

15-721 DATABASE SYSTEMS

Lecture #02 – In-Memory Databases

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TODAY'S AGENDA

Background

In-Memory DBMS Architectures

Peloton Overview

Project #1



BACKGROUND

Much of the history of DBMSs is about avoiding the slowness of disks.

Hardware was much different when the original DBMSs were designed:

- Uniprocessor (single-core CPU)
- RAM was severely limited.
- The database had to be stored on disk.



BACKGROUND

But now DRAM capacities are large enough that most databases can fit in memory.

So why not just use a “traditional” disk-oriented DBMS with a really large cache?



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 blocks called **slotted pages**.

The system uses an in-memory (volatile) buffer pool to cache blocks fetched from disk.

→ Its job is to manage the movement of those blocks back and forth between disk and memory.

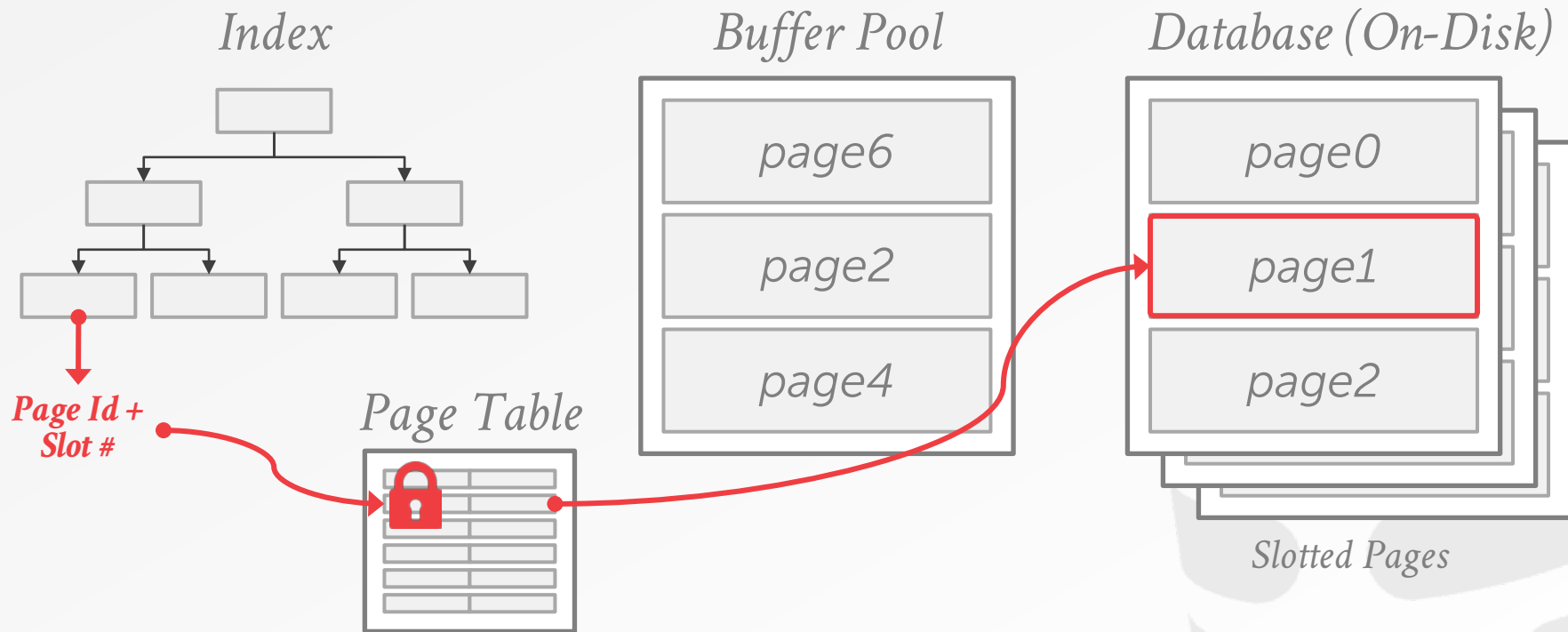
BUFFER POOL

When a query accesses a page, the DBMS checks to see if that page is already in memory:

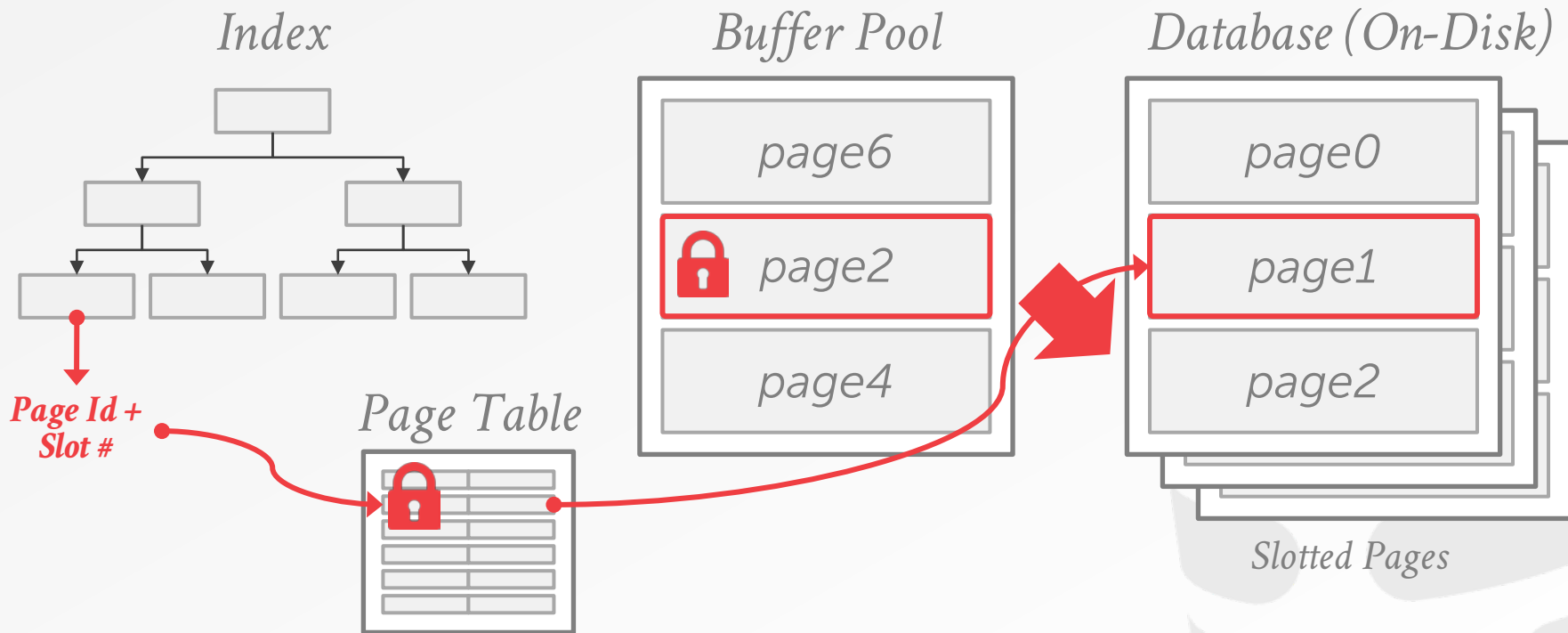
- If it's not, then the DBMS has to retrieve it from disk and copy it into a frame in its buffer pool.
- If there are no free frames, then find a page to evict.
- If the page being evicted is dirty, then the DBMS has to write it back to disk.

Once the page is in memory, the DBMS translates any on-disk addresses to their in-memory addresses.

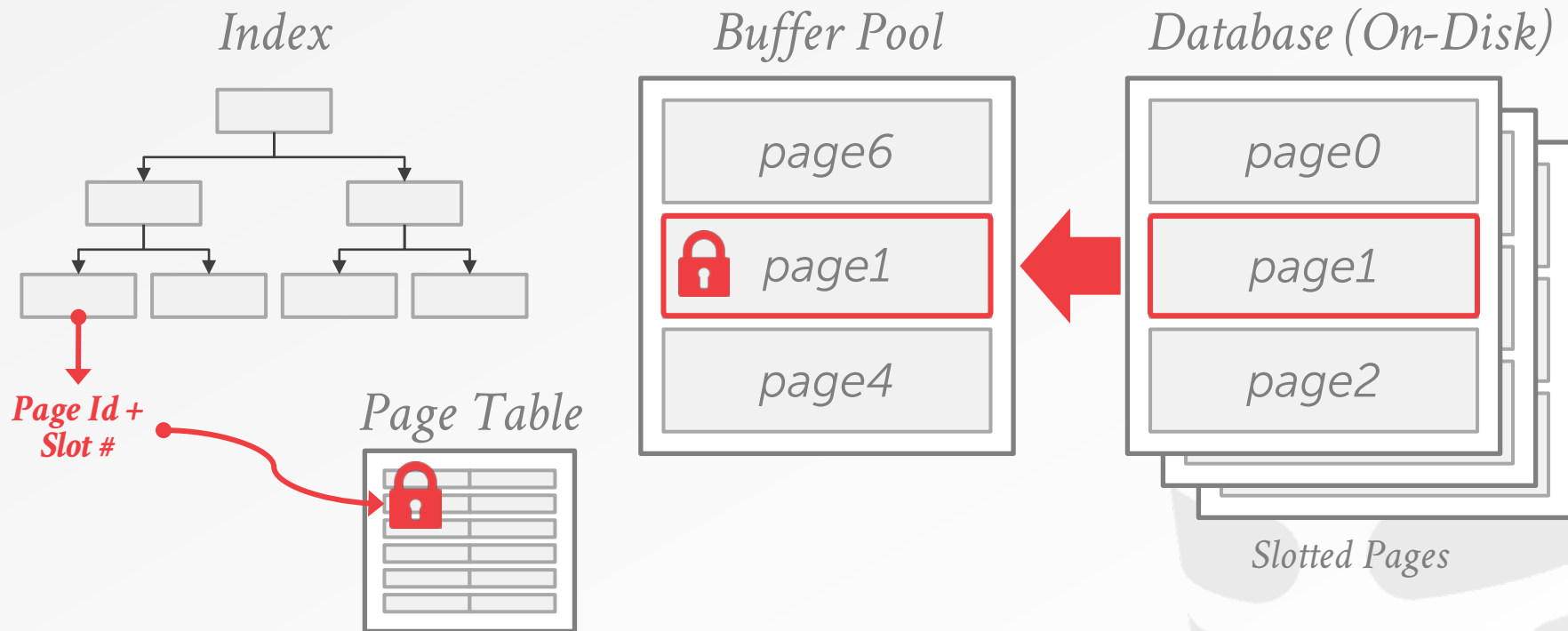
DATA ORGANIZATION



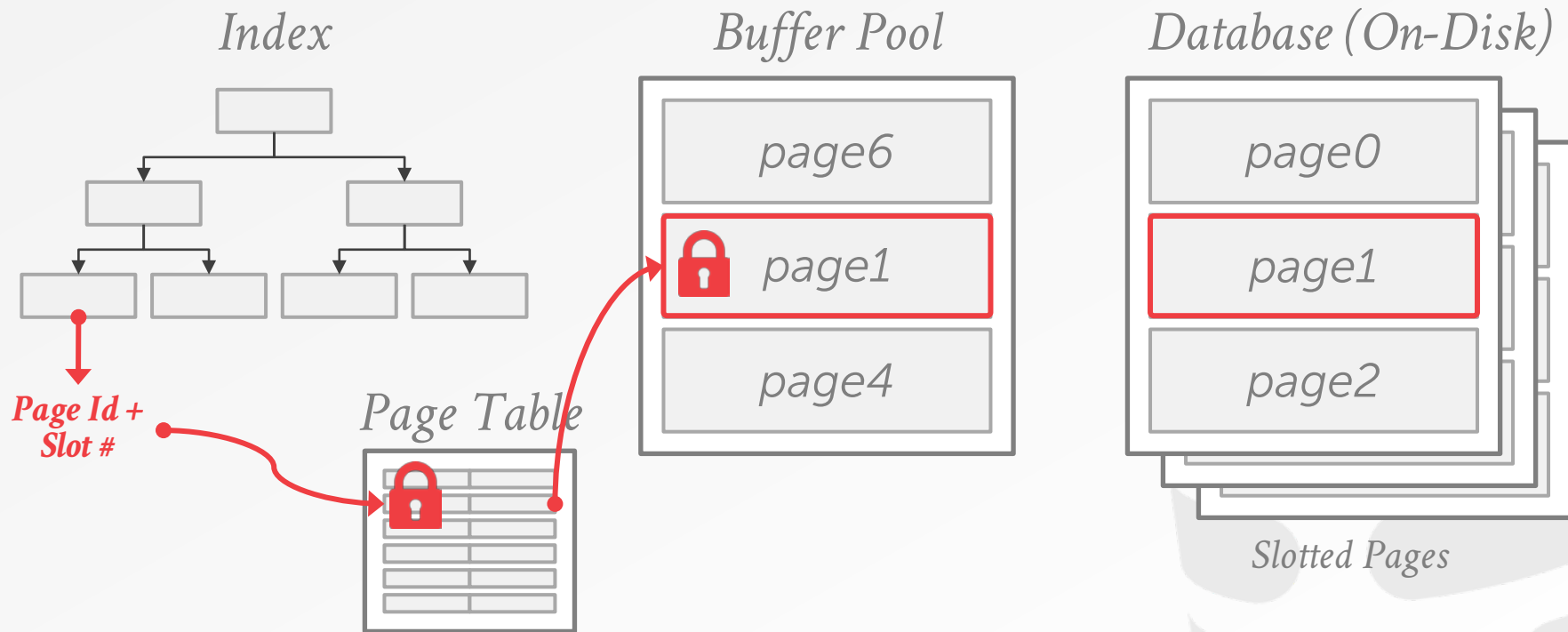
DATA ORGANIZATION



DATA ORGANIZATION



DATA ORGANIZATION



SLOTTED PAGES



SLOTTED PAGES

Variable-length Data



Fixed-length Data Slots

SLOTTED PAGES

Variable-length Data



Fixed-length Data Slots

BUFFER POOL

Every tuple access has to go through the buffer pool manager regardless of whether that data will always be in memory.

- Always have to translate a tuple's record id to its memory location.
- Worker thread has to **pin** pages that it needs to make sure that they are not swapped to disk.



CONCURRENCY CONTROL

In a disk-oriented DBMS, the system assumes that a txn could stall at any time when it tries to access data that is not in memory.

Execute other txns at the same time so that if one txn stalls then others can keep running.

- Has to set locks and latches to provide ACID guarantees for txns.
- Locks are stored in a separate data structure to avoid being swapped to disk.

LOGGING & RECOVERY

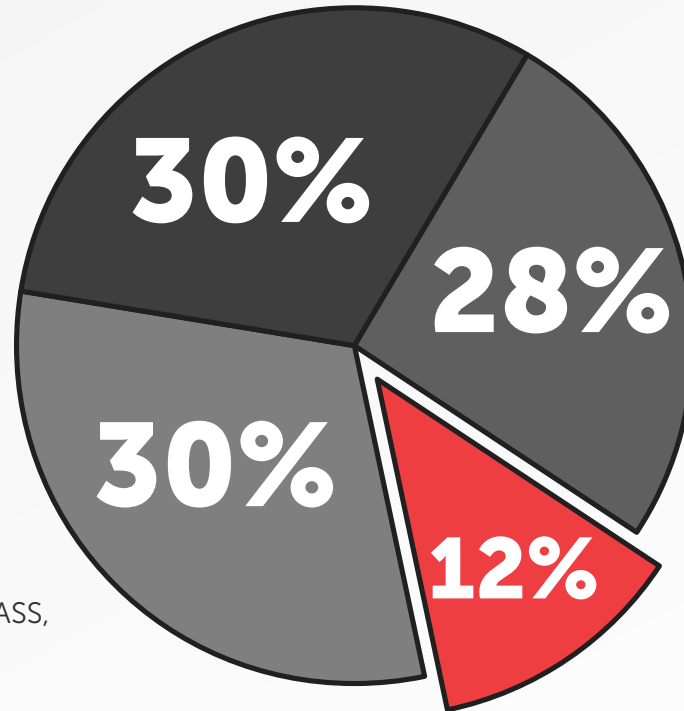
Most DBMSs use **STEAL + NO-FORCE** buffer pool policies, so all modifications have to be flushed to the **WAL** before a txn can commit.

Each log entry contains the before and after image of record modified.



DISK-ORIENTED DBMS OVERHEAD

Measured CPU Cycles



■ BUFFER POOL

■ LOCKING

■ RECOVERY

■ REAL WORK

OLTP THROUGH THE LOOKING GLASS,
AND WHAT WE FOUND THERE
SIGMOD, pp. 981-992, 2008.

IN-MEMORY DBMSS

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.



WHY NOT MMAP?

Memory-map a database file into DRAM and let the OS be in charge of swapping data in and out as needed.

Use **madvise** and **msync** to give hints to the OS about what data is safe to flush.

Notable mmap DBMSs:

- [MongoDB](#) (pre [WiredTiger](#))
- [MonetDB](#)
- [LMDB](#)



WHY NOT MMAP?

Using **mmap** gives up fine-grained control on the contents of memory.

- Cannot perform non-blocking memory access.
- The “on-disk” representation has to be the same as the “in-memory” representation.
- The DBMS has no way of knowing what pages are in memory or not.

A well-written DBMS always knows best.

BOTTLENECKS

If I/O is no longer the slowest resource, much of the DBMS's architecture will have to change account for other bottlenecks:

- Locking/latching
- Cache-line misses
- Pointer chasing
- Predicate evaluations
- Data movement & copying
- Networking (between application & DBMS)



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



LET'S TALK ABOUT STORAGE & RECOVERY
METHODS FOR NON-VOLATILE MEMORY
DATABASE SYSTEMS
SIGMOD, pp. 707-722, 2015.

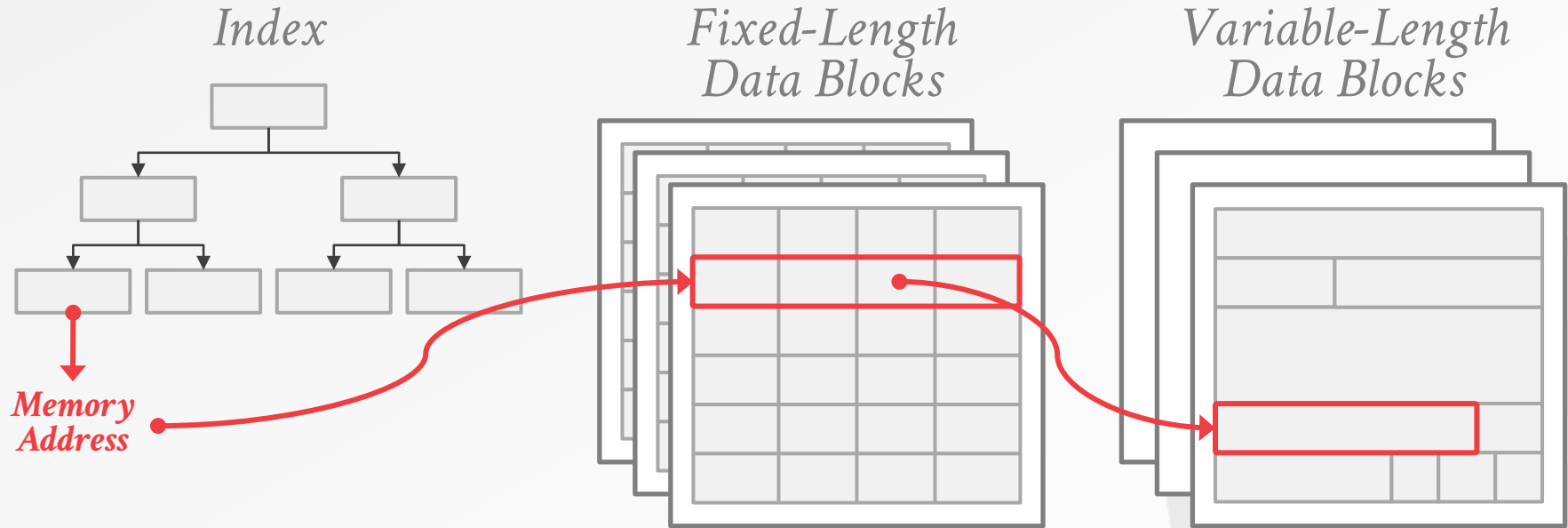
DATA ORGANIZATION

An in-memory DBMS does not need to store the database in slotted pages but it will still organize tuples in blocks:

- Direct memory pointers vs. record ids
- Fixed-length vs. variable-length data pools
- Use block checksums to detect software errors from trashing the database.



DATA ORGANIZATION



CONCURRENCY CONTROL

Observation: The cost of a txn acquiring a lock is the same as accessing data.

In-memory DBMS may want to detect conflicts between txns at a different granularity.

- **Fine-grained locking** allows for better concurrency but requires more locks.
- **Coarse-grained locking** requires fewer locks but limits the amount of concurrency.

CONCURRENCY CONTROL

The DBMS can store locking information about each tuple together with its data.

→ This helps with CPU cache locality.

→ Mutexes are too slow. Need to use CAS instructions.

New bottleneck is contention caused from txns trying access data at the same time.



INDEXES

Main-memory indexes were proposed in 1980s when cache and memory access speeds were roughly equivalent.

But then caches got faster than main memory:

→ Memory-optimized indexes performed worse than the B+trees because they were not cache aware.

Indexes are usually rebuilt in an in-memory DBMS after restart to avoid logging overhead.

QUERY PROCESSING

The best strategy for executing a query plan in a DBMS changes when all of the data is already in memory.

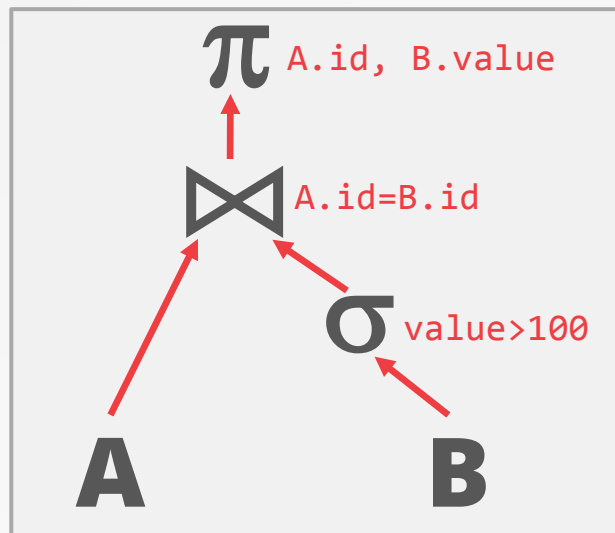
→ Sequential scans are no longer significantly faster than random access.

The traditional **tuple-at-a-time** iterator model is too slow because of function calls.

→ This problem is more significant in OLAP DBMSs.

QUERY PROCESSING

```
SELECT A.id, B.value
FROM A, B
WHERE A.id = B.id
AND B.value > 100
```



Tuple-at-a-time

→ Each operator calls **next** on their child to get the next tuple to process.

Operator-at-a-time

→ Each operator materializes their entire output for their parent operator.

Vector-at-a-time

→ Each operator calls **next** on their child to get the next chunk of data to process.

LOGGING & RECOVERY

The DBMS still needs a WAL on non-volatile storage since the system could halt at anytime.

- Use **group commit** to batch log entries and flush them together to amortize **fsync** cost.
- May be possible to use more lightweight logging schemes if using coarse-grained locking (redo only).



LOGGING & RECOVERY

The system also still takes checkpoints to speed up recovery time.

Different methods for checkpointing:

- Old idea: Maintain a second copy of the database in memory that is updated by replaying the WAL.
- Switch to a special “copy-on-write” mode and then write a dump of the database to disk.
- Fork the DBMS process and then have the child process write its contents to disk.

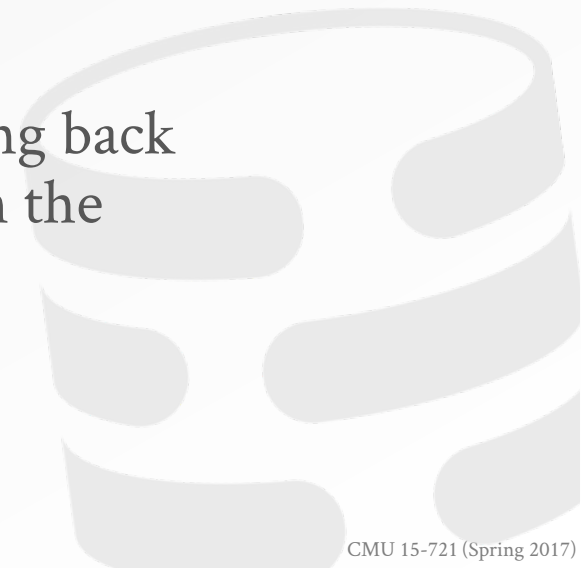
LARGER-THAN-MEMORY DATABASES

DRAM is fast, but data is not accessed with the same frequency and in the same manner.

→ Hot Data: OLTP Operations

→ Cold Data: OLAP Queries

We will study techniques for how to bring back disk-resident data without slowing down the entire system.



NON-VOLATILE MEMORY

Emerging hardware that is able to get almost the same read/write speed as DRAM but with the persistence guarantees of an SSD.

→ Also called *storage class memory*

→ Examples: Phase-Change Memory, Memristors

It's not clear how to build a DBMS to operate on this kind memory.

Again, we'll cover this topic later.



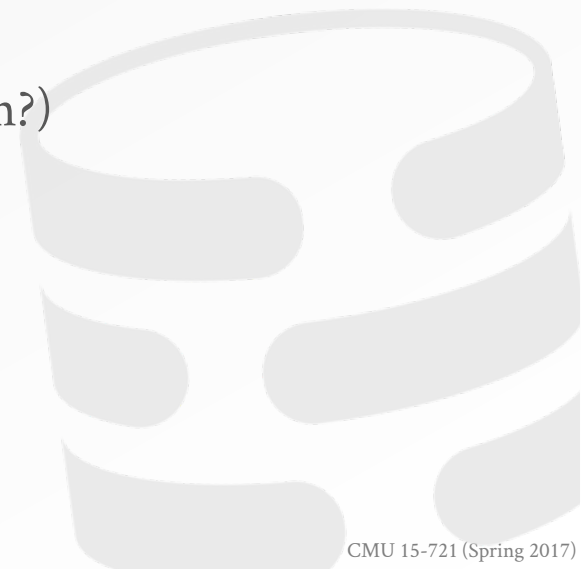


PELTON DBMS

CMU's in-memory hybrid relational DBMS

- Multi-version concurrency control.
- Lock-free Bw-Tree Index
- Tile-based storage manager.
- Multi-threaded architecture.
- Write-Ahead Logging + Checkpoints (broken?)

Currently supports some of SQL-92.



PROJECT #1

Implement the **EXTRACT** SQL function.



PROJECT #1 – TESTING

We are providing you with a basic C++ unit test for you check your implementation.

We also have a SQL batch script that will execute a couple different queries.

We strongly encourage you to do your own additional testing.



PROJECT #1 – GRADING

We will run additional tests beyond what we provided you for grading.

We will also use Valgrind when testing your code.

All source code must pass ClangFormat syntax formatting checker.

→ See Peloton [documentation](#) for formatting guidelines

DEVELOPMENT ENVIRONMENT

Peloton only builds on 64-bit Linux.

But you can do development on either Linux or OSX (through a VM).

→ We have a Vagrant config file to automatically create a development Ubuntu VM for you.

This is CMU so I'm going to assume that each of you are capable of getting access to a machine.

PROJECT #1

Due Date: January 31st, 2017 @ 11:59pm
Projects will be turned in using Autolab.

Full description and instructions:

<http://15721.courses.cs.cmu.edu/spring2017/project1.html>

PARTING THOUGHTS

Disk-oriented DBMSs are a relic of the past.

→ Most databases fit entirely in DRAM on a single machine.

The world has finally become comfortable with in-memory data storage and processing.

Never use **mmap** for your DBMS.



NEXT CLASS

Transactions & Concurrency Control