15-721 ADVANCED DATABASE SYSTEMS

Lecture #23 – Larger-than-Memory Databases

@Andy_Pavlo // Carnegie Mellon University // Spring 2017

ADMINISTRIVIA

Final Exam: May 4th @ 12:00pm
→ Multiple choice + short-answer questions.
→ I will provide sample questions this week.

Code Review #2: May 3rd @ 11:59pm
→ We will use the same group pairings as before.

Final Presentations: May 9th @ 5:30pm
→ **WEH Hall 7500**
→ 12 minutes per group
→ Food and prizes for everyone!

SIGMOD 2017 INNOVATION AWARD

SIGMOD Edgar F. Codd Innovations Award

Goetz Graefe

Graefe

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.

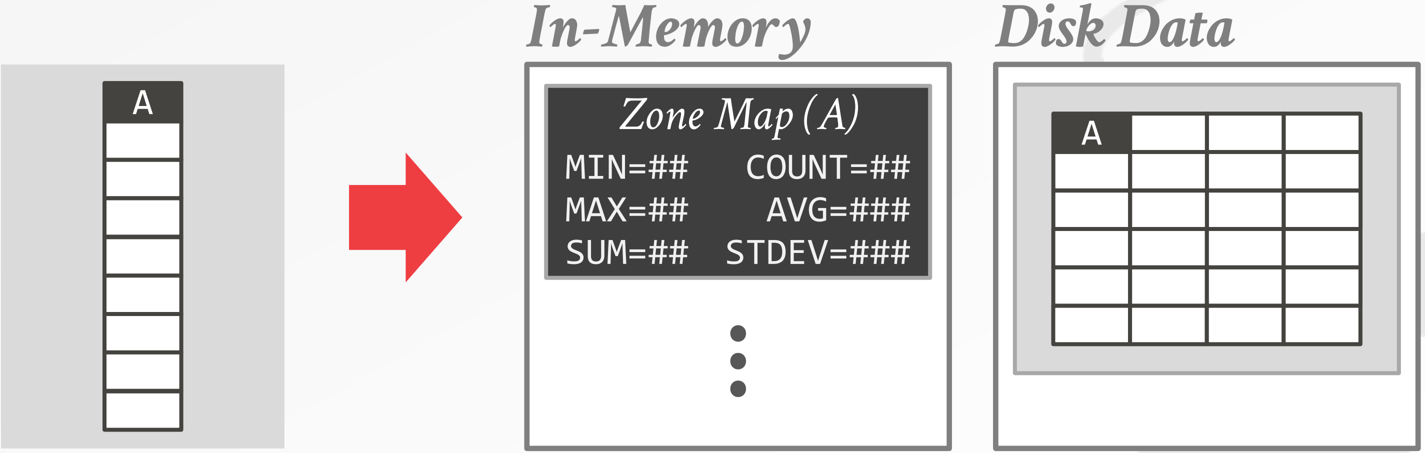
LARGER-THAN-MEMORY DATABASES

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.



OLTP

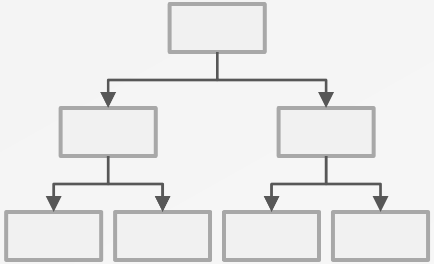
OLTP workloads almost always have **<u>hot</u>** and **<u>cold</u>** portions of the database.

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

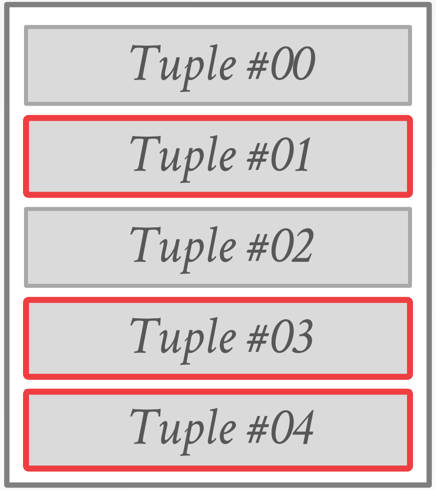
The DBMS needs a mechanism to move cold data out to disk and then retrieve it if it is ever needed again.

LARGER-THAN-MEMORY DATABASES

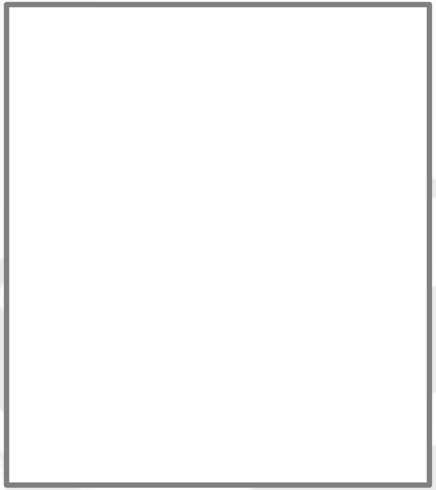
In-Memory Index



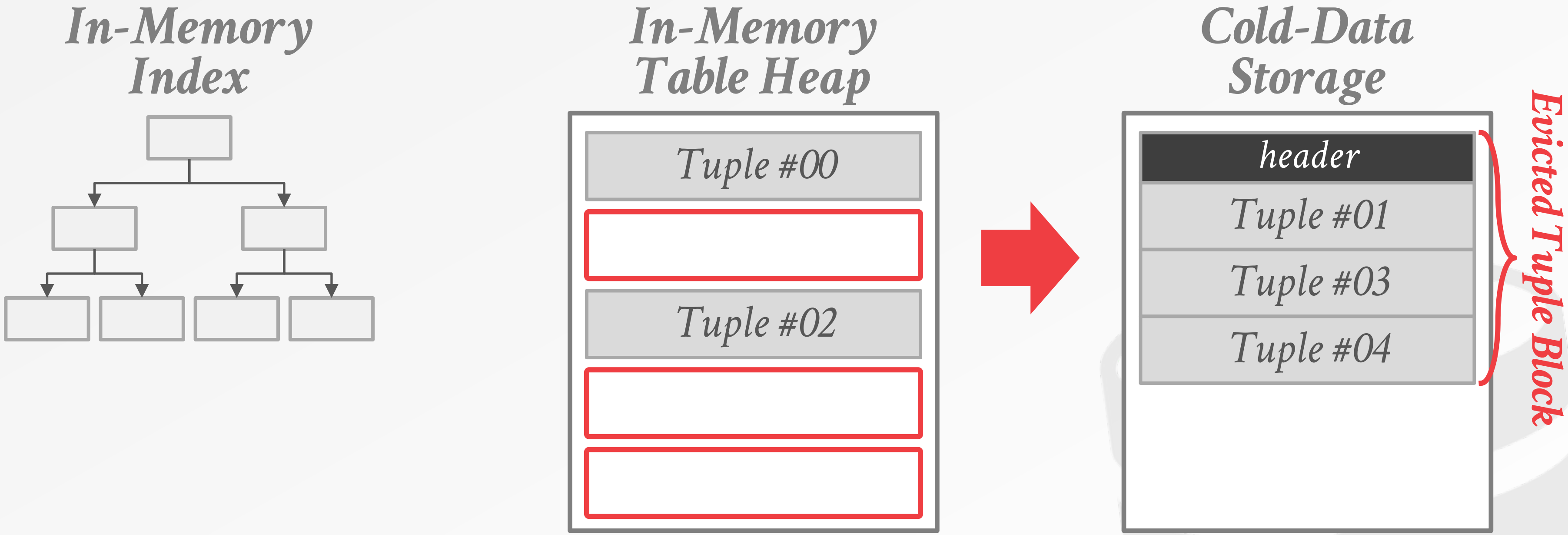
In-Memory Table Heap



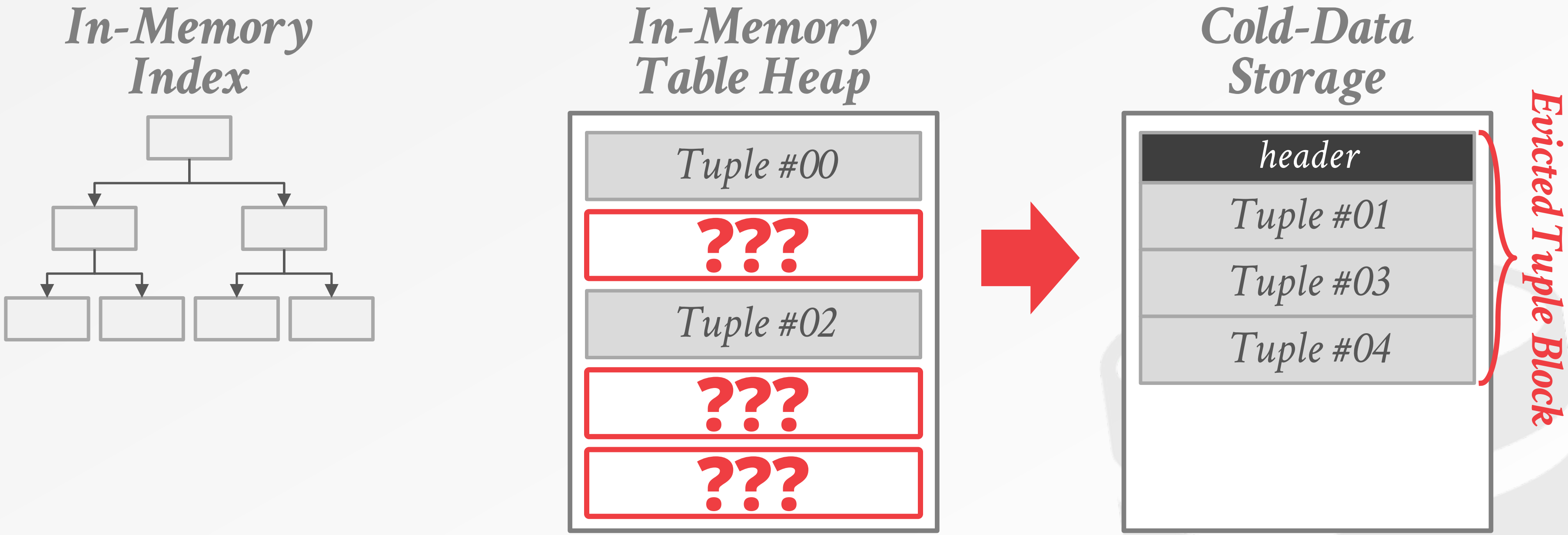
Cold-Data Storage



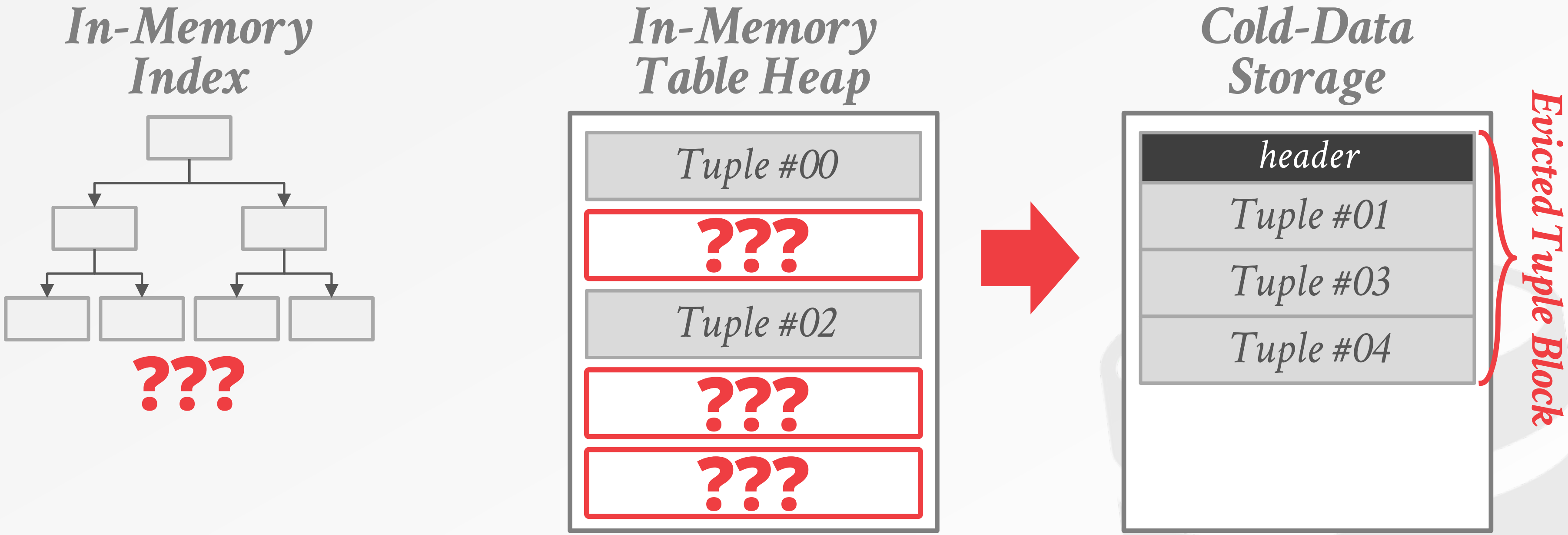
LARGER-THAN-MEMORY DATABASES



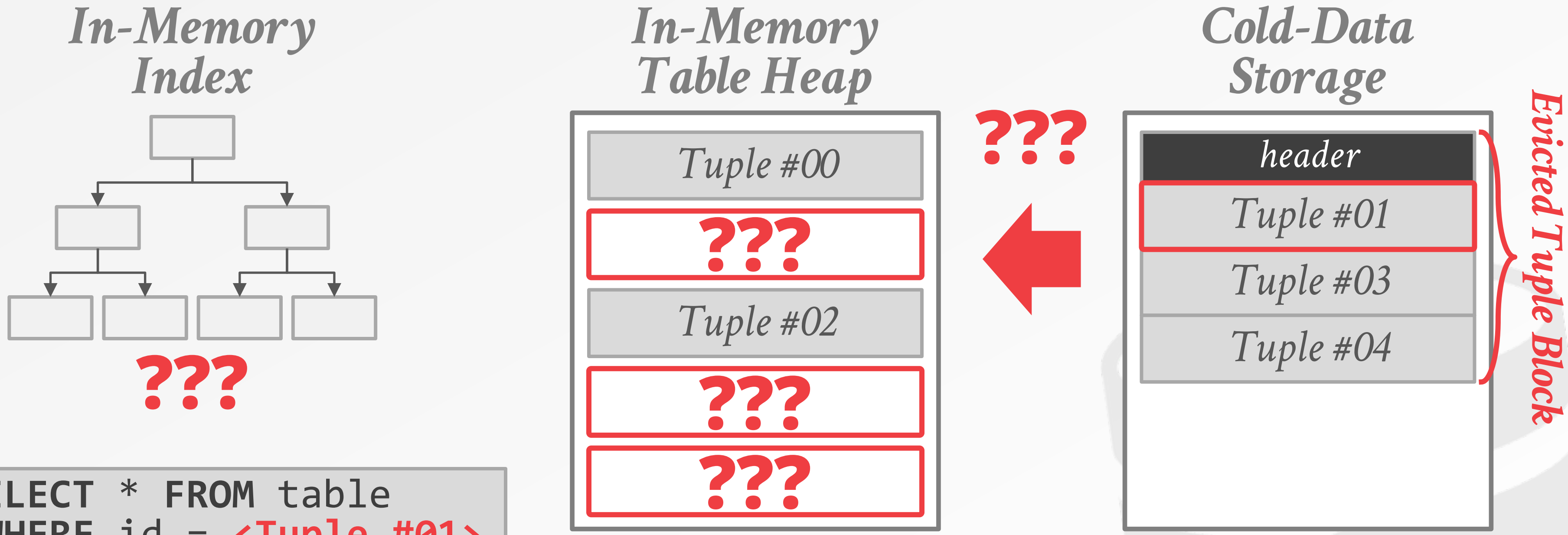
LARGER-THAN-MEMORY DATABASES



LARGER-THAN-MEMORY DATABASES

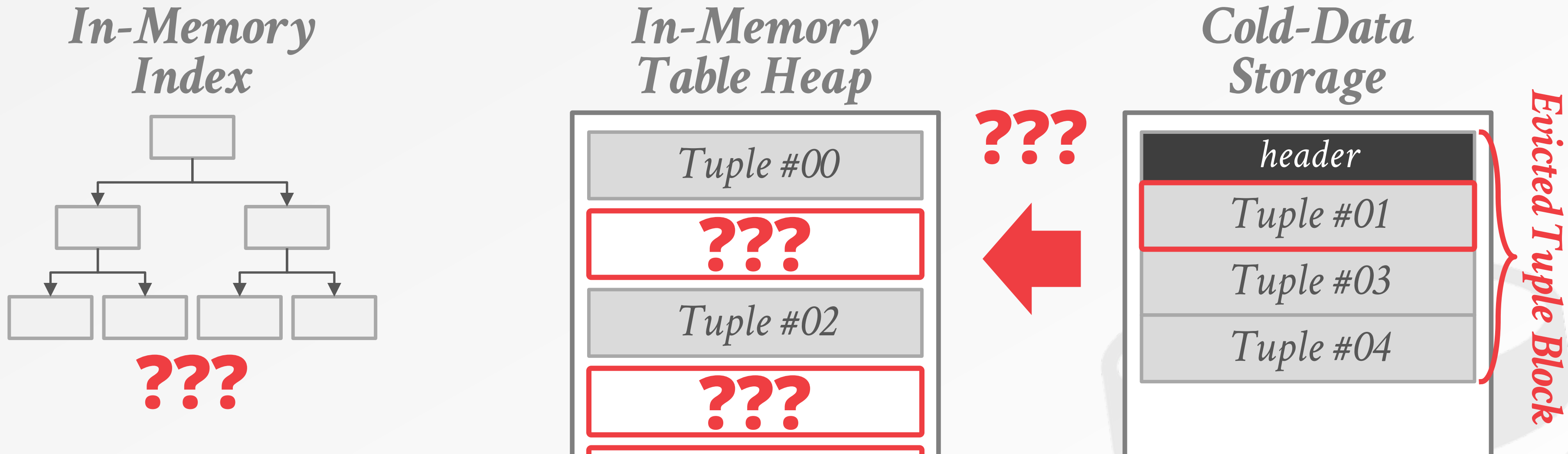


LARGER-THAN-MEMORY DATABASES




```
SELECT * FROM table
 WHERE id = <Tuple #01>
```

LARGER-THAN-MEMORY DATABASES




```
SELECT * FROM table
 WHERE id = <Tuple #01>
```

???

AGAIN, WHY NOT MMAP?

Write-ahead logging requires that a modified page cannot be written to disk before the log records that made those changes is written.

There are no mechanisms for asynchronous read-ahead or writing multiple pages concurrently.

IN-MEMORY PERFORMANCE FOR BIG DATA
VLDB 2014

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

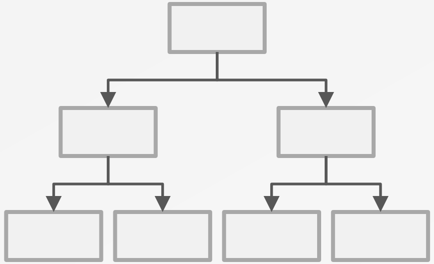
→ Use approximate data structure for each index.
→ Check both index + filter for each query.

Choice #3: OS Virtual Memory

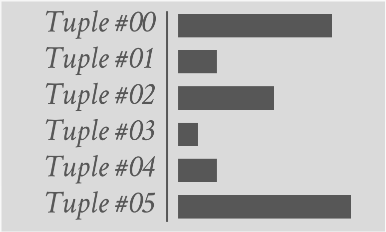
→ The OS tracks what data is on disk. The DBMS does not need to maintain any additional metadata.

EVICTED TUPLE METADATA

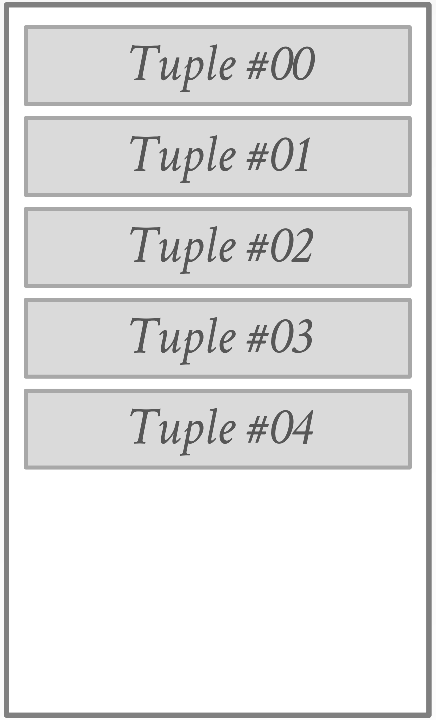
In-Memory Index



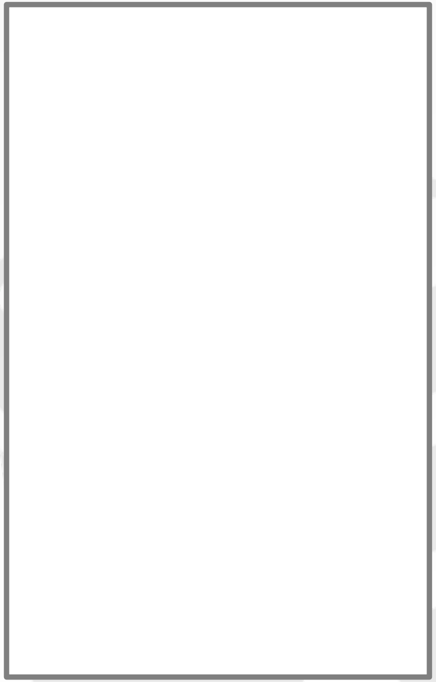
Access Frequency



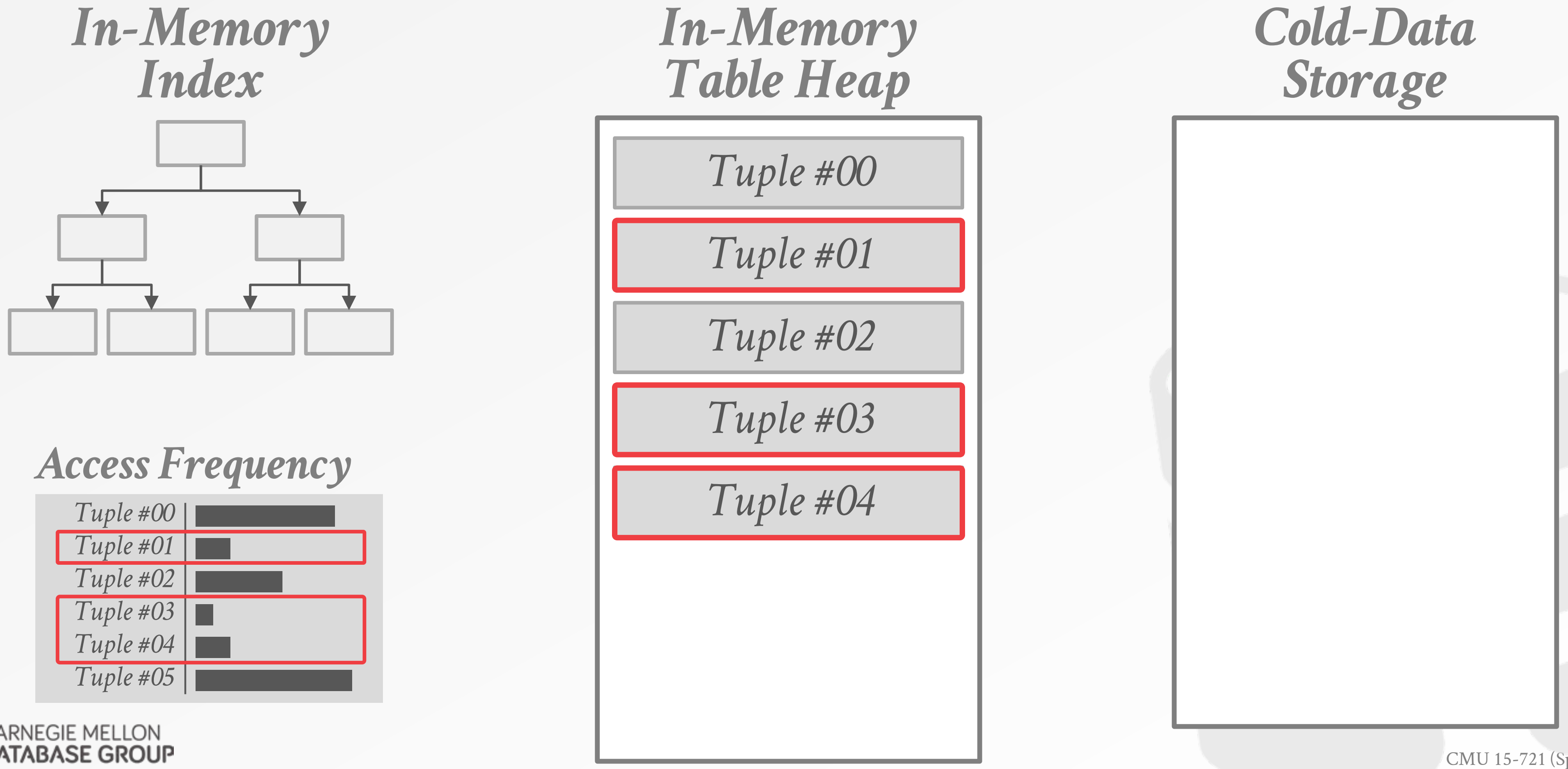
In-Memory Table Heap



Cold-Data Storage



EVICTED TUPLE METADATA



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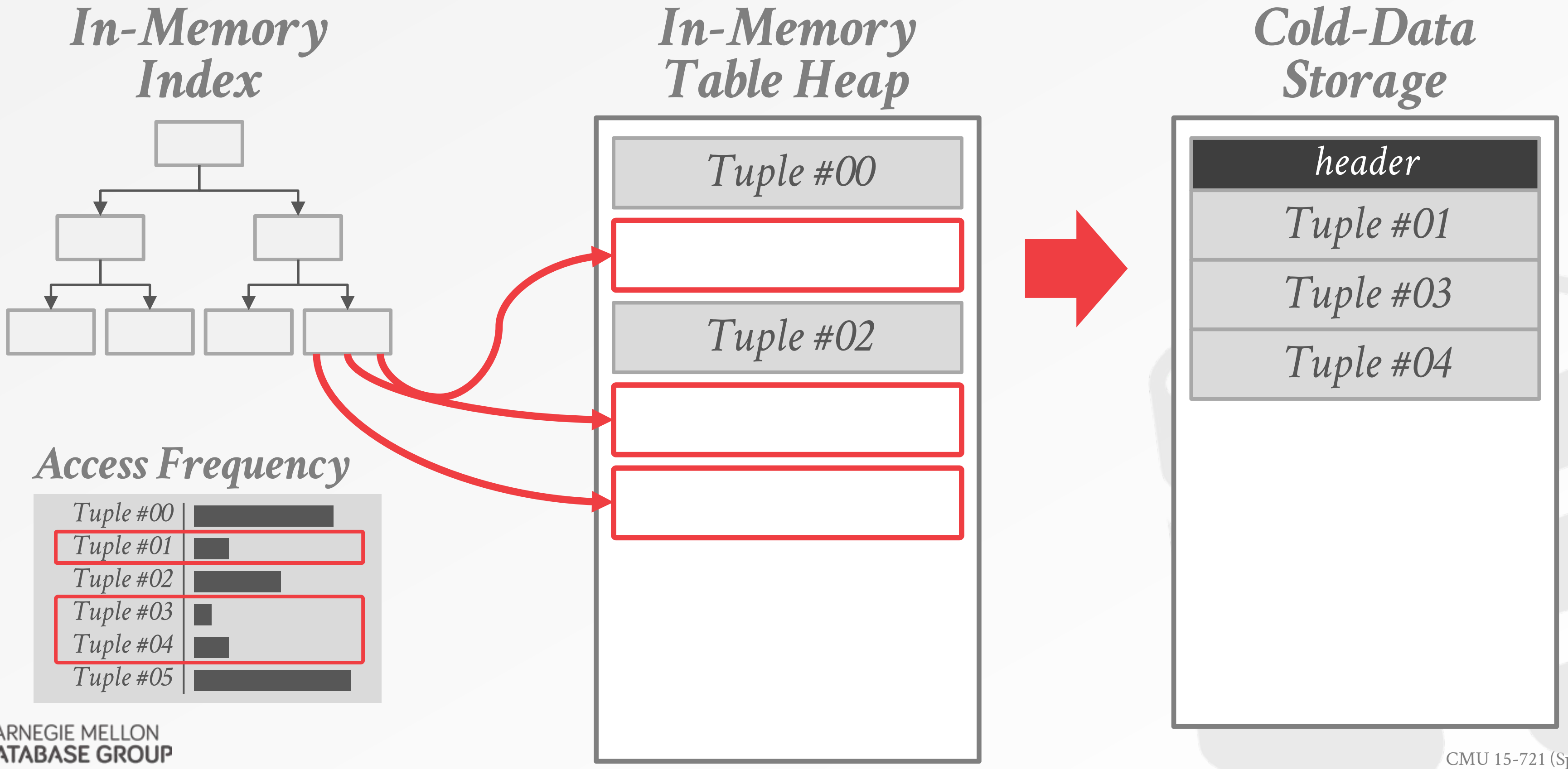

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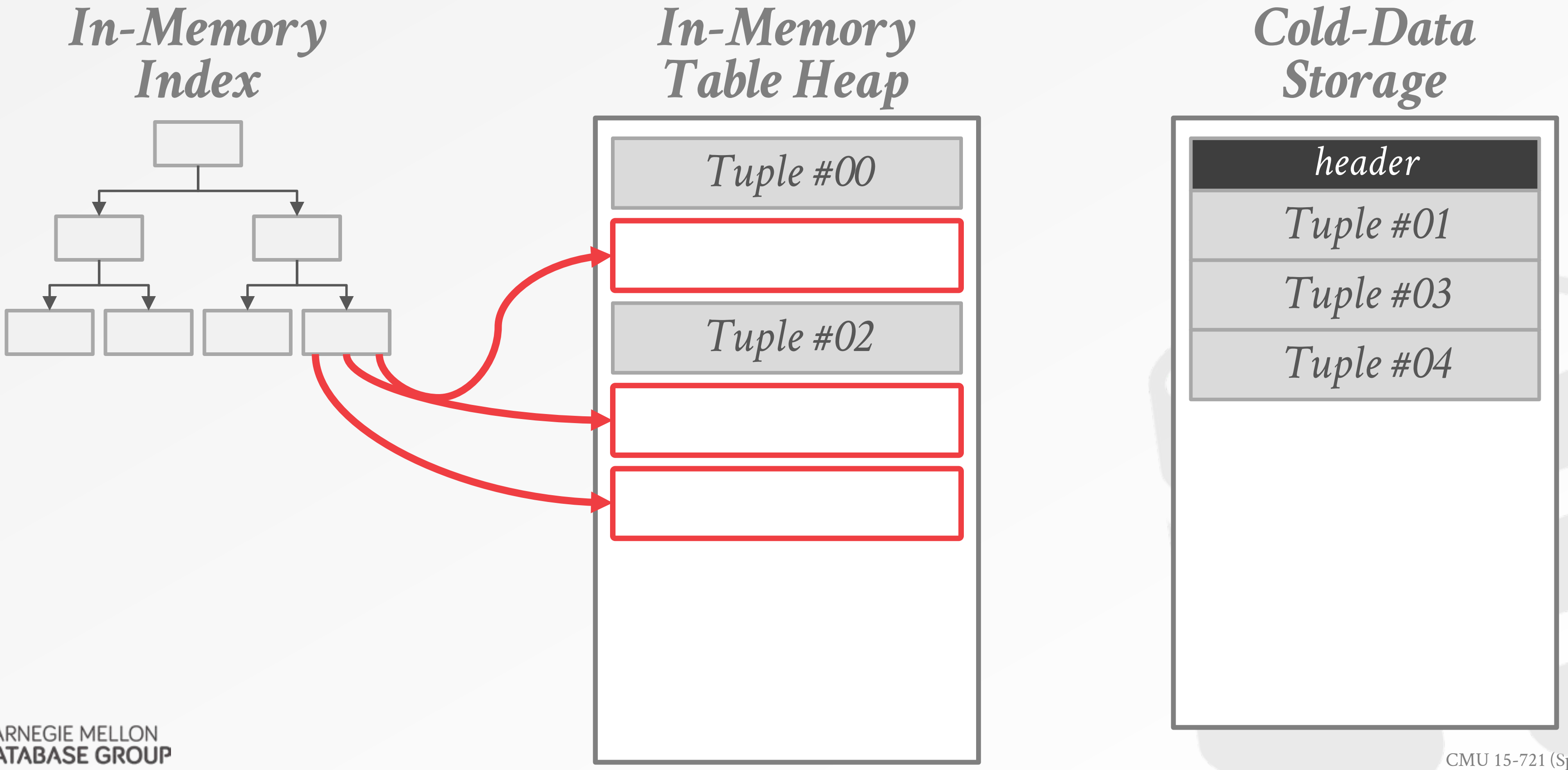

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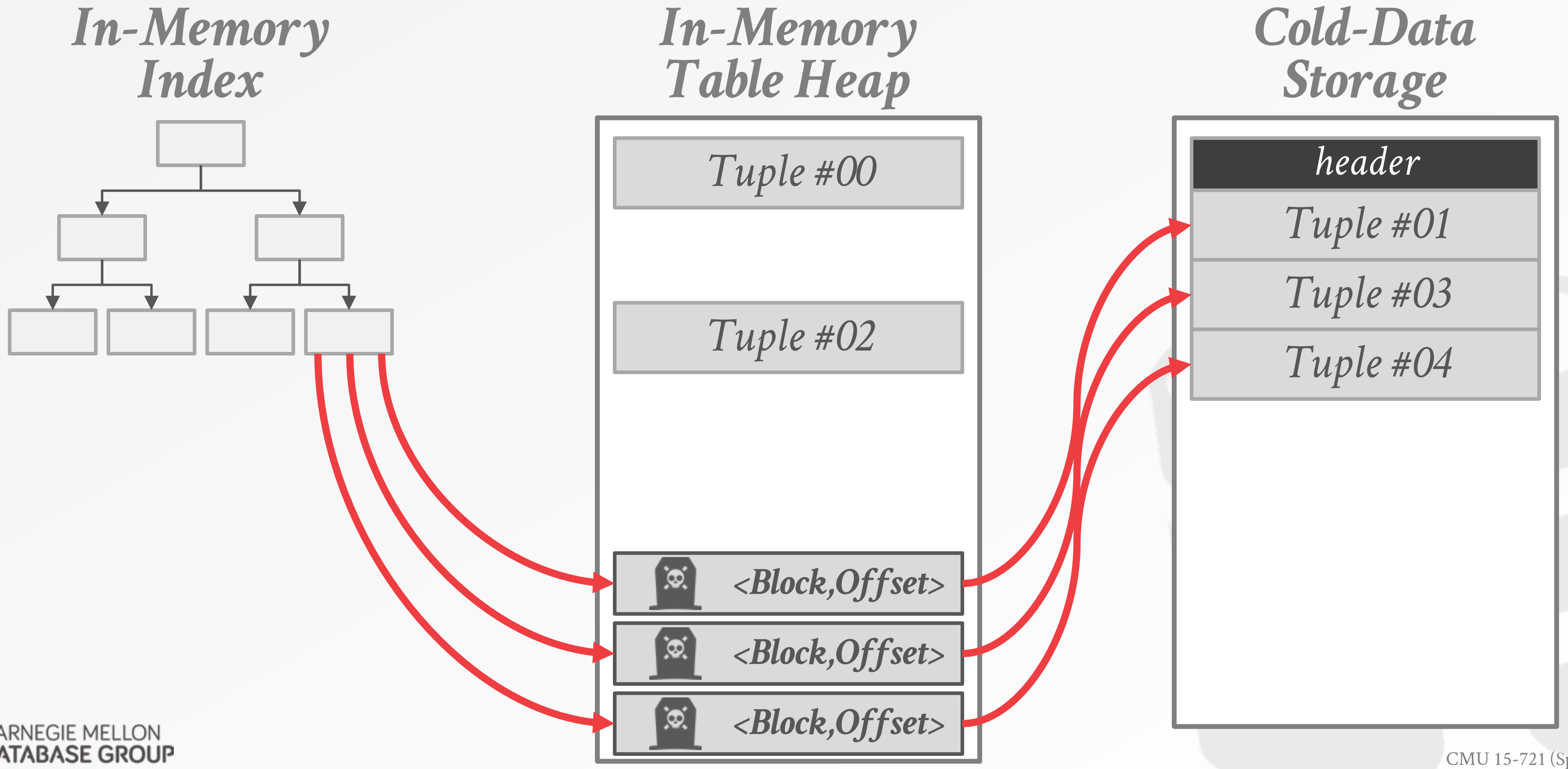

EVICTED TUPLE METADATA

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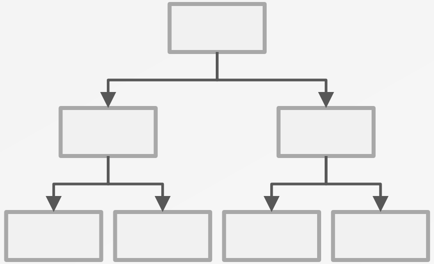
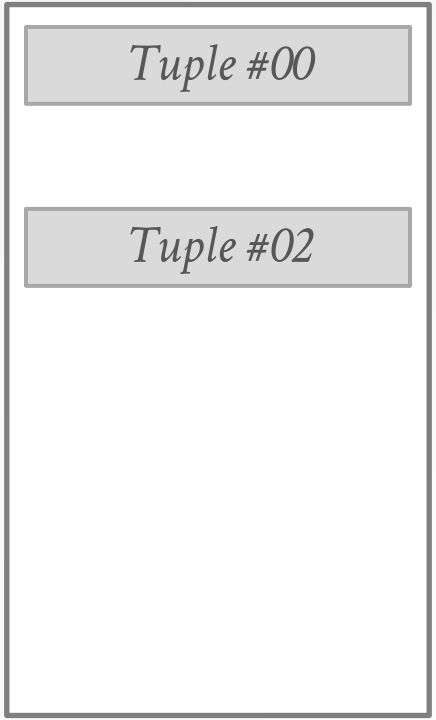


Bloom Filter

In-Memory Table Heap



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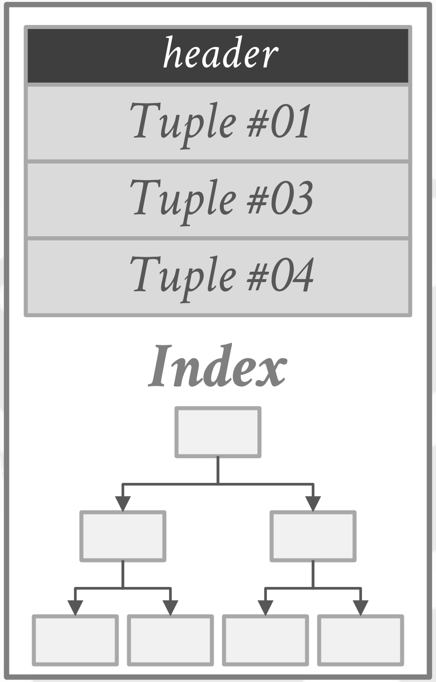

DATA RETRIEVAL GRANULARITY

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

Off-line Identification

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Synchronous Retrieval

Page-level Granularity

Always Merge

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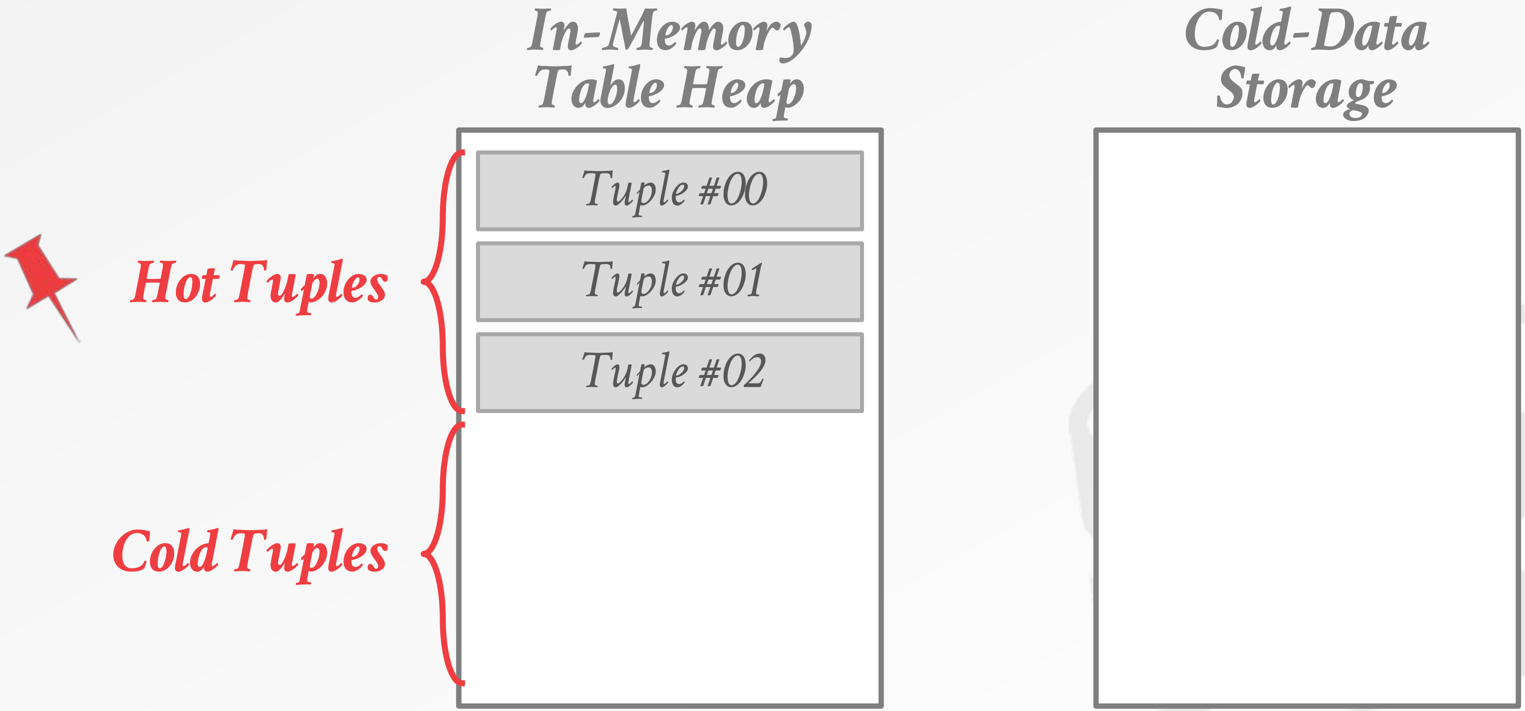
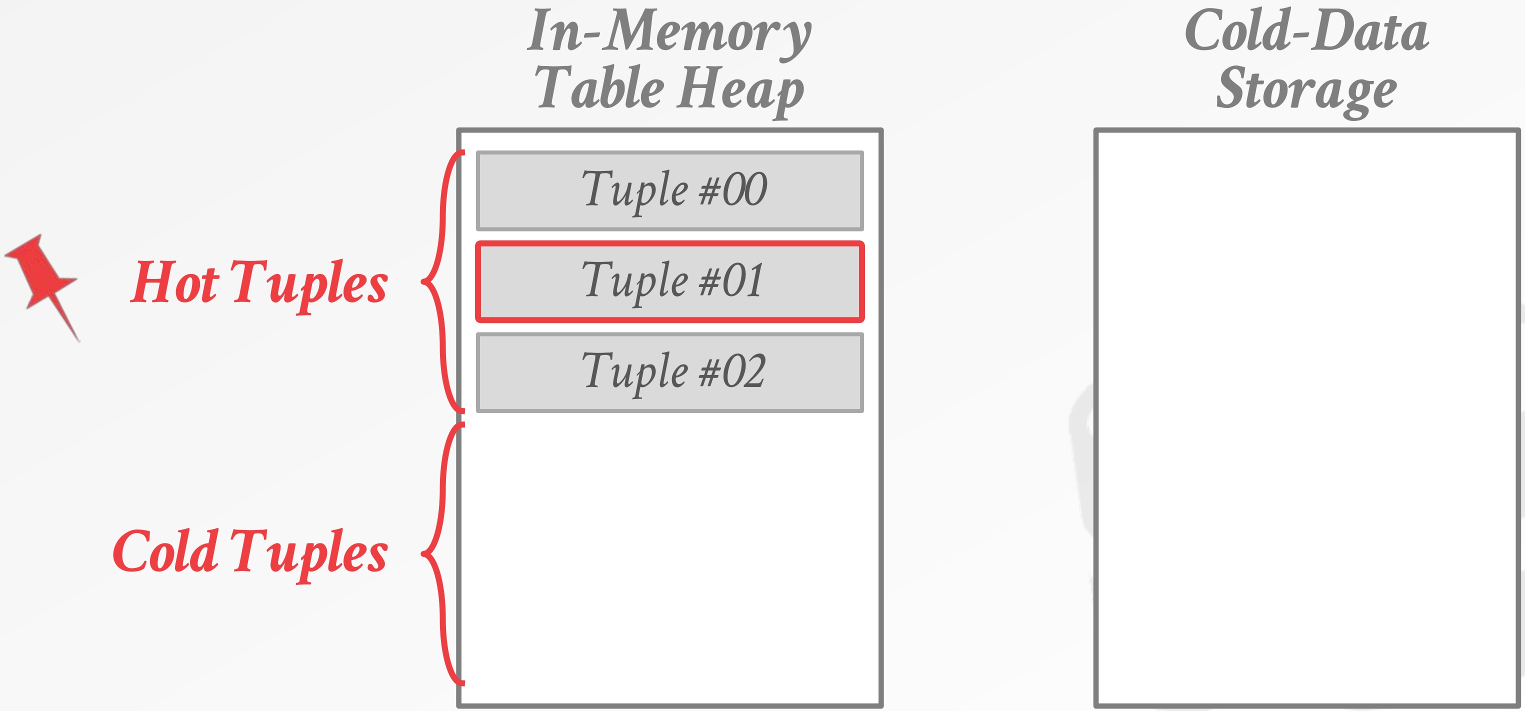
DAMON 2013

EPFL VOLTDB


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

EPFL VOLTDB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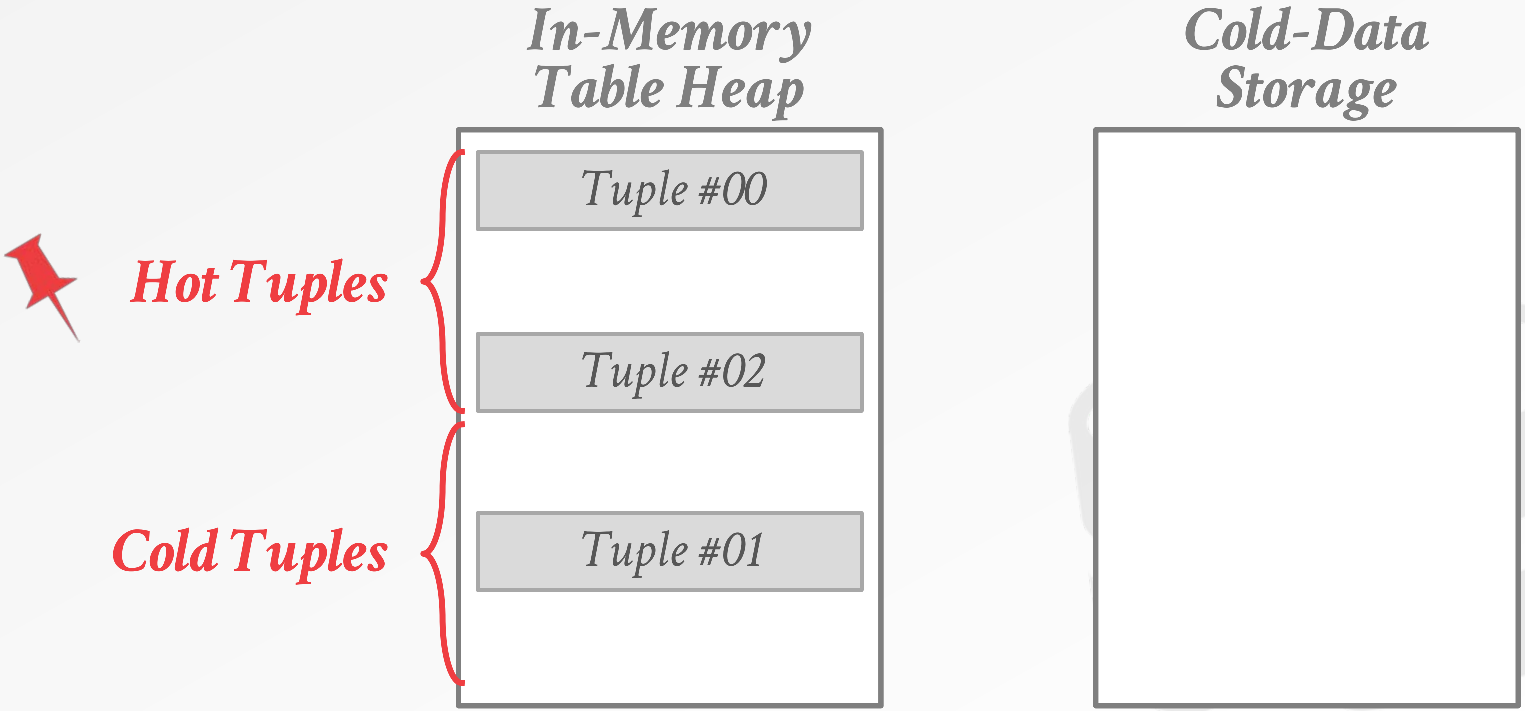
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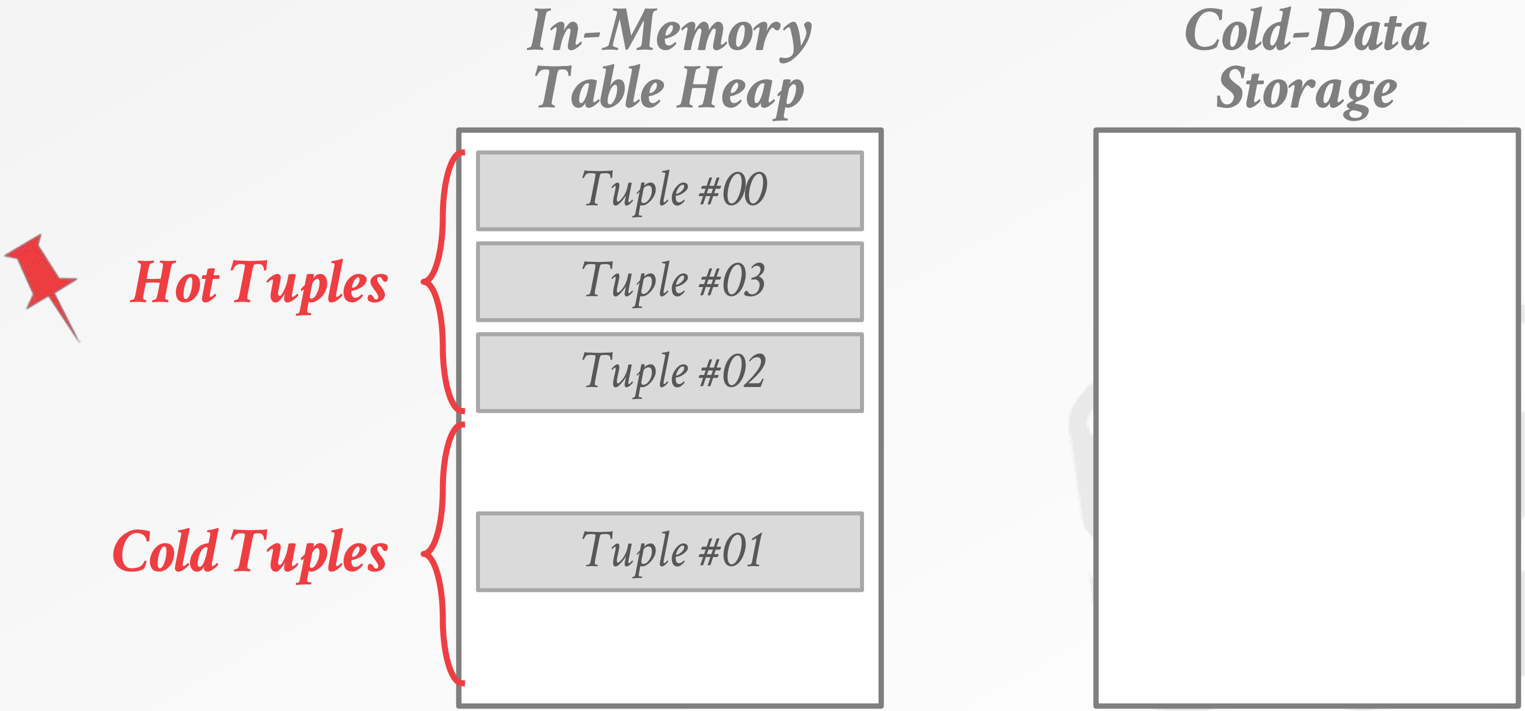
In-Memory Table Heap
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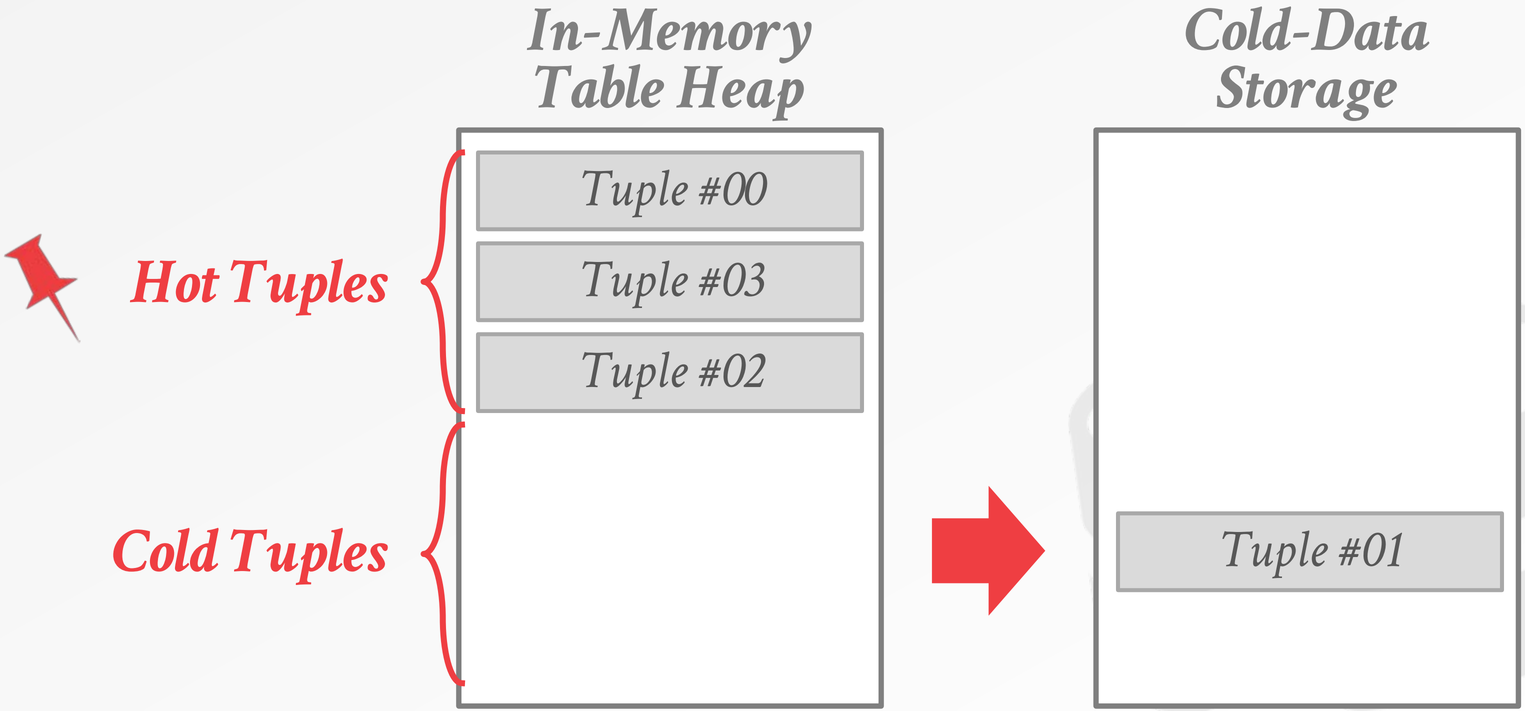
Cold Tuples
Tuple #00
Tuple #03
Tuple #02
Tuple #01

EPFL VOLTDB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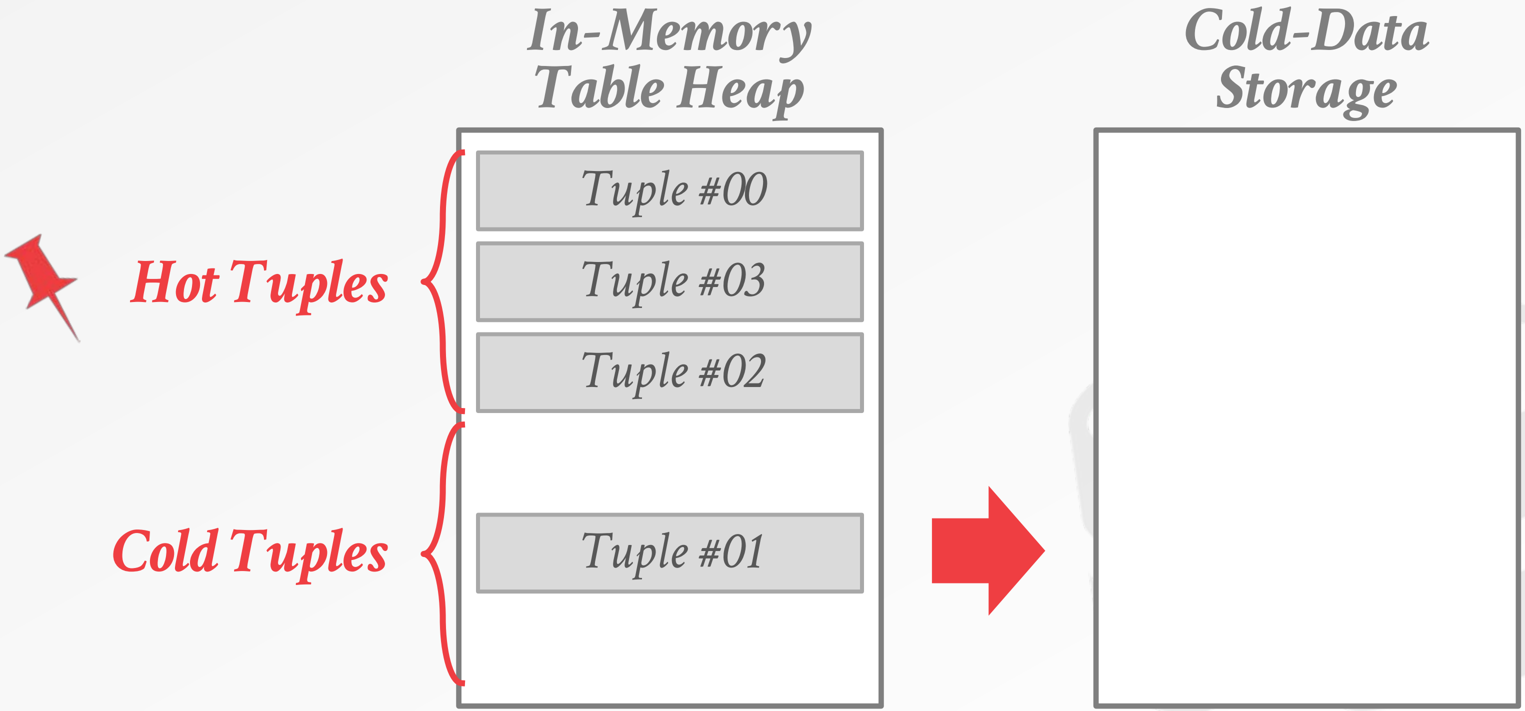
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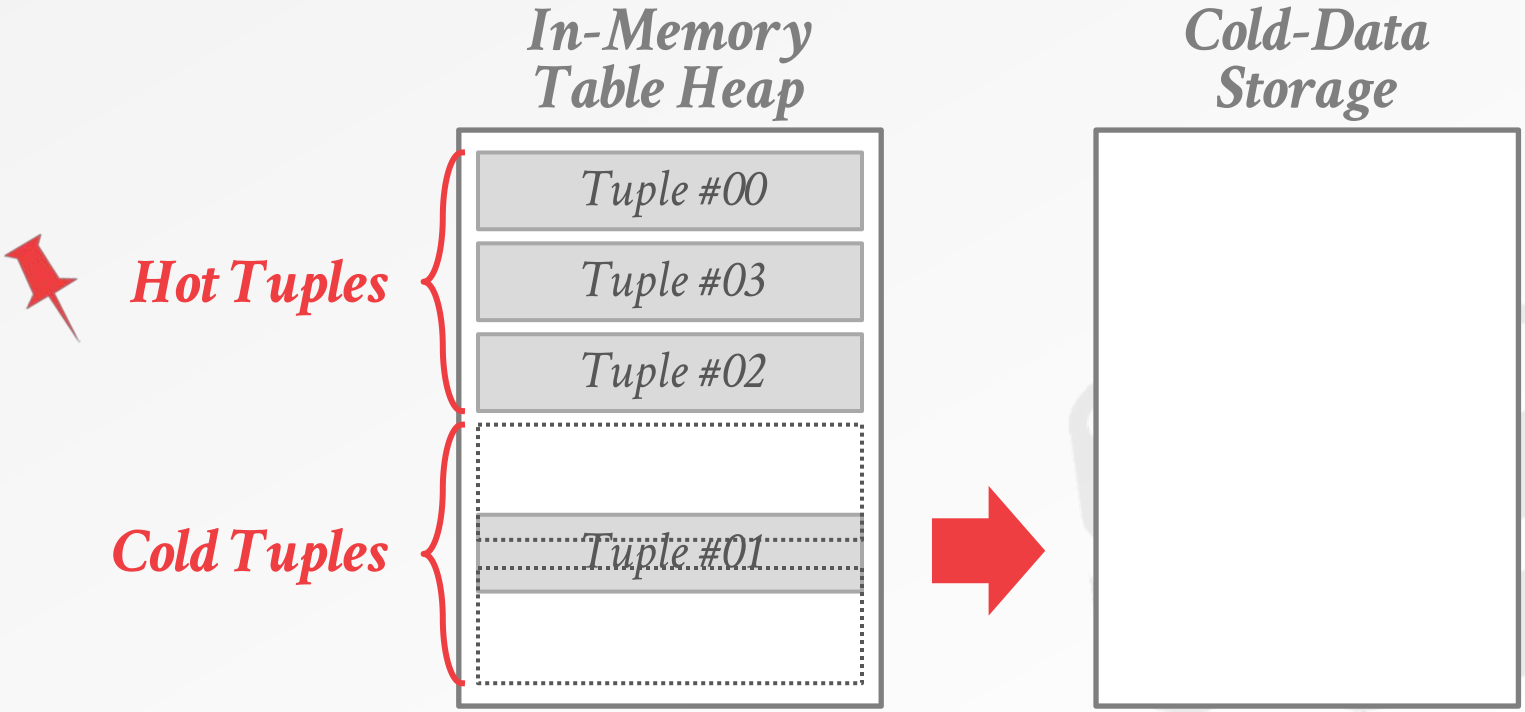
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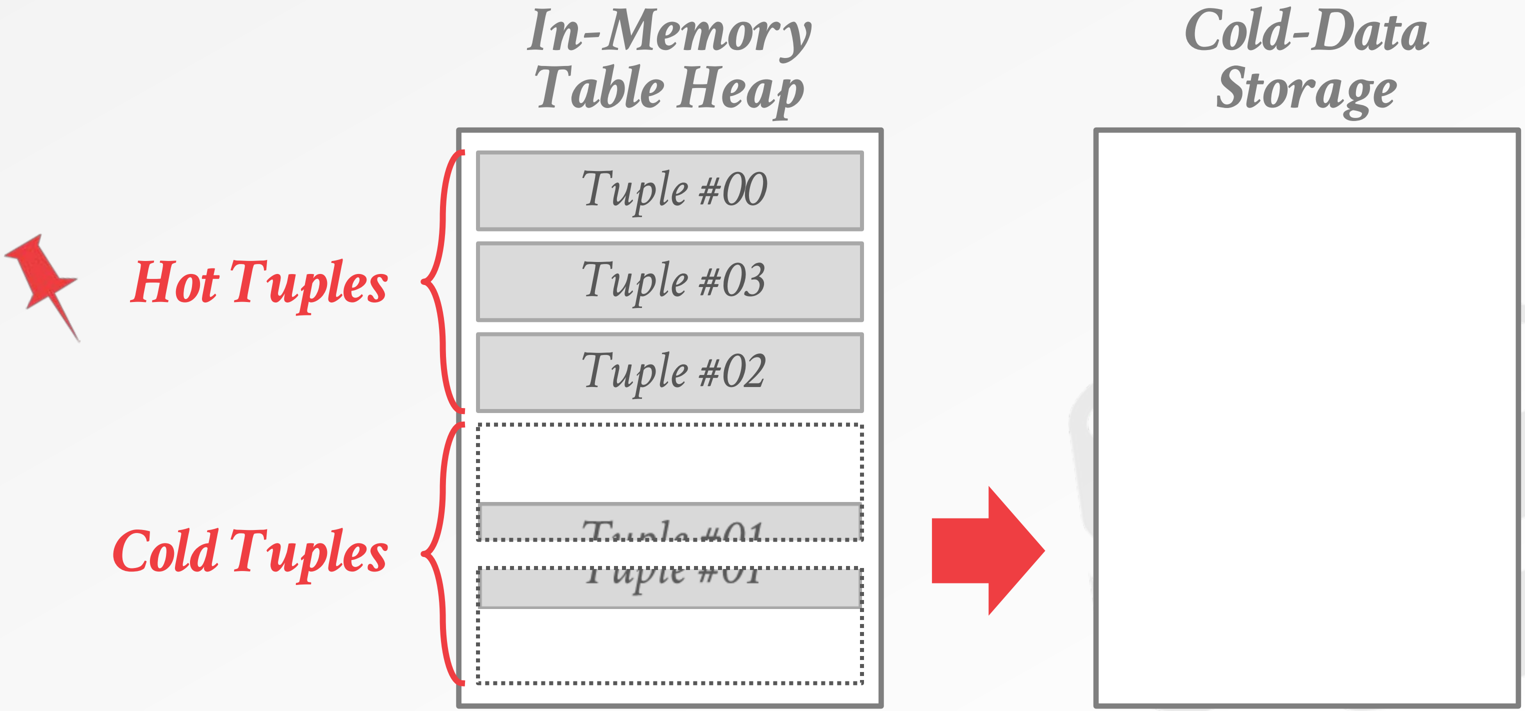
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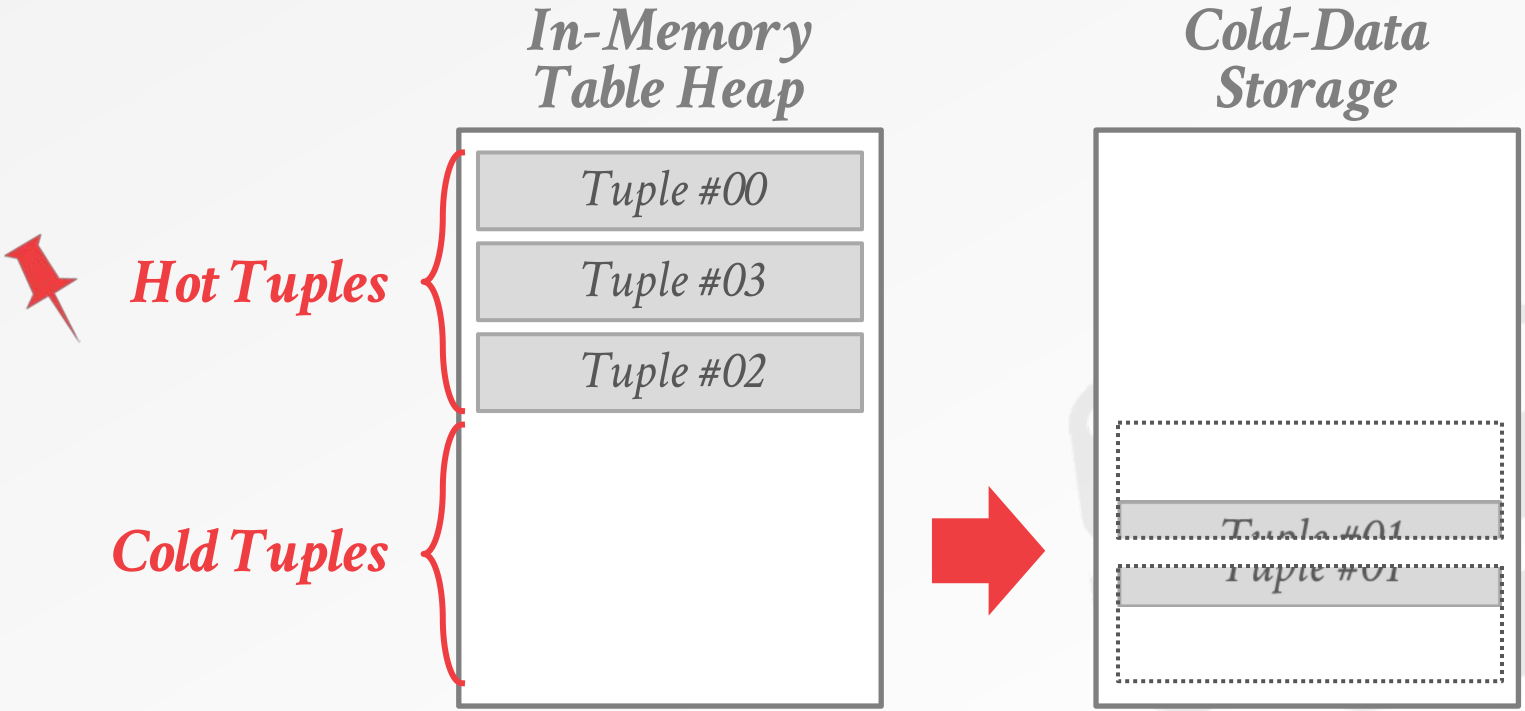
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APACHE GEODE – OVERFLOW TABLES

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

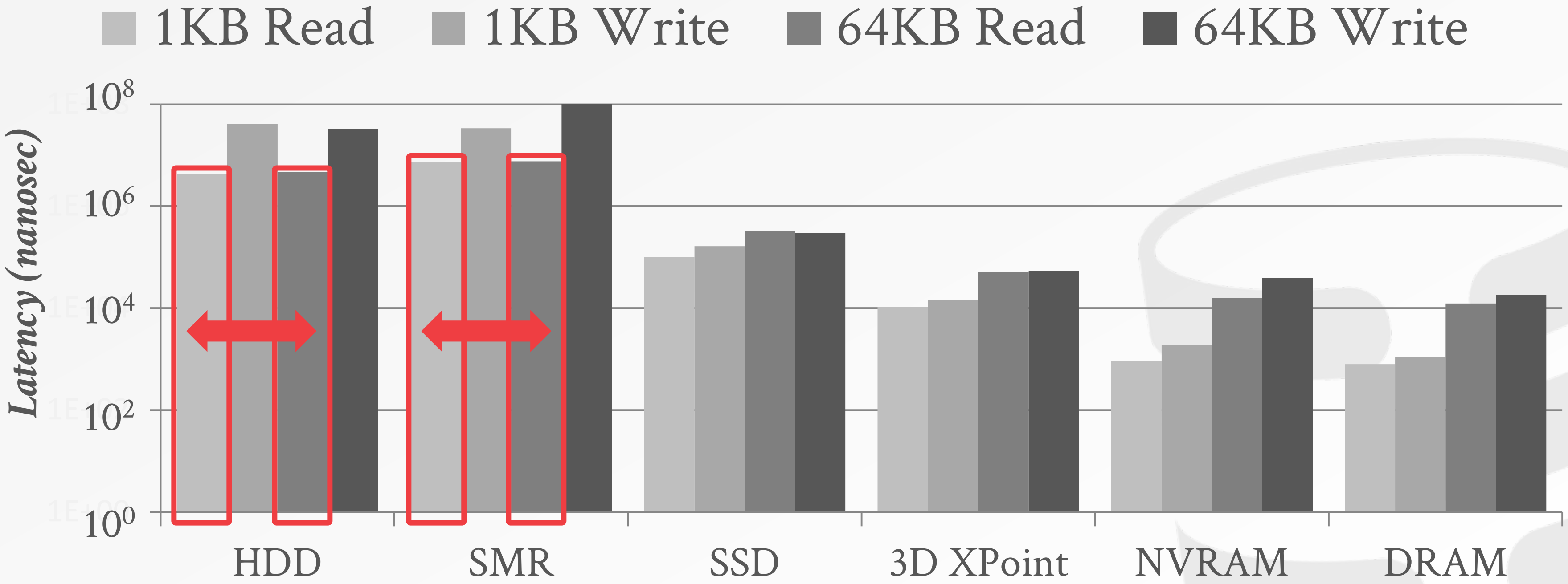
Compare different design decisions in H-Store with anti-caching.

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
DAMON 2016

MICROBENCHMARK

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



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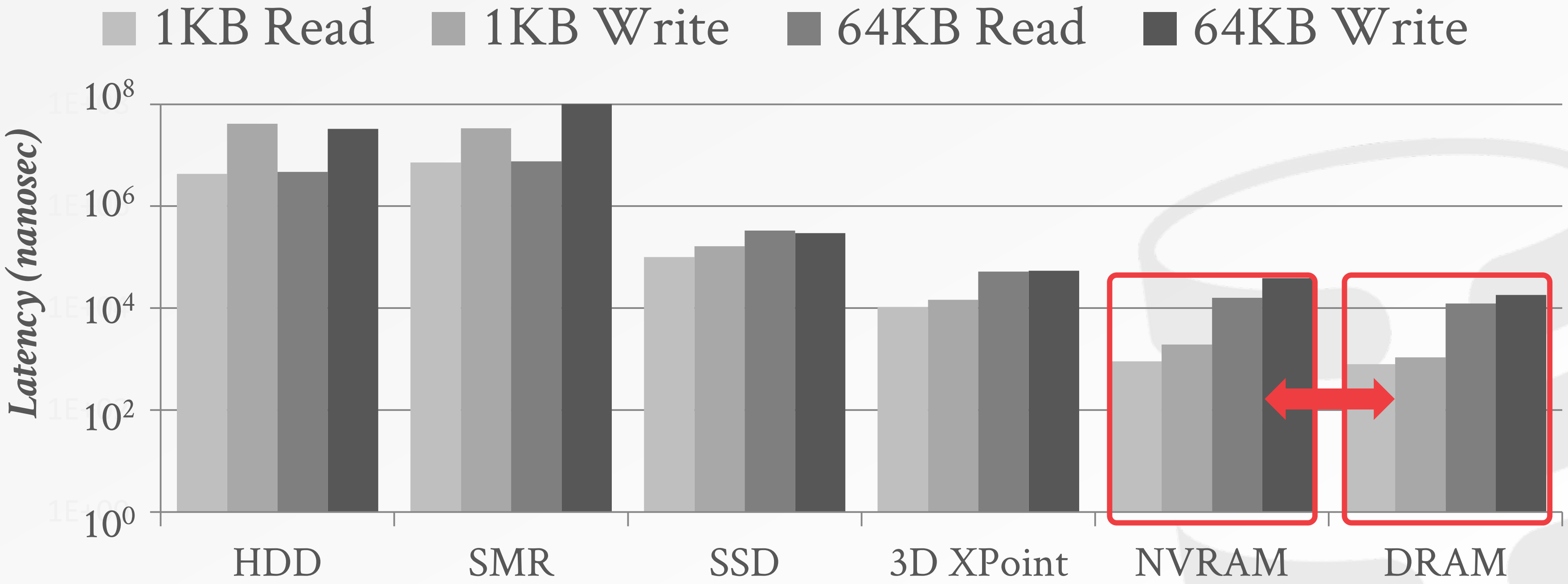
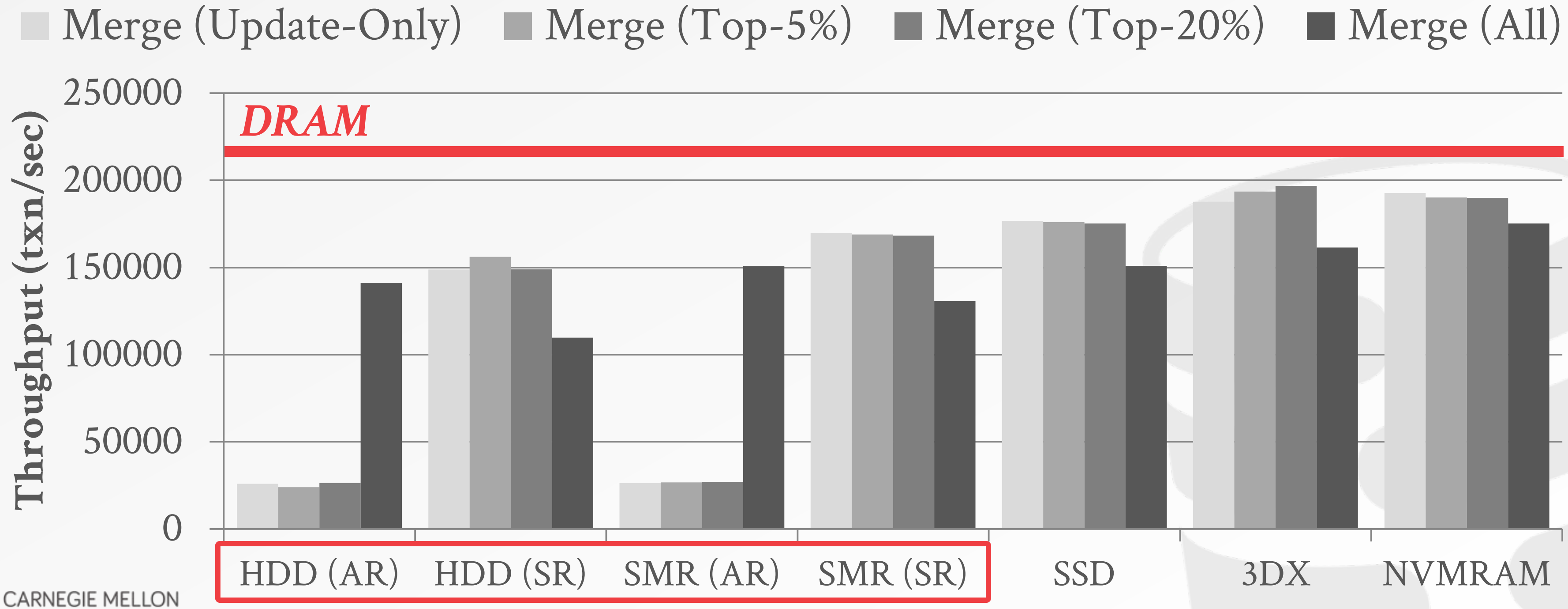


MERGING THRESHOLD

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



CONFIGURATION COMPARISON

Generic Configuration

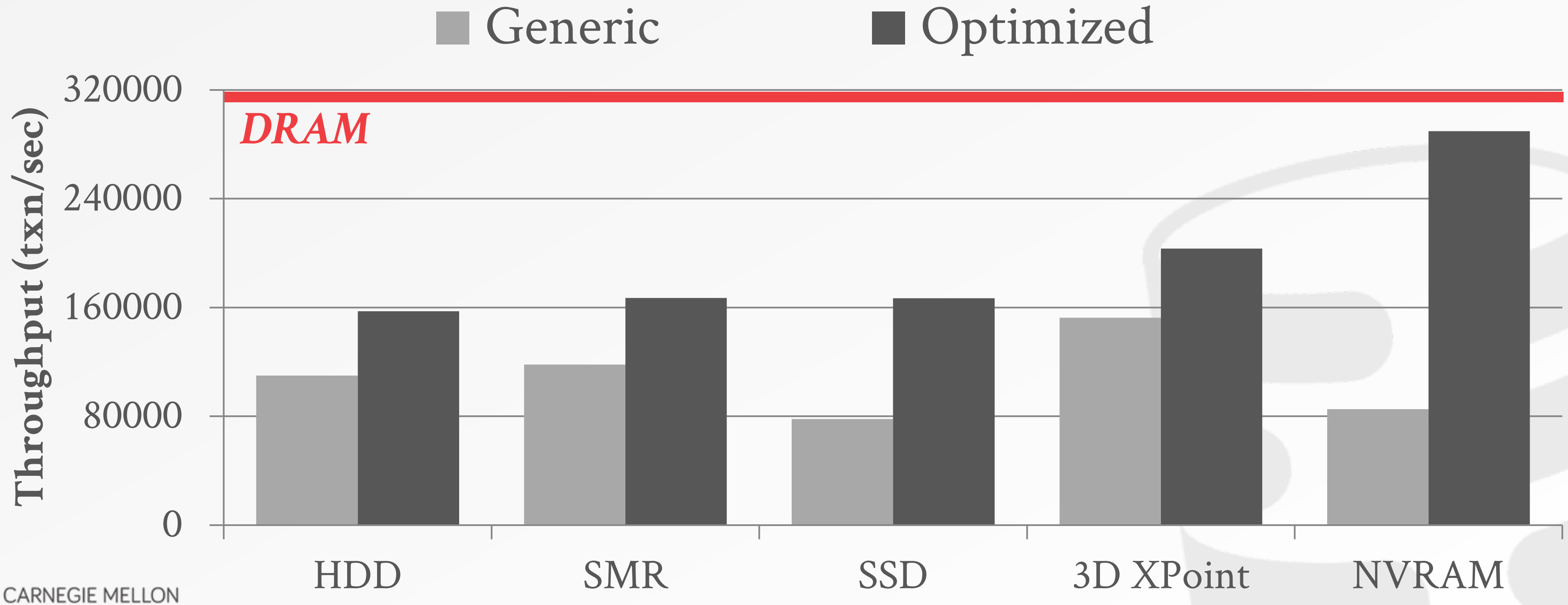
→ Abort-and-Restart Retrieval
→ Merge (All) Threshold
→ 1024 KB Block Size

Optimized Configuration

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

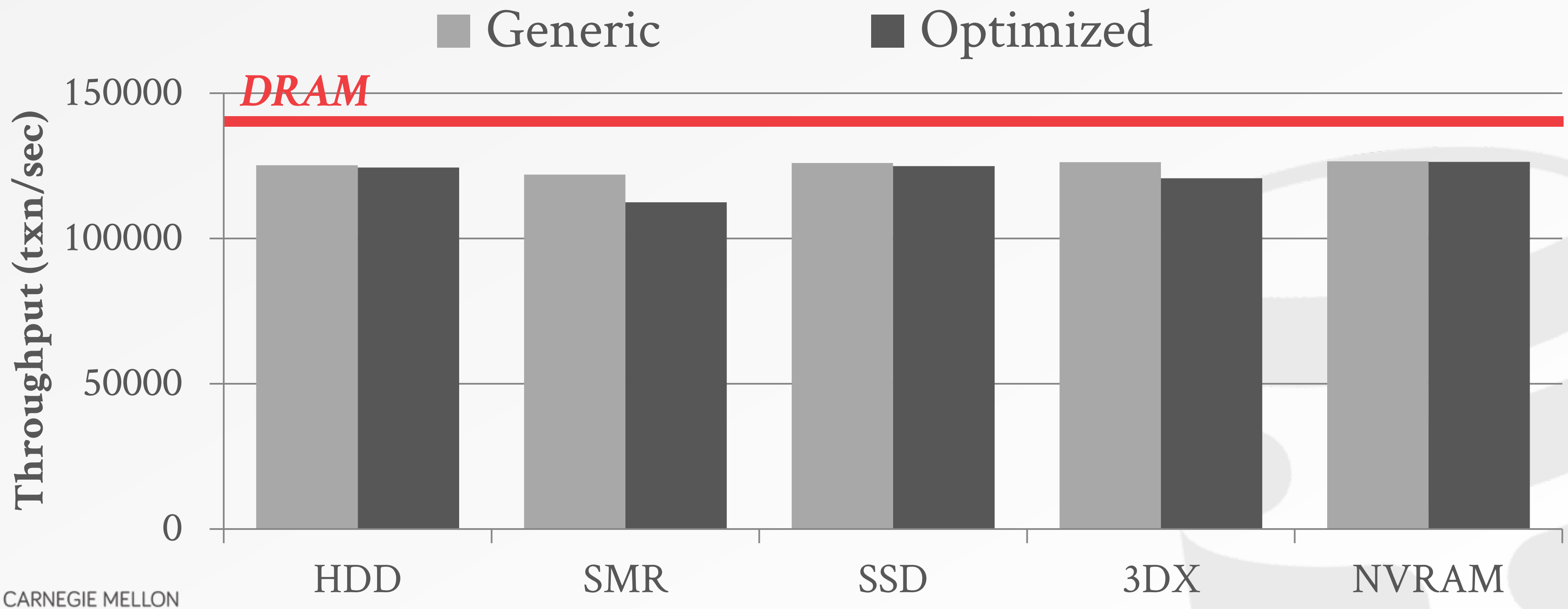
TATP BENCHMARK

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.

None of these techniques handle index memory.

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

NEXT CLASS

Non-Volatile Memory

Sample Final Exam