

Lecture #06: Buffer Pools

15-445/645 Database Systems (Fall 2023)

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Carnegie Mellon University

Andy Pavlo + Jignesh Patel

1 Introduction

The DBMS is responsible for managing its memory and moving data back-and-forth from the disk. Since, for the most part, data cannot be directly operated on in the disk, any database must be able to efficiently move data represented as files from its disk into memory so that it can be used. A diagram of this interaction is shown in Figure 1. Ideally from the execution engine's perspective, it should "appear" as if all the data is in memory. It should not have to worry about how data is fetched into memory.

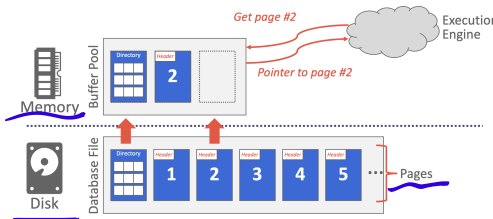


Figure 1: Disk-oriented DBMS.

Another way to think of this problem is in terms of spatial and temporal control.

Spatial Control refers to where pages are physically written on disk. The goal of spatial control is to keep pages that are used together often as physically close together as possible on disk.

Temporal Control refers to when to read pages into memory and when to write them to disk. Temporal control aims to minimize the number of stalls from having to read data from disk.

2 Locks vs. Latches

We need to make a distinction between locks and latches when discussing how the DBMS protects its internal elements.

Locks: A lock is a higher-level, logical primitive that protects the contents of a database (e.g., tuples, tables, databases) from other transactions. Transactions will hold a lock for its entire duration. Database systems can expose to the user which locks are being held as queries are run. Locks need to be able to rollback changes.

Latches: A latch is a low-level protection primitive that the DBMS uses for the critical sections in its internal data structures (e.g., hash tables, regions of memory). Latches are held for only the duration of the operation being made. Latches do not need to be able to rollback changes.

3 Buffer Pool

The *buffer pool* is an in-memory cache of pages read from disk. It is essentially a large memory region allocated inside of the database to store pages that are fetched from disk.

The buffer pool's region of memory organized as an array of fixed size pages. Each array entry is called a *frame*. When the DBMS requests a page, it is copied from disk into one of the frames of the buffer pool. When a page is

requested, the database system can search the buffer pool first. Only if the page is not found, the system fetches a copy of the page from the disk. Dirty pages are buffered and not written back immediately. See Figure 2 for a diagram of the buffer pool's memory organization.

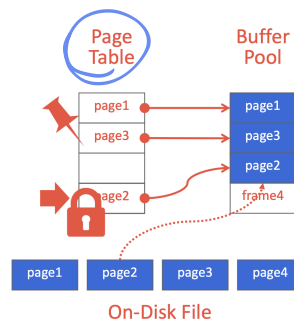


Figure 2: Buffer pool organization and meta-data

Buffer Pool Meta-data

The buffer pool must maintain certain meta-data in order to be used efficiently and correctly.

Firstly, the *page table* is an in-memory hash table that keeps track of pages that are currently in memory. It maps page ids to frame locations in the buffer pool. Since the order of pages in the buffer pool does not necessarily reflect the order on the disk, this extra indirection layer allows for the identification of page locations in the pool.

Note: The page table is not to be confused with the *page directory*, which is the mapping from page ids to page locations in database files. All changes to the page directory must be recorded on disk to allow the DBMS to find on restart.

The page table also maintains additional meta-data per page, a dirty-flag and a pin/reference counter.

The *dirty-flag* is set by a thread whenever it modifies a page. This indicates to storage manager that the page must be written back to disk.

The *pin/reference Counter* tracks the number of threads that are currently accessing that page (either reading or modifying it). A thread has to increment the counter before they access the page. If a page's pin count is greater than zero, then the storage manager is not allowed to evict that page from memory. Pinning does not prevent other transactions from accessing the page concurrently.

Memory Allocation Policies

Memory in the database is allocated for the buffer pool according to two policies.

Global policies deal with decisions that the DBMS should make to benefit the entire workload that is being executed. It considers all active transactions to find an optimal decision for allocating memory.

An alternative is *local policies*, which makes decisions that will make a single query or transaction run faster, even if it isn't good for the entire workload. Local policies allocate frames to a specific transactions without considering the behavior of concurrent transactions.

Most systems use a combination of both global and local views.

4 Buffer Pool Optimizations

There are a number of ways to optimize a buffer pool to tailor it to the application's workload.

Multiple Buffer Pools

locality: related data physically close to each other to improve performance

The DBMS can maintain multiple buffer pools for different purposes (i.e. per-database buffer pool, per-page type buffer pool). Then, each buffer pool can adopt local policies tailored for the data stored inside of it. This method can help reduce latch contention and improves locality.

Two approaches to mapping desired pages to a buffer pool are object IDs and hashing.

- ① Object IDs involve extending the record IDs to have an object identifier. Then through the object identifier, a mapping from objects to specific buffer pools can be maintained.
- ② Another approach is hashing where the DBMS hashes the page id to select which buffer pool to access.

Pre-fetching

The DBMS can also optimize by pre-fetching pages based on the query plan. Then, while the first set of pages is being processed, the second can be pre-fetched into the buffer pool. This method is commonly used by DBMS's when accessing many pages sequentially. It is also possible for a buffer pool manager to prefetch leaf pages in a tree index data structure.

Scan Sharing (Synchronized Scans)

reduce I/O operation

Query cursors can reuse data retrieved from storage or operator computations. This allows multiple queries to attach to a single cursor that scans a table. If a query starts a scan and if there one already doing this, then the DBMS will attach the second query's cursor to the existing 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.

Buffer Pool Bypass

The sequential scan operator will not store fetched pages in the buffer pool to avoid overhead. Instead, memory is local to the running query. This works well if operator needs to read a large sequence of pages that are contiguous on disk. Buffer Pool Bypass can also be used for temporary data (sorting, joins).

5 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.

A replacement policy is an algorithm that the DBMS implements that makes a decision on which pages to evict from buffer pool when it needs space.

Implementation goals of replacement policies are improved correctness, accuracy, speed, and meta-data overhead.

Least Recently Used (LRU)

The Least Recently Used replacement policy maintains a timestamp of when each page was last accessed. The DBMS picks to evict the page with the oldest timestamp. This timestamp can be stored in a separate data structure, such as a queue, to allow for sorting and improve efficiency by reducing sort time on eviction.

CLOCK

The CLOCK policy is an approximation of LRU without needing a separate timestamp per page. In the CLOCK policy, each page is given a reference bit. When a page is accessed, set to 1.

To visualize this, 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 it. In this way, the clock hand remembers position between evictions.

Alternatives

There are a number of problems with LRU and CLOCK replacement policies.

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



Figure 3: Visualization of CLOCK replacement policy. Page 1 is referenced and set to 1. When the clock hand sweeps, it sets the reference bit for page 1 to 0 and evicts page 5.

Namely, LRU and CLOCK are susceptible to sequential flooding, where the buffer pool's contents are corrupted due to a sequential scan. Since sequential scans read many pages quickly, the buffer pool fills up and pages from other queries are evicted as they would have earlier timestamps. In this scenario, the most recent timestamp does not accurately reflect which page we actually want to evict.

There are three solutions to address the shortcomings of LRU and CLOCK policies.

One solution is LRU-K which tracks the history of the last K references as timestamps and computes the interval between subsequent accesses. This history is used to predict the next time a page is going to be accessed.

Another optimization is localization per query. The DBMS chooses which pages to evict on a per transaction/query basis. This minimizes the pollution of the buffer pool from each query.

Lastly, priority hints allow transactions to tell the buffer pool whether page is important or not based on the context of each page during query execution.

Dirty Pages

There are two methods to handling pages with dirty bits. The fastest option is to drop any page in the buffer pool that is not dirty. A slower method is to write back dirty pages to disk to ensure that its changes are persisted.

These two methods illustrate the trade-off between fast evictions versus dirty writing pages that will not be read again in the future.

One way to avoid the problem of having to write out pages unnecessarily is background writing. Through 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.

6 Other Memory Pools

The DBMS needs memory for things other than just tuples and indexes. These other memory pools may not always be backed by disk depending on implementation.

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

7 OS Page Cache

Most disk operations go through the OS API. Unless explicitly told otherwise, the OS maintains its own filesystem cache.

Most DBMS use direct I/O to bypass the OS's cache in order to avoid redundant copies of pages and having to manage different eviction policies.

Postgres is an example of a database system that uses the OS's Page Cache.

8 Disk I/O Scheduling

The DBMS maintains internal queue(s) to track page read/write requests from the entire system. The priority of the tasks are determined 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