Lecture #23

Carnegie Mellon University

ADVANCED DATABASE SYSTEMS

Larger-than-Memory Databases

@Andy_Pavlo // 15-721 // Spring 2020

ADMINISTRIVIA

April 22: Final Exam Released

April 29: Guest Speaker (Live)

May 4: Code Review #2 Submission

May 5: Final Presentations (Live)

May 13: Final Exam Due Date

OBSERVATION

DRAM is expensive, son.
→ Expensive to buy.
→ Expensive to maintain.

It would be nice if our in-memory DBMS could use cheaper storage without having to bring in the entire baggage of a disk-oriented architecture.

TODAY'S AGENDA

Background

Implementation Issues

Real-world Examples

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.

→ Minimize the changes that we make to the DBMS that are required to deal with disk-resident data.

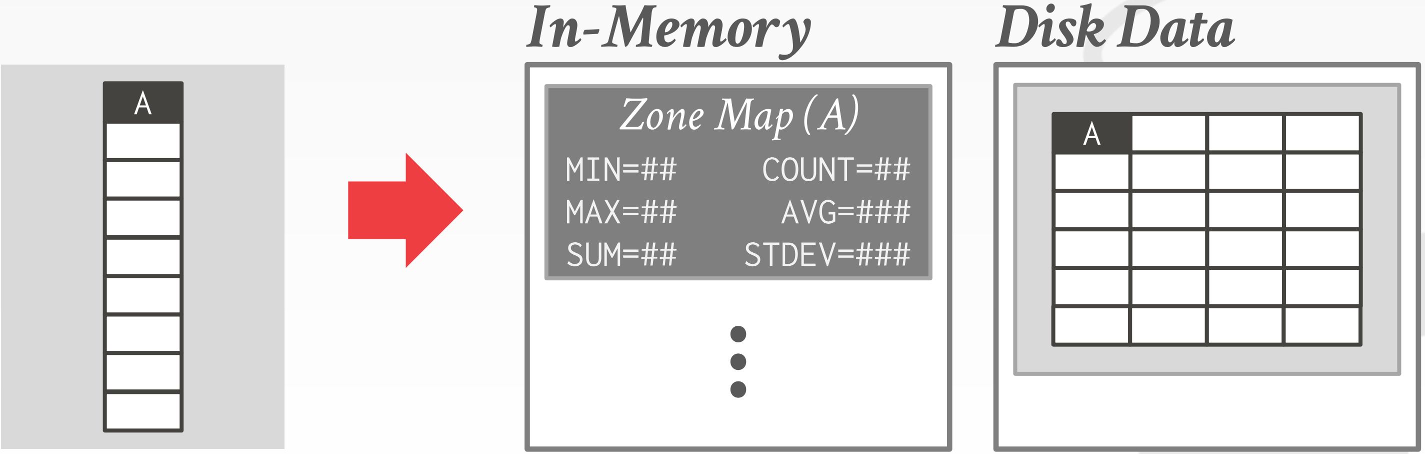
Need to be aware of hardware access methods

→ In-memory Storage = Tuple-Oriented

→ Disk Storage = Block-Oriented

OLAP

OLAP queries generally access the entire table. Thus, there is not anything about OLAP queries that an in-memory DBMS would handle differently than a disk-oriented DBMS.



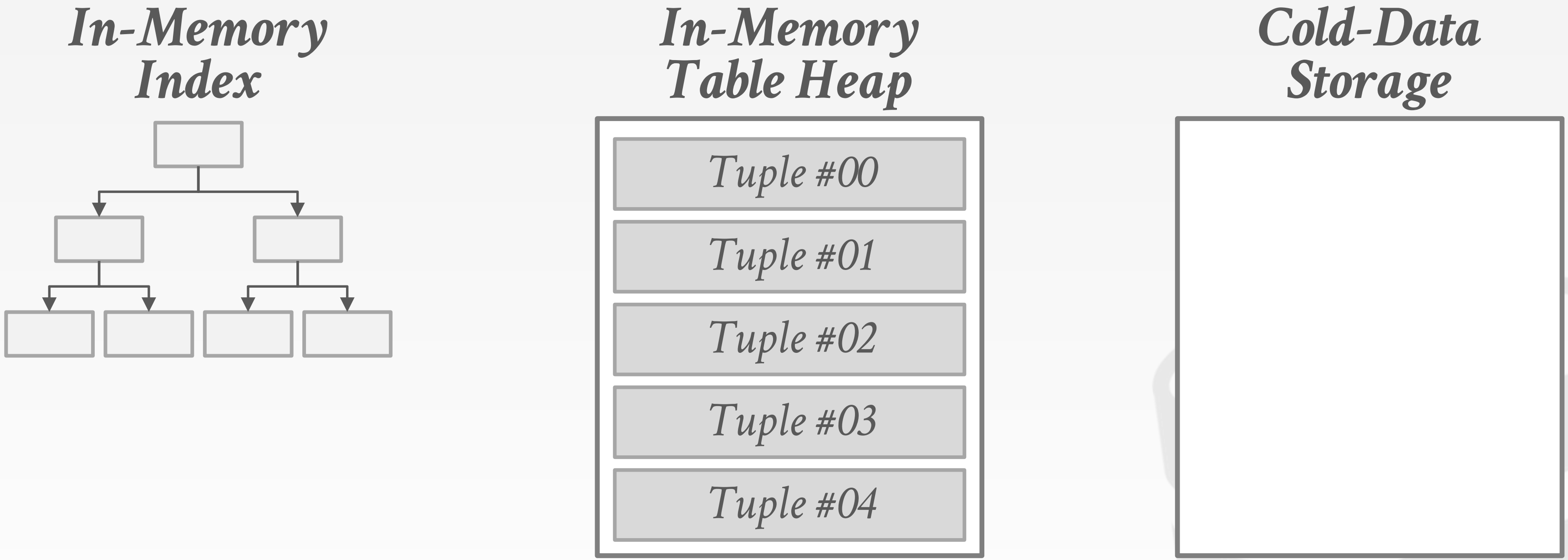
OLTP

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

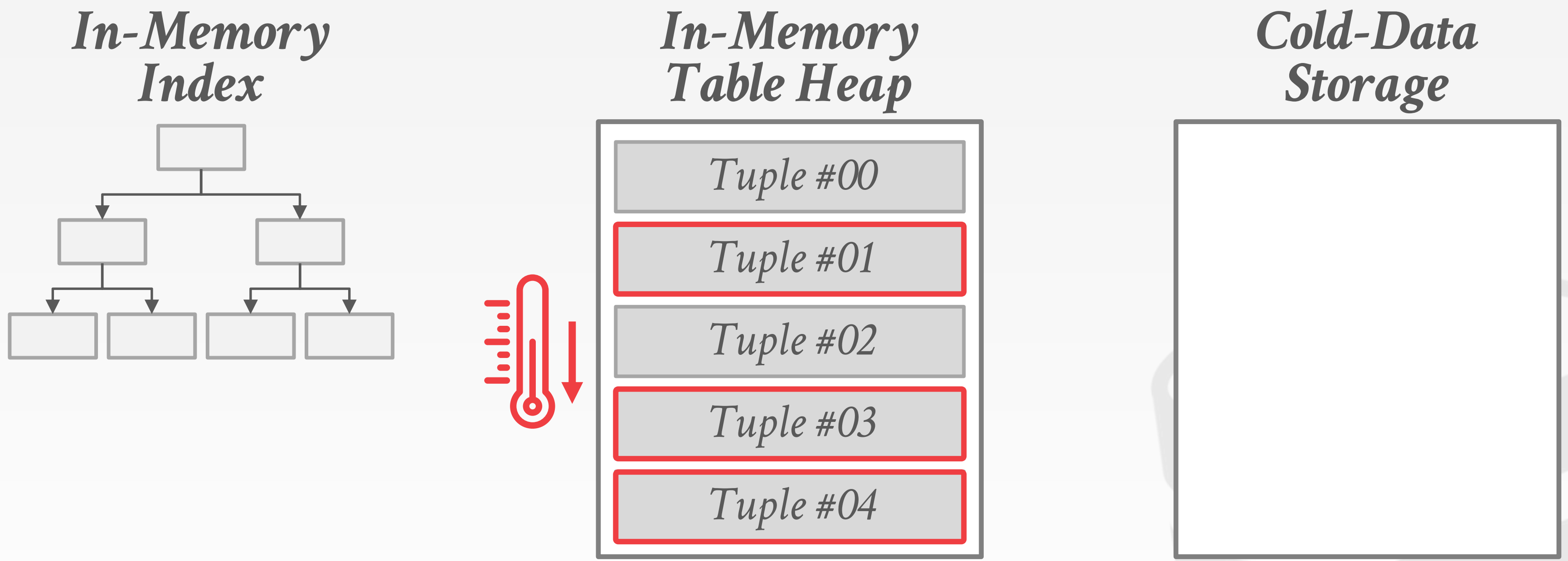
→ We can assume txns will almost always access hot tuples.

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

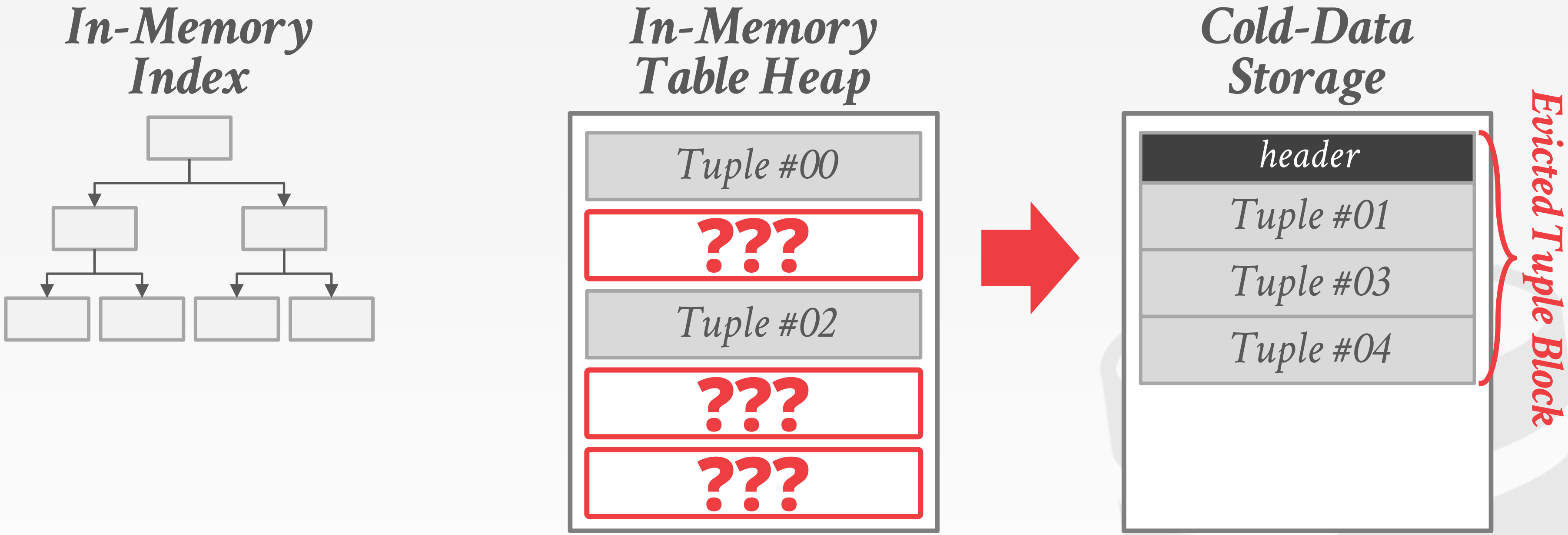
LARGER-THAN-MEMORY DATABASES



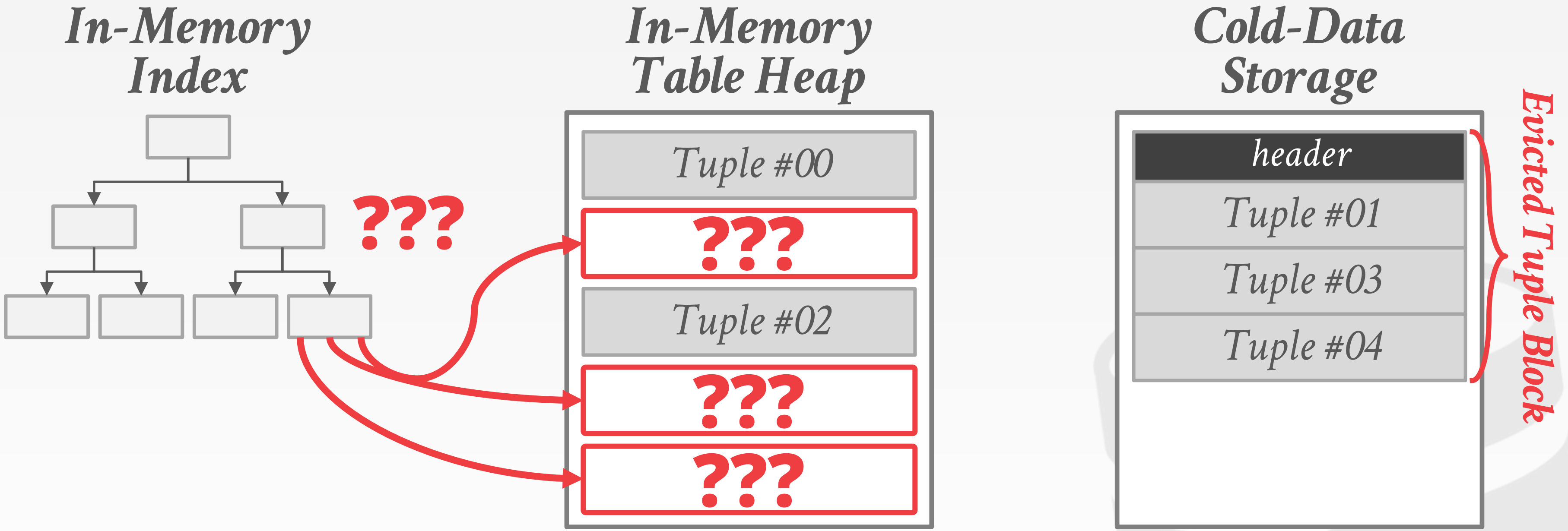
LARGER-THAN-MEMORY DATABASES



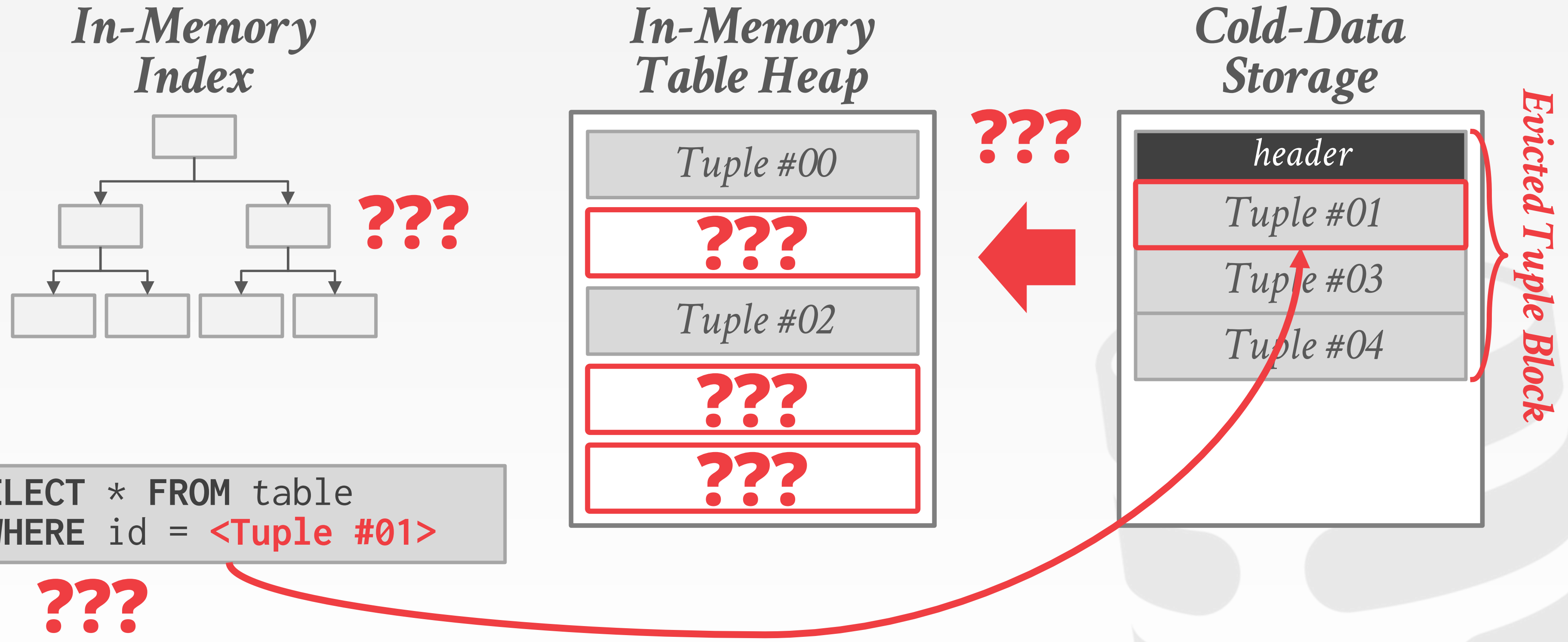
LARGER-THAN-MEMORY DATABASES



LARGER-THAN-MEMORY DATABASES



LARGER-THAN-MEMORY DATABASES




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

???

OLTP ISSUES

Run-time Operations
→ Cold Data Identification

Eviction Policies
→ Timing, Evicted Metadata

Data Retrieval Policies
→ Granularity, Retrieval Mechanism, Merging

LARGER-THAN-MEMORY DATA MANAGEMENT ON MODERN STORAGE HARDWARE FOR IN-MEMORY OLTP DATABASE SYSTEMS
DAMON 2016

COLD DATA IDENTIFICATION

Choice #1: On-line

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

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 must manually move data.

Choice #2: On Demand

→ The DBMS/OS runs a replacement policy to decide when to evict data to free space for new data that is needed.

EVICTED TUPLE METADATA

Choice #1: Tuple 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: DBMS Managed Pages

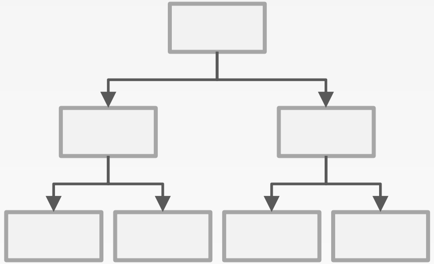
→ DBMS tracks what data is in memory vs. on disk.

Choice #4: OS Virtual Memory

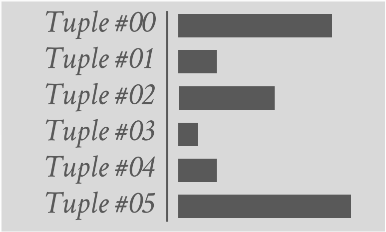
→ OS tracks what data is on in memory vs. on disk.

EVICTED TUPLE METADATA

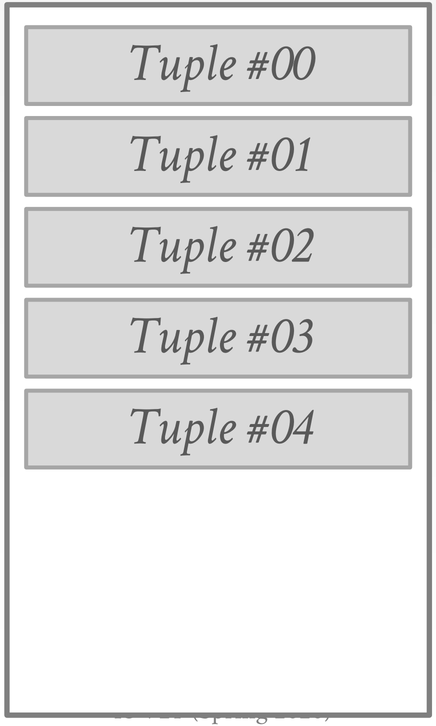
In-Memory Index



Access Frequency

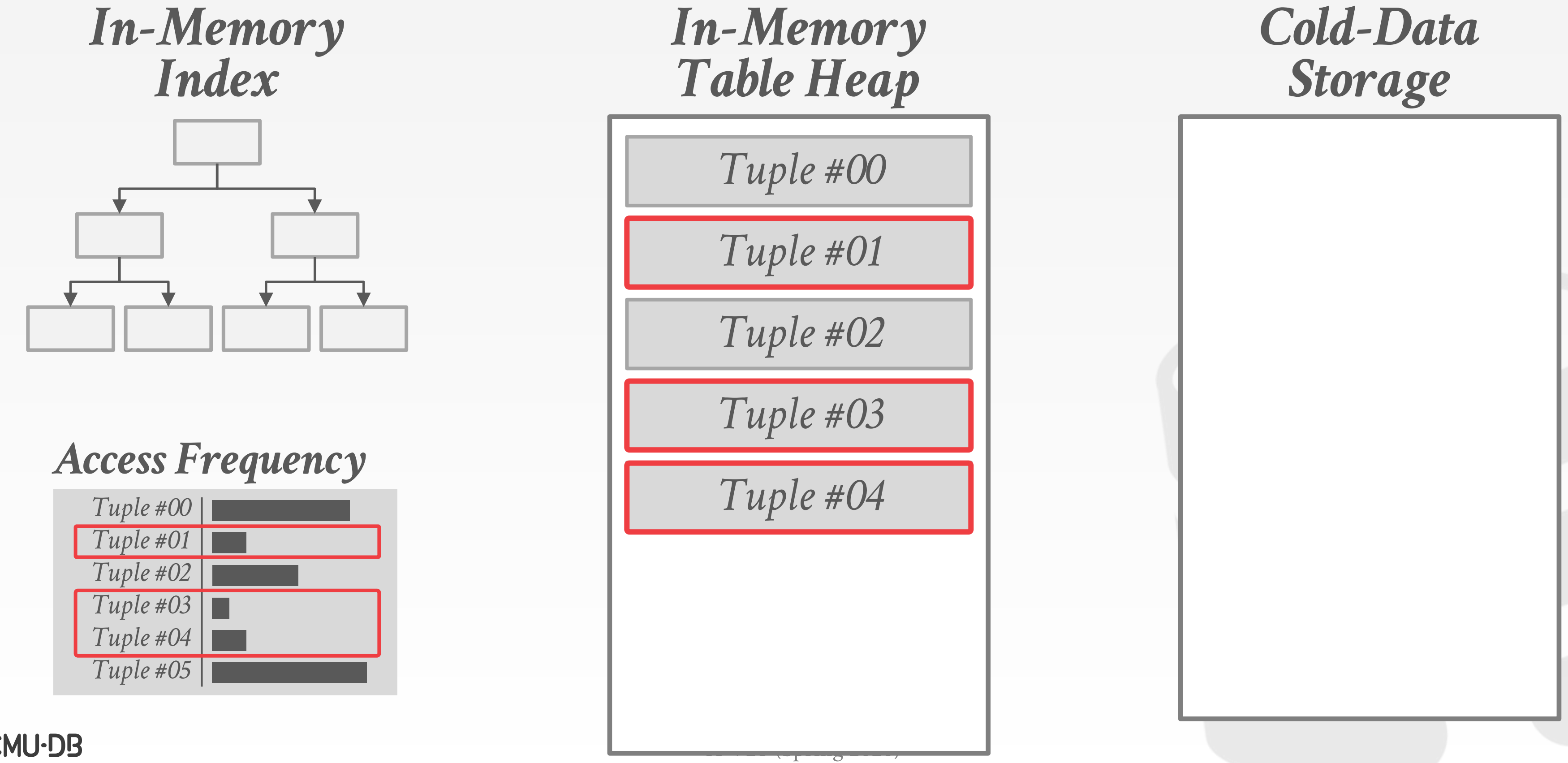


In-Memory Table Heap

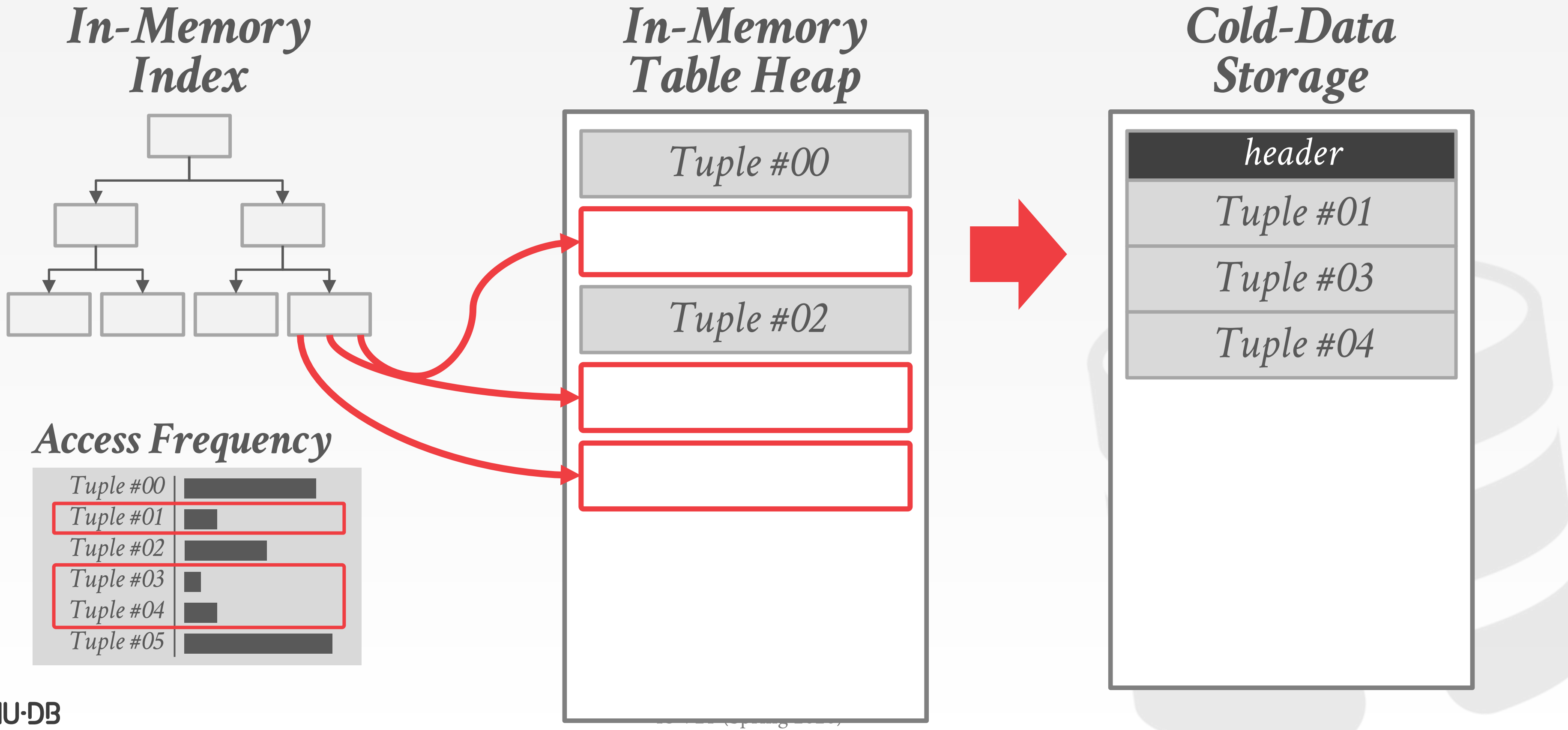


Cold-Data Storage

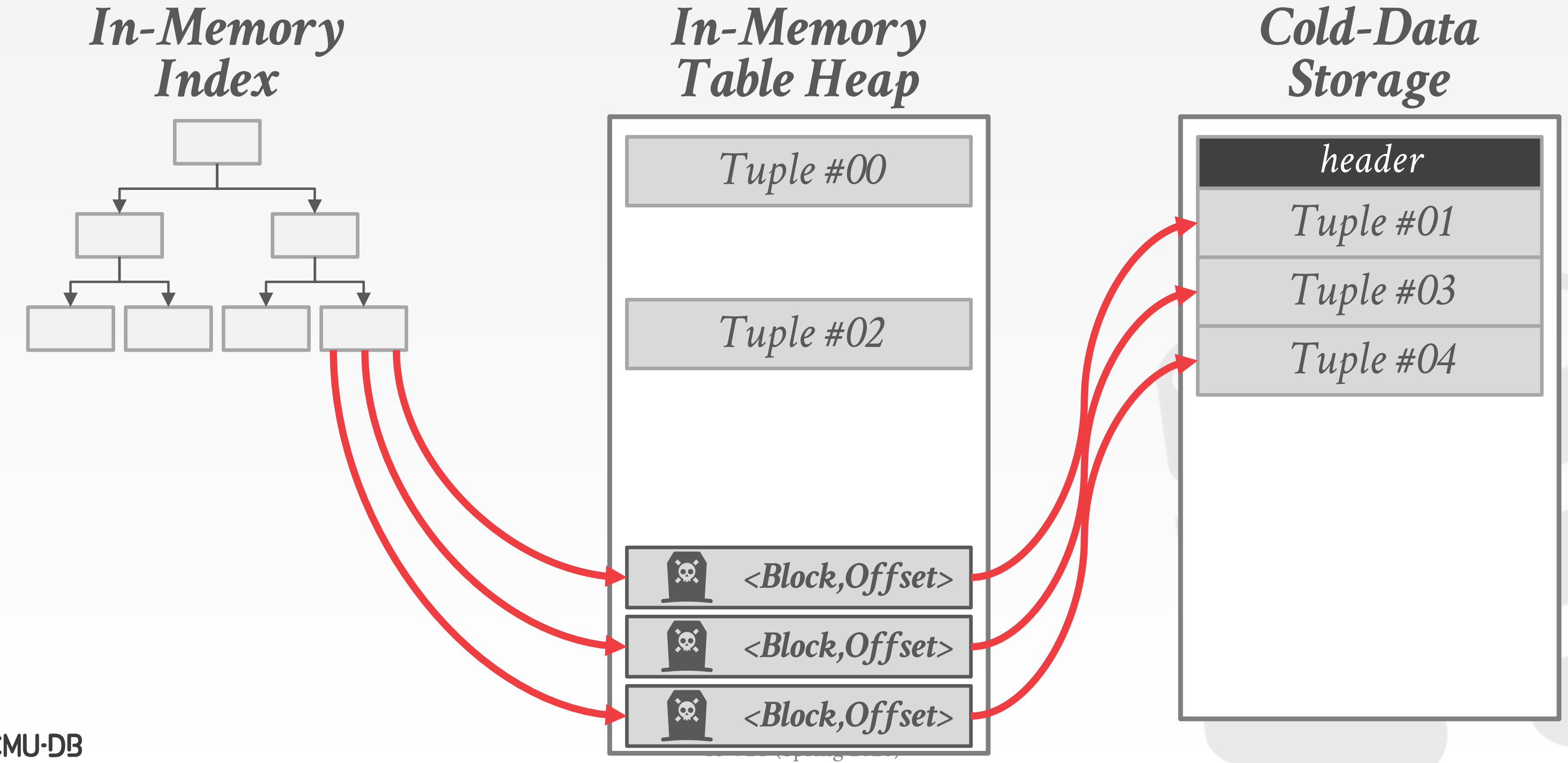
EVICTED TUPLE METADATA



EVICTED TUPLE METADATA



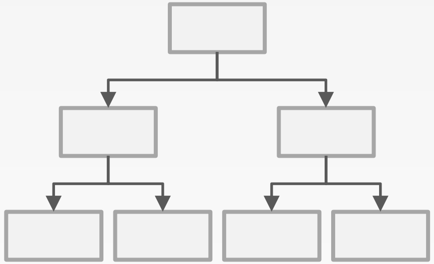
EVICTED TUPLE METADATA



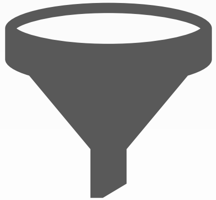
EVICTED TUPLE METADATA

Does 'x' exist?

In-Memory Index



Bloom Filter



In-Memory Table Heap

Tuple #00

Tuple #02

Cold-Data Storage

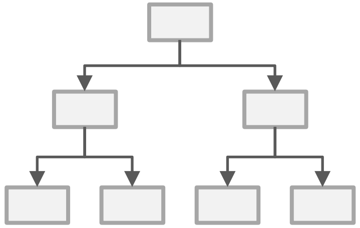
header

Tuple #01

Tuple #03

Tuple #04

Index



EVICTED TUPLE METADATA

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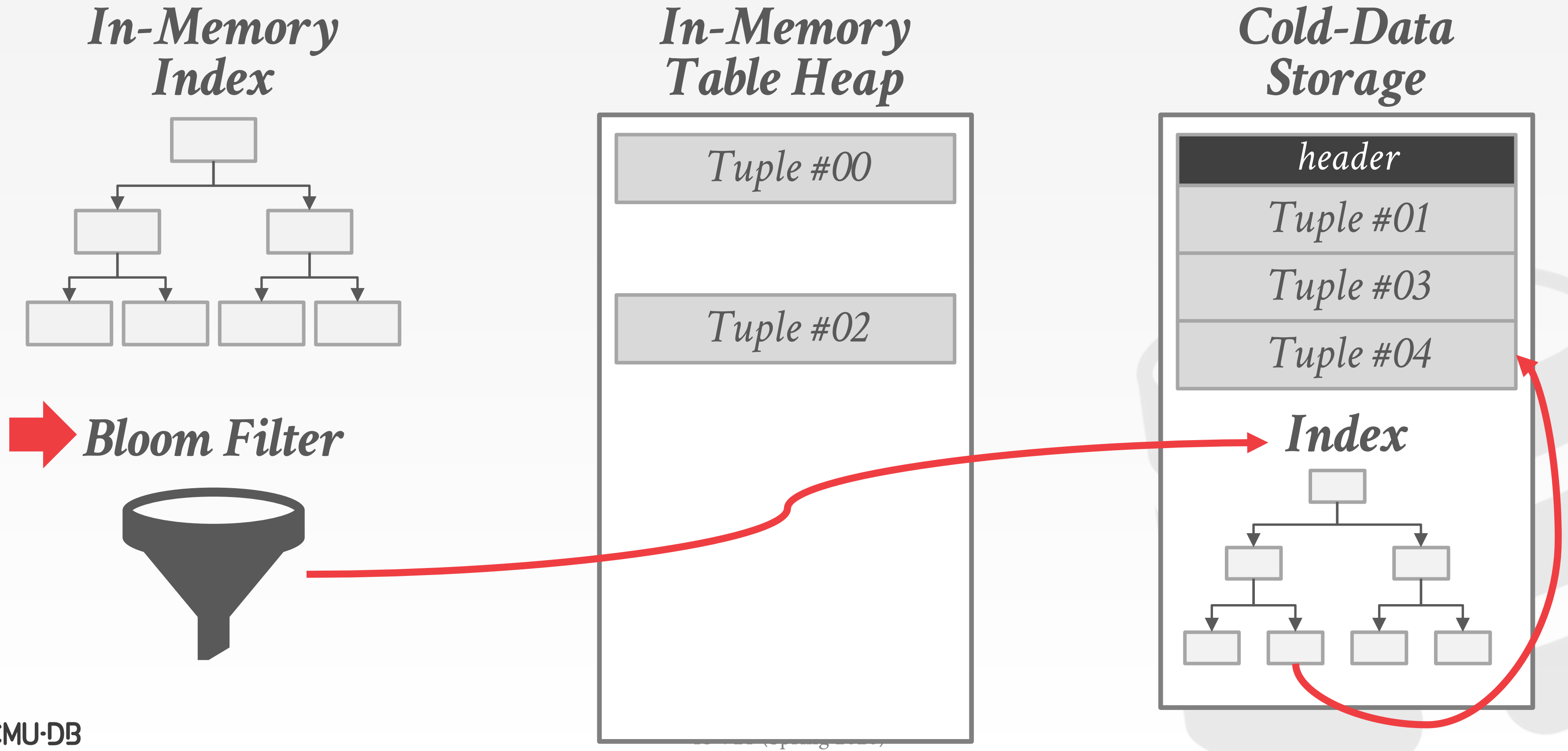


DATA RETRIEVAL GRANULARITY

Choice #1: 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.

Choice #2: 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.

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.

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.
→ Requires MVCC to guarantee consistency for large txns that access data that does not fit in memory.

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.

IMPLEMENTATIONS

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

Pages
- LeanStore – Hierarchical Buffer Pool
- Umbra – Variable-length Buffer Pool
- 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

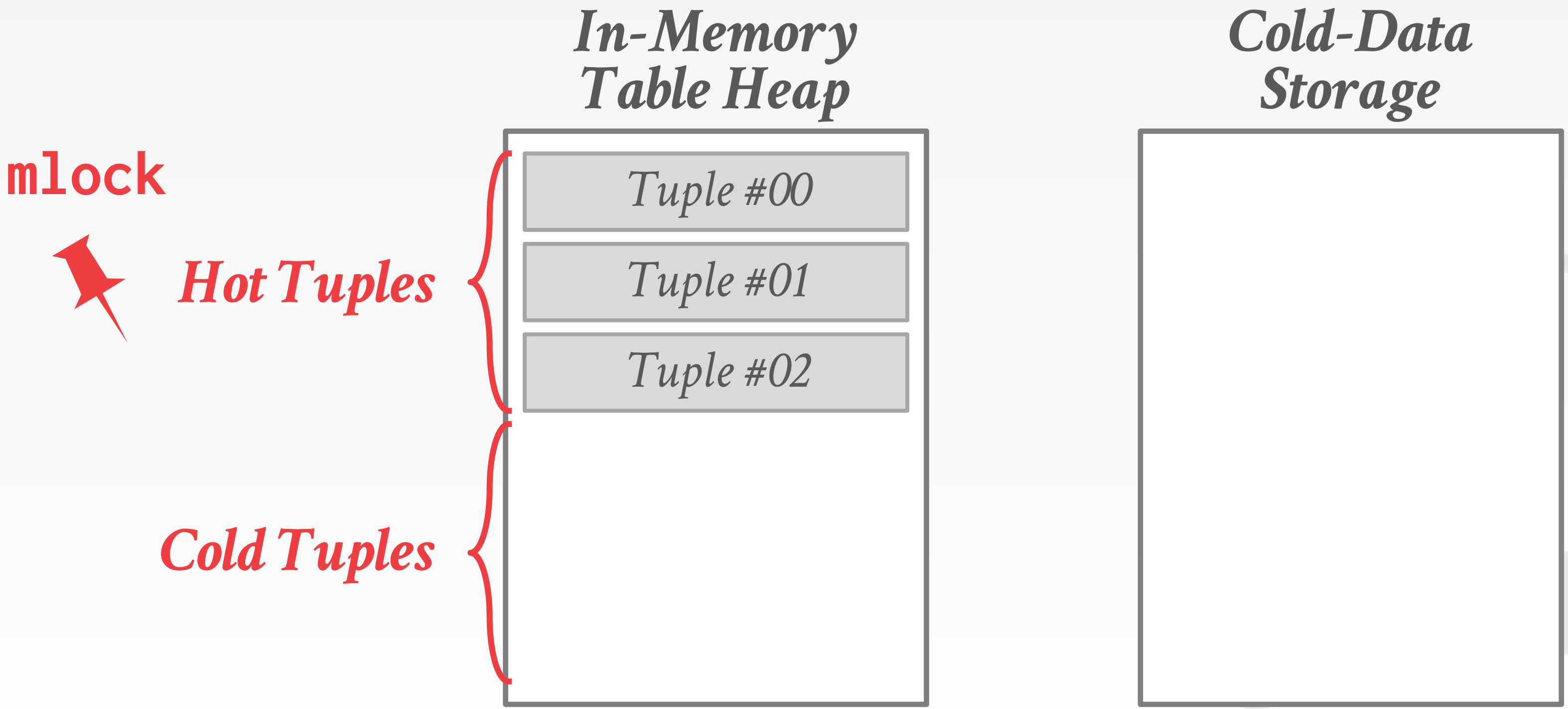
Synchronous Retrieval

Page-level Granularity

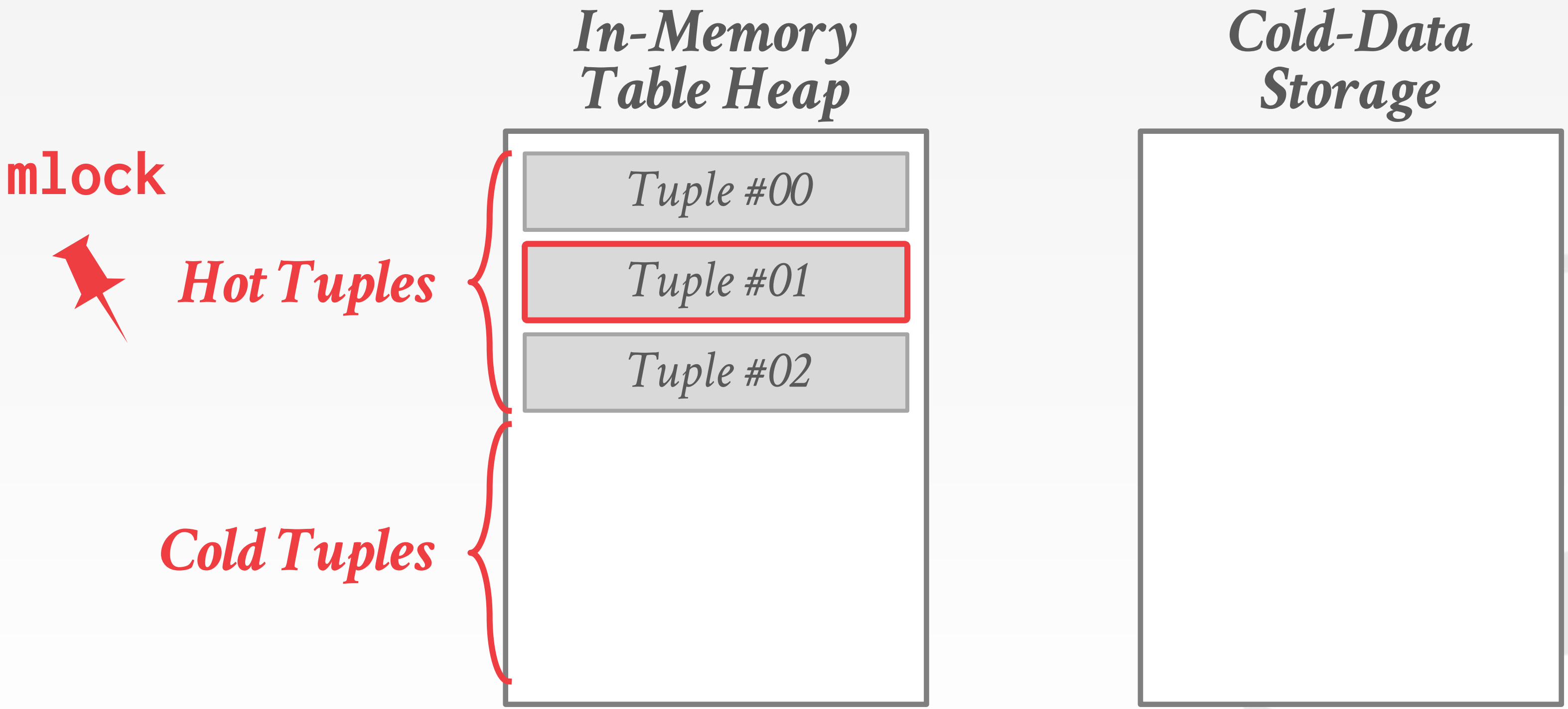
Always Merge

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

EPFL VOLTDB


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

EPFL VOLTDB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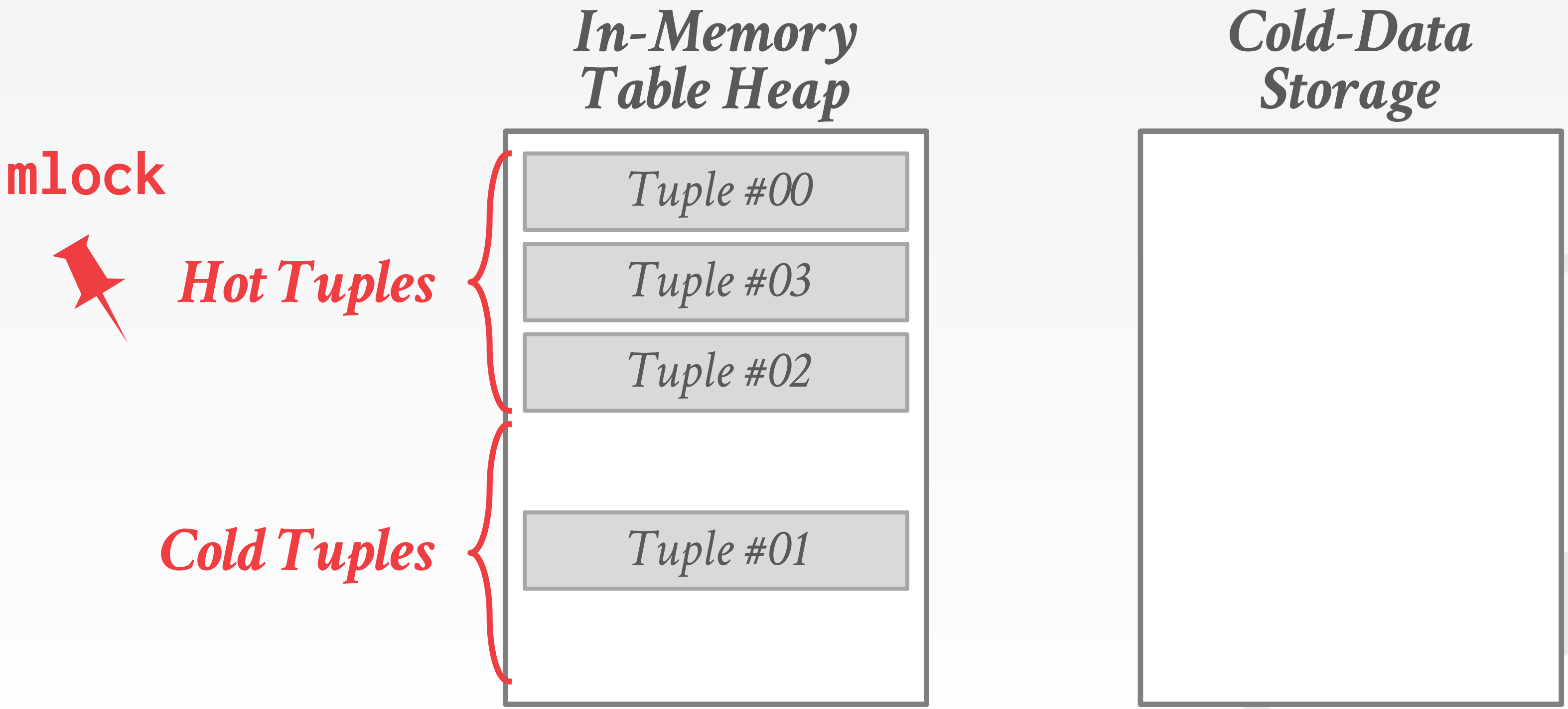
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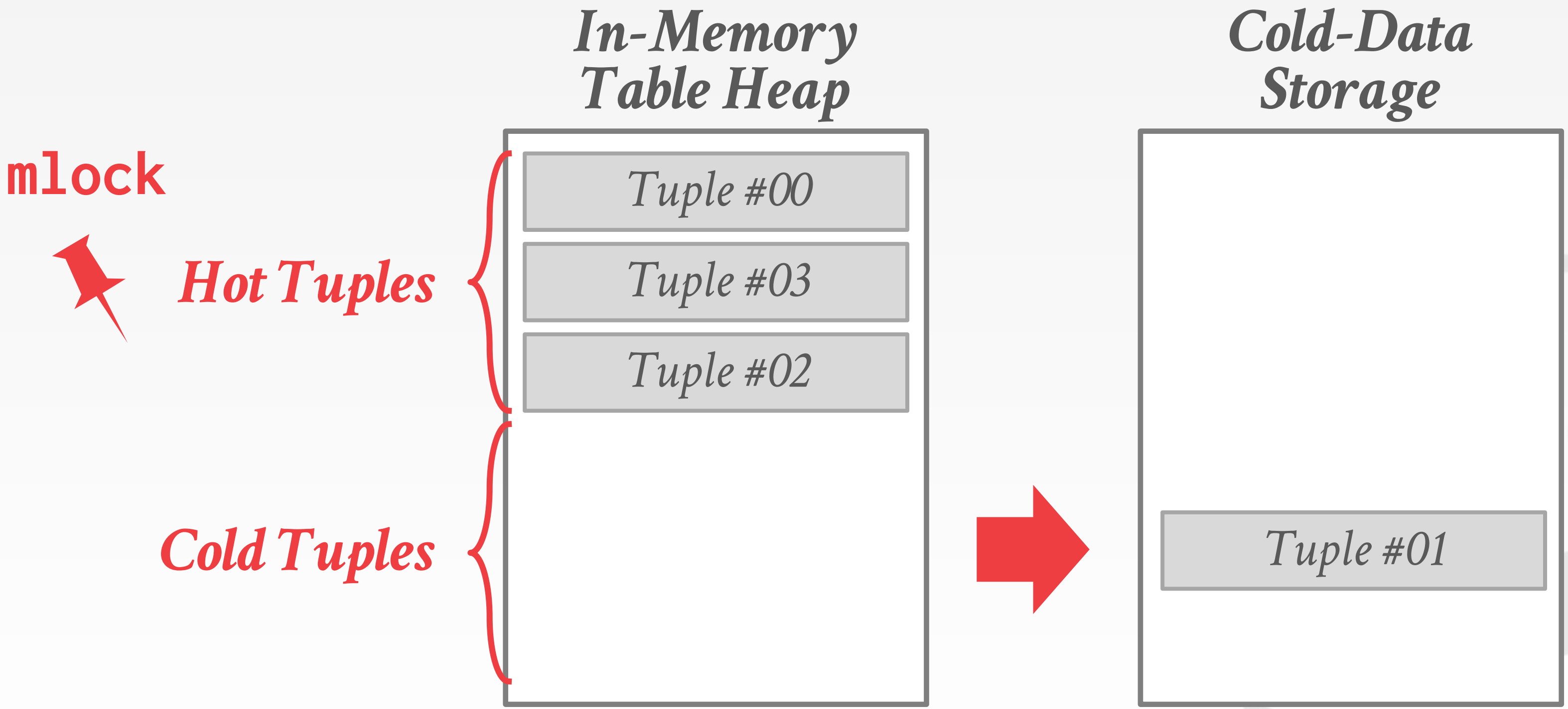
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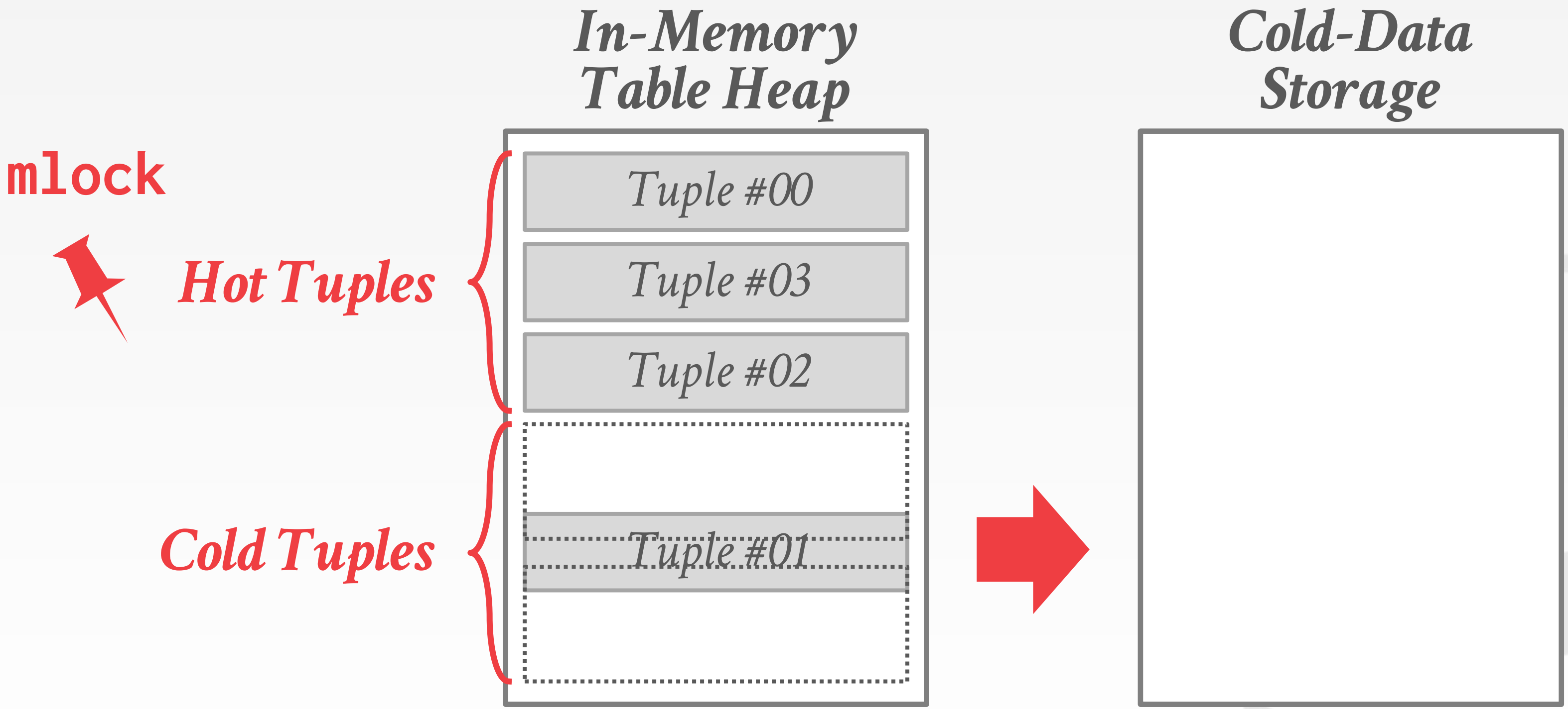

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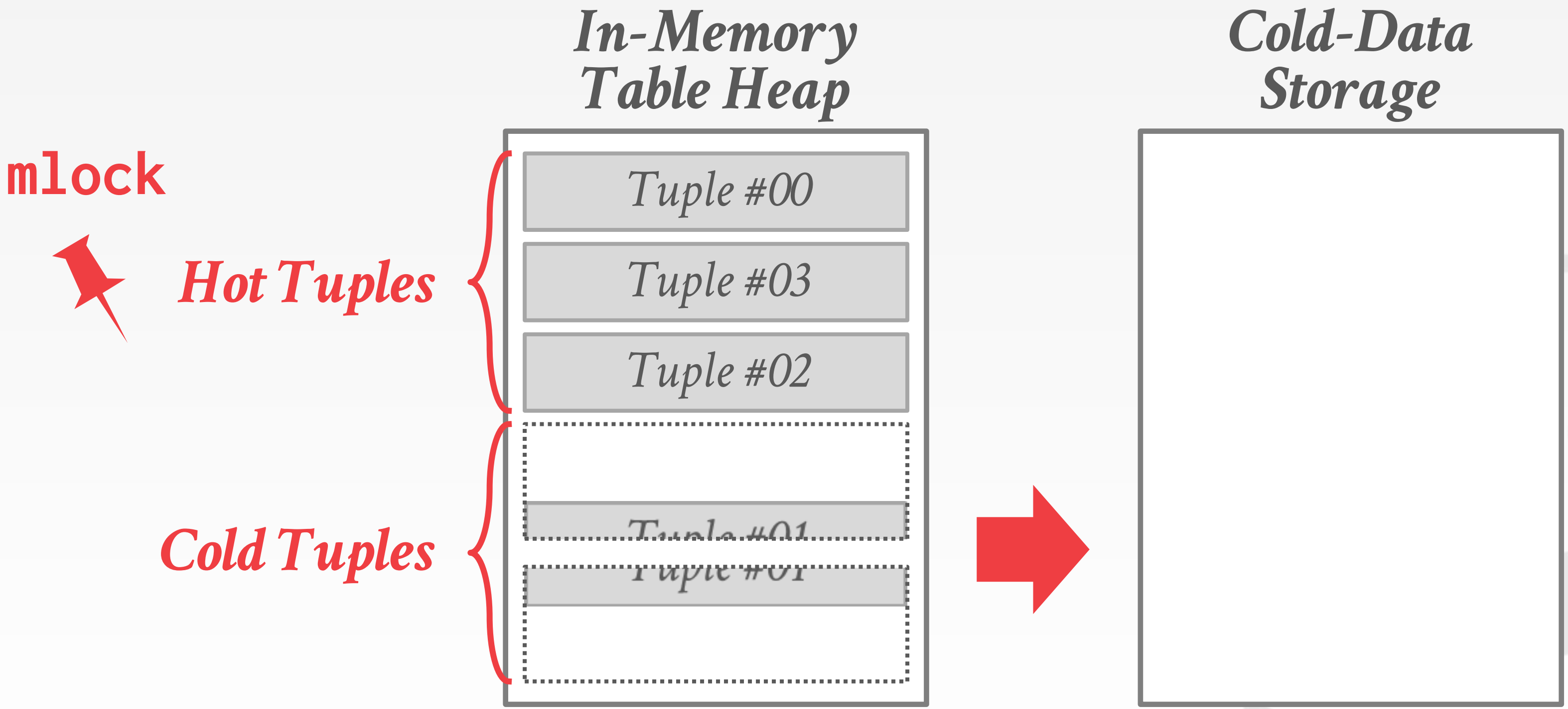

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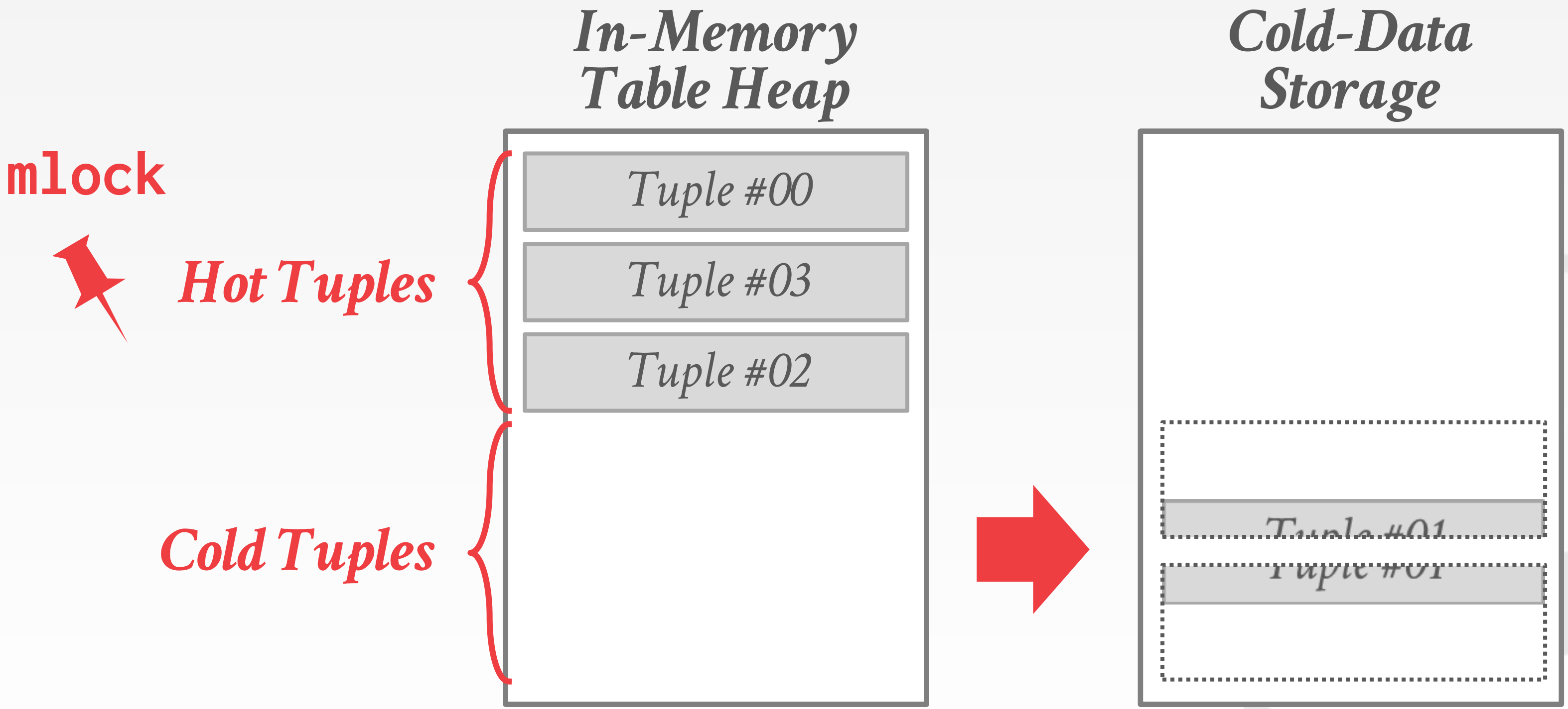
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APACHE GEODE – OVERFLOW TABLES

On-line Identification

Administrator-defined Threshold

Tombstones (?)

Synchronous Retrieval

Tuple-level Granularity

Merge Only on Update (?)

Source: Apache Geode

OBSERVATION

The approaches that we have discussed so far are based on tuples.

→ The DBMS must track meta-data about individual tuples.
→ Not reducing storage overhead of indexes.

Need a unified way to evict cold data from both tables and indexes with low overhead…

LEANSTORE

Prototype in-memory storage manager from TUM that supports larger-than-memory databases.

→ Handles both tuples + indexes

→ Not part of the HyPer project.

Hierarchical + Randomized Block Eviction

→ Use pointer swizzling to determine whether a block is evicted or not.

LEANSTORE: IN-MEMORY DATA MANAGEMENT BEYOND MAIN MEMORY
ICDE 2018

POINTER SWIZZLING

Switch the contents of pointers based on whether the target object resides in memory or on disk.

→ Use first bit in address to tell what kind of address it is.

→ Only works if there is only one pointer to the object.

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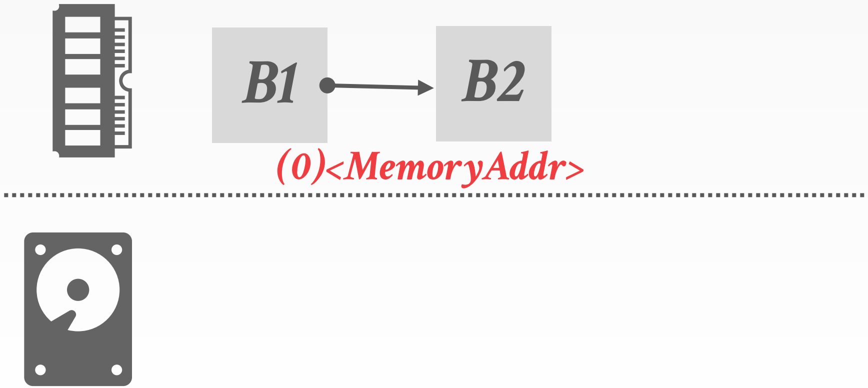


REPLACEMENT STRATEGY

Randomly select blocks for eviction.

→ Don't have to maintain meta-data every time a txn accesses a hot block.

→ Only track accesses for cold data, which should be rare if it is cold.

Unswizzle their pointer but leave in memory.

→ Add to a FIFO queue of blocks staged for eviction.

→ If page is accessed again, remove from queue.

→ Otherwise, evict pages when reaching front of queue.

BLOCK HIERARCHY

Blocks are organized in a tree hierarchy.

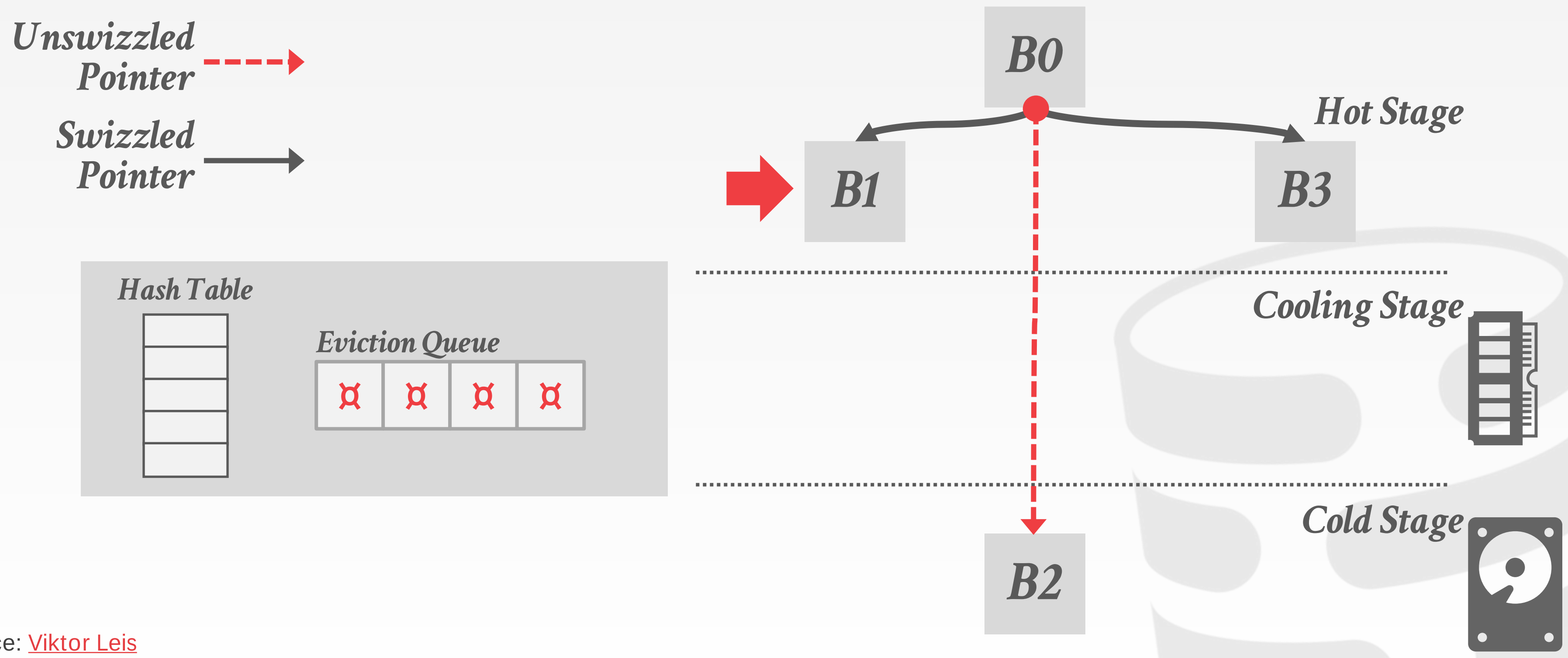
→ Each page has only one parent, which means that there is only a single pointer.

The DBMS can only evict a block if its children are also evicted.

→ This avoids the problem of evicting blocks that contain swizzled pointers.

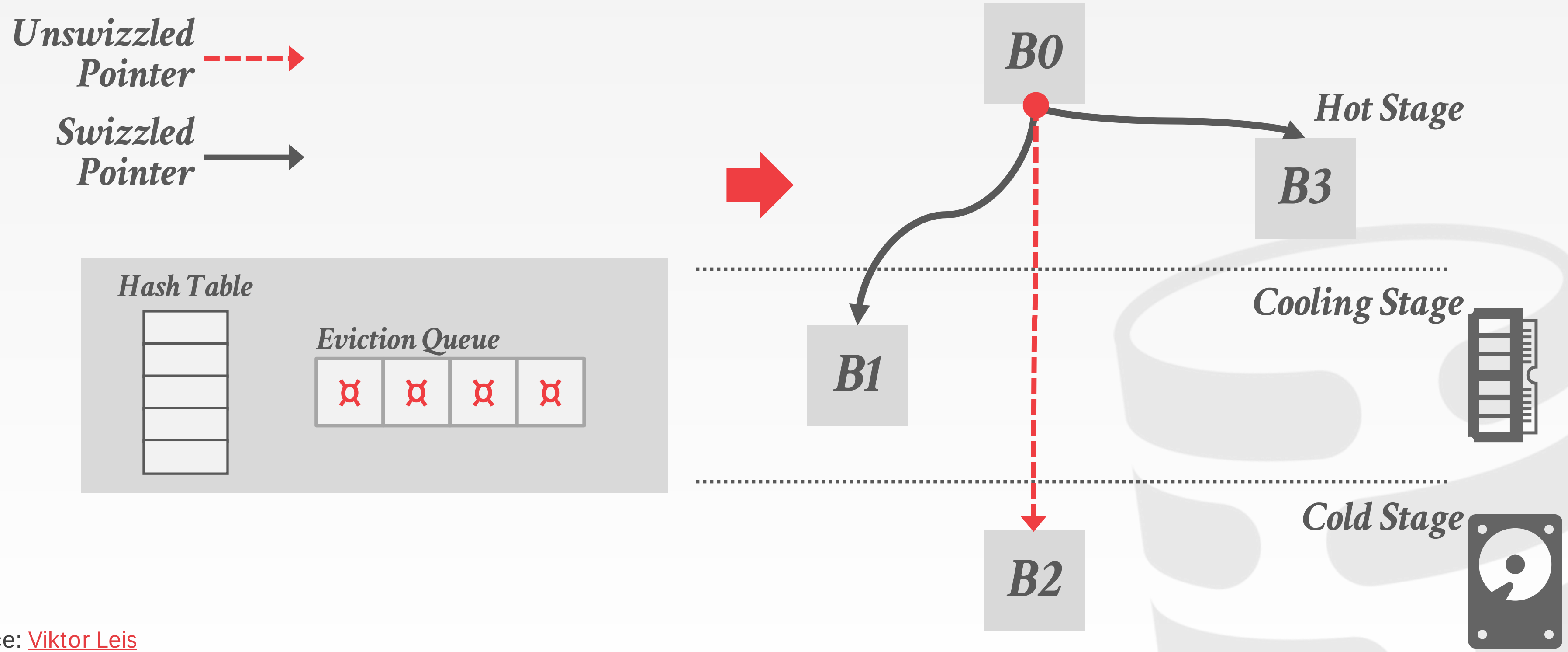
→ If a block is selected but it has in-memory children, then it automatically switches to select one of its children.

BLOCK HIERARCHY



Source: Viktor Leis

BLOCK HIERARCHY



Source: [Viktor Leis]

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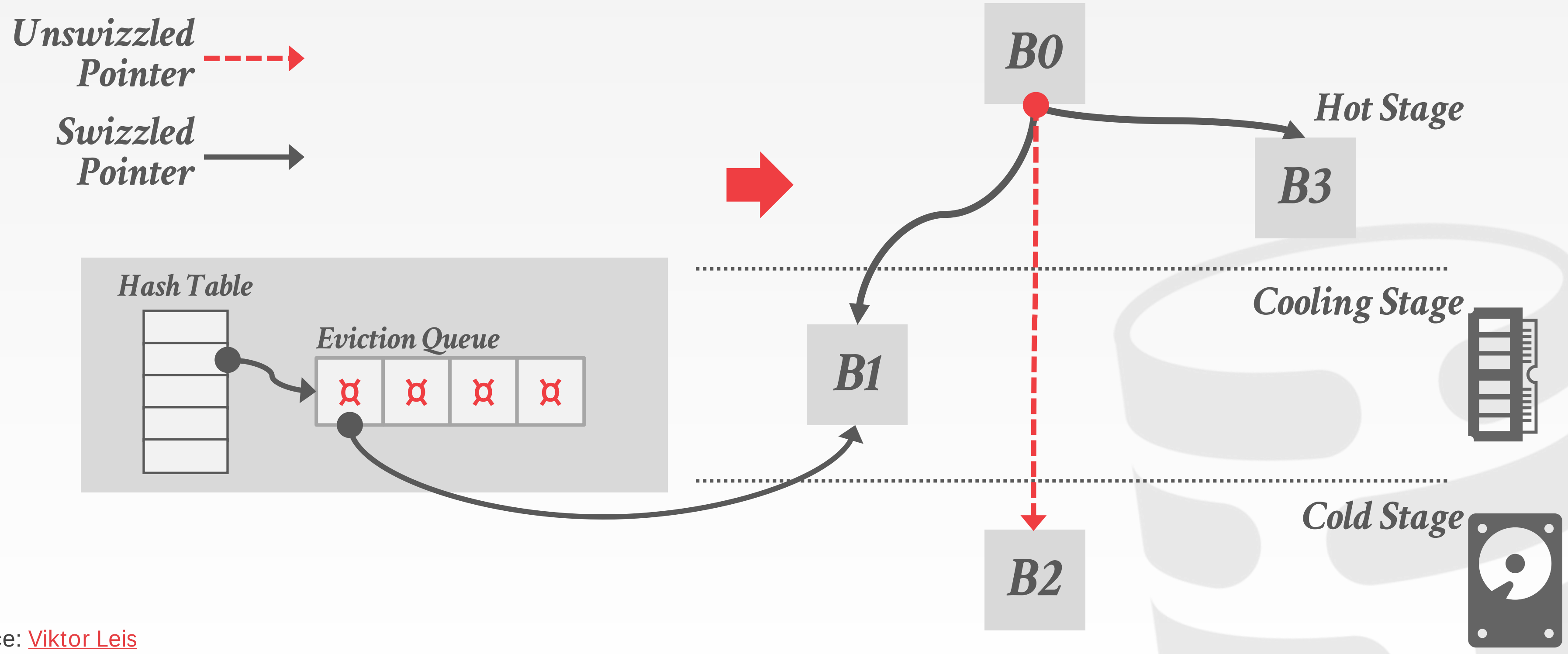

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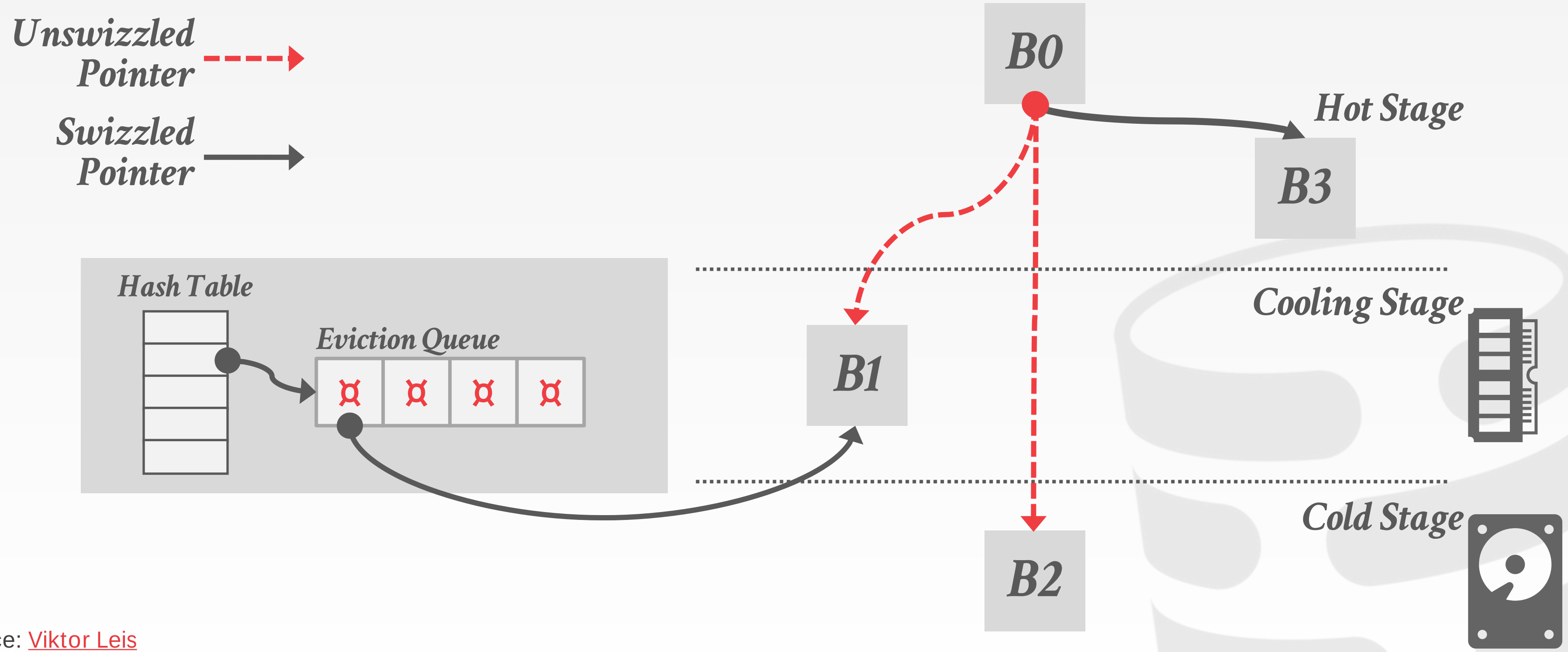


Source: Viktor Leis

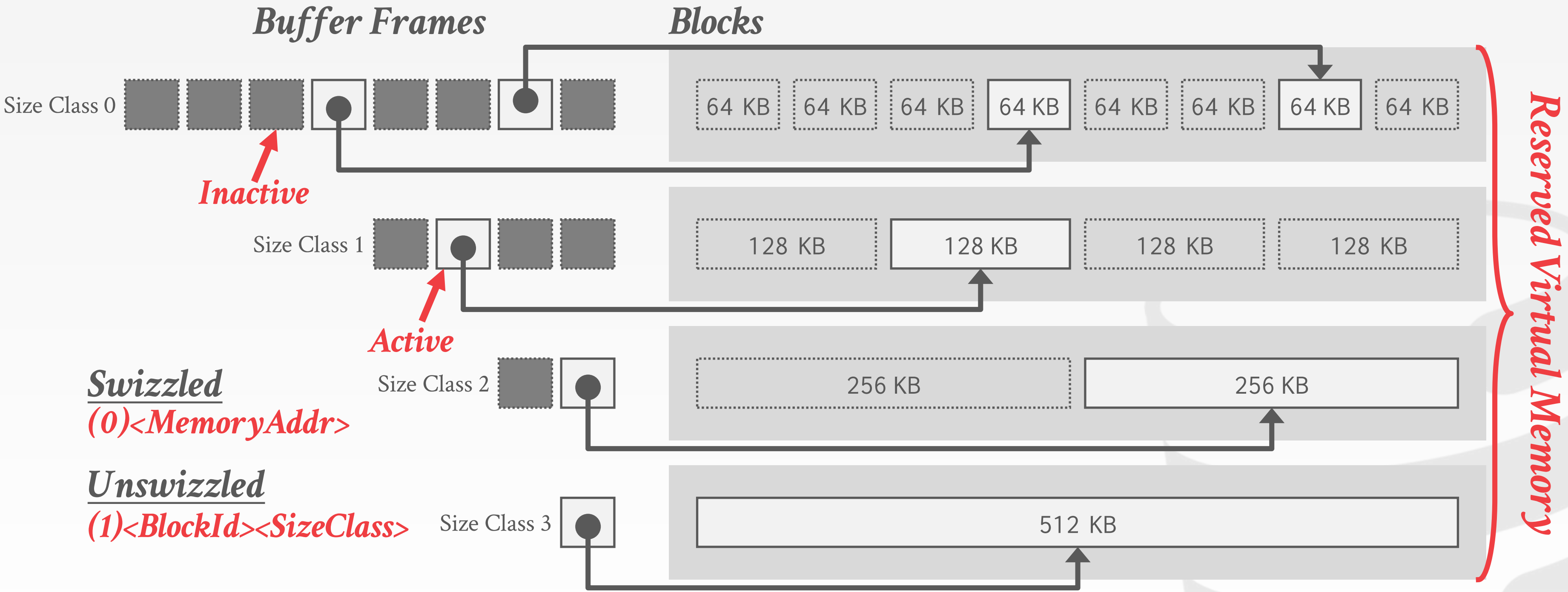
UMBRA

New DBMS from German HyPer team at TUM.
→ Low overhead buffer pool with variable-sized pages.
→ Employs the same hierarchical organization and randomized block eviction algorithm from LeanStore.
→ Uses virtual memory to allocate storage but the DBMS manages block eviction on its own.

DBMS stores relations as index-organized tables, so there is no separate management needed to handle index blocks.

UMBRA: A DISK-BASED SYSTEM WITH IN-MEMORY PERFORMANCE
CIDR 2020

VARIABLE-SIZED BUFFER POOL



Source: Thomas Neumann

MEMSQL – COLUMNAR TABLES

Administrator manually declares a table as a disk-resident columnar table with zone maps.

→ Pre-2017: Used **mmap** but this was a bad idea.
→ Pre-2019: DBMS splits columns into 1m tuple segments.
→ Current: Unified single logical table format that combines delta store with column store.

No Evicted Metadata

Synchronous Retrieval

Always Merge

Source: MemSQL

PARTING THOUGHTS

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

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

NEXT CLASS

Server-side Application Logic