Carnegie Mellon University

Lecture #23

ADVANCED DATABASE SYSTEMS

Larger-than-Memory Databases

@Andy_Pavlo // 15-721 // Spring 2018

ADMINISTRIVIA

Snowflake Guest Speaker: May 2nd

Final Exam Handout: May 2nd

Code Review #2: May 2nd

Project #3 Final Presentation: May 14th @ 8:30am

FoundationDB

Documentation Blog Download

FoundationDB is Open Source

Published April 19, 2018

The next chapter

Starting today, FoundationDB starts its next chapter as an open source project!

FoundationDB is a distributed datastore, designed from the ground up to be deployed on clusters of commodity hardware. These clusters scale well as you add machines, automatically heal from hardware failures, and have a simple API. The key-value store supports fully global, cross-row ACID transactions. That's the highest level of data consistency possible. What does this mean for you? Strong consistency makes your application code simpler, your data models more efficient, and your failure modes less surprising.

The great thing is that FoundationDB is already well-established — it's actively developed and has years of production use. We intend to drive FoundationDB forward as a community project and we welcome your participation.

FoundationDB

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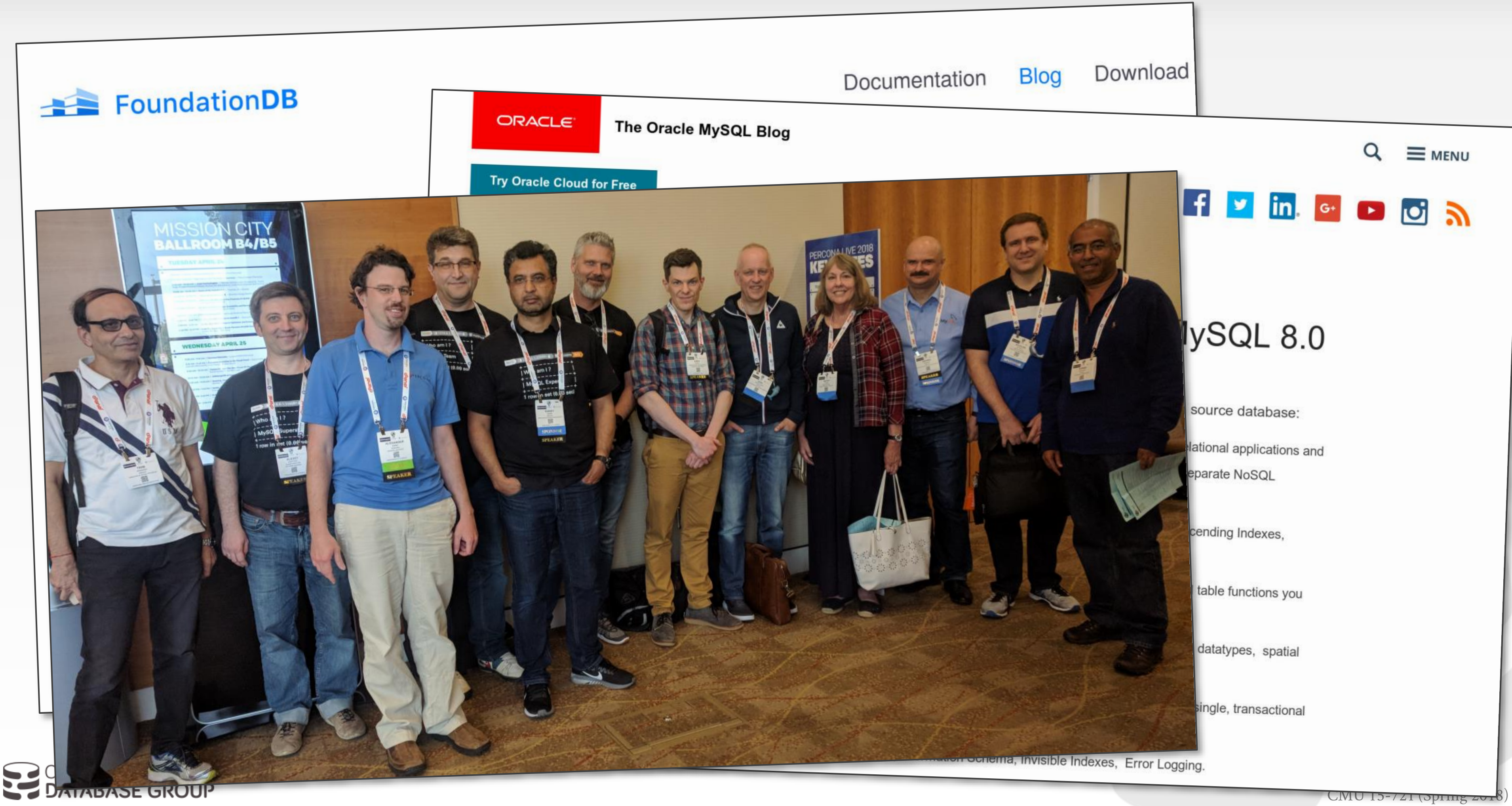
MYSQL, THE ORACLE MYSQL | Thursday, April 19, 2018

Announcing General Availability of MySQL 8.0

By: Mike Frank | Product Management Director

MySQL adds NoSQL and many new enhancements to the world's most popular open source database:

1. **NoSQL** Document Store gives developers the flexibility of developing traditional SQL relational applications and NoSQL, schema-free document database applications. This eliminates the need for a separate NoSQL document database.
2. **SQL** Window functions, Common Table Expressions, NOWAIT and SKIP LOCKED, Descending Indexes, Grouping, Regular Expressions, Character Sets, Cost Model, and Histograms.
3. **JSON** Extended syntax, new functions, improved sorting, and partial updates. With JSON table functions you can use the SQL machinery for JSON data.
4. **GIS** Geography support. Spatial Reference Systems (SRS), as well as SRS aware spatial datatypes, spatial indexes, and spatial functions.
5. **Reliability** DDL statements have become atomic and crash safe, meta-data is stored in a single, transactional data dictionary
6. **Observability** Performance Schema, Information Schema, Invisible Indexes, Error Logging.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source database:
table functions you
datatypes, spatial
Invisible Indexes, Error Logging.

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.

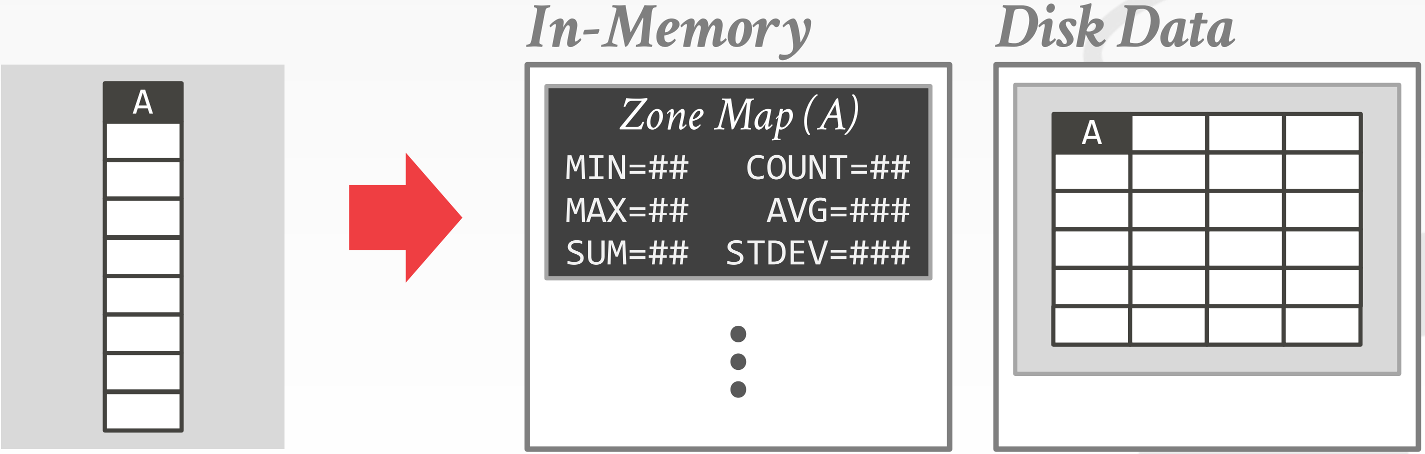
LARGER-THAN-MEMORY DATABASES

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.



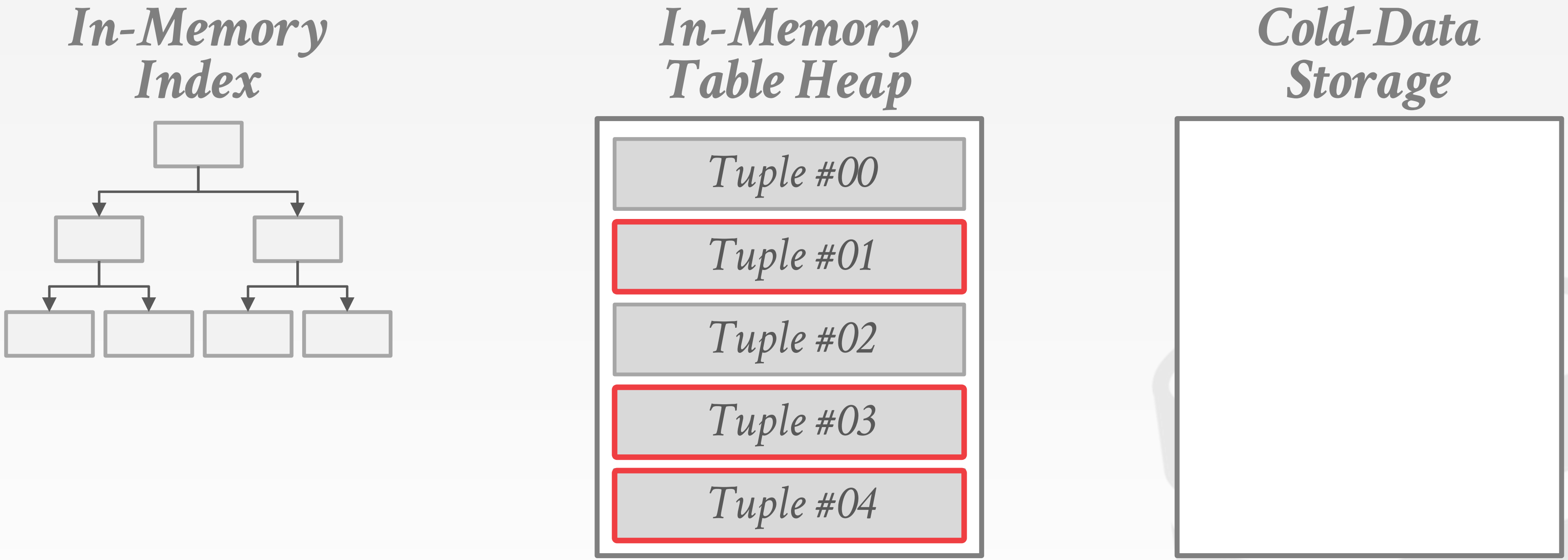
OLTP

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

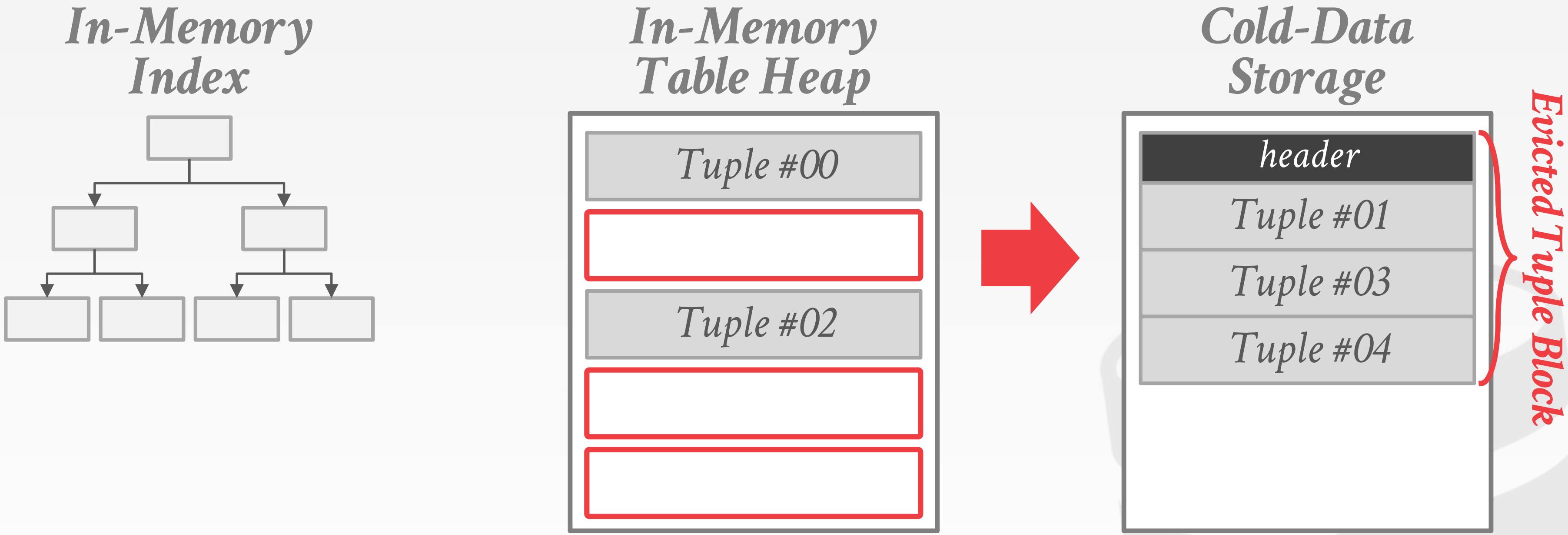
→ We can assume that txns will almost always access hot tuples.

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

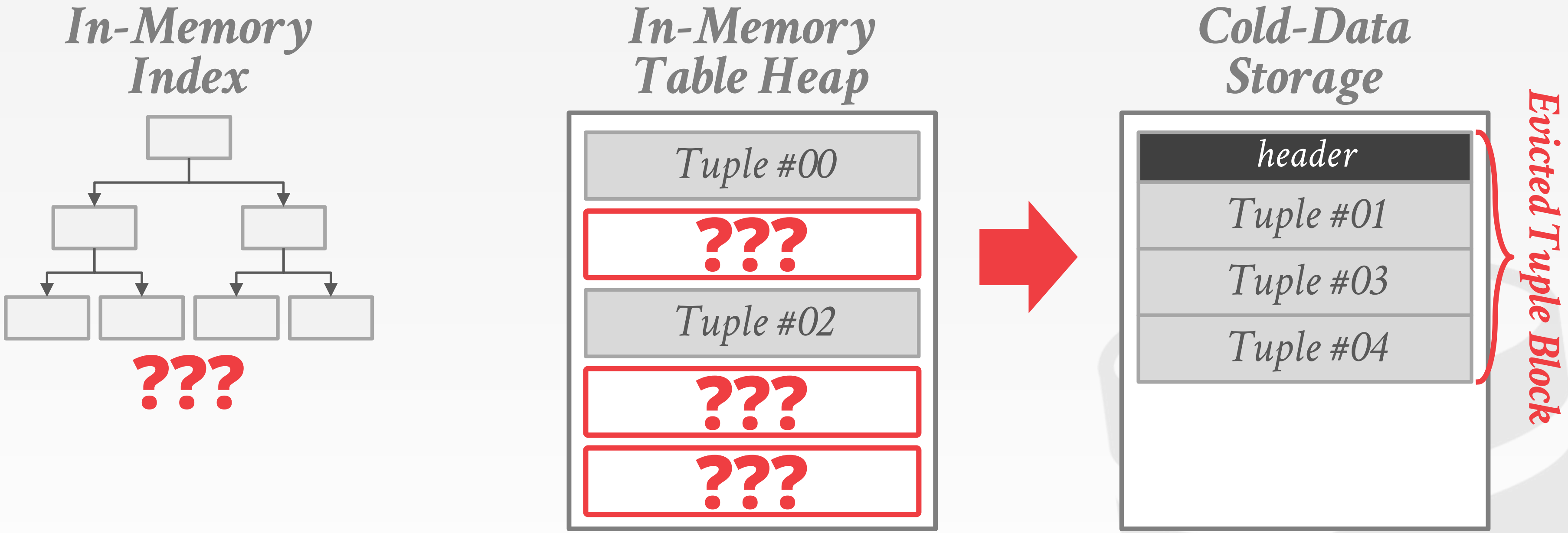
LARGER-THAN-MEMORY DATABASES



LARGER-THAN-MEMORY DATABASES

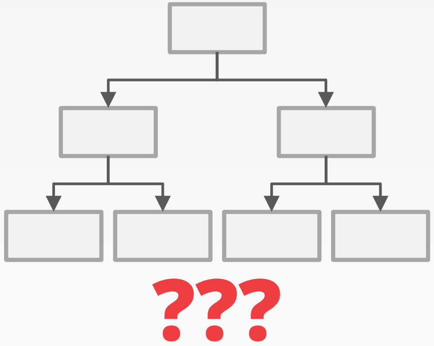


LARGER-THAN-MEMORY DATABASES



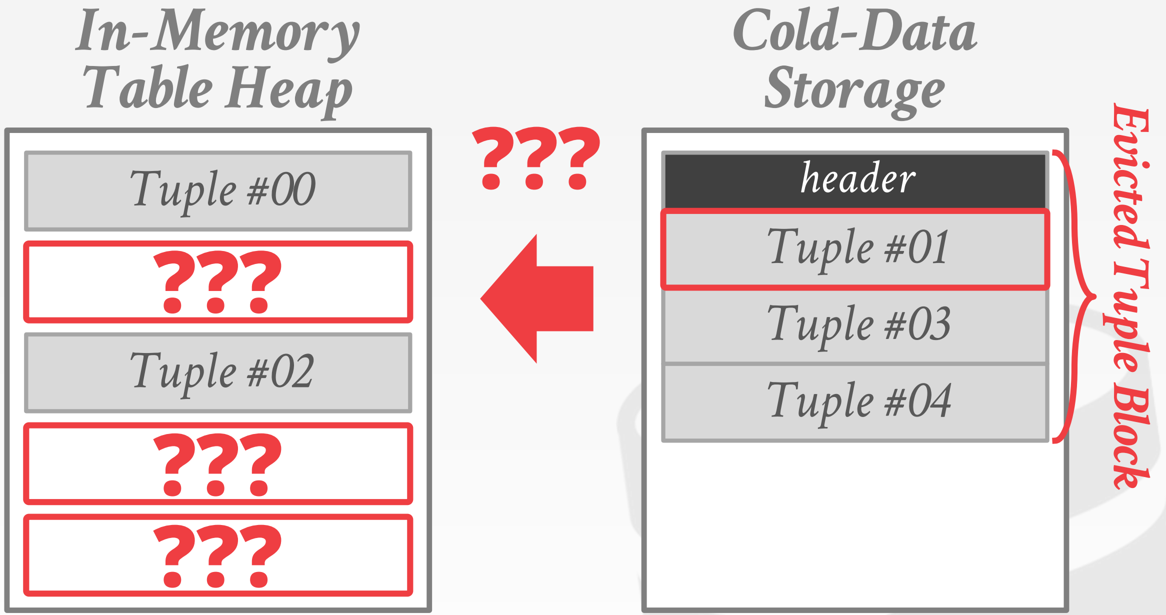
LARGER-THAN-MEMORY DATABASES

In-Memory Index




```
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

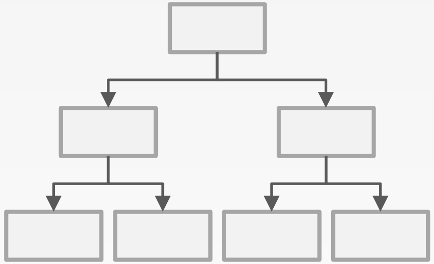
→ Use approximate data structure for each index.
→ Check both index + filter for each query.

Choice #3: OS Virtual Memory

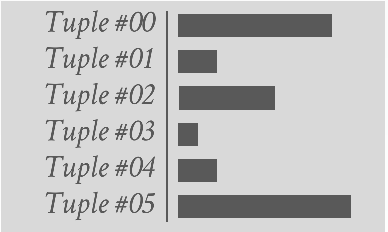
→ The OS tracks what data is on disk. The DBMS does not need to maintain any additional metadata.

EVICTED TUPLE METADATA

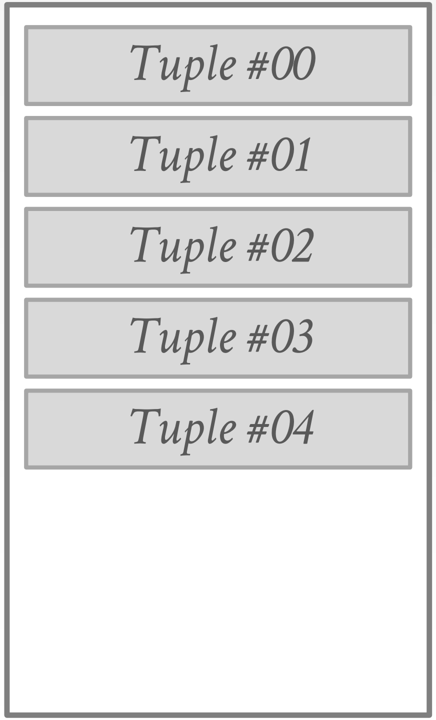
In-Memory Index



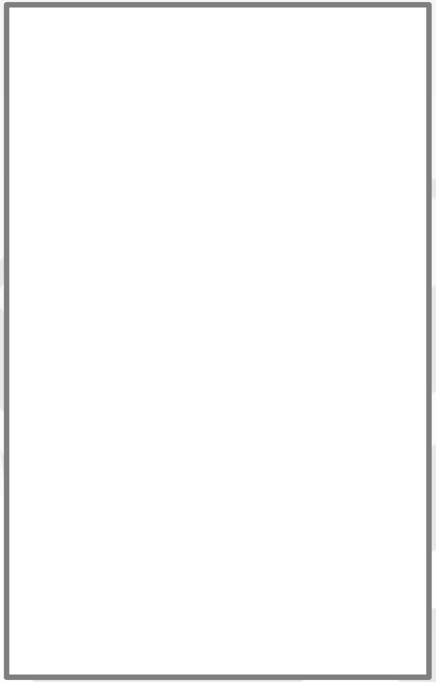
Access Frequency



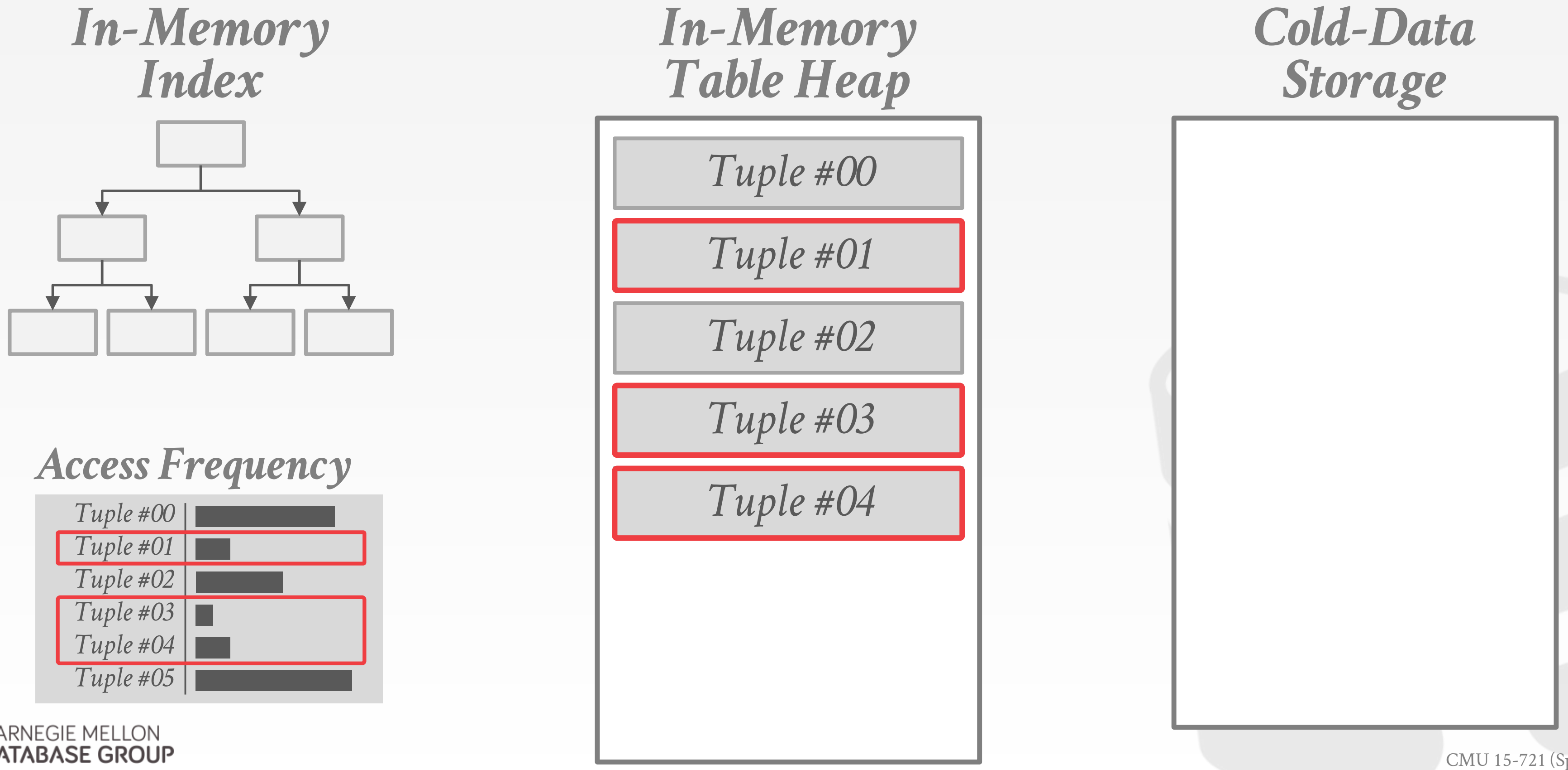
In-Memory Table Heap



Cold-Data Storage



EVICTED TUPLE METADATA



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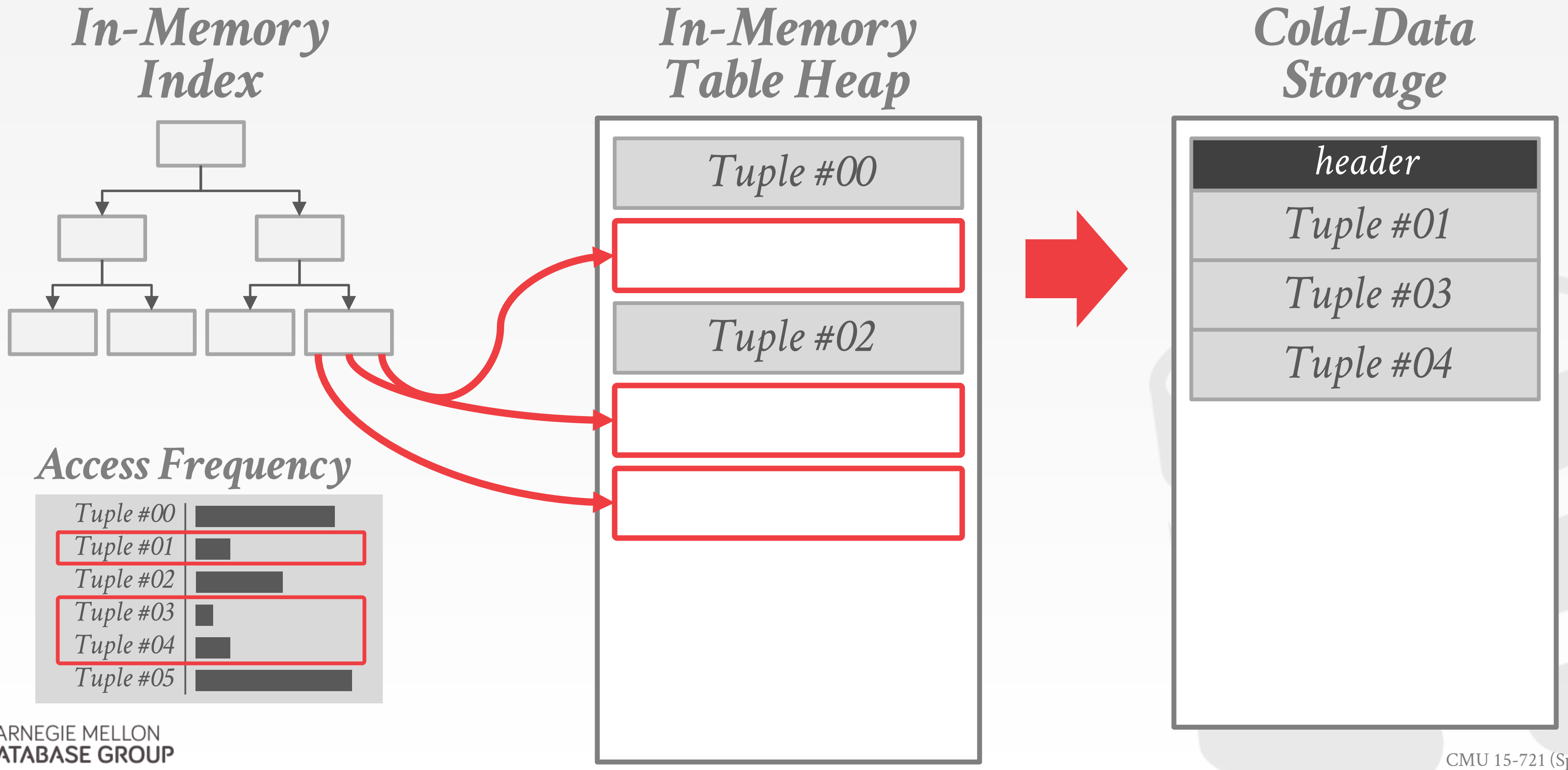

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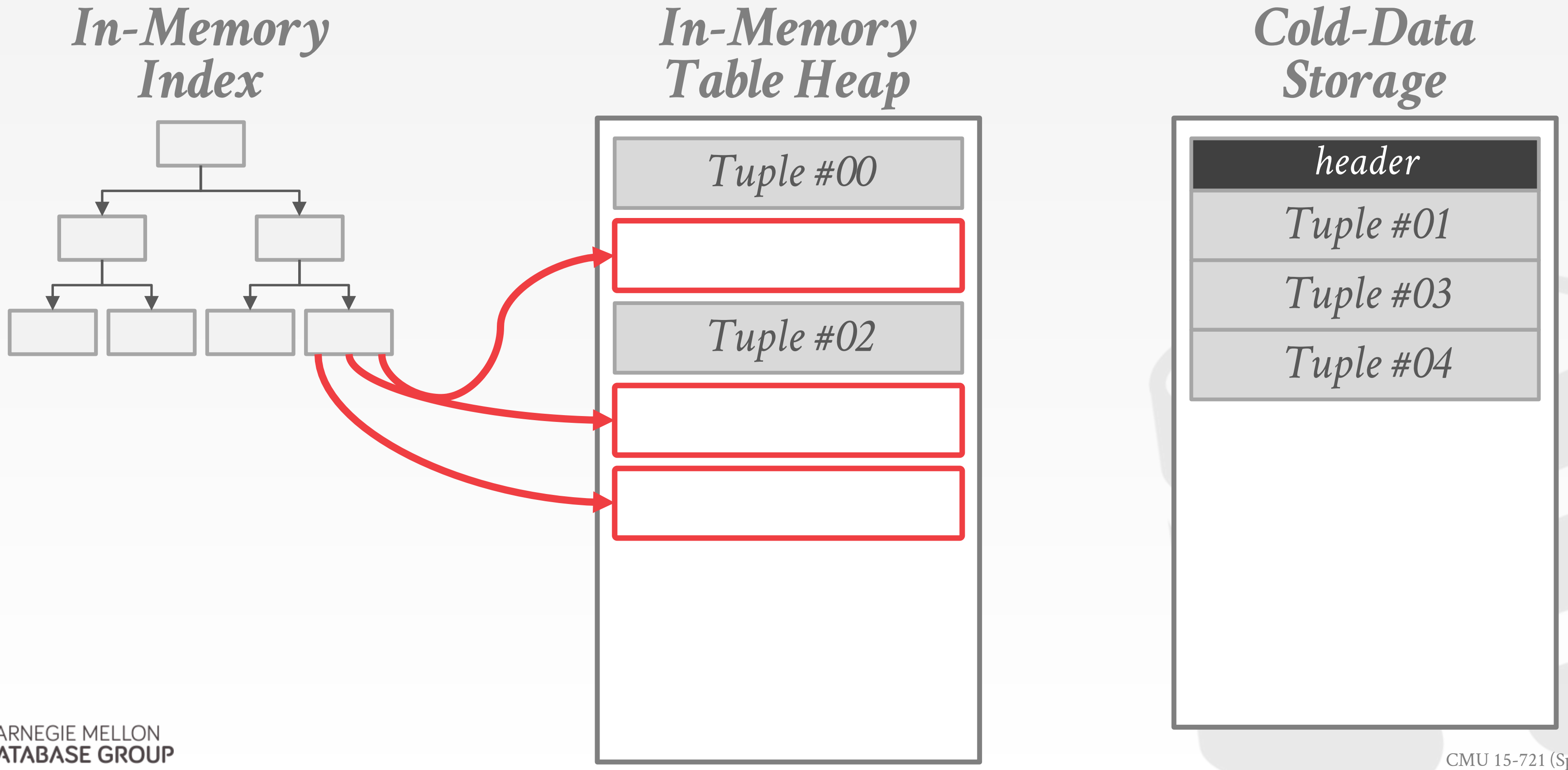

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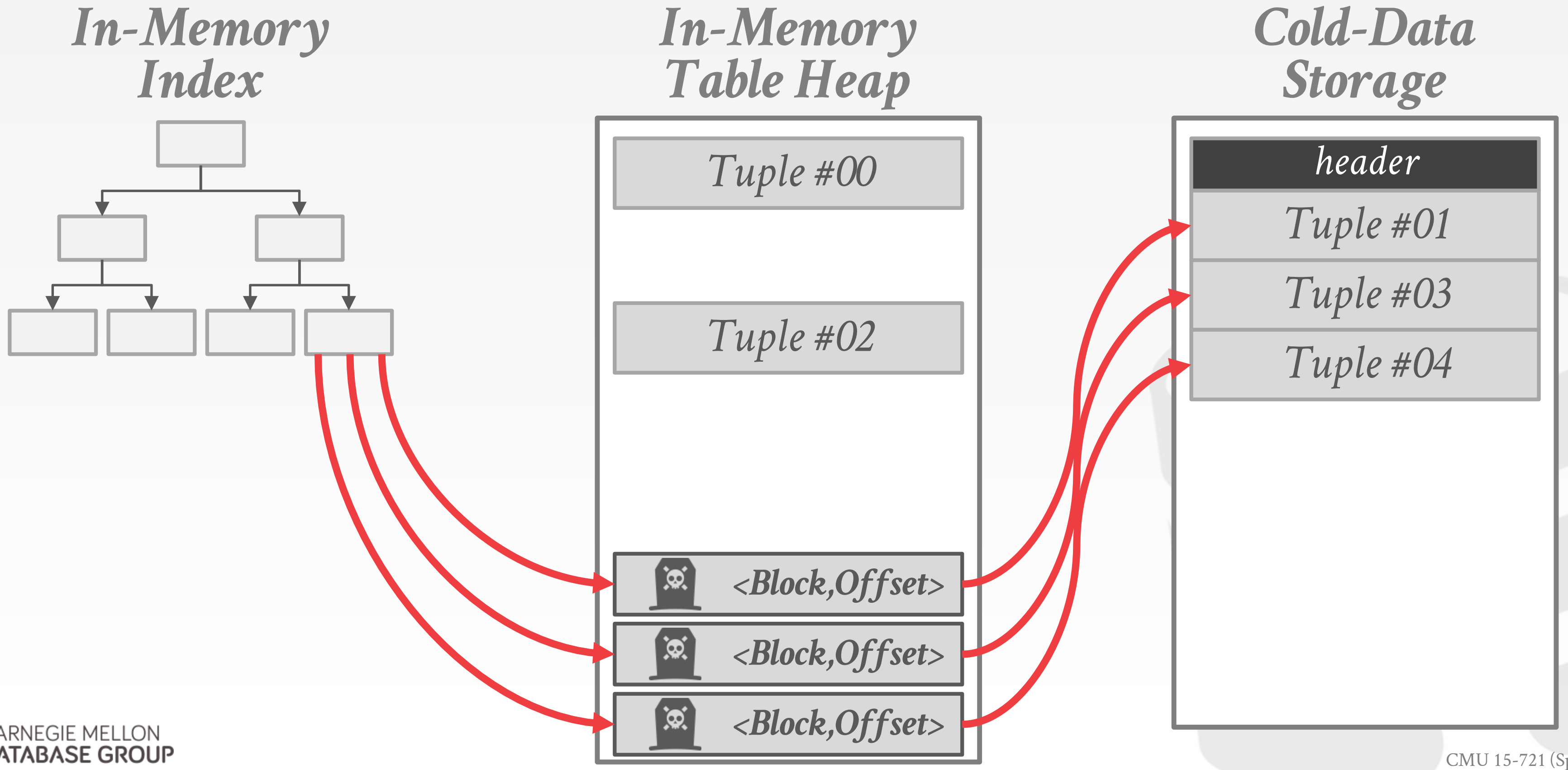

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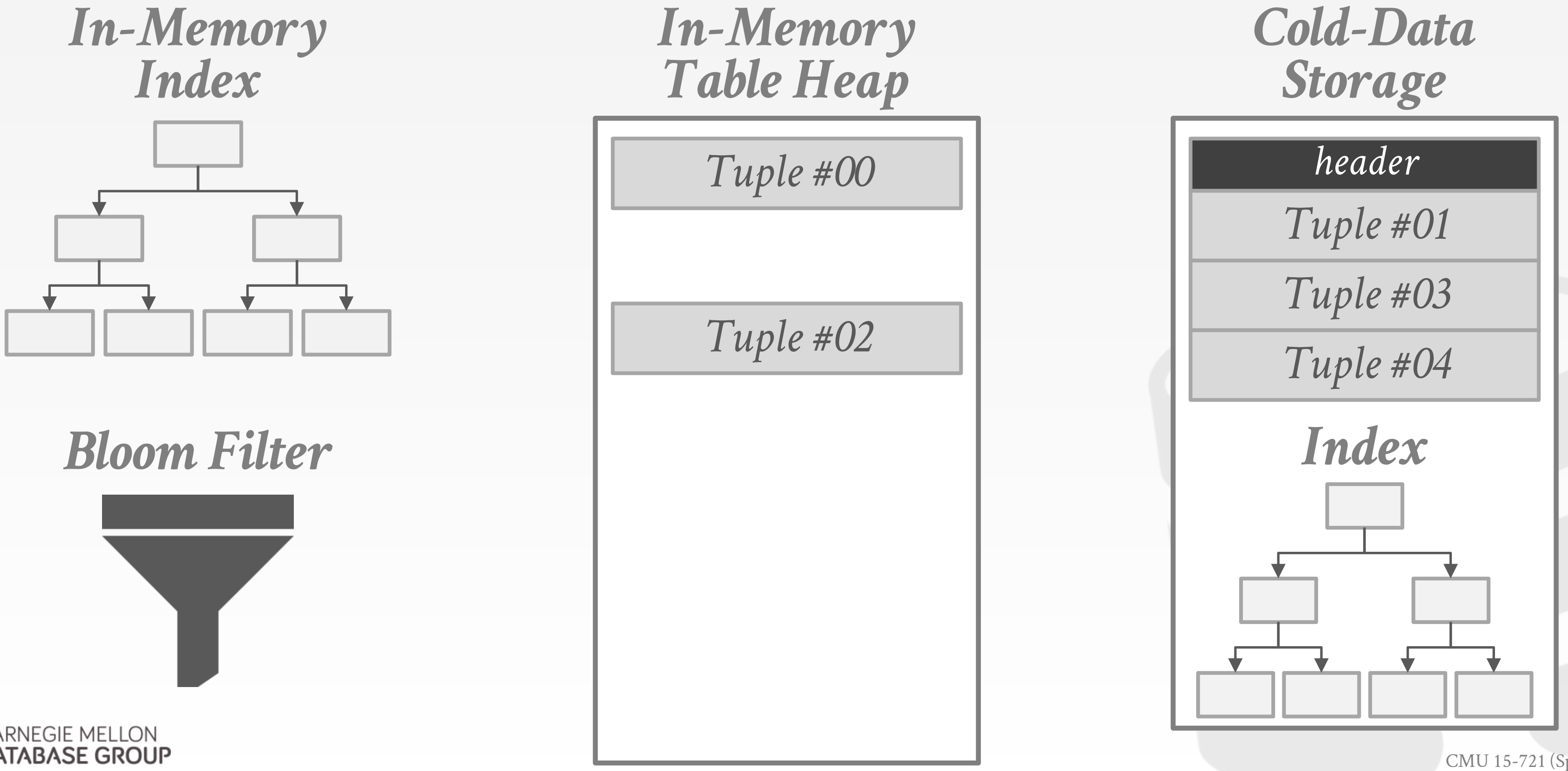


DATA RETRIEVAL GRANULARITY

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

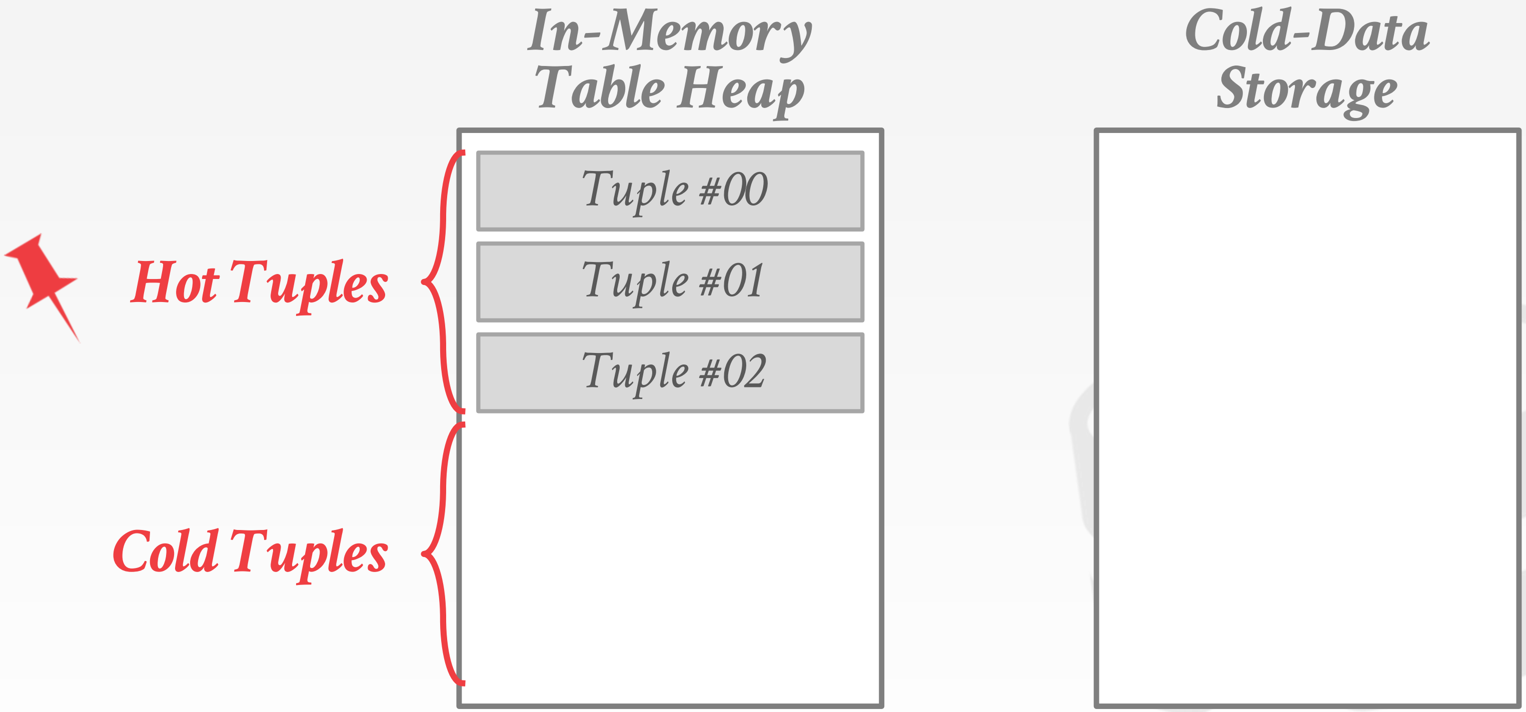
Synchronous Retrieval

Page-level Granularity

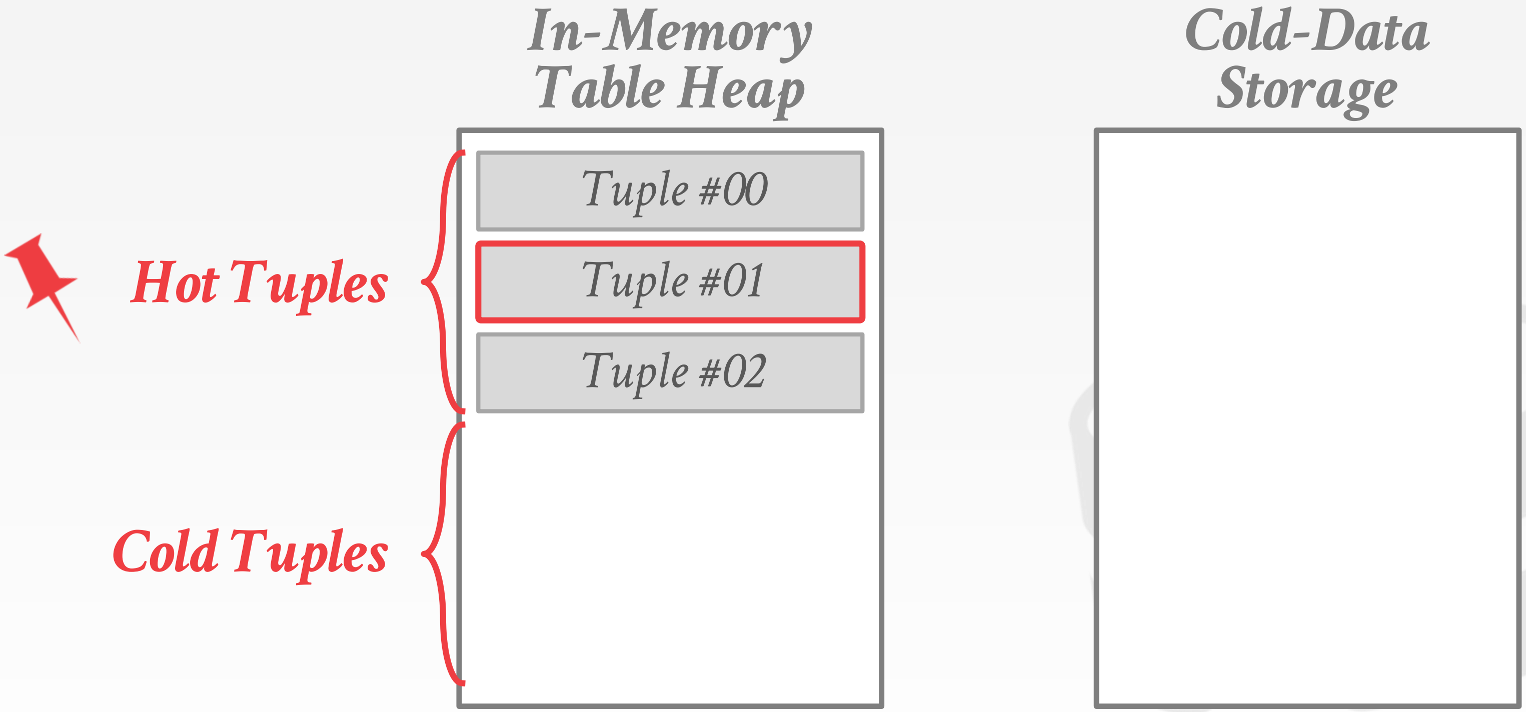
Always Merge

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

EPFL VOLTDB


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

EPFL VOLTDB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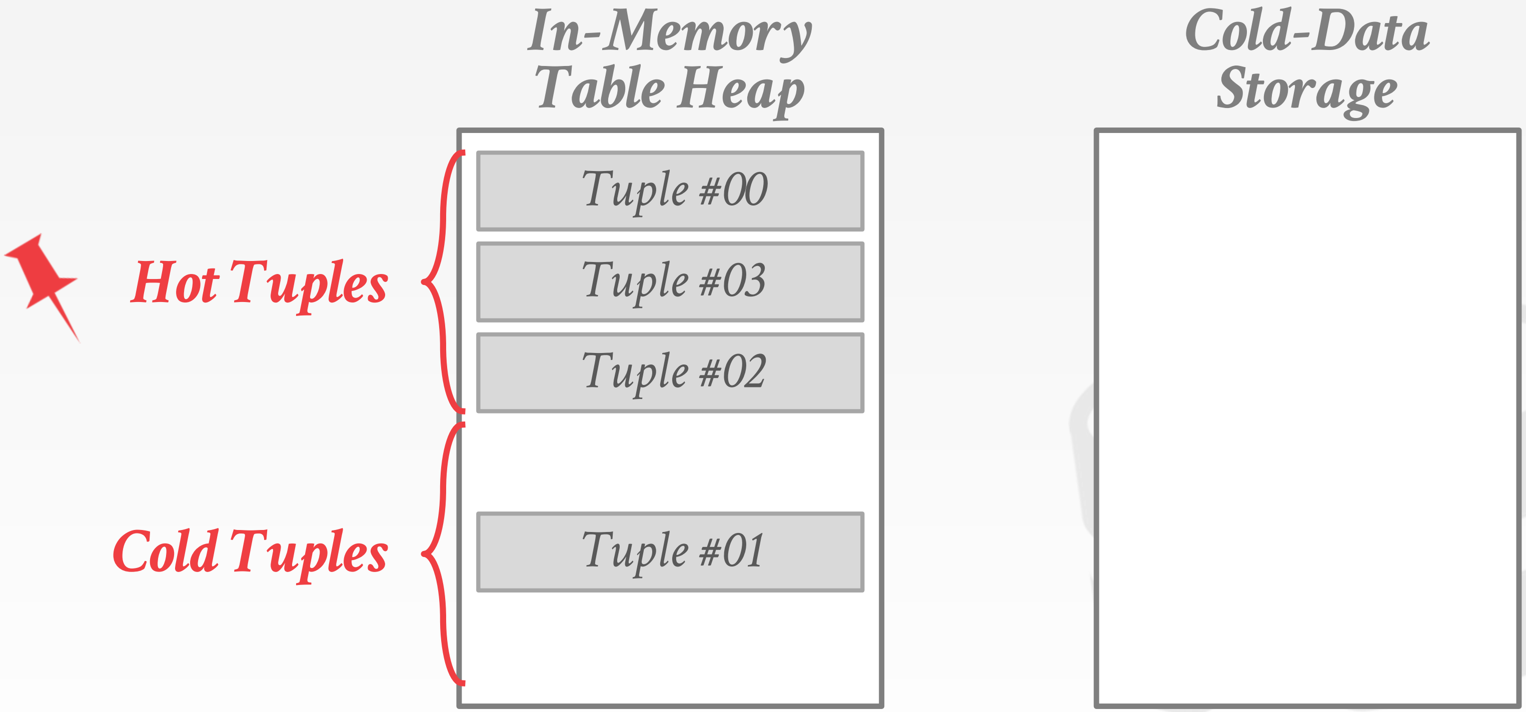
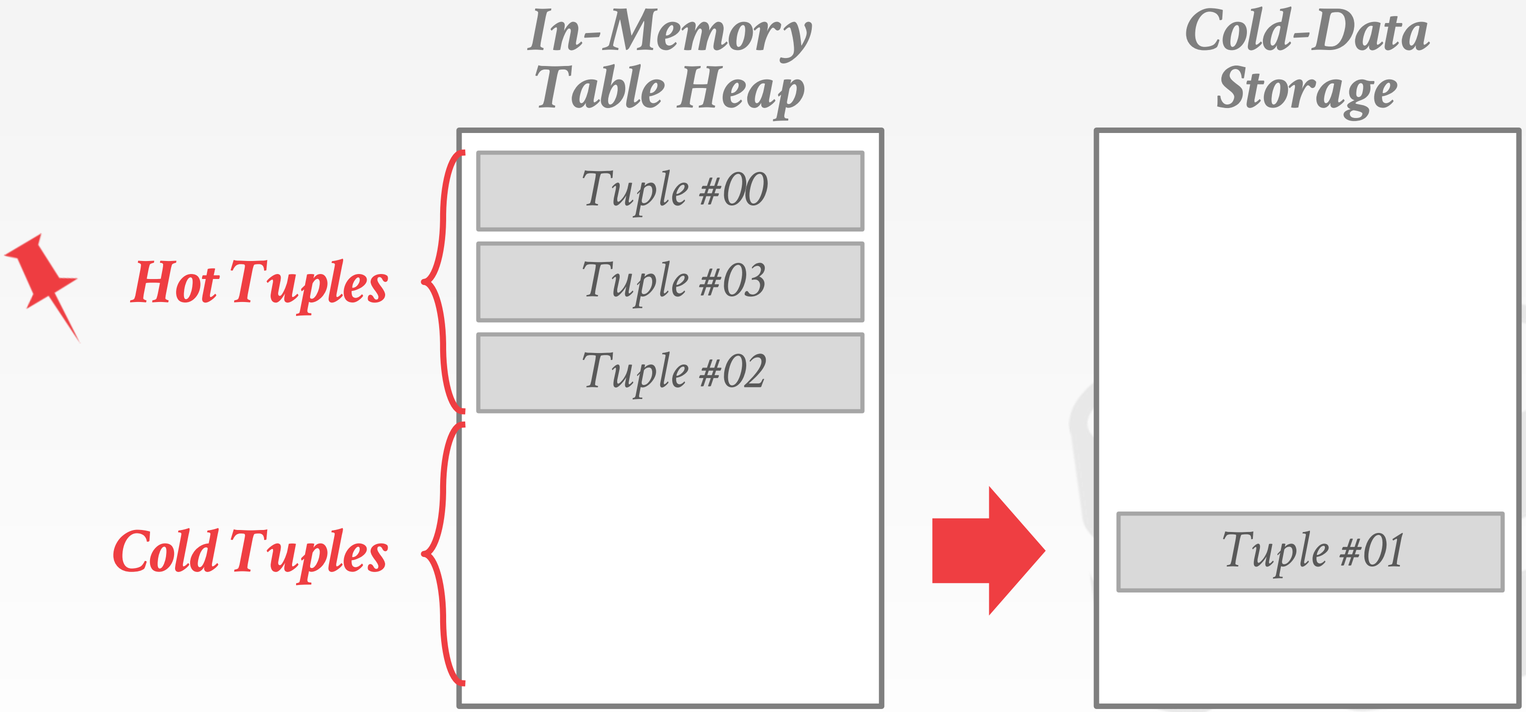

In-Memory Table Heap
Cold-Data Storage
Hot Tuples
Cold Tuples
Tuple #00
Tuple #03
Tuple #02
Tuple #01

EPFL VOLTDB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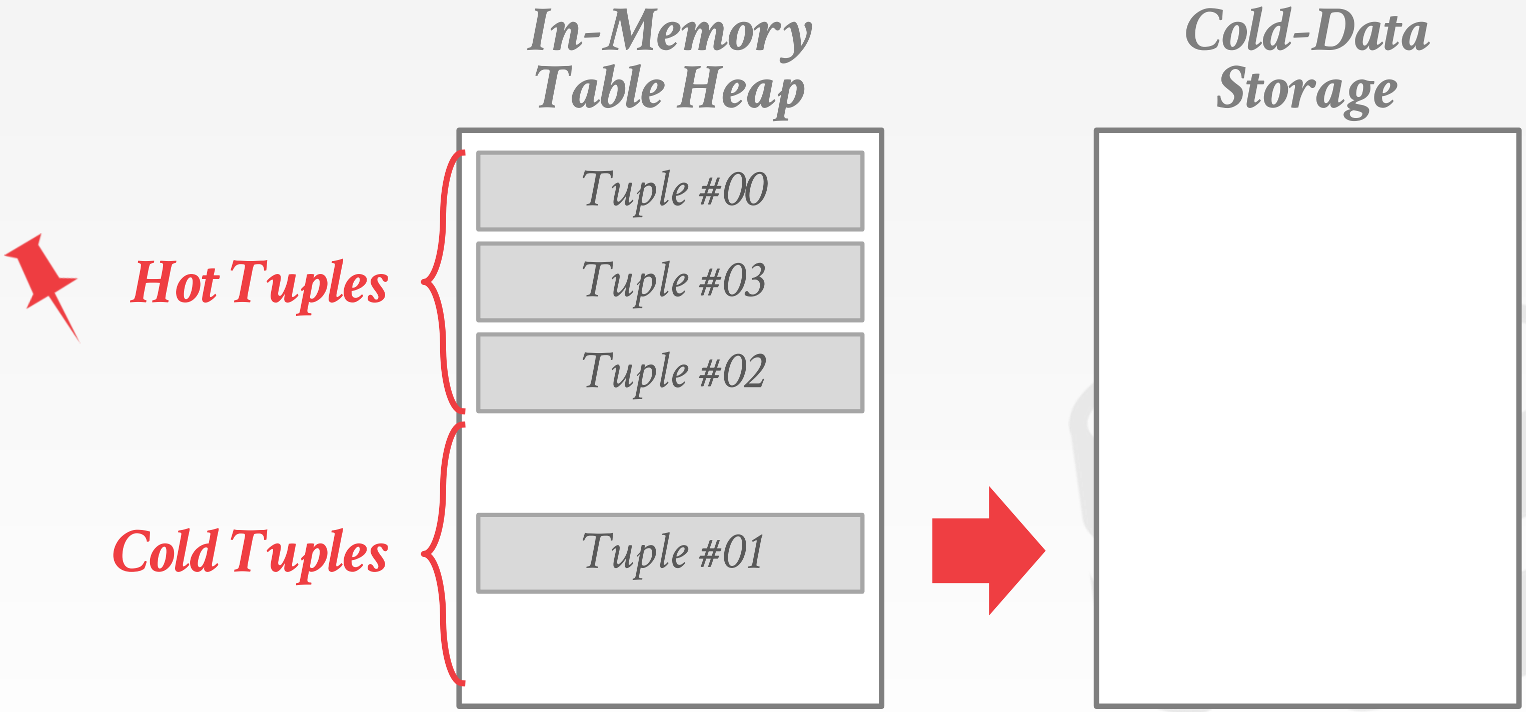

In-Memory Table Heap
Cold-Data Storage
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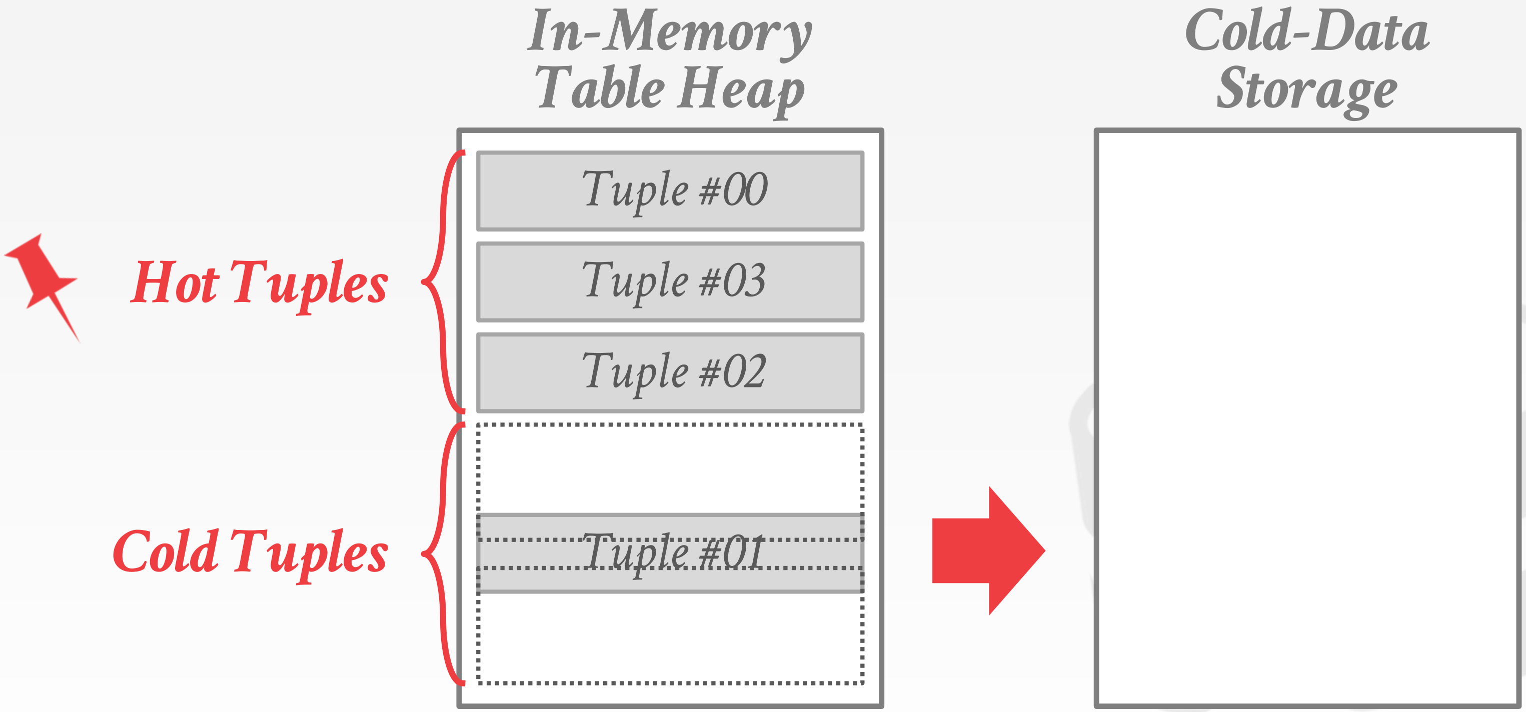
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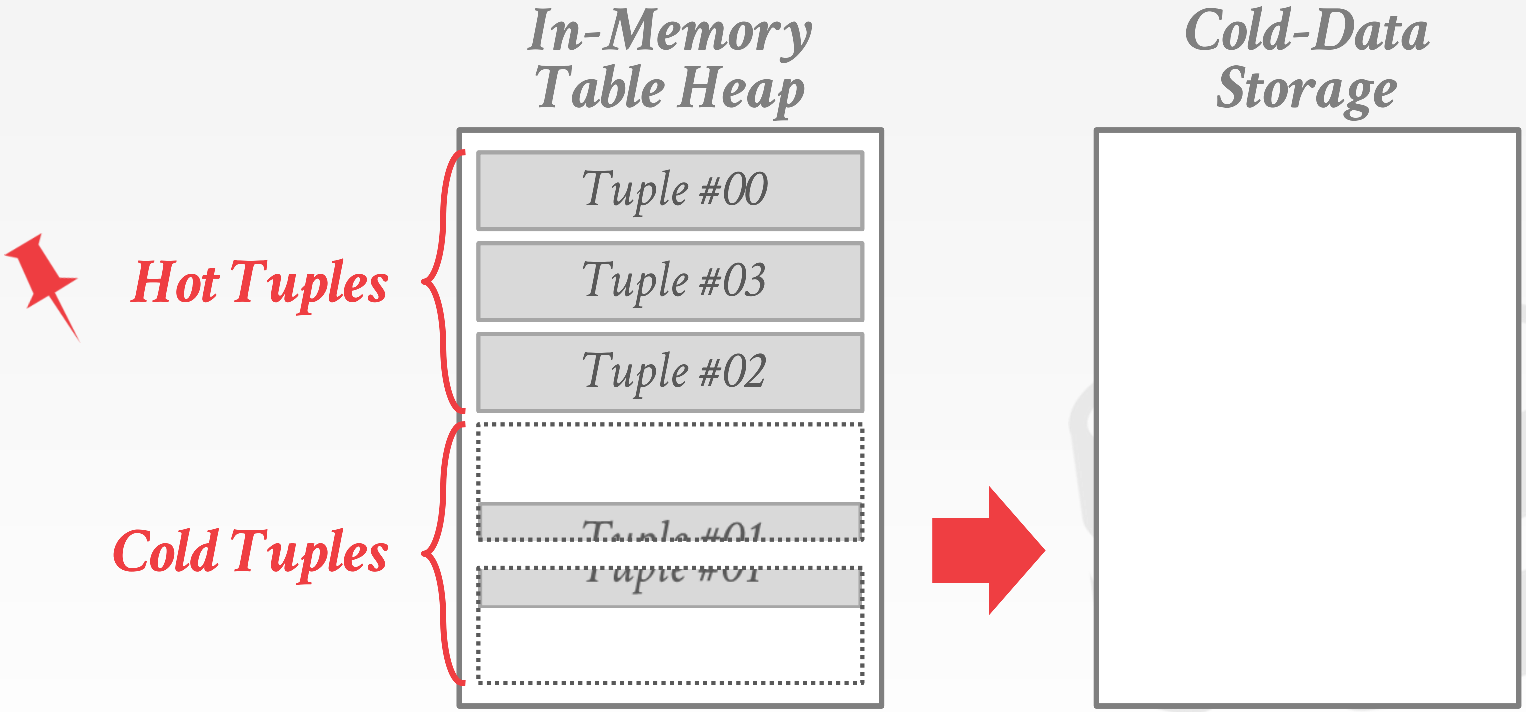
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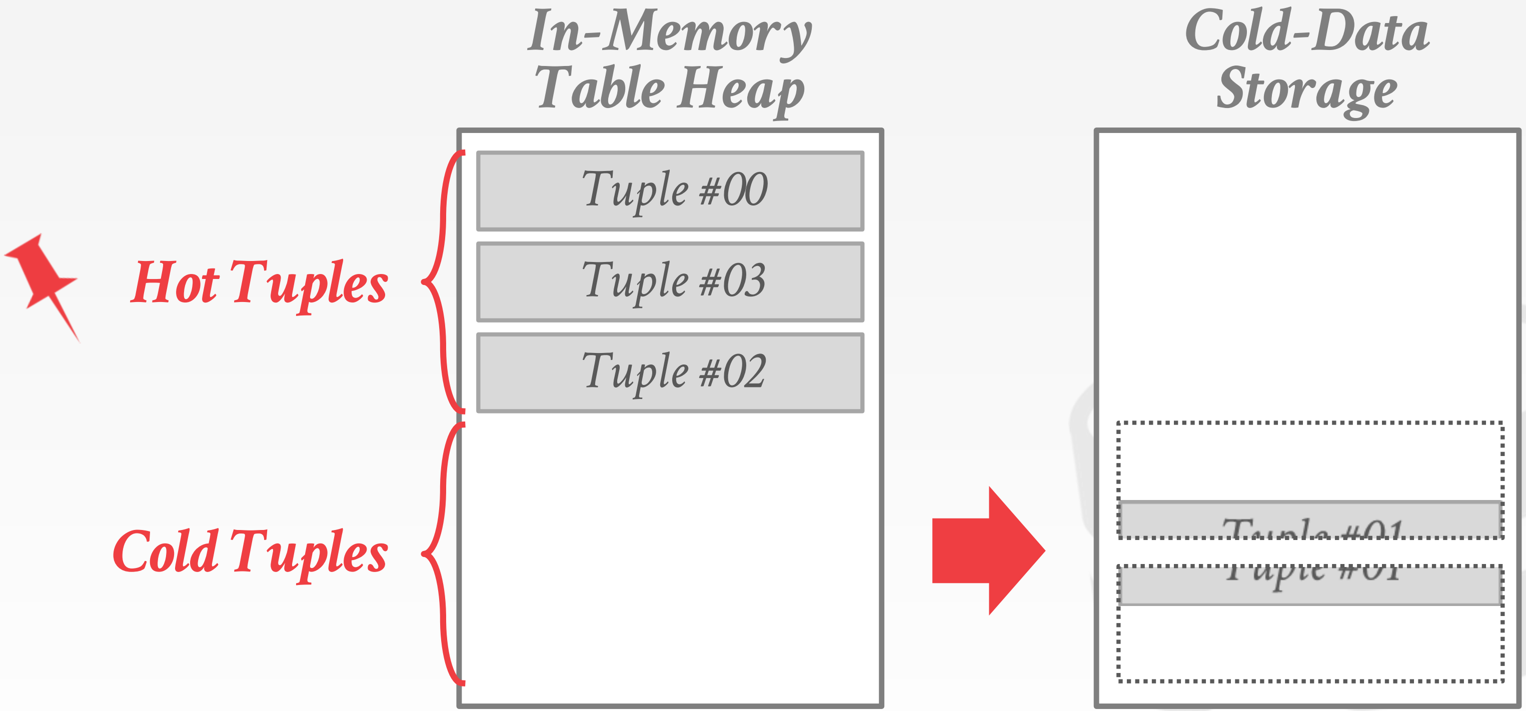
EPFL VOLTDB


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

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

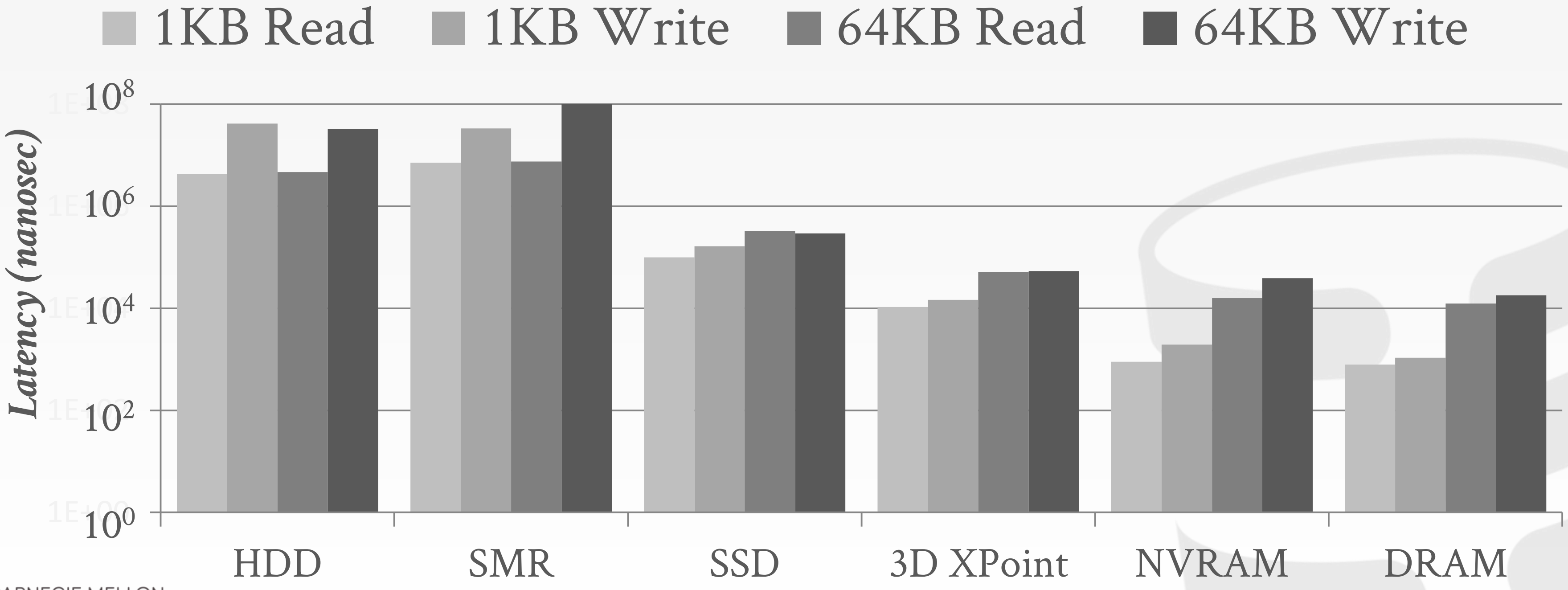
Compare different design decisions in H-Store with anti-caching.

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

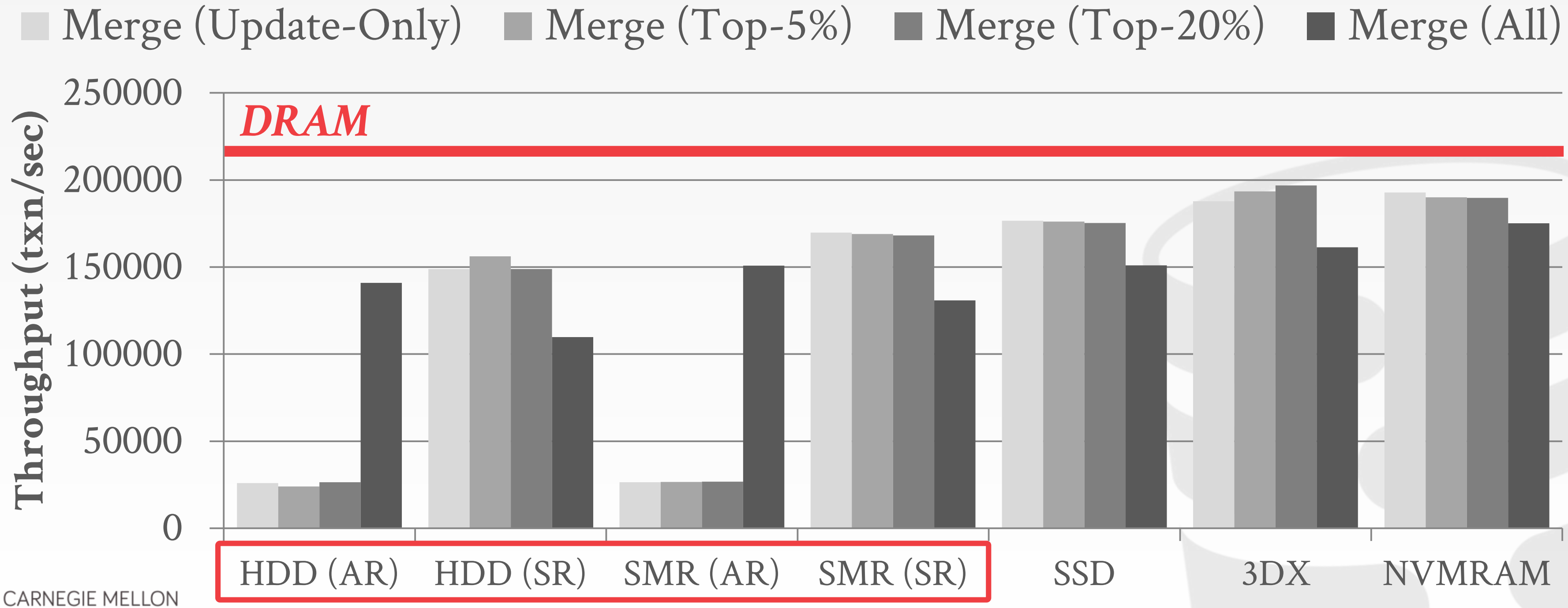
MICROBENCHMARK

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



MERGING THRESHOLD

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



CONFIGURATION COMPARISON

Generic Configuration

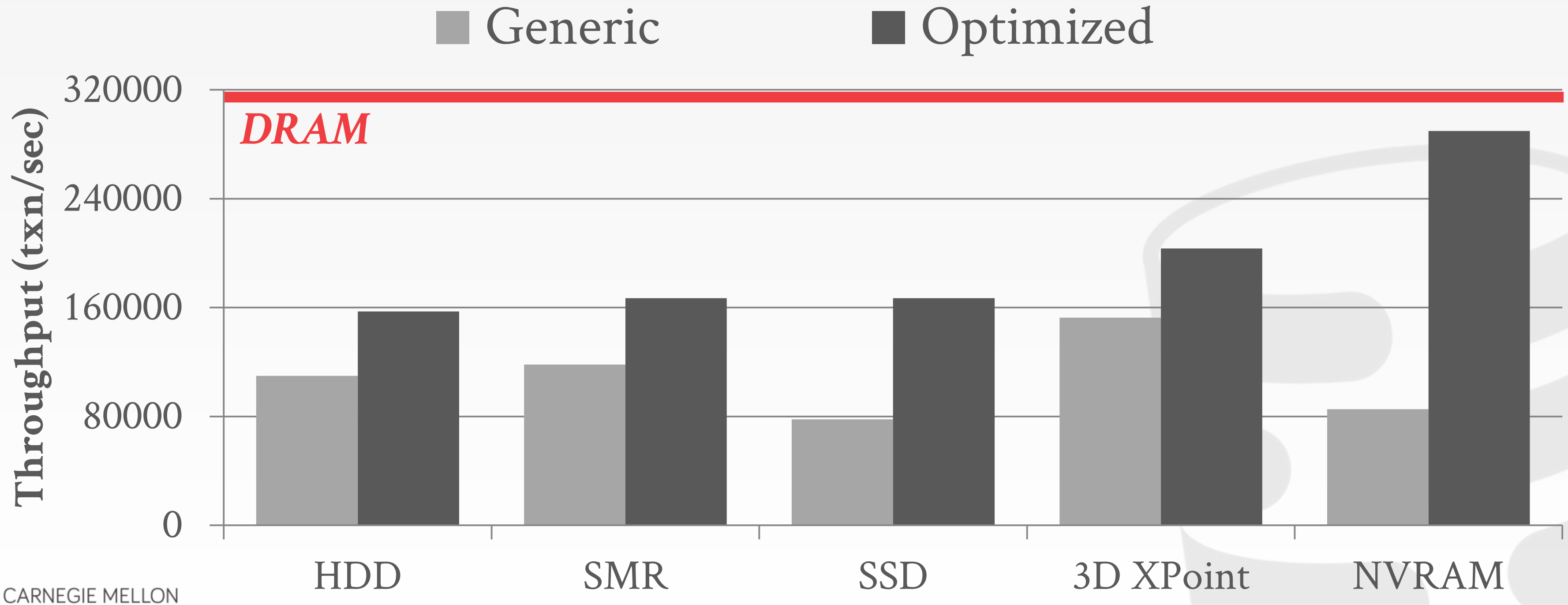
→ Abort-and-Restart Retrieval
→ Merge (All) Threshold
→ 1024 KB Block Size

Optimized Configuration

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

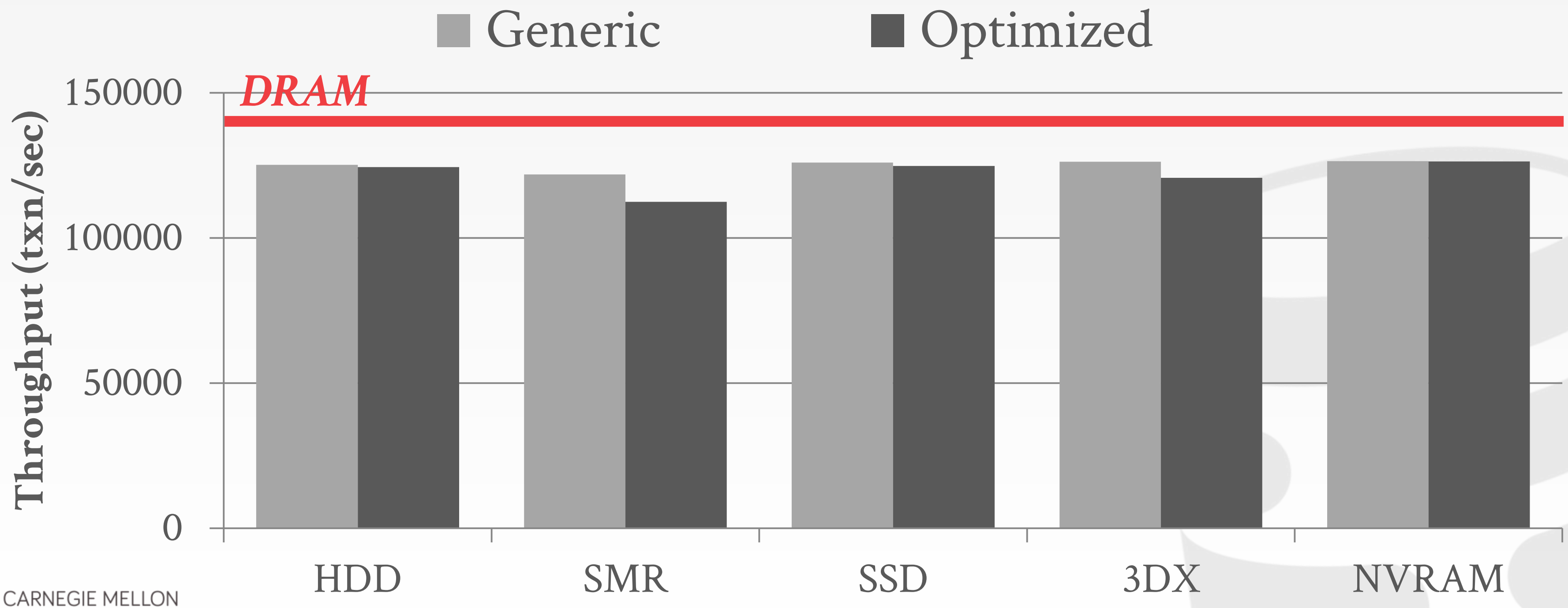
TATP BENCHMARK

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

Hardware! NVM! GPUs! HTM!