Carnegie Mellon University

05 Buffer Pools

Intro to Database Systems
15-445/15-645
Fall 2019

AP
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Carnegie Mellon University

ADMINISTRIVIA

Homework #1 is due TODAY @ 11:59pm

Project #1 is due Fri Sept 26th @ 11:59pm

DATABASE WORKLOADS

On-Line Transaction Processing (OLTP)

→ Fast operations that only read/update a small amount of data each time.

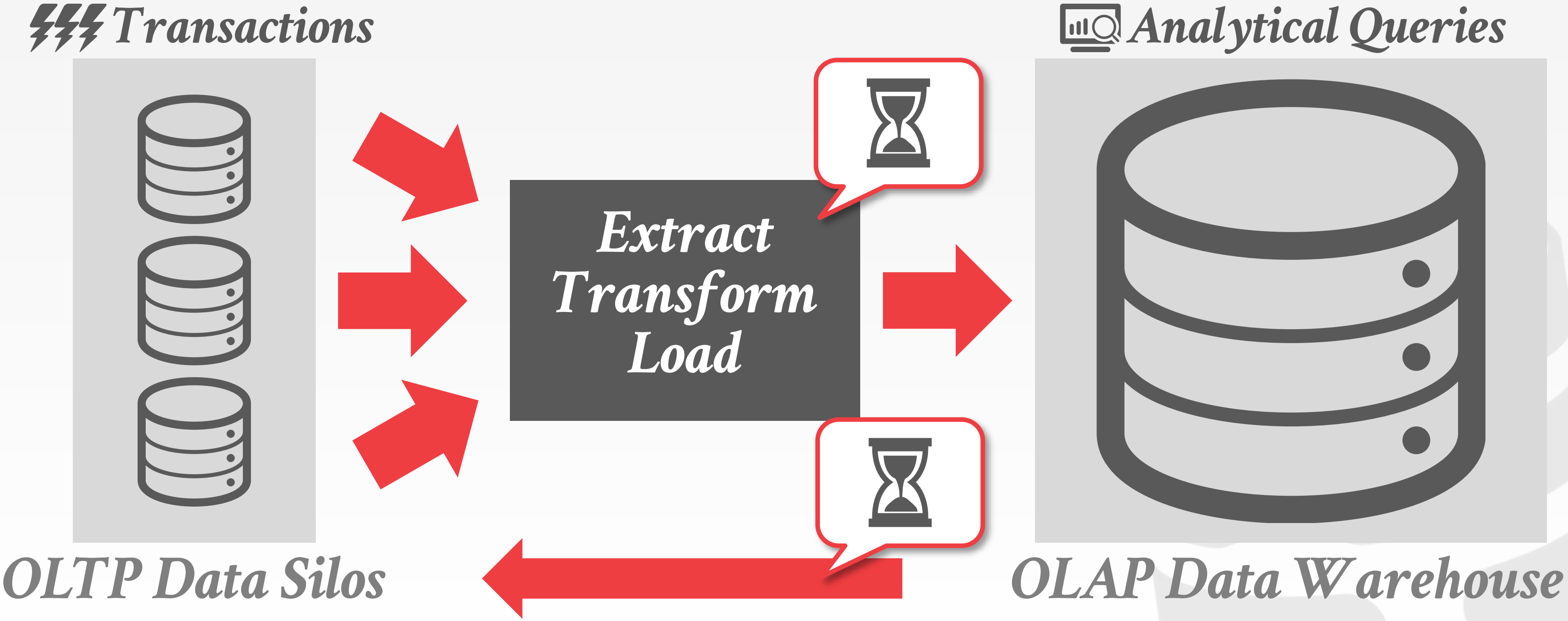
On-Line Analytical Processing (OLAP)

→ Complex queries that read a lot of data to compute aggregates.

Hybrid Transaction + Analytical Processing

→ OLTP + OLAP together on the same database instance

BIFURCATED ENVIRONMENT



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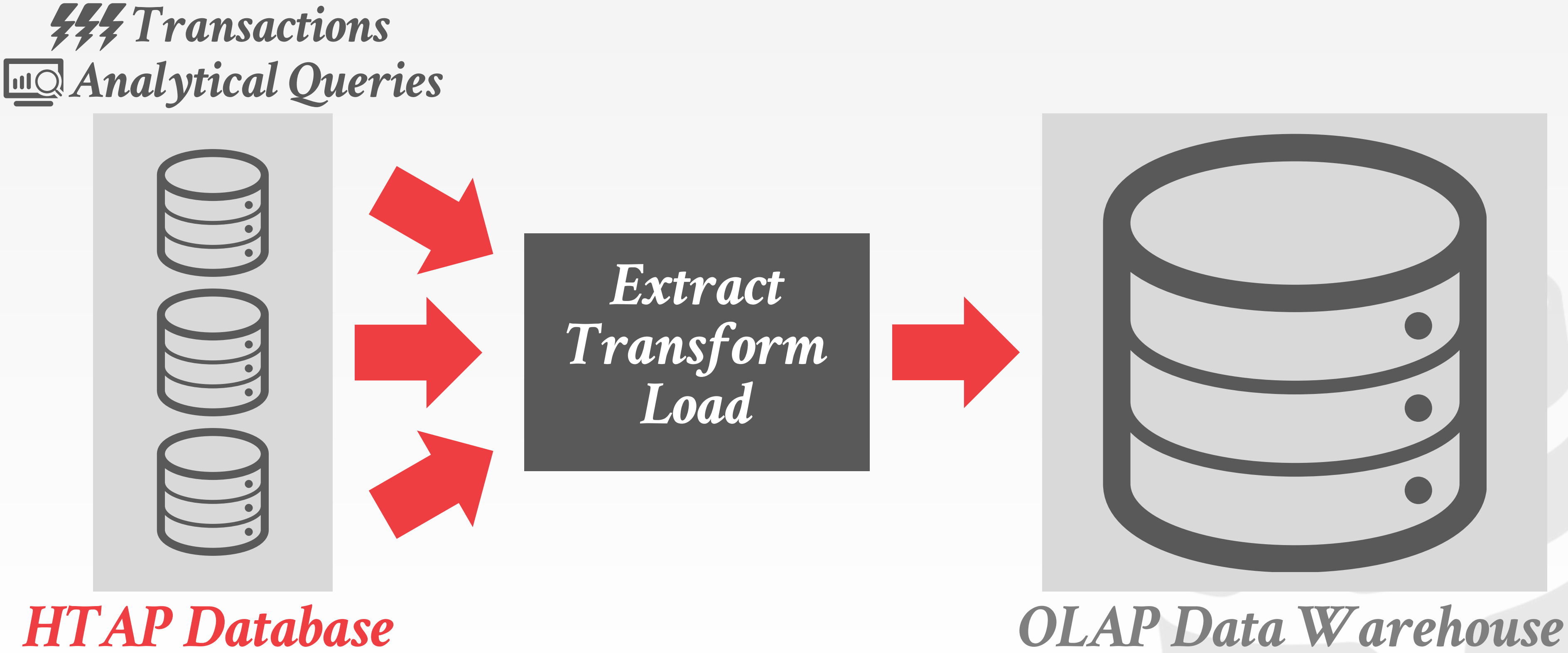


DATABASE STORAGE

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

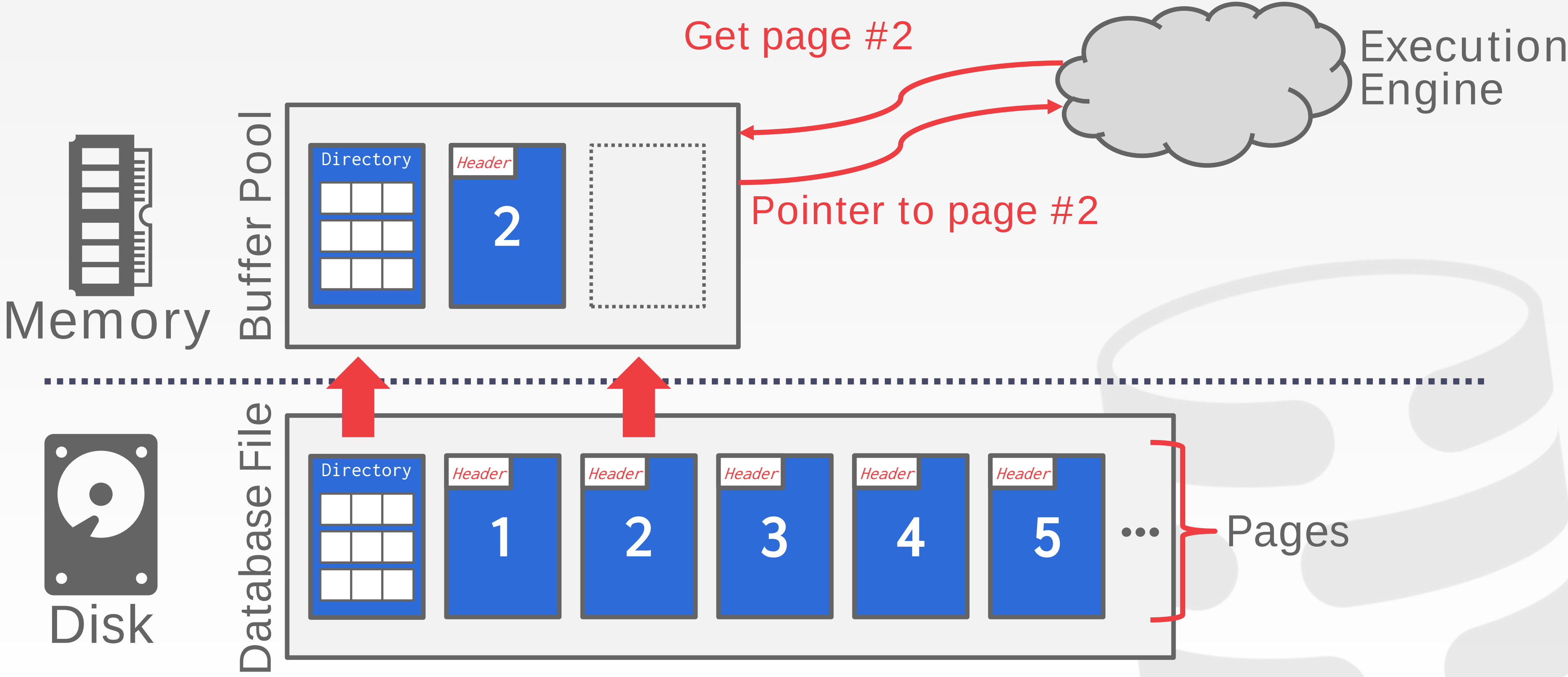
Spatial Control:

→ 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

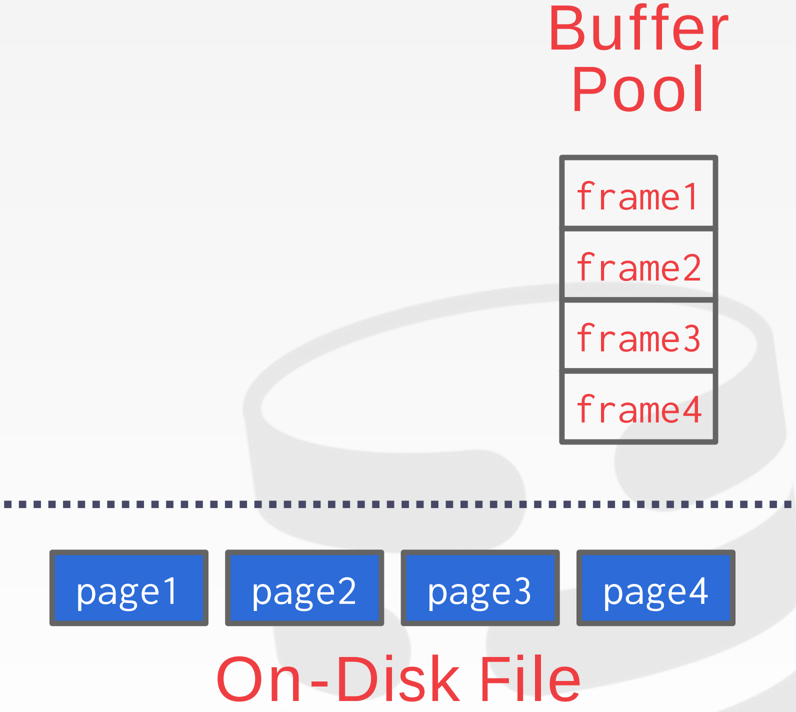
Replacement Policies

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.



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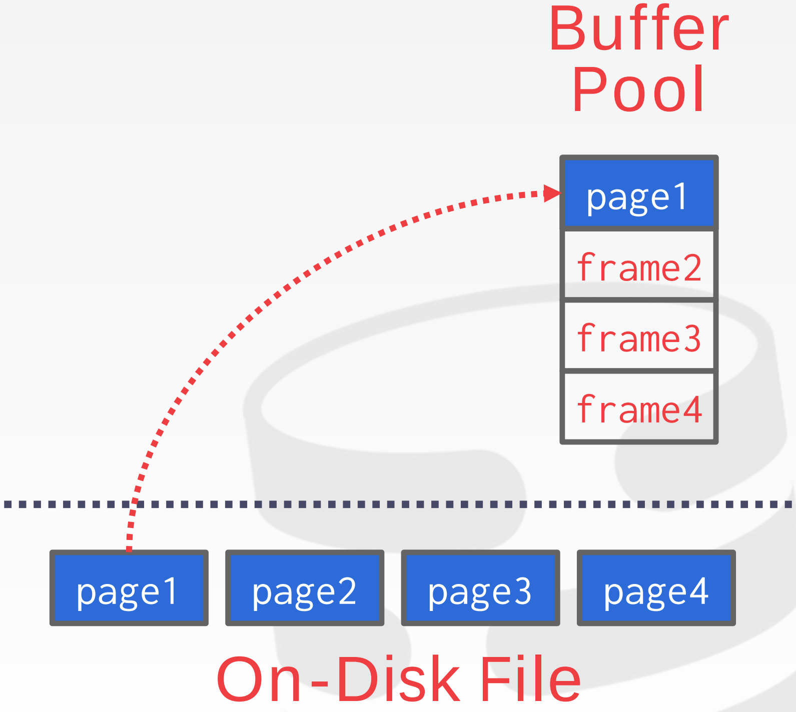

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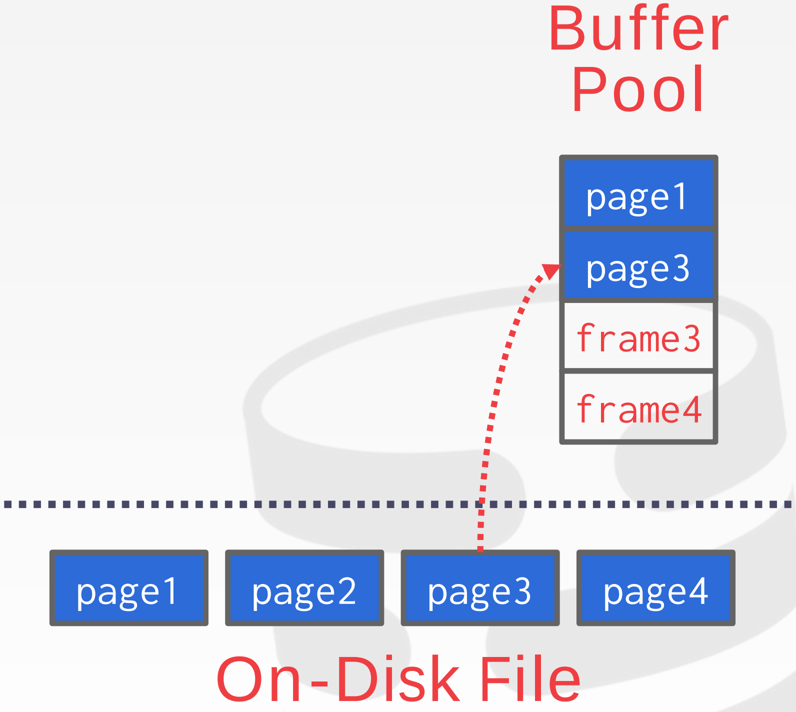
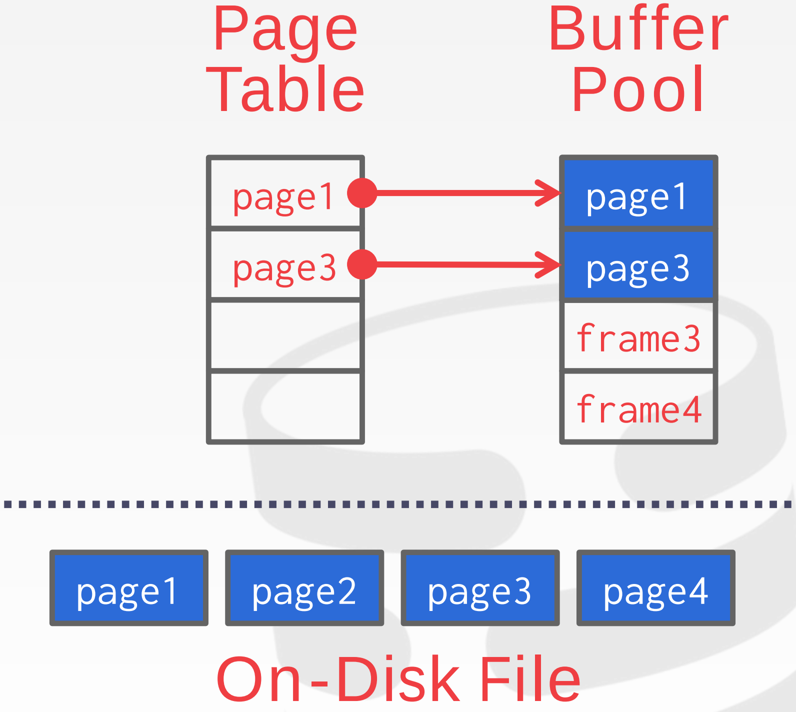


BUFFER POOL META-DATA

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

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



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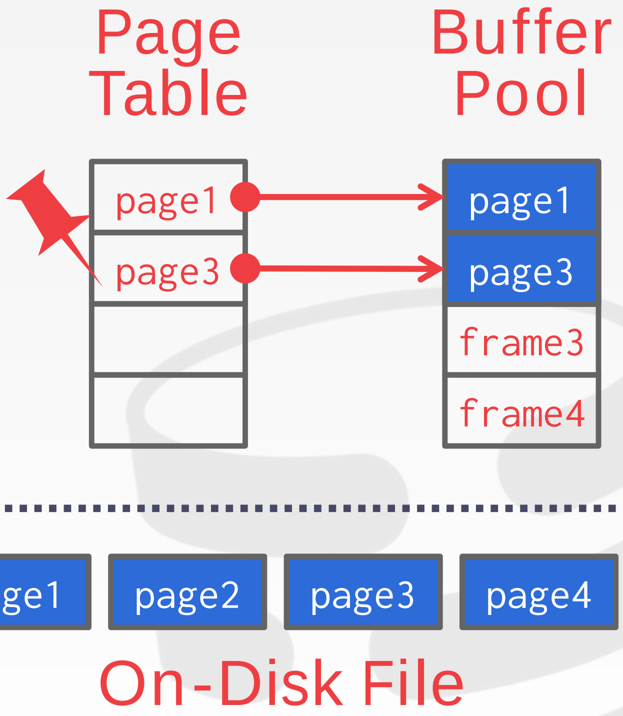

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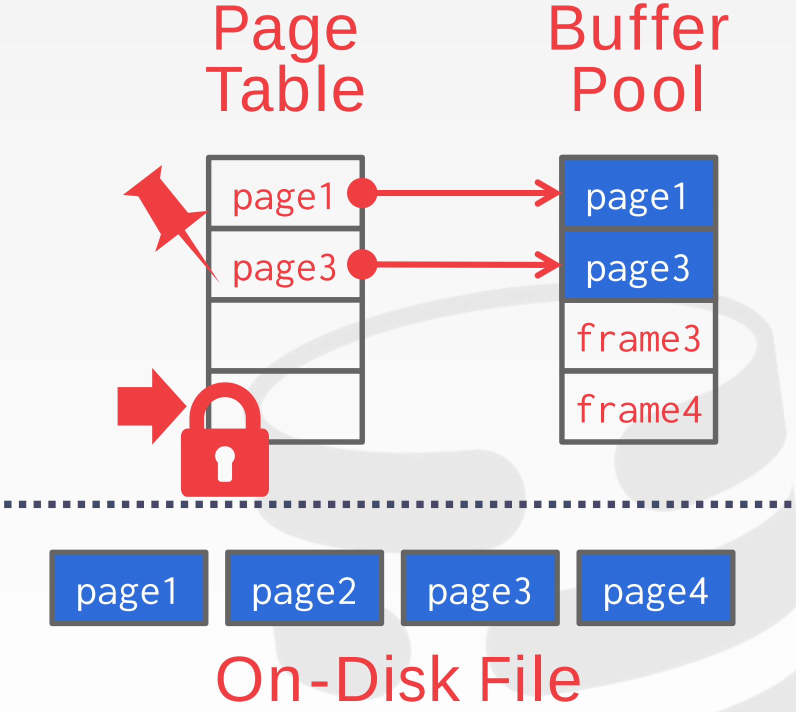

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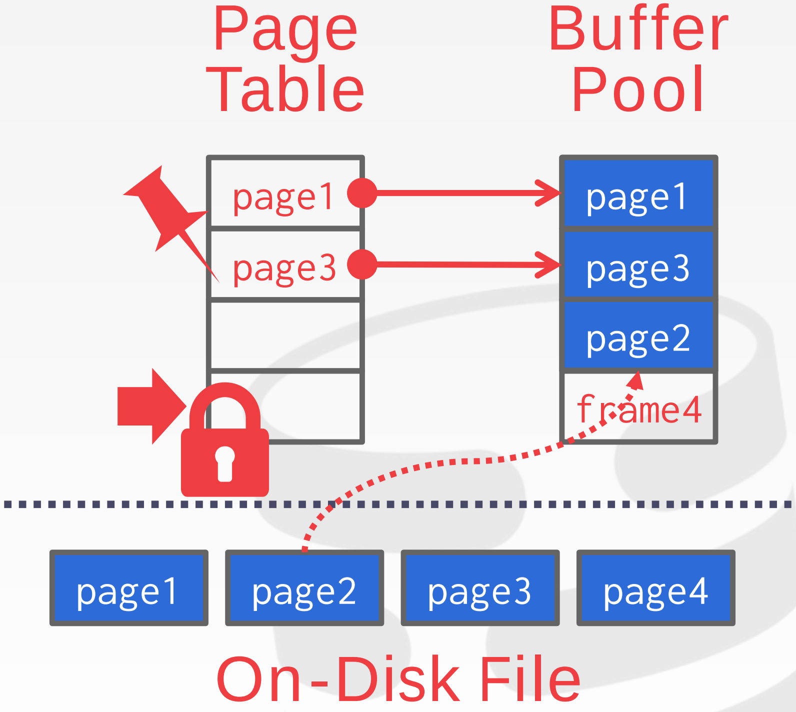

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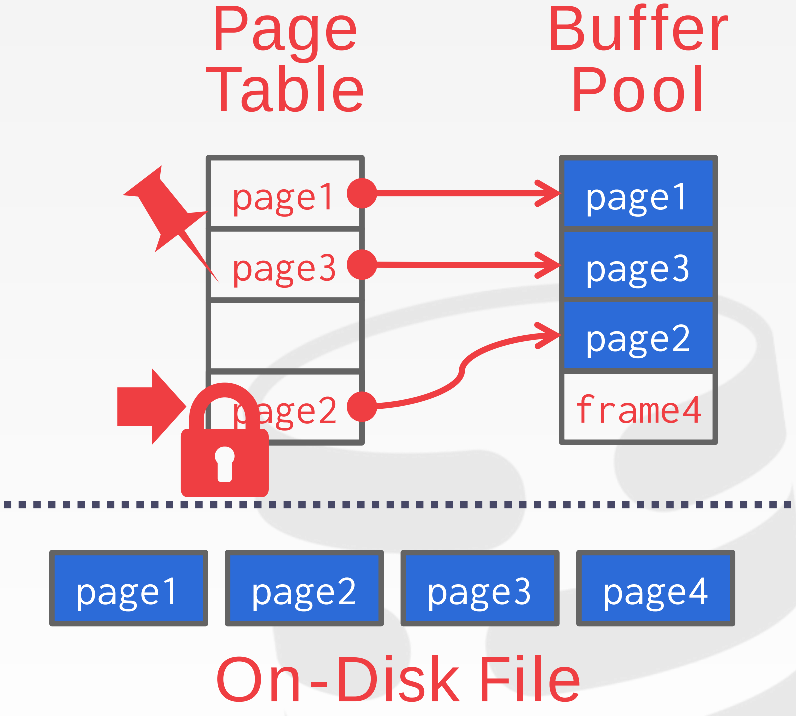


LOCKS VS. LATCHES

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.

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.

BUFFER POOL OPTIMIZATIONS

Multiple Buffer Pools

Pre-Fetching

Scan Sharing

Buffer Pool Bypass

MULTIPLE BUFFER POOLS

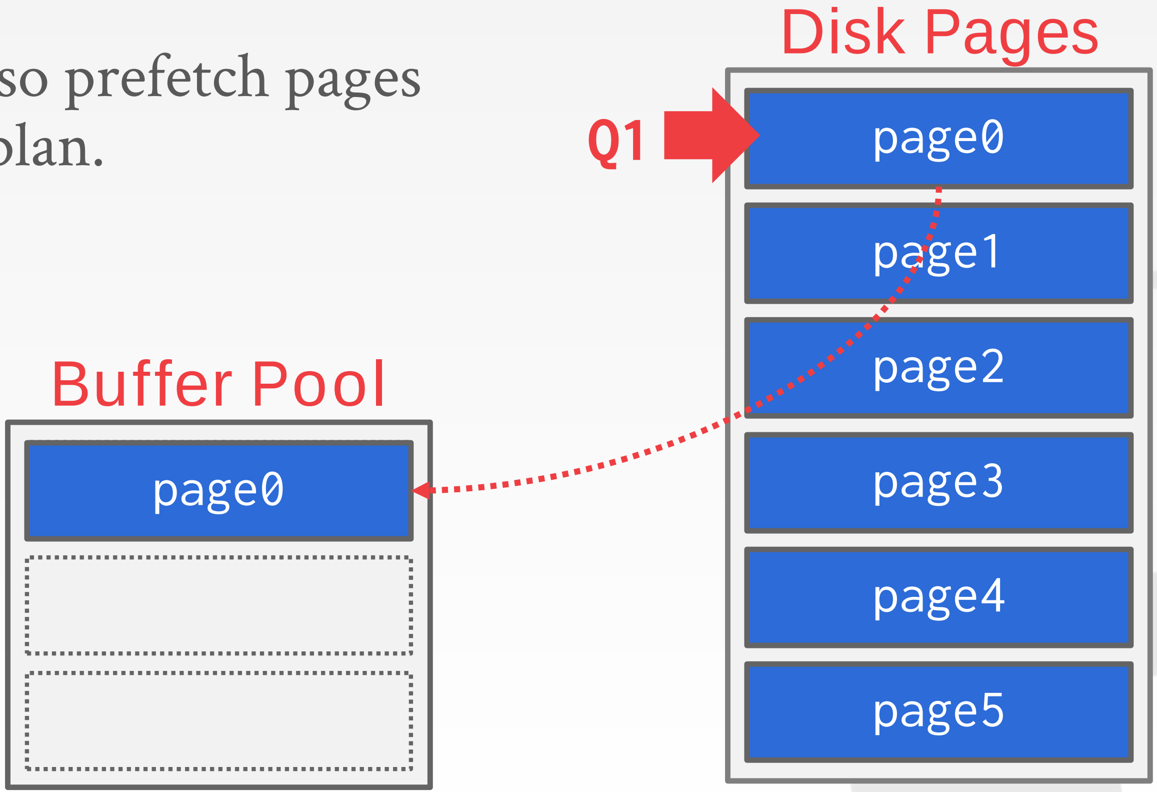
The DBMS does not always have a single buffer pool for the entire system.

→ 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



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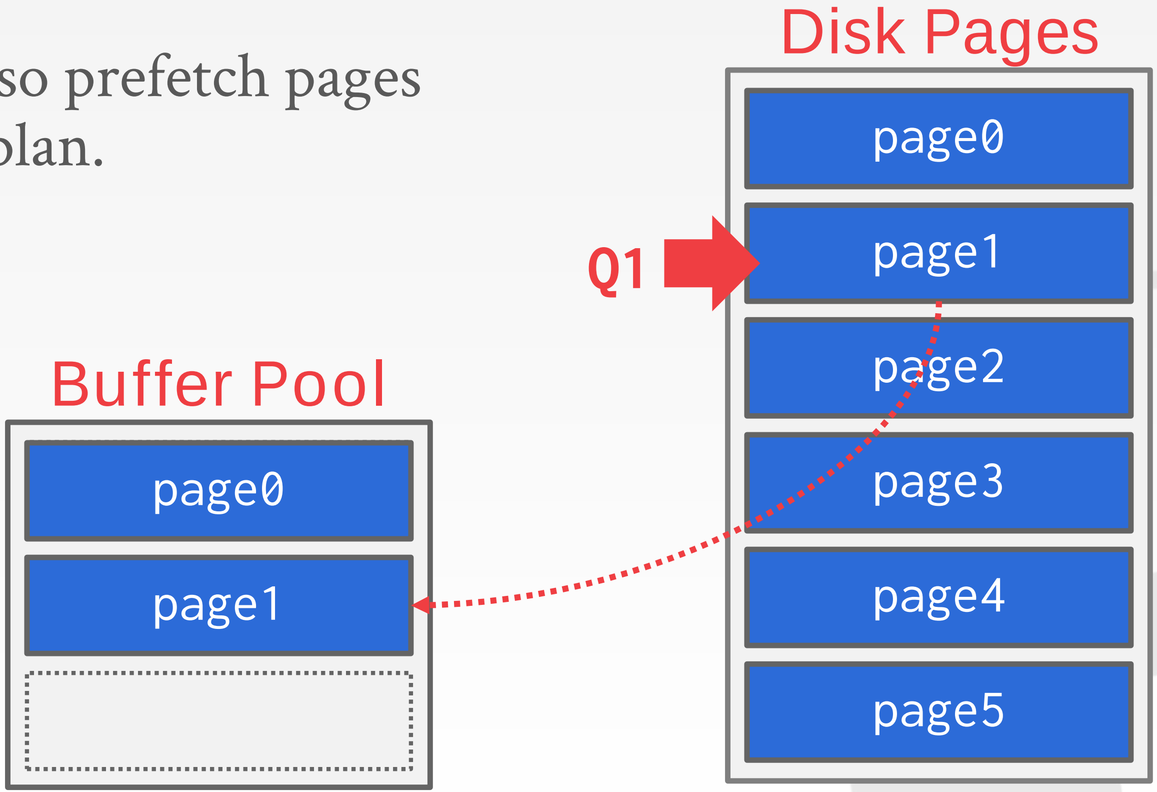

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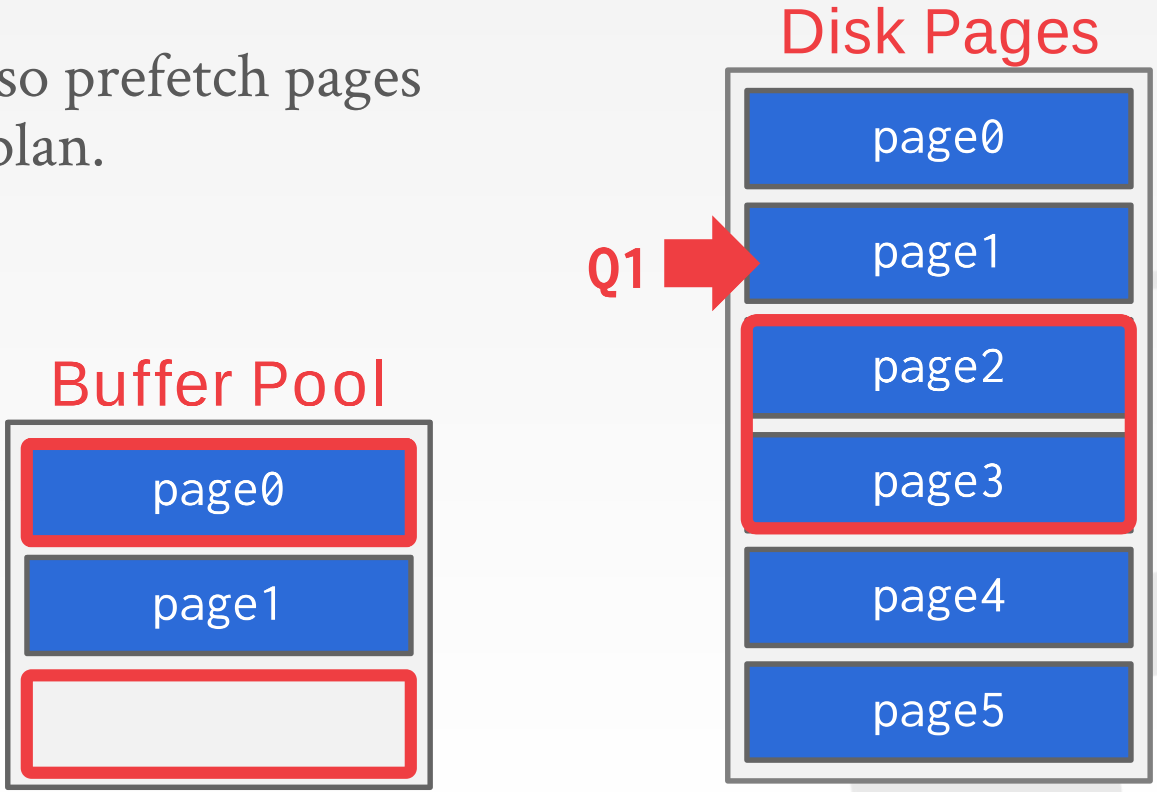

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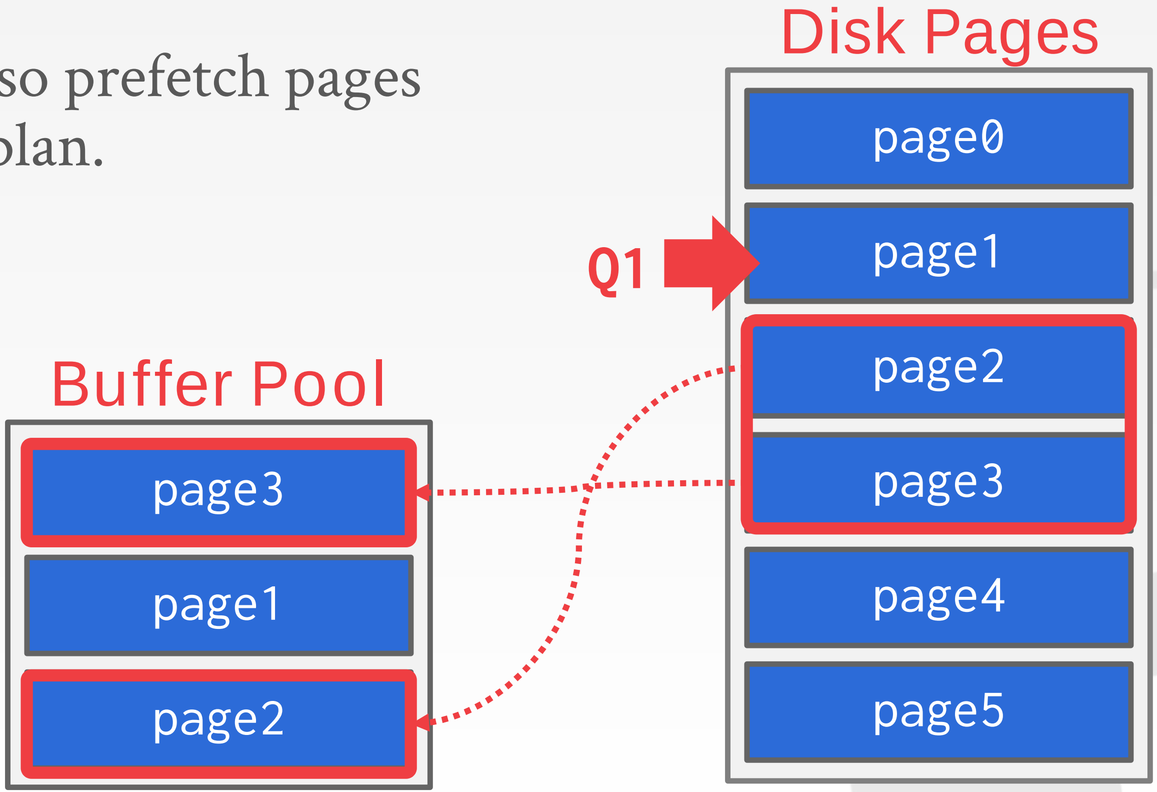

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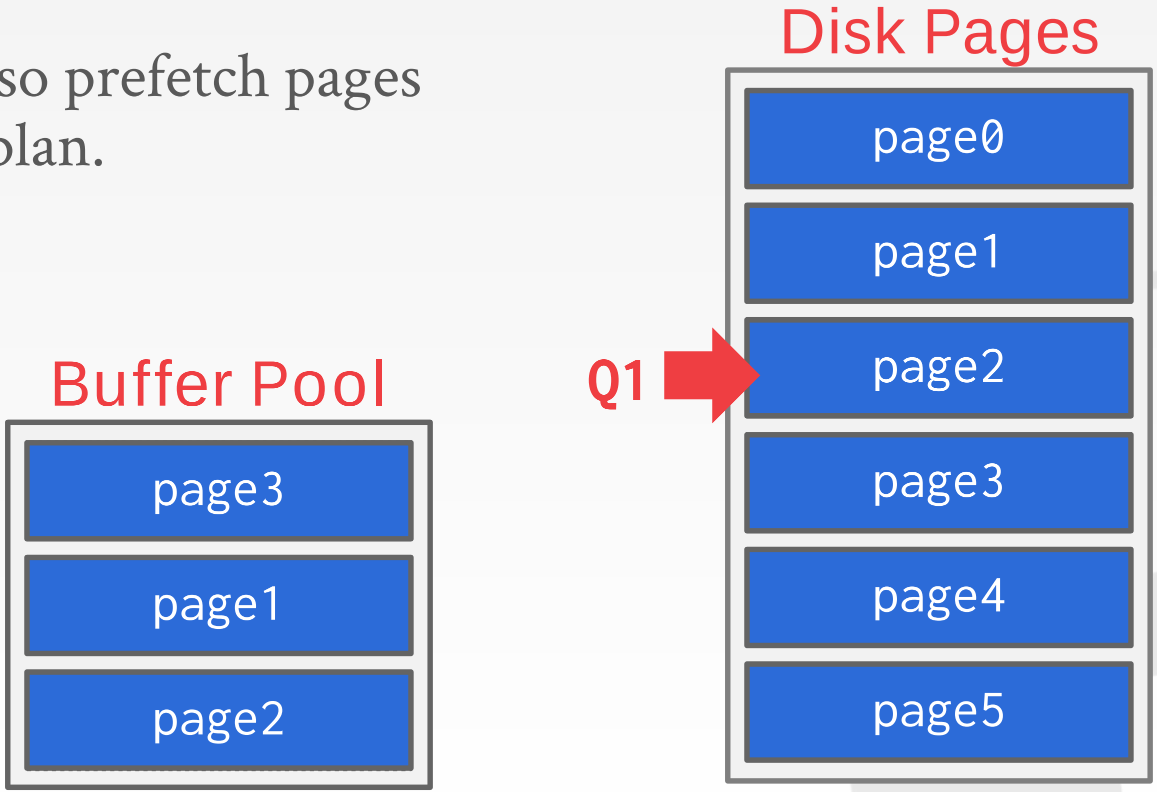

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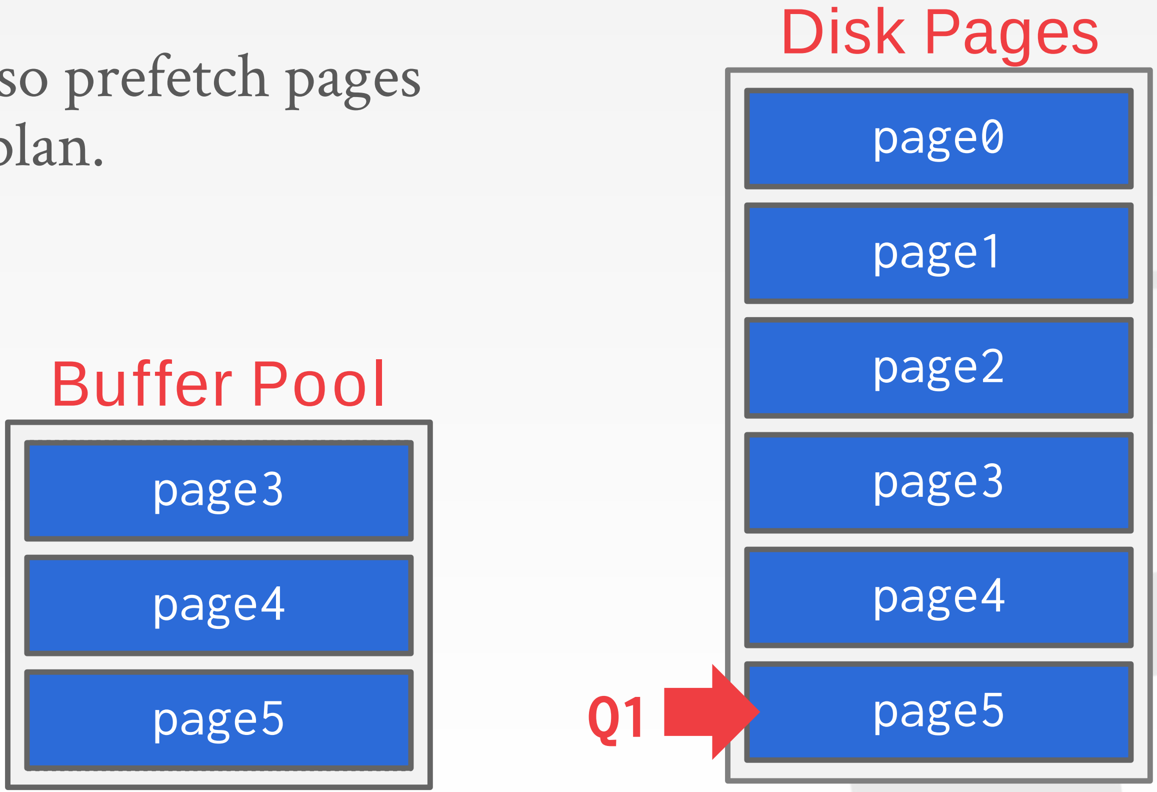
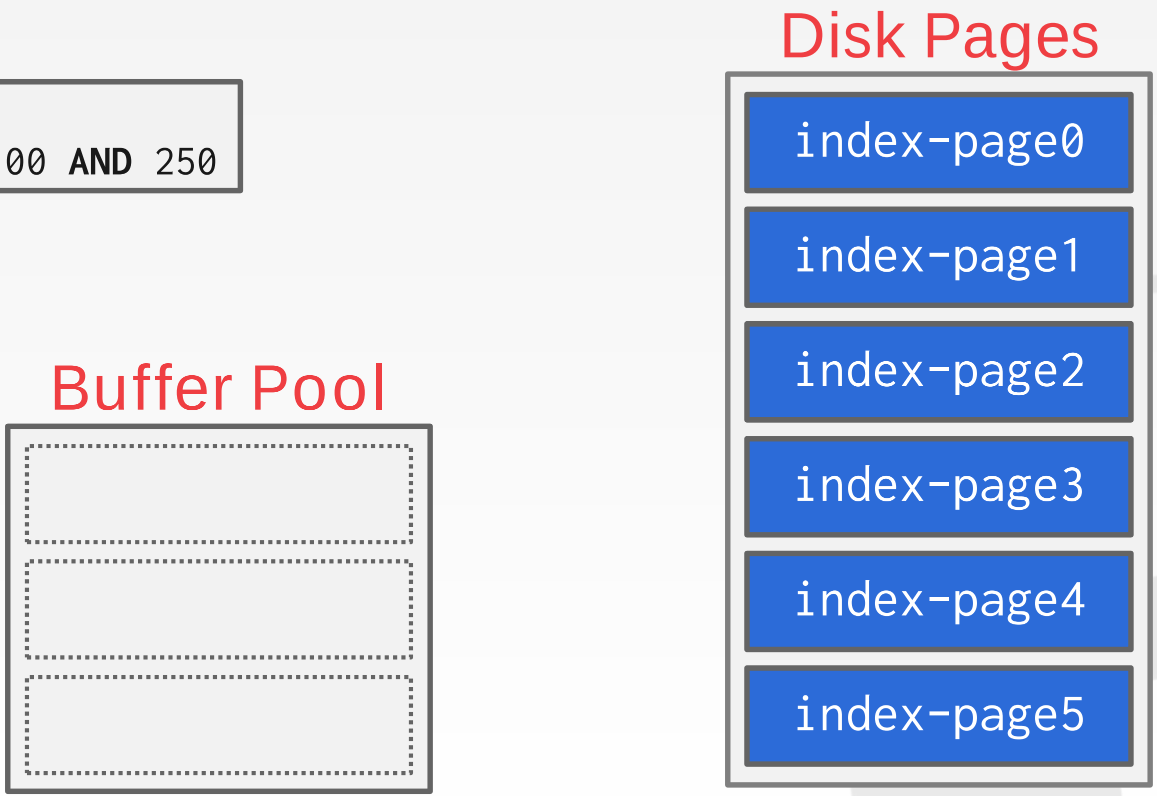


PRE-FETCHING

Q1

```
SELECT * FROM A
 WHERE val BETWEEN 100 AND 250
```



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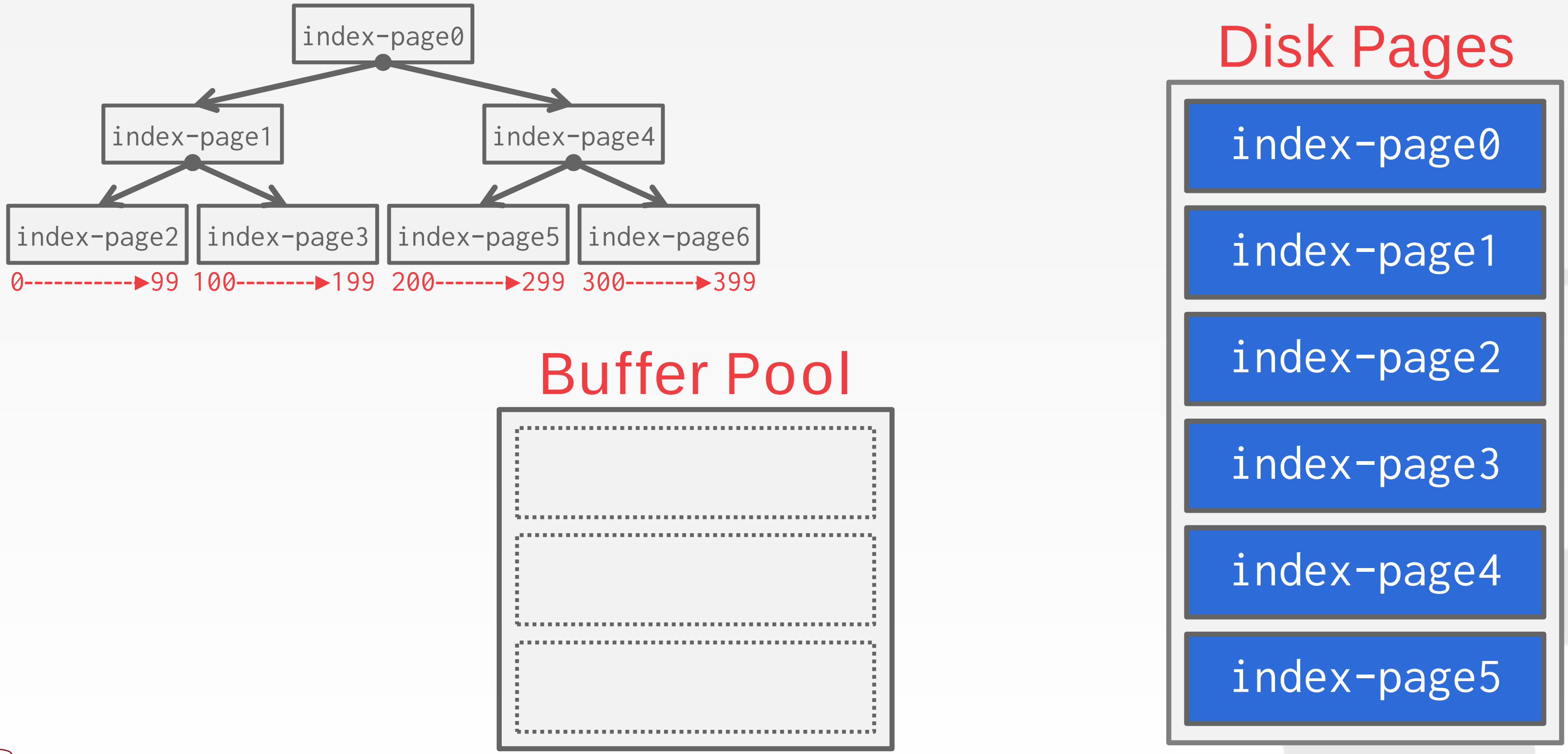

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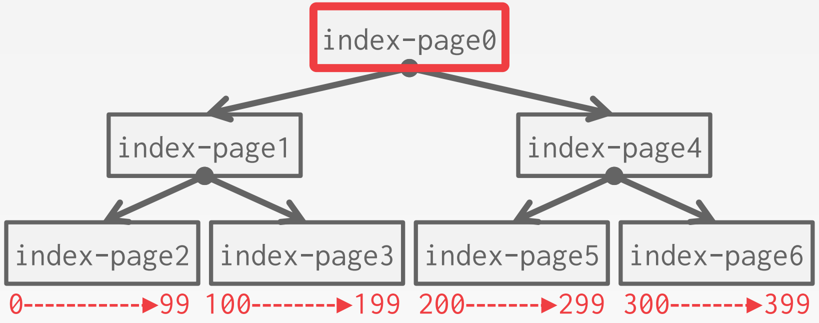

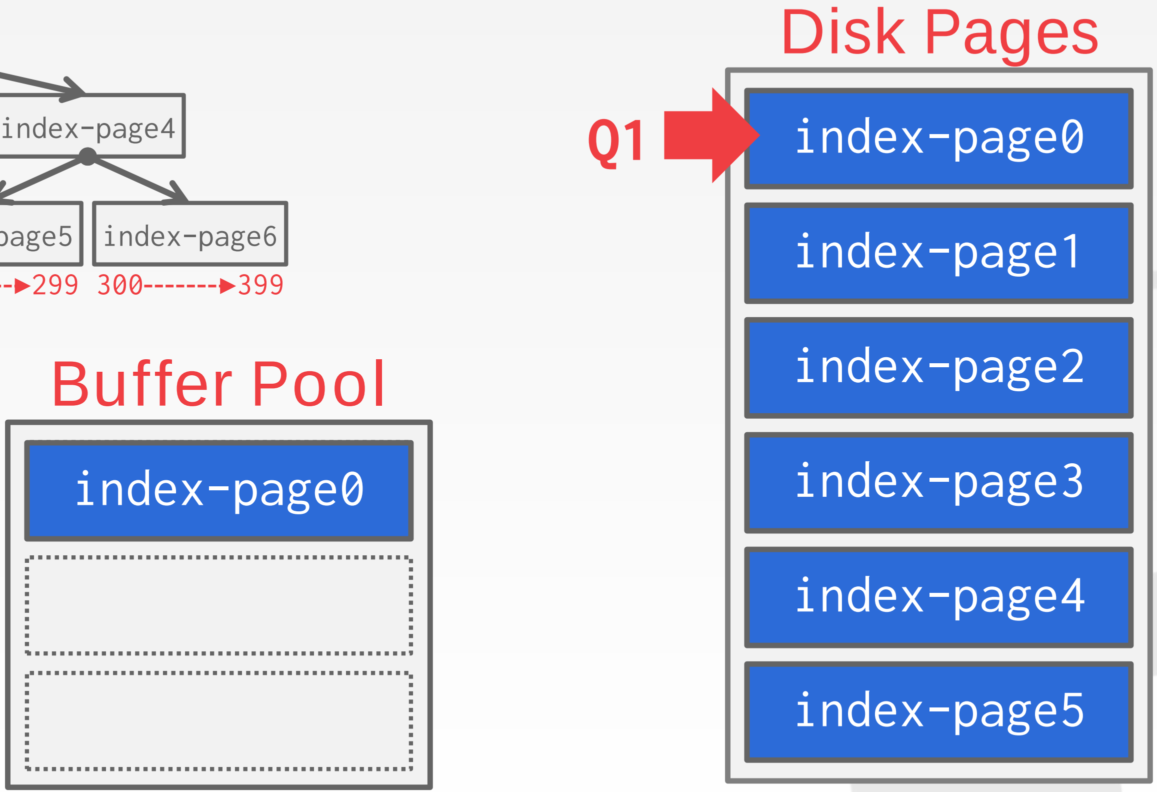

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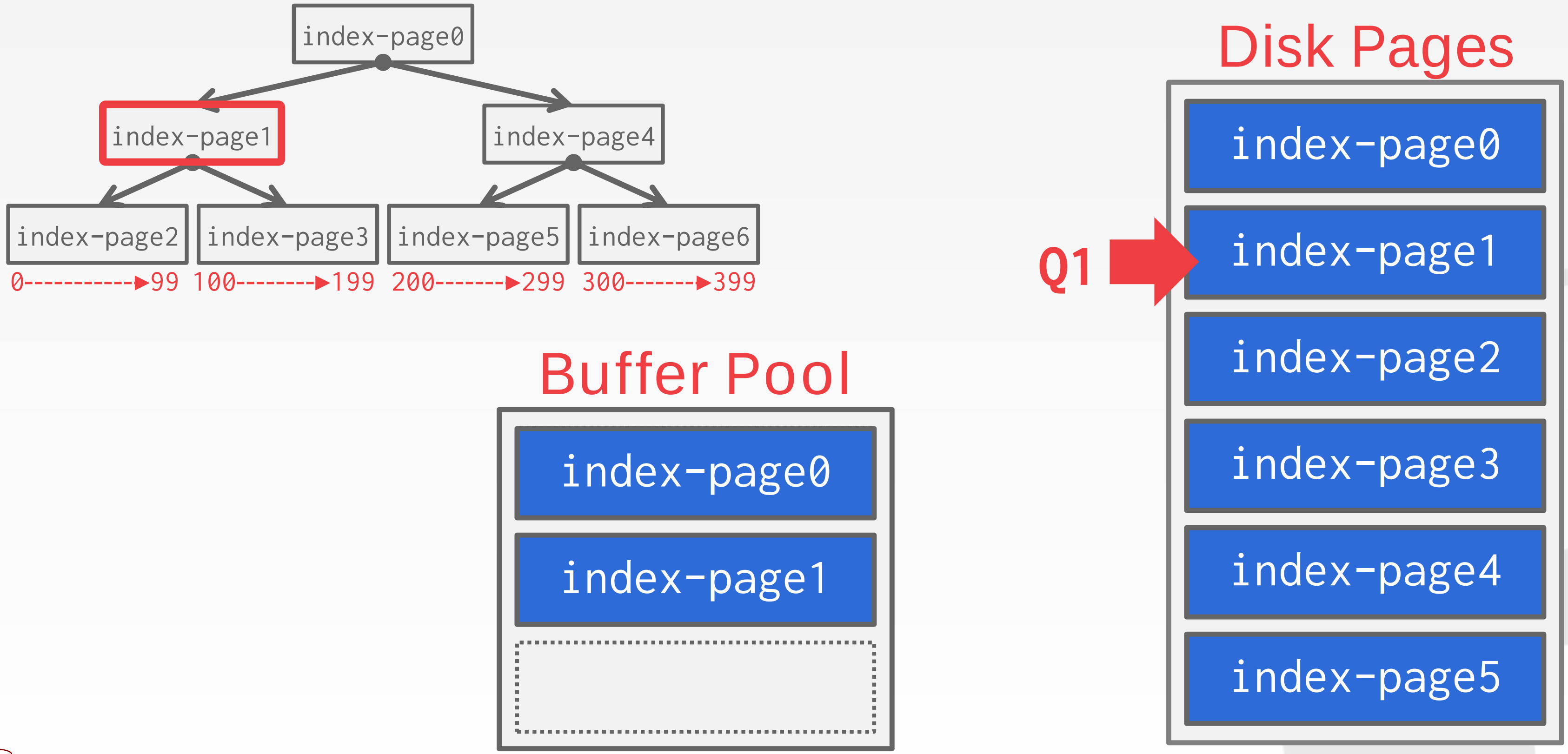

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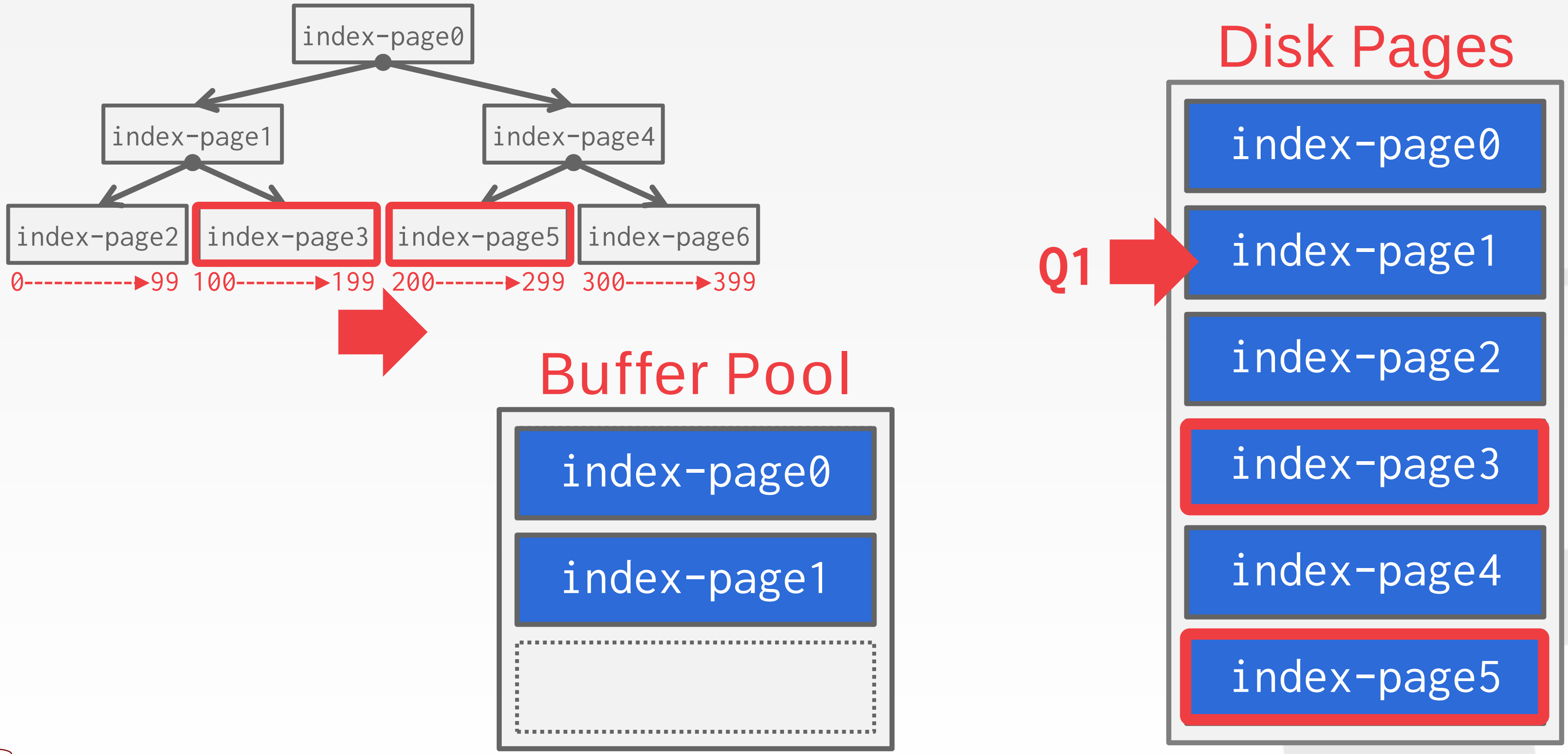


SCAN SHARING

Queries can 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 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.

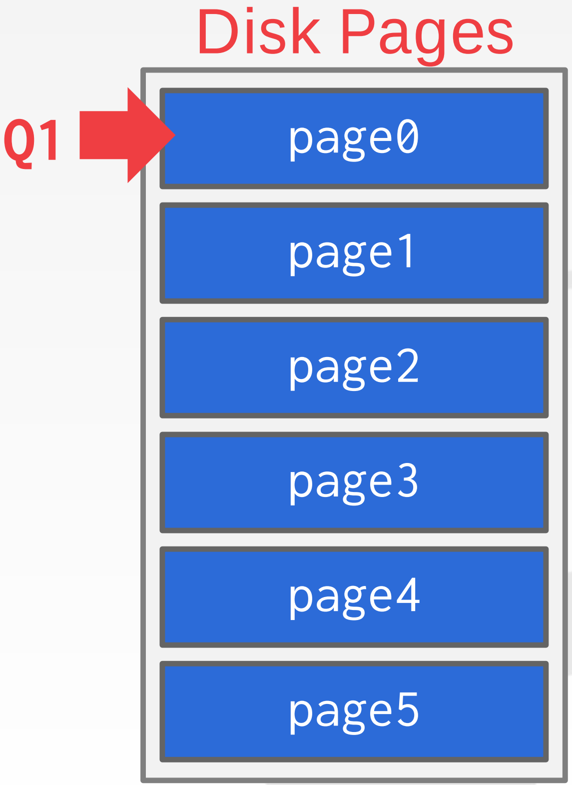
→ The DBMS keeps track of where the second query joined with the first so that it can finish the scan when it reaches the end of the data structure.

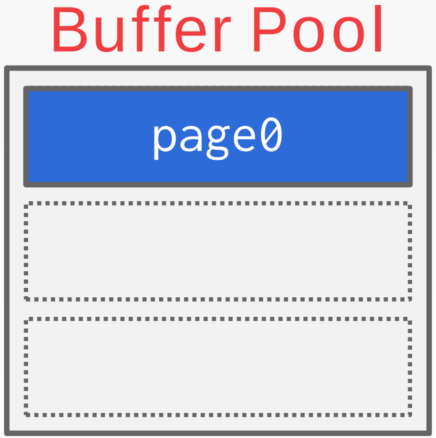
Fully supported in IBM DB2 and MSSQL.

Oracle only supports cursor sharing for identical queries.

SCAN SHARING

Q1 `SELECT SUM(val) FROM A`





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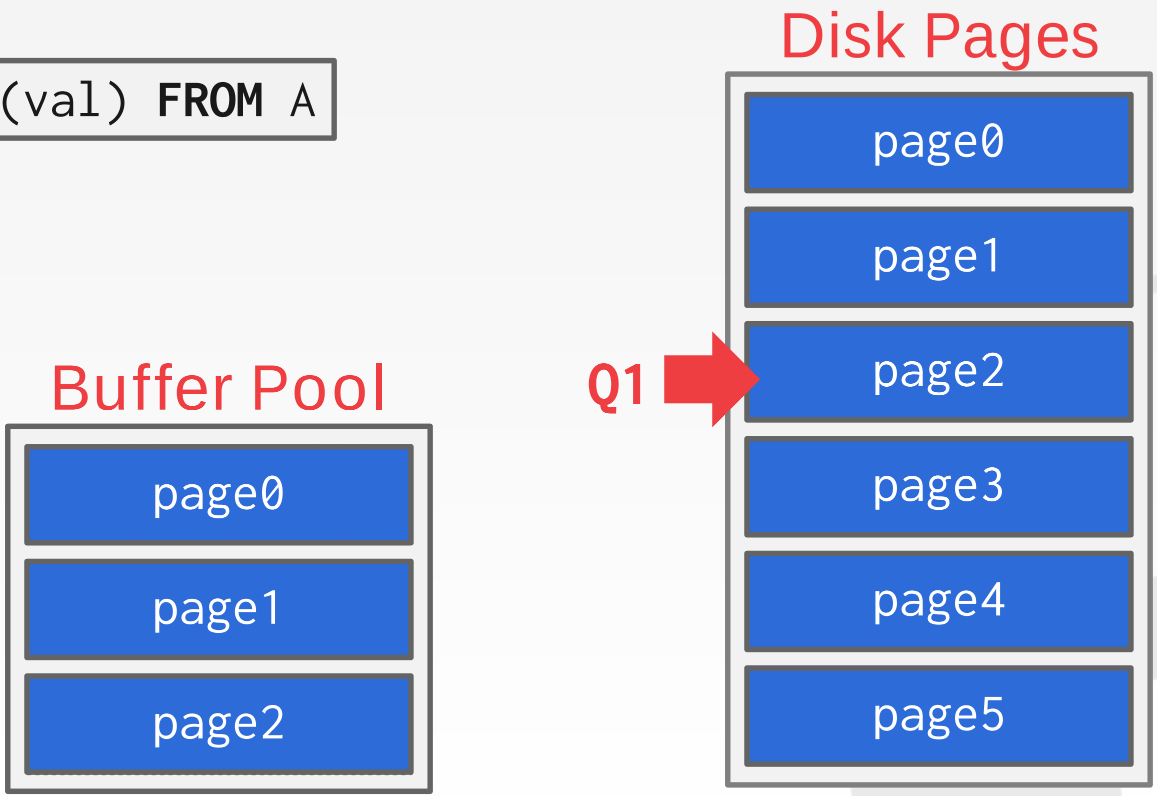

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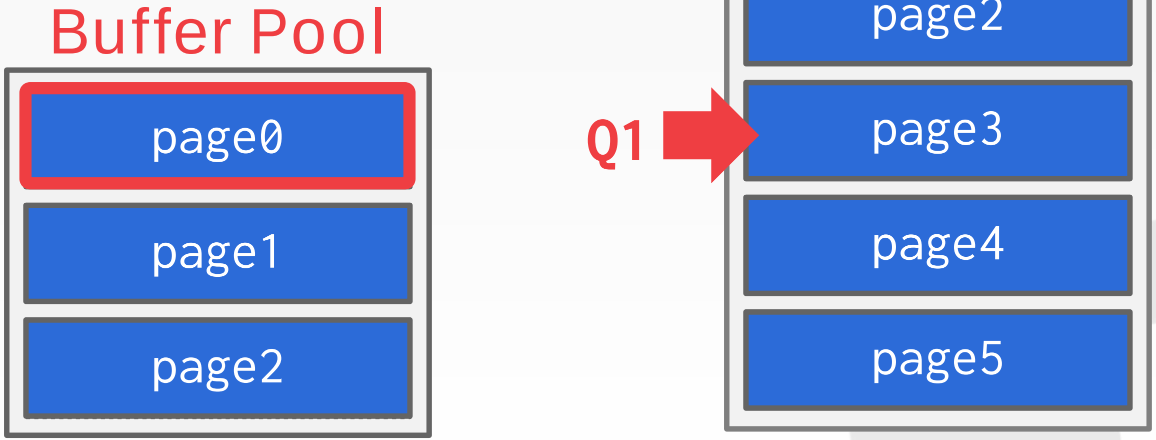

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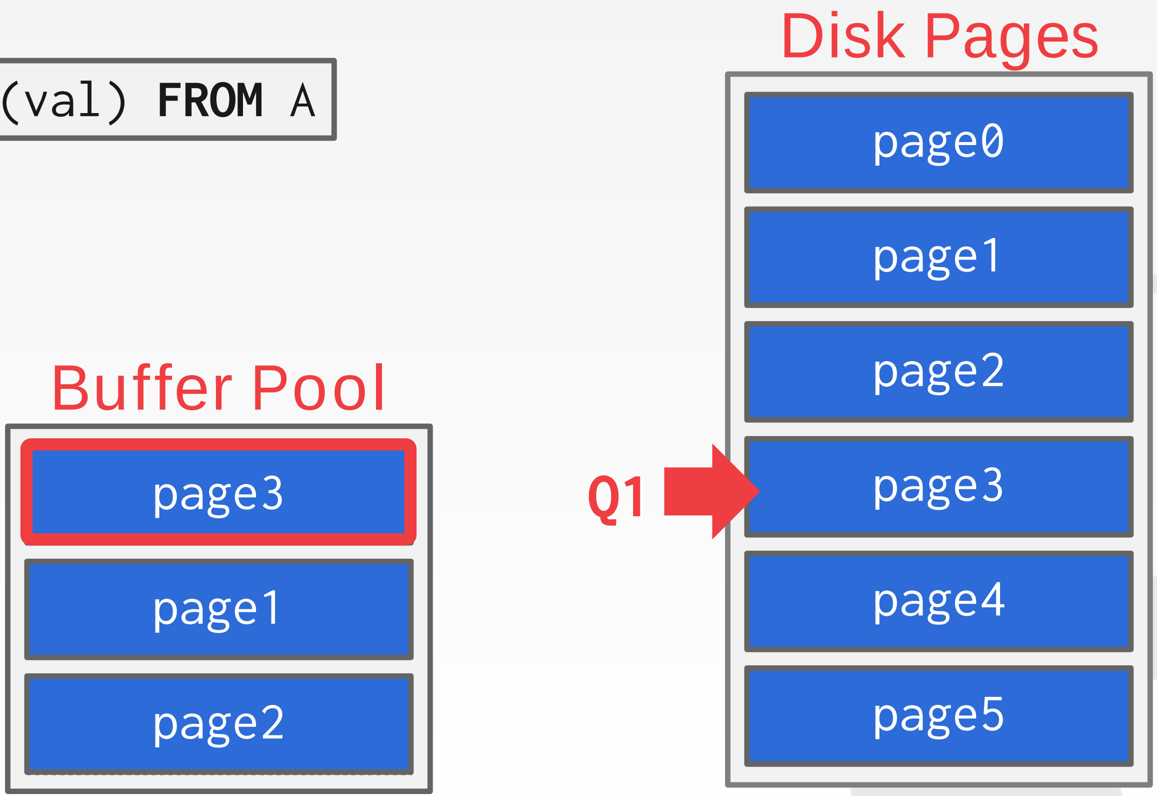
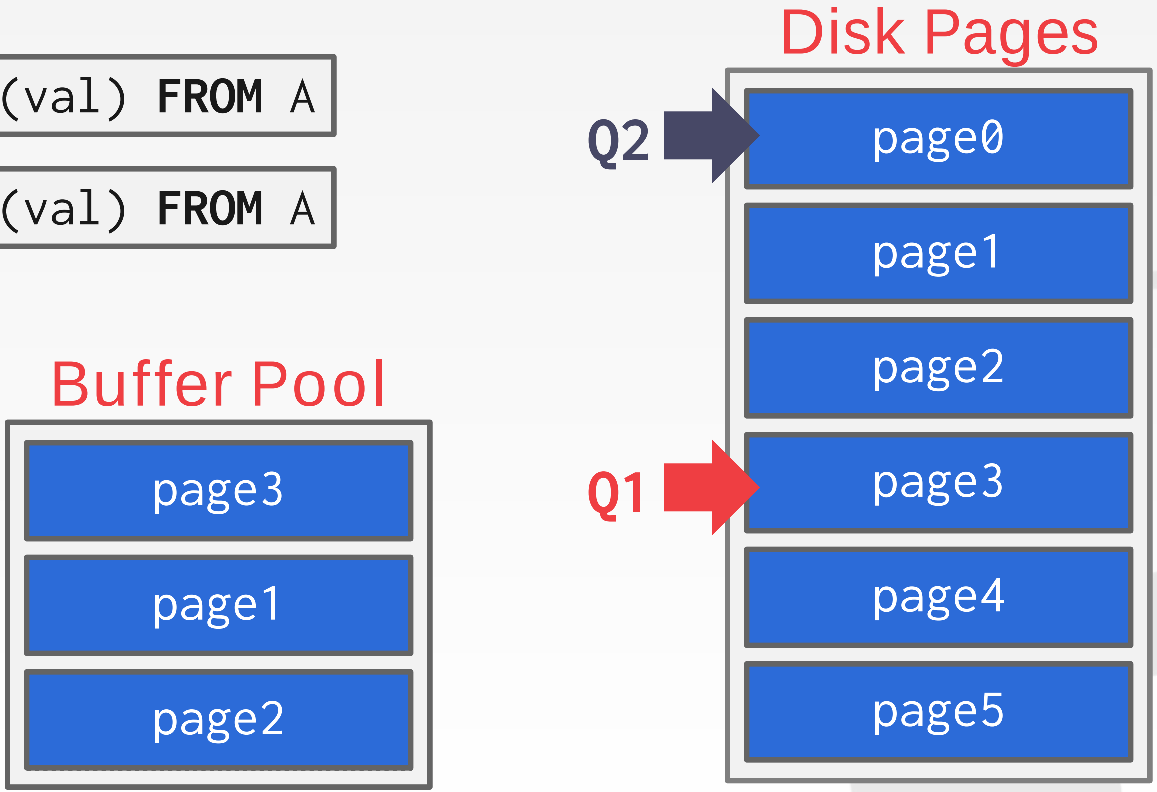


SCAN SHARING

Q1 `SELECT SUM(val) FROM A`

Q2 `SELECT AVG(val) FROM A`



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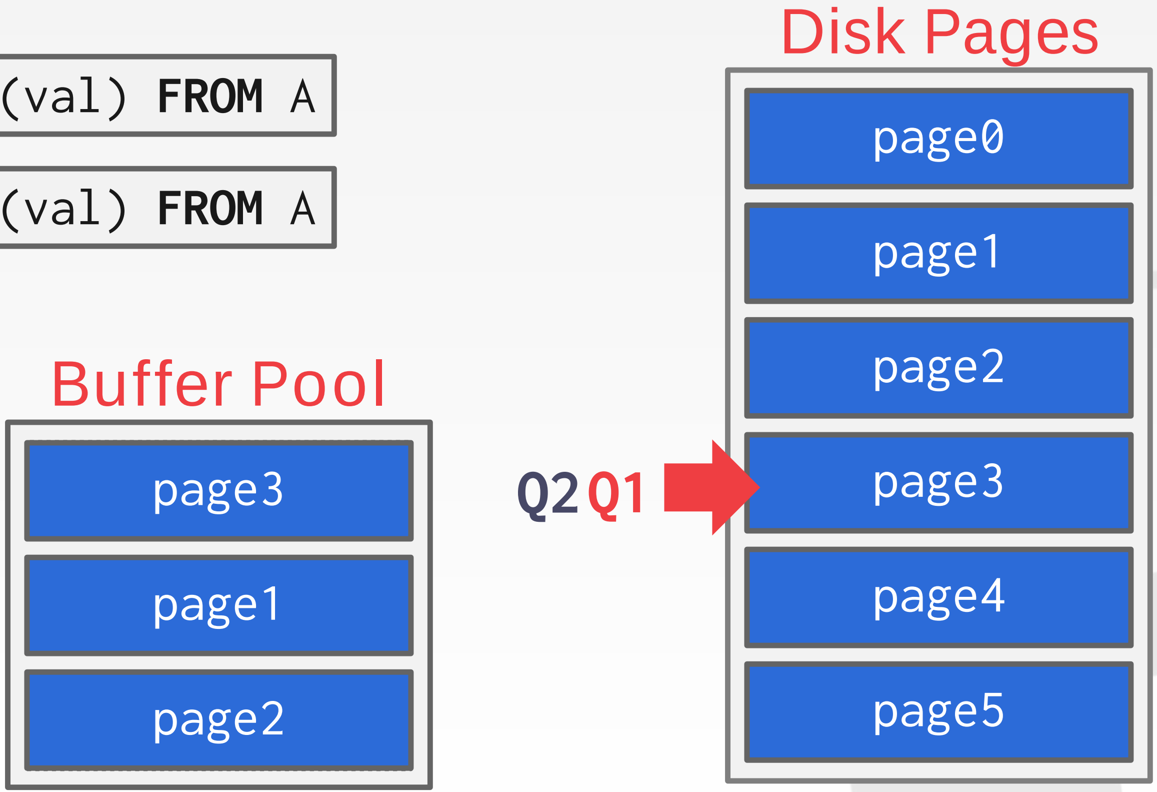

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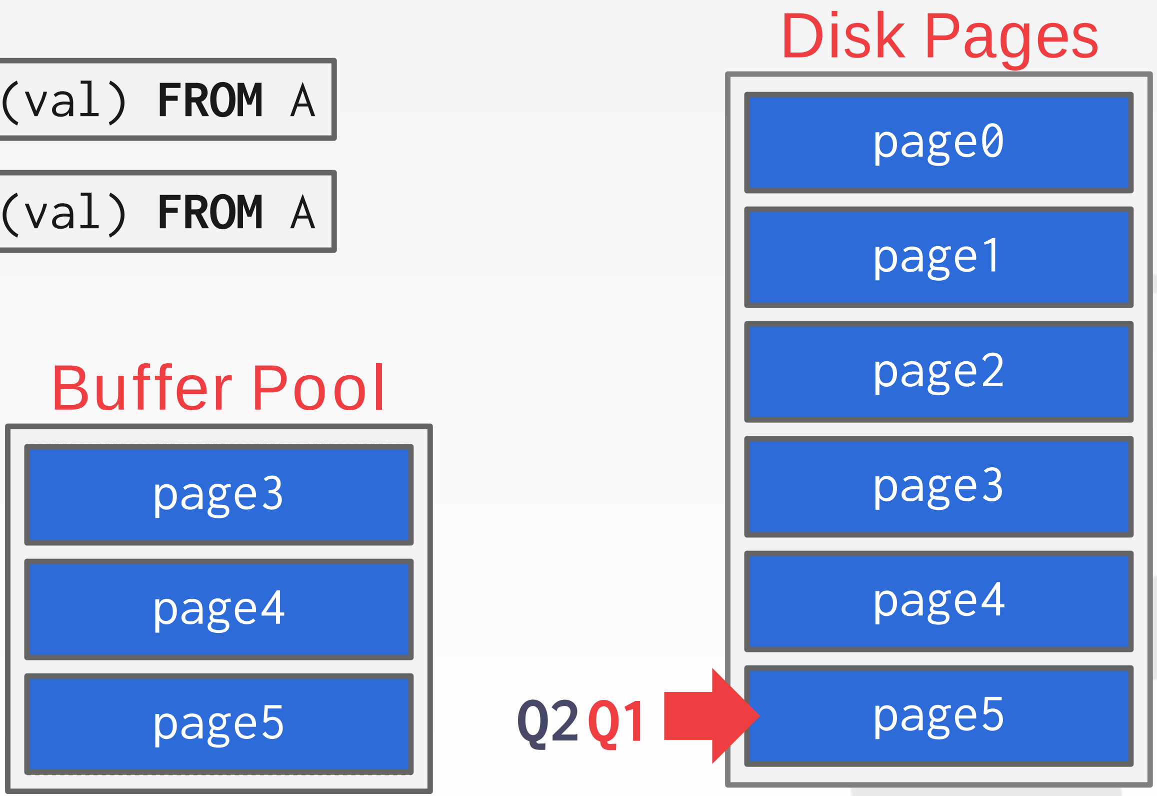

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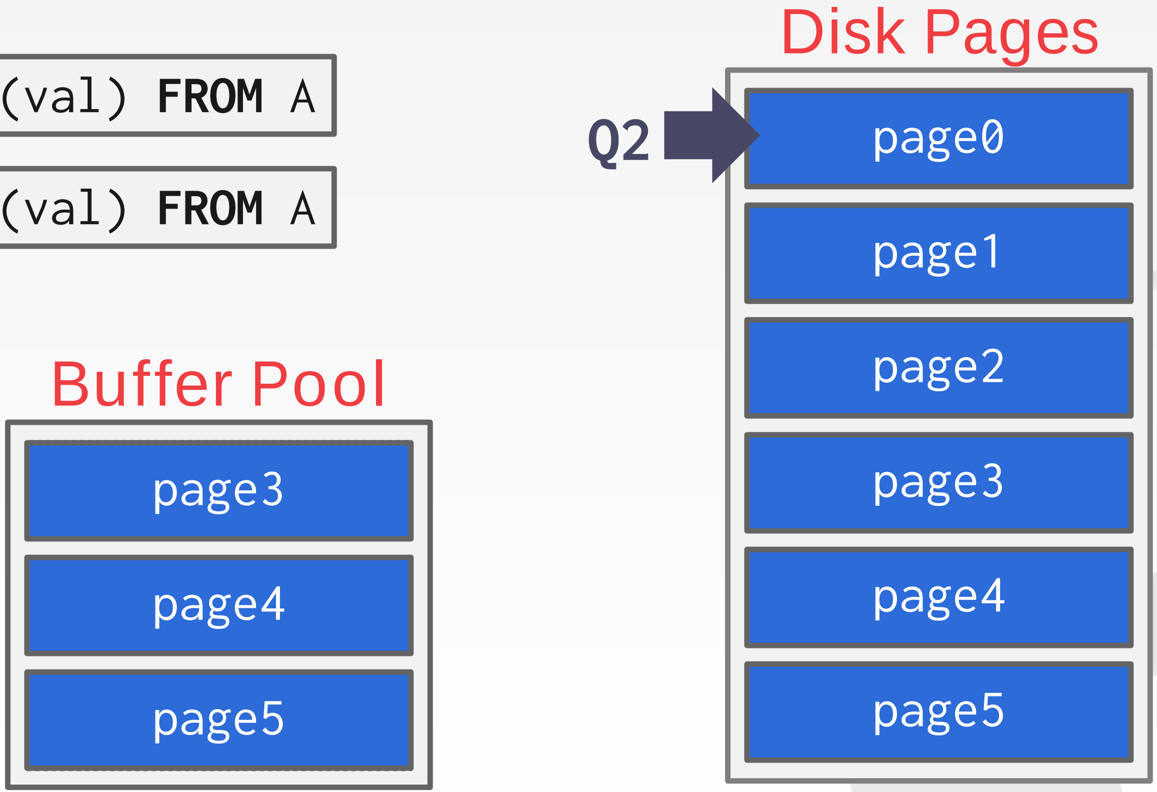

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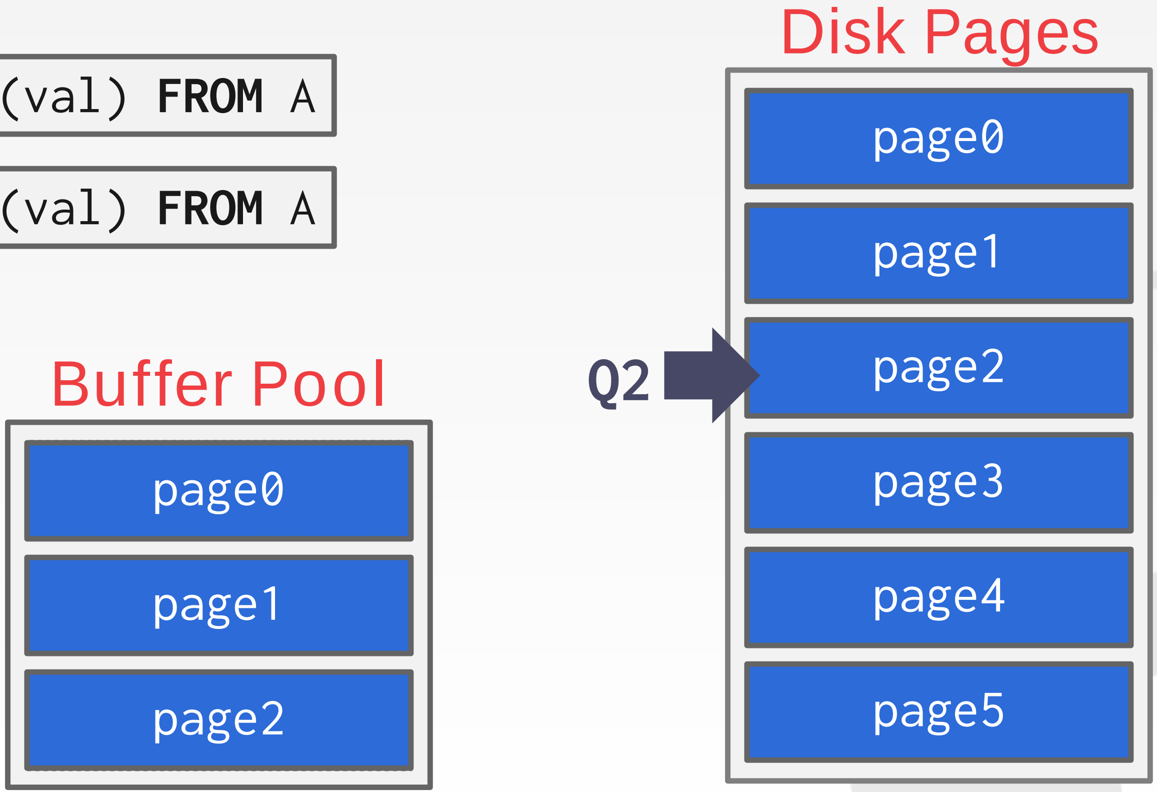
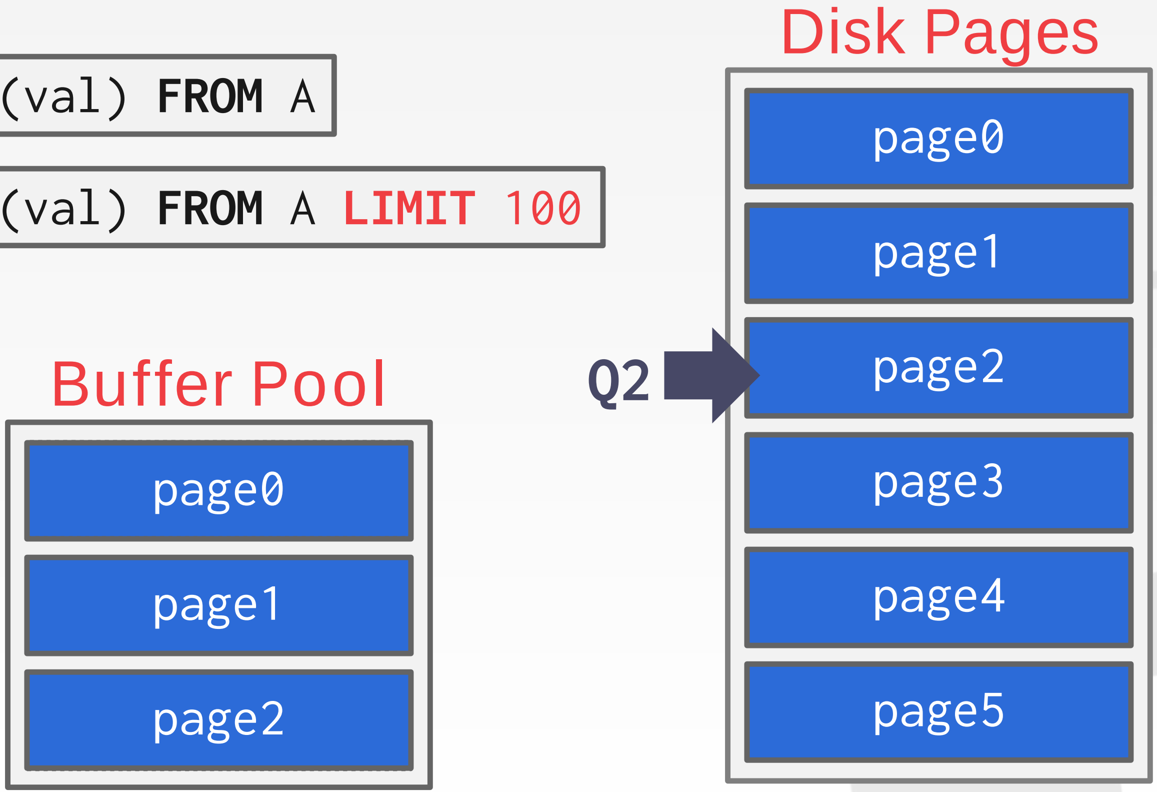


SCAN SHARING

Q1 `SELECT SUM(val) FROM A`

Q2 `SELECT AVG(val) FROM A LIMIT 100`



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.
→ Can also be used for temporary data (sorting, joins).

Called "Light Scans" in Informix.

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.

Demo: Postgres

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.

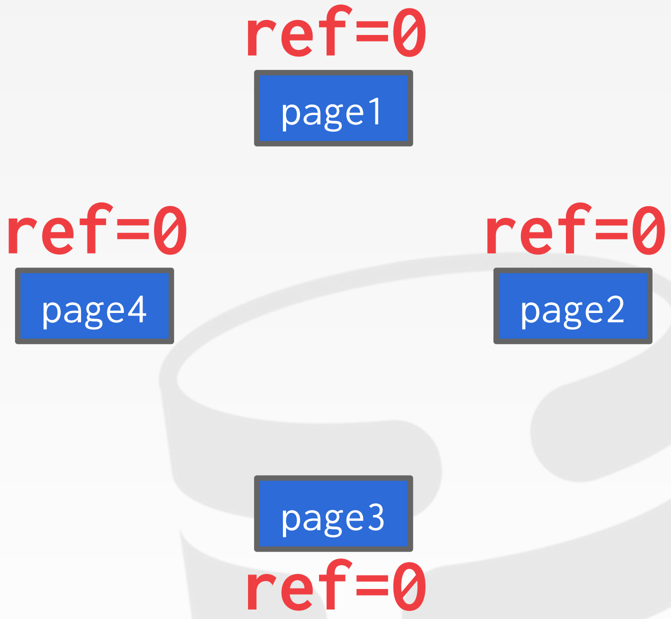
→ Each page has a reference bit.

→ 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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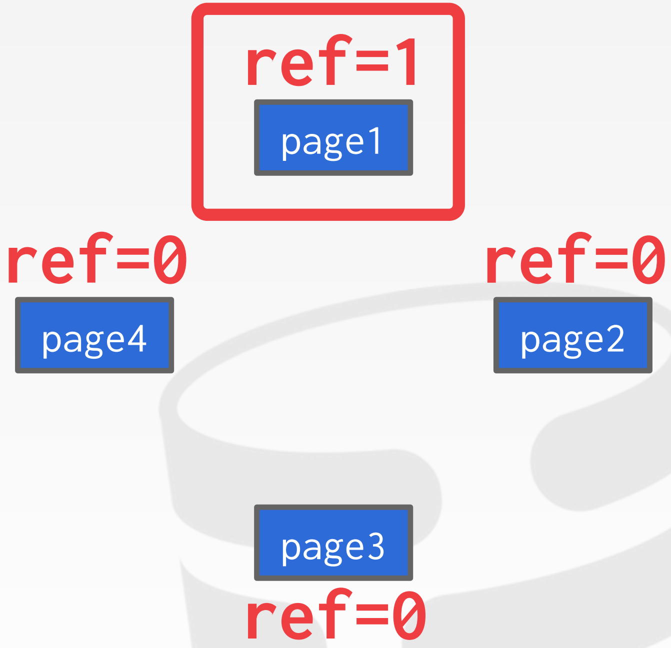

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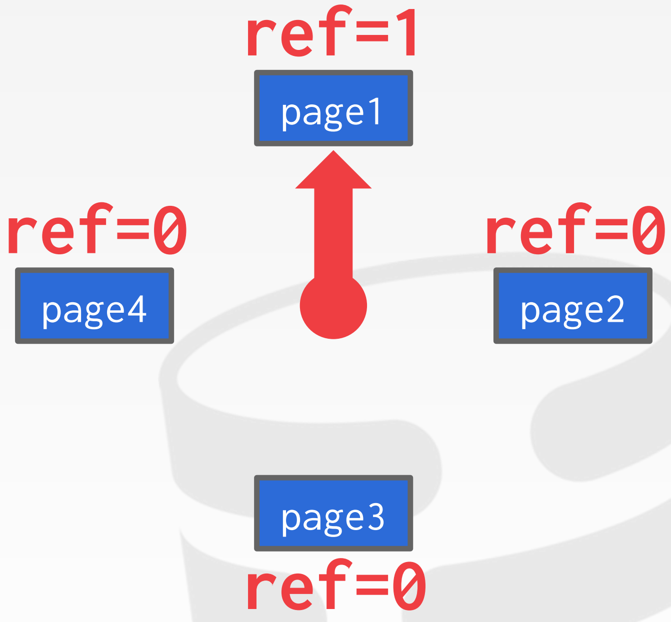

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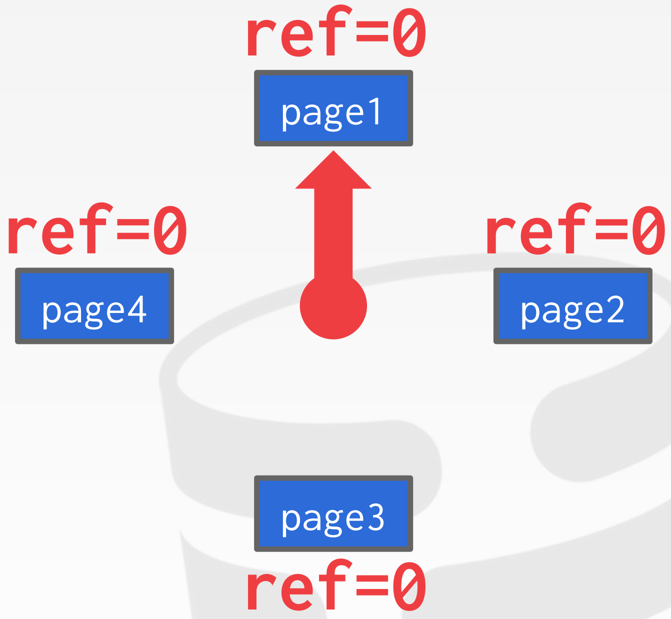

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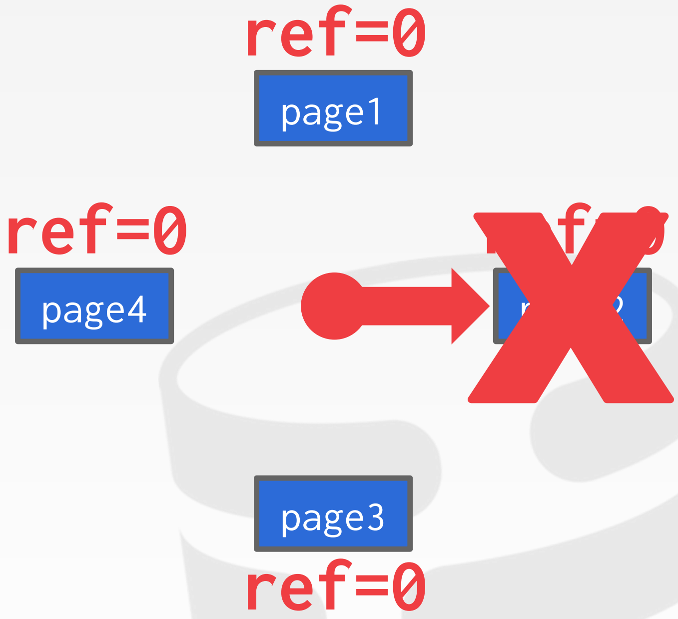

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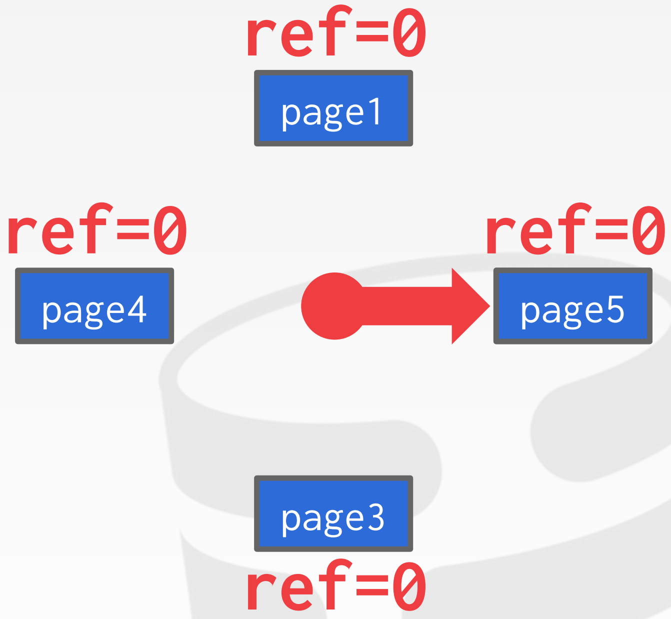

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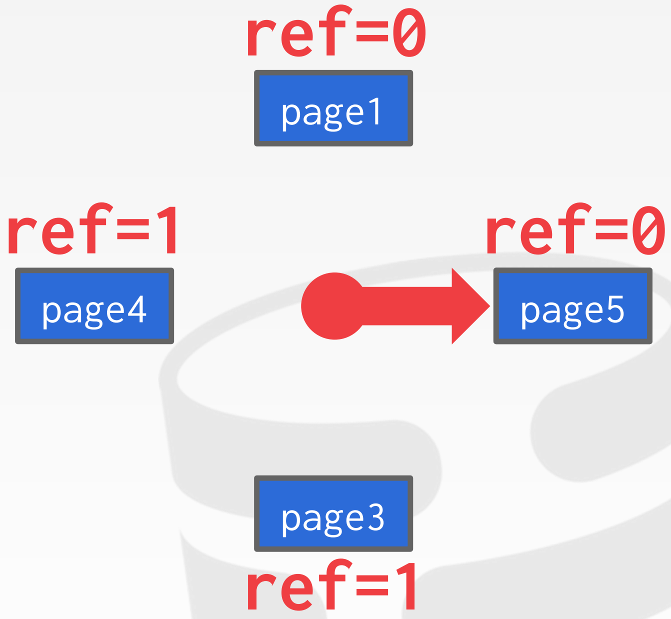

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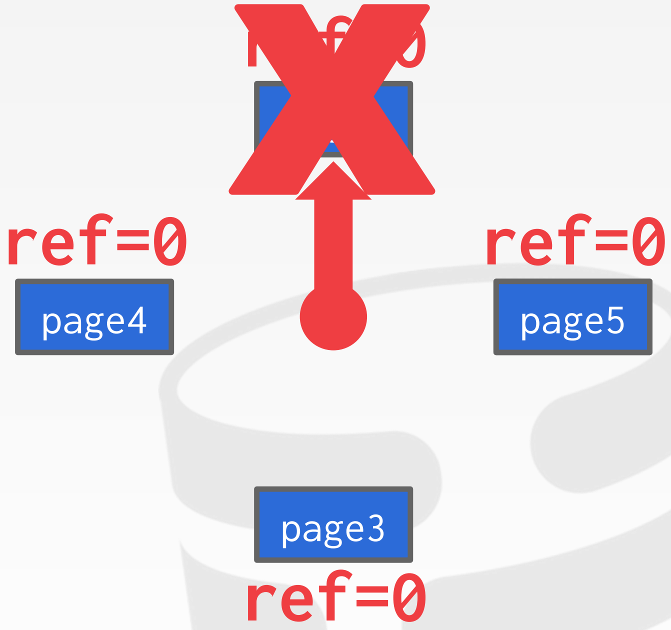


PROBLEMS

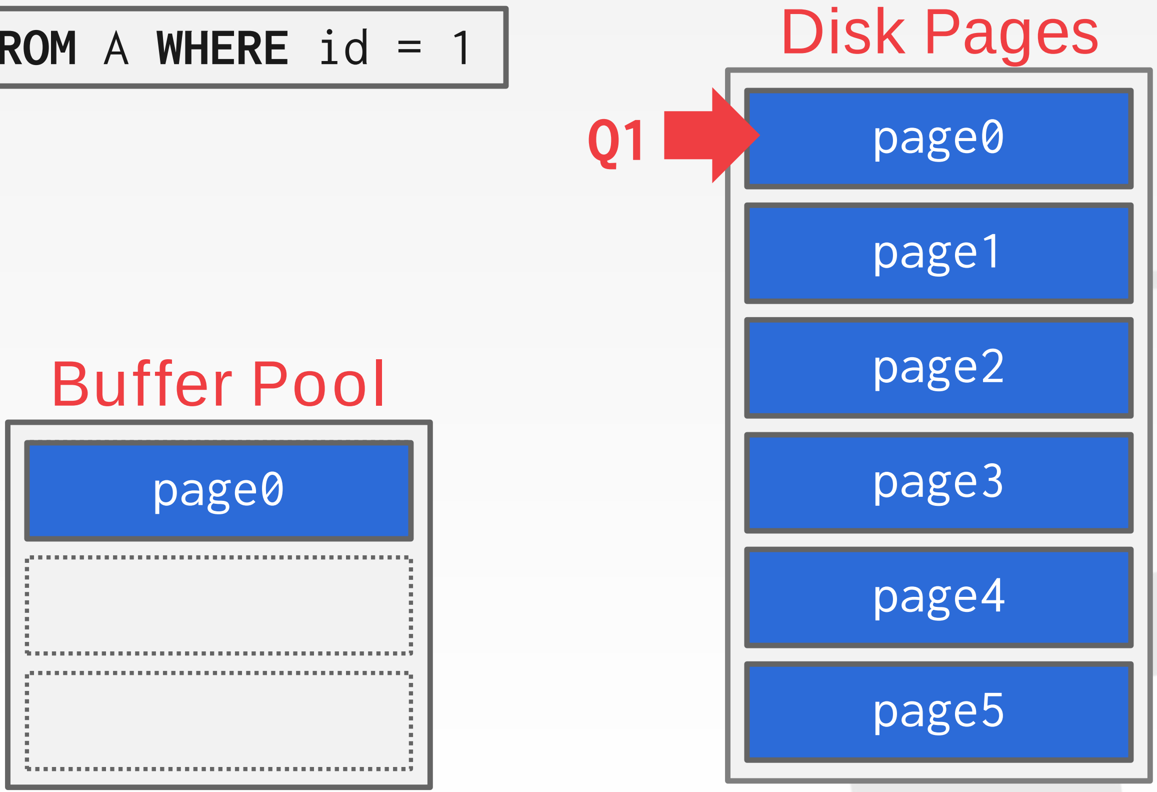
LRU and CLOCK replacement policies are susceptible to sequential flooding.

→ 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`



SEQUENTIAL FLOODING

Q1 `SELECT * FROM A WHERE id = 1`

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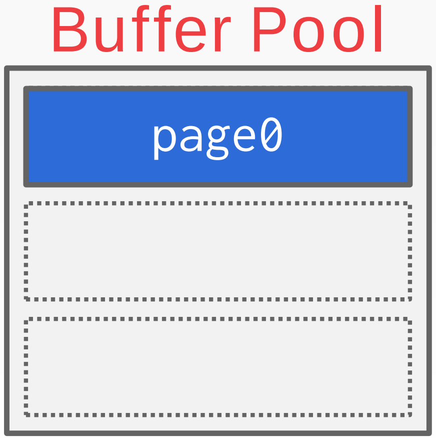

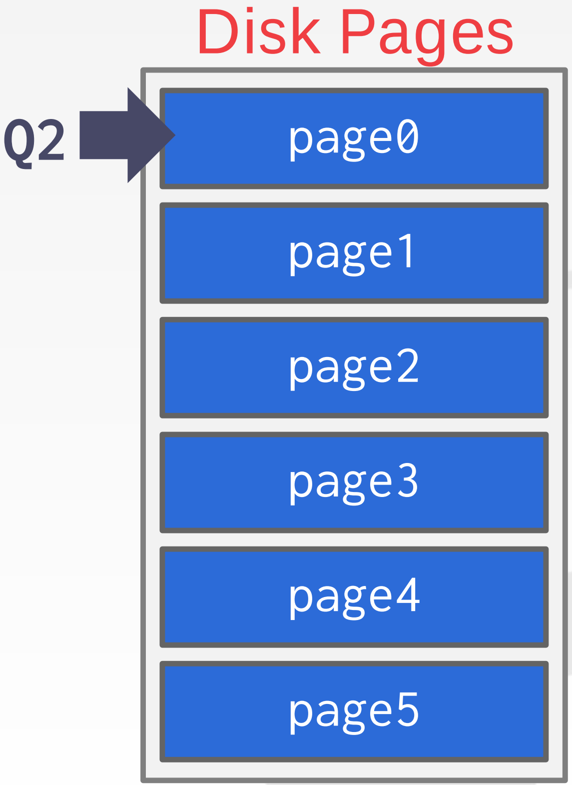

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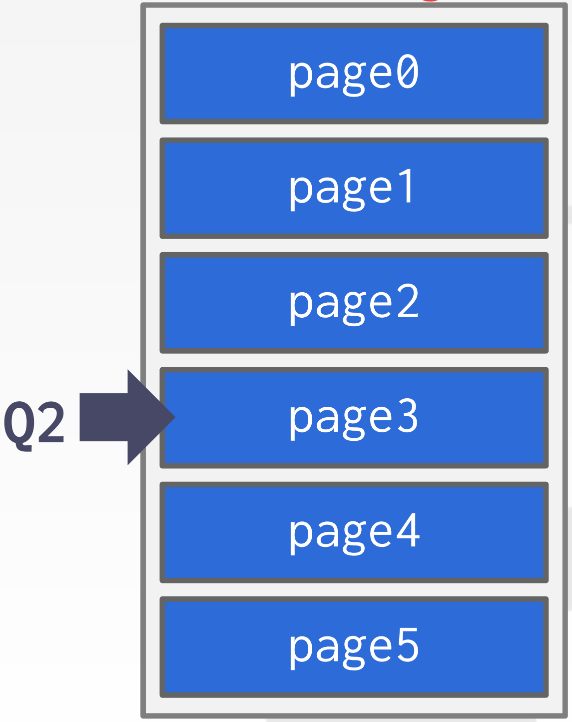
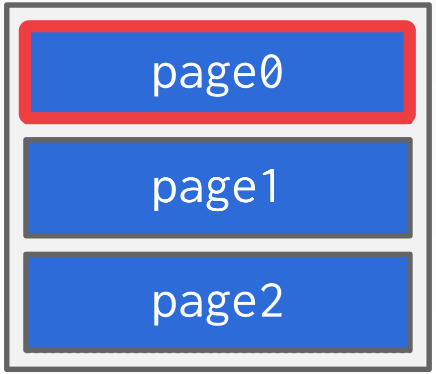
Disk Pages



Buffer Pool



SEQUENTIAL FLOODING

Q1 `SELECT * FROM A WHERE id = 1`

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Buffer Pool

- page3
- page1
- page2

Disk Pages

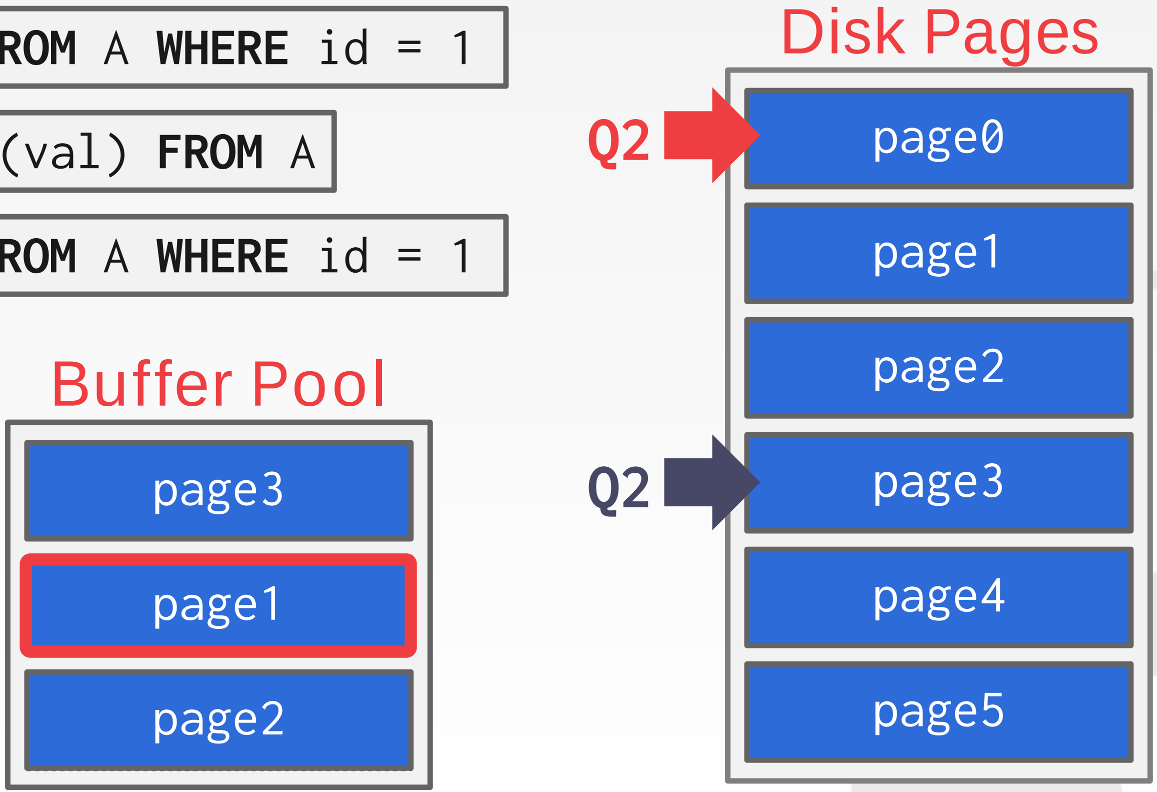
- page0
- page1
- page2
- Q2 → page3
- page4
- page5

SEQUENTIAL FLOODING

Q1 `SELECT * FROM A WHERE id = 1`

Q2 `SELECT AVG(val) FROM A`

Q3 `SELECT * FROM A WHERE id = 1`



BETTER POLICIES: LRU-K

Track the 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.

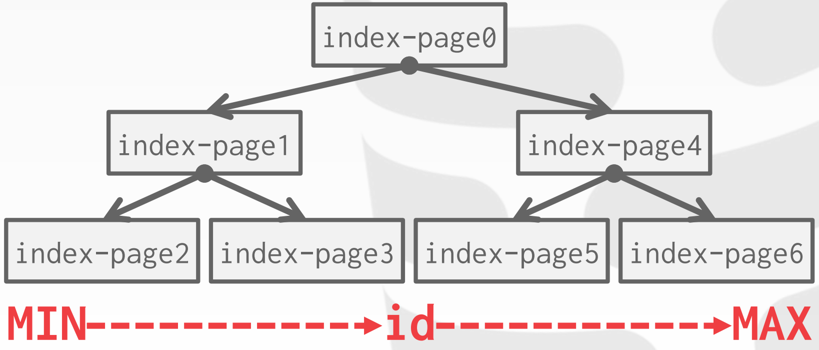
Example: Postgres maintains a small ring buffer that is private to the query.

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.

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



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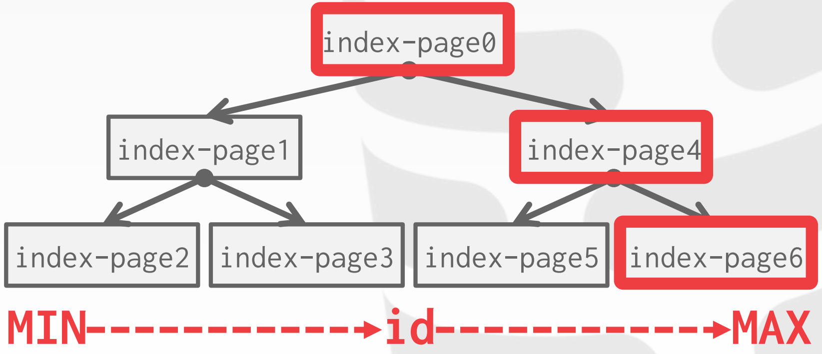


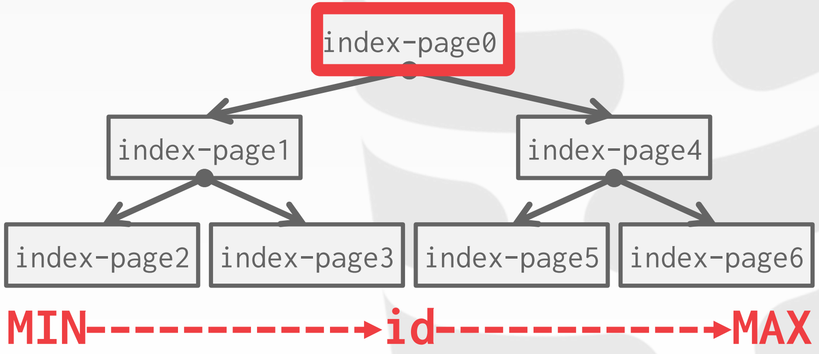
BETTER POLICIES: PRIORITY HINTS

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.

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

Q2 `SELECT * FROM A WHERE id = ?`



DIRTY PAGES

FAST: If a page in the buffer pool is <u>not</u> 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…

OTHER MEMORY POOLS

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

These other memory pools may not always 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.

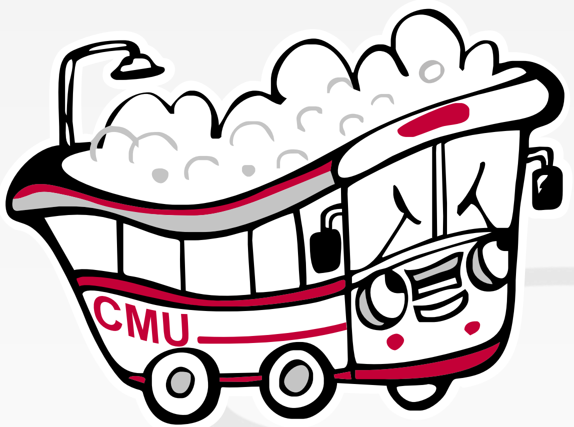
Leverage the semantics about the query plan to make better decisions:
→ Evictions
→ Allocations
→ Pre-fetching

PROJECT #1

You will build the first component of your storage manager.

→ Clock Replacement Policy
→ Buffer Pool Manager

We will provide you with the disk manager and page layouts.



BusTub

Due Date:
Friday Sept 27th @ 11:59pm

TASK #1 – CLOCK REPLACEMENT POLICY

Build a data structure that tracks the usage of `frame_ids` using the CLOCK policy.

General Hints:

→ Your `ClockReplacer` needs to check the "pinned" status of a `Page`.

→ If there are no pages touched since last sweep, then return the lowest page id.

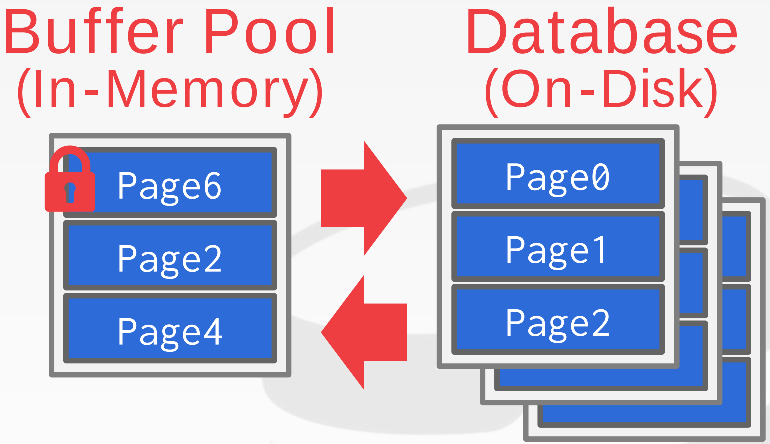
TASK #2 – BUFFER POOL MANAGER

Use your CLOCK replacer 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.

→ Use whatever data structure you want for the page table.



General Hints:

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

GETTING STARTED

Download the source code from GitHub.

Make sure you can build it on your machine.
→ We've tested Ubuntu, OSX, and Windows (WSL2).
→ We are also providing a docker file to setup your environment.
→ It does **not** compile on the Andrews machines. Please contact me if this is a problem.

THINGS TO NOTE

Do **not** change any file other than the four that you must 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.

CODE QUALITY

We will automatically check whether you are writing good code.

→ Google C++ Style Guide
→ Doxygen Javadoc Style

You need to run these targets before you submit your implementation to Gradescope.

→ `make format`
→ `make check-lint`
→ `make check-censored`
→ `make check-clang-tidy`

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!