Carnegie Mellon University

Database Systems

Distributed Databases

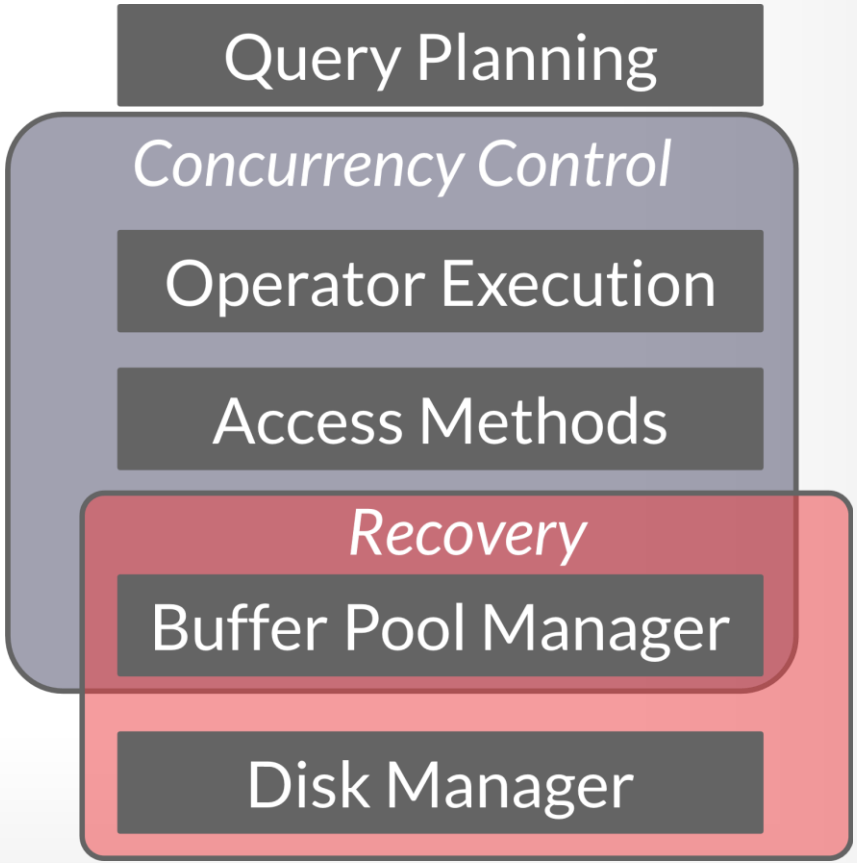
15-445/645 FALL 2024 » PROF. A[illegible] PA[illegible]

~~WAN SHEN LIM~~

COURSE STATUS

Databases are hard.

Distributed databases are harder.



COURSE STATUS

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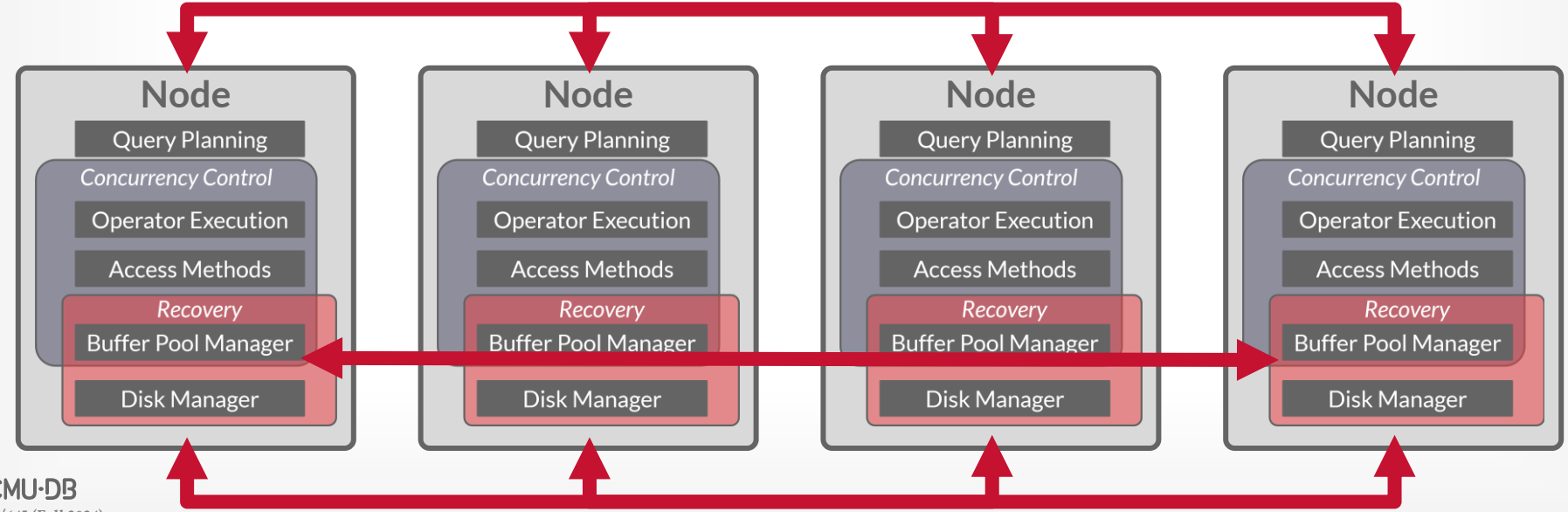


PARALLEL VS. DISTRIBUTED

Parallel DBMSs:

→ Nodes are physically close to each other.
→ Nodes connected with high-speed LAN.
→ Communication cost is assumed to be small.

Distributed DBMSs:

→ Nodes can be far from each other.
→ Nodes connected using public network.
→ Communication cost and problems cannot be ignored.

DISTRIBUTED DBMSs

Use the building blocks that we covered in single-node DBMSs to now support transaction processing and query execution in distributed environments.

→ Optimization & Planning
→ Concurrency Control
→ Logging & Recovery

TODAY'S AGENDA

System Architectures

Design Issues

Partitioning Schemes

Distributed Concurrency Control

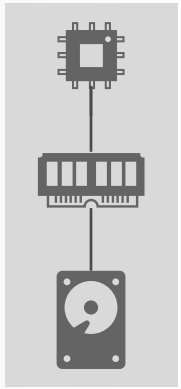
DB Flash Talk: DataStax

SYSTEM ARCHITECTURE

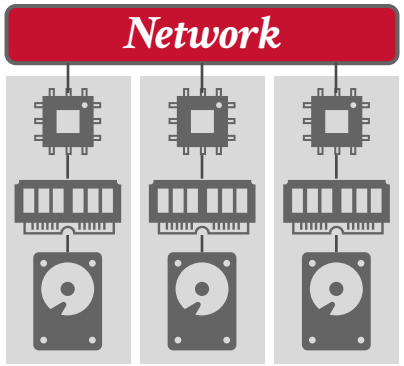
A distributed DBMS's system architecture specifies what shared resources are directly accessible to CPUs.

This affects how CPUs coordinate with each other and where they retrieve/store objects in the database.

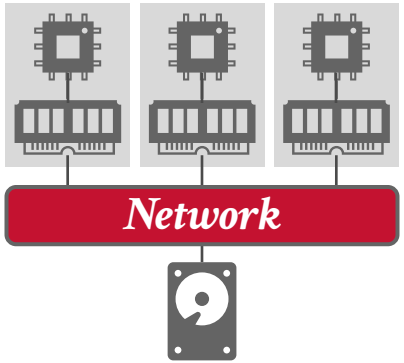
SYSTEM ARCHITECTURE



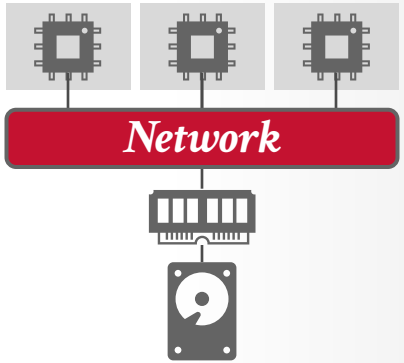
Shared Everything



Shared Nothing



Shared Disk



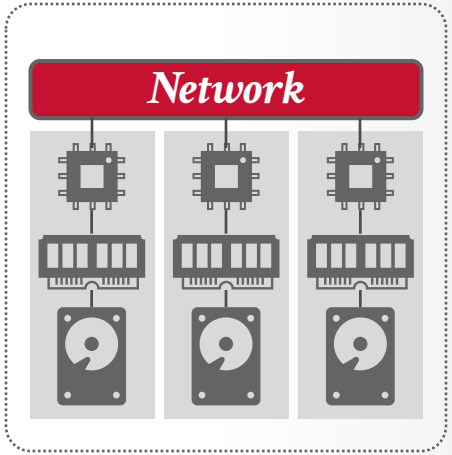
Shared Memory

SHARED NOTHING

Each DBMS node has its own CPU, memory, and local disk.

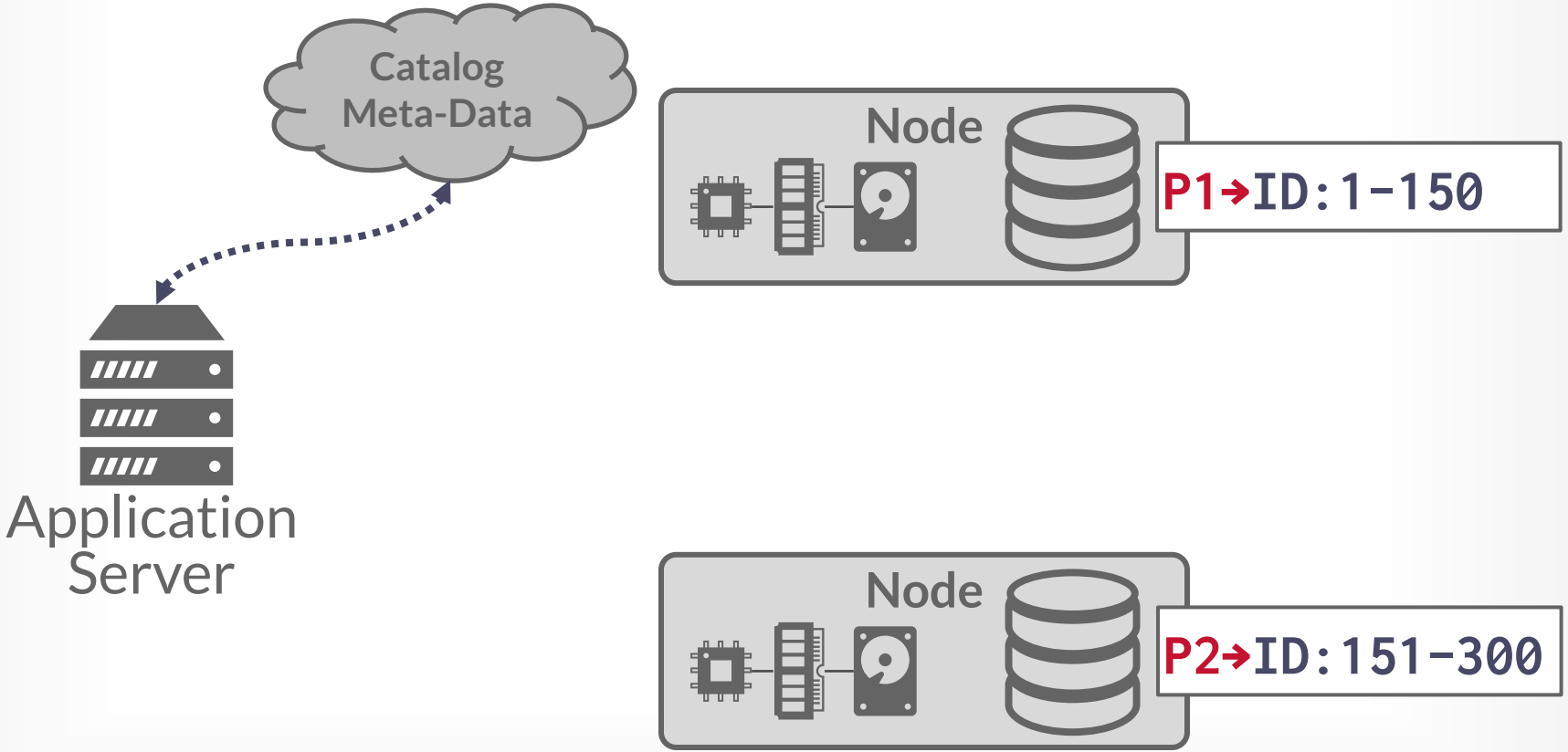
Nodes only communicate with each other via network.

→ Better performance & efficiency.
→ Harder to scale capacity.
→ Harder to ensure consistency.



kinetica
TigerBeetle
ORACLE NOSQL DATABASE
Yellowbrick
MEMCACHED
elastic
etcd
SciDB
fauna
Dgraph
CockroachDB
Exasol
MongoDB.
citusdata
FOUNDATIONDB
ClickHouse
cassandra
H-Store
VOLTDB
CrateDB
Comdb2
APACHE GEODE
orbit db
APACHE ZooKeeper
Greenplum
AEROSPIKE
SingleStore
VERTICA
RonDB
TiDB
redis
TERADATA
OCEANBASE
Couchbase

SHARED NOTHING EXAMPLE



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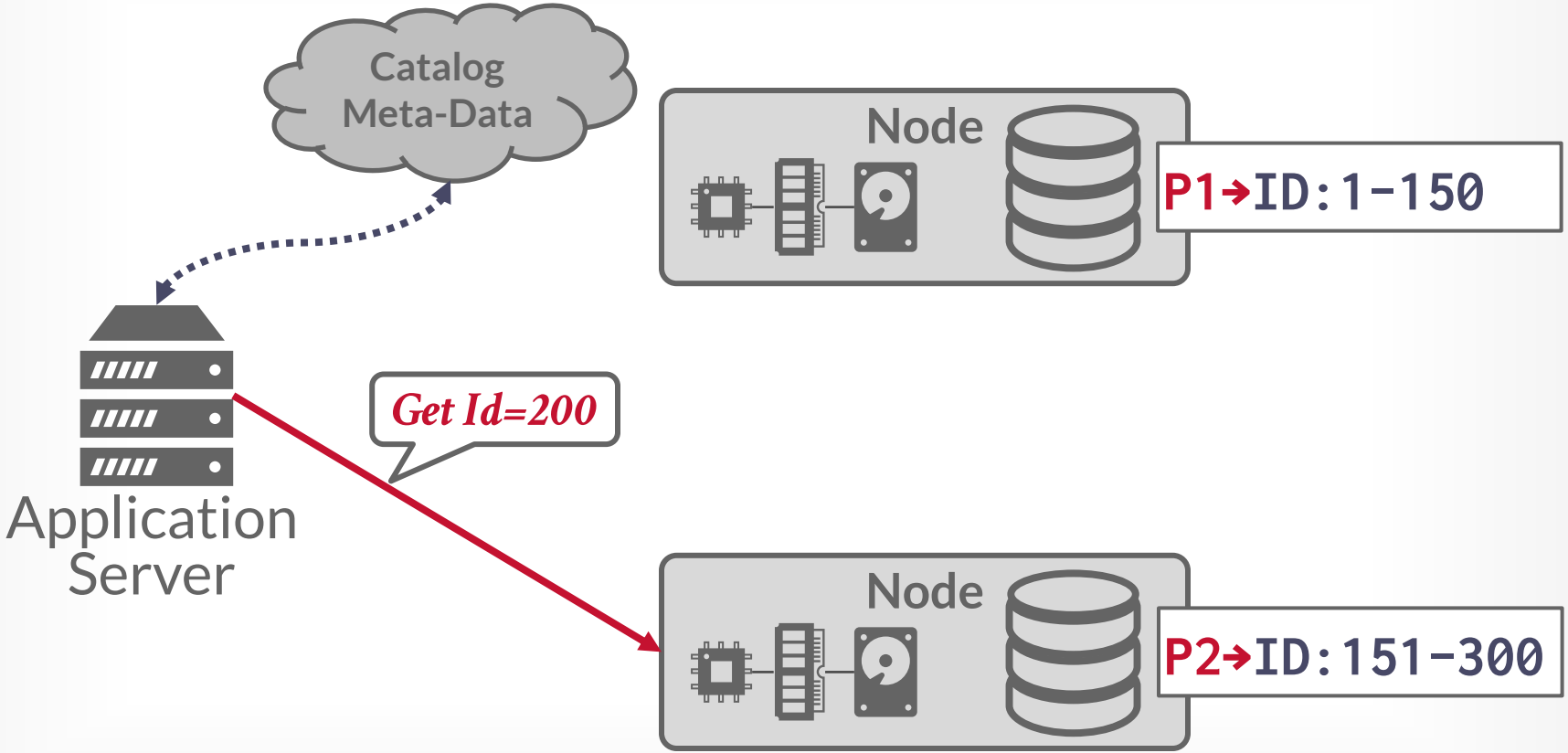

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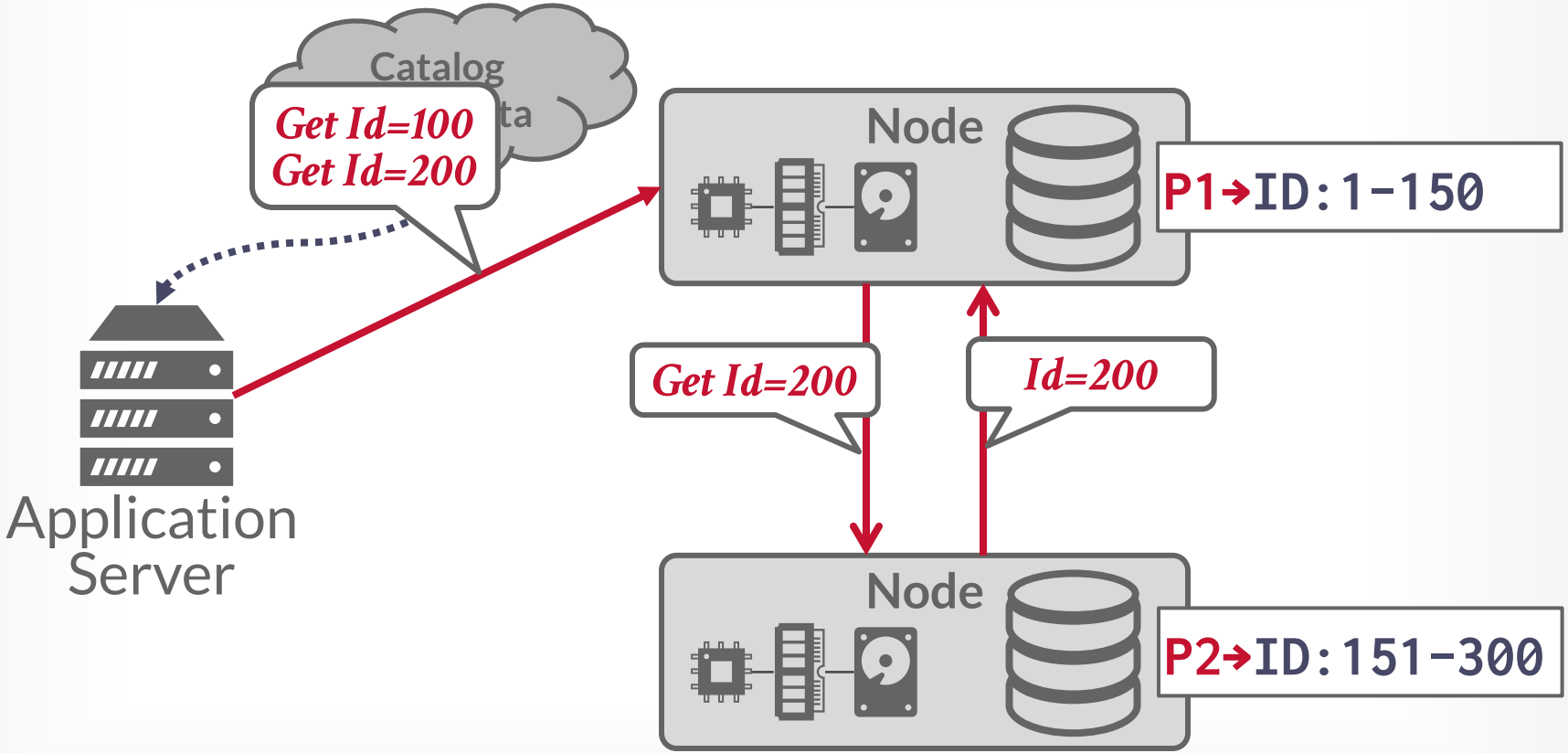

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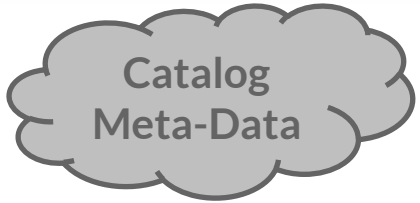
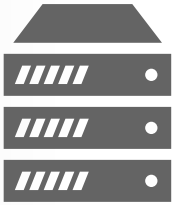
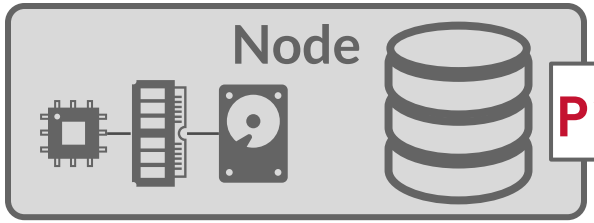
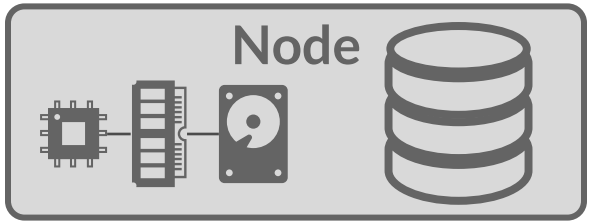
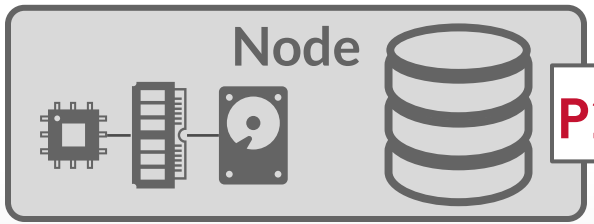




Application Server







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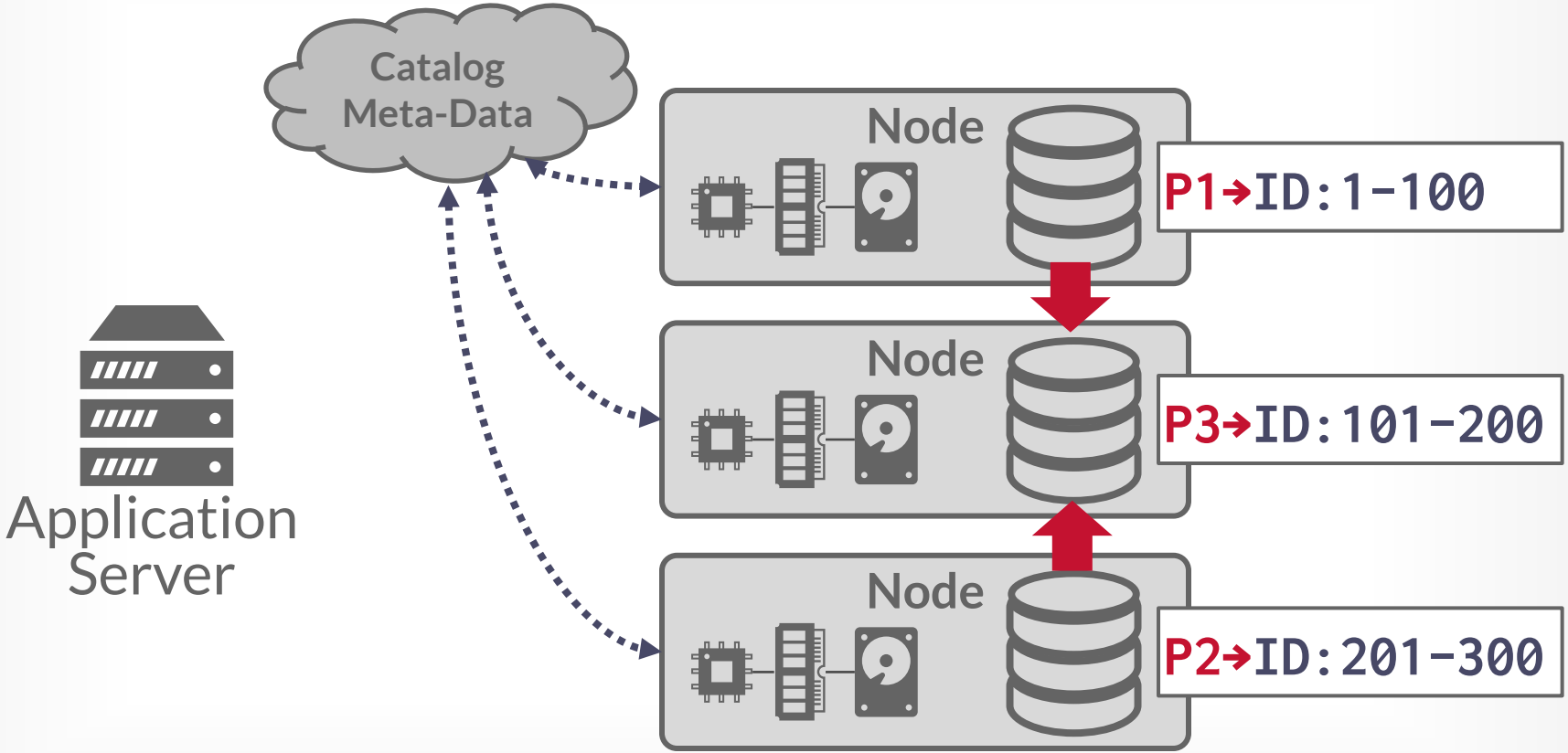


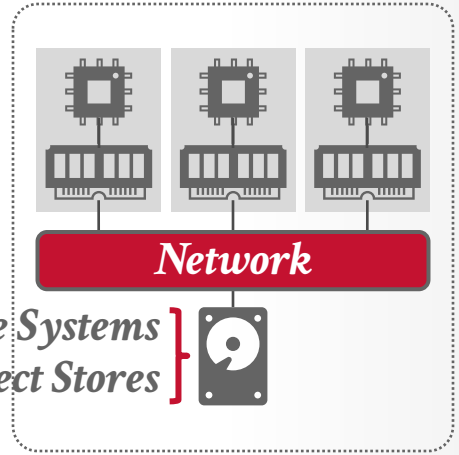
SHARED DISK

Nodes access a single logical disk via an interconnect, but each have their own private memories.

→ Scale execution layer independently from the storage layer.

→ Nodes can still use direct attached storage as a slower/larger cache.

→ This architecture facilitates **data lakes** and **serverless** systems.



databricks FIREBOLT dremio

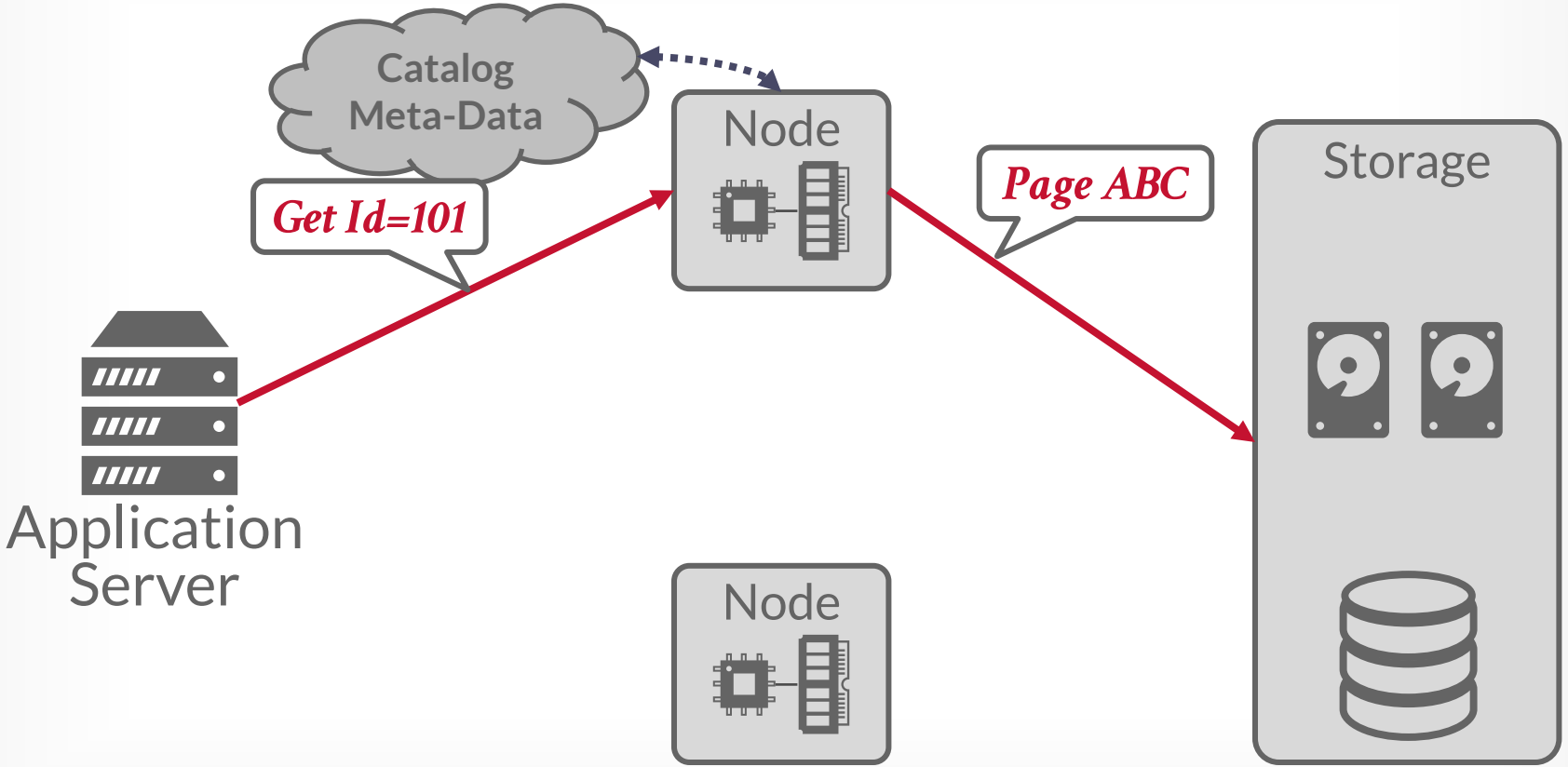
APACHE HBASE Google Big Query trino

YDB yugabyteDB druid

ROCKSET ORACLE EXADATA sqrrl presto cloudera IMPALA APACHE Spark NUODB amazon REDSHIFT

ORACLE RAC splice MACHINE Hortonworks STINGER APACHE HBASE snowflake Google Spanner Amazon Aurora

SHARED DISK EXAMPLE



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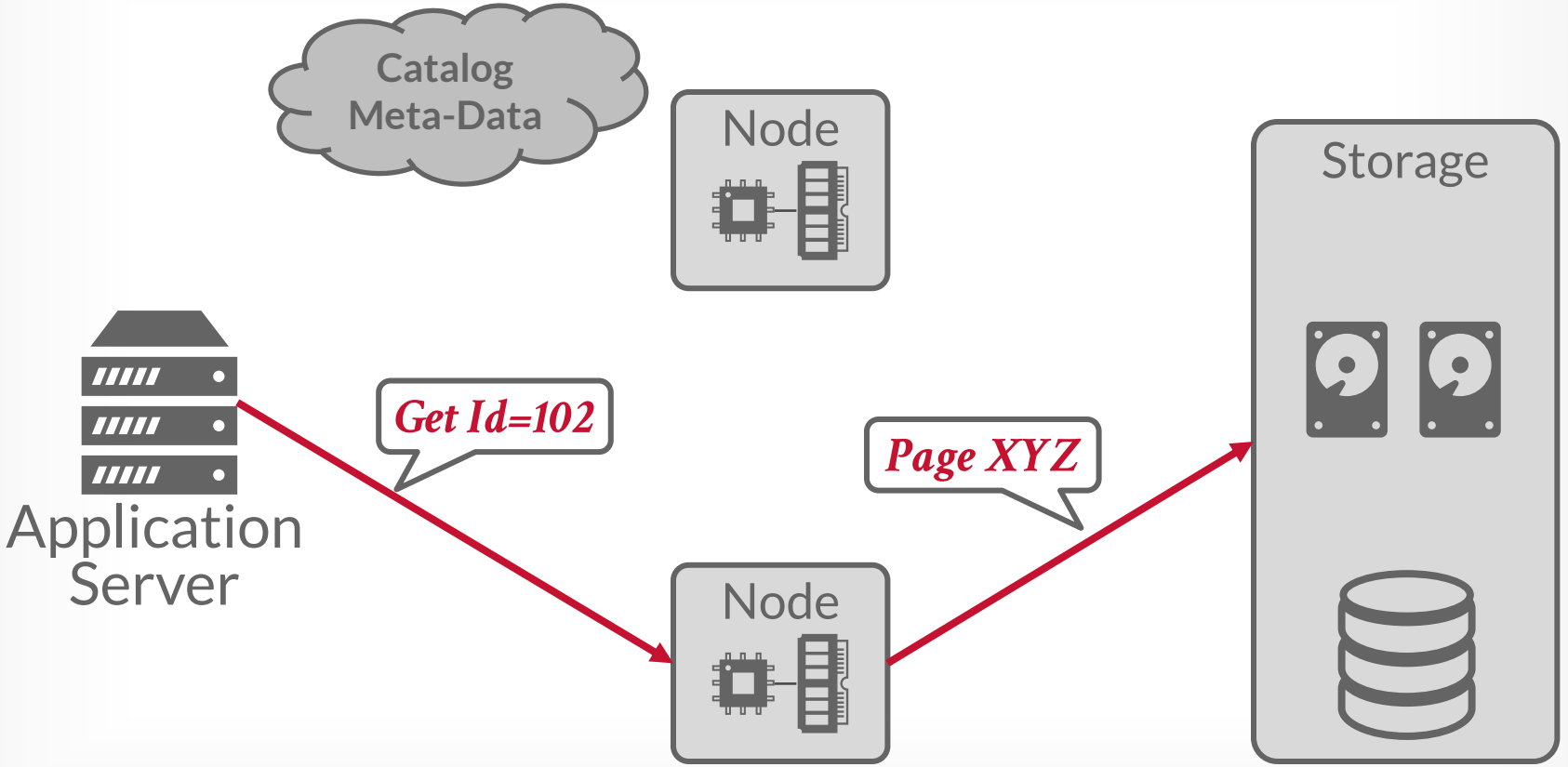

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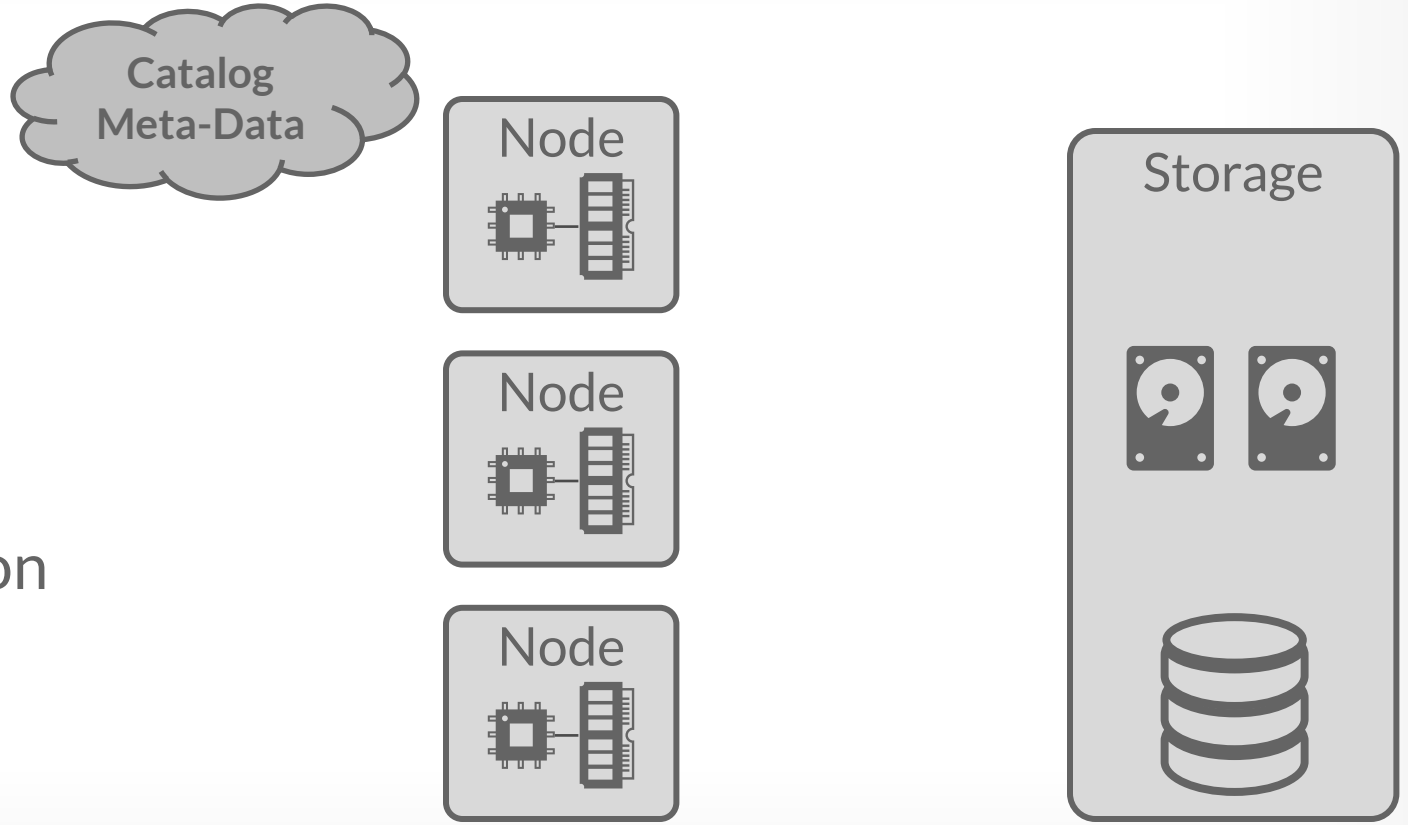

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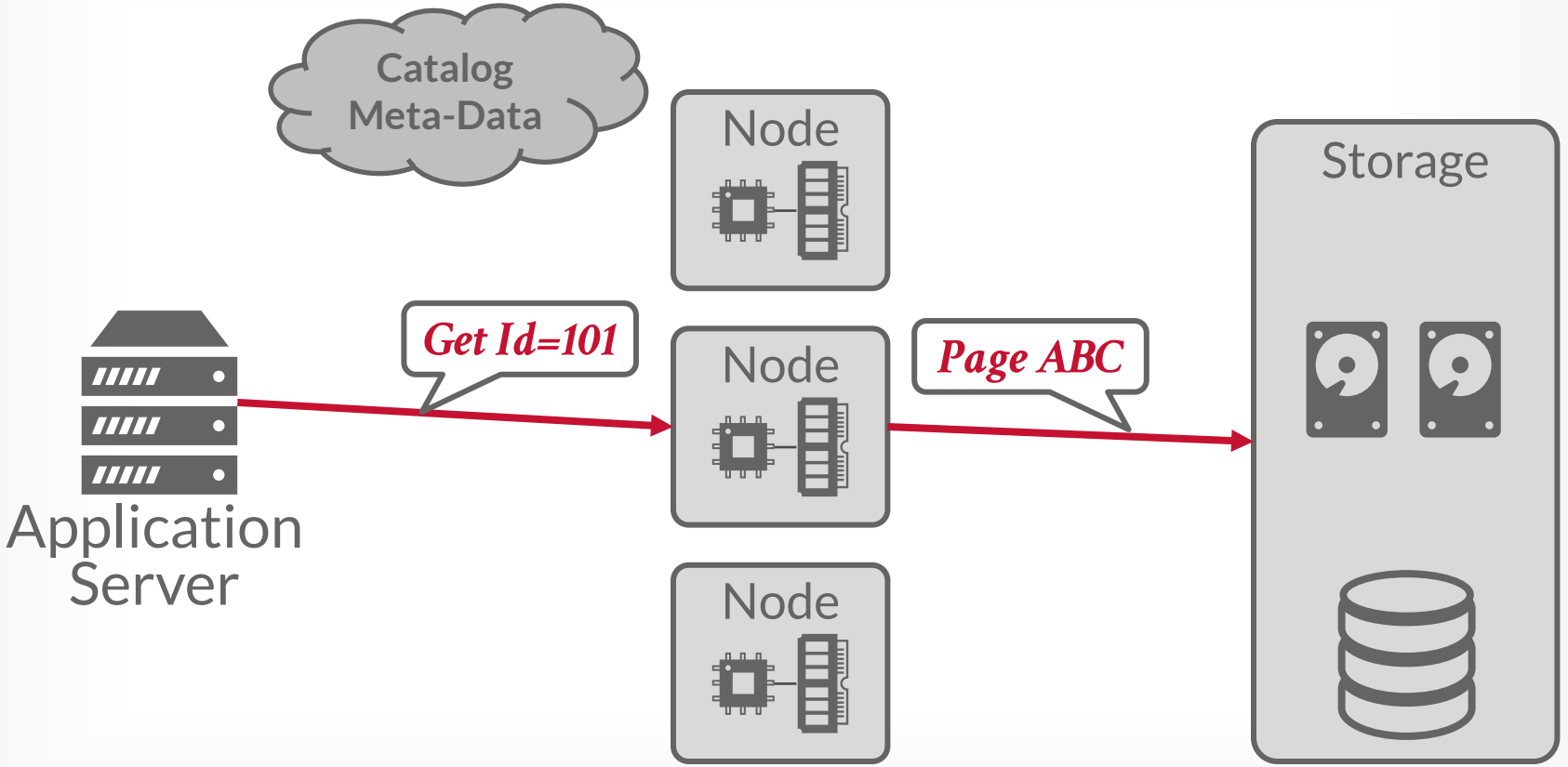

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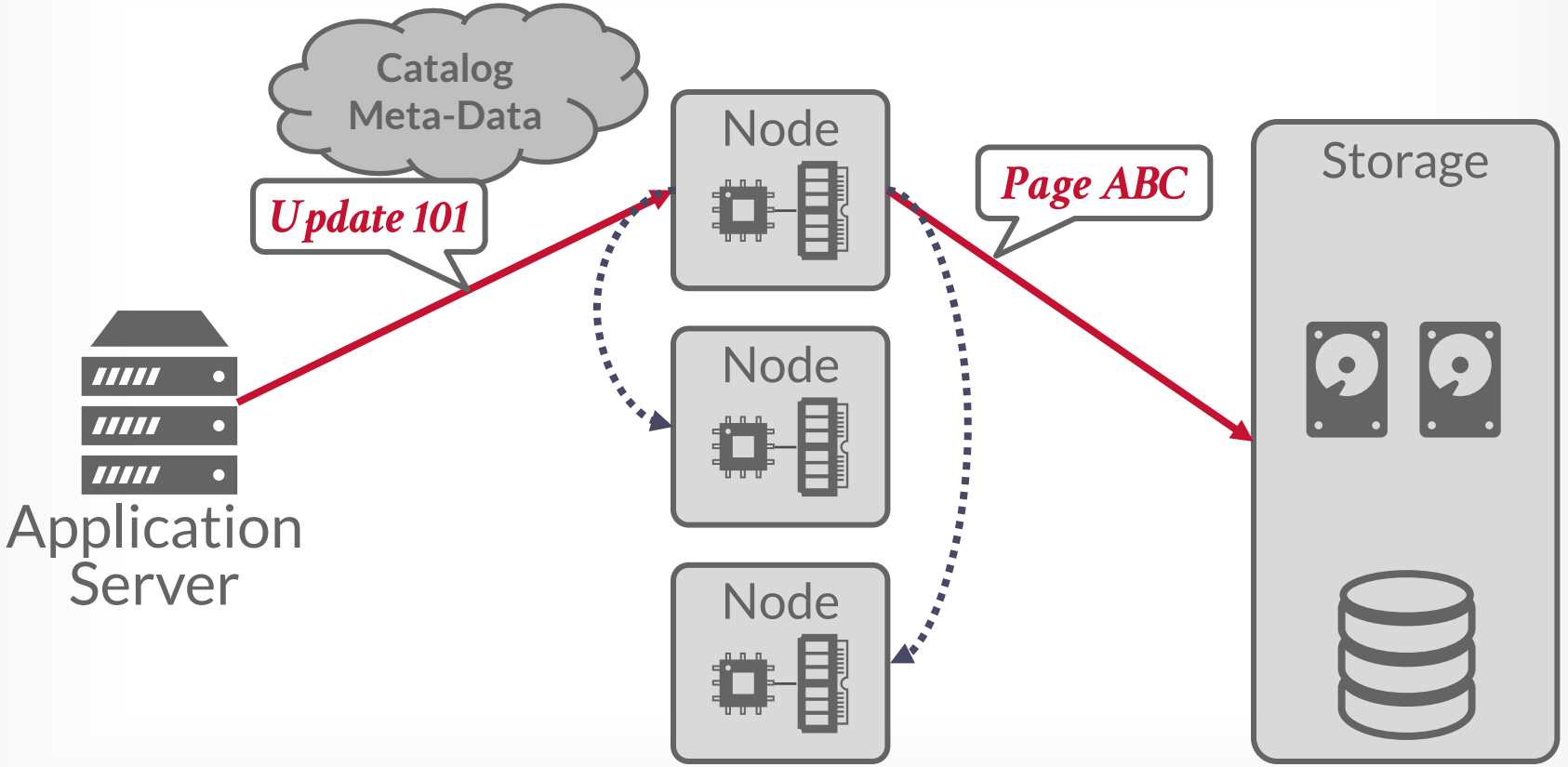

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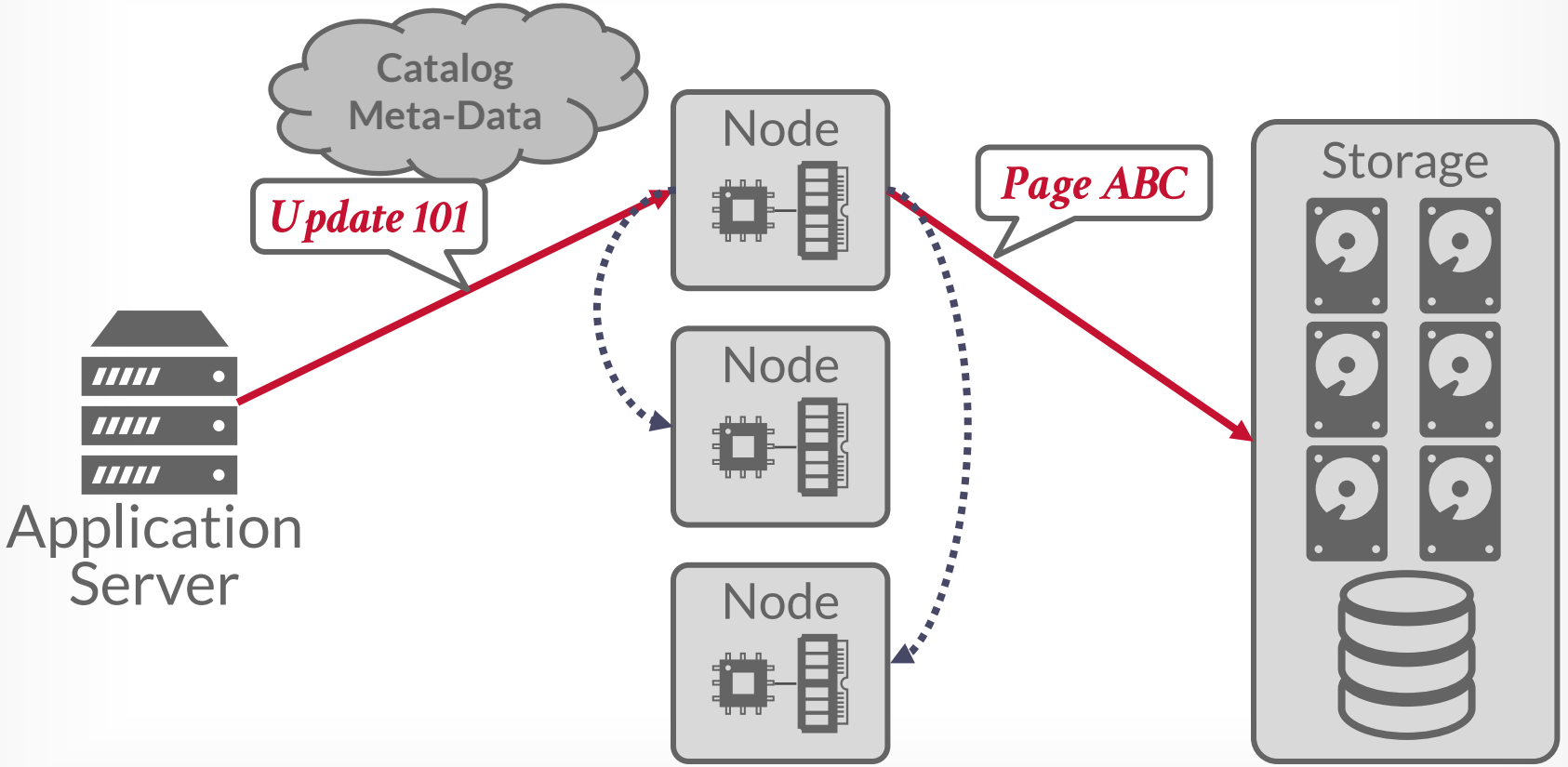


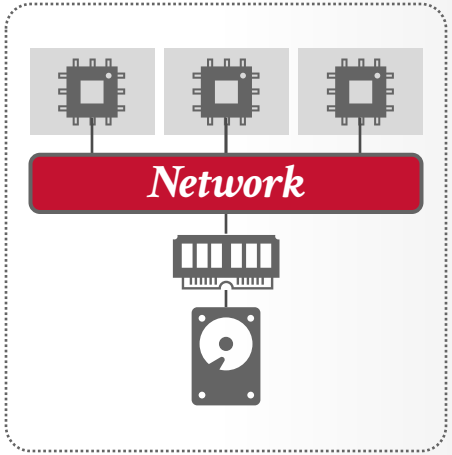
SHARED MEMORY

Nodes access a common memory address space via a fast interconnect.

→ Each node has a global view of all the in-memory data structures.

→ Can still use local memory / disk for intermediate results.

This looks a lot like shared-everything. Nobody does this.



DESIGN ISSUES

How does the application find data?

Where does the application send queries?

How to execute queries on distributed data?

→ Push query to data.

→ Pull data to query.

How do we divide the database across resources?

How does the DBMS ensure correctness? ***Next Class***

DATA TRANSPARENCY

Applications should not be required to know where data is physically located in a distributed DBMS.

→ Any query that run on a single-node DBMS should produce the same result on a distributed DBMS.

In practice, developers need to be aware of the communication costs of queries to avoid excessively "expensive" data movement.

DATABASE PARTITIONING

Split database across multiple resources:
→ Disks, nodes, processors.
→ Called "sharding" in NoSQL systems.

The DBMS executes query fragments on each partition and then combines the results to produce a single answer.

NAÏVE TABLE PARTITIONING

Assign an entire table to a single node.

Assumes that each node has enough storage space for an entire table.

Ideal if queries never join data across tables stored on different nodes and access patterns are uniform.

NAÏVE TABLE PARTITIONING

Table1

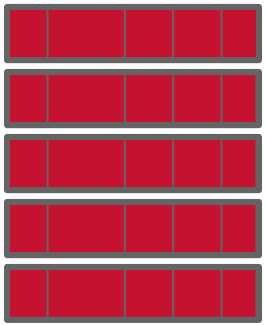
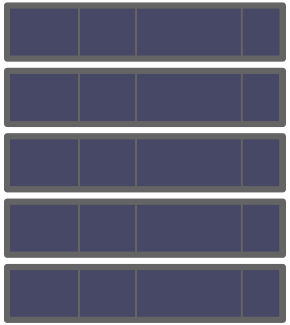
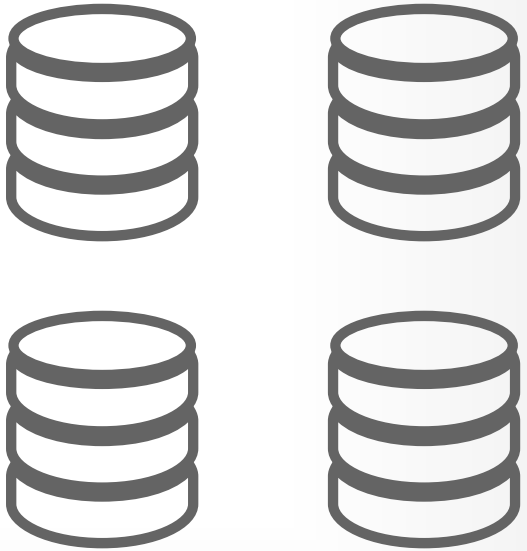


Table2



Partitions



Ideal Query:

```
SELECT * FROM table1
```

NAÏVE TABLE PARTITIONING

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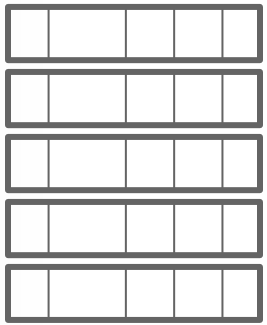

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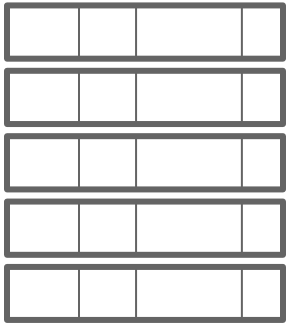

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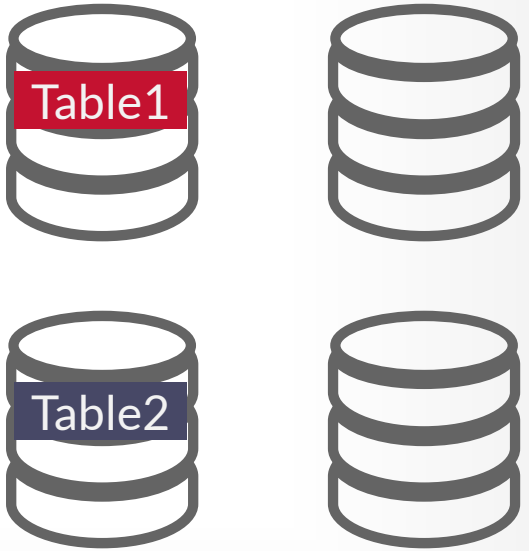

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VERTICAL PARTITIONING

Split a table's attributes into separate partitions.

Must store tuple information to reconstruct the original record.

```
CREATE TABLE foo (
  attr1 INT,
  attr2 INT,
  attr3 INT,
  attr4 TEXT
);
```

Tuple#1	attr1	attr2	attr3	attr4
Tuple#2	attr1	attr2	attr3	attr4
Tuple#3	attr1	attr2	attr3	attr4
Tuple#4	attr1	attr2	attr3	attr4

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```

Partition #1

Tuple#1	attr1	attr2	attr3
Tuple#2	attr1	attr2	attr3
Tuple#3	attr1	attr2	attr3
Tuple#4	attr1	attr2	attr3

Partition #2

Tuple#1	attr4
Tuple#2	attr4
Tuple#3	attr4
Tuple#4	attr4

HORIZONTAL PARTITIONING

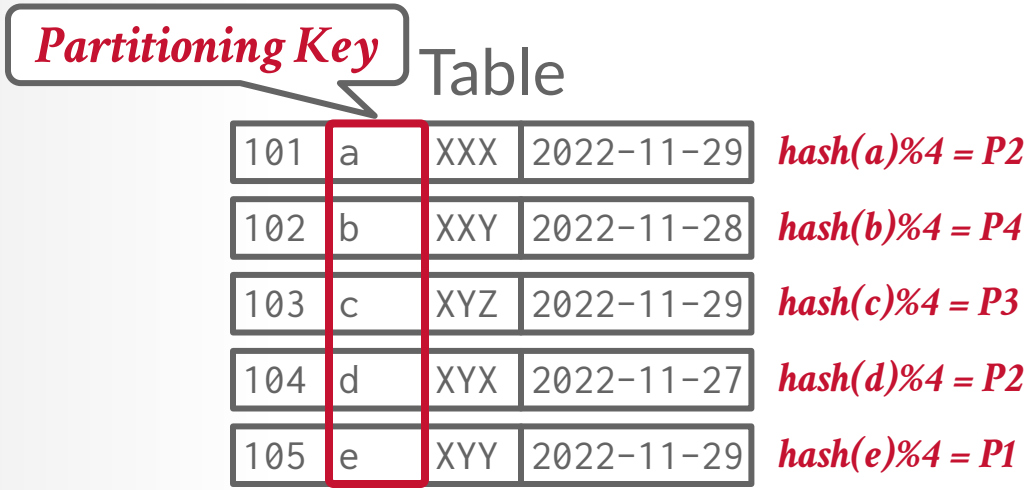
Split a table's tuples into disjoint subsets based on some partitioning key and scheme.

→ Choose column(s) that divides the database equally in terms of size, load, or usage.

Partitioning Schemes:

→ Hashing
→ Ranges
→ Predicates

HORIZONTAL PARTITIONING



Ideal Query:

```
SELECT * FROM table
 WHERE partitionKey = ?
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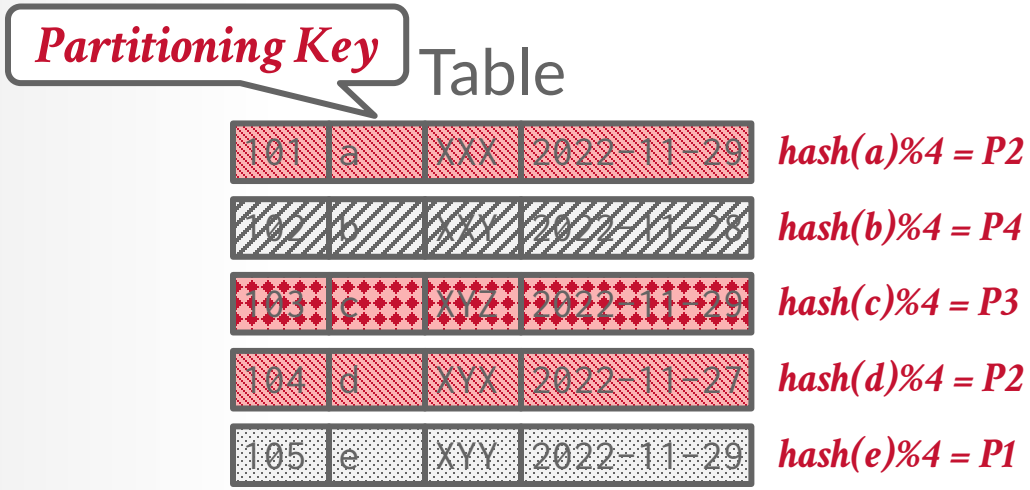
HORIZONTAL PARTITIONING



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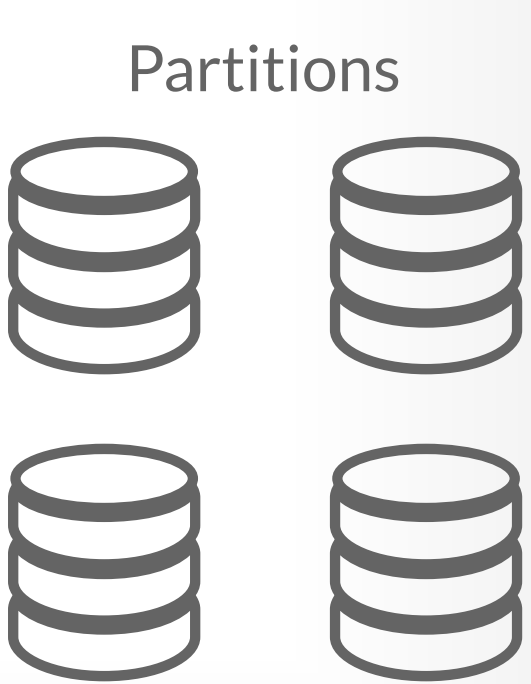

HORIZONTAL PARTITIONING

Partitioning Key

Table

101	a	XXX	2022-11-29	*hash(a)%4 = P2*
102	b	XXY	2022-11-28	*hash(b)%4 = P4*
103	c	XYZ	2022-11-29	*hash(c)%4 = P3*
104	d	XYX	2022-11-27	*hash(d)%4 = P2*
105	e	XYY	2022-11-29	*hash(e)%4 = P1*

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```
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```
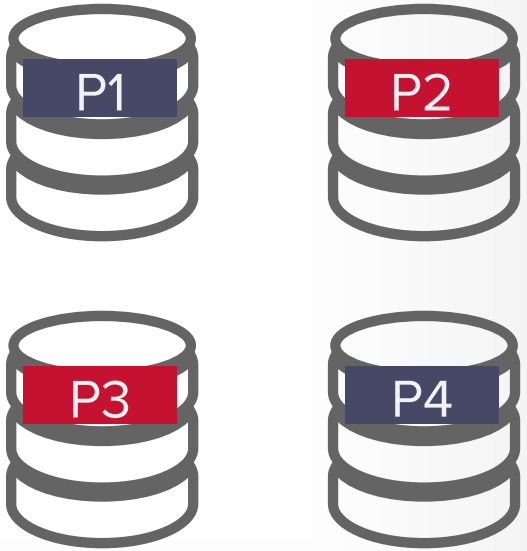
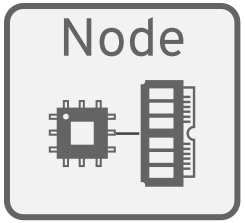
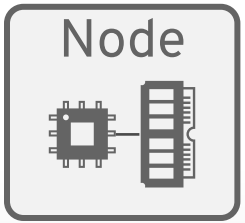
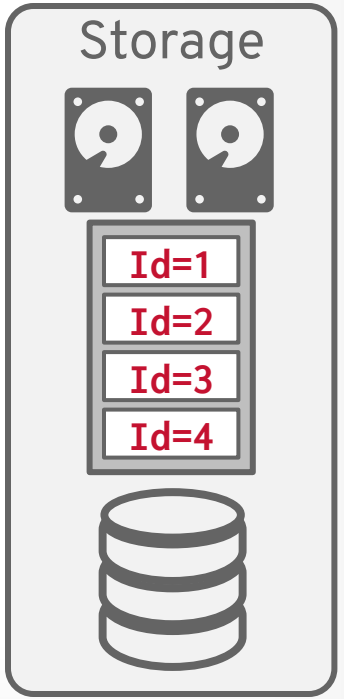

Partitions



SHARED-DISK PARTITIONING







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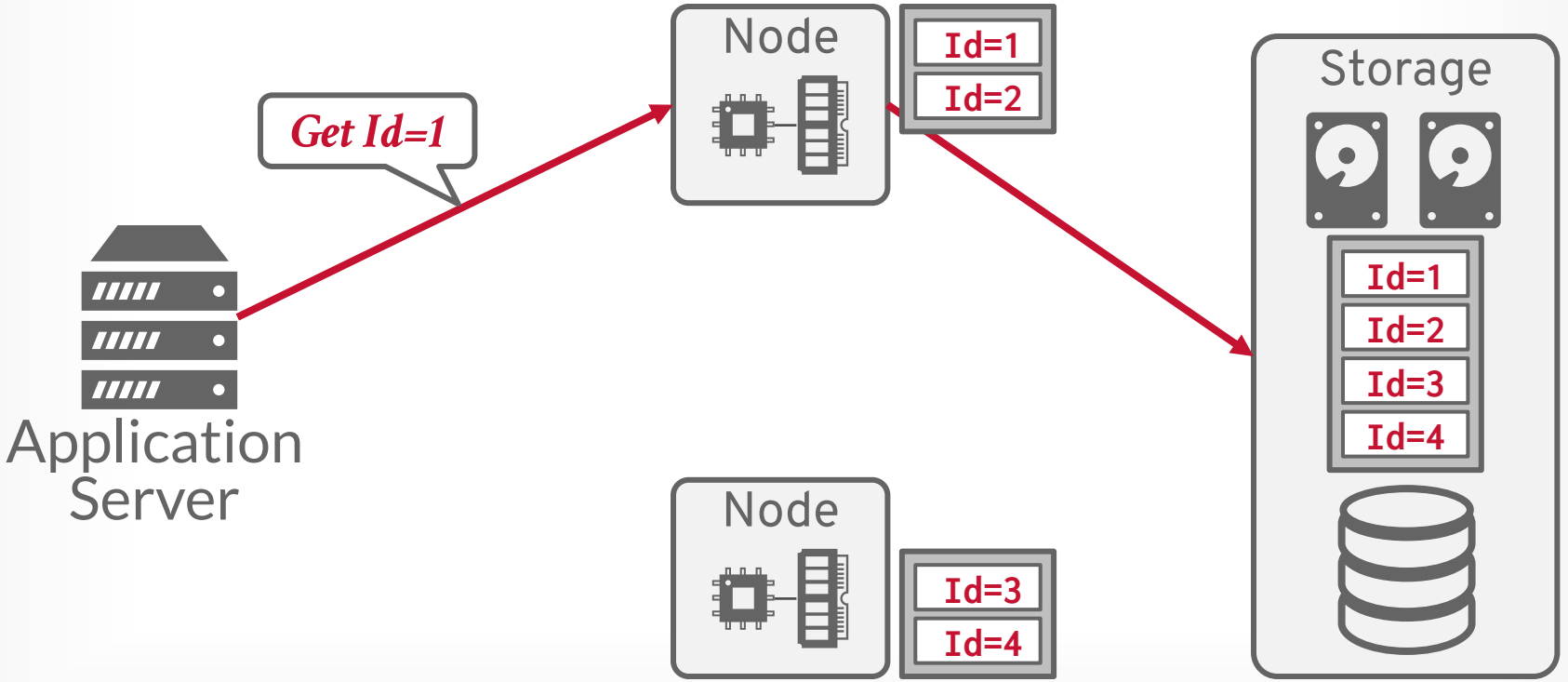

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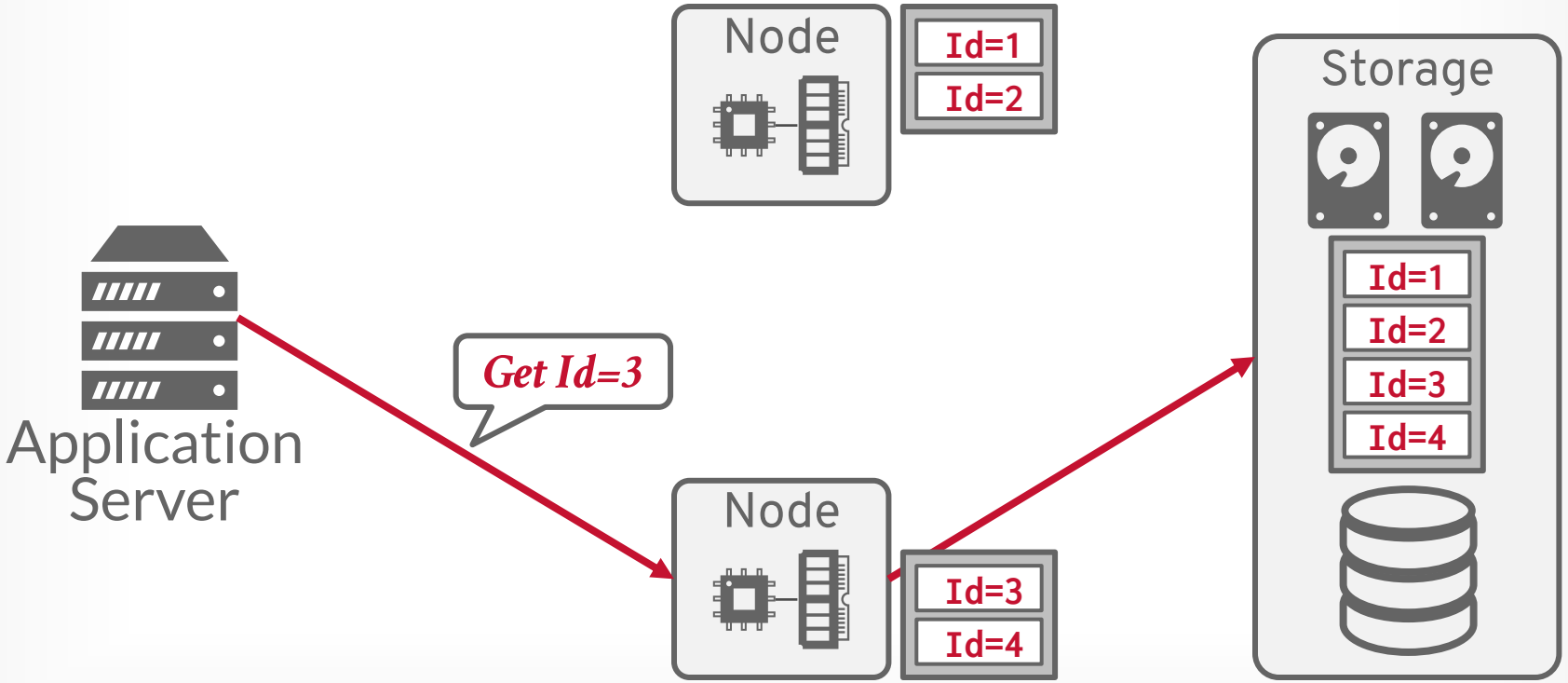

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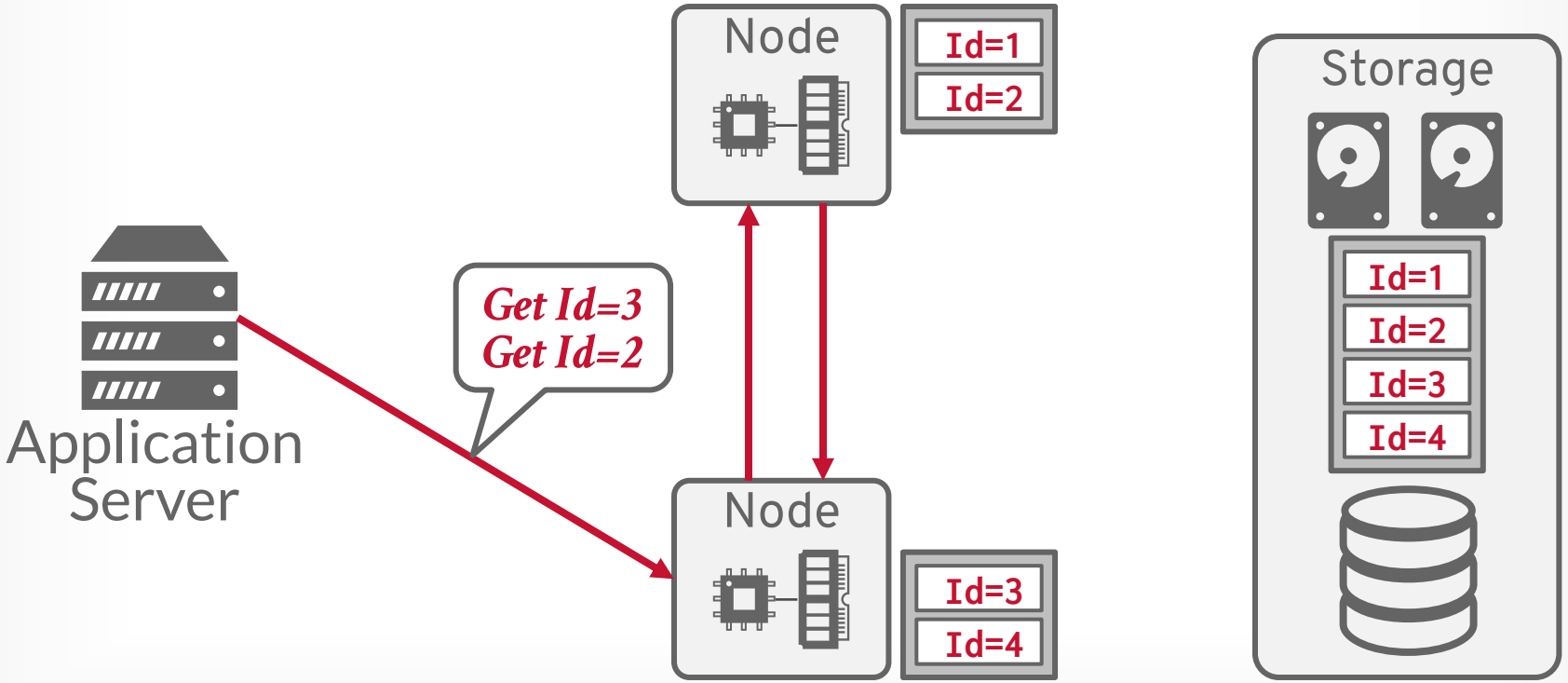
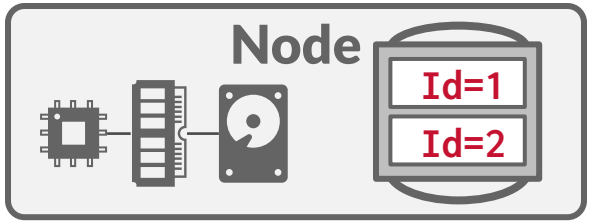
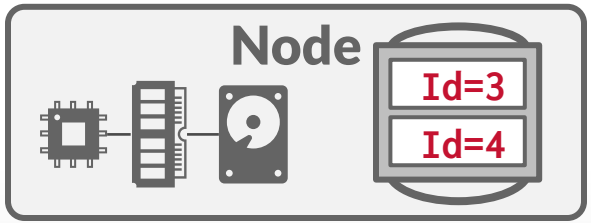


SHARED-NOTHING PARTITIONING





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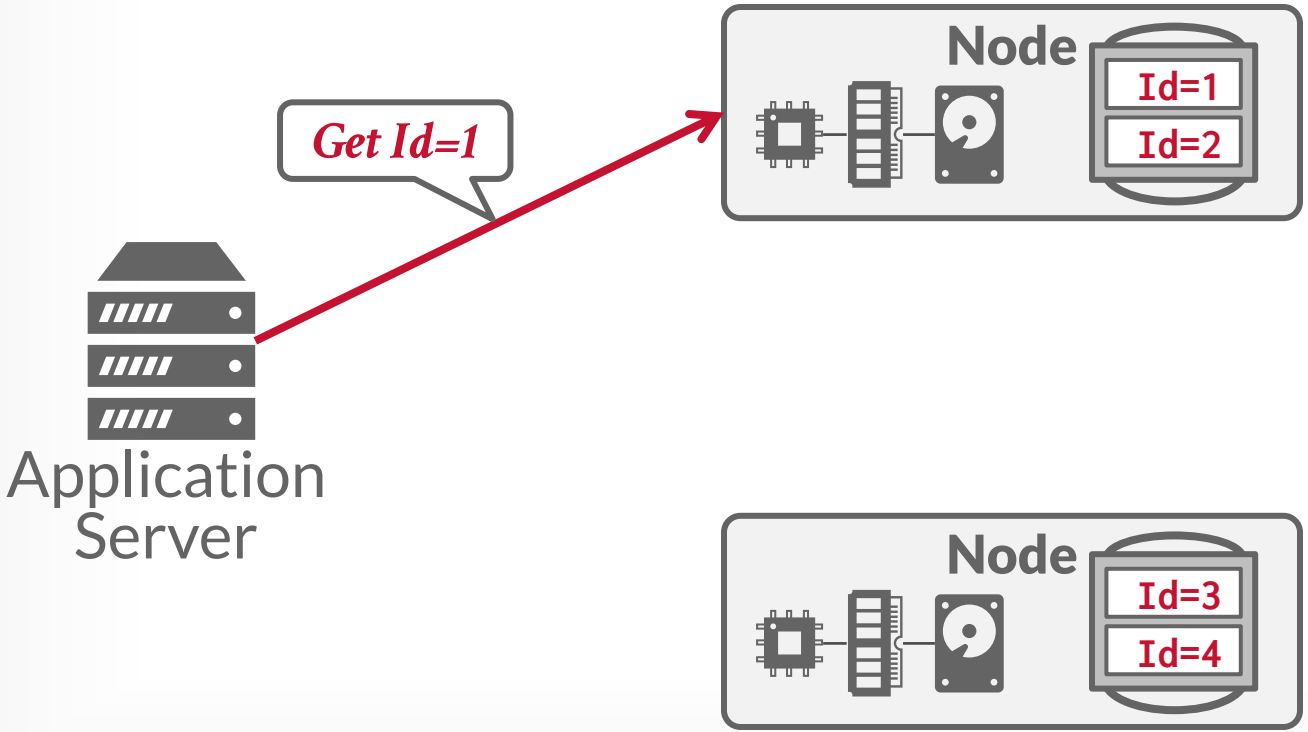

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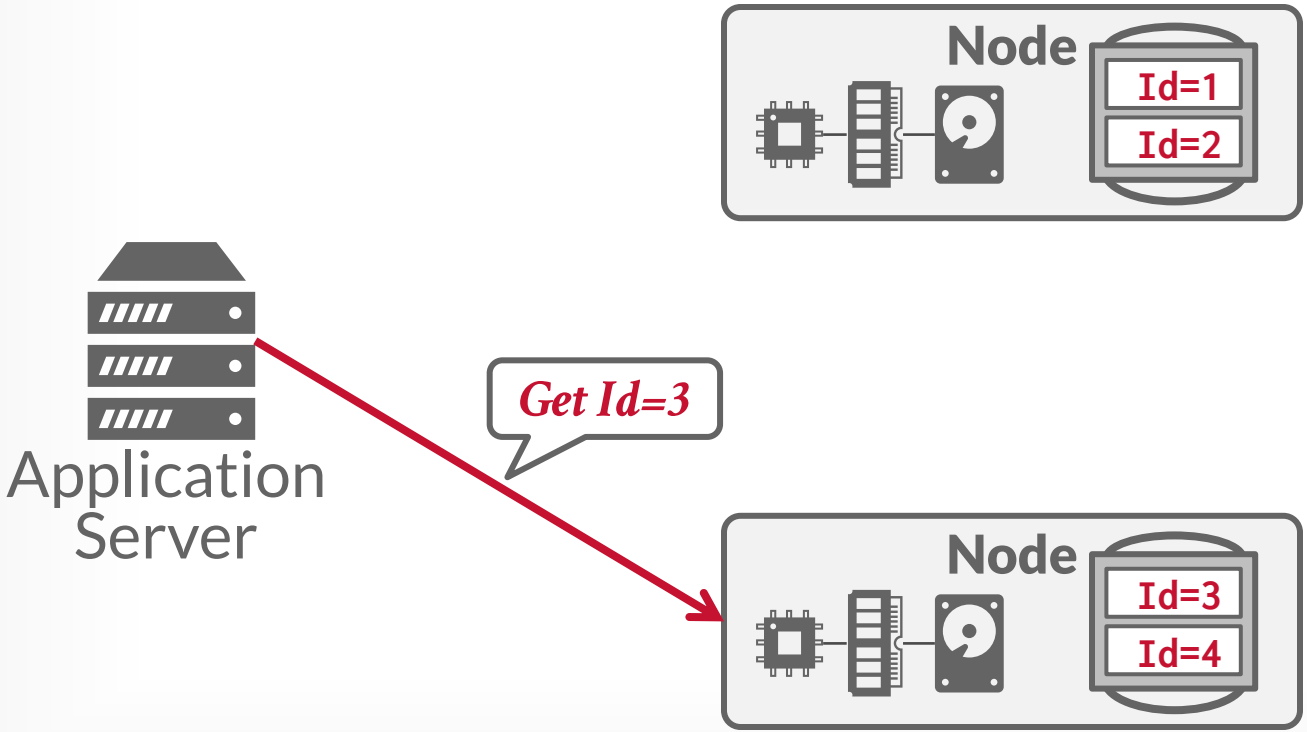

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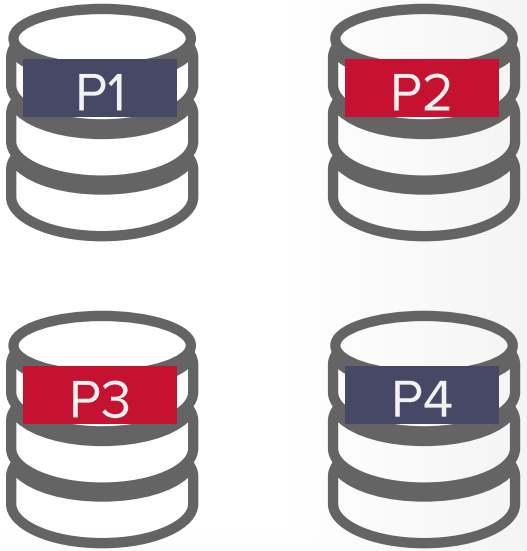

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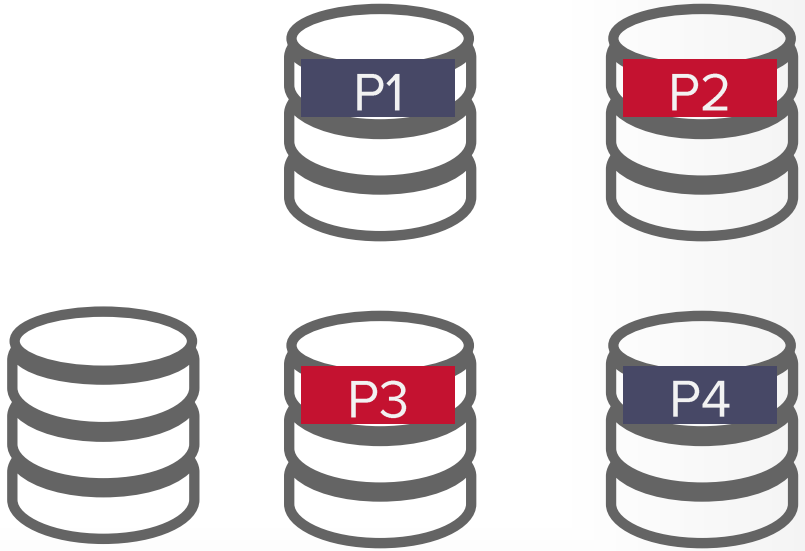
102	b	XXY	2022-11-28	*hash(b)%4 = P4*
103	c	XYZ	2022-11-29	*hash(c)%4 = P3*
104	d	XYX	2022-11-27	*hash(d)%4 = P2*
105	e	XYY	2022-11-29	*hash(e)%4 = P1*

Ideal Query:

```
SELECT * FROM table
 WHERE partitionKey = ?
```

Partitions



HORIZONTAL PARTITIONING

Partitioning Key

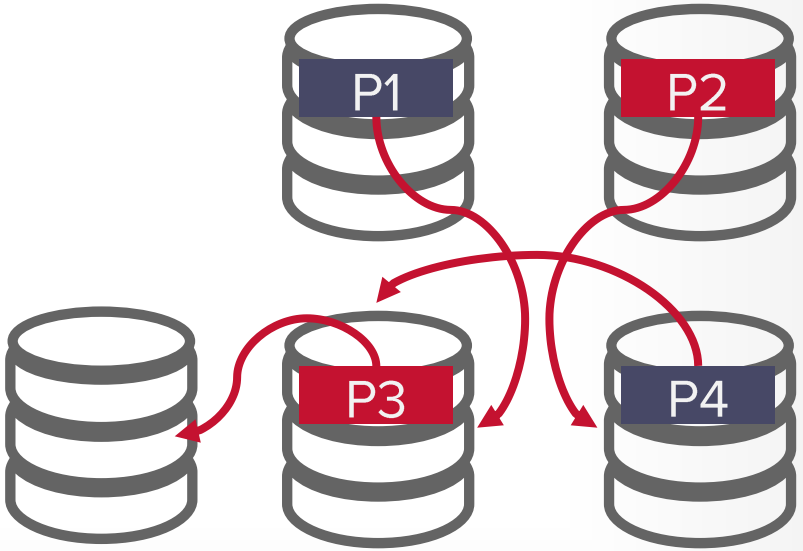
Table

101	a	XXX	2022-11-29	*hash(a)%5 = P4*
102	b	XXY	2022-11-28	*hash(b)%5 = P3*
103	c	XYZ	2022-11-29	*hash(c)%5 = P5*
104	d	XYX	2022-11-27	*hash(d)%5 = P1*
105	e	XYY	2022-11-29	*hash(e)%5 = P3*

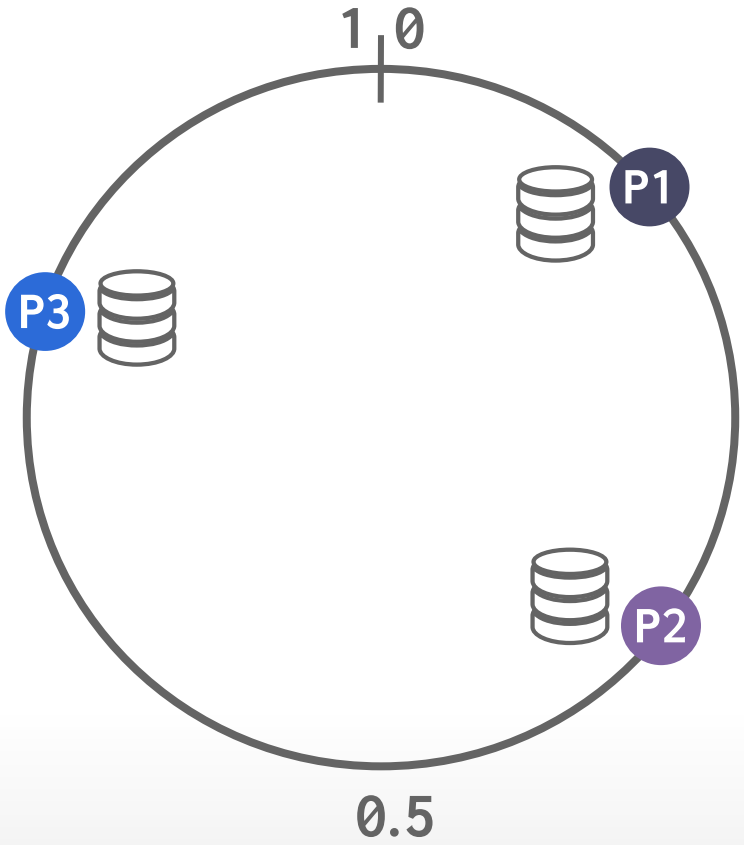
Ideal Query:

```
SELECT * FROM table
 WHERE partitionKey = ?
```

Partitions



CONSISTENT HASHING



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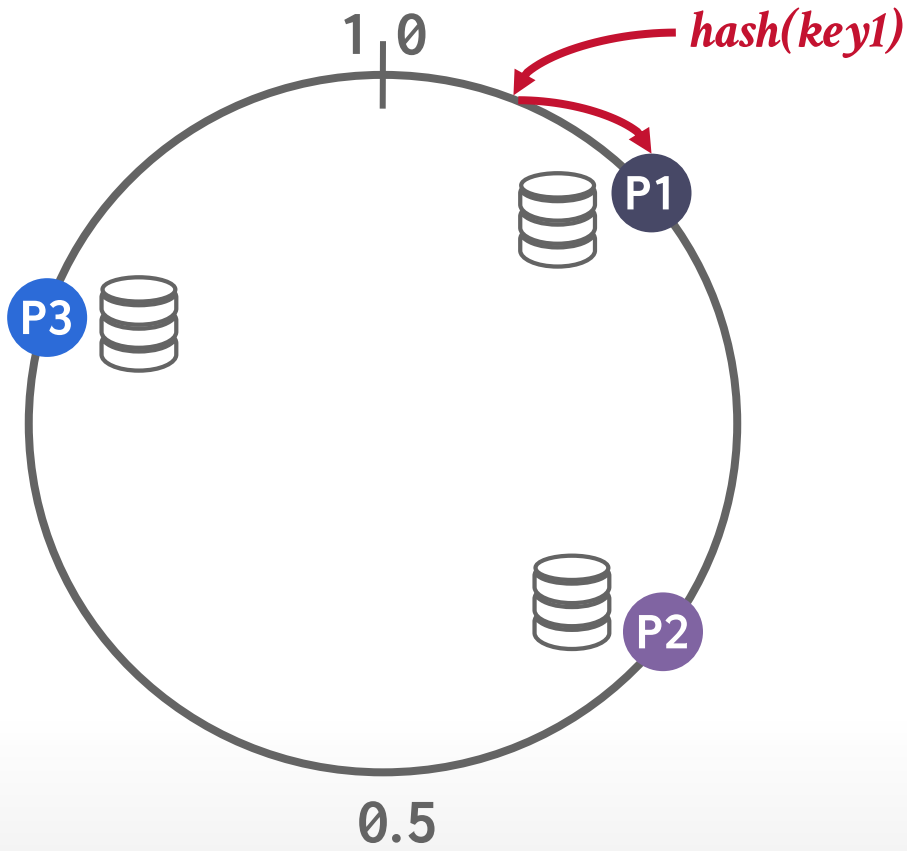

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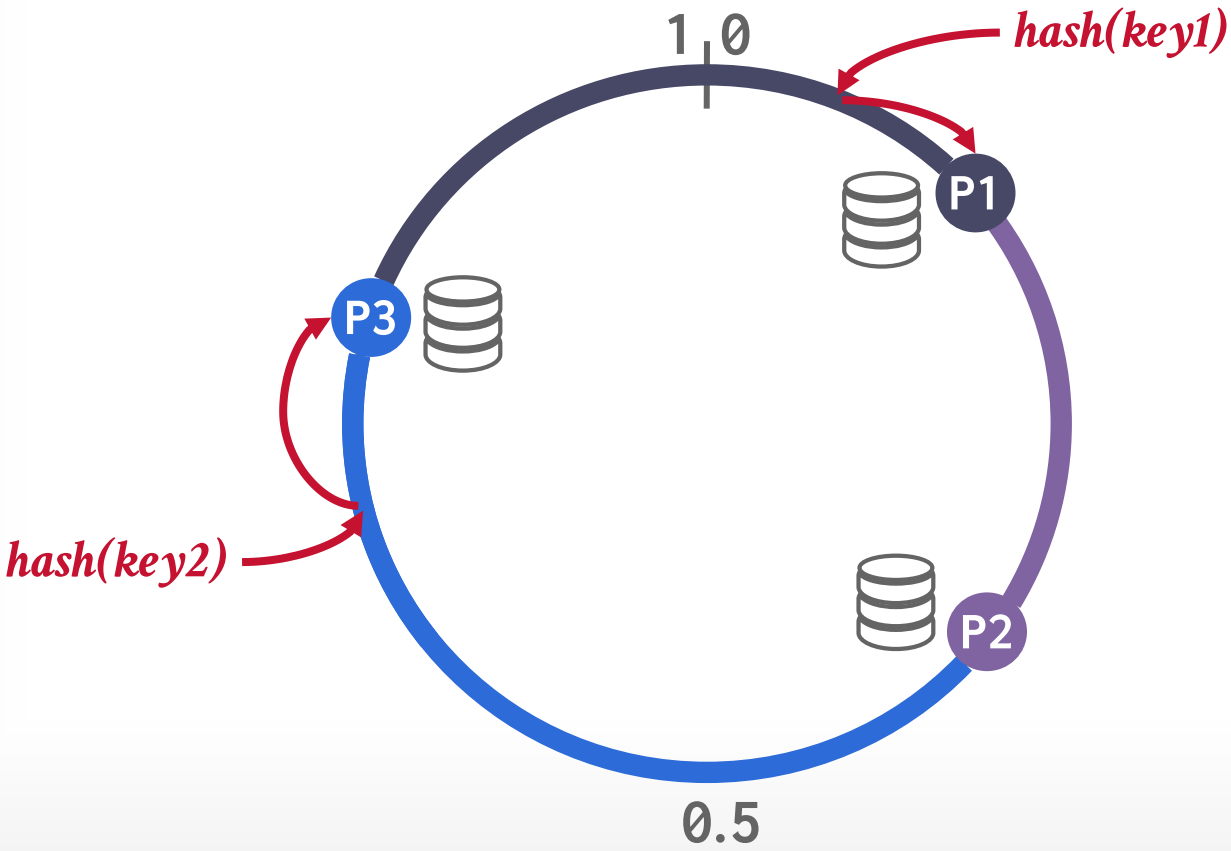

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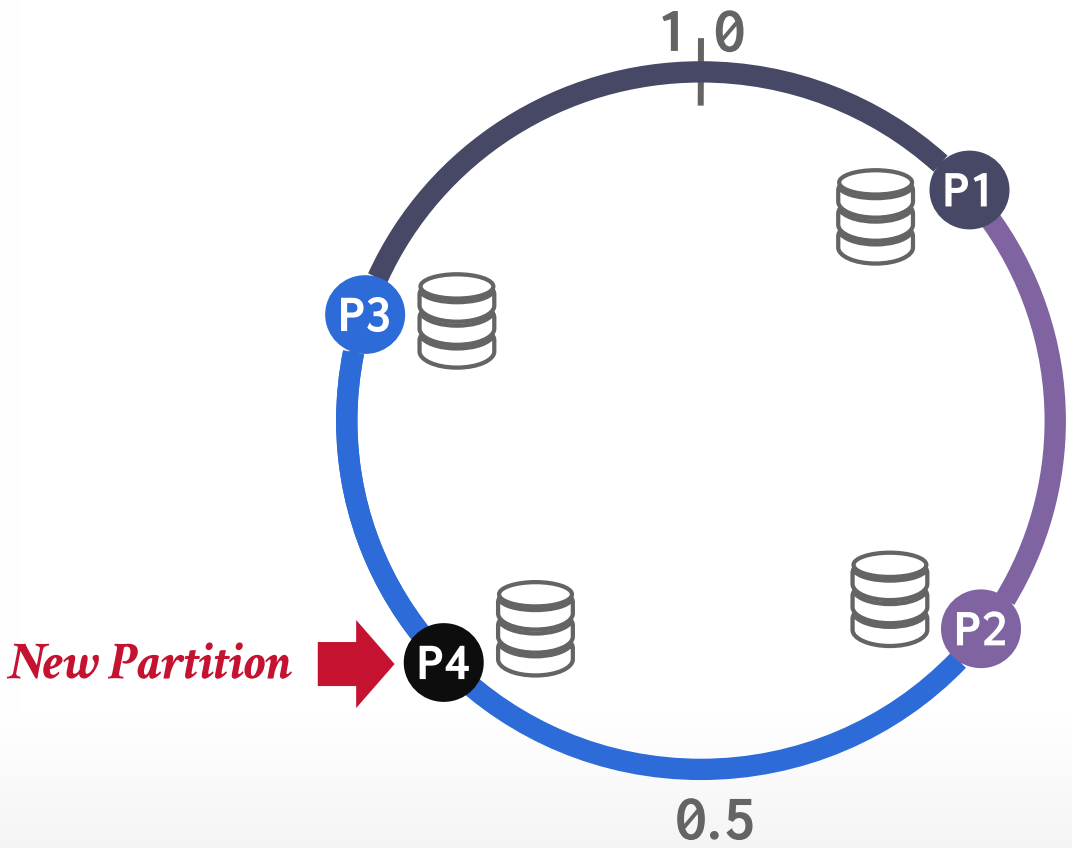

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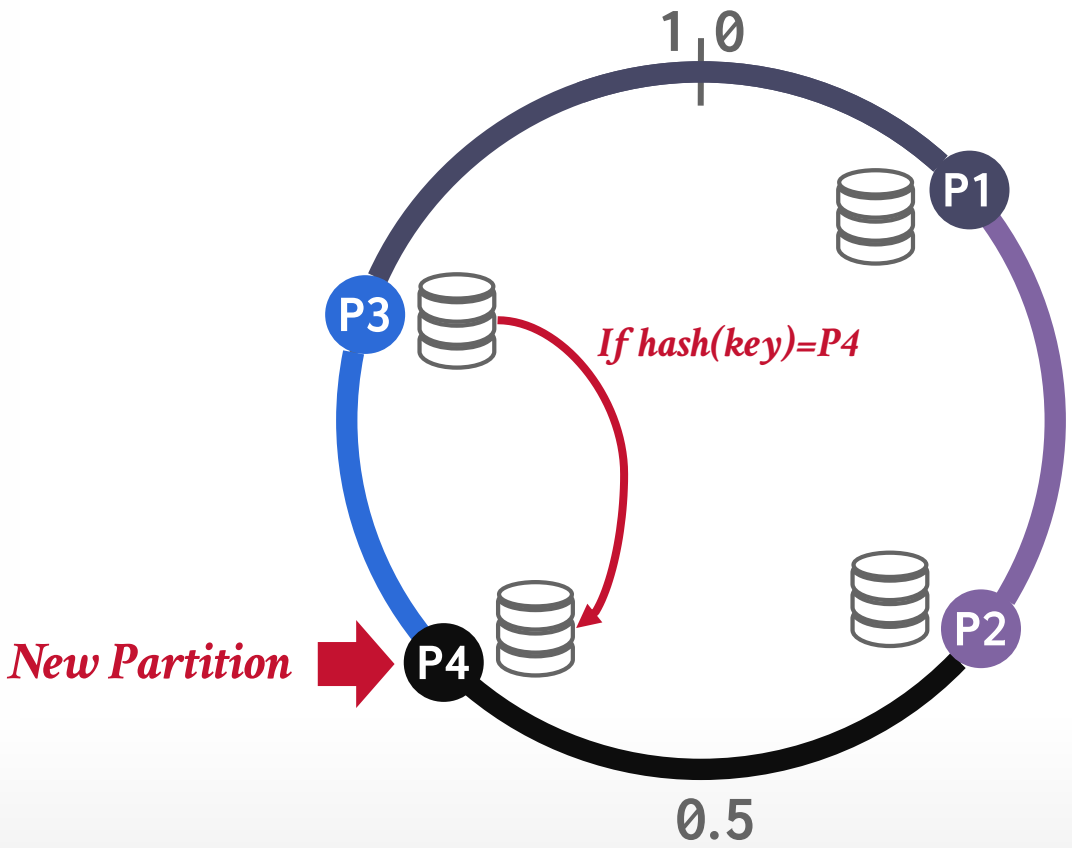

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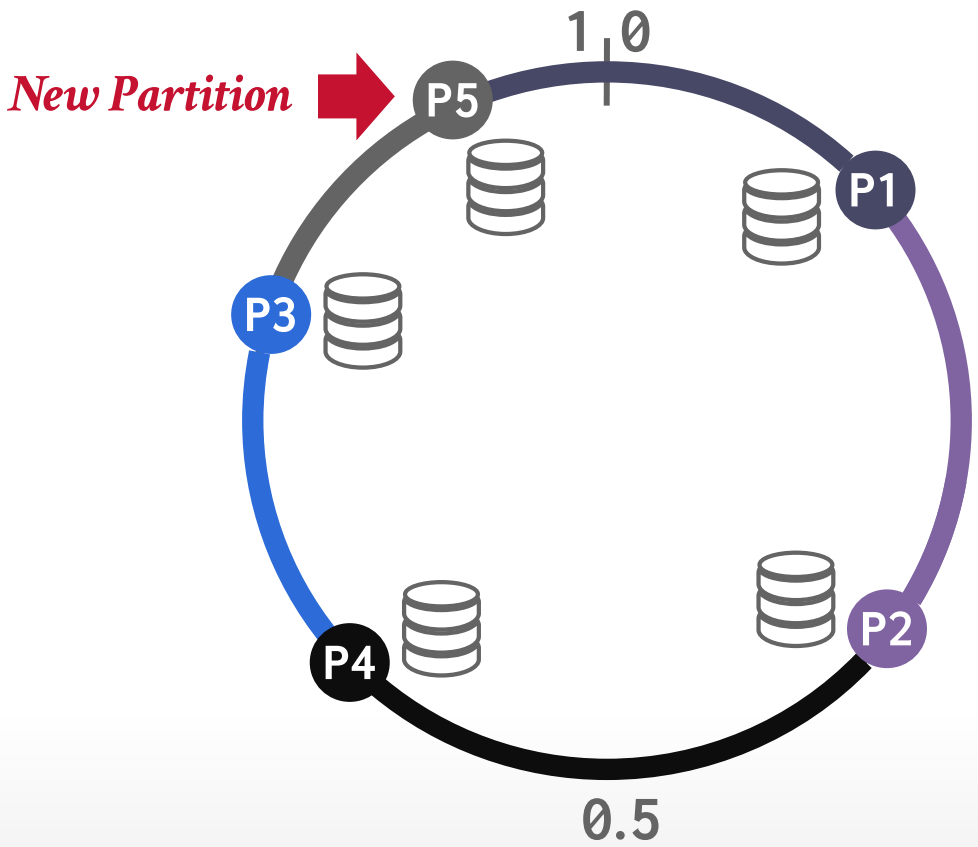

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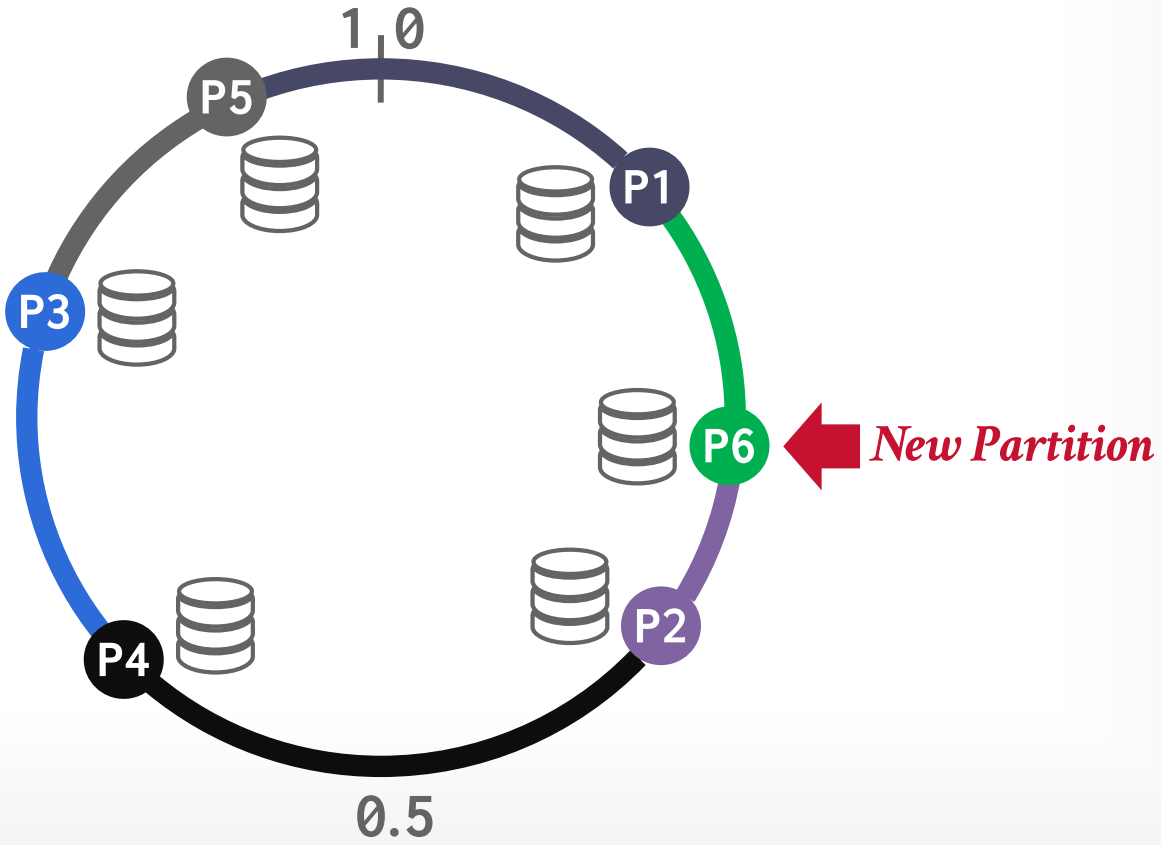

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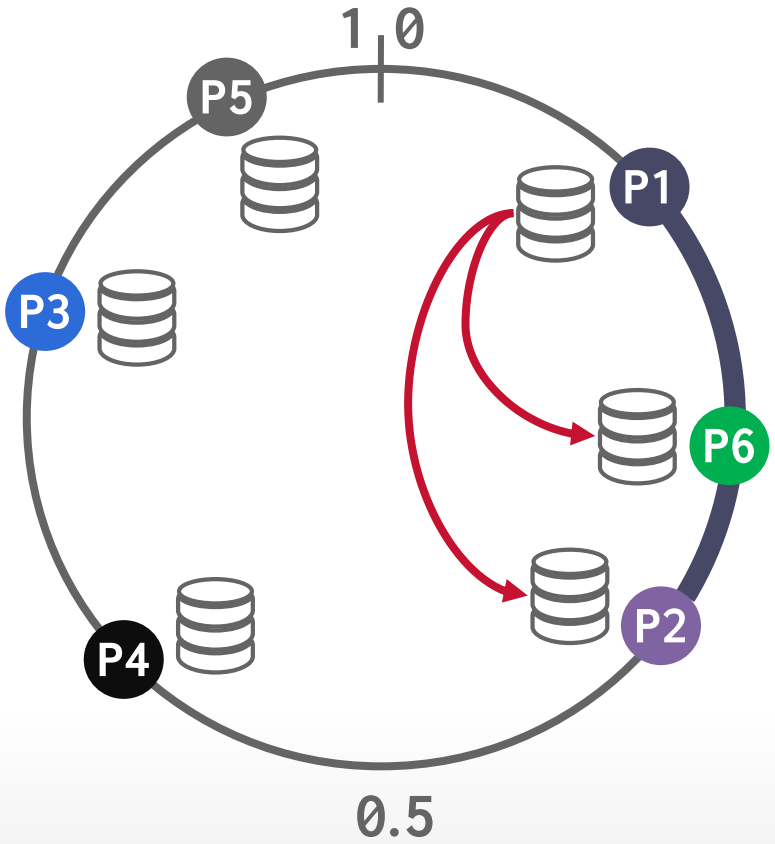
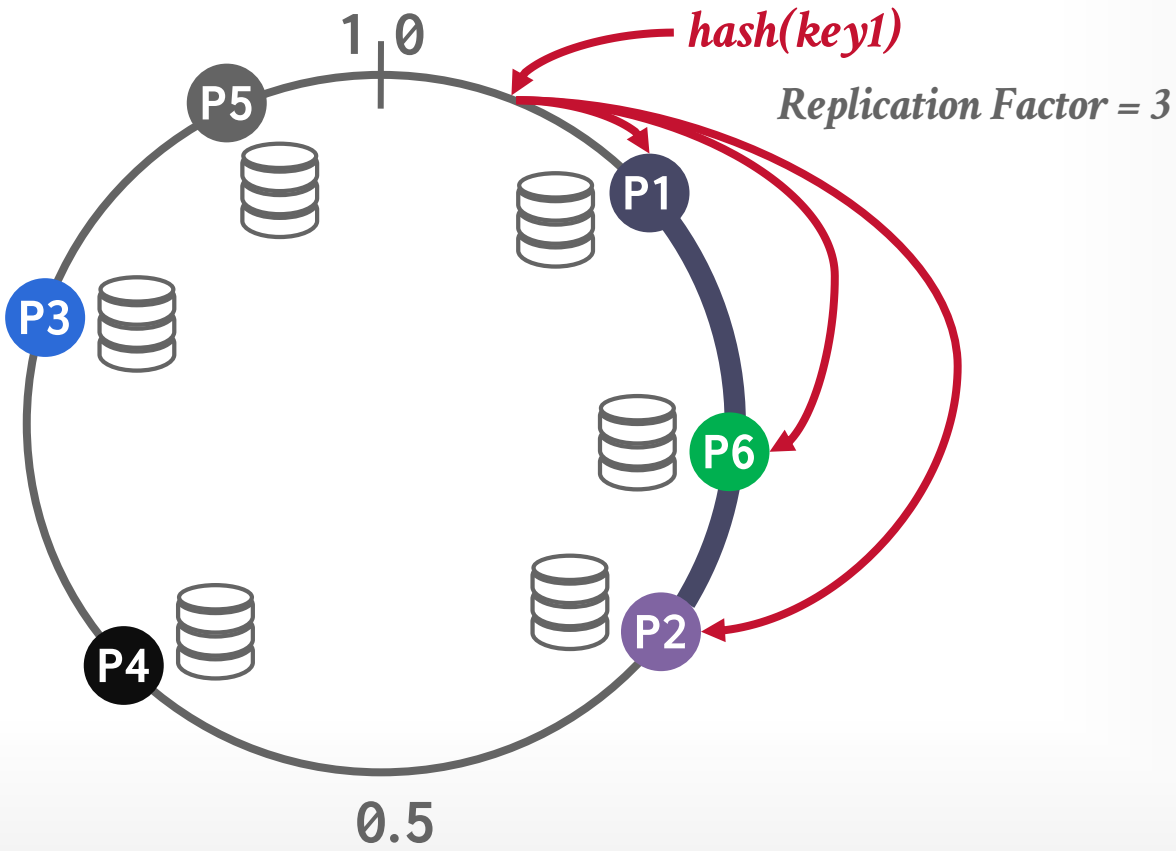


Replication Factor = 3

CONSISTENT HASHING



CONSISTENT HASHING

Couchbase

snowflake

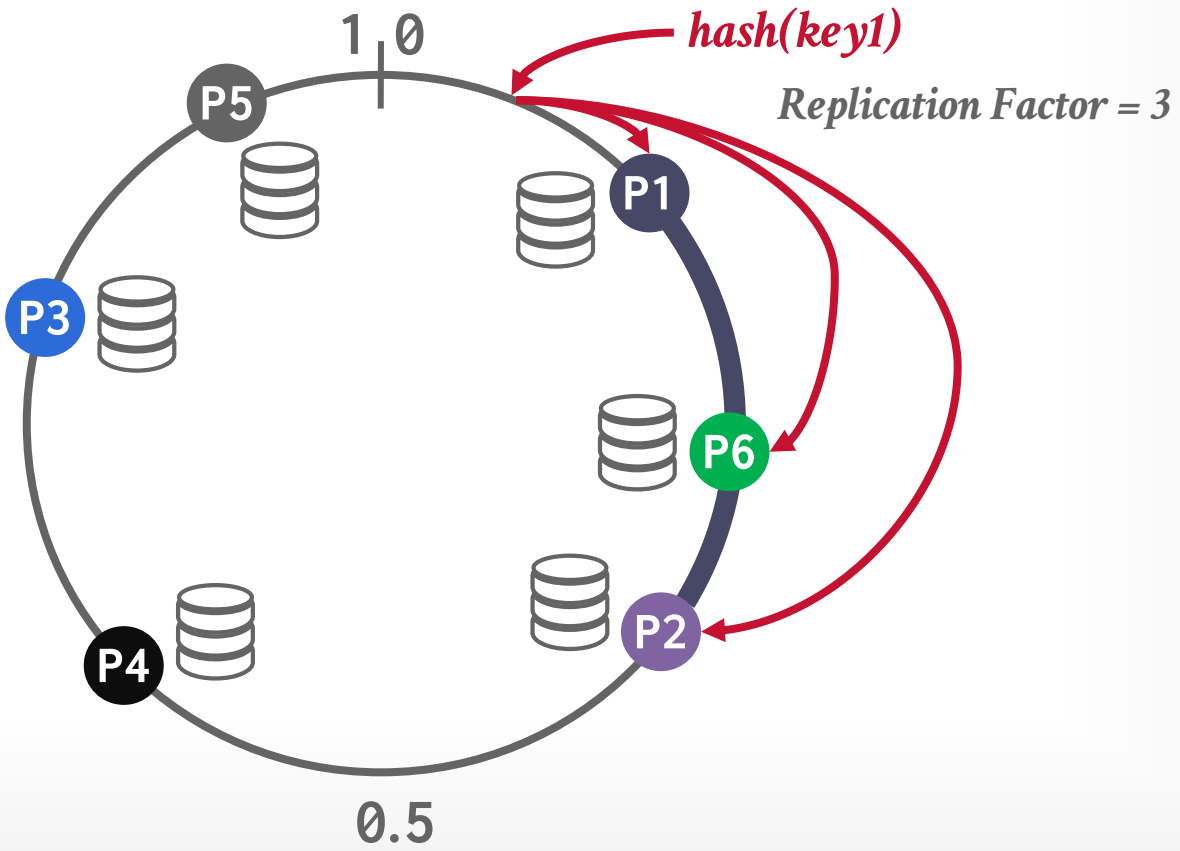
AEROSPIKE

MEMCACHED

cassandra

riak

SCYLLA.



SINGLE-NODE VS. DISTRIBUTED

A **single-node** txn only accesses data that is contained on one partition.

→ The DBMS may not need check the behavior concurrent txns running on other nodes.

A **distributed** txn accesses data at one or more partitions.

→ Requires expensive coordination.

TRANSACTION COORDINATION

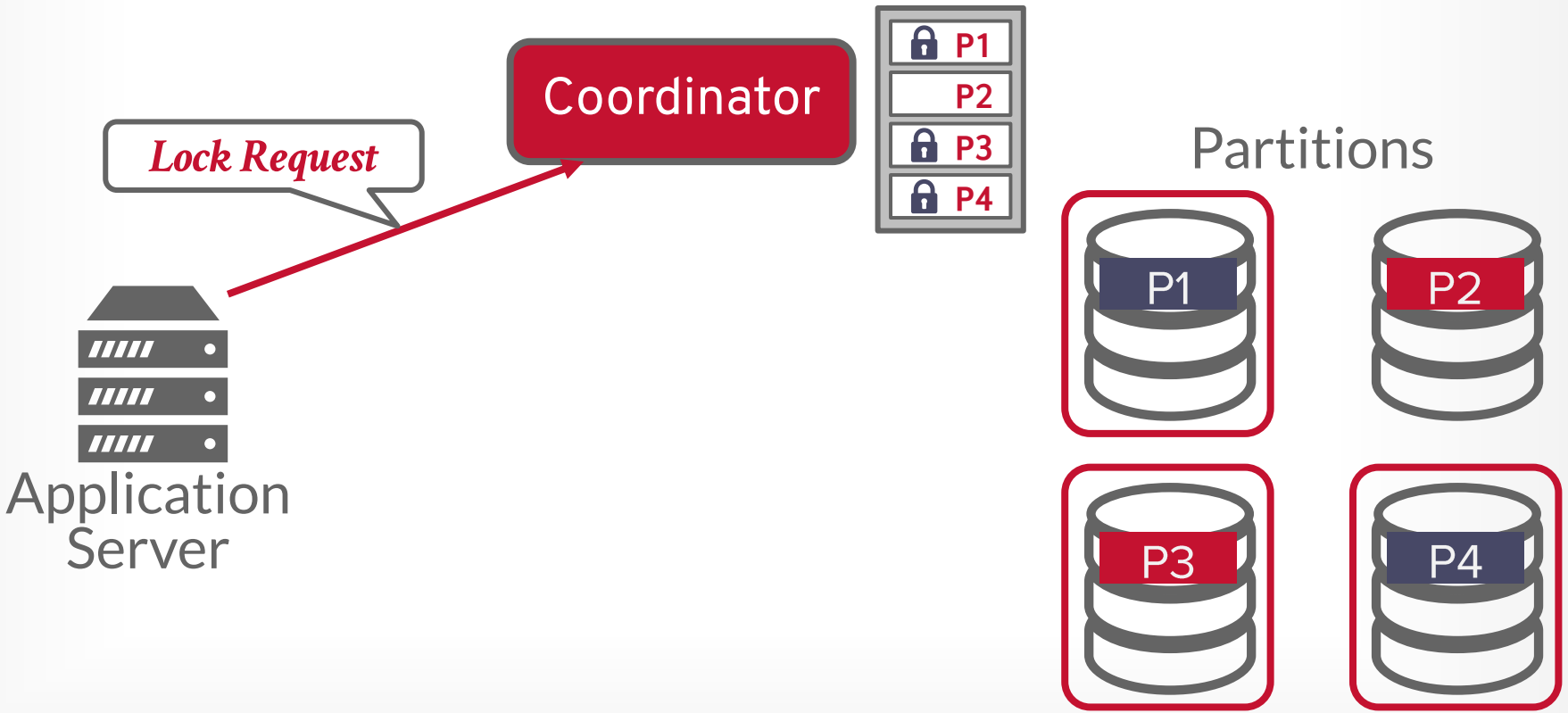
If our DBMS supports multi-operation and distributed txns, we need a way to coordinate their execution in the system.

Two different approaches:
→ **Centralized**: Global "traffic cop".
→ **Decentralized**: Nodes organize themselves.

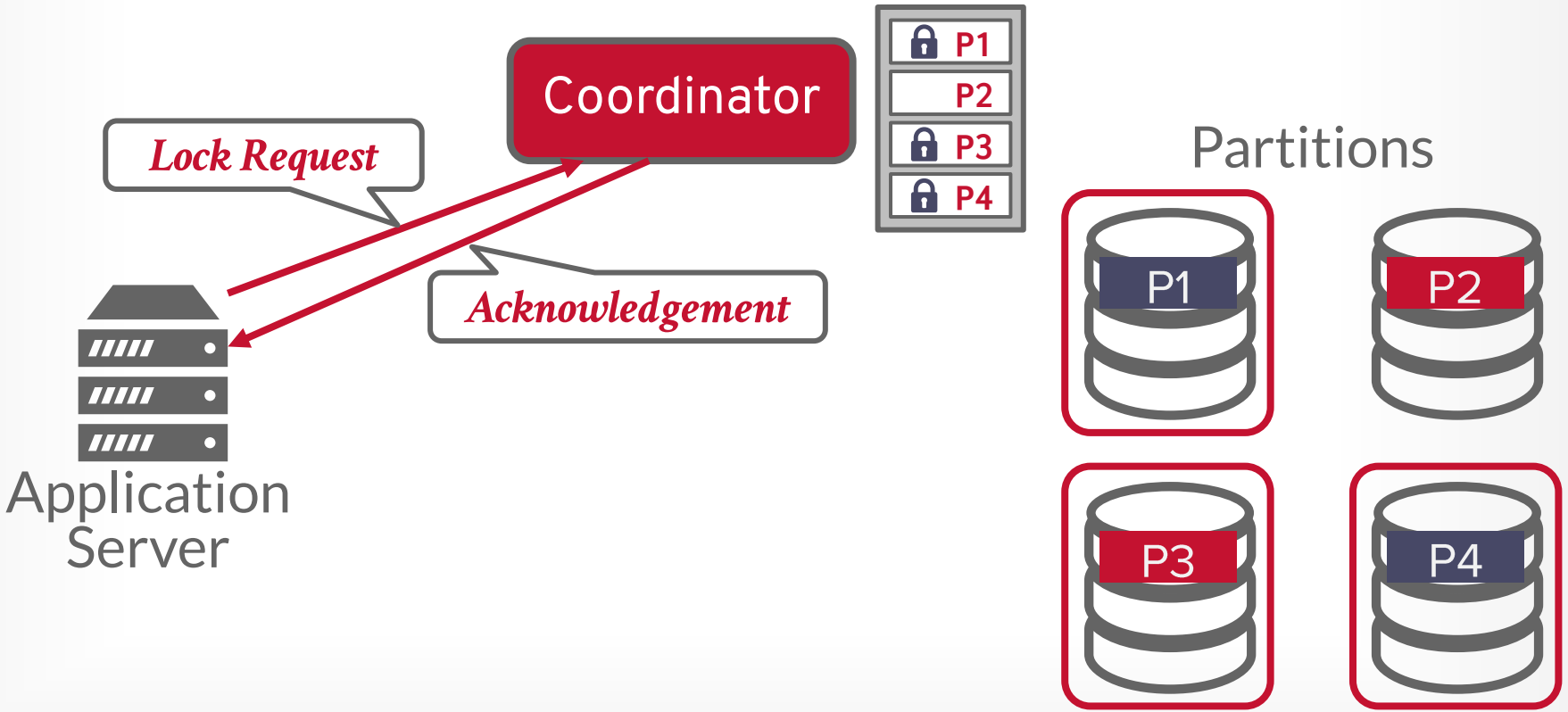
Most distributed DBMSs use a hybrid approach where they periodically elect some node to be a temporary coordinator.

CENTRALIZED COORDINATOR

CENTRALIZED COORDINATOR



CENTRALIZED COORDINATOR



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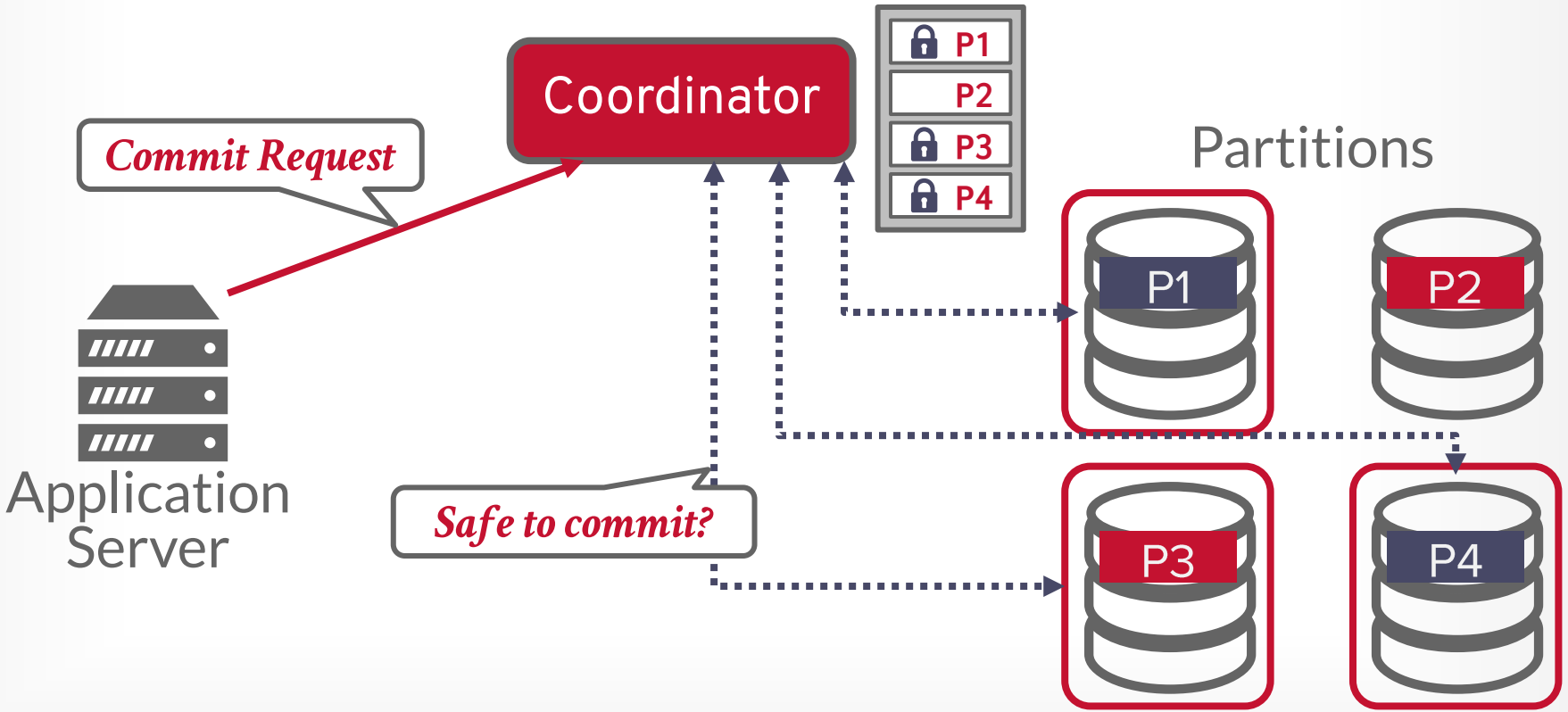
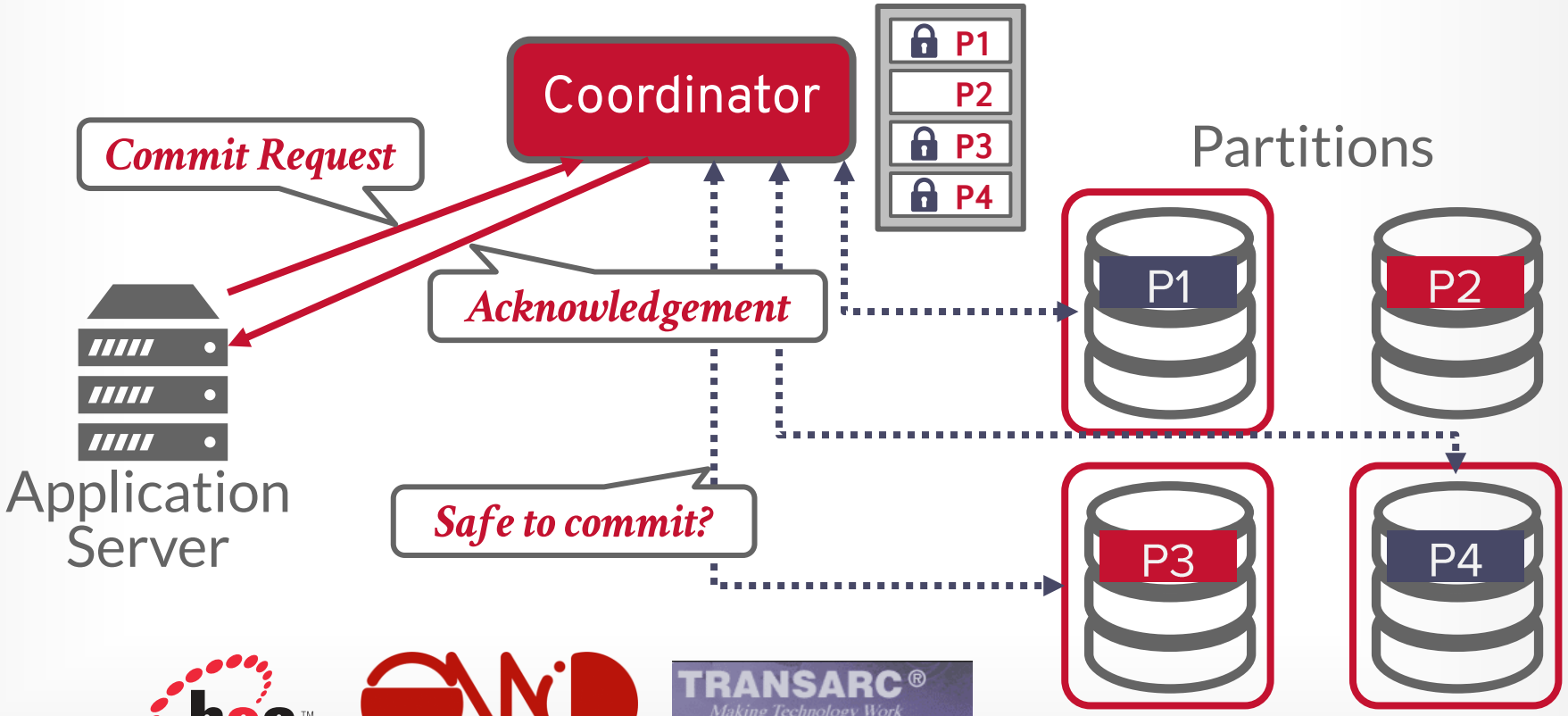


CENTRALIZED COORDINATOR



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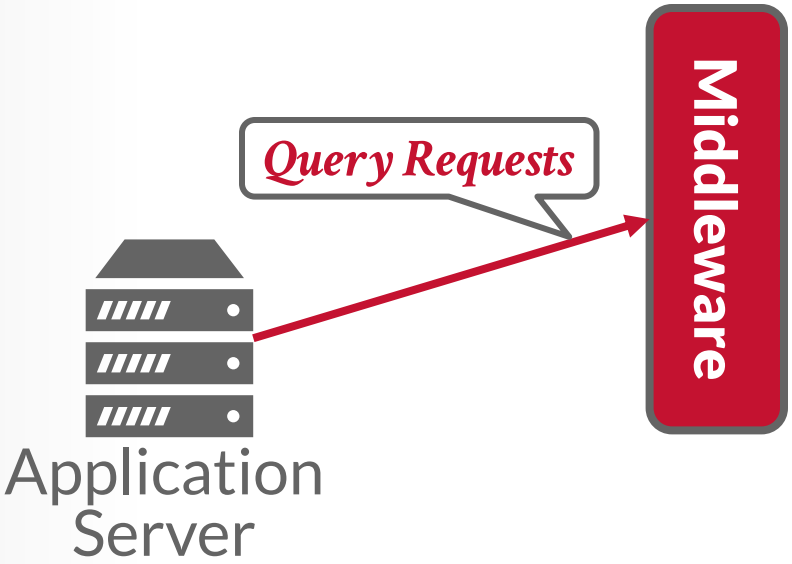

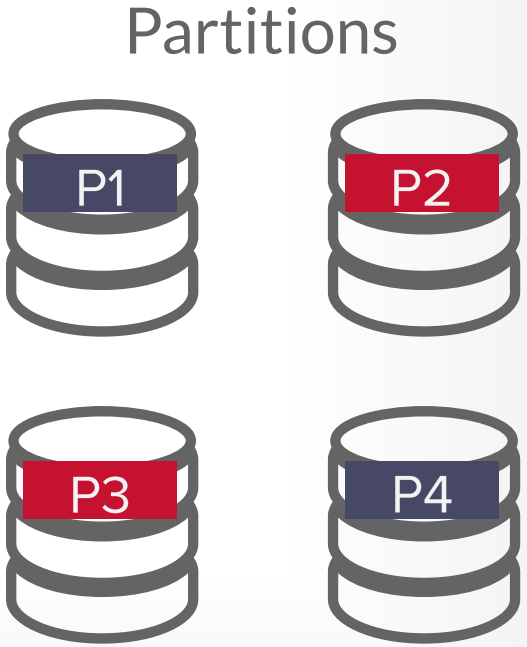

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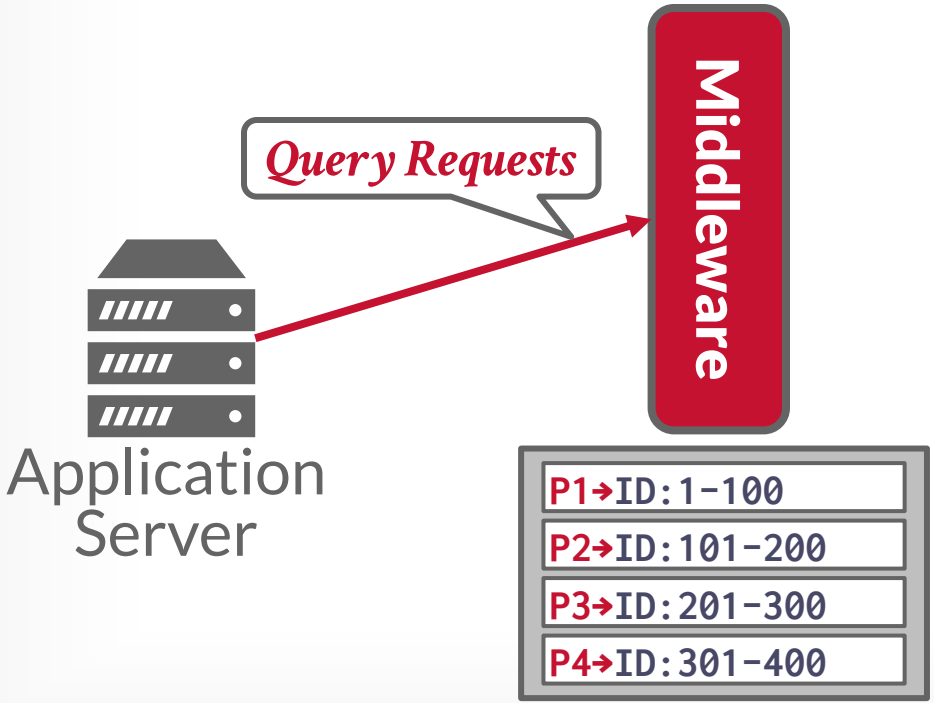

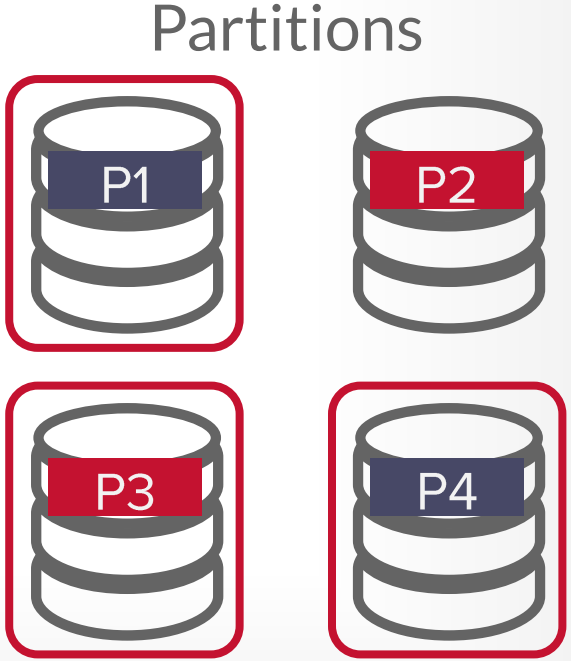

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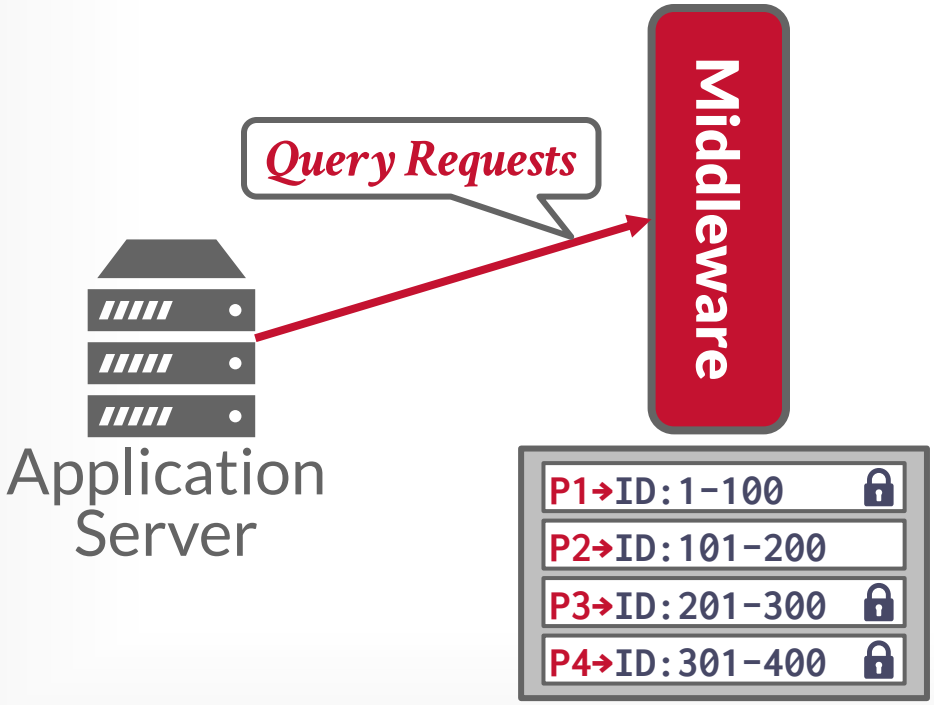
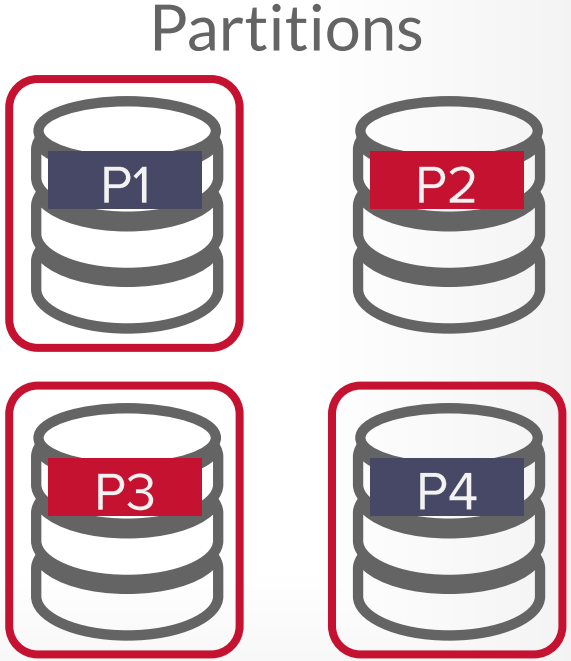
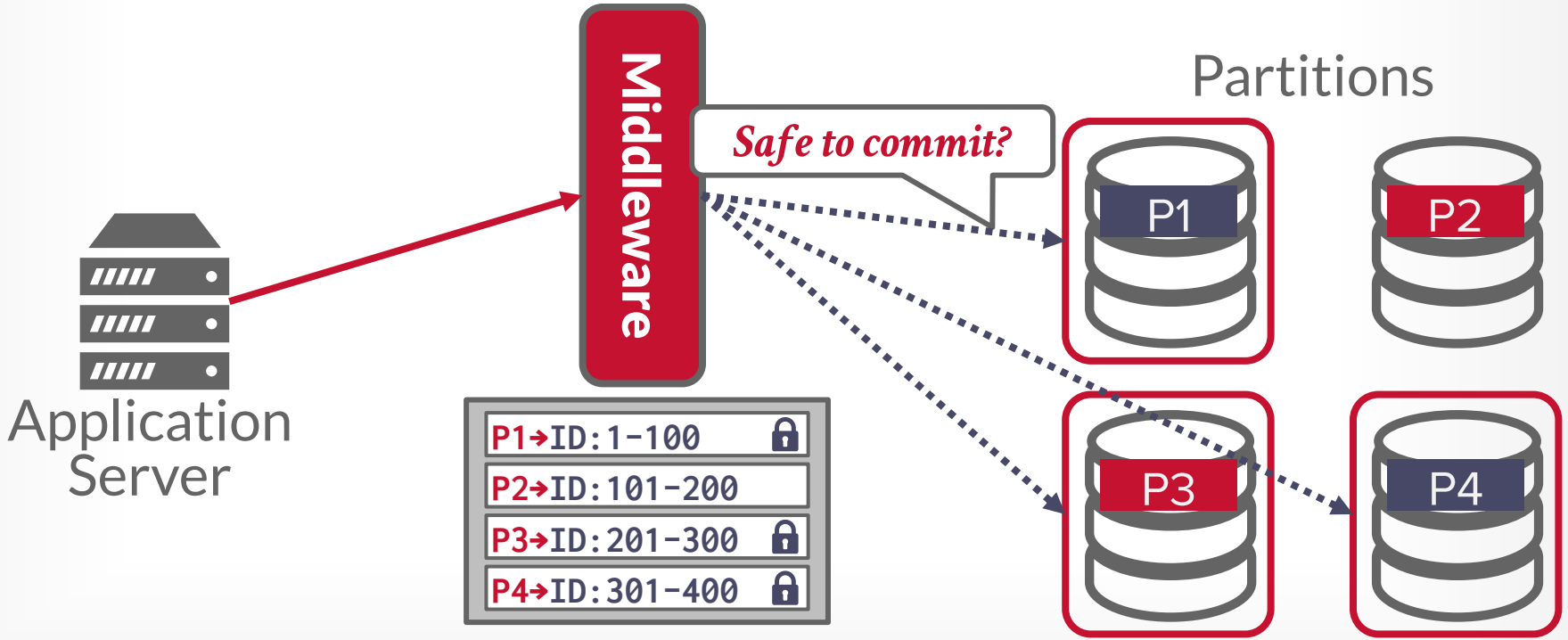
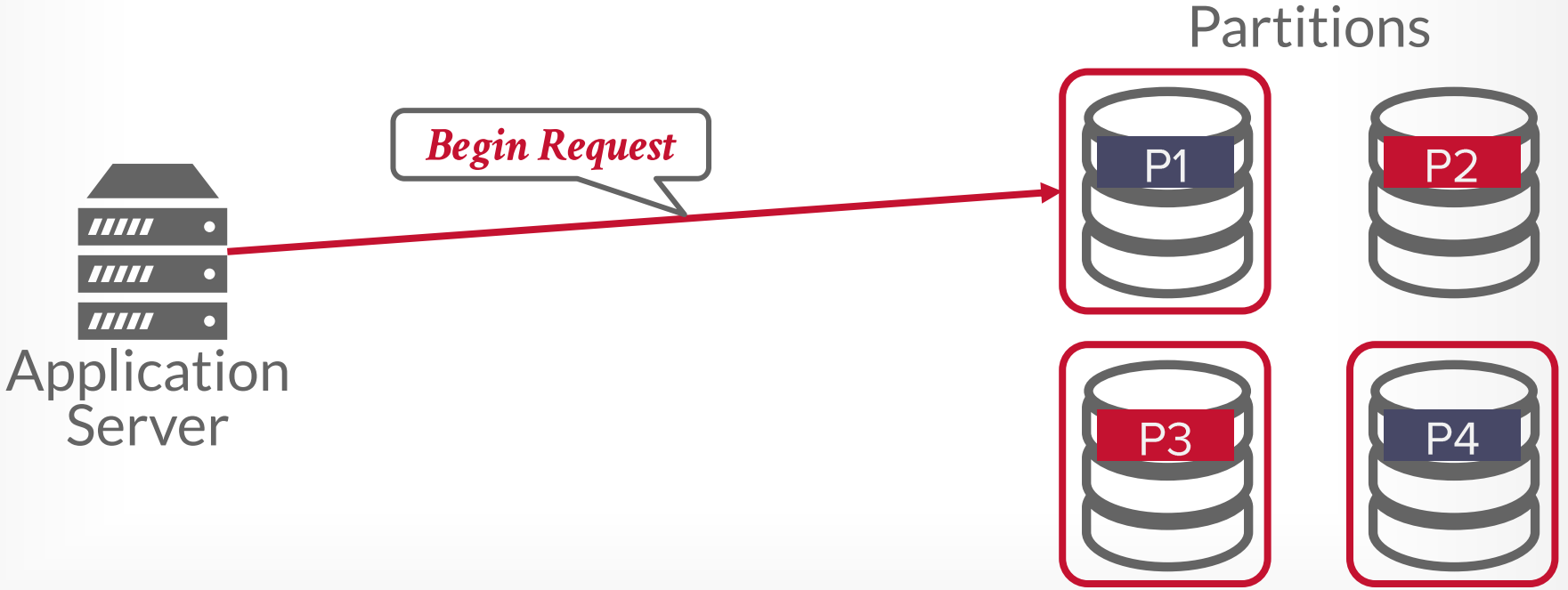




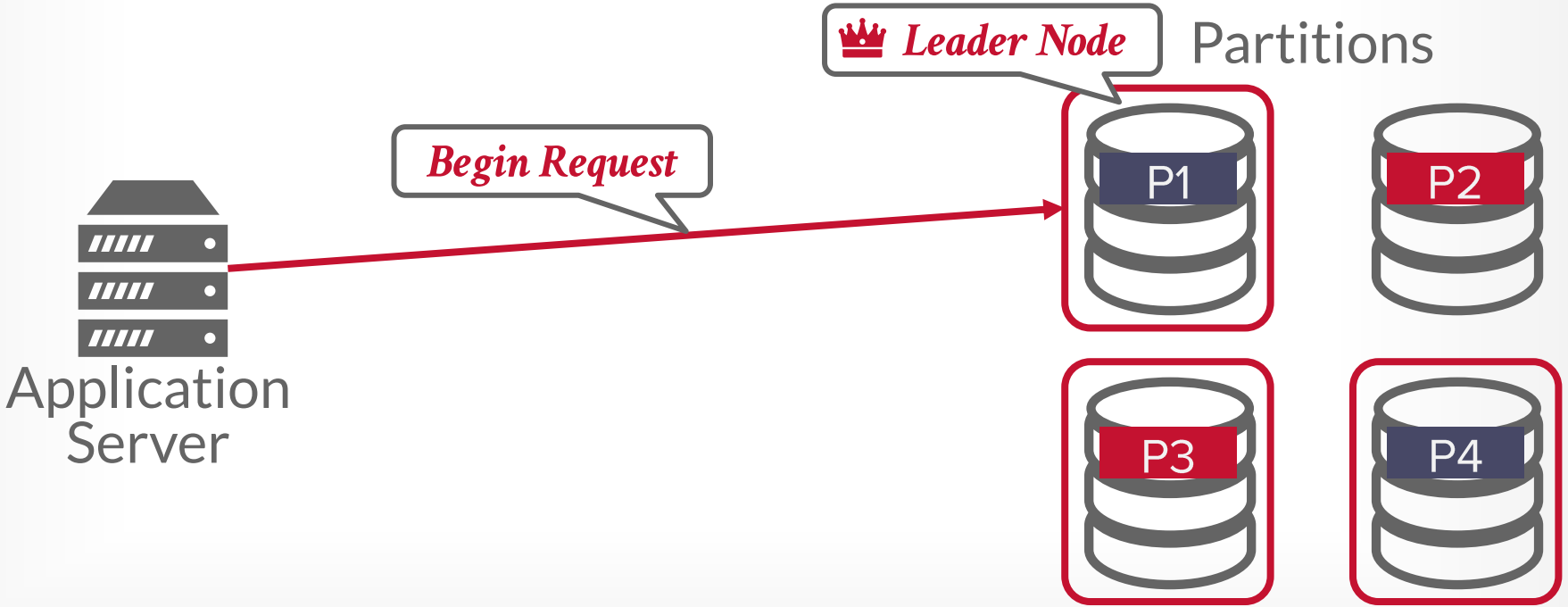
CENTRALIZED COORDINATOR



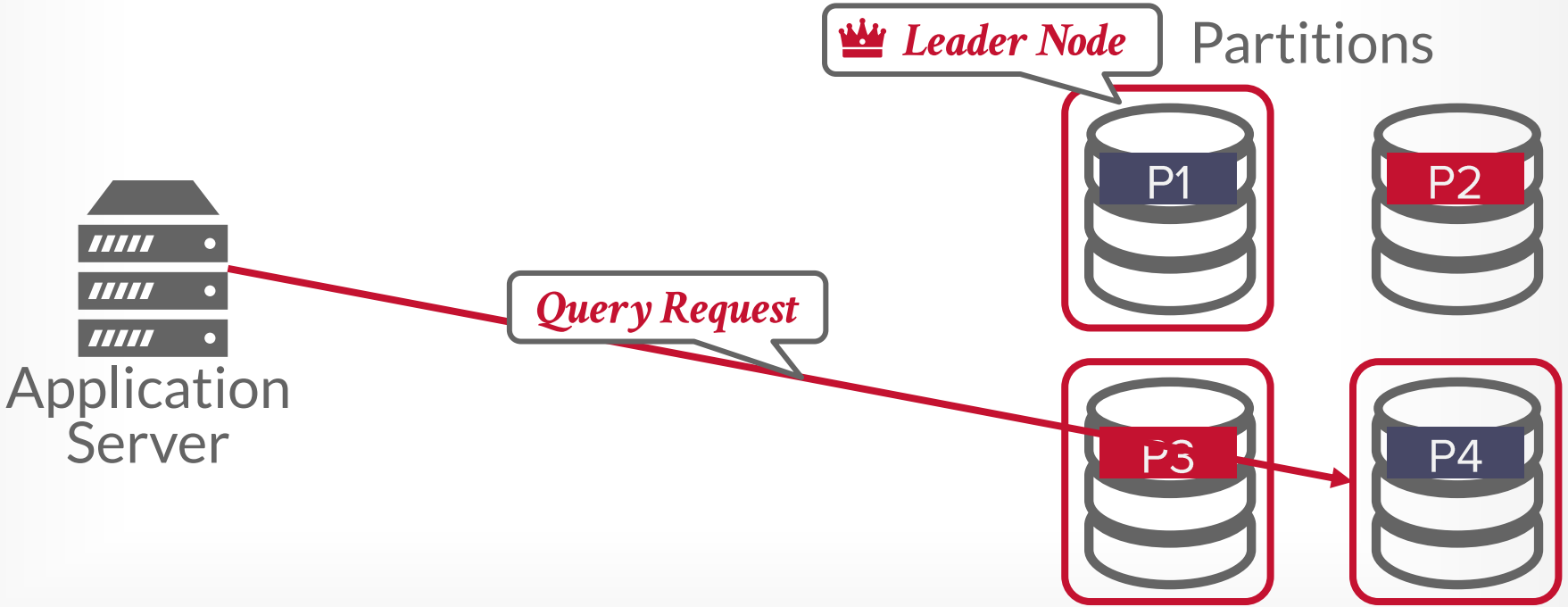
DECENTRALIZED COORDINATOR



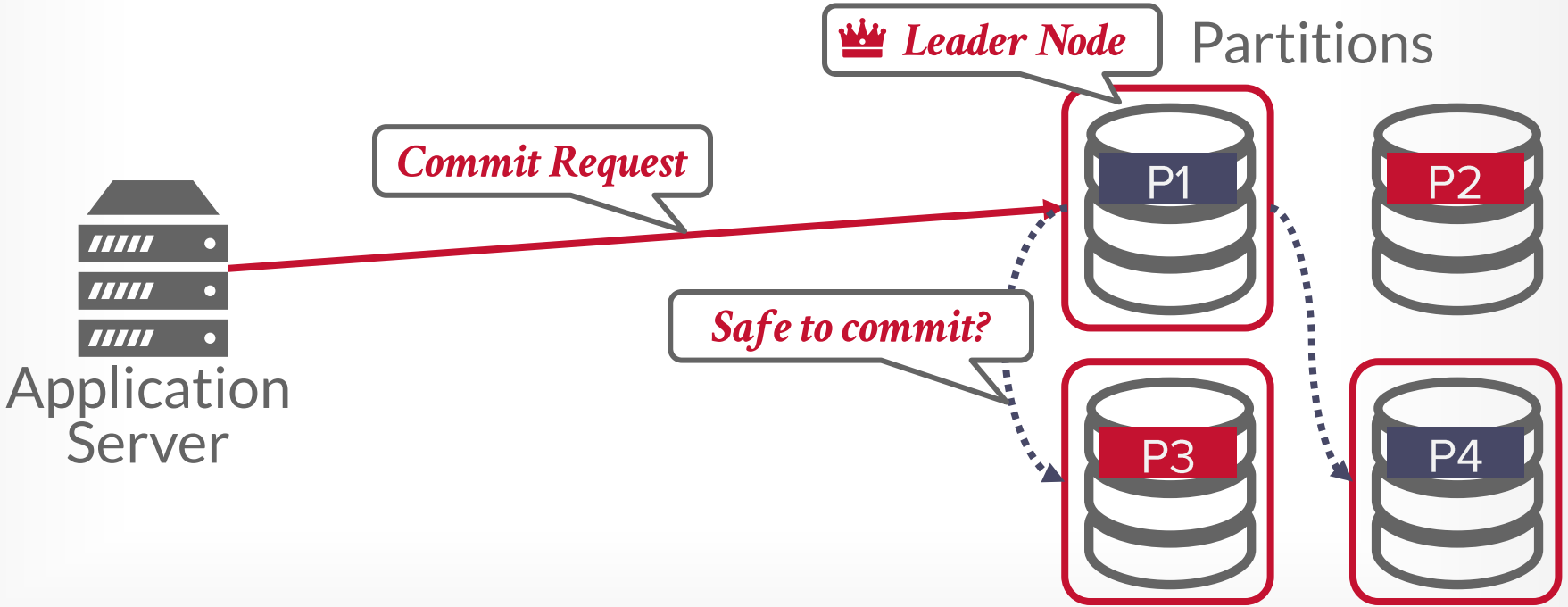
DECENTRALIZED COORDINATOR



DECENTRALIZED COORDINATOR



DECENTRALIZED COORDINATOR



OBSERVATION

We have assumed that the nodes in our distributed systems are running the same DBMS software.

But organizations often run many different DBMSs in their applications.

It would be nice if we could have a single interface for all our data.

FEDERATED DATABASES

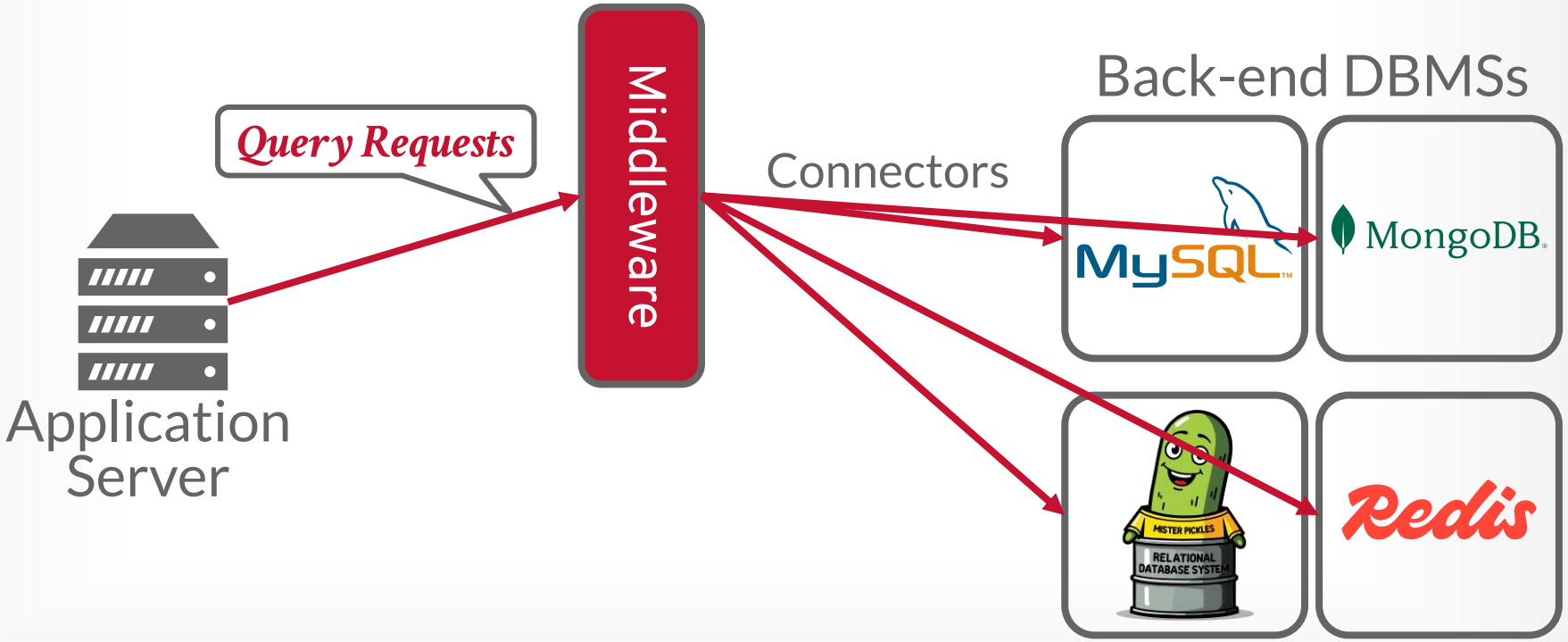
Distributed architecture that connects disparate DBMSs into a single logical system.

→ Expose a single query interface that can access data at any location.

This is hard and nobody does it well

→ Different data models, query languages, limitations.
→ No easy way to optimize queries
→ Lots of data copying (bad).

FEDERATED DATABASE EXAMPLE



DISTRIBUTED CONCURRENCY CONTROL

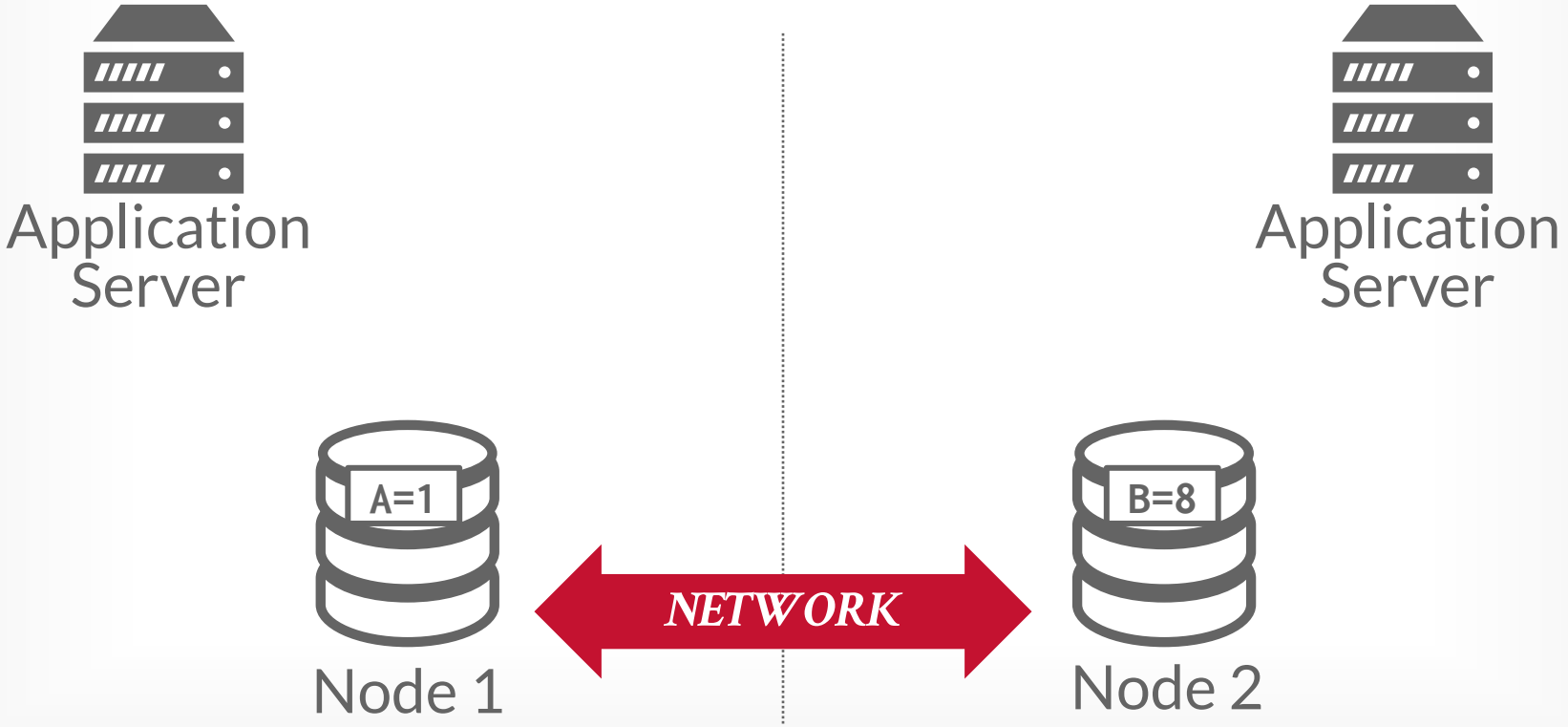
Need to allow multiple txns to execute simultaneously across multiple nodes.

→ Many of the same protocols from single-node DBMSs can be adapted.

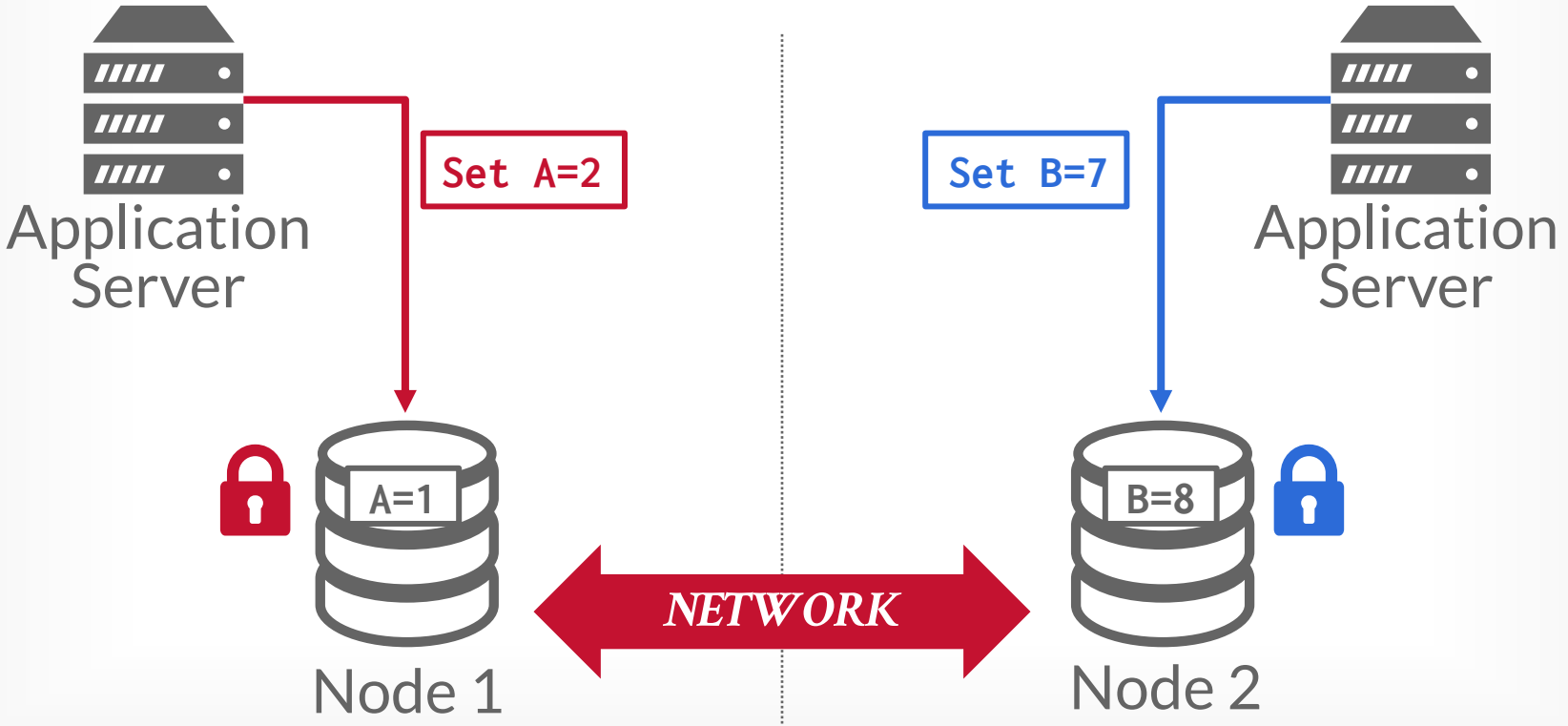
This is harder because of:

→ Replication.
→ Network Communication Overhead.
→ Node Failures (Permanent + Ephemeral).
→ Clock Skew.

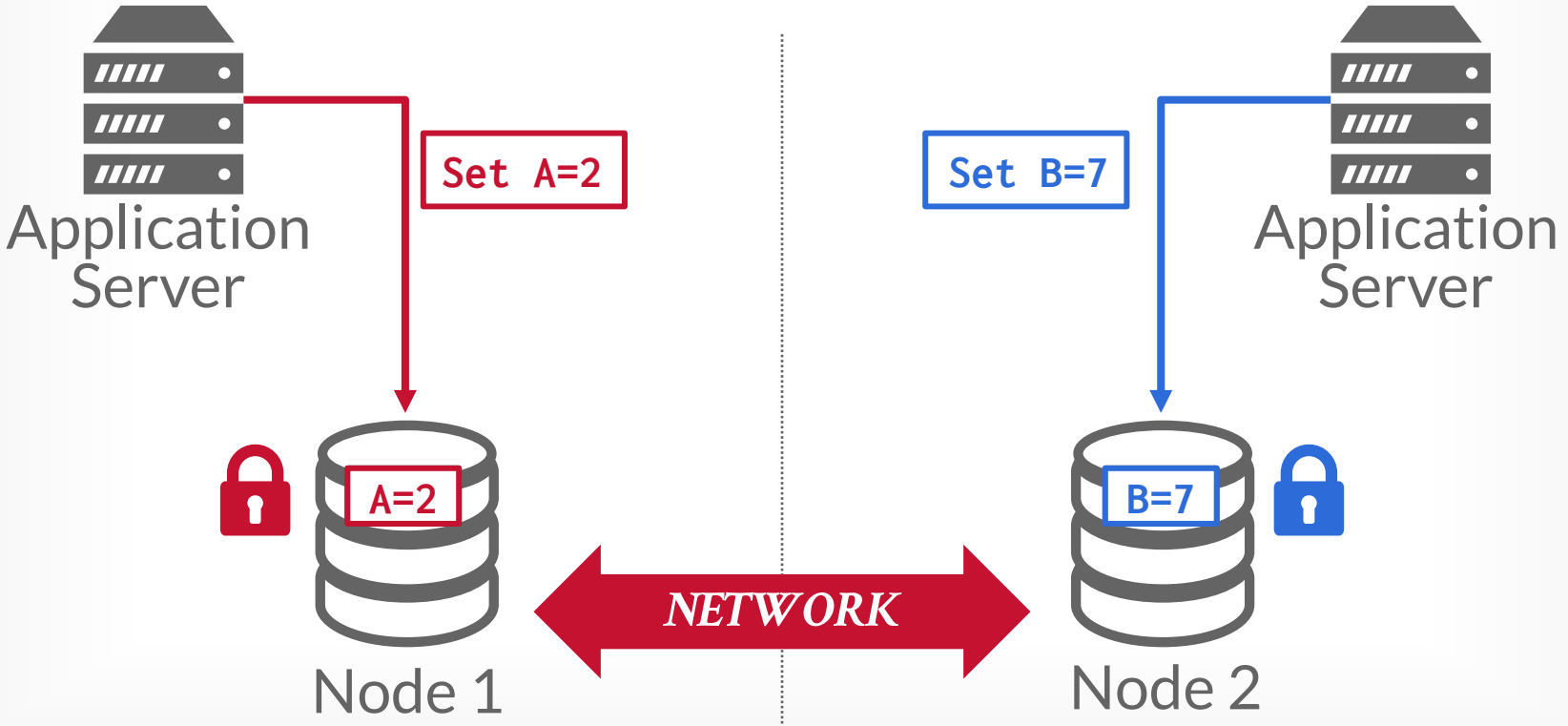
DISTRIBUTED 2PL



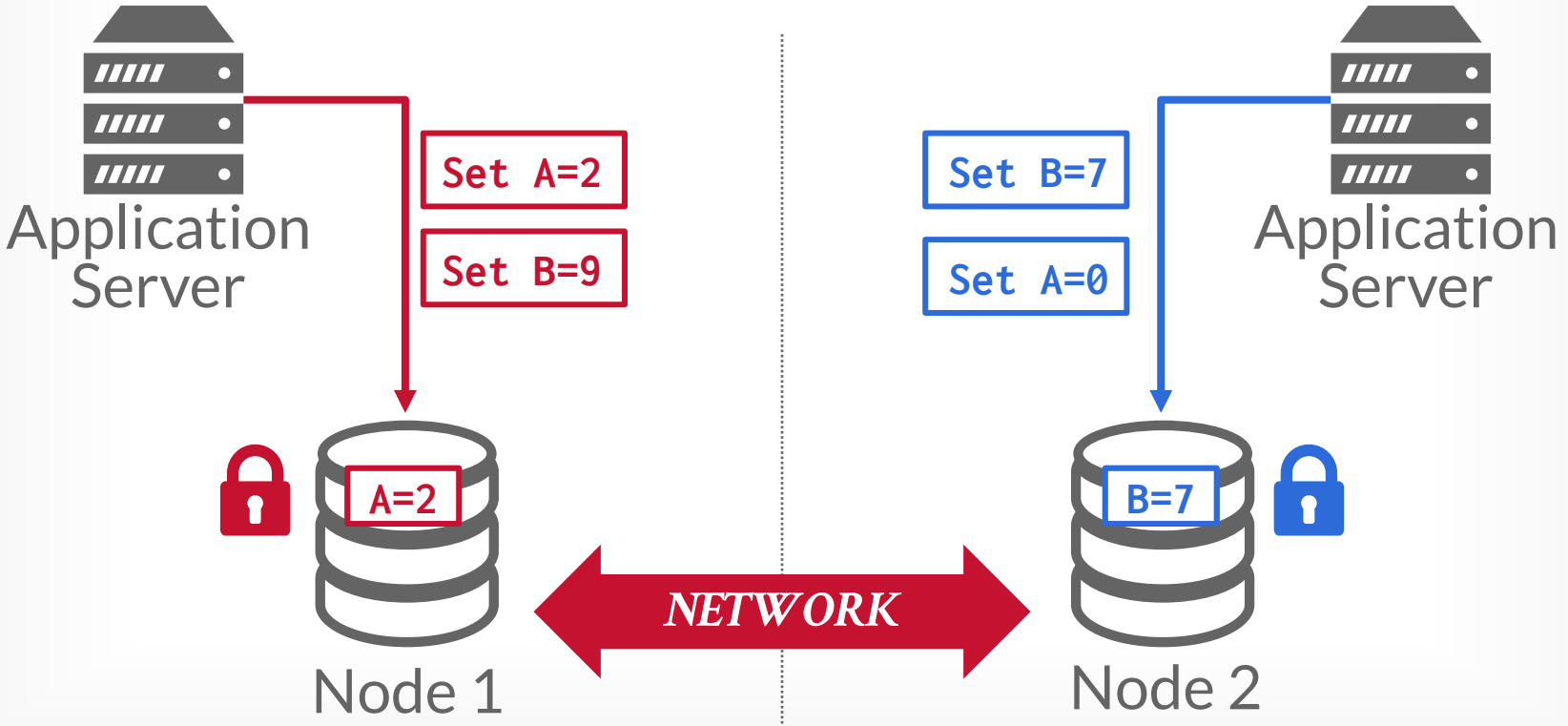
DISTRIBUTED 2PL



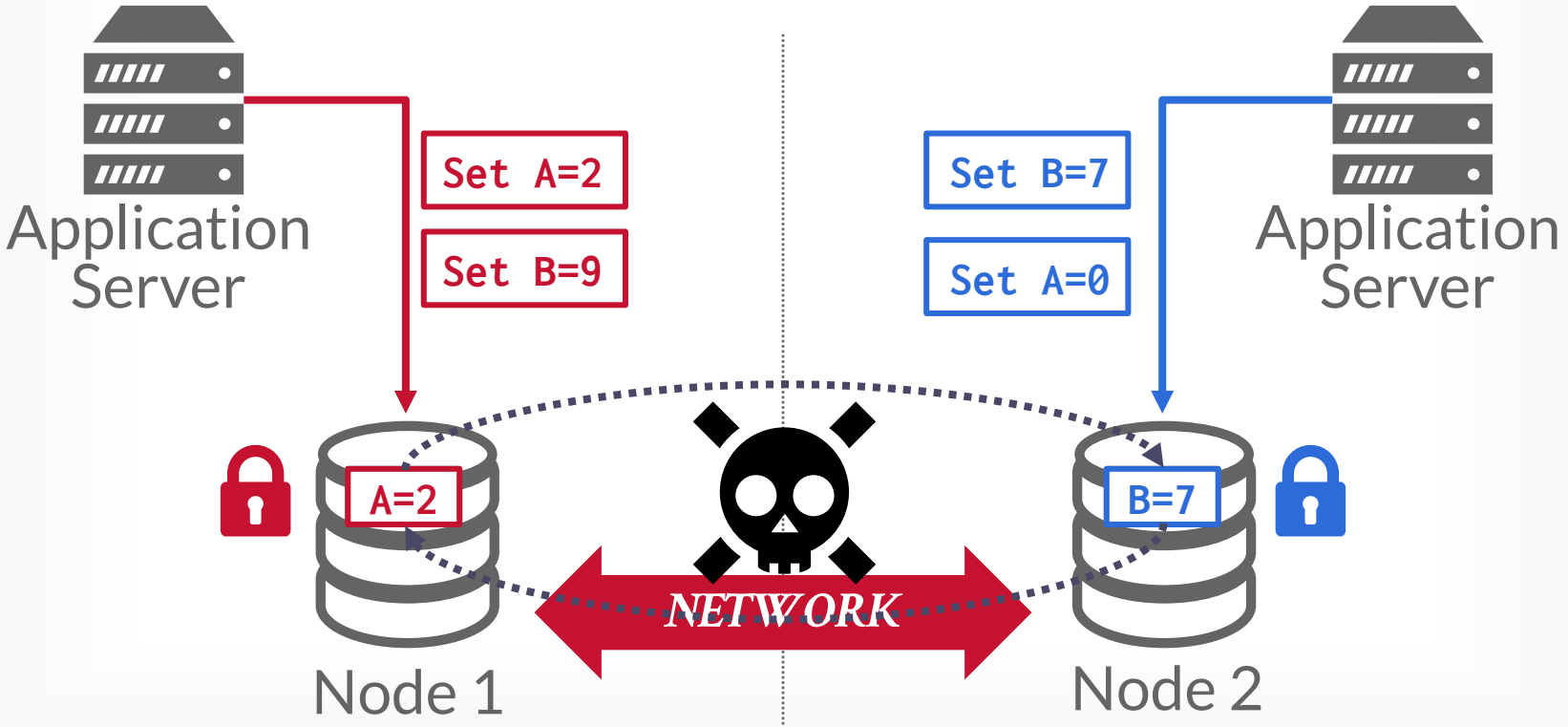
DISTRIBUTED 2PL



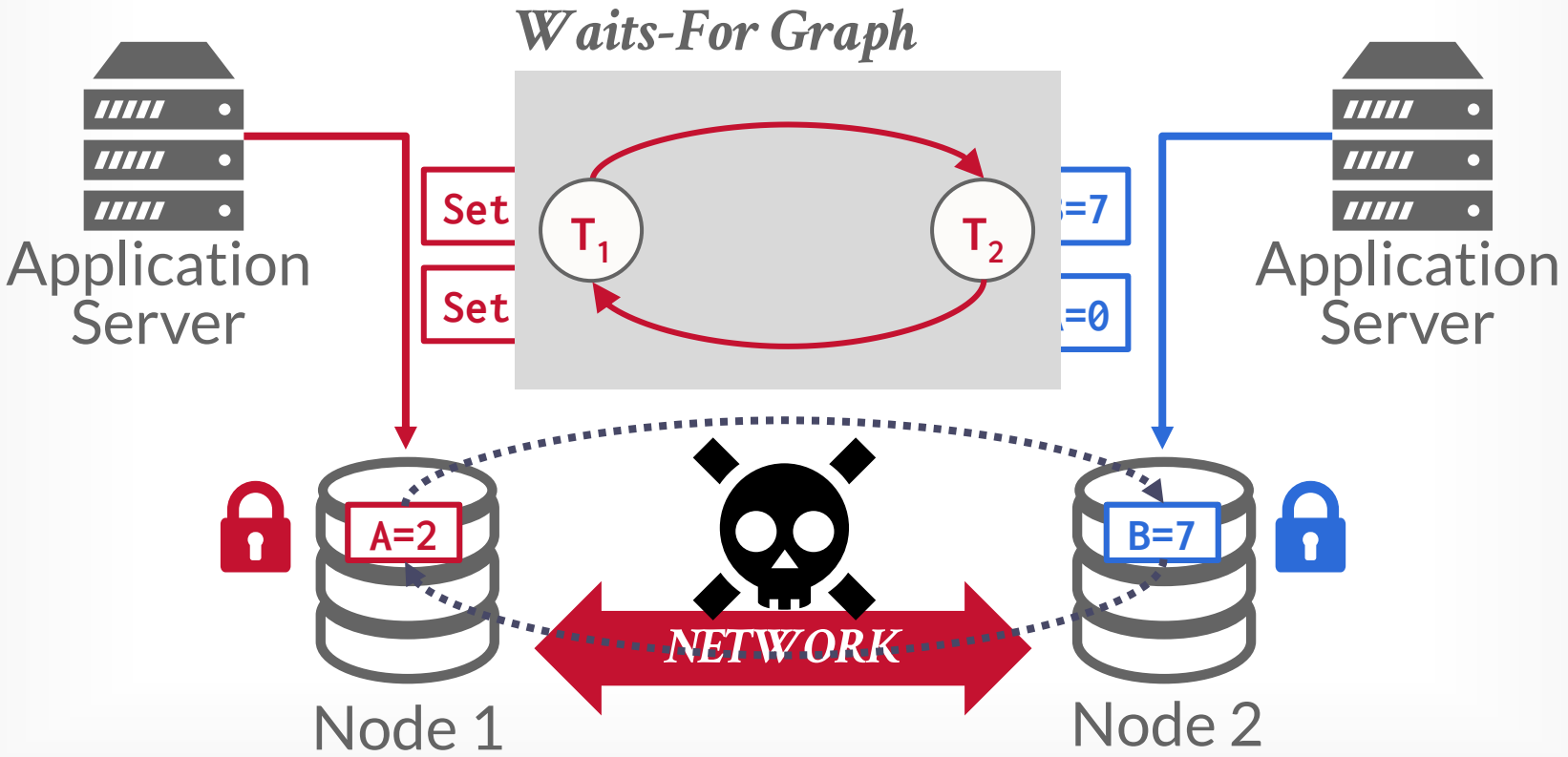
DISTRIBUTED 2PL



DISTRIBUTED 2PL



DISTRIBUTED 2PL



CONCLUSION

We have barely scratched the surface on distributed database systems…

It is **hard** to get this right.

NEXT CLASS

Distributed OLTP Systems

Replication

CAP Theorem

Real-World Examples