Ack: Prof. Jignesh Patel @ CMU
Prof. Andy Pavlo @CMU

CSC3170
6: Memory & Disk I/O Management

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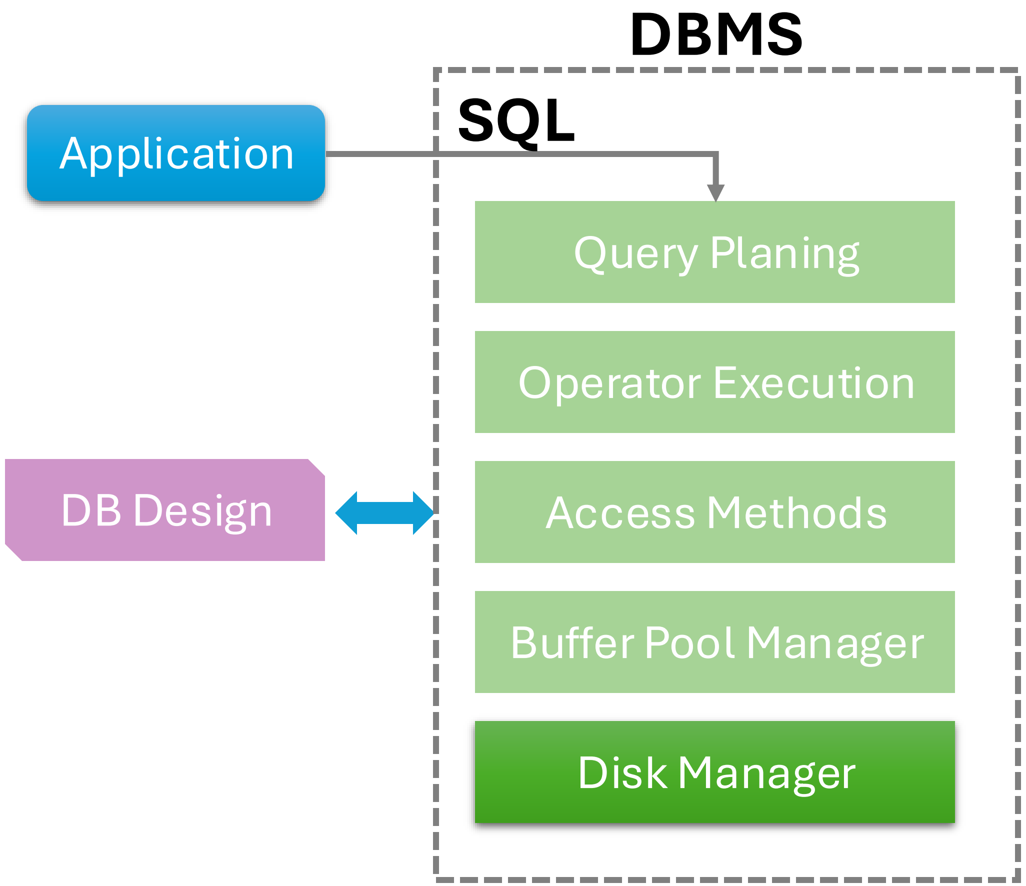
Last Lecture

- **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.

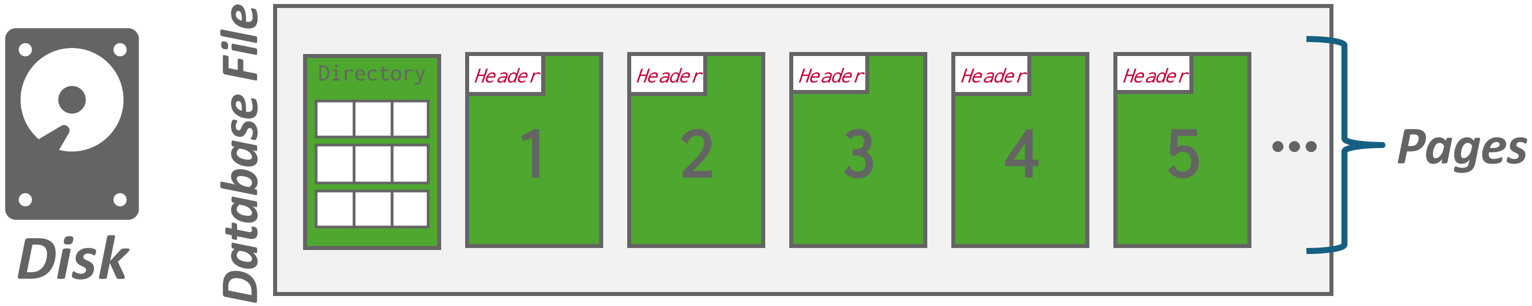


Database Storage

- **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 to minimize the number of stalls from having to read data from disk.

Disk-oriented DBMS



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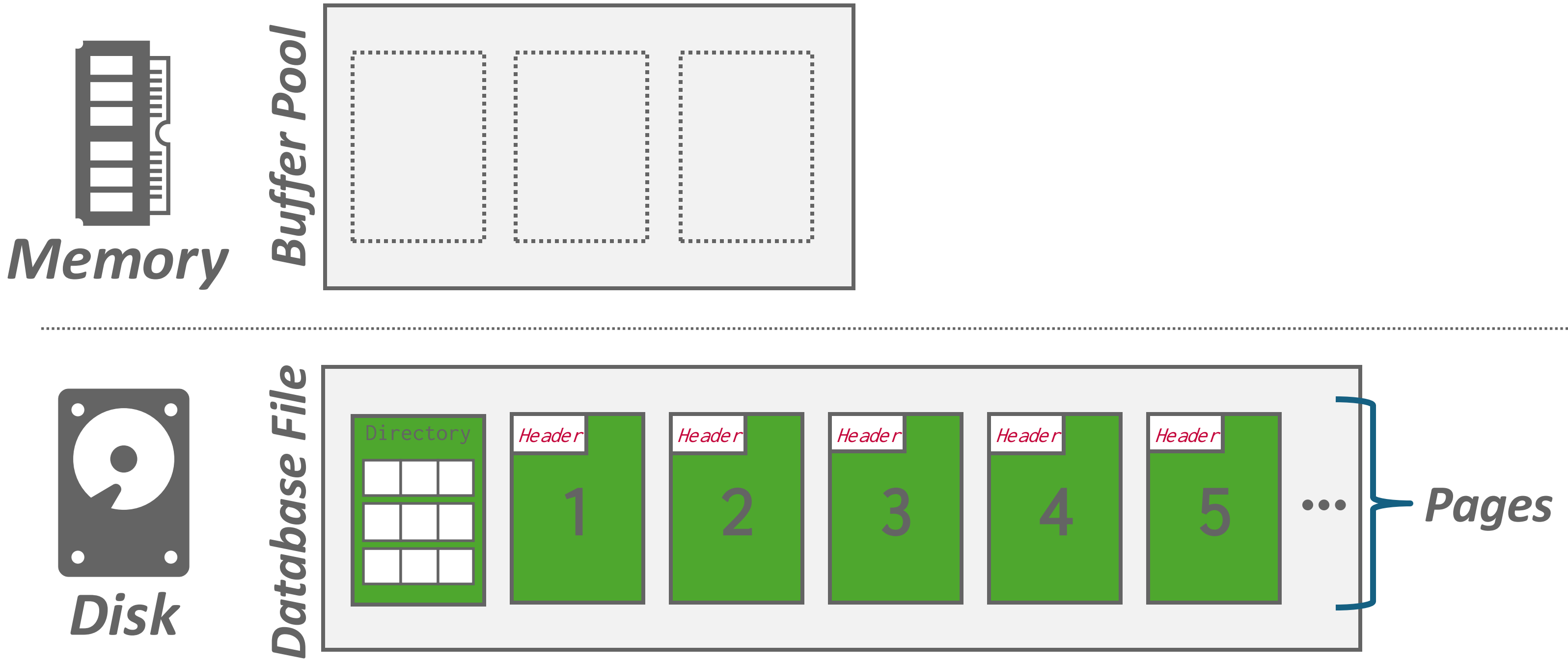

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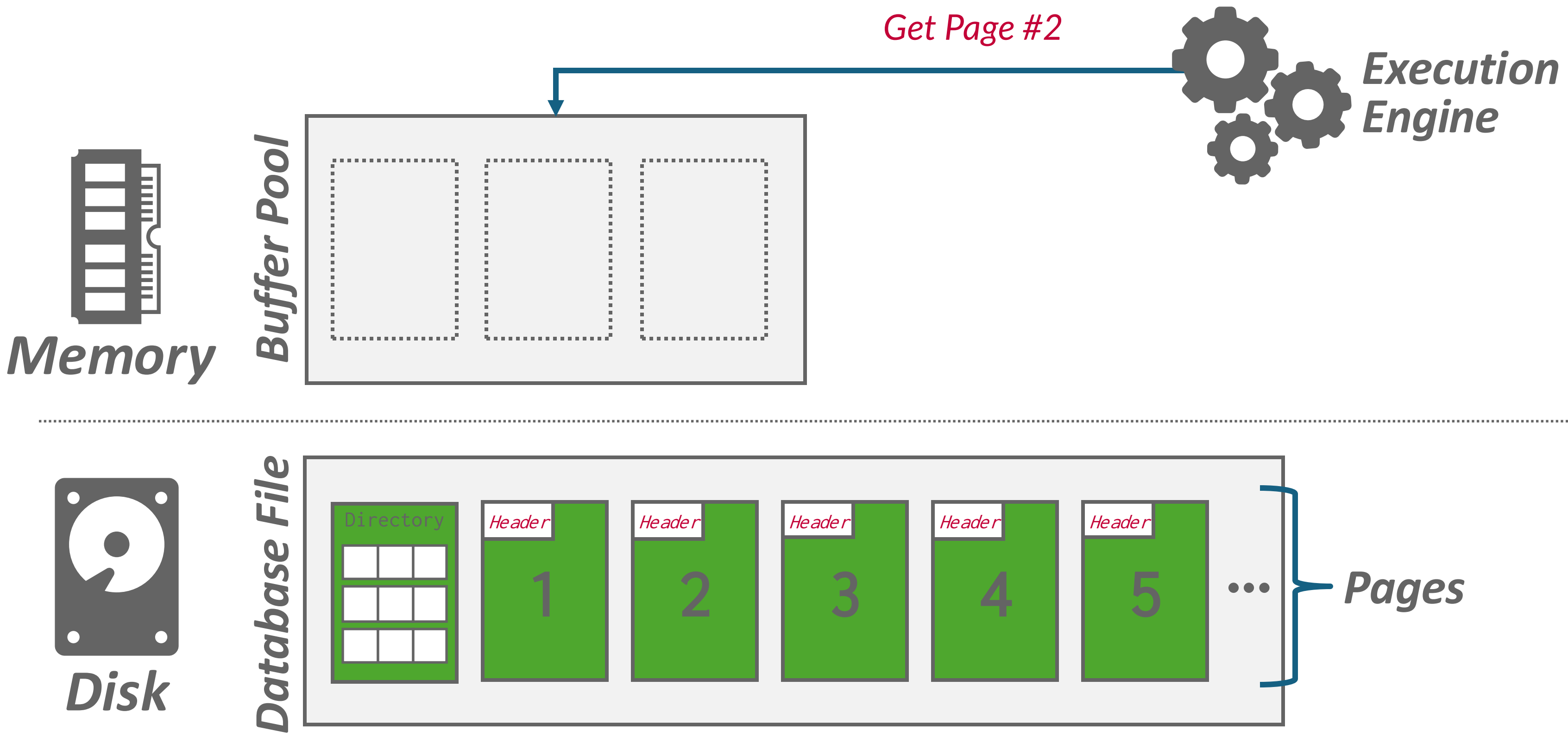

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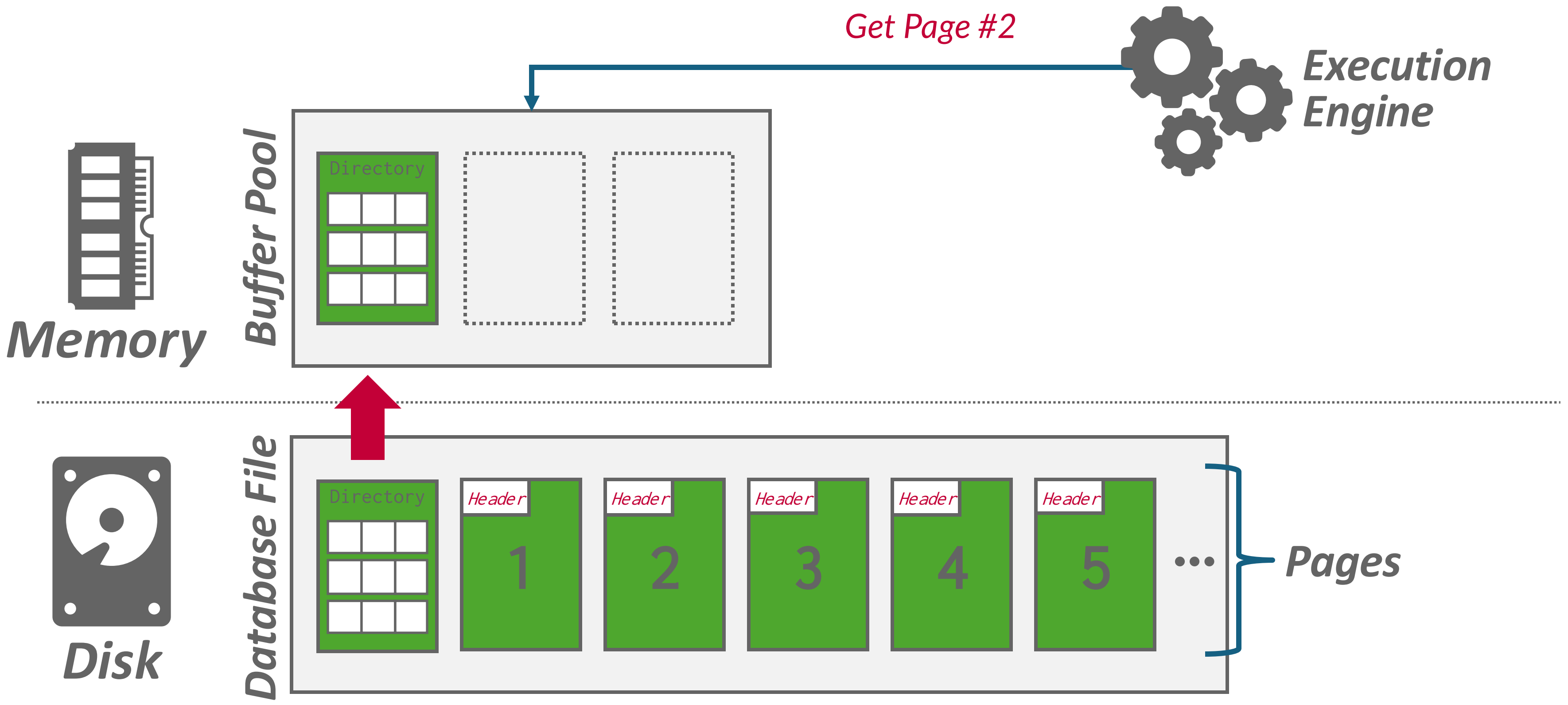

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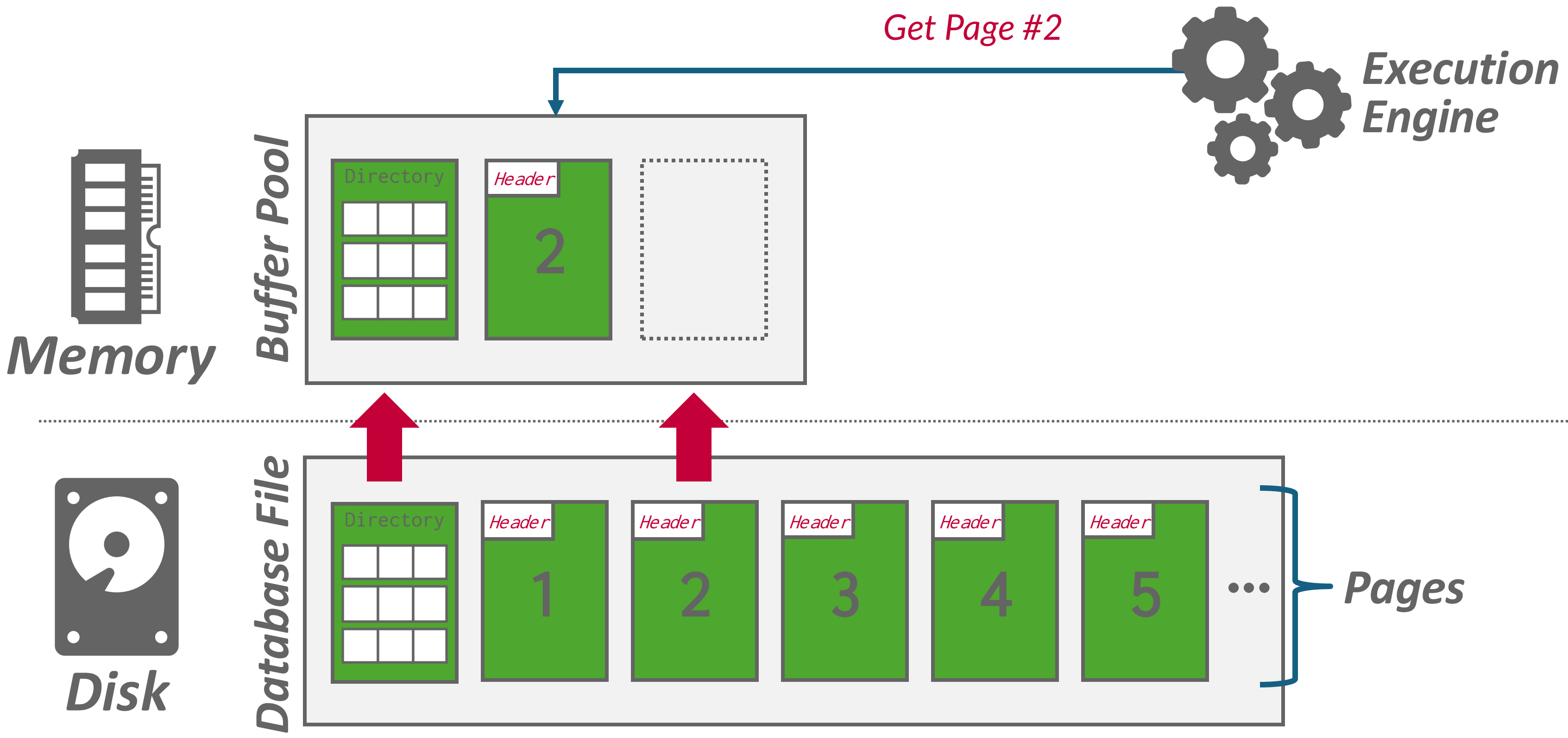

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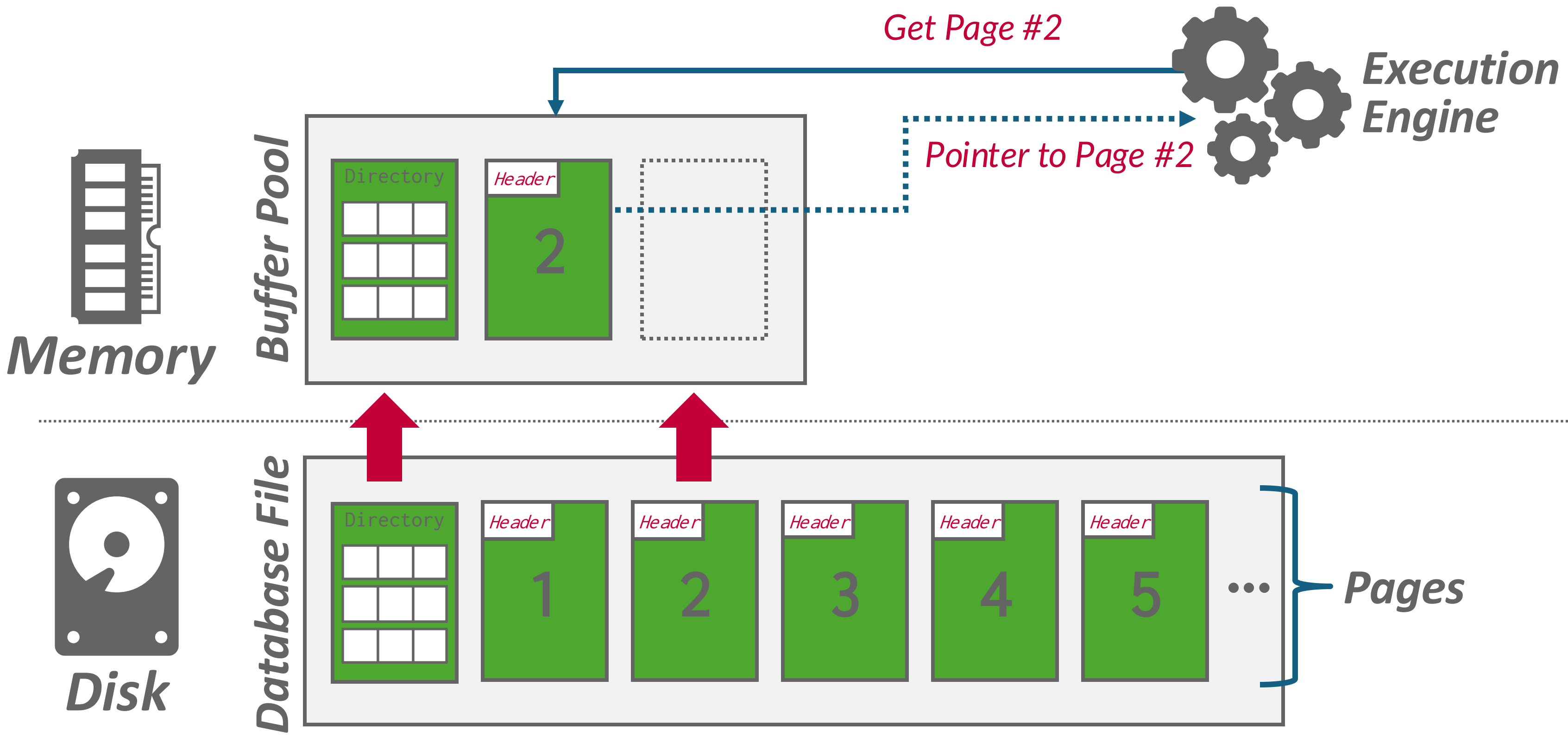

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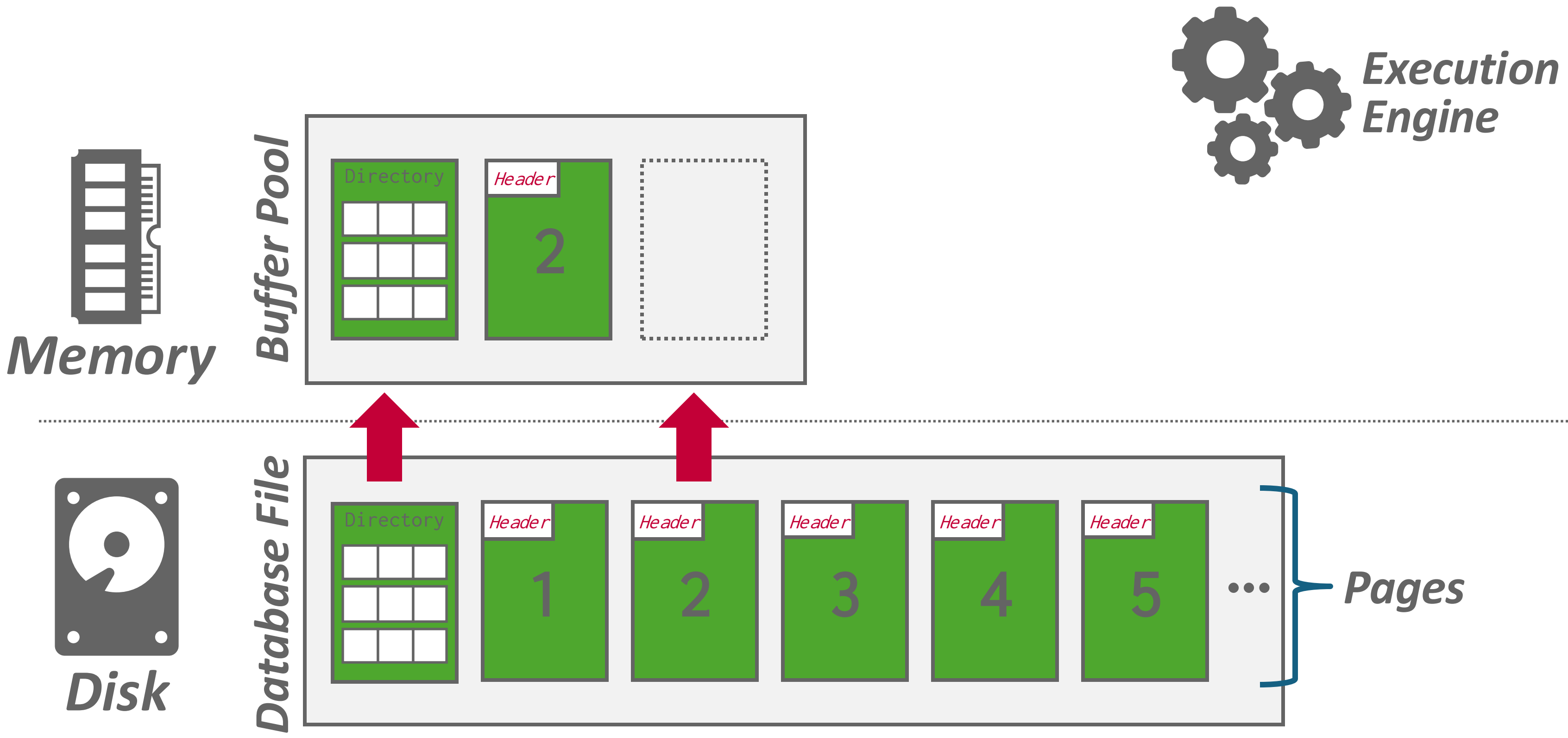

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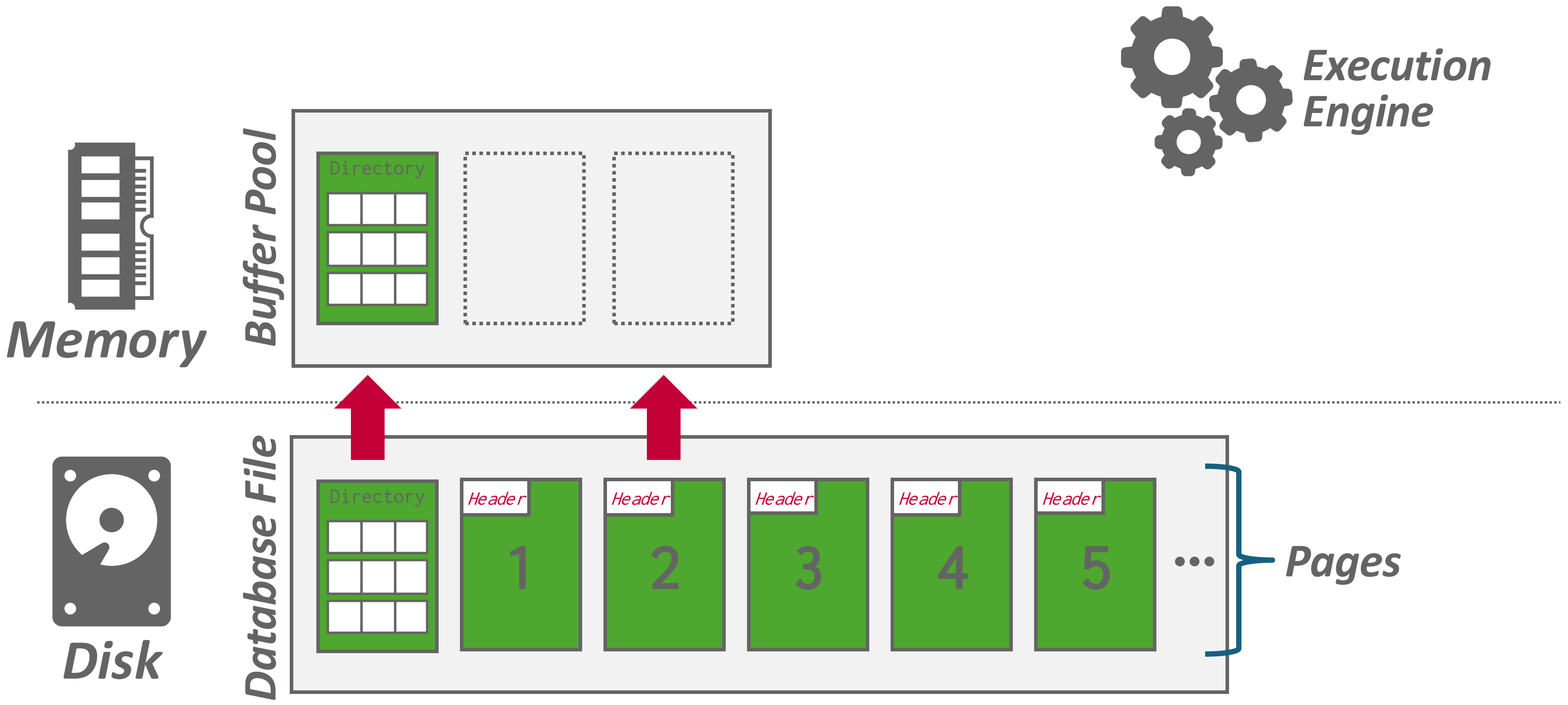

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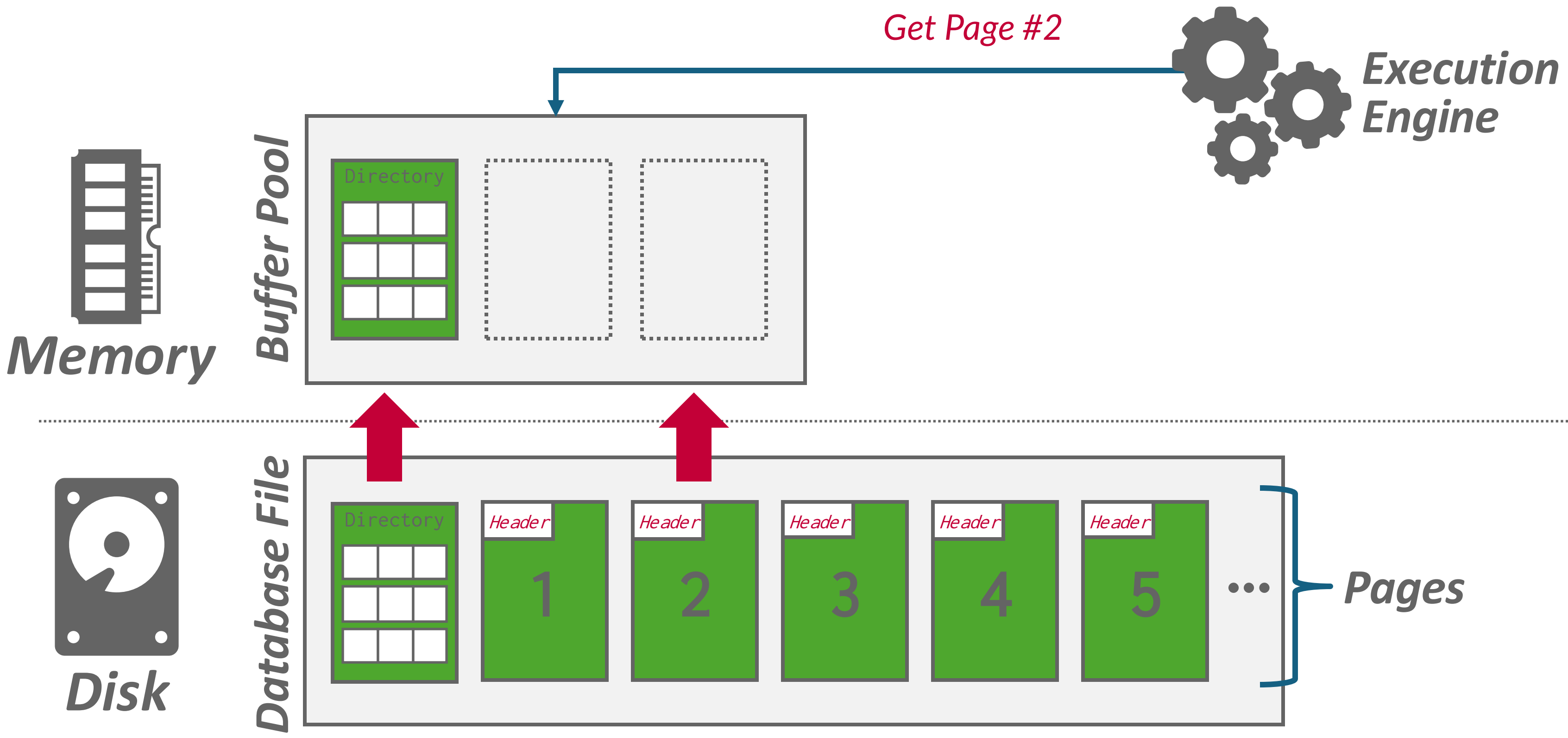

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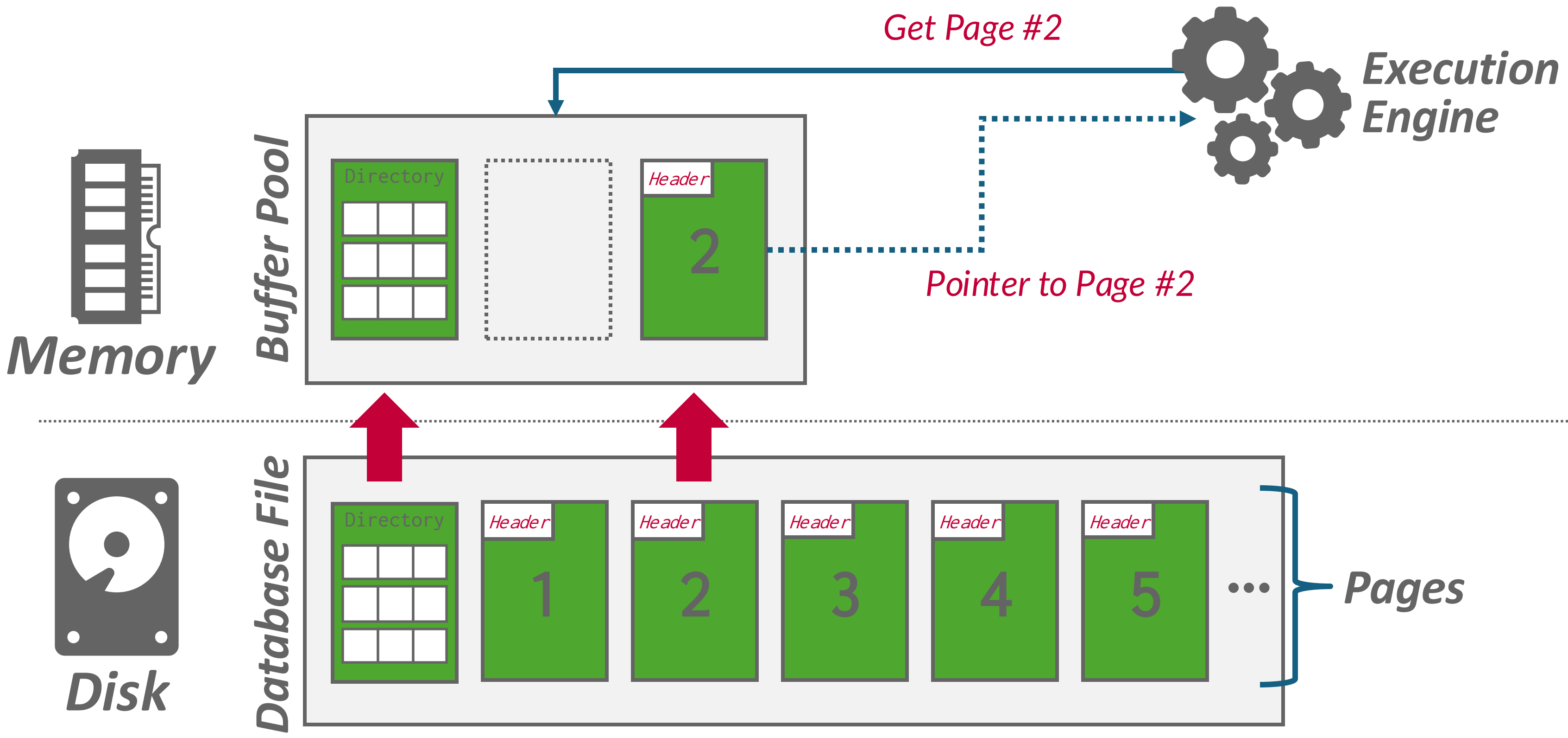

This Lecture

- Buffer Pool Manager
- Disk I/O Scheduling
- Replacement Policies
- Other Memory Pools

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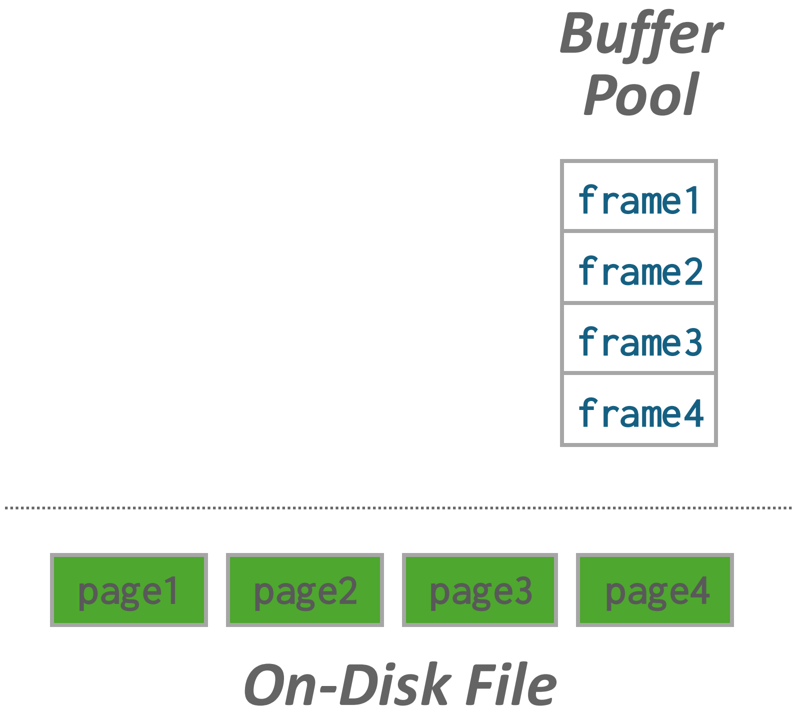
Buffer Pool Manager

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.
- Dirty pages are buffered and not written to disk immediately
  - Write-Back Cache



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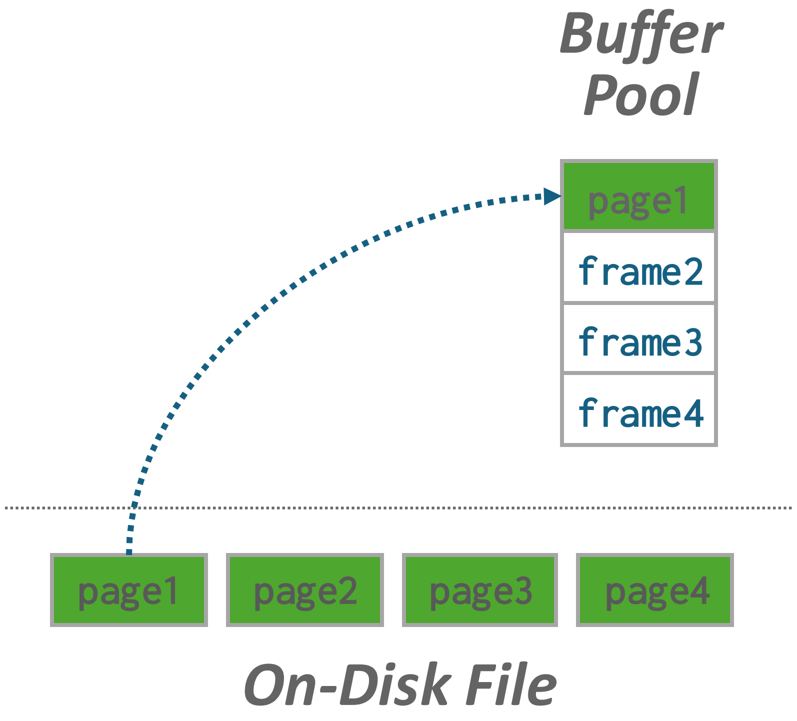

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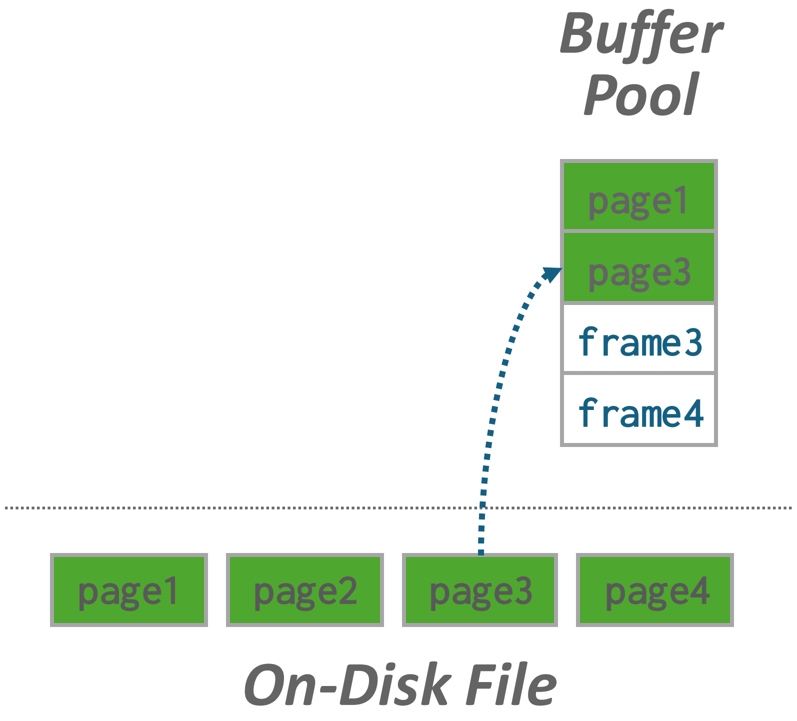
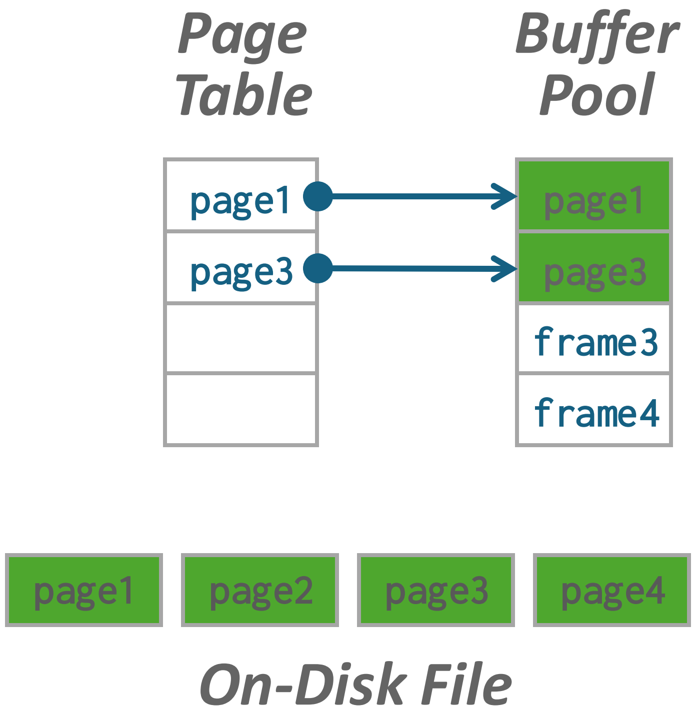


Buffer Pool Meta-data

- The **<u>page table</u>** keeps track of pages that are currently in memory.
  - Usually a fixed-size hash table protected with latches to ensure thread-safe access.

- Additional meta-data per page:
  - **Dirty Flag**
  - **Pin/Reference Counter**
  - **Access Tracking Information**



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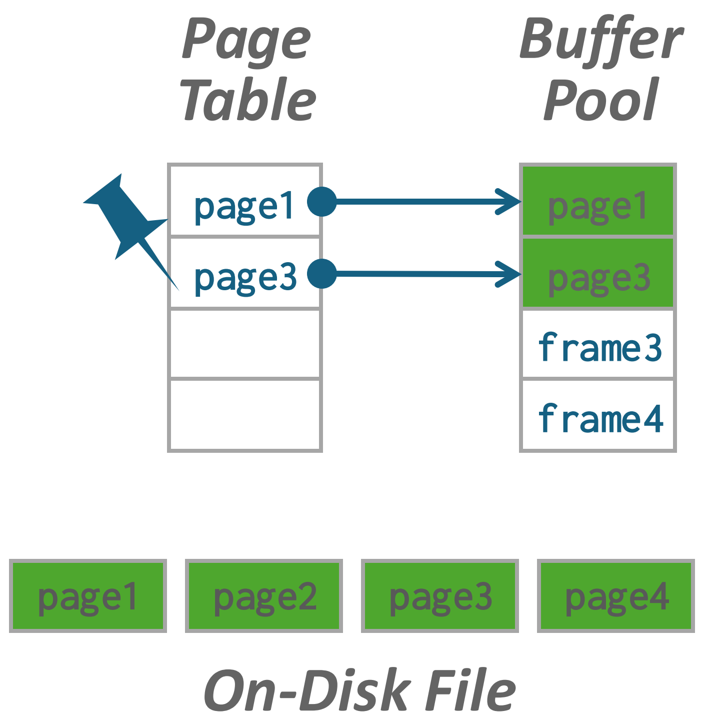

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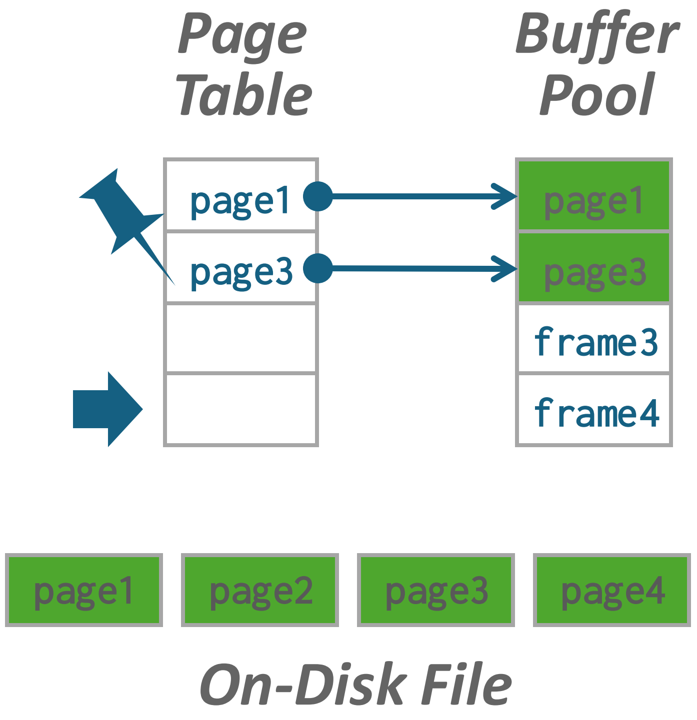

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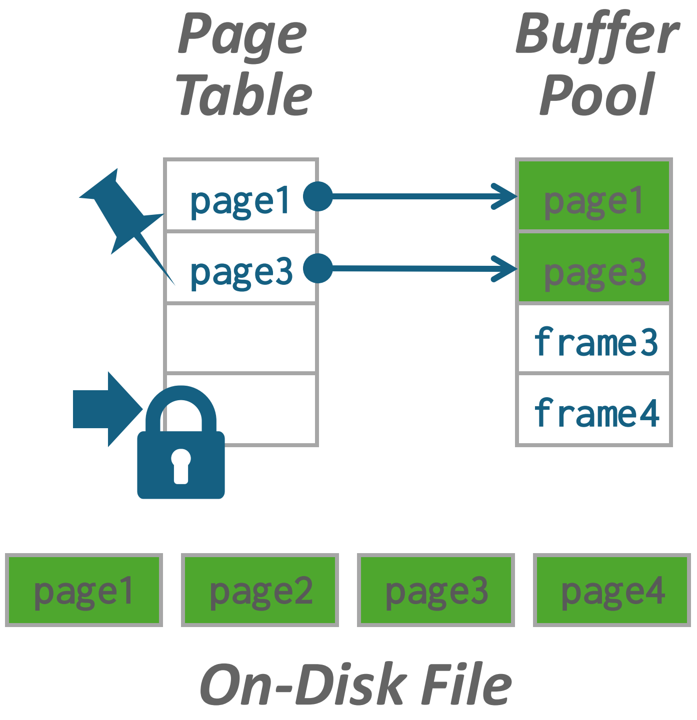

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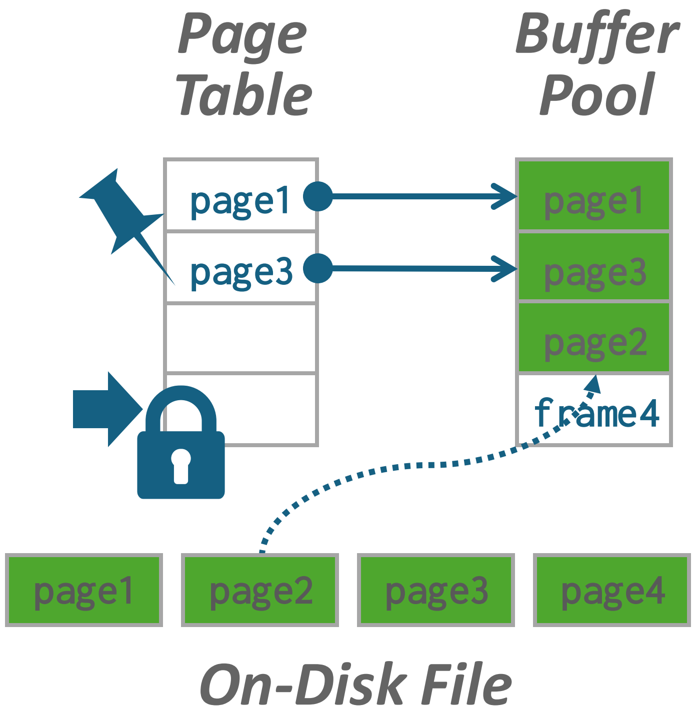

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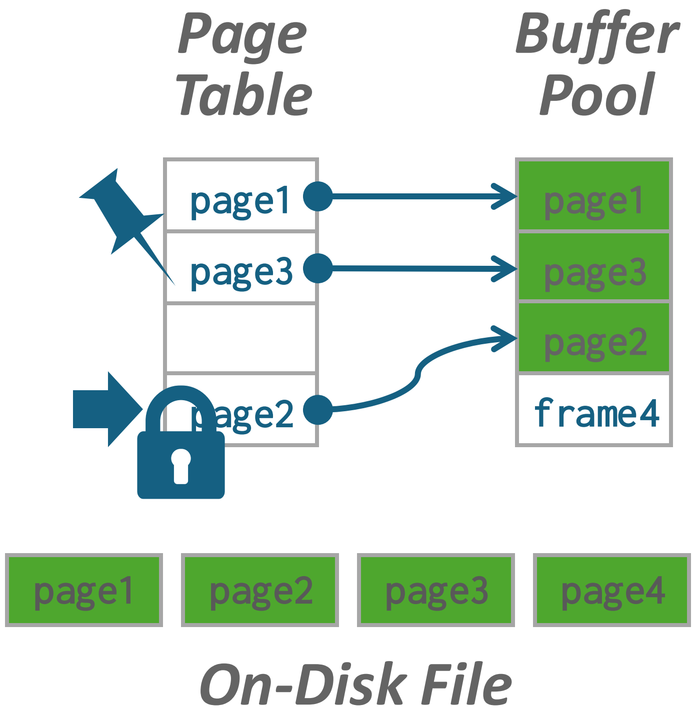

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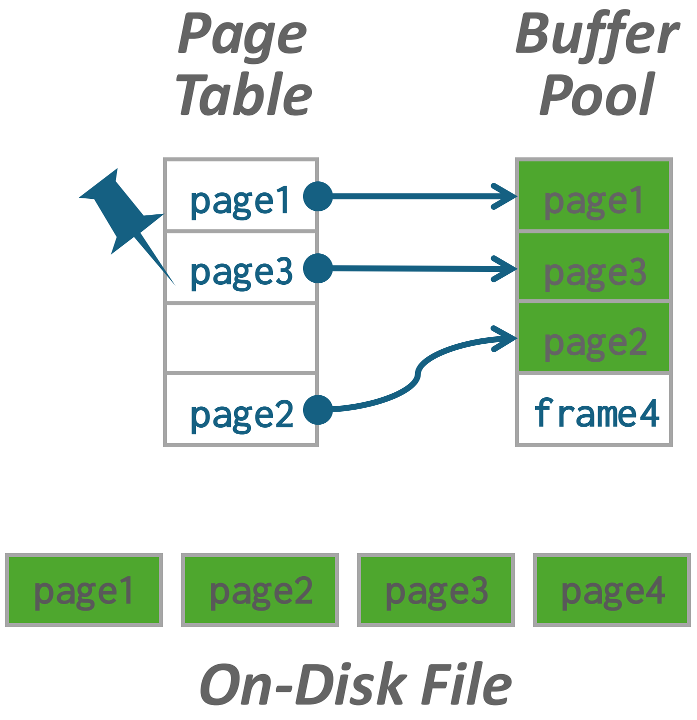

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Locks vs. Latches

- **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.
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←Mutex

Page Tables 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.

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Allocation Policies

- **Global Policies:**
  - Make decisions for all active queries.
- **Local Policies:**
  - Allocate frames to a specific queries without considering the behavior of concurrent queries.
  - Still need to support sharing pages.

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Buffer Pool Optimizations

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

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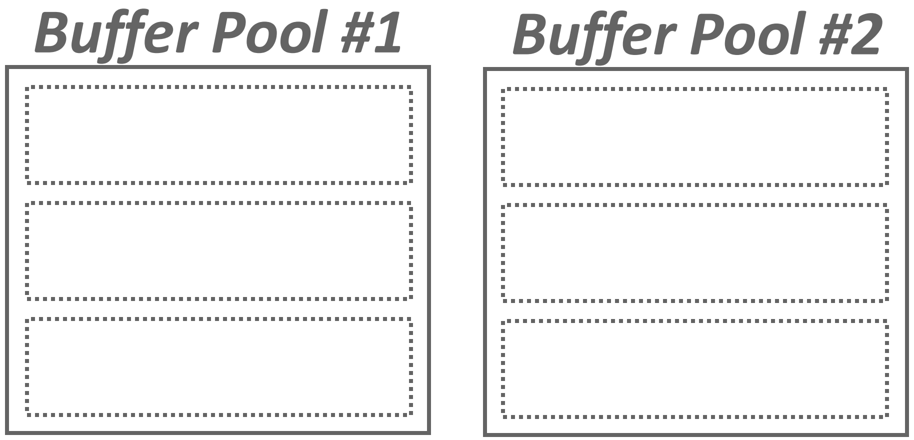
Multiple Buffer Pools

- **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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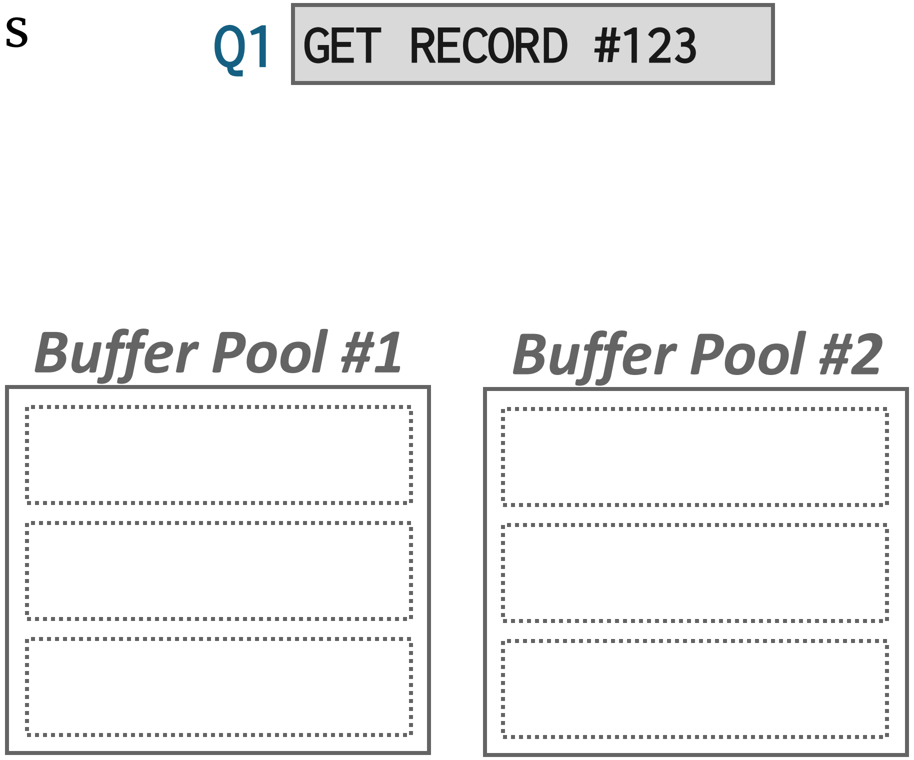

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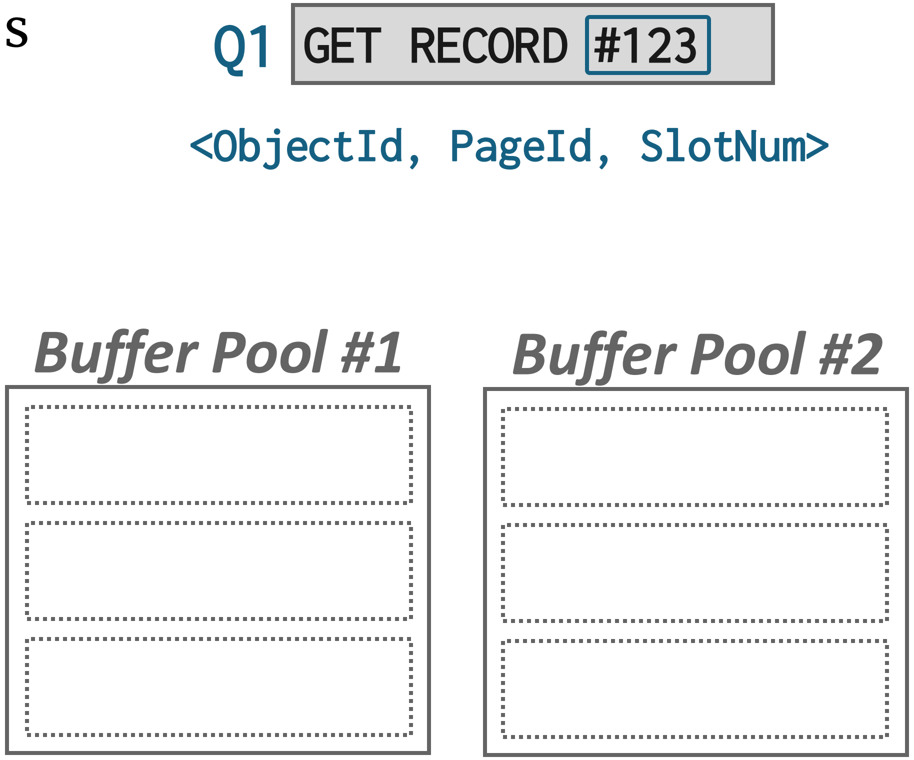

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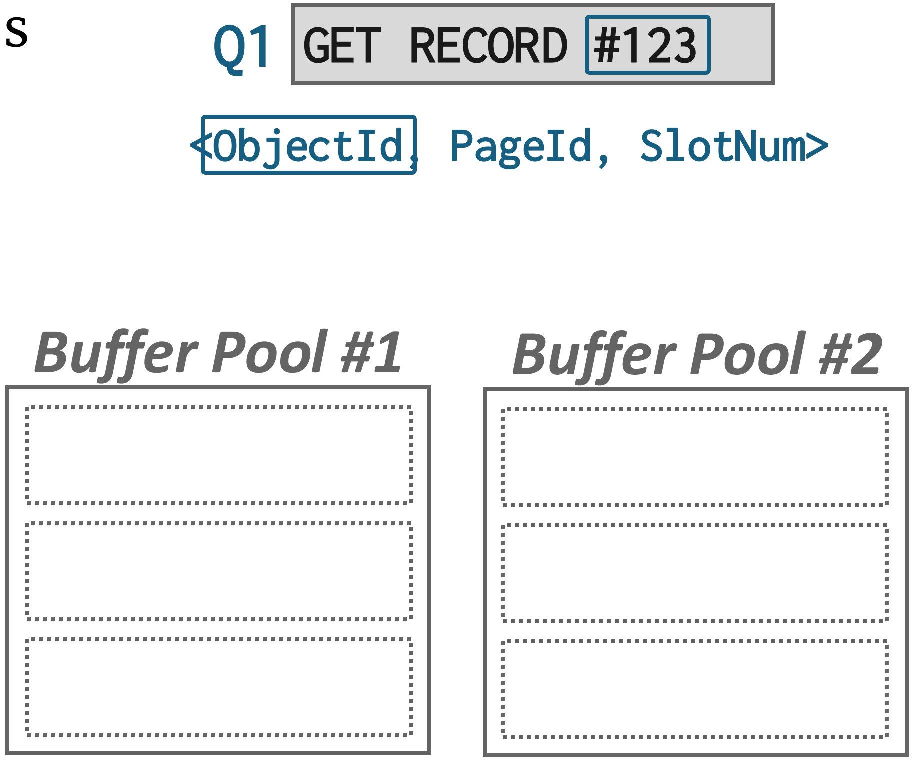

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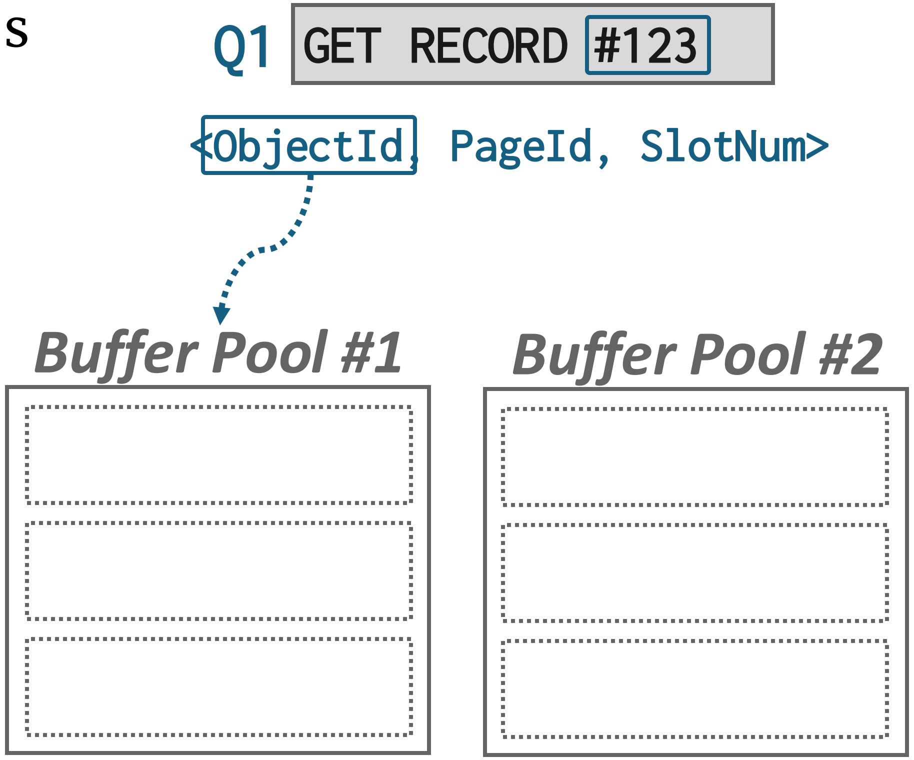

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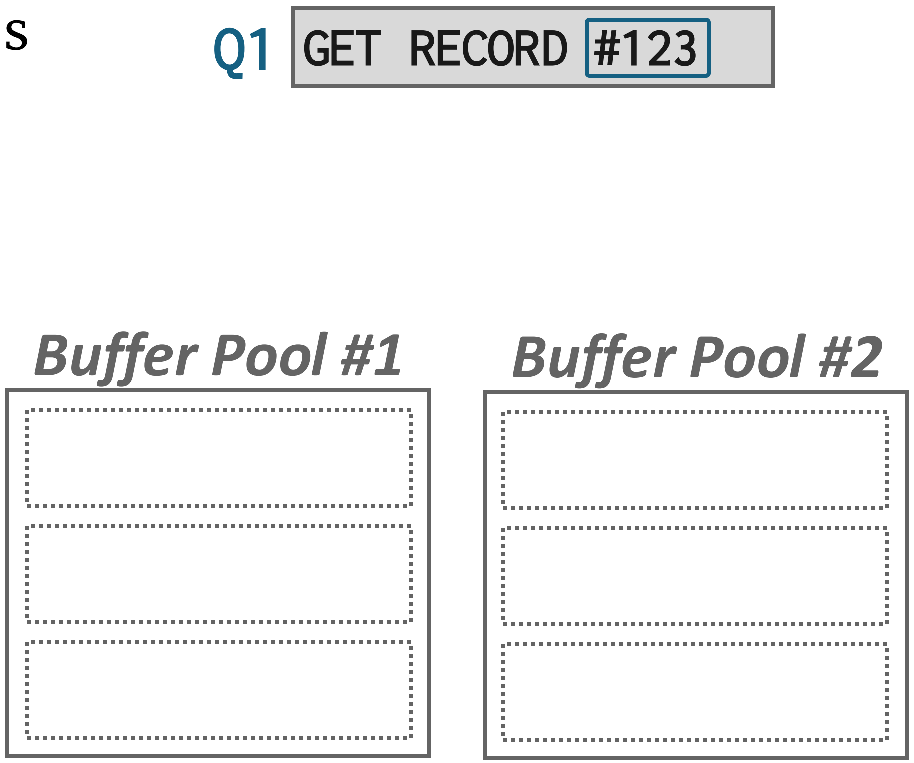

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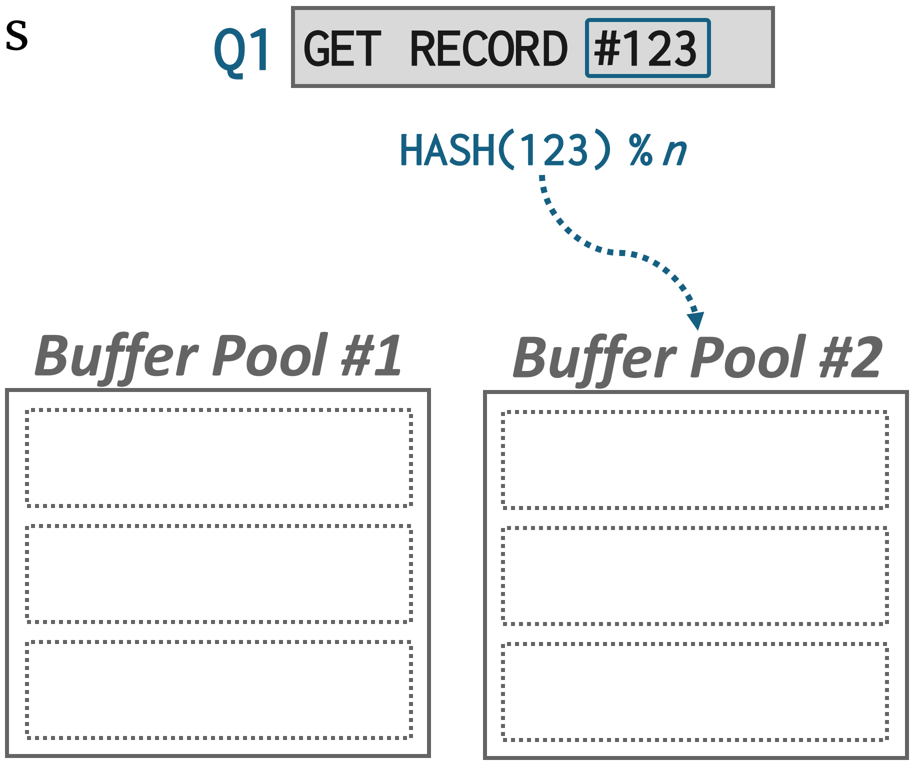
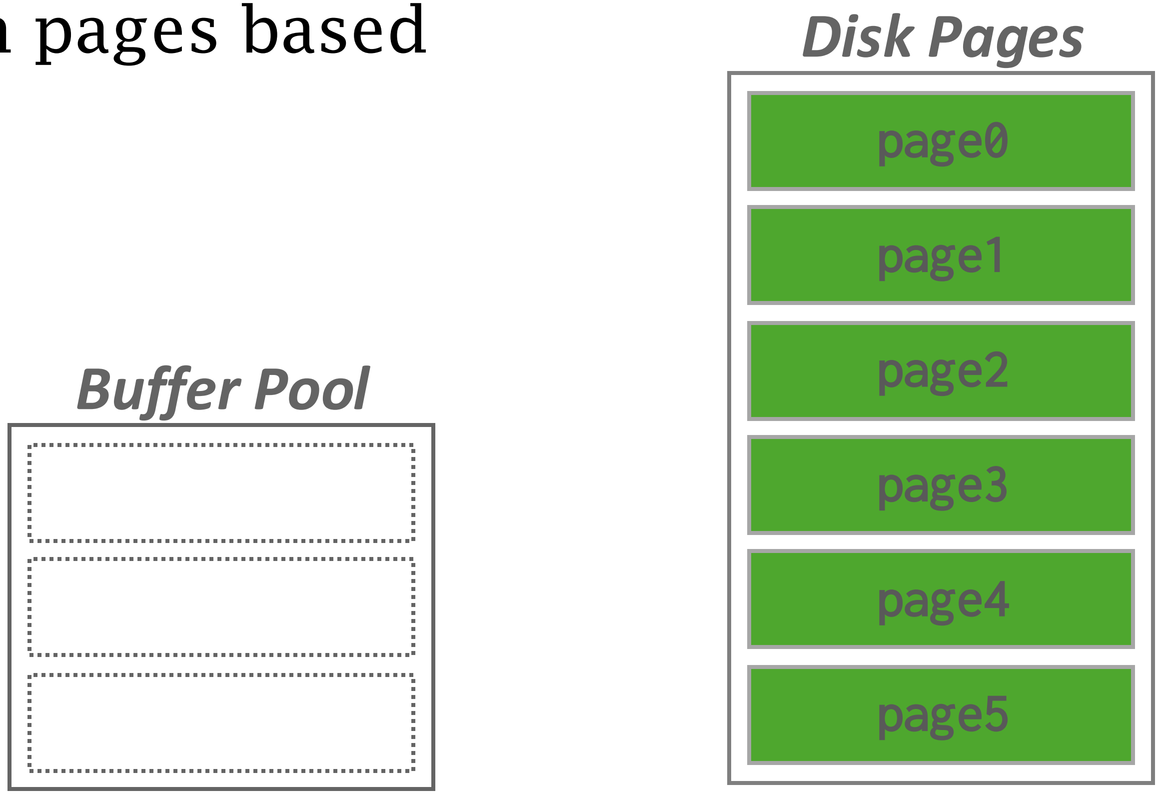


Pre-fetching

- The DBMS can also prefetch pages based on a query plan.
  - Sequential Scans
  - Index Scans



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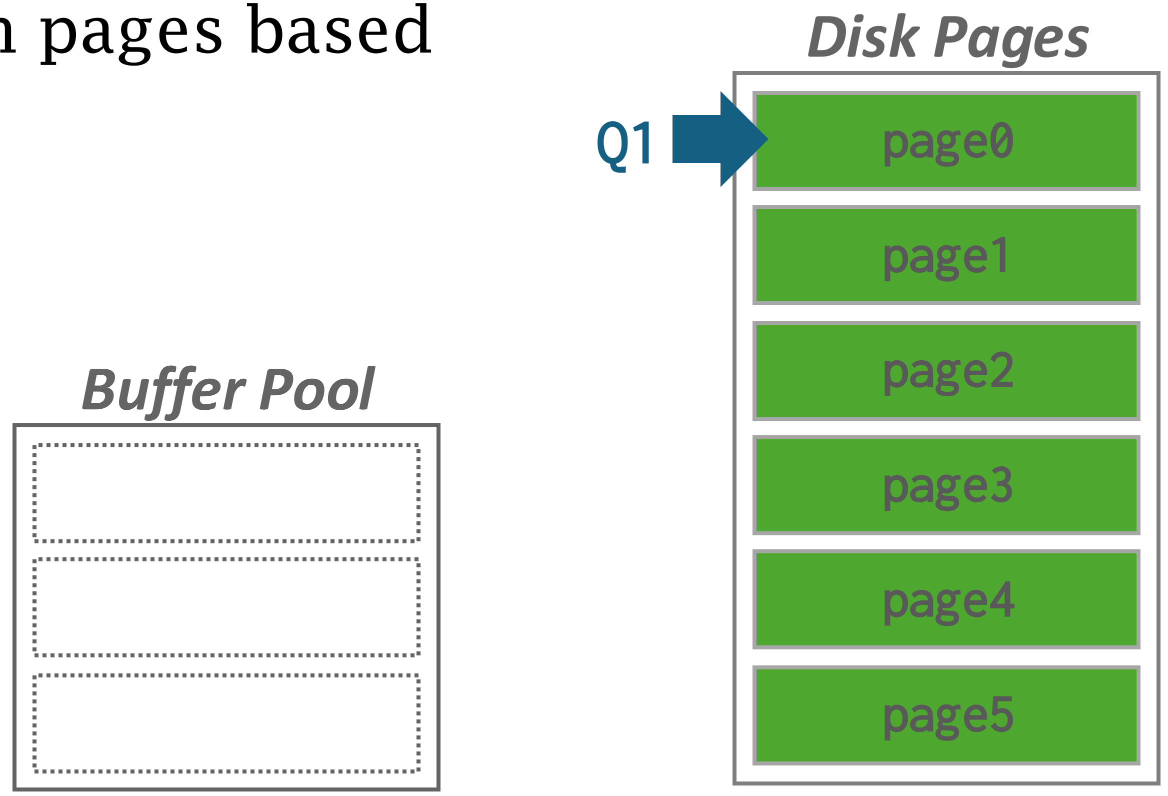

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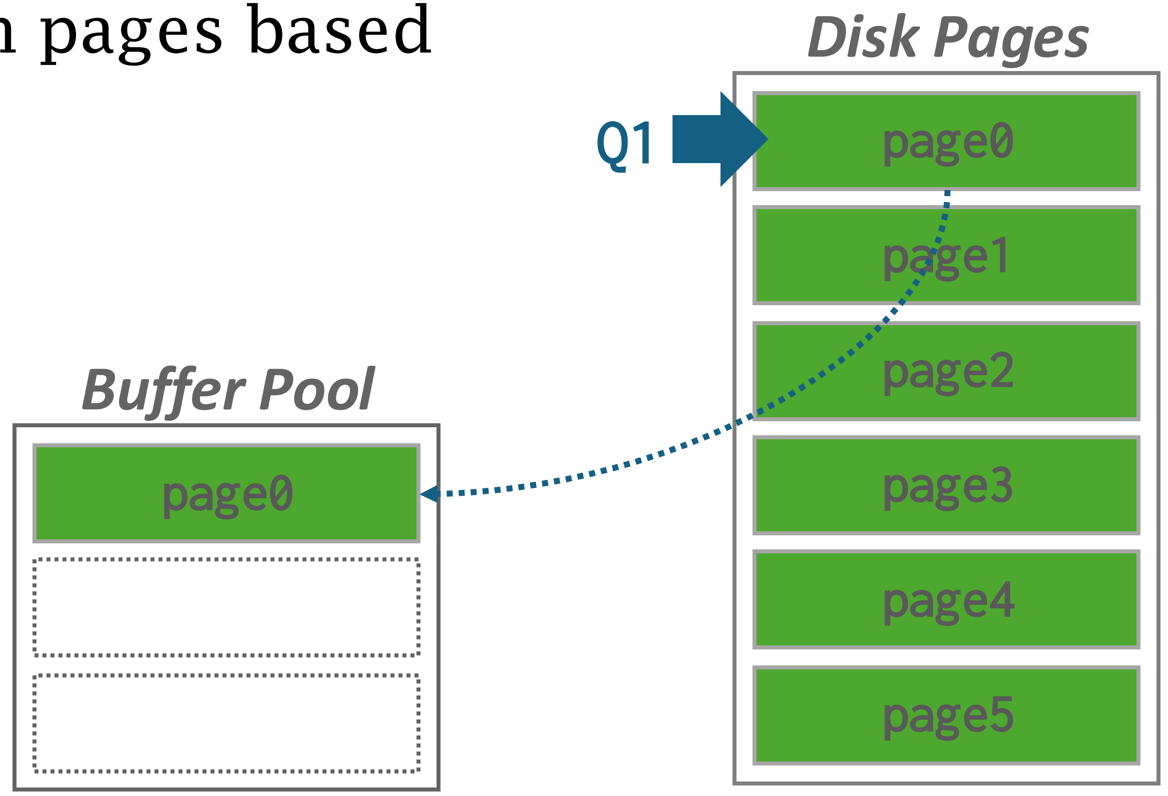

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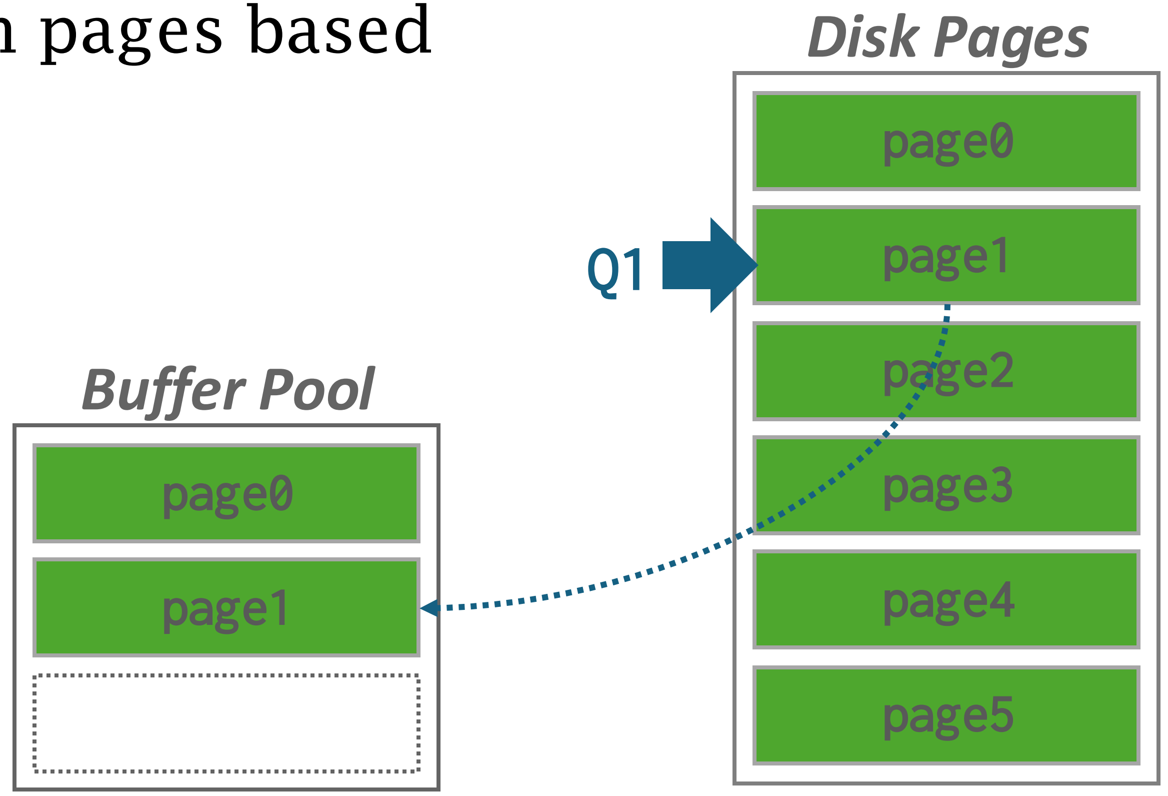

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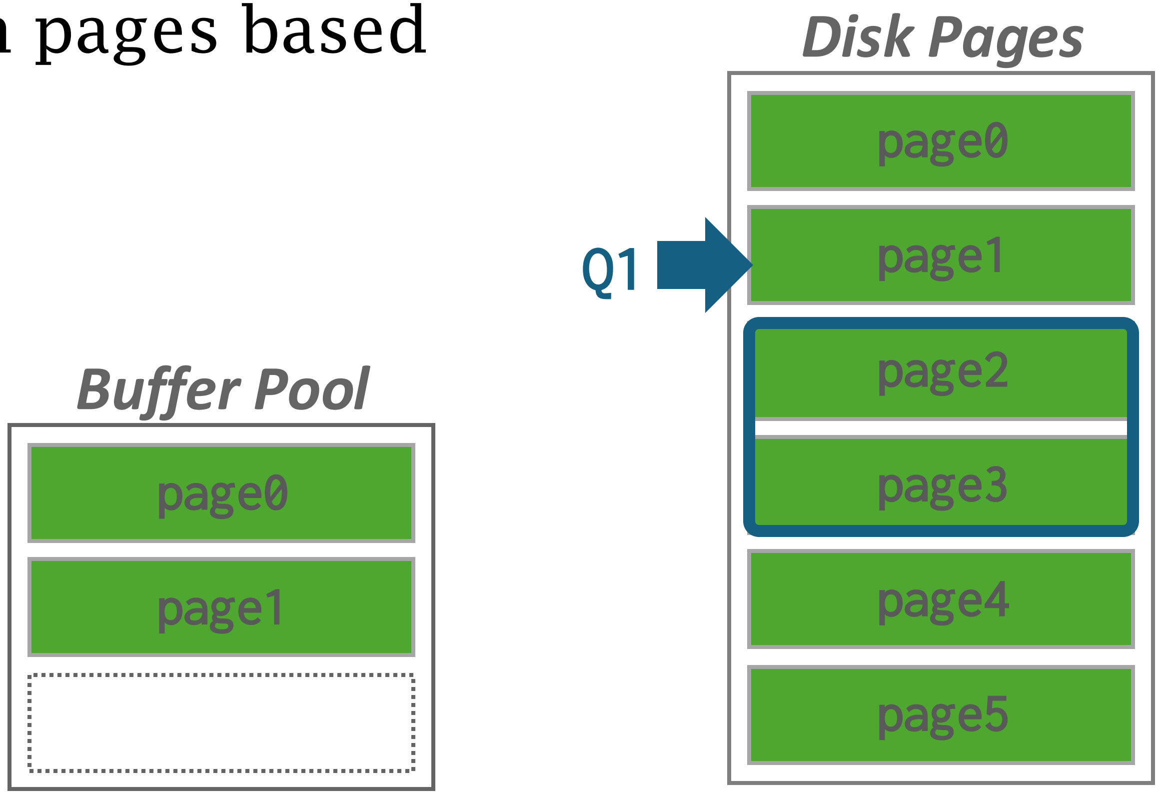

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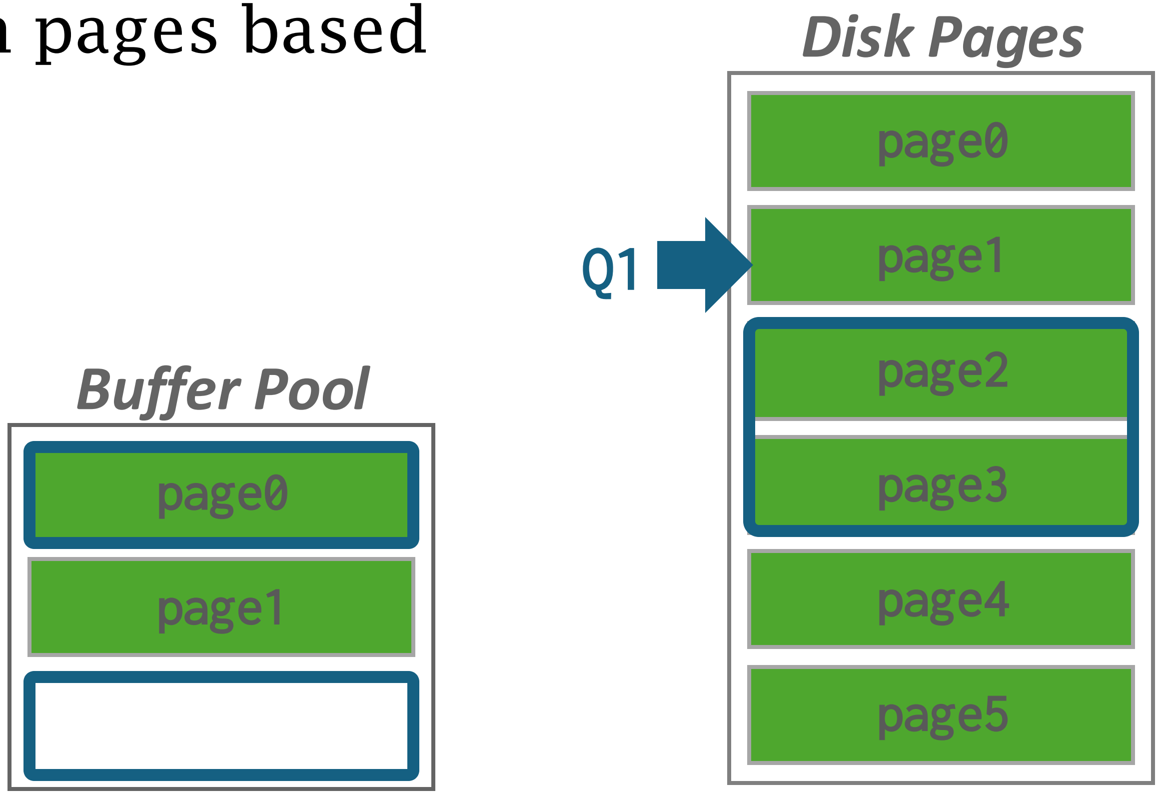

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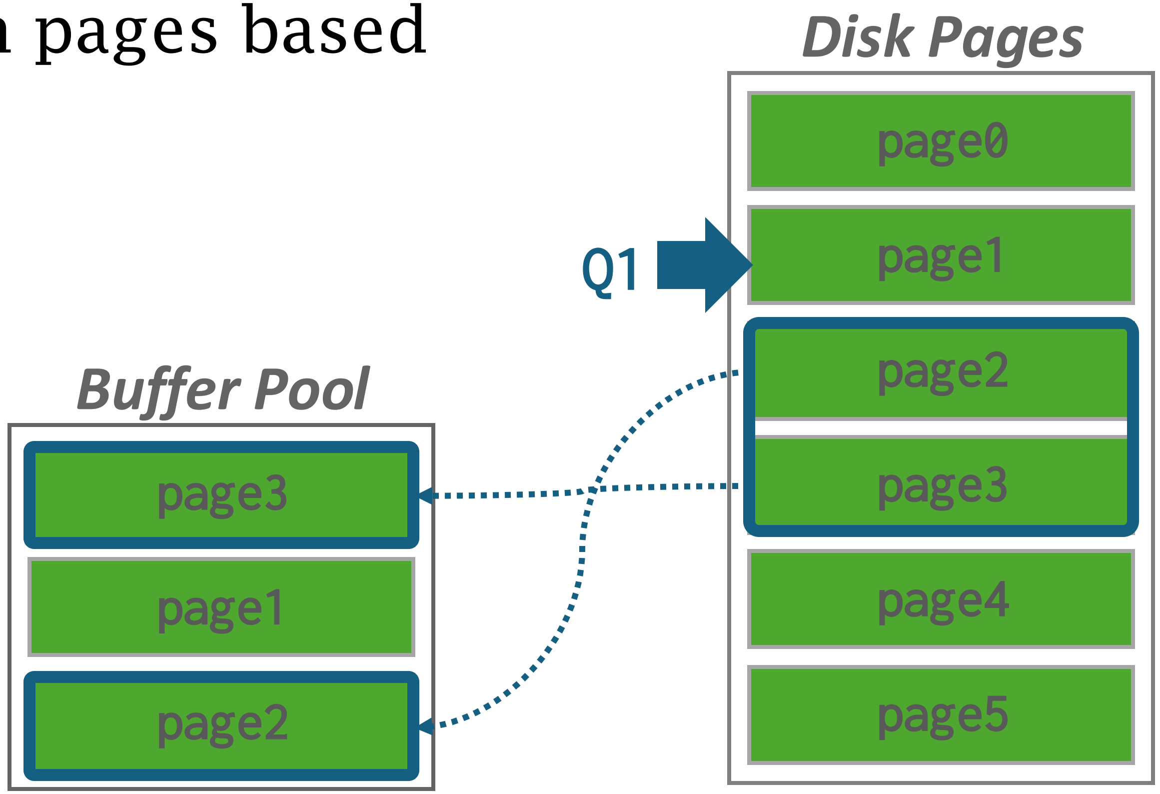

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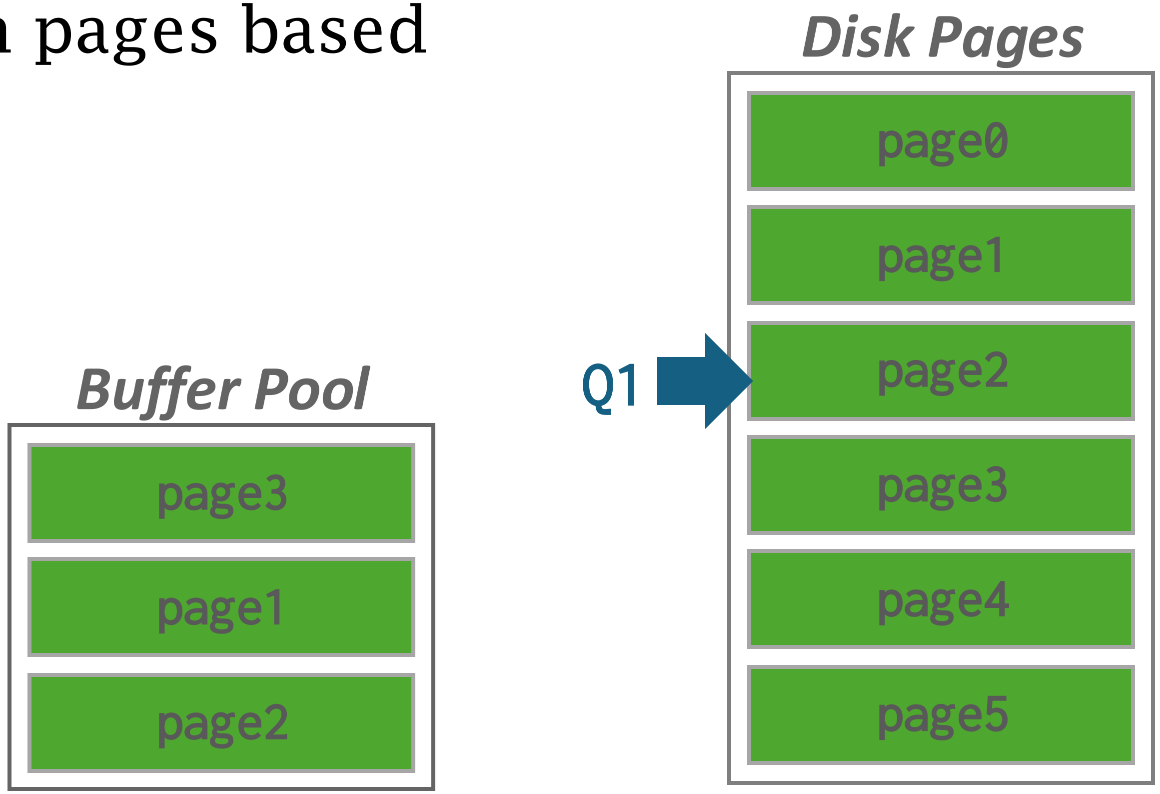

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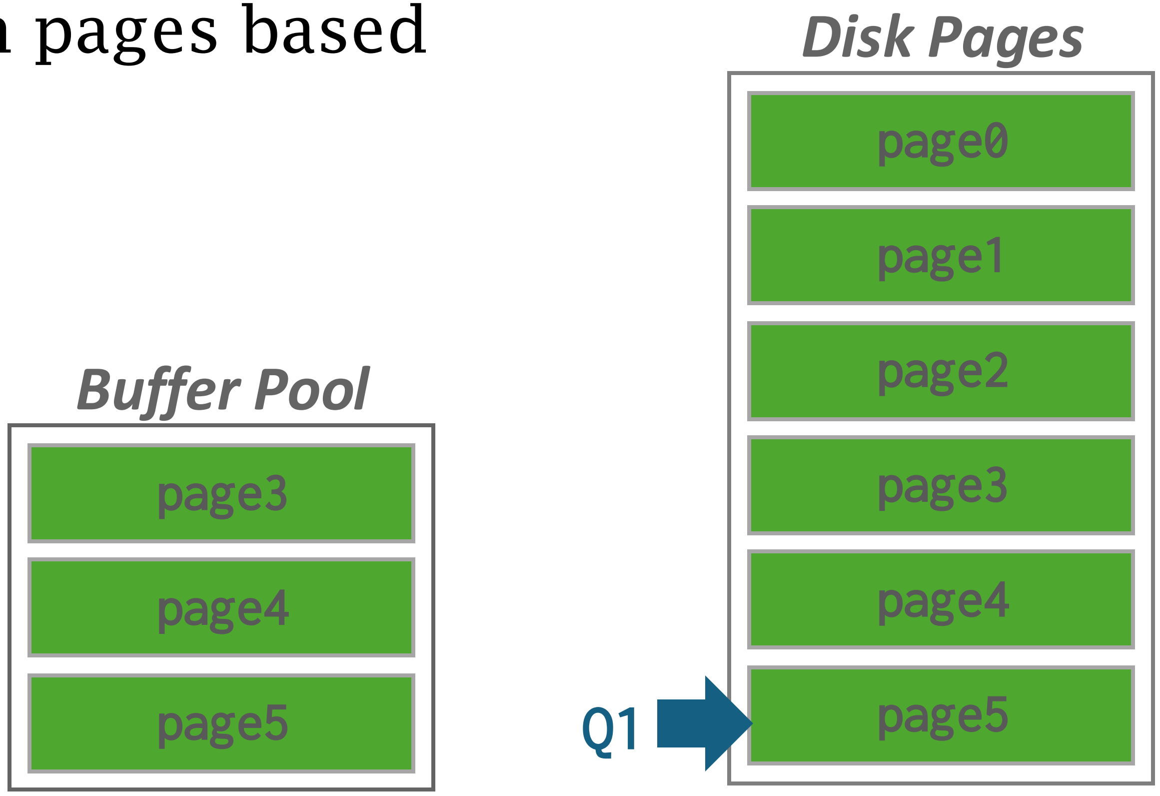

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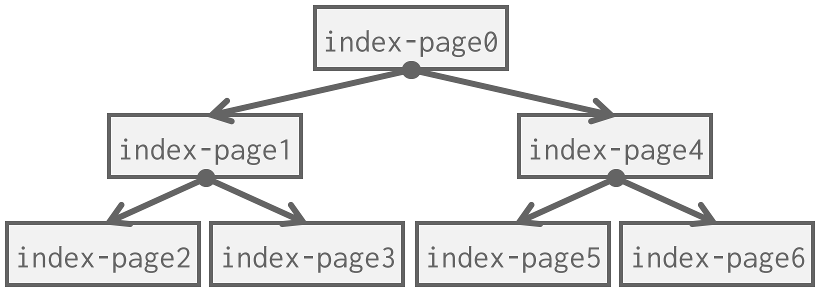

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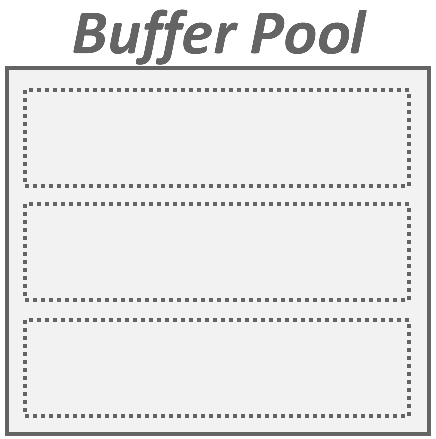

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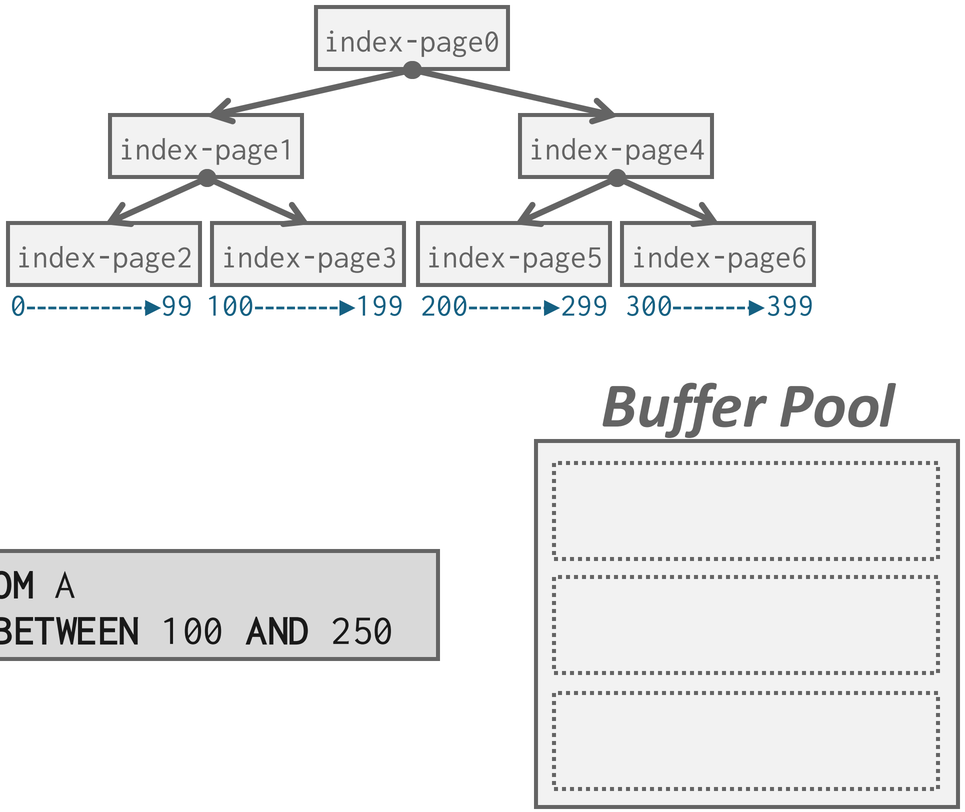

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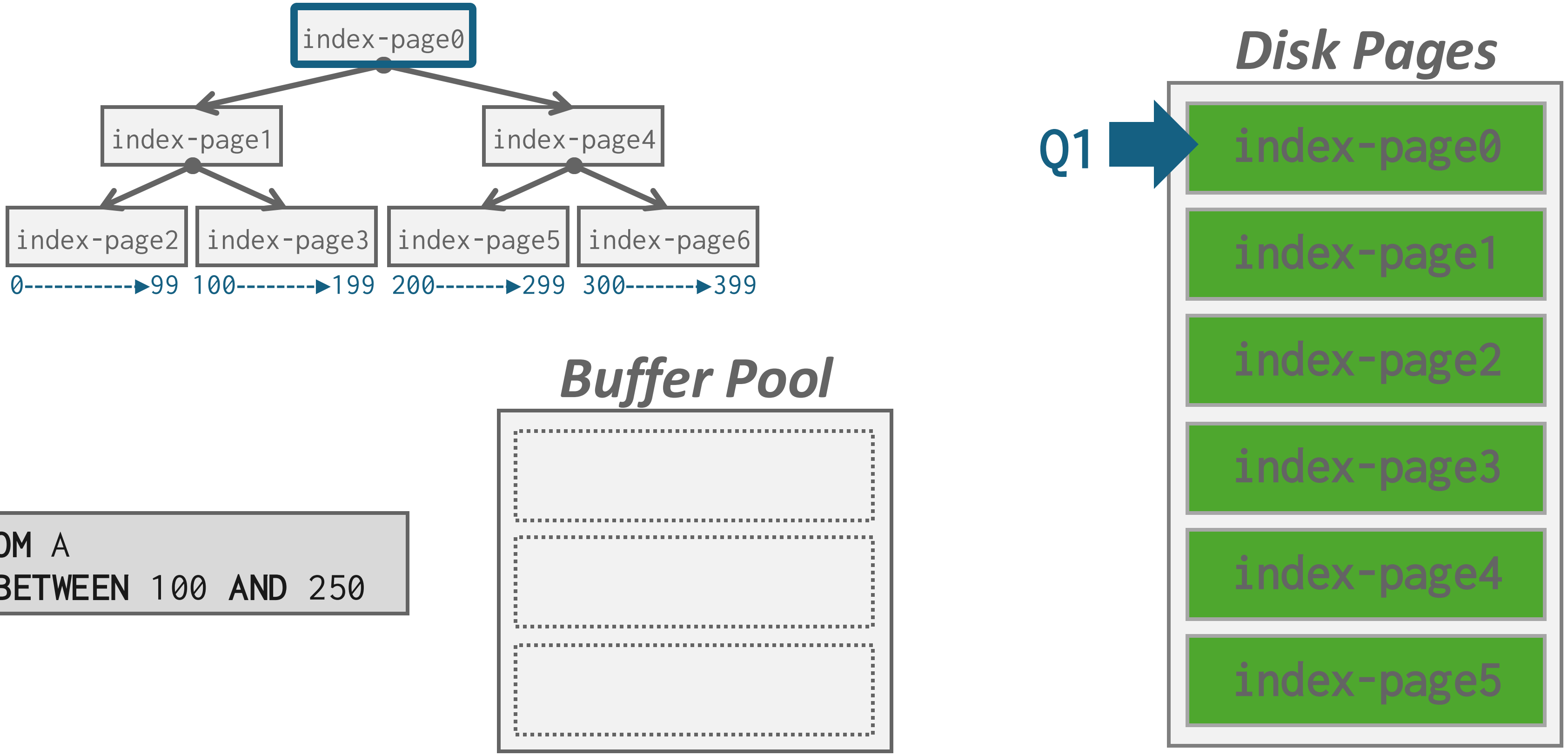

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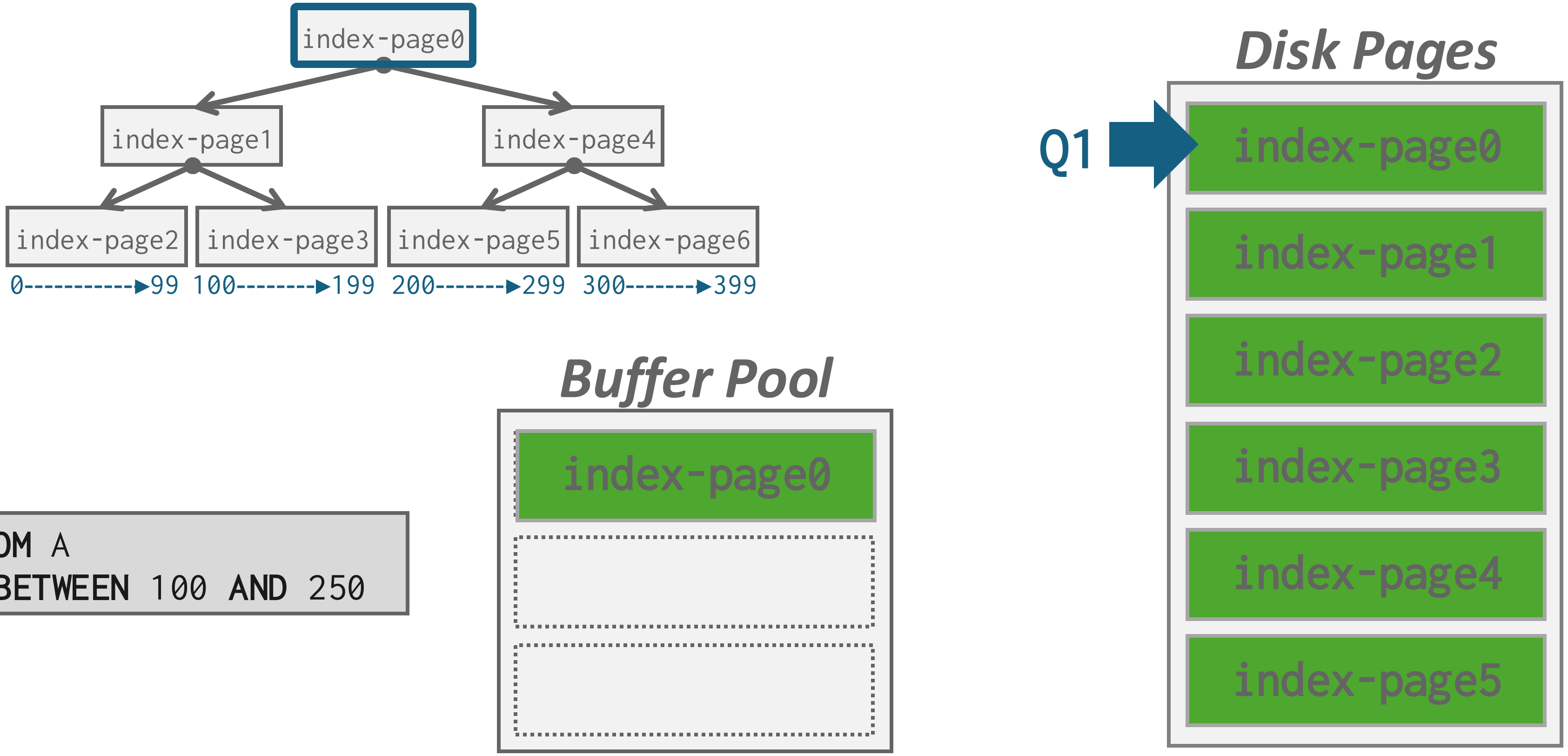

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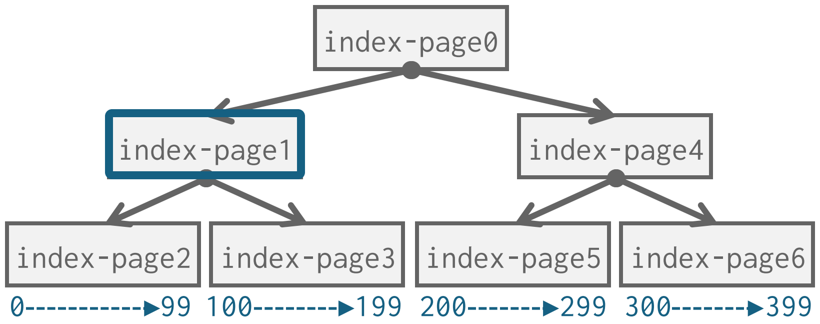

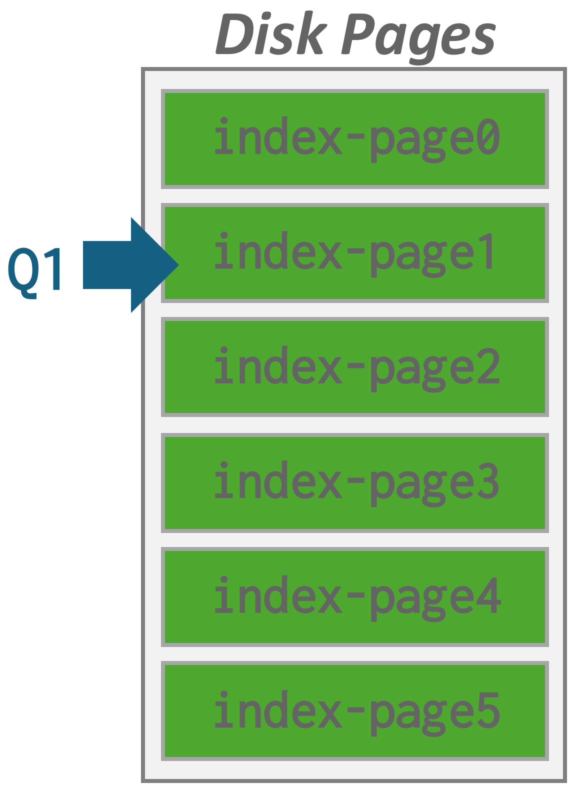

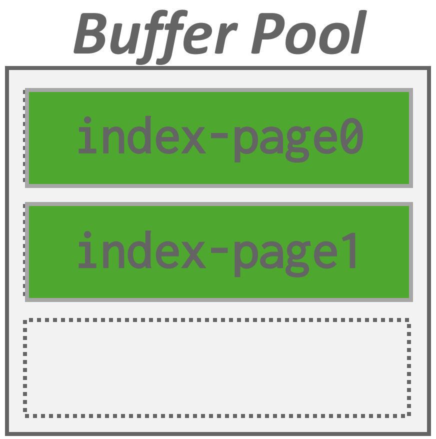

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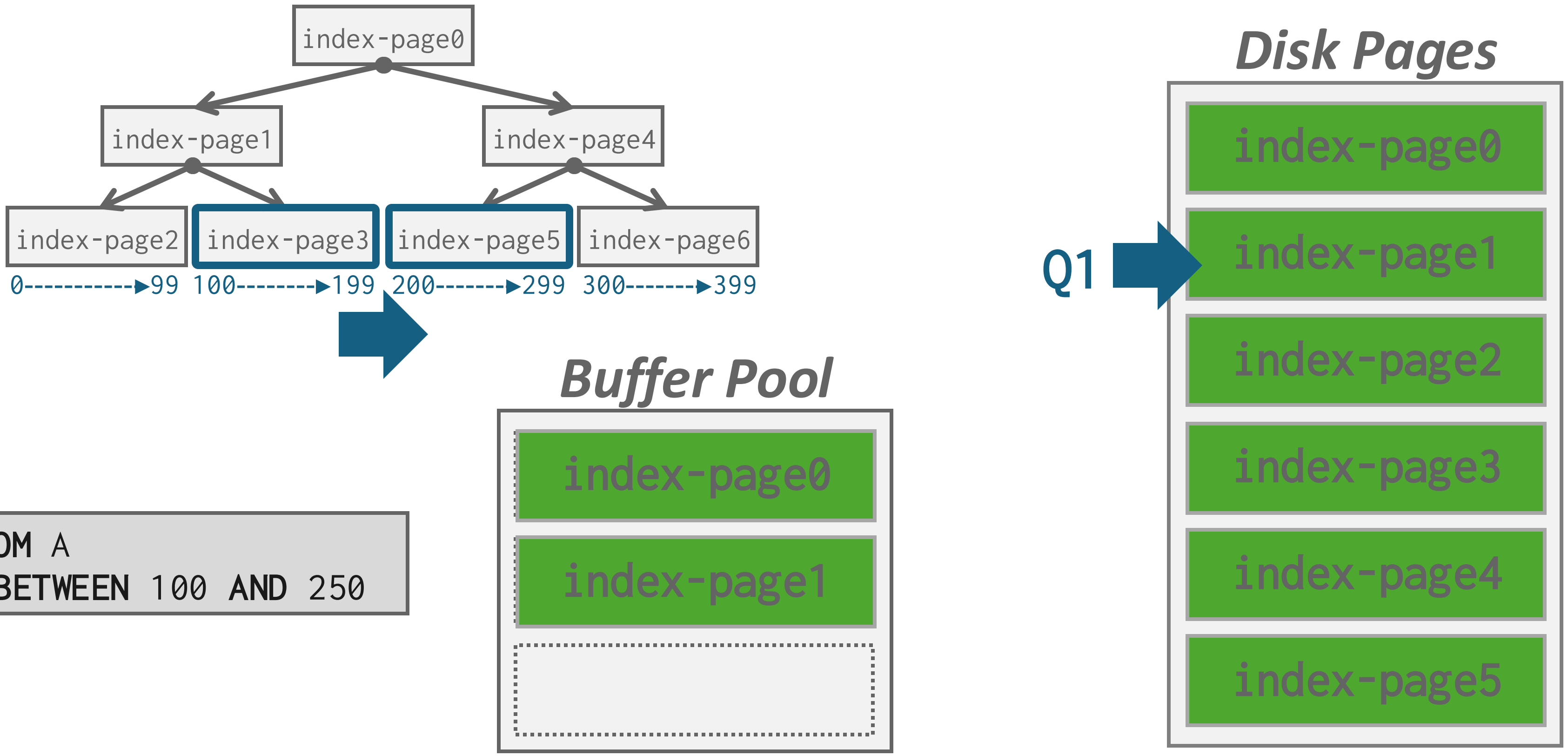

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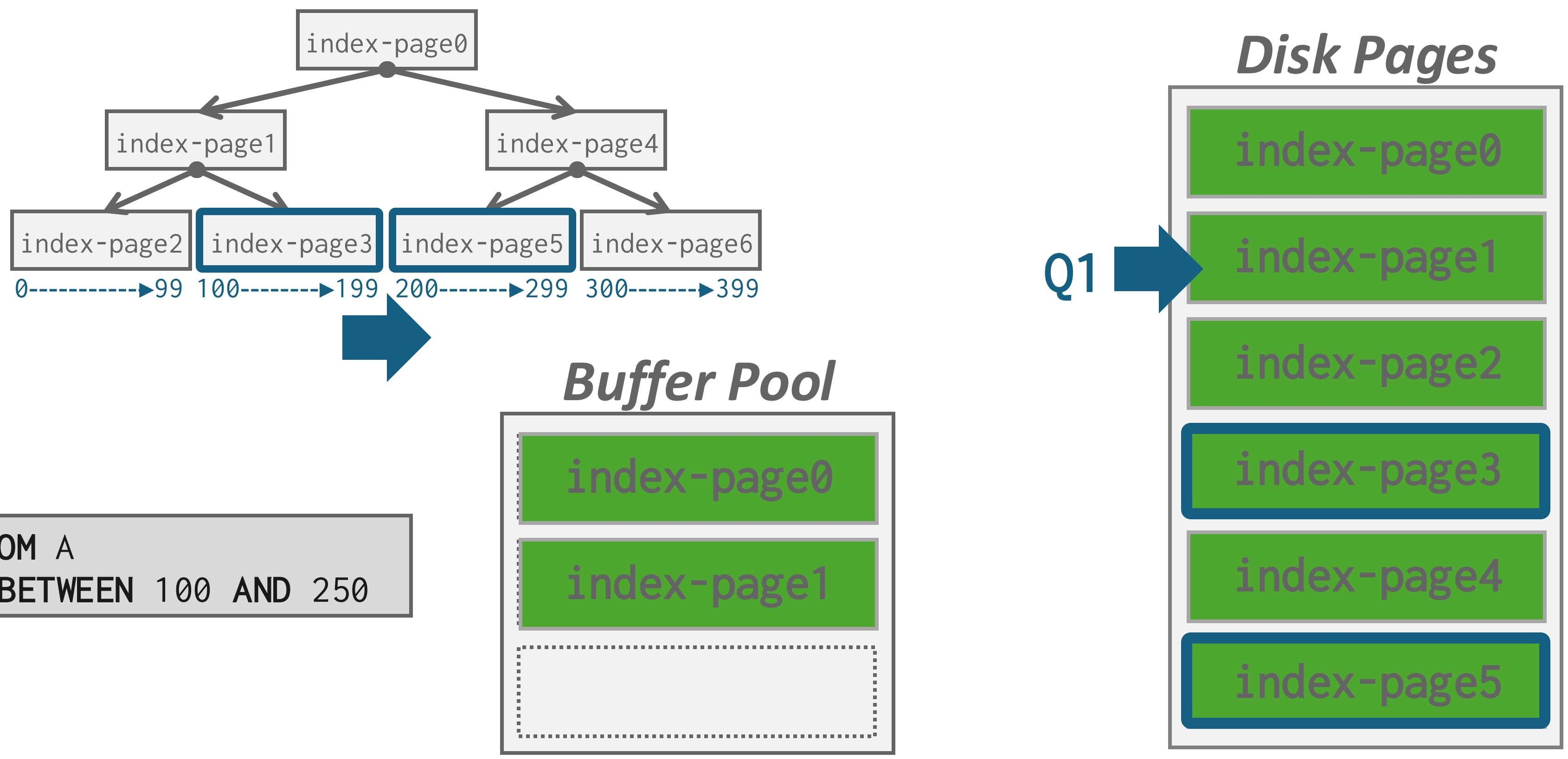

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Scan Sharing

- 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 DB2, MSSQL, Teradata, and Postgres.
  - Oracle only supports cursor sharing for identical queries.

TERADATA Microsoft SQL Server IBM DB2 ORACLE PostgreSQL

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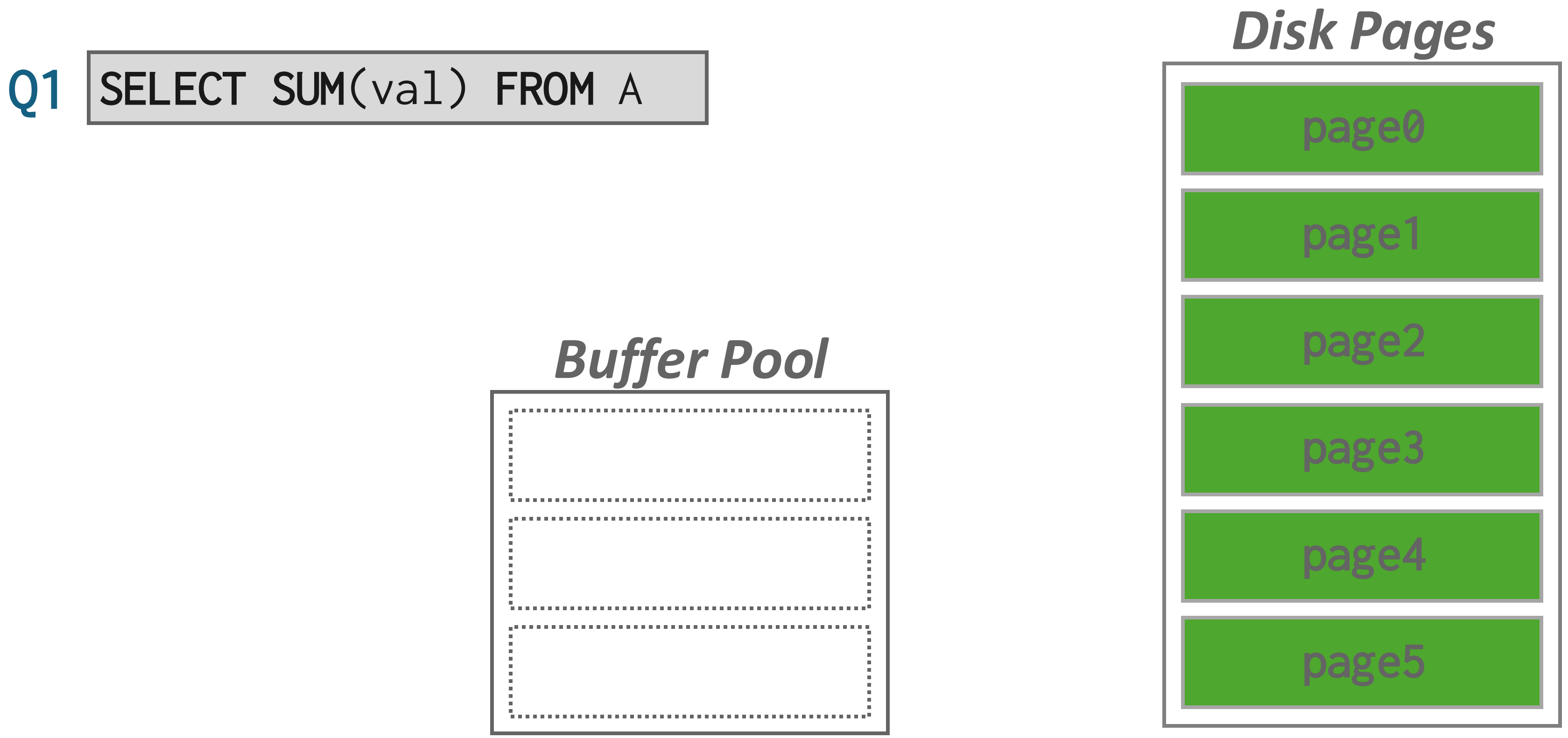
For a textual match to occur, the text of the SQL statements or PL/SQL blocks must be character-for-character identical, including spaces, case, and comments. For example, the following statements cannot use the same shared SQL area:

```
SELECT * FROM employees;
SELECT * FROM Employees;
SELECT *  FROM employees;
```

Scan Sharing



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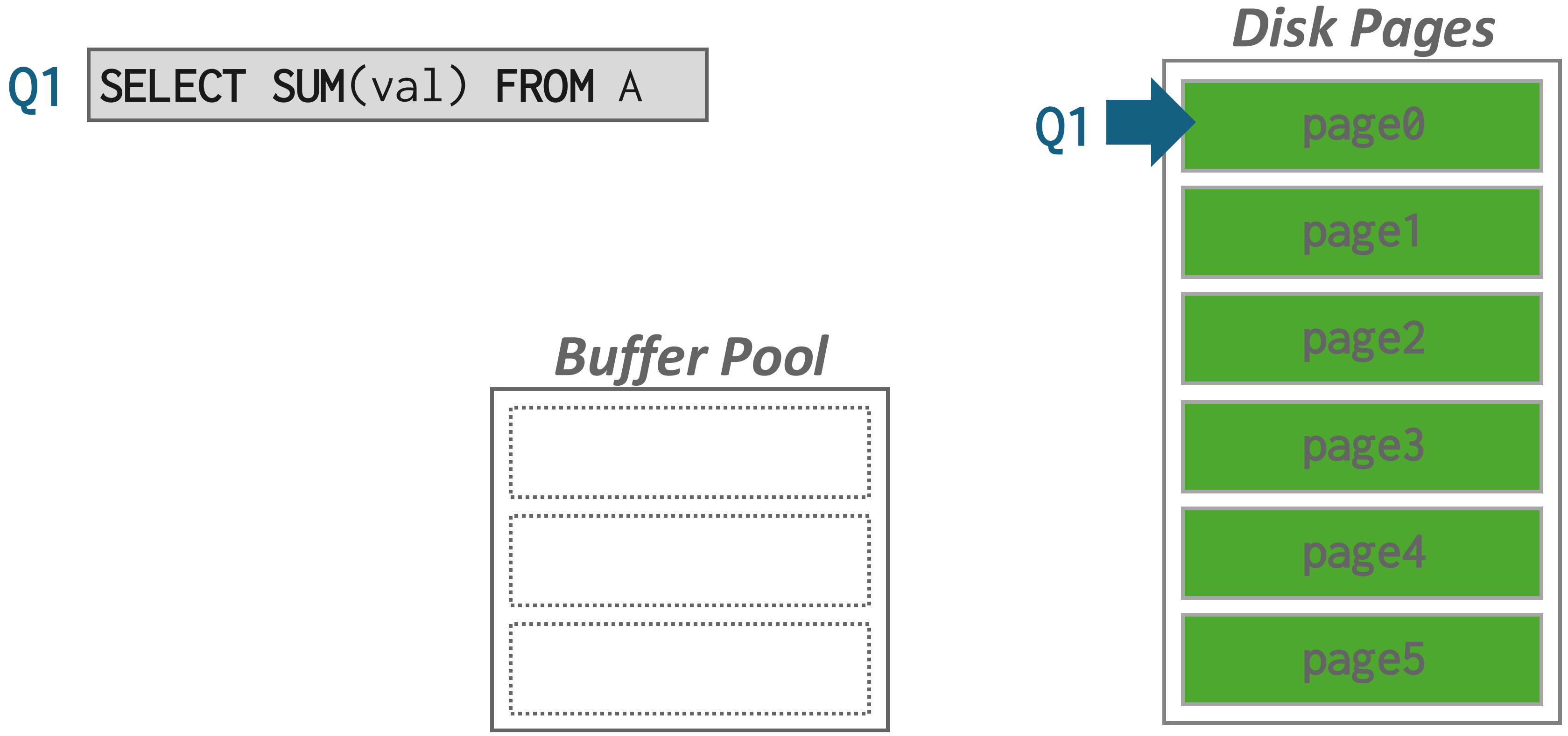

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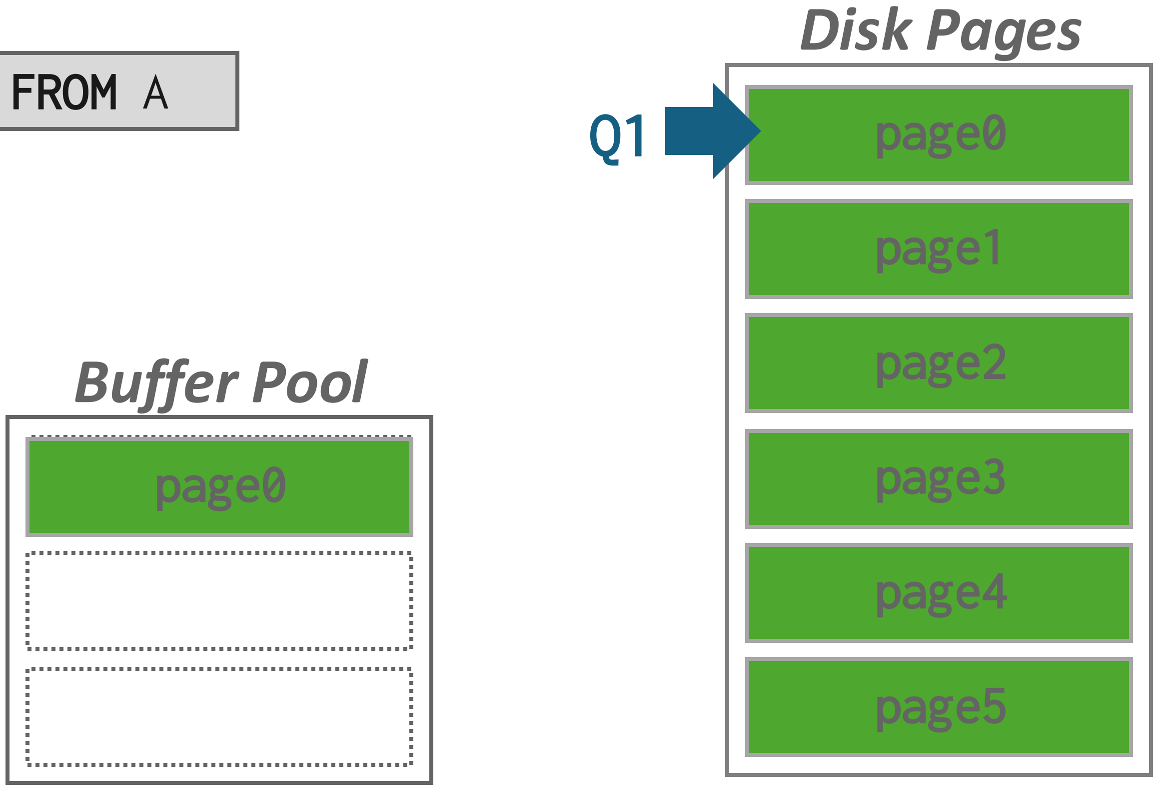

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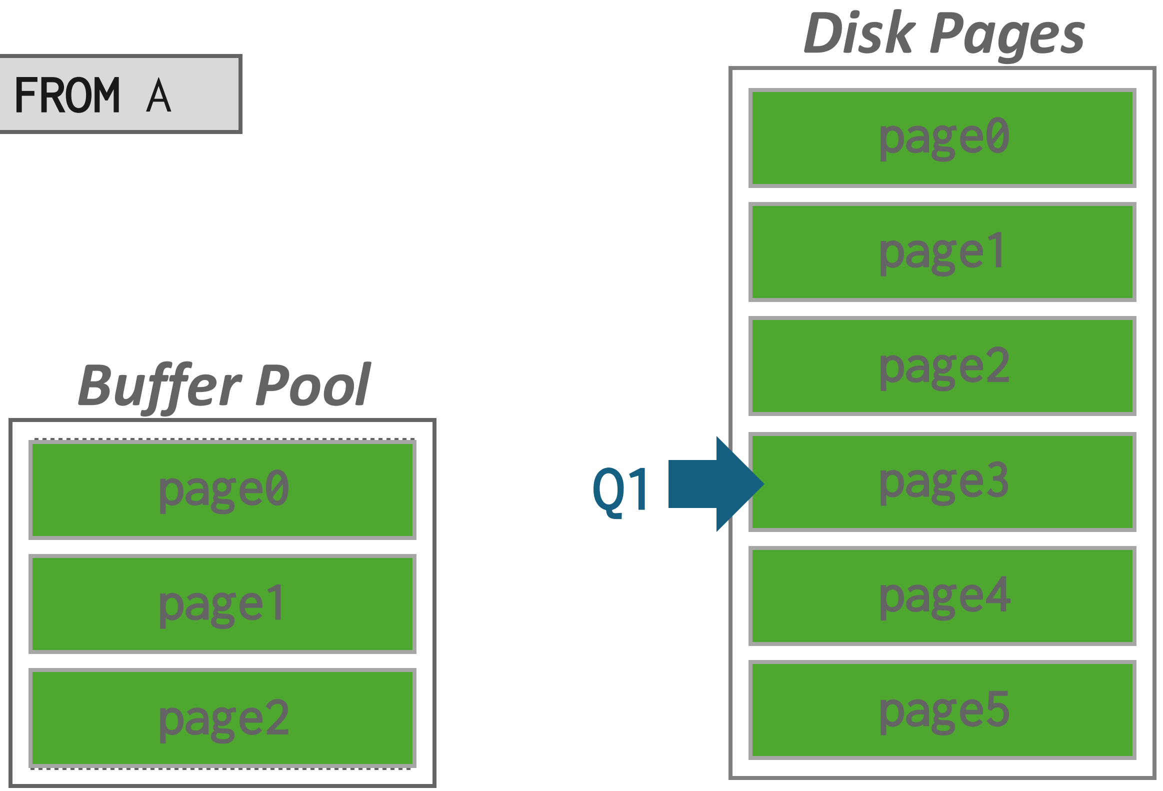

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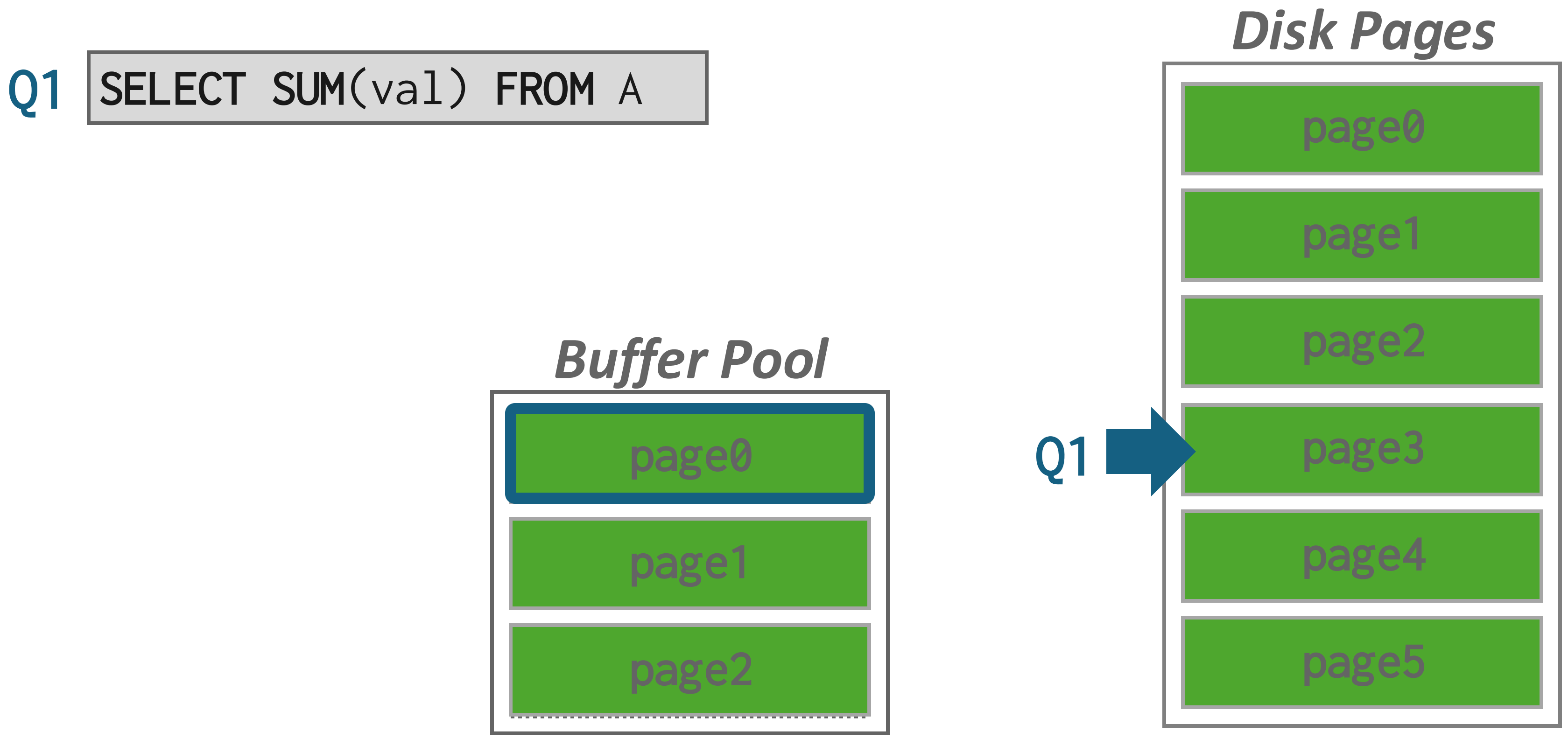

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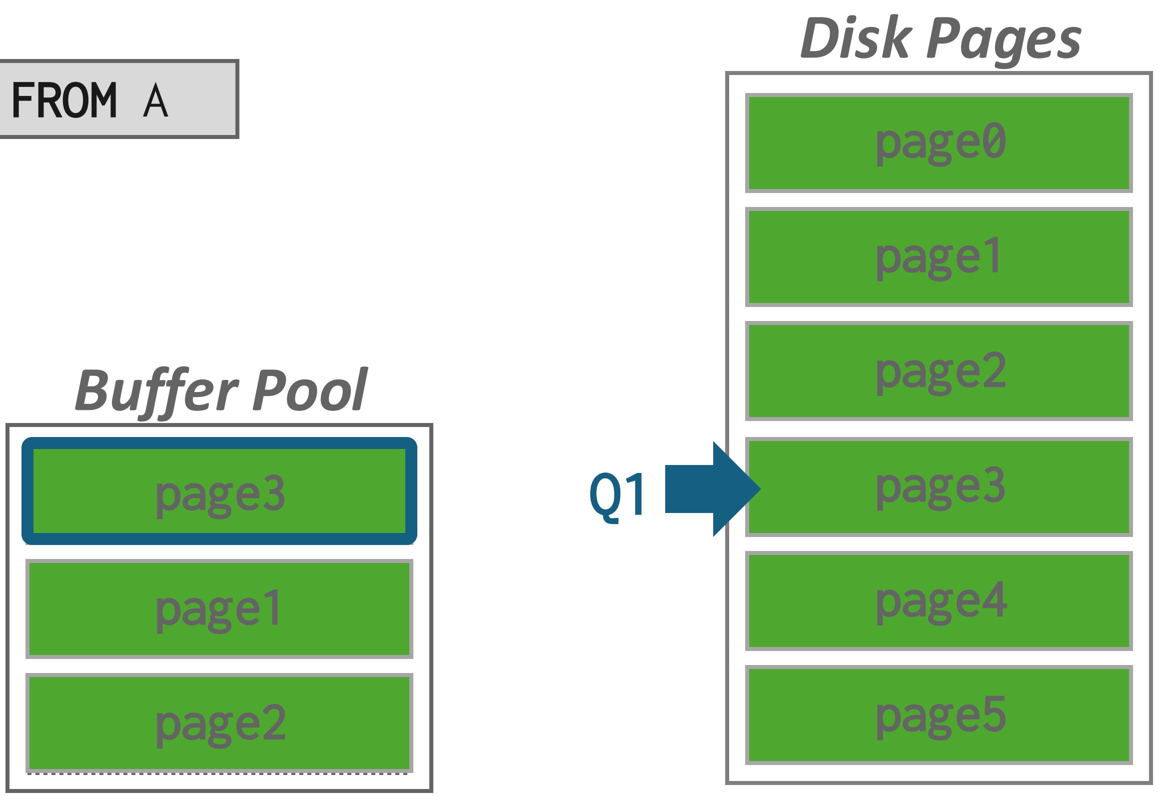

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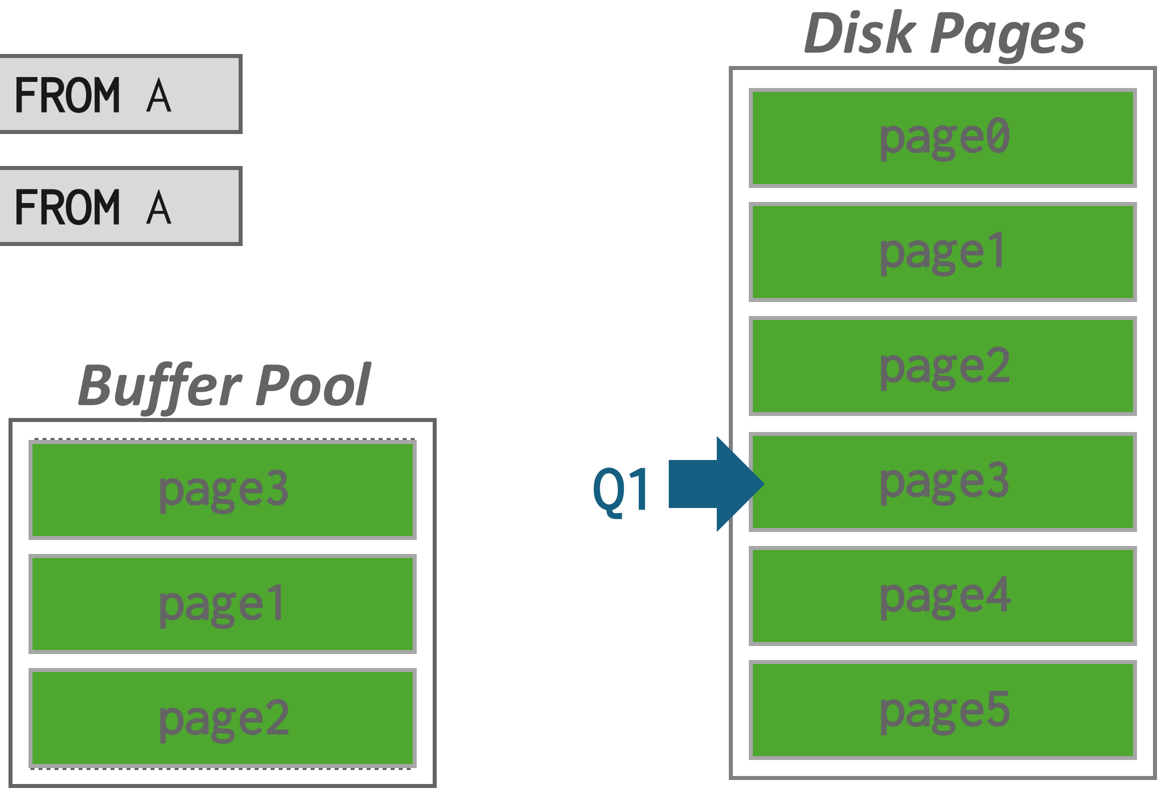

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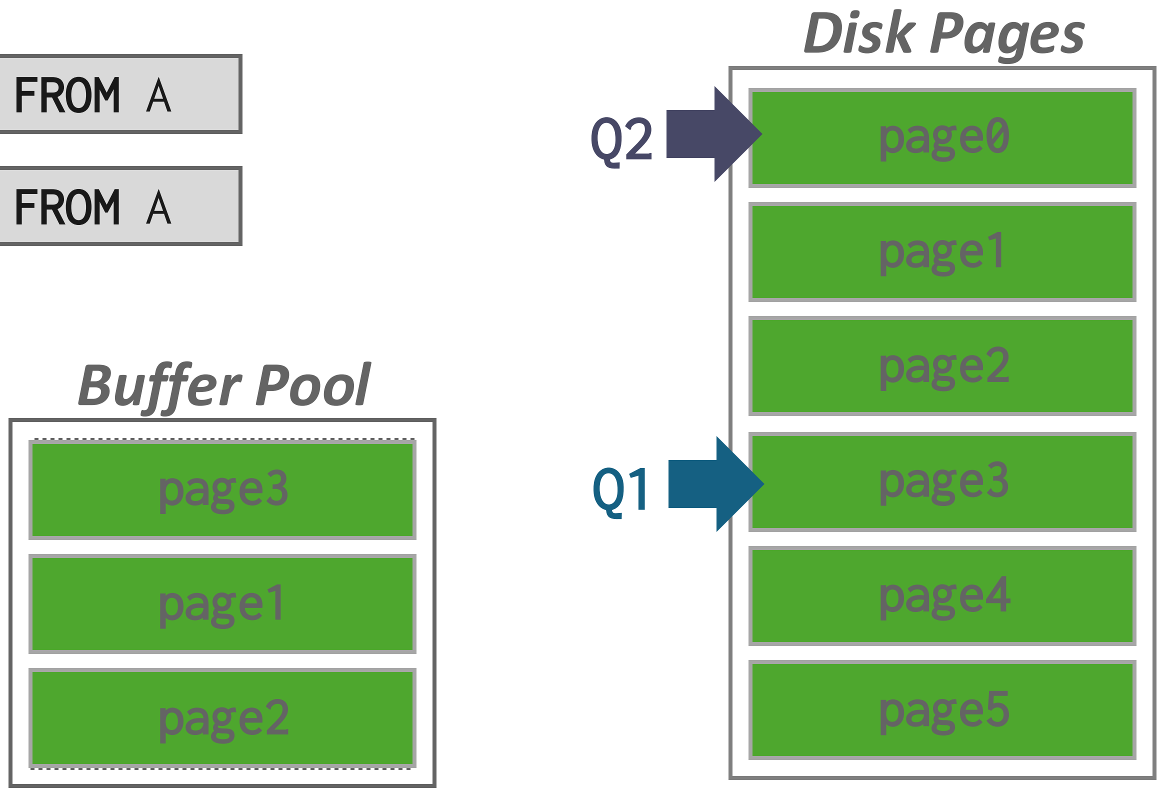

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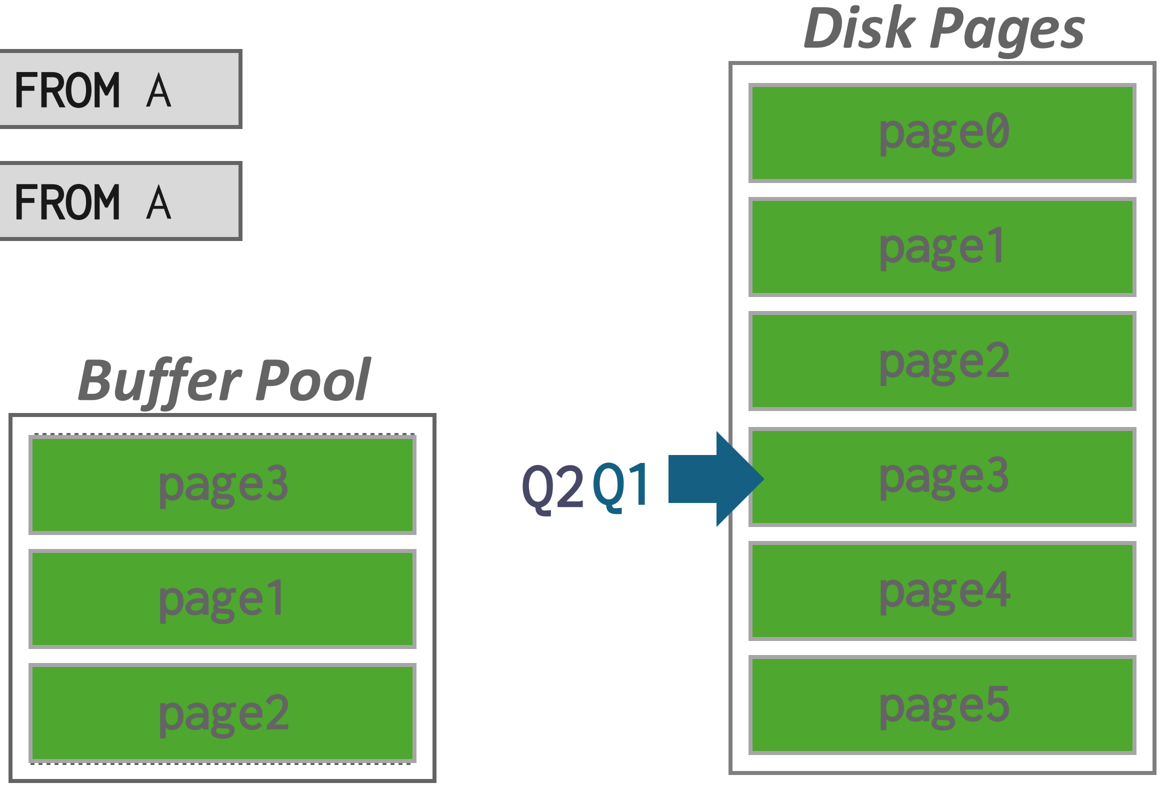

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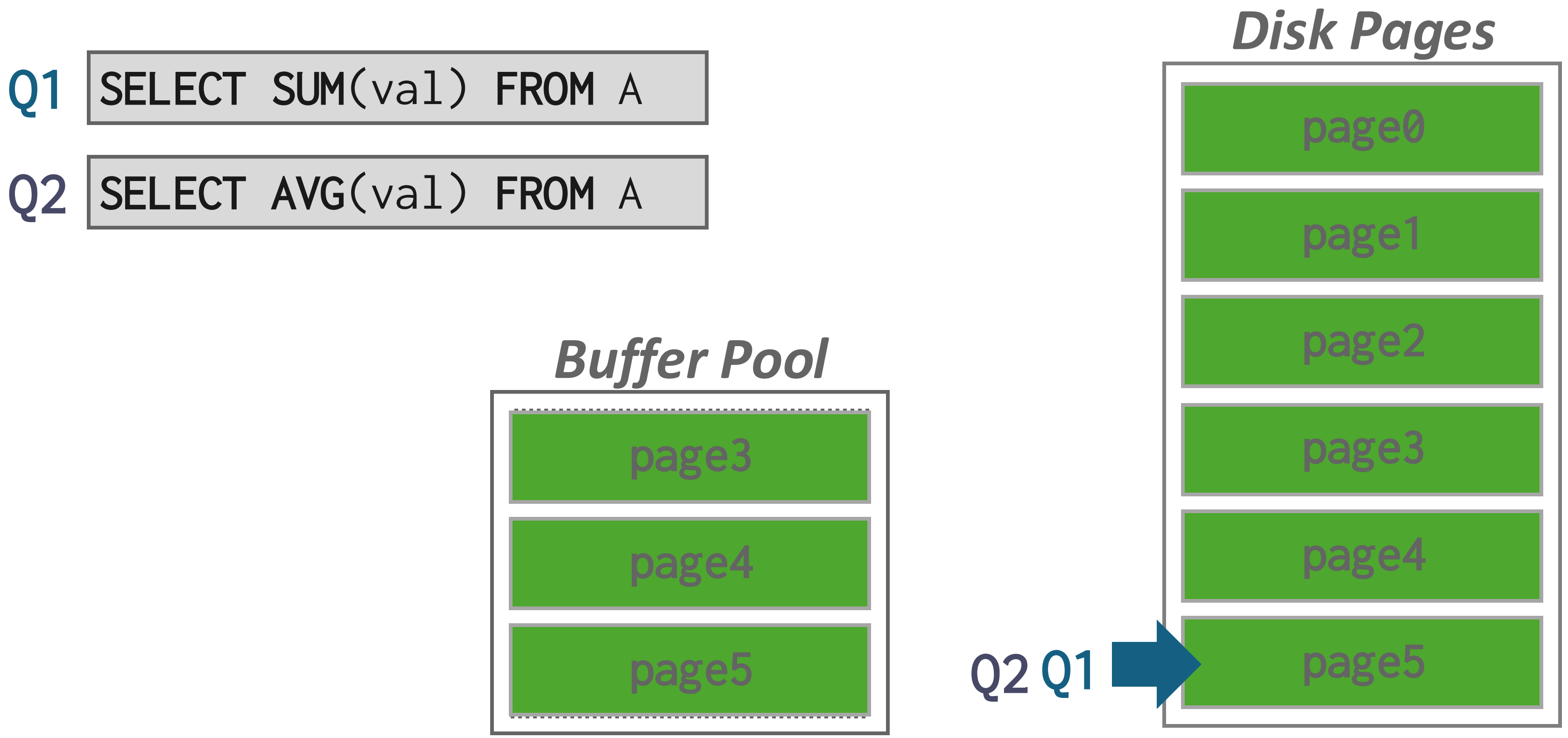

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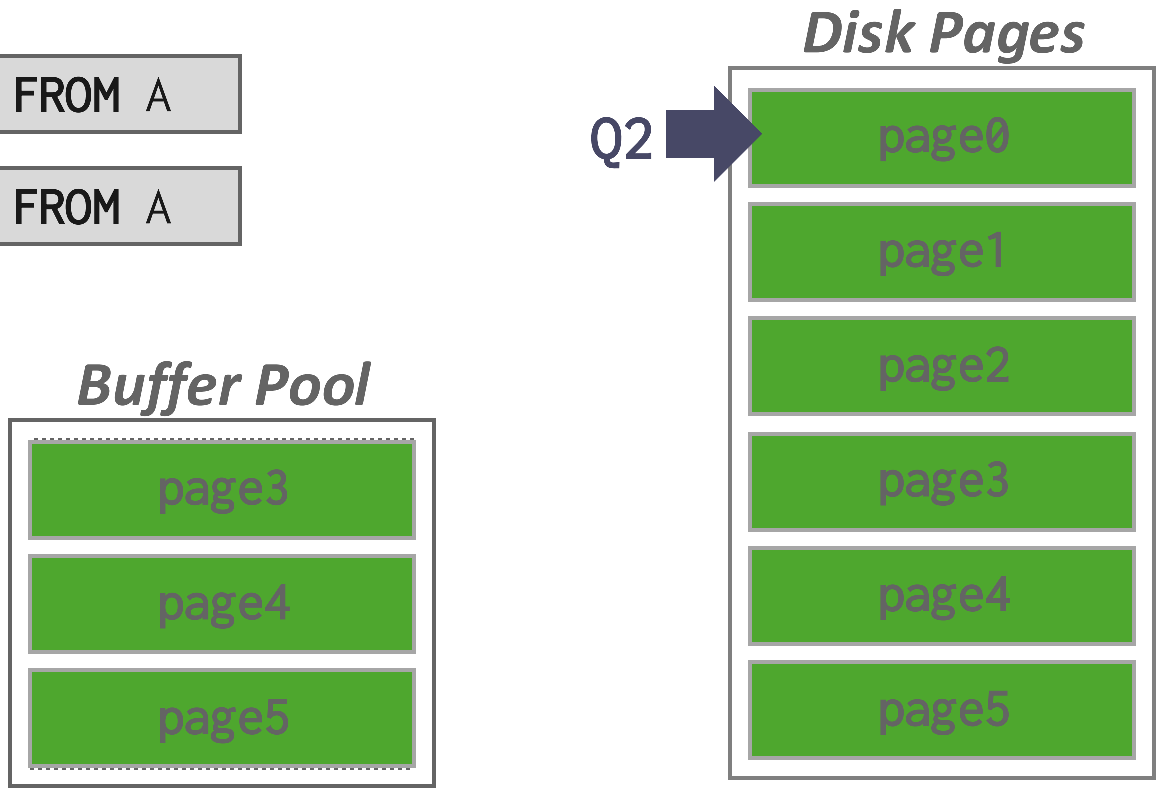

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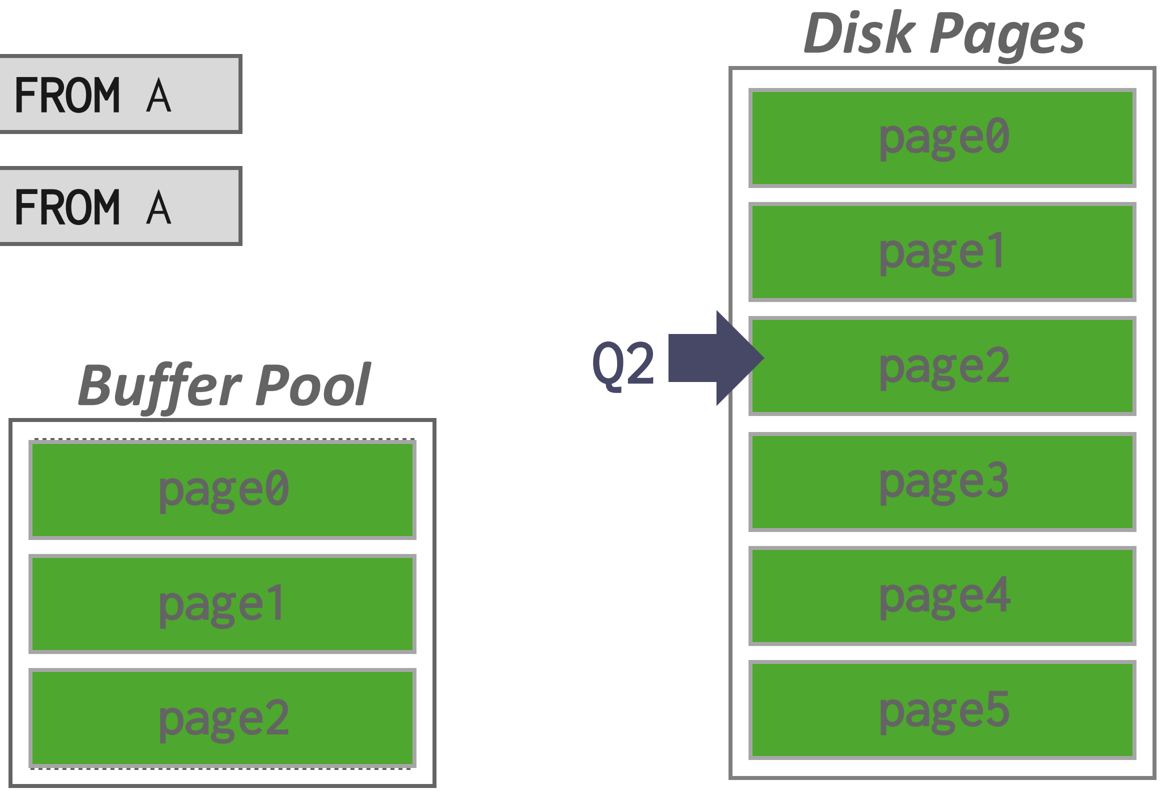

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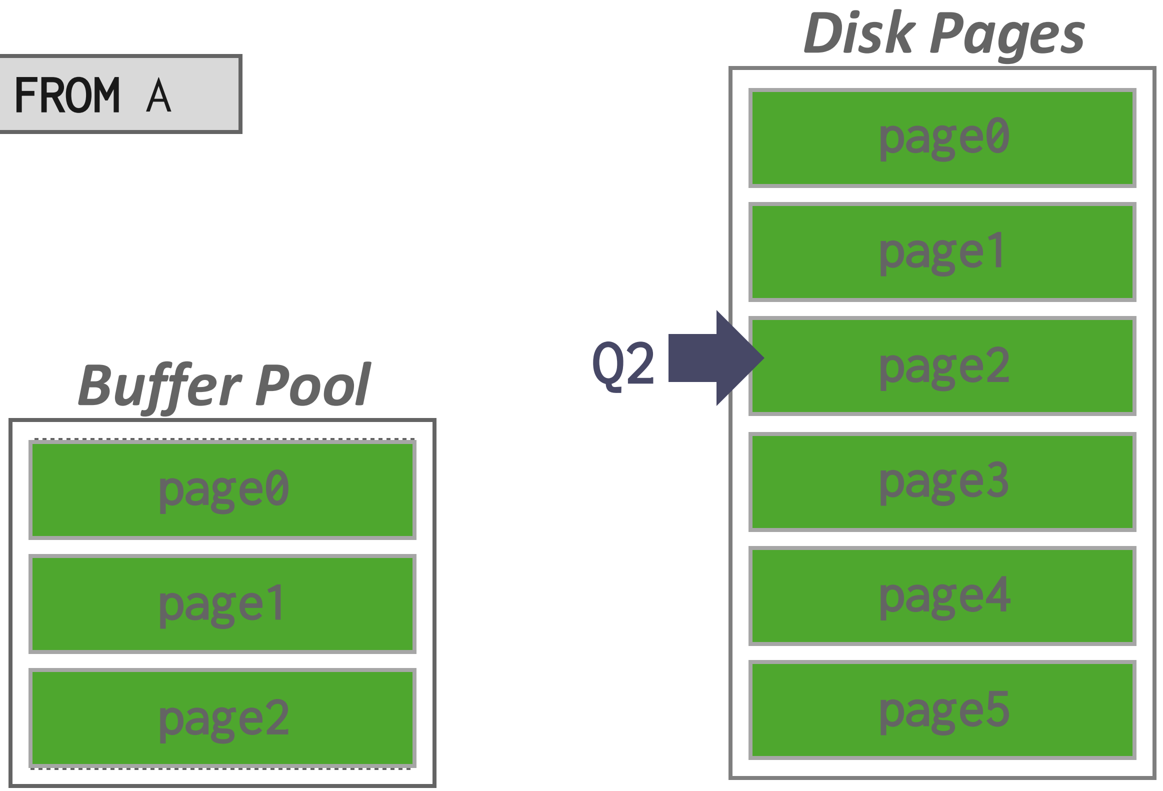

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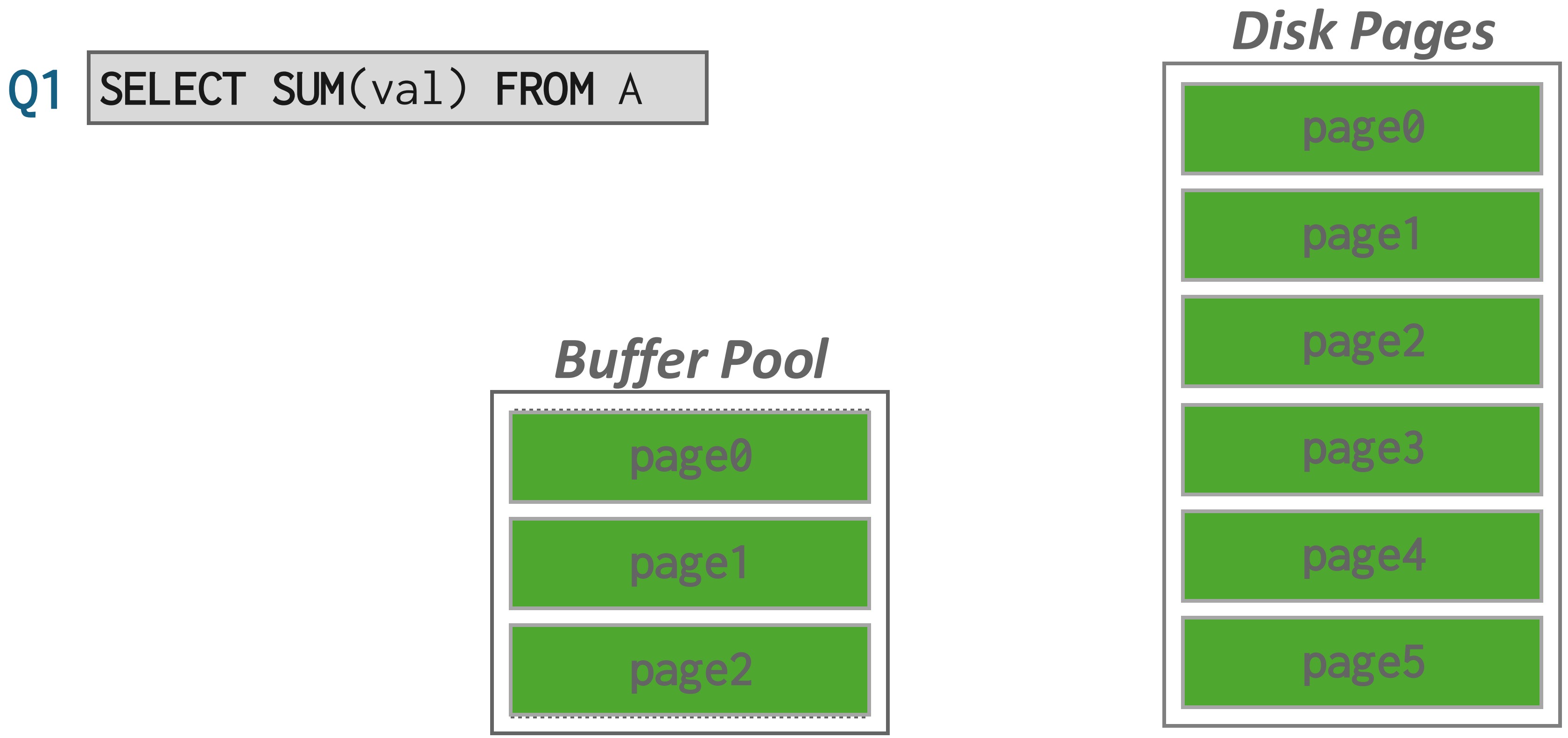
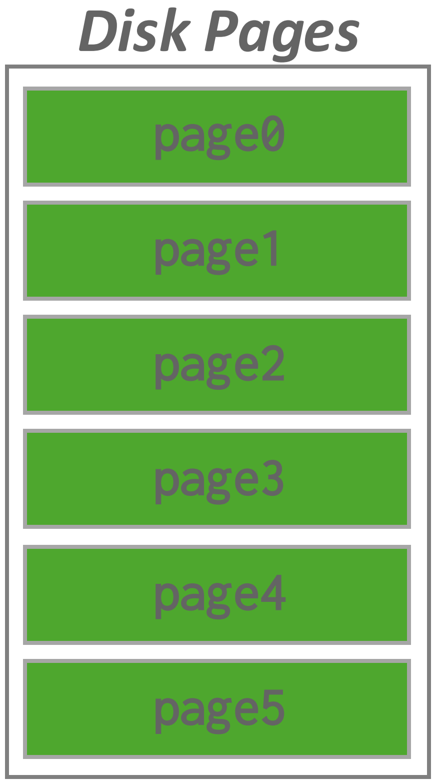


Continuous Scan Sharing

- Instead of trying to be clever, the DBMS continuously scans the database files repeatedly.
    - One continuous cursor per table.
    - Queries "hop" on board the cursor while it is running and then disconnect once they have enough data.
- Not viable if you pay per IOP.
  Only done in academic prototypes.



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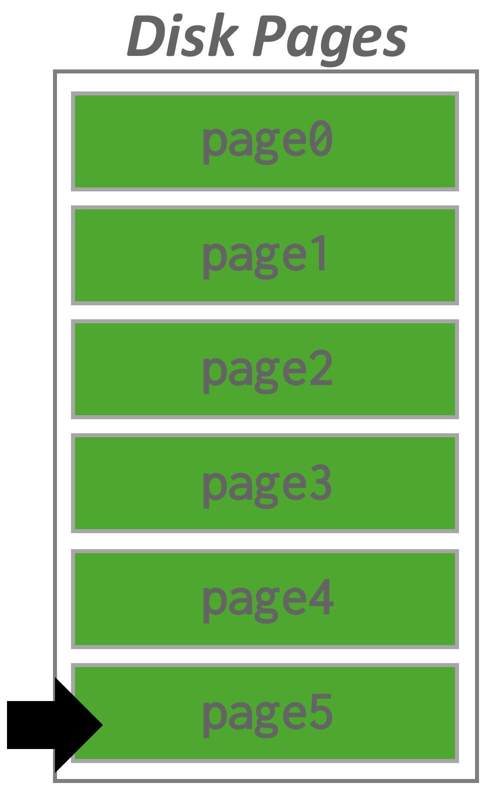

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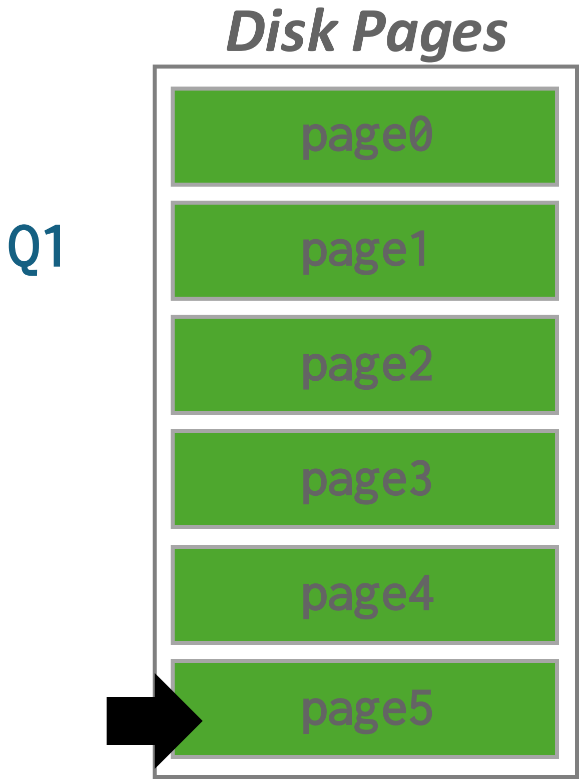

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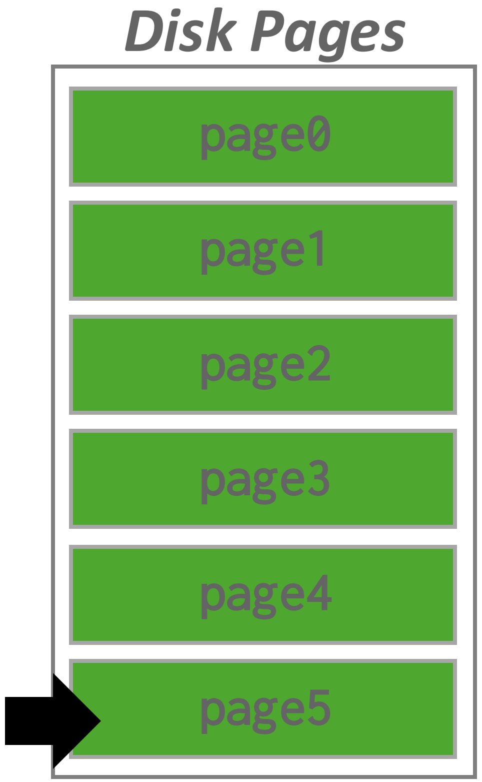


Buffer Pool Bypass

- 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.

ORACLE® Microsoft® SQL Server® PostgreSQL Informix®

Buffer Replacement Policies

Buffer Replacement Policies

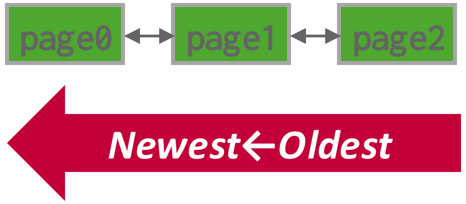
- When the DBMS needs to free up a frame to make room for a new page, it must decide which page to <u>evict</u> from the buffer pool.

- Goals:
  - Correctness
  - Accuracy
  - Speed
  - Metadata overhead

Least-Recently Used

- Maintain a single 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.

LRU List



Disk Pages

Least-Recently Used

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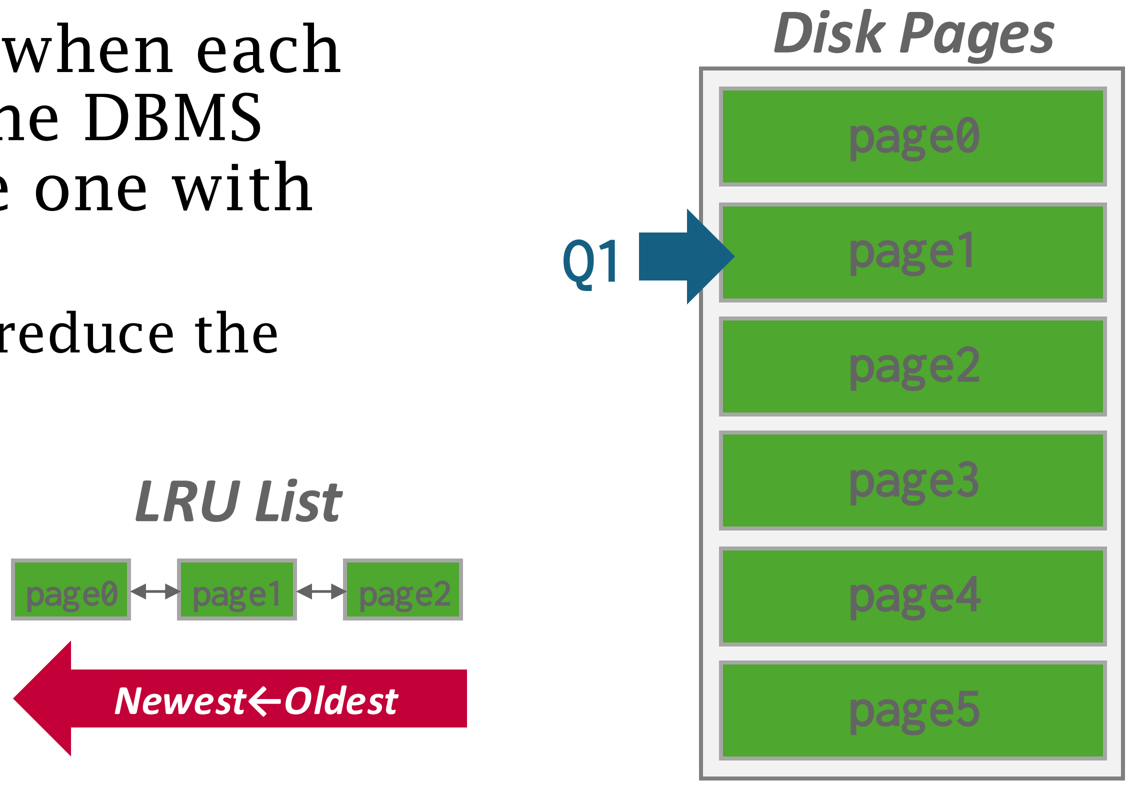

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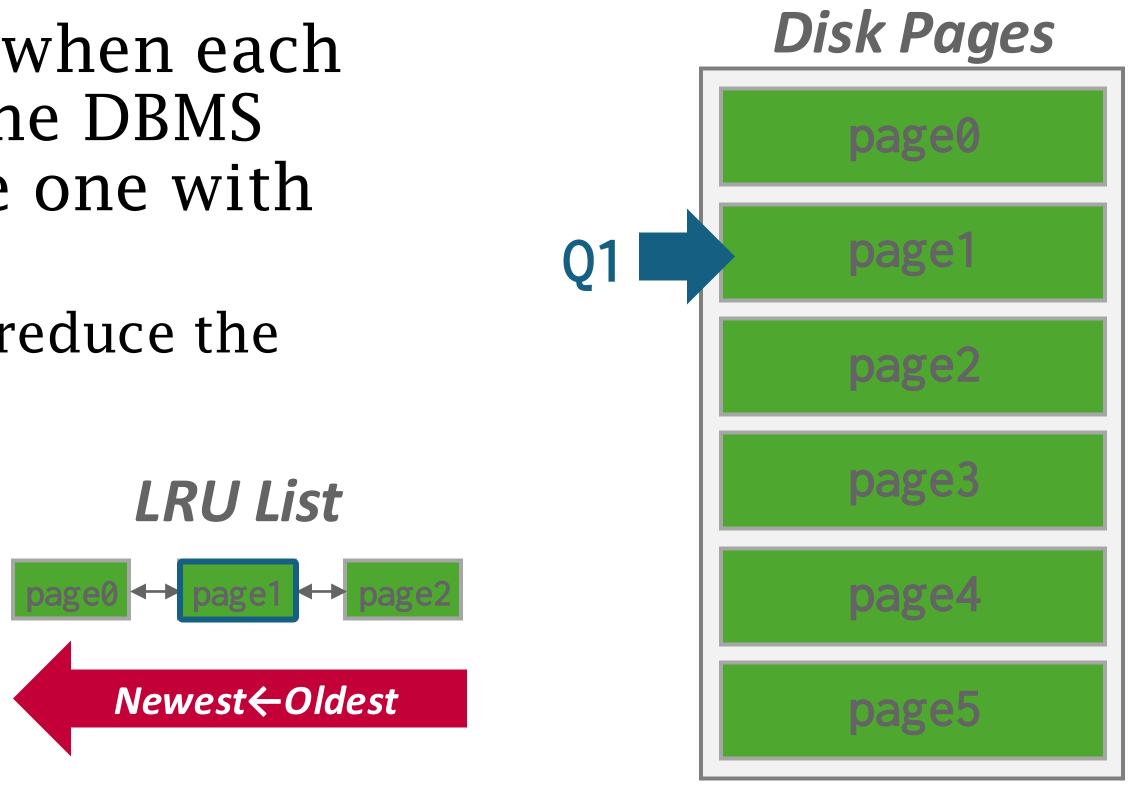

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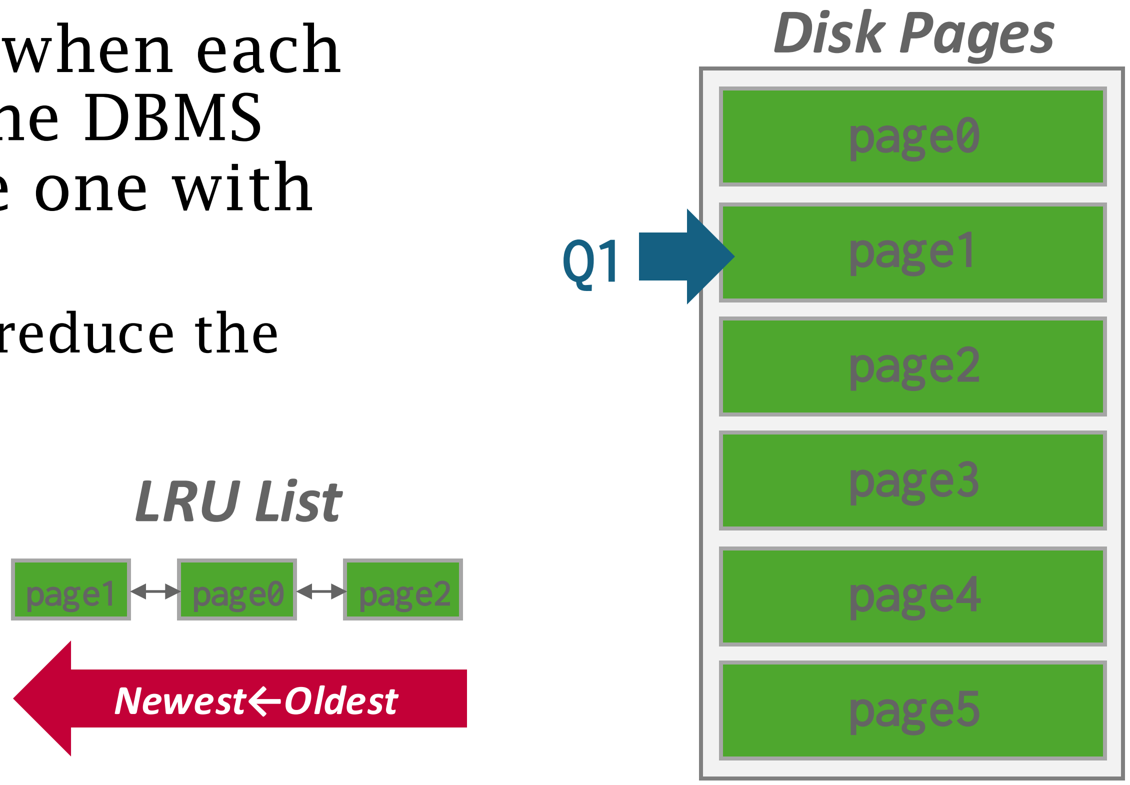

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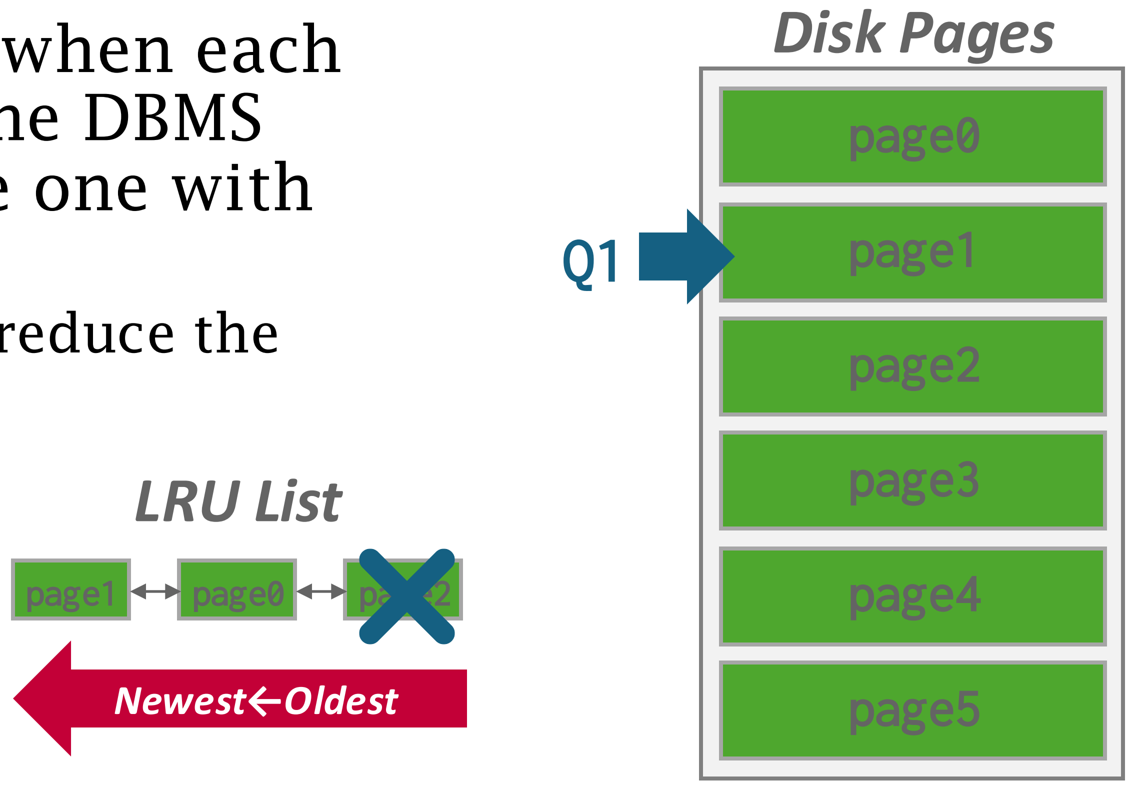

Clock

- 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.
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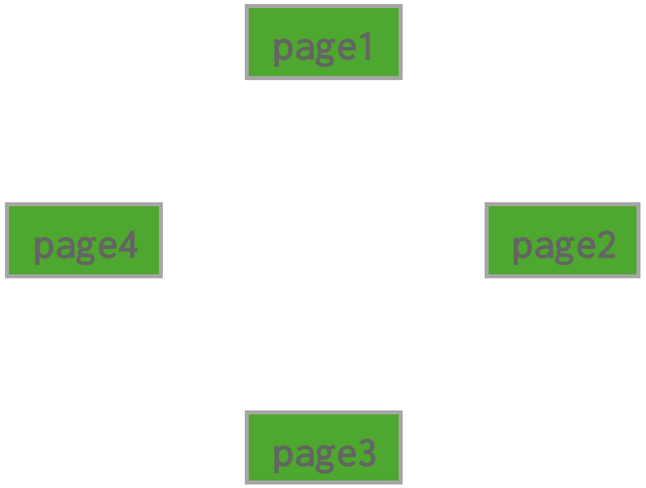

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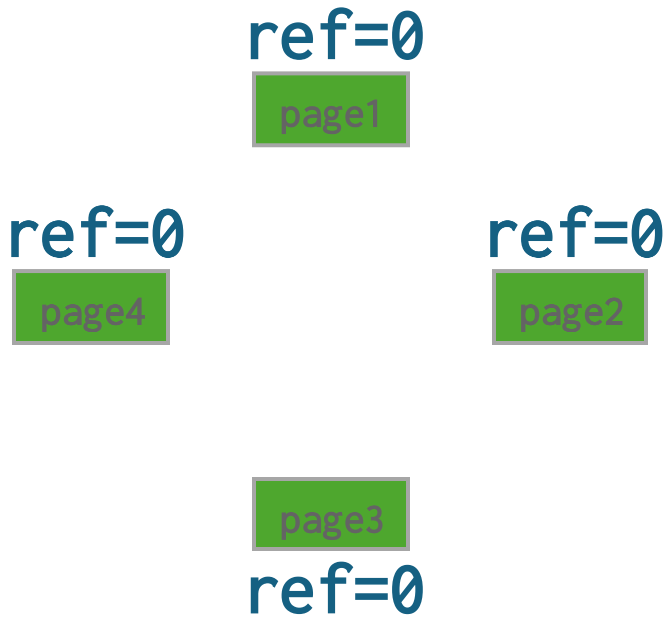

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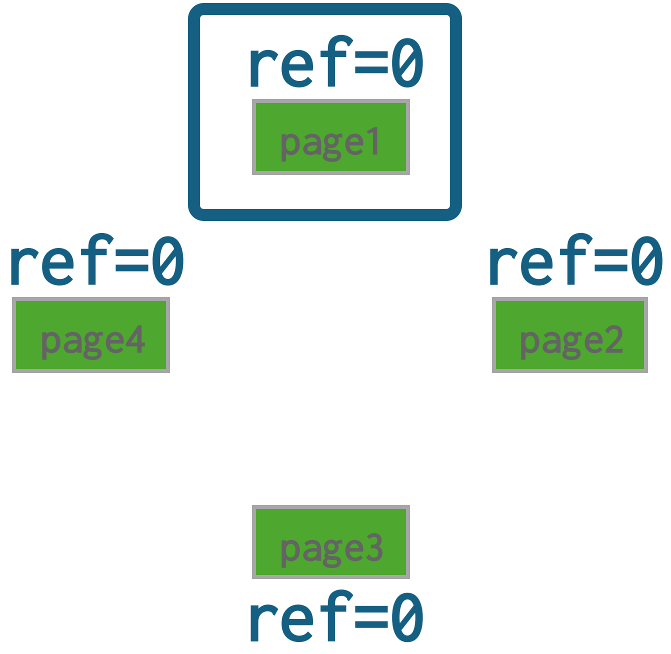

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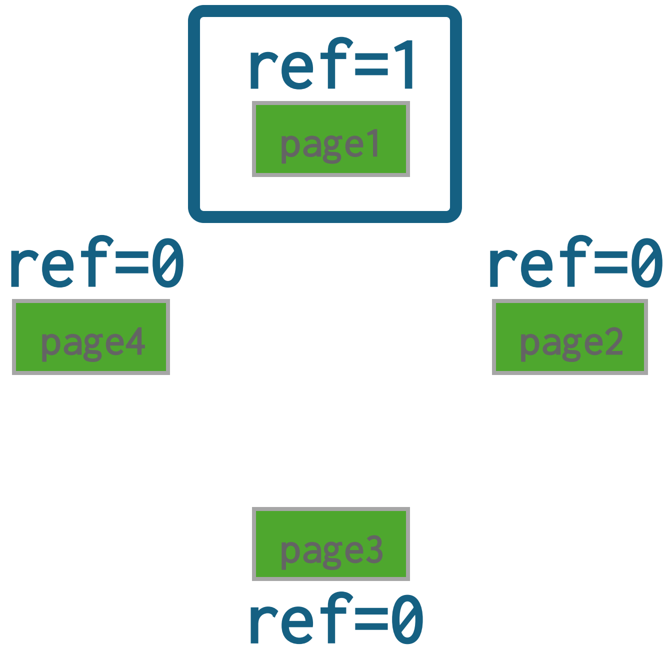

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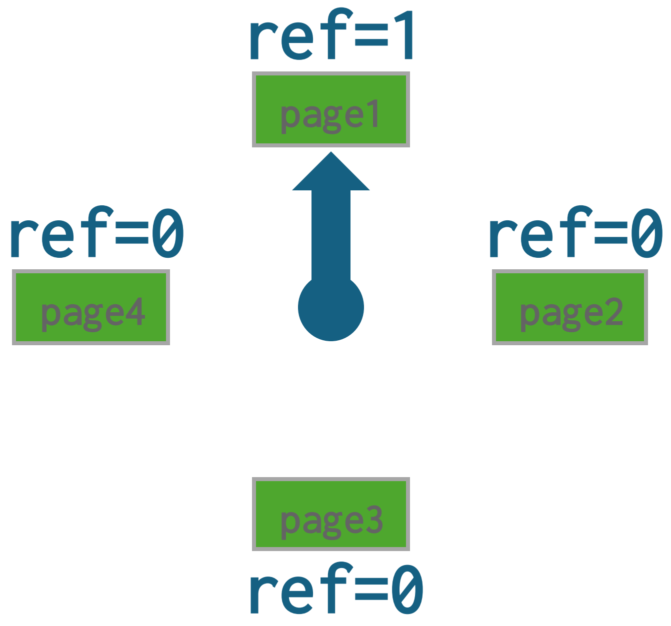

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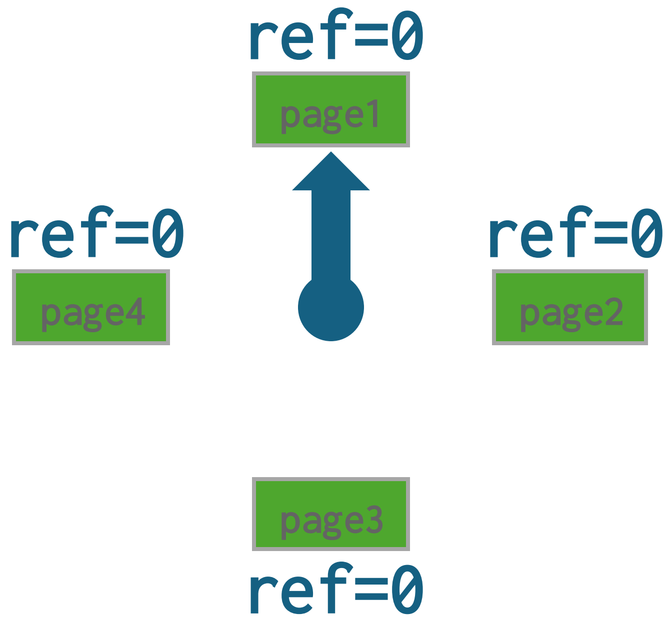

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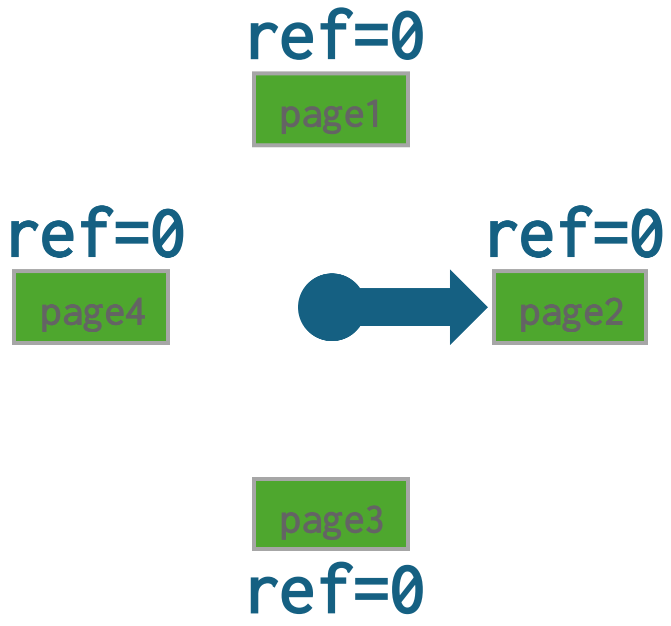

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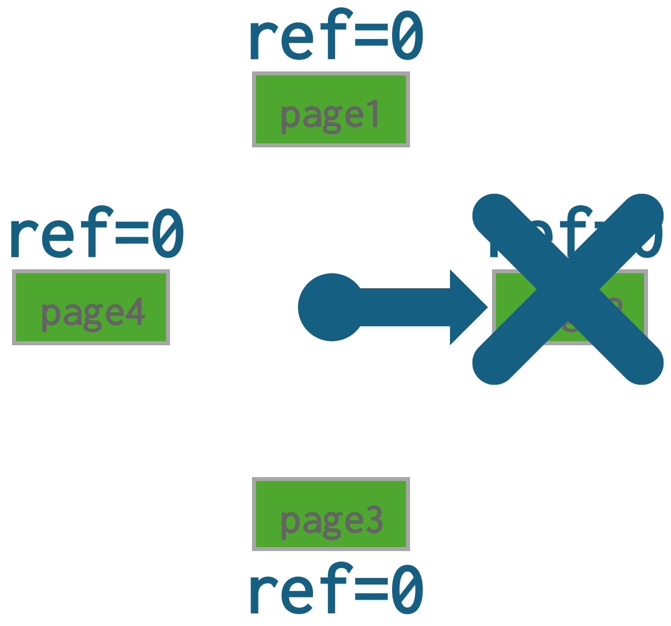

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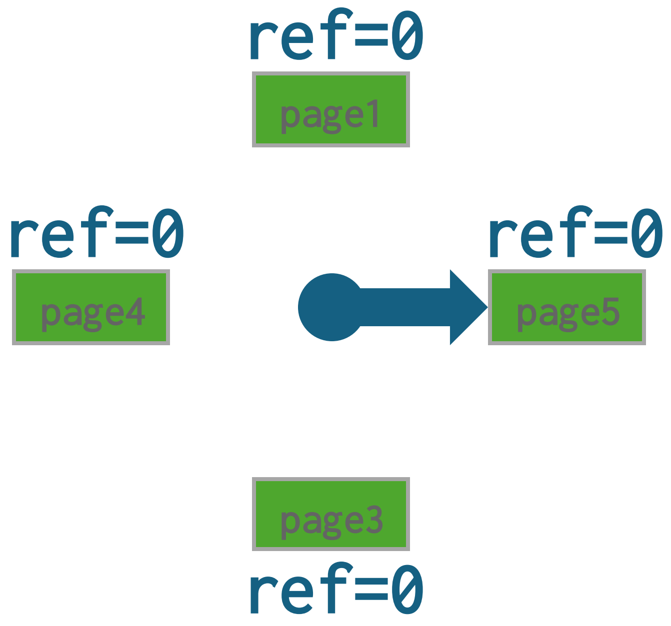

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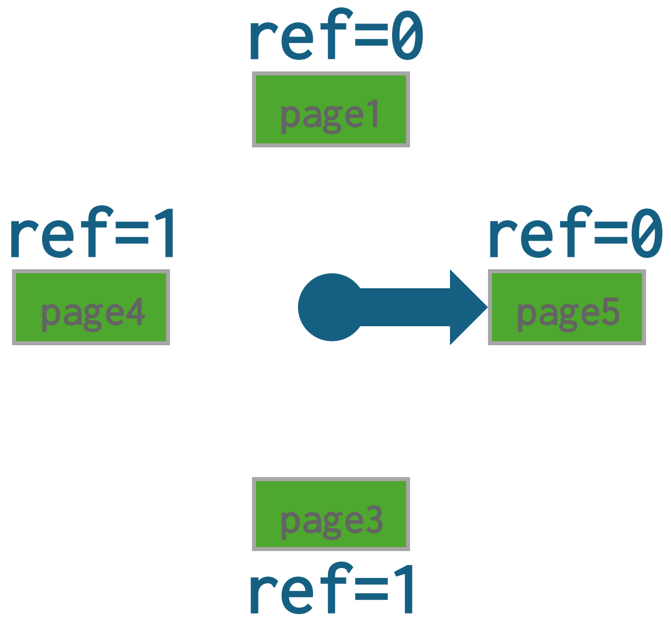

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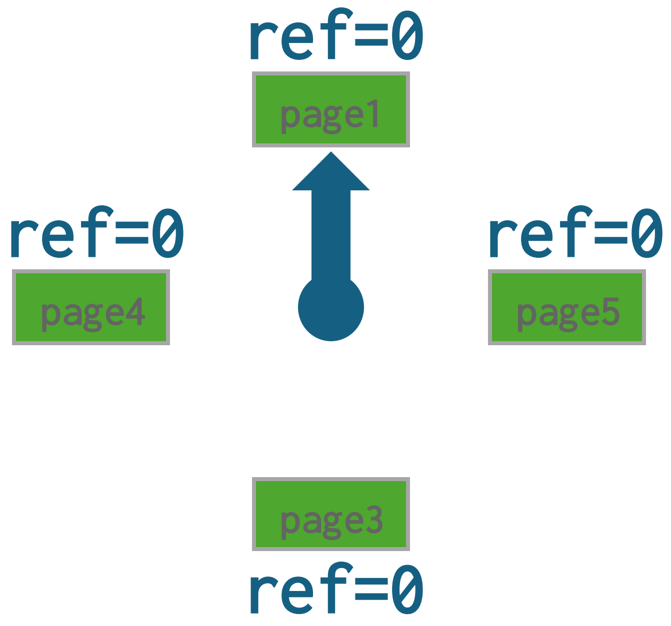

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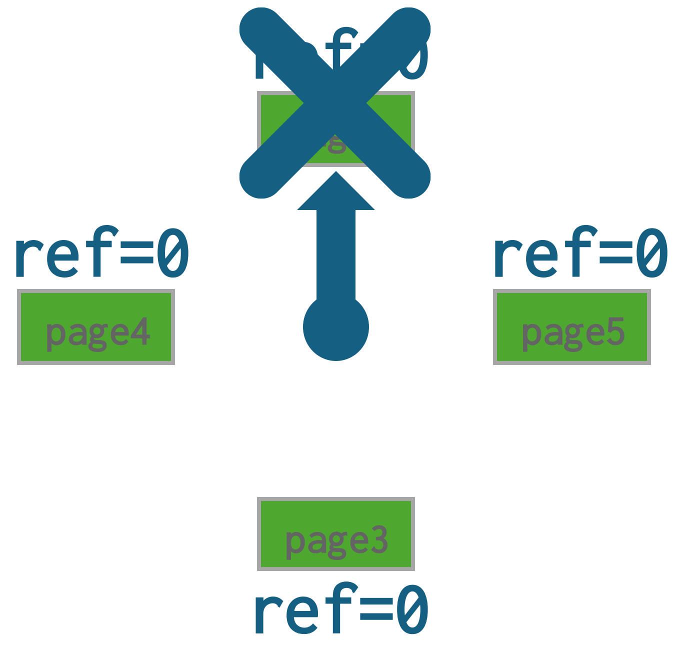

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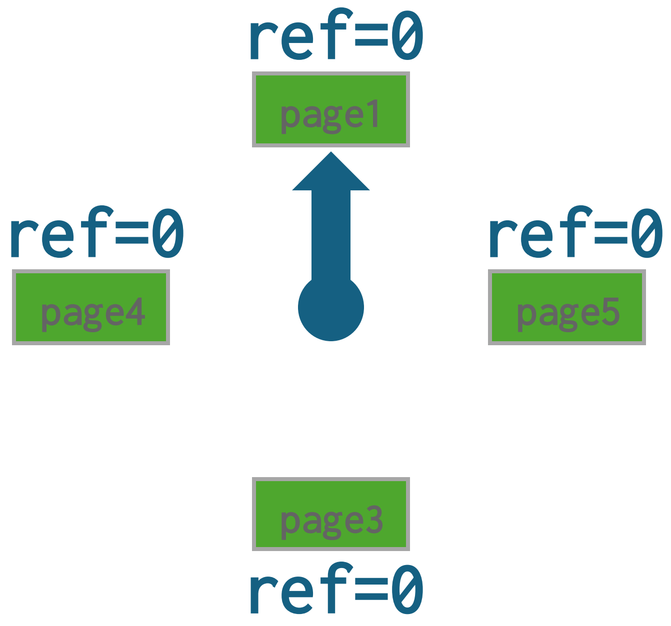


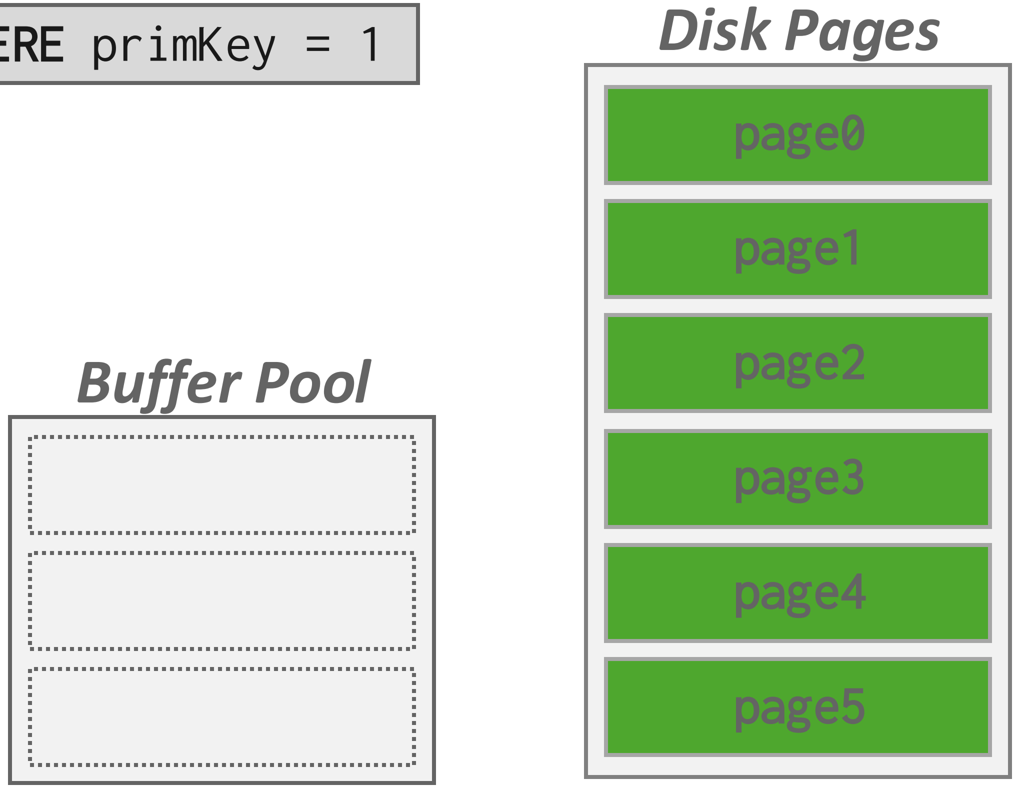
Observation

- LRU + 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.
  - In OLAP workloads, the ***most recently used*** page is often the best page to evict.

- LRU + CLOCK only tracks when a page was last accessed, but not how often a page is accessed.

Sequential Flooding

Q1
```
SELECT * FROM A WHERE primKey = 1
```



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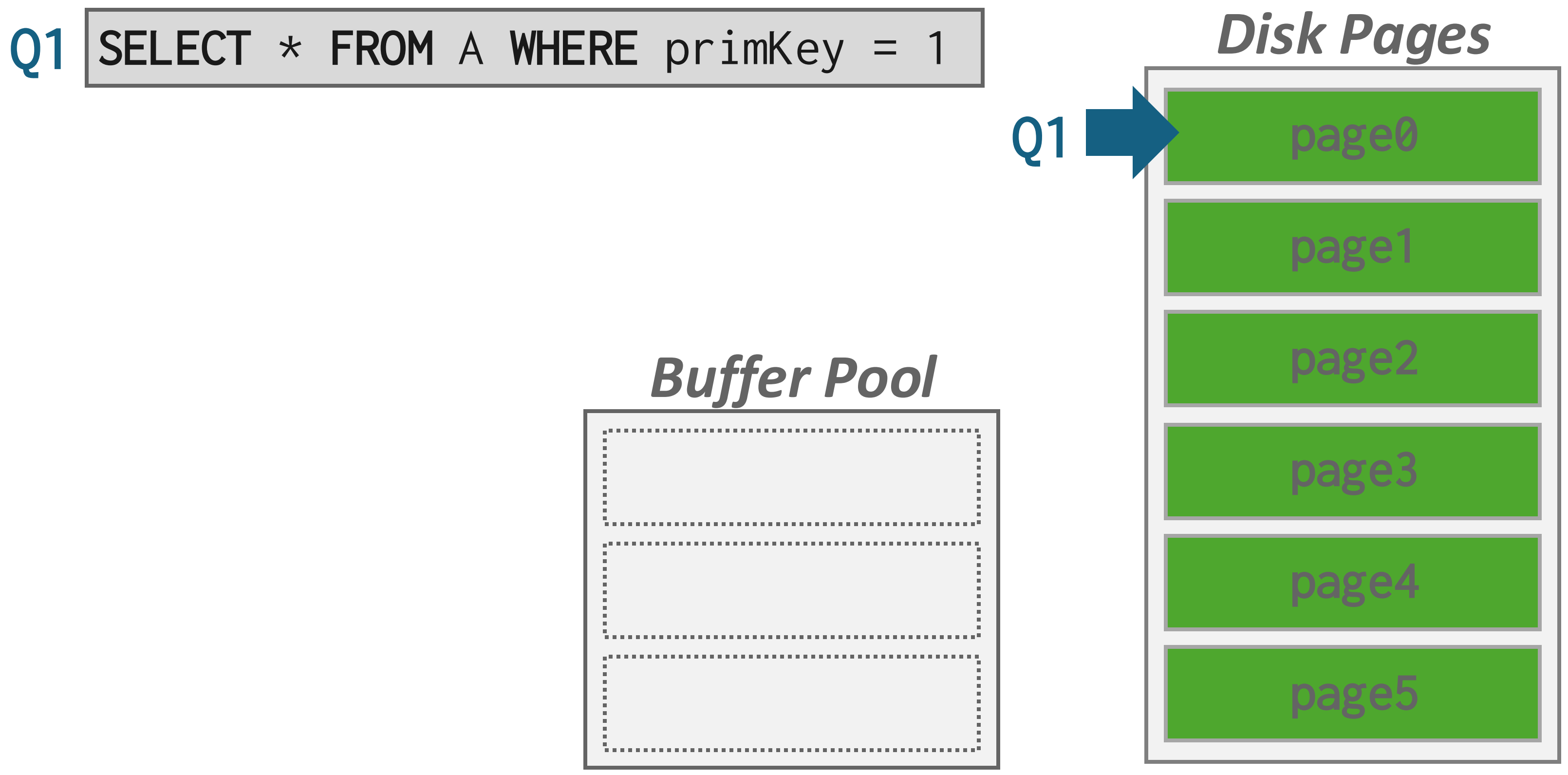

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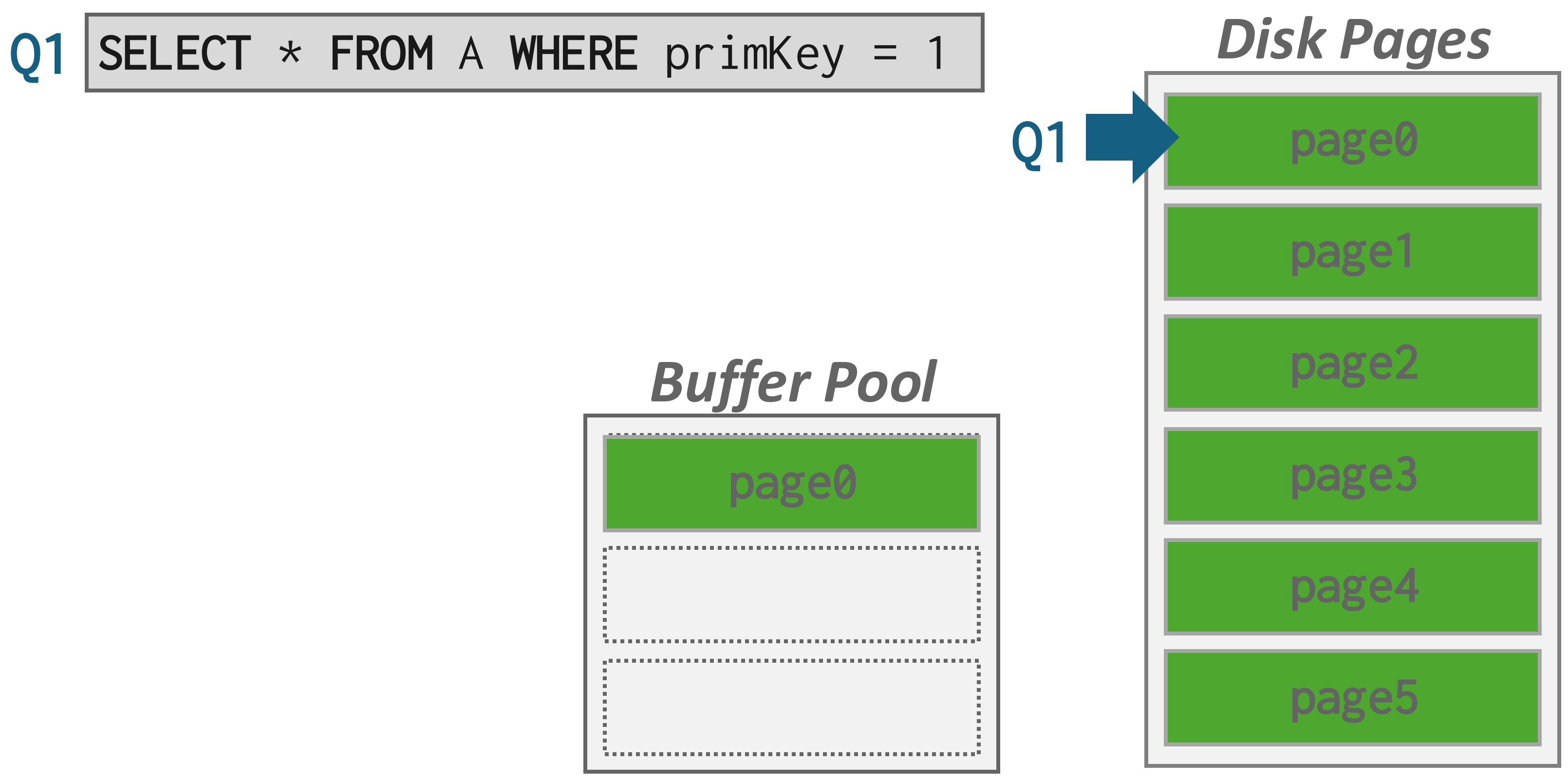

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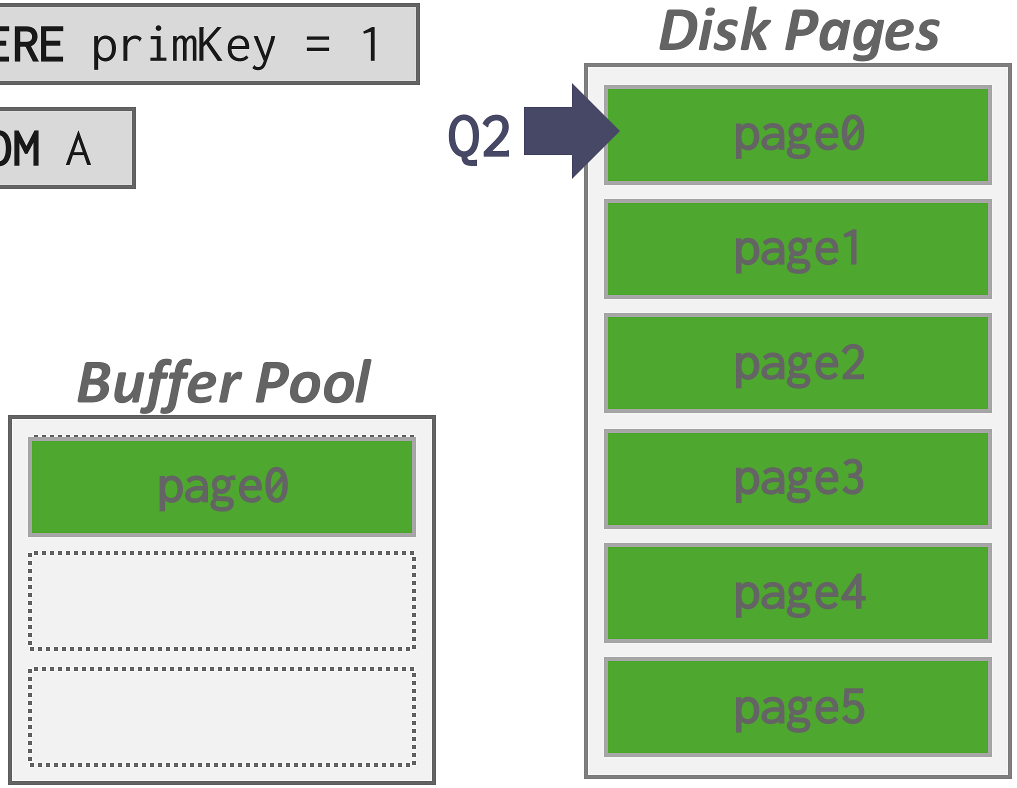

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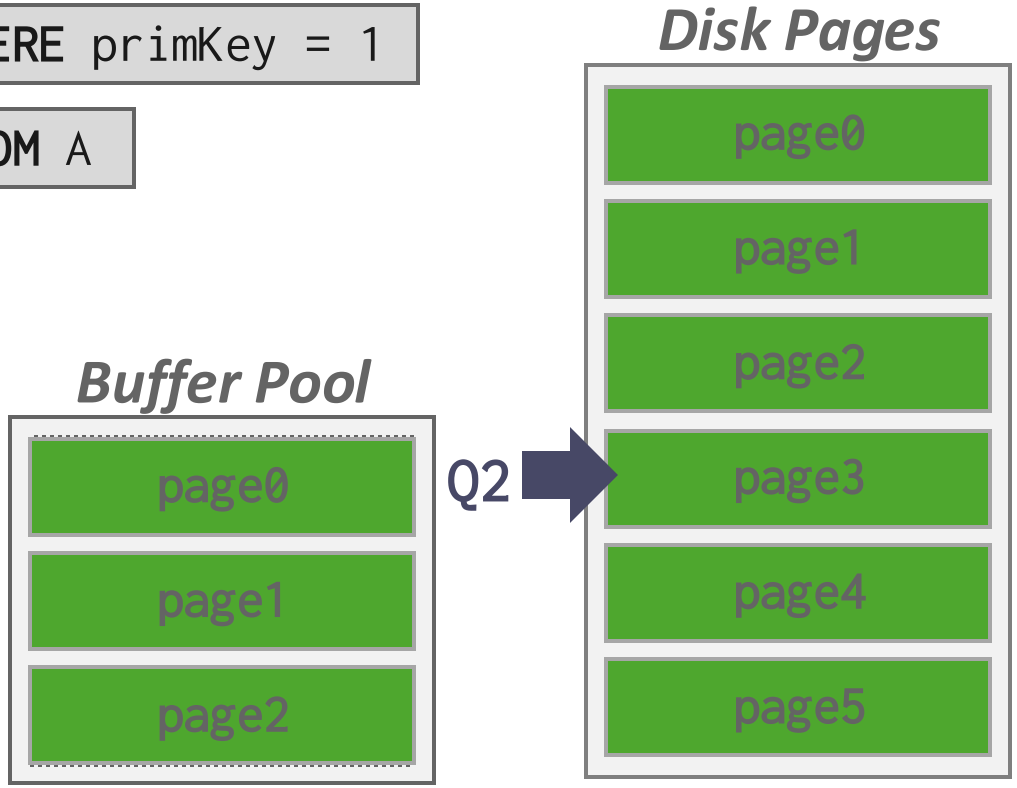

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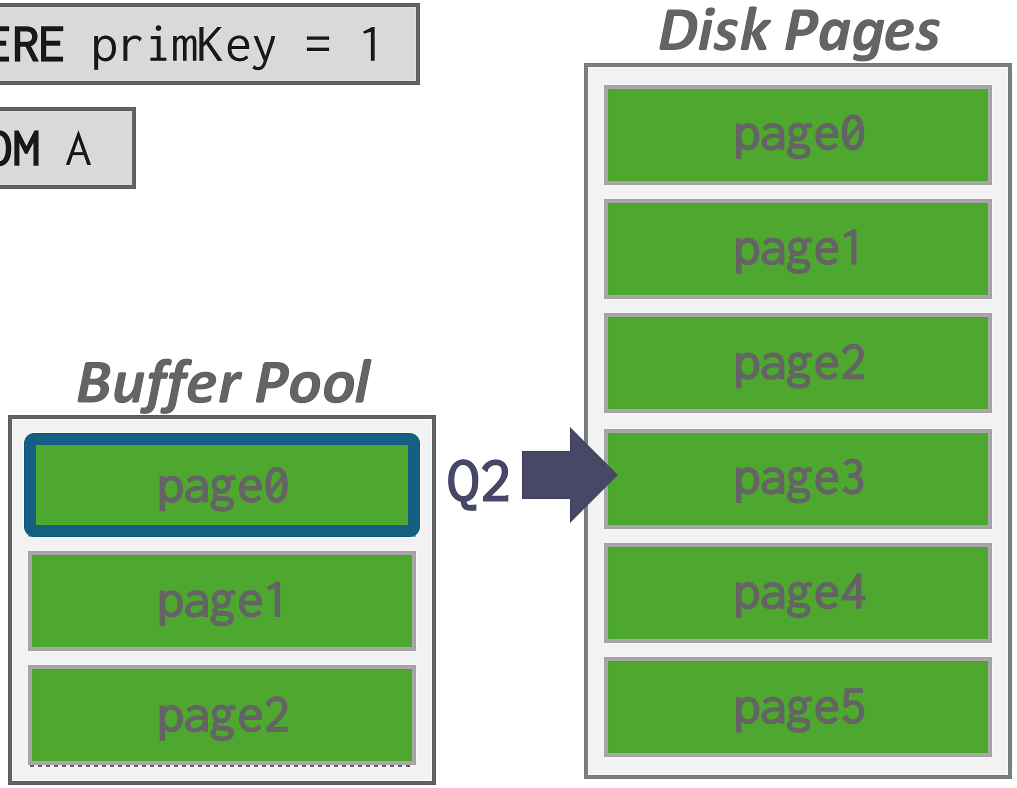

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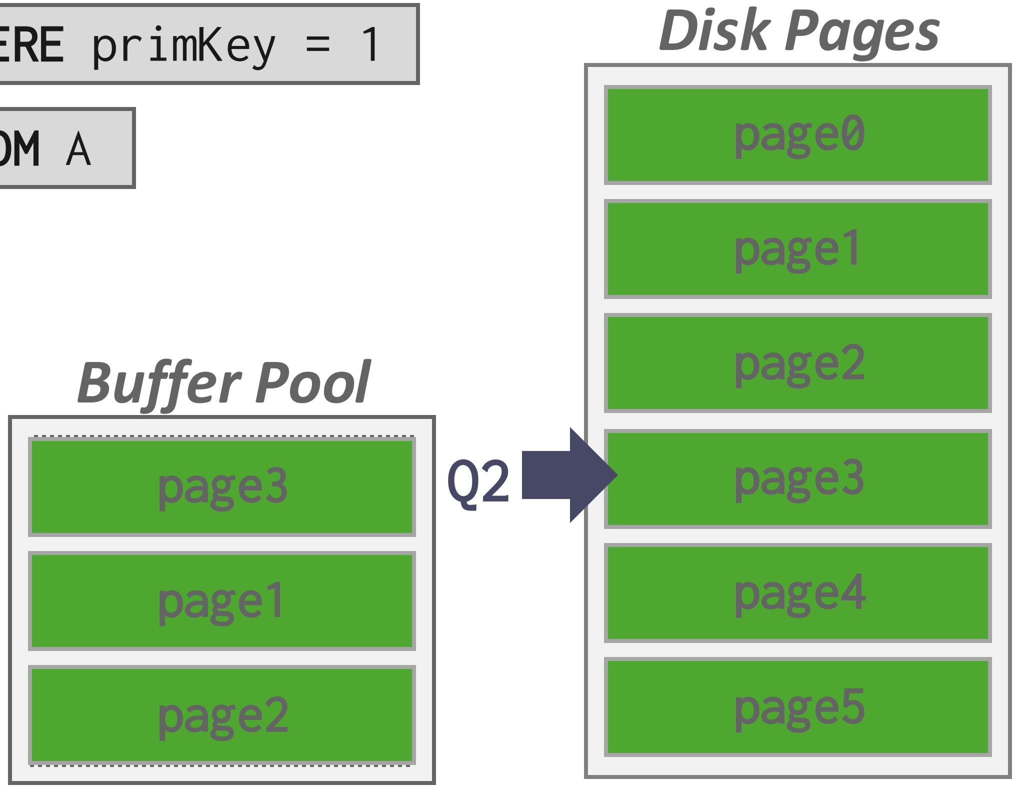

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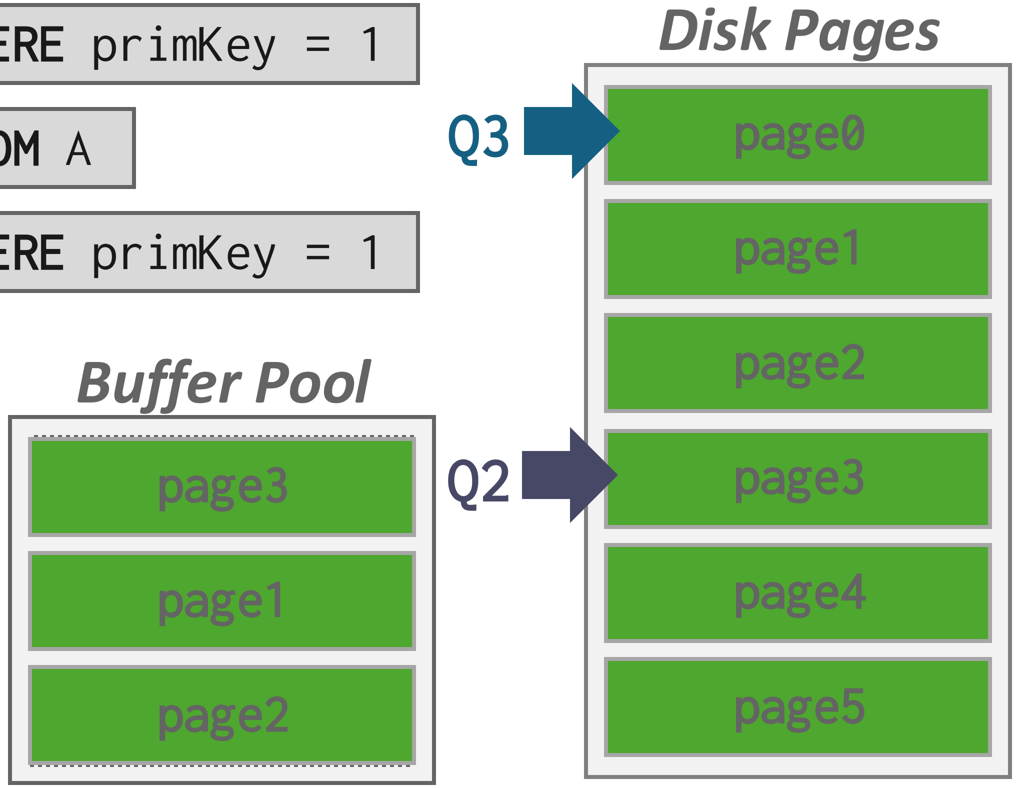
Q3 `SELECT * FROM A WHERE primKey = 1`



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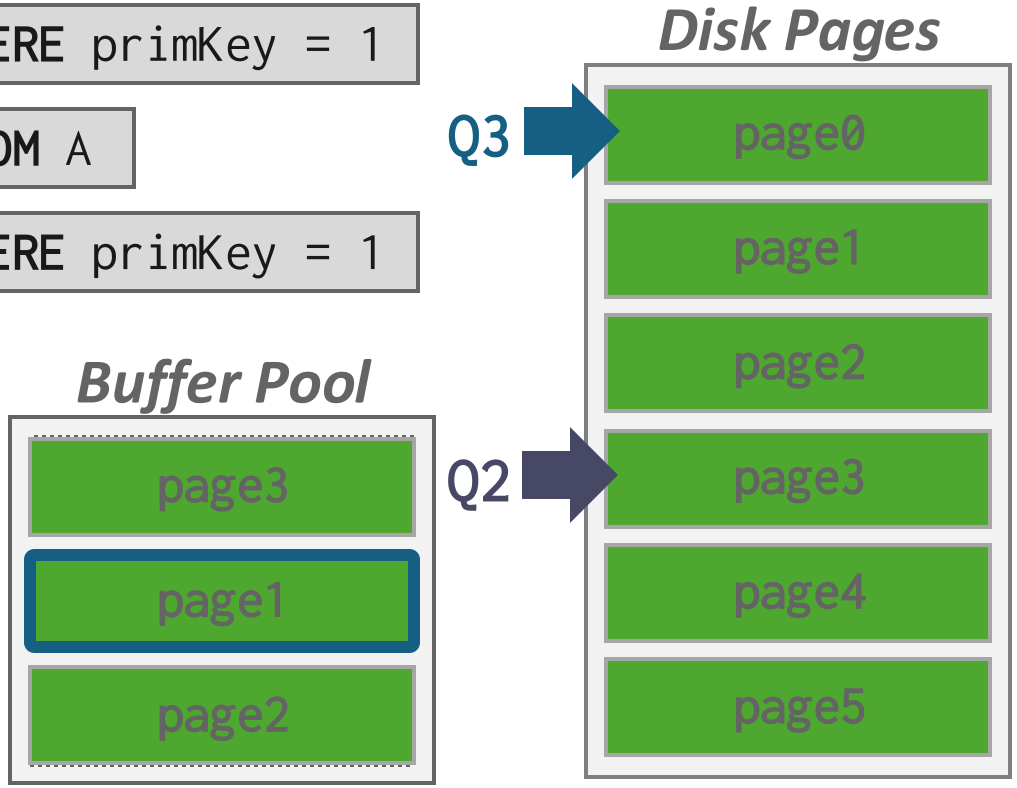

Sequential Flooding

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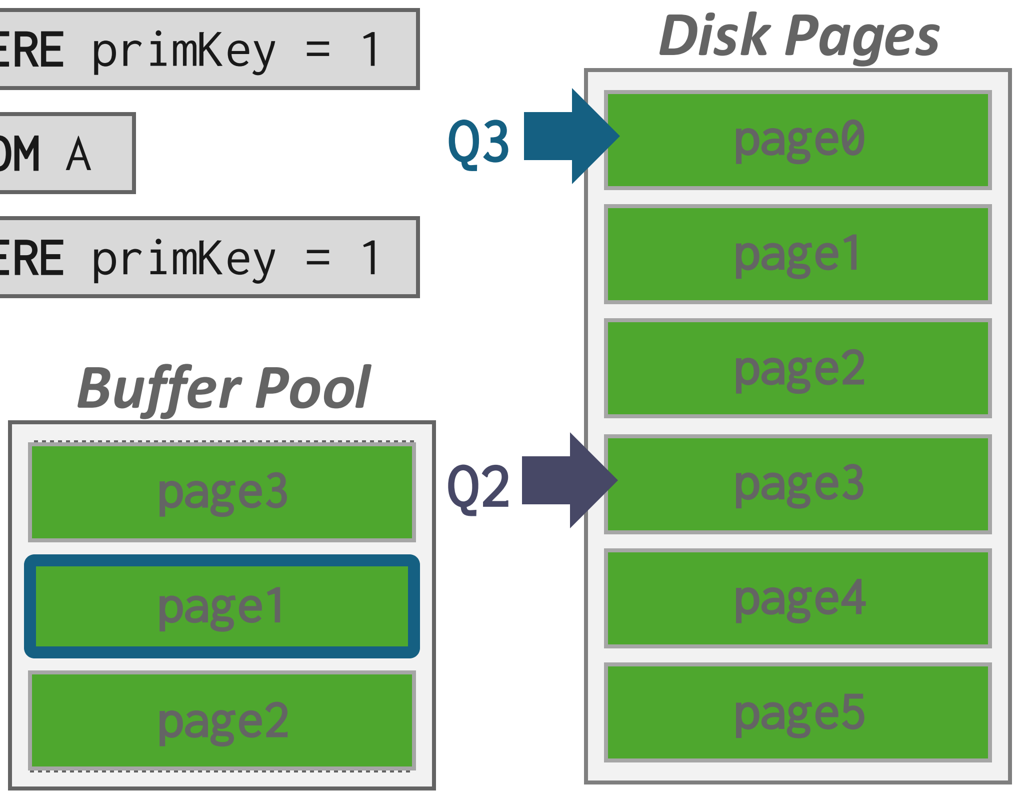
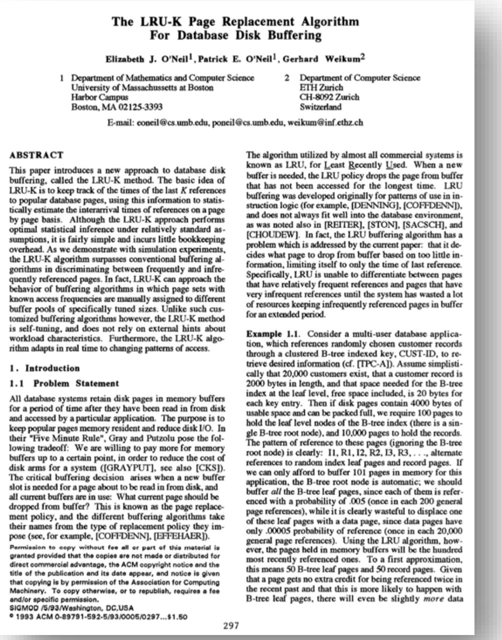
Sequential flooding can occur when a table is scanned multiple times within one query, such as with a Nested-Blocks Join.



Better Policies: LRU-*k*

- Track the last *k* references to each page and compute the interval between subsequent accesses.
  - Can get fancy with distinguishing between reference types.
- The DBMS then uses this history to estimate the next time that page is going to be accessed.
  - Replace the page with the oldest "*k*-th" access.
  - A balance between recency and frequency of access.
  - Maintain an ephemeral in-memory cache for recently evicted pages to prevent them from always being evicted.



The LRU-K Page Replacement Algorithm For Database Disk Buffering

Elizabeth J. O'Neil[1], Patrick E. O'Neil[1], Gerhard Weikum[2]

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ABSTRACT

This paper introduces a new approach to database disk buffering, called the LRU-K method. The basic idea of LRU-K is to keep track of the times of the last *K* references to popular database pages, using this information to statistically estimate the interarrival times of references on a page by page basis. Although the LRU-K approach performs optimal statistical inference under relatively standard assumptions, it is fairly simple and incurs little bookkeeping overhead. As we demonstrate with simulation experiments, the LRU-K algorithm surpasses conventional buffering algorithms in discriminating between frequently and infrequently referenced pages. In fact, LRU-K can approach the behavior of buffering algorithms in which page sets with known access frequencies are manually assigned to different buffer pools of specifically tuned sizes. Unlike such customized buffering algorithms however, the LRU-K method is self-tuning, and does not rely on external hints about workload characteristics. Furthermore, the LRU-K algorithm adapts in real time to changing patterns of access.

1. Introduction

1.1 Problem Statement

All database systems retain disk pages in memory buffers for a period of time after they have been read in from disk and accessed by a particular application. The purpose is to keep popular pages memory resident and reduce disk I/O. In their "Five Minute Rule", Gray and Putzolu pose the following tradeoff: We are willing to pay more for memory buffers up to a certain point, in order to reduce the cost of disk arms for a system ([GRAYPUT], see also [CKS]). The critical buffering decision arises when a new buffer slot is needed for a page about to be read in from disk, and all current buffers are in use: What current page should be dropped from buffer? This is known as the page replacement policy, and the different buffering algorithms take their names from the type of replacement policy they impose (see, for example, [COFFDENN], [EFFEHAER]).

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The algorithm utilized by almost all commercial systems is known as LRU, for Least Recently Used. When a new buffer is needed, the LRU policy drops the page from buffer that has not been accessed for the longest time. LRU buffering was developed originally for patterns of use in instruction logic (for example, [DENNING], [COFFDENN]), and does not always fit well into the database environment, as was noted also in [REITER], [STON], [SACSCH], and [CHOUDEW]. In fact, the LRU buffering algorithm has a problem which is addressed by the current paper: that it decides what page to drop from buffer based on too little information, limiting itself to only the time of last reference. Specifically, LRU is unable to differentiate between pages that have relatively frequent references and pages that have very infrequent references until the system has wasted a lot of resources keeping infrequently referenced pages in buffer for an extended period.

Example 1.1. Consider a multi-user database application, which references randomly chosen customer records through a clustered B-tree indexed key, CUST-ID, to retrieve desired information (cf. [TPC-A]). Assume simplistically that 20,000 customers exist, that a customer record is 2000 bytes in length, and that space needed for the B-tree index at the leaf level, free space included, is 20 bytes for each key entry. Then if disk pages contain 4000 bytes of usable space and can be packed full, we require 100 pages to hold the leaf level nodes of the B-tree index (there is a single B-tree root node), and 10,000 pages to hold the records. The pattern of reference to these pages (ignoring the B-tree root node) is clearly: I1, R1, I2, R2, I3, R3, . . ., alternate references to random index leaf pages and record pages. If we can only afford to buffer 101 pages in memory for this application, the B-tree root node is automatic; we should buffer *all* the B-tree leaf pages, since each of them is referenced with a probability of .005 (once in each 200 general page references), while it is clearly wasteful to displace one of these leaf pages with a data page, since data pages have only .00005 probability of reference (once in each 20,000 general page references). Using the LRU algorithm, however, the pages held in memory buffers will be the hundred most recently referenced ones. To a first approximation, this means 50 B-tree leaf pages and 50 record pages. Given that a page gets no extra credit for being referenced twice in the recent past and that this is more likely to happen with B-tree leaf pages, there will even be slightly *more* data

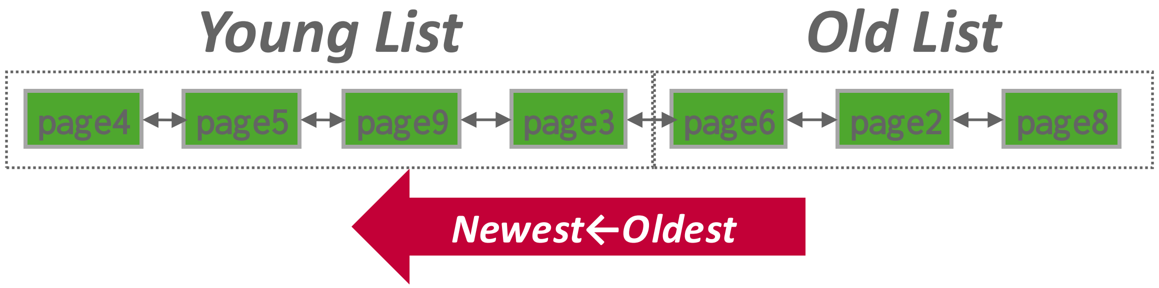
297

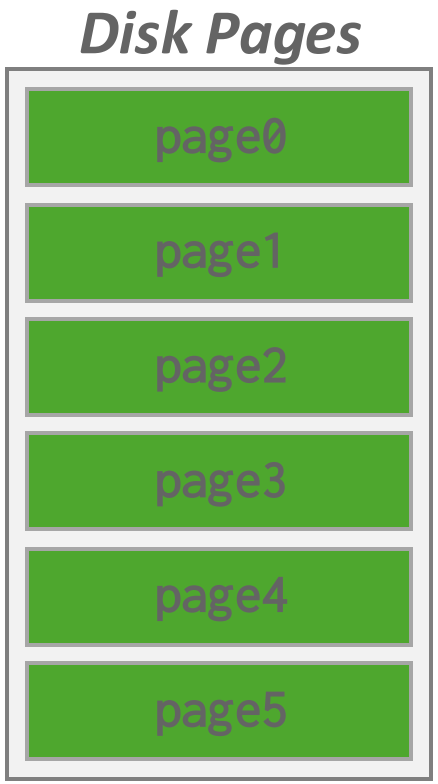
Microsoft SQL Server

PostgreSQL

MySQL Approximate LRU-k

- Single LRU linked list but with two entry points ("old" vs "young").
  - New pages are always inserted to the head of the old list.
  - If pages in the old list is accessed again, then insert into the head of the young list.





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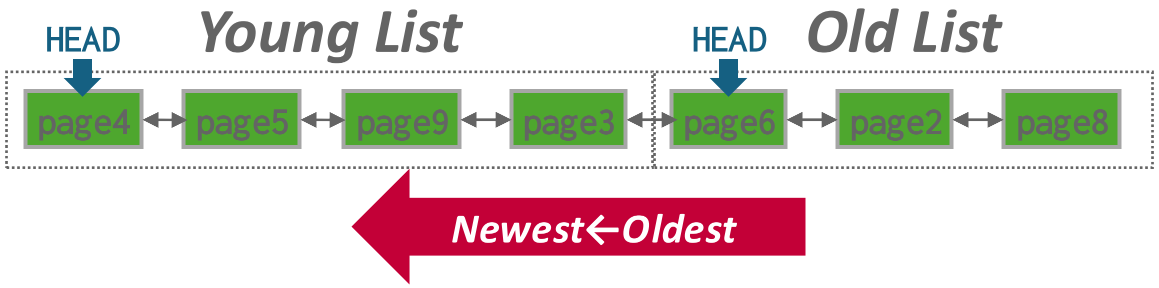

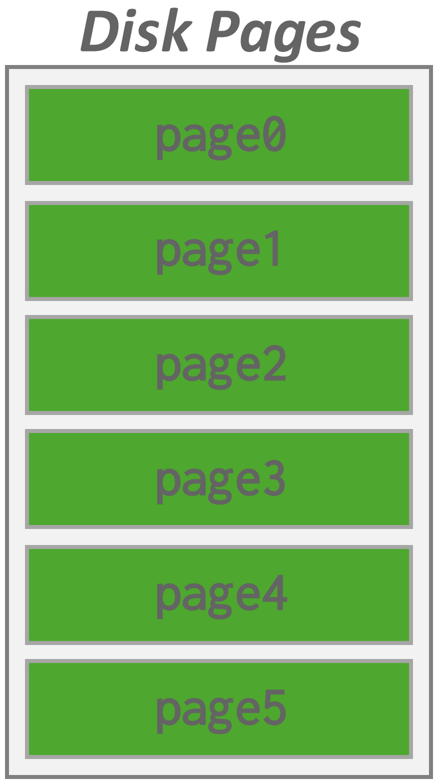

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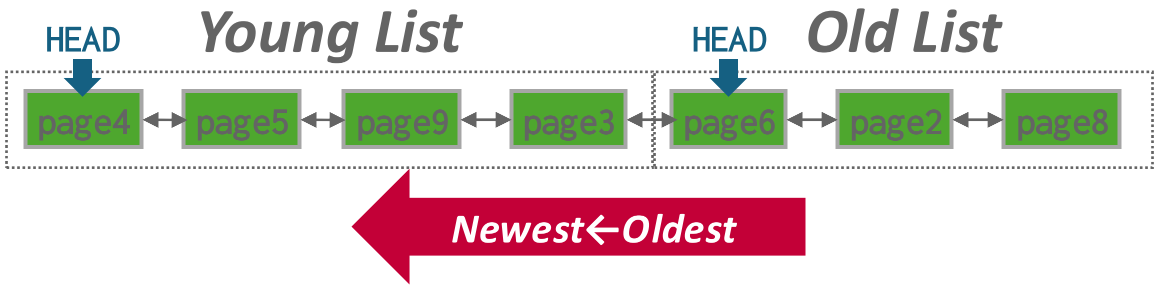

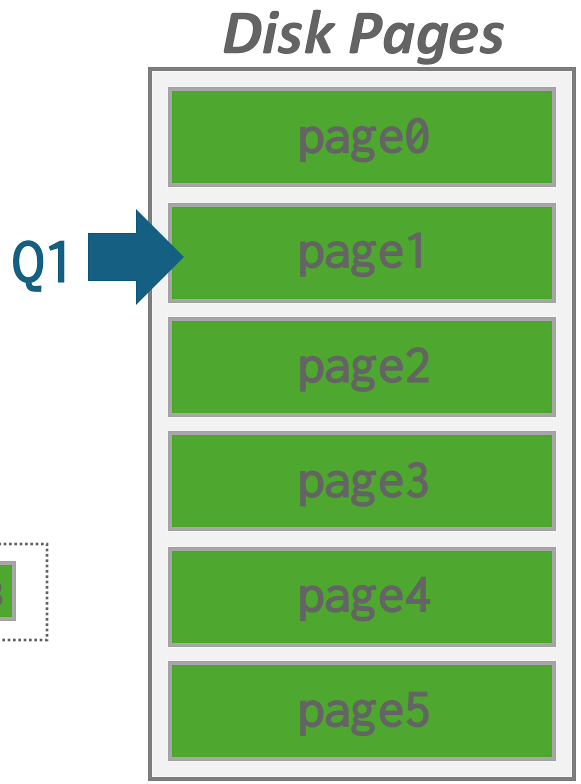

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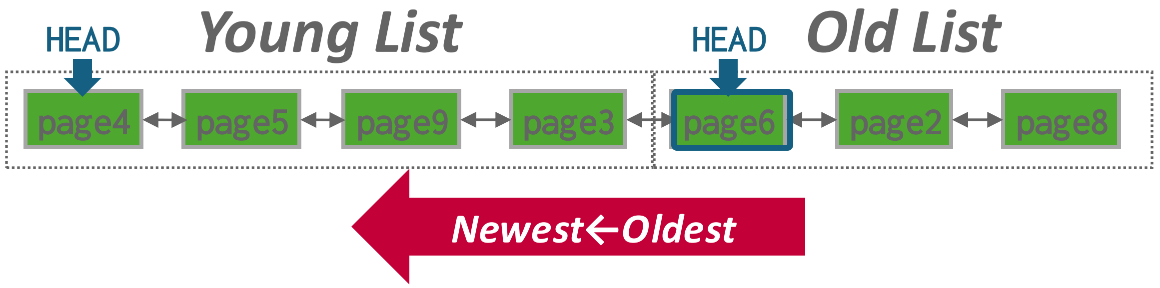

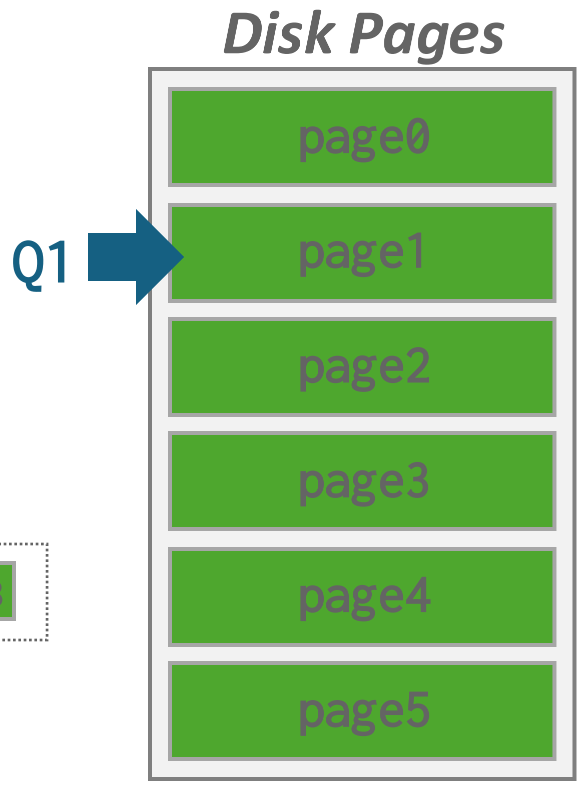

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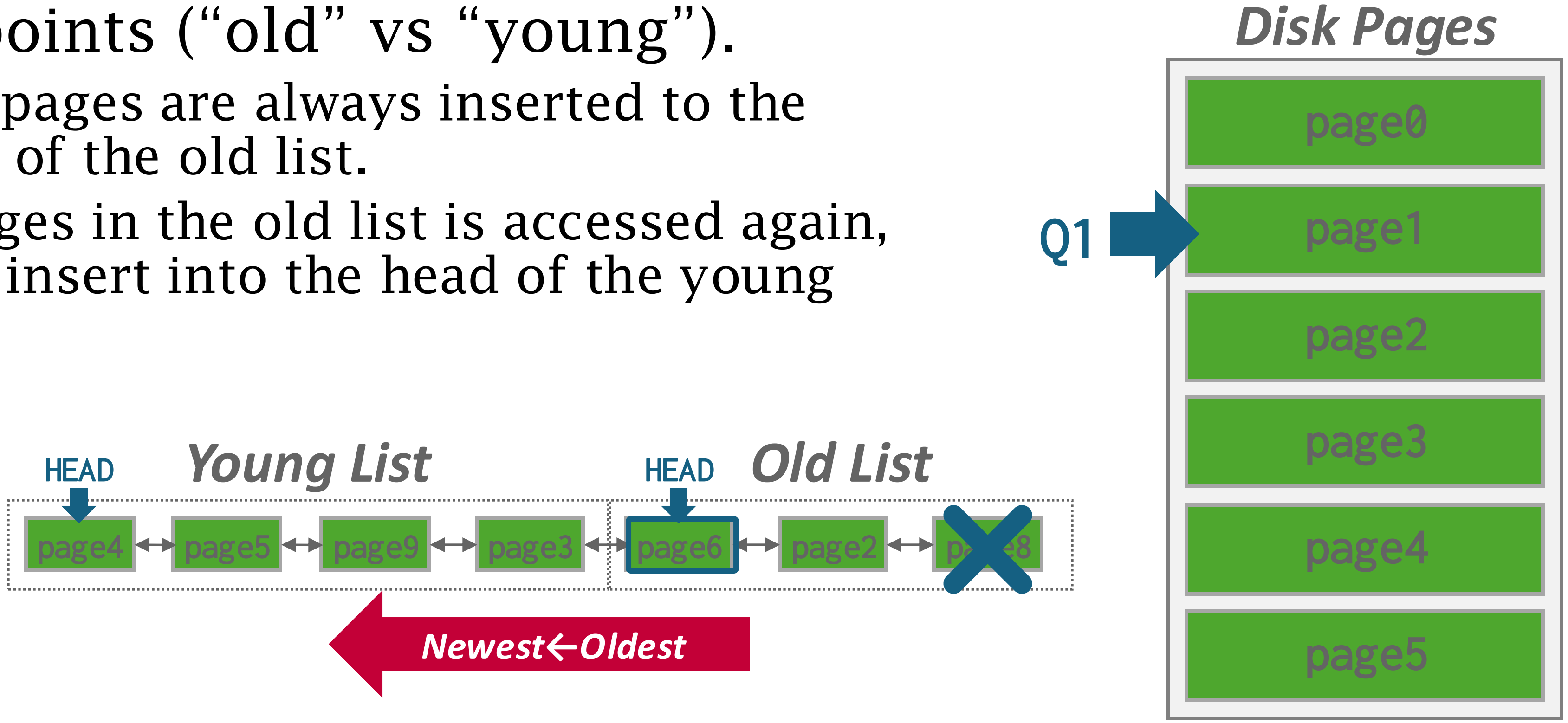

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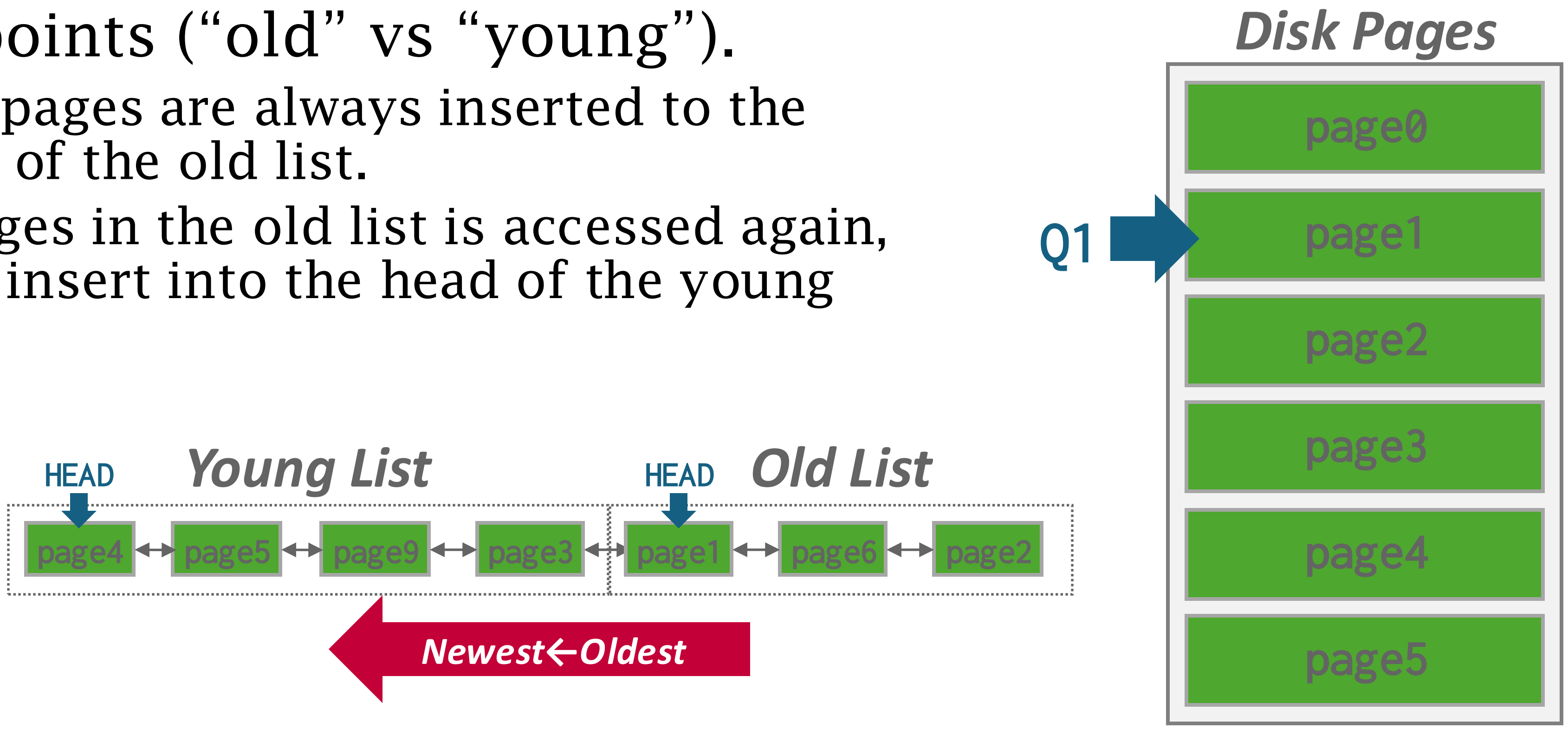

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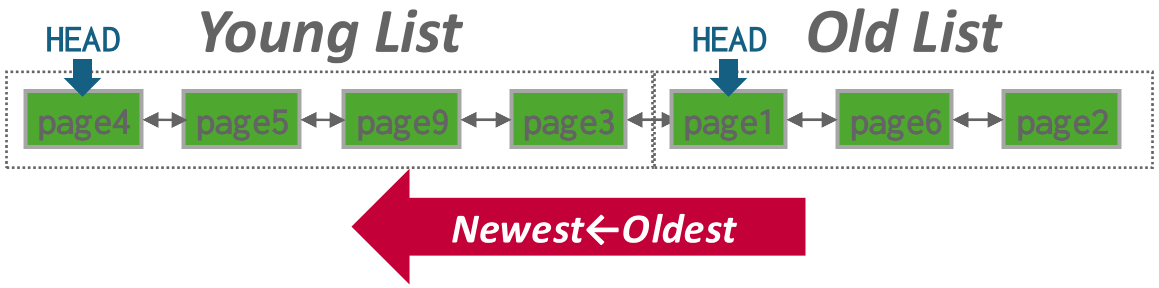

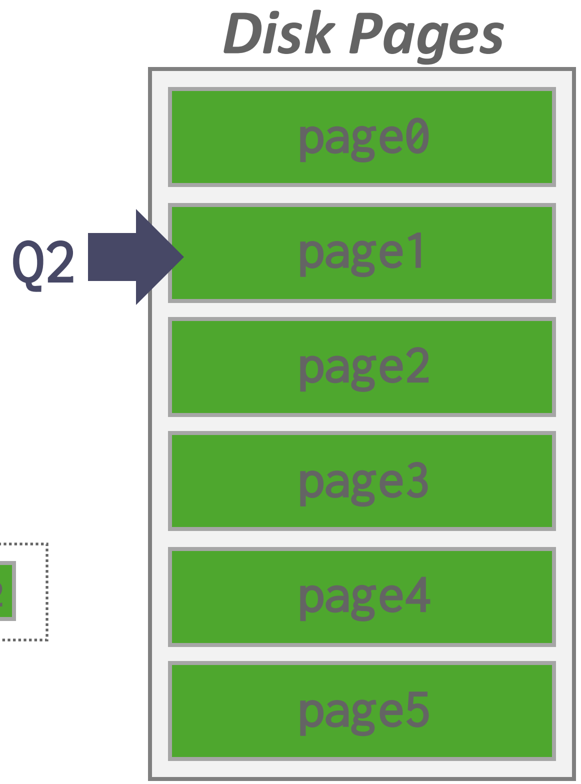

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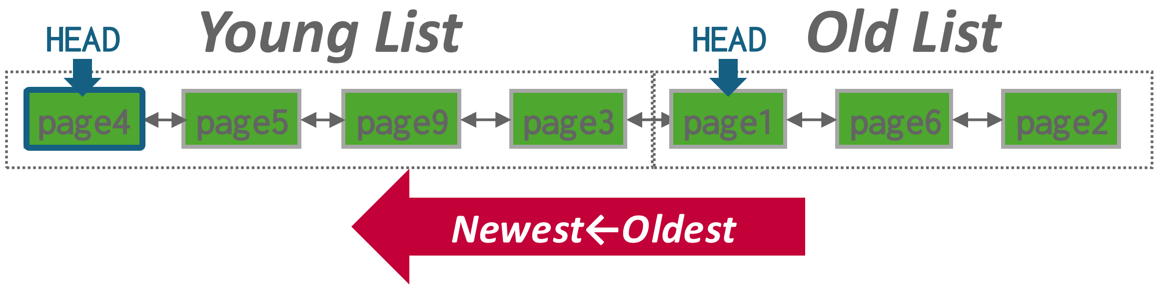

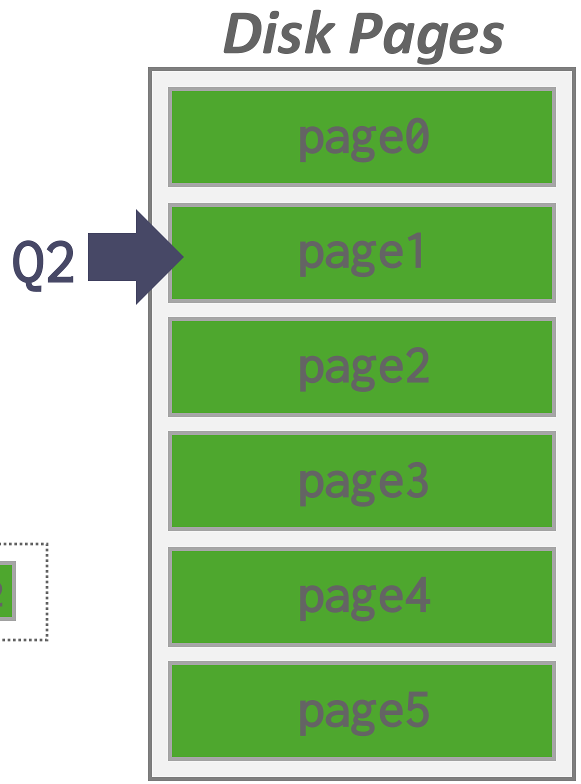

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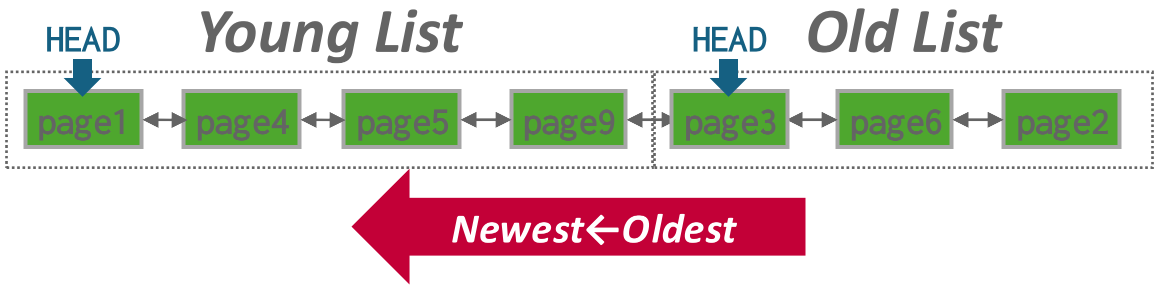

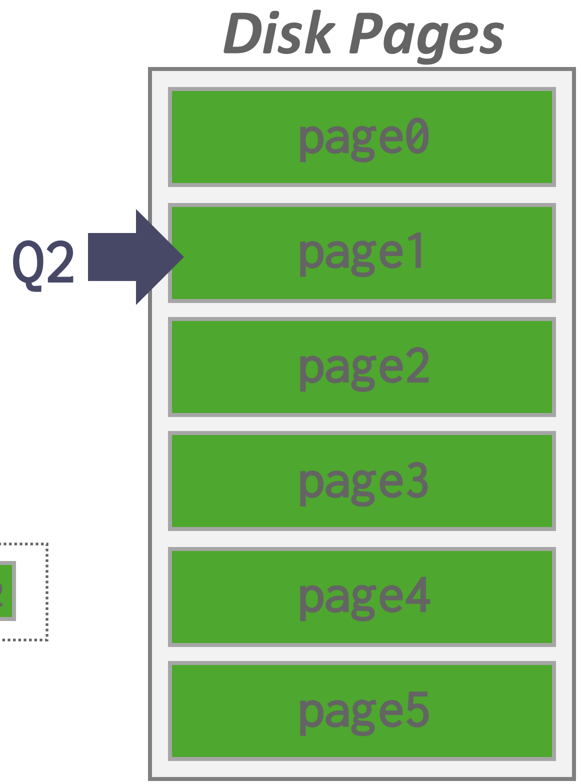

Better Policies: Localization

- 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 on whether a page is important or not.

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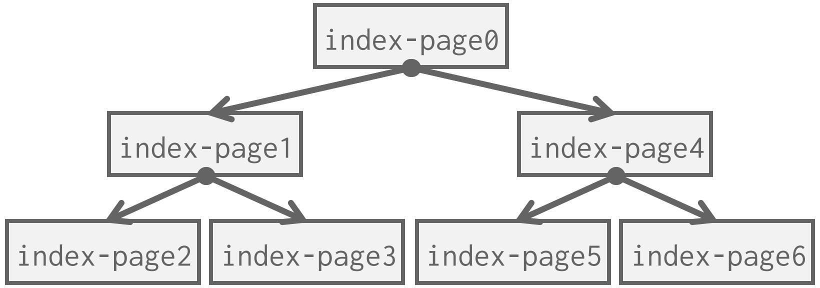

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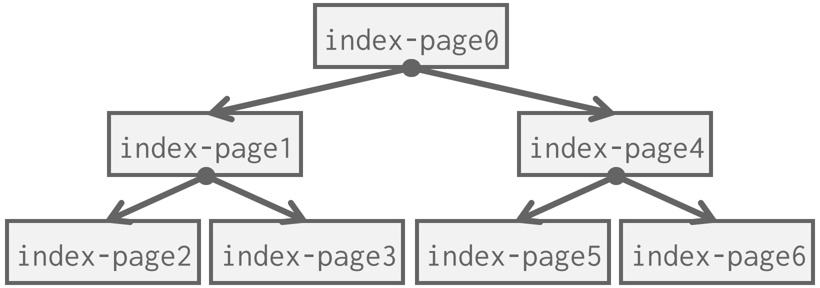

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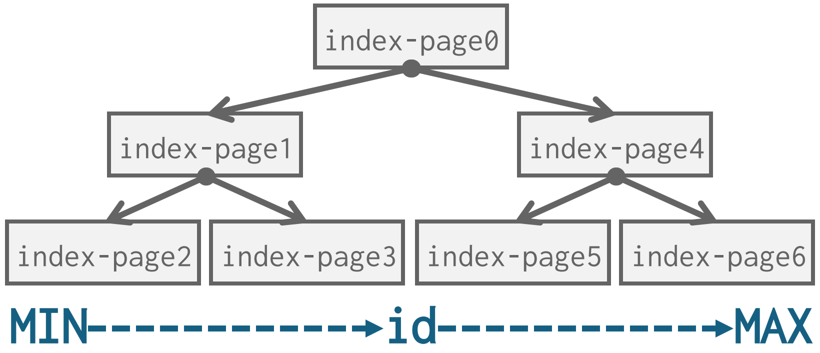

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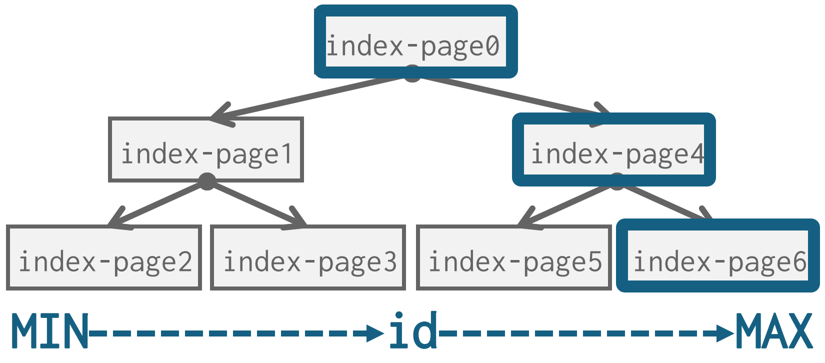

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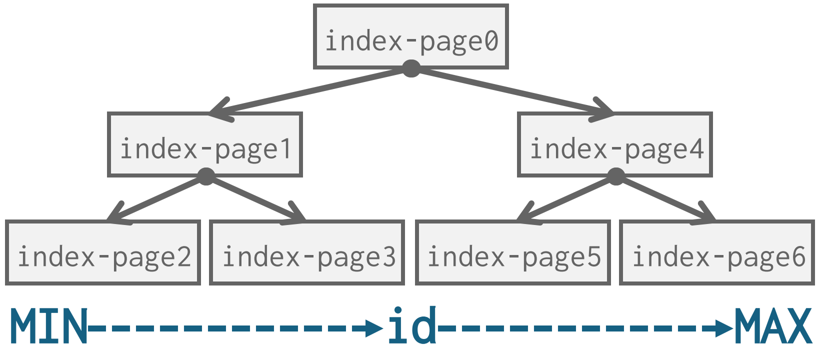

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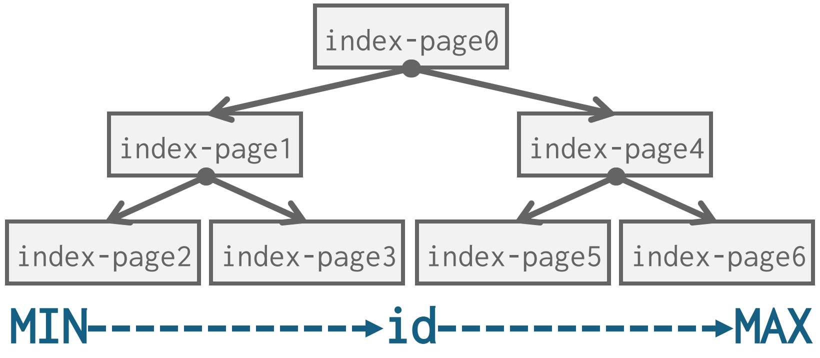

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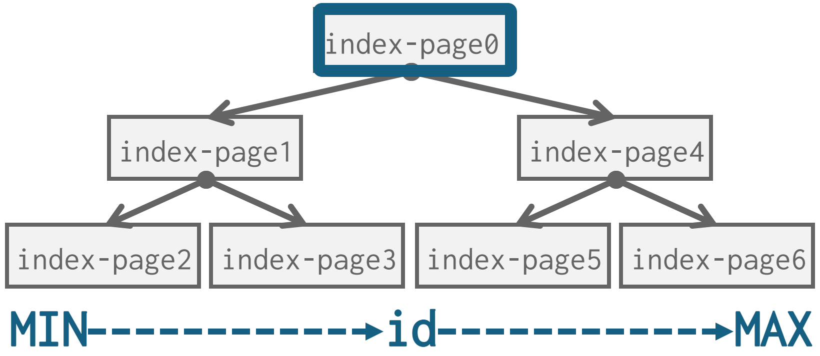

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Dirty Pages

- **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 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 the system doesn't write dirty pages before their log records are written...

Disk I/O Scheduling

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Observation

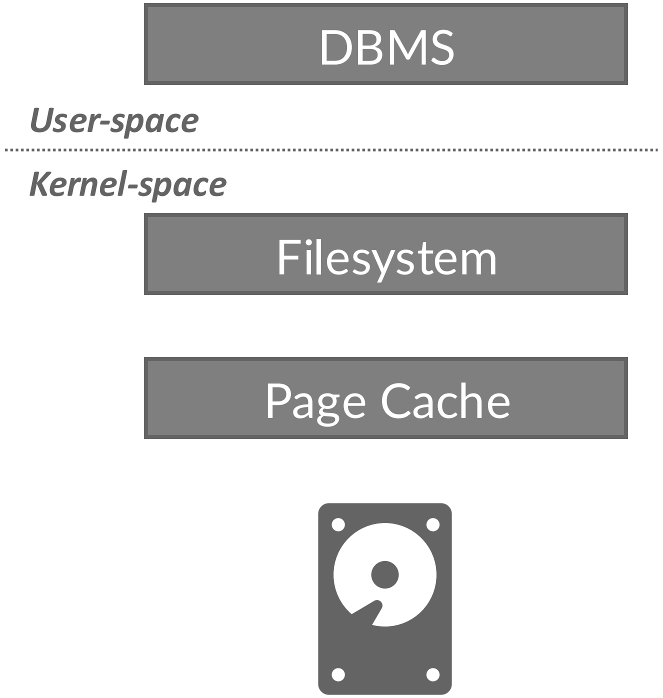
- OS/hardware tries to maximize disk bandwidth by reordering and batching I/O requests.
- But they do not know which I/O requests are more important than others.
- Many DBMSs tell you to switch Linux to use the deadline or noop (FIFO) scheduler.
  - Example: Oracle, Vertica, MySQL

Disk I/O Scheduling

- The DBMS maintain internal queue(s) to track page read/write requests from the entire system.
- Compute priorities based on several factors:
  - Sequential vs. Random I/O
  - Critical Path Task vs. Background Task
  - Table vs. Index vs. Log vs. Ephemeral Data
  - Transaction Information
  - User-based SLAs
- The OS doesn’t know these things and is going to get into the way…

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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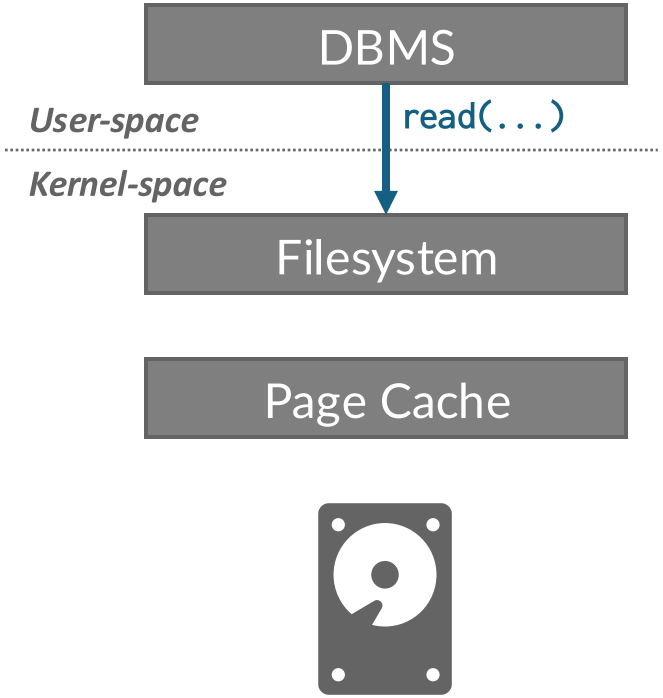

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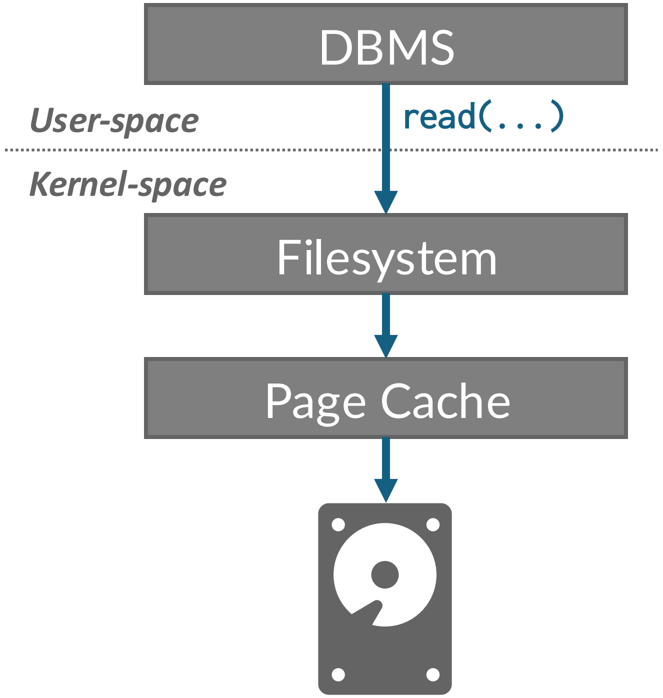

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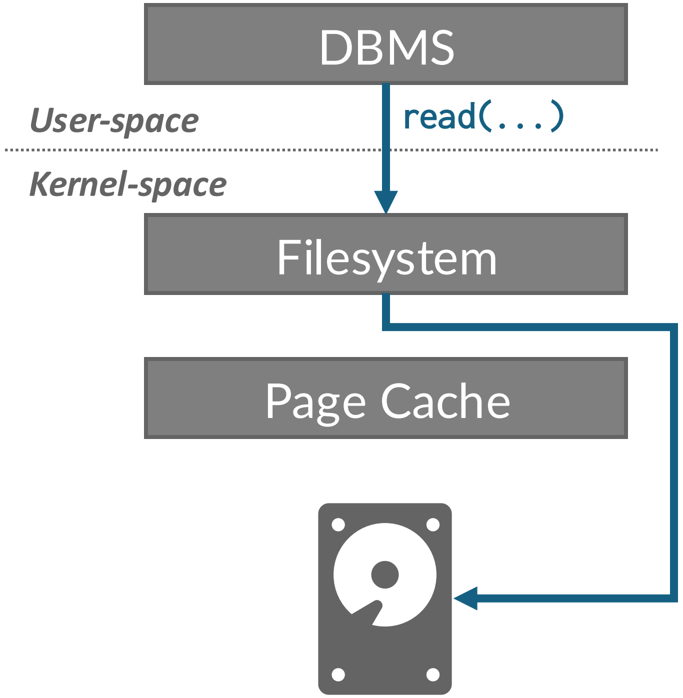

FSYNC Problems

- If the DBMS calls `fwrite`, what happens?
- If the DBMS calls `fsync`, what happens?
- If `fsync` fails (EIO), what happens?
  - Linux marks the dirty pages as clean.
  - If the DBMS calls `fsync` again, then Linux tells you that the flush was successful.

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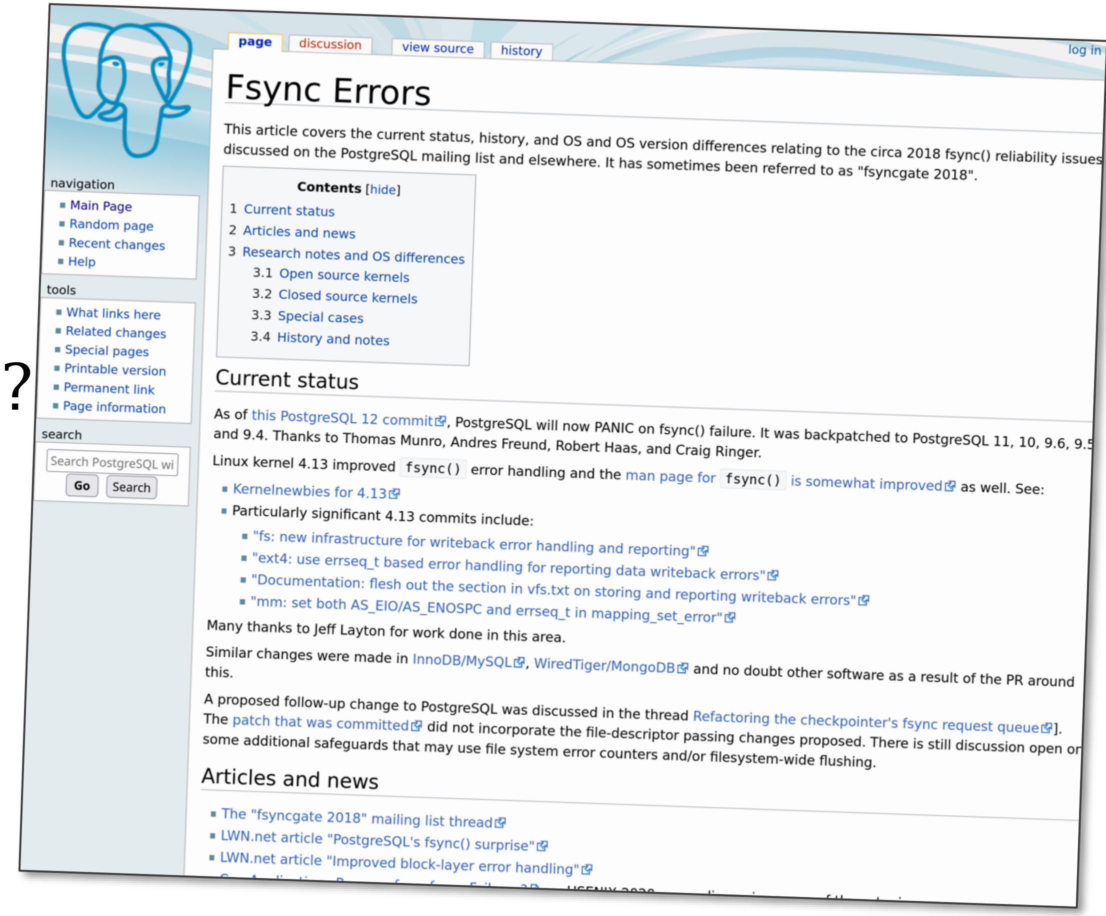

page | discussion | view source | history | log in

Fsync Errors

This article covers the current status, history, and OS and OS version differences relating to the circa 2018 fsync() reliability issues discussed on the PostgreSQL mailing list and elsewhere. It has sometimes been referred to as "fsyncgate 2018".

navigation
- Main Page
- Random page
- Recent changes
- Help

tools
- What links here
- Related changes
- Special pages
- Printable version
- Permanent link
- Page information

search

Search PostgreSQL wi

Go | Search

Contents [hide]
1 Current status
2 Articles and news
3 Research notes and OS differences
3.1 Open source kernels
3.2 Closed source kernels
3.3 Special cases
3.4 History and notes

Current status

As of this PostgreSQL 12 commit, PostgreSQL will now PANIC on fsync() failure. It was backpatched to PostgreSQL 11, 10, 9.6, 9.5 and 9.4. Thanks to Thomas Munro, Andres Freund, Robert Haas, and Craig Ringer.

Linux kernel 4.13 improved `fsync()` error handling and the man page for `fsync()` is somewhat improved as well. See:
- Kernelnewbies for 4.13
- Particularly significant 4.13 commits include:
  - "fs: new infrastructure for writeback error handling and reporting"
  - "ext4: use errseq_t based error handling for reporting data writeback errors"
  - "Documentation: flesh out the section in vfs.txt on storing and reporting writeback errors"
  - "mm: set both AS_EIO/AS_ENOSPC and errseq_t in mapping_set_error"

Many thanks to Jeff Layton for work done in this area.

Similar changes were made in InnoDB/MySQL, WiredTiger/MongoDB and no doubt other software as a result of the PR around this.

A proposed follow-up change to PostgreSQL was discussed in the thread Refactoring the checkpointer's fsync request queue]. The patch that was committed did not incorporate the file-descriptor passing changes proposed. There is still discussion open on some additional safeguards that may use file system error counters and/or filesystem-wide flushing.

Articles and news

- The "fsyncgate 2018" mailing list thread
- LWN.net article "PostgreSQL's fsync() surprise"
- LWN.net article "Improved block-layer error handling"

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 almost always manage memory better than the OS.
- Leverage the semantics about the query plan to make better decisions:
  - Evictions
  - Allocations
  - Pre-fetching
- Next: Hash Table