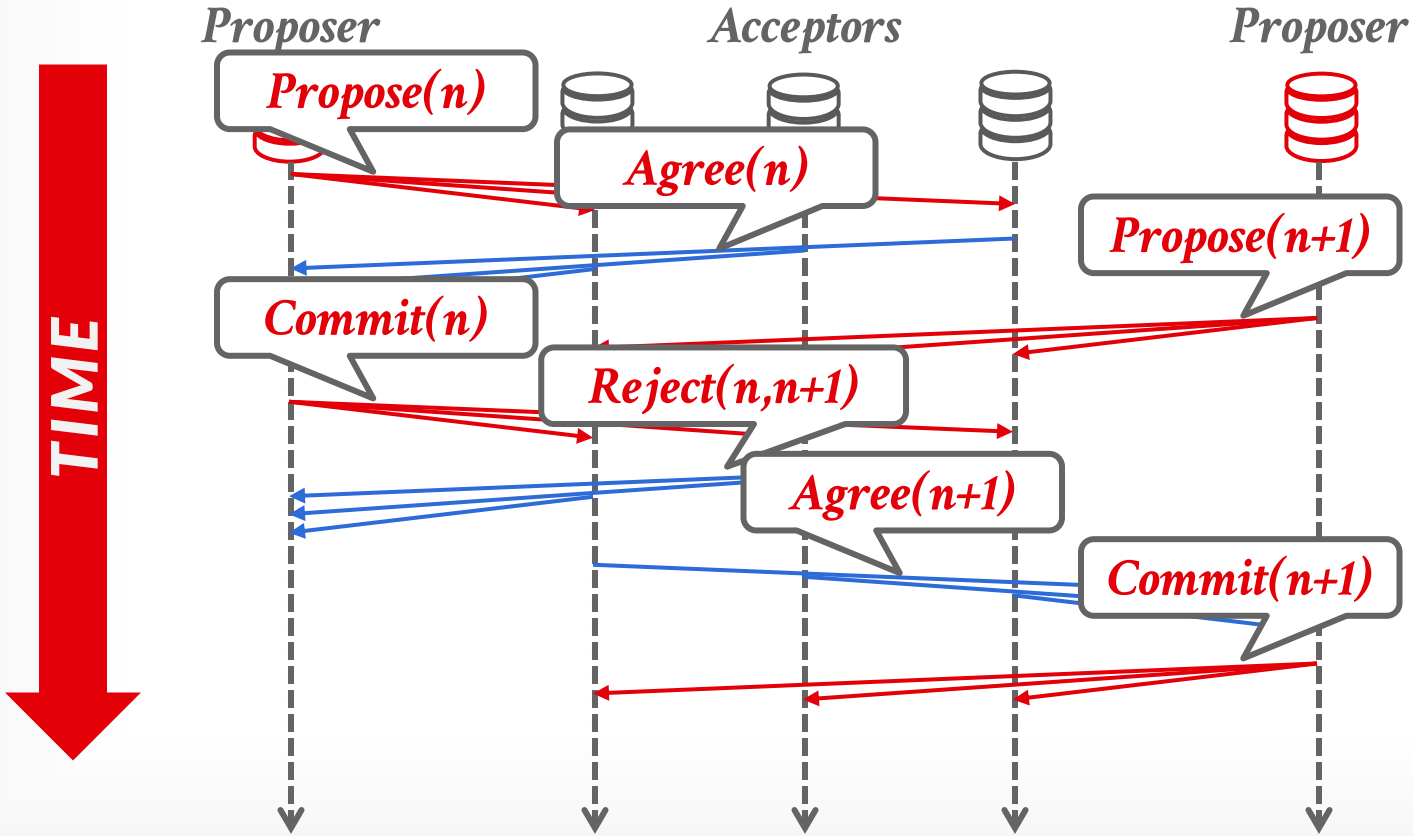
Agree(n+1)
TIME

PAXOS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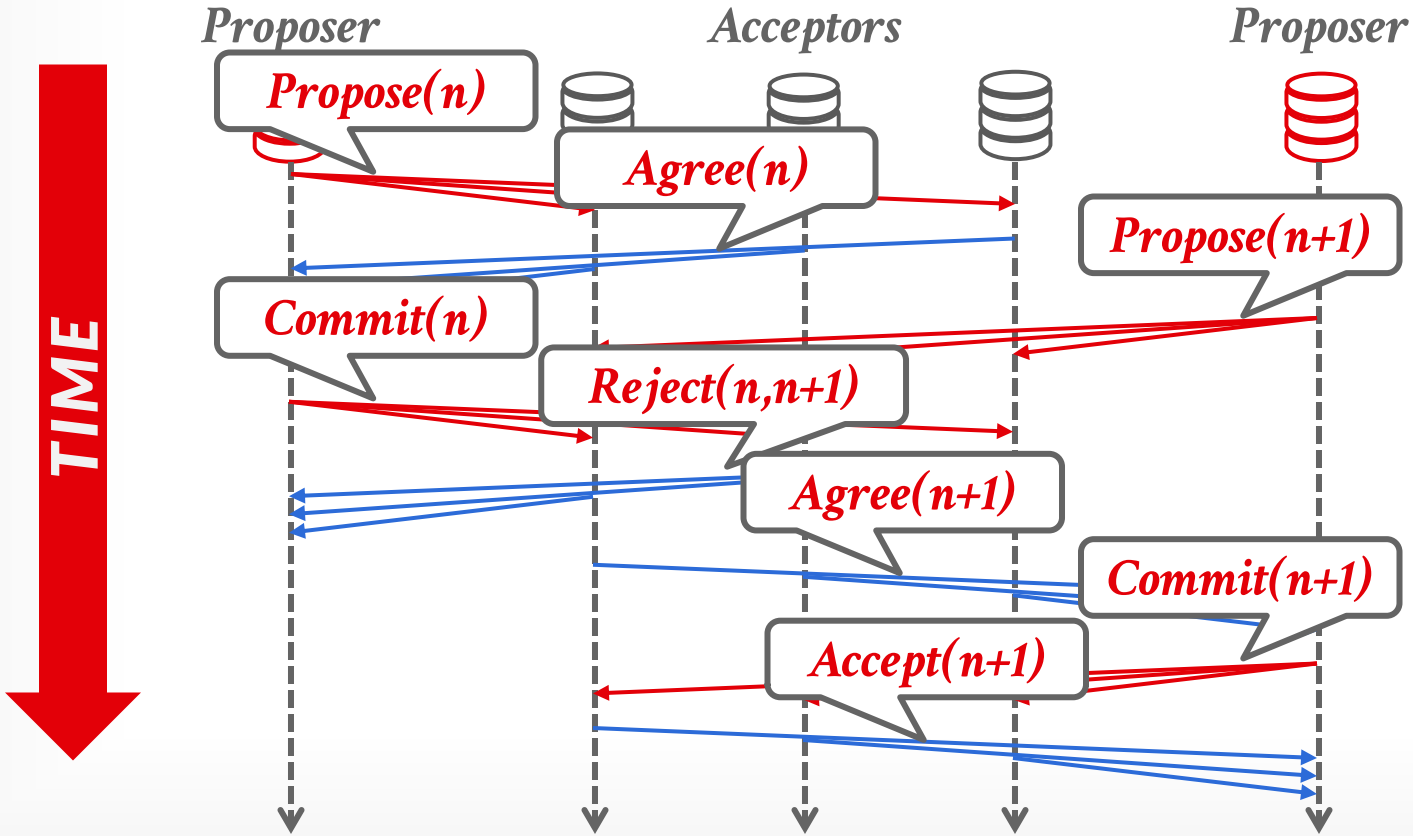
Agree(n+1)
Commit(n+1)
TIME

PAXOS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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.

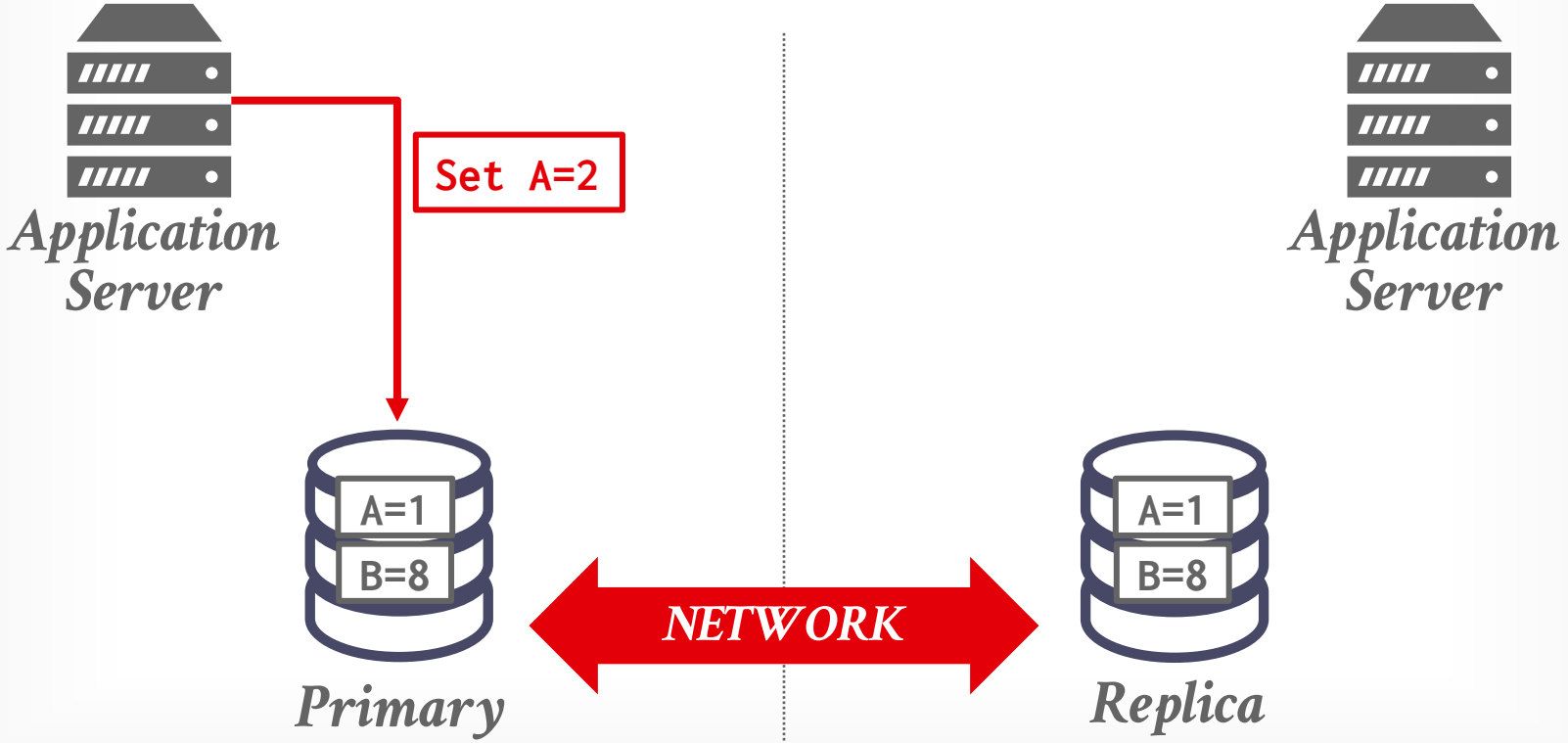
CAP THEOREM

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

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

Whether a DBMS provides **C**onsistency or **A**vailability during a **N**etwork partition.

CONSISTENCY



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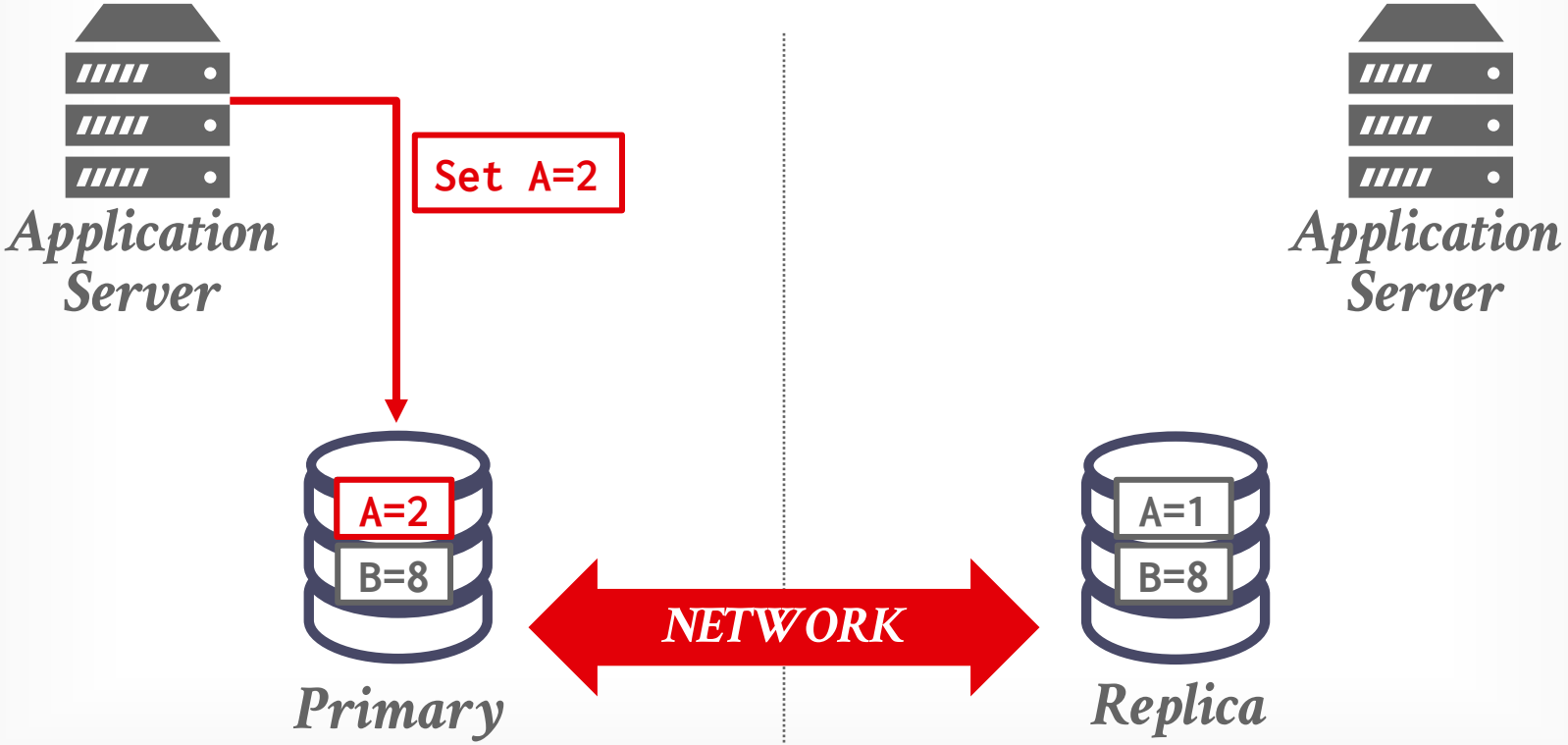

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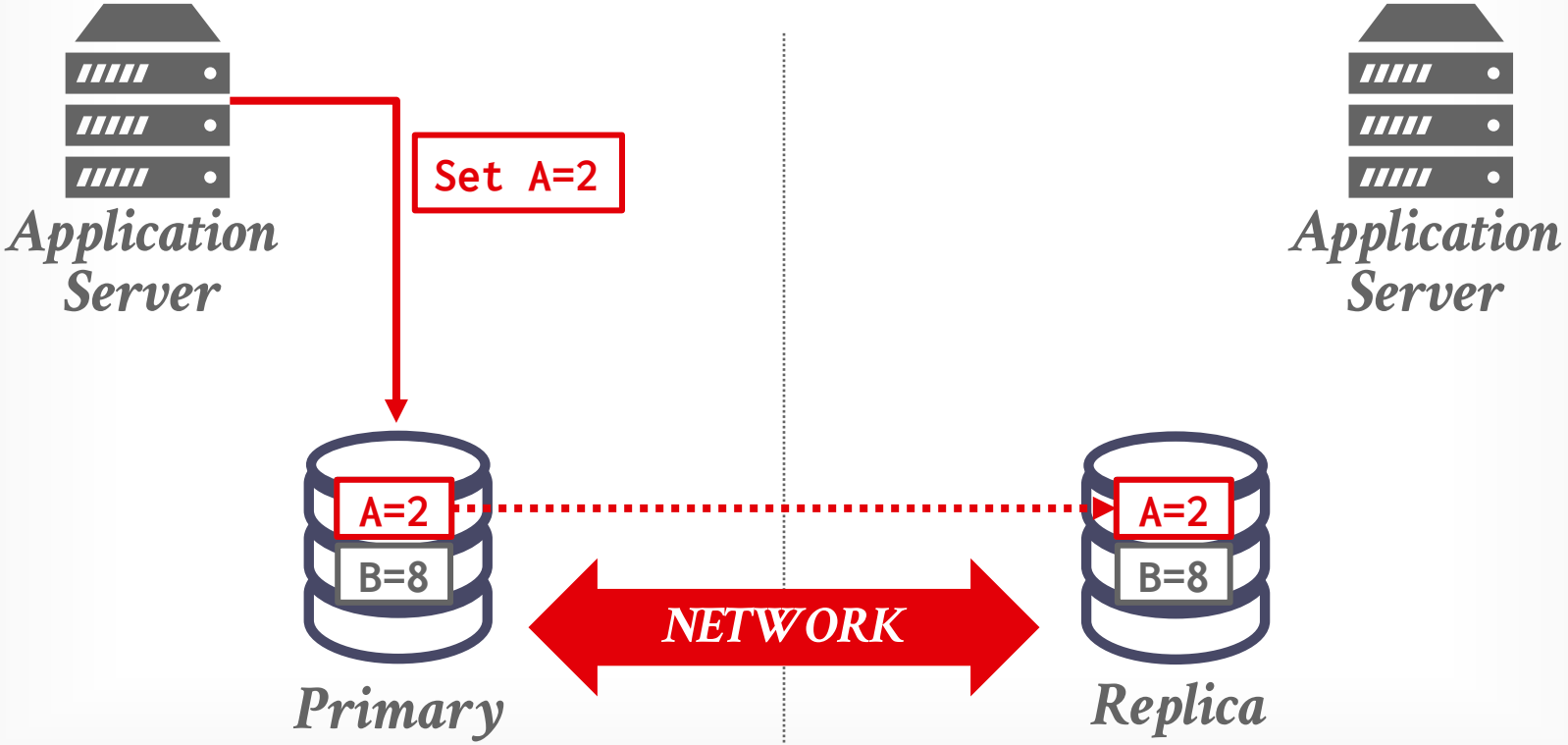

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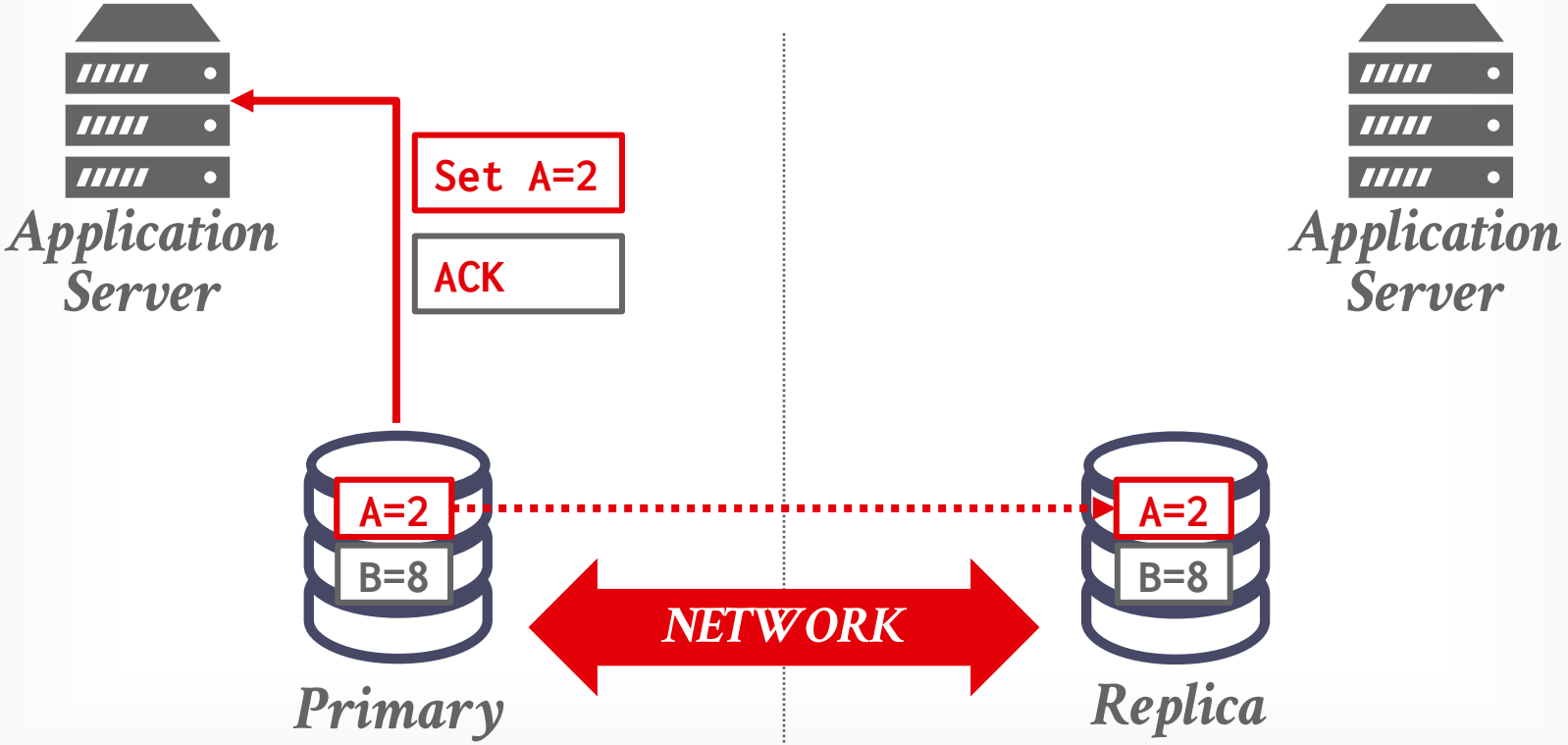

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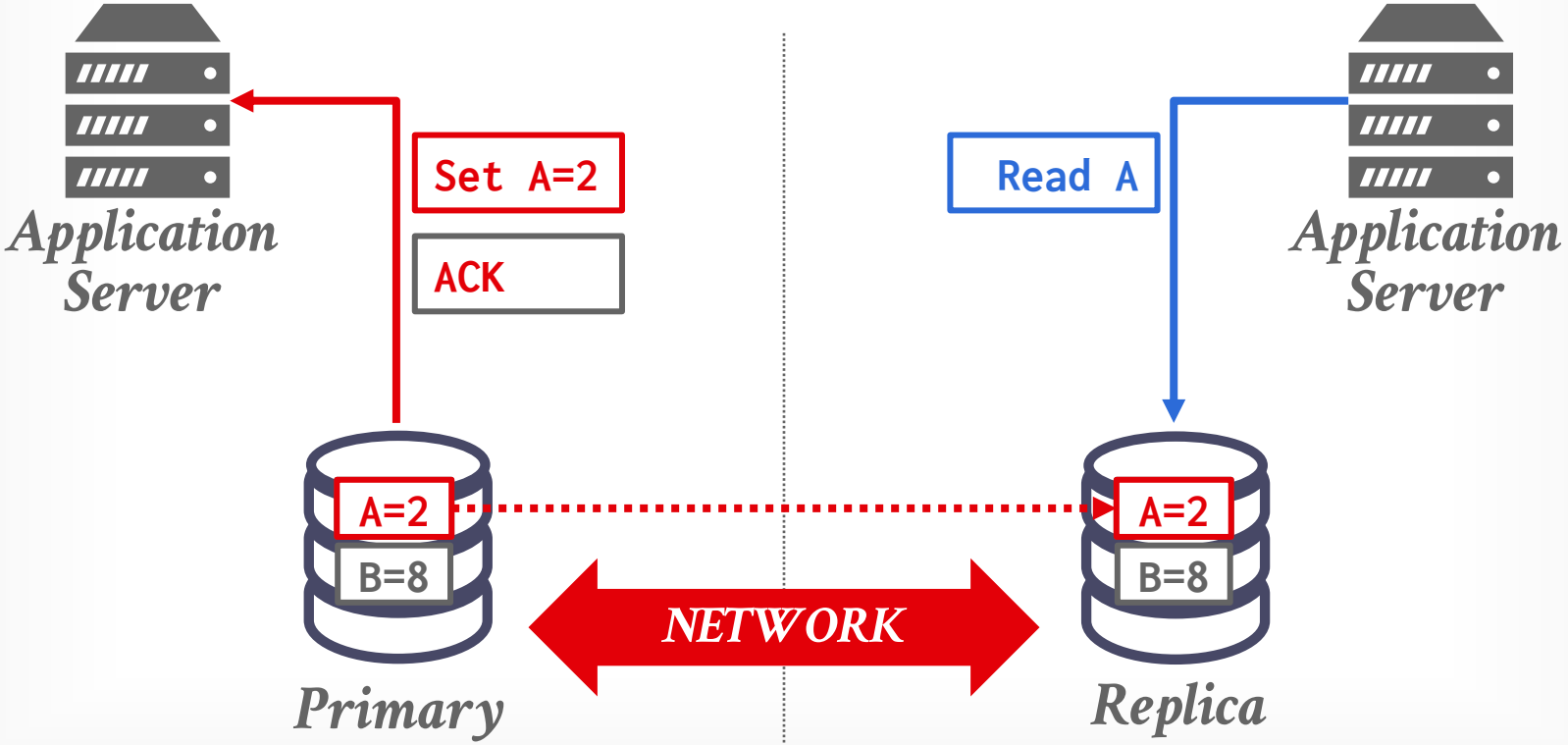

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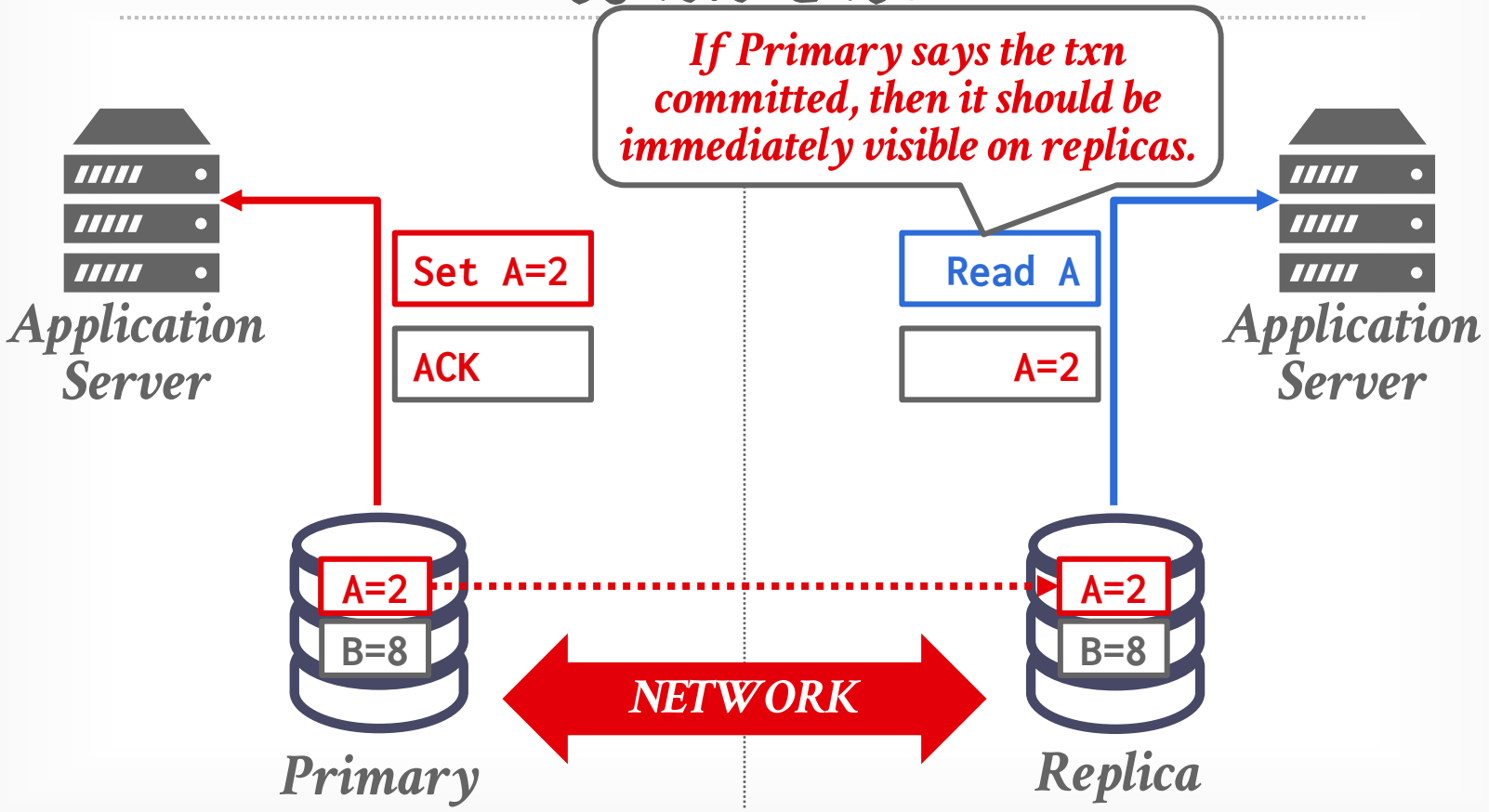
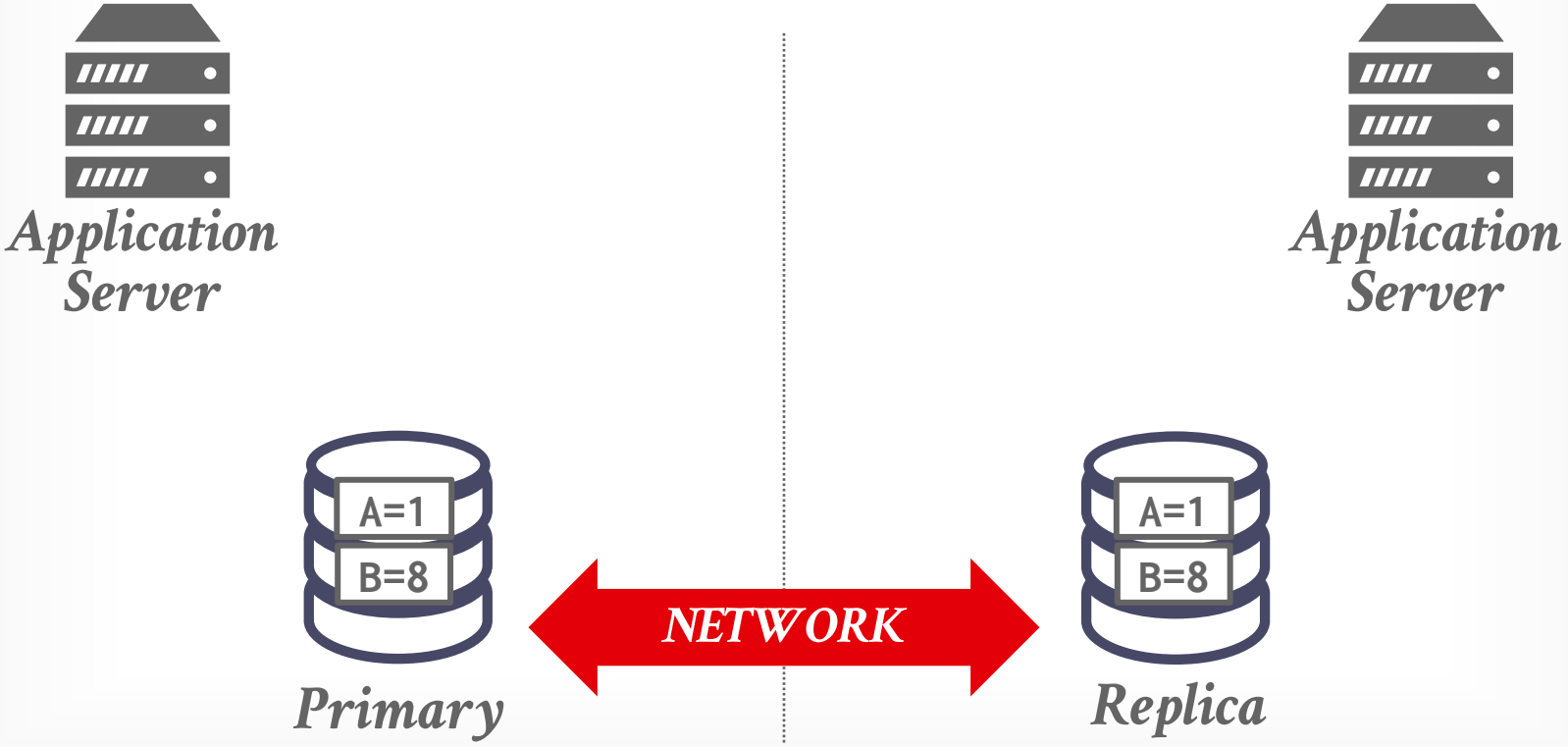
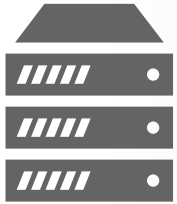


AVAILABILITY



AVAILABILITY

Application Server



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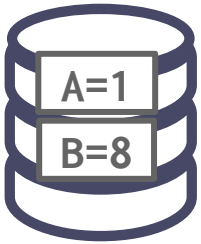
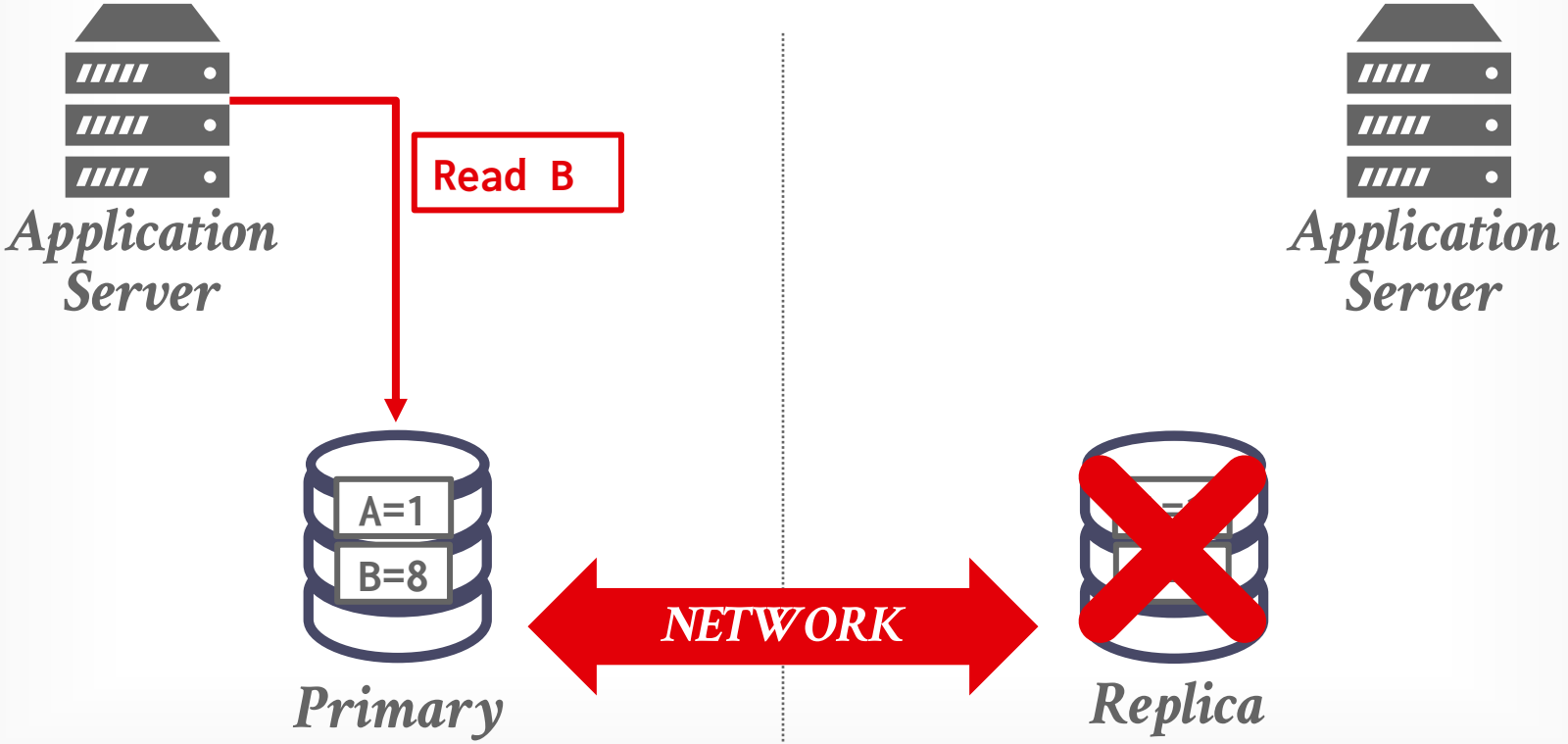


Primary

Replica

AVAILABILITY



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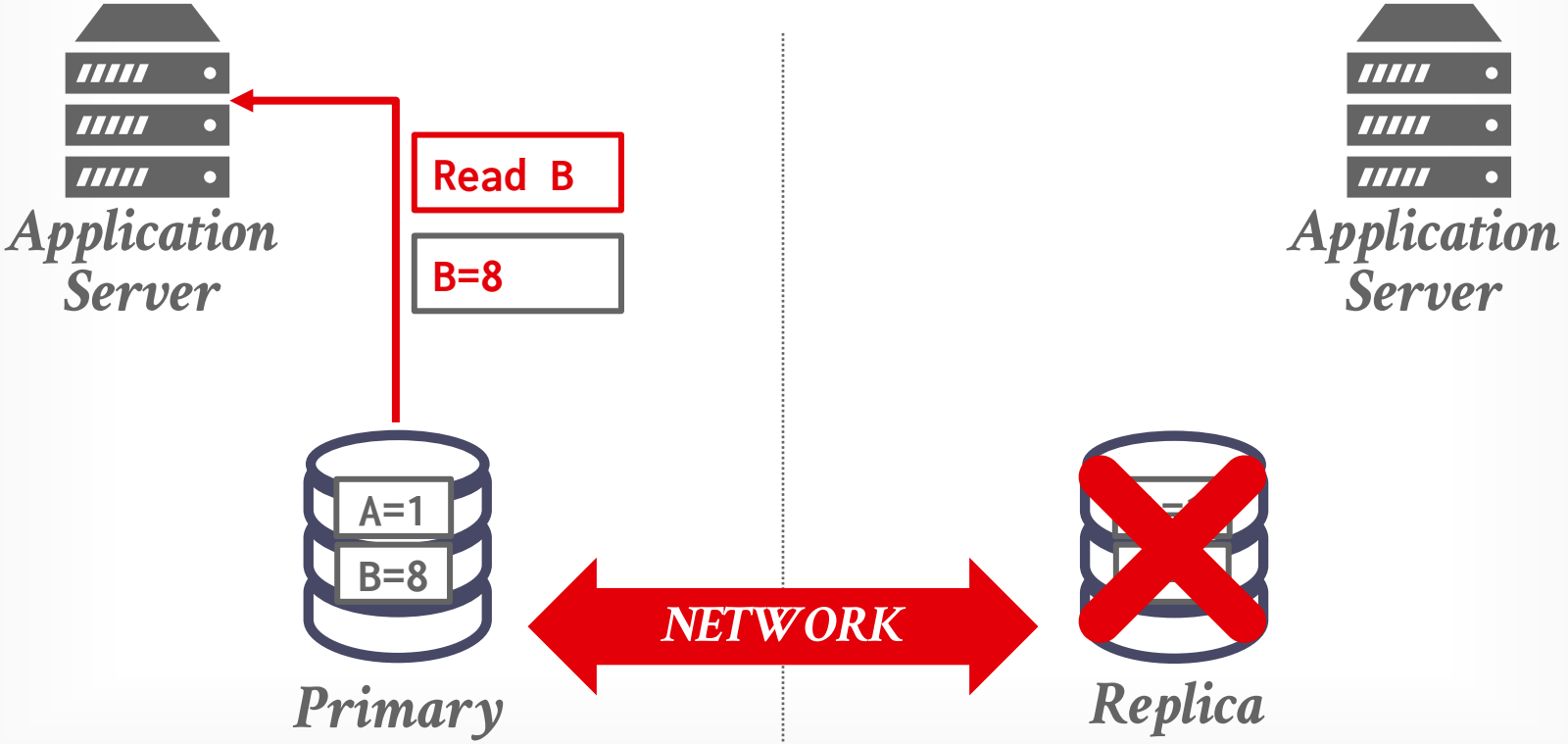
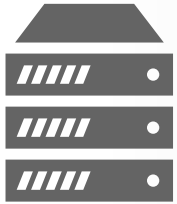


AVAILABILITY

Application Server



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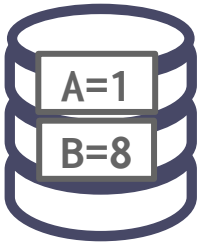
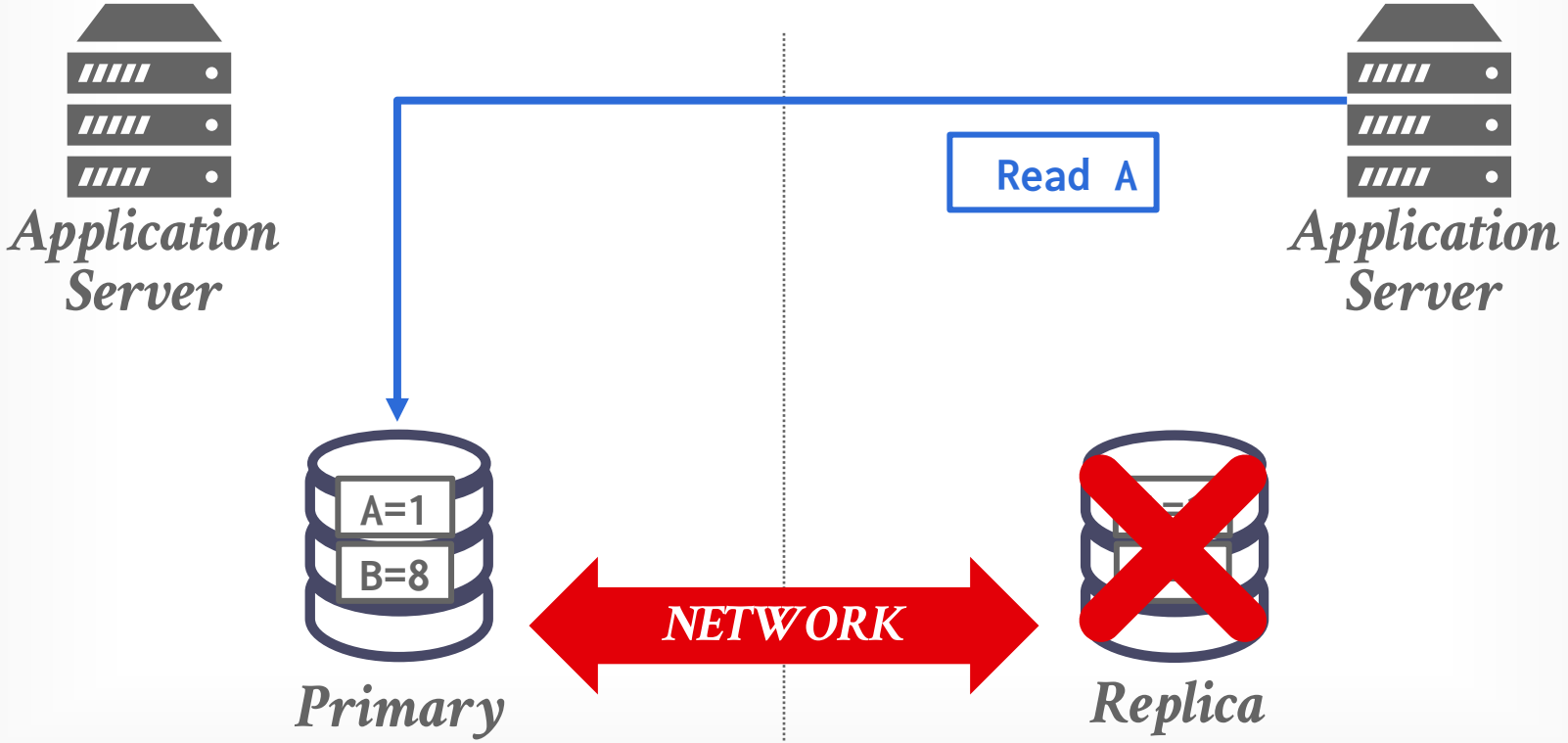


Primary

Replica

AVAILABILITY



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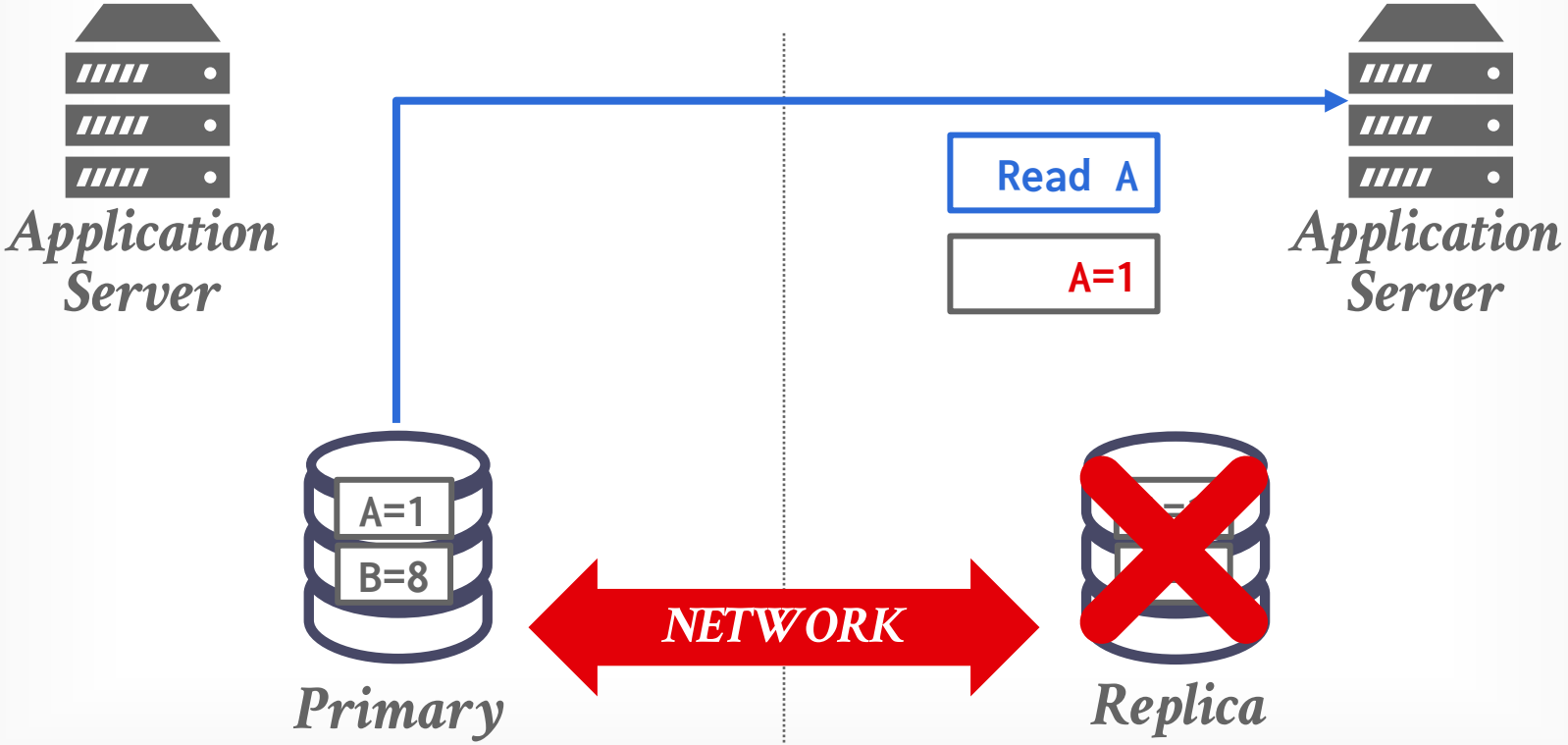

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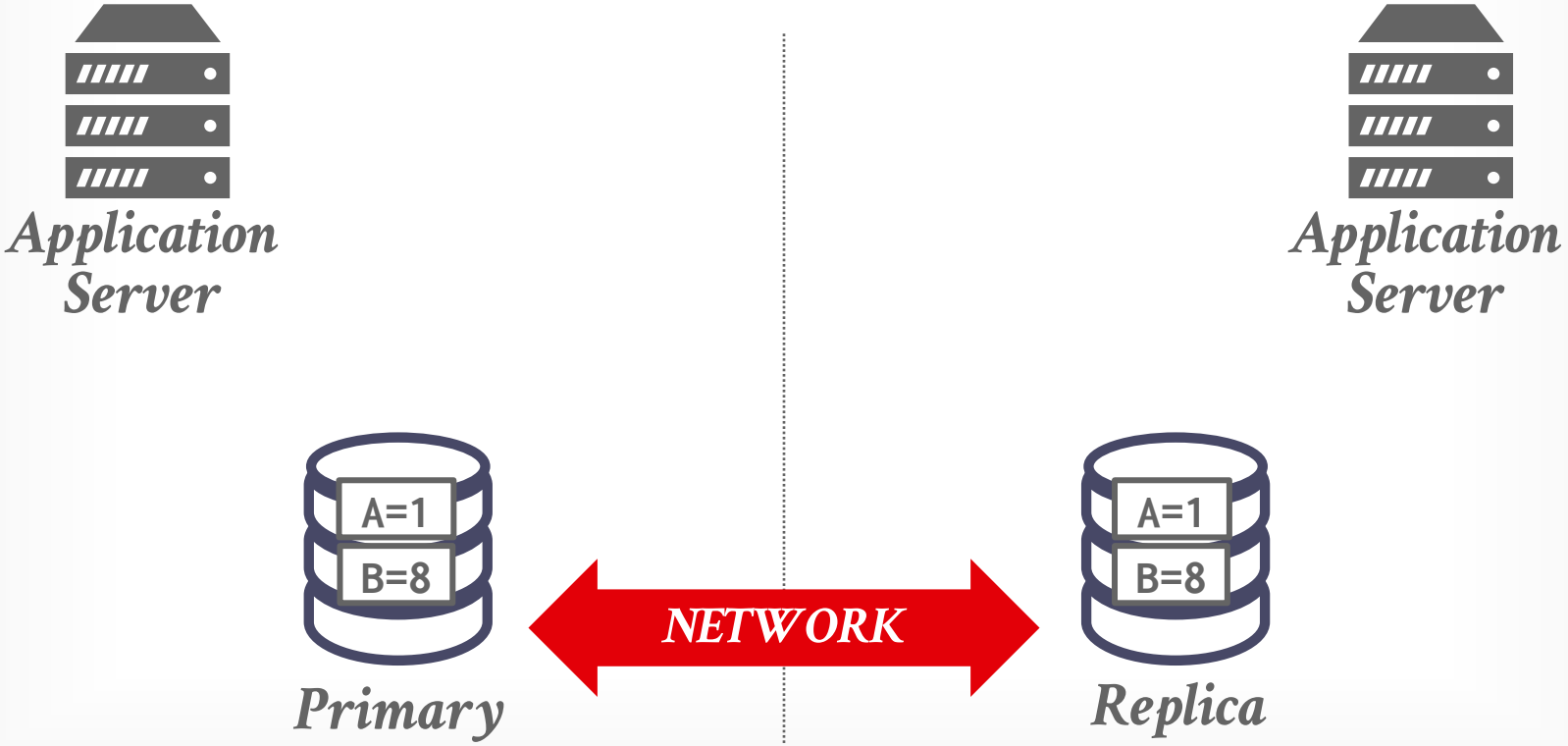

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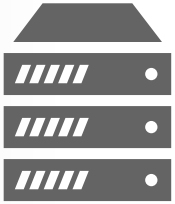

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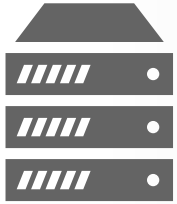

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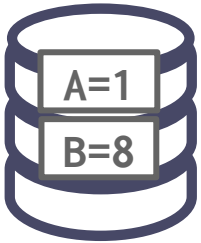

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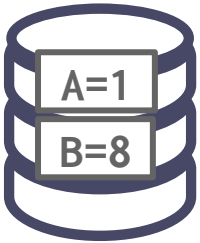

Replica

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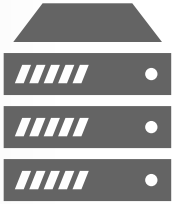

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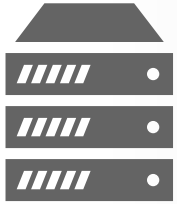

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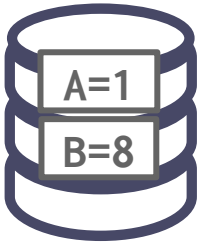

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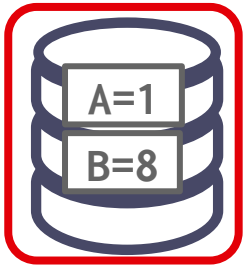

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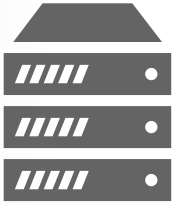

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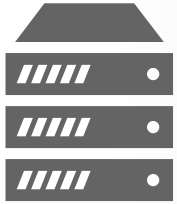

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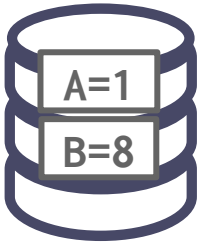

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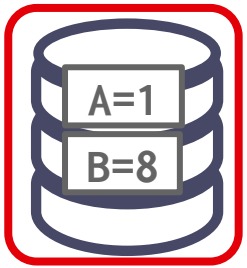

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PARTITION TOLERANCE

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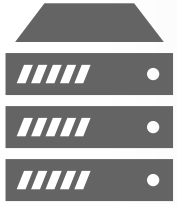

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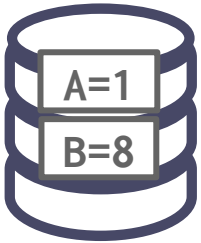

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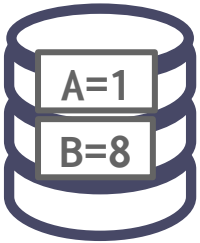

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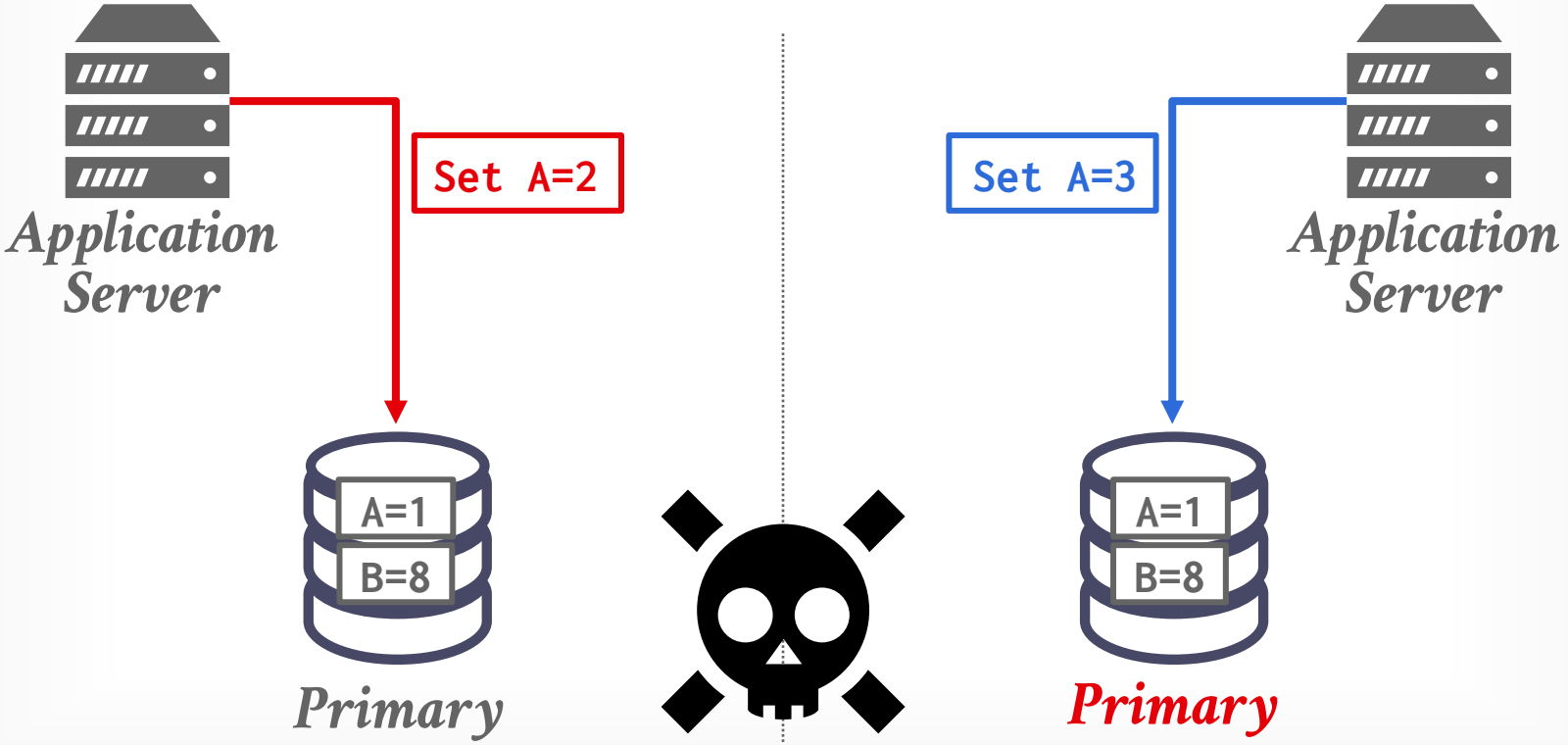

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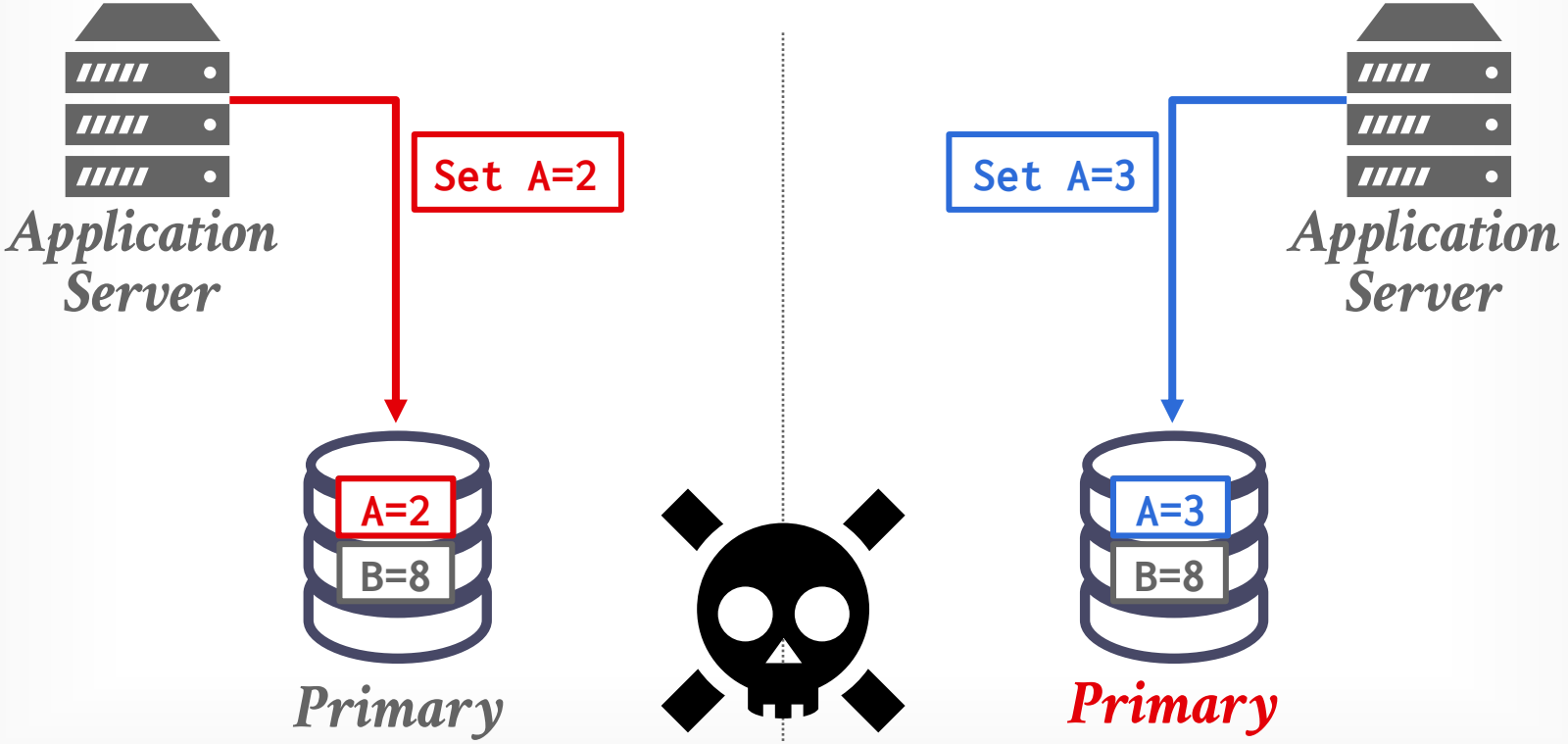

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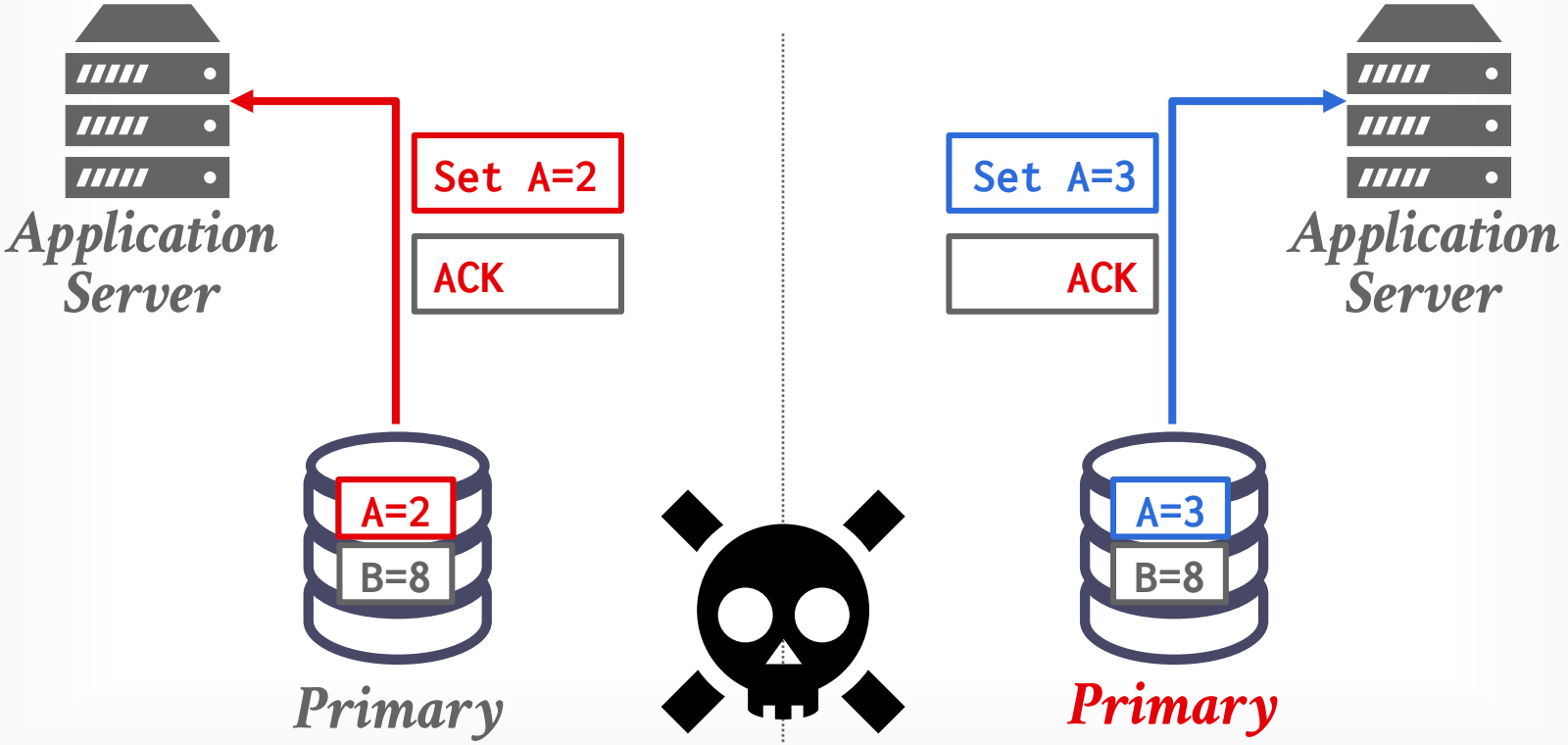

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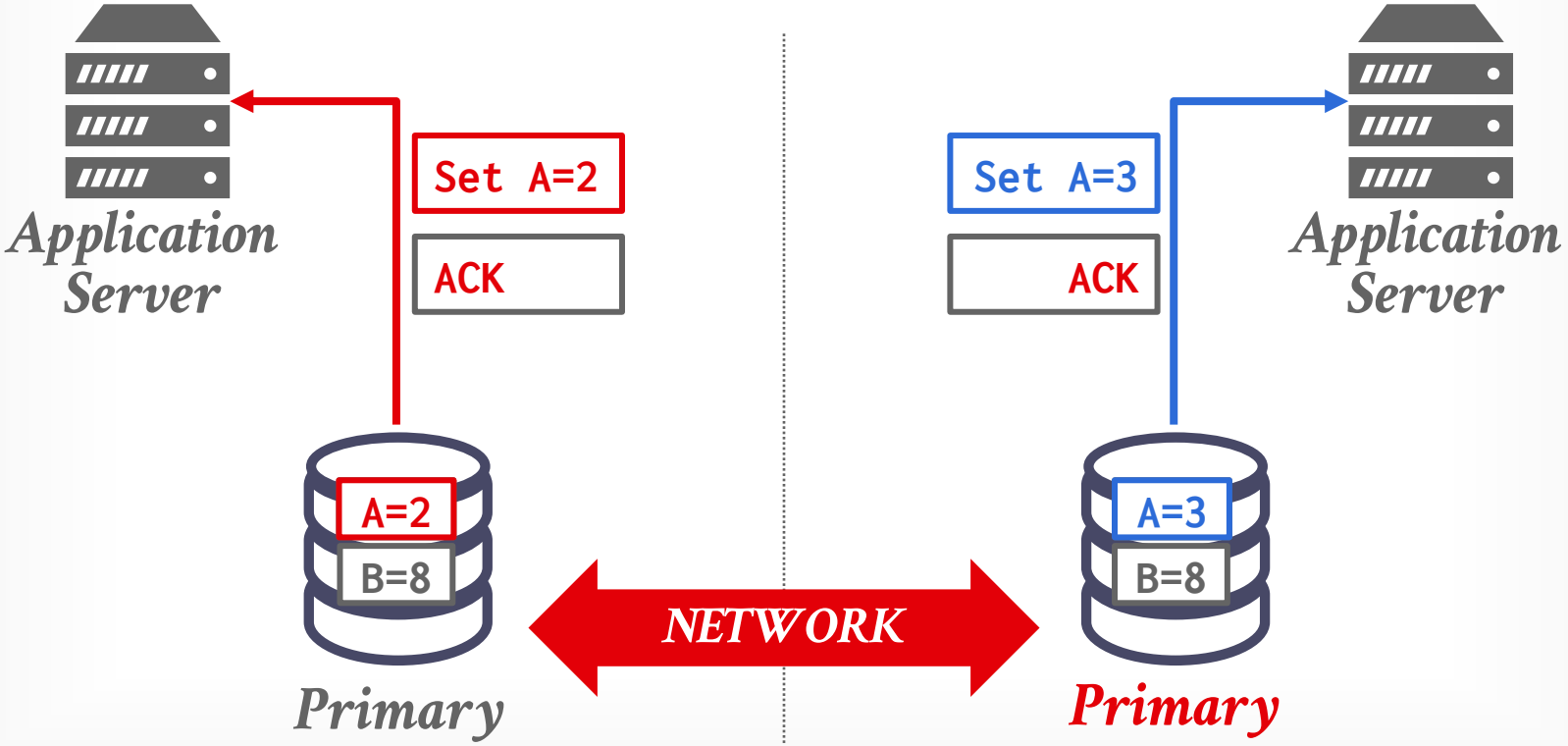

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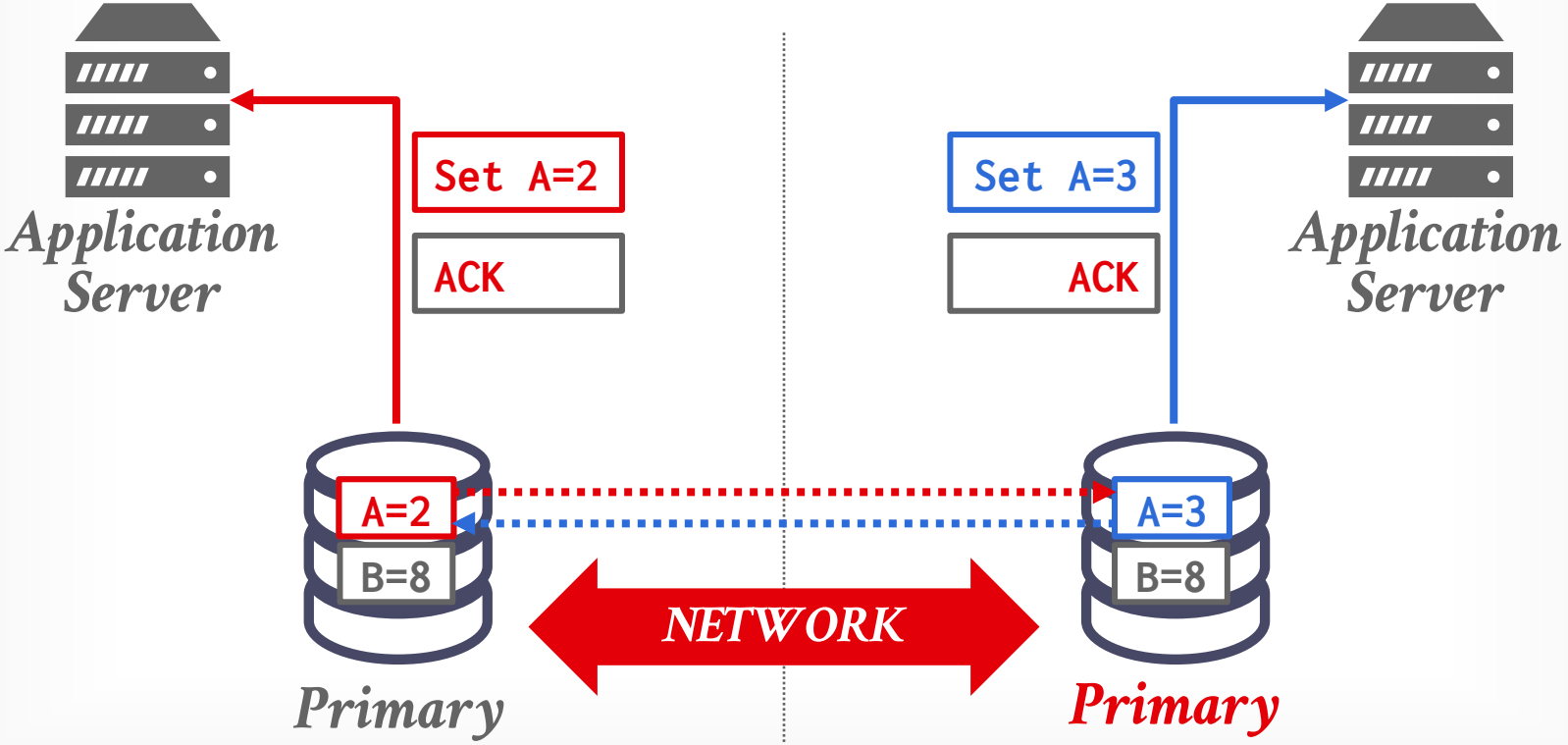


PARTITION TOLERANCE

Choice #1: Halt the System

→ Stop accepting updates in any partition that does not have a majority of the nodes.

Choice #2: Allow Split, Reconcile Changes

→ Allow each side of partition to keep accepting updates.
→ Upon reconnection, perform reconciliation to determine the "correct" version of any updated record
→ Server-side: Last Update Wins
→ Client-side: Vector Clocks

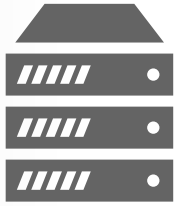
Don't Do This!

PACELC THEOREM

Extension to CAP proposed in 2010 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

LATENCY VS. CONSISTENCY



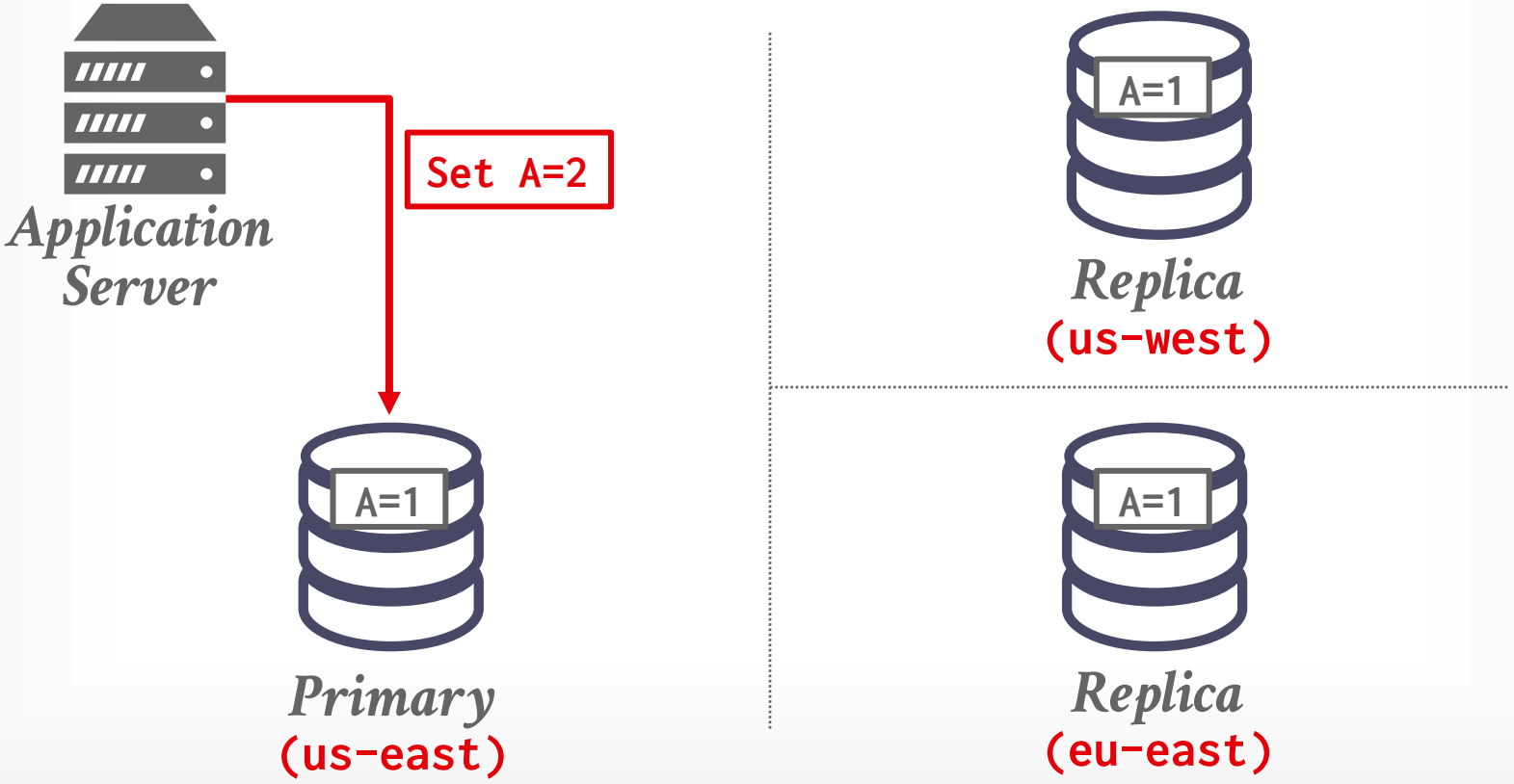
Application Server

Replica
(us-west)

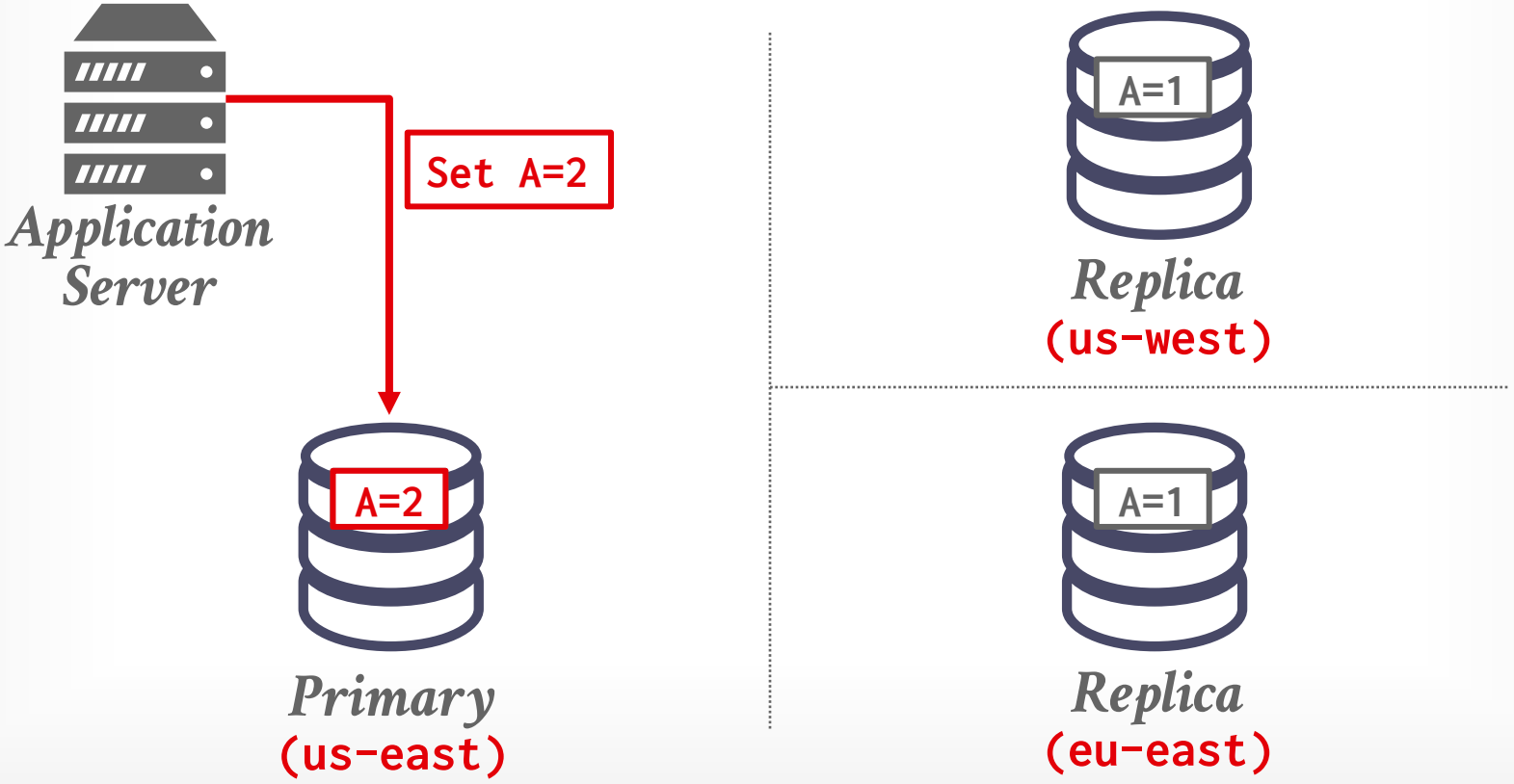
Primary
(us-east)

Replica
(eu-east)

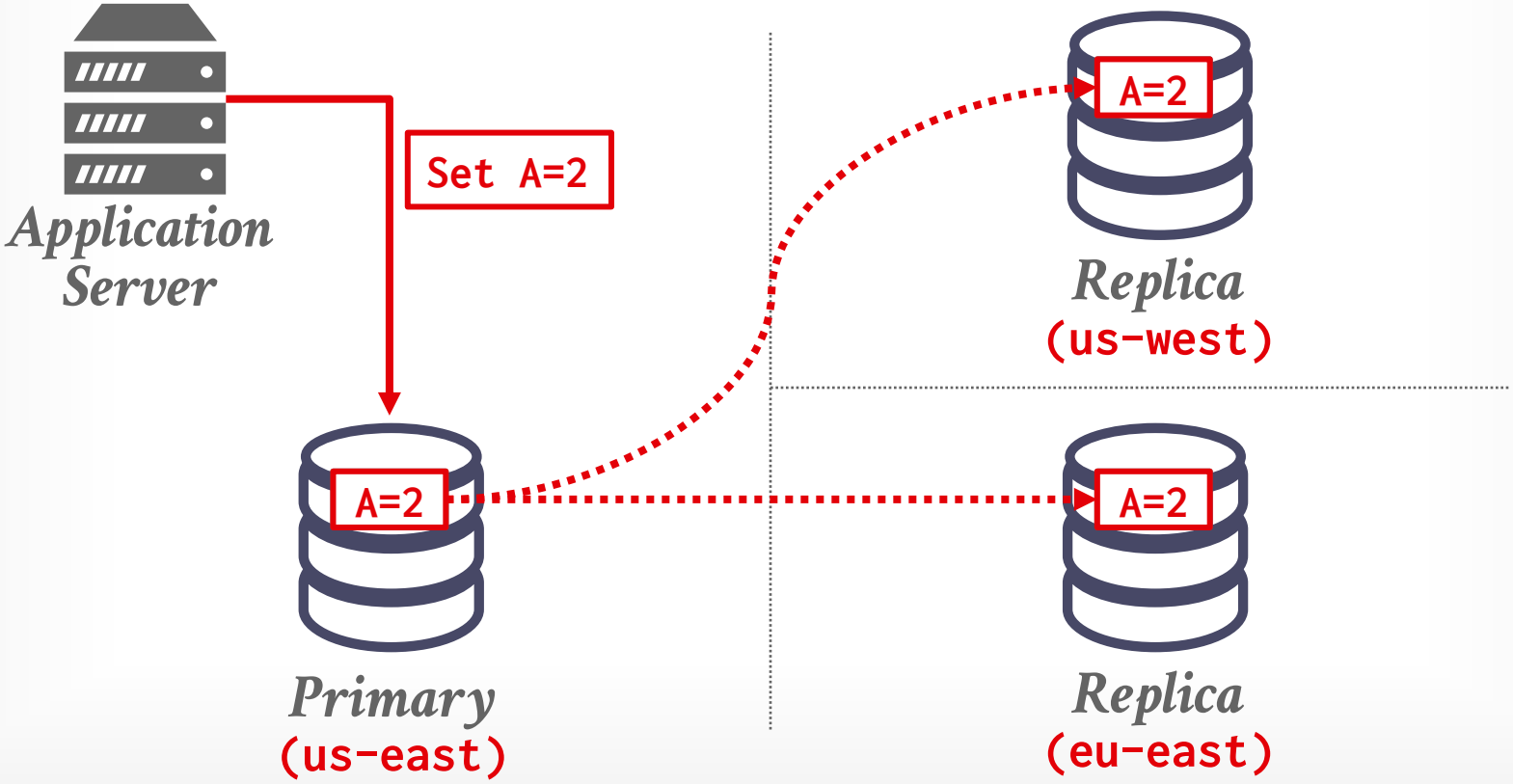
LATENCY VS. CONSISTENCY



LATENCY VS. CONSISTENCY



LATENCY VS. CONSISTENCY



LATENCY VS. CONSISTENCY

Application Server

Primary
(us-east)

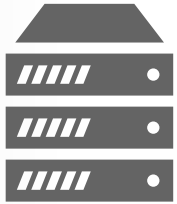
ACK

Replica
(us-west)

ACK

Replica
(eu-east)

LATENCY VS. CONSISTENCY



Application

Trade-off between how long to wait for acknowledgements and the latency of the DBMS.

Primary
(us-east)

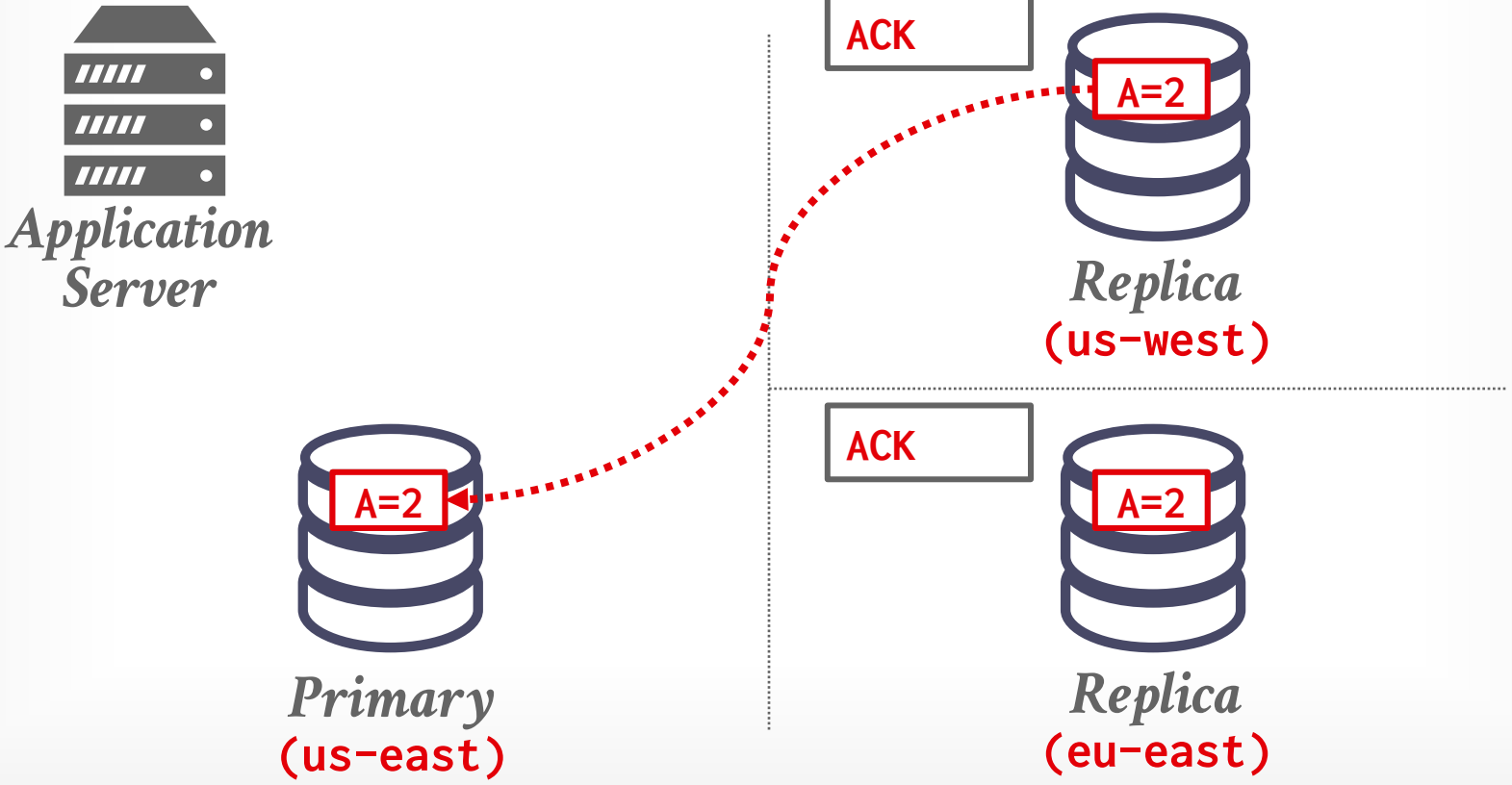
ACK

Replica
(us-west)

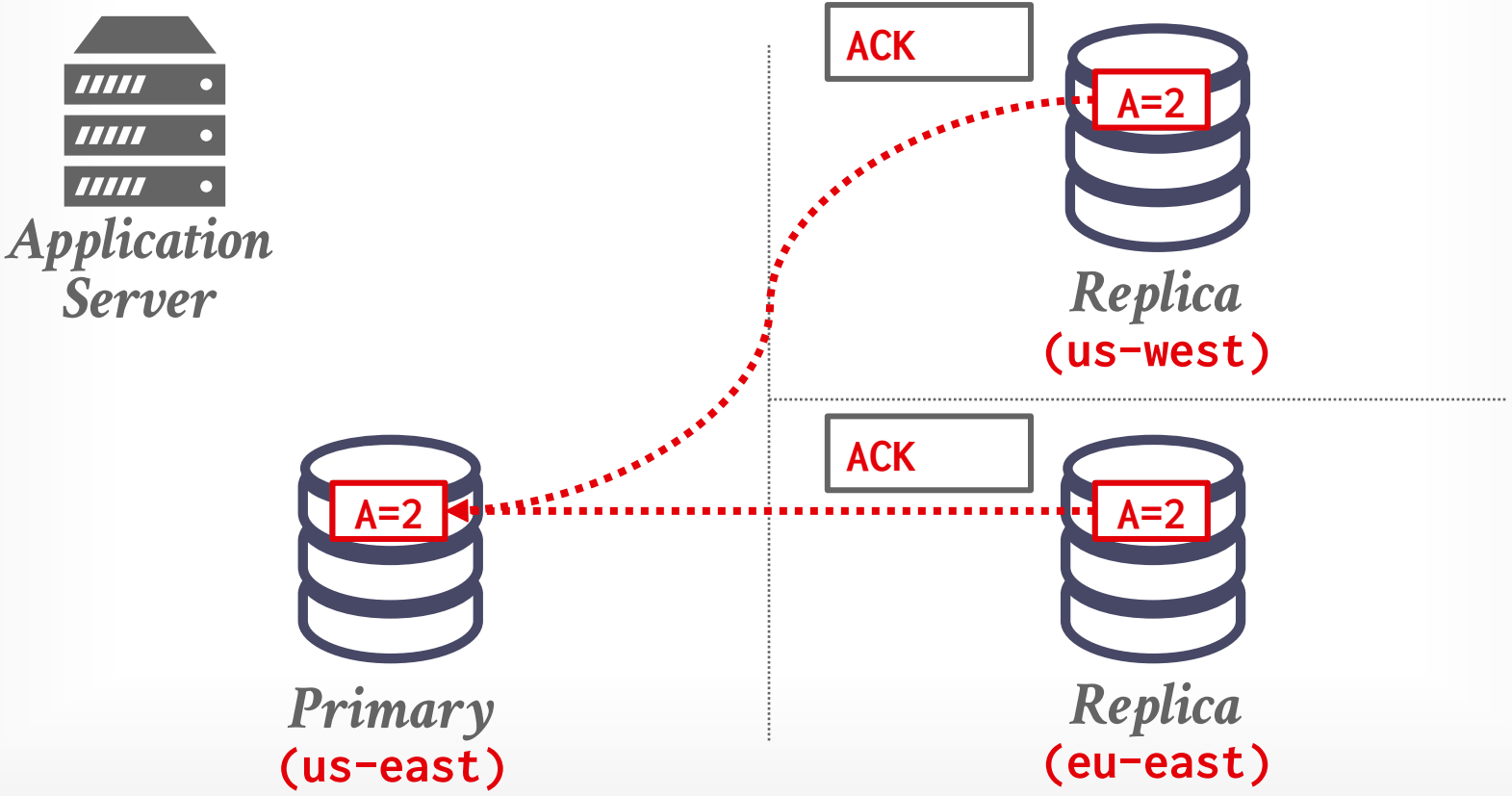
ACK

Replica
(eu-east)

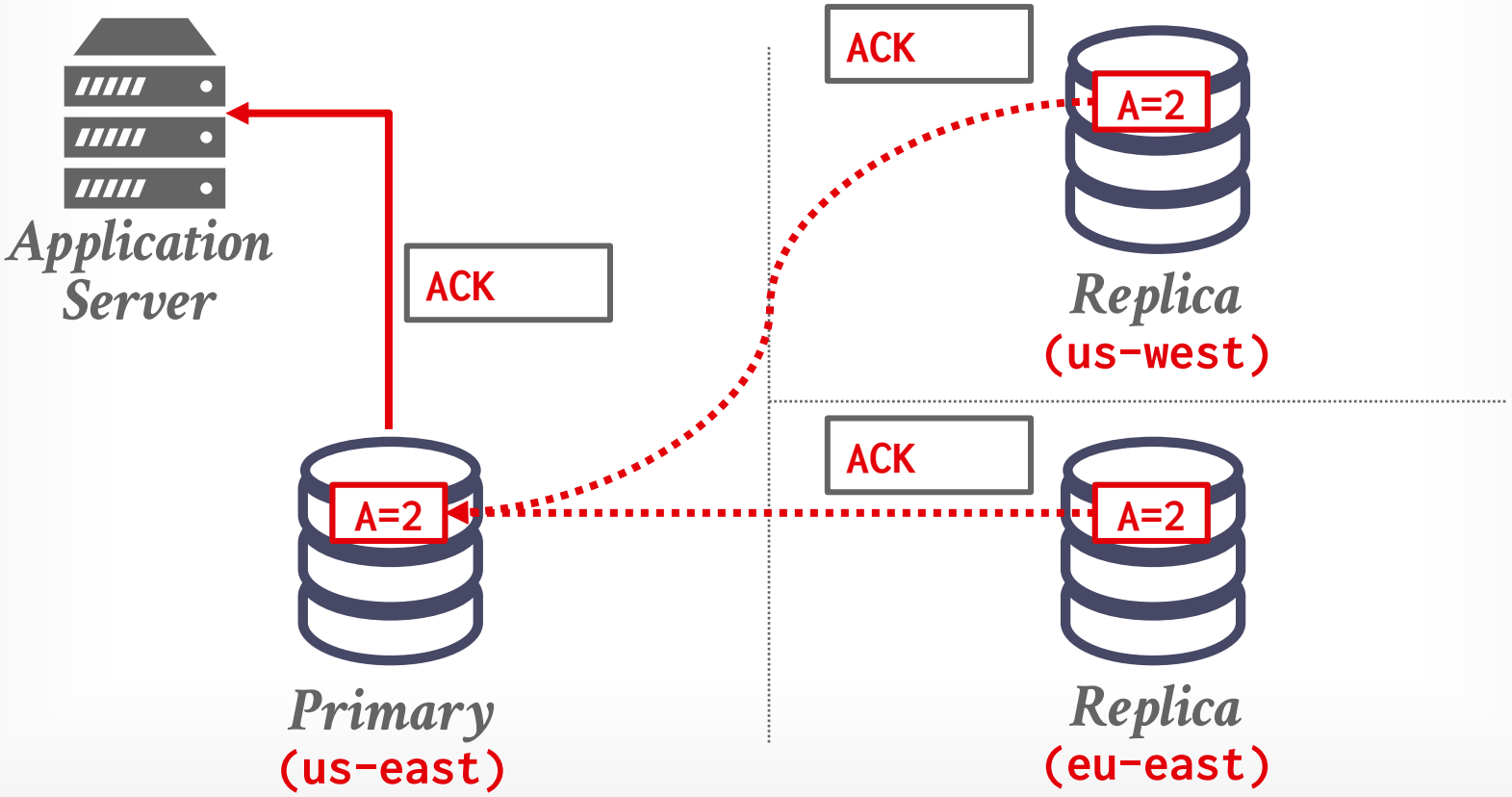
LATENCY VS. CONSISTENCY



LATENCY VS. CONSISTENCY



LATENCY VS. CONSISTENCY



OBSERVATION

The efficiency of a distributed join depends on the target tables' partitioning schemes.

One approach is to put entire tables on a single node and then perform the join.

→ You lose the parallelism of a distributed DBMS.

→ Costly data transfer over the network.

DISTRIBUTED JOIN ALGORITHMS

To join tables **R** and **S**, the DBMS needs to get the proper tuples on the same node.

Once the data is at the node, the DBMS then executes the same join algorithms that we discussed earlier in the semester.

→ Need to produce the correct answer as if all the data is located in a single node system.

SCENARIO #1

The entire copy of one data set is replicated at every node.
→ Think of it as a small dimension table.

Each node joins its local data in parallel and then sends their results to a coordinating node.

```
SELECT * FROM R JOIN S
  ON R.id = S.id
```

SCENARIO #1

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→ Think of it as a small dimension table.

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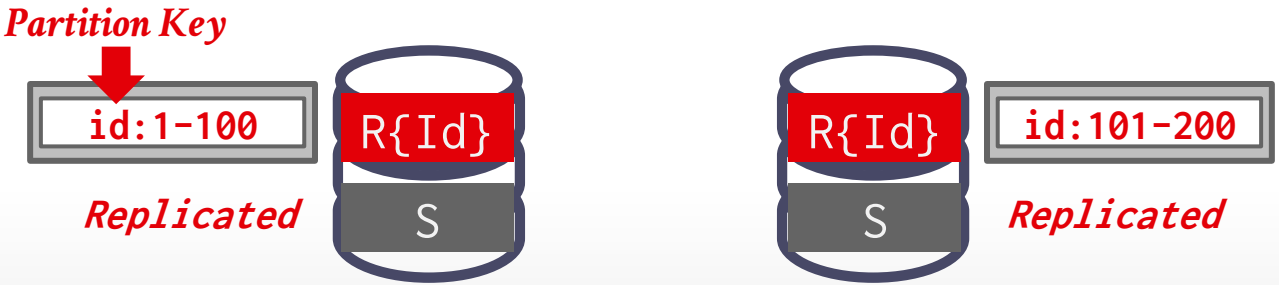

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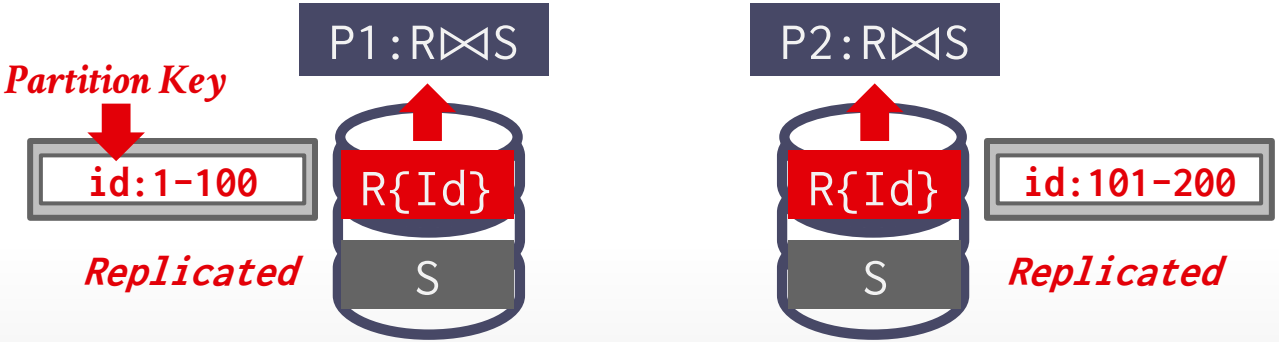

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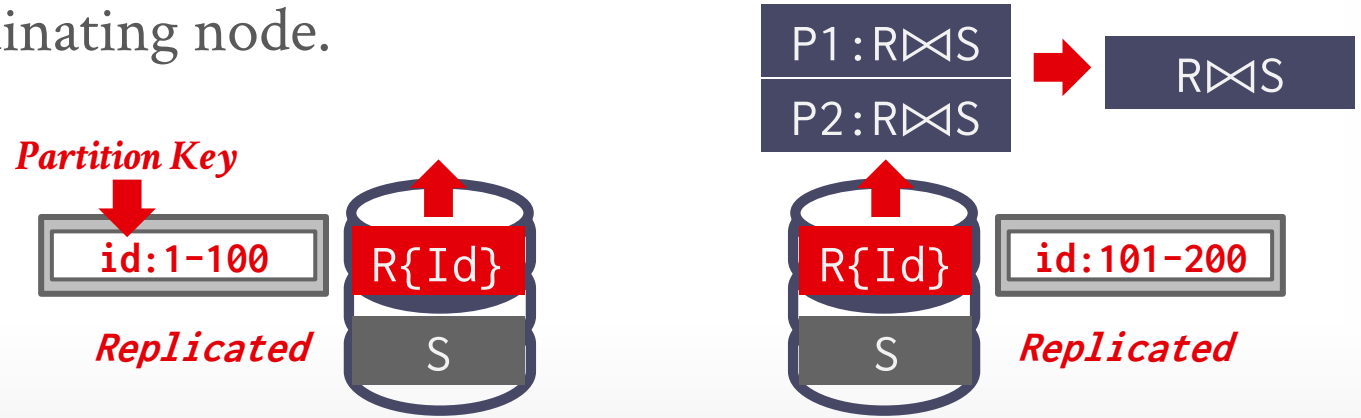

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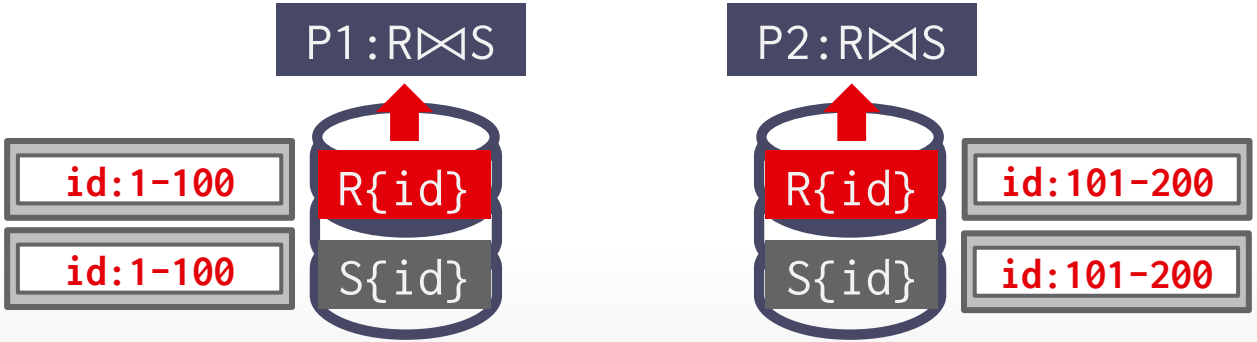

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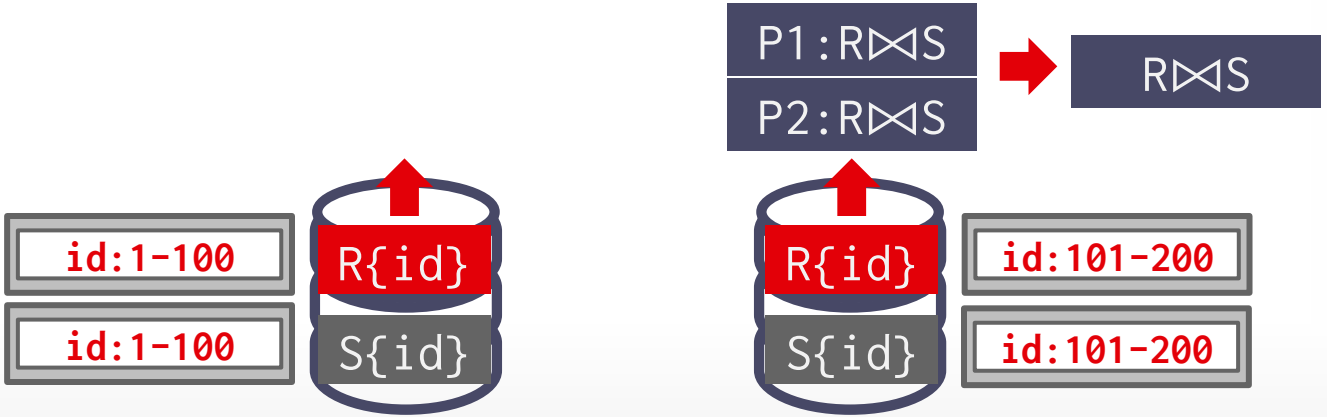

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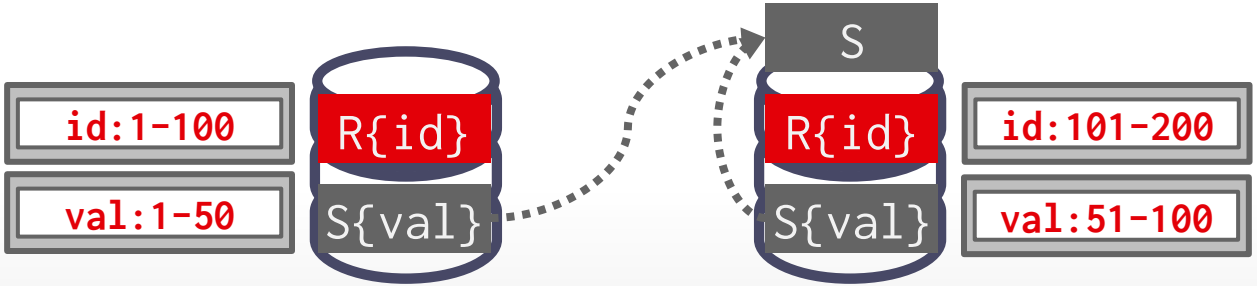

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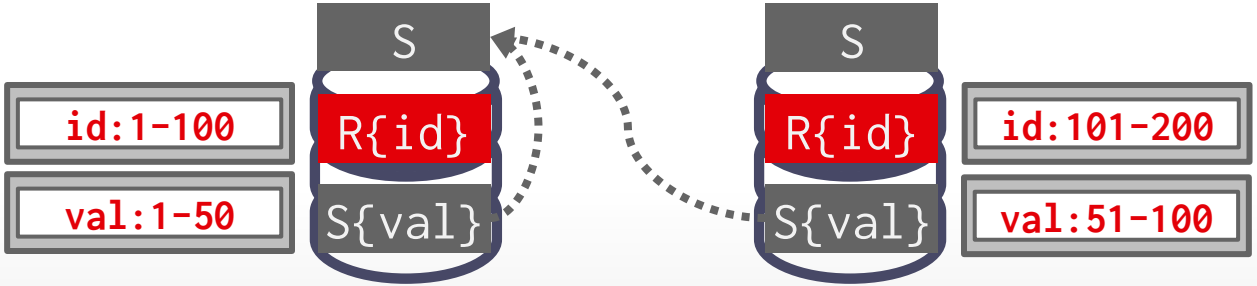

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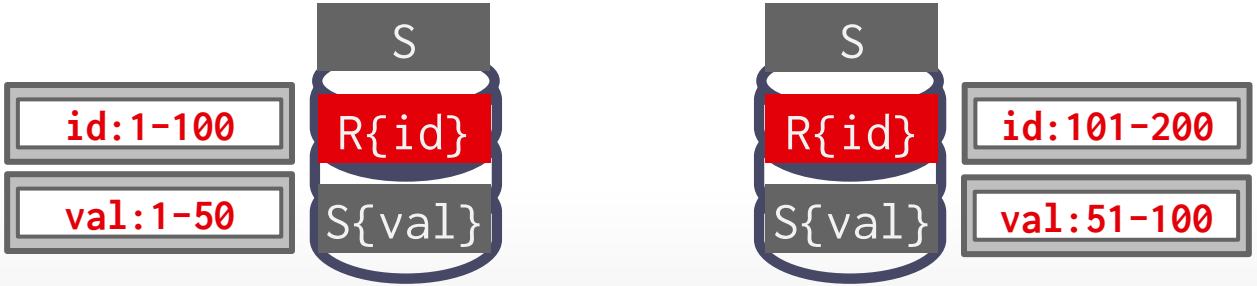

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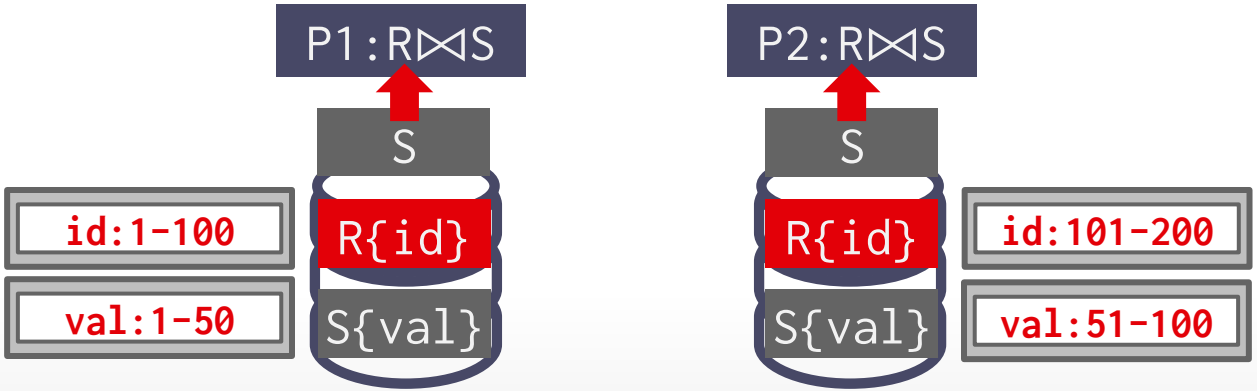

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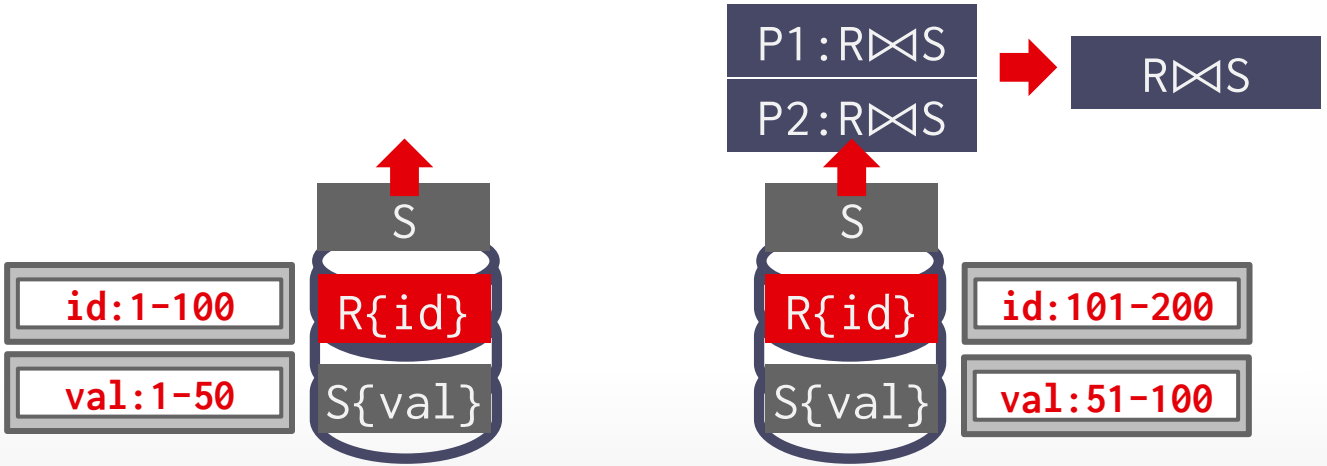

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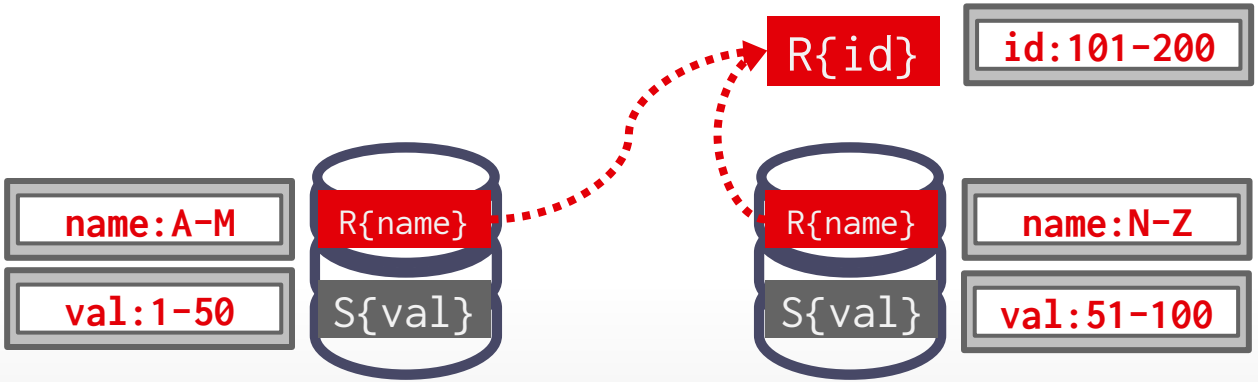

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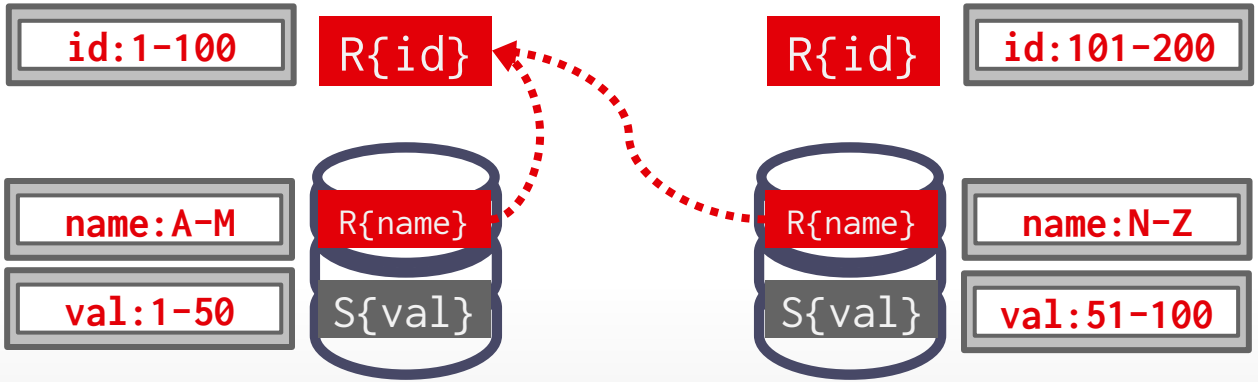

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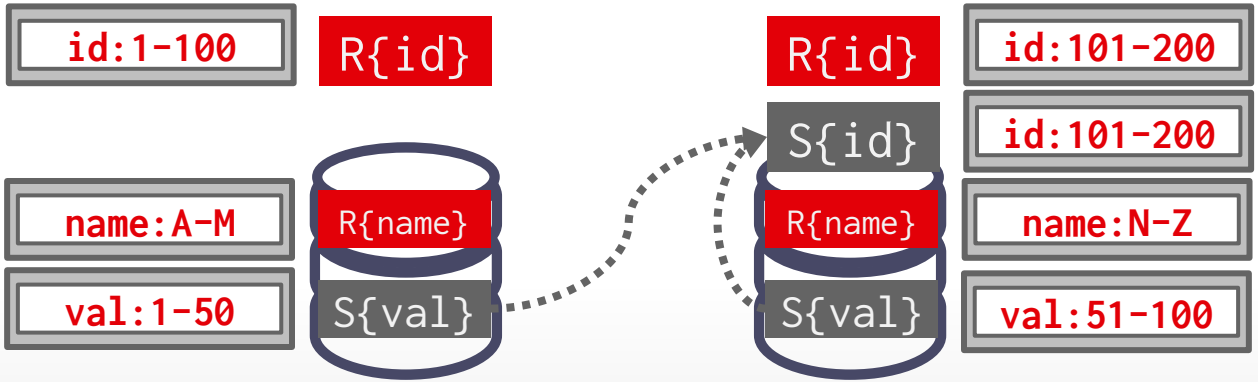

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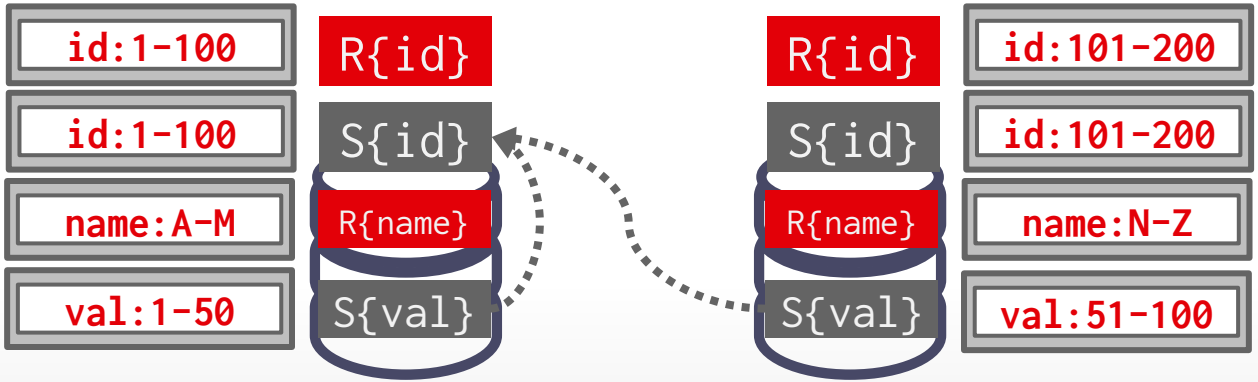

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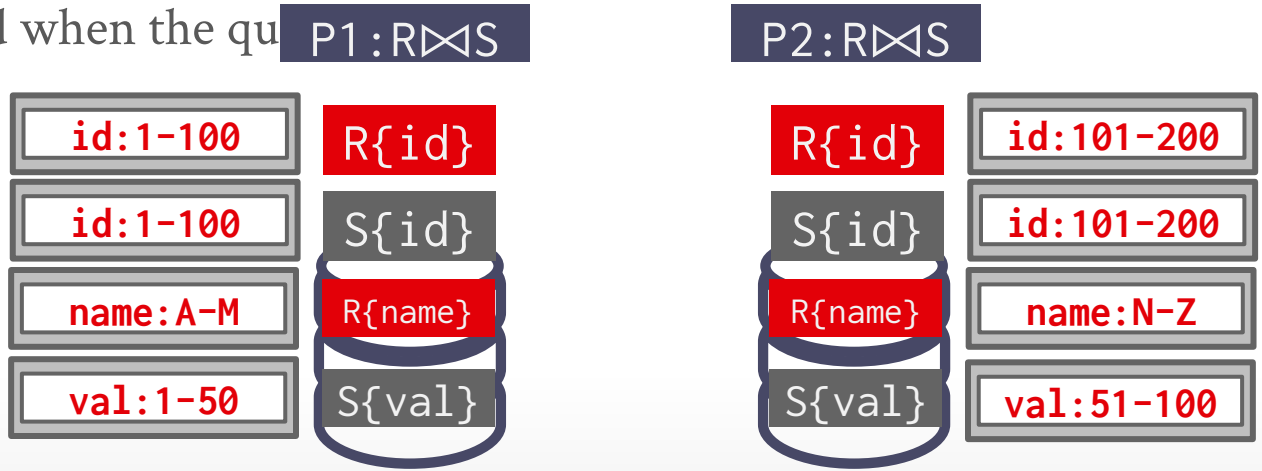

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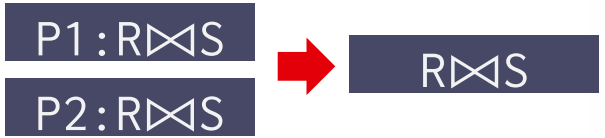

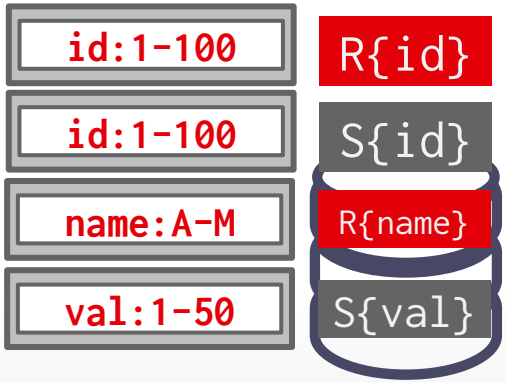

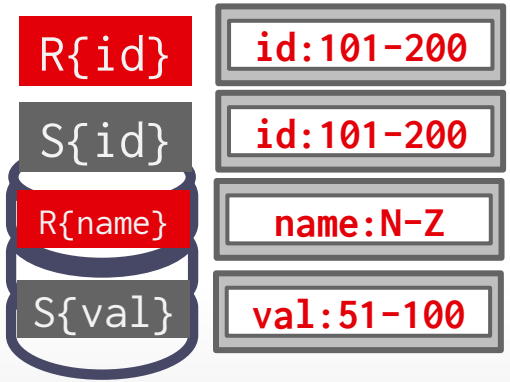

SEMI-JOIN OPTIMIZATION

Before pulling data from another node, send a **semi-join filter** to reduce data movement.

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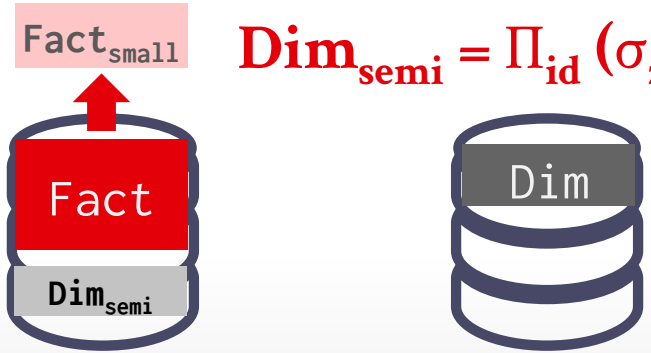

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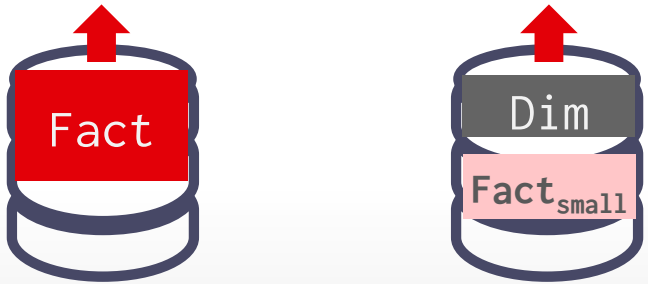


OBSERVATION

Direct communication between compute nodes means the DBMS knows which nodes will participate in query execution ahead of time.

But data skew can cause imbalances…

A better approach is to dynamically adjust compute resources on the fly as a query executes.

SHUFFLE PHASE

Redistribute of intermediate data across nodes between query plan pipelines.

→ Can repartition / rebalance data based on observed data characteristics.

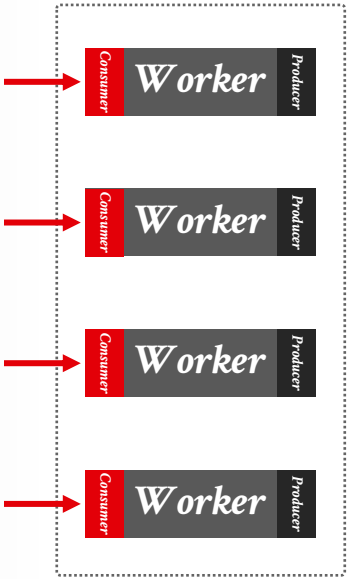
Google Big Query

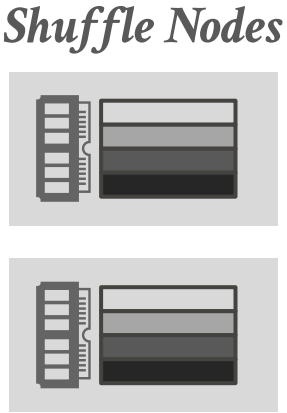
Some DBMSs support standalone fault-tolerant shuffle services.

→ Example: You can replace Spark's built-in in-memory shuffle implementation or replace it with a separate service.

Apache Uniffle

SHUFFLE PHASE





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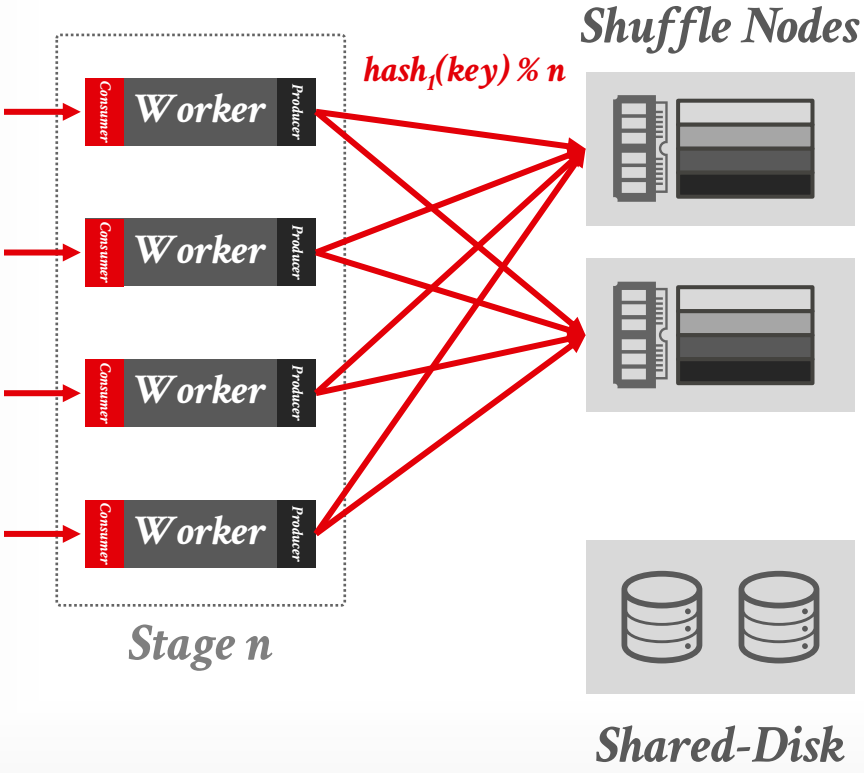

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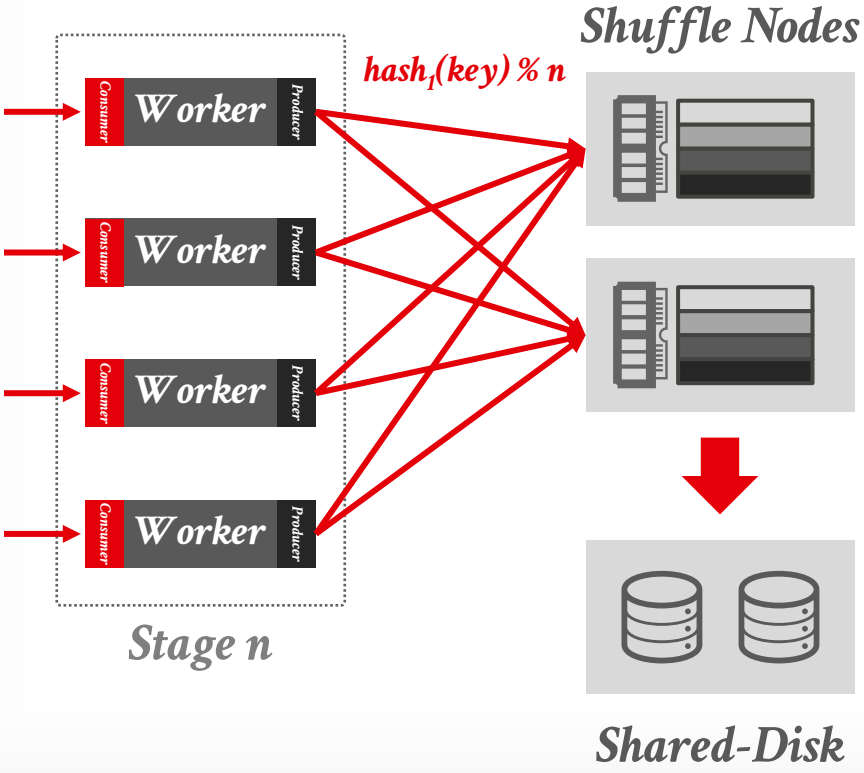

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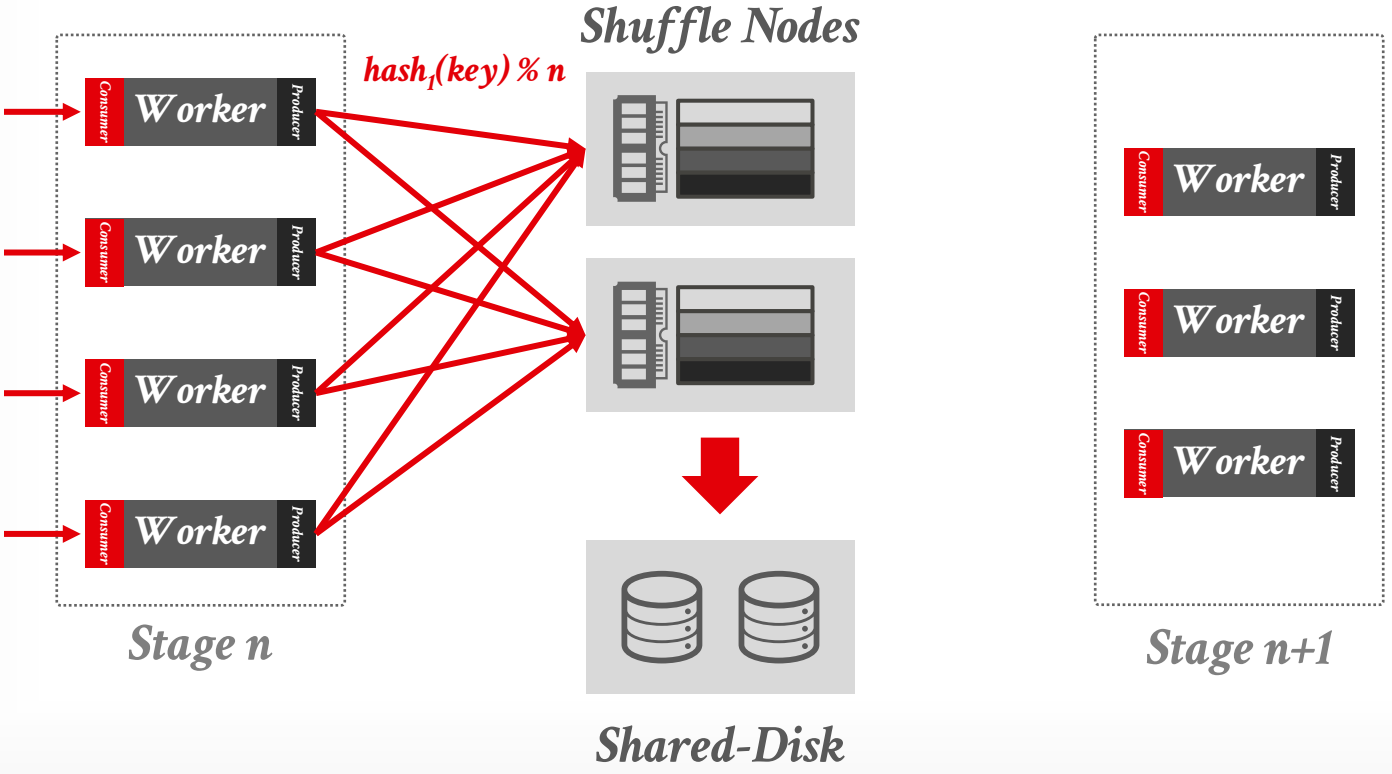

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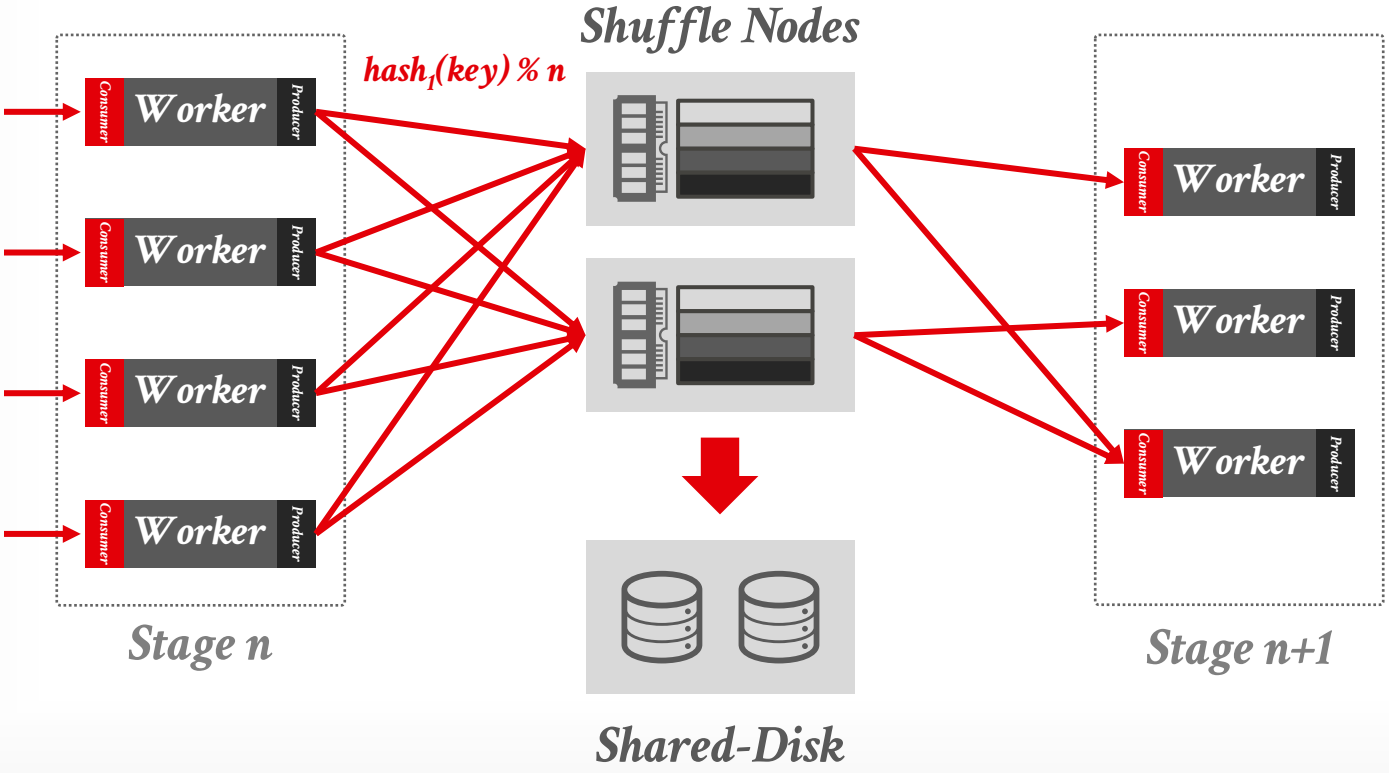

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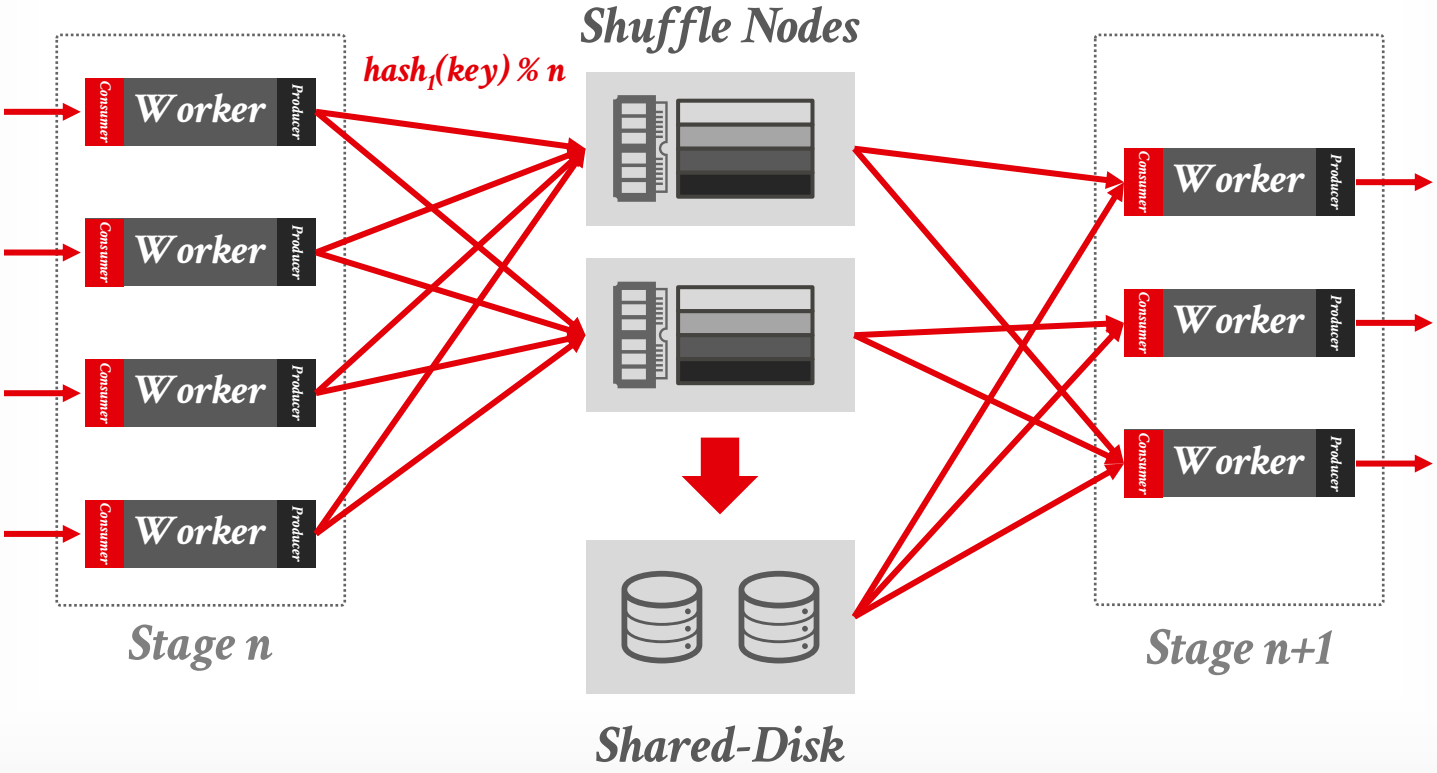

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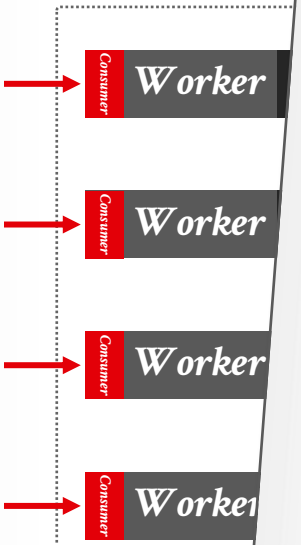
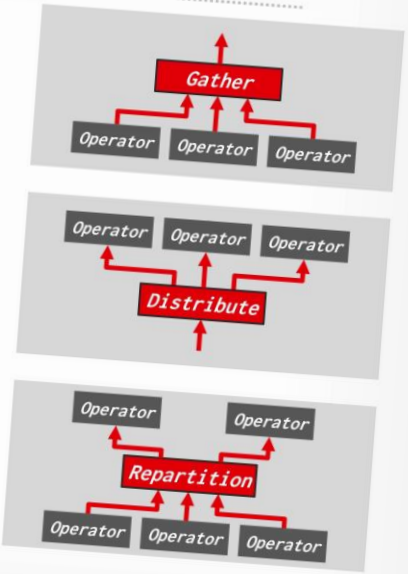


EXCHANGE OPERATOR

Exchange Type #1 – Gather
→ Combine the results from multiple workers into a single output stream.

Exchange Type #2 – Distribute
→ Split a single input stream into multiple output streams.

Exchange Type #3 – Repartition
→ Shuffle multiple input streams across multiple output streams.
→ Some DBMSs always perform this step after every pipeline (e.g., Google BigQuery).



Source: Craig Freedman

DATABASE SYSTEMS (FALL 2025)

Shared-Disk

CONCLUSION

Maintaining transactional consistency across multiple nodes is hard. Bad things will happen.
→ Don't let the "unwashed masses" go without txns!

2PC / Paxos / Raft are the most common protocols to ensure correctness in a distributed DBMS.

Moving data during distributed joins is expensive.

NEXT CLASS

Final Review

15-721 in a single lecture!