

Carnegie Mellon University

# Database Systems

Distributed  
OLTP Databases



15-445/645 FALL 2024 » PROF. ANDY PAVLO

# ADMINISTRIVIA

---

**No Class** on Thursday Nov 27<sup>th</sup>

**DBMS Potpourri Lecture** on Wednesday Dec 4<sup>th</sup>

**Project #4** is due Sunday Dec 8<sup>th</sup> @ 11:59pm

**Homework #6** is due Monday Dec 9<sup>th</sup> @ 11:59pm

**Final Exam** is on Friday Dec 13<sup>th</sup> @ 8:30am

→ Early exam will not be offered.

→ Do not get locked up in jail before this date.

# UPCOMING DATABASE TALKS

---

## GreptimeDB (DB Seminar)

→ Monday Nov 25<sup>th</sup> @ 4:30pm

→ Zoom



## OpenDAL / DataBend (DB Seminar)

→ Monday Nov 25<sup>th</sup> @ 4:30pm

→ Zoom



# LAST CLASS

---

## **System Architectures**

→ Shared-Everything, Shared-Disk, Shared-Nothing

## **Partitioning/Sharding**

→ Hash, Range, Round Robin

## **Transaction Coordination**

→ Centralized vs. Decentralized

# OLTP VS. OLAP

---

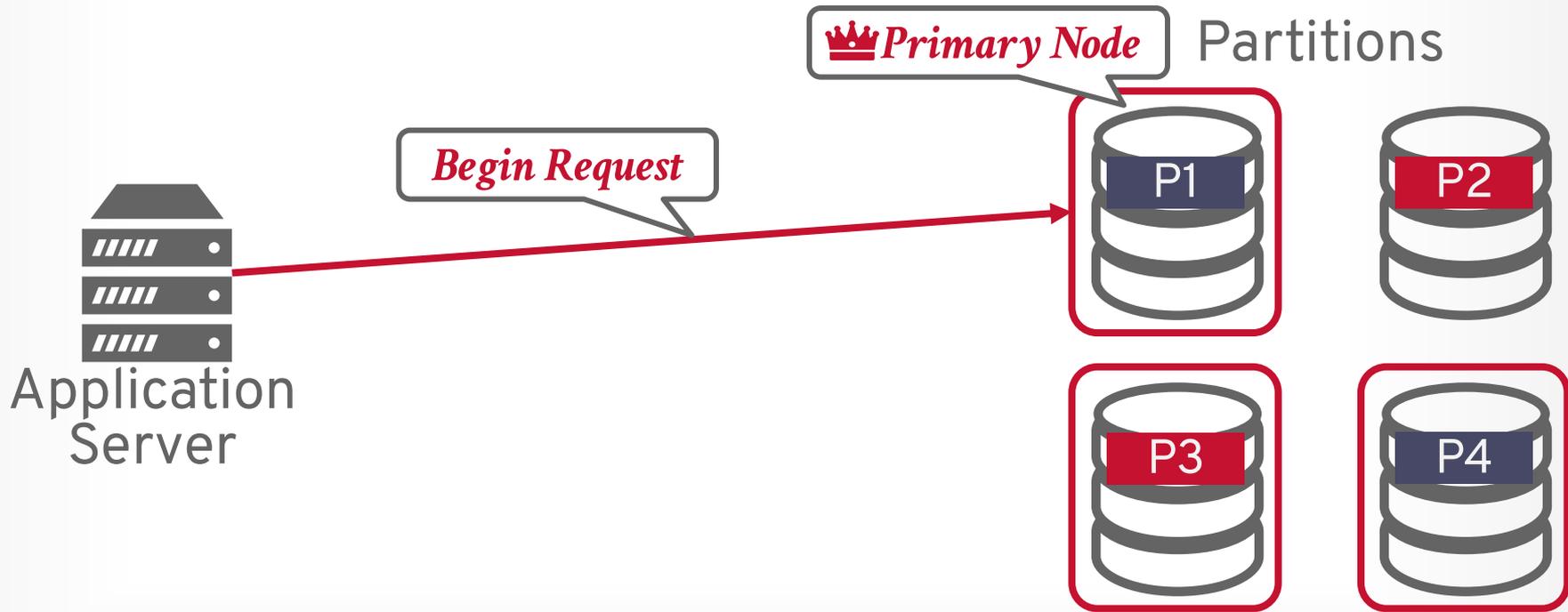
## **On-line Transaction Processing (OLTP):**

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

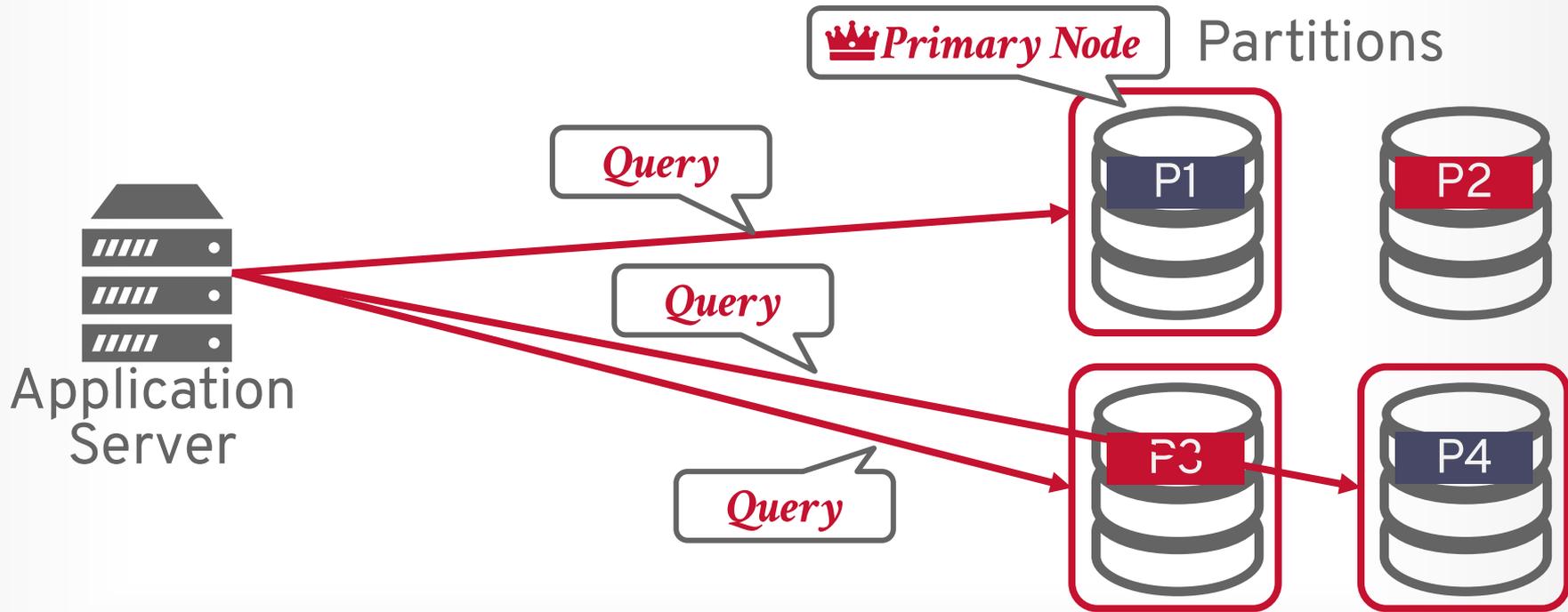
## **On-line Analytical Processing (OLAP):**

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

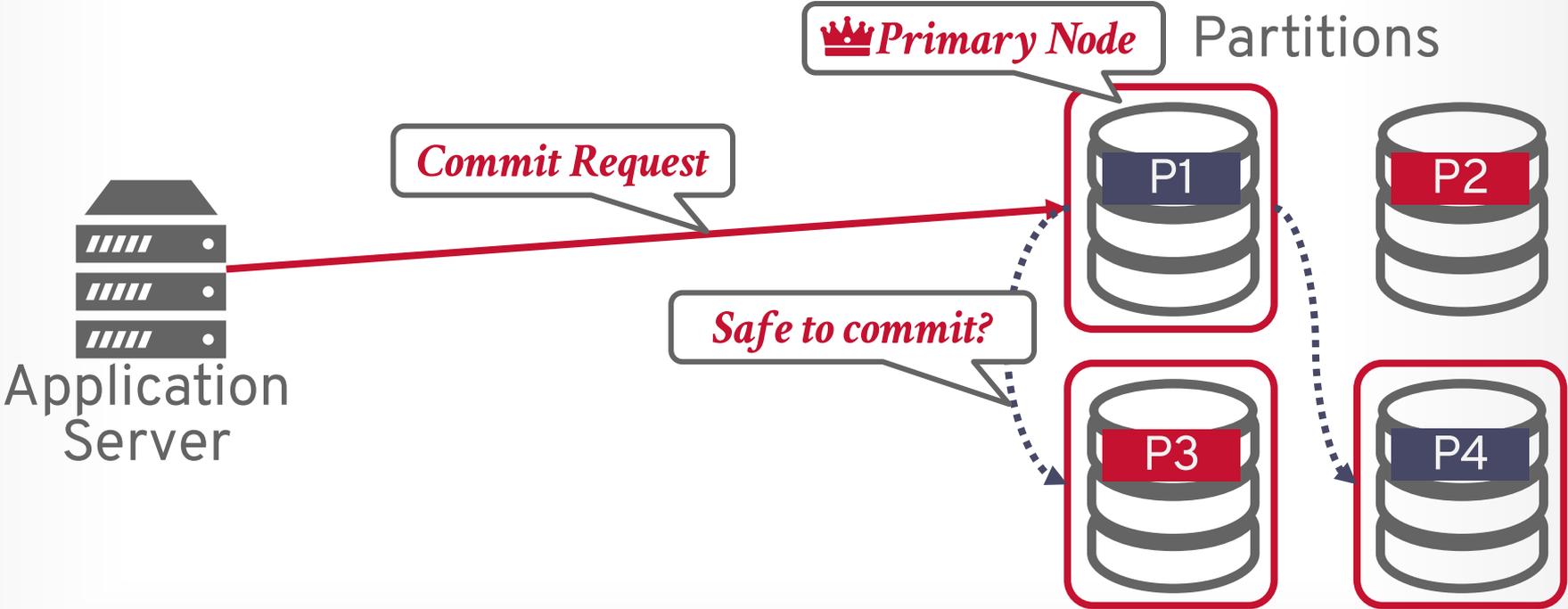
# DECENTRALIZED COORDINATOR



# DECENTRALIZED COORDINATOR



# DECENTRALIZED COORDINATOR



# 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 workloads.



*Don't  
Do This!*

# TODAY'S AGENDA

---

Replication

Atomic Commit Protocols

Consistency Issues (CAP / PACELC)

# 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

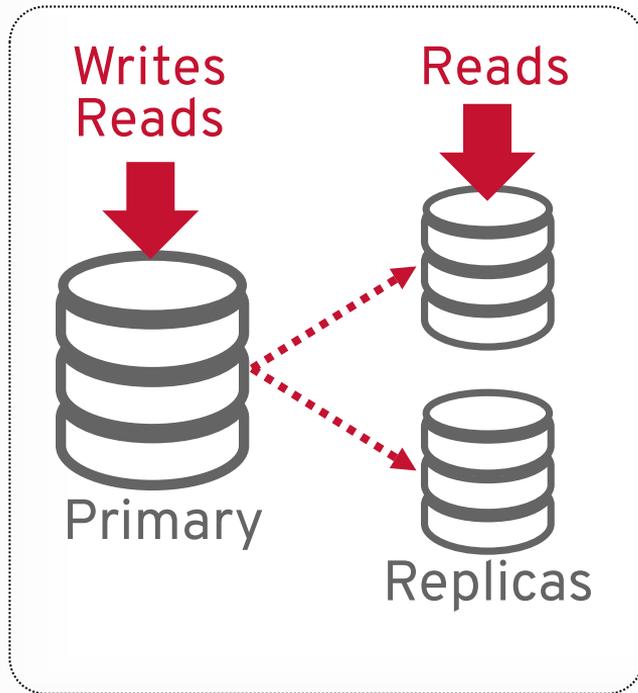
- All updates go to a designated primary for each object.
- The primary propagates updates to its replicas by shipping logs.
- Read-only txns may be allowed to access replicas.
- If the primary goes down, then hold an election to select a new primary.

## Approach #2: Multi-Primary

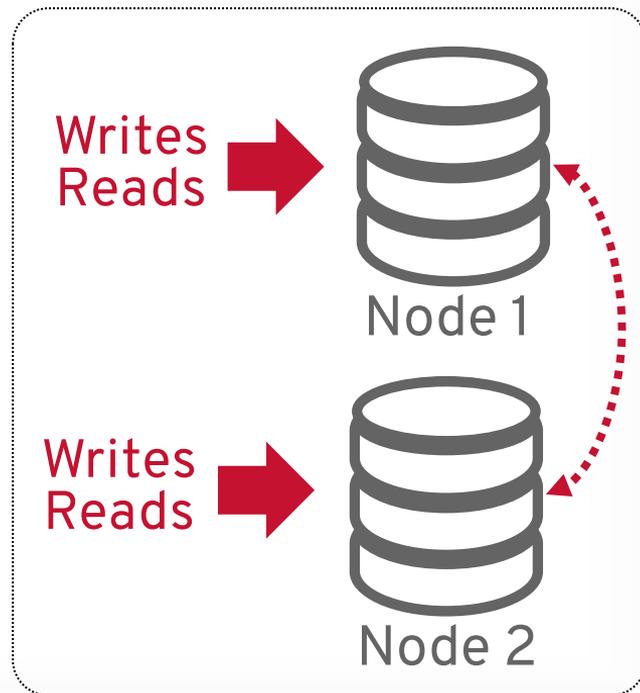
- Txns can update data objects at any replica.
- Replicas must synchronize with each other using an atomic commit protocol.

# REPLICA CONFIGURATIONS

## *Primary-Replica*



## *Multi-Primary*



# 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:

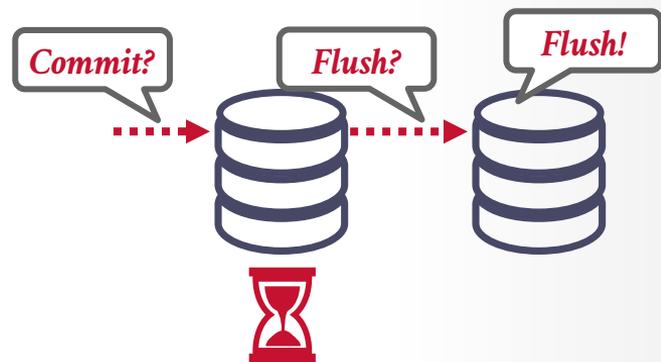
- Synchronous (*Strong Consistency*)
- Asynchronous (*Eventual Consistency*)

# 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.

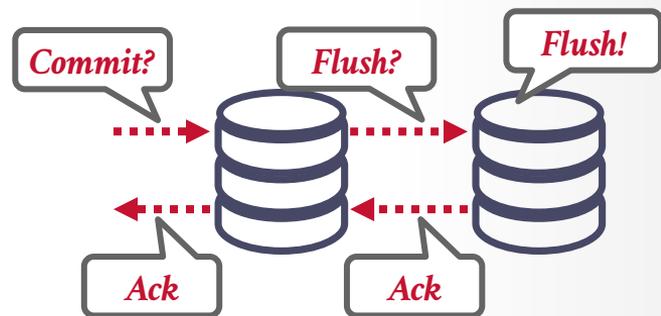


# PROPAGATION SCHEME

---

## Approach #1: Synchronous

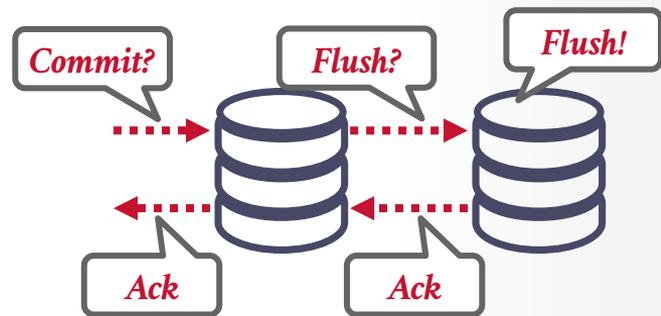
→ The primary sends updates to replicas and then waits for them to acknowledge that they fully applied (i.e., logged) the changes.



# PROPAGATION SCHEME

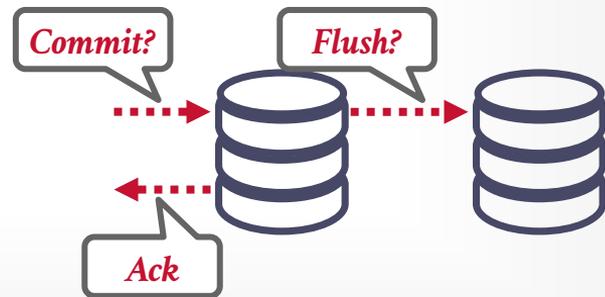
## Approach #1: Synchronous

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



## Approach #2: Asynchronous

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



# 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

# OBSERVATION

---

If only one node decides whether a txn is allowed to commit, then making that decision is easy.

Life is much harder when multiple nodes are allowed to decide:

- What if multiple nodes need to agree a txn is allowed to commit?
- What if a primary node goes down and the system needs to choose a new 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)

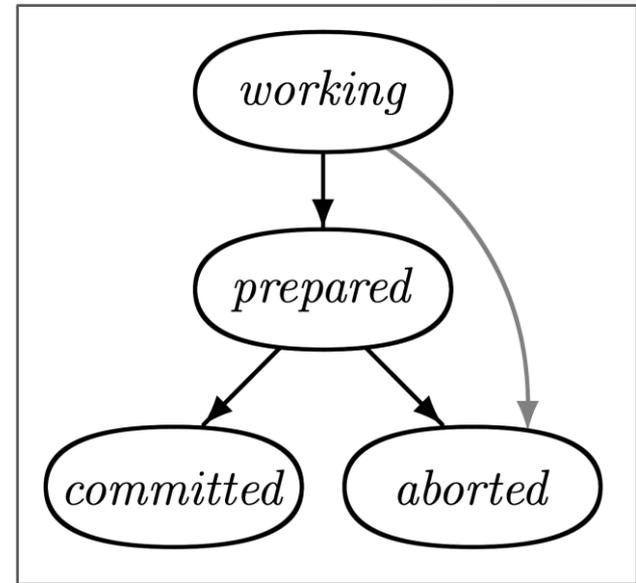
- Execute on different nodes
- Coordinate to decide fate of a txn.

## Properties of the Commit Protocol

- **Stability:** Once the fate is decided, it cannot be changed.
- **Consistency:** All RMs end up 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.

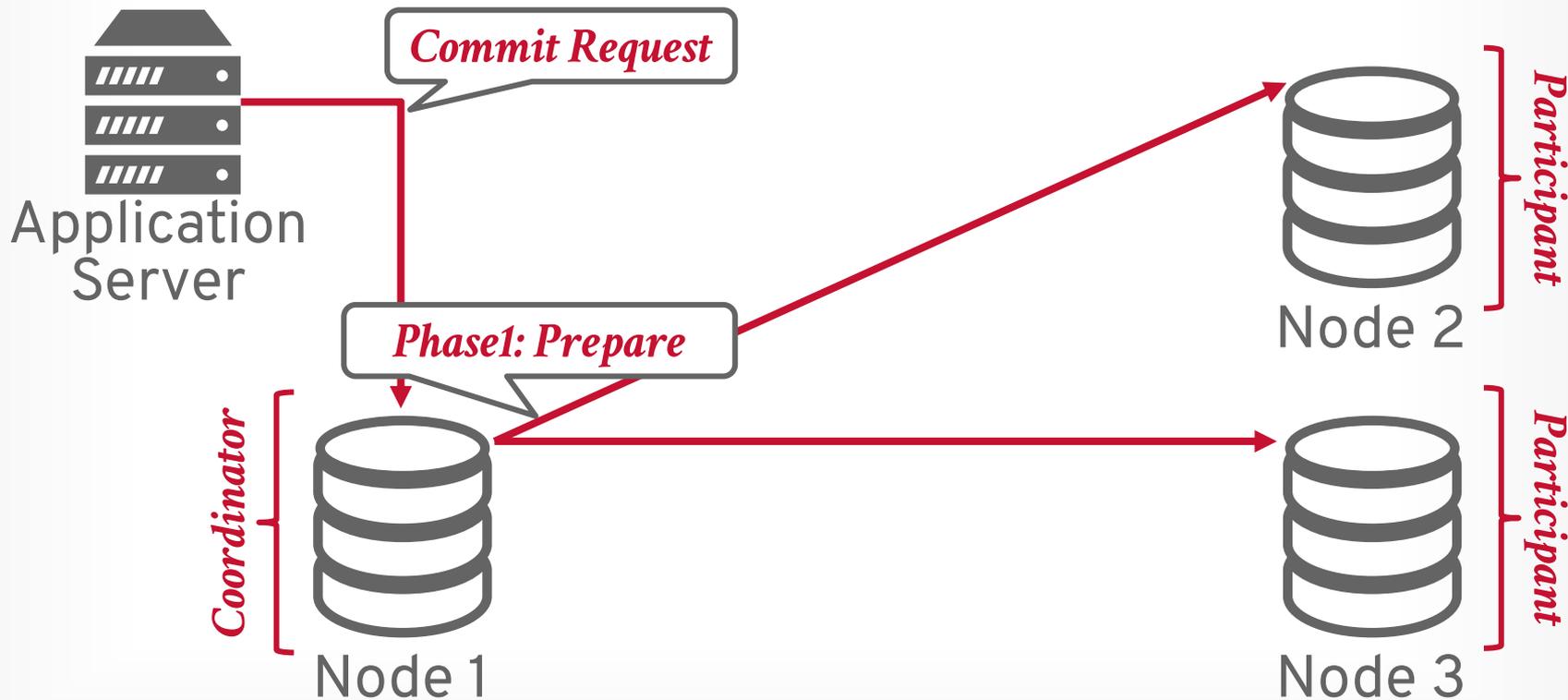


<https://www.microsoft.com/en-us/research/publication/consensus-on-transaction-commit/>

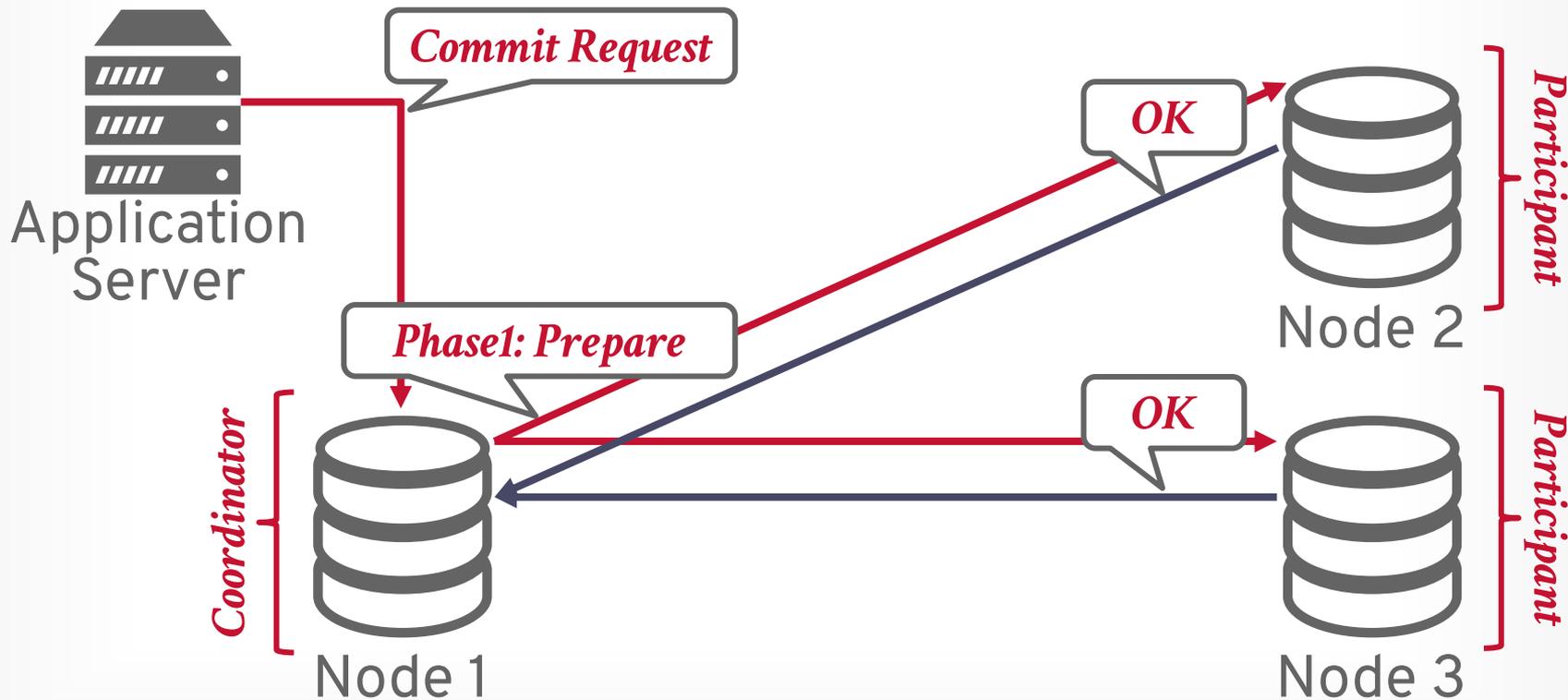
# TWO-PHASE COMMIT (SUCCESS)



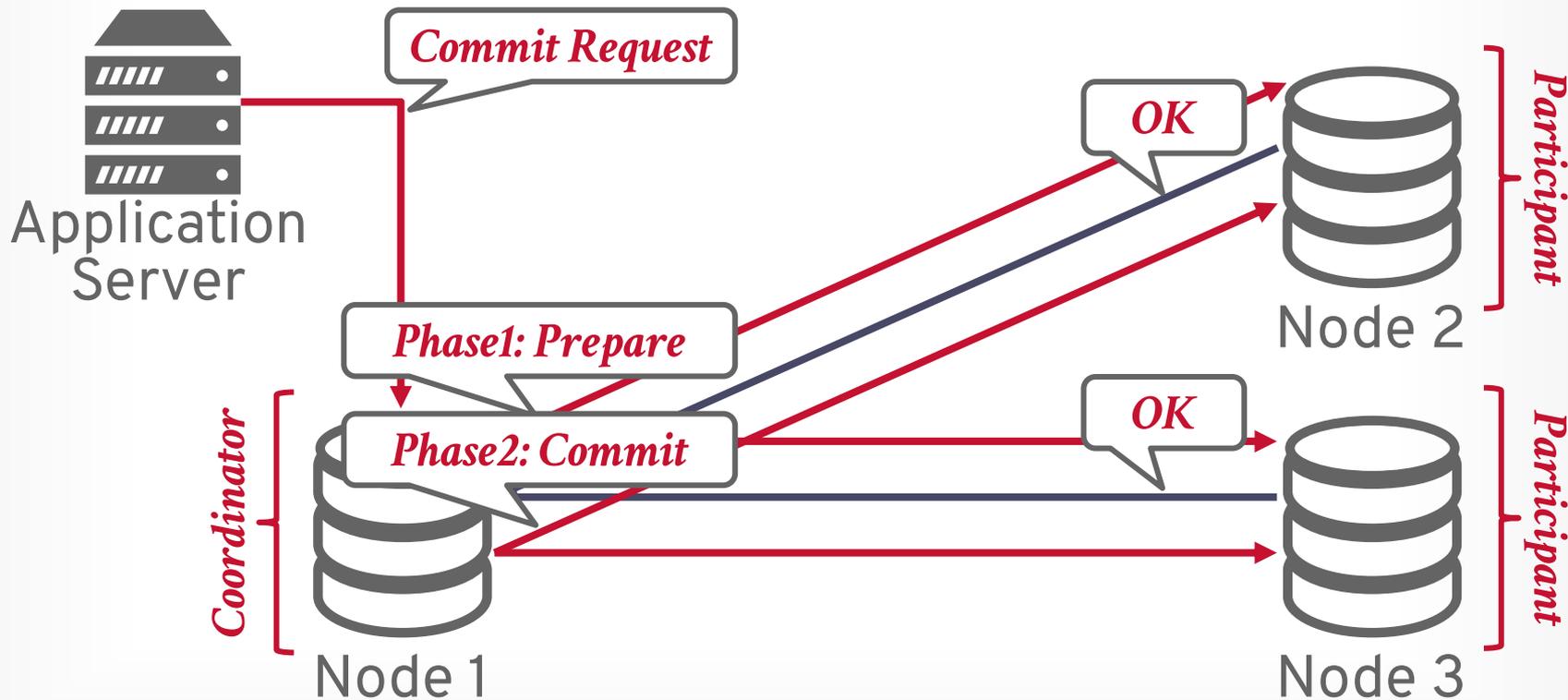
# TWO-PHASE COMMIT (SUCCESS)



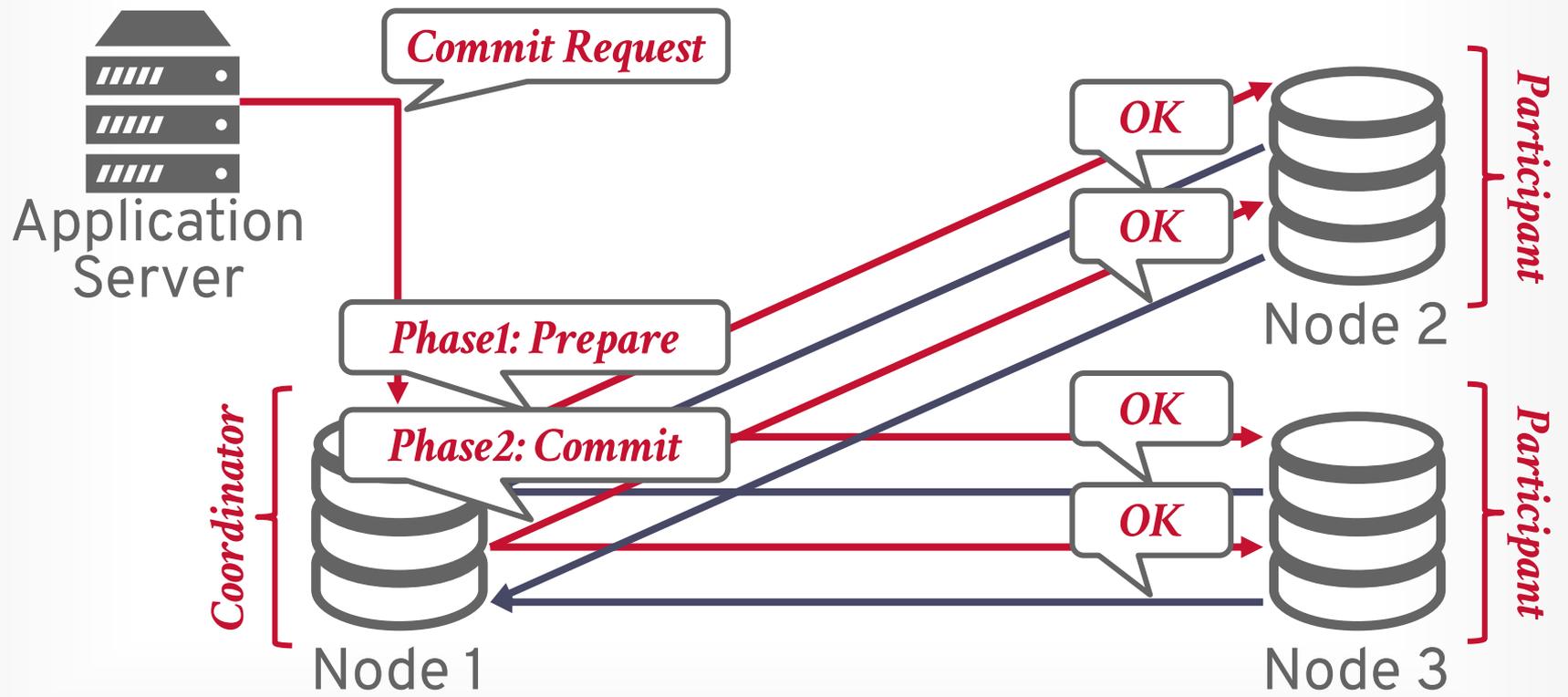
# TWO-PHASE COMMIT (SUCCESS)



# TWO-PHASE COMMIT (SUCCESS)



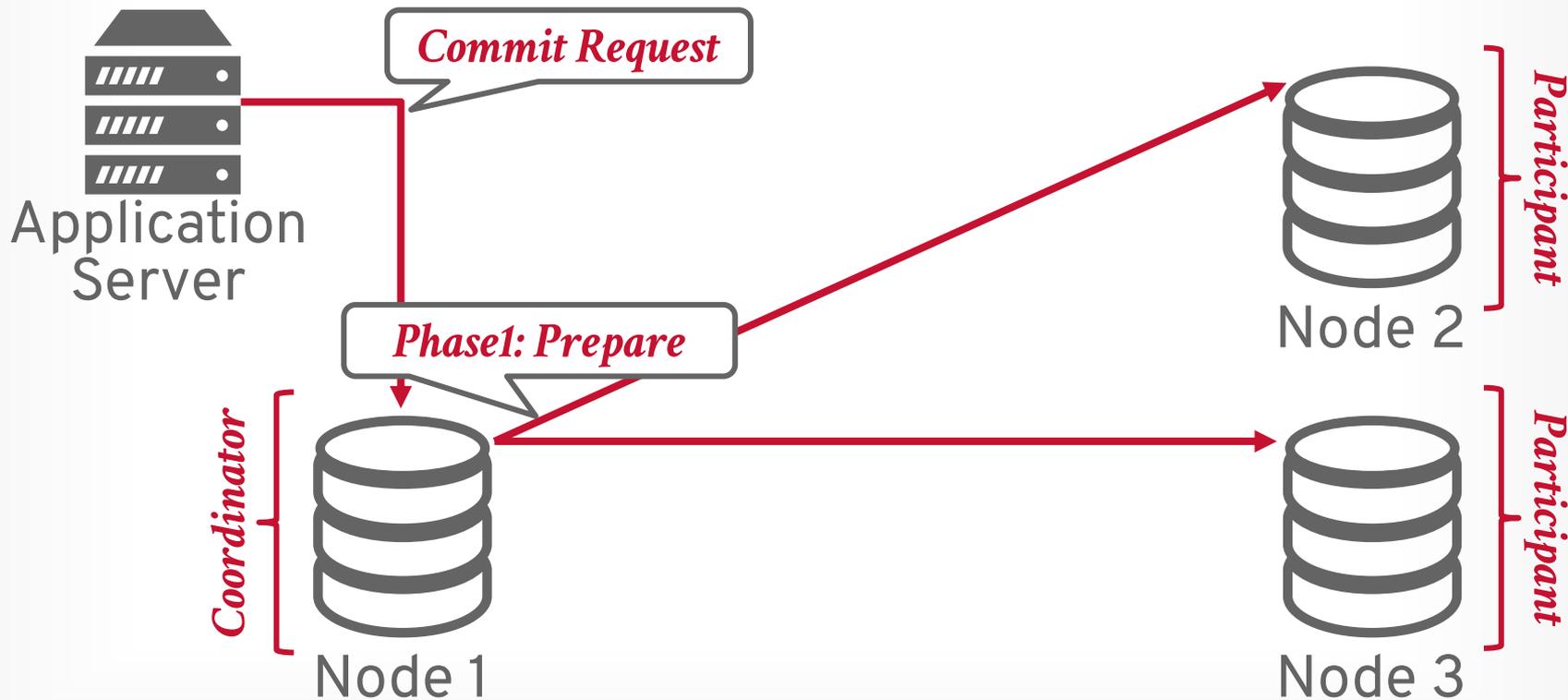
# TWO-PHASE COMMIT (SUCCESS)



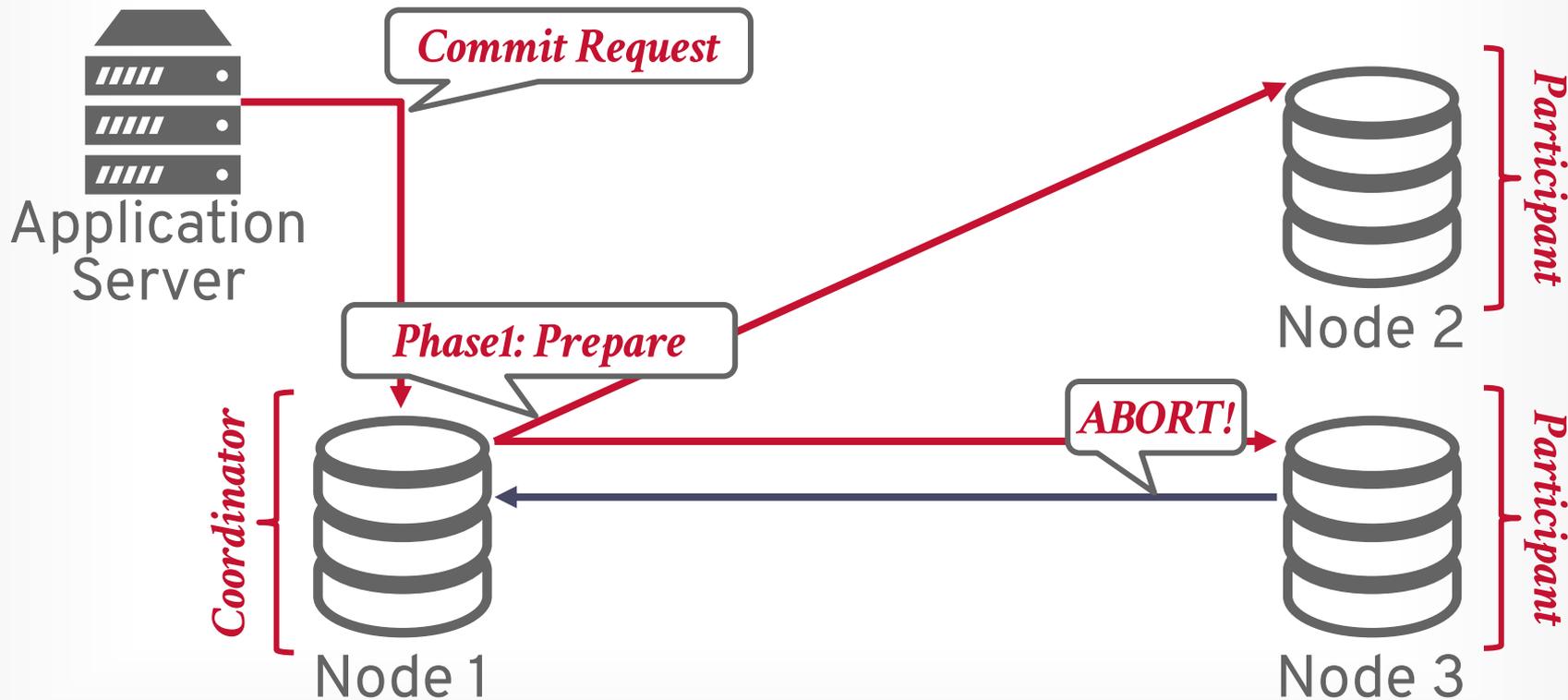
# TWO-PHASE COMMIT (SUCCESS)



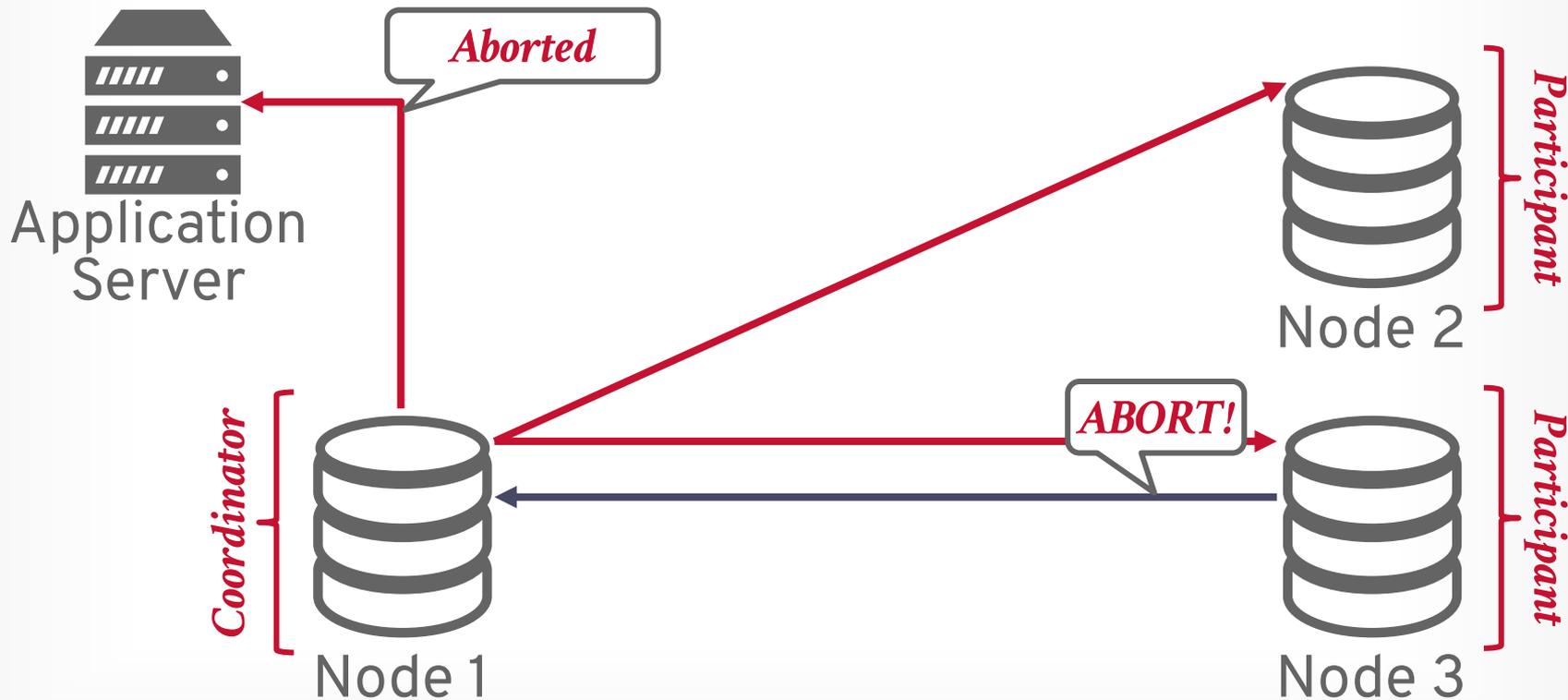
# TWO-PHASE COMMIT (ABORT)



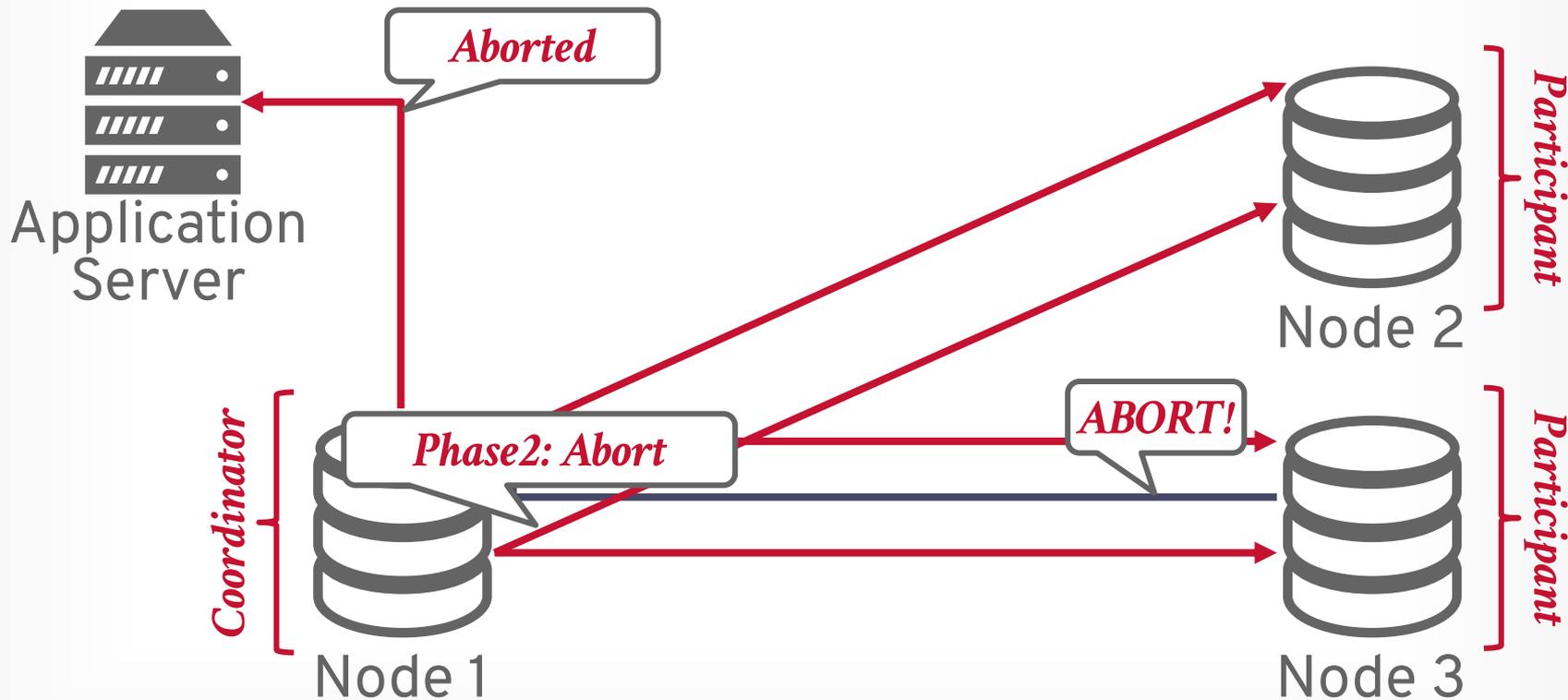
# TWO-PHASE COMMIT (ABORT)



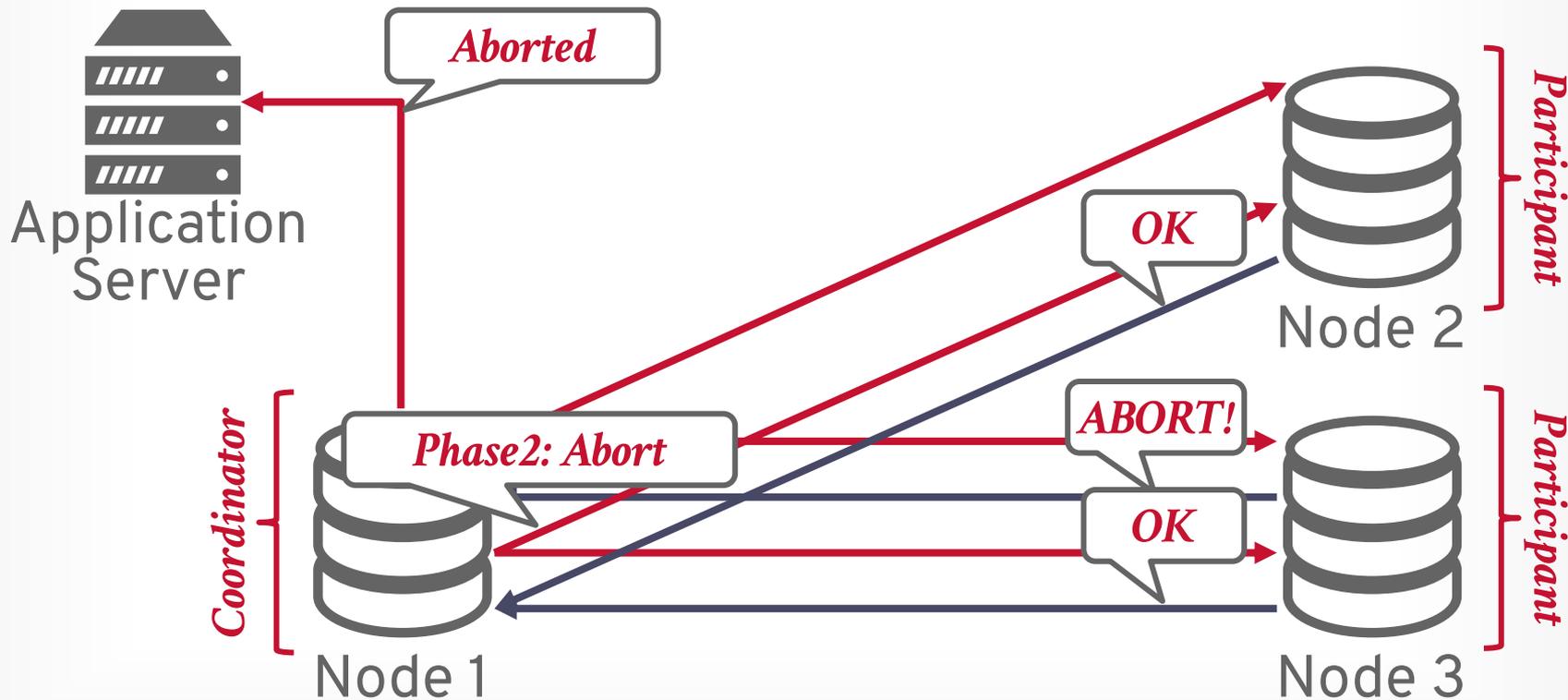
# TWO-PHASE COMMIT (ABORT)



# TWO-PHASE COMMIT (ABORT)



# TWO-PHASE COMMIT (ABORT)



# 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.

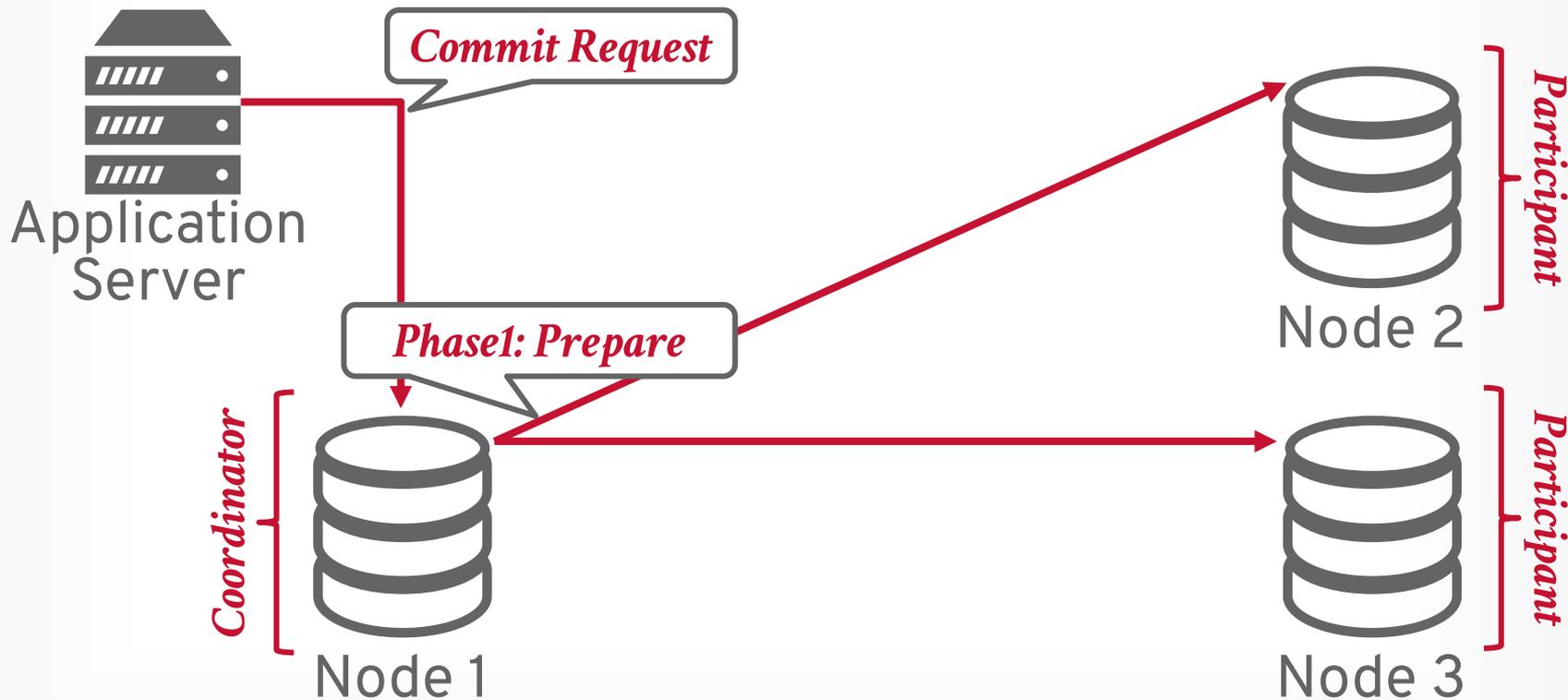
## **Early Ack After Prepare** (*Common*)

→ 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.

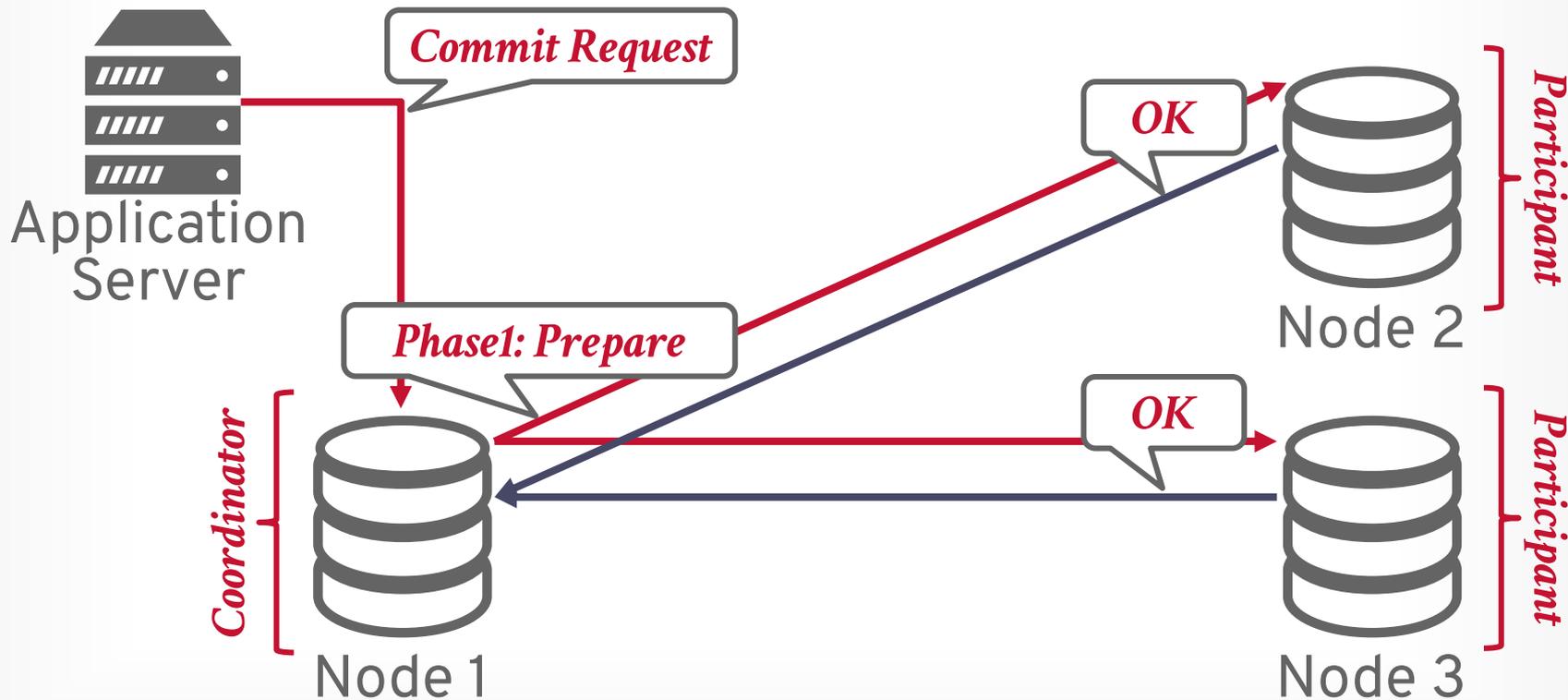
# EARLY ACKNOWLEDGEMENT



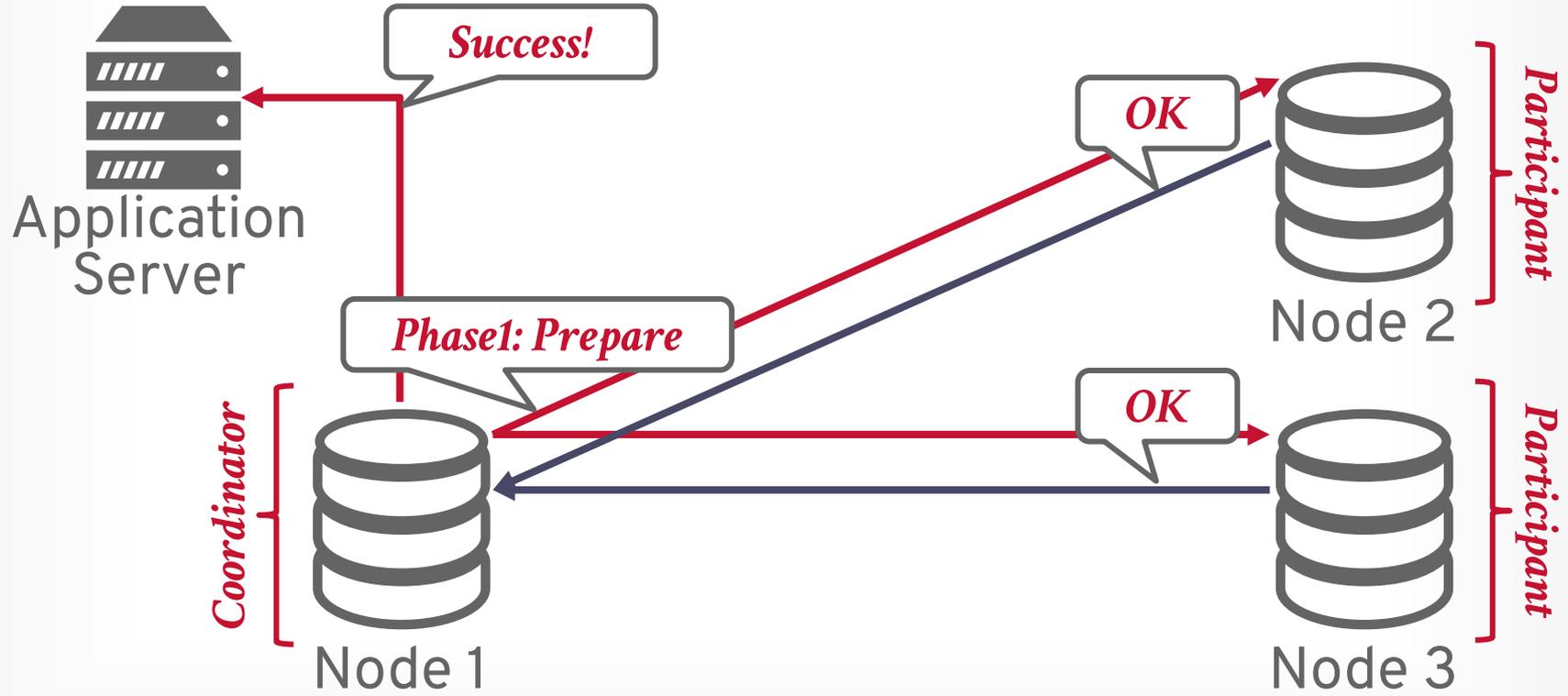
# EARLY ACKNOWLEDGEMENT



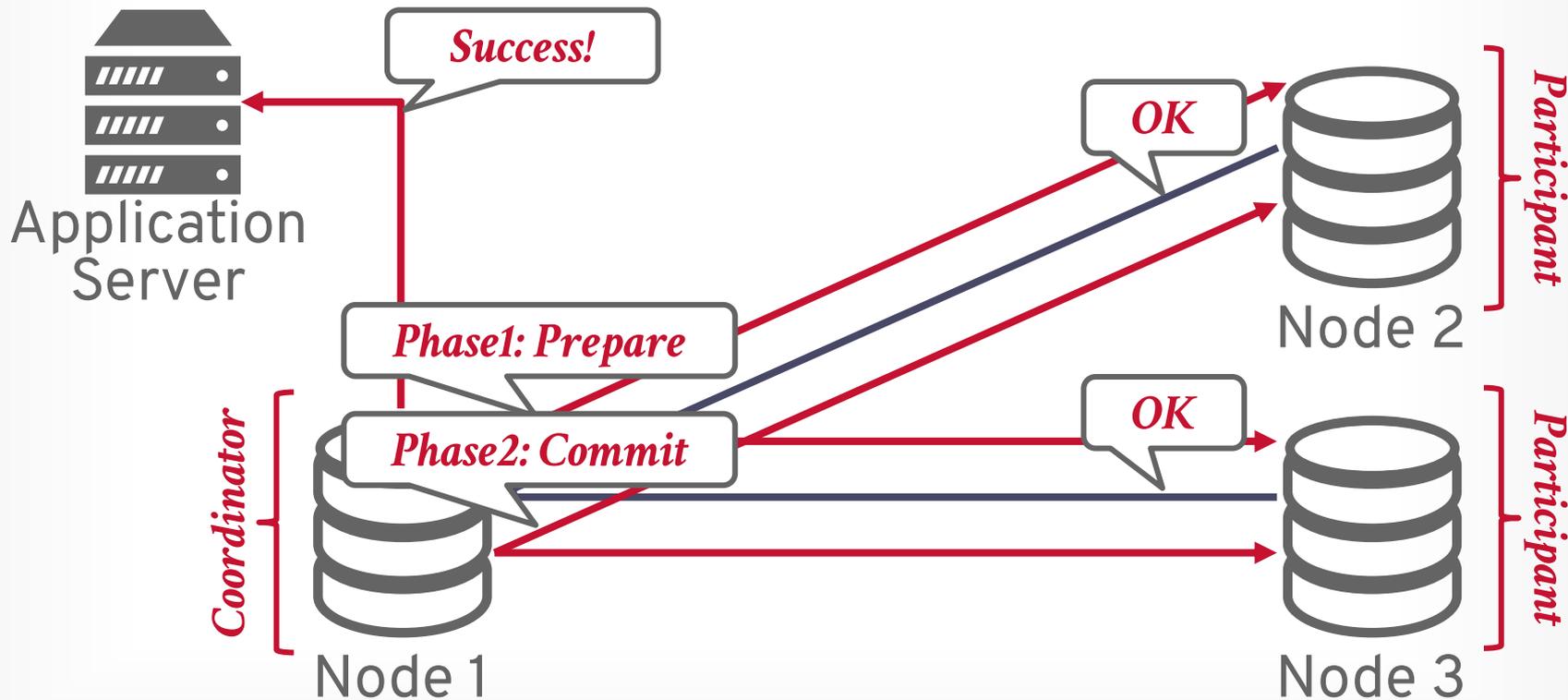
# EARLY ACKNOWLEDGEMENT



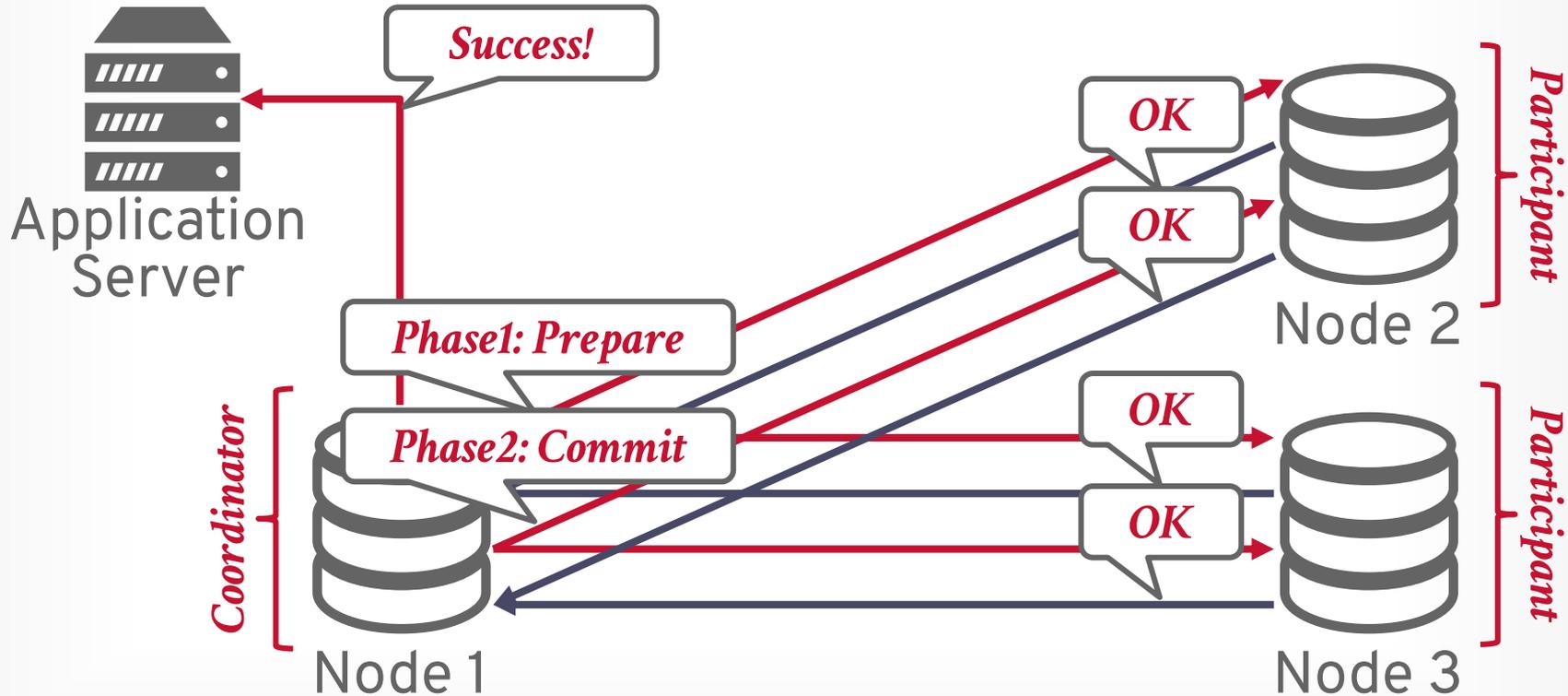
# EARLY ACKNOWLEDGEMENT



# EARLY ACKNOWLEDGEMENT



# 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 Paxos 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 Paxos 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 Paxos made to their protocol appear to be unknown in the systems literature.

The author does give a brief discussion of the Paxos 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 Lamport [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.

Keith Marzullo  
University of California, San Diego

Authors' address: Systems Research Center, Digital Equipment Corporation, 130 Lytton Avenue, Palo Alto, CA 94301.

Permission to copy without fee all or part of this material is granted provided that the copies are not made or distributed for direct commercial advantage, the ACM copyright notice and the title of the publication and its date appear, and notice is given that copying is by permission of the Association for Computing Machinery. To copy otherwise, or to republish, requires a fee and/or specific permission.

© 1998 ACM 0000-0000/98/0000-0000 \$00.00

## PAX

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 the best case.

## Consensus on Transaction Commit

JIM GRAY and LESLIE LAMPART  
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 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 distributed system is not trivial. The requirements for transaction commit are stated precisely in Section 2.

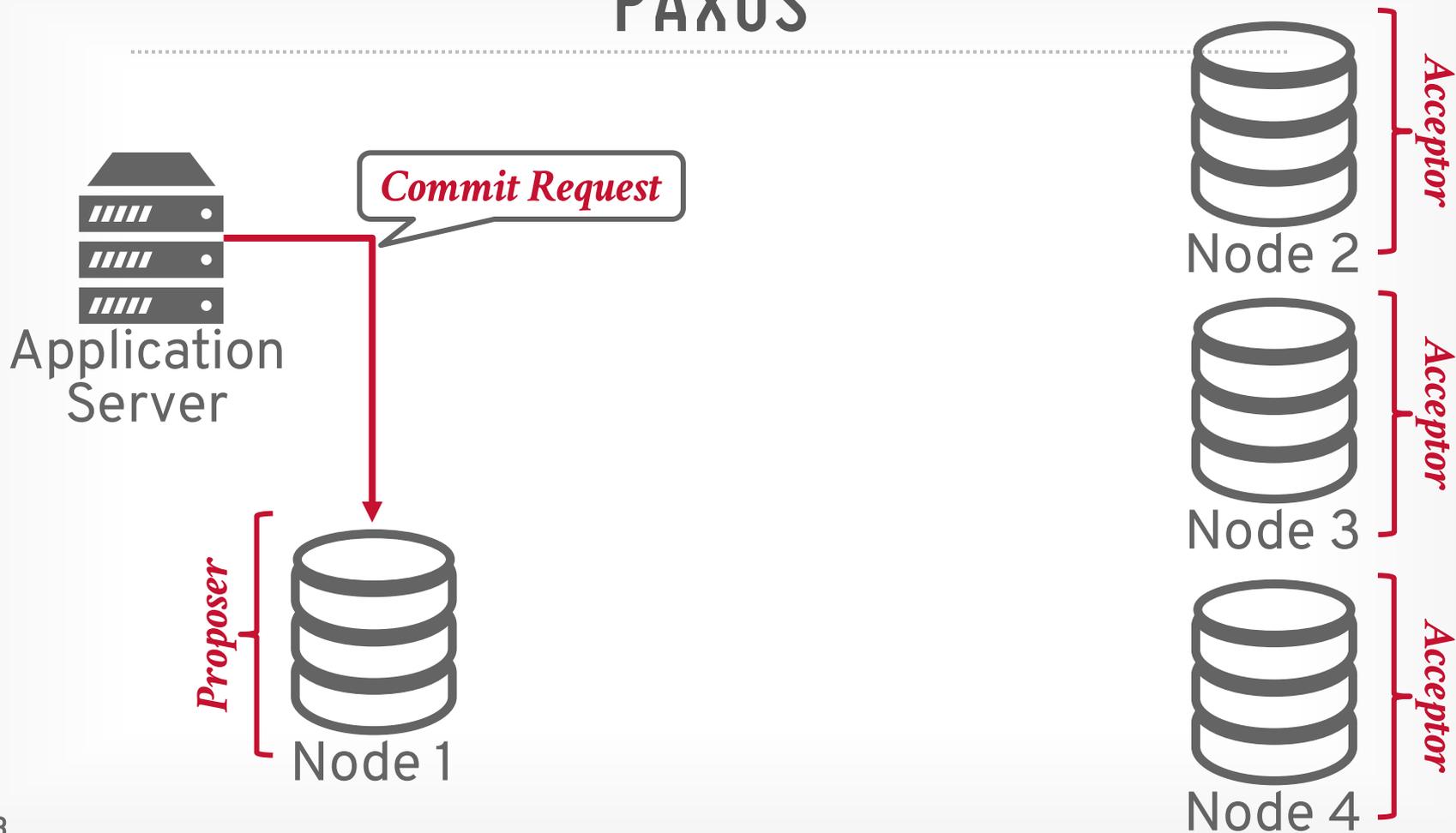
The classic transaction commit protocol is Two-Phase Commit [Gray 1978], described in Section 3. It uses a single coordinator to reach agreement. The failure of that coordinator can cause the protocol to block, with no process knowing the outcome, until the coordinator is repaired. In Section 4, we use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

Authors' addresses: J. Gray, Microsoft Research, 455 Market St., San Francisco, CA 94105; email: [Jia.Gray@microsoft.com](mailto:Jia.Gray@microsoft.com); L. Lamport, Microsoft Research, 1065 La Avenida, Mountain View, CA 94043.

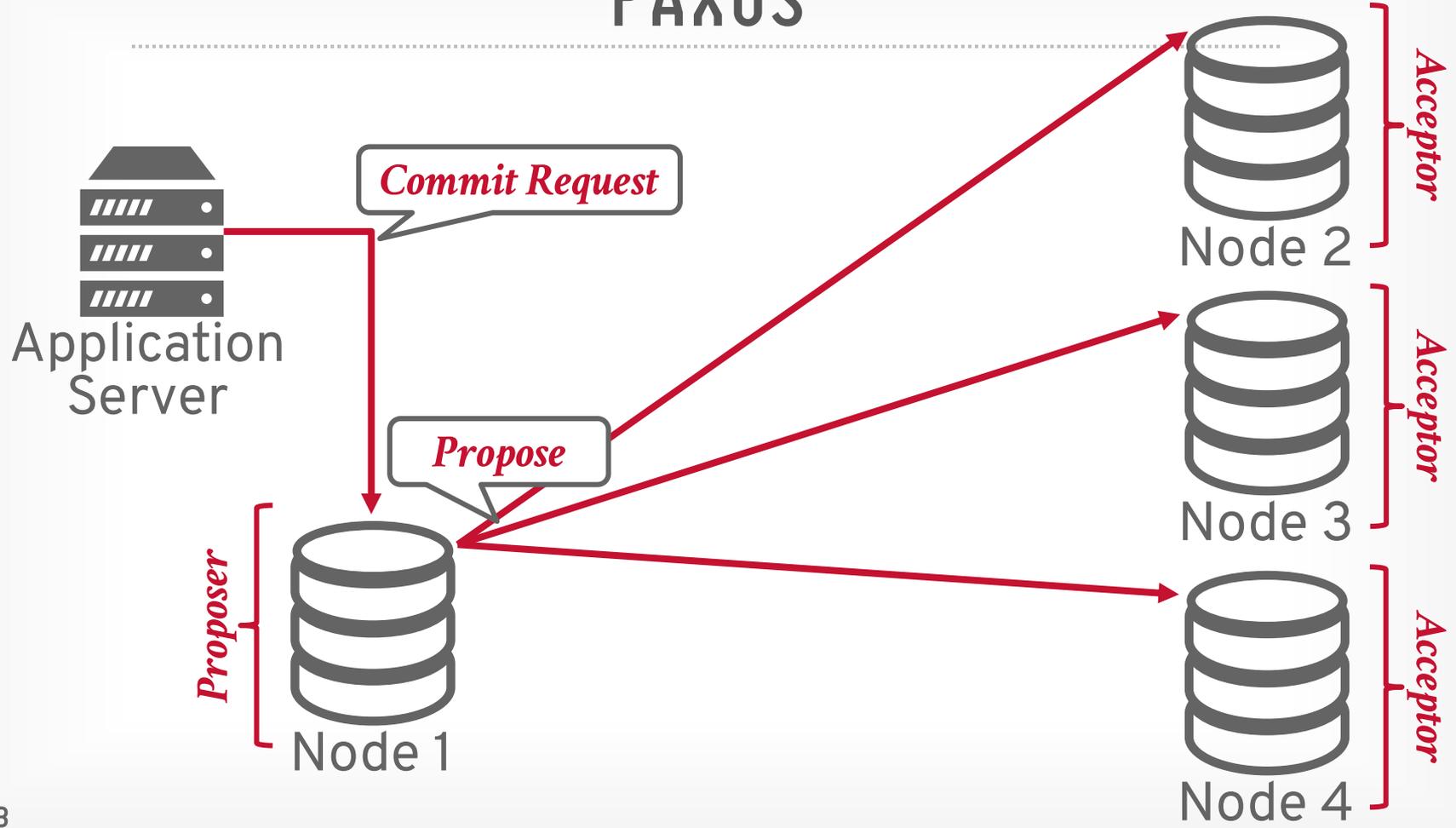
Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or direct commercial advantage and that copies show this notice on the first page or initial screen of a display along with the full citation. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, to republish, to post on servers, permission and/or a fee. Permissions may be requested from Publications Dept., ACM, Inc., 1515 Broadway, New York, NY 10036 USA, fax: +1 (212) 869-0481, or [permissions@acm.org](mailto:permissions@acm.org).  
© 2006 ACM 0362-5915/06/0300-0133 \$5.00

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

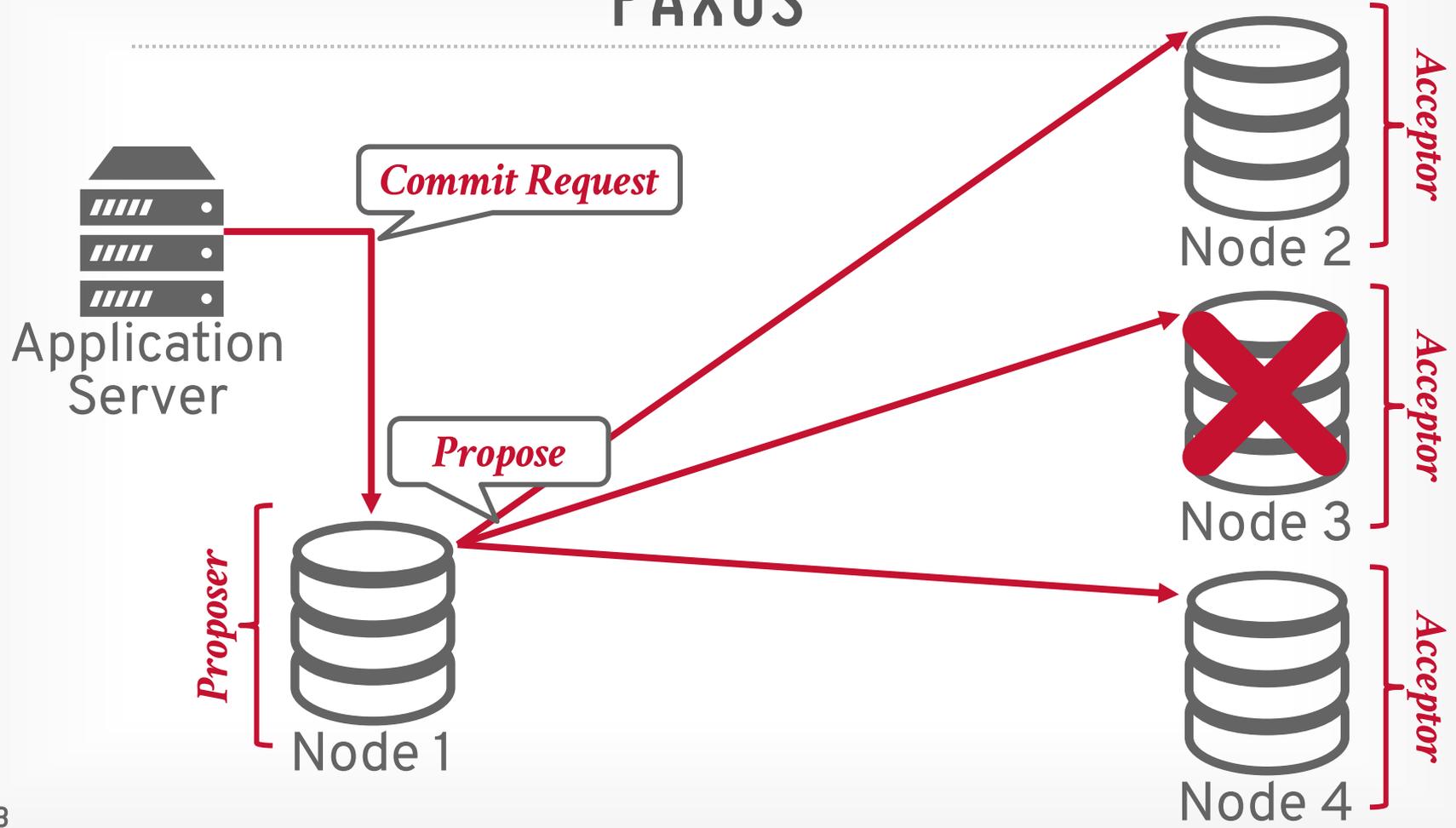
# PAXOS



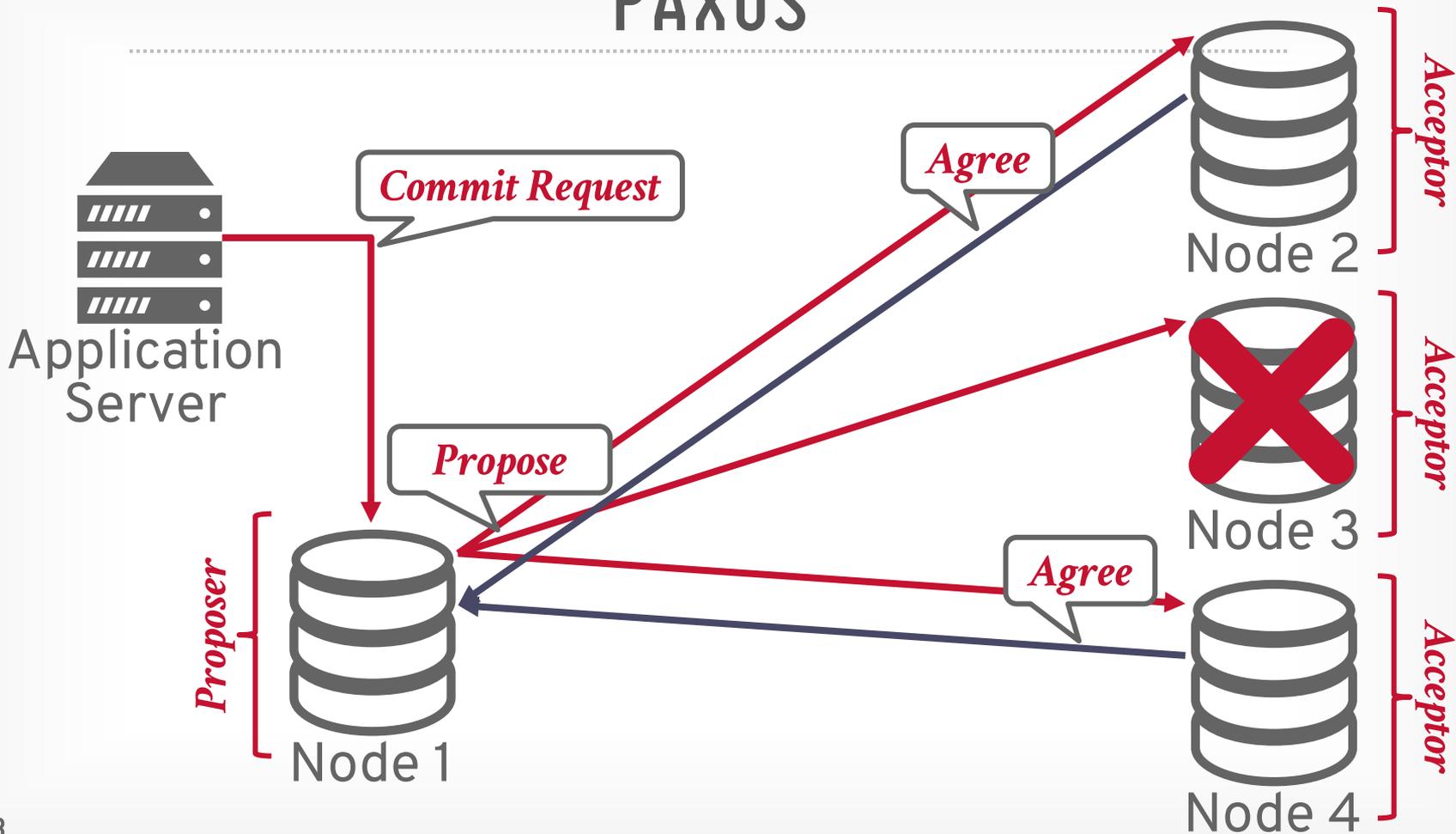
# PAXOS



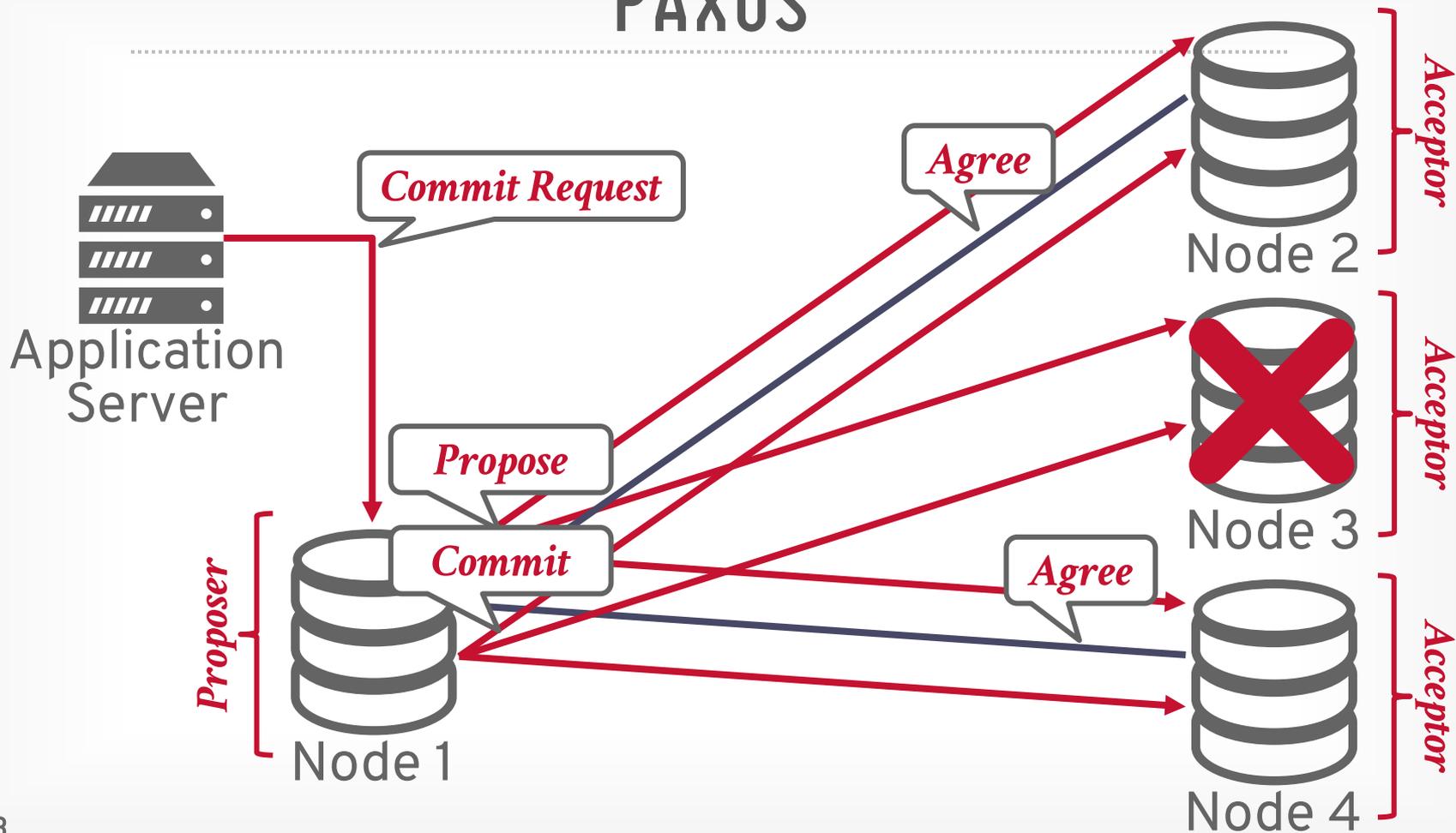
# PAXOS



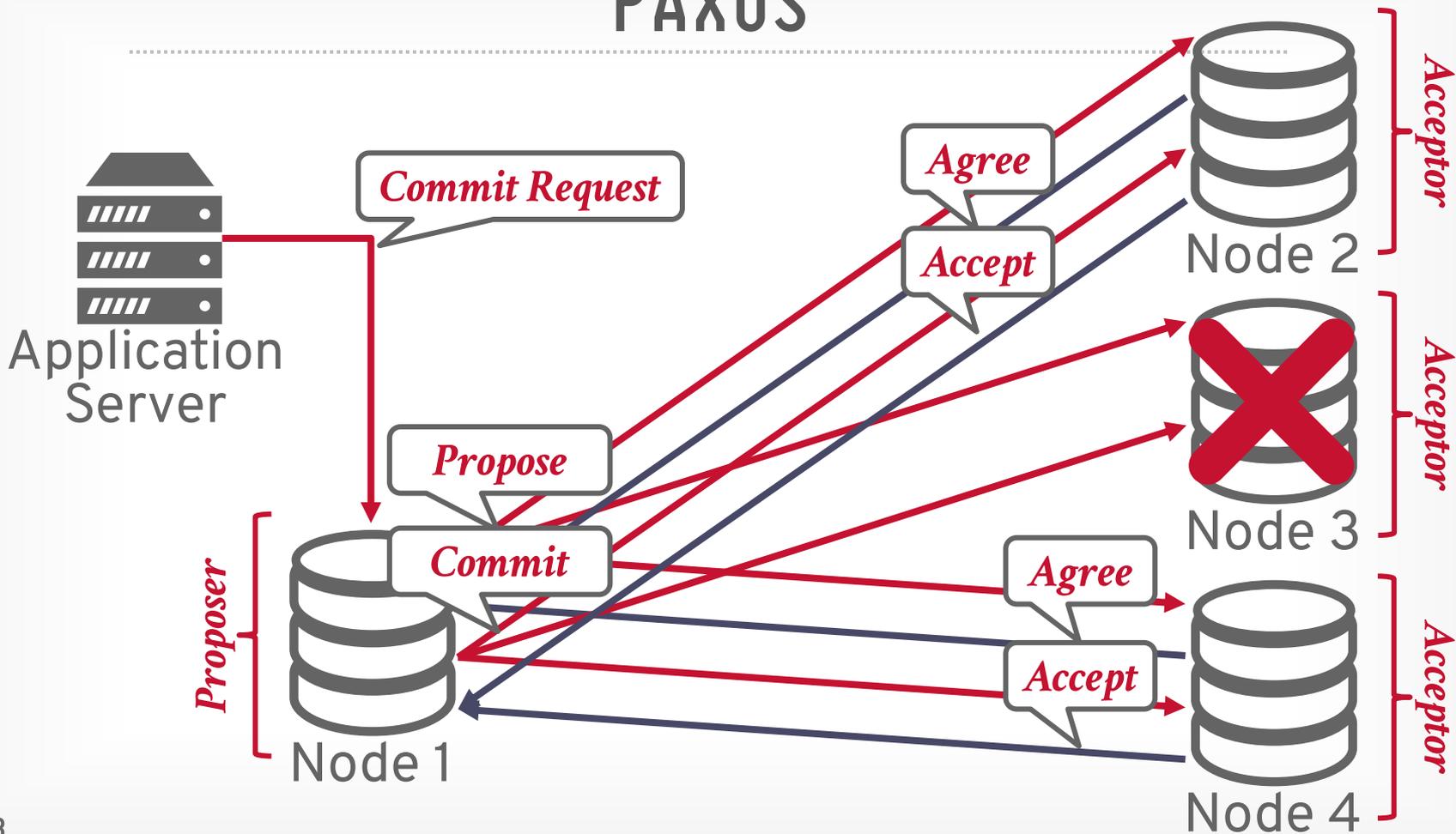
# PAXOS



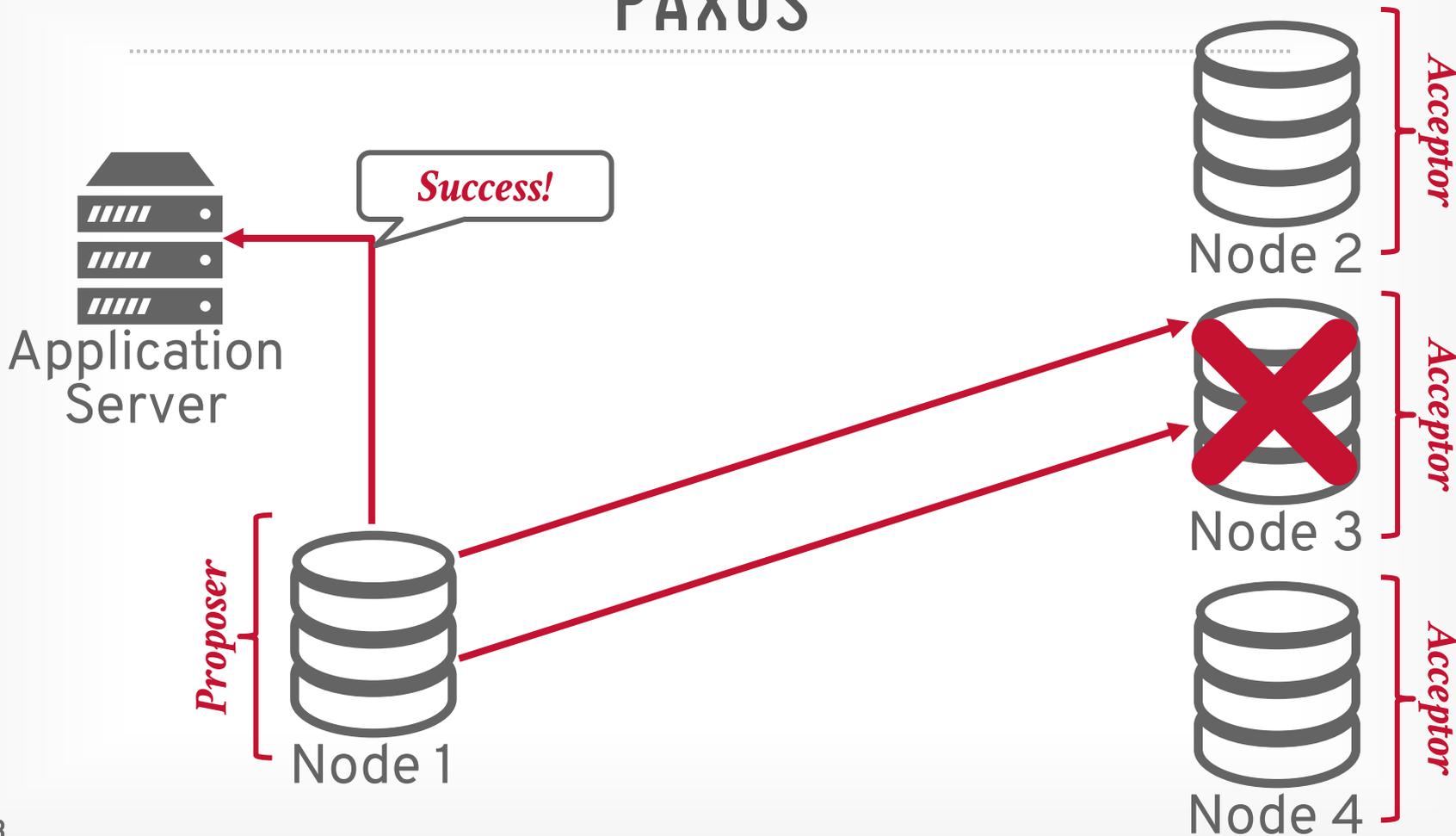
# PAXOS



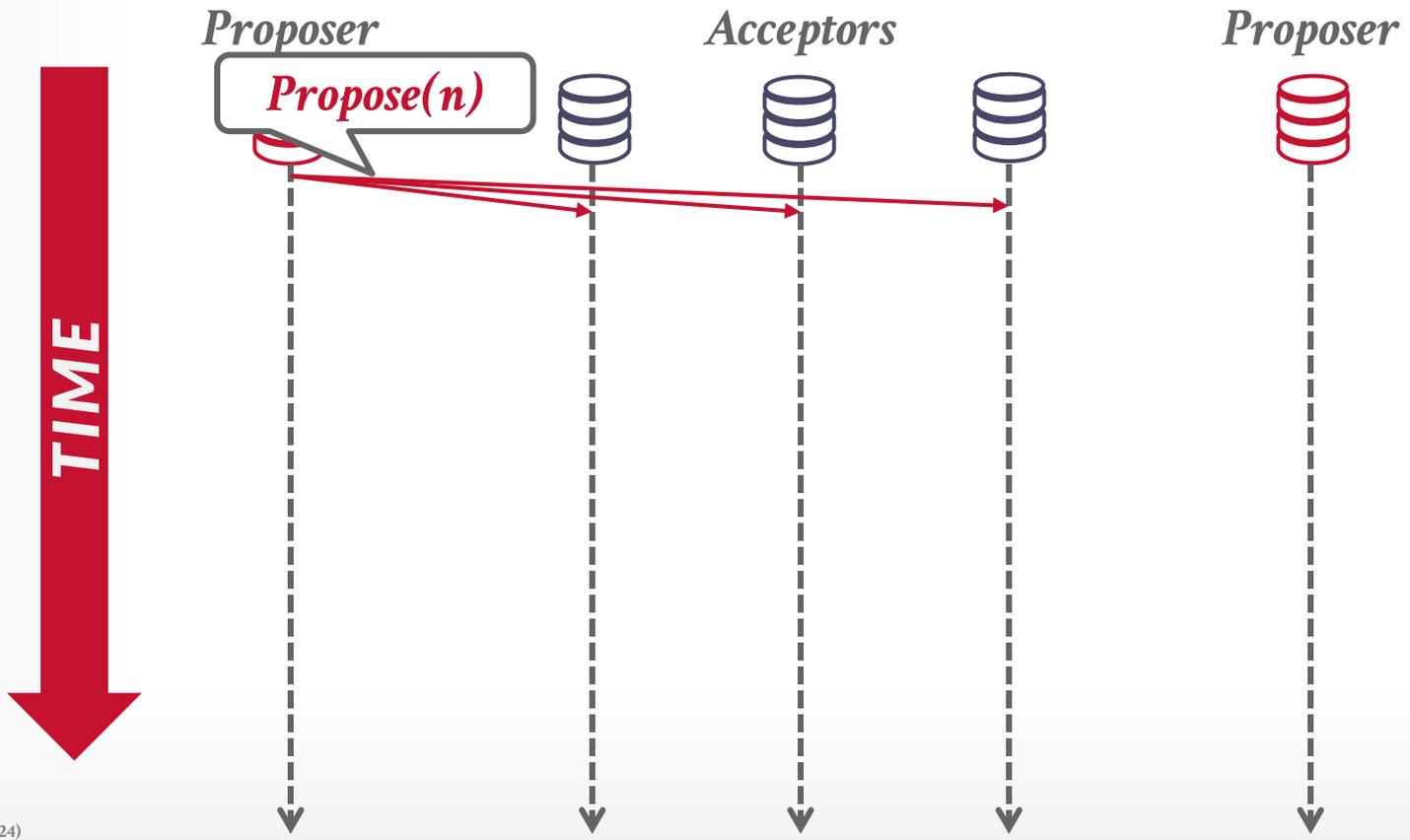
# PAXOS



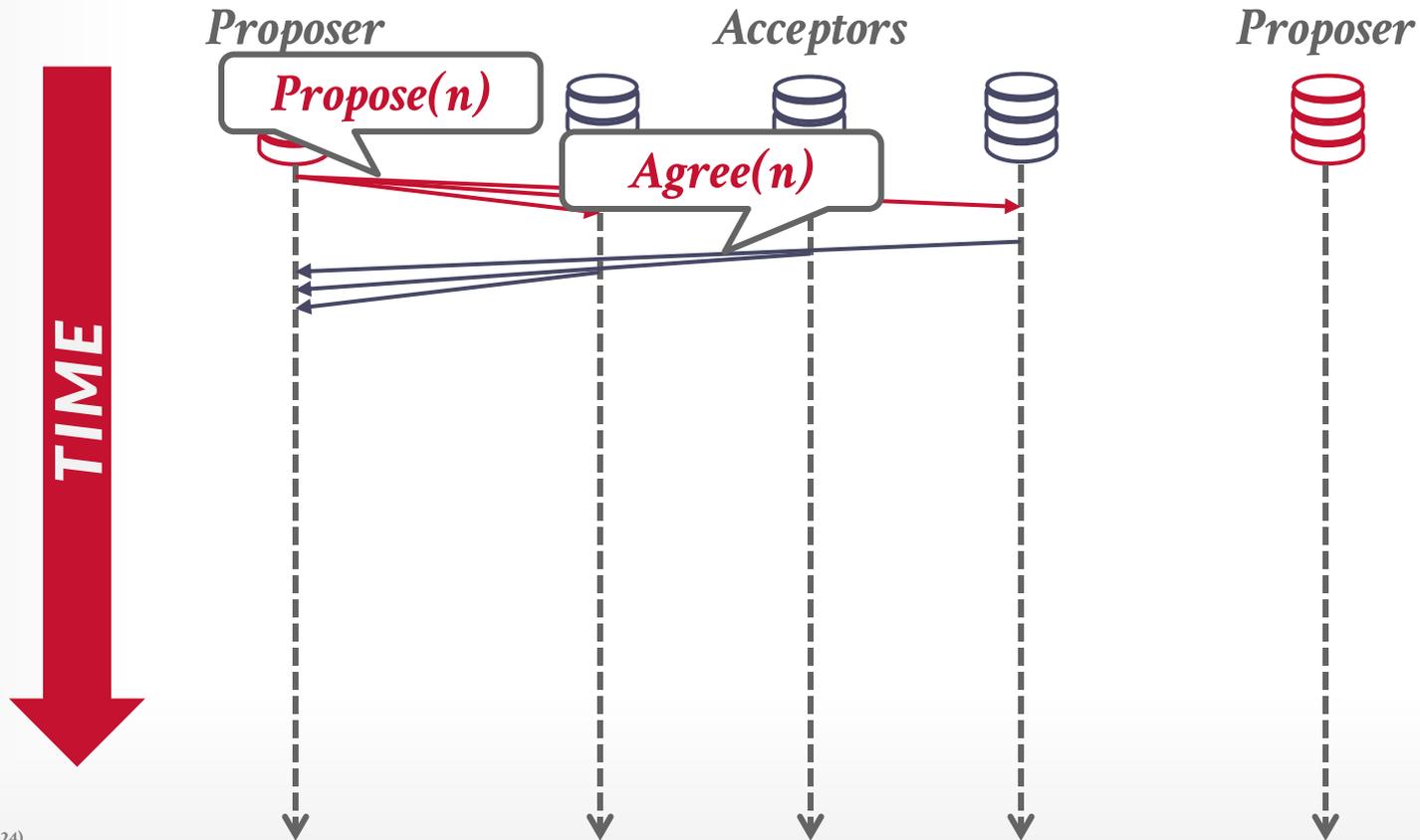
# PAXOS



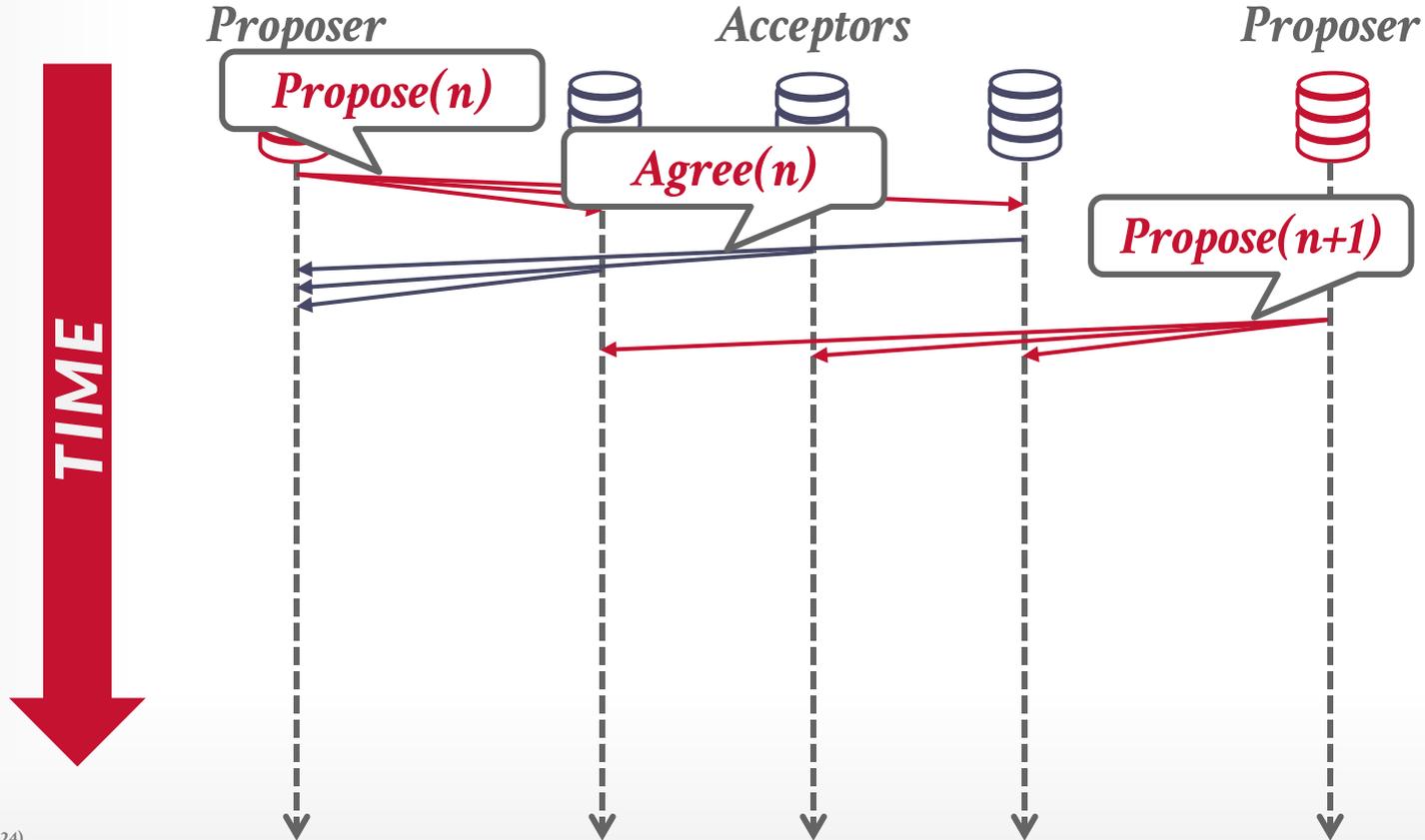
# PAXOS



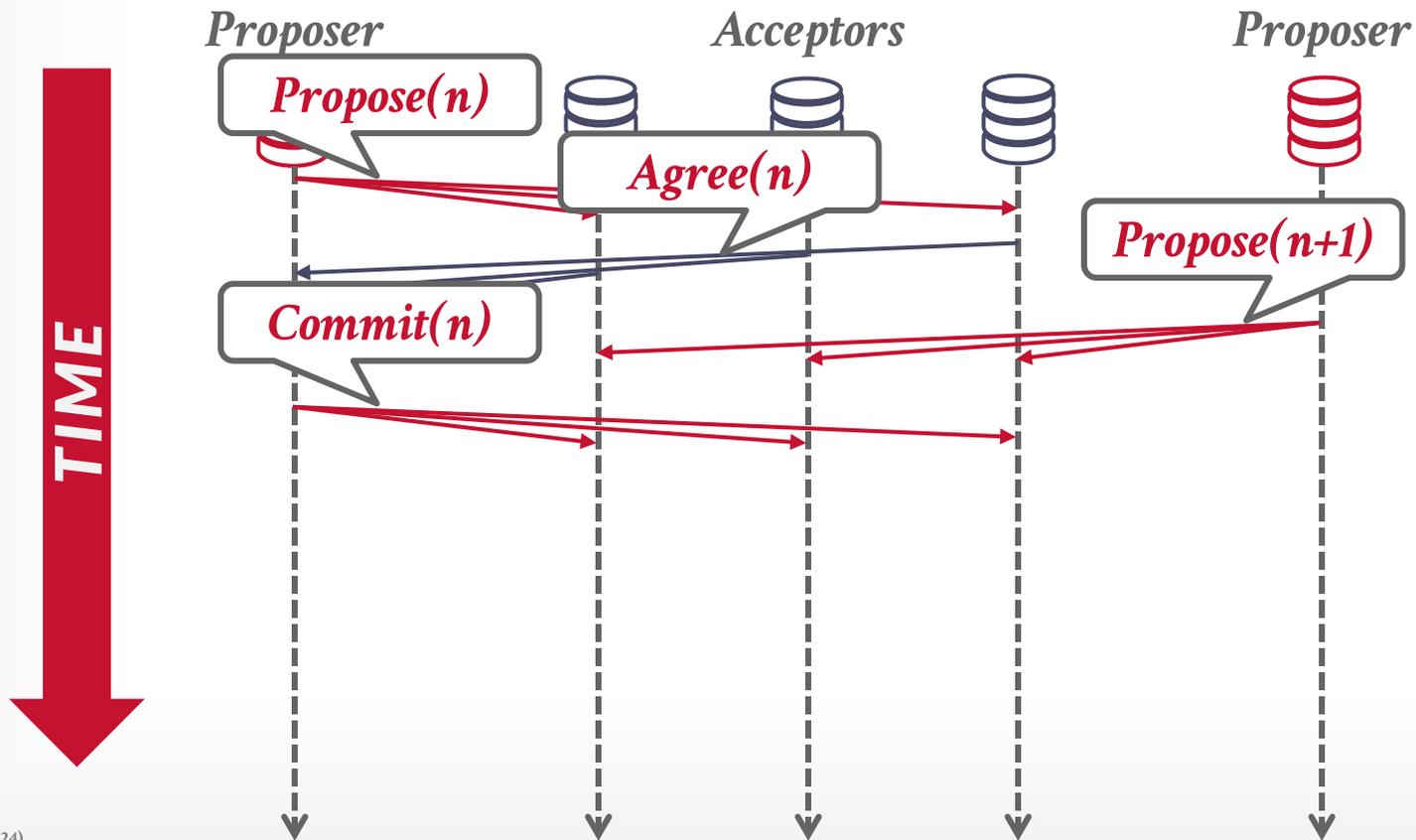
# PAXOS



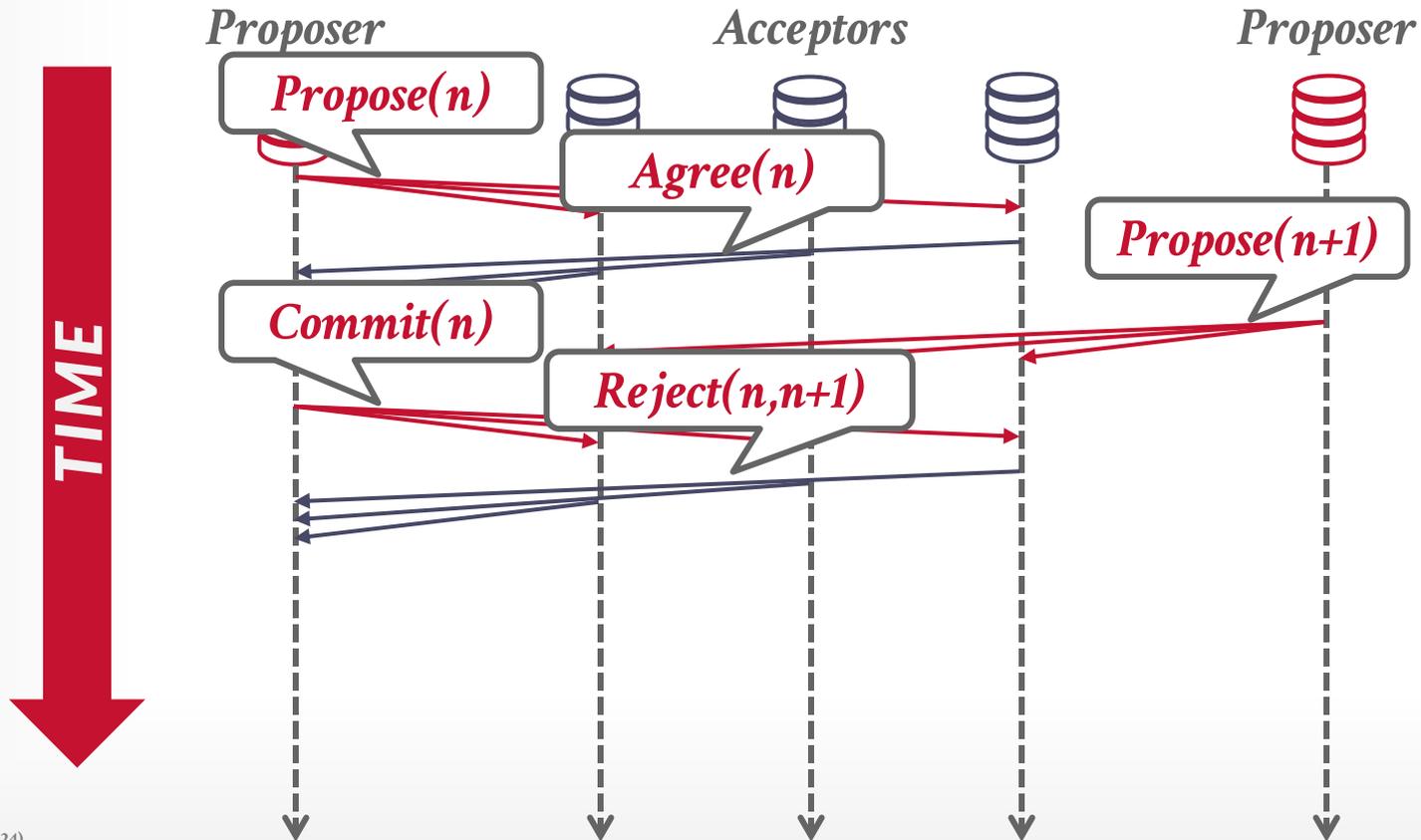
# PAXOS



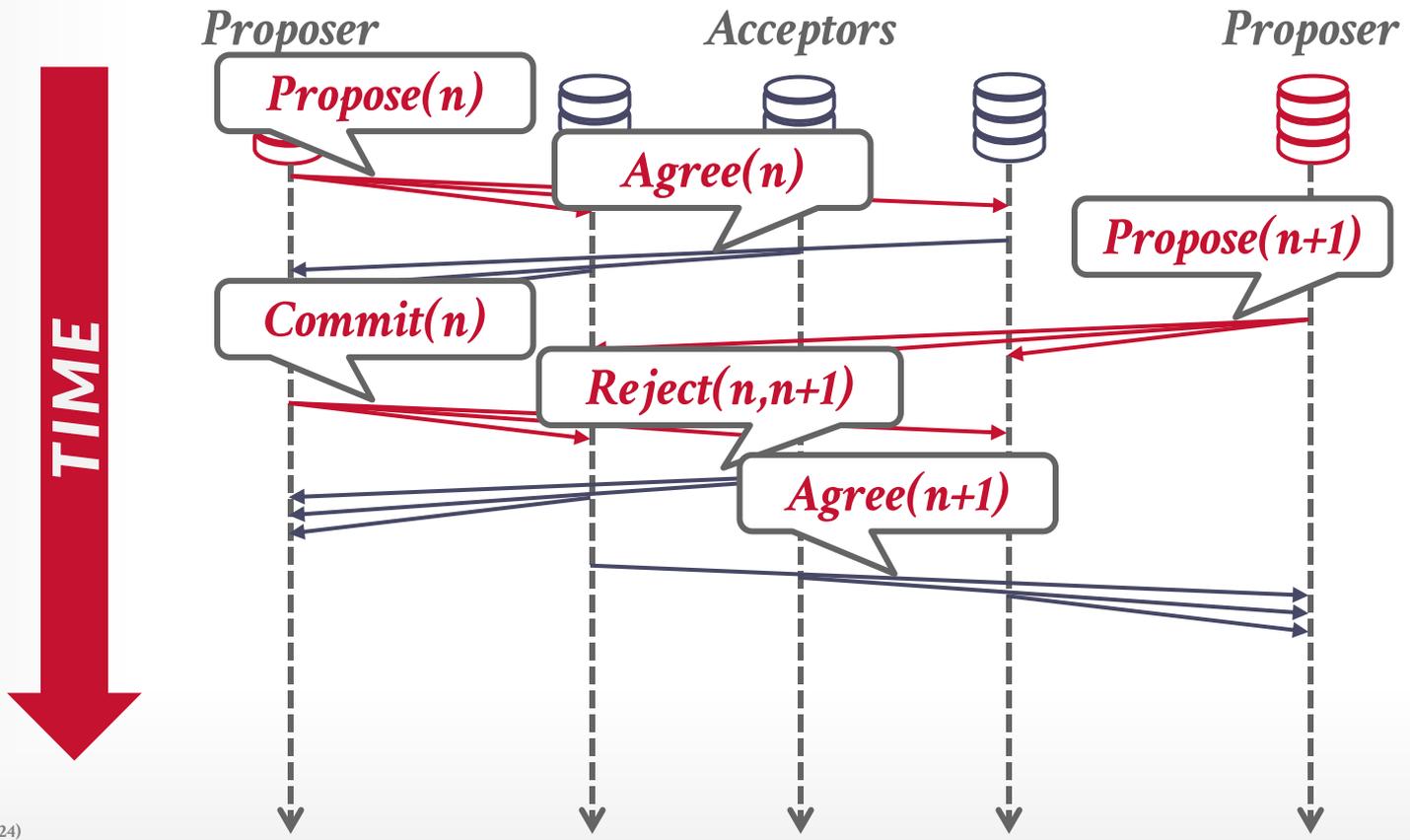
# PAXOS



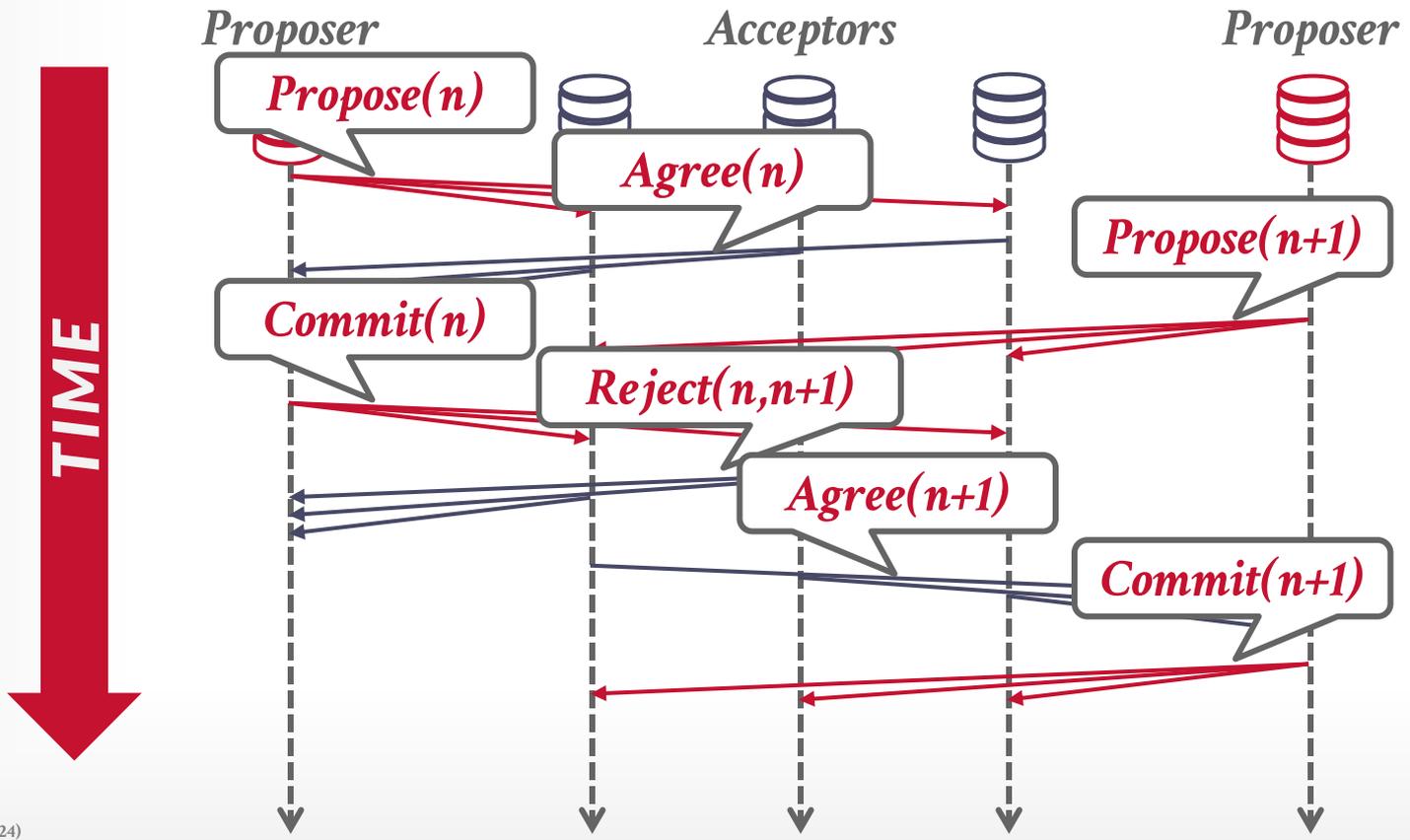
# PAXOS



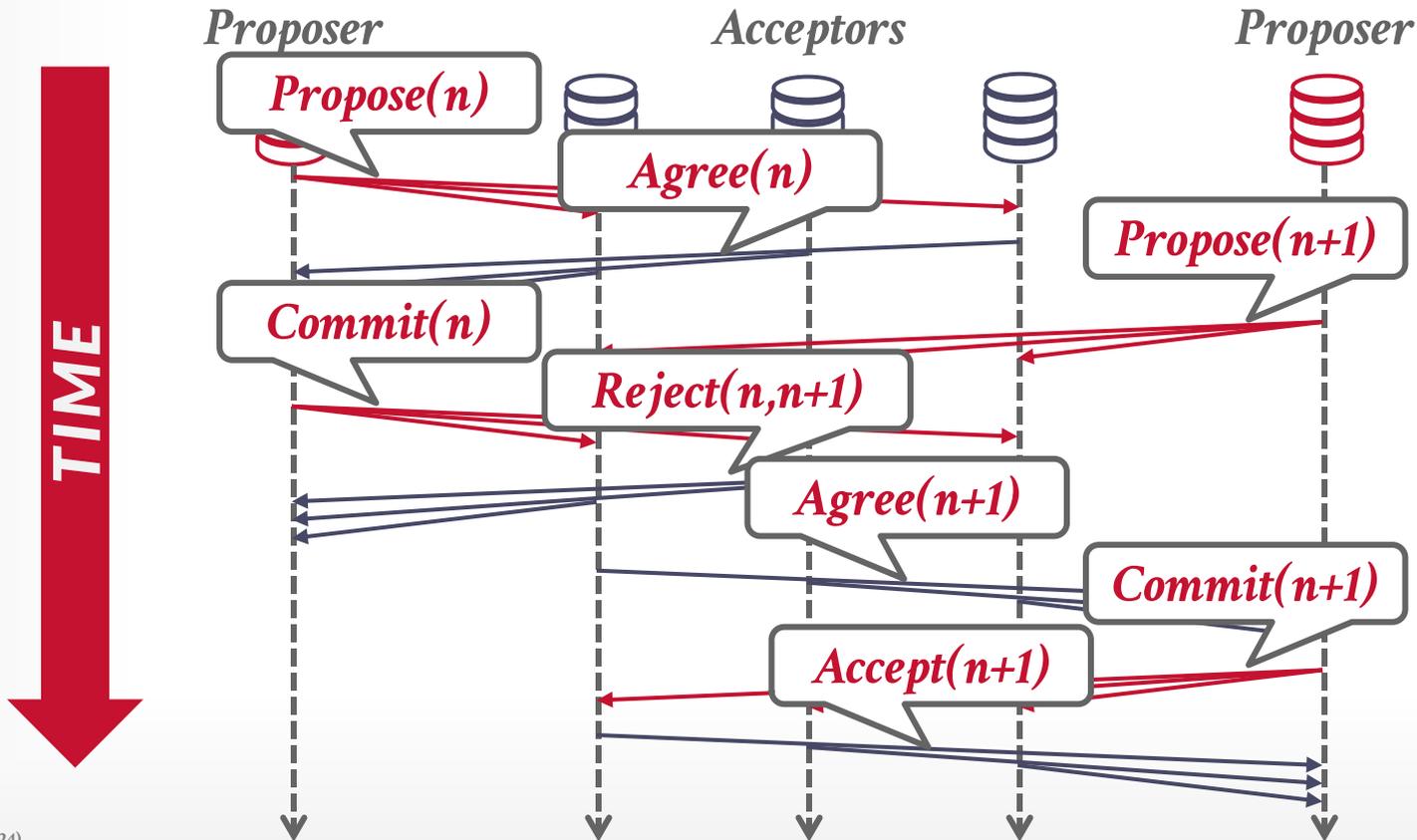
# PAXOS



# PAXOS



# PAXOS



# 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

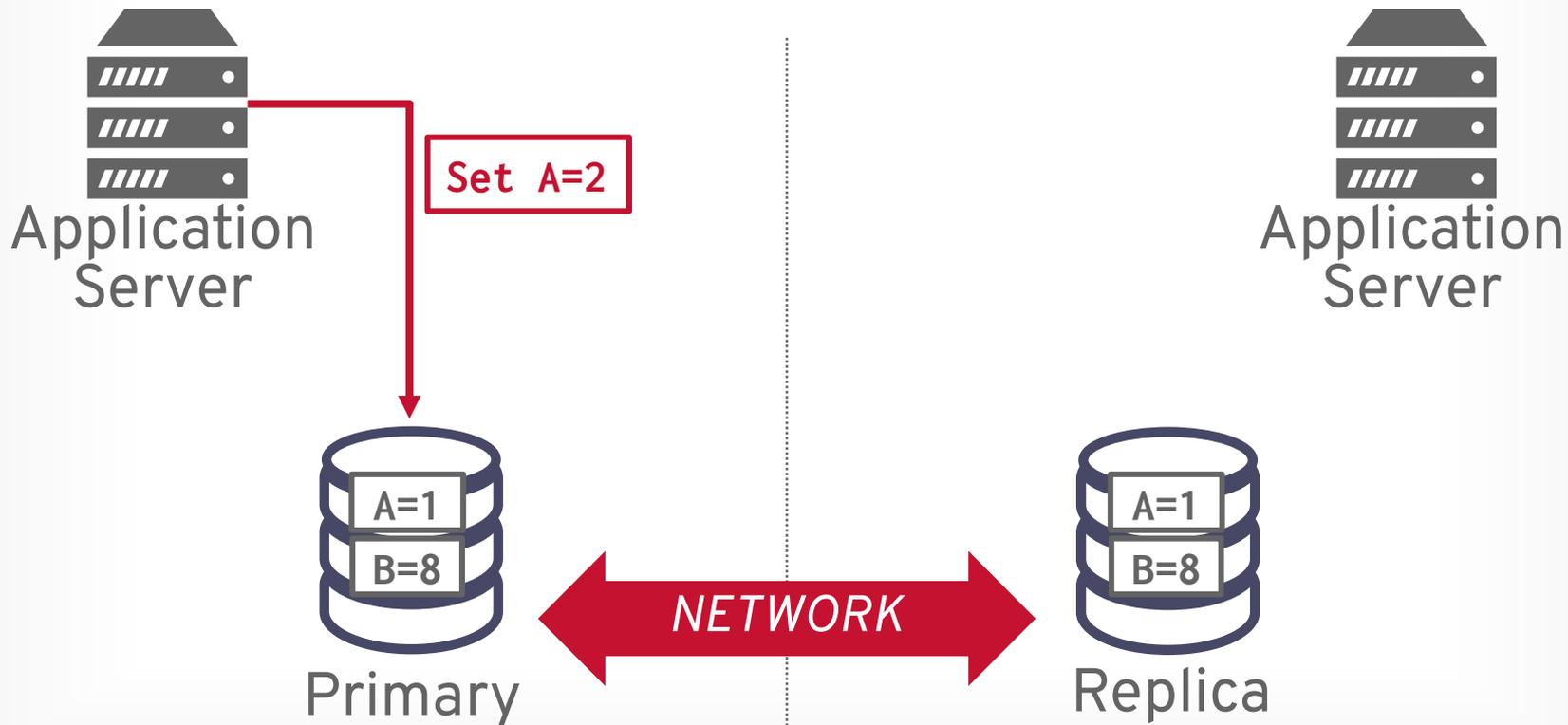
---

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

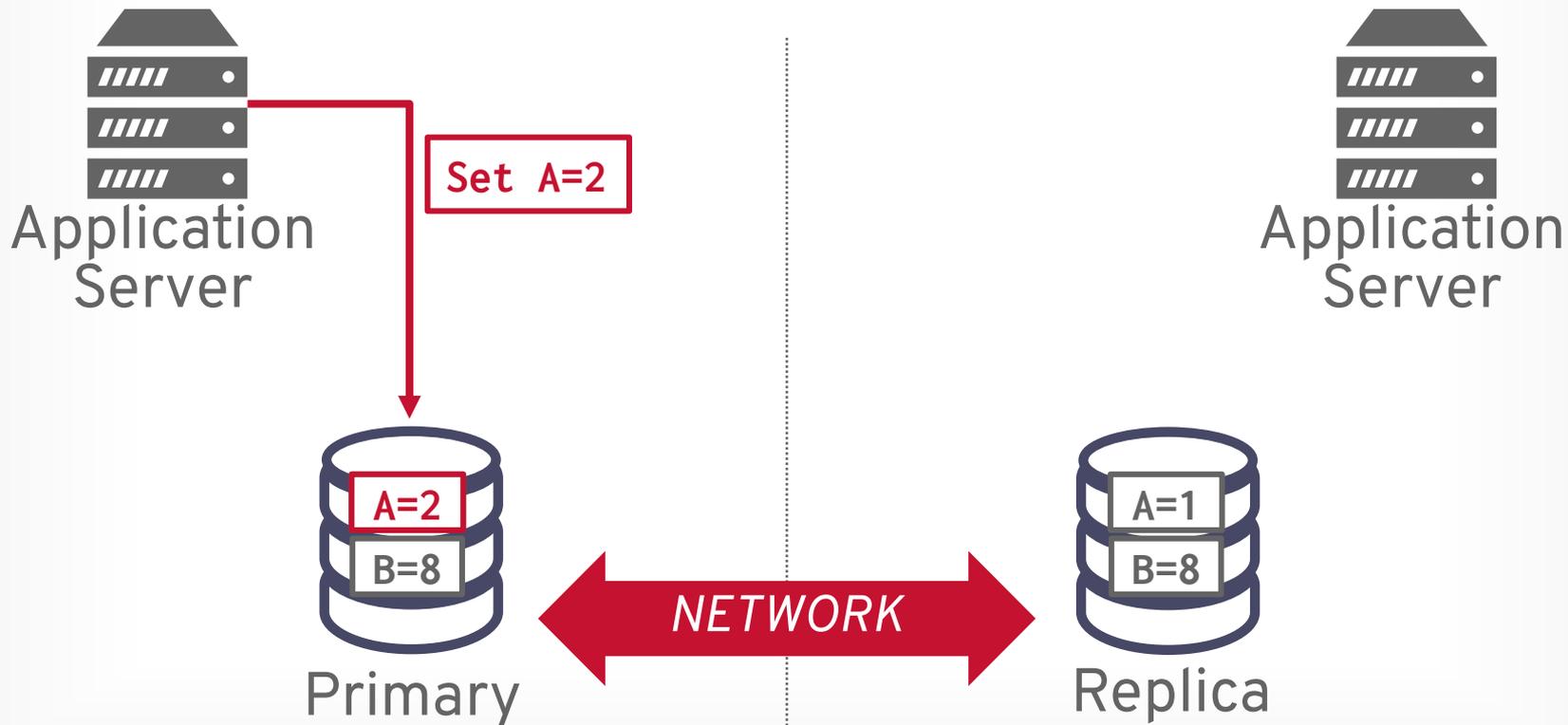
- Consistent
- Always Available
- Network Partition Tolerant

Whether a DBMS provides Consistency or Availability during a Network partition.

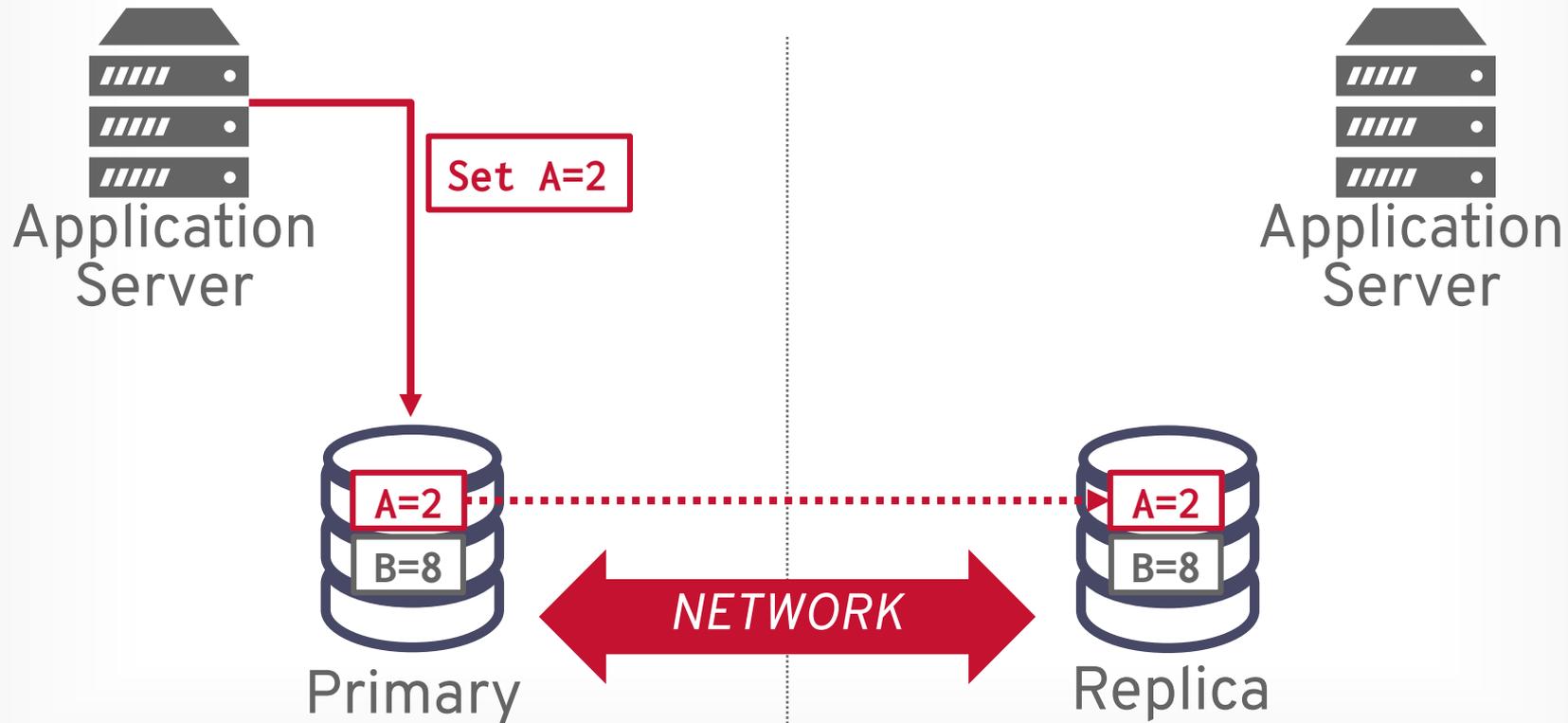
# CONSISTENCY



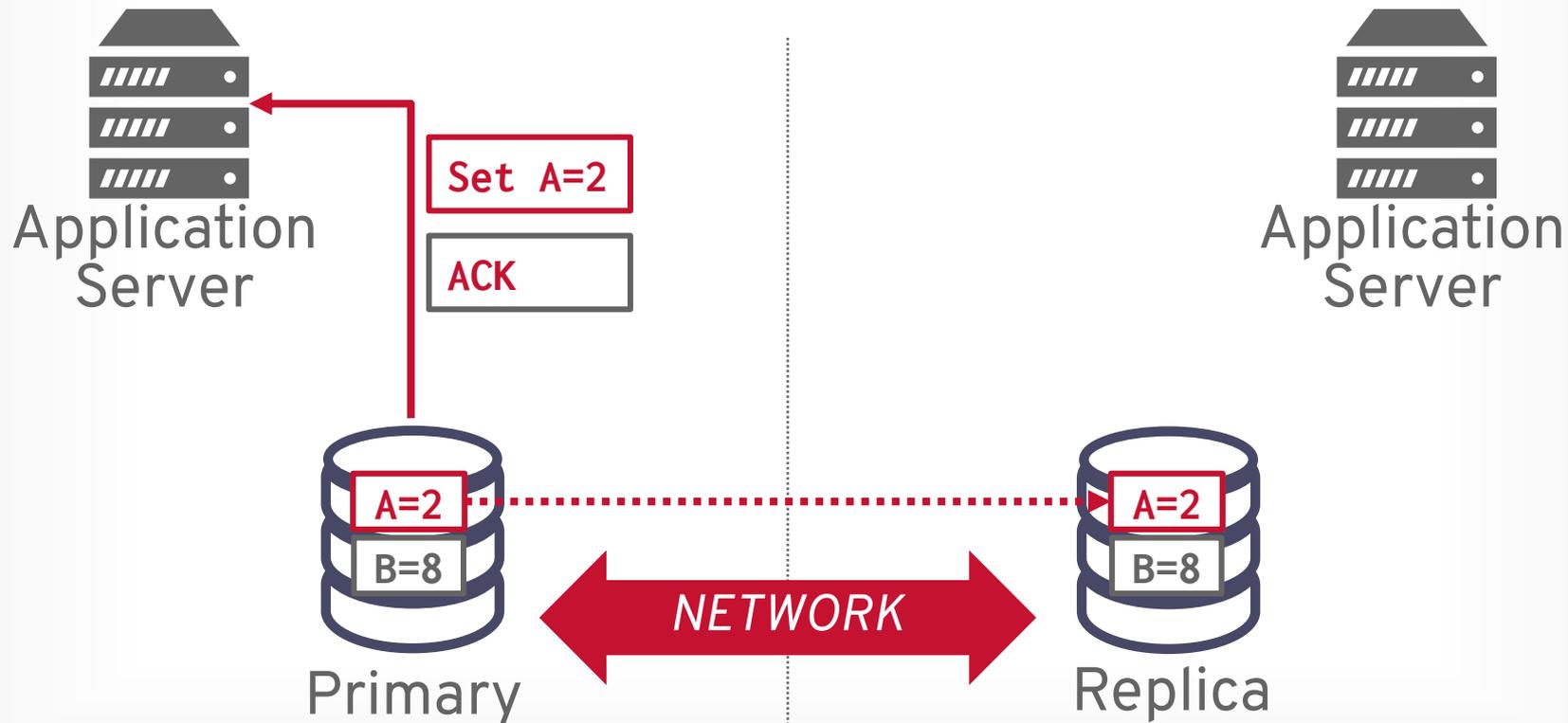
# CONSISTENCY



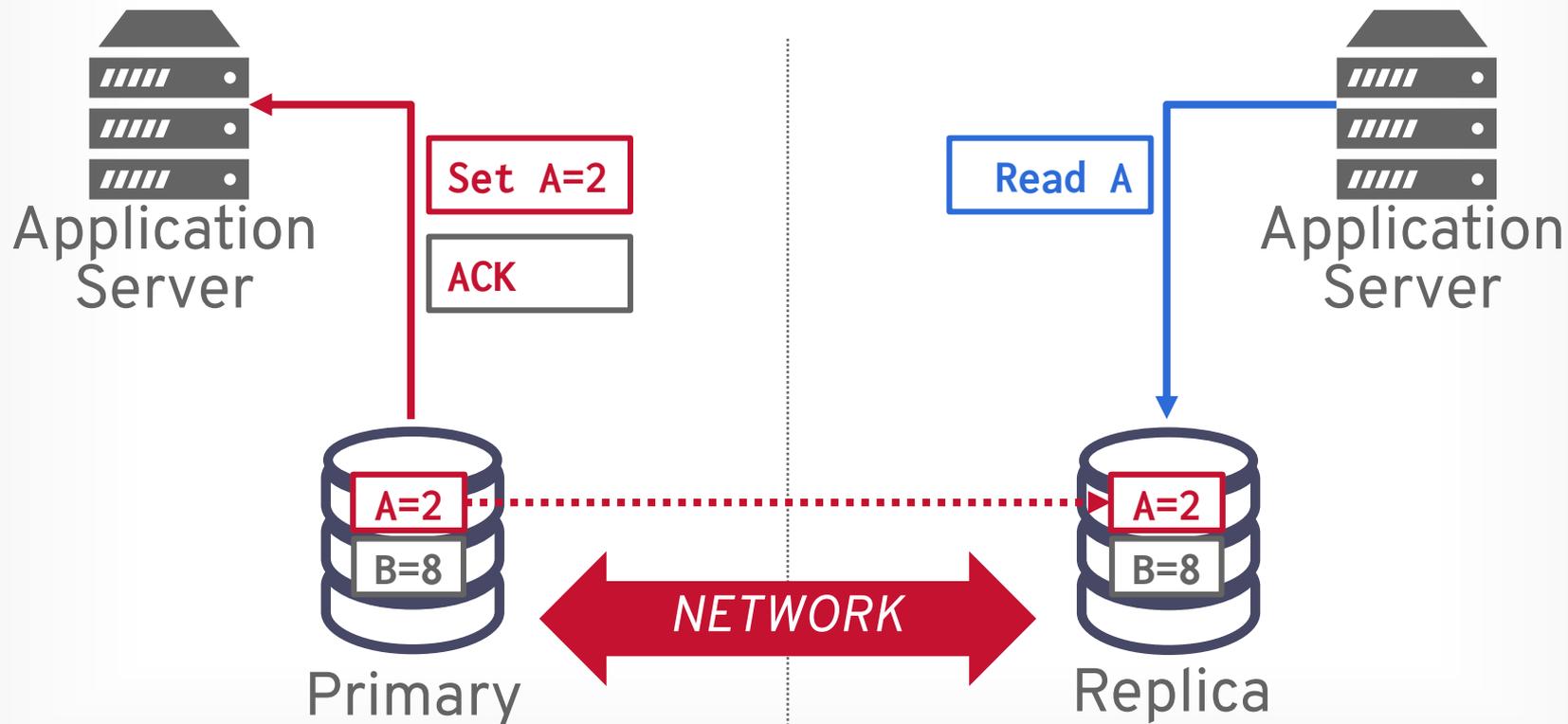
# CONSISTENCY



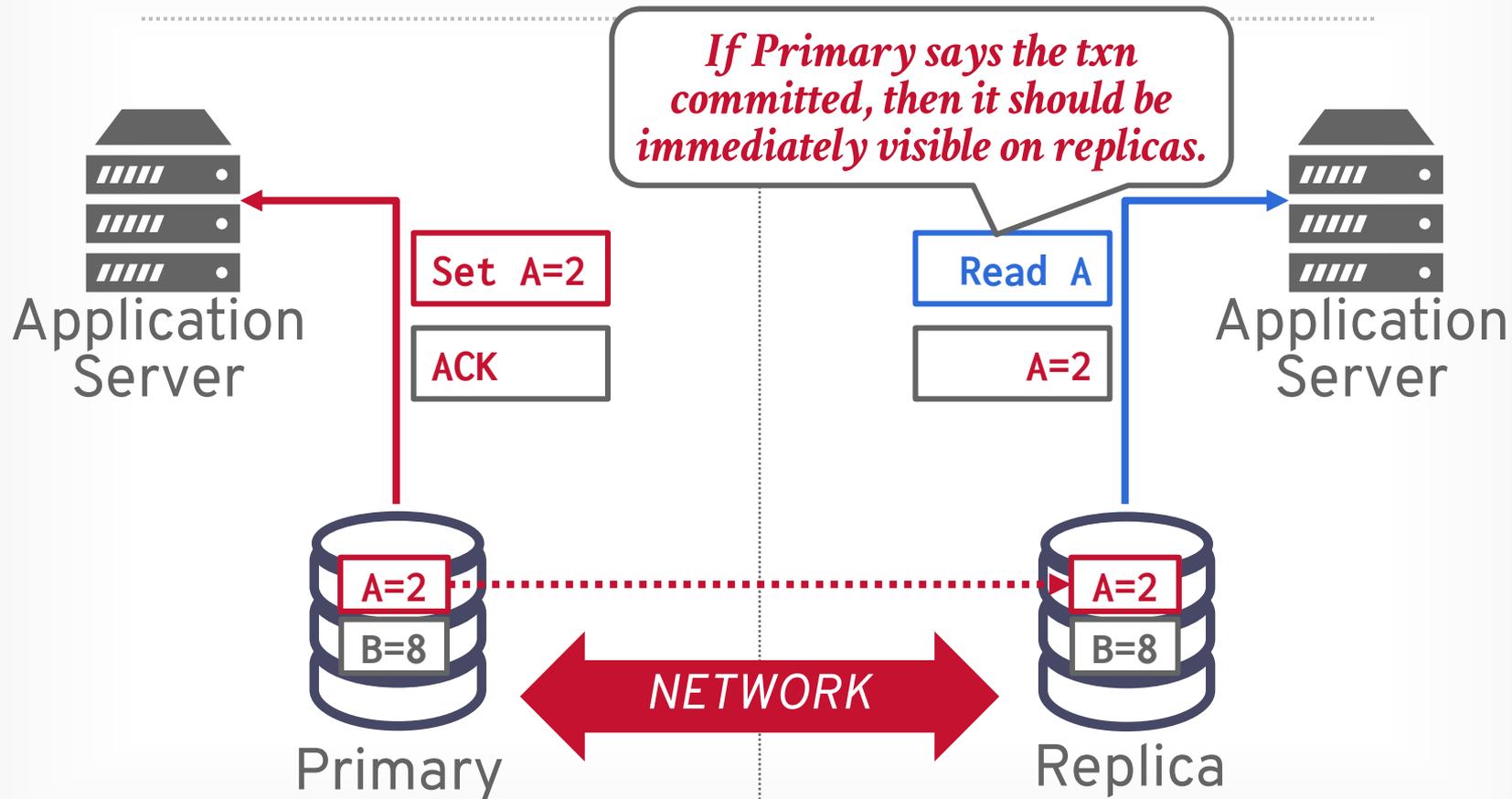
# CONSISTENCY



# CONSISTENCY

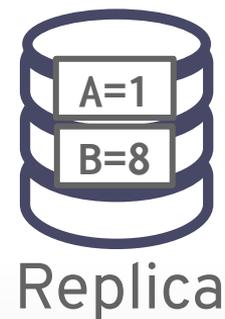
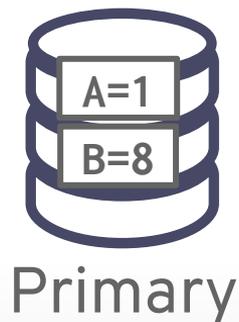
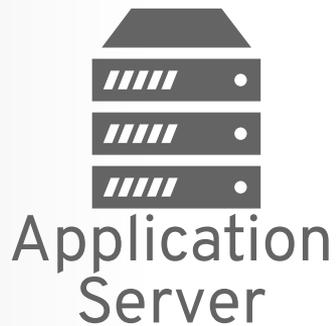


# CONSISTENCY



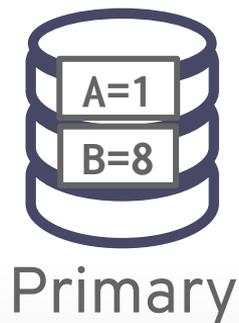
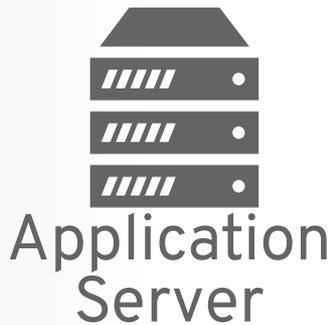
# AVAILABILITY

---

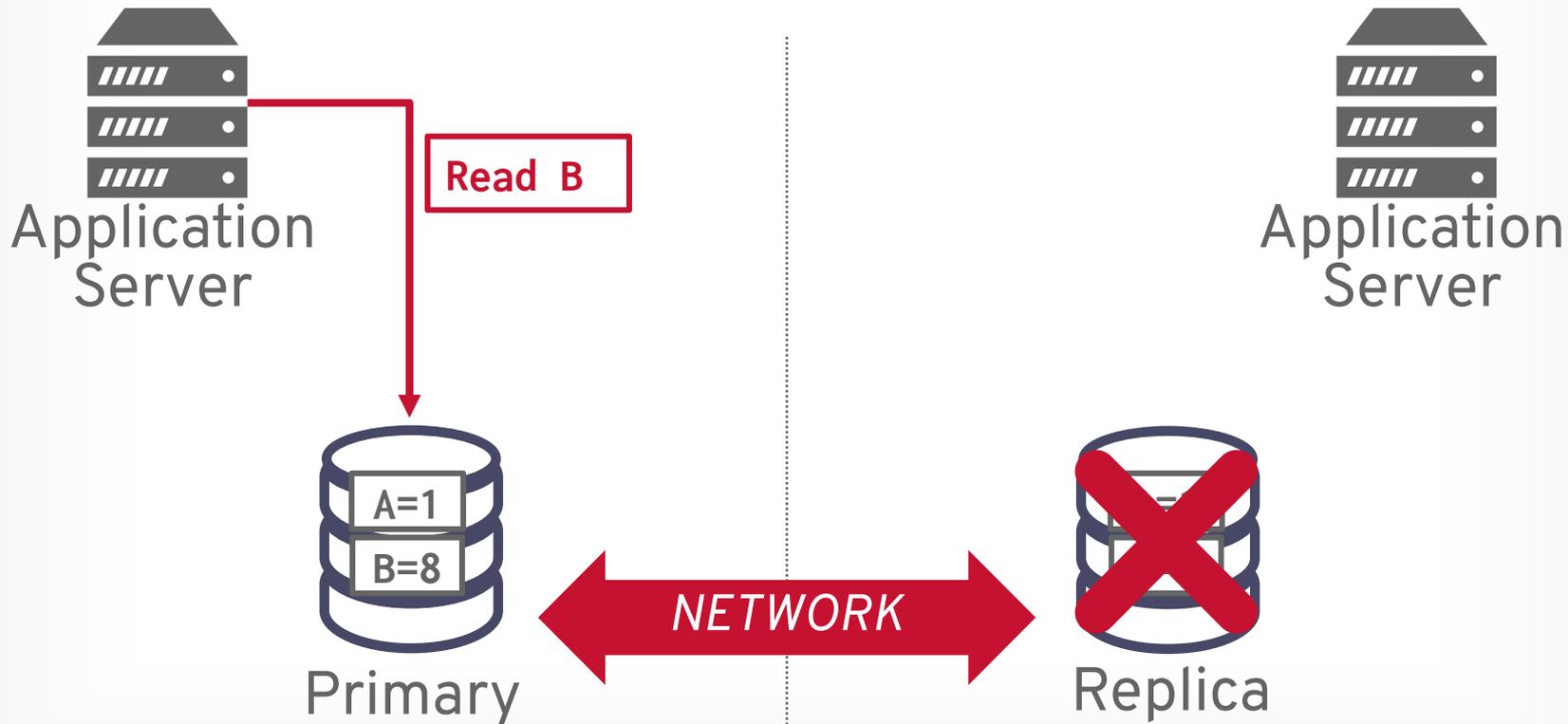


# AVAILABILITY

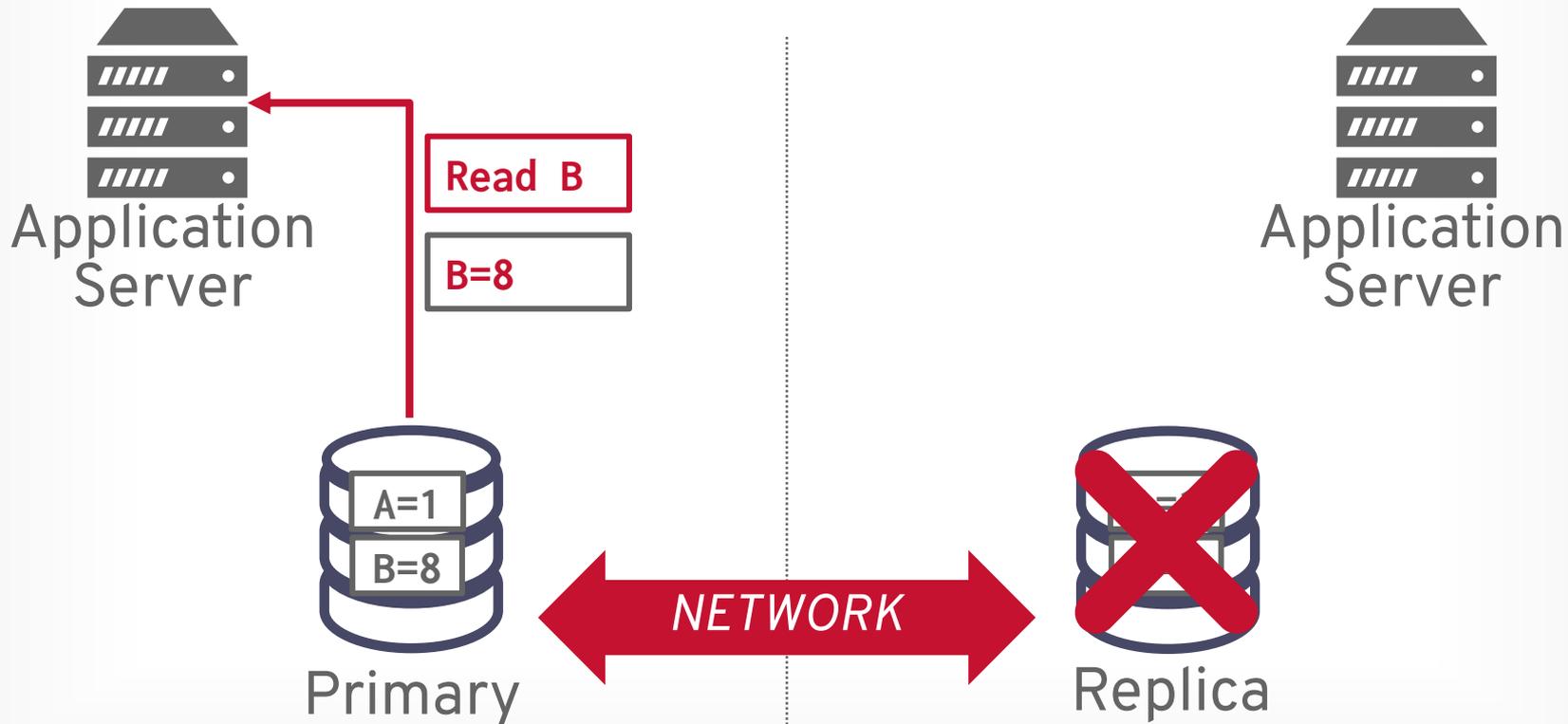
---



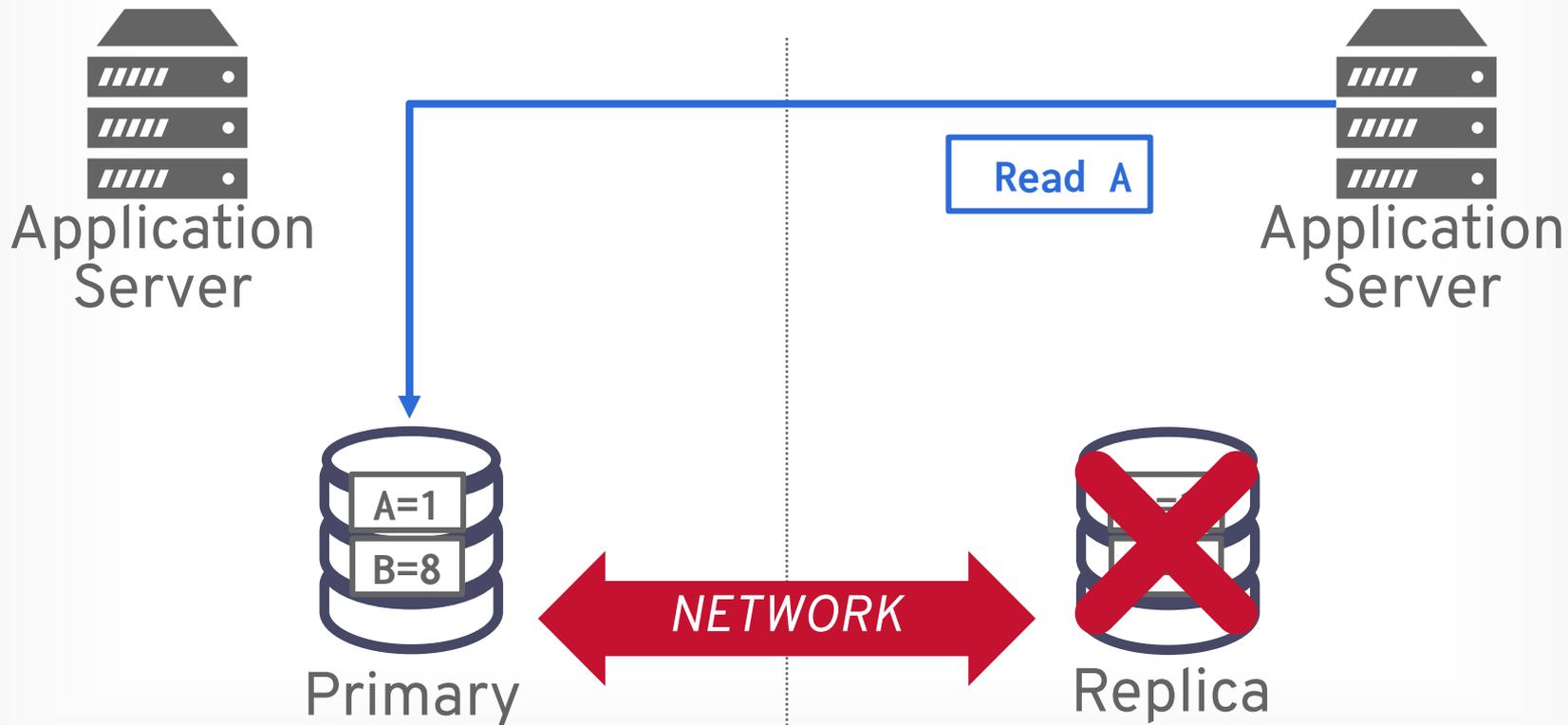
# AVAILABILITY



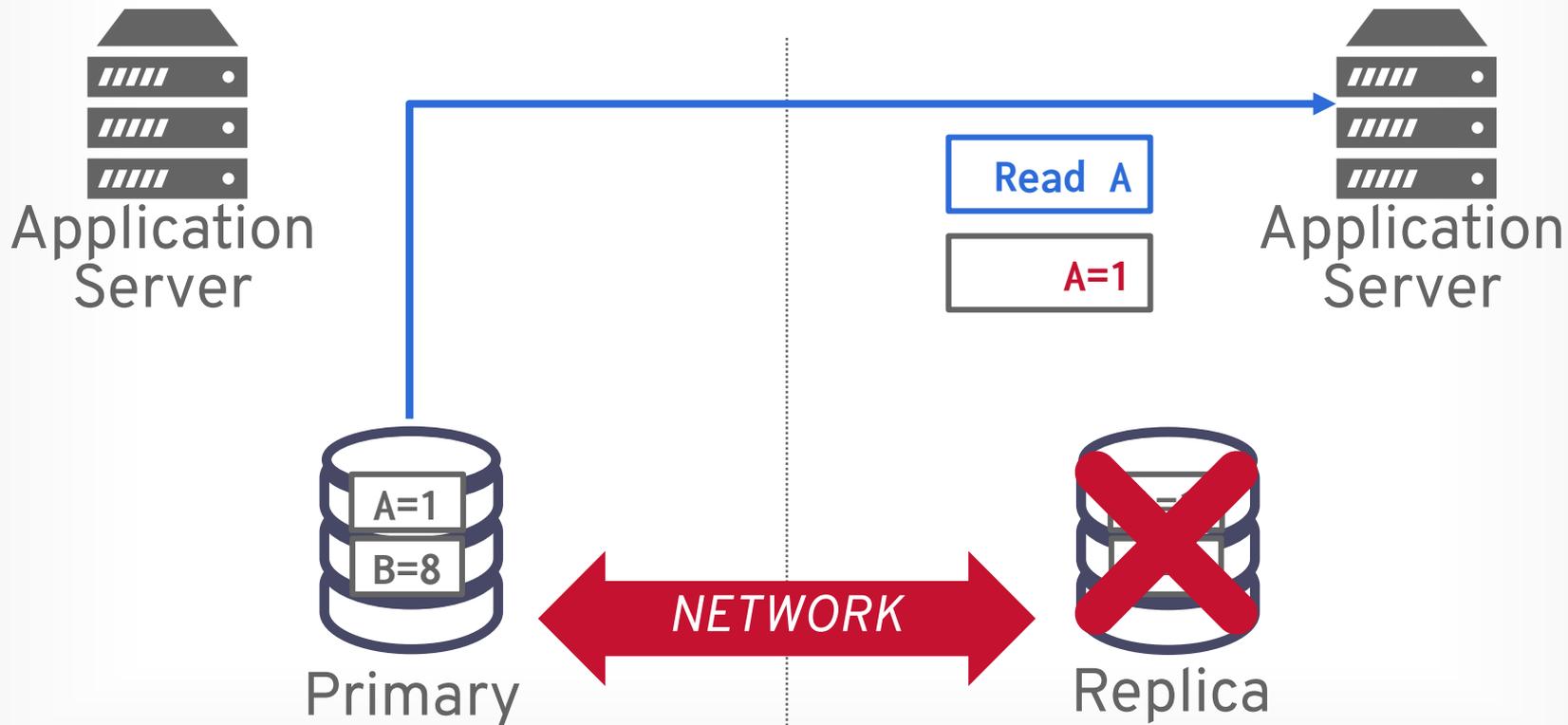
# AVAILABILITY



# AVAILABILITY

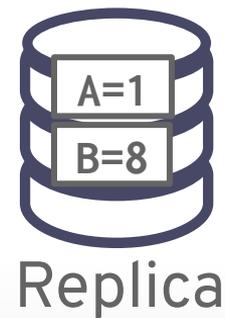
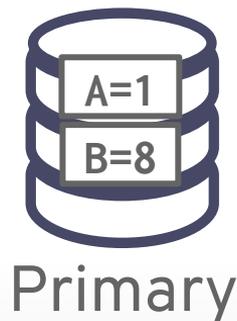
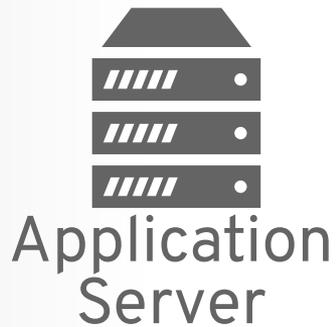


# AVAILABILITY



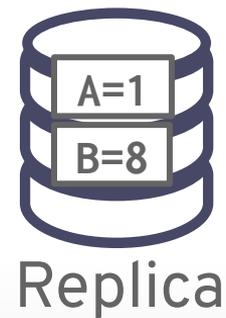
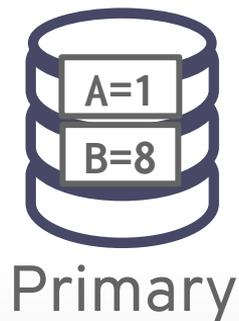
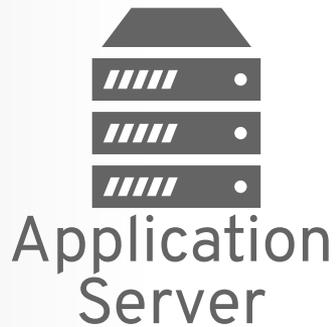
# PARTITION TOLERANCE

---



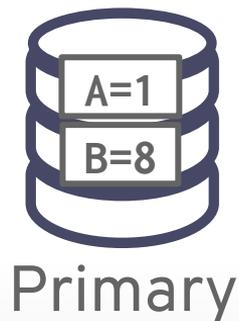
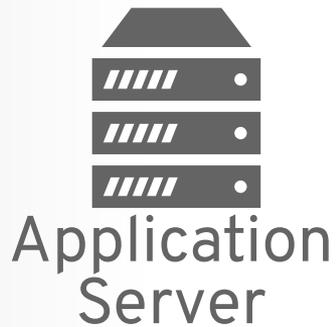
# PARTITION TOLERANCE

---

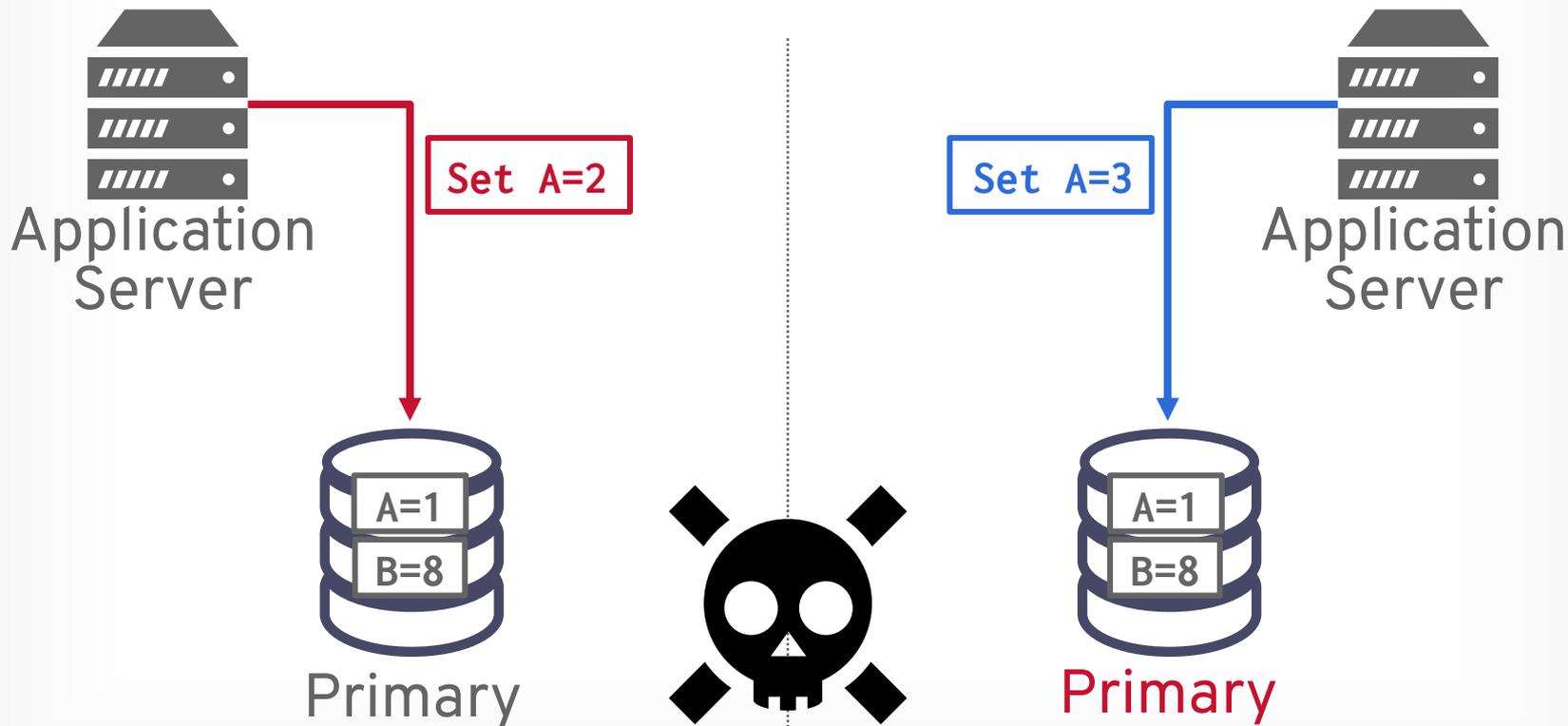


# PARTITION TOLERANCE

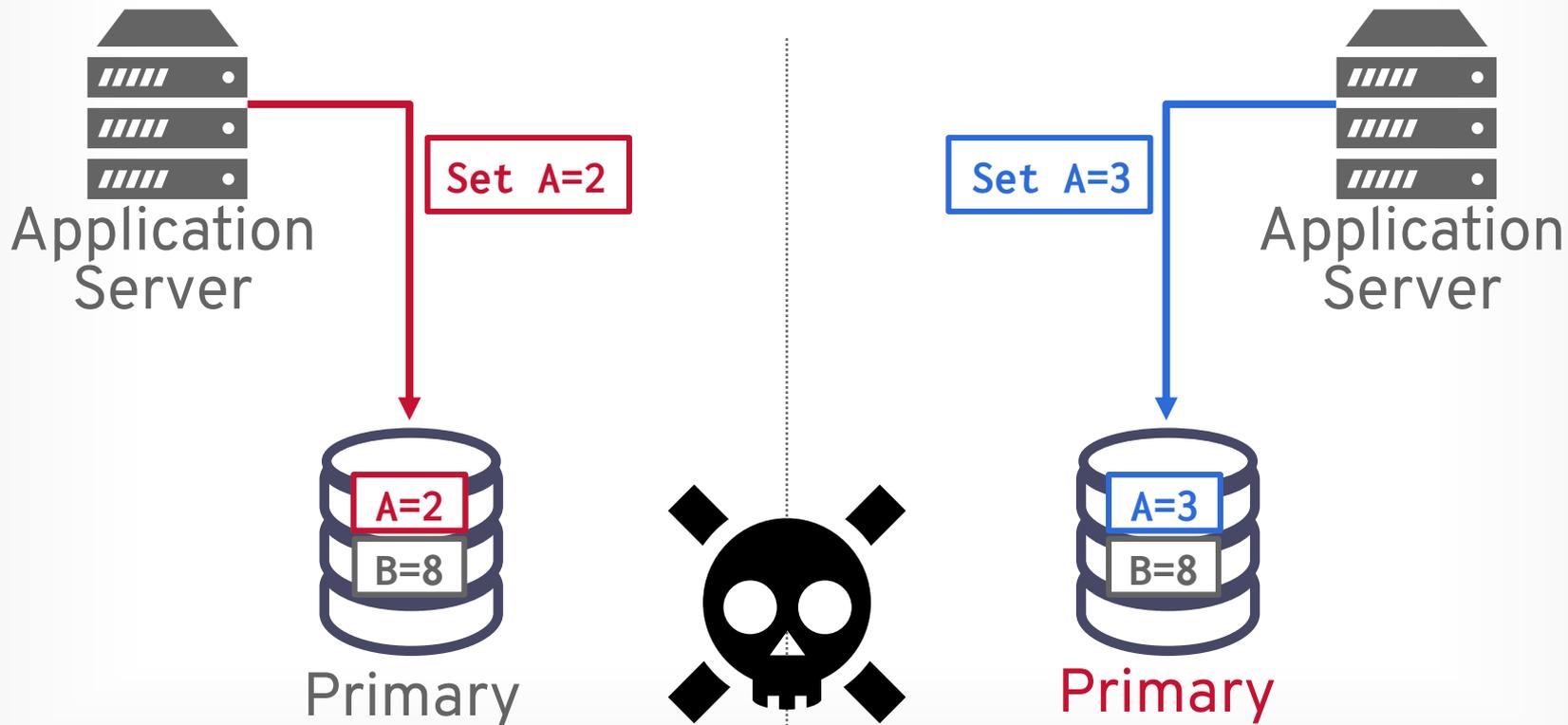
---



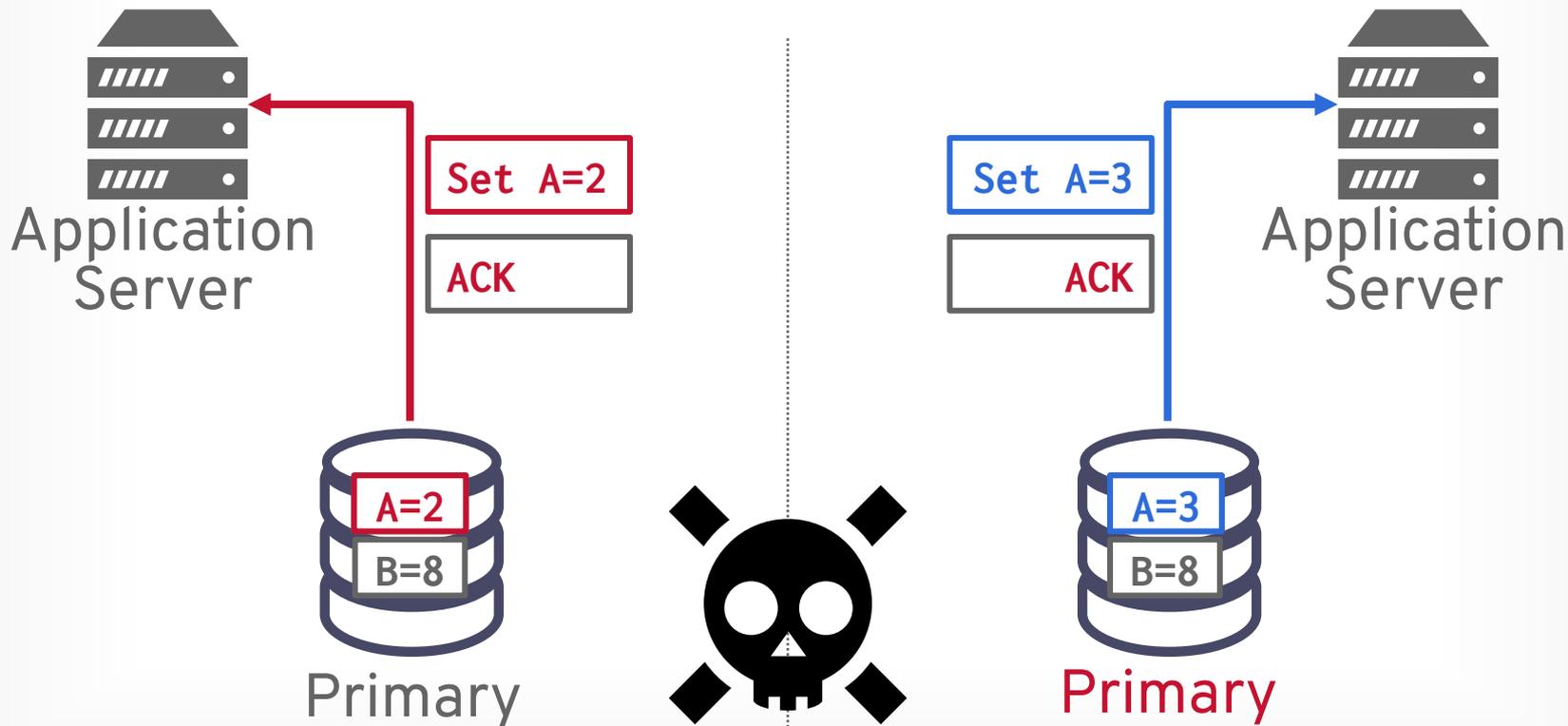
# PARTITION TOLERANCE



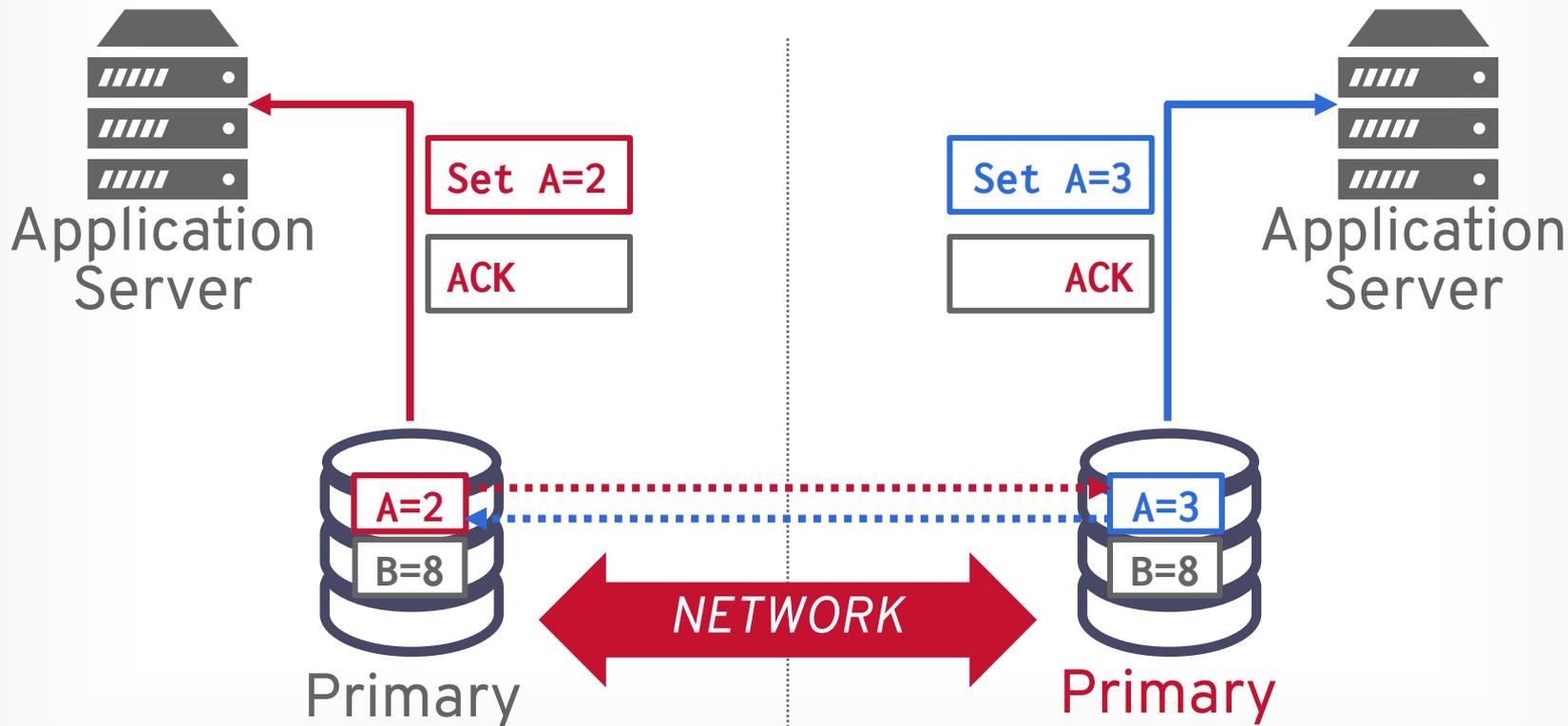
# PARTITION TOLERANCE



# PARTITION TOLERANCE



# PARTITION TOLERANCE



# 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!*

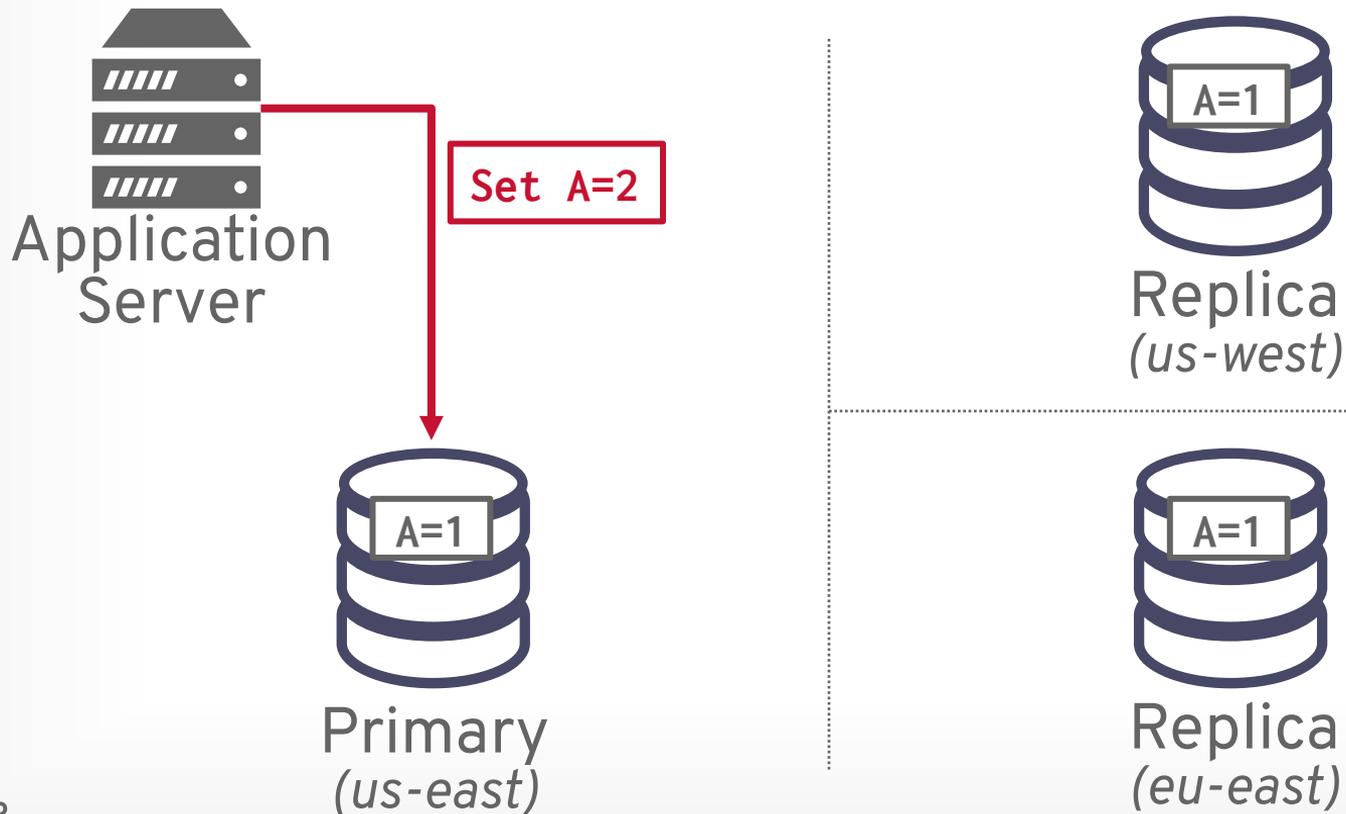
# PACELC THEOREM

---

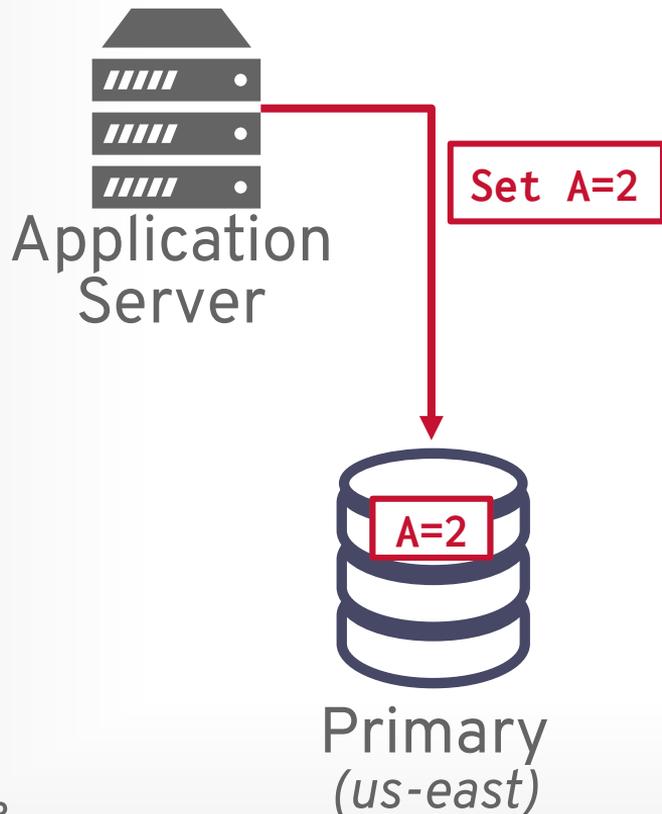
Extension to CAP proposed in 2010 to include consistency vs. latency trade-offs:

- Partition Tolerant
- Always Available
- Consistent
- Else, choose during normal operations
- Latency
- Consistency

# LATENCY VS. CONSISTENCY



# LATENCY VS. CONSISTENCY

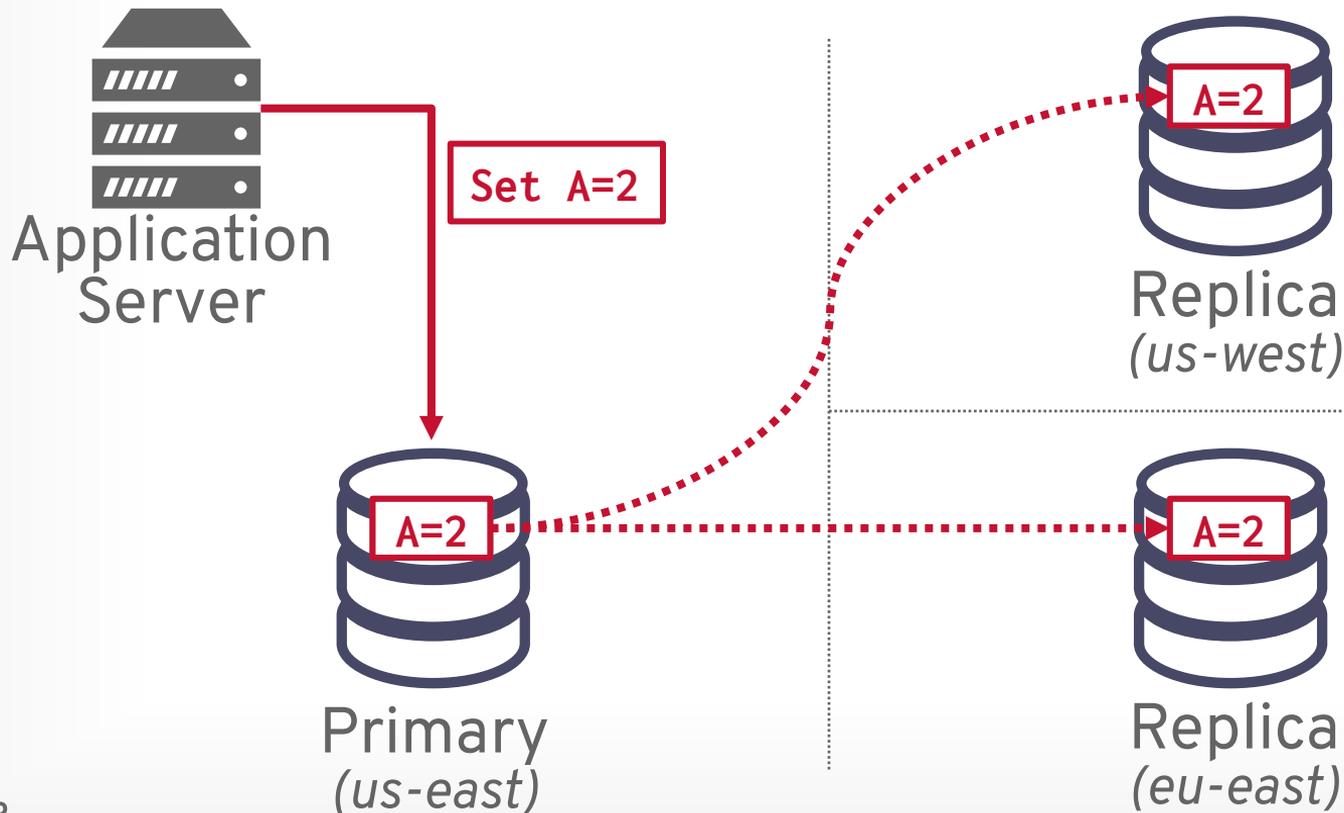


Replica  
(us-west)



Replica  
(eu-east)

# LATENCY VS. CONSISTENCY



# LATENCY VS. CONSISTENCY



Application

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



Primary  
(us-east)

ACK



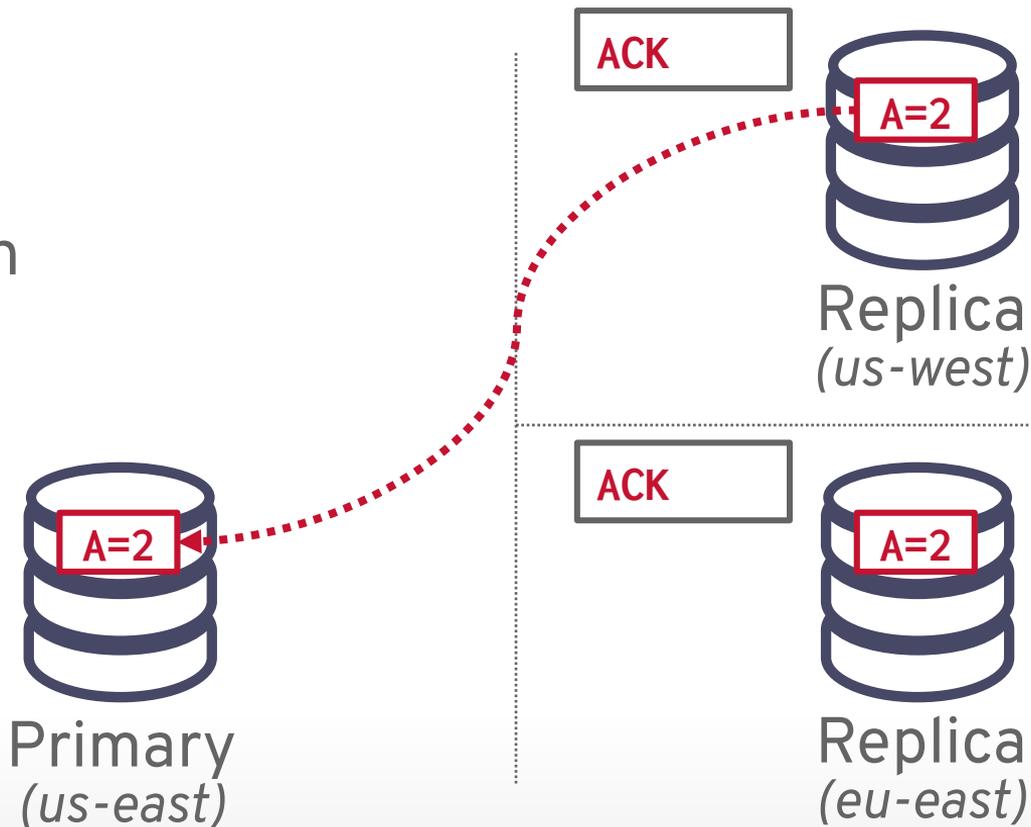
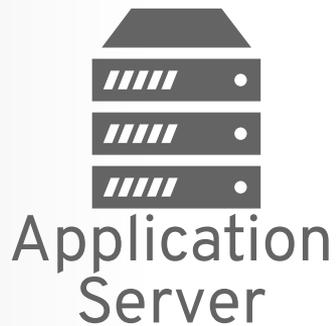
Replica  
(us-west)

ACK

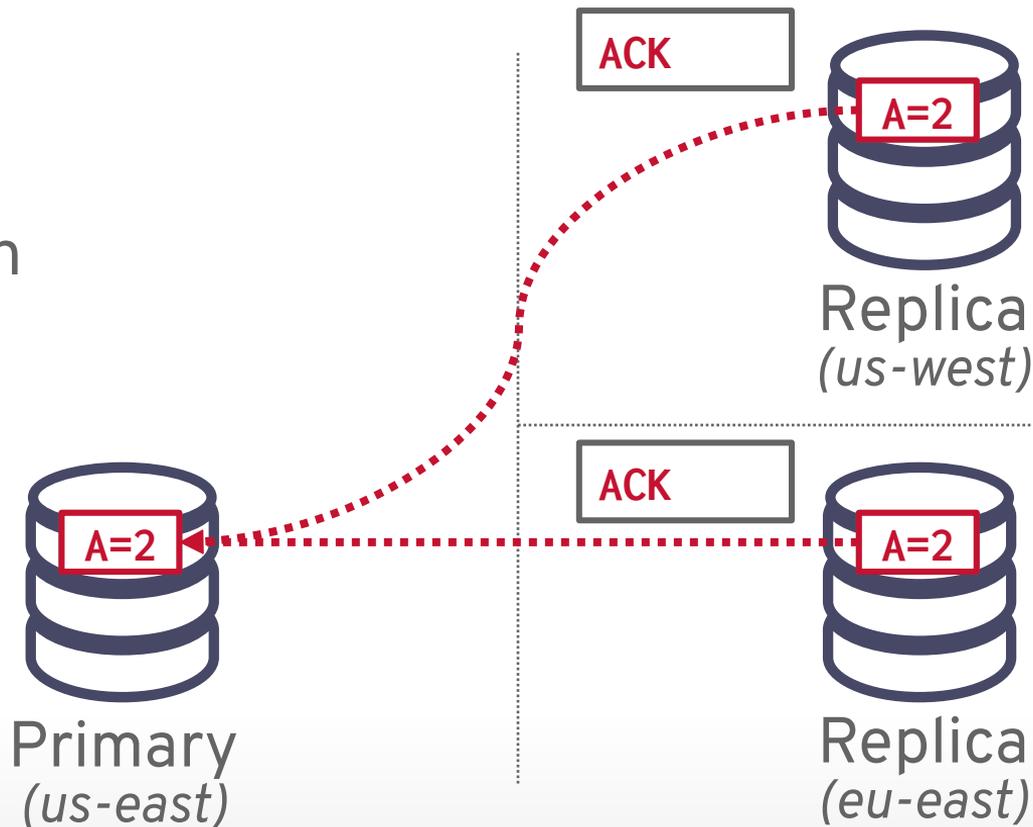
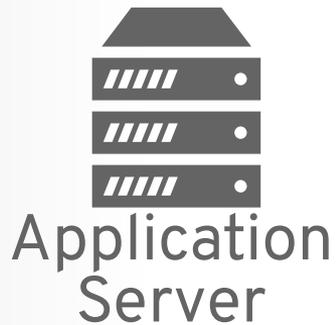


Replica  
(eu-east)

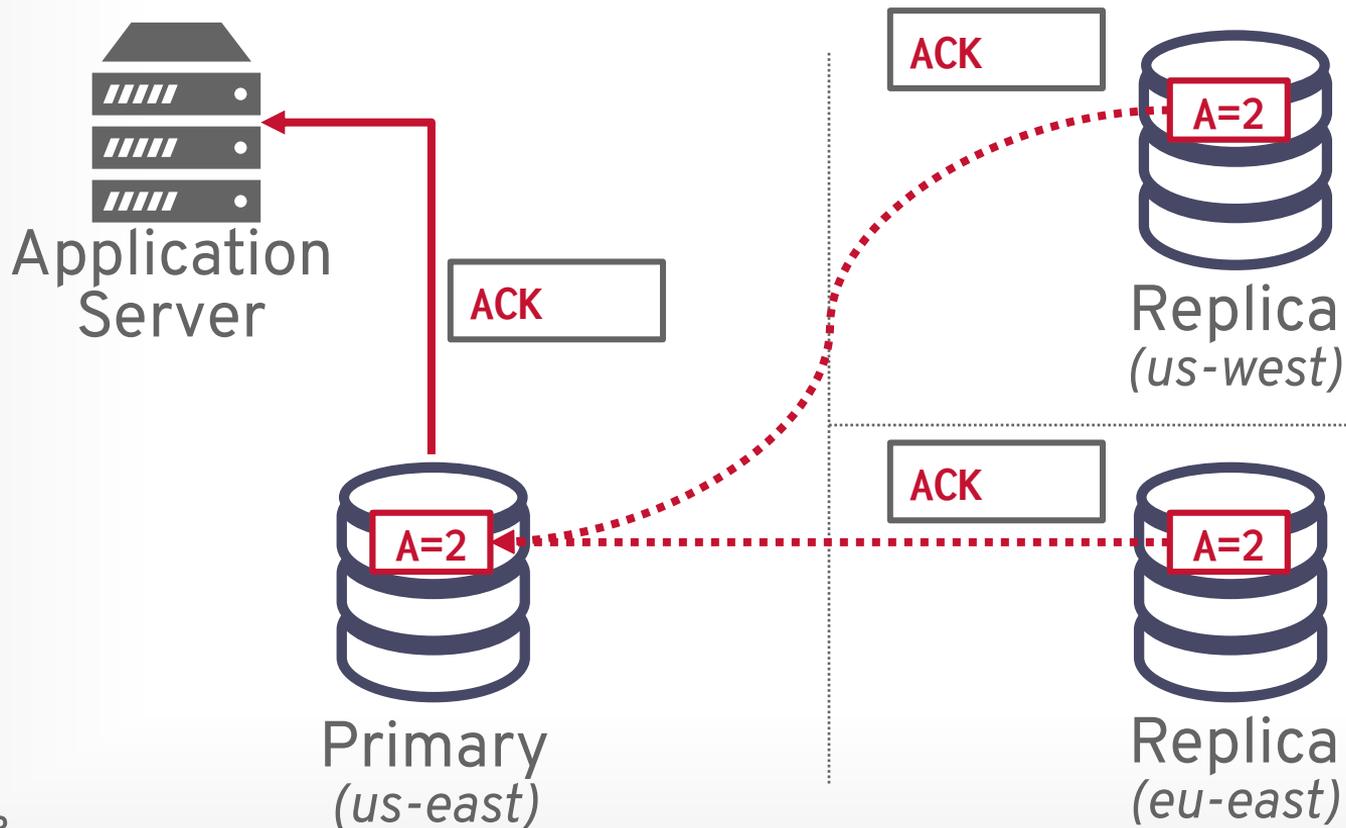
# LATENCY VS. CONSISTENCY



# LATENCY VS. CONSISTENCY



# LATENCY VS. CONSISTENCY



# CONCLUSION

---

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

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

More info (and humiliation):

→ [Kyle Kingsbury's Jepsen Project](#)

# NEXT CLASS

---

## Distributed OLAP Systems