# Intro to Databases (COMP_SCI 339)

# 04 Memory Management

Northwestern University

WINTER 2024

Andrew Crotty

# ADMINISTRIVIA

**Project #1** is due Sunday 1/21 @ 11:59pm

**Project #2** will be released tonight and is due Sunday 2/4 @ 11:59pm

**Exam #1** will be on 1/29 from 3:30-4:50pm

# DATABASE STORAGE

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

**Problem #2:** How the DBMS manages memory and transfers data to/from disk.

# DATABASE STORAGE

**Spatial Control:**

→ Where to write pages on disk.

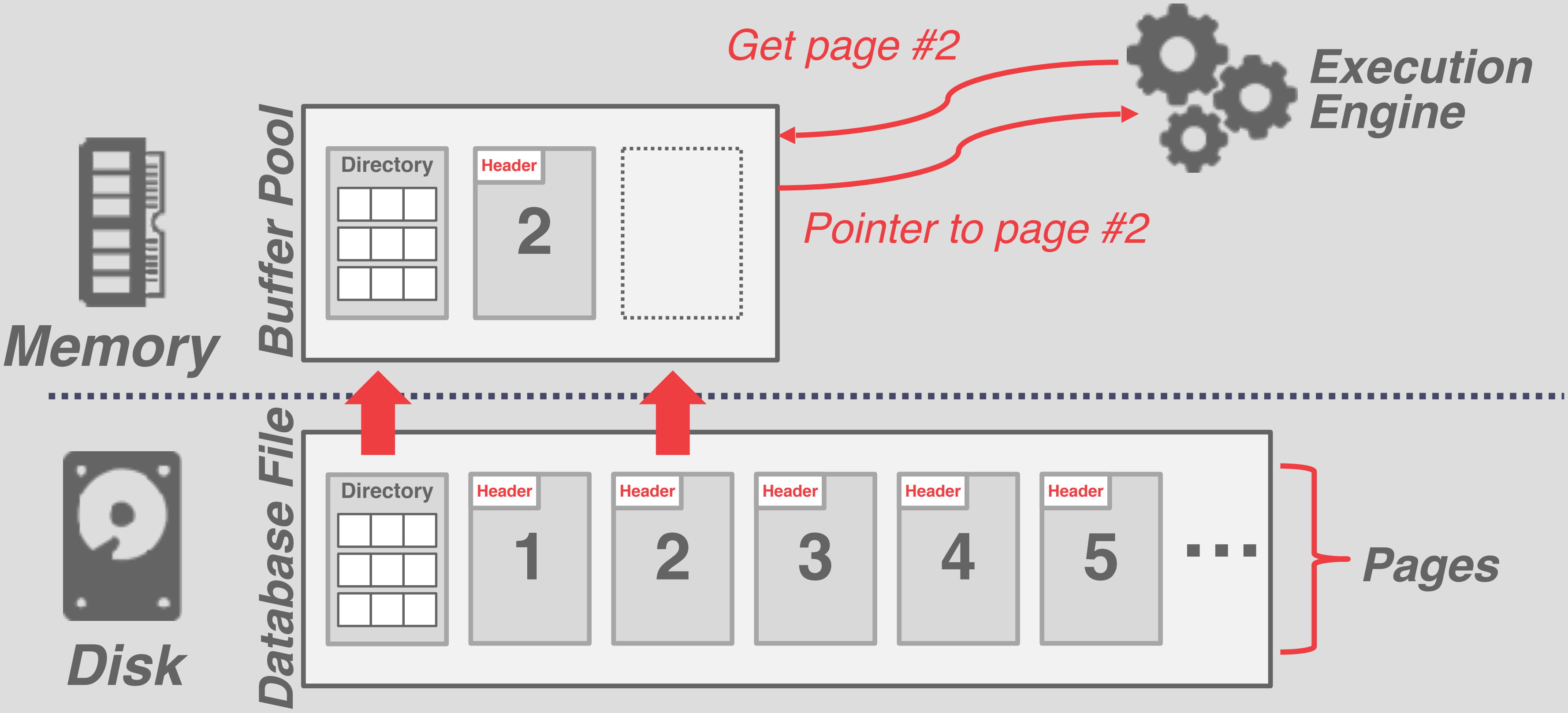
→ The goal is to keep pages that are often accessed together physically close on disk.

**Temporal Control:**

→ When to read pages into memory, and when to write them out to disk.

→ The goal is to minimize the number of stalls from having to perform disk I/O.

# DISK-BASED DBMS



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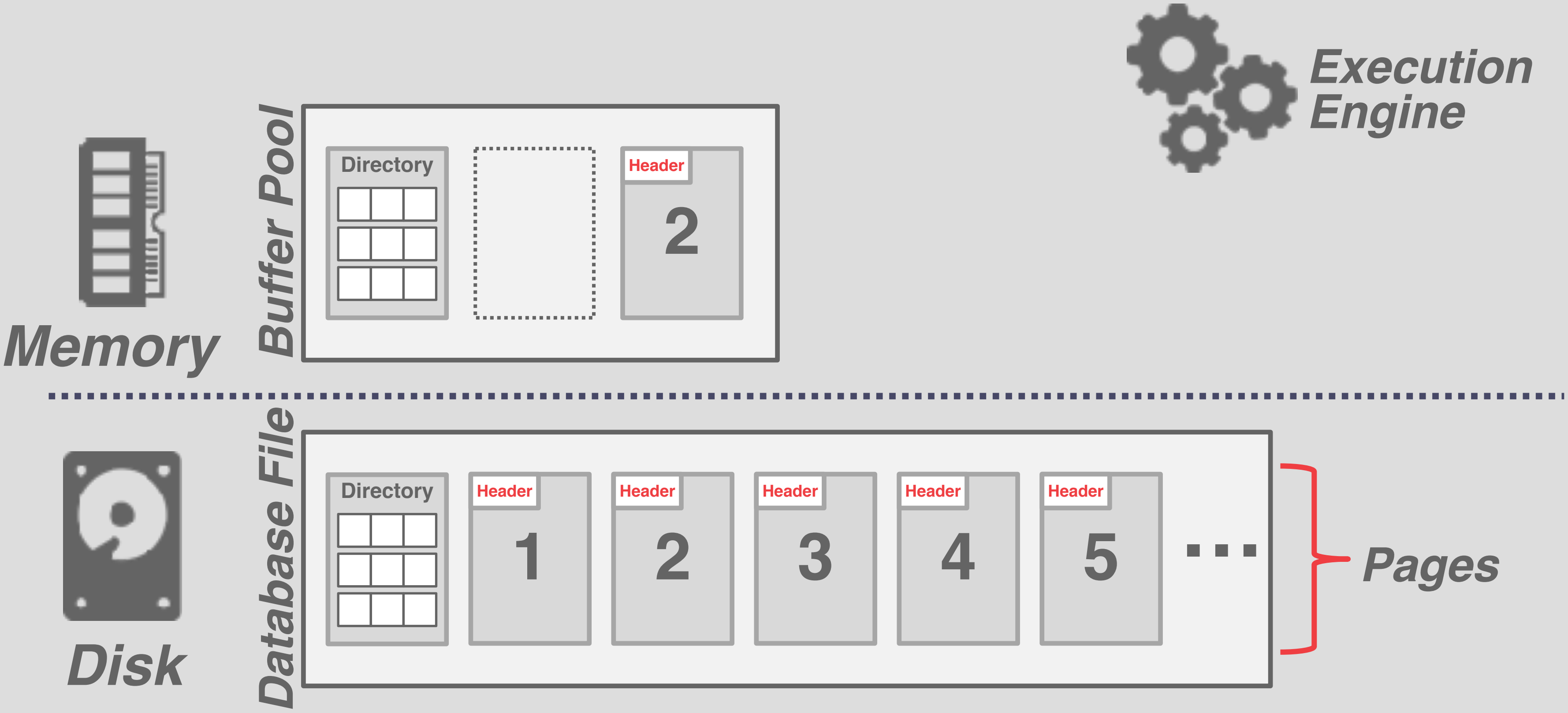


# TODAY'S AGENDA

Buffer Pool Manager

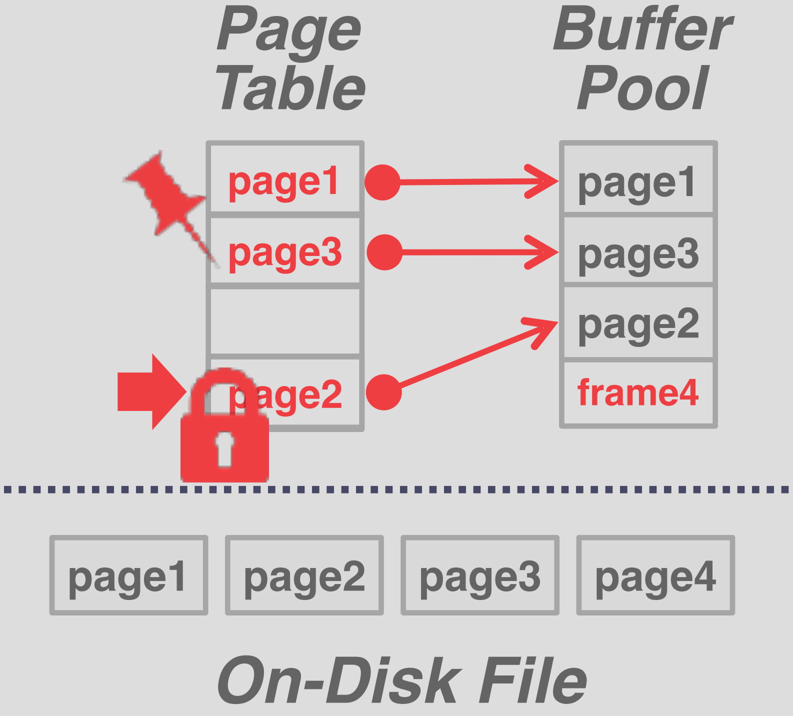
Replacement Policies

Other Optimizations

# 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 VS. PAGE DIRECTORY

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

→ All changes must be recorded on disk to allow the DBMS to find them 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.

# 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.

Considerations:

→ Correctness
→ Accuracy
→ Speed
→ Meta-data overhead

# LEAST-RECENTLY USED

Maintain a single timestamp for 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 that does not need a separate timestamp per page.

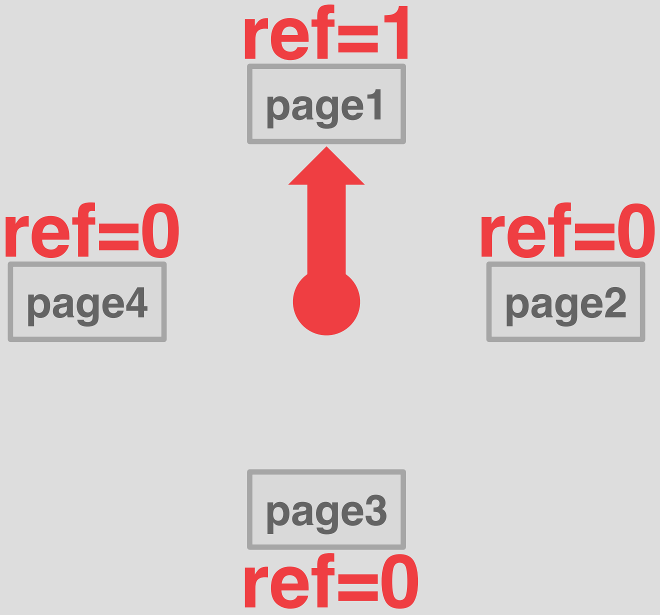
→ Each page has a reference bit.

→ 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 0. If no, then evict.



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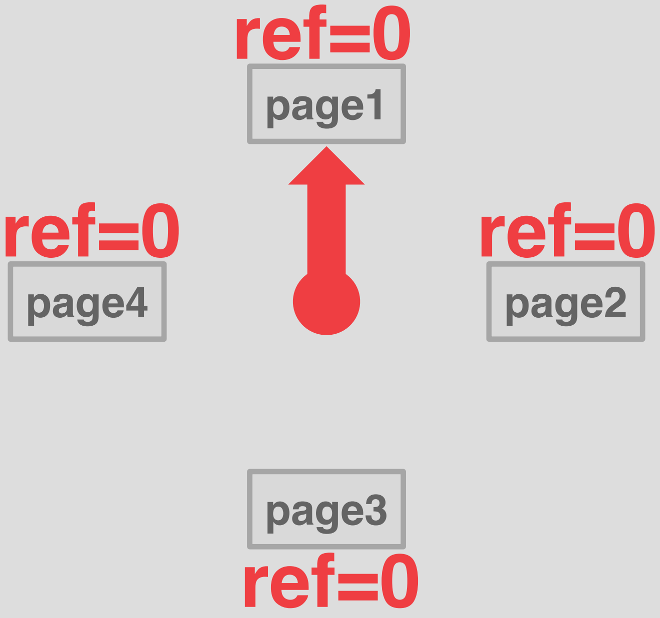

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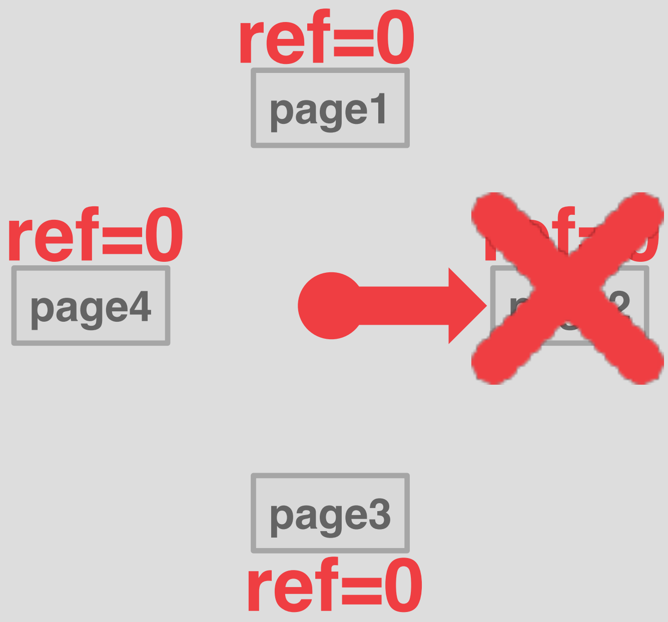

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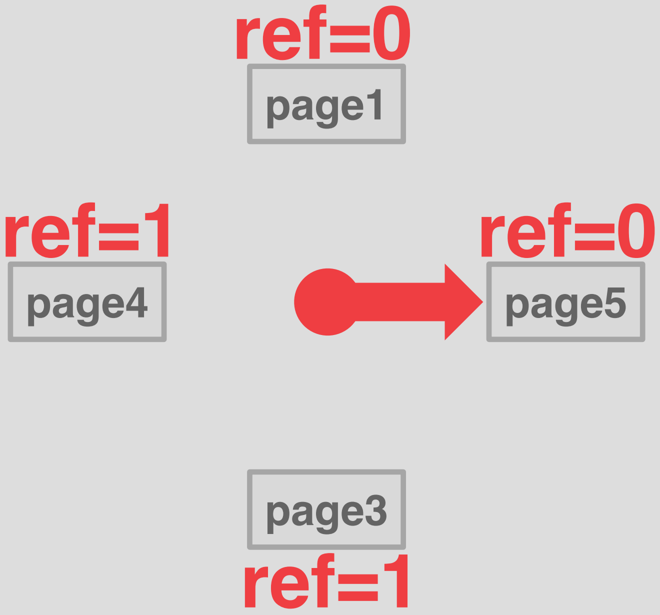

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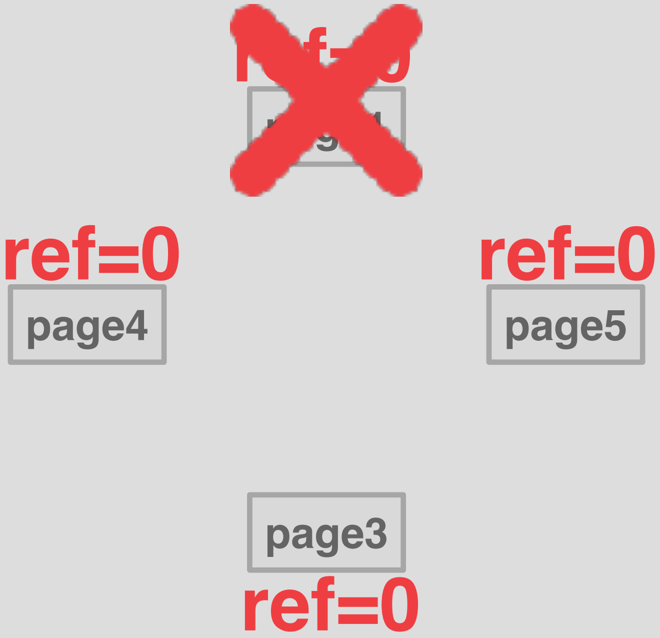


# PROBLEMS

LRU and CLOCK replacement policies are susceptible to <u>sequential flooding</u>.

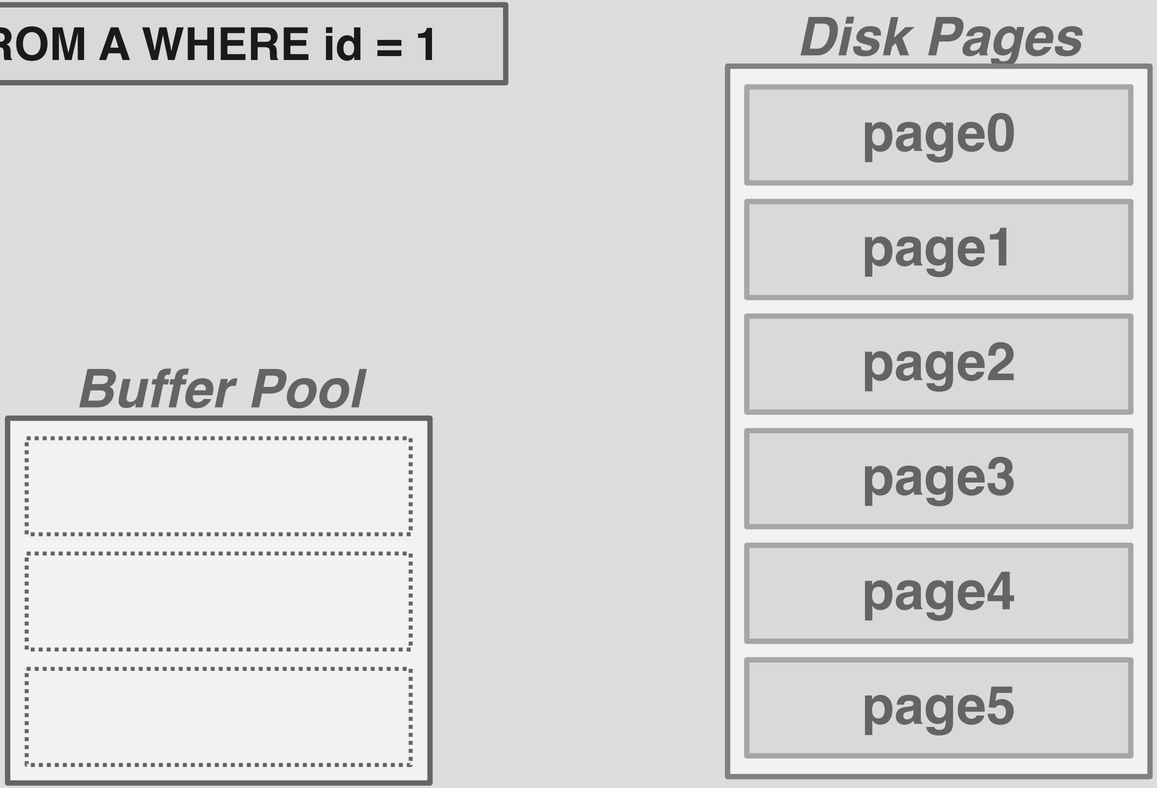
→ A query performs a sequential scan that reads every page.

→ This pollutes the buffer pool with pages that are read once and then never again.

In some workloads, the most recently used (MRU) page is the most unneeded page.

# SEQUENTIAL FLOODING

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



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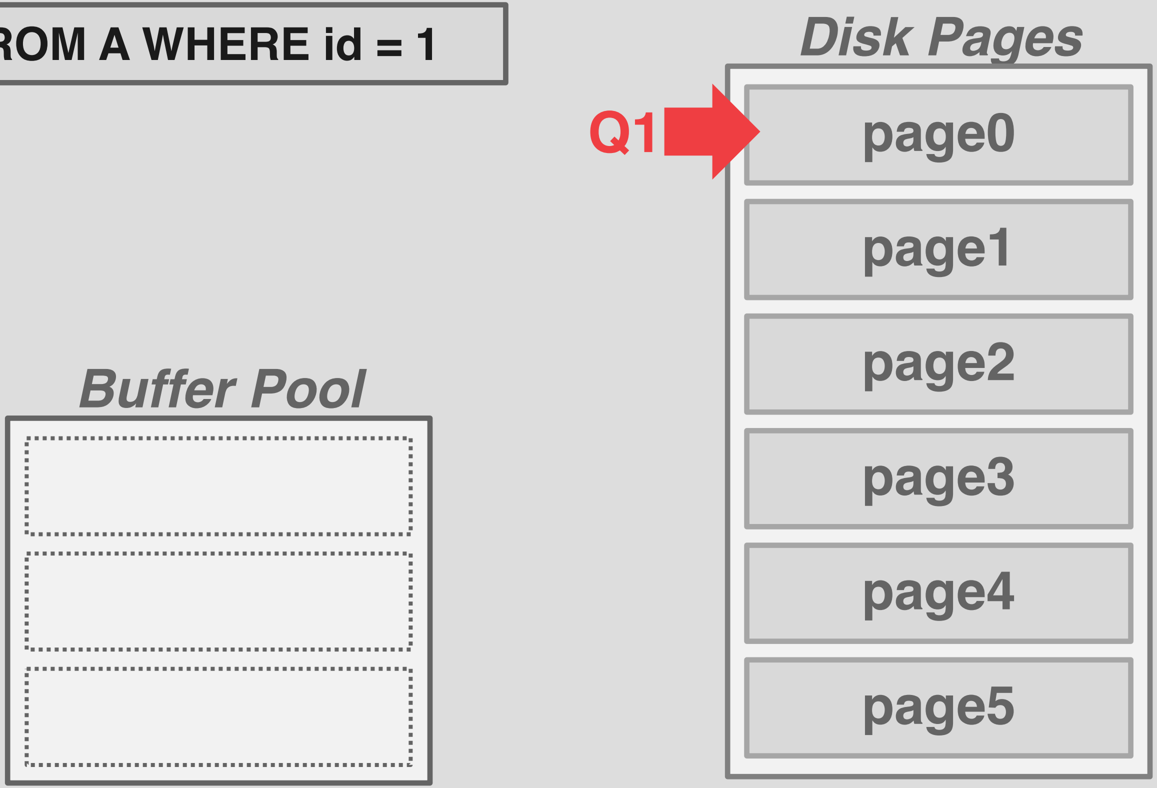

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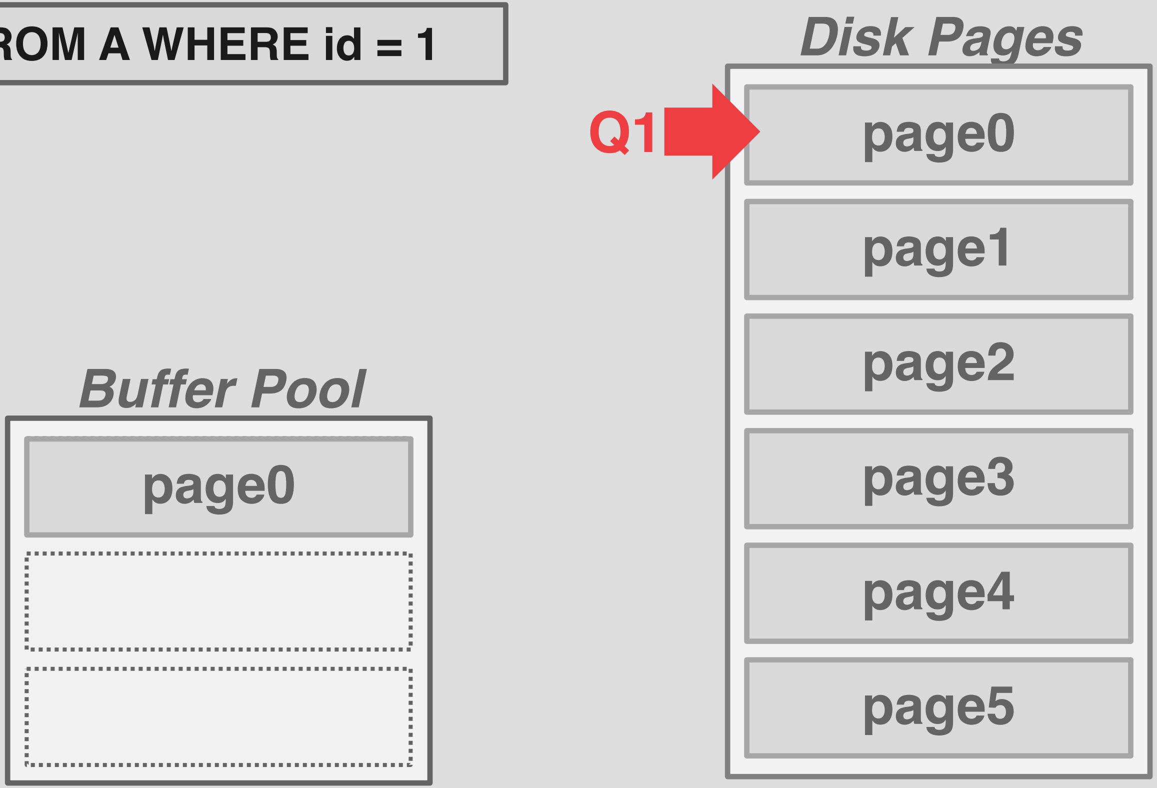

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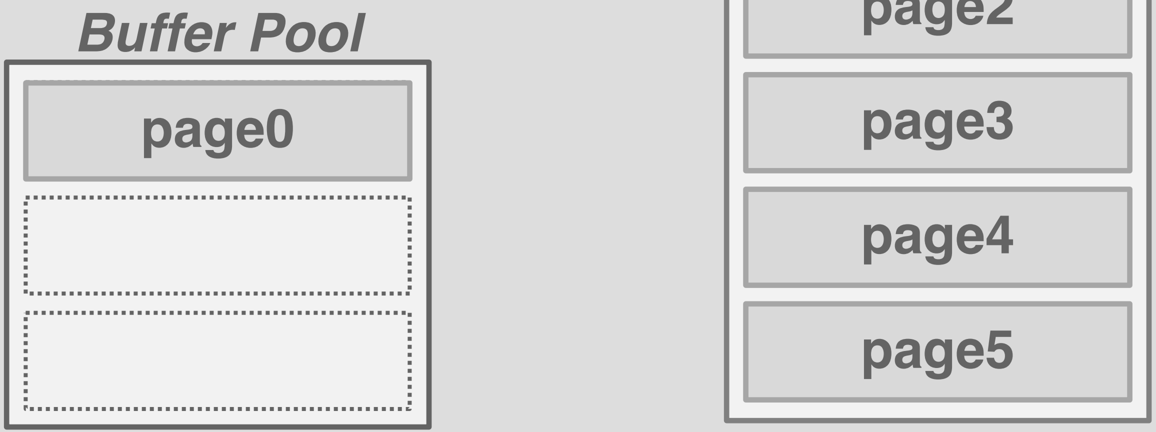
Q1 SELECT * FROM A WHERE id = 1

Q2 SELECT AVG(val) FROM A



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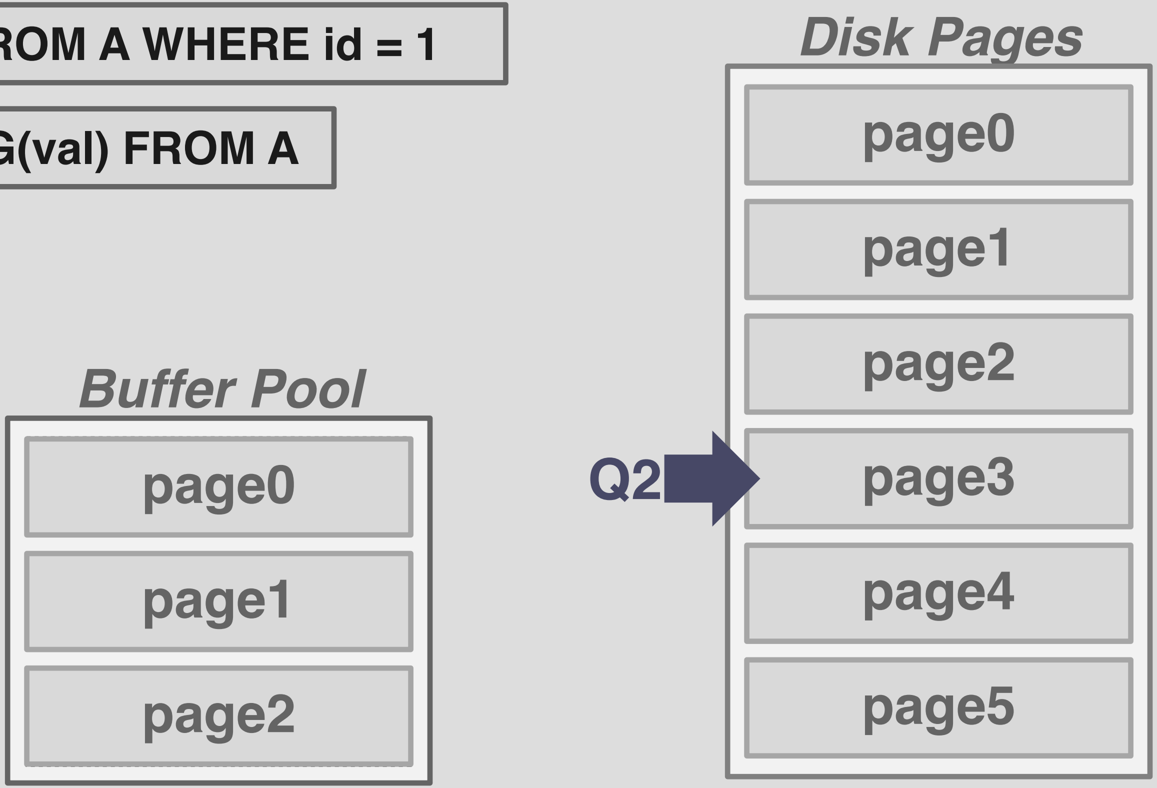

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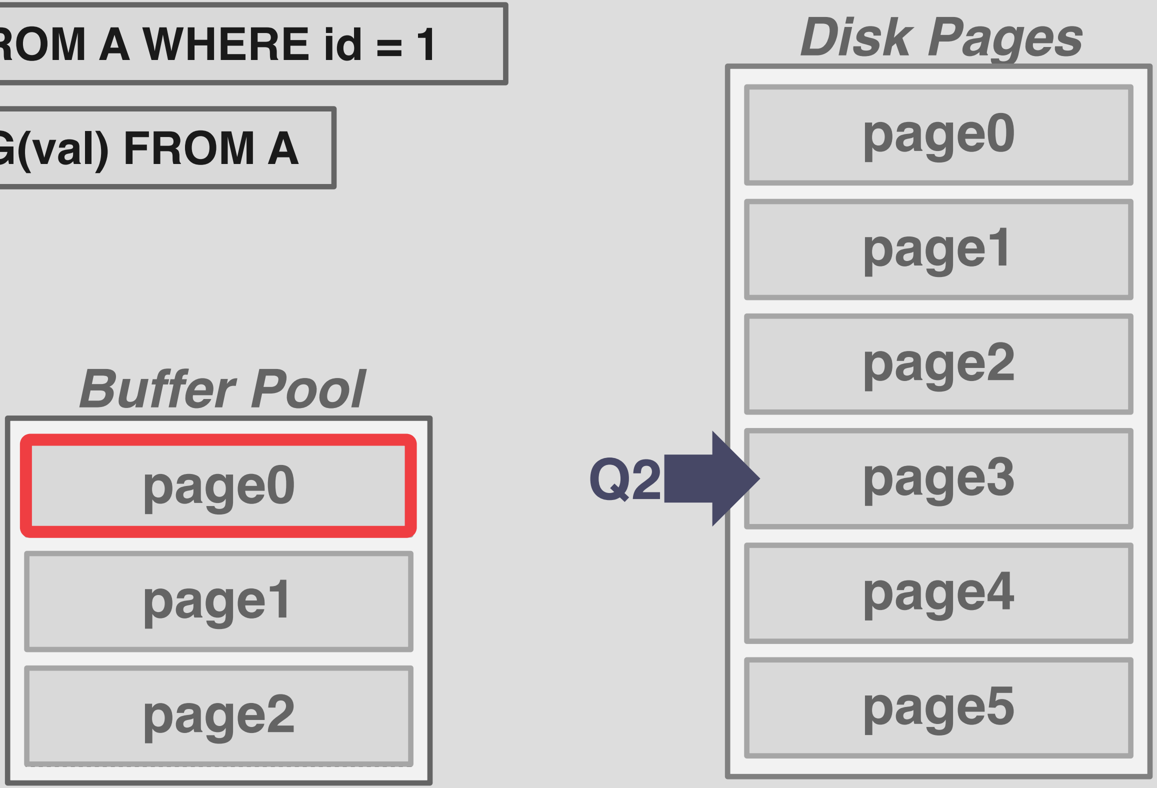

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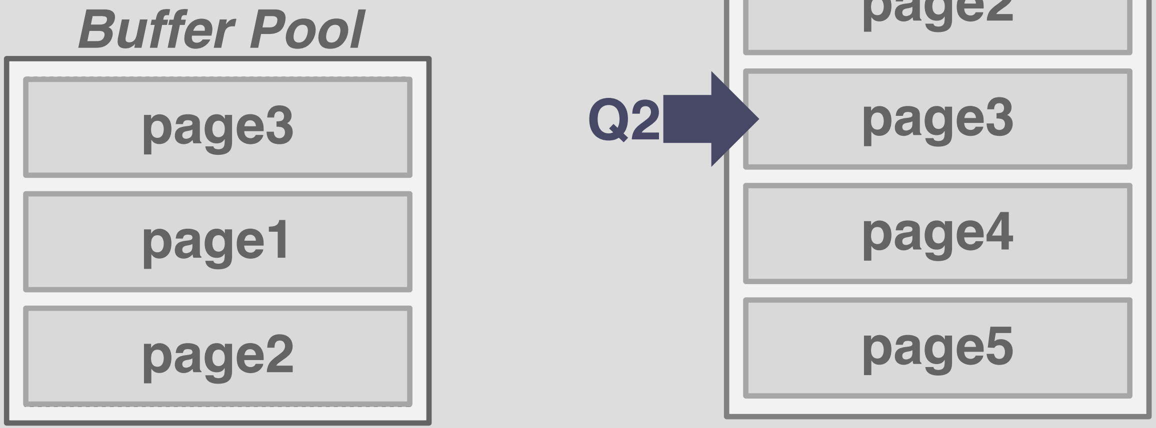

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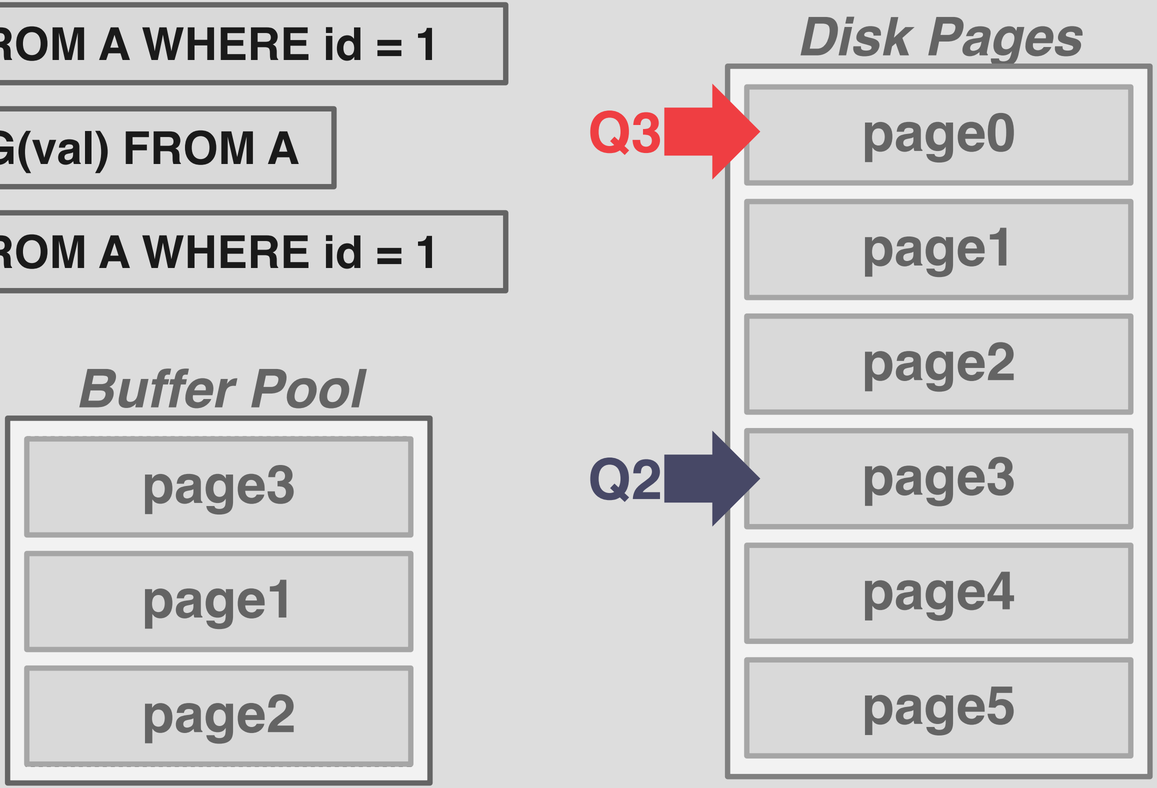

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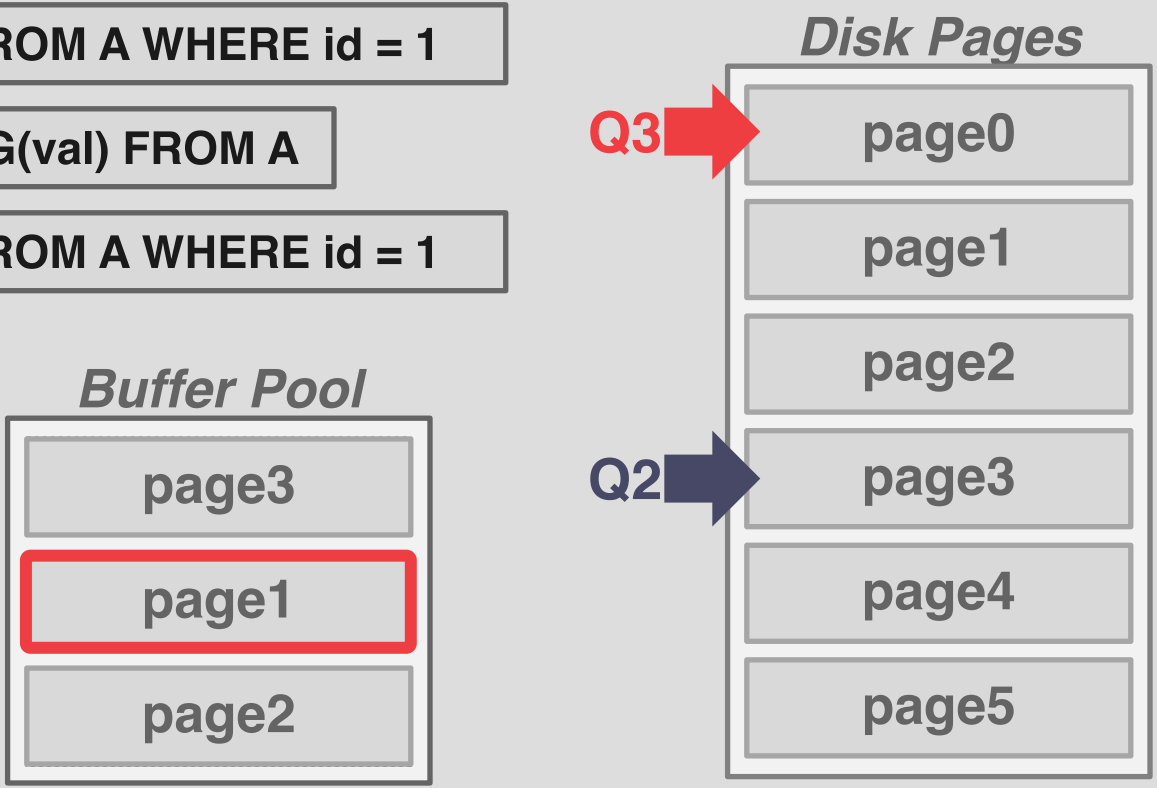

# BETTER POLICIES: LRU-K

Track the history of last *K* references to each page 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 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 about the context of each page during query execution.

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

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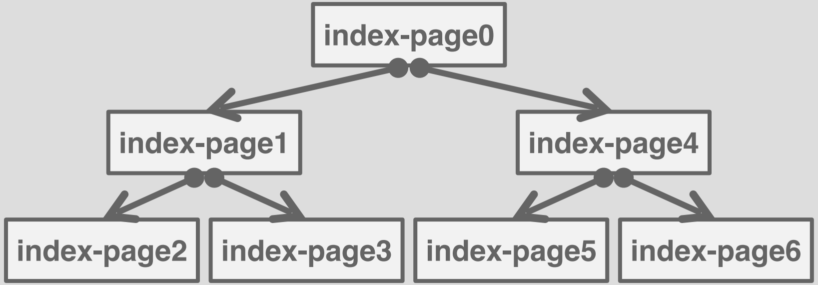

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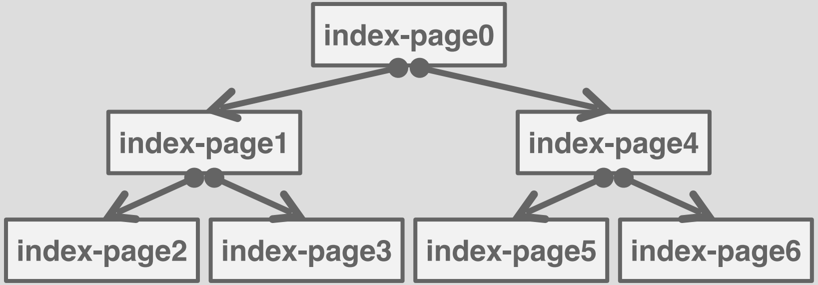

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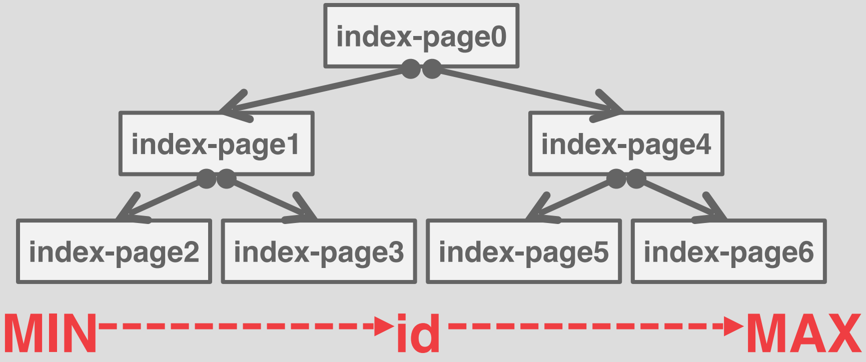

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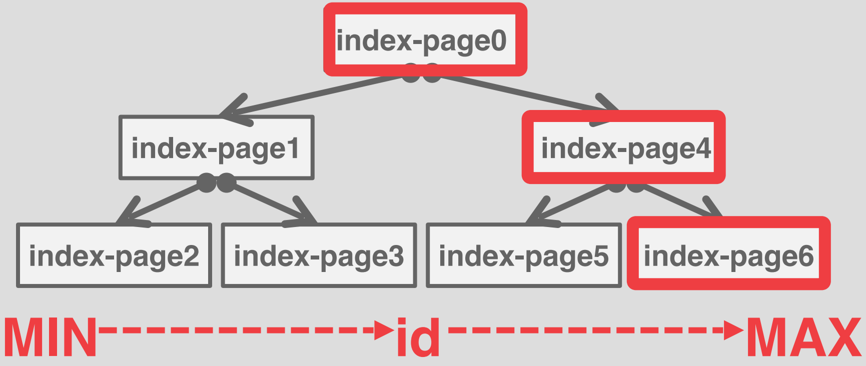

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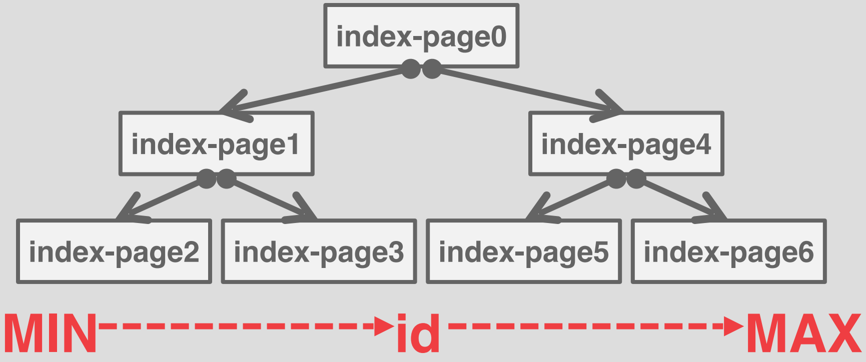

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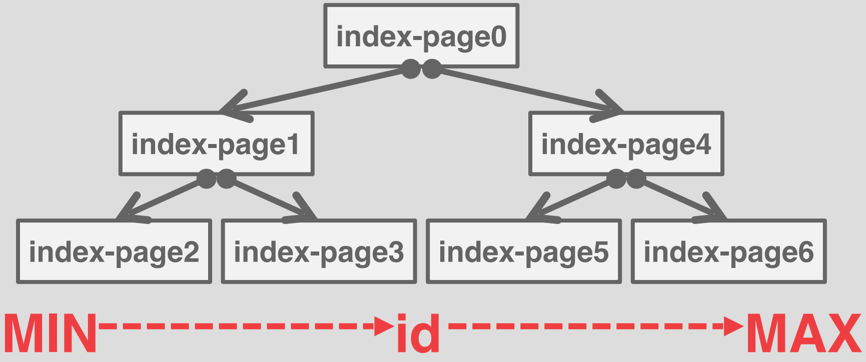
Q2 **SELECT * FROM A WHERE id = ?**



# BUFFER POOL OPTIMIZATIONS

Dirty Page Eviction

Background Writing

Avoiding the OS

Multiple Buffer Pools

Pre-Fetching

Scan Sharing

Buffer Pool Bypass

# DIRTY PAGE EVICTION

**Fast Path:** If a page in the buffer pool is <u>not</u> dirty, then the DBMS can simply "drop" it.

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

Trade-off between fast evictions vs. writing dirty 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.

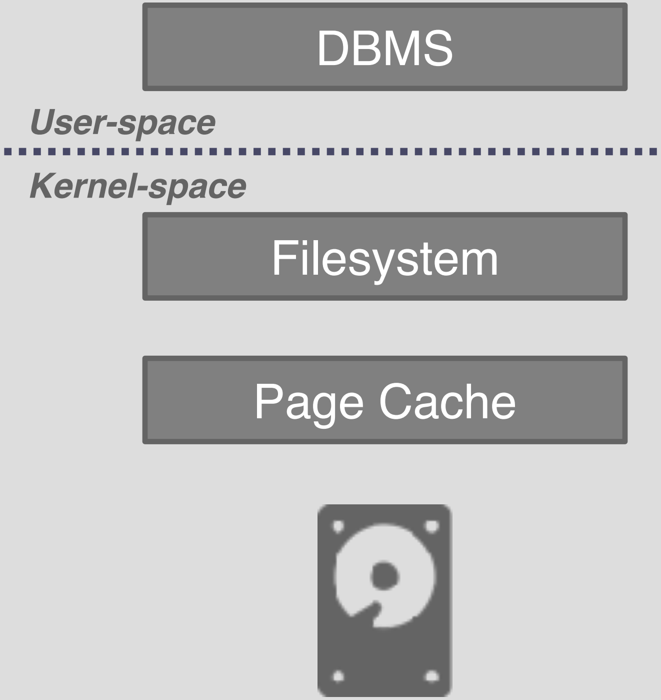
When a dirty page is safely written, the DBMS can either evict the page or just unset the dirty flag.

Need to be careful that the system doesn't write dirty pages before their log records are written…

# OS PAGE CACHE

Most disk operations go through the OS API. Unless the DBMS tells it not to, the OS maintains its own filesystem cache (aka page cache, buffer cache).

Most DBMSs use direct I/O (**O_DIRECT**) to bypass the OS's cache.
→ Redundant copies of pages.
→ Different eviction policies.
→ Loss of control over file I/O.



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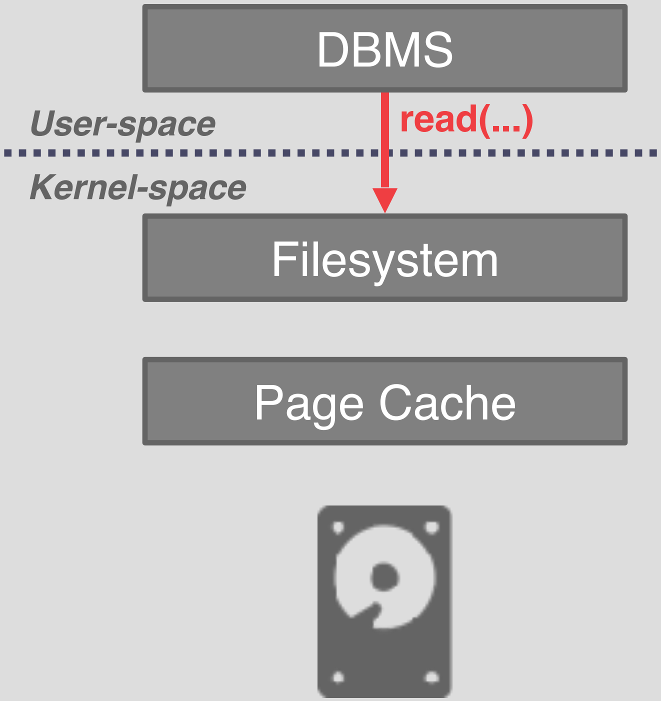

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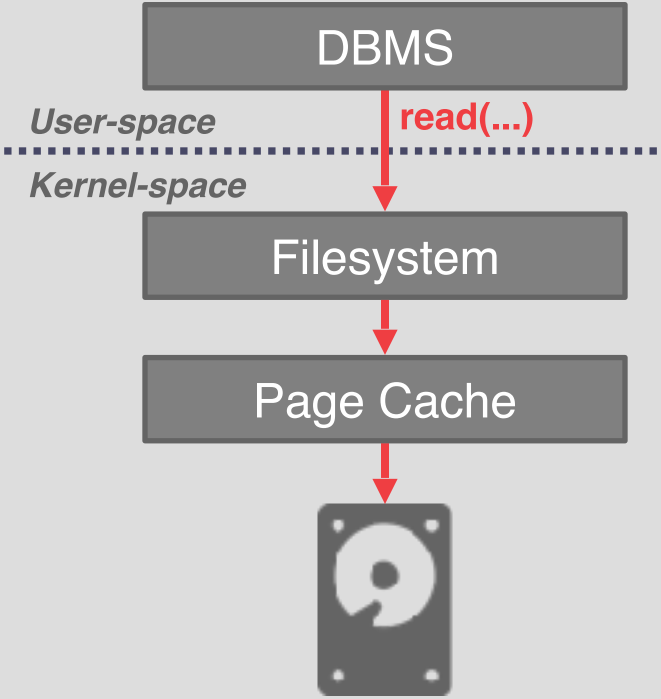

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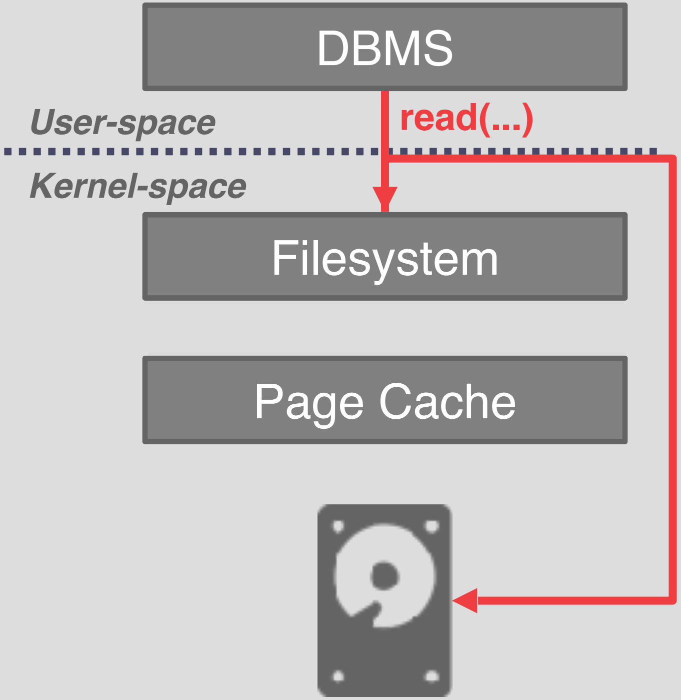


# MULTIPLE BUFFER POOLS

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

Partitioning memory across multiple pools helps reduce latch contention and improve locality.

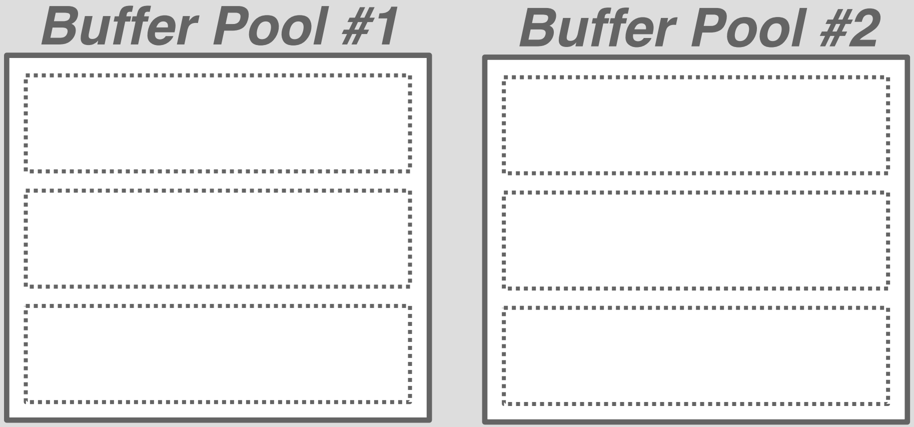
# MULTIPLE BUFFER POOLS

**Approach #1: Object Id**

→ Embed an object identifier in record ids and then maintain a mapping from objects to specific buffer pools.

**Approach #2: Hashing**

→ Hash the page id to select which buffer pool to access.



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Q1 GET RECORD #123

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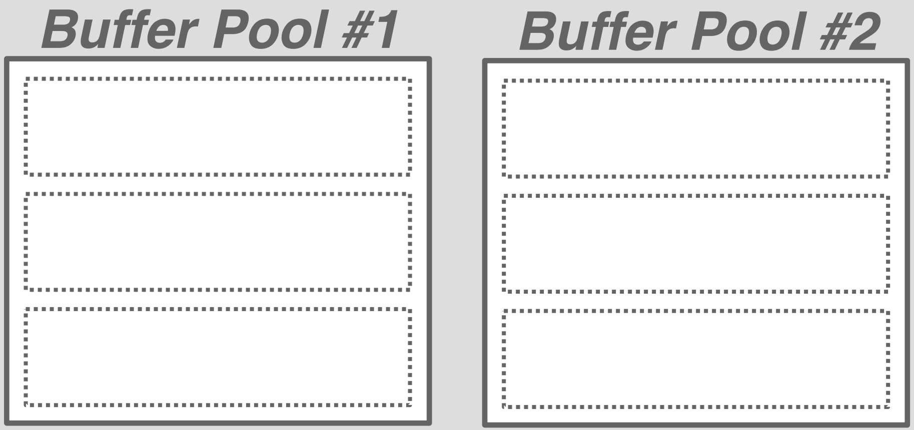

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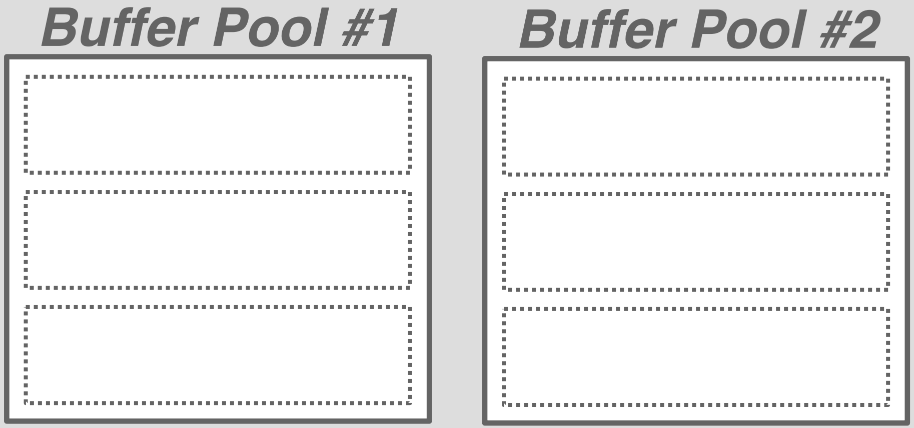

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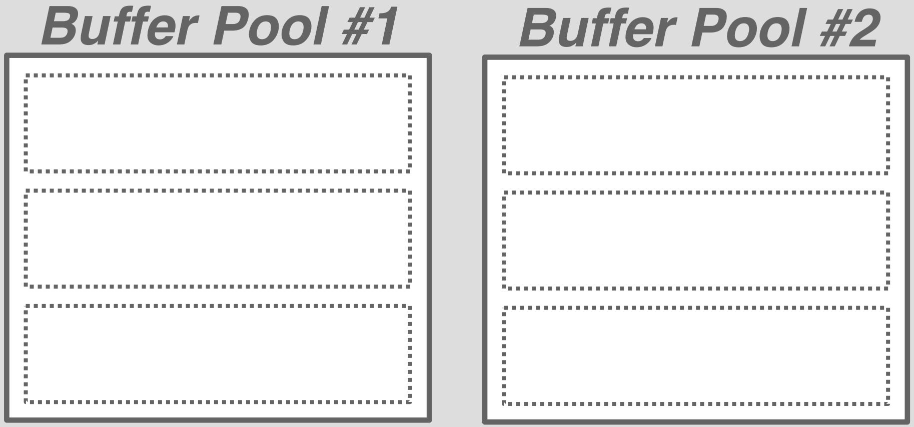

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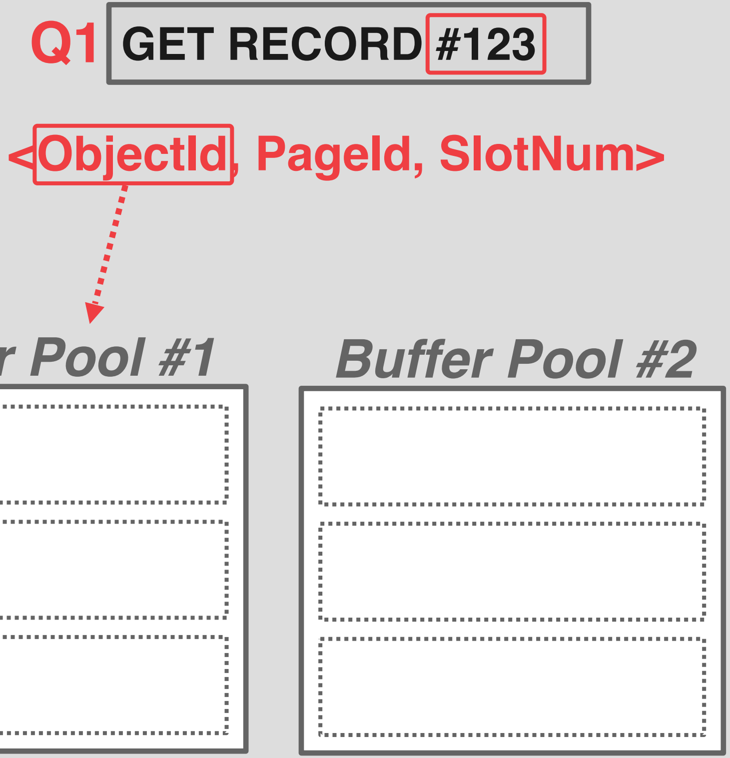

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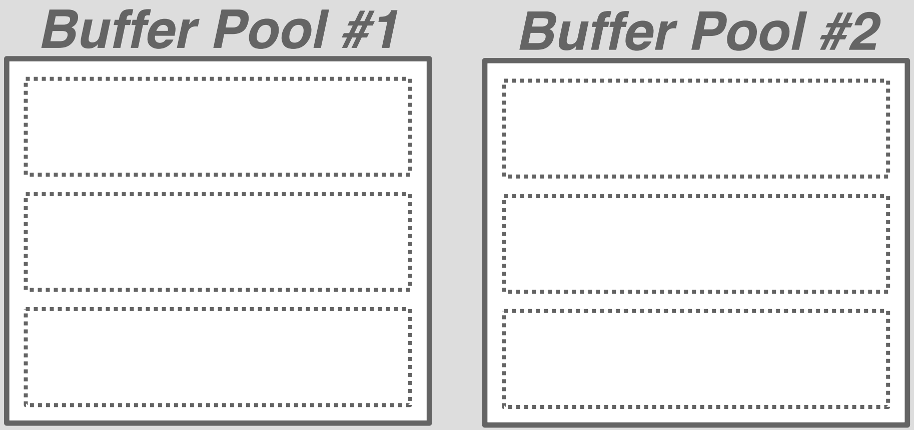

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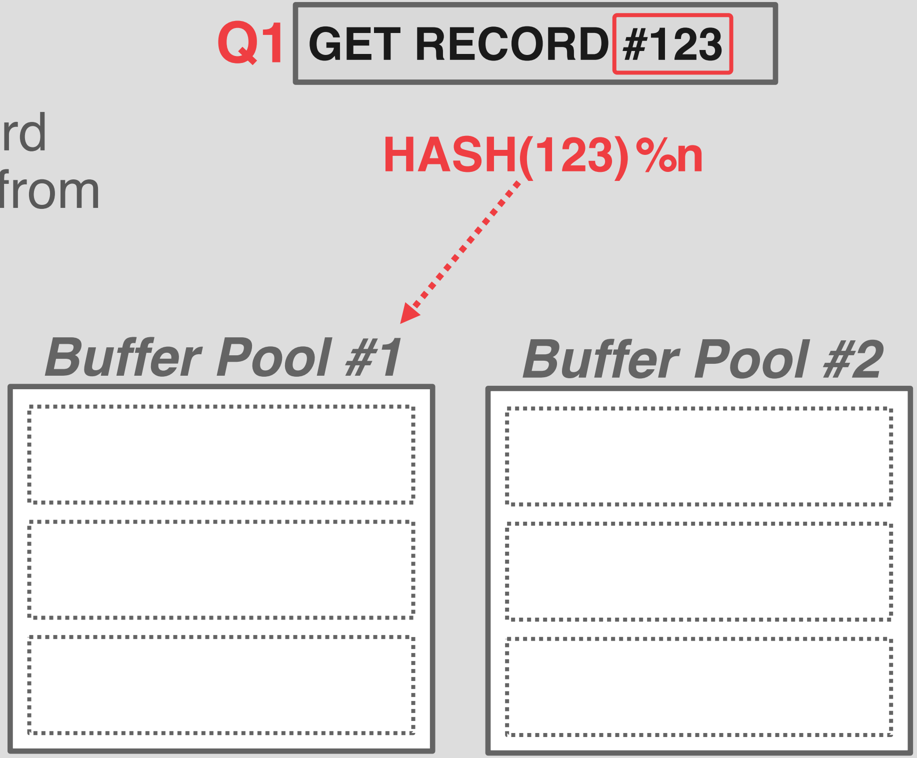
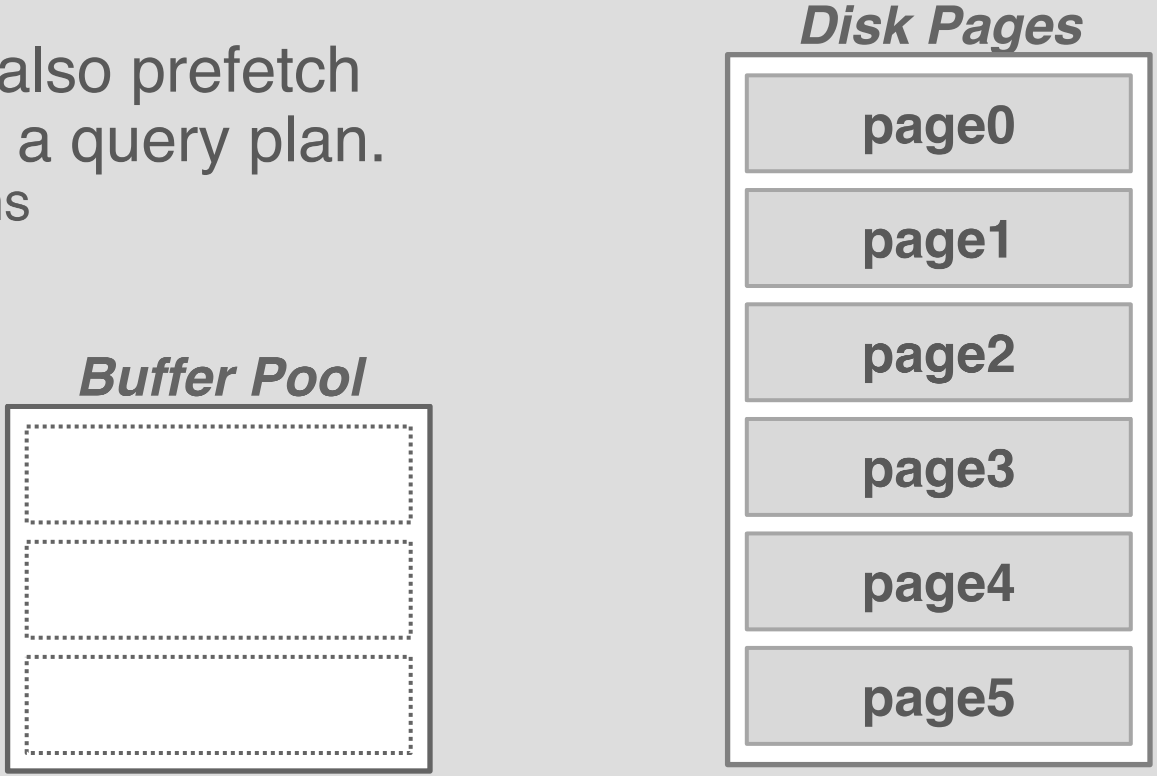


# PRE-FETCHING

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

→ Sequential Scans
→ Index Scans



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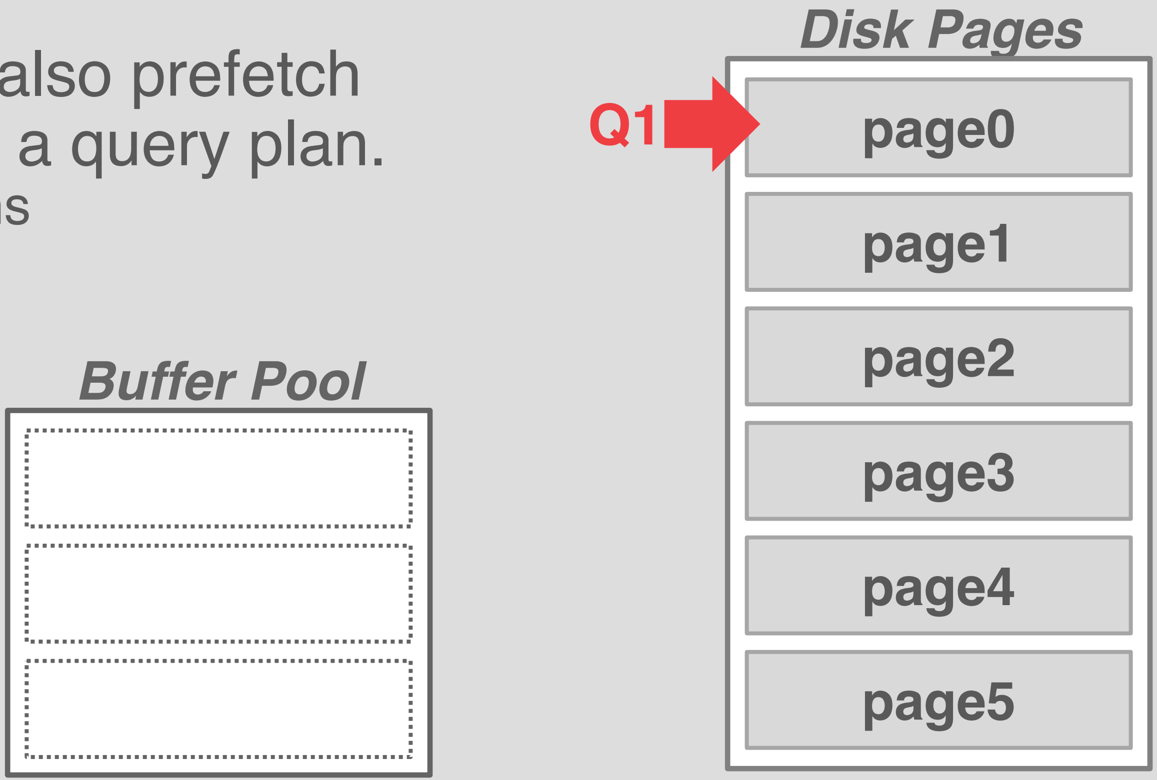

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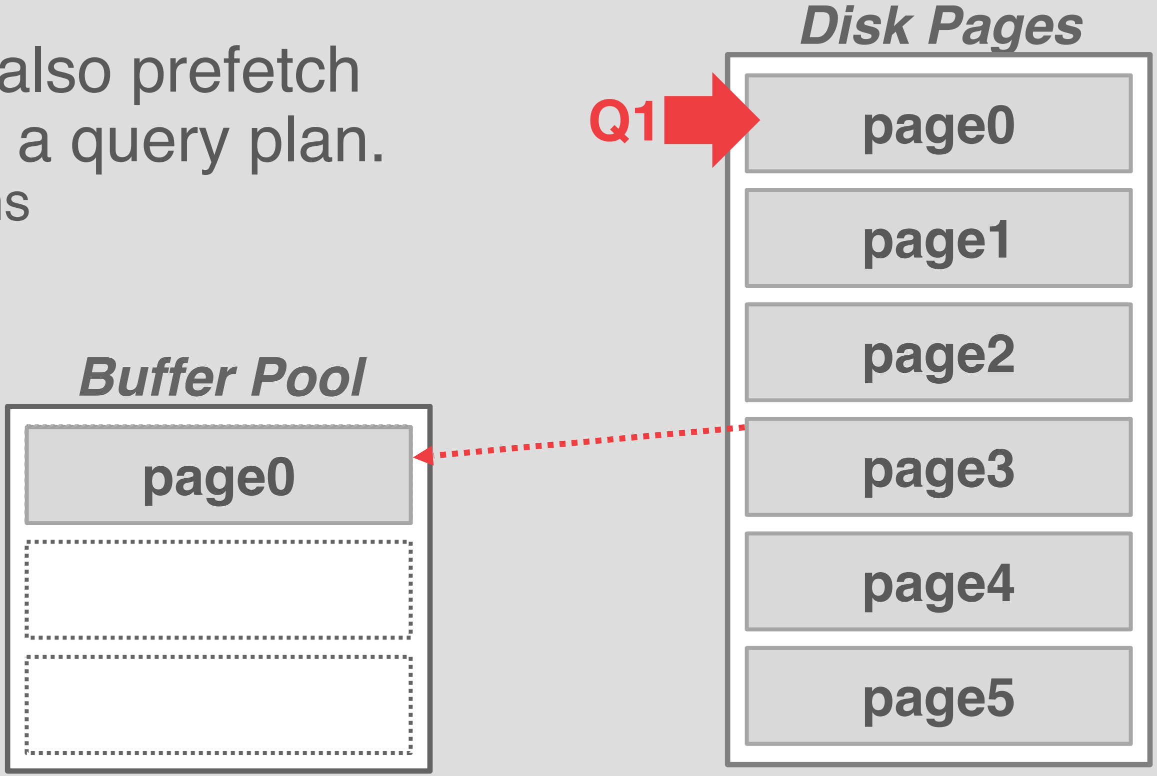

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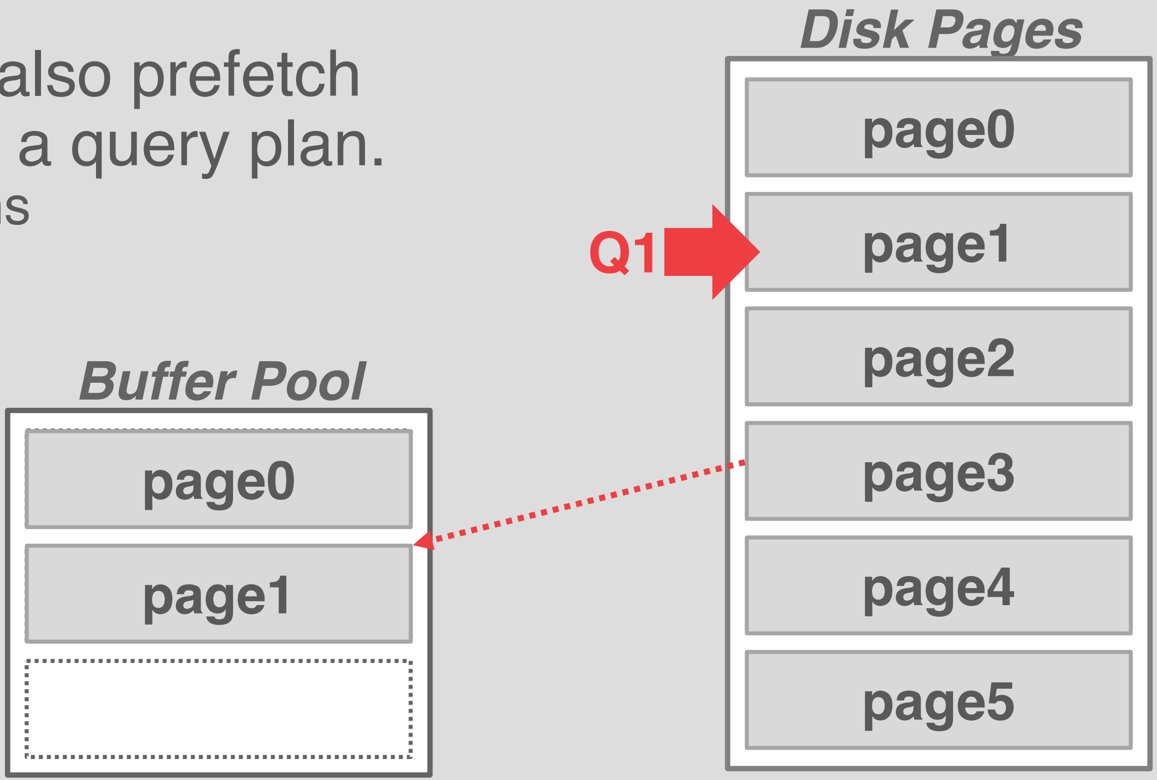

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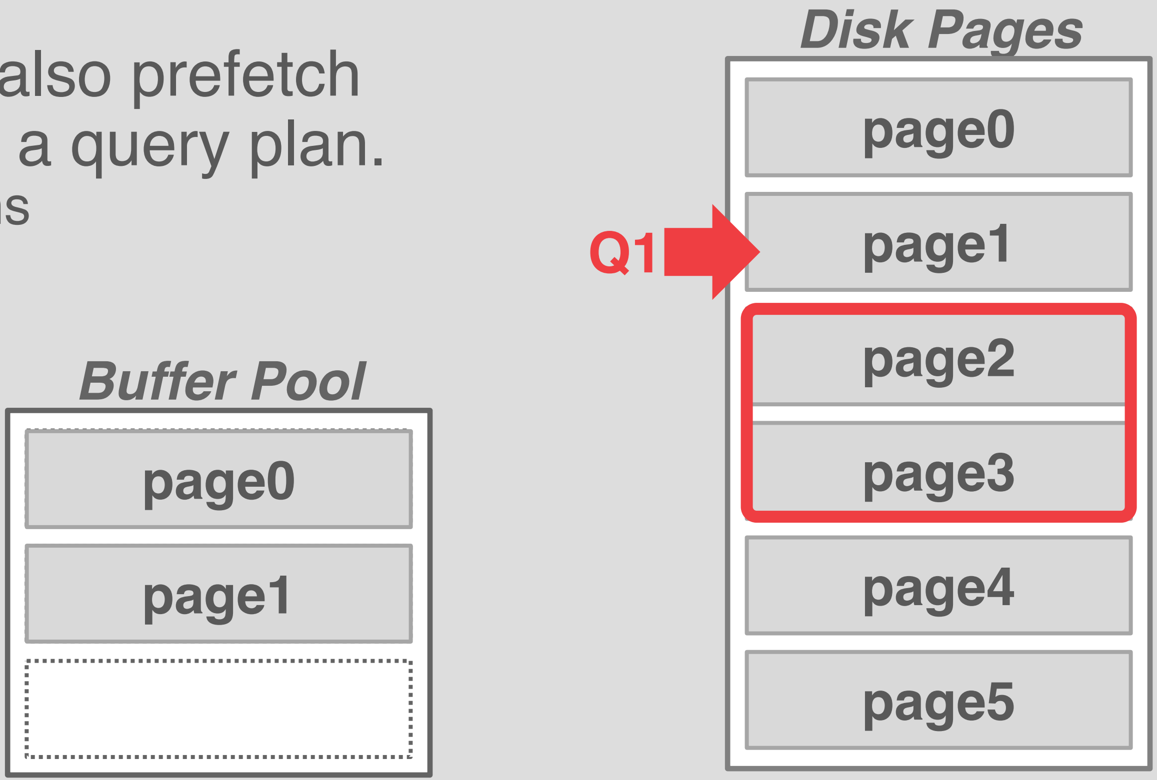

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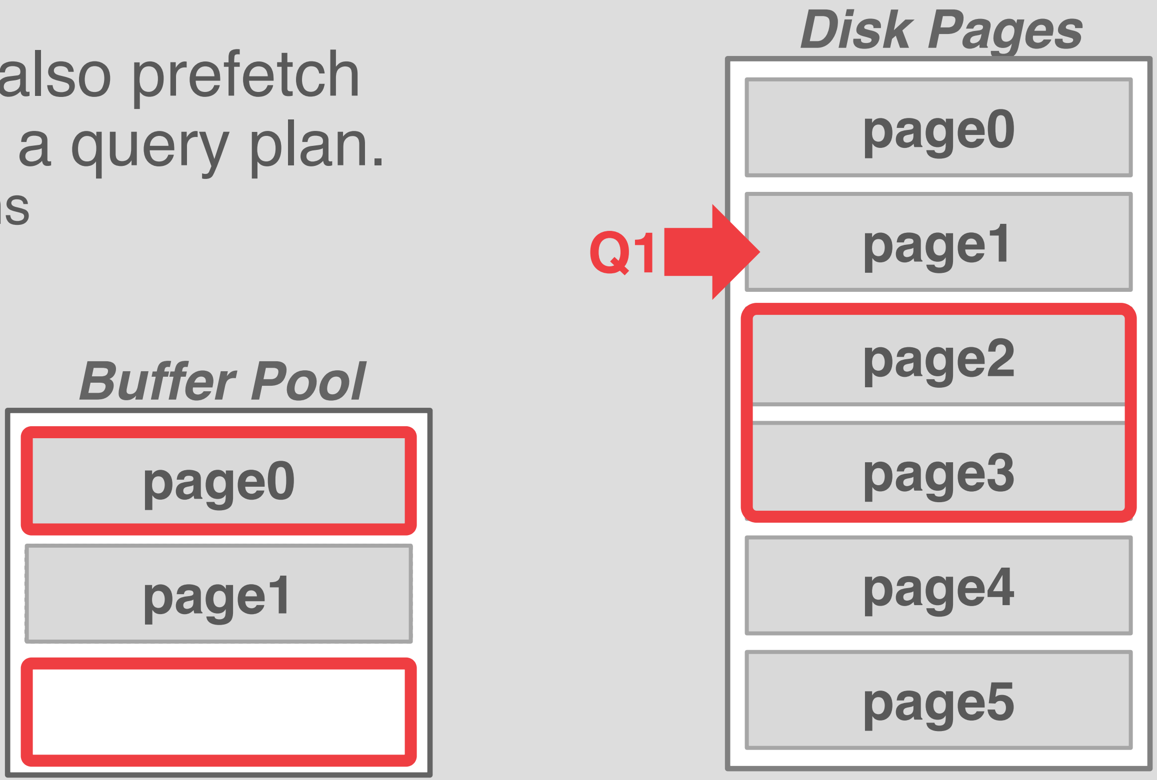

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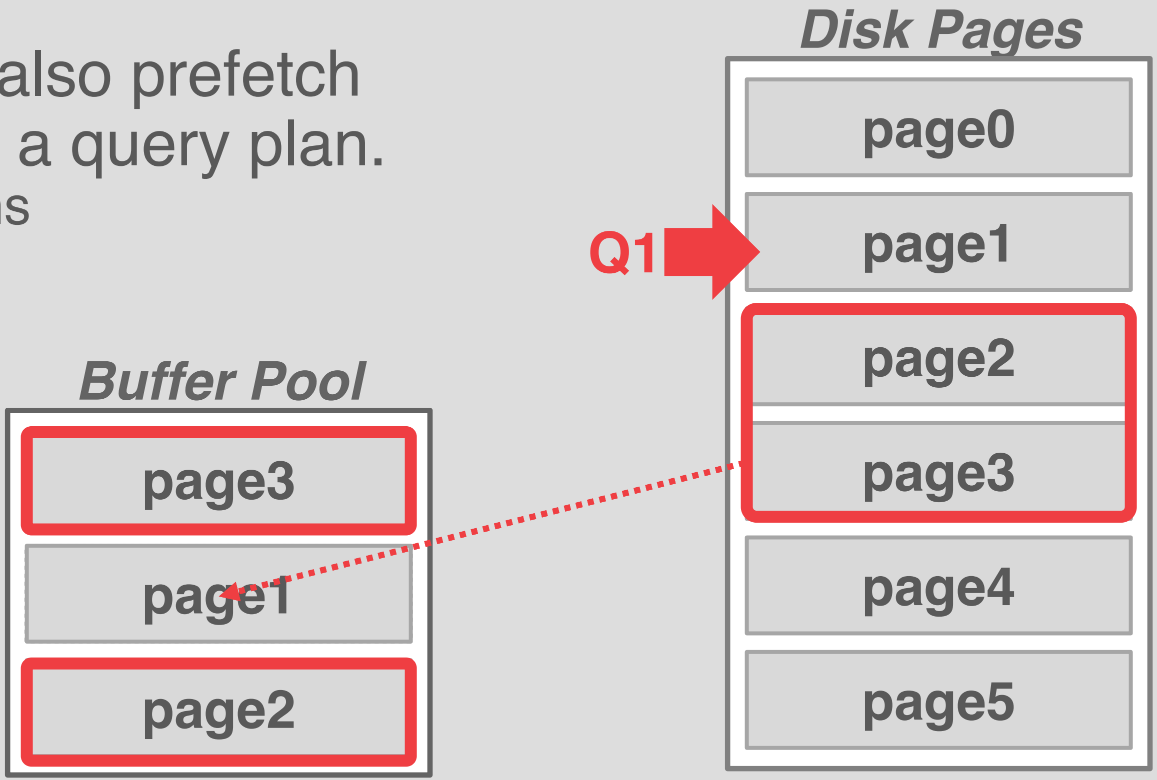

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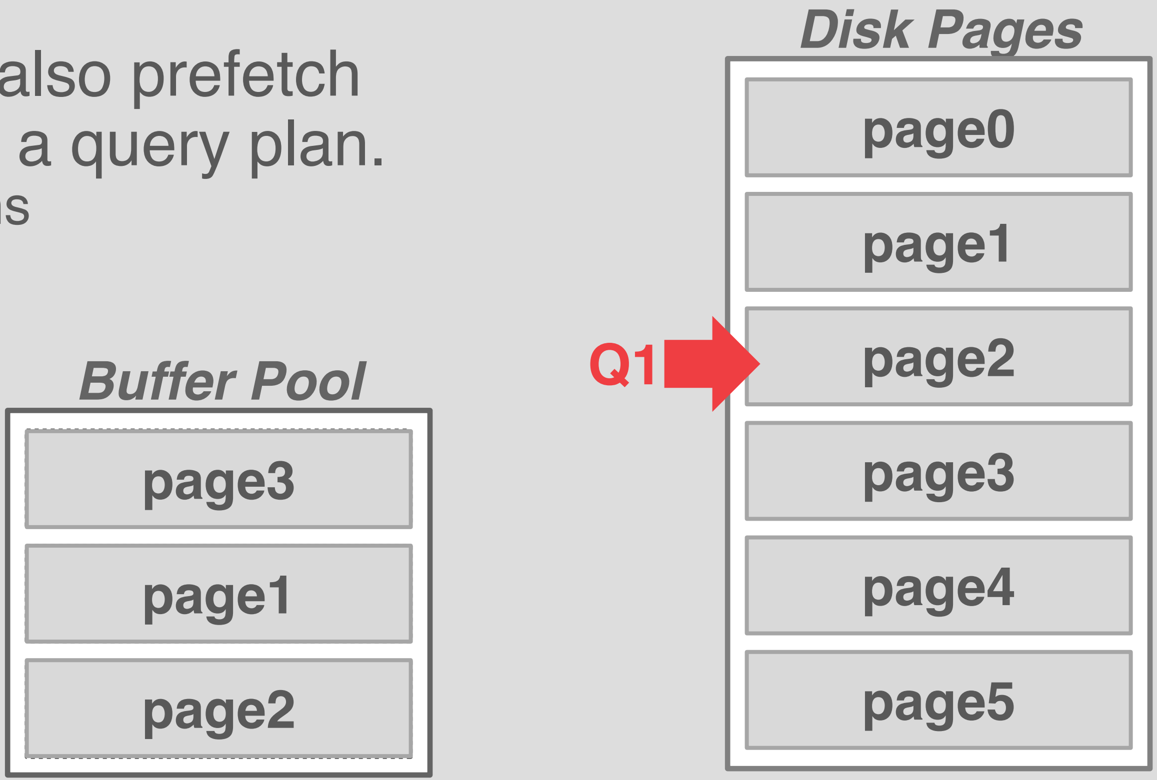

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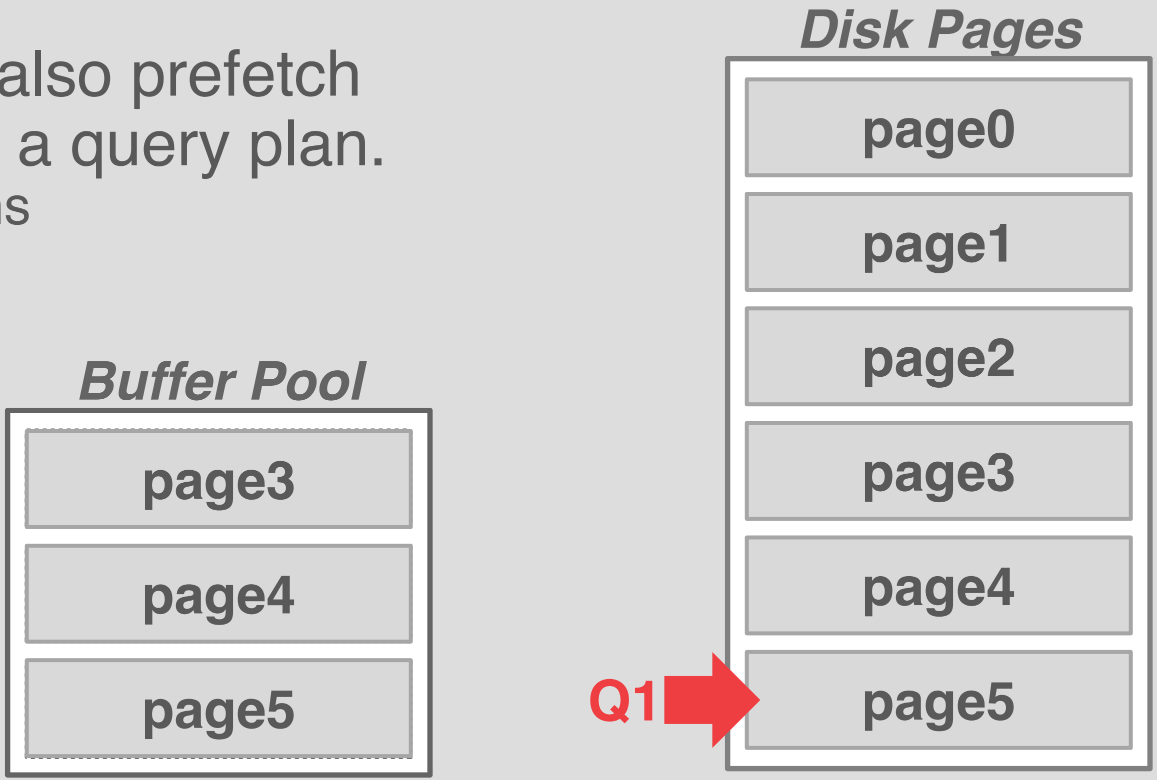
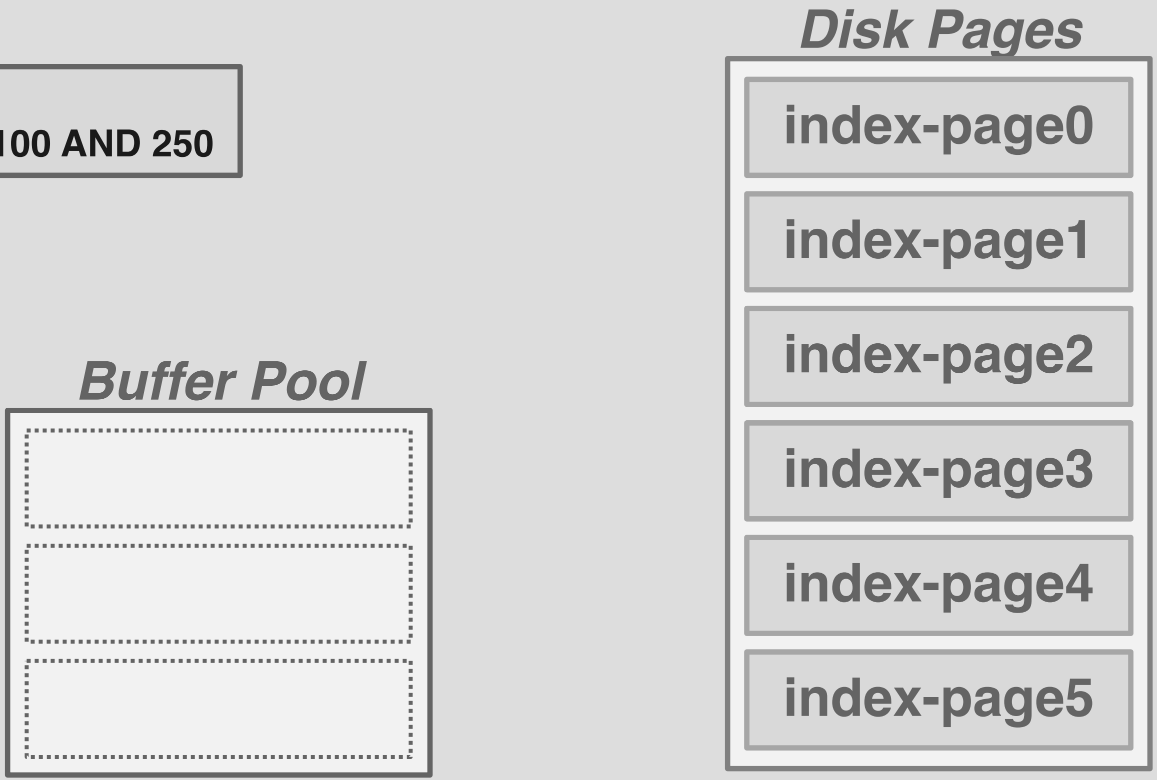


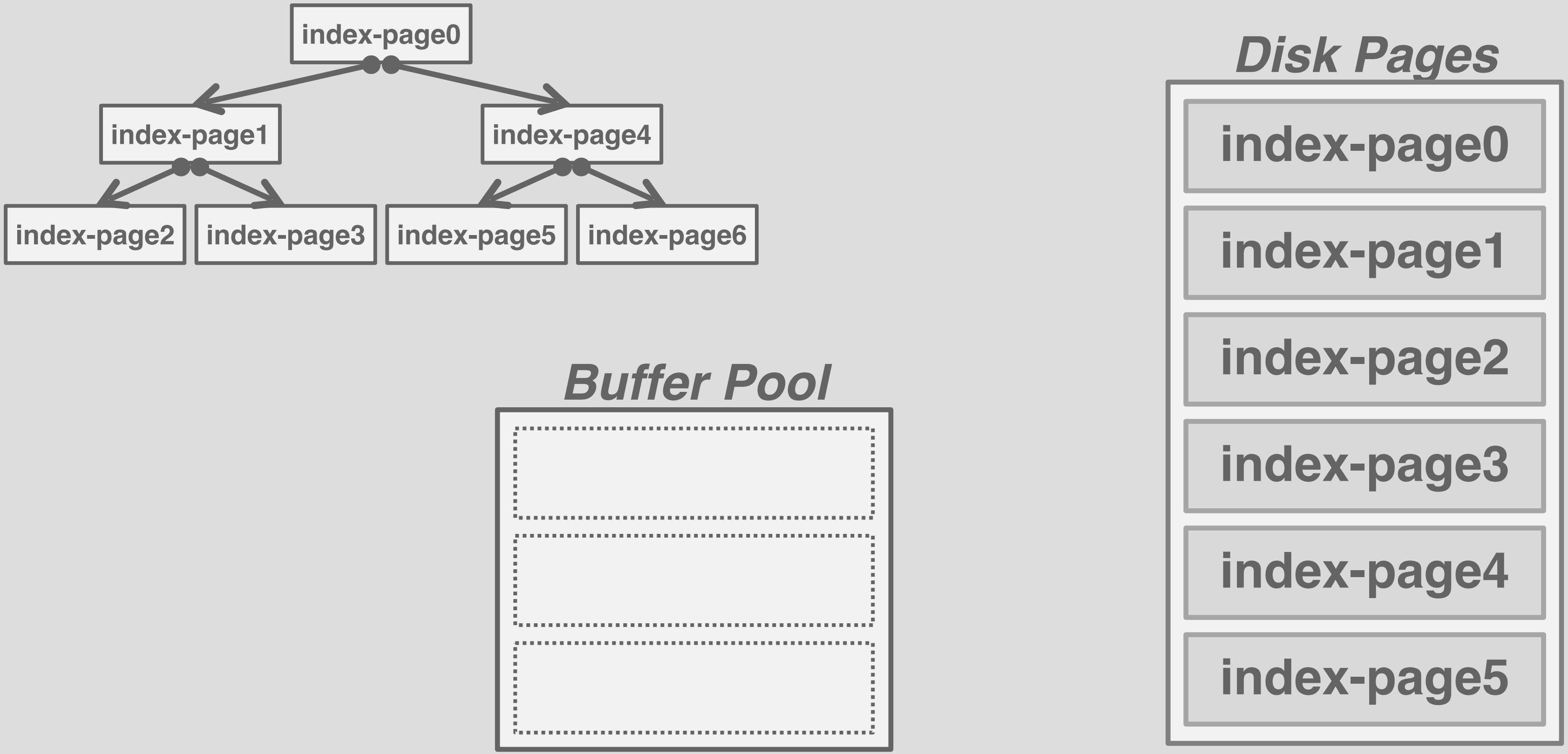
# PRE-FETCHING

**Q1**

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



# PRE-FETCHING



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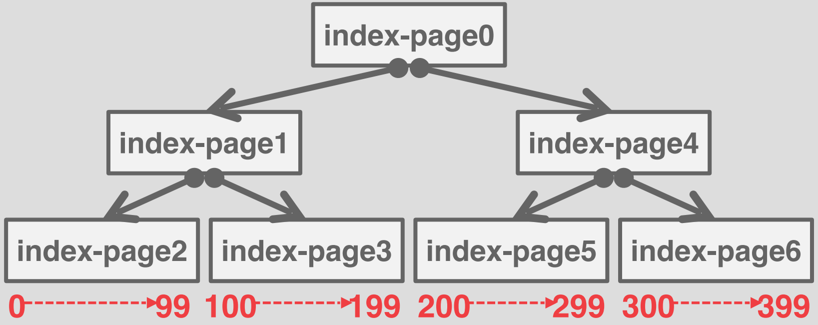
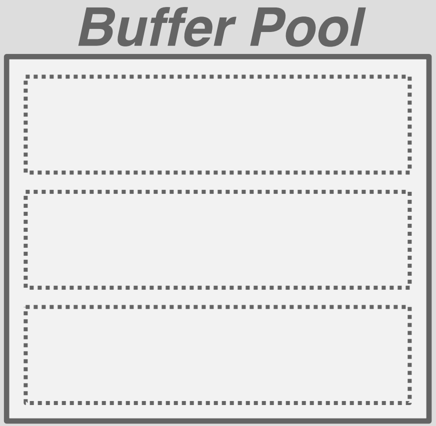
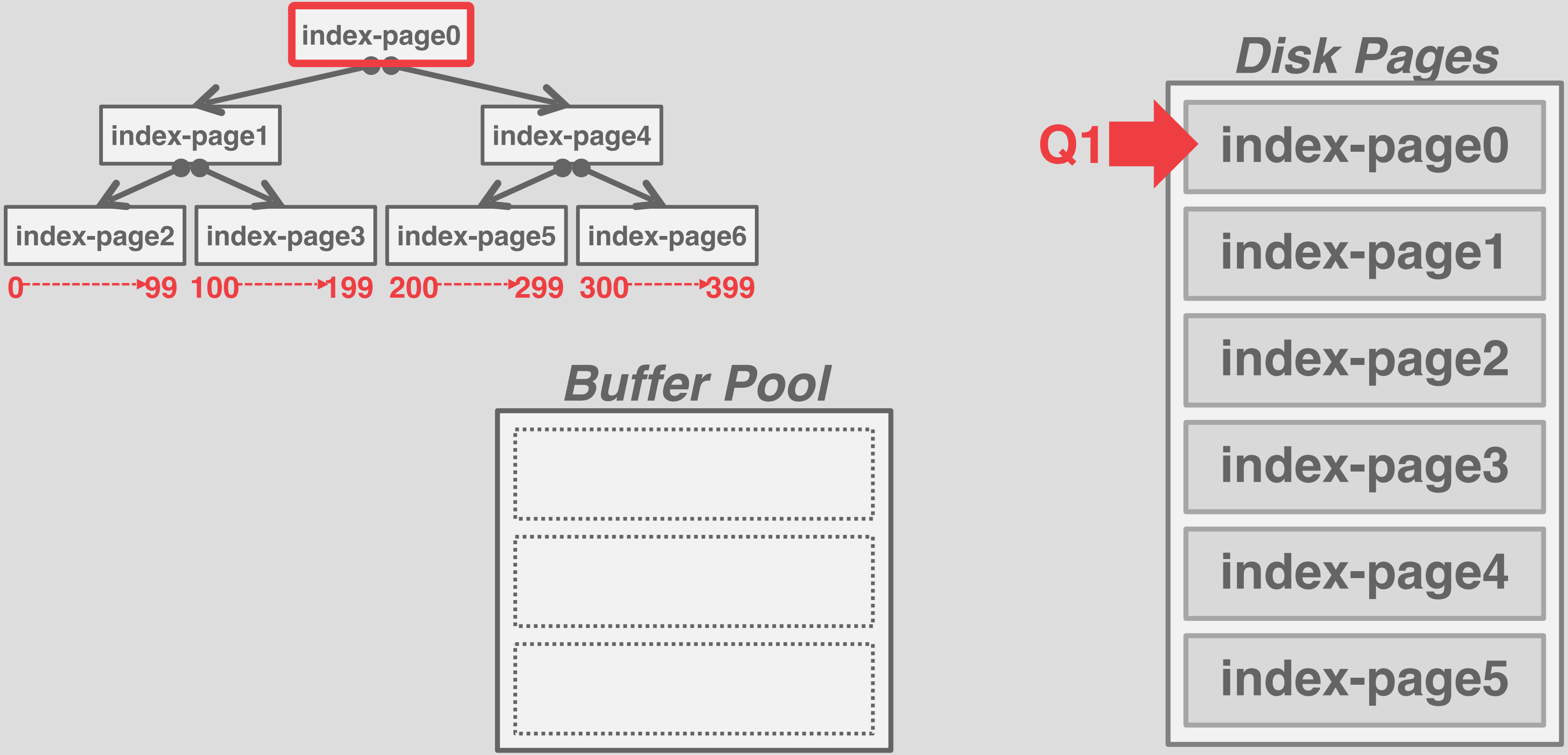
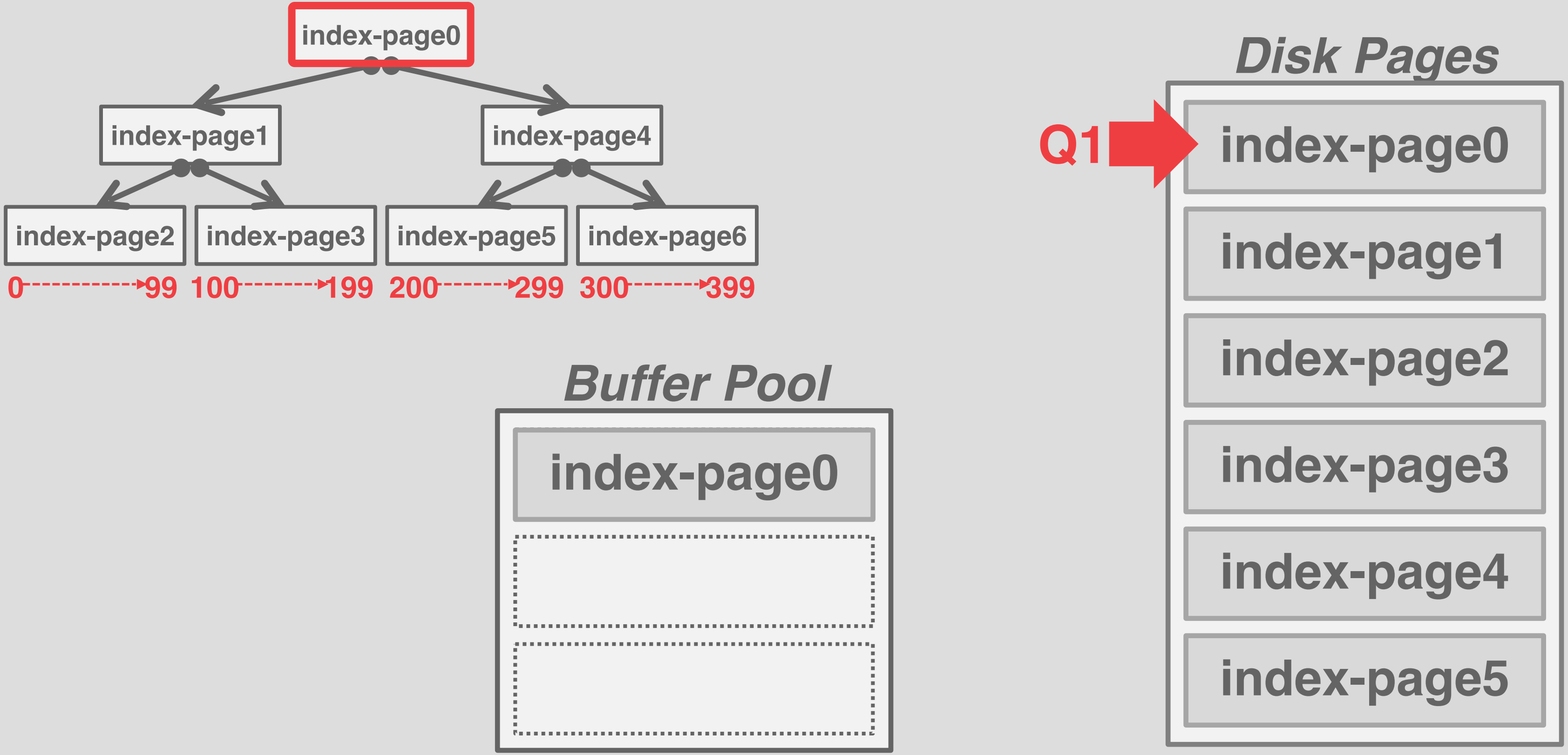


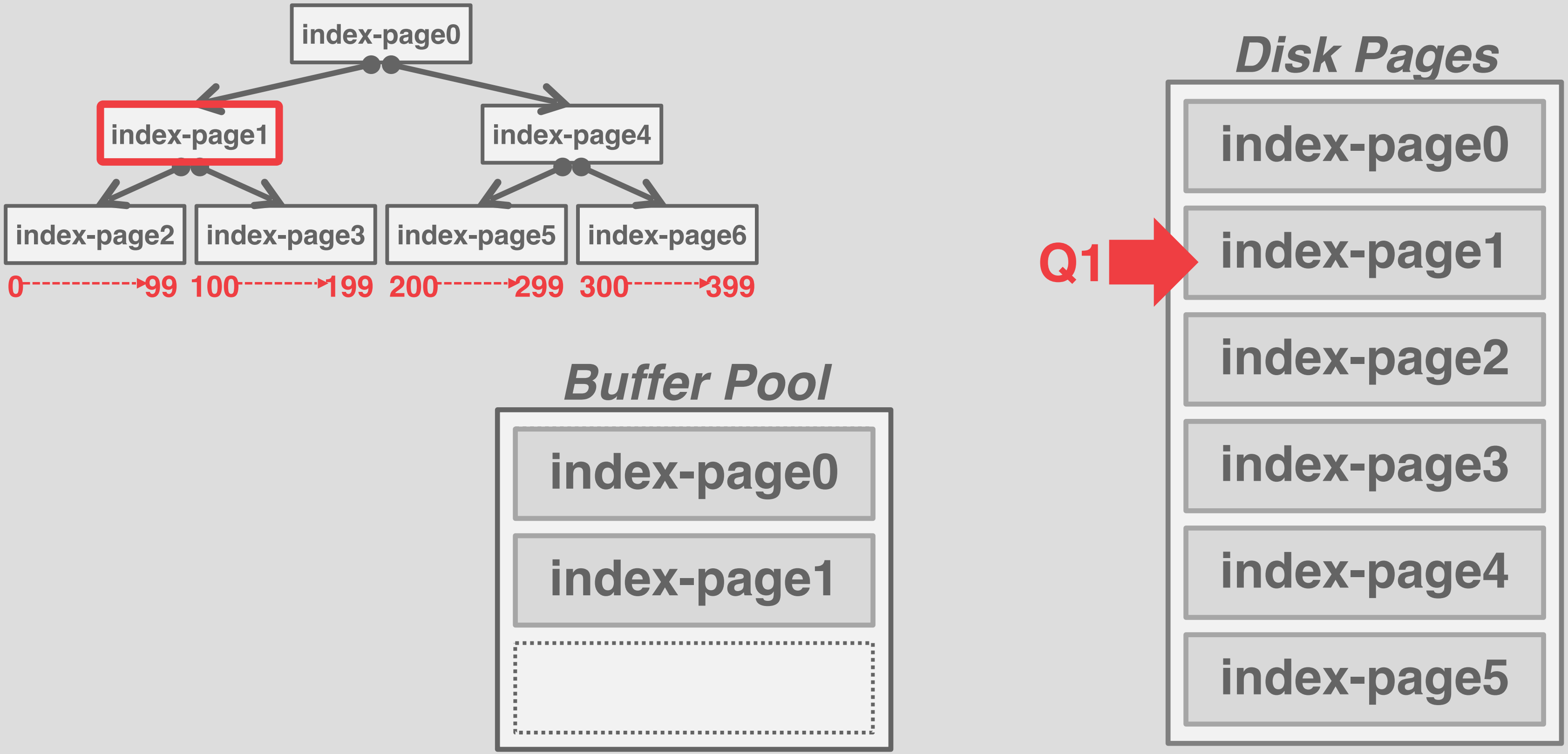

# PRE-FETCHING



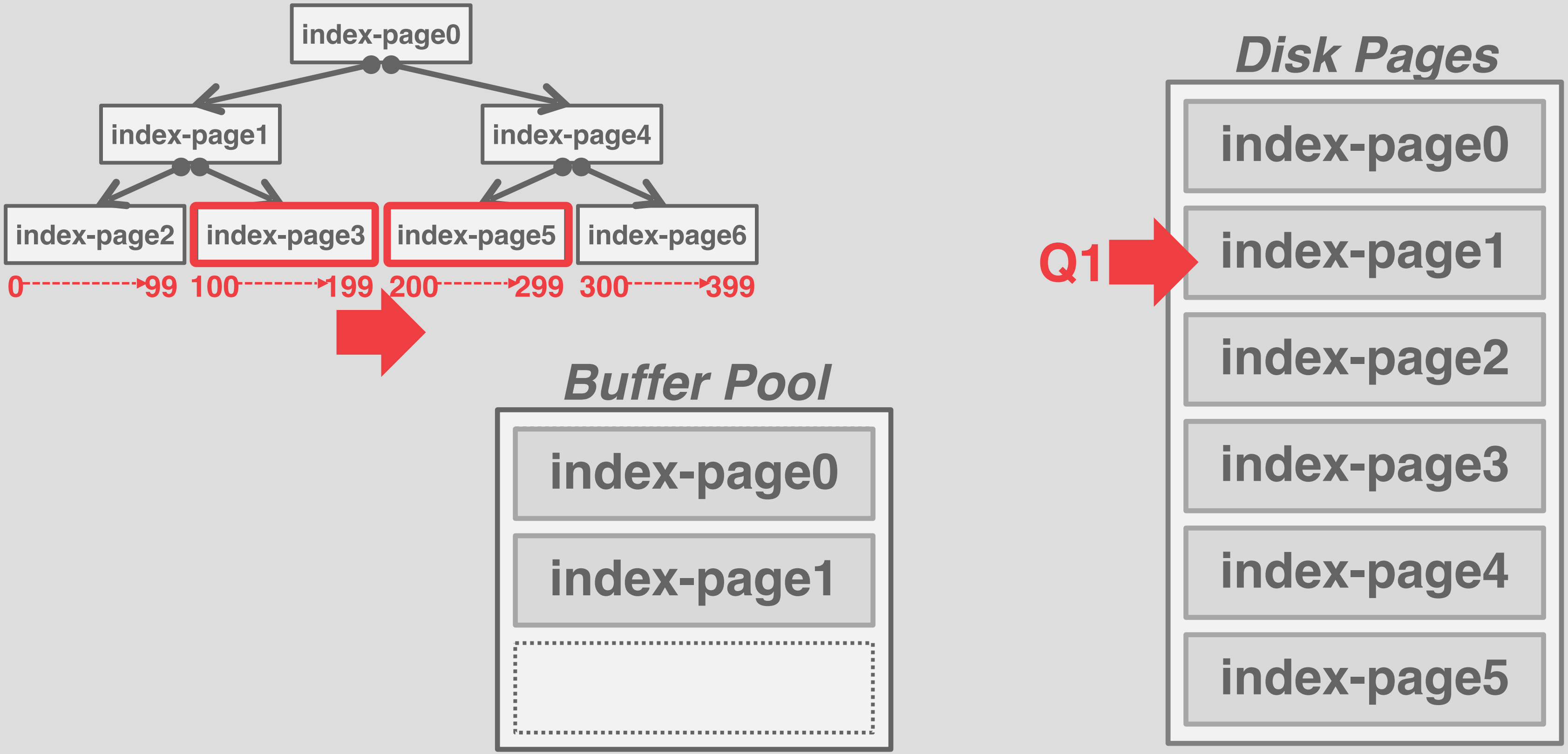
# PRE-FETCHING



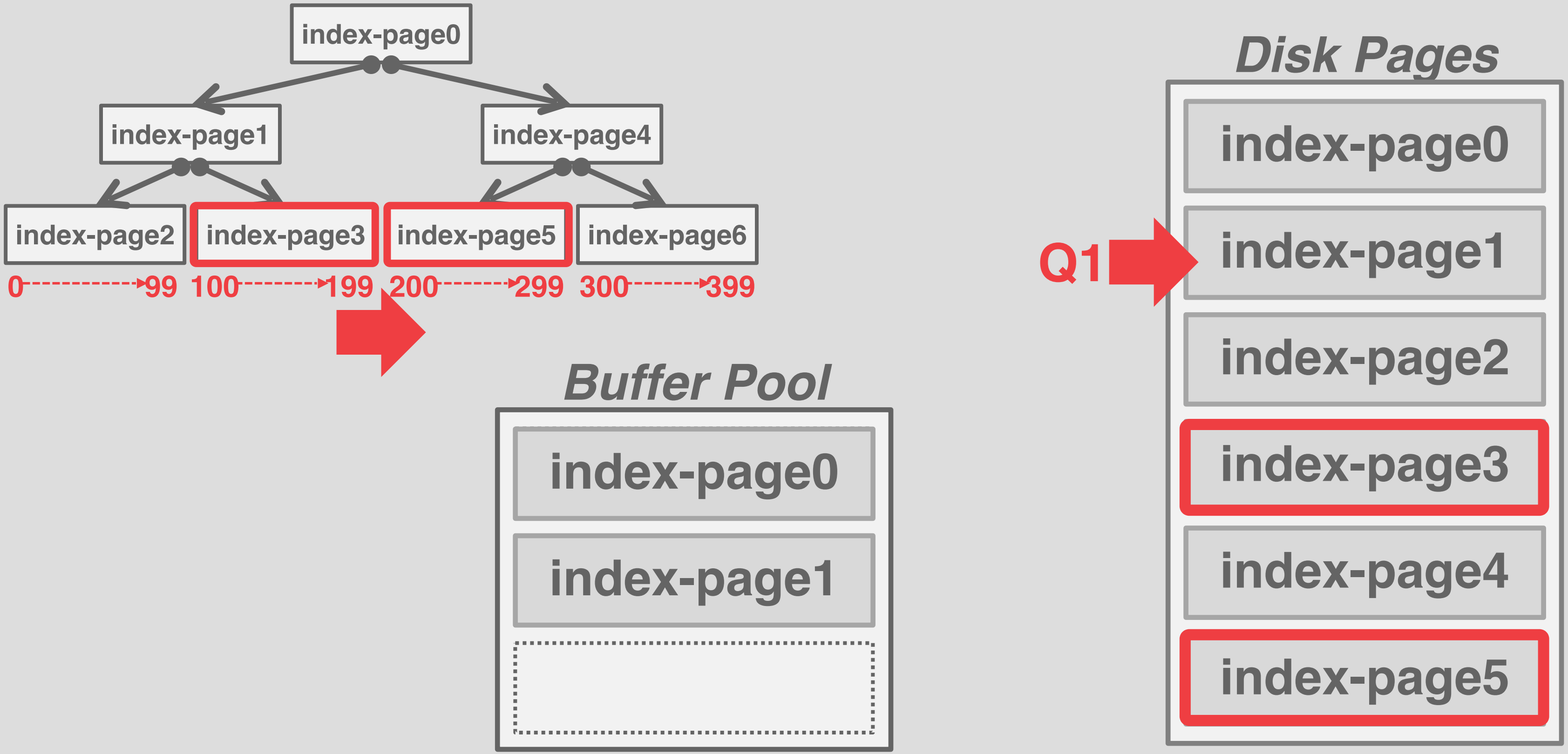
# PRE-FETCHING



# PRE-FETCHING



# PRE-FETCHING



# SCAN SHARING

Queries can reuse data retrieved from storage or operator computations.
→ Also called ***synchronized scans***.
→ 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 wants to scan a table and another query is already doing this, then the DBMS will attach the second query's cursor to the existing cursor.

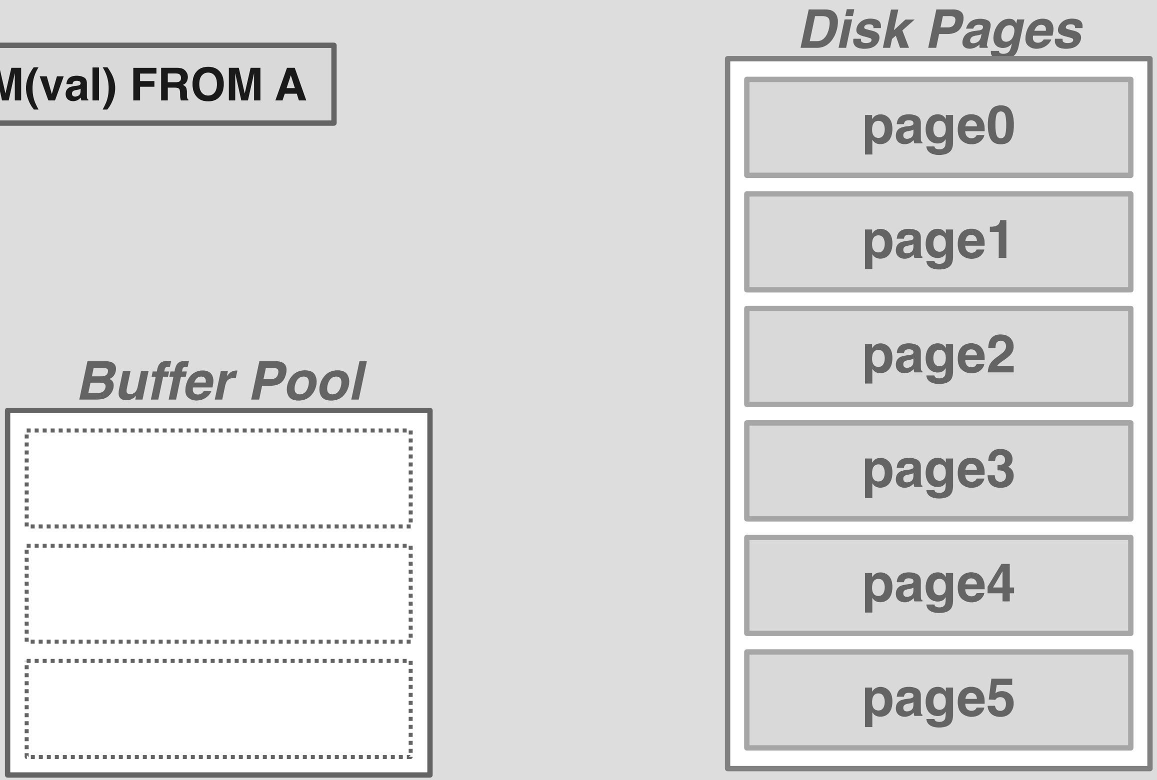
Examples:

→ Fully supported in IBM DB2, MSSQL, and Postgres.

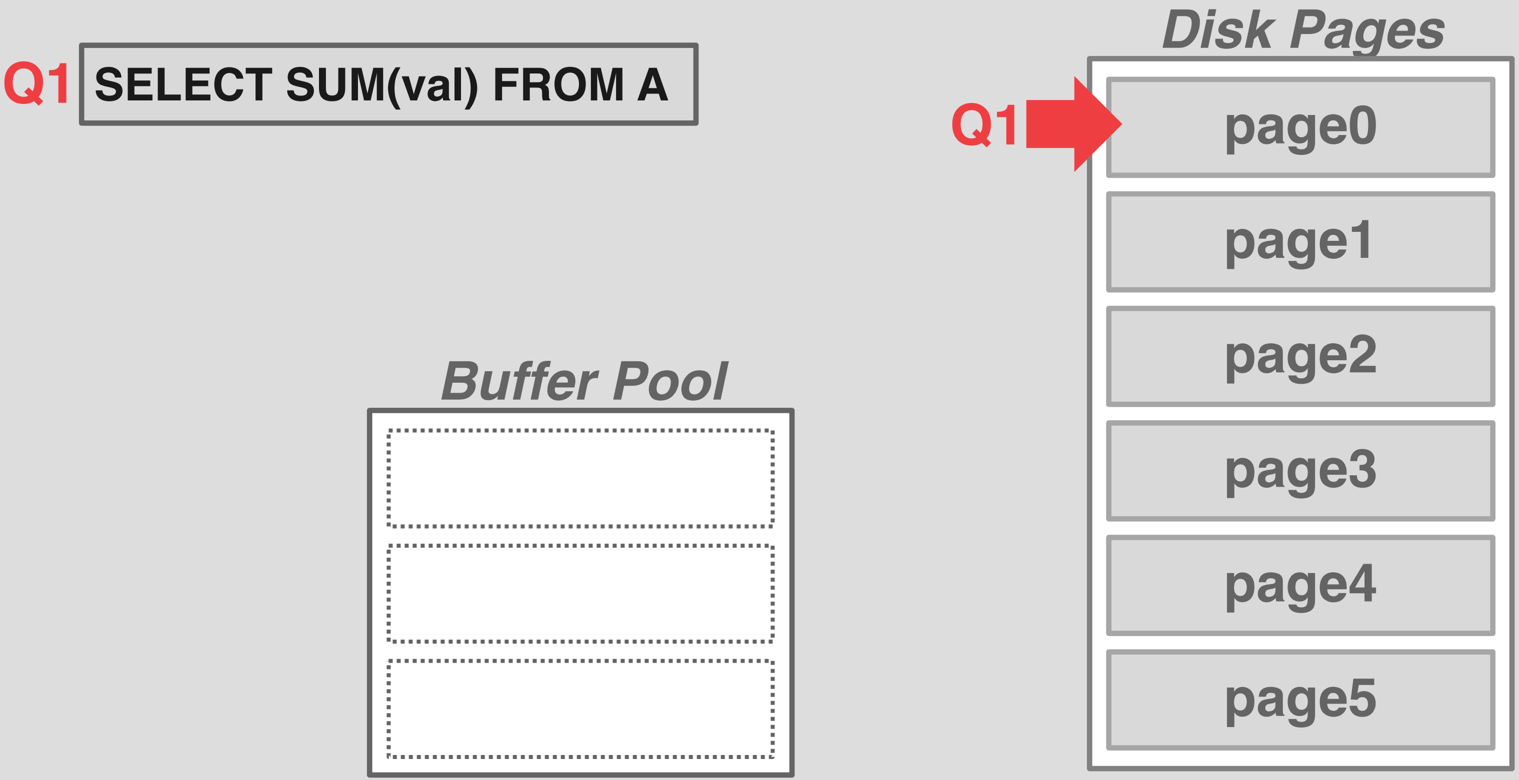
→ Oracle only supports cursor sharing for identical queries.

# SCAN SHARING

Q1 SELECT SUM(val) FROM A

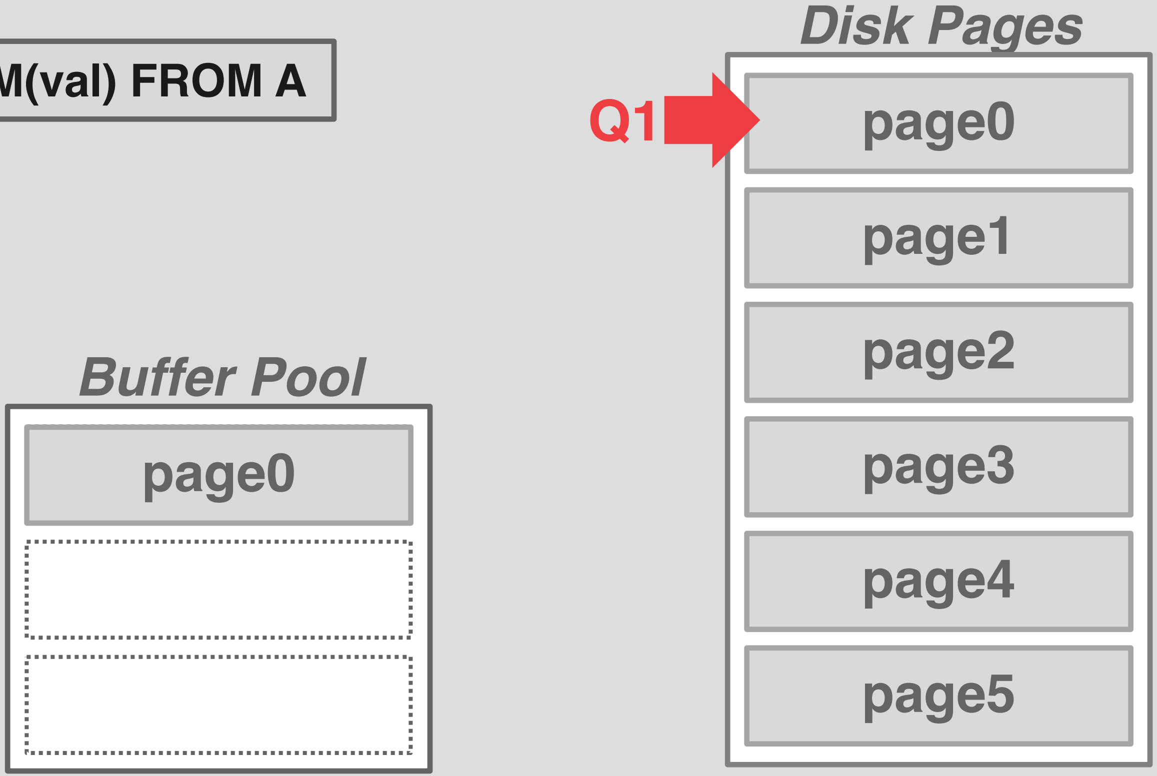


# SCAN SHARING

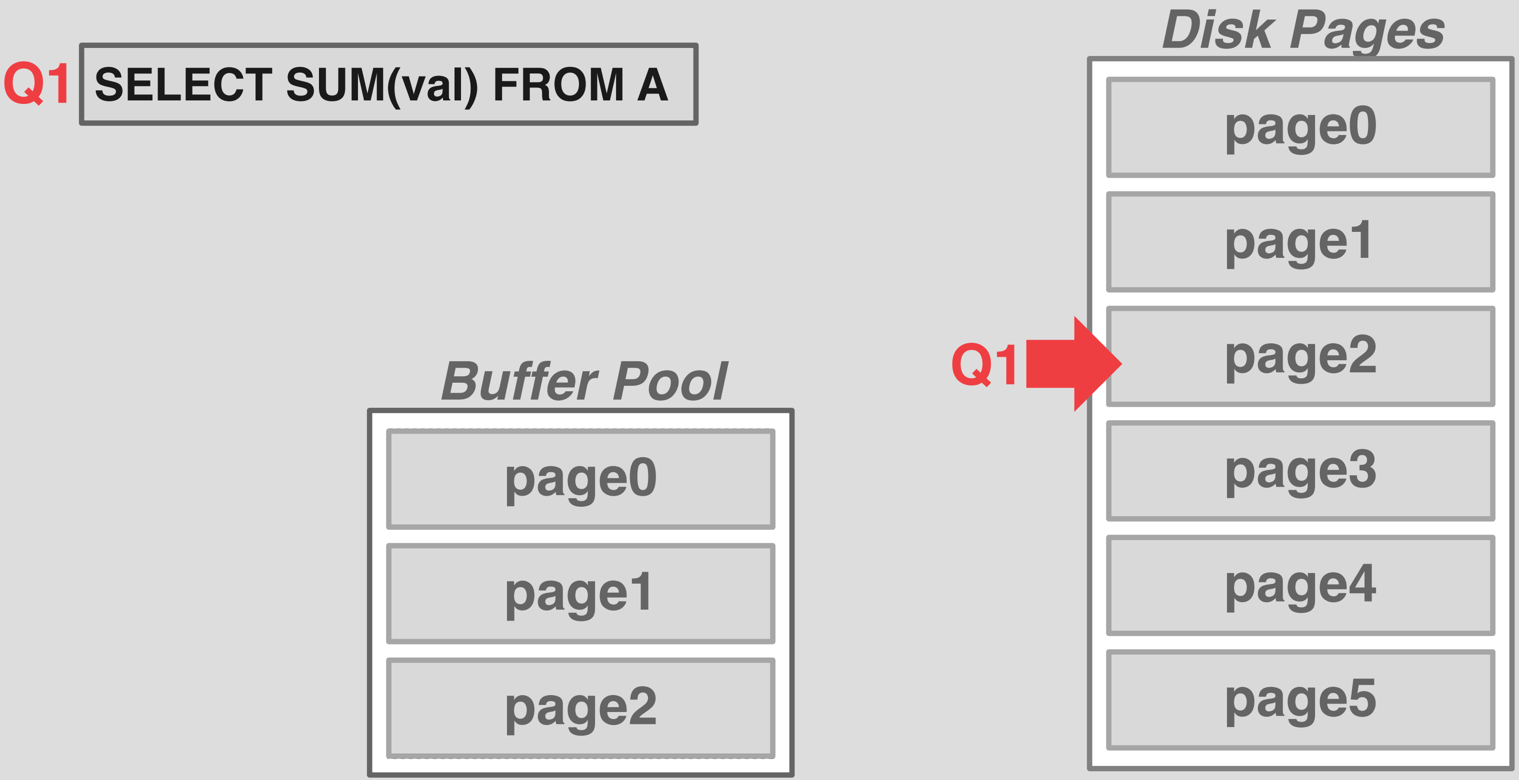


# SCAN SHARING

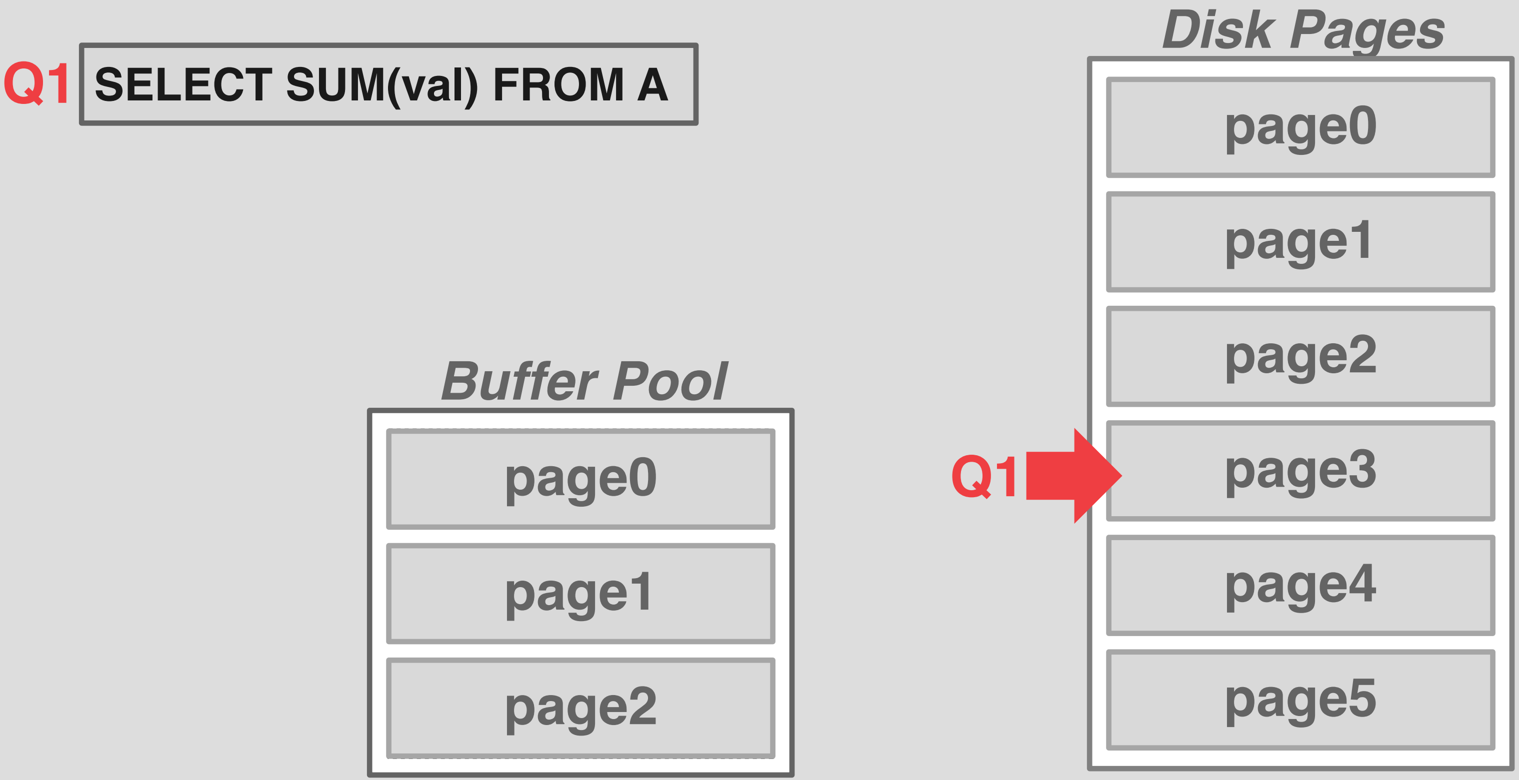
Q1 `SELECT SUM(val) FROM A`



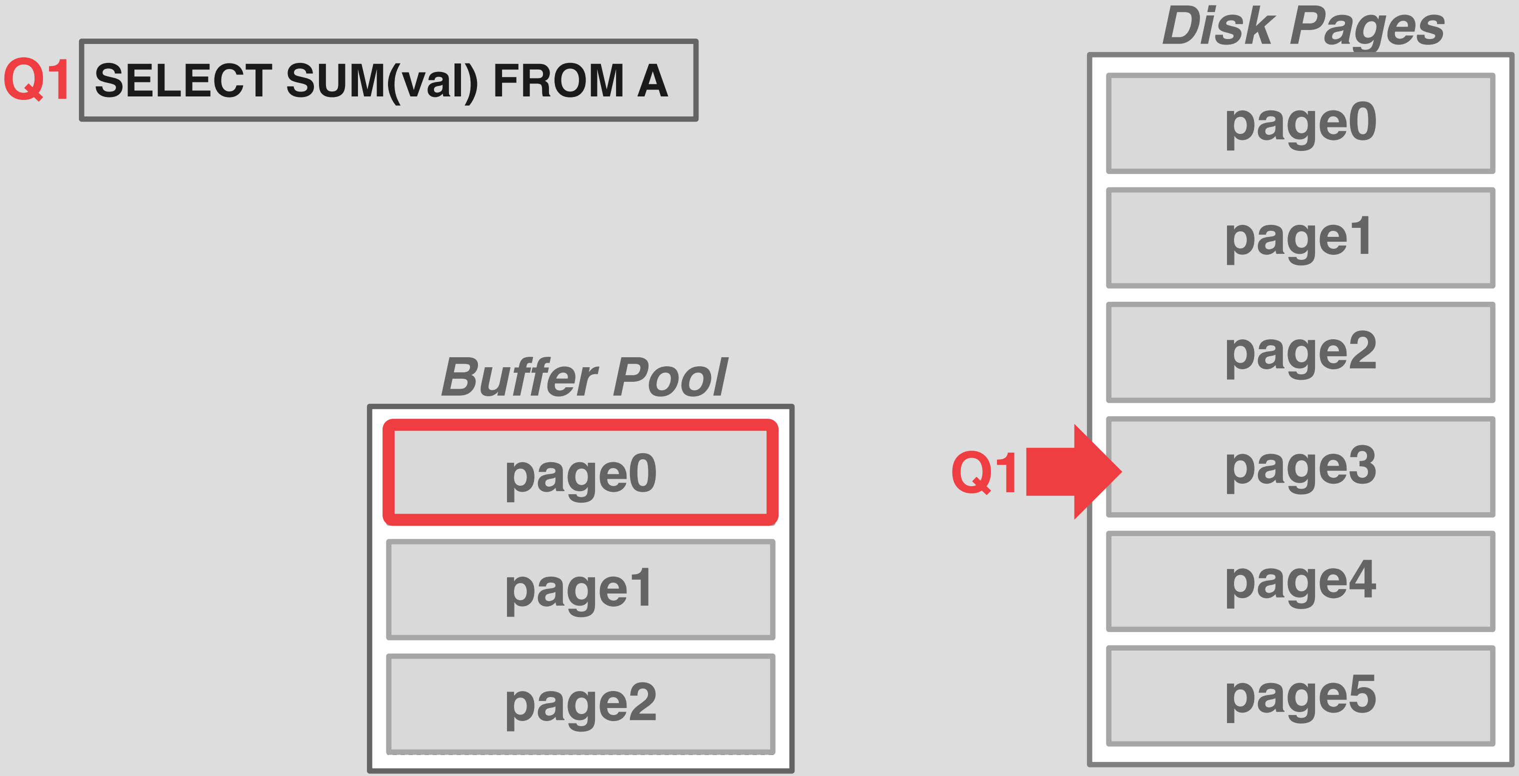
# SCAN SHARING



# SCAN SHARING

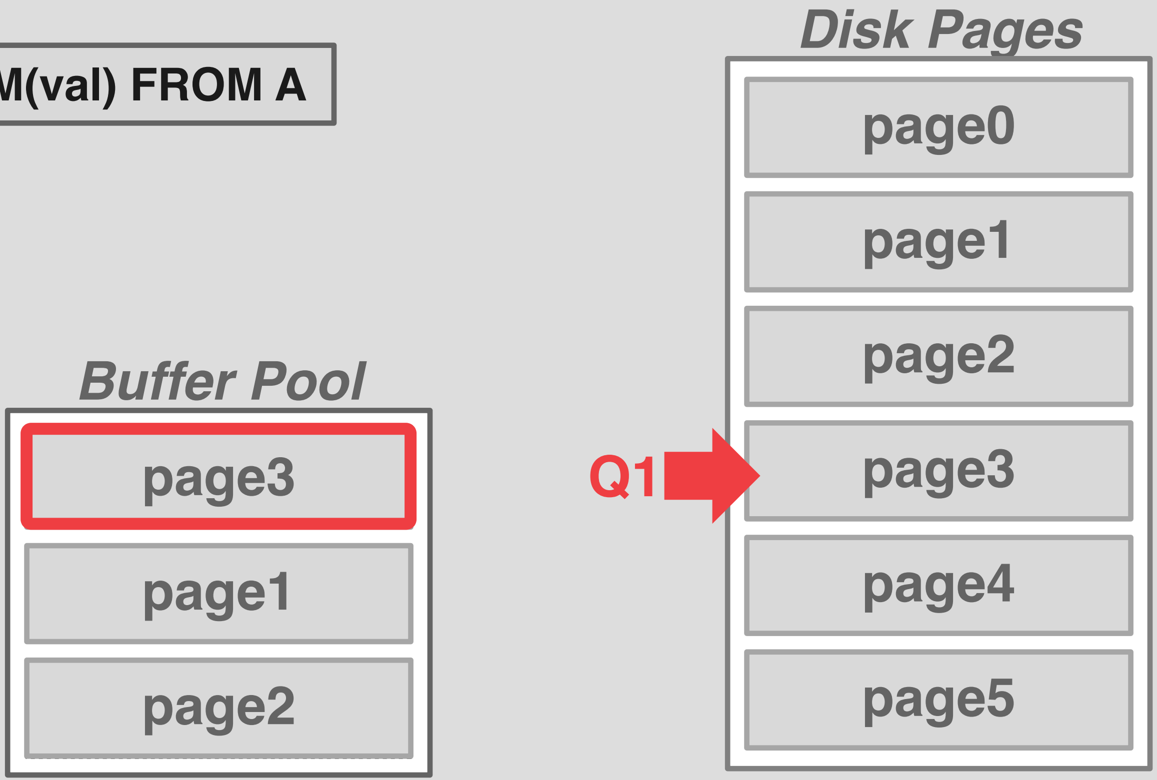


# SCAN SHARING



# SCAN SHARING

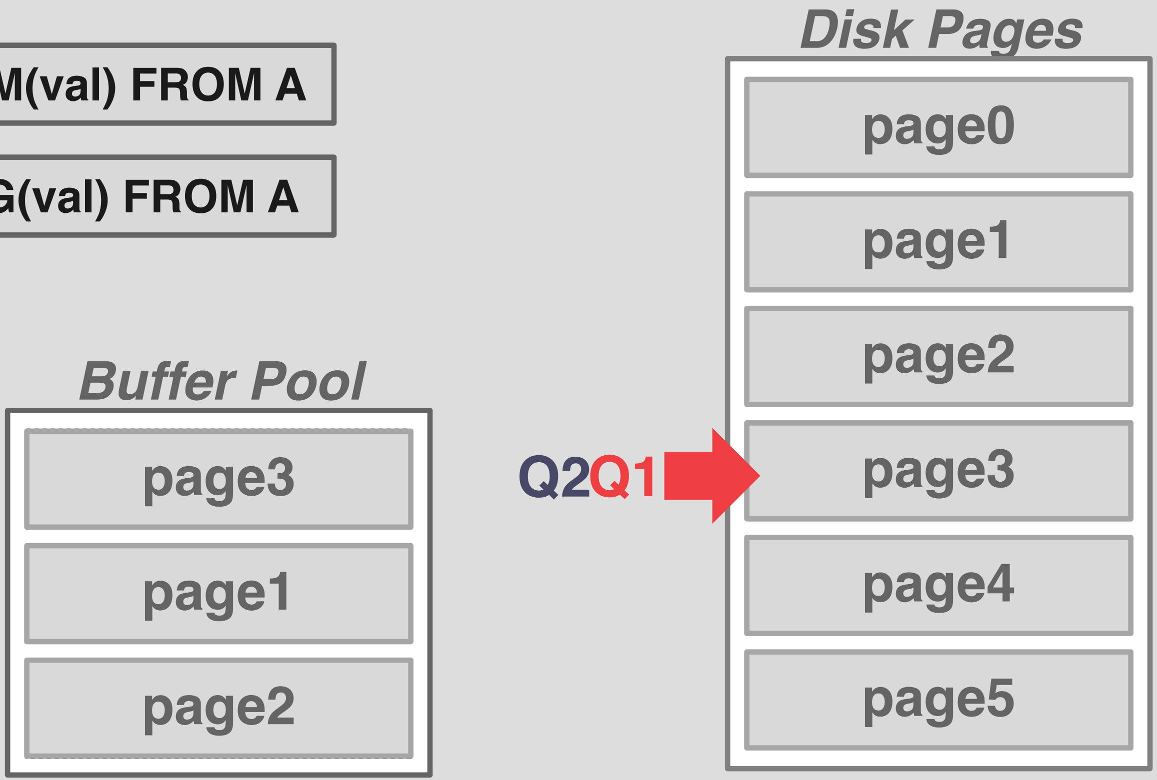
Q1 `SELECT SUM(val) FROM A`



# SCAN SHARING

Q1 SELECT SUM(val) FROM A

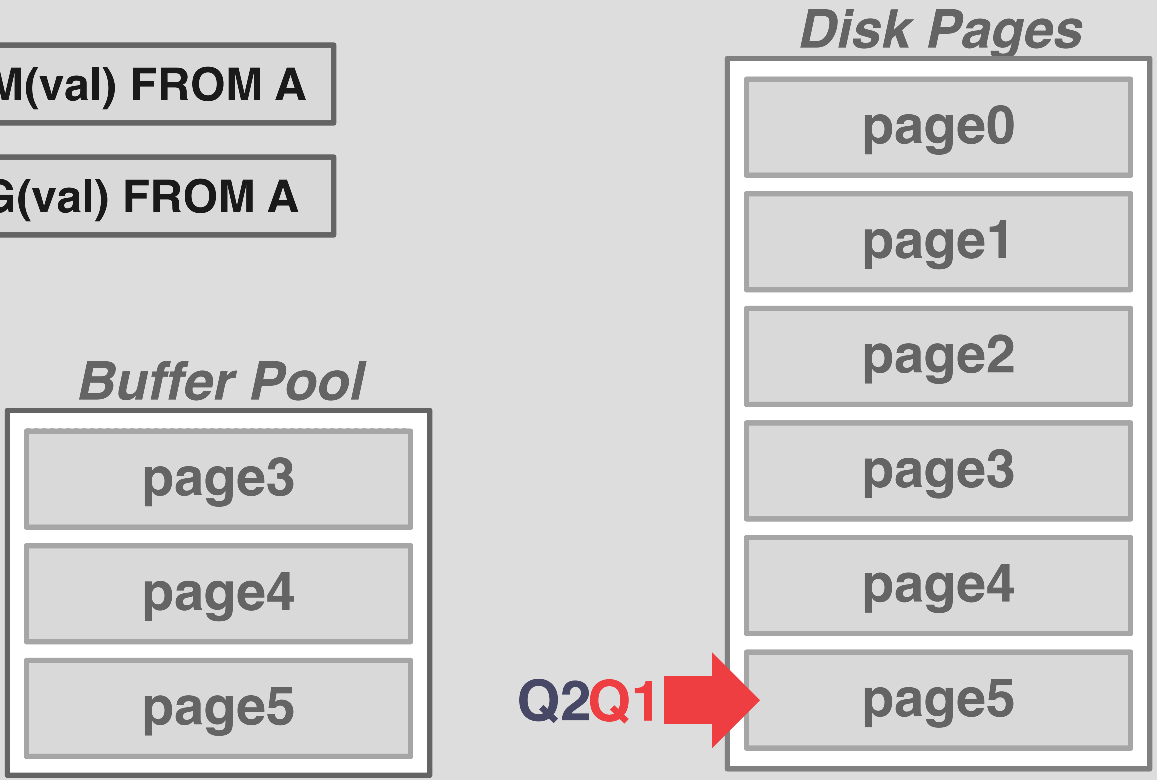
Q2 SELECT AVG(val) FROM A



# SCAN SHARING

Q1 SELECT SUM(val) FROM A

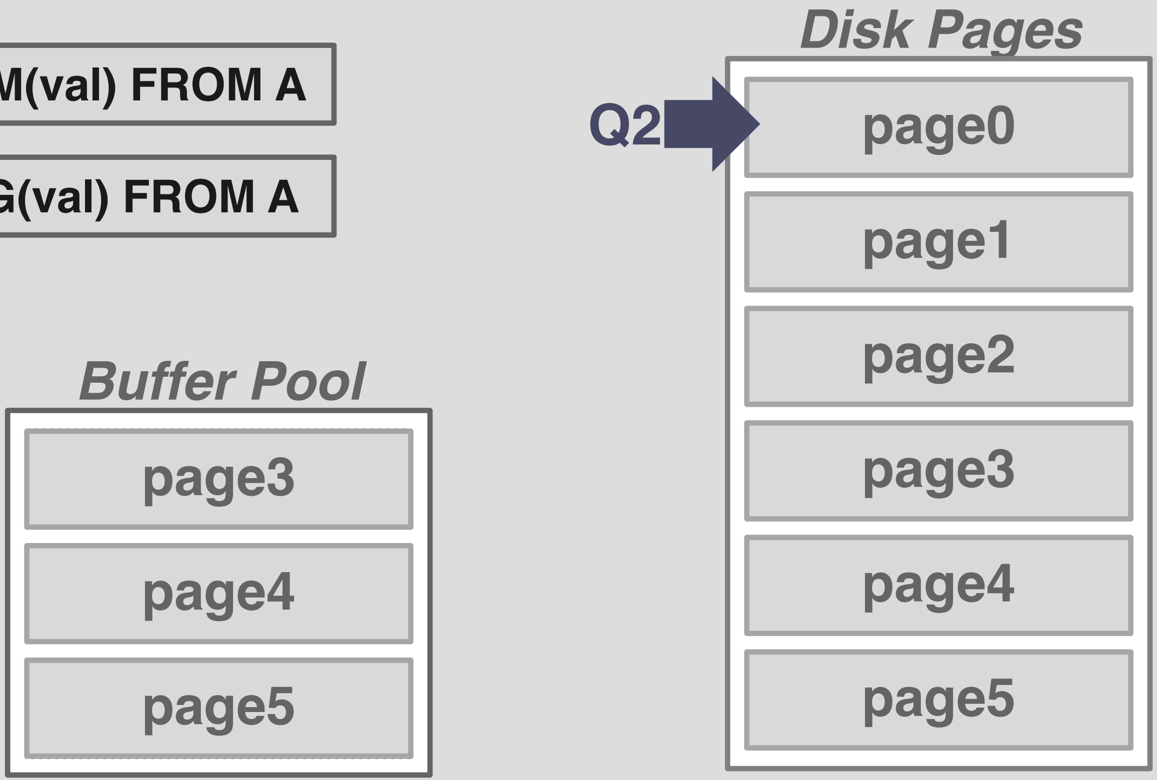
Q2 SELECT AVG(val) FROM A



# SCAN SHARING

Q1 SELECT SUM(val) FROM A

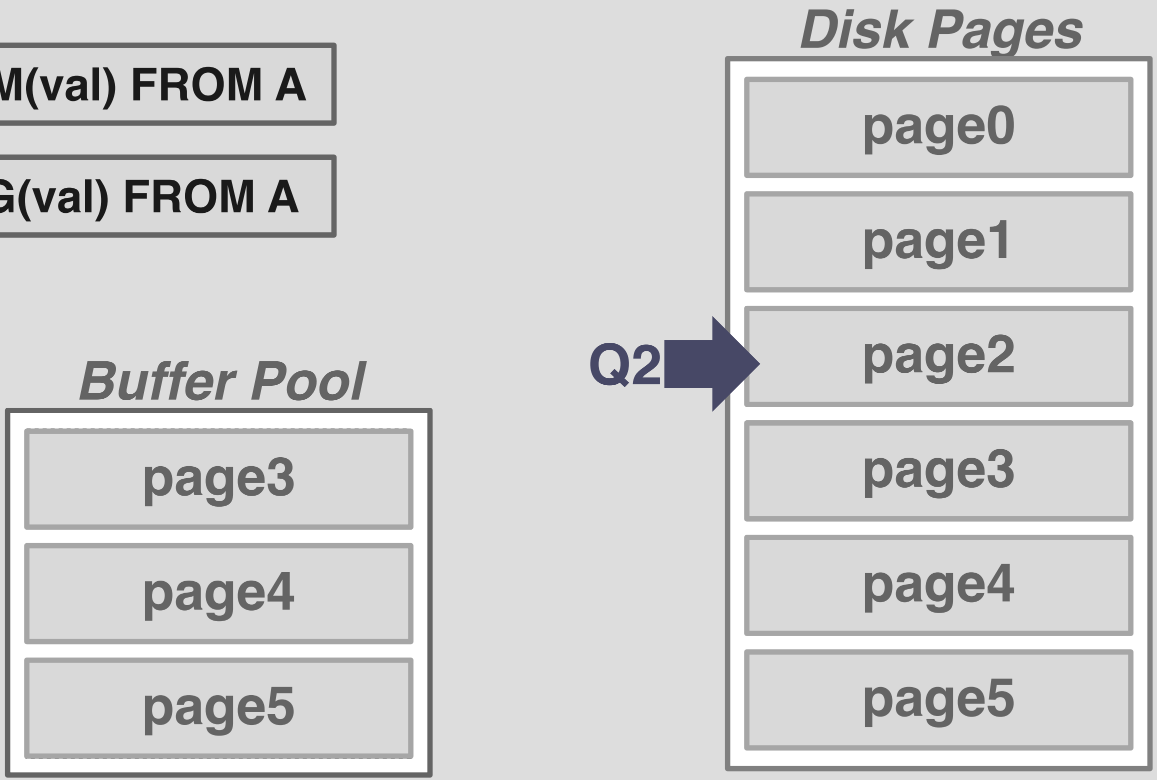
Q2 SELECT AVG(val) FROM A



# SCAN SHARING

Q1 SELECT SUM(val) FROM A

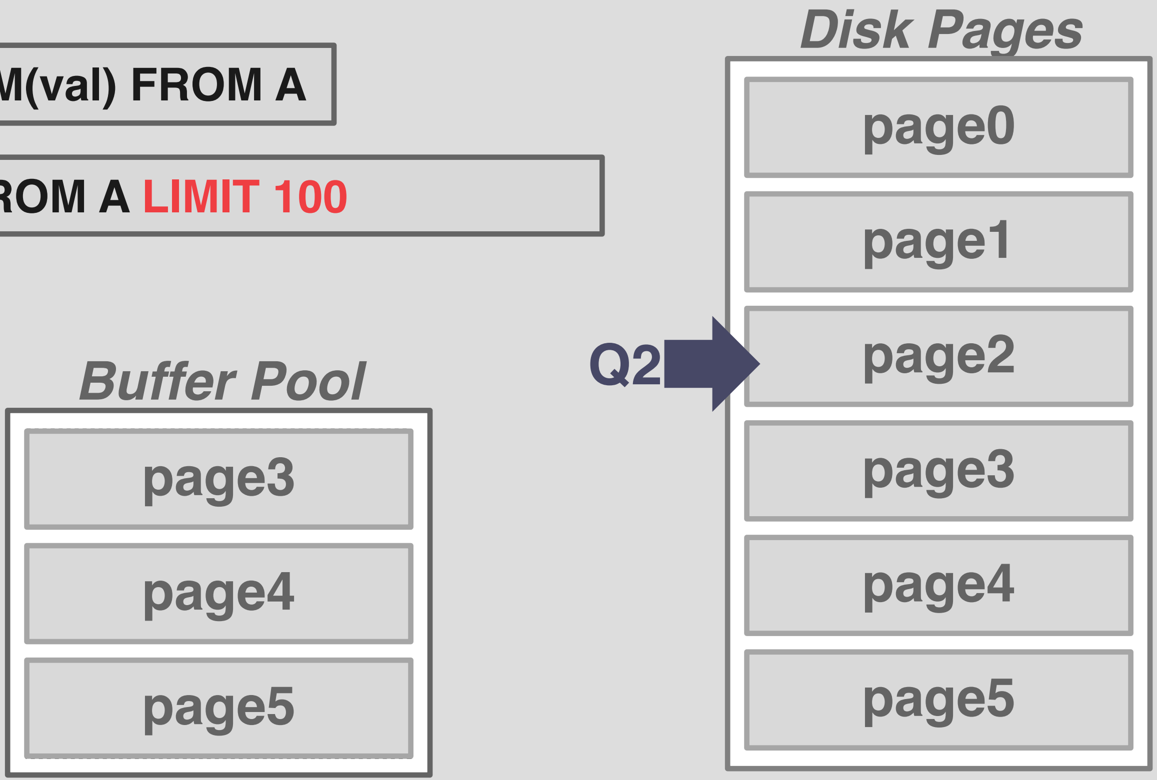
Q2 SELECT AVG(val) FROM A



# SCAN SHARING

Q1 SELECT SUM(val) FROM A

Q2 SELECT * 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.

# OTHER MEMORY POOLS

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

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

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

# CONCLUSION

The DBMS can almost always manage memory better than the OS.

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

# NEXT CLASS

Hash Tables