15-721 DATABASE SYSTEMS

Lecture #22 – Larger-than-Memory Databases

Andy Pavlo // Carnegie Mellon University // Spring 2016

ADMINISTRIVIA

Final Exam: April 27th @ 12:00pm

→ Three short-essay questions.
→ I will provide sample questions this week.

"Final" Presentations: May 6th @ 1:00pm

→ 10 minutes per group
→ Food and prizes for everyone!

Code Reviews: May 8th @ 11:59pm

→ I will announce group assignments and guidelines next class.

QUICKSTEP

Pivotal has submitted QuickStep to be an Apache Project.
They are also working on a distributed version of the system.

https://wiki.apache.org/incubator/QuickstepProposal

TODAY'S AGENDA

Background
Implementation Issues
Real-world Examples
Evaluation

MOTIVATION

DRAM is expensive, son.

It would be nice if our in-memory DBMS could use cheaper storage.

LARGER-THAN-MEMORY DATABASES

Allow an in-memory DBMS to store/access data on disk **without** bringing back all the slow parts of a disk-oriented DBMS.

Need to be aware of hardware access methods
→ In-memory Storage = Tuple-Oriented
→ Disk Storage = Block-Oriented

OLAP

OLAP queries generally access the entire table. Thus, there isn't anything about the workload for the DBMS to exploit that a disk-oriented buffer pool can't handle.

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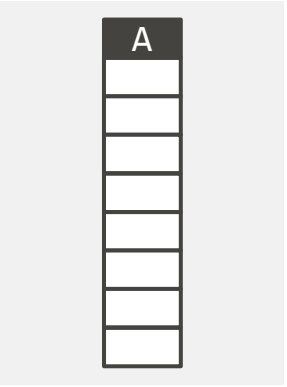

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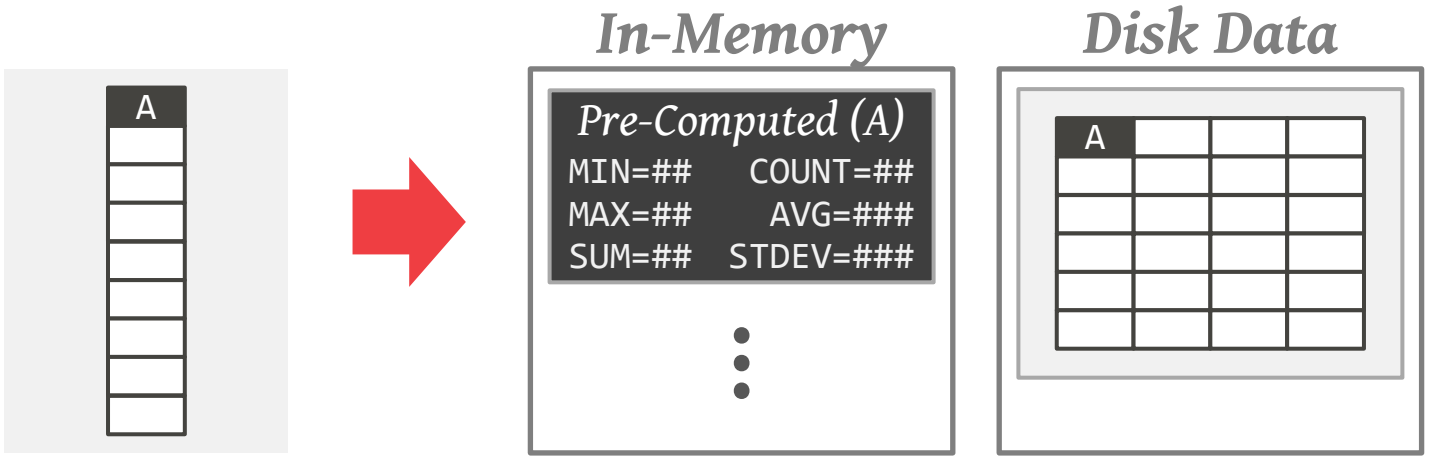


OLTP

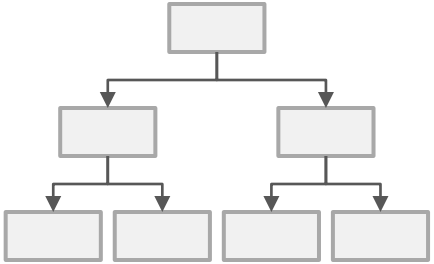
OLTP workloads almost always have **hot** and **cold** portions of the database.

→ We can assume that txns will almost always access hot tuples.

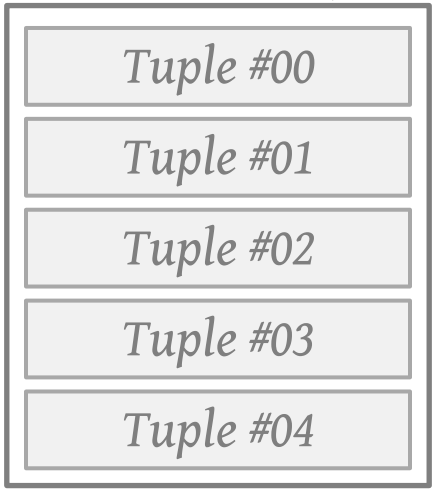
The DBMS needs a mechanism to move cold data out to disk and then retrieve it if it is ever needed again.

LARGER-THAN-MEMORY DATABASES

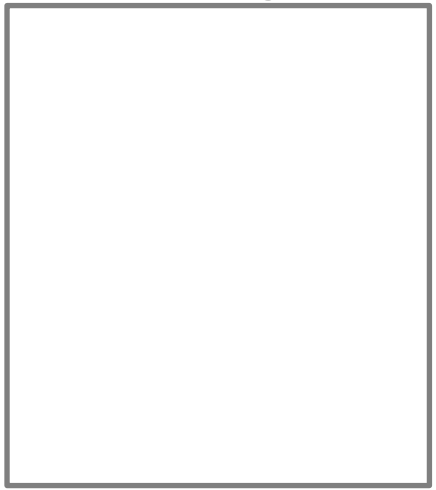
In-Memory Index



In-Memory Table Heap



Cold-Data Storage



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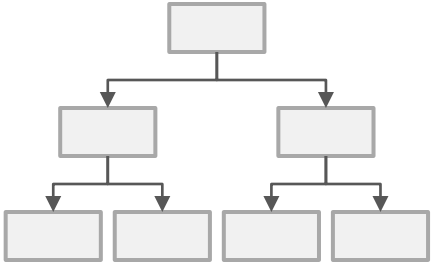

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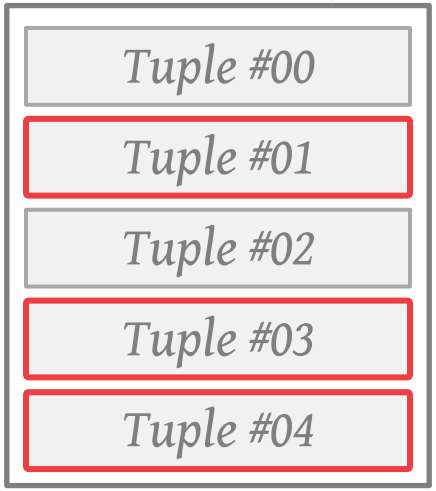

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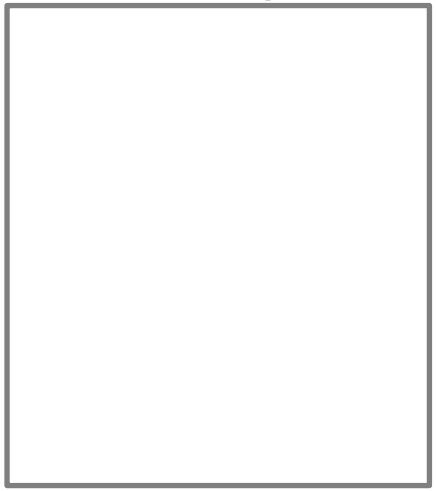

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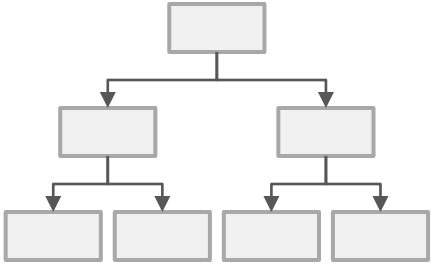

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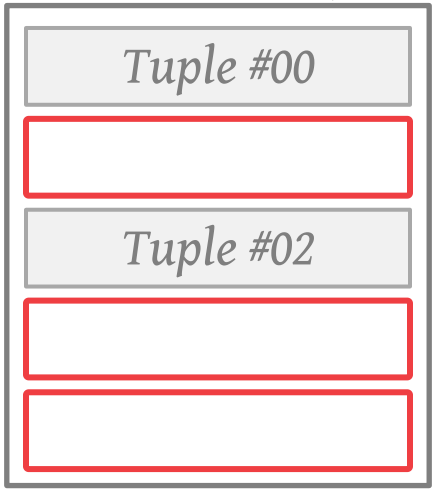

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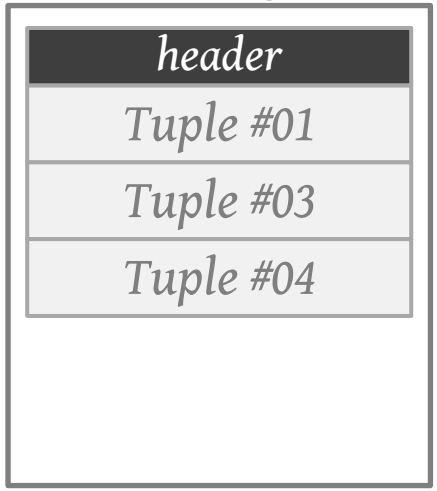

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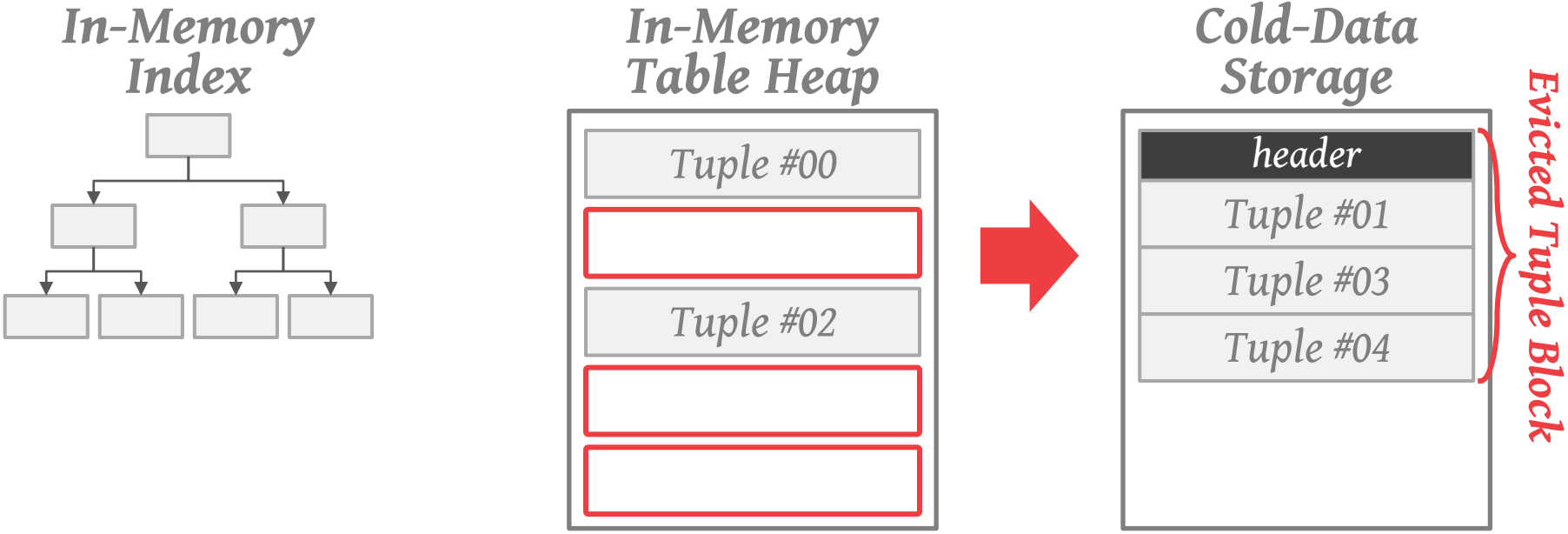

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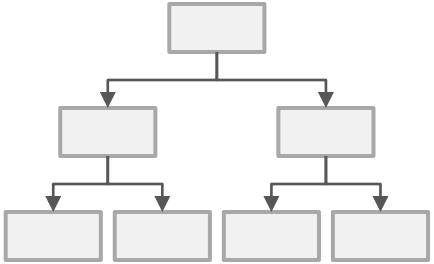

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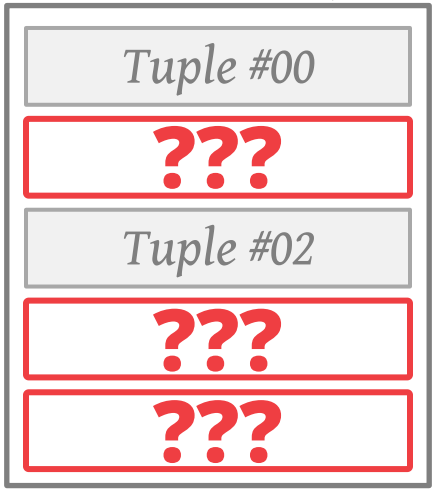

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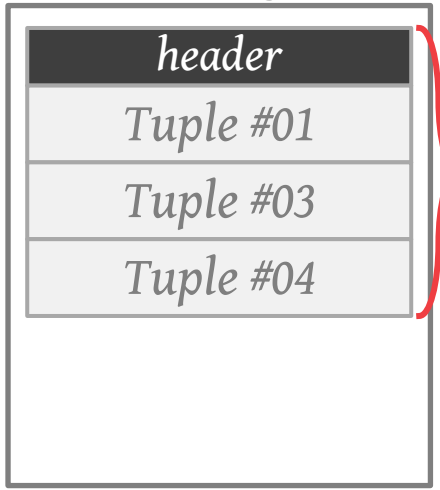

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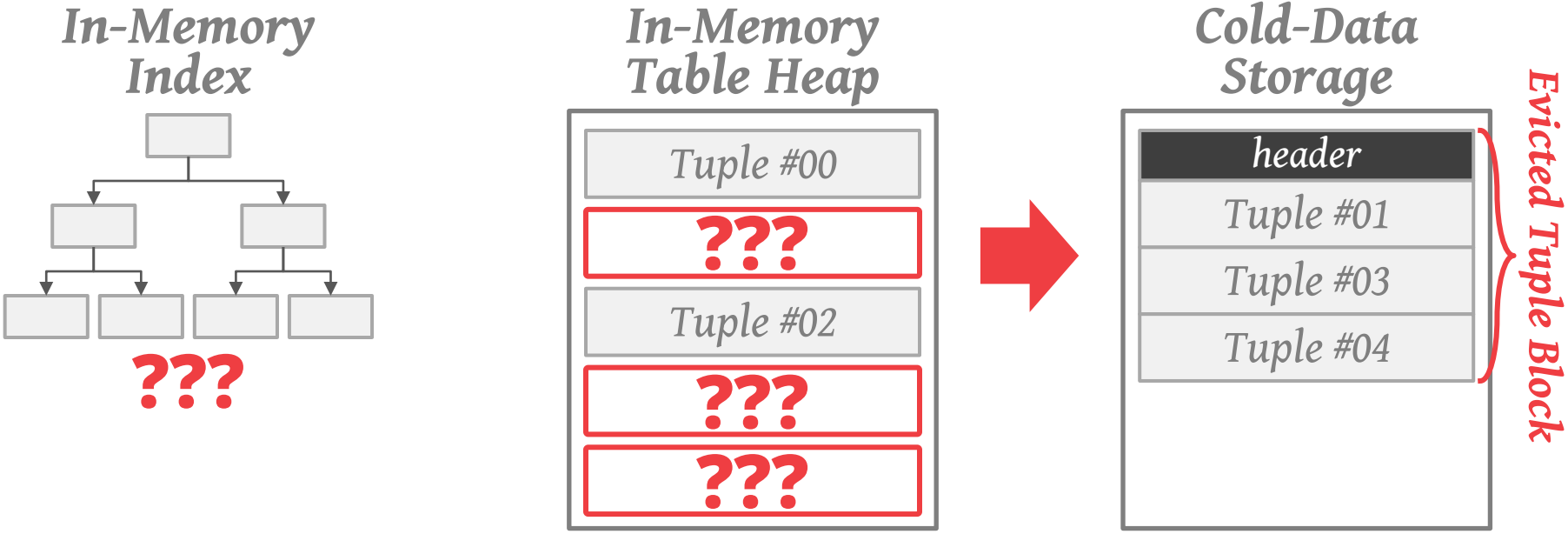

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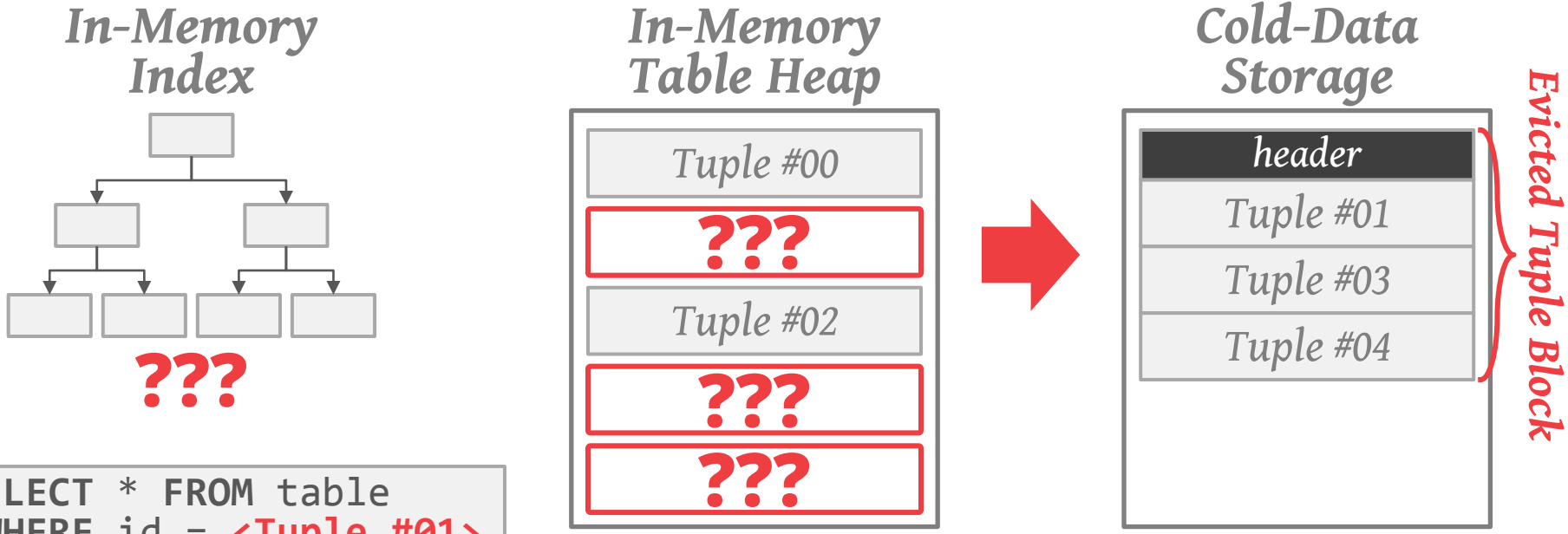


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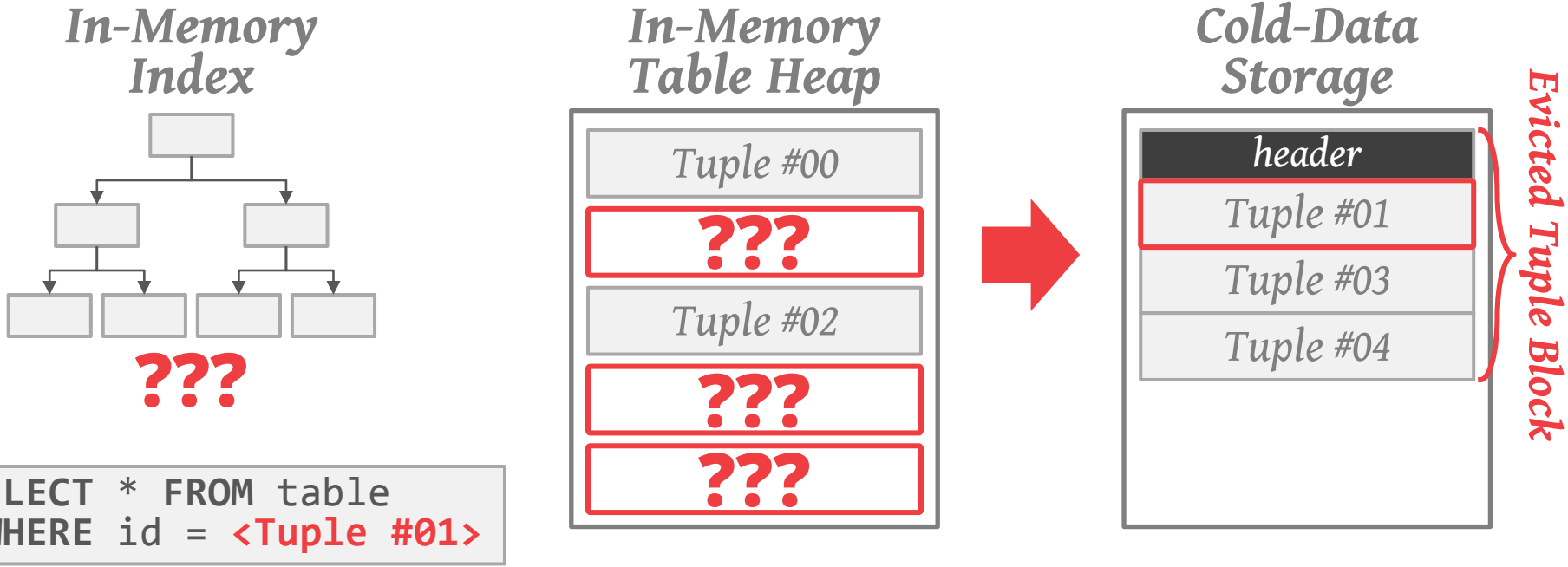


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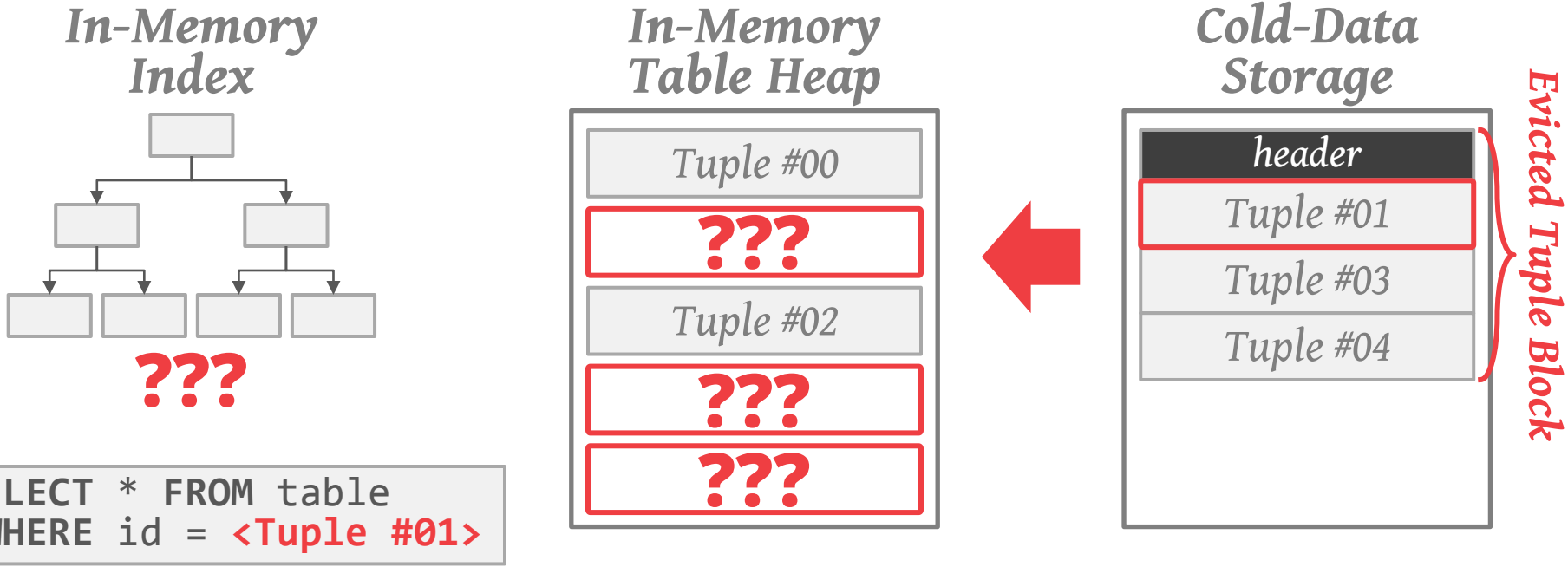


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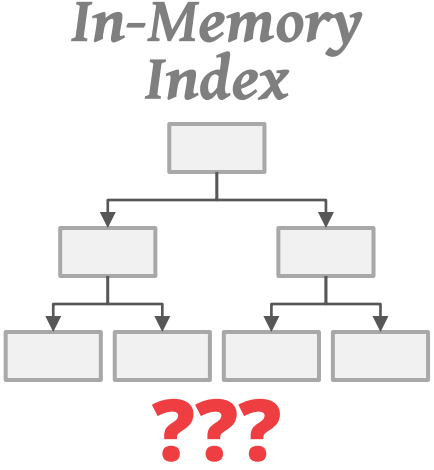


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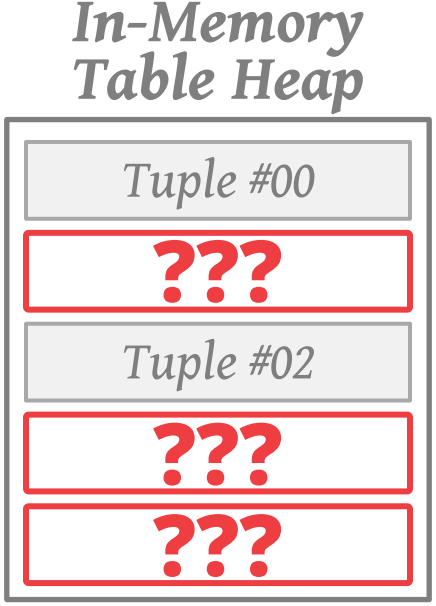

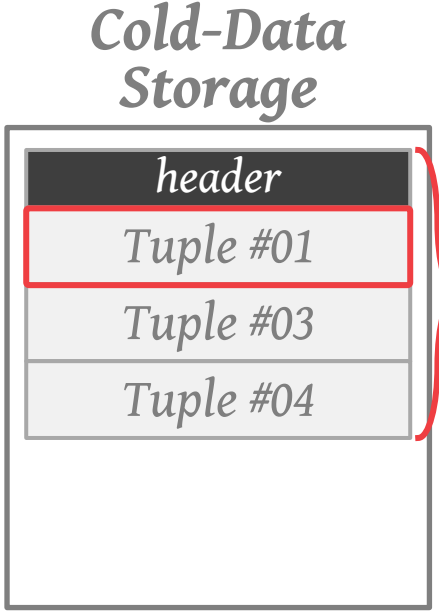

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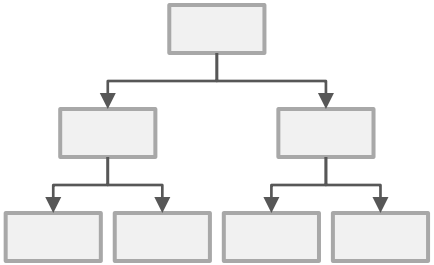

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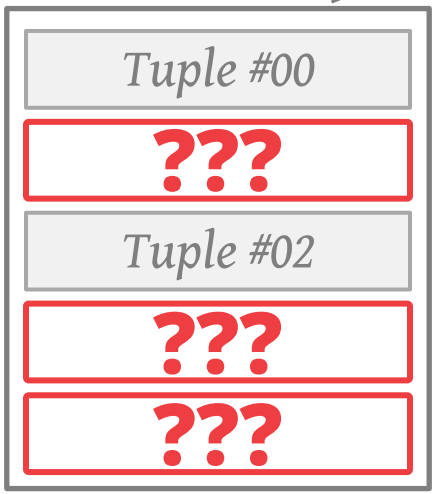

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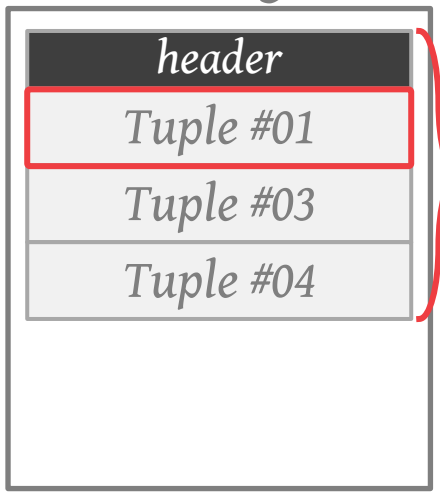

Evicted Tuple Block

OLTP ISSUES

Run-time Operations
→ Cold Tuple Identification

Eviction Policies
→ Timing
→ Evicted Tuple Metadata

Data Retrieval Policies
→ Granularity
→ Retrieval Mechanism
→ Merging back to memory

COLD TUPLE IDENTIFICATION

Choice #1: On-line

→ The DBMS monitors txn access patterns and tracks how often tuples are used.
→ Embed the tracking meta-data directly in tuples.

Choice #2: Off-line

→ Maintain a tuple access log during txn execution.
→ Process in background to compute frequencies.

EVICTION TIMING

Choice #1: Threshold

→ The DBMS monitors memory usage and begins evicting tuples when it reaches a threshold.
→ The DBMS has to manually move data.

Choice #2: OS Virtual Memory

→ The OS decides when it wants to move data out to disk. This is done in the background.

EVICTED TUPLE METADATA

Choice #1: Tombstones

→ Leave a marker that points to the on-disk tuple.
→ Update indexes to point to the tombstone tuples.

Choice #2: Bloom Filters

→ Use approximate data structure for each index.
→ Check both index + filter for each query.

Choice #3: OS Virtual Memory

→ The OS tracks what data is on disk. The DBMS does not need to maintain any additional metadata.

EVICTED TUPLE METADATA

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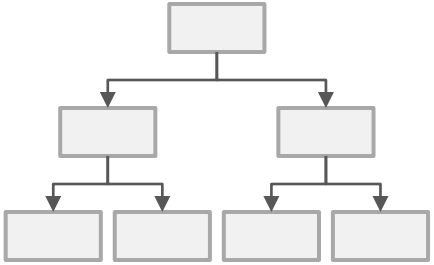

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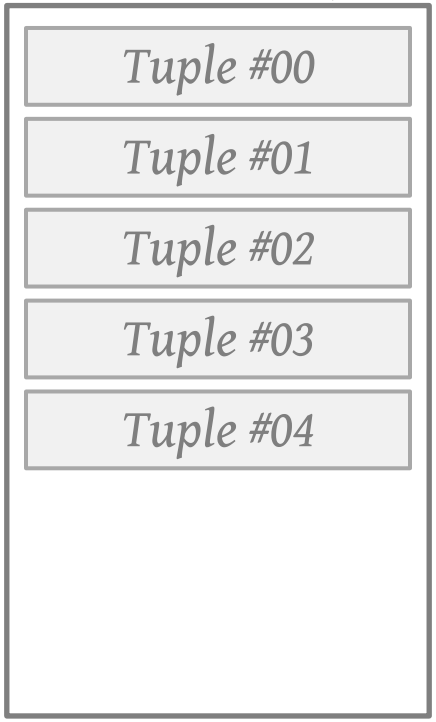

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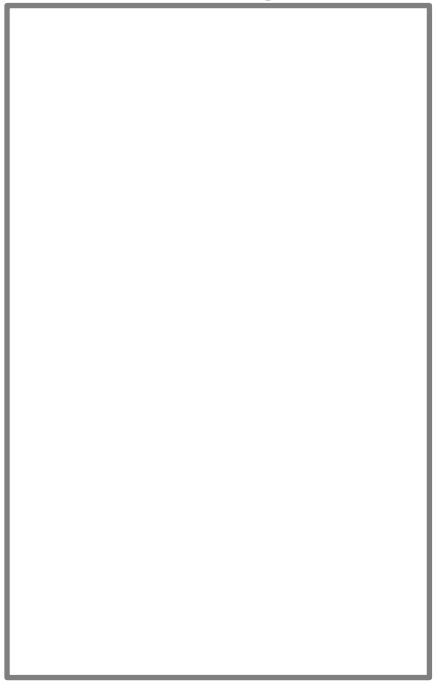

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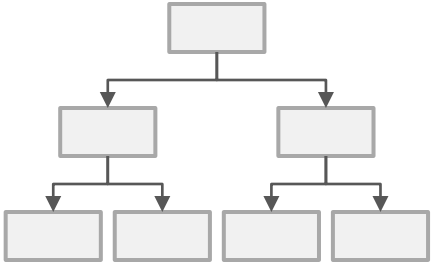
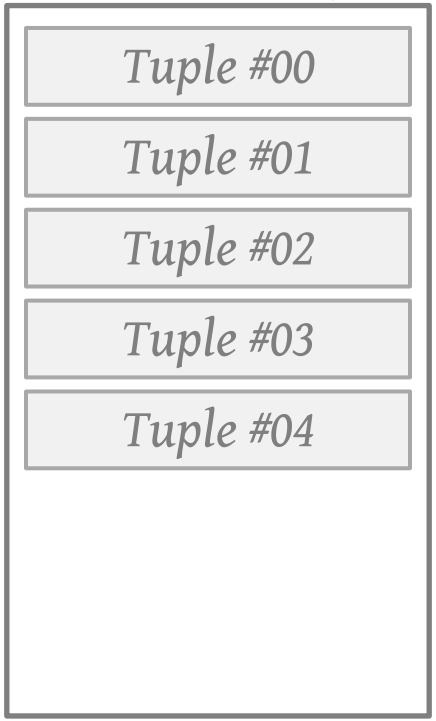


Access Frequency

In-Memory Table Heap



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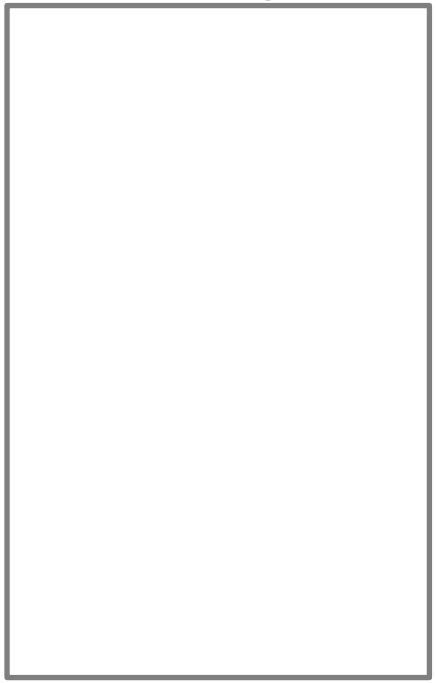

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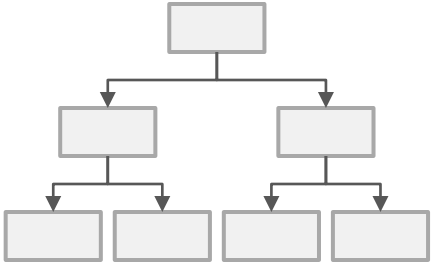

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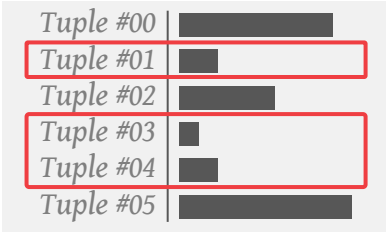

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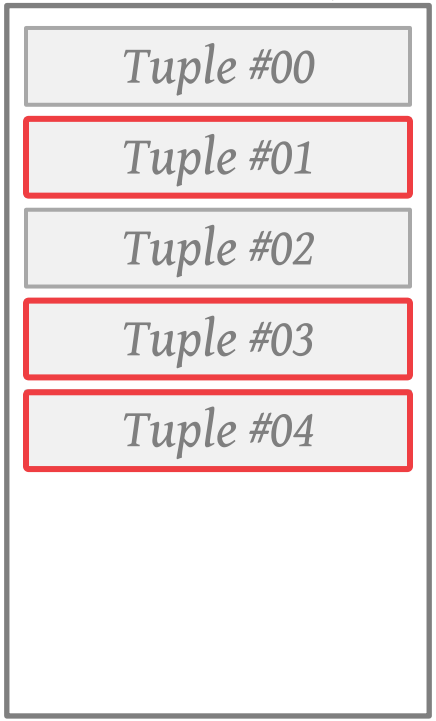

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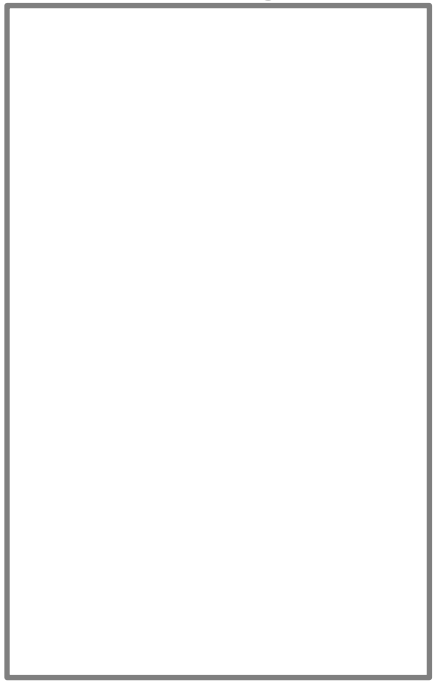

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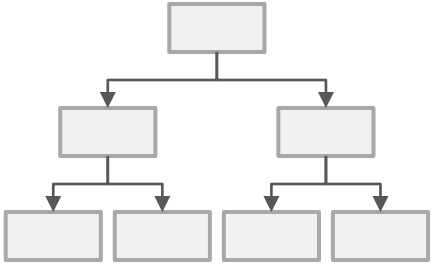

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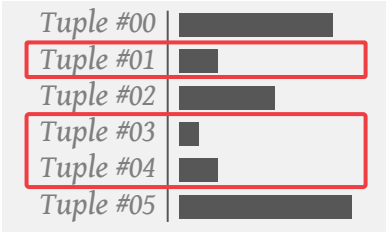

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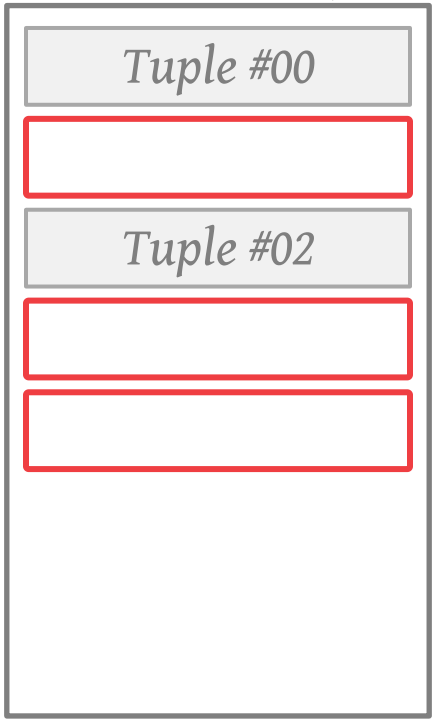

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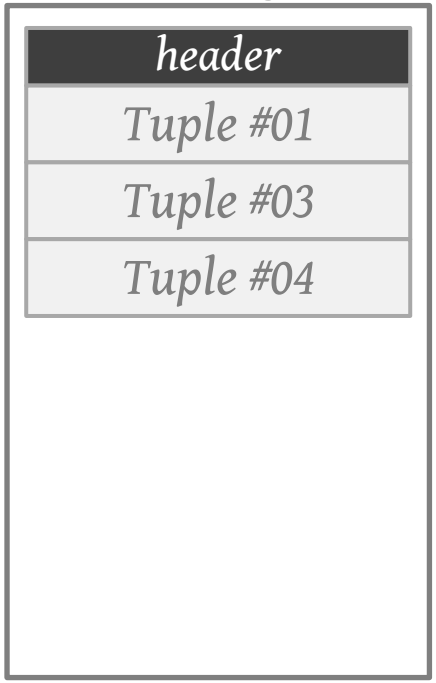

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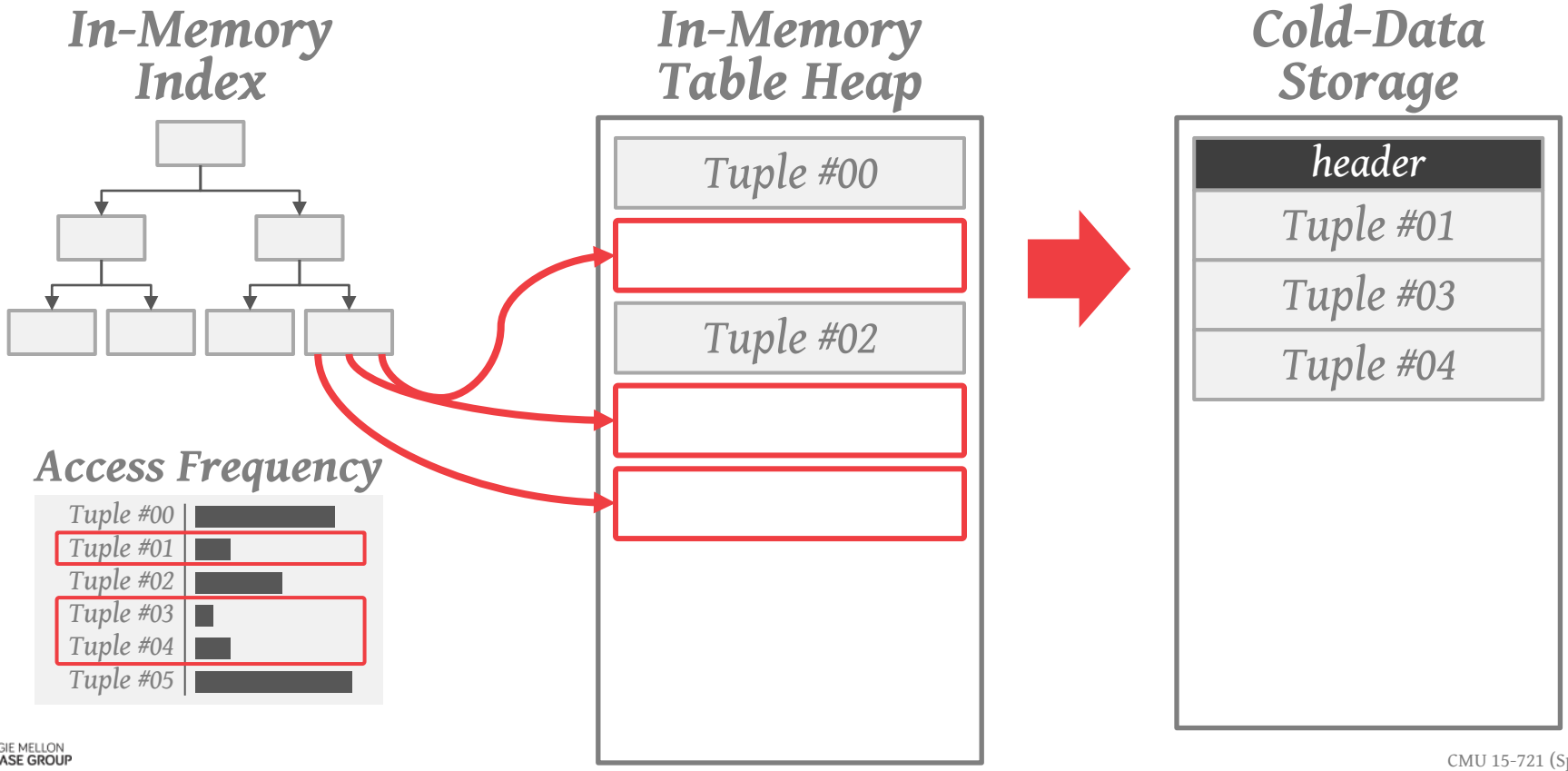

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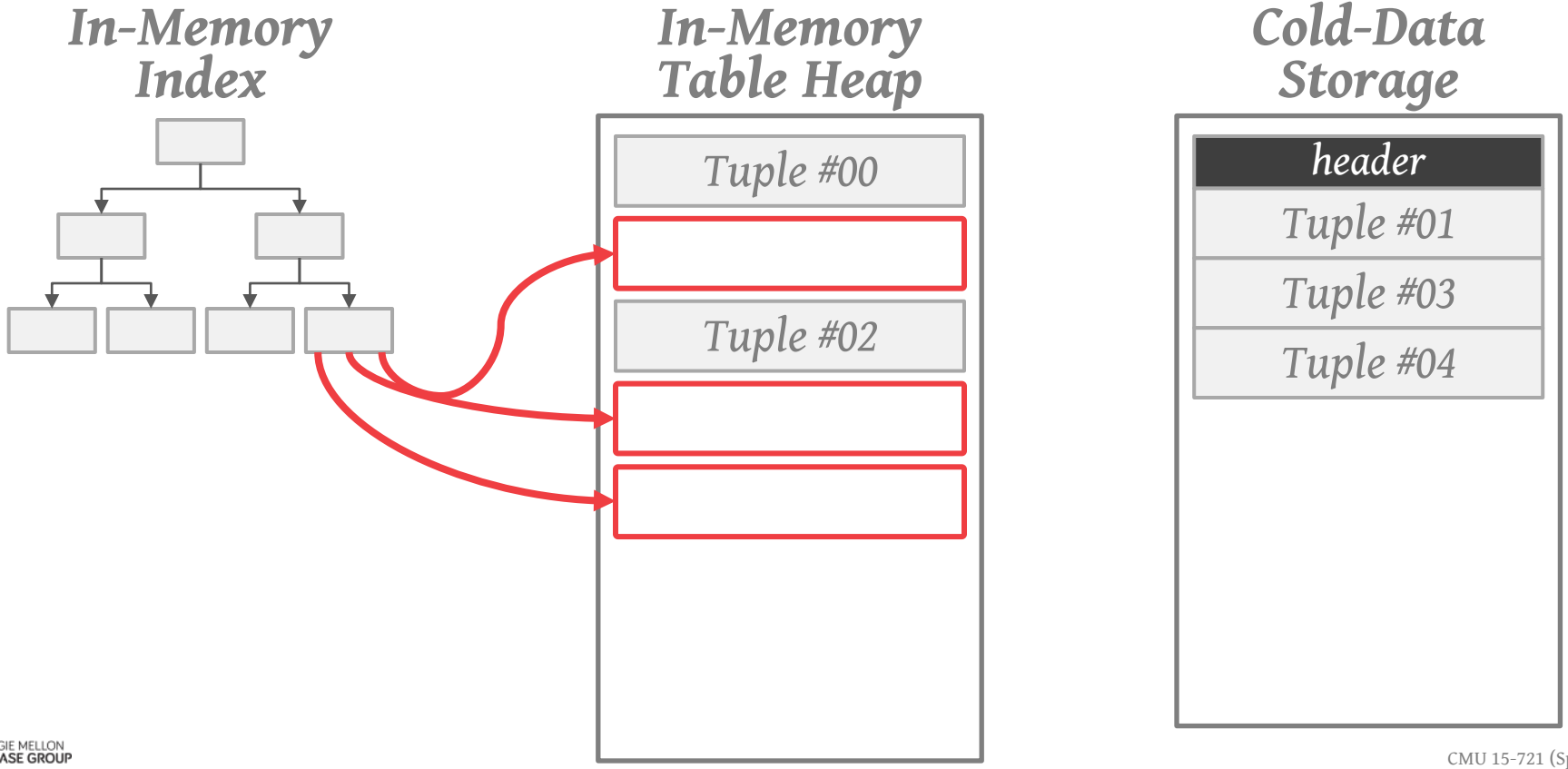

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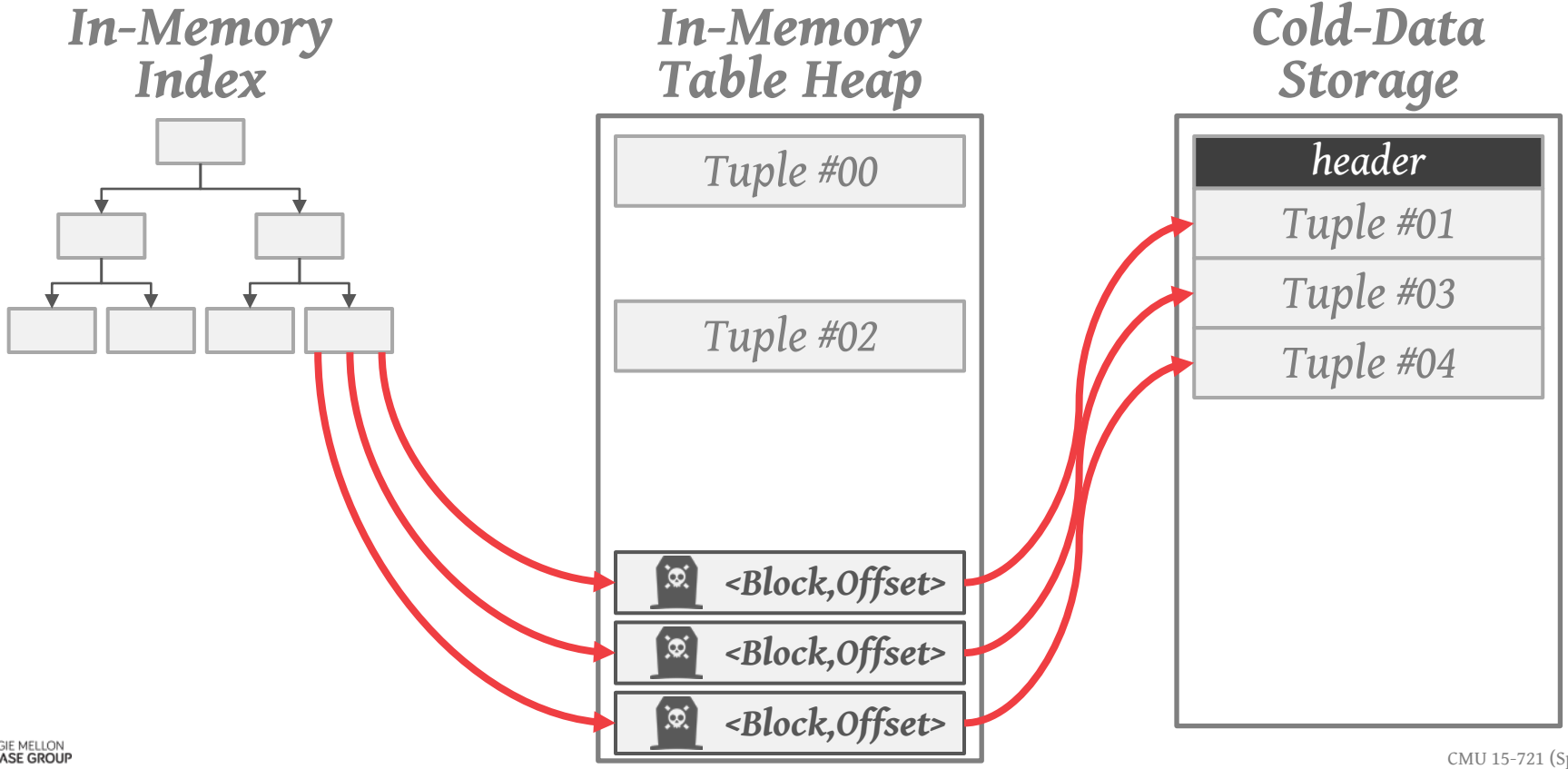

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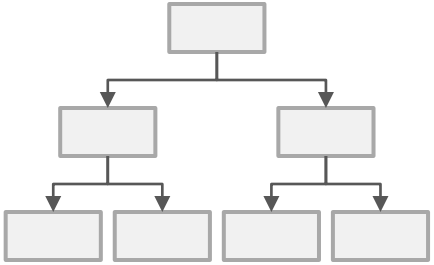
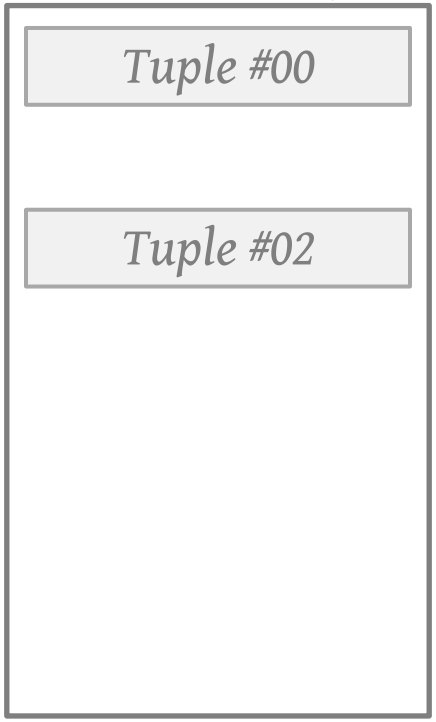


Bloom Filter

In-Memory Table Heap



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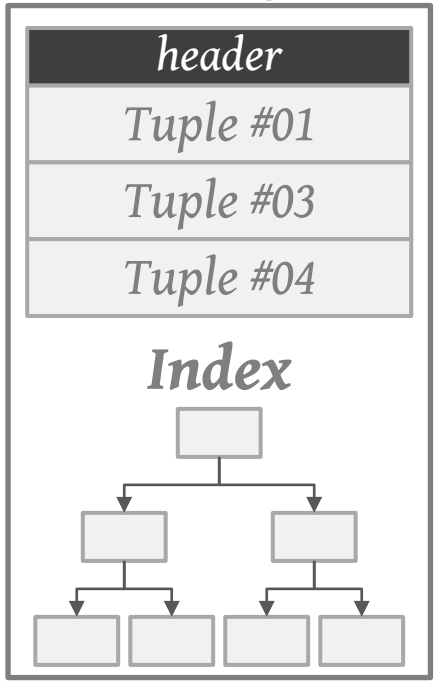


DATA RETRIEVAL GRANULARITY

Choice #1: Only Tuples Needed

→ Only merge the tuples that were accessed by a query back into the in-memory table heap.
→ Requires additional bookkeeping to track holes.

Choice #2: All Tuples in Block

→ Merge all the tuples retrieved from a block regardless of whether they are needed.
→ More CPU overhead to update indexes.
→ Tuples are likely to be evicted again.

RETRIEVAL MECHANISM

Choice #1: Abort-and-Restart

→ Abort the txn that accessed the evicted tuple.
→ Retrieve the data from disk and merge it into memory with a separate background thread.
→ Restart the txn when the data is ready.
→ Cannot guarantee consistency for large queries.

Choice #2: Synchronous Retrieval

→ Stall the txn when it accesses an evicted tuple while the DBMS fetches the data and merges it back into memory.

MERGING THRESHOLD

Choice #1: Always Merge
→ Retrieved tuples are always put into table heap.

Choice #2: Merge Only on Update
→ Retrieved tuples are only merged into table heap if they are used in an **UPDATE** query.
→ All other tuples are put in a temporary buffer.

Choice #3: Selective Merge
→ Keep track of how often each block is retrieved.
→ If a block's access frequency is above some threshold, merge it back into the table heap.

REAL-WORLD IMPLEMENTATIONS

H-Store – Anti-Caching
Hekaton – Project Siberia
EPFL's VoltDB Prototype
Apache Geode – Overflow Tables
MemSQL – Columnar Tables

H-STORE – ANTI-CACHING

On-line Identification
Administrator-defined Threshold
Tombstones
Abort-and-restart Retrieval
Block-level Granularity
Always Merge

ANTI-CACHING: A NEW APPROACH TO DATABASE MANAGEMENT SYSTEM ARCHITECTURE
VLDB 2013

HEKATON – PROJECT SIBERIA

Off-line Identification
Administrator-defined Threshold
Bloom Filters
Synchronous Retrieval
Tuple-level Granularity
Always Merge

TREKKING THROUGH SIBERIA: MANAGING COLD DATA IN A MEMORY-OPTIMIZED DATABASE
VLDB 2014

EPFL VOLTDB

Off-line Identification

OS Virtual Memory

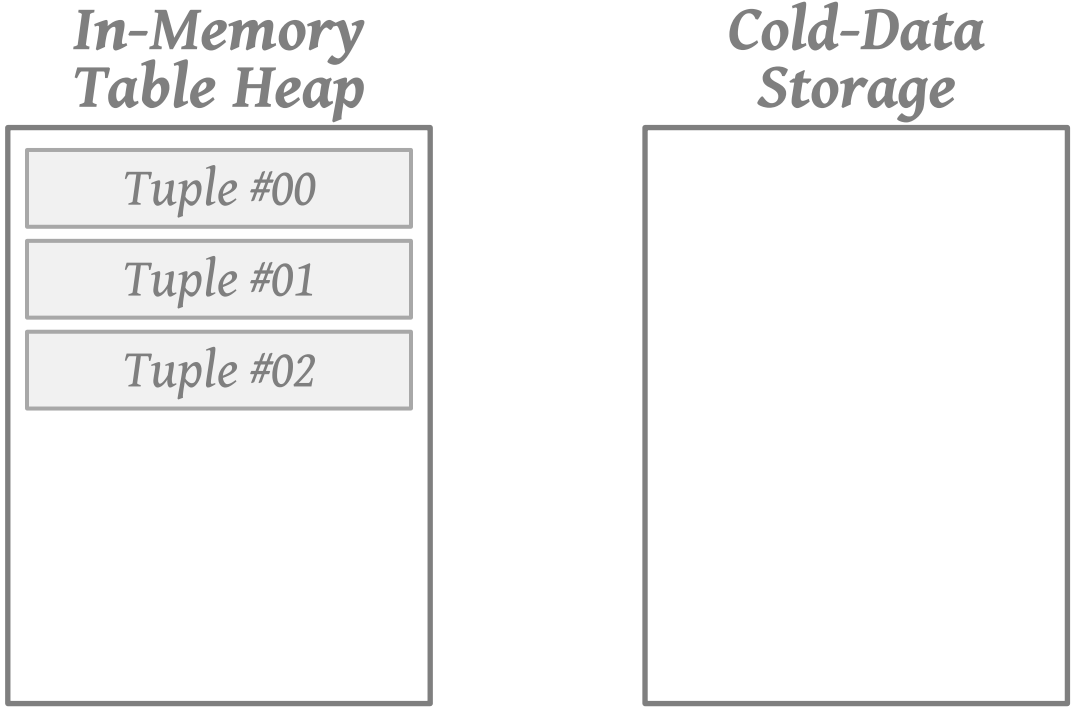
Synchronous Retrieval

Page-level Granularity

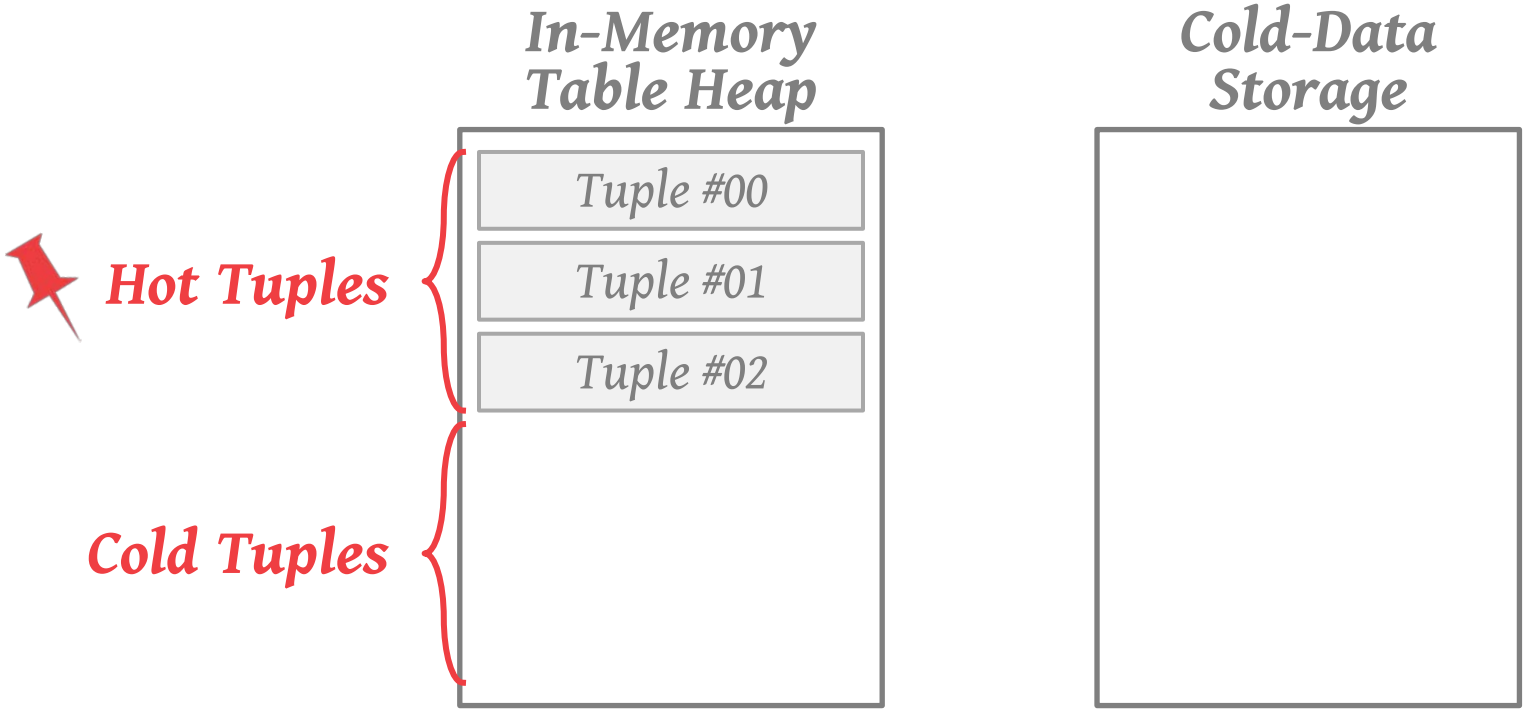
Always Merge

ENABLING EFFICIENT OS PAGING FOR MAIN-MEMORY OLTP DATABASES
DAMON 2013

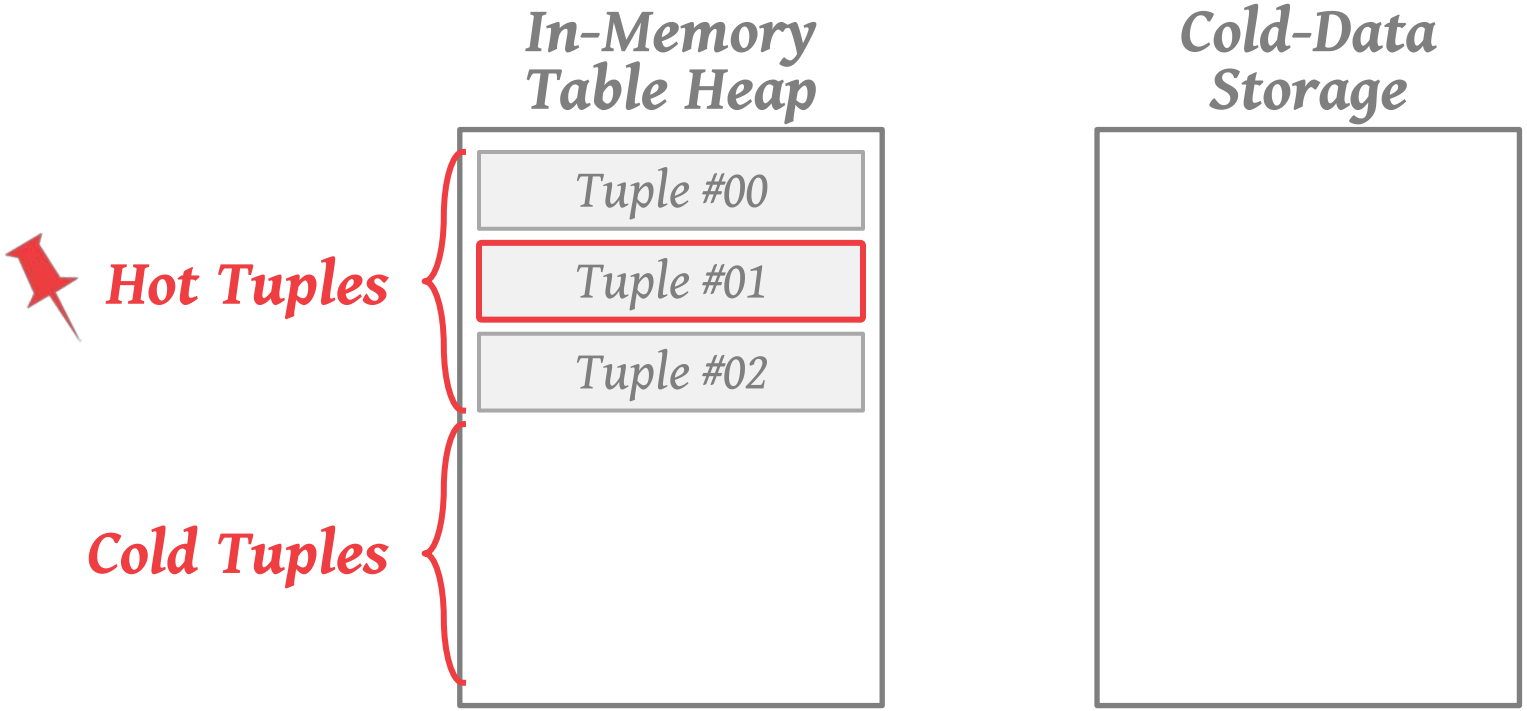
EPFL VOLTDB


In-Memory
Table Heap
Tuple #00
Tuple #01
Tuple #02
Cold-Data
Storage

EPFL VOLTDB


In-Memory
Table Heap
Cold-Data
Storage
Tuple #00
Tuple #01
Tuple #02
Hot Tuples
Cold Tuples

EPFL VOLTDB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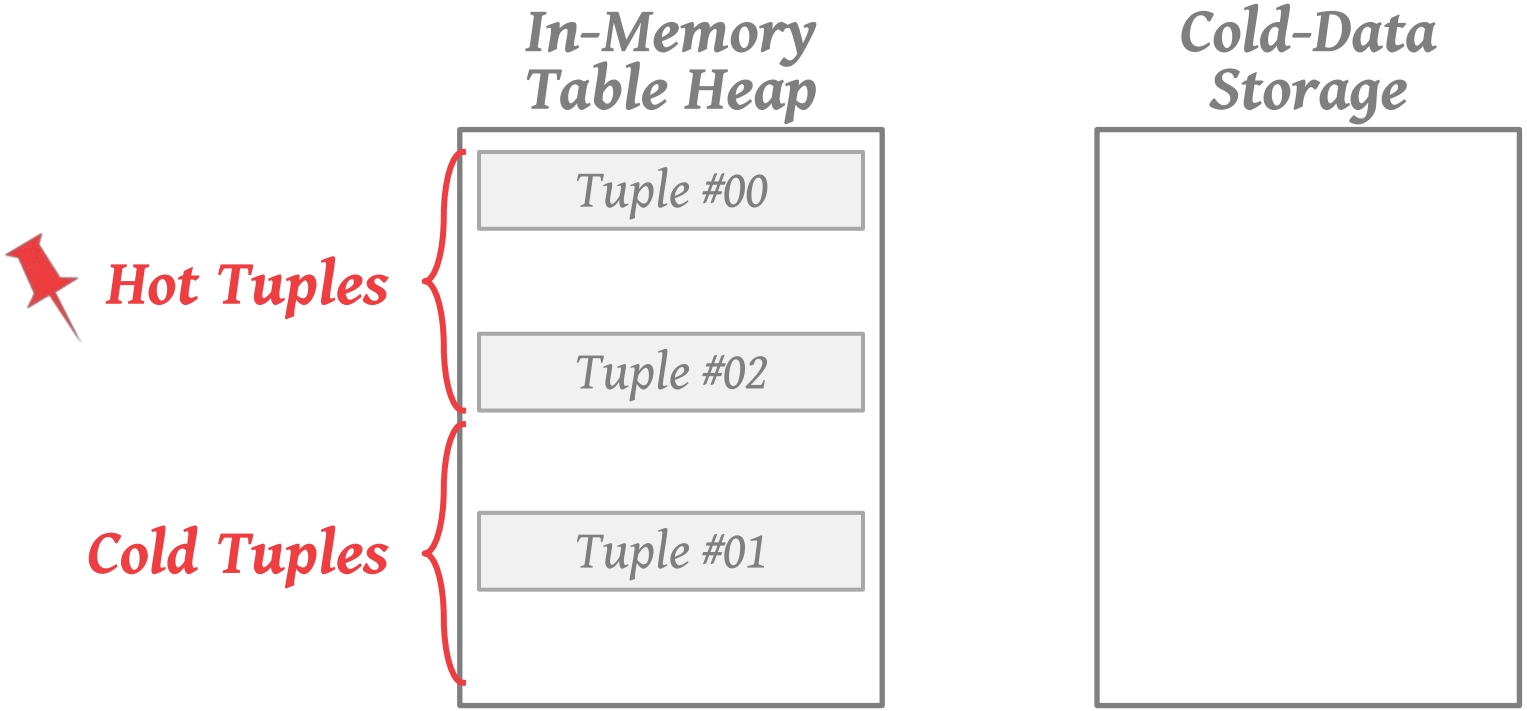
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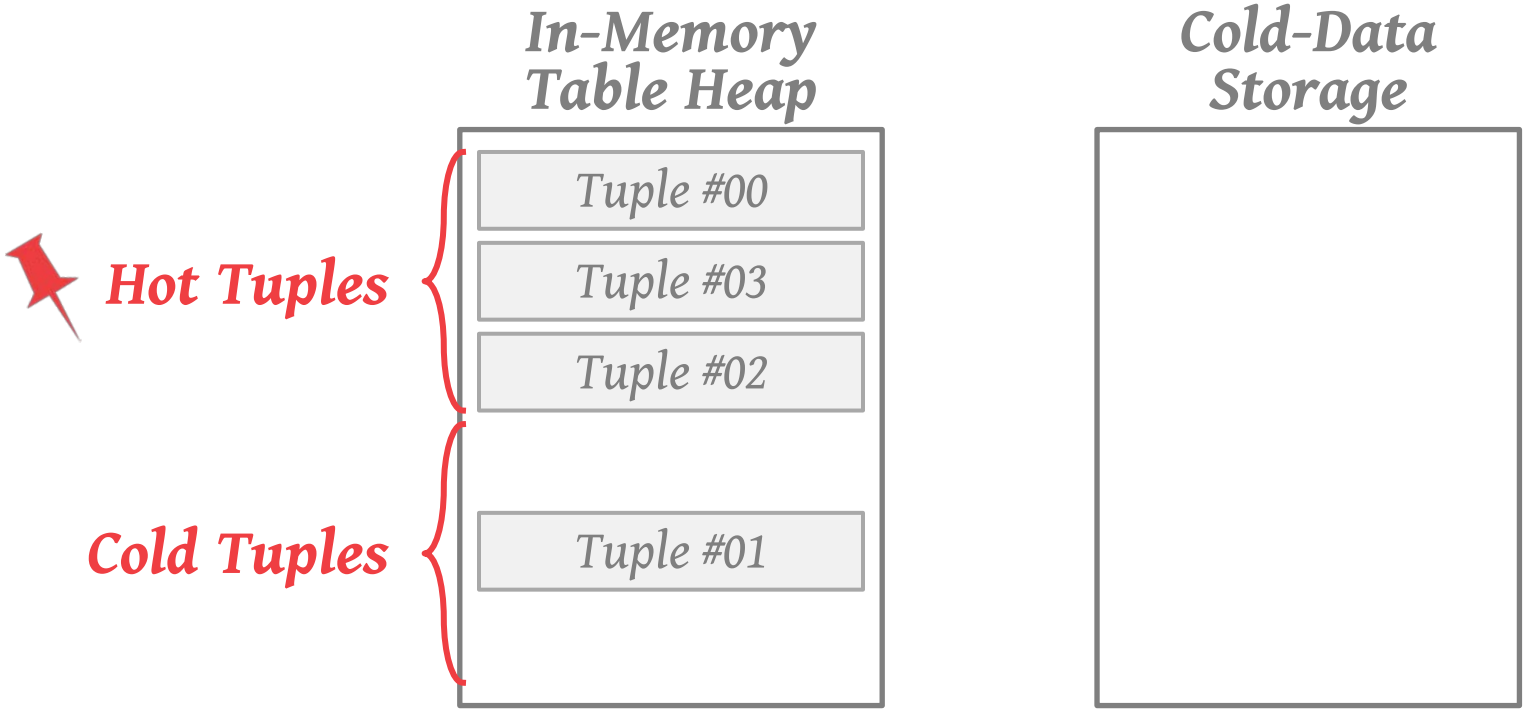
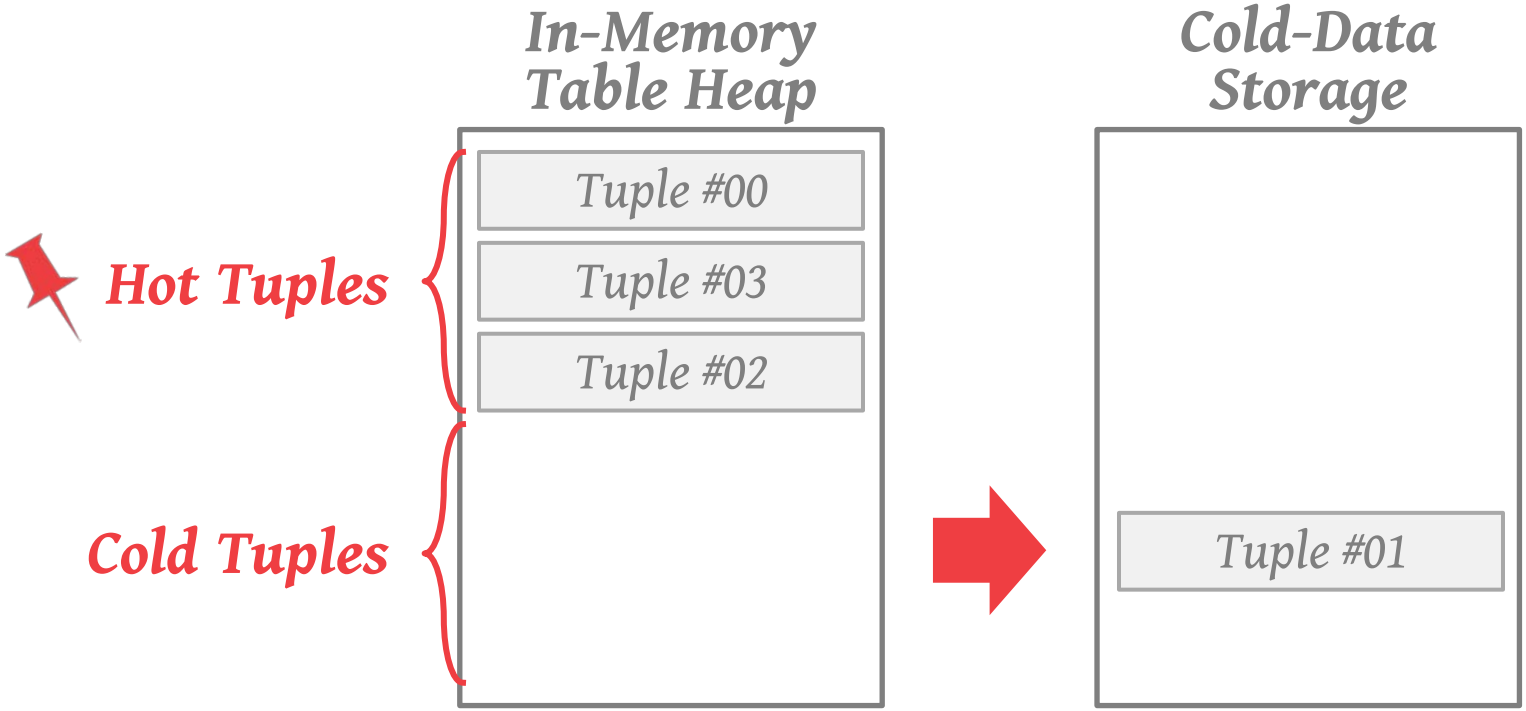

In-Memory
Table Heap
Cold-Data
Storage
Hot Tuples
Cold Tuples
Tuple #00
Tuple #03
Tuple #02
Tuple #01

EPFL VOLTDB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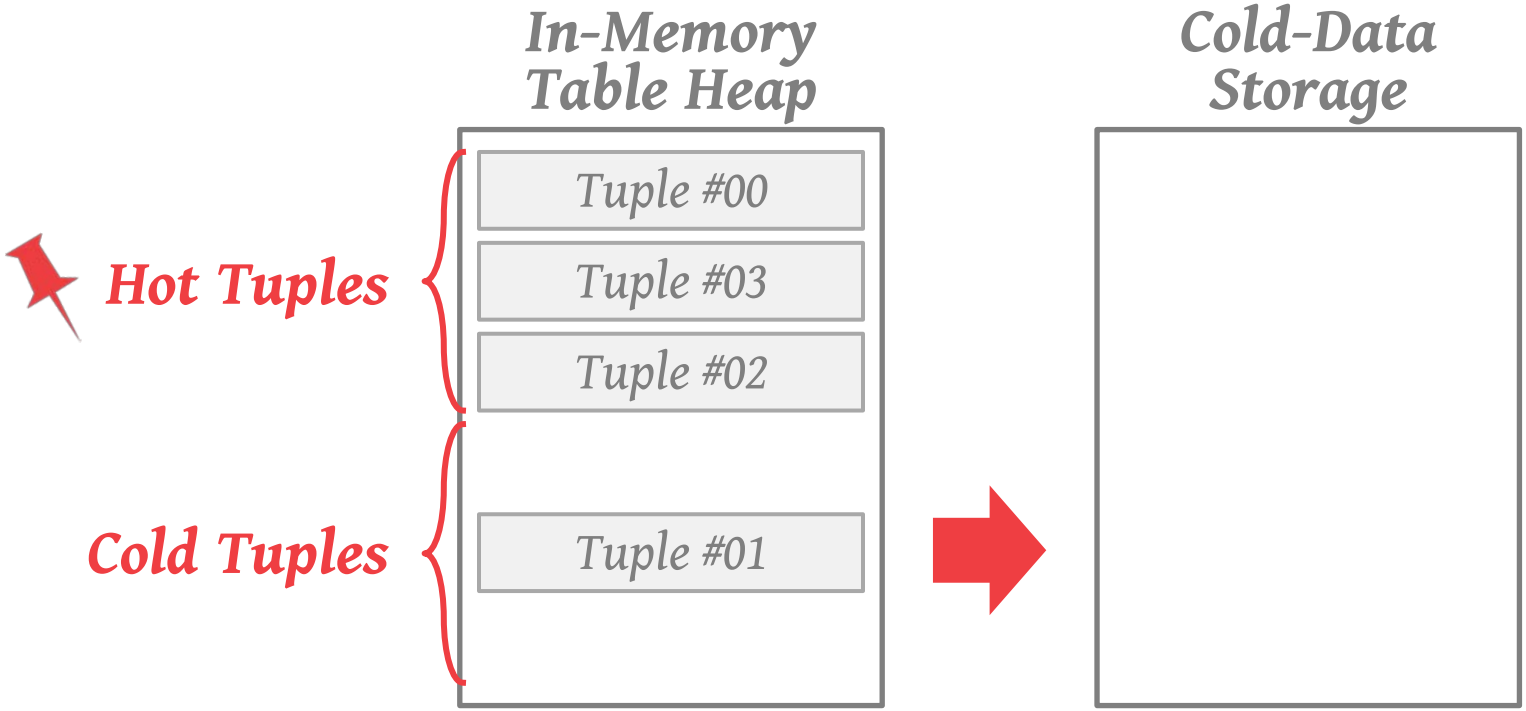
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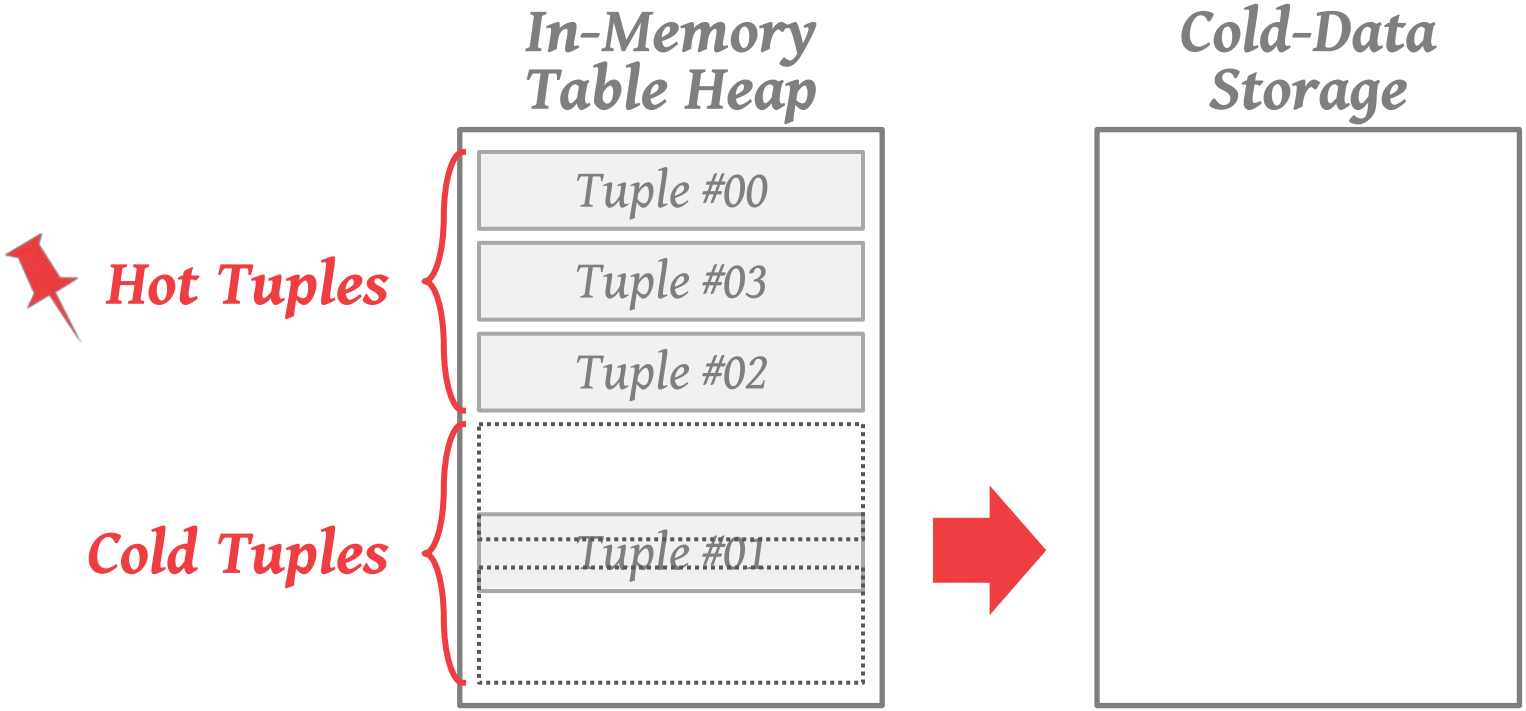
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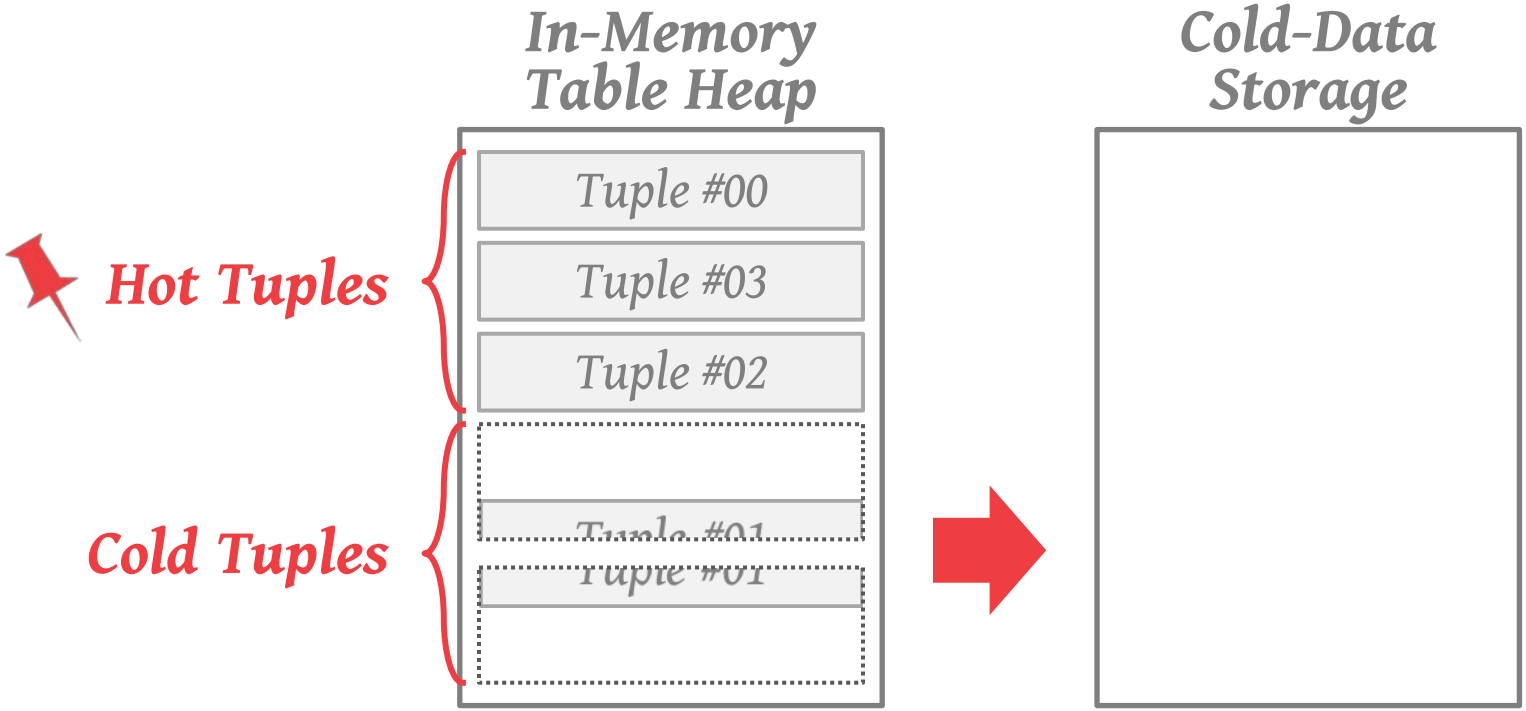
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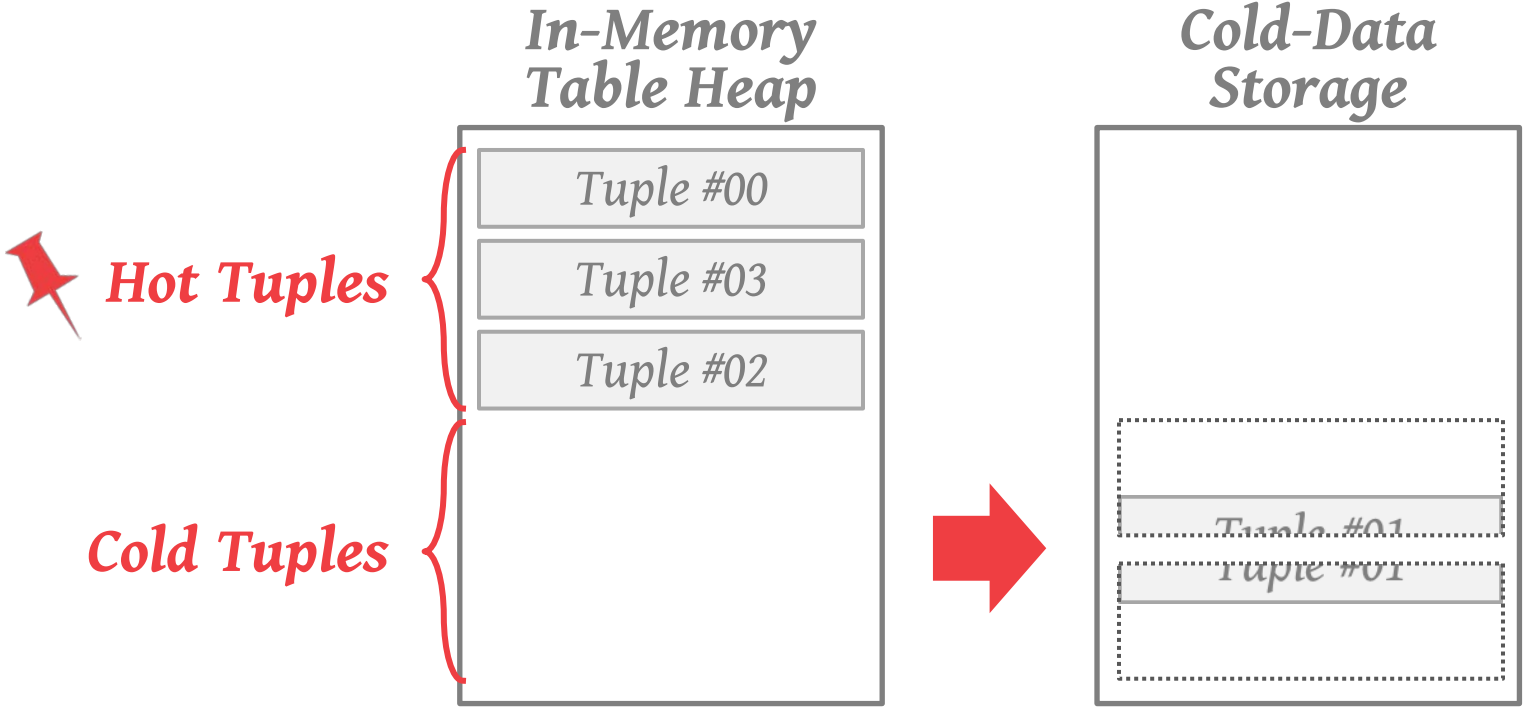
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APACHE GEODE – OVERFLOW TABLES

On-line Identification
Administrator-defined Threshold
Tombstones (?)
Synchronous Retrieval
Tuple-level Granularity
Merge Only on Update (?)

Source: Apache Geode Documentation

MEMSQL – COLUMNAR TABLES

Administrator manually declares a table as a distinct disk-resident columnar table.

→ Appears as a separate logical table to the application.
→ Uses `mmap` to manage buffer pool.
→ Pre-computed aggregates per block always in memory.

Manual Identification

No Evicted Metadata is needed.

Synchronous Retrieval

Always Merge

Source: MemSQL Documentation

EVALUATION

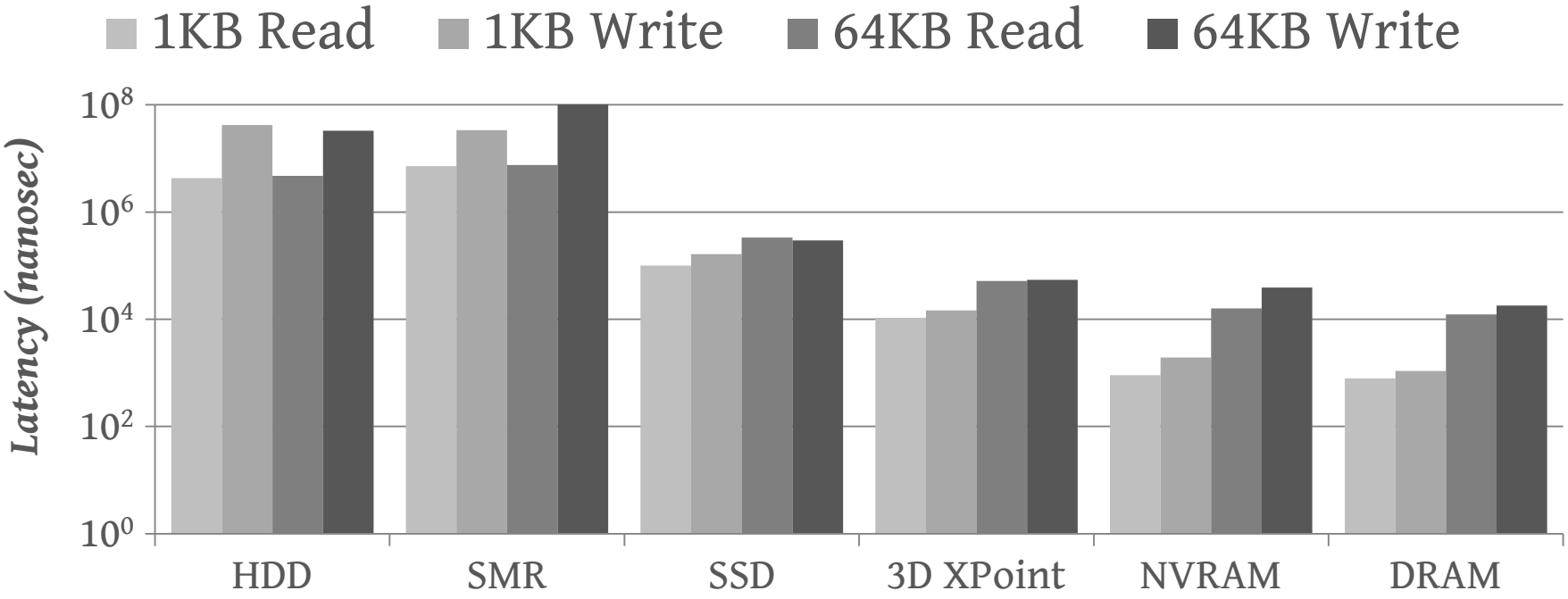
Compare different design decisions in H-Store with anti-caching.

Storage Devices:
→ Hard-Disk Drive (HDD)
→ Shingled Magnetic Recording Drive (SMR)
→ Solid-State Drive (SSD)
→ 3D XPoint (3DX)
→ Non-volatile Memory (NVRAM)

LARGER-THAN-MEMORY DATA MANAGEMENT ON MODERN STORAGE HARDWARE FOR IN-MEMORY OLTP DATABASE SYSTEMS
UNDER SUBMISSION

MICROBENCHMARK

10m Tuples – 1KB each
50% Reads / 50% Writes – Synchronization Enabled



MICROBENCHMARK

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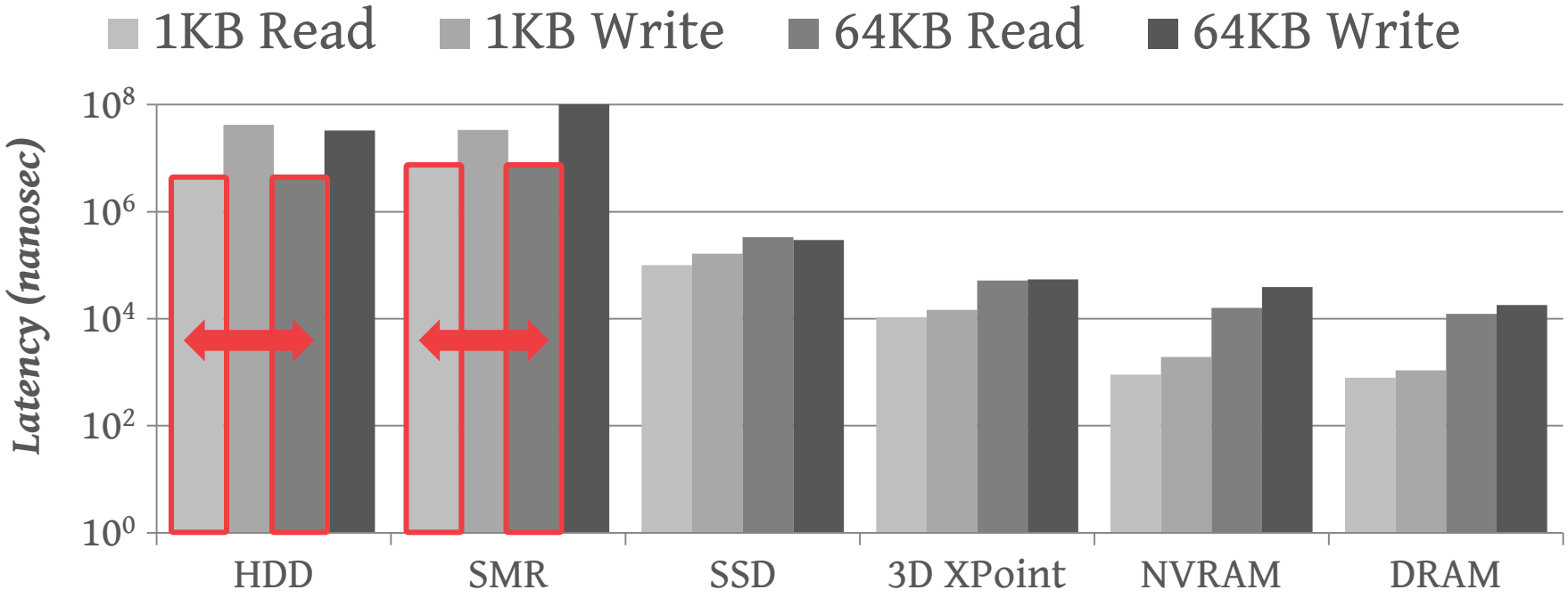

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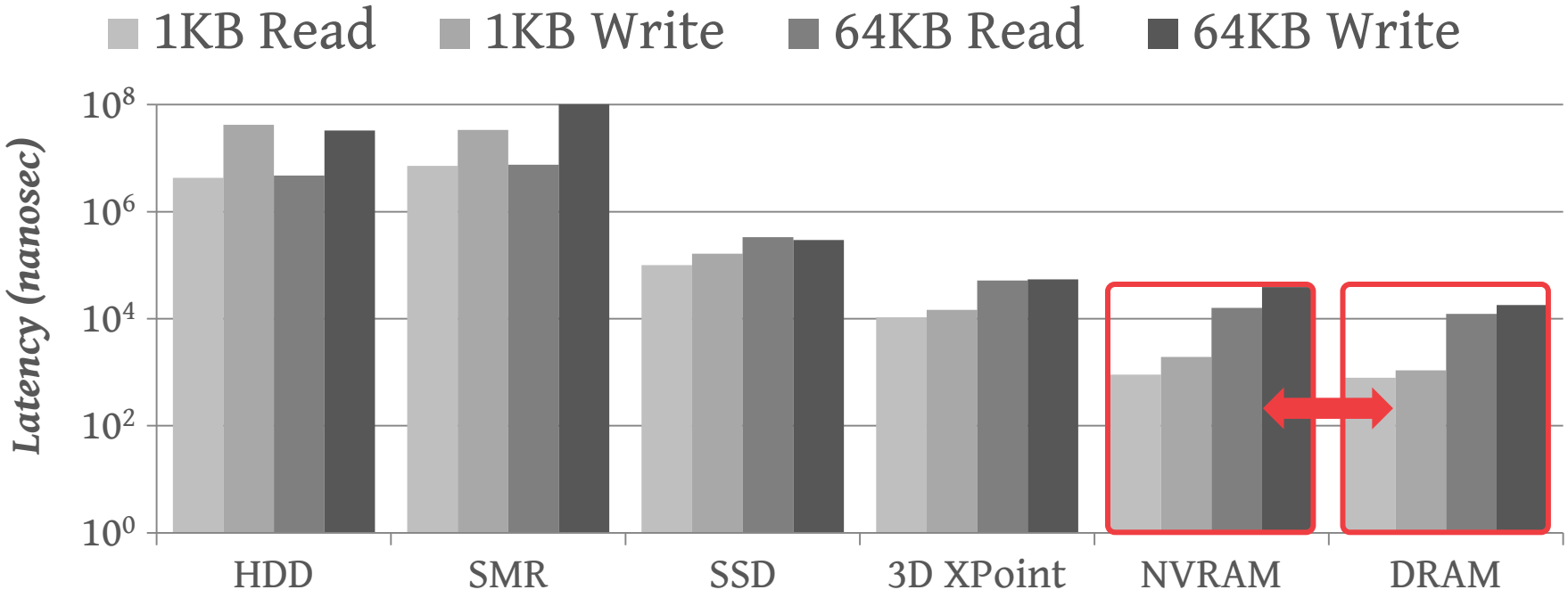
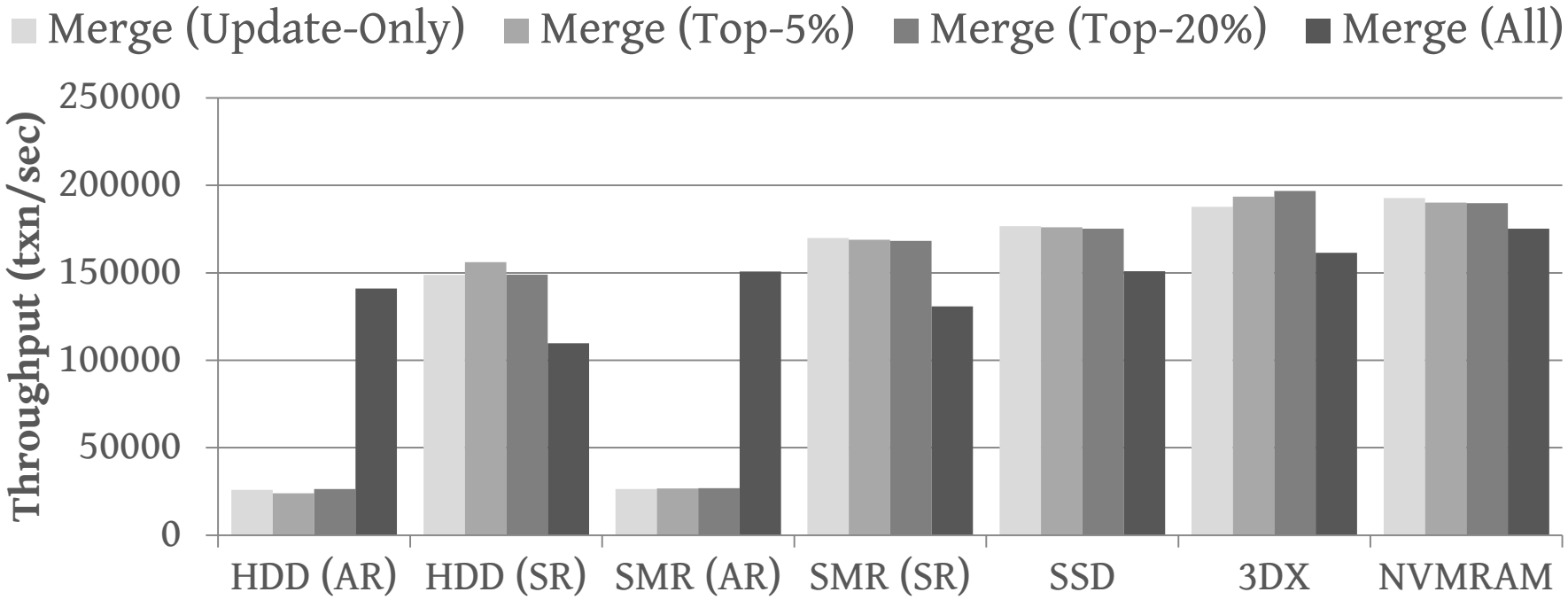


MERGING THRESHOLD

YCSB Workload – 90% Reads / 10% Writes
10GB Database using 1.25GB Memory



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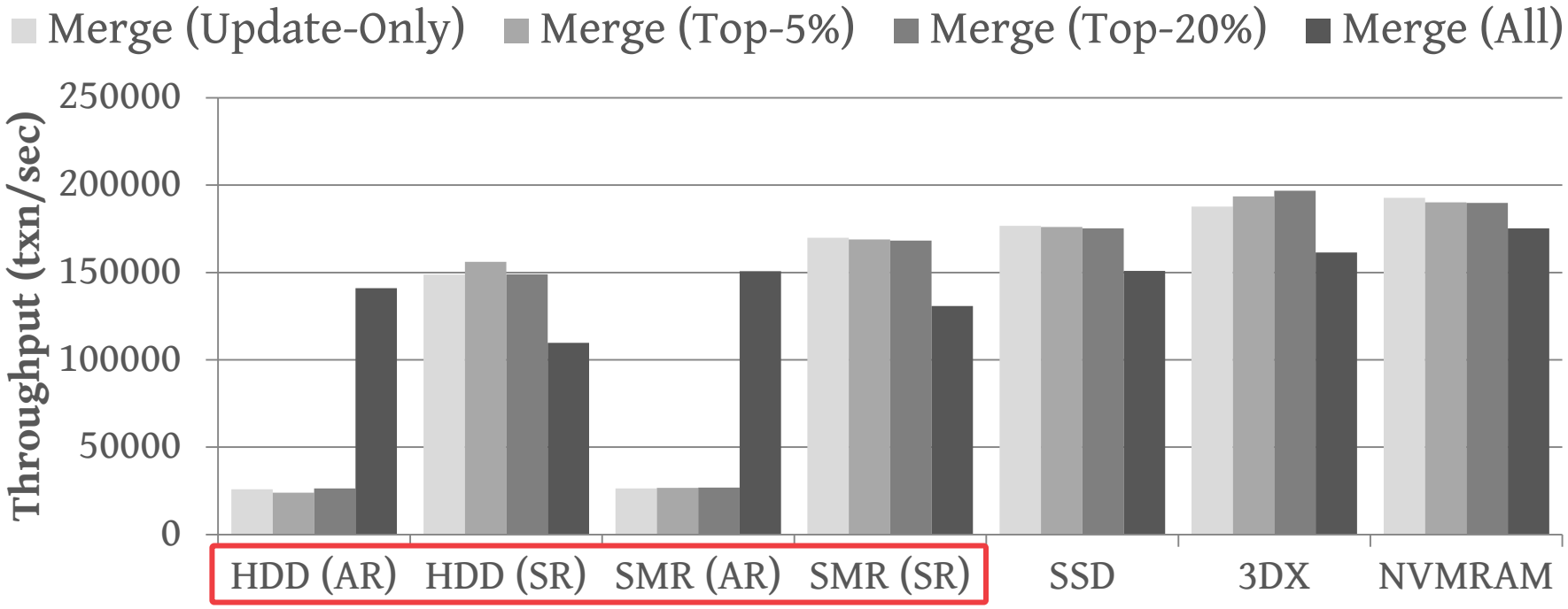

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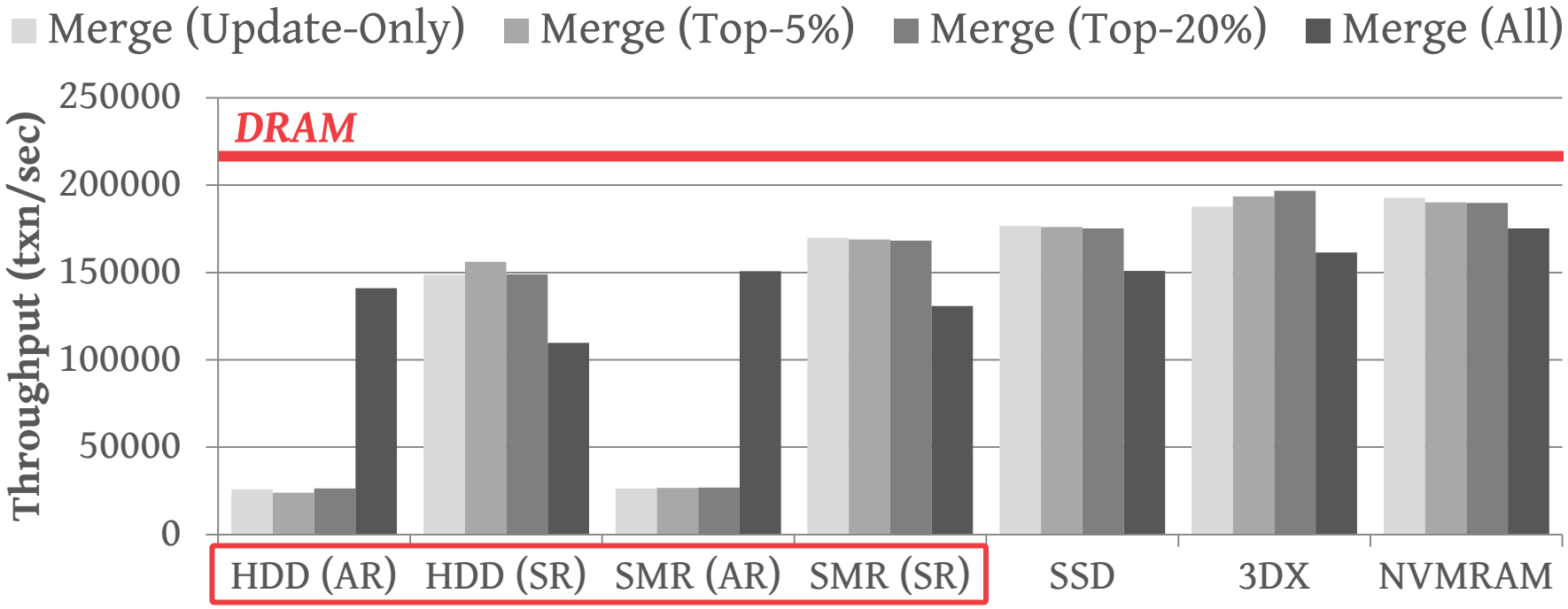


CONFIGURATION COMPARISON

Generic Configuration

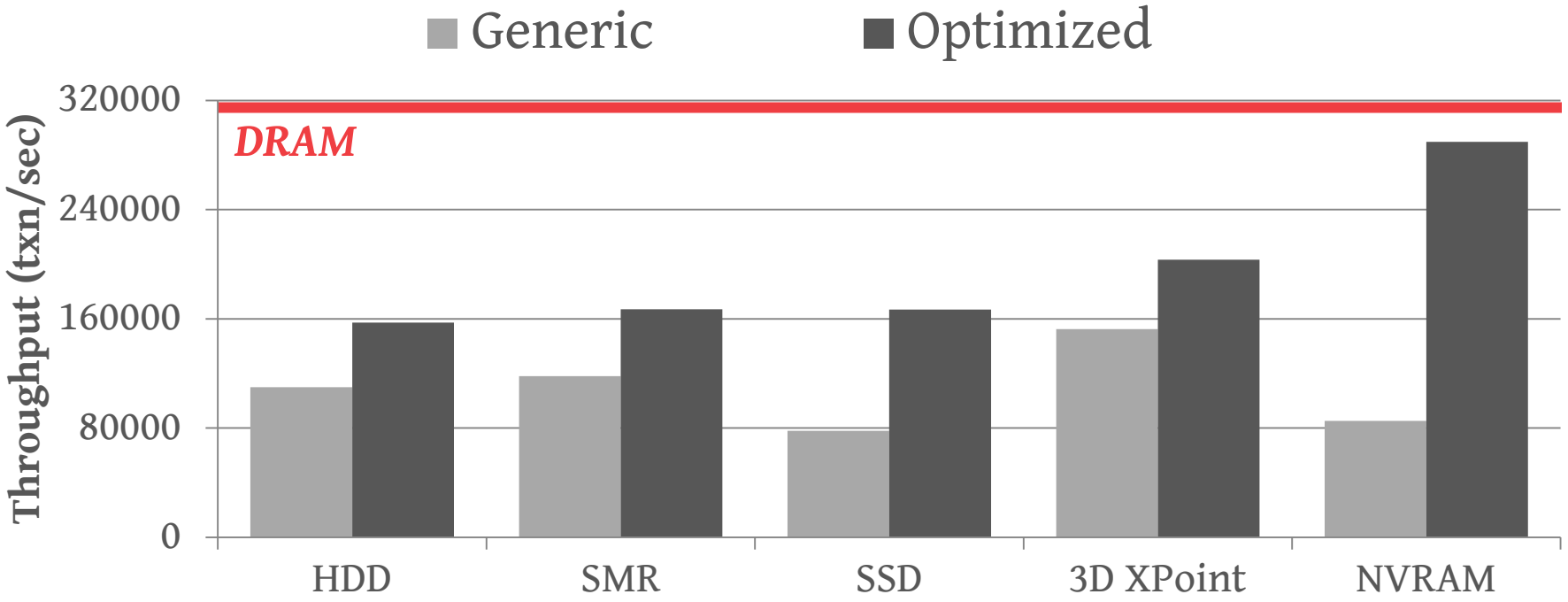
→ Abort-and-Restart Retrieval
→ Merge (All) Threshold
→ 1024 KB Block Size

Optimized Configuration

→ Synchronous Retrieval
→ Top-5% Merge Threshold
→ Block Sizes (HDD/SMR - 1024 KB) (SSD/3DX - 16 KB)

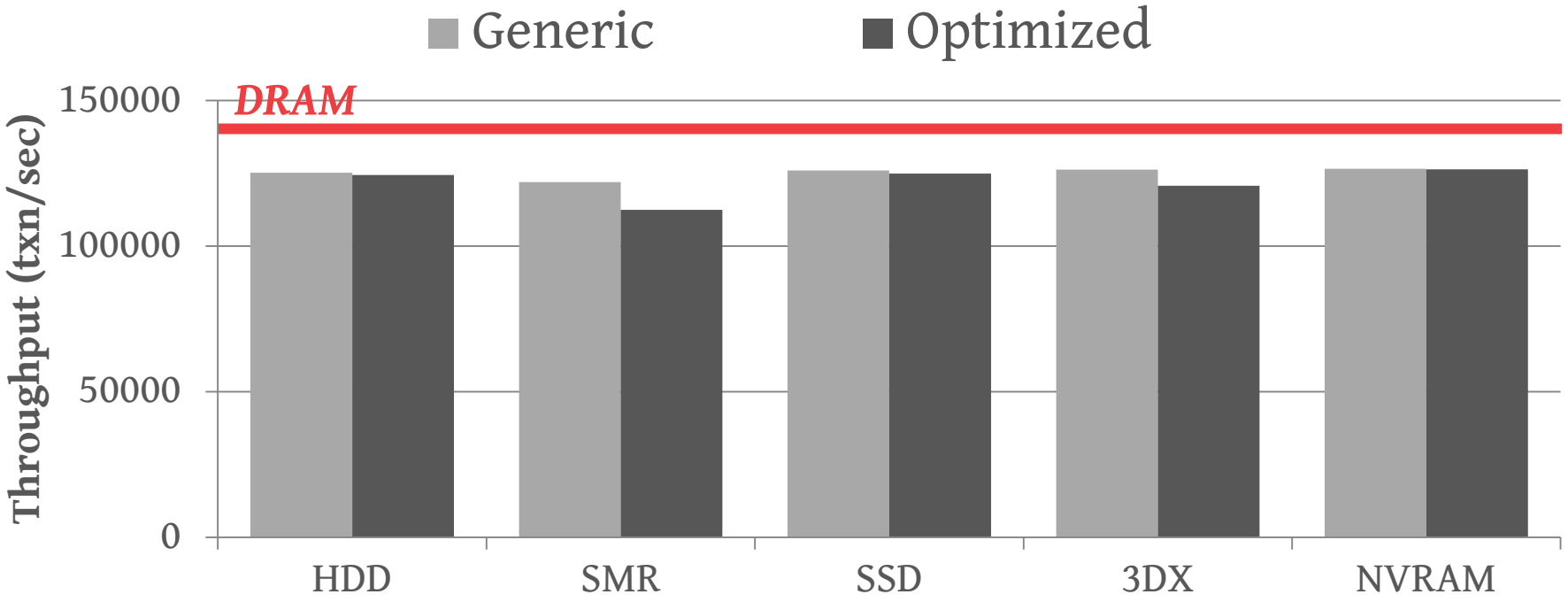
TATP BENCHMARK

Optimal Configuration per Storage Device
1.25GB Memory



VOTER BENCHMARK

Optimal Configuration per Storage Device
1.25GB Memory



PARTING THOUGHTS

Today was about working around the block-oriented access and slowness of secondary storage.

Fast & cheap byte-addressable NVM will make this lecture unnecessary.

NEXT CLASS

Non-Volatile Memory

Project #3 Code Reviews