

Buffer Pools



Lecture #05



Database Systems
15-445/15-645
Fall 2018

AP

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Computer Science
Carnegie Mellon Univ.

UPCOMING DATABASE EVENTS

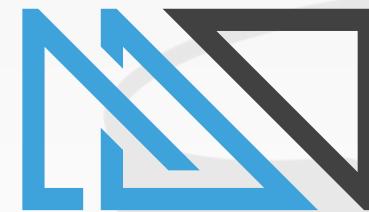
Relational AI Talk

- Wednesday Sep 12th @ 4:00pm
- GHC 8102

MapD Talk

- Thursday Sept 20th @ 12pm
- CIC 4th Floor

relationalAI



MAPD

DATABASE STORAGE

Problem #1: How the DBMS represents the database in files on disk.

Problem #2: How the DBMS manages its memory and move data back-and-forth from disk.



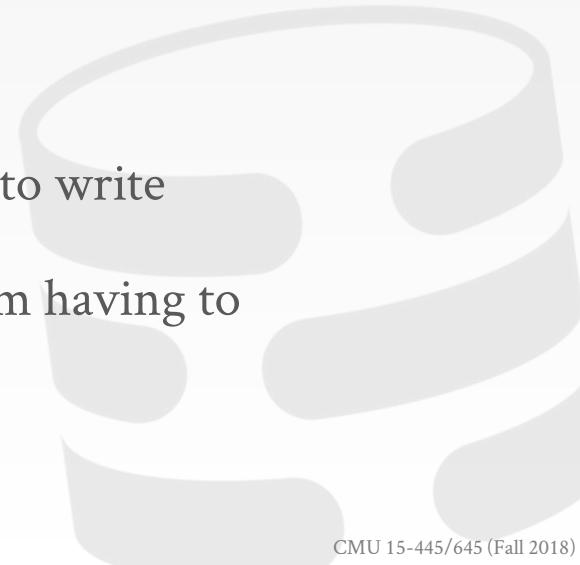
DATABASE STORAGE

Spatial Control:

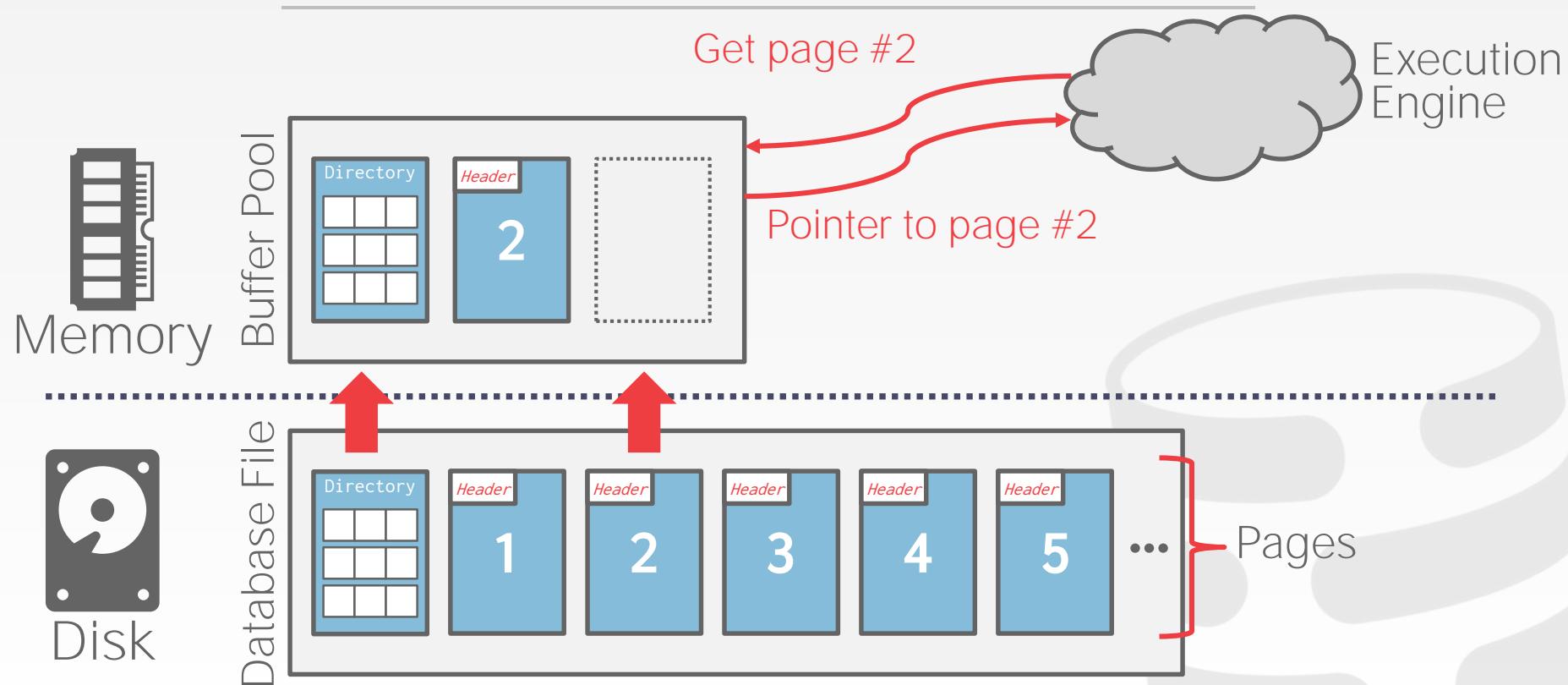
- Where to write pages on disk.
- The goal is to keep pages that are used together often as physically close together as possible on disk.

Temporal Control:

- When to read pages into memory, and when to write them to disk.
- The goal is minimize the number of stalls from having to read data from disk.



DISK-ORIENTED DBMS



TODAY'S AGENDA

Buffer Pool Manager
Replacement Policies
Allocation Policies
Other Memory Pools



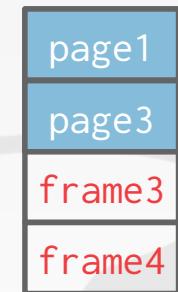
BUFFER POOL ORGANIZATION

Memory region organized as an array of fixed-size pages.

An array entry is called a frame.

When the DBMS requests a page, an exact copy is placed into one of these frames.

Buffer
Pool



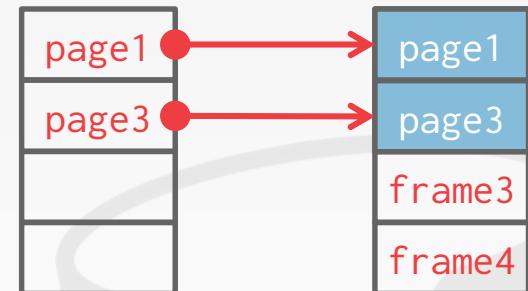
On-Disk File

BUFFER POOL META-DATA

The page table keeps track of pages that are currently in memory.

Also maintains additional meta-data per page:
→ Dirty Flag
→ Pin/Reference Counter

Page Table Buffer Pool

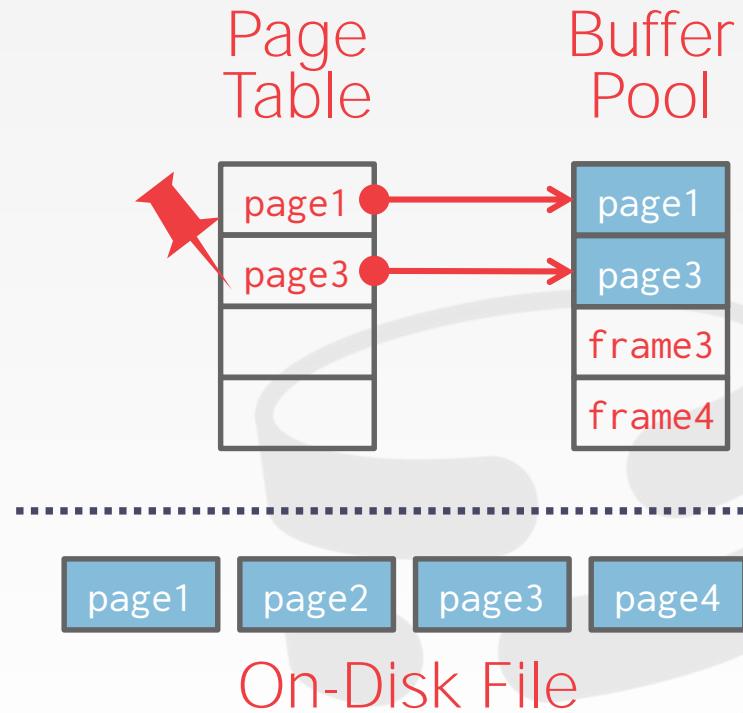


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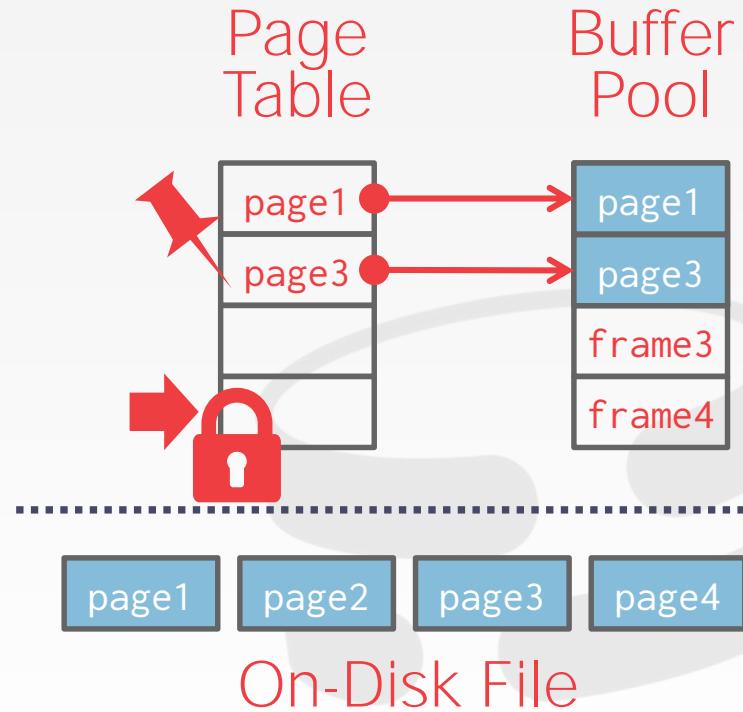
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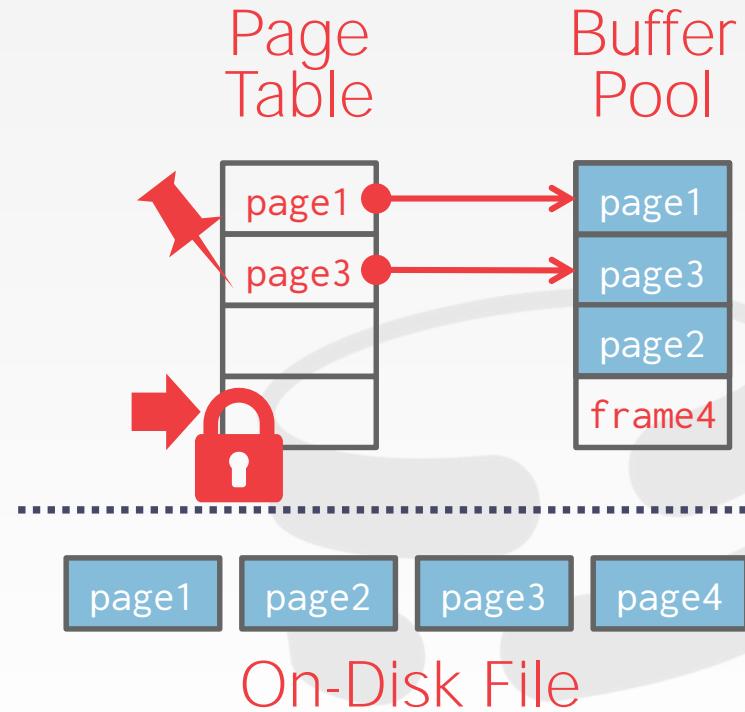
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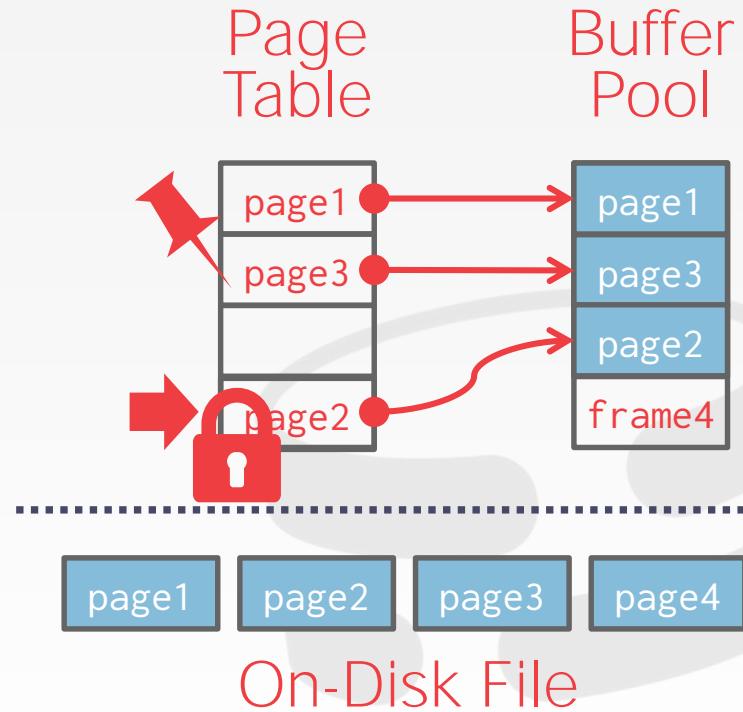
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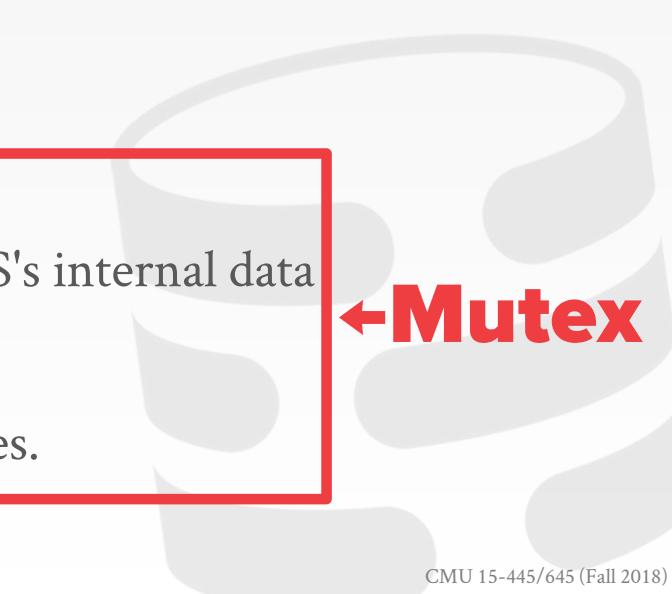
LOCKS VS. LATCHES

Locks:

- Protects the database's logical contents from other transactions.
- Held for transaction duration.
- Need to be able to rollback changes.

Latches:

- Protects the critical sections of the DBMS's internal data structure from other threads.
- Held for operation duration.
- Do not need to be able to rollback changes.



←Mutex

PAGE TABLE VS. PAGE DIRECTORY

The **page directory** is the mapping from page ids to page locations in the database files.

- All changes must be recorded on disk to allow the DBMS to find on restart.

The **page table** is the mapping from page ids to a copy of the page in buffer pool frames.

- This is an in-memory data structure that does not need to be stored on disk.

MULTIPLE BUFFER POOLS

The DBMS does not always have a single buffer pool for the entire system.

- Multiple buffer pool instances
- Per-database buffer pool
- Per-page type buffer pool

Helps reduce latch contention and improve locality.



PRE-FETCHING

The DBMS can also prefetch pages based on a query plan.

- Sequential Scans
- Index Scans

Buffer Pool

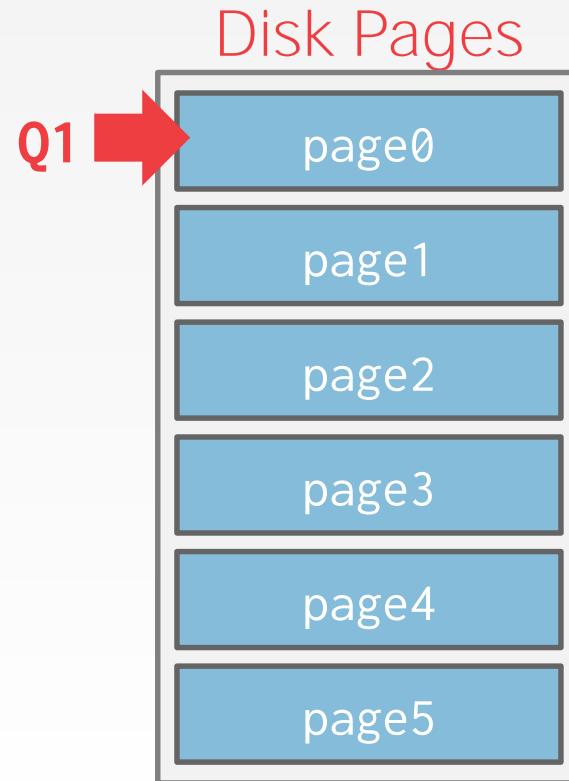
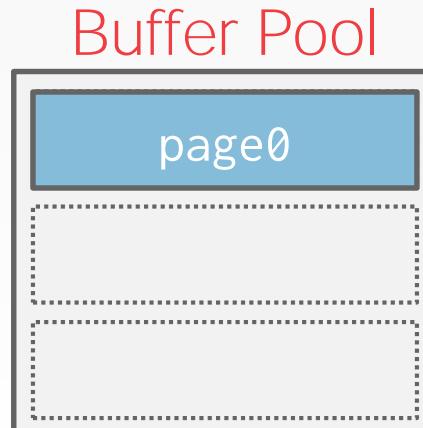


Disk Pages



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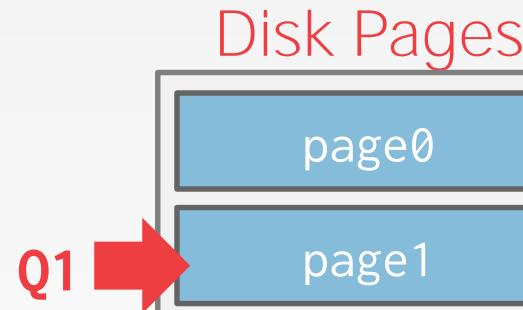


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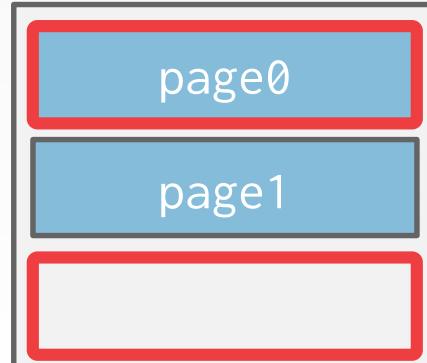


PRE-FETCHING

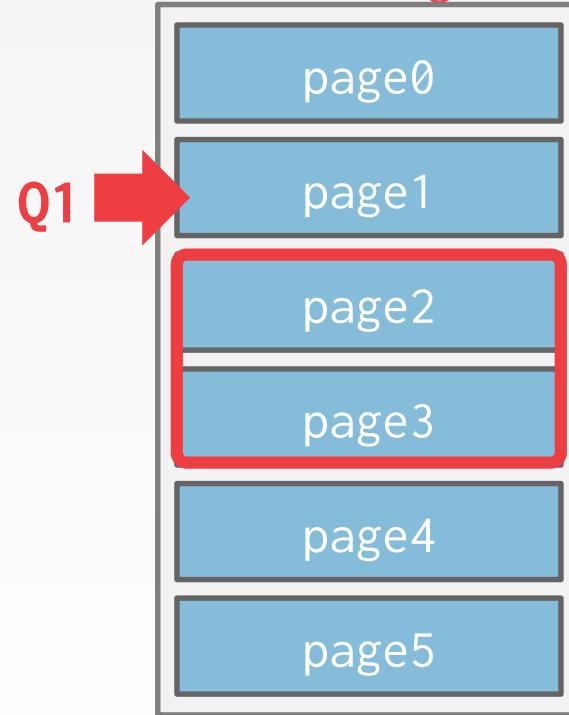
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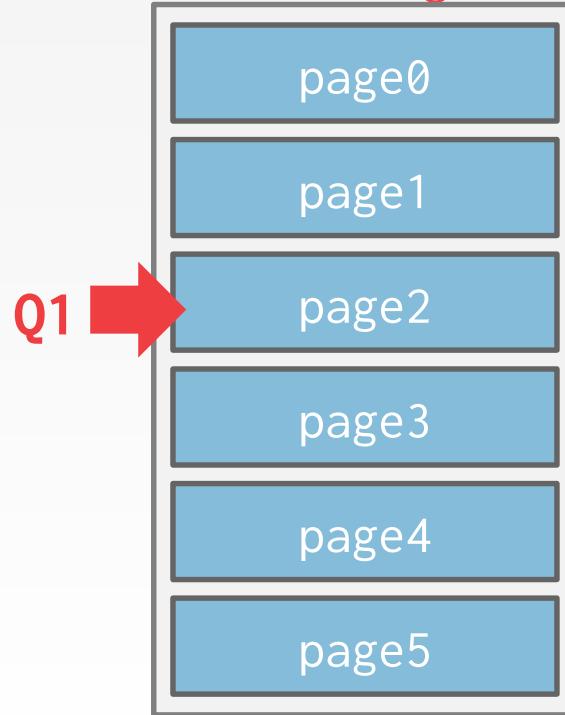
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Disk Pages



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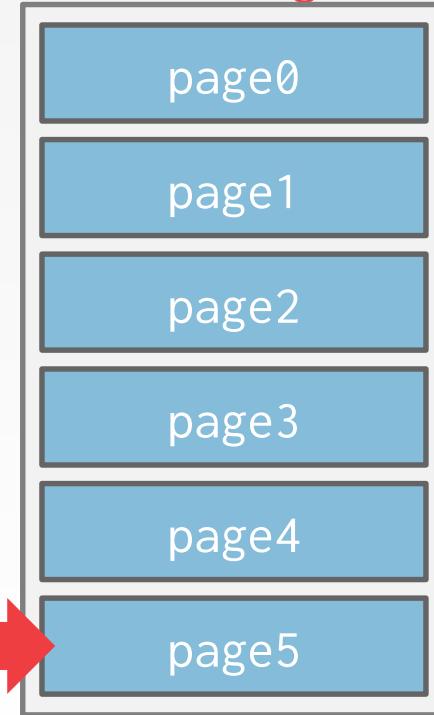
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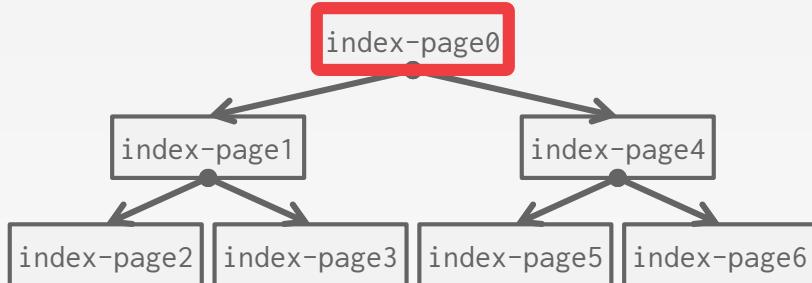
Buffer Pool



Disk Pages



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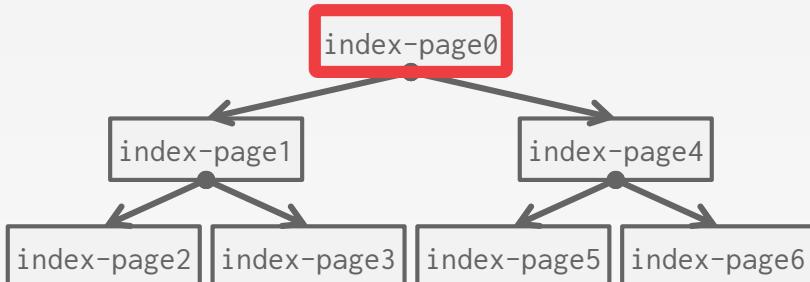
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Disk Pages



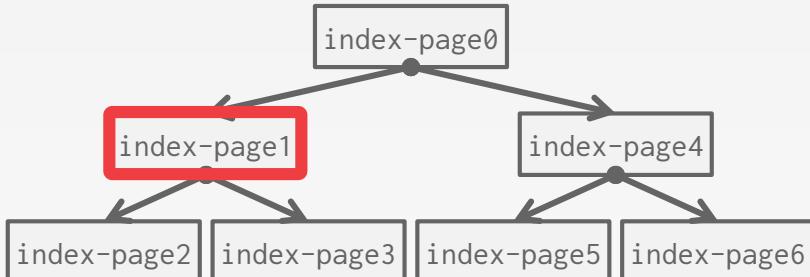
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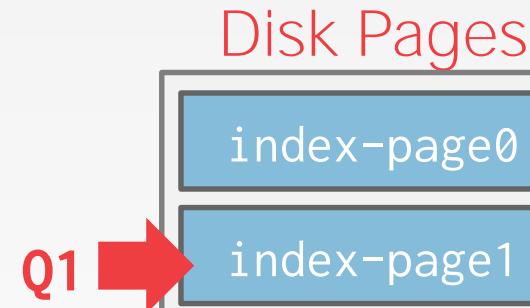
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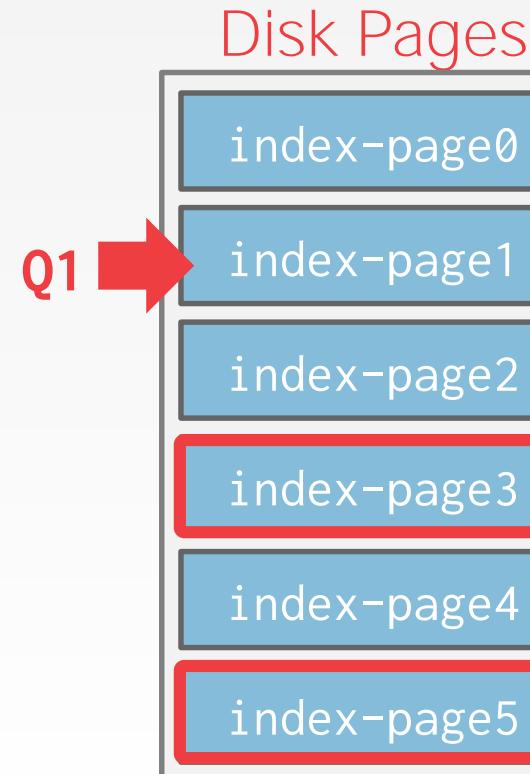
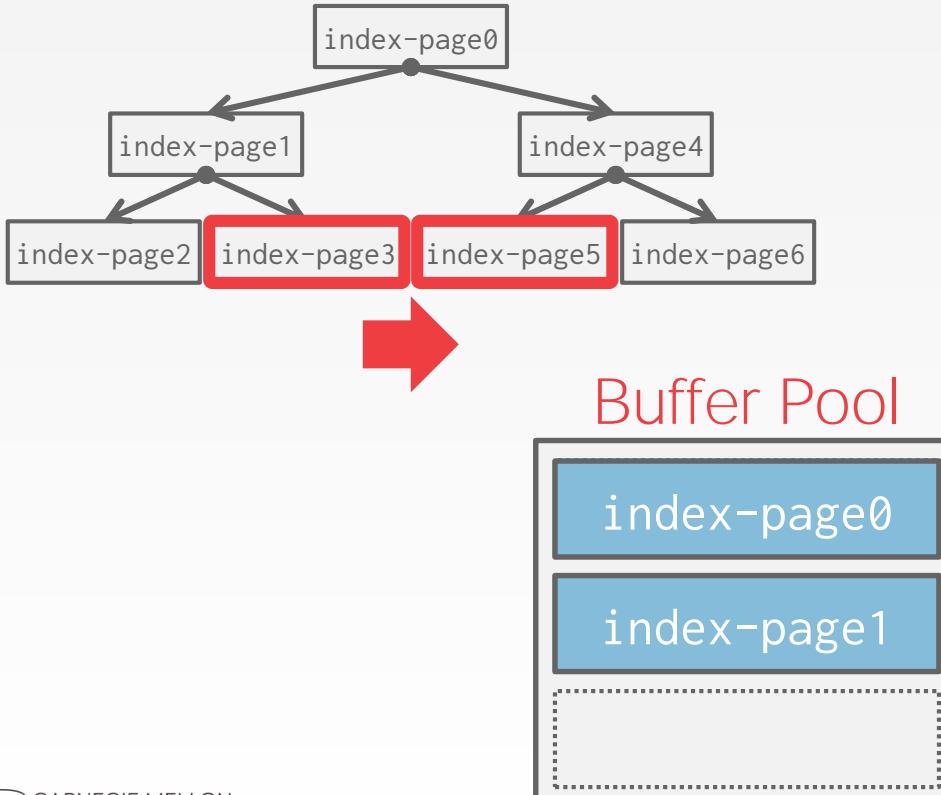
PRE-FETCHING



Buffer Pool



PRE-FETCHING



SCAN SHARING

Queries are able to reuse data retrieved from storage or operator computations.

- This is different from result caching.

Allow multiple queries to attach to a single cursor that scans a table.

- Queries do not have to be exactly the same.
- Can also share intermediate results.



SCAN SHARING

If a query starts a scan and if there one already doing this, then the DBMS will attach to the second query's cursor.

→ The DBMS keeps track of where the second query joined with the first so that it can finish the scan when it reaches the end of the data structure.

Fully supported in IBM DB2 and MSSQL.

Oracle only supports cursor sharing for identical queries.



Microsoft®
SQL Server

IBM DB2

ORACLE

SCAN SHARING

Q1 `SELECT SUM(val) FROM A`

Buffer Pool



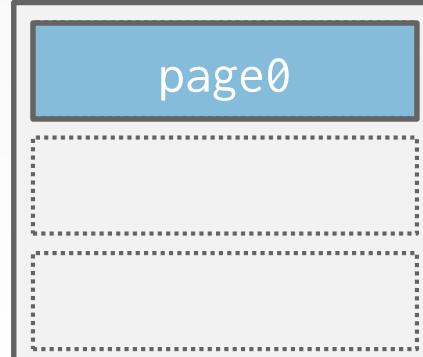
Disk Pages



SCAN SHARING

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Disk Pages



SCAN SHARING

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Buffer Pool



Disk Pages

Q1



SCAN SHARING

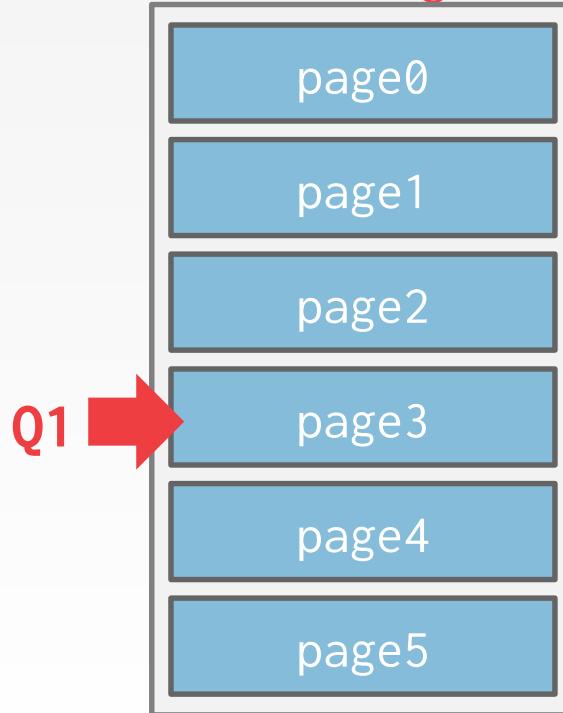
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Buffer Pool



Disk Pages



SCAN SHARING

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Disk Pages

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SCAN SHARING

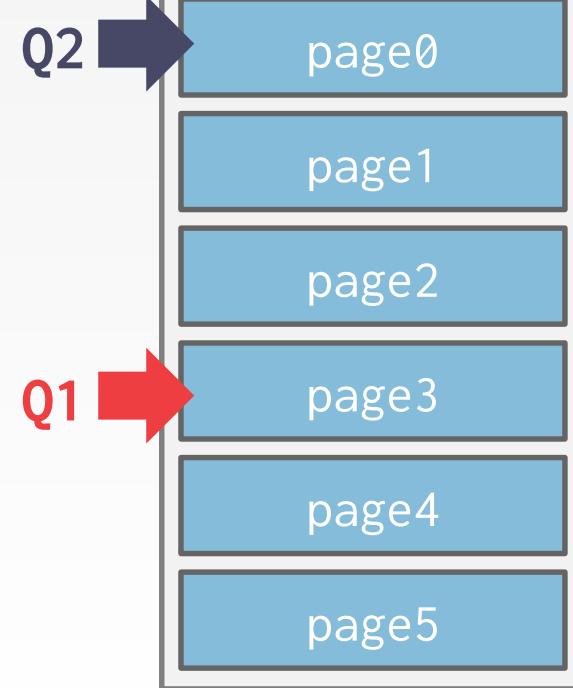
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Q2 `SELECT AVG(val) FROM A`

Buffer Pool



Disk Pages



SCAN SHARING

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Disk Pages

Q2 Q1 



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Disk Pages

Q2 Q1



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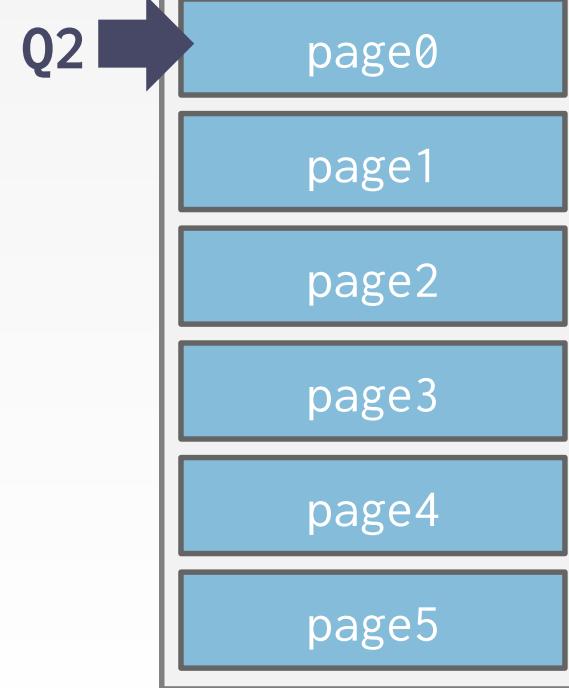
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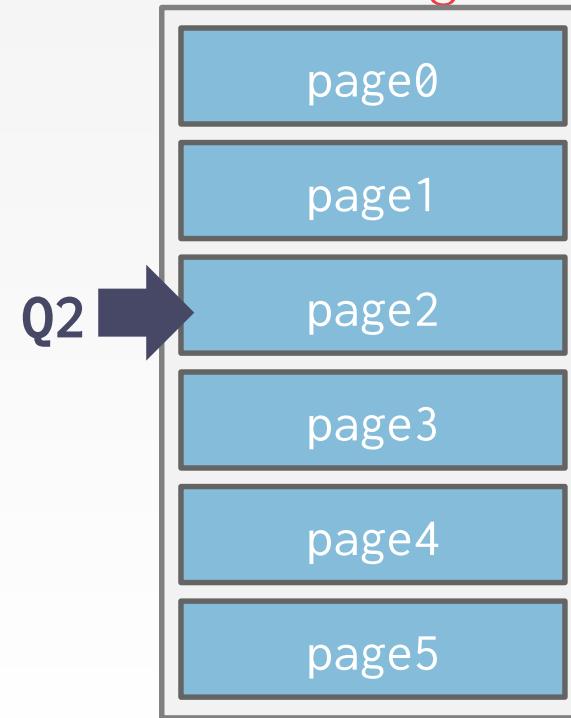
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Buffer Pool



Disk Pages



BUFFER POOL BYPASS

The sequential scan operator will not store fetched pages in the buffer pool to avoid overhead.

- Memory is local to running query.
- Works well if operator needs to read a large sequence of pages that are contiguous on disk.

Called "Light Scans" in Informix.

The Informix logo features the word "Informix" in a bold, black, sans-serif font. The letter "i" is stylized with a red dot above it, and the letter "x" is replaced by a blue graphic consisting of three horizontal bars of decreasing length from left to right.[®]

OS PAGE CACHE

Most disk operations go through the OS API.

Unless you tell it not to, the OS maintains its own filesystem cache.

Most DBMSs use direct I/O (O_DIRECT) to bypass the OS's cache.

- Redundant copies of pages.
- Different eviction policies.

BUFFER REPLACEMENT POLICIES

When the DBMS needs to free up a frame to make room for a new page, it must decide which page to evict from the buffer pool.

Goals:

- Correctness
- Accuracy
- Speed
- Meta-data overhead



LEAST-RECENTLY USED

Maintain a timestamp of when each page was last accessed.

When the DBMS needs to evict a page, select the one with the oldest timestamp.

→ Keep the pages in sorted order to reduce the search time on eviction.



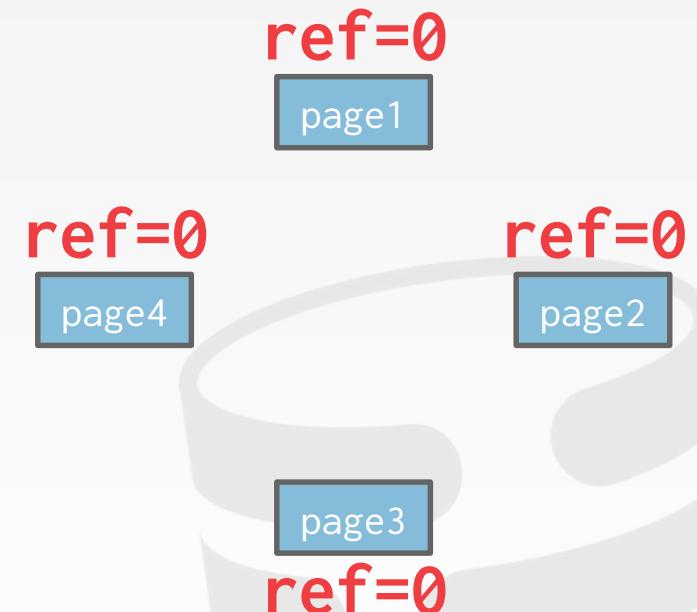
CLOCK

Approximation of LRU without needing a separate timestamp per page.

- Each page has a reference bit.
- When a page is accessed, set to 1.

Organize the pages in a circular buffer with a "clock hand":

- Upon sweeping, check if a page's bit is set to 1.
- If yes, set to zero. If no, then evict.



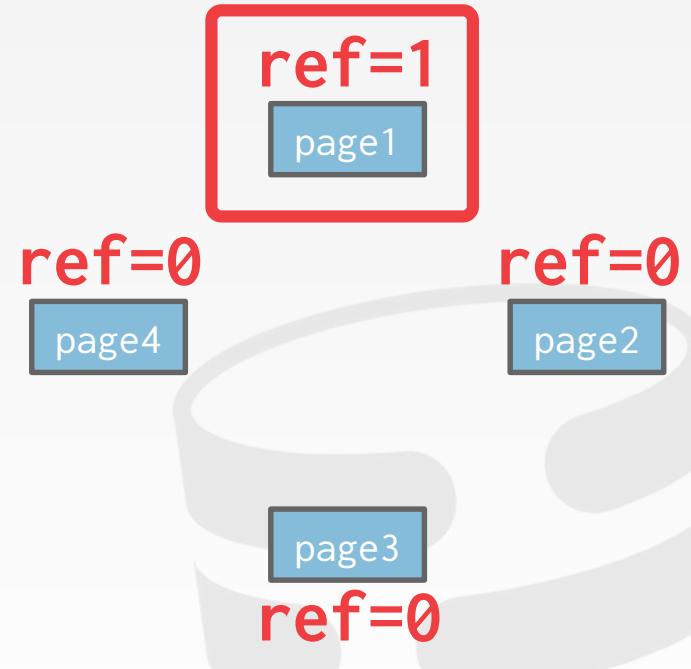
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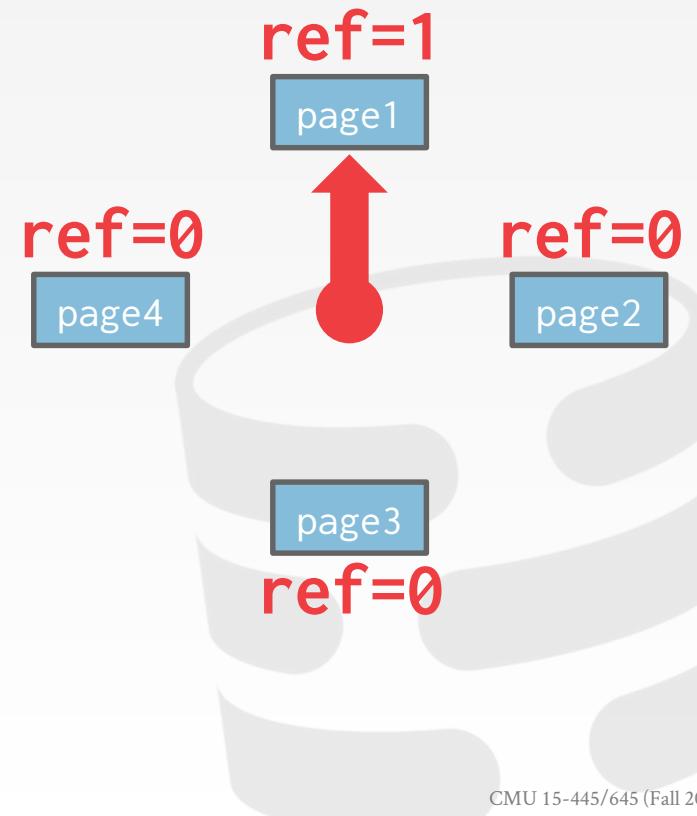
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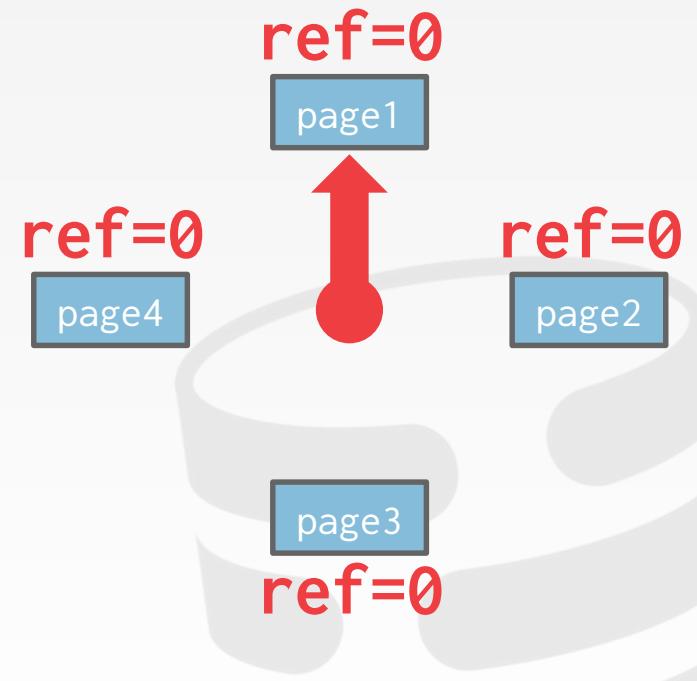
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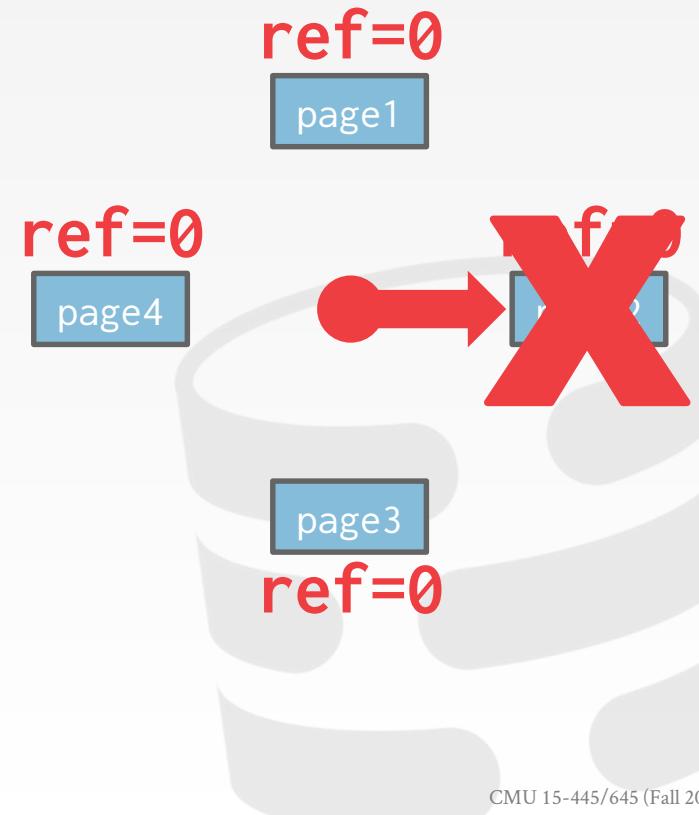
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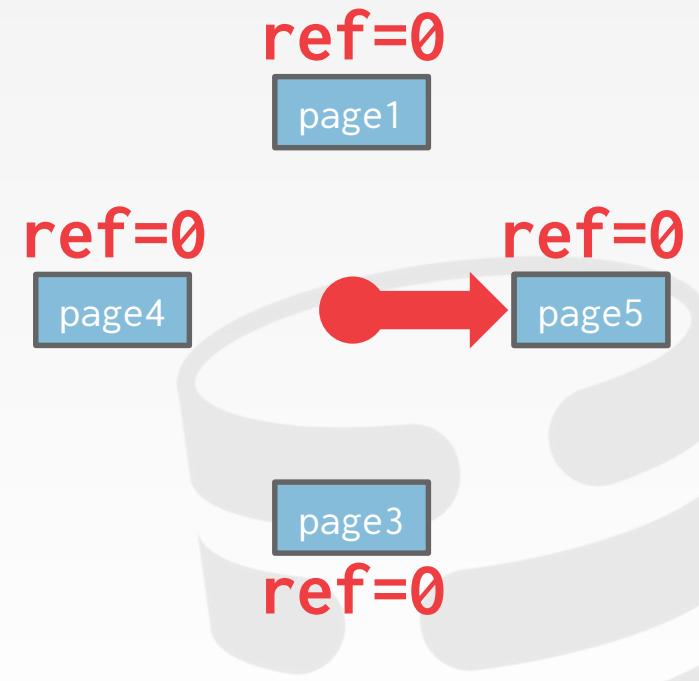
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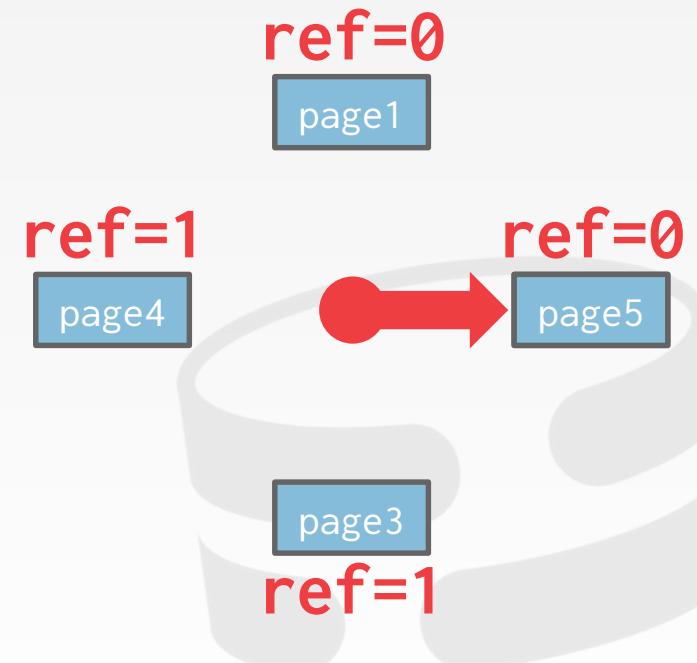
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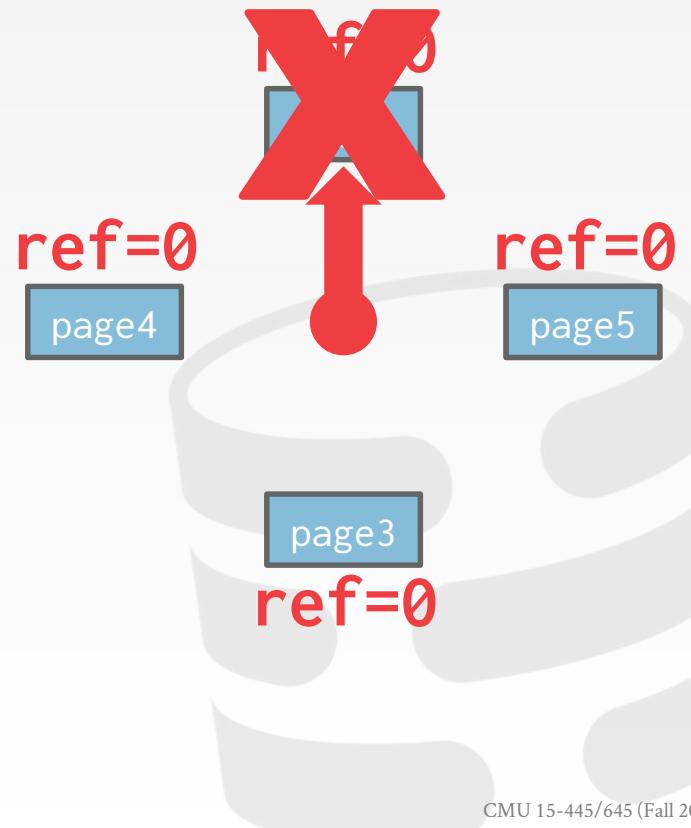
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PROBLEMS

LRU and CLOCK replacement policies are susceptible to sequential flooding.

- A query performs a sequential scan that reads every page.
- This pollutes the buffer pool with pages that are read once and then never again.

The most recently used page is actually the most unneeded page.



SEQUENTIAL FLOODING

Q1 **SELECT * FROM A WHERE id = 1**

Buffer Pool



Disk Pages



SEQUENTIAL FLOODING

Q1 `SELECT * FROM A WHERE id = 1`

Q2 `SELECT AVG(val) FROM A`

Buffer Pool



Disk Pages

Q2



SEQUENTIAL FLOODING

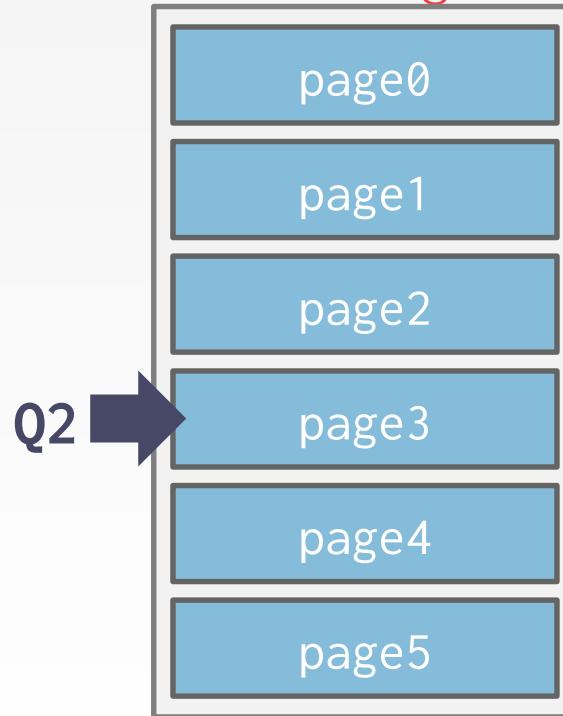
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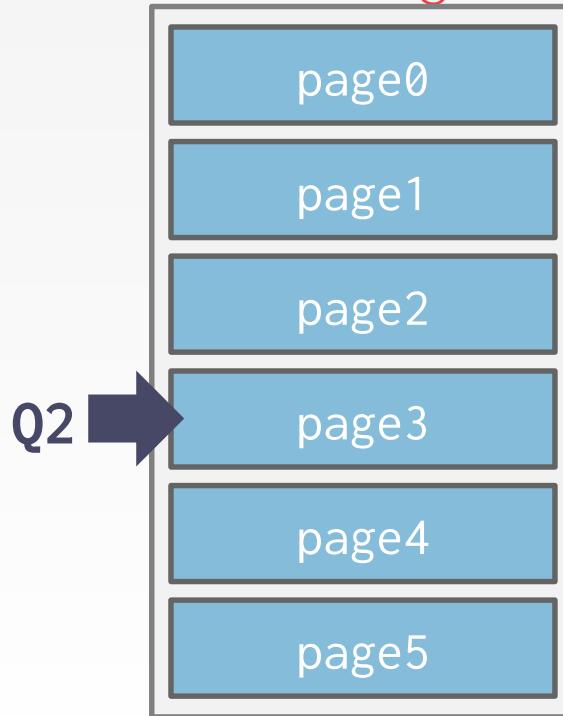
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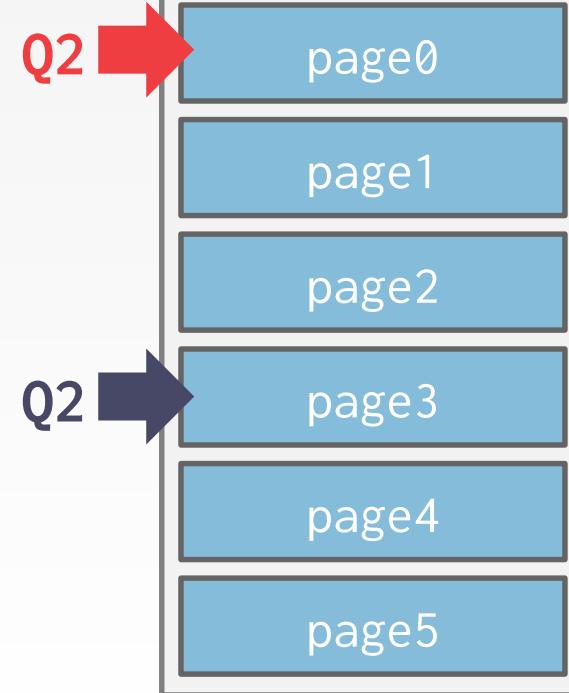
Q2 `SELECT AVG(val) FROM A`

Q3 `SELECT * FROM A WHERE id = 1`

Buffer Pool



Disk Pages



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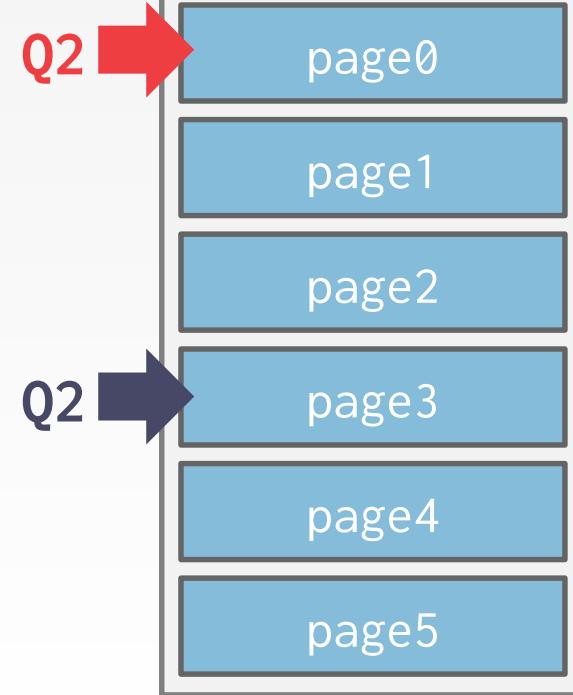
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Buffer Pool



Disk Pages



BETTER POLICIES: LRU-K

Take into account history of the last K references as timestamps and compute the interval between subsequent accesses.

The DBMS then uses this history to estimate the next time that page is going to be accessed.

BETTER POLICIES: LOCALIZATION

The DBMS chooses which pages to evict on a per txn/query basis. This minimizes the pollution of the buffer pool from each query.

→ Keep track of the pages that a query has accessed.

Example: Postgres maintains a small ring buffer that is private to the query.



BETTER POLICIES: PRIORITY HINTS

The DBMS knows what the context of each page during query execution.

It can provide hints to the buffer pool on whether a page is important or not.

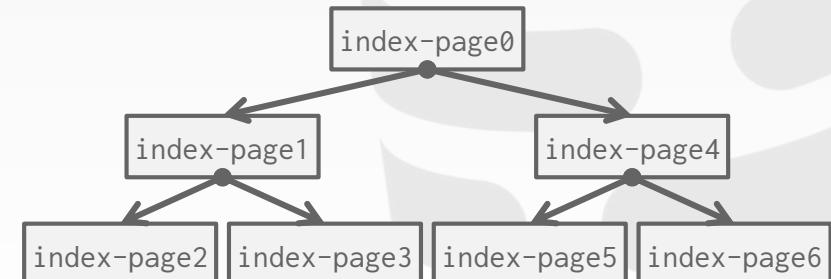


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Q1 **INSERT INTO A VALUES (*id++*)**

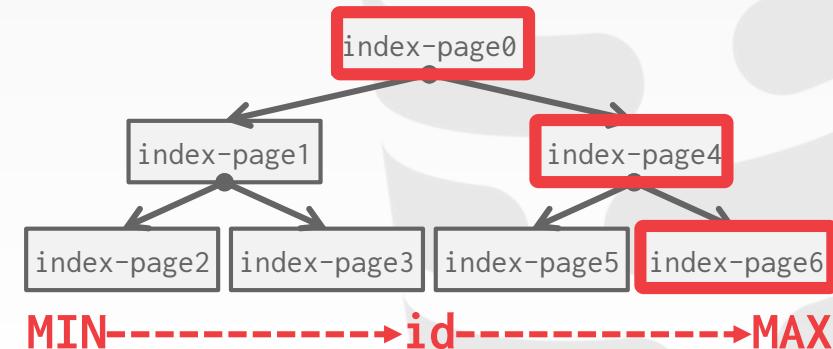


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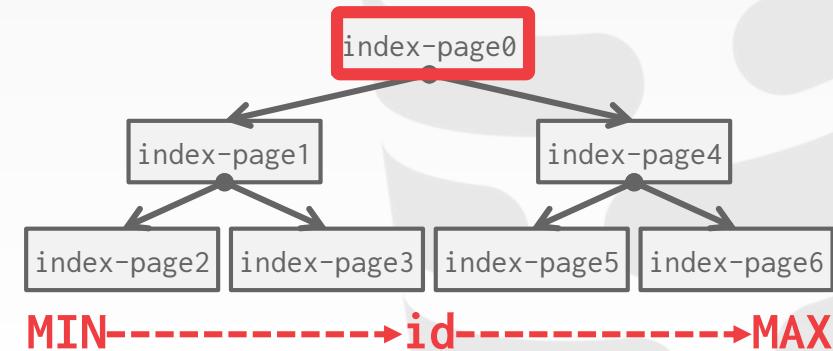
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Q1 `INSERT INTO A VALUES (id++)`

Q2 `SELECT * FROM A WHERE id = ?`



DIRTY PAGES

better not drop indexes like root easily

FAST: If a page in the buffer pool is not dirty, then the DBMS can simply "drop" it.

SLOW: If a page is dirty, then the DBMS must write back to disk to ensure that its changes are persisted.

Trade-off between fast evictions versus dirty writing pages that will not be read again in the future.

BACKGROUND WRITING

The DBMS can periodically walk through the page table and write dirty pages to disk.

When a dirty page is safely written, the DBMS can either evict the page or just unset the dirty flag.

Need to be careful that we don't write dirty pages before their log records have been written...

ALLOCATION POLICIES

Global Policies:

- Make decisions for all active txns.

Local Policies:

- Allocate frames to a specific txn without considering the behavior of concurrent txns.
- Still need to support sharing pages.



store in buffer pool: need to manage page table and extra data
store in heap: fast, convenient but may not have full control

OTHER MEMORY POOLS

The DBMS needs memory for things other than just tuples and indexes.

These other memory pools may not always be backed by disk. Depends on implementation.

- Sorting + Join Buffers
- Query Caches
- Maintenance Buffers
- Log Buffers
- Dictionary Caches



CONCLUSION

The DBMS can manage that sweet, sweet memory better than the OS.

Leverage the semantics about the query plan to make better decisions:

- Evictions
- Allocations
- Pre-fetching



PROJECT #1

You will build the first component of your storage manager.

- Extendible Hash Table
- LRU Replacement Policy
- Buffer Pool Manager

All of the projects are based on SQLite, but you will not be able to use your storage manger just yet after this first project.



Due Date:
Wed Sept 26th @ 11:59pm

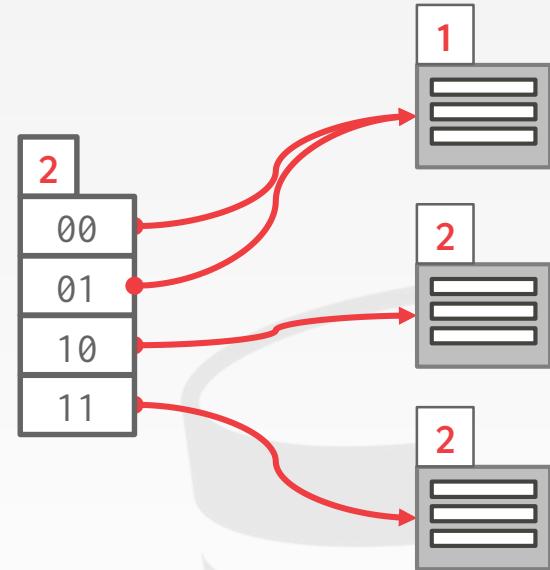
TASK #1 – EXTENDIBLE HASH TABLE

Build a thread-safe extendible hash table.

- Use unordered buckets to store key/value pairs.
- You must support growing table size.
- You do not need to support shrinking.

General Hints:

- You can use **std::hash** and **std::mutex**.



TASK #2 – LRU REPLACEMENT POLICY

Build a data structure that tracks the usage of **Page** objects in the buffer pool using the least-recently used policy.

General Hints:

- Your **LRUReplacer** does not need to worry about the "pinned" status of a **Page**.



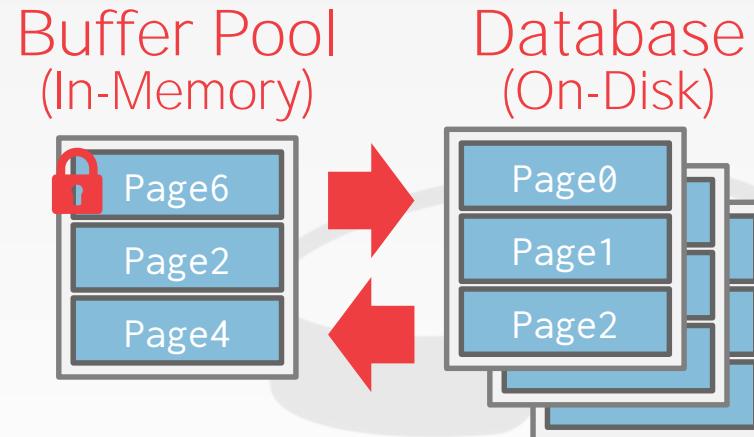
TASK #3 – BUFFER POOL MANAGER

Combine your hash table and LRU replacer together to manage the allocation of pages.

- Need to maintain an internal data structures of allocated + free pages.
- We will provide you components to read/write data from disk.

General Hints:

- Make sure you get the order of operations correct when pinning.

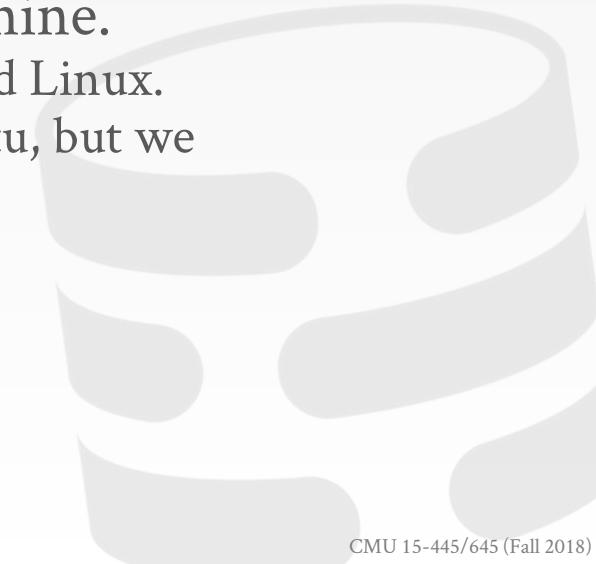


GETTING STARTED

Download the source code from the project webpage.

Make sure you can build it on your machine.

- We've test it on Andrew machines, OSX, and Linux.
- It should compile on Windows 10 w/ Ubuntu, but we haven't tried it.



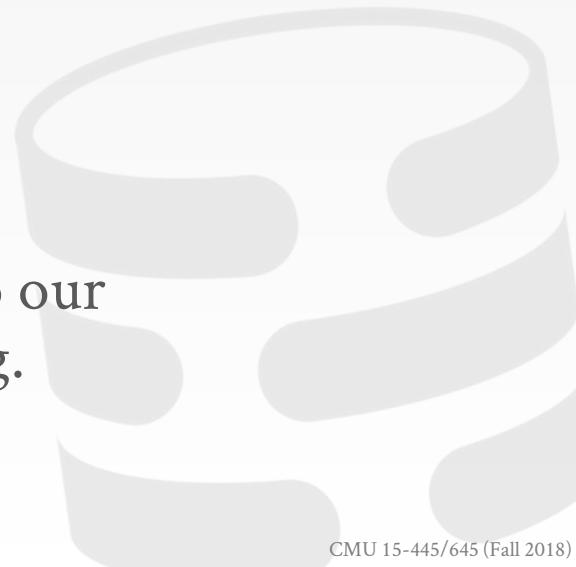
THINGS TO NOTE

Do not change any file other than the six that you have to hand in.

The projects are cumulative.

We will not be providing solutions.

Post your questions on Piazza or come to our office hours. We will not help you debug.



PLAGIARISM WARNING

Your project implementation must be your own work.

- You may not copy source code from other groups or the web.
- Do not publish your implementation on Github.

Plagiarism will not be tolerated.

See [CMU's Policy on Academic Integrity](#) for additional information.



NEXT CLASS

HASH TABLES!

