Georgia Tech

Lecture 10: Larger-than-Memory Databases

CREATING THE NEXT®

Administrivia

- Deadline pushed to Oct 1
- Assignment and sheet 3 will be released on time.
- Exam on next Thursday in class.

Today's Agenda

- Recap
- Disk-oriented vs In-Memory DBMSs
- Larger-than-Memory Databases
- Design Decisions
- Case Studies

Recap

Naïve Compression

- Choice 1: **Entropy** Encoding
  - More common sequences use less bits to encode, less common sequences use more bits to encode.
- Choice 2: **Dictionary** Encoding
  - Build a data structure that maps data segments to an identifier.
  - Replace the segment in the original data with a reference to the segment's position in the dictionary data structure.

Columnar Compression

- Null Suppression
- Run-length Encoding
- Bitmap Encoding
- Delta Encoding
- Incremental Encoding
- Mostly Encoding
- Dictionary Encoding

Disk-oriented vs In-Memory DBMSs

Background

- Much of the development history of DBMSs is about dealing with the limitations of hardware.
- Hardware was much different when the original DBMSs were designed in 1970s:
  - Uniprocessor (single-core CPU)
  - DRAM capacity was very limited.
  - The database had to be stored on disk.
  - Disks were even slower than they are now.

Background

- But now DRAM capacities are large enough that most databases can fit in memory.
  - Structured data sets are smaller.
- We need to understand why we can't always use a "traditional" disk-oriented DBMS with a large cache to get the best performance.

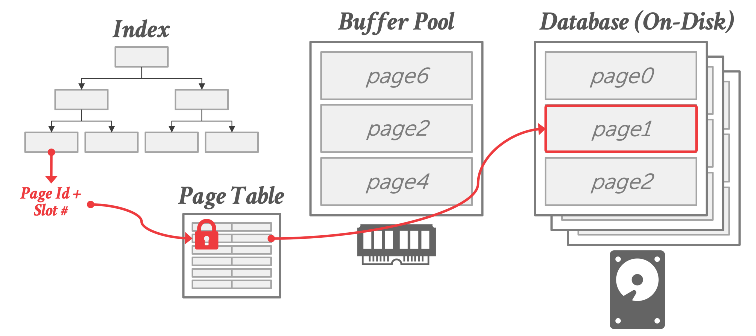
Disk-Oriented DBMS

- The primary storage location of the database is on non-volatile storage (*e.g.*, HDD, SSD).
- The database is organized as a set of fixed-length **pages** (aka blocks).
- The system uses an in-memory **buffer pool** to cache pages fetched from disk.
  - Its job is to manage the movement of those pages back and forth between disk and memory.

Buffer Pool

- When a query accesses a page, the DBMS checks to see if that page is already in memory:
  - If it's not, then the DBMS must retrieve it from disk and copy it into a **frame** in its buffer pool.
  - If there are no free frames, then find a page to evict.
  - If the page being evicted is dirty, then the DBMS must write it back to disk.
- Once the page is in memory, the DBMS translates any **on-disk addresses** to their **in-memory addresses**.

Disk-oriented DBMS: Data Organization



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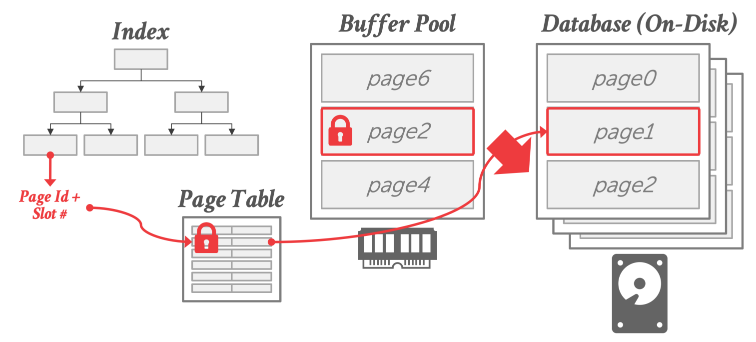

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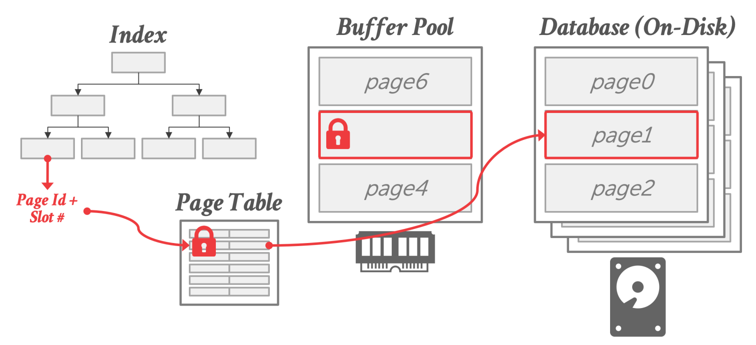

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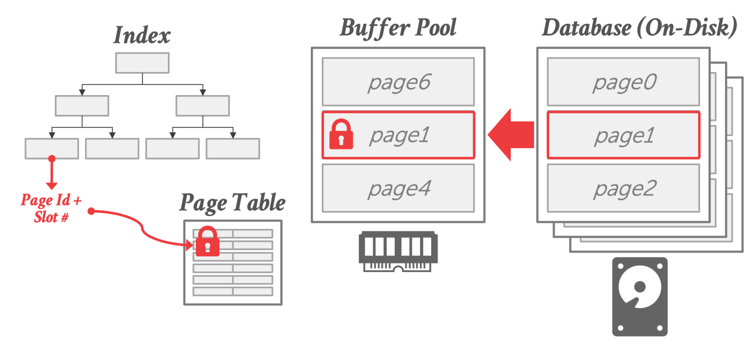
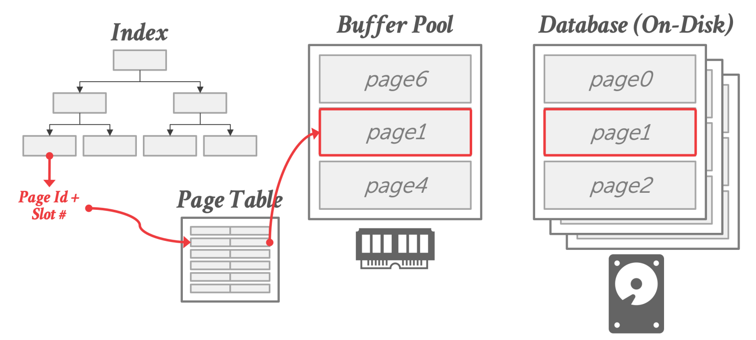


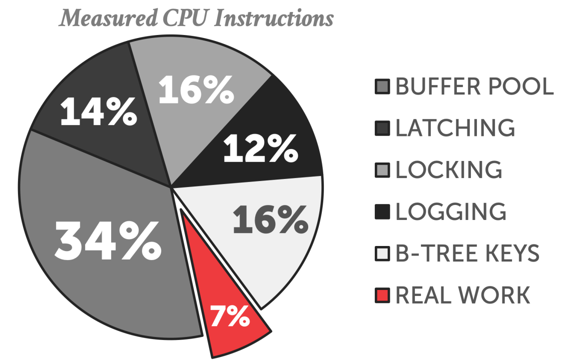
Disk-oriented DBMS: Data Organization



Buffer Pool

- Every tuple access goes through the buffer pool manager regardless of whether that data will always be in memory.
  - Always translate a tuple's record id to its memory location.
  - Worker thread must **pin** pages that it needs to make sure that they are not **swapped to disk**.

Disk-Oriented DBMS Overhead



Reference

In-memory DBMS

- Assume that the primary storage location of the database is **permanently** in memory.
- Early ideas proposed in the 1980s but it is now feasible because DRAM prices are low and capacities are high.
- First commercial in-memory DBMSs were released in the 1990s.
  - **Examples:** TimesTen, DataBlitz, Altibase

Storage Access Latencies

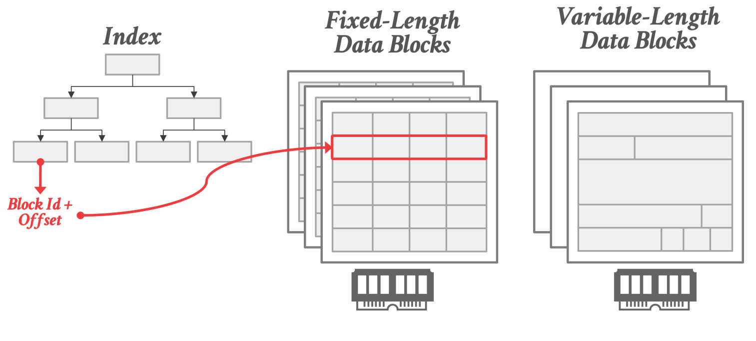
	L3	DRAM	SSD	HDD
Read Latency	20 ns	60 ns	25,000 ns	10,000,000 ns
Write Latency	20 ns	60 ns	300,000 ns	10,000,000 ns

Reference

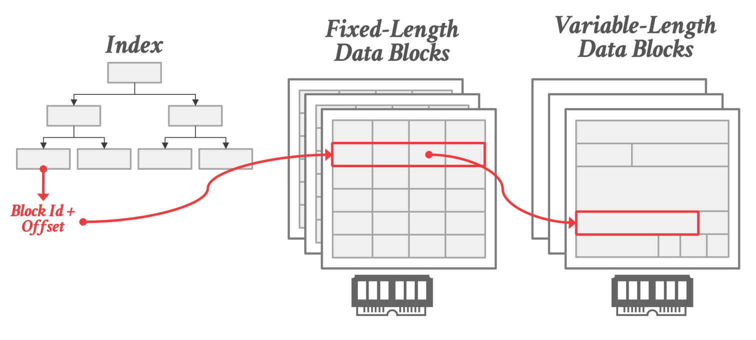
In-Memory DBMS: Data Organization

- An in-memory DBMS does **not** need to store the database in slotted pages but it will still organize tuples in pages:
  - **Direct memory pointers** vs. record ids
  - Fixed-length vs. variable-length data **memory pools**
  - Use checksums to detect software errors from trashing the database.
- The OS organizes memory in pages too. We already covered this.

In-Memory DBMS: Data Organization



In-Memory DBMS: Data Organization



Larger-than-Memory Databases

Observation

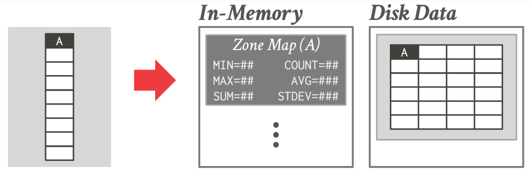
- DRAM is expensive (roughly $? per GB)
  - Expensive to buy.
  - Expensive to maintain (*e.g.*, energy associated with refreshing DRAM state).
- SSD is $? times cheaper than DRAM (roughly $? per GB)
- It would be nice if an in-memory DBMS could use cheaper storage without having to bring in the entire baggage of a disk-oriented DBMS.

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.
  - It is better to have only the **buffer manager** deal with moving data around
  - Rest of the DBMS can assume that data is in DRAM.
- Need to be aware of hardware access methods
  - In-memory Access = **Tuple**-Oriented. Why?
  - Disk Access = **Block**-Oriented.

OLAP

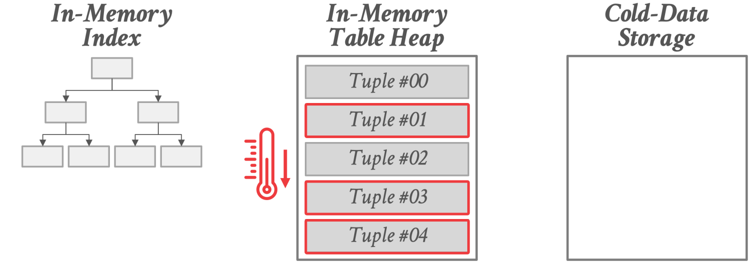
- OLAP queries generally access the entire table.
- Thus, an in-memory DBMS may handle OLAP queries in the same a disk-oriented DBMS does.
- All the optimizations in a disk-oriented DBMS apply here (*e.g.*, scan sharing, buffer pool bypass).



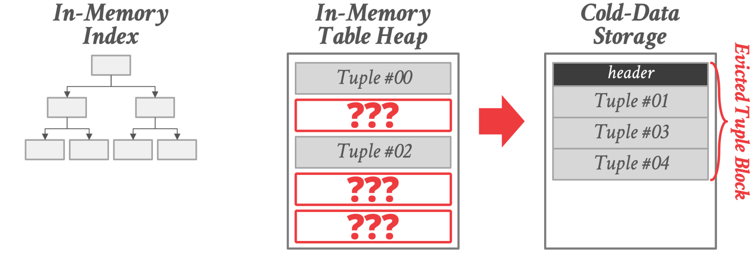
OLTP

- OLTP workloads almost always have **hot** and **cold** portions of the database.
  - We can assume txns will almost always access hot tuples.
- **Goal:** The DBMS needs a mechanism to move cold data out to disk and then retrieve it if it is ever needed again.

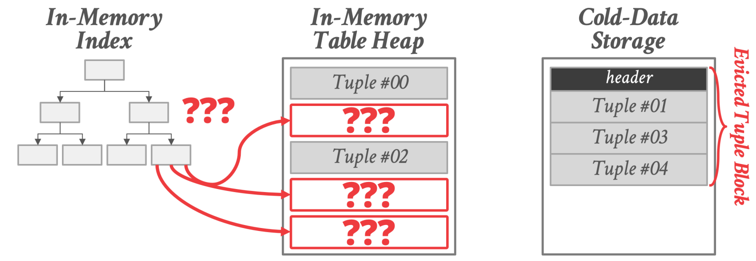
Larger-than-Memory Databases



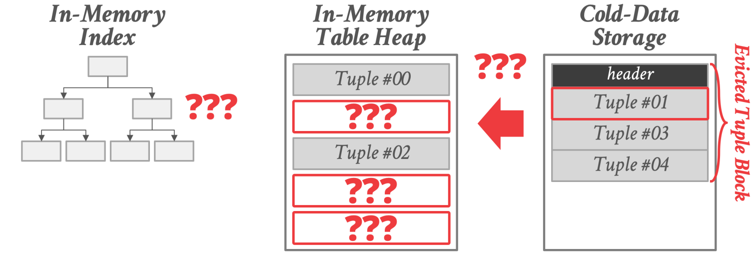
Larger-than-Memory Databases



Larger-than-Memory Databases



Larger-than-Memory Databases




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

Design Decisions

Design Decisions

- **Run-time Operation**
  - Cold Data Identification: When the DBMS runs out of DRAM space, what data should we evict?
- **Eviction Policies**
  - Timing: When to evict data?
  - Evicted Tuple Metadata: During eviction, what meta-data should we keep in DRAM to track disk-resident data and avoid false negatives?
- **Data Retrieval Policies**
  - Granularity: When we need data, how much should we bring in?
  - Merging: Where to put the retrieved data?

Reference

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.

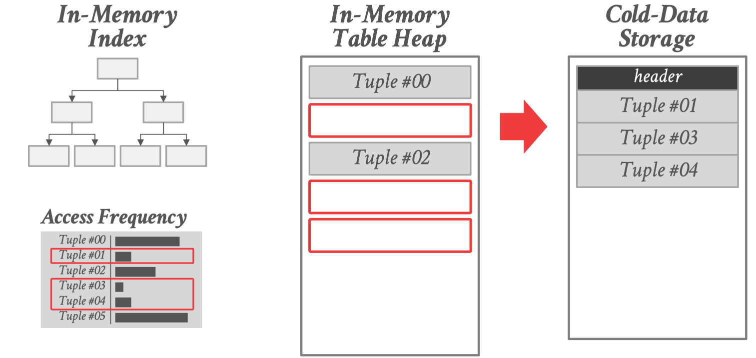
Eviction Timing

- **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.

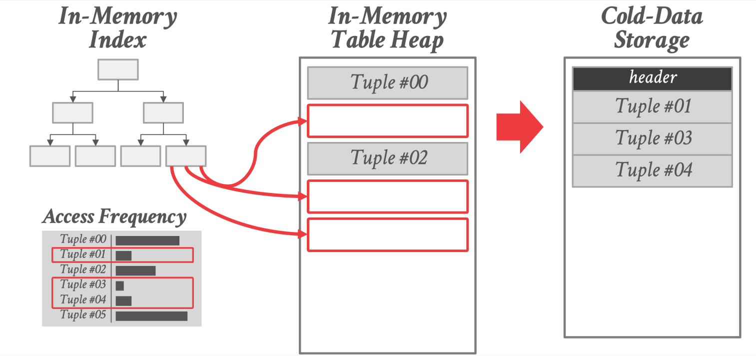
Evicted Tuple Metadata

- **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 an in-memory, **approximate** data structure for each index.
  - Only tells us whether tuple exists or not (with potential **false positives**)
  - Check on-disk index to find actual location
- **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



Evicted Tuple Metadata



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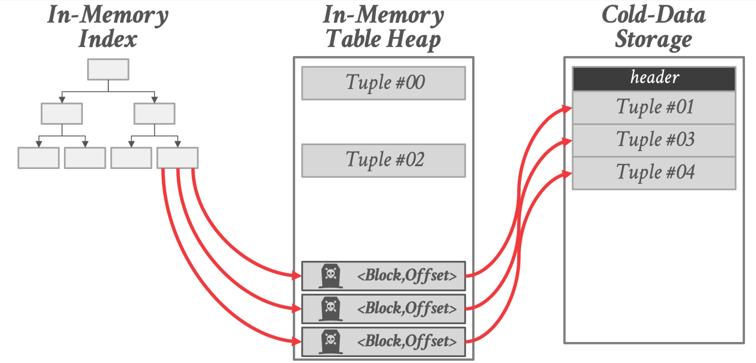
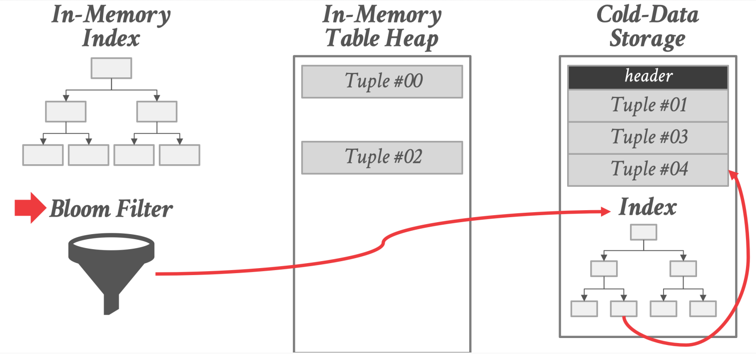


Evicted Tuple Metadata



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 statement.
  - 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.

Case Studies

Case Studies

- **Tuple-Oriented Systems**
  - H-Store – Anti-Caching
  - Hekaton – Project Siberia
  - EPFL's VoltDB Prototype
- **Block-Oriented Systems**
  - LeanStore – Hierarchical Buffer Pool
  - Umbra – Variable-length Buffer Pool

H-Store – Anti-Caching

- **Cold Tuple Identification:** On-line Identification
- **Eviction Timing:** Administrator-defined Threshold
- **Evicted Tuple Metadata:** Tombstones
- **Retrieval Mechanism:** Abort-and-restart Retrieval
- **Retrieval Granularity:** Block-level Granularity
- **Merging Threshold:** Always Merge
- Reference

HEKATON – PROJECT SIBERIA

- **Cold Tuple Identification:** Off-line Identification
- **Eviction Timing:** Administrator-defined Threshold
- **Evicted Tuple Metadata:** Bloom Filters
- **Retrieval Mechanism:** Synchronous Retrieval
- **Retrieval Granularity:** Tuple-level Granularity
- **Merging Threshold:** Always Merge
- Reference

EPFL VOLTDB

- **Cold Tuple Identification:** Off-line Identification
- **Eviction Timing:** OS Virtual Memory
- **Evicted Tuple Metadata:** N/A
- **Retrieval Mechanism:** Synchronous Retrieval
- **Retrieval Granularity:** Page-level Granularity
- **Merging Threshold:** Always Merge
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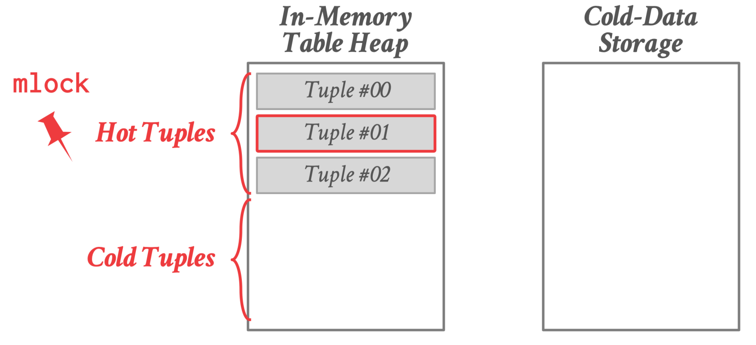
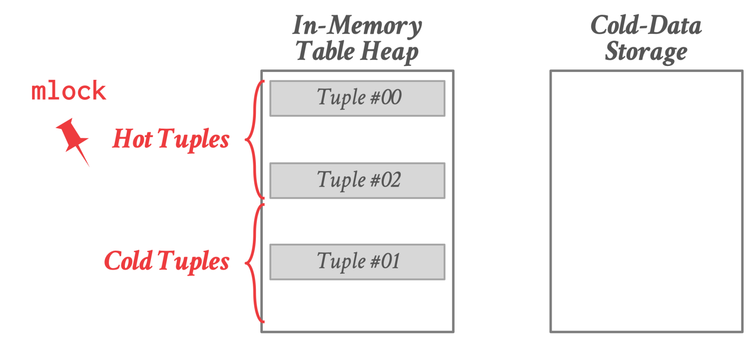
EPFL VOLTDB


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

EPFL VOLTDB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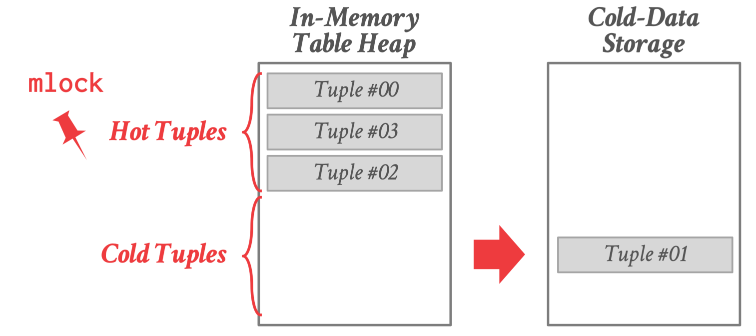
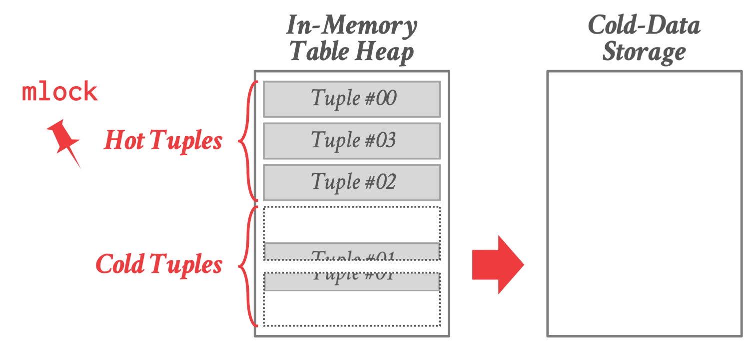


In-Memory Table Heap
Cold-Data Storage
mlock
Hot Tuples
Cold Tuples
Tuple #00
Tuple #03
Tuple #02
Tuple #01

EPFL VOLTDB



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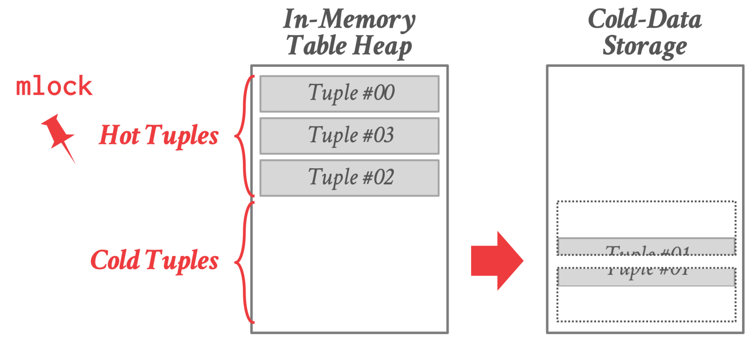
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Observation

- The systems that we have discussed so far are **tuple-oriented**.
  - The DBMS must track meta-data about individual tuples.
  - Does not reduce storage overhead of indexes.
  - Indexes may occupy up to 60% of DRAM in an OLTP database.
- **Goal:** Need an unified way to evict cold data from both tables and indexes with low overhead...

LeanStore

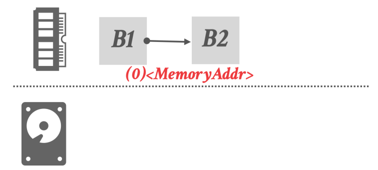
- In-memory storage manager from TUM that supports larger-than-memory databases.
  - Handles both tuples + indexes
  - Not part of the HyPer project.
- Hierarchical + Randomized Block Eviction
  - Use pointer swizzling to determine whether a block is evicted or not.
  - Instead of tracking when pages are accessed, randomly evict pages and then track whether they ended up getting used.
  - If yes, put it back in the hot space.
  - If not, then evict it.
- Reference

Pointer Swizzling

- Switch the contents of pointers based on whether the target object resides in memory **or** on disk.
- **Decentralized** way to track whether a page is in memory or not.
- We track everything with 64-bit pointers, but currently only use 48-bits.
  - Use **first bit** in address to tell what kind of address it is.
  - Only works if there is only one pointer to the object.

Pointer Swizzling

Pointer Swizzling



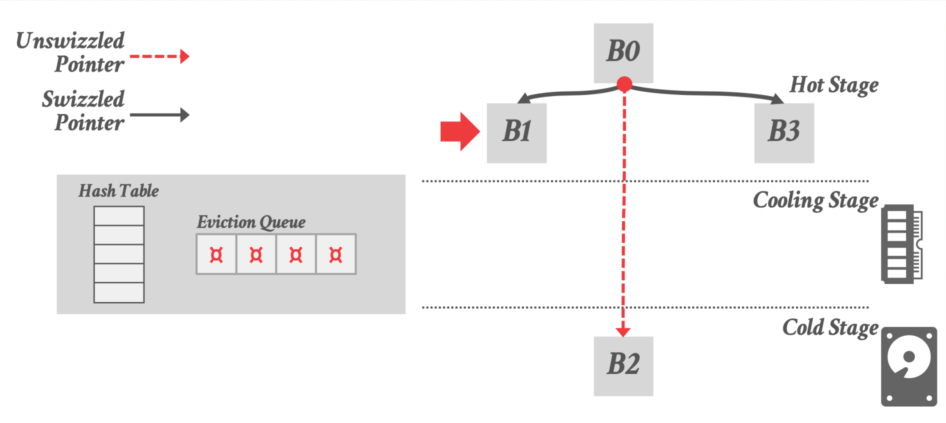
Replacement Strategy

- 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.
  - No centralized page table (as is the case in a disk-oriented DBMS).
- The DBMS can only evict a block if its children are also evicted.
  - This avoids the problem of evicting blocks that contain swizzled pointers
  - Otherwise, these pointers are invalid because they will point to old locations in memory.
  - If a block is selected but it has in-memory children, then it automatically switches to select one of its children.

Block Hierarchy



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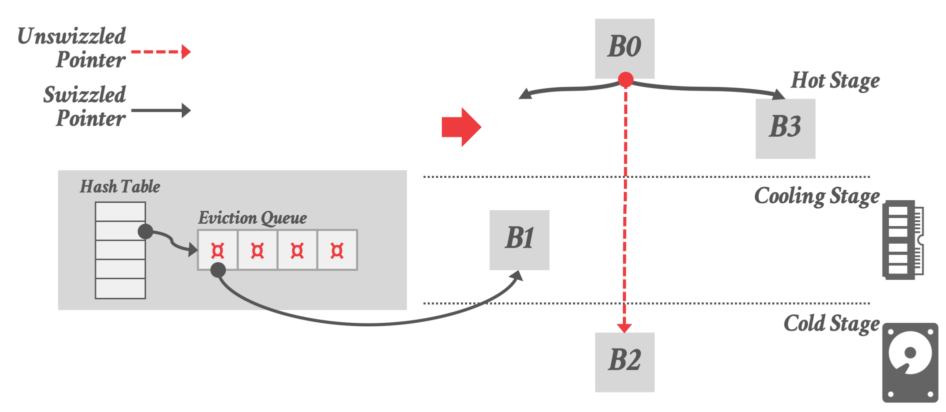

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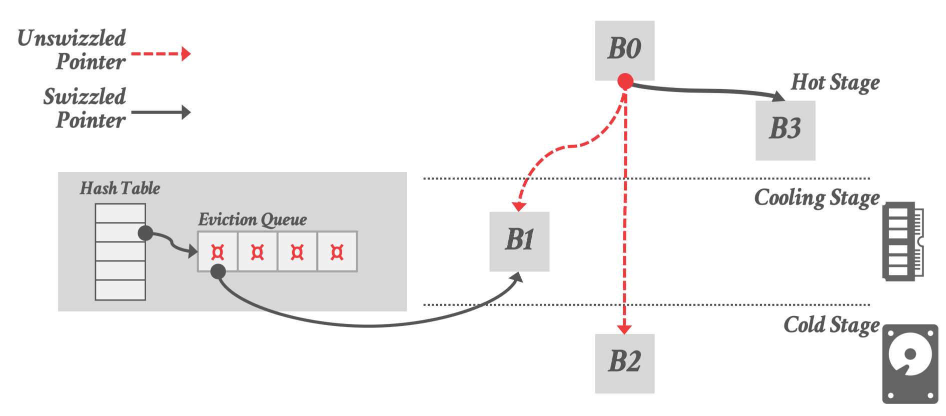
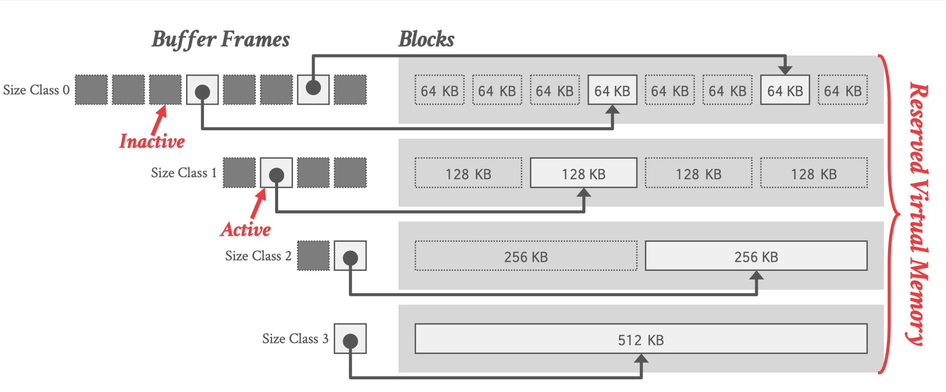


Umbra

- New DBMS from 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.
- Reference

Variable-Sized Buffer Pool



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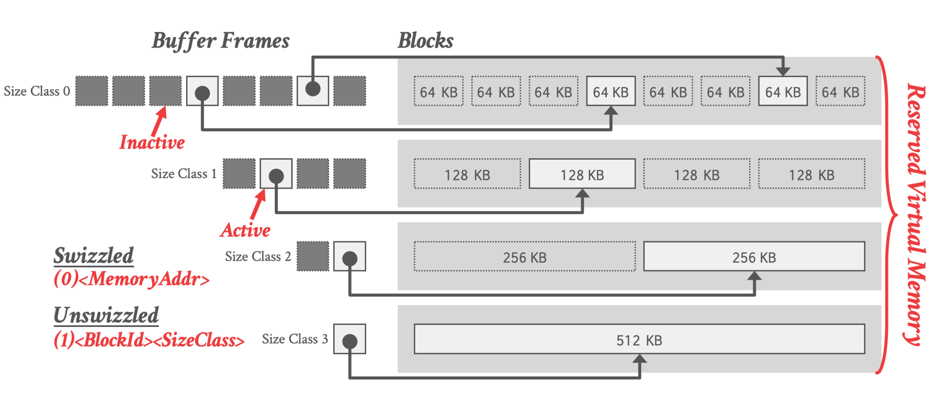

Conclusion

- We focused on working around the block-oriented access granularity and lower bandwidth of secondary storage.