

Are You Sure You Want to Use MMAP in Your Database Management System?

MMAP = ☺

Junpeng Zhu

Greenplum, VMware, Inc.

May, 5, 2022





- 1 Background
 - Recap
 - What's the Problems We Concern ?
- 2 Problem with MMAP : The Four Deadly Sins
- 3 Experimental Analysis
- 4 Conclusions
 - Authors Opinions
 - My Opinions
- 5 Acknowledgements and Questions

Outline



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Andrew Crotty

Carnegie Mellon University

Viktor Leis

Friedrich-Alexander-Universität

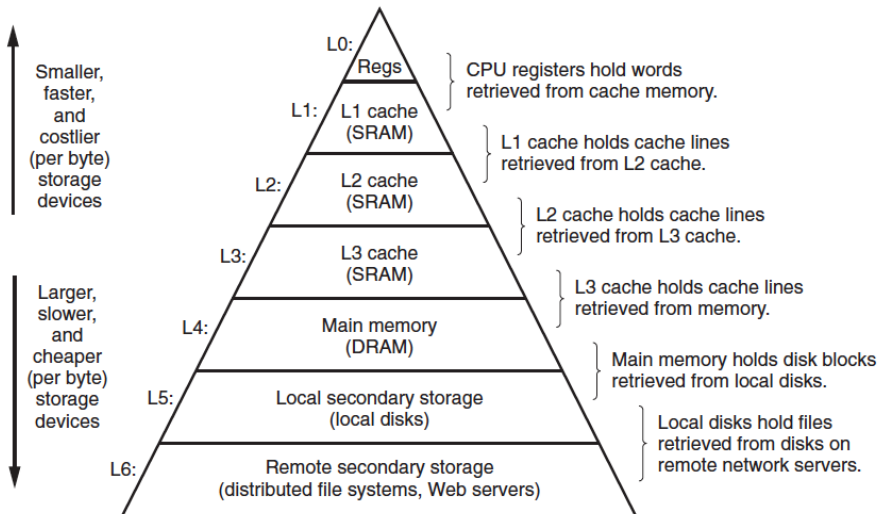
Andy Pavlo

Carnegie Mellon University

- Andrew Crotty
 - ✓ [Andrew Crotty's Bio](#)
 - ✓ Ph.D at Brown, in 2019. Post-doctoral at CMU.
- Viktor Leis
 - ✓ [Viktor Leis Bio](#)
 - ✓ Ph.D at TUM, full professor at Friedrich Schiller University Jena.
- Andy Pavlo
 - ✓ [Andy Pavlo Bio](#)
 - ✓ Ph.D at Brown, associate professor at CMU.
 - ✓ **Never use mmap in a DBMS at his tombstone.**



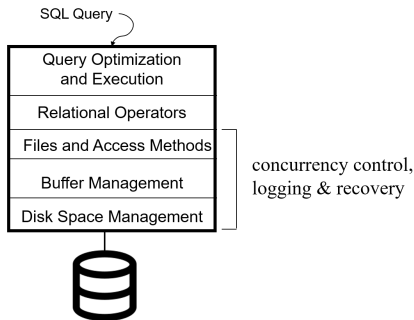
Storage hierarchy, Cont.





Architecture of RDBMS, Cont.

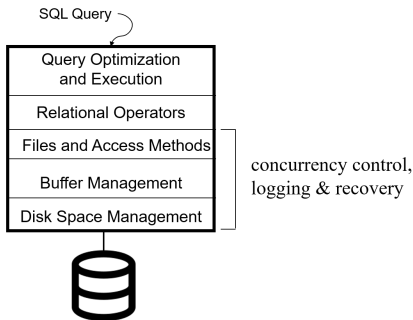
- Query optimization and execution
- Relational operators
- Files and access methods
- Buffer pool management
- Disk space management





Architecture of RDBMS, Cont.

- Query optimization and execution
- Relational operators
- Files and access methods
- Buffer pool management
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- Crash recovery is awfully difficult !
 - * The recovery system **depends on behavior of many other components** of DBMS, such as concurrency control, buffer management, disk management, and query processing.

Buffer Pool Management, Cont.



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- **Force policy** – make sure that every update is on the DB disk before **commit**.
 - ✓ Provides durability without REDO logging.
 - ✓ But, can cause poor performance **due to a large random write operations**.

Buffer Pool Management, Cont.



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- **No Steal policy** – don't allow buffer pool frames with uncommitted updates to overwrite committed data on DB disk.
 - ✓ Useful for ensuring atomicity without UNDO logging.
 - ✓ But can cause poor performance due to **(1) A larger buffer is required ; or (2) writing that data to temporary location on non-volatile storage (e.g., swap area)**.



Buffer Pool Management, Cont.

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In practice, even to get Force/No-Steal to work requires some nasty details for handling unexpected failures. . .

Buffer Pool Replace Policy, Cont.



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- **No Force**

- ▶ What if system crashes before a modified page written by a committed transaction makes it to DB disk?
 - ✓ Write as little as possible, in a convenient place, at commit time, to support REDOing modifications. → **WAL Logging**.

Buffer Pool Replace Policy, Cont.



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- **Steal**

- ▶ What if a transaction that performed updates aborts? → **WAL Logging**
- ▶ What if system crashes before transaction is finished? → **WAL Logging**
 - ✓ Must remember the old value of P (to support UNDOing the write to page P).



Buffer Pool Replace Policy, Cont.

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No force and steal buffer pool policy is commonly used in modern DBMSs.

Buffer Pool Management, Cont.



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	No Steal	Steal
No Force		Fastest
Force	Slowest	

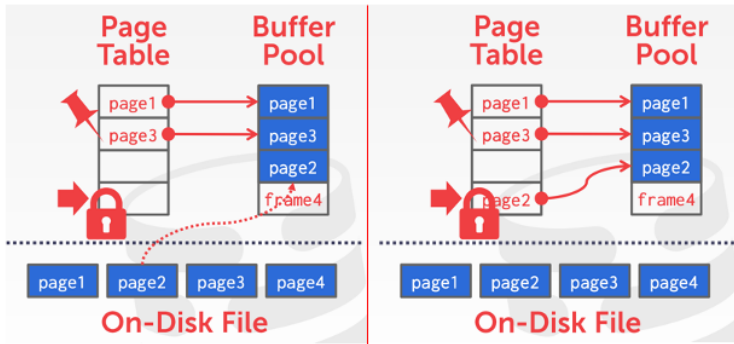
Performance Implications

	No Steal	Steal
No Force	No UNDO REDO	UNDO REDO
Force	No UNDO No REDO	UNDO No REDO

Log/Recovery Implications



Buffer Pool Management, Cont. ²



2. CMU 15-445/645 Fall 2021 Buffer Pool Slide

MMAP as Buffer Pool, Cont. ³

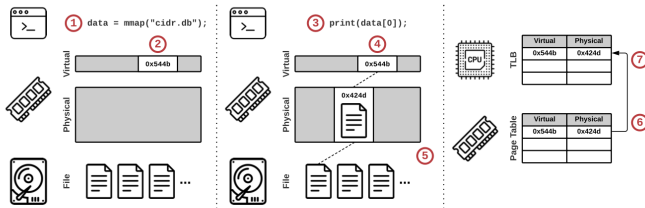


- Memory-mapped (mmap) file I/O is an OS-provided feature.
 - ✓ It maps **the contents of a file** on secondary storage into a **program's virtual address space**.



MMAP as Buffer Pool, Cont. ³

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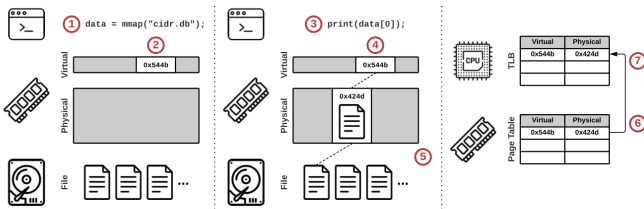
Step-by-step illustration of how a program accesses a file using mmap.

3. Ethanzjp MMAP Gendata Demo

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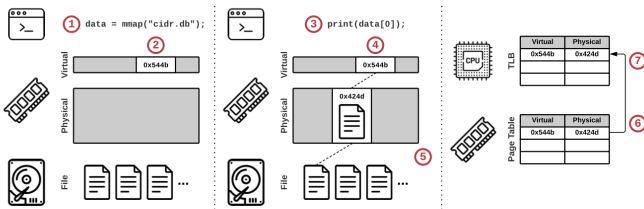
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 - The program then accesses pages via **pointers** as if the file resided entirely in memory.
 - The OS **transparently loads pages** only when the program references them.
 - The OS **automatically evicts pages** if memory fills up.



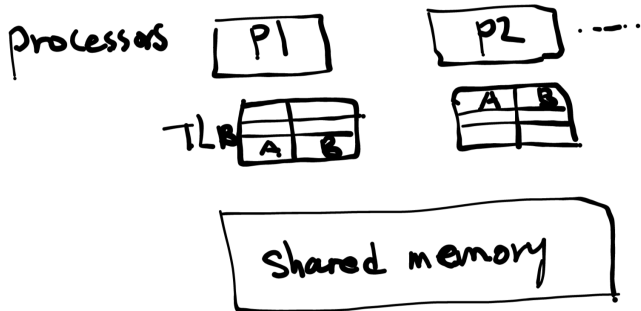
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3. Ethanzjp MMAP Gendata Demo



TLB shutdown

- Shared Memory Model⁴



4. Ethanzjp Shared Memory Demo

Comparision of Buffer Pool and MMAP



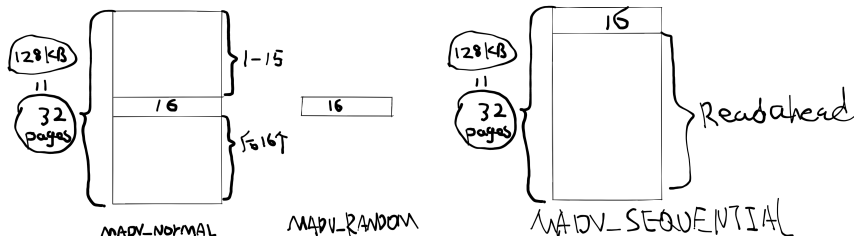
- Buffer Pool
 - ✓ The DBMS maintaining complete control over how and when it transfers pages.
- MMAP
 - ✓ The OS handles all necessary paging behind the scenes rather than the DBMS's buffer pool.
- Stonebraker 1981 opinion⁵

However, many DBMSs including INGRES [20] and System R [4] choose to put a DBMS managed buffer pool in user space to reduce overhead. Hence, each of these systems has gone to the trouble of constructing its own buffer pool manager to enhance performance.



POSIX API, Cont.

- `mmap`⁶
- `madvise` hints to the OS about expected data access patterns⁷



- `mlock`⁸ allows DBMS pin memory. But OS is permitted to flush dirty pages to the backing file at any time, even if the page is pinned.
- `msync`⁹ explicitly flushes the specified memory range to secondary storage.

-
6. `mmap` man7 page
 7. `madvise` man7 page
 8. `mlock` man7 page
 9. `msync` man7 page

Modern MMAP-based DBMS



DBMS	MMAP Use	Details
MonetDB	2002–	[12, 21]
MongoDB	2009–2019	[14, 3]
LevelDB	2011–	[5]
LMDB	2011–	[20]
SQLite	2013–	[7]
SingleStore	2013–2015	[32]
QuestDB	2014–	[34]
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WiredTiger	2020–	[17]

10. LevelDB Snapshot Demo

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- InfluxDB replaced mmap after observing I/O spikes for writes when a database grew larger than a few GB in size.

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- RocksDB replace mmap as a fork of LevelDB ¹⁰.

10. LevelDB Snapshot Demo



What is the truth ?

The DBMS seems no longer needs to manage its own buffer pool, as it cedes this responsibility to the OS.



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When Building a Database, We Need¹¹

- Reading the data from disk.
- Concurrency between different threads reading the same data.
- Caching and buffer management.
- Eviction of pages from memory.
- Playing nice with other processes in the machine.
- Tracking dirty pages and writing to disk.

11. CMU-15-445/645 Buffer Pool Management

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Transactional Safety

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- A database needs to know when the data is persisted to disk. When using mmap, we explicitly give up that knowledge.
 - * Single writer and multiple readers are common in embedded systems, e.g. LMDB, LevelDB, Lucene.
 - * The interleaving writes is a must for Postgres due that may have a transaction spanning multiple network calls.
- The challenges inherent with guaranteeing transactional safety of modified pages in mmap-based DBMSs are well-known.
 - * Due to transparent paging, **the OS can flush a dirty page (steal)** to secondary storage **at any time**, irrespective of whether the writing transaction has committed.
 - * The DBMS cannot prevent these flushes and receives **no warning** when they occur.

Handling Updates When it May Use MMAP

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- Three categories for handling updates :
 - * OS CoW

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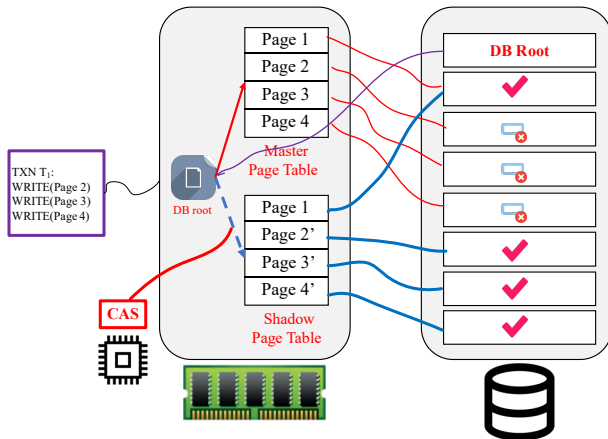
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 - * Shadow Paging



System R's Shadow paging



- Master : Contains only changes from committed txns.
- Shadow : Temporary db with changes made from uncommitted txns.

IO Stalls

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- Accessing any page could result in an unexpected I/O stall because the DBMS cannot know whether the page is in memory.
 - ✓ Pinning memory.
 - ✓ mlock the memory.
 - ✓ madvise, but os is free ignore the advise.



Error Handling

- Page-level checksums
- Gracefully handling I/O errors
 - * Error return value for system calls.
 - * SIGBUS.



Performance Issues

- Page table contention
 - * PTE and PMD split spin_lock.¹²
- Single-threaded page eviction and for larger-than- memory DBMS workloads on high-bandwidth secondary storage devices.
- TLB shutdowns
 - * Fast I/O
 - * Working set that significantly exceeds memory
 - * No other work that needs to be done for processing a request

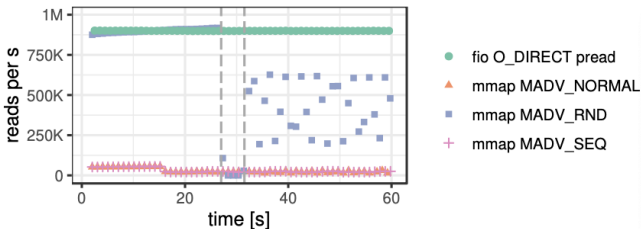


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Random Reads on Bandwidth¹³



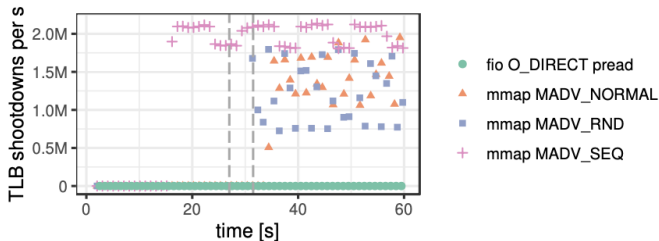
(a) Bandwidth

- Random access pattern over a 2 TB SSD range to simulate a larger-than-memory OLTP workload.
- The page cache had only 100 GB of memory, 95% of all accesses resulted in page faults
- fio baseline exhibited stable performance and achieved close to 900K reads per second

13. mmapbenchmark



Random Reads on TLB Shutdown



(b) TLB Shutdowns

- we measured using `/proc/interrupt`



Sequential Scan on Bandwidth

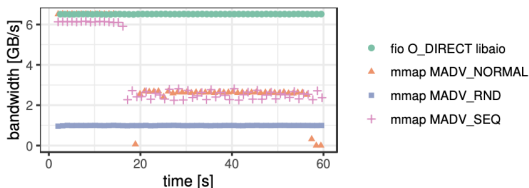


Figure 3: Sequential Scan – 1 SSD (mmap: 20 threads; fio: libaio, 1 thread, iodepth 256)

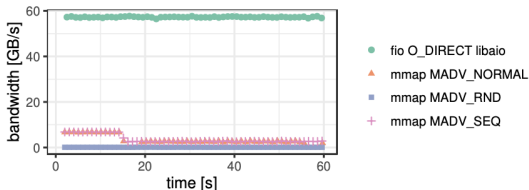


Figure 4: Sequential Scan – 10 SSDs (mmap: 20 threads; fio: libaio, 4 threads, iodepth 256)

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 - ✓ Otherwise, never.

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Unfair Comparision



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- The problem exists, but the reasons and experiments are not sufficient.
- There are also many problems with buffer pool management.
- DBs have better knowledge of workloads and access pattern than OS. But the OS knows more knowledges for the processes. **The DB is not the only process running on the machine especially the cloud environment.**

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Welcome for any questions !



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