Lecture #10

Carnegie Mellon University

ADVANCED DATABASE SYSTEMS

Recovery Protocols

@Andy_Pavlo // 15-721 // Spring 2020

DATABASE RECOVERY

Recovery algorithms are techniques to ensure database **consistency**, **atomicity** and **durability** despite failures.

Recovery algorithms have two parts:
→ Actions during normal txn processing to ensure that the DBMS can recover from a failure.
→ Actions after a failure to recover the database to a state that ensures atomicity, consistency, and durability.

OBSERVATION

Many of the early papers (1980s) on recovery for in-memory DBMSs assume that there is non-volatile memory.

→ Battery-backed DRAM is large / finnicky
→ Real NVM is finally here as of 2019!

This hardware is still not widely available, so we want to use existing SSD/HDDs.

A RECOVERY ALGORITHM FOR A HIGH-PERFORMANCE MEMORY-RESIDENT DATABASE SYSTEM
SIGMOD 1987

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SIGMOD 1987

IN-MEMORY DATABASE RECOVERY

Slightly easier than in a disk-oriented DBMS because the system must do less work:

→ Do not track dirty pages in case of crash during recovery.
→ Do not store undo records (only need redo).
→ Do not log changes to indexes.

But the DBMS is still stymied by the slow sync time of non-volatile storage.

TODAY'S AGENDA

Logging Schemes
Checkpoint Protocols
Restart Protocols

LOGGING SCHEMES

Approach #1: Physical Logging

→ Record the changes made to a specific record in the database.

→ Example: Store the original value and after value for an attribute that is changed by a query.

Approach #2: Logical Logging

→ Record the high-level operations executed by txns.

→ Example: The **UPDATE**, **DELETE**, and **INSERT** queries invoked by a txn.

LOG FLUSHING

Approach #1: All-at-Once Flushing

→ Wait until a txn has fully committed before writing out log records to disk.

→ Do not need to store abort records because uncommitted changes are never written to disk.

Approach #2: Incremental Flushing

→ Allow the DBMS to write a txn's log records to disk before it has committed.

GROUP COMMIT

Batch together log records from multiple txns and flush them together with a single **fsync**.

→ Logs are flushed either after a timeout or when the buffer gets full.

→ Originally developed in [IBM IMS FastPath] in the 1980s

This amortizes the cost of I/O over several txns.

EARLY LOCK RELEASE

A txn's locks can be released before its commit record is written to disk if it does not return results to the client before becoming durable.

Other txns that speculatively read data updated by a **pre-committed** txn become dependent on it and must wait for their predecessor's log records to reach disk.

OBSERVATION

The delta records in an MVCC DBMS are like the log records generated in physical logging.

Instead of generating separate data structures for MVCC and logging, what if the DBMS could use the same information?

MSSQL CONSTANT TIME RECOVERY

Physical logging protocol that uses the DBMS's MVCC **time-travel** table as the recovery log.

→ The version store is a persistent append-only storage area that is flushed to disk.

→ Leverage versions meta-data to "undo" updates without having to process undo records in WAL.

Recovery time is measured based on the number of version store records that must be read from disk.

CONSTANT TIME RECOVERY IN AZURE SQL DATABASE
VLDB 2019

MSSQL: VERSION STORE

Main Table

	COL1	COL2	POINTER
A_4	xxx	\$444	
B_2	yyy	\$22	
C_5	zzz	\$5	

Version Store

	COL1	COL2	POINTER
A_2	xxx	\$222	Ø
B_1	yyy	\$11	Ø
A_3	xxx	\$333	
C_4	zzz	\$4	Ø

MSSQL: VERSION STORE

Main Table

	COL1	COL2	POINTER
A_4	xxx	\$444	●
B_2	yyy	\$22	●
C_5	zzz	\$5	●

Version Store

	COL1	COL2	POINTER
A_2	xxx	\$222	Ø
B_1	yyy	\$11	Ø
A_3	xxx	\$333	●
C_4	zzz	\$4	Ø
A_4	xxx	\$444	●

MSSQL: VERSION STORE

Main Table

	COL1	COL2	POINTER
A_5	xxx	\$555	●
B_2	yyy	\$22	●
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Version Store

	COL1	COL2	POINTER
A_2	xxx	\$222	Ø
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A_3	xxx	\$333	●
C_4	zzz	\$4	Ø
A_4	xxx	\$444	●

MSSQL CTR: PERSISTENT VERSION STORE

Approach #1: In-row Versioning

→ Store small updates to a tuple as a delta record embedded with the latest version in the main table.
→ Same as Cicada "best-effort in-lining" technique.

Approach #2: Off-row Versioning

→ Specialized data table to store the old versions that is optimized for concurrent inserts.
→ Versions from all tables are stored in a <u>single</u> table.
→ Store redo records for inserts on this table in WAL.

MSSQL CTR: IN-ROW VERSIONING

Main Table

	COL1	COL2	DELTA	POINTER
A_4	xxx	$444	Ø	Ø
B_2	yyy	$22	Ø	
C_5	zzz	$5	Ø	

Store small updates to a tuple as a delta record embedded with the latest version in the main table.

The delta record space is **not** pre-allocated per tuple in a disk-oriented DBMS.

MSSQL CTR: IN-ROW VERSIONING

Main Table

	COL1	COL2	DELTA	POINTER
A_4	xxx	$444	TXNID: T_2, COL2: $444	Ø
B_2	yyy	$22	Ø	
C_5	zzz	$5	Ø	

Store small updates to a tuple as a delta record embedded with the latest version in the main table.

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MSSQL CTR: IN-ROW VERSIONING

Main Table

	COL1	COL2	DELTA	POINTER
A_5	xxx	\$555	TXNID: T_2, COL2: \$444	Ø
B_2	yyy	\$22	Ø	
C_5	zzz	\$5	Ø	

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MSSQL CTR: RECOVERY PROTOCOL

Phase #1: Analysis

→ Identify the sate of every txn in the log.

Phase #2: Redo

→ Recover the main table and version store to their state at the time of the crash.

→ The database is available and online after this phase.

Phase #3: Undo

→ Mark uncommitted txns as aborted in a global txn state map so that future txns ignore their versions.

→ Incrementally remove older versions via **logical revert**.

MSSQL CTR: LOGICAL REVERT

Approach #1: Background Cleanup

→ GC thread scans all blocks and removes reclaimable versions.

→ If latest version in main table is from an aborted txn, then it will move the committed version back to main table.

Approach #2: Aborted Version Overwrite

→ Txns can overwrite the latest version in the main table if that version is from an aborted txn.

SILO

In-memory OLTP DBMS from Harvard/MIT.

→ Single-versioned OCC with epoch-based GC.

→ Same authors of the Masstree.

→ Eddie Kohler is unstoppable.

SiloR uses physical logging + checkpoints to ensure durability of txns.

→ It achieves high performance by parallelizing all aspects of logging, checkpointing, and recovery.

FAST DATABASES WITH FAST DURABILITY AND RECOVERY THROUGH MULTICORE PARALLELISM
OSDI 2014

SILOR: LOGGING PROTOCOL

The DBMS assumes that there is one storage device per CPU socket.

→ Assigns one logger thread per device.
→ Worker threads are grouped per CPU socket.

As the worker executes a txn, it creates new log records that contain the values that were written to the database (i.e., REDO).

SILOR: LOGGING PROTOCOL

Each logger thread maintains a pool of log buffers that are given to its worker threads.

When a worker's buffer is full, it gives it back to the logger thread to flush to disk and attempts to acquire a new one.

→ If there are no available buffers, then it stalls.

SILOR: LOG FILES

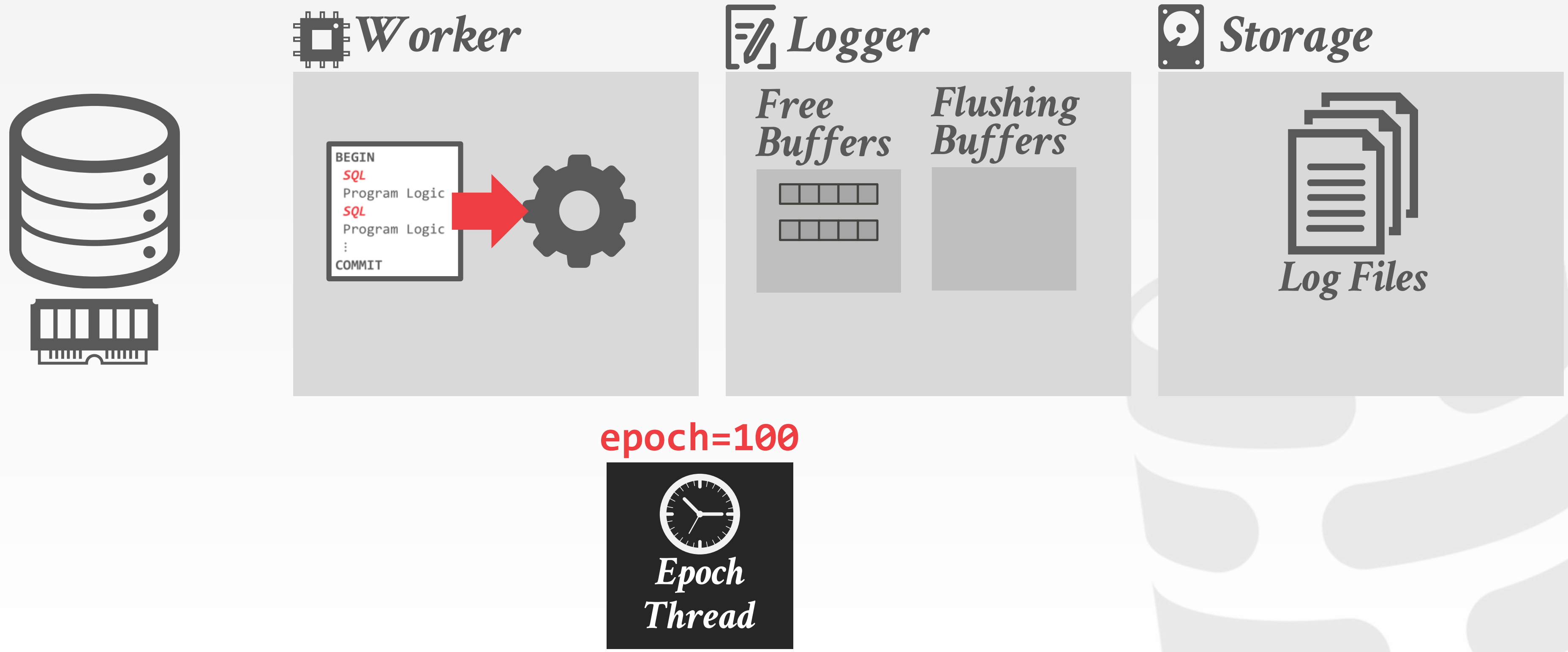
The logger threads write buffers out to files:
- → After 100 epochs, it creates a new file.
- → The old file is renamed with a marker indicating the max epoch of records that it contains.

Log record format:
- → Id of the txn that modified the record (TID).
- → A set of value log triplets (Table, Key, Value).
- → The value can be a list of attribute + value pairs.

```
UPDATE people
   SET isLame = true
 WHERE name IN ('Matt','Andy')
```

```
Txn#1001
[people, 888, (isLame→true)]
[people, 999, (isLame→true)]
```

SILOR: ARCHITECTURE



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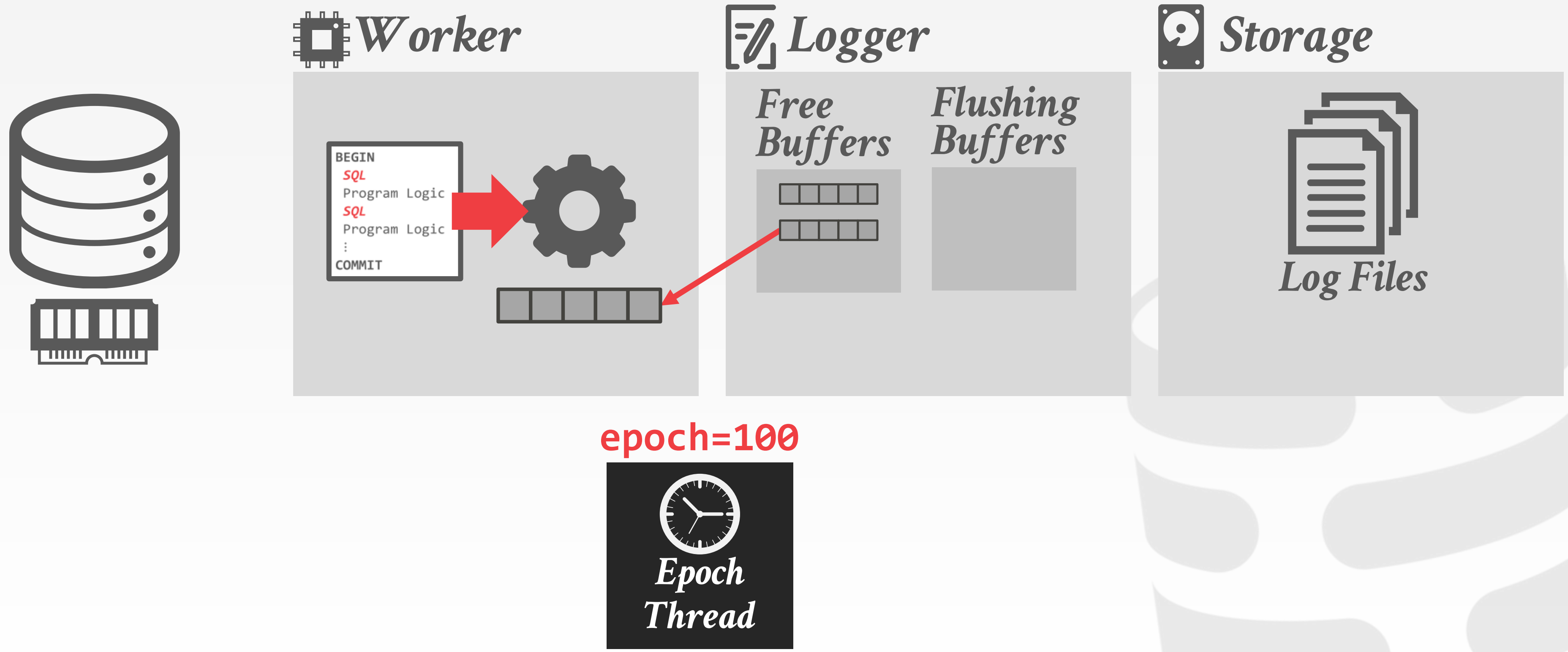

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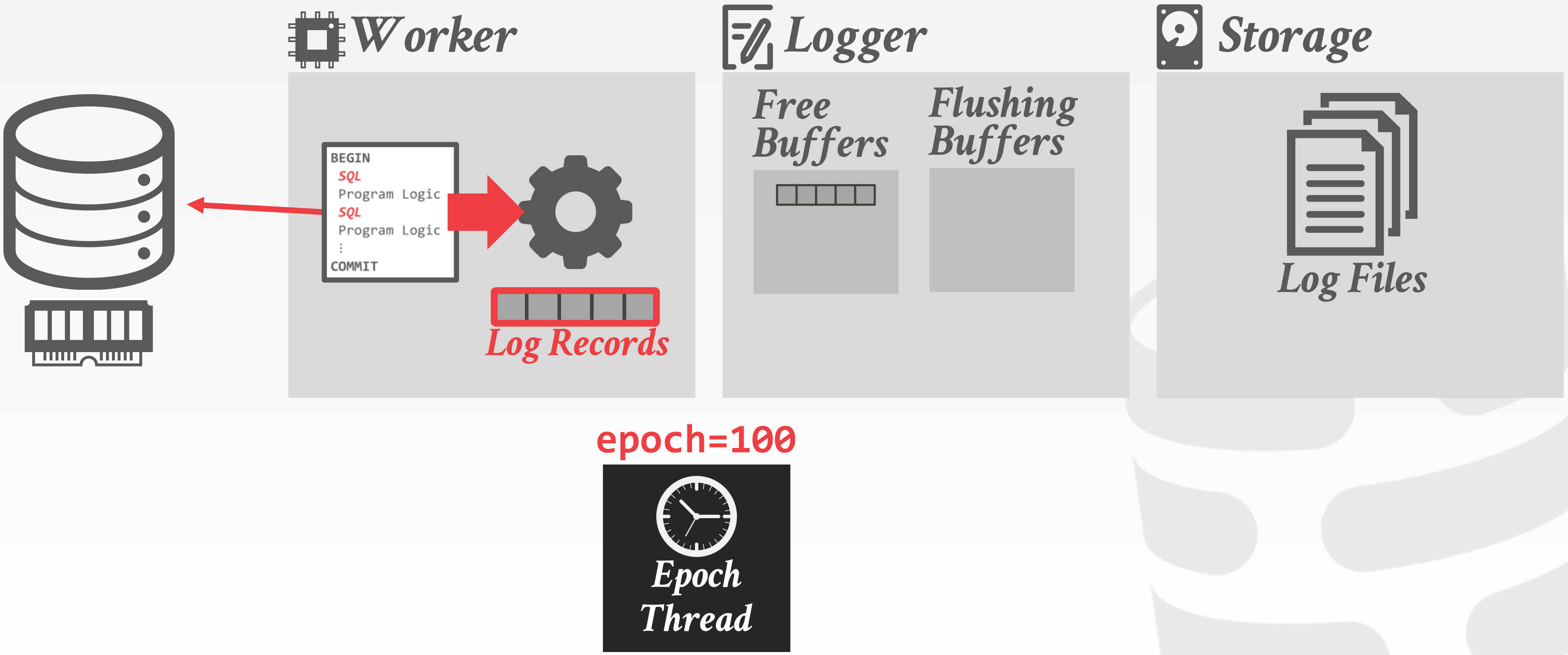

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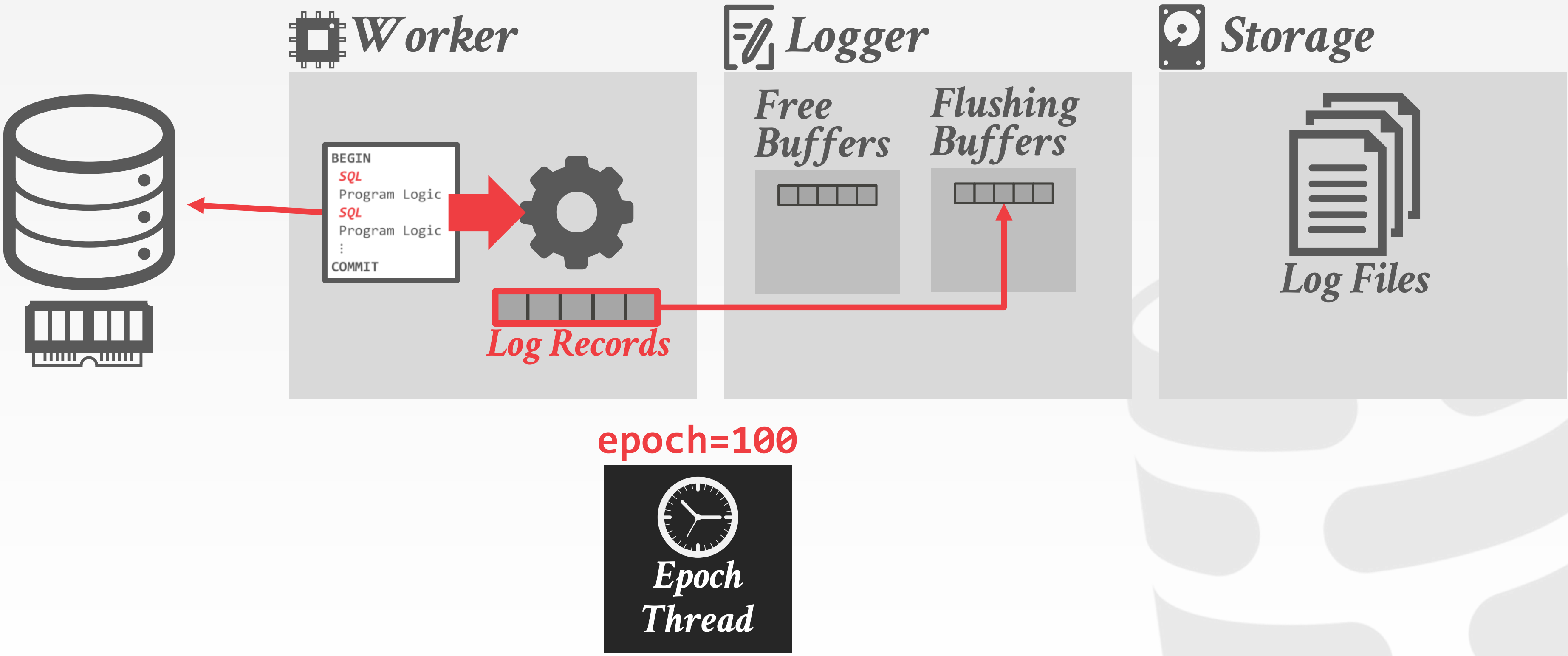

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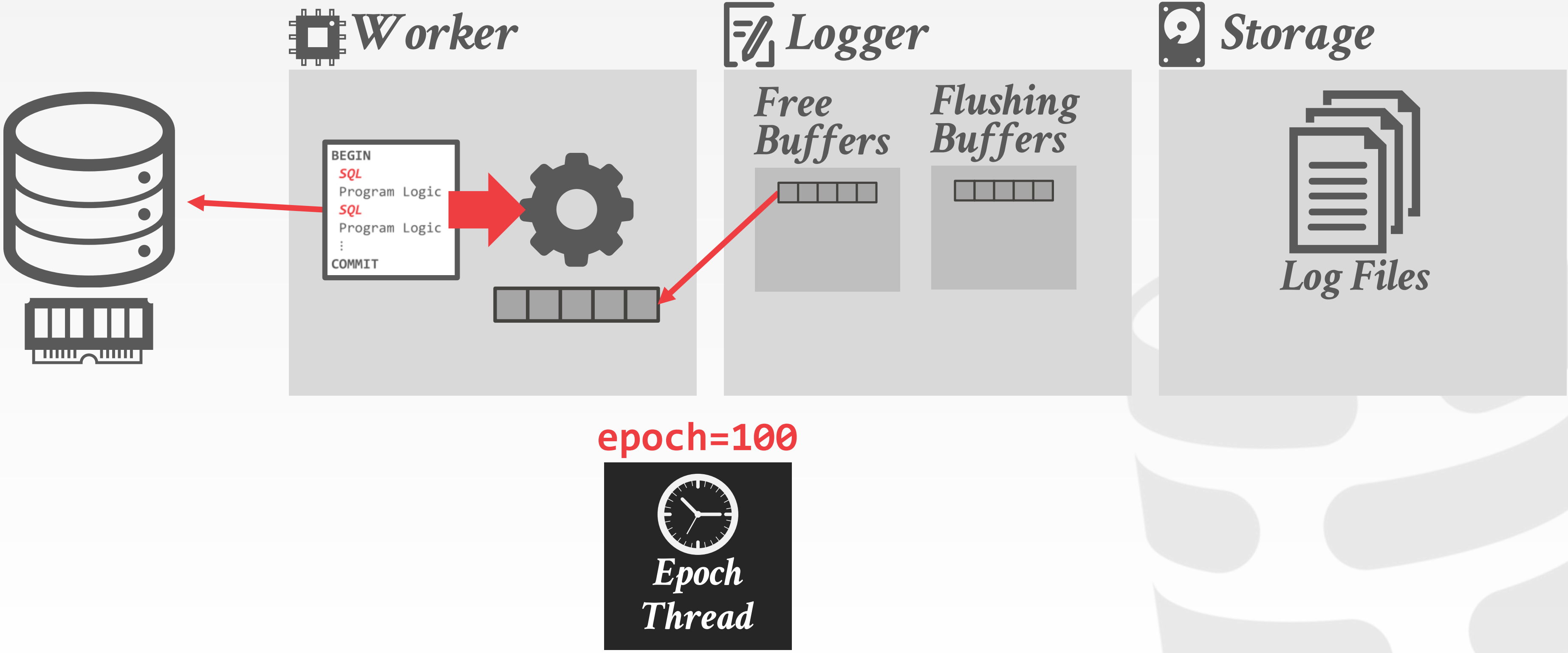

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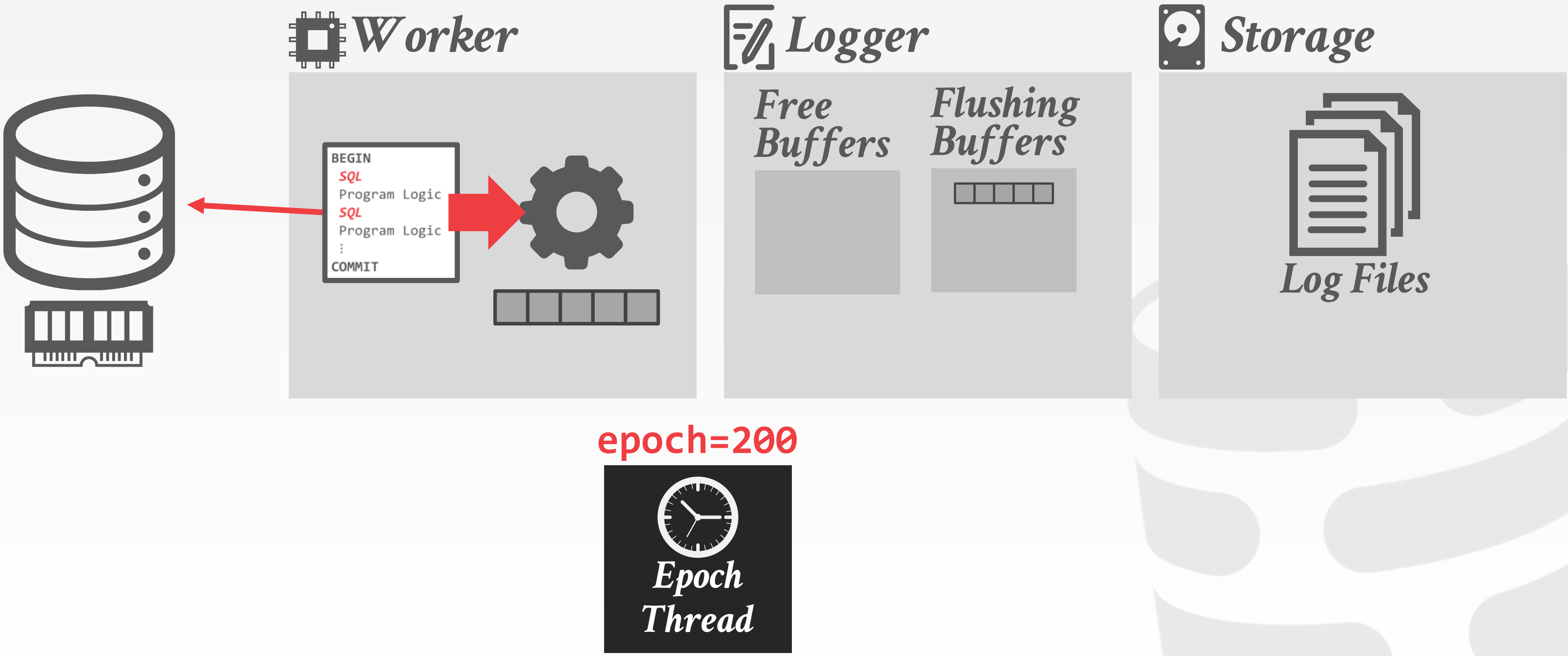

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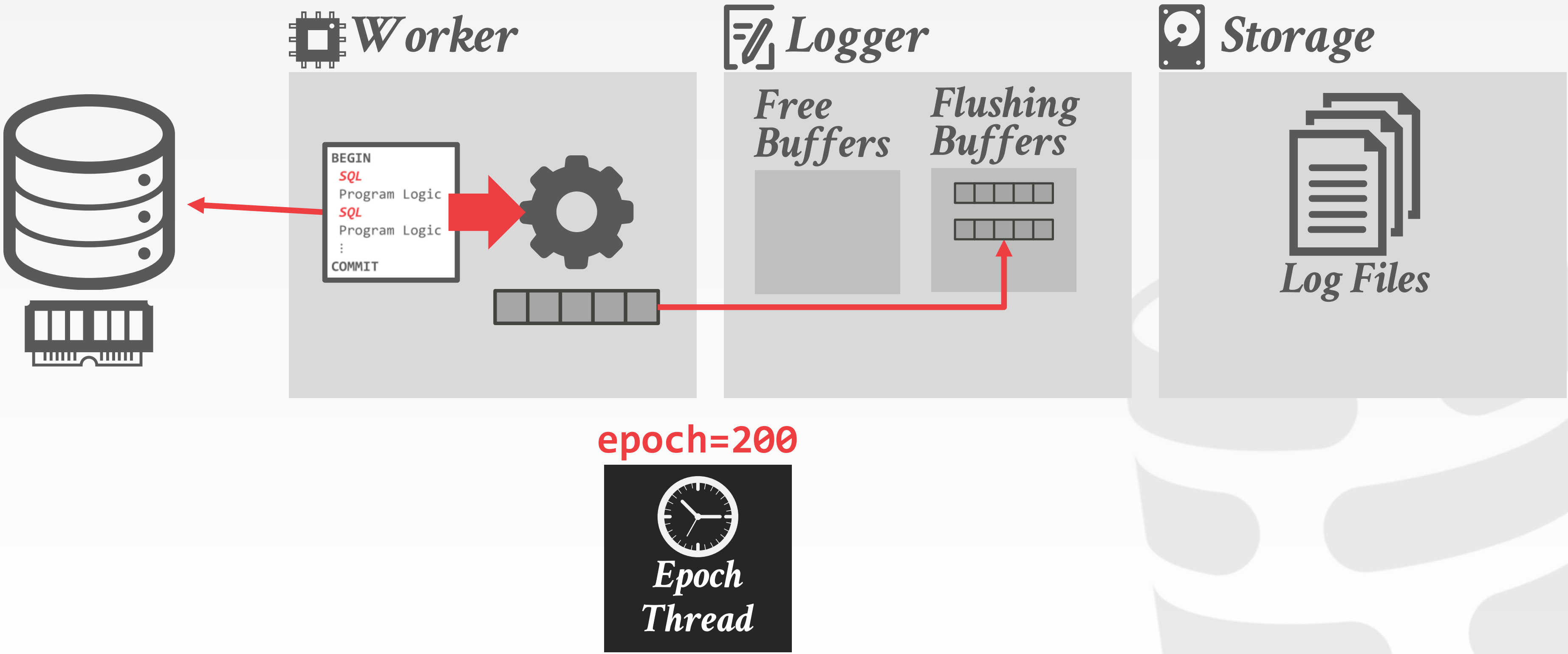

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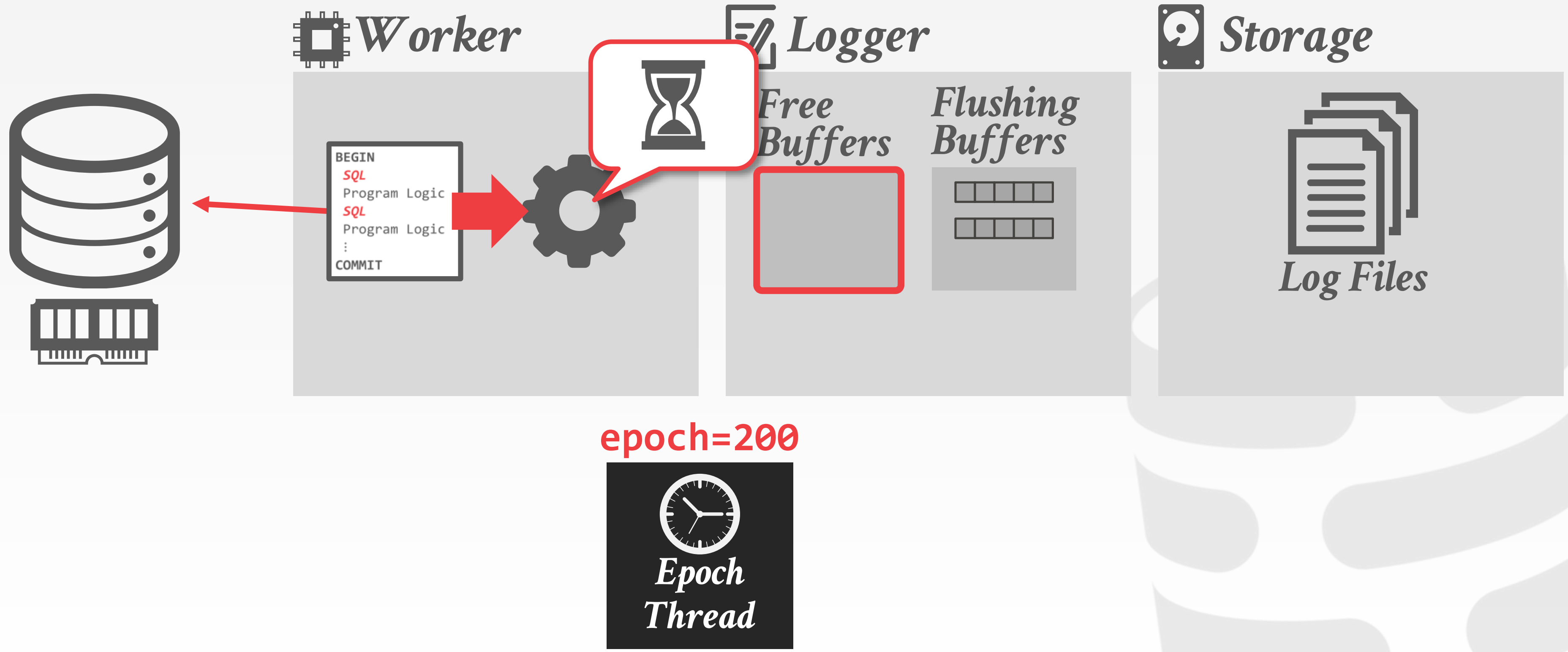

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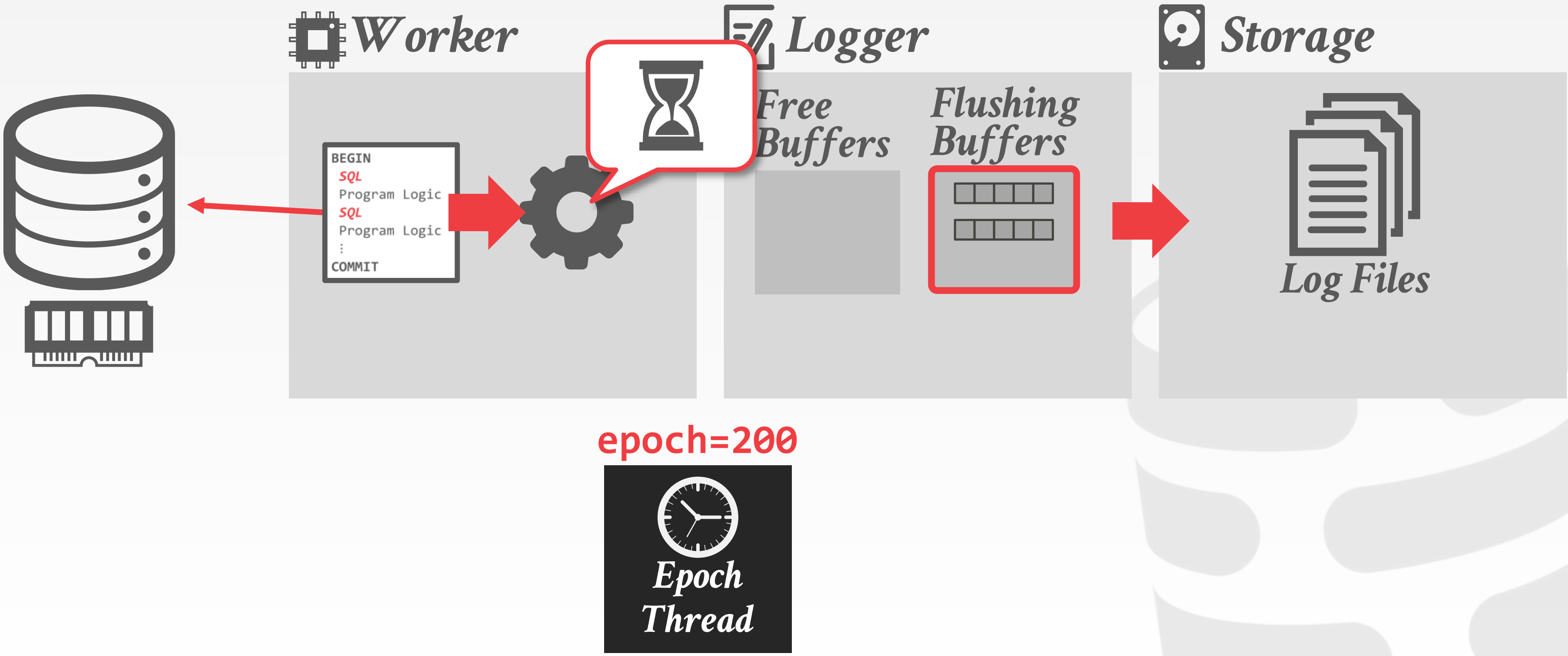

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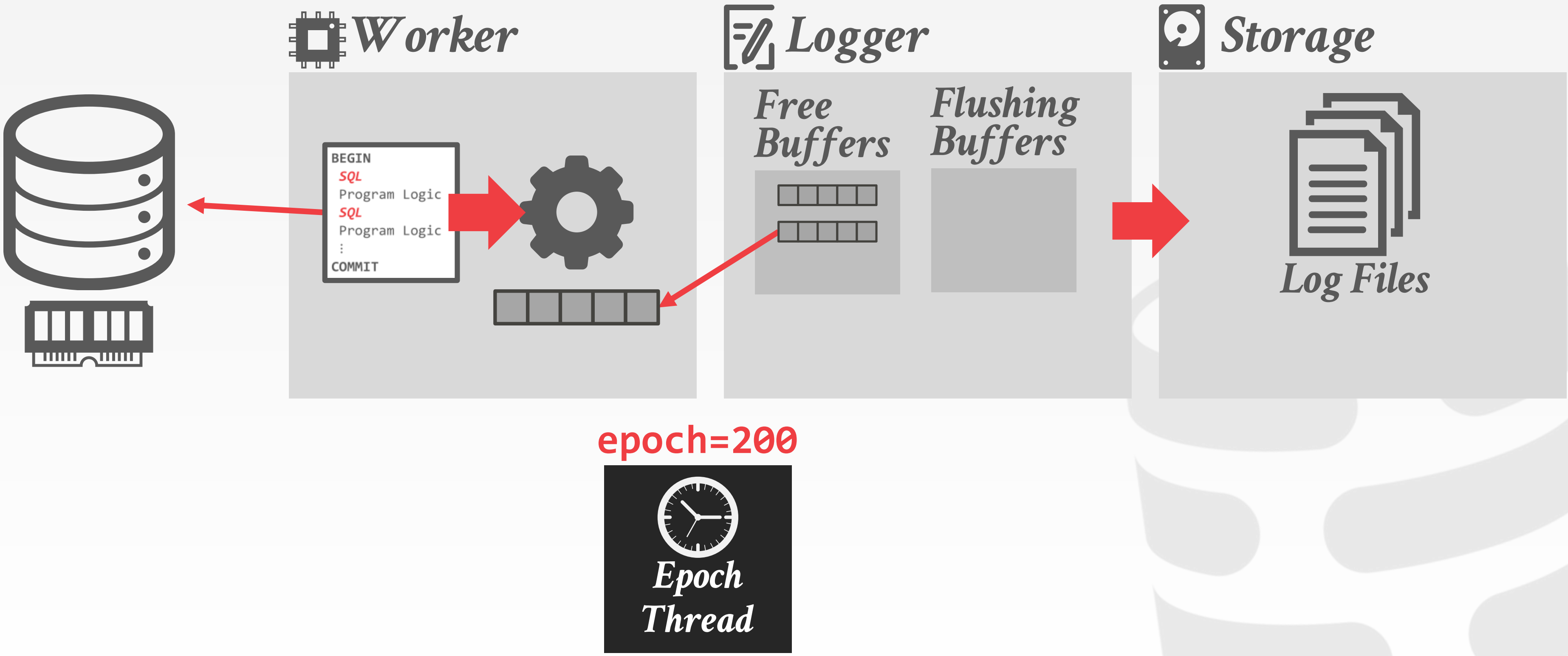


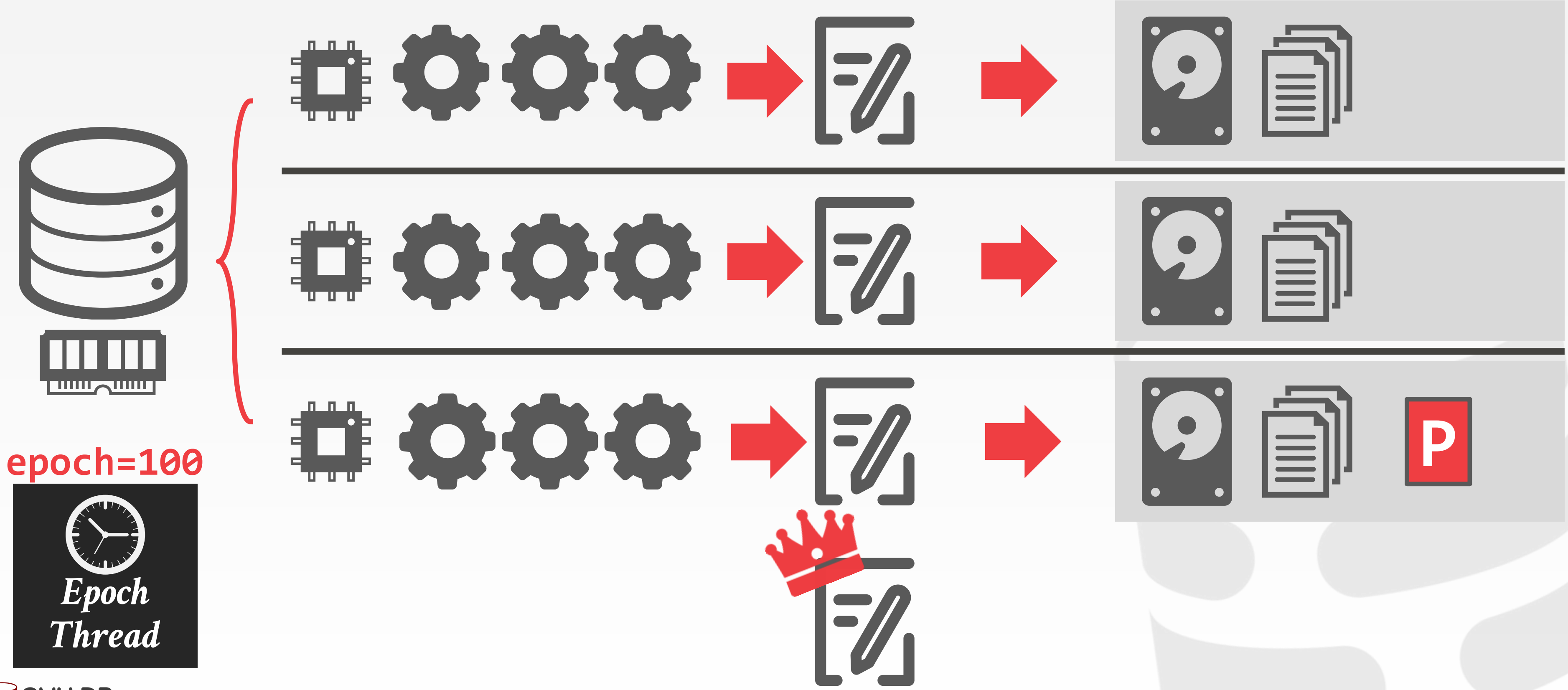
SILOR: PERSISTENT EPOCH

A special logger thread keeps track of the current persistent epoch (***pepoch***)

→ Special log file that maintains the highest epoch that is durable across all loggers.

Txns that executed in epoch ***e*** can only release their results when the ***pepoch*** is durable to non-volatile storage.

SILOR: ARCHITECTURE



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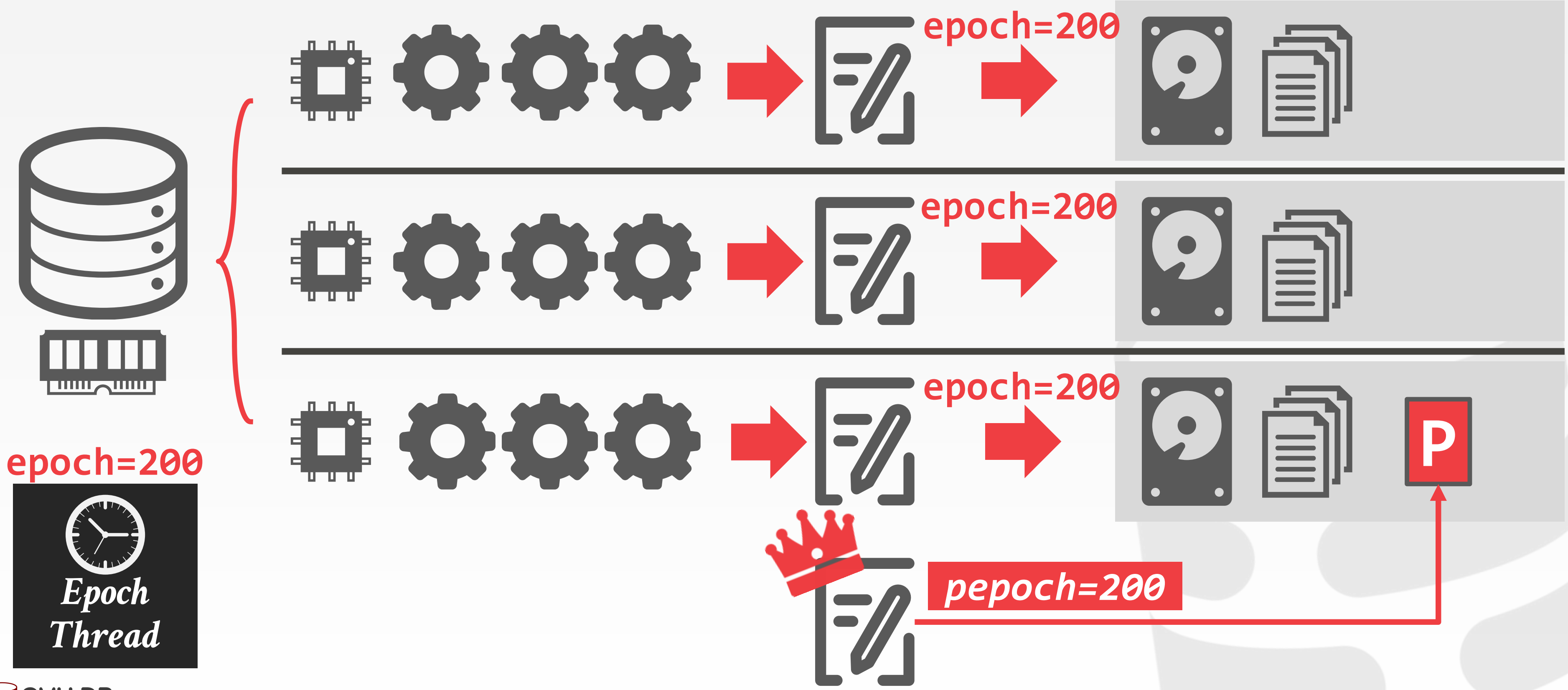


SILOR: RECOVERY PROTOCOL

Phase #1: Load Last Checkpoint

→ Install the contents of the last checkpoint that was saved into the database.
→ All indexes must be rebuilt from checkpoint.

Phase #2: Log Replay

→ Process logs in reverse order to reconcile the latest version of each tuple.
→ The txn ids generated at runtime are enough to determine the serial order on recovery.

SILOR: LOG REPLAY

First check the ***pepoch*** file to determine the most recent persistent epoch.
→ Any log record from after the ***pepoch*** is ignored.

Log files are processed from newest to oldest.
→ Value logging can be replayed in any order.
→ For each log record, the thread checks to see whether the tuple already exists.
→ If it does not, then it is created with the value.
→ If it does, then the tuple's value is overwritten only if the log TID is newer than tuple's TID.

OBSERVATION

Logging allows the DBMS to recover the database after a crash/restart. But this system will have to replay the entire log each time.

Checkpoints allows the systems to ignore large segments of the log to reduce recovery time.

IN-MEMORY CHECKPOINTS

The different approaches for how the DBMS can create a new checkpoint for an in-memory database are tightly coupled with its concurrency control scheme.

The checkpoint thread(s) scans each table and writes out data asynchronously to disk.

IDEAL CHECKPOINT PROPERTIES

Do **not** slow down regular txn processing.

Do **not** introduce unacceptable latency spikes.

Do **not** require excessive memory overhead.

LOW-OVERHEAD ASYNCHRONOUS CHECKPOINTING IN MAIN-MEMORY DATABASE SYSTEMS
SIGMOD 2016

CONSISTENT VS. FUZZY CHECKPOINTS

Approach #1: Consistent Checkpoints

→ Represents a consistent snapshot of the database at some point in time. No uncommitted changes.

→ No additional processing during recovery.

Approach #2: Fuzzy Checkpoints

→ The snapshot could contain records updated from transactions that committed after the checkpoint started.

→ Must do additional processing to figure out whether the checkpoint contains all updates from those txns.

CHECKPOINT MECHANISM

Approach #1: Do It Yourself

- → The DBMS is responsible for creating a snapshot of the database in memory.
- → Can leverage multi-versioned storage to find snapshot.

Approach #2: OS Fork Snapshots

- → Fork the process and have the child process write out the contents of the database to disk.
- → This copies everything in memory.
- → Requires extra work to remove uncommitted changes.

HYPER – OS FORK SNAPSHOTS

Create a snapshot of the database by forking the DBMS process.

→ Child process contains a consistent checkpoint if there are not active txns.

→ Otherwise, use the in-memory undo log to roll back txns in the child process.

Continue processing txns in the parent process.

HYPER: A HYBRID OLTP&OLAP MAIN MEMORY DATABASE SYSTEM BASED ON VIRTUAL MEMORY SNAPSHOTS
ICDE 2011

CHECKPOINT CONTENTS

Approach #1: Complete Checkpoint

→ Write out every tuple in every table regardless of whether were modified since the last checkpoint.

Approach #2: Delta Checkpoint

→ Write out only the tuples that were modified since the last checkpoint.

→ Can merge checkpoints together in the background.

FREQUENCY

Approach #1: Time-based

→ Wait for a fixed period of time after the last checkpoint has completed before starting a new one.

Approach #2: Log File Size Threshold

→ Begin checkpoint after a certain amount of data has been written to the log file.

Approach #3: On Shutdown (Mandatory)

→ Perform a checkpoint when the DBA instructs the system to shut itself down. Every DBMS (hopefully) does this.

CHECKPOINT IMPLEMENTATIONS

	Type	*Contents*	*Frequency*
MemSQL	Consistent	Complete	Log Size
VoltDB	Consistent	Complete	Time-Based
Altibase	Fuzzy	Complete	Time-based
TimesTen	Consistent (*Blocking*) Fuzzy (*Non-Blocking*)	Complete Complete	On Shutdown Time-Based
Hekaton	Consistent	Delta	Log Size
SAP HANA	Fuzzy	Complete	Time-Based

OBSERVATION

Not all DBMS restarts are due to crashes.

→ Updating OS libraries
→ Hardware upgrades/fixes
→ Updating DBMS software

Need a way to be able to quickly restart the DBMS without having to re-read the entire database from disk again.

FACEBOOK SCUBA: FAST RESTARTS

Decouple the in-memory database lifetime from the process lifetime.

By storing the database shared memory, the DBMS process can restart, and the memory contents will survive without having to reload from disk.

FAST DATABASE RESTARTS AT FACEBOOK
SIGMOD 2014

FACEBOOK SCUBA

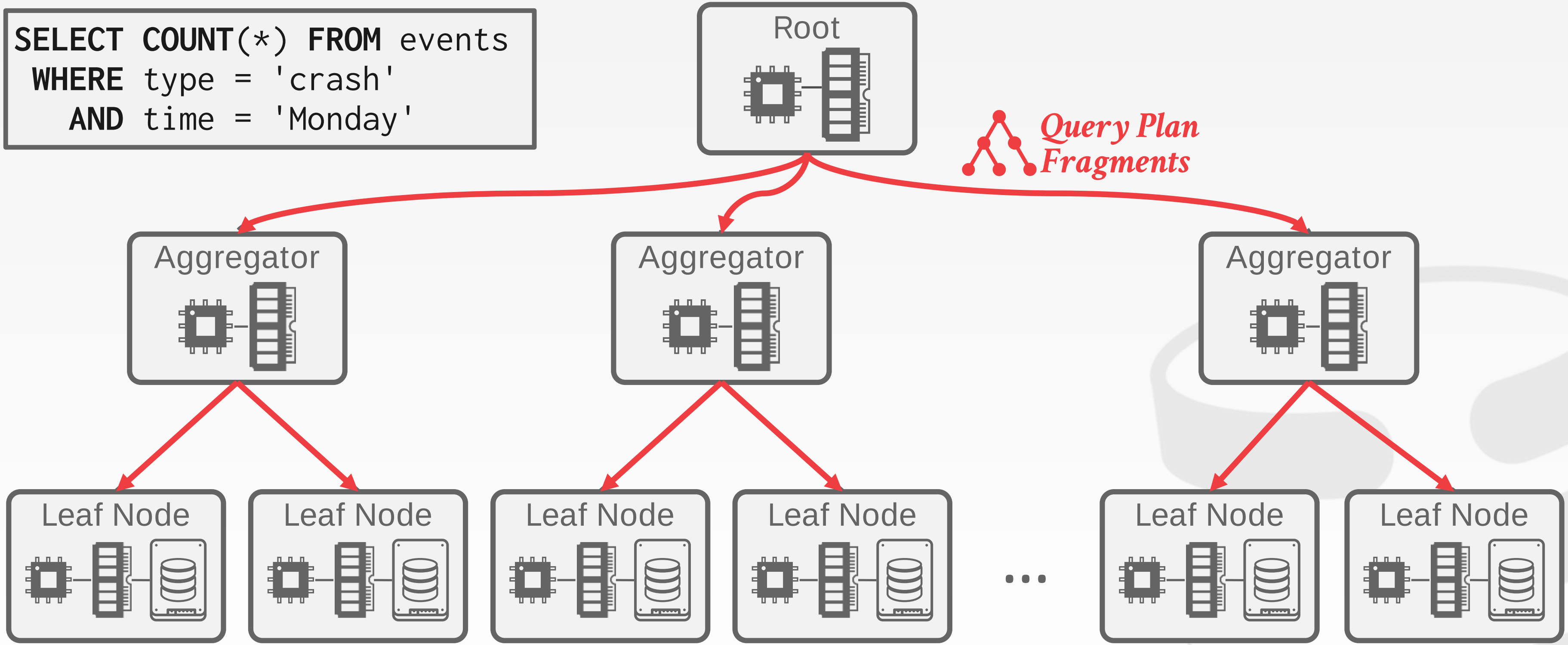
Distributed, in-memory DBMS for time-series event analysis and anomaly detection.

Heterogeneous architecture

→ **Leaf Nodes**: Execute scans/filters on in-memory data
→ **Aggregator Nodes:** Combine results from leaf nodes

FACEBOOK SCUBA: ARCHITECTURE

```
SELECT COUNT(*) FROM events
 WHERE type = 'crash'
   AND time = 'Monday'
```



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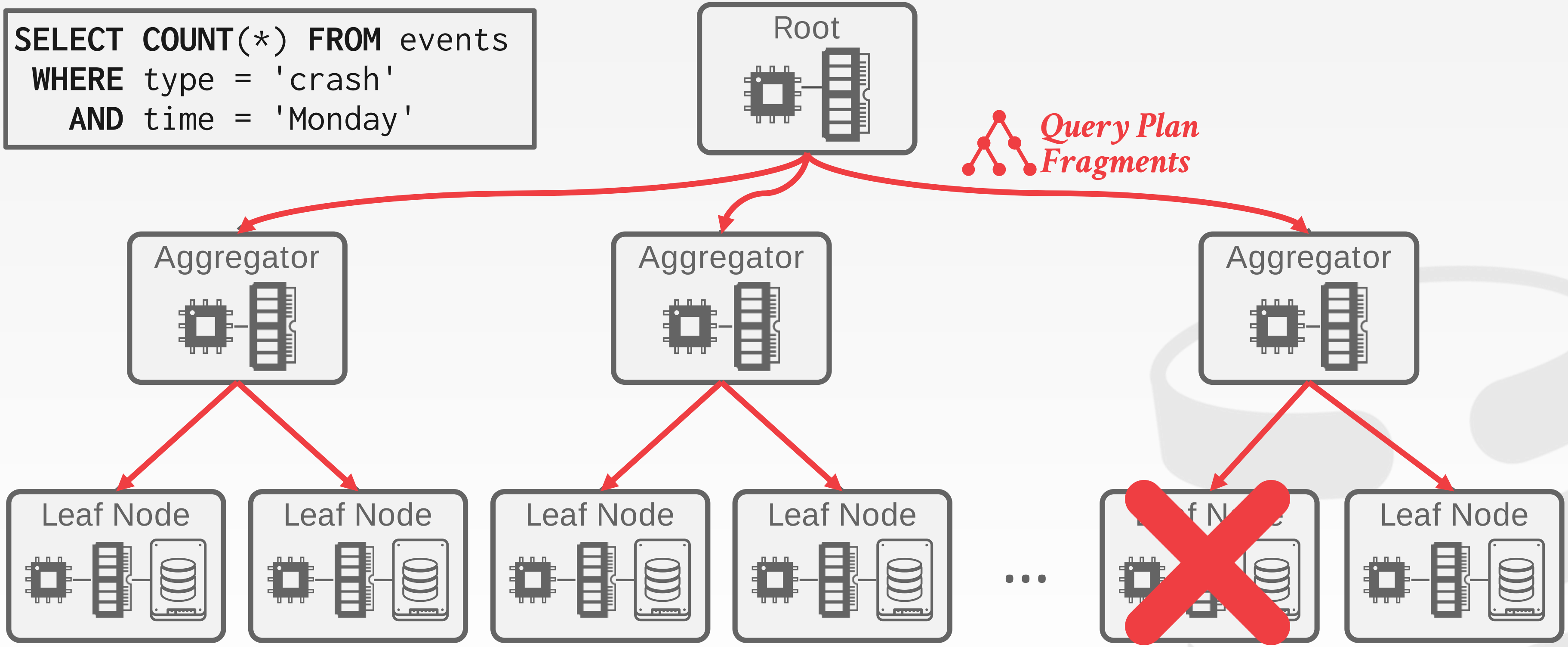

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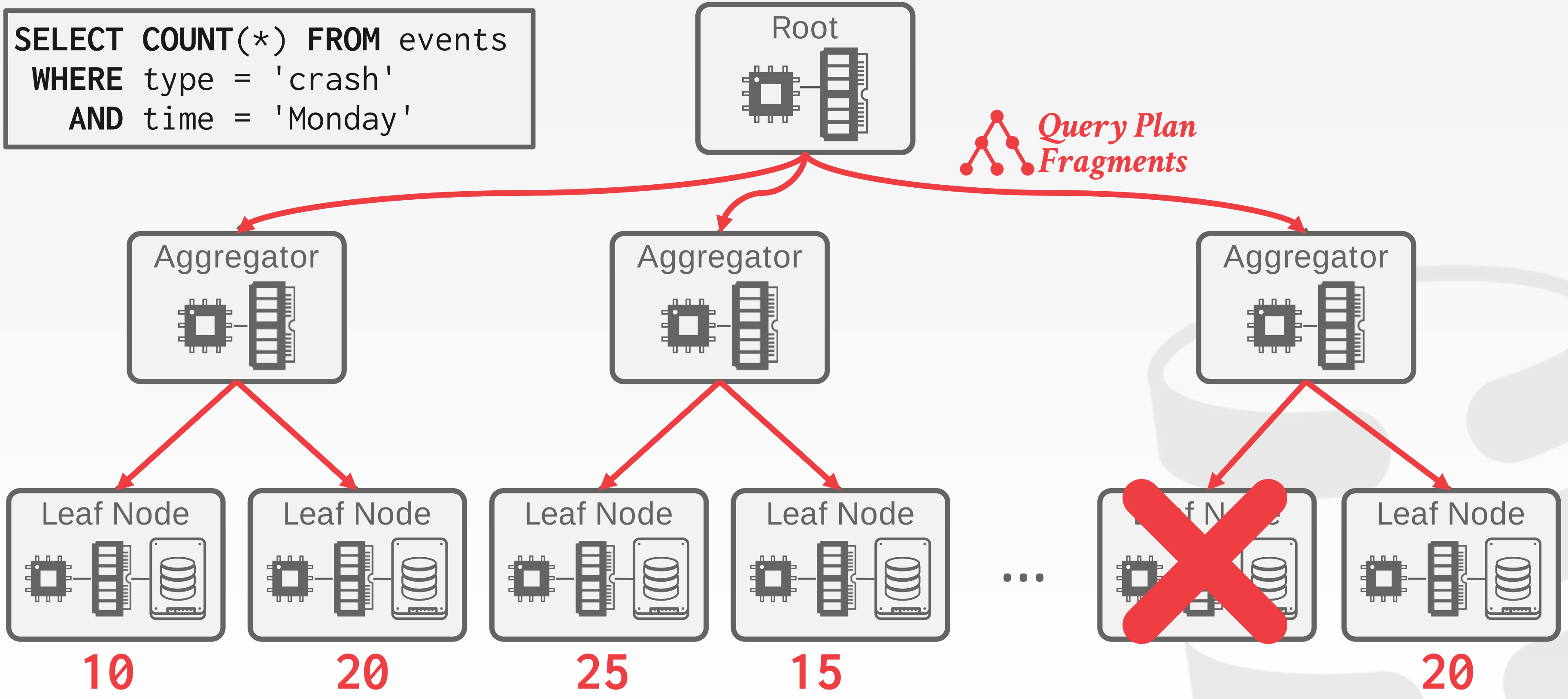

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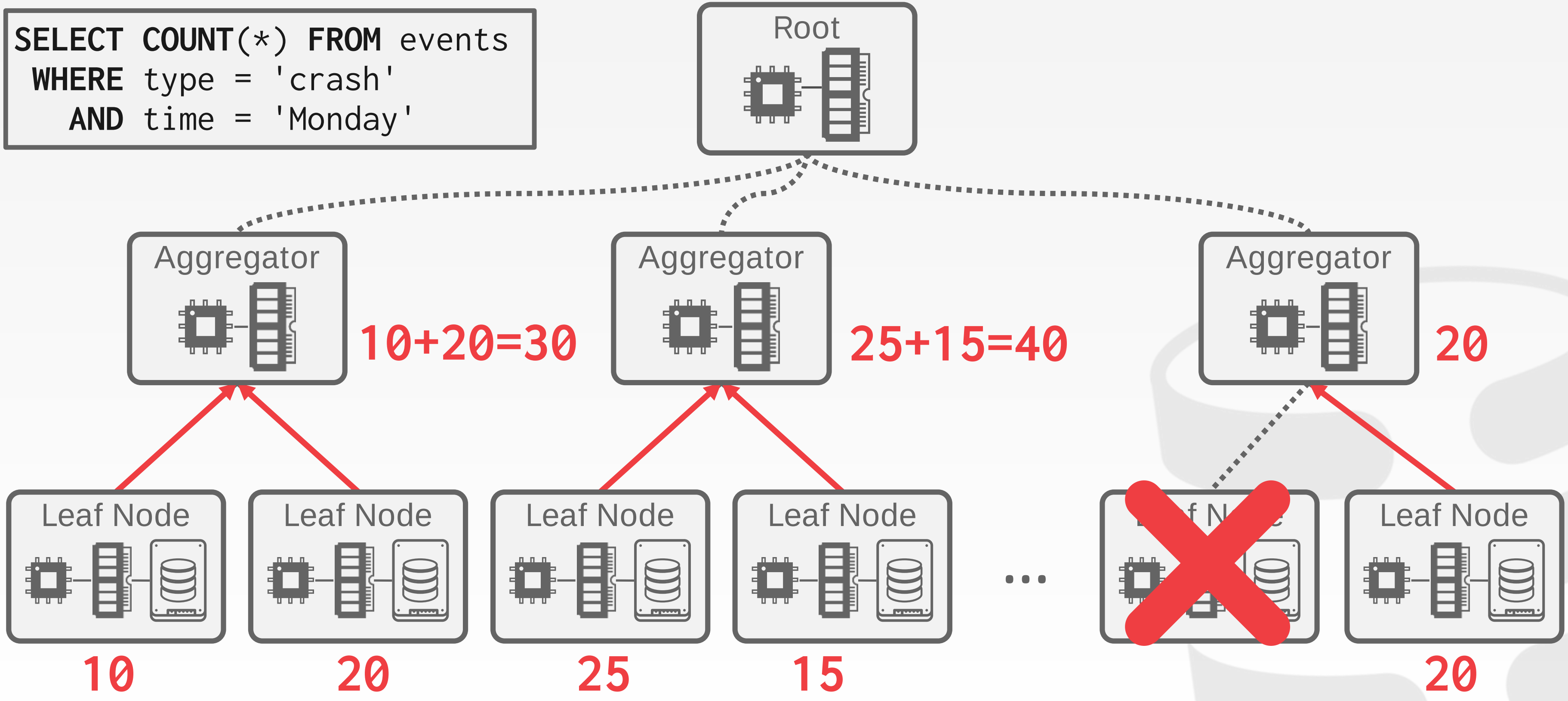

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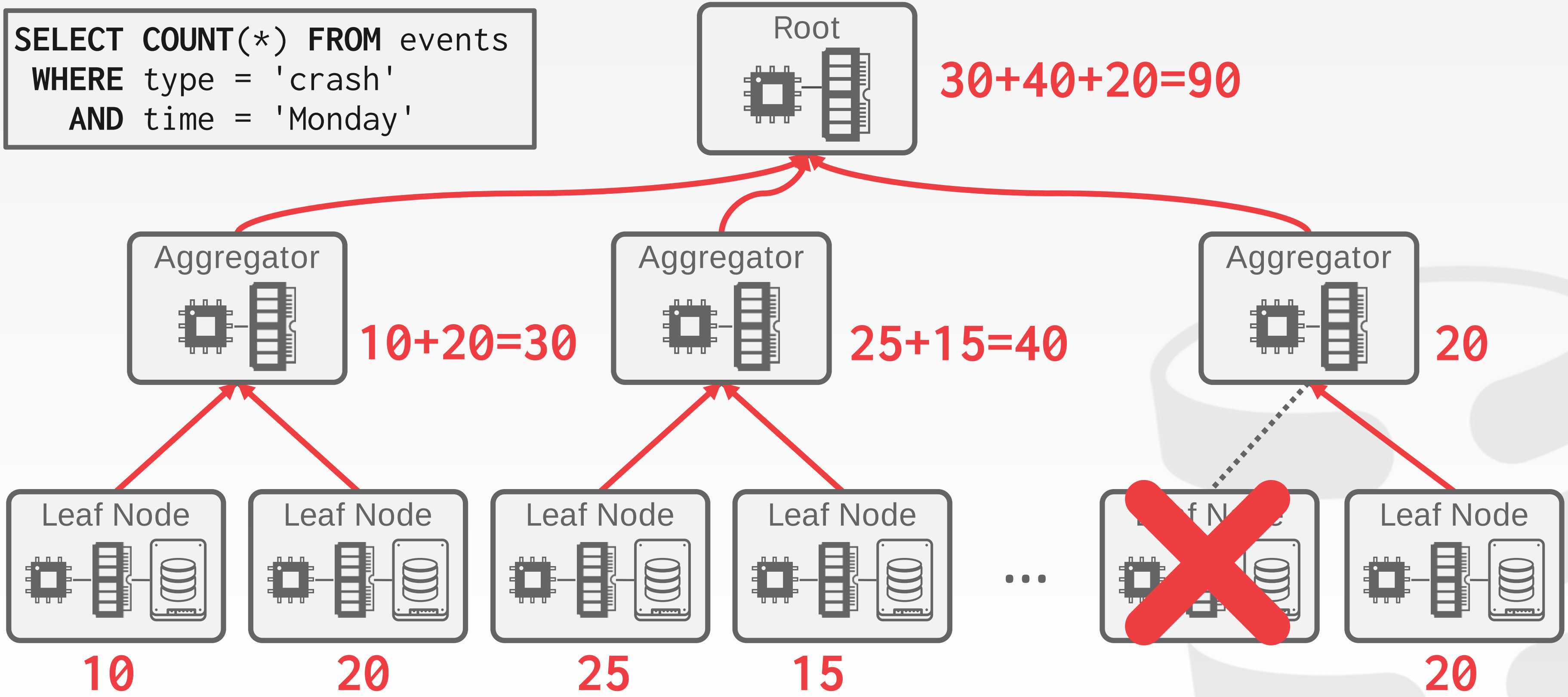

SHARED MEMORY RESTARTS

Approach #1: Shared Memory Heaps

→ All data is allocated in SM during normal operations.
→ Have to use a custom allocator to subdivide memory segments for thread safety and scalability.
→ Cannot use lazy allocation of backing pages with SM.

Approach #2: Copy on Shutdown

→ All data is allocated in local memory during normal operations.
→ On shutdown, copy data from heap to SM.

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FACEBOOK SCUBA: FAST RESTARTS

When the admin initiates restart command, the node halts ingesting updates.

DBMS starts copying data from heap memory to shared memory.
→ Delete blocks in heap once they are in SM.

Once snapshot finishes, the DBMS restarts.
→ On start up, check to see whether the there is a valid database in SM to copy into its heap.
→ Otherwise, the DBMS restarts from disk.

PARTING THOUGHTS

Physical logging is a general-purpose approach that supports all concurrency control schemes.
→ Logical logging is faster but not universal.

Copy-on-update checkpoints are the way to go especially if you are using MVCC

Non-volatile memory is here!

NEXT CLASS

Networking Protocols