

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

MMAP = 😊

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Greenplum, VMware, Inc.

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- 1 Background
- 2 Problem with MMAP: The Four Deadly Sins
- 3 Experimental Analysis
- 4 Conclusions
- 5 References
- 6 Acknowledgements and Questions

Outline

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[Andrew Crotty](#)

Carnegie Mellon University

[Viktor Leis](#)

Friedrich-Alexander-Universität

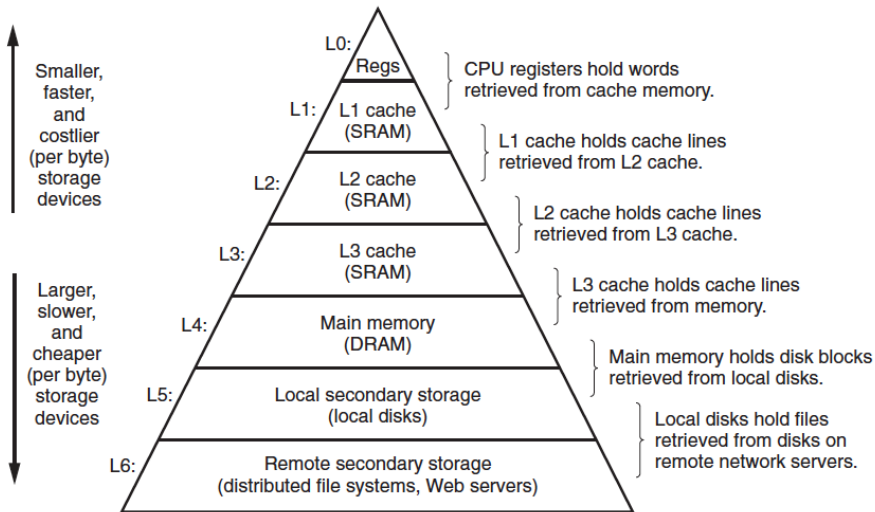
[Andy Pavlo](#)

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.**



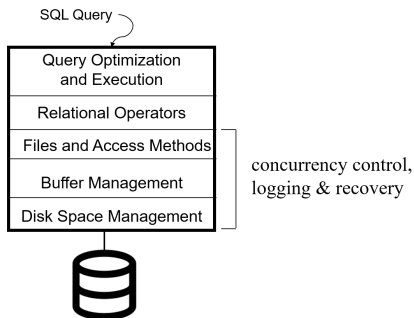
Storage hierarchy, Cont.



Architecture of RDBMS, Cont.



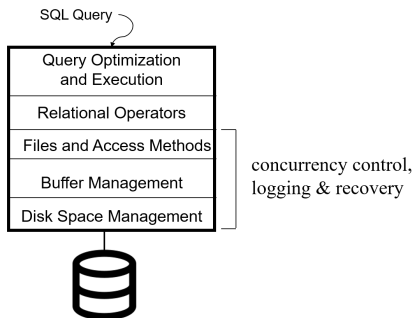
- Query optimization and execution
- Relational operators
- Files and access methods
- Buffer pool management
- Disk space management





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.



- **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.**



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 - ✓ Provides durability without REDO logging.
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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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 - ✓ 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).

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

Buffer Pool Replace Policy, Cont.



- 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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- What if system crashes before a modified page written by a committed transaction makes it to DB disk?
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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).



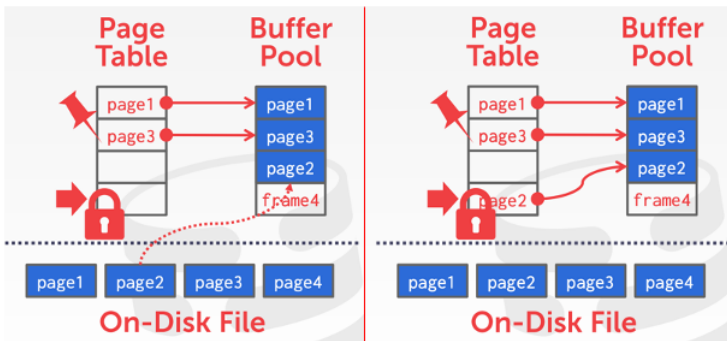
Buffer Pool Management, Cont.

	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. ¹GREENPLUM
DATABASE®¹CMU 15-445/645 Fall 2021 Buffer Pool Slide

MMAP as Buffer Pool, Cont. ²

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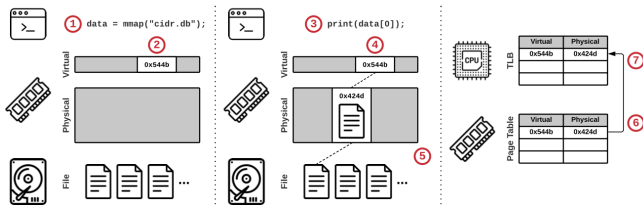
- Memory-mapped (mmap) file I/O is an OS-provided feature.
 - ✓ It maps **the contents of a file** on secondary storage into a **program's virtual address space**.

²Ethanzjp MMAP Gendata Demo



MMAP as Buffer Pool, Cont. ²

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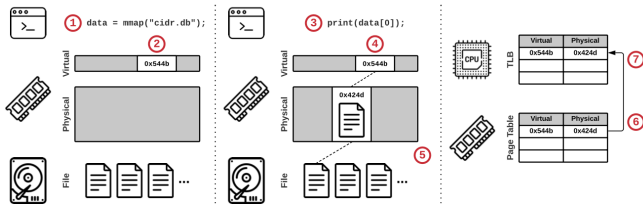


Step-by-step illustration of how a program accesses a file using mmap.



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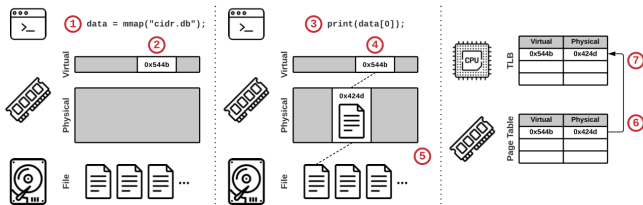


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 - ✓ The program then accesses pages via **pointers** as if the file resided entirely in memory.
 - ✓ The OS **transparently loads pages** only when the program references them.
 - ✓ The OS **automatically evicts pages** if memory fills up.

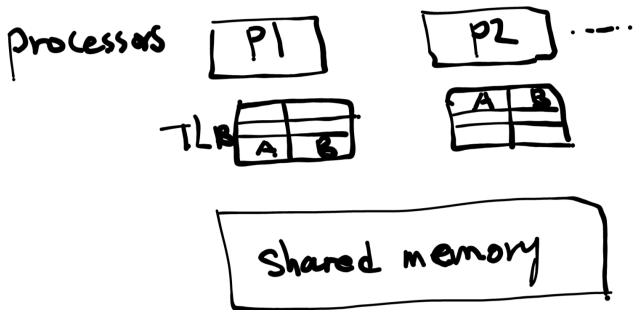


Step-by-step illustration of how a program accesses a file using mmap.

TLB shutdown



- Shared Memory Model³



³Ethanzjp Shared Memory Demo

Comparison 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 opinion ⁴

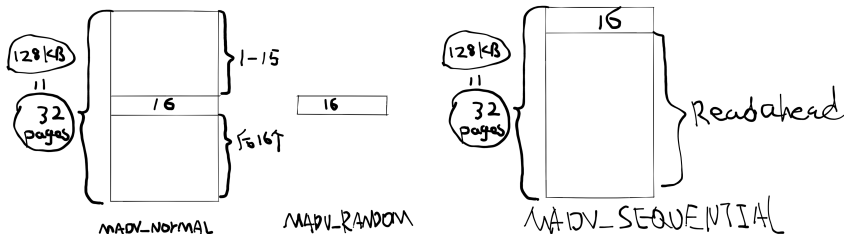
However, many DBMSs including INGRES [20] and System R [4] choose to put a DBMS managed buffer pool in user space to reduce overhead. Hence, each of these systems has gone to the trouble of constructing its own buffer pool manager to enhance performance.

⁴1981 Stonebraker's Paper



POSIX API, Cont.

- mmap⁵
- madvise hints to the OS about expected data access patterns⁶



- mlock⁷ 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.
- msync⁸ explicitly flushes the specified memory range to secondary storage.

⁵mmap man7 page

⁶madvise man7 page

⁷mlock man7 page

⁸msync man7 page

Modern MMAP-based DBMS

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

⁹LevelDB Snapshot Demo

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- MonetDB use WiredTiger and MMAPv1 (optional) as storage engine.
- 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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- SingleStore removed mmap-based file I/O after encountering poor performance on simple sequential scan queries.
- RocksDB replace mmap as a fork of LevelDB ⁹.

⁹LevelDB 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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Transactional Safety

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 - * Due to transparent paging, **the OS can flush a dirty page** 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.
- Three categories for handling updates:
 - * OS CoW

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 - * User space CoW

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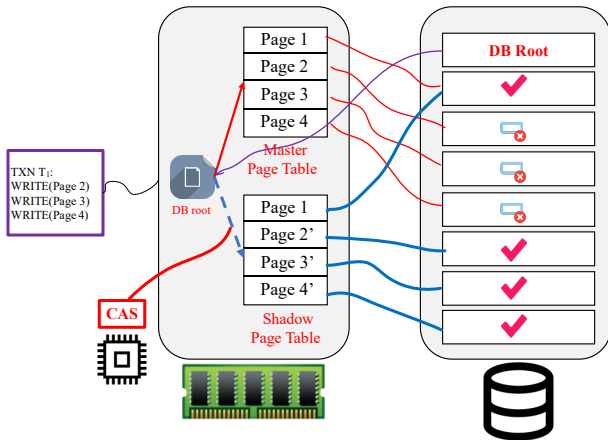
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 - * Shadow Paging



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

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- page-level checksums
- gracefully handling I/O errors

Performance Issues

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- page table contention
- single-threaded page eviction and for larger-than- memory DBMS workloads on high-bandwidth secondary storage devices.
- TLB shootdowns.

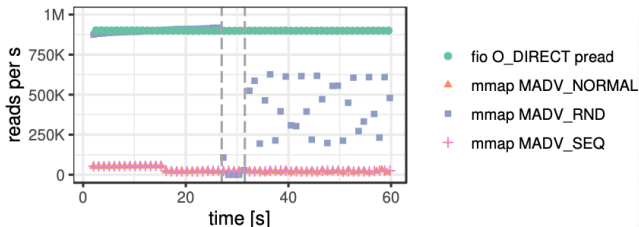
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Random Reads on Bandwidth¹⁰



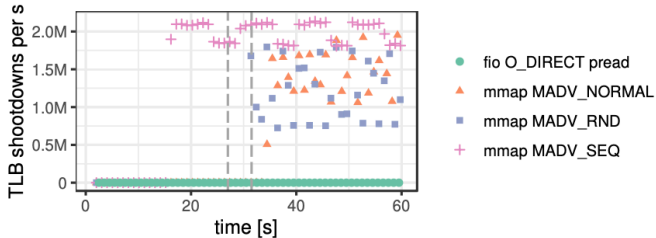
(a) Bandwidth

- 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

¹⁰mmapbenchmark



Random Reads on TLB Shutdown



(b) TLB Shootdowns

- we measured using `/proc/interrupt`



Sequential Scan on Bandwidth

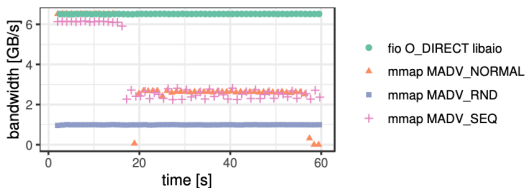


Figure 3: Sequential Scan – 1 SSD (mmap: 20 threads; fio: libaio, 1 thread, iodepth 256)

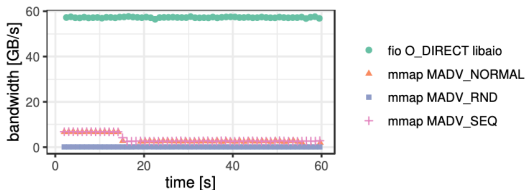


Figure 4: Sequential Scan – 10 SSDs (mmap: 20 threads; fio: libaio, 4 threads, iodepth 256)

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 - ✓ You need to rush a product to the market and do not care about data consistency or long-term engineering headaches.
 - ✓ Otherwise, never.

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Welcome for any questions!



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